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#### Multiplicity (_M) Parameter

- 4-1

### 5 Devices and Models, MOS

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<tr>
<td>BSIM3SOI_Model</td>
<td>5-23</td>
</tr>
<tr>
<td>BSIM3 Silicon On Insulator Transistor, Floating Body (NMOS and PMOS)</td>
<td>5-36</td>
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<td>BSIM3 Silicon On Insulator Transistor with 5th Terminal, External Body Contact (NMOS and PMOS)</td>
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<td>EE_MOS1_Model (EEsof Nonlinear MOSFET Model)</td>
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</tr>
<tr>
<td>HP_MOS (HP_Root MOS Transistor)</td>
<td>5-55</td>
</tr>
<tr>
<td>HP_MOS_Model (HP_Root MOS Transistor Model)</td>
<td>5-56</td>
</tr>
<tr>
<td>LEVEL1_Model (MOSFET Level-1 Model)</td>
<td>5-57</td>
</tr>
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<td>LEVEL2_Model (MOSFET Level-2 Model)</td>
<td>5-64</td>
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<td>LEVEL3_MOD_Model (LEVEL 3 NMOD MOSFET Model)</td>
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Chapter 1: Devices and Models, Diode

Bin Model

The BinModel in the Diodes library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

For information on the use of the binning feature, refer to the section “Bin Model (Bin Model for Automatic Model Selection.” This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section “Multiplicity.” This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.
Diode (PN-Junction Diode)

Symbol

Parameters

Model = name of a Diode Model

Area = scaling factor that scales certain parameter values of the Diode Model (default 1)

Periph = scaling factor that affects the sidewall parameters of the Diode Model (default=0)

Width = Geometric width of diode junction (meters, default = 0)

Length = Geometric length of diode junction (meters, default = 1)

Region = state of the diode: off, on (default: on) that the DC simulator will use as its initial guess. Its sole purpose is to give the DC simulator a good initial guess to enhance its convergence properties.

Temp = device operating temperature, in °C (default: 25)

Mode = simulation mode for this device: nonlinear, linear (default: nonlinear) (refer to Note 2)

Noise = noise generation (yes = 1; default) (no =0)

_M = number of devices in parallel (default: 1)

Range of Usage

Area > 0

Periph ≥ 0

Width =0

Length = 0

Notes/Equations/References

The size of the diode may be specified geometrically using the Width and Length parameters if the Area and Periph parameters are not explicitly specified. Default values for the width and length are taken from the width and length specified in the model if they are not specified in the instance. The model
parameters Shrink and Dwl are also used. The area and periphery are calculated using the following:

\[ W' = \text{Width} \times \text{Shrink} + \text{Dwl} \]
\[ L' = \text{Length} \times \text{Shrink} + \text{Dwl} \]
\[ \text{Area} = W' \times L' \]
\[ \text{Periph} = 2 \times W' + 2 \times L' \]

1. If the width and length are not specified, then the area and periphery are taken as specified. If the area is not specified on the instance, then the default area is taken from the model if a non-zero value is specified there; otherwise the area defaults to 1. If the periphery is not specified on the instance, then the default periphery is taken from the model if a non-zero value is specified there; otherwise the periphery defaults to 0.

2. In either case, the area must be greater than zero. The periphery may be zero, in which case the sidewall components are not simulate.

3. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated Diode_Model) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to Diode_Model to see which parameter values are scaled.

4. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.

5. This device has no default artwork associated with it.

6. SPICE2: A Computer Program to Simulate Semiconductor Circuits, University of California, Berkeley.

Diode.Model (PN-Junction Diode Model)

Symbol

Parameters

Model parameters must be specified in SI units.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>Model level selector (1=standard, 3=geometry)</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Is\†, ††</td>
<td>saturation current (with N, determines diode dc characteristics)</td>
<td>A</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>Rs\†</td>
<td>ohmic resistance</td>
<td>ohm</td>
<td>0.0</td>
</tr>
<tr>
<td>N</td>
<td>emission coefficient (with Is, determines diode dc characteristics)</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Tt</td>
<td>transit time</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Cjo\†, ††</td>
<td>zero-bias junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Vj††</td>
<td>junction potential</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>M</td>
<td>grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Fc</td>
<td>forward-bias depletion capacitance coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Imax</td>
<td>explosion current beyond which diode junction current is linearized</td>
<td>A</td>
<td>1.0</td>
</tr>
<tr>
<td>Isr\†, ††</td>
<td>recombination current parameter</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>Nr</td>
<td>emission coefficient for Isr</td>
<td></td>
<td>2.0</td>
</tr>
</tbody>
</table>

\† Parameter value is scaled with Area specified with the Diode device.
\†† Value varies with temperature based on model Tnom and device Temp.
\††† Sbd = Schottky Barrier Diode.
\‡ jn=PN junction diode.
\‡‡ Value 0.0 is interpreted as infinity.
* Parameter value is scaled with the Periph specified with the Diode device.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{kf}$†</td>
<td>high-injection knee current</td>
<td>A</td>
<td>infinity‡‡</td>
</tr>
<tr>
<td>$I_{kr}$†</td>
<td>Reverse high injection knee current</td>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>$I_{kModel}$</td>
<td>Model to use for $I_{kf}/I_{kr}$: 1=ADS/Libra/Pspice, 2=Hspice</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$X_{ti}$</td>
<td>saturation-current temperature exponent</td>
<td></td>
<td>3.0 $j_n$ ‡</td>
</tr>
<tr>
<td></td>
<td>(with $E_g$, helps define the dependence of $I_S$ on temperature)</td>
<td></td>
<td>2.0 Sbd</td>
</tr>
<tr>
<td>$B_v$</td>
<td>reverse breakdown voltage</td>
<td>V</td>
<td>infinity‡‡</td>
</tr>
<tr>
<td>$I_{bv}$†</td>
<td>current at reverse breakdown voltage</td>
<td>A</td>
<td>0.001</td>
</tr>
<tr>
<td>$N_{bv}$</td>
<td>reverse breakdown ideality factor</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>$I_{bvl}$†</td>
<td>low-level reverse breakdown knee current</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>$N_{bvl}$</td>
<td>low-level reverse breakdown ideality factor</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>$K_f$</td>
<td>flicker noise coefficient</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>$A_f$</td>
<td>flicker noise exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>$F_{fe}$</td>
<td>flicker noise frequency exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>$J_{sw}^*$††</td>
<td>sidewall saturation current</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>$C_{jsw}^*$††</td>
<td>sidewall zero-bias capacitance</td>
<td>F</td>
<td>0.9</td>
</tr>
<tr>
<td>$M_{sw}$</td>
<td>sidewall grating coefficient</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>$V_{jsw}^*$††</td>
<td>sidewall junction potential</td>
<td>V</td>
<td>$V_j$</td>
</tr>
<tr>
<td>$F_{csw}$</td>
<td>sidewall forward-bias depletion capacitance</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>$Area$</td>
<td>Default area for diode</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>$Periph$</td>
<td>Default periphery for diode</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

† Parameter value is scaled with Area specified with the Diode device.
‡‡ Value varies with temperature based on model Tnom and device Temp.
††† $Sbd =$ Schottky Barrier Diode.
‡ $j_n$=PN junction diode.
‡‡ Value 0.0 is interpreted as infinity.
* Parameter value is scaled with the Periph specified with the Diode device/
Table 1-1. Diode_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>Default width for diode</td>
<td>m</td>
<td>0</td>
</tr>
<tr>
<td>Length</td>
<td>Default length for diode</td>
<td>m</td>
<td>0</td>
</tr>
<tr>
<td>Dwl</td>
<td>Geometry width and length addition</td>
<td>m</td>
<td>0</td>
</tr>
<tr>
<td>Shrink</td>
<td>Geometry shrink factor</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Tnom</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tlev</td>
<td>Temperature equation selector (0/1/2)</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Tlevc</td>
<td>Temperature equation selector for capacitance (0/1/2/3)</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Xti</td>
<td>saturation-current temperature exponent (with Eg, helps</td>
<td></td>
<td>3.0 jn</td>
</tr>
<tr>
<td></td>
<td>define the dependence of Is on temperature)</td>
<td></td>
<td>‡</td>
</tr>
<tr>
<td>Eg</td>
<td>energy gap (with Xti, helps define the dependence of Is</td>
<td>eV</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>on temperature)</td>
<td></td>
<td>0.69 Sbd</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.67 Ge</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.43 GaAs</td>
</tr>
<tr>
<td>EgAlpha</td>
<td>Energy gap temperature coefficient alpha</td>
<td>eV/°C</td>
<td>7.02e-4</td>
</tr>
<tr>
<td>EgBeta</td>
<td>Energy gap temperature coefficient beta</td>
<td>K</td>
<td>1108</td>
</tr>
<tr>
<td>Tcjo</td>
<td>Cj linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Tcjsw</td>
<td>Cjsw linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Ttt1</td>
<td>Tt linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Ttt2</td>
<td>Tt quadratic temperature coefficient</td>
<td>1/(°C)^2</td>
<td>0</td>
</tr>
<tr>
<td>Tm1</td>
<td>Mj linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Tm2</td>
<td>Mj quadratic temperature coefficient</td>
<td>1/(°C)^2</td>
<td>0</td>
</tr>
</tbody>
</table>

† Parameter value is scaled with Area specified with the Diode device.
‡ Value varies with temperature based on model Tnom and device Temp.
+++ Sbd = Schottky Barrier Diode.
‡‡ jn=PN junction diode.
†† Value 0.0 is interpreted as infinity.
* Parameter value is scaled with the Periph specified with the Diode device.
Table 1-1. Diode_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{vj}$</td>
<td>$V_j$ linear temperature coefficient</td>
<td>$1^\circ C$</td>
<td>0</td>
</tr>
<tr>
<td>$T_{vjsw}$</td>
<td>$V_{jsw}$ linear temperature coefficient</td>
<td>$1^\circ C$</td>
<td>0</td>
</tr>
<tr>
<td>$T_{rs}$</td>
<td>$R_s$ linear temperature coefficient</td>
<td>$1^\circ C$</td>
<td>0</td>
</tr>
<tr>
<td>$T_{bv}$</td>
<td>$B_v$ linear temperature coefficient</td>
<td>$1^\circ C$</td>
<td>0</td>
</tr>
<tr>
<td>$w_{Bv}$</td>
<td>reverse breakdown voltage (warning)</td>
<td>W</td>
<td>0.0</td>
</tr>
<tr>
<td>$w_{Pmax}$</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td>0.0</td>
</tr>
<tr>
<td>AllParams</td>
<td>name of DataAccessComponent for file-based parameter values</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value is scaled with Area specified with the Diode device.
‡ Value varies with temperature based on model $T_{nom}$ and device $T_{temp}$.
§ $Sbd =$ Schottky Barrier Diode.
‡‡ Value 0.0 is interpreted as infinity.
* Parameter value is scaled with the Periph specified with the Diode device.
Notes/Equations/References

1. This model supplies values for a Diode device.
2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams.

3. Temperature Effects

Parameters $E_g$, $I_s$, $I_{sr}$, $C_{jo}$, and $V_j$ are temperature dependent.

**Note**

Expressions for temperature dependence of energy gap and intrinsic carrier concentration are for silicon only. Depletion capacitances for non-silicon diodes may not scale properly with temperature even if values of $E_g$ and $X_t$ are altered as noted in the parameters Table 1-1.

For more information on Diode_Model, its parameters and equations, see [1].
Parameters $E_g$, $I_s$, $I_{sr}$, $V_j$, $J_{sw}$, $C_{jsw}$ and $V_{jsw}$ are temperature-dependent.

4. Temperature Scaling

The model specifies $T_{nom}$, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than $T_{nom}$, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation currents $I_s$, $I_{sr}$, and $J_{sw}$ scale as:

\[
I_s^{\text{NEW}} = I_s \times \exp\left(\frac{T_{\text{temp}}}{T_{\text{nom}}} - 1\right) \frac{q \times E_g}{k \times N \times T_{\text{temp}}} \times \frac{X_t}{N} \times \ln\left(\frac{T_{\text{temp}}}{T_{\text{nom}}}\right) \]

\[
I_{sr}^{\text{NEW}} = I_{sr} \times \exp\left(\frac{T_{\text{temp}}}{T_{\text{nom}}} - 1\right) \frac{q \times E_g}{k \times N_r \times T_{\text{temp}}} + \frac{X_t}{N_r} \times \ln\left(\frac{T_{\text{temp}}}{T_{\text{nom}}}\right) \]

\[
J_{sw}^{\text{NEW}} = J_{sw} \times \exp\left(\frac{T_{\text{temp}}}{T_{\text{nom}}} - 1\right) \frac{q \times E_g}{k \times N \times T_{\text{temp}}} + \frac{X_t}{N} \times \ln\left(\frac{T_{\text{temp}}}{T_{\text{nom}}}\right) \]

The junction depletion capacitances $C_{jo}$ and $C_{jsw}$ vary as:
\[ C_{jo^{NEW}} = C_{jo} \frac{1 + M \left[ 4 \times 10^{-4} (Temp - T_{REF}) - \gamma_{Temp} \right]}{1 + M \left[ 4 \times 10^{-4} (T_{nom} - T_{REF}) - \gamma_{Temp} \right]} \]

\[ C_{jsw^{NEW}} = C_{jsw} \frac{1 + M \left[ 4 \times 10^{-4} (Temp - T_{REF}) - \gamma_{Temp} \right]}{1 + M \left[ 4 \times 10^{-4} (T_{nom} - T_{REF}) - \gamma_{Temp} \right]} \]

where \( \gamma \) is a function of the junction potential and the energy gap variation with temperature.

The junction potential \( V_J \) and \( V_{jsw} \) vary as:

\[ V_{j^{NEW}}^{NEW} = \frac{Temp}{T_{nom}} \times V_j + \frac{2k \times Temp}{q} \left( \frac{n_{i}^{T_{nom}}}{n_{i}^{Temp}} \right) \]

\[ V_{jsw^{NEW}}^{NEW} = \frac{Temp}{T_{nom}} \times V_{jsw} + \frac{2k \times Temp}{q} \left( \frac{n_{i}^{T_{nom}}}{n_{i}^{Temp}} \right) \]

where \( n_i \) is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

**Noise Model**

Thermal noise generated by resistor \( R_s \) is characterized by the following spectral density:

\[ \frac{<i^2>}{\Delta f} = \frac{4kT}{R} \]

Shot noise and flicker noise (\( K_f, A_f, F_{fe} \)) generated by the dc current flow through the diode is characterized by the following spectral density:

\[ \frac{<i_d^2>}{\Delta f} = 2q|I_D| + \frac{k_f}{f_f} \]

In the preceding expressions, \( k \) is Boltzmann's constant, \( T \) is the operating temperature in Kelvin, \( q \) is the electron charge, \( k_f, a_f, \) and \( f_{fe} \) are model parameters, \( f \) is the simulation frequency, and \( \Delta f \) is the noise bandwidth.
5. The sidewall model parameters model a second ideal diode that scales with the instance parameter Periph, in parallel with the main diode that scales with the instance parameter Area. The series resistance Rs scales only with Area, not with Periph.

6. To model a Zener diode, the model parameters Bv and Ibv can be used. Bv should be set to the Zener reverse breakdown voltage as a positive number. Ibv is set to the breakdown current that flows at that voltage as a positive number; typically this is in the range of 1 to 10 mA. The series resistance Rs should also be set; a typical value is 1 Ohm.

References:


Equivalent Circuit

![Equivalent Circuit Diagram]
**HPDiode (HP_Root Diode)**

**Symbol**

![Symbol Diagram]

**Parameters**
- **Model** = name of model instance
- **Area** = junction (default: 1.0)
- **_M** = number of devices in parallel (default: 1)

**Range of Usage**
- **Area** > 0
**HP_Diode_Model (HP_Root Diode Model)**

**Symbol**

```
\[\text{Symbol}\]
```

**Parameters**

- File = name of rawfile
- Rs = series resistance (default: 0)
- Ls = parasitic inductance (default: 0)
- Tt = transit time, in seconds (default: 0.0)
- All Params = DataAccessComponent-based parameters

**Range of Usage**

N/A

**Notes/Equations/References**

1. This model supplies values for an HPDiode device.
2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.
3. Because this model is measurement-based, extrapolation warning messages may occur if the Newton iteration exceeds the measurement range. If these messages occur frequently, check that the measurement data is within the simulation range.
4. For more information refer to:
D. E. Root, M. Pirola, S. Fan, W. J. Anklam, and A. Cognata,
“Measurement-based large-signal diode modeling system for circuit and device
1993.

D. E. Root and B. Hughes, “Principles of nonlinear active device modeling for

D. E. Root, S. Fan, and J. Meyer, “Technology-independent large-signal non
quasi static FET models by direct extraction from automatically characterized
device data,” in 21st European Microwave Conf. Proc., Stuttgart, Germany,

D. E. Root and S. Fan, “Experimental evaluation of large-signal modeling
assumptions based on vector analysis of bias-dependent S-parameters data
from MESFET's and HEMT's,” in IEEE MTT-S Int. Microwave Symp. Tech.
Dig., 1992, pp. 927-932.
JUNCAP (Philips JUNCAP Device)

Symbol

Parameters

Model = name of a JUNCAP device

Ab = Diffusion area, m^2 (default: 1.0e-12)

Ls = Length of sidewall of the diffusion area that is not under the gate, m. (default = 1.0e-6)

Lg = Length of sidewall of the diffusion area that is under the gate, m. (default = 1.0e-6)

Region = DC operating region; 0 = on, 2 = rev, 3 = sat (default = on)

Temp = Device operating temperature (default = 25)

Mode = simulation mode: linear, nonlinear, standard (default = nonlinear)

Noise = noise generation; yes, no, standard. (default = yes)

_M = number of devices in parallel (default = 1)

Notes/Equations/References

1. Additional information is available from the following website:
   http://www.semiconductors.com/Philips_Models/documentation/add_models/
Juncap_MODEL (Philips JUNCAP Model)

Symbol

Parameters

Tr = Temperature at which the parameters for the reference transistor have been determined, in Celsius (default: 25)

Vr = Voltage at which parameters have been determined (default: 0.0)

Jsgr = Bottom saturation-current density due to electron-hole generation at V = Vr. A/m^2 (default: 1.0e-3)

Jsdbr = Bottom saturation-current density due to diffusion from back contact. A/m^2 (default: 1.0e-3)

Jssr = Sidewall saturation-current density due to electron-hole generation at V = Vr. A/m (default: 1.0e-3)

Jsdsr = Sidewall saturation-current density due to diffusion from back contact. A/m (default: 1.0e-3)

Jsggr = Gate-edge saturation-current density due to due to electron-hole generation at V = Vr. A/m^2 (default: 1.0e-3)

Jsdgr = Gate-edge saturation-current density due to diffusion from back contact. A/m (default: 1.0e-3)

Cjbr = Bottom-junction capacitance at V = Vr. F/m^2 (default = 1.0e-12)

Cjsr = Sidewall-junction capacitance at V = Vr. F/m (default = 1.0e-12)

Cjgr = Gate-edge junction capacitance at V = Vr. F/m (default = 1.0e-12)

Vdbr = Diffusion voltage of the bottom junction at T = Tr (default = 1.0)

Vdsr = Diffusion voltage of the sidewall junction at T = Tr (default = 1.0)

Vdgr = Diffusion voltage of the gate-edge junction at T = Tr (default = 1.0)

Pb = Bottom-junction grading coefficient (default: 0.4)

Ps = Sidewall-junction grading coefficient (default: 0.4)

Pg = Gate-edge-junction grading coefficient (default: 0.4)
Devices and Models, Diode

\[ \text{Nb} = \text{Emission coefficient of the bottom forward current (default: 1.0)} \]
\[ \text{Ns} = \text{Emission coefficient of the sidewall forward current (default: 1.0)} \]
\[ \text{Ng} = \text{Emission coefficient of the gate-edge forward current (default: 1.0)} \]
\[ \text{All Params} = \text{DataAccessComponent-based parameters} \]

**Notes/Equations/References**

1. Additional information is available from the following website:
   http://www.semiconductors.com/Philips_Models/documentation/add_models/

2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.
PinDiode (PIN Diode)

Symbol

Parameters
Model = name of a PinDiode Model
Area = junction area (default: 1)
Region = state of the diode: off, on (default: on) that the DC simulator will use as its initial guess. Its sole purpose is to give the DC simulator a good initial guess to enhance its convergence properties.
Temp = default operating temperature, in °C (default: 25)
Mode = simulation mode for this device: nonlinear, linear (default: nonlinear) (refer to Note 2)
_M = number of devices in parallel (default: 1)

Range of Usage
Area > 0

Notes/Equations/References
1. The Temp parameter is only used to calculate the noise performance of this device. Temperature scaling of model parameters is not performed for this device.

2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.

3. This device has no default artwork associated with it.
PinDiodeModel (PIN Diode Model)

Symbol

![Pin Diode Model Symbol]

Parameters

Model parameters must be specified in SI units.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iₜ†</td>
<td>saturation current</td>
<td>A</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Vᵢ</td>
<td>I-region forward bias voltage drop</td>
<td>V</td>
<td>0</td>
</tr>
<tr>
<td>Uₑ</td>
<td>electron mobility</td>
<td>cm²/(V×S)</td>
<td>900</td>
</tr>
<tr>
<td>Wᵢ</td>
<td>I-region width</td>
<td>m</td>
<td>10⁻⁶</td>
</tr>
<tr>
<td>Rᵣ†</td>
<td>I-region reverse bias resistance</td>
<td>ohm</td>
<td>0</td>
</tr>
<tr>
<td>Cᵣmin†</td>
<td>P-I-N punchthrough capacitance</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>τₐ</td>
<td>ambipolar lifetime within I region</td>
<td>sec</td>
<td>10⁻⁷</td>
</tr>
<tr>
<td>Rₛ†</td>
<td>ohmic resistance</td>
<td>ohm</td>
<td>0</td>
</tr>
<tr>
<td>Cᵣjo†</td>
<td>zero-bias junction capacitance</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>Vⱼ</td>
<td>junction potential</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>M</td>
<td>grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Fₖ</td>
<td>coefficient for forward-bias depletion capacitance</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Iₘₜ</td>
<td>explosion current</td>
<td>A/m²</td>
<td>1</td>
</tr>
<tr>
<td>Kₙ</td>
<td>flicker-noise coefficient</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Aₙ</td>
<td>flicker-noise exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Fₙfe</td>
<td>flicker noise frequency exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>wBᵥ</td>
<td>diode reverse breakdown voltage (warning)</td>
<td>V</td>
<td>0.0</td>
</tr>
</tbody>
</table>

† Parameter value is scaled by Area specified with the PinDiode device.
1. This model supplies values for a PinDiode device.

2. PinDiodeModel is based on its high-frequency characteristics. The following assumptions have been made in this model derivation and, therefore, its usefulness.
   • You must first bias the PIN diode in either forward or reverse condition and determine its characteristic.
   • Periods of all time-variant signals applied to the circuit in transient analysis are much shorter than the ambipolar lifetime in the I-region.
   • In reverse bias, the I-region is punchthrough.

3. Limitations of PinDiodeModel:
   • After dc condition of the diode model has been determined, the PIN diode characteristics are fixed. The model will not respond correctly with subsequent changing in dc condition of the diode during transient analysis.
   • Periods of all time variant signals applied to the circuit in transient analysis must be shorter compared to the ambipolar lifetime in the I-region; otherwise, a regular diode should be used.
   • The model does not vary with temperature.

4. The equation for $V_i$, the I-region forward bias voltage drop is:
   • $R=R_i, \ C=\text{depletion capacitance if forward bias}$
   • $R=R_r, \ C=C_{\text{min}}$ if reverse bias
   where
   $R_i=V_i/I_{dc}$

5. $I_{dc}$ is the DC current through the pin diode in DC analysis. It replaces $R$ with a DC voltage source with $V_i$ volt.

Table 1-2. PinDiodeModel Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>$wP_{max}$</td>
<td>maximum power dissipation warning</td>
<td>W</td>
<td>0.0</td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent-based parameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value is scaled by Area specified with the PinDiode device.
6. If \( V_i \) is not specified or equal to zero,

\[
V_i = \frac{3}{4} \frac{W_i^2}{U_n \cdot 10^{-3} \cdot \text{Tau}}
\]

(1-1)

7. Depletion capacitance:

\[
V_c < F_c \cdot V_j \]

(1-2)

\[
C = \text{Cjo} \cdot \left(1 - \frac{V_c}{V_j}\right)^M
\]

(1-3)

If \( V_c \geq F_c \cdot V_j \)

\[
C = \text{Cjo} \cdot \left(1 - \frac{F_c (1 + M) + M}{(1 - F_c (1 + M))} \frac{V_c}{V_j}\right)
\]

(1-4)

8. Noise Model. Thermal noise generated by resistor \( R_s \) is characterized by the spectral density:

\[
\frac{<i^2>}{\Delta f} = \frac{4kT}{R}
\]

Shot noise and flicker noise (\( K_f, A_f, F_{fe} \)) generated by dc current flow through the diode is characterized by the spectral density:

\[
\frac{<i_{ds}^2>}{\Delta f} = 2q|I_D| \cdot \frac{k_f}{f_{fe}} + \frac{a_f}{f_{fe}}
\]

In the preceding expressions, \( k \) is Boltzmann's constant, \( T \) is the operating temperature in Kelvin, \( q \) is the electron charge, \( k_f, a_f, \) and \( f_{fe} \) are model parameters, \( f \) is the simulation frequency, and \( \Delta f \) is the noise bandwidth.

9. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.


Equivalent Circuit

\[ \begin{array}{c}
1 & \text{Rs} & R & \text{Vc} & 2 \\
\hline
\text{Idc} & \end{array} \]
Devices and Models, Diode
Chapter 2: Devices and Models, BJT

Bin Model

The BinModel in the BJT library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

For information on the use of the binning feature, refer to the section “Bin Model (Bin Model for Automatic Model Selection).” This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section “Multiplicity.” This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.
BJT Model (Bipolar Transistor Model)

**Symbol**

![BJT Symbol]

**Parameters**

Model parameters must be specified in SI units:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPN</td>
<td>NPN bipolar transistor</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>PNP</td>
<td>PNP bipolar transistor</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Is</td>
<td>saturation current</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Bf</td>
<td>forward beta</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Nf</td>
<td>forward emission coefficient</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Vaf</td>
<td>forward early voltage</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Ifkf</td>
<td>High current corner for forward beta</td>
<td>A</td>
<td>infinity†††</td>
</tr>
<tr>
<td>Ise</td>
<td>base-emitter leakage saturation current</td>
<td>A</td>
<td>1.5</td>
</tr>
<tr>
<td>Ne</td>
<td>base-emitter leakage emission coefficient</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Br†</td>
<td>reverse beta</td>
<td></td>
<td>1.0††</td>
</tr>
<tr>
<td>Nr</td>
<td>reverse emission coefficient</td>
<td></td>
<td>infinity†††</td>
</tr>
<tr>
<td>Var</td>
<td>reverse early voltage</td>
<td>V</td>
<td>infinity†††</td>
</tr>
<tr>
<td>Ifkr</td>
<td>high current corner for reverse beta</td>
<td>A</td>
<td>infinity†††</td>
</tr>
<tr>
<td>Iscl††</td>
<td>base-collector leakage saturation current</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>Nc</td>
<td>base-collector leakage emission coefficient</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Rb‡</td>
<td>zero-bias base resistance (Rb may be high-current dependent)</td>
<td>ohms</td>
<td>0.0</td>
</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.
Table 2-1. BJT Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irb</td>
<td>Current for base resistance midpoint</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Rbm</td>
<td>Minimum base resistance for high currents</td>
<td>Ohms</td>
<td></td>
</tr>
<tr>
<td>Re</td>
<td>Emitter resistance</td>
<td>Ohms</td>
<td></td>
</tr>
<tr>
<td>Rc</td>
<td>Collector resistance</td>
<td>Ohms</td>
<td></td>
</tr>
<tr>
<td>Imax</td>
<td>Explosion current</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Cje† ††</td>
<td>base-emitter zero-bias depletion capacitance (Cje, Vje and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Vje†</td>
<td>base-emitter junction built-in potential (Cje, Vje and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)</td>
<td>V</td>
<td>0.75</td>
</tr>
<tr>
<td>Mje</td>
<td>base-emitter junction exponential factor (Cje, Vje and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Cjc† ††</td>
<td>base-collector zero-bias depletion capacitance (Cjc, Vjc and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Vjc†</td>
<td>base-collector junction built-in potential (Cjc, Vjc and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)</td>
<td>V</td>
<td>0.75</td>
</tr>
<tr>
<td>Mjc</td>
<td>base-collector junction exponential factor (Cjc, Vjc and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Xjc</td>
<td>fraction of Cjc that goes to internal base pin</td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.
Table 2-1. BJT_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cjs†, ††</td>
<td>zero-bias collector substrate (ground) capacitance (Cjs, Mjs and Vjs determine nonlinear depletion-layer capacitance for C-S junction)</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Vjs†</td>
<td>substrate junction built-in potential (Cjs, Vjs, Mjs determine nonlinear depletion-layer capacitance for C-S junction)</td>
<td>V</td>
<td>0.75</td>
</tr>
<tr>
<td>Mjs</td>
<td>substrate junction exponential factor (Cjs, Vjs, Mjs determine nonlinear depletion-layer capacitance for C-S junction)</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Fc</td>
<td>forward-bias depletion capacitance coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Tf</td>
<td>ideal forward transit time (Tr and Tf, along with the depletion-layer capacitances model base charge storage effects; Tf may be bias-dependent)</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Xtf</td>
<td>coefficient of bias-dependence for Tf</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Vtf</td>
<td>voltage dependence of Tf on base-collector voltage</td>
<td>V</td>
<td>infinity†††</td>
</tr>
<tr>
<td>Itf†††</td>
<td>high-current effect on Tf</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>Ptf</td>
<td>excess phase at frequency = 1 / (Tf × 2π)</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Tr</td>
<td>ideal reverse transit time (Tr, Tf, and depletion-layer capacitances model base charge storage effects)</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Kf</td>
<td>flicker-noise coefficient</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Af</td>
<td>flicker-noise exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Kb</td>
<td>burst noise coefficient</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Ab</td>
<td>burst noise exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Fb</td>
<td>burst noise corner frequency</td>
<td>hertz</td>
<td>1.0</td>
</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.
Table 2-1. BJT_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iss ††</td>
<td>collector-substrate P-N junction saturation current</td>
<td>A</td>
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</tr>
<tr>
<td>Ns</td>
<td>collector-substrate P-N junction emission coefficient</td>
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<tr>
<td>Nk</td>
<td>high-current roll-off coefficient</td>
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<tr>
<td>Ffe</td>
<td>flicker noise frequency exponent</td>
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<td>1.0</td>
</tr>
<tr>
<td>Lateral</td>
<td>lateral substrate geometry type</td>
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<td>no</td>
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<tr>
<td>RbModel</td>
<td>base resistance model: Spice=1, MDS=0</td>
<td></td>
<td>MDS</td>
</tr>
<tr>
<td>Approxb</td>
<td>use approximation for Qb vs early voltage</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>Tnom</td>
<td>nominal ambient temperature at which these model parameters were derived</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>Tlev</td>
<td>temperature equation selector (0/1/2/3)</td>
<td></td>
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<td>Tlevc</td>
<td>temperature equation selector for capacitance (0/1/2/3)</td>
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<td>energy gap temperature coefficient beta</td>
<td>K</td>
<td>1108</td>
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<td>1/°C</td>
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<tr>
<td>Tbf2</td>
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<td>1/(°C)^2</td>
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</tr>
<tr>
<td>Tbr1</td>
<td>Br linear temperature coefficient</td>
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</tr>
<tr>
<td>Tbr2</td>
<td>Br quadratic temperature coefficient</td>
<td>1/(°C)^2</td>
<td>0</td>
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<td>Tbc</td>
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<tr>
<td>Tcbe</td>
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</tr>
<tr>
<td>Tccs</td>
<td>Ccs linear temperature coefficient</td>
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<td>0</td>
</tr>
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<td>Tikf1</td>
<td>Ikf linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
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</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.
Table 2-1. BJT Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tikf2</td>
<td>I kf quadratic temperature coefficient</td>
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</tr>
<tr>
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<td>I kr linear temperature coefficient</td>
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</tr>
<tr>
<td>Tikr2</td>
<td>I kr quadratic temperature coefficient</td>
<td>1/(°C)^2</td>
<td>0</td>
</tr>
<tr>
<td>Tirb1</td>
<td>I rb linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Tirb2</td>
<td>I rb quadratic temperature coefficient</td>
<td>1/(°C)^2</td>
<td>0</td>
</tr>
<tr>
<td>Tis1</td>
<td>I s/Ibe/Ibc linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Tis2</td>
<td>I s/Ibe/Ibc quadratic temperature coefficient</td>
<td>1/(°C)^2</td>
<td>0</td>
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<tr>
<td>Tisc1</td>
<td>I sc linear temperature coefficient</td>
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<td>0</td>
</tr>
<tr>
<td>Tisc2</td>
<td>I sc quadratic temperature coefficient</td>
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<td>0</td>
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<td>Tise1</td>
<td>I se linear temperature coefficient</td>
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<td>Tise2</td>
<td>I se quadratic temperature coefficient</td>
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<td>Tiss2</td>
<td>I ss quadratic temperature coefficient</td>
<td>1/(°C)^2</td>
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<td>Titf1</td>
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</tr>
<tr>
<td>Titf2</td>
<td>I tf quadratic temperature coefficient</td>
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<td>Tmjc1</td>
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<td>Tmjs2</td>
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<td>Tnc1</td>
<td>N c linear temperature coefficient</td>
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</tr>
<tr>
<td>Tnc2</td>
<td>N c quadratic temperature coefficient</td>
<td>1/(°C)^2</td>
<td>0</td>
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</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
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††† A value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tne1</td>
<td>Ne linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
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<tr>
<td>Tne2</td>
<td>Ne quadratic temperature coefficient</td>
<td>1/(°C)²</td>
<td>0</td>
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<tr>
<td>Tnf1</td>
<td>Nf linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Tnf2</td>
<td>Nf quadratic temperature coefficient</td>
<td>1/(°C)²</td>
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<td>Tnr1</td>
<td>Nr linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Tnr2</td>
<td>Nr quadratic temperature coefficient</td>
<td>1/(°C)²</td>
<td>0</td>
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<tr>
<td>Tns1</td>
<td>Ns linear temperature coefficient</td>
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<td>Tns2</td>
<td>Ns quadratic temperature coefficient</td>
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<td>Trb2</td>
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<td>Trc1</td>
<td>Rc linear temperature coefficient</td>
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<td>Trc2</td>
<td>Rc quadratic temperature coefficient</td>
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<td>Tre2</td>
<td>Re quadratic temperature coefficient</td>
<td>1/(°C)²</td>
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<td>Rbm linear temperature coefficient</td>
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<td>Trm2</td>
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<td>Tf linear temperature coefficient</td>
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<tr>
<td>Ttf2</td>
<td>Tf quadratic temperature coefficient</td>
<td>1/(°C)²</td>
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<tr>
<td>Ttr1</td>
<td>Tr linear temperature coefficient</td>
<td>1/°C</td>
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<td>Ttr2</td>
<td>Tr quadratic temperature coefficient</td>
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<td>Tvaf1</td>
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<td>Vaf quadratic temperature coefficient</td>
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<td>Tvar1</td>
<td>Var linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
</tbody>
</table>

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†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.
Table 2-1. BJT_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
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<tbody>
<tr>
<td>Tvar2</td>
<td>Var quadratic temperature coefficient</td>
<td>$1/(^\circ\text{C})^2$</td>
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<tr>
<td>Tvjc</td>
<td>Vjc linear temperature coefficient</td>
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<td>Tvje</td>
<td>Vje linear temperature coefficient</td>
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</tr>
<tr>
<td>Tvjs</td>
<td>Vjs linear temperature coefficient</td>
<td>$1/^\circ\text{C}$</td>
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<tr>
<td>Xtb</td>
<td>temperature exponent for forward- and reverse-beta. Xtb partly defines dependence of base current on temp.</td>
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<tr>
<td>Xti</td>
<td>temperature exponent for saturation current</td>
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<td>wVsubfwd</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
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</tr>
<tr>
<td>wBvsub</td>
<td>substrate junction reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvbe</td>
<td>base-emitter reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvbc</td>
<td>base-collector reverse breakdown voltage (warning)</td>
<td>V</td>
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</tr>
<tr>
<td>wVbcfwd</td>
<td>base-collector forward bias (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
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<td>maximum base current (warning)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wl_cmax</td>
<td>maximum collector current (warning)</td>
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</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td></td>
</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.  
†† This parameter value scales with Area specified with the BJT or BJT4 model.  
††† A value of 0.0 is interpreted as infinity.

Notes/Equations/References

BJT_Model supplies values for BJ T devices (BJ T4 devices include a substrate terminal). Adapted from the integral charge control model of Gummel and Poon, it includes several effects at high bias levels. It reduces to the simpler Ebers-Moll model when certain parameters required for Gummel-Poon are not specified.
Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams.

The dc characteristics of a modified Gummel-Poon BJT are defined by:

- $I_s$, $B_f$, $I_{kf}$, $N_f$, $I_{se}$, and $N_e$, which determine forward-current gain characteristics.
- $I_s$, $B_r$, $I_{kr}$, $N_r$, $I_{sc}$, and $N_c$, which determine reverse-current gain characteristics.
- $V_{af}$ and $V_{ar}$, which determine output conductances for forward and reverse regions.
- $I_s$ (saturation current). $E_g$ and $X_{ti}$ partly determine temperature dependence of $I_s$.
- $X_{tb}$ determines base current temperature dependence.
- $R_b$, $R_c$, and $R_e$ are ohmic resistances. $R_b$ is current dependent.

The nonlinear depletion layer capacitances are determined by:

- $C_{je}$, $V_{je}$ and $M_{je}$ for the base-emitter junction.
- $C_{jc}$, $V_{jc}$ and $M_{jc}$ for the base-collector junction.
- $C_{js}$, $V_{js}$ and $M_{js}$ for the collector-substrate junction (if vertical BJT), or for the base-substrate junction (if lateral BJT).

The collector or base to substrate junction is modeled as a PN junction.

**Substrate Terminal**

There are five model parameters that control the modeling of the substrate junction. $C_{js}$, $V_{js}$ and $M_{js}$ model the nonlinear substrate junction capacitance. $I_{ss}$ and $N_s$ model the nonlinear substrate P-N junction current.

When the BJ T4_NPN or BJ T4_PNP devices are used, explicitly connect the substrate terminal as required. But when the three terminal BJ T_NPN or BJ T_PNP devices are used, the substrate terminal is implicitly grounded. This should not affect the simulation if the substrate model parameters $C_{js}$ and $I_{ss}$ are not specified, as they default to zero.

The model parameter Lateral changes the connection of the substrate junction. At its default setting of no, the substrate junction models a vertical bipolar transistor with the substrate junction connected to the collector. When Lateral=yes, a lateral bipolar transistor is modeled with the substrate junction connected to the base.
DC Equations

There are two components of base current associated with the bias on each junction. For the emitter junction, an ideal exponential voltage term, $I_{bei}$ arises, due to recombination in the inactive base region and carrier injected into the emitter. A non-ideal exponential voltage term, $I_{ben}$, predominates at low bias due to recombination in the emitter junction spaced charge region.

$$I_{bei} = I_s \left( \exp \left( \frac{V_{be}}{N_f \times V_T} \right) - 1 \right) \quad (2-1)$$

$$I_{ben} = I_c \left( \exp \left( \frac{V_{be}}{N_e \times V_T} \right) - 1 \right) \quad (2-2)$$

Similarly, emission and recombination near the collector junction result in similar terms.

$$I_{bci} = I_s \left( \exp \left( \frac{V_{bc}}{N_r \times V_T} \right) - 1 \right) \quad (2-3)$$

$$I_{bcn} = I_c \left( \exp \left( \frac{V_{bc}}{N_c \times V_T} \right) - 1 \right) \quad (2-4)$$

Base Terminal Current (without substrate current)

$$I_b = \frac{I_{bei}}{B_f} + I_{ben} + \frac{I_{bci}}{B_r} + I_{bcn} \quad (2-5)$$

Collector Terminal Current (without substrate current)

$$I_c = \frac{I_{bei} - I_{bci}}{Q_b} - \frac{I_{bci}}{B_r} - I_{bcn} \quad (2-6)$$

Collector-emitter current

$$I_{ce} = \frac{I_{bei} - I_{bci}}{Q_b} \quad (2-7)$$

where the normalized base charge is $Q_b$.

If Approx qb = yes
$$Q_b = \frac{1}{2 \left(1 - \frac{V_{bc}}{V_{af}} - \frac{V_{be}}{V_{ar}}\right)} \times \left(1 + \left(1 + 4 \left(\frac{I_{bei}}{I_{kf}} + \frac{I_{bc}}{I_{kr}}\right)\right)^{Nk}\right)$$  \hspace{1cm} (2-8)

If $\text{Approxqb} = \text{no}$

$$Q_b = \frac{1 + \frac{V_{bc}}{V_{af}} + \frac{V_{bc}}{V_{ar}}}{2} \times \left(1 + \left(1 + 4 \left(\frac{I_{bei}}{I_{kf}} + \frac{I_{bc}}{I_{kr}}\right)\right)^{Nk}\right)$$  \hspace{1cm} (2-9)

**Substrate Current**

Lateral $=$ no (Vertical BJT)

$$I_{sc} = I_{ss} \left(\exp\left(\frac{V_{sc}}{N_s V_T}\right) - 1\right)$$  \hspace{1cm} (2-10)

Lateral $=$ yes (Lateral BJT)

$$I_{bs} = I_{ss} \left(\exp\left(\frac{V_{bs}}{N_s V_T}\right) - 1\right)$$  \hspace{1cm} (2-11)

**Base Resistance**

The base resistance $R_{bb}$ consists of two separate resistances. The contact and sheet resistance $R_{bm}$ and the resistance of the internal (active) base register, $v_{bi}$, which is a function of the base current.

If $R_{bm}$ is zero or $IB < 0$, $R_{bb} = R_b$

If $I_{vb}$ is not specified

$$R_{bb} = R_{bm} + \frac{R_b - R_{bm}}{Q_b}$$  \hspace{1cm} (2-12)

If $I_{vb}$ is specified

$$R_{bb} = R_{bm} + v_{bi}$$  \hspace{1cm} (2-13)

There are two equations for $v_{bi}$. $R_{bModel}$ determines which equations to use.

If $R_{bModel} =$ Spice
where

\[ z = \sqrt{\frac{1 + \frac{144}{\pi^2} \times \frac{I_b}{I_{rb}} - 1}{\frac{24}{\pi^2} \sqrt{I_{rb}}}} \] (2-15)

If \( R_{b\text{Model}} = \text{MDS} \)

\[ v_{bi} = \frac{R_b - R_{bm}}{\sqrt{1 + 3 \left( \frac{I_b}{I_{rb}} \right)^{0.852}}} \] (2-16)

**Capacitance Equations**

The capacitances in the small-signal model contain the junction depletion layer capacitance and the diffusion capacitance due to the minority charge storage in the base region.

**Base-Emitter Depletion Capacitances**

\[ V_{be} < F_c \times V_{je} \] (2-17)

\[ C_{bedep} = C_{je} \left( 1 - \frac{V_{be}}{V_{je}} \right)^{M_{je}} \] (2-18)

\[ V_{be} \geq F_c \times V_{je} \] (2-19)

\[ C_{bedep} = C_{je} \left( \frac{1 - F_c (1 + M_{je}) + M_{je} \left( \frac{V_{be}}{V_{je}} \right)}{(1 - F_c)(1 + M_{je})} \right) \] (2-20)
Base-Emitter Diffusion Capacitance

\[ C_{\text{bediff}} = \frac{2Q_{\text{bediff}}}{2V_{\text{be}}} \]  

(2-21)

where the transit charge

\[ Q_{\text{bediff}} = T_f \left( 1 + x_t f \times \exp \left( \frac{V_{bc}}{1.442695V_{tf}} \right) \left( \frac{I_{\text{bei}}}{I_{\text{bei}} + I_{tf}} \right)^2 \times \frac{I_{\text{bei}}}{Q_b} \right) \]  

(2-22)

\[ C_{\text{be}} = C_{\text{bedep}} + C_{\text{bediff}} \]  

(2-23)

Base-Collector Depletion Capacitances

When \( X_{\text{jc}} \) is not equal to one, the base-collector depletion capacitance is modeled as a distributed capacitance.

The internal base-internal collector depletion capacitance

\[ V_{bc} < F_c \times V_{jc} \]  

(2-24)

\[ C_{\text{bcdep}} = X_{\text{jc}} \times C_{\text{jc}} \left( 1 - \frac{V_{bc}}{V_{jc}} \right)^{M_{jc}} \]  

(2-25)

\[ V_{bc} \geq F_c \times V_{jc} \]  

(2-26)

\[ C_{\text{bcdep}} = X_{\text{jc}} \times C_{\text{jc}} \left( \frac{1 - F_c(1 + M_{jc}) + M_{jc} \left( \frac{V_{bc}}{V_{jc}} \right)}{1 - fc(1 + M_{jc})} \right) \]  

(2-27)

The external base-internal collector depletion capacitance

\[ V_{Bc} < f_c \times V_{jc} \]  

(2-28)

\[ C_{\text{bcdep}} = (1 - X_{\text{jc}}) \times C_{\text{jc}} \left( 1 - \frac{V_{bc}}{V_{jc}} \right)^{M_{jc}} \]  

(2-29)

\[ V_{Bc} \geq F_c \times V_{jc} \]  

(2-30)
CBcdep = \( (1 - X_{jc})C_{jc} \left( 1 - \frac{F_c(1 + M_{jc}) + M_{jc} \left( \frac{V_{bc}}{V_{jc}} \right)}{(1 - F_c(1 + M_{jc}))} \right) \) (2-31)

CBc = CBcdep (2-32)

**Base-Collector Diffusion Capacitances**

\[ C_{bc\text{diff}} = \frac{2Q_{bc\text{diff}}}{2V_{bc}} \] (2-33)

where the transit charge
\[ Q_{bc\text{diff}} = Tr \times I_{bc} \] (2-34)

\[ C_{bc} = C_{bc\text{dep}} + C_{bc\text{diff}} \] (2-35)

**Base-Collector Substrate Capacitance**

Lateral = no (vertical BJT)

\[ V_{sc} < 0 \] (2-36)

\[ C_{sc} = C_{js} \left( 1 - \frac{V_{sc}}{V_{js}} \right)^{-M_{js}} \] (2-37)

\[ V_{sc} \geq 0 \] (2-38)

\[ C_{sc} = C_{js} \left( 1 + M_{js} \times \frac{V_{sc}}{V_{js}} \right) \] (2-39)

Lateral = yes (Lateral BJT)

\[ V_{bs} < 0 \] (2-40)

\[ C_{bs} = C_{js} \left( 1 - \frac{V_{bs}}{V_{js}} \right)^{-M_{js}} \] (2-41)

\[ V_{bs} \geq 0 \] (2-42)

\[ C_{bs} = C_{js} \left( 1 + M_{js} \times \frac{V_{bs}}{V_{js}} \right) \] (2-43)
Excess Phase

An additional phase shift at high frequencies is added to the frequent transconductance model to account for the distributed phenomena in the transistor. The effective phase shift added to the \( I_{bei} \) item in the \( I_c \) equation is calculated as follows for \( I_{bei} \) (with excess phase):

\[
I_{bei} = \frac{3Wo^2}{S^2 + 3Wo + 3Wo^2} \times I_{bei}
\]  \hspace{1cm} (2-44)

where

\[
Wo = \frac{1}{Ptf \times Tf \times \frac{Tc}{180}}
\]  \hspace{1cm} (2-45)

The current implementation in ADS is applying the shifting factor to the collector current \( I_C \).

Temperature Scaling

The model specifies \( T_{nom} \), the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than \( T_{nom} \), several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device Temp parameter. (Temperatures in the following equations are in Kelvin.)

Saturation currents \( I_s \), \( I_{se} \), \( I_{sc} \) and \( I_{ss} \) scale as:

\[
I_{s_{NEW}} = I_s \times \exp\left(\frac{T_{nom}}{T_{nom} - 1}\right) \frac{q \times Eg}{k \times N \times Temp} + \frac{X_{ti}}{N} \ln\left(\frac{T_{nom}}{T_{nom}}\right)
\]  \hspace{1cm} (2-46)

\[
I_{se_{NEW}} = I_{se} \times \exp\left(\frac{T_{nom}}{T_{nom} - 1}\right) \frac{q \times Eg}{k \times N \times Temp} + \frac{X_{ti}}{N_n} \ln\left(\frac{T_{nom}}{T_{nom}}\right)
\]  \hspace{1cm} (2-47)

\[
I_{sc_{NEW}} = I_{sc} \times \exp\left(\frac{T_{nom}}{T_{nom} - 1}\right) \frac{q \times Eg}{k \times N \times Temp} + \frac{X_{ti}}{N_c} \ln\left(\frac{T_{nom}}{T_{nom}}\right)
\]  \hspace{1cm} (2-48)

\[
I_{ss_{NEW}} = I_{ss} \times \exp\left(\frac{T_{nom}}{T_{nom} - 1}\right) \frac{q \times Eg}{k \times N \times Temp} + \frac{X_{ti}}{N_s} \ln\left(\frac{T_{nom}}{T_{nom}}\right)
\]  \hspace{1cm} (2-49)
Depletion capacitances $C_{je}$, $C_{jc}$ and $C_{js}$ vary as:

\[
C_{je}^{NEW} = \frac{C_{je} \left[ 1 + M_{je} \left( 4 \times 10^{-4} (Temp - T_{REF}) - \gamma^{Temp} \right) \right]}{1 + M_{je} \left( 4 \times 10^{-4} (T_{nom} - T_{REF}) - \gamma^{T_{nom}} \right)}
\]  \hspace{1cm} (2-50)

\[
C_{jc}^{NEW} = \frac{C_{jc} \left[ 1 + M_{jc} \left( 4 \times 10^{-4} (Temp - T_{REF}) - \gamma^{Temp} \right) \right]}{1 + M_{jc} \left( 4 \times 10^{-4} (T_{nom} - T_{REF}) - \gamma^{T_{nom}} \right)}
\]  \hspace{1cm} (2-51)

\[
C_{js}^{NEW} = \frac{C_{js} \left[ 1 + M_{js} \left( 4 \times 10^{-4} (Temp - T_{REF}) - \gamma^{Temp} \right) \right]}{1 + M_{js} \left( 4 \times 10^{-4} (T_{nom} - T_{REF}) - \gamma^{T_{nom}} \right)}
\]  \hspace{1cm} (2-52)

where $\gamma$ is a function of the junction potential and the energy gap variation with temperature.

Junction potentials $V_{je}$, $V_{jc}$ and $V_{js}$ vary as:

\[
V_{je}^{NEW} = \frac{Temp}{T_{nom}} \times V_{je} + \frac{2k \times Temp}{q} \ln \left( \frac{n_{i}^{T_{nom}}}{n_{i}^{Temp}} \right)
\]  \hspace{1cm} (2-53)

\[
V_{jc}^{NEW} = \frac{Temp}{T_{nom}} \times V_{jc} + \frac{2k \times Temp}{q} \ln \left( \frac{n_{i}^{T_{nom}}}{n_{i}^{Temp}} \right)
\]  \hspace{1cm} (2-54)

\[
V_{js}^{NEW} = \frac{Temp}{T_{nom}} \times V_{js} + \frac{2k \times Temp}{q} \ln \left( \frac{n_{i}^{T_{nom}}}{n_{i}^{Temp}} \right)
\]  \hspace{1cm} (2-55)

where $n_{i}$ is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

Both forward beta $B_{f}$ and reverse beta $B_{r}$ vary with temperature:
Noise Model

Thermal noise generated by resistors $R_b$, $R_c$, and $R_e$ is characterized by the spectral density:

$$<i^2> = \frac{4kT}{R}$$  \hspace{1cm} (2-58)

Shot noise, flicker noise ($K_f$, $A_f$, $F_{fe}$), and burst noise ($K_b$, $A_b$, $F_b$) generated by the dc base current is characterized by the spectral density:

$$\frac{<i^2_{be}>}{\Delta f} = 2qI_{BE} + k_f \frac{l_{BE}^{a_f}}{f_{fe}} + k_b \frac{l_{BE}^{a_b}}{1 + (f/f_b)^2}$$  \hspace{1cm} (2-59)

Shot noise generated by the dc collector-to-emitter current is characterized by the spectral density:

$$\frac{<i^2_{ce}>}{\Delta f} = 2qI_{CE}$$  \hspace{1cm} (2-60)

Shot noise generated by the dc collector-to-substrate current (BJT4 only) is characterized by the spectral density:

$$\frac{<i^2_{cs}>}{\Delta f} = 2qI_{CS}$$  \hspace{1cm} (2-61)

In the preceding expressions, $k$ is Boltzmann's constant, $T$ is the operating temperature in Kelvin, $q$ is the electron charge, $k_f$, $a_f$, $f_{fe}$, $k_b$, $a_b$, and $f_b$ are model parameters, $f$ is the simulation frequency, and $\Delta f$ is the noise bandwidth.
Area Dependence of the BJT Model Parameters

The AREA factor used for the BJT model determines the number of equivalent parallel devices of a specified model. The BJT model parameters affected by the AREA factor are:

\[ \text{ls} = \text{ls} \times \text{AREA} \]
\[ \text{lse} = \text{lse} \times \text{AREA} \]
\[ \text{lsc} = \text{lsc} \times \text{AREA} \]
\[ \text{lkf} = \text{lkf} \times \text{AREA} \]
\[ \text{lkr} = \text{lkr} \times \text{AREA} \]
\[ \text{lrb} = \text{lbr} \times \text{AREA} \]
\[ \text{ltf} = \text{ltf} \times \text{AREA} \]

\[ \text{Cjc}(0) = \text{Cjc}(0) \times \text{AREA} \]
\[ \text{Cje}(0) = \text{Cje}(0) \times \text{AREA} \]
\[ \text{Cjs}(0) = \text{Cjs}(0) \times \text{AREA} \]

\[ rB = rB/\text{AREA} \]
\[ rBM = rBM/\text{AREA} \]
\[ rE = rE/\text{AREA} \]
\[ rC = rC/\text{AREA} \]

The default value for the AREA parameter is 1.

DC Operating Point Device Information

Definitions

- \text{Ic} (collector current)
- \text{Ib} (base current)
- \text{Ie} (emitter current)
- \text{Is} (substrate current)
- \text{Ice} (collection-emitter current)
• power (dissipated power)

\[ \text{BetaDc} = \frac{Ic}{Ib} \]

where

\[ Ib = \text{sign}(ib) \times \text{Max}(\text{Abs}(ib), 10^{-20}) \quad (2-62) \]

\[ Gm = \frac{\frac{\text{d}I_{ce}}{\text{d}V_{be}}} + \frac{\text{d}I_{ce}}{\text{d}V_{bc}} \quad (2-63) \]

\[ R_{pi} = \frac{1}{\frac{\text{d}I_{bc}}{\text{d}V_{bc}}} \quad (2-64) \]

\[ R_{mu} = \frac{1}{\frac{\text{d}I_{ce}}{\text{d}V_{bc}}} \quad (2-65) \]

\[ R_x = R_{Bb} \quad (2-66) \]

\[ R_o = -\frac{1}{\frac{\text{d}I_{ce}}{\text{d}V_{bc}}} \quad (2-67) \]

\[ C_{pi} = C_{be} \quad (2-68) \]

\[ C_{mu} = C_{bc} \quad (2-69) \]

\[ C_{bx} = C_{Bx} \quad (2-70) \]

\[ C_{cs} = C_{cs} \text{ if vertical BJT} \quad (2-71) \]

\[ = C_{bs} \text{ if lateral BJT} \quad (2-72) \]

\[ \text{BetAc} = Gm \times R_{pi} \quad (2-73) \]

\[ F_t = \frac{1}{(2\pi(tau + (Rc + Re)(C_{mu} + C_{bx}))} \quad (2-74) \]

where

\[ tau = \frac{\text{Max}(C_{pi} + C_{nm} + C_{bx}, 10^{-20})}{\text{Max}(Gm, 10^{-20})} \quad (2-75) \]

\[ V_{be} = \nu(B) - \nu(E) \quad (2-76) \]
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\[ V_{bc} = v(B) - v(C) \]  \hspace{1cm} (2-77)

\[ V_{ce} = v(BC) - v(E) \]  \hspace{1cm} (2-78)

References:

BJT (Bipolar Junction Transistors)

BJT_NPN (Bipolar Junction Transistor, NPN)
BJT_PNP (Bipolar Junction Transistor, PNP)

Symbol

Parameters

Model = name of BJT_Model, EE_BJT_T2_Model, or MEXTRAM_Model
Area = factor that scales certain parameter values of the model (default: 1)
Region = dc operating region: 0 = off, 1 = on, 2 = rev, 3 = sat (default: on)
Temp = device operating temperature, in °C (default: 25)
Mode = simulation mode for this device: nonlinear, linear (default: nonlinear)
_M = number of devices in parallel (default: 1)

Range of Usage

N/A

Notes/Equations/Reference

1. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.

2. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated model) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to the associated model to see which parameter values are scaled.
3. This device has no default artwork associated with it.

4. The substrate terminal is connected to ground. The substrate current is affected by the ISS and CJ S model parameters. There should be no problems with this except perhaps in a PNP transistor where the ISS model parameter is specified. This could cause excess current flow as the substrate PN junction might end up being forward biased. If the connection of the substrate terminal to ground is not acceptable, use the BJ T4 component and connect its substrate terminal to the appropriate place.

5. For information on area dependence, refer to the section “Area Dependence of the BJ T Model Parameters” for the BJ T_Model component.


BJT4 (Bipolar Junction Transistors w/Substrate Terminals)

BJT4_NPN (Bipolar Junction Transistor w/Substrate Terminal, NPN)

BJT4_PNP (Bipolar Junction Transistor w/Substrate Terminal, PNP)

Symbol

Parameters

Model = name of BJ T_Model or MEXTRAM_Model
Area = factor that scales certain parameter values of the model (default: 1)
Region = dc operating region: 0 = off, 1 = on, 2 = rev, 3 = sat (default: on)
Temp = device operating temperature, in °C (default: 25)
Mode = simulation mode for this device: nonlinear, linear (default: nonlinear) (refer to Note 2)
_M = number of devices in parallel (default: 1)

Range of Usage

N/A

Notes/Equations/References

1. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated model) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to the model to see which parameter values are scaled.

2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in
their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.

3. The fourth terminal (substrate) is available for connection to an external circuit.

4. This device has no default artwork associated with it.


EE_BJT2_Model (EEsof Bipolar Transistor Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 2-2. EE_BJT2_Model Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>NPN or PNP</td>
<td></td>
<td>NPN</td>
</tr>
<tr>
<td>Nf</td>
<td>forward-current emission coefficient</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Ne</td>
<td>base-emitter leakage emission coefficient</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>forward base emission coefficient</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>Vaf</td>
<td>forward Early voltage</td>
<td>V</td>
<td>infinity†</td>
</tr>
<tr>
<td>Ise</td>
<td>base-emitter leakage saturation current</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>Tf</td>
<td>ideal forward transit time (Tr and Tf, along with the depletion-layer capacitances, model base charge storage effects; Tf may be bias-dependent)</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Ikf</td>
<td>corner for forward-beta high current roll-off</td>
<td>A</td>
<td>infinity†</td>
</tr>
<tr>
<td>Xtf</td>
<td>coefficient of bias-dependence for Tf</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Vtf</td>
<td>voltage dependence of Tf on base-collector voltage</td>
<td>V</td>
<td>infinity†</td>
</tr>
<tr>
<td>Itf</td>
<td>parameter for high-current effect on Tf</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>Nbr</td>
<td>reverse base emission coefficient</td>
<td></td>
<td>1.04</td>
</tr>
<tr>
<td>Nr</td>
<td>reverse-current emission coefficient</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Nc</td>
<td>base-collector leakage emission coefficient</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Isc</td>
<td>base-collector leakage saturation current</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>Ikf</td>
<td>corner for reverse-beta high-current roll-off</td>
<td>A</td>
<td>infinity†</td>
</tr>
</tbody>
</table>

† A value of 0.0 is interpreted as infinity
<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Var</td>
<td>reverse Early voltage</td>
<td>V</td>
<td>infinity†</td>
</tr>
<tr>
<td>Tr</td>
<td>ideal reverse transit time (Tr and Tf, along with the depletion-layer capacitances, model base charge storage effects)</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Isf</td>
<td>forward saturation current</td>
<td>A</td>
<td>9.53×10⁻¹⁵</td>
</tr>
<tr>
<td>Ibif</td>
<td>forward base saturation current</td>
<td>A</td>
<td>1.48×10⁻¹⁶</td>
</tr>
<tr>
<td>Isr</td>
<td>reverse saturation current</td>
<td>A</td>
<td>1.01×10⁻¹⁴</td>
</tr>
<tr>
<td>Ibir</td>
<td>reverse base saturation current</td>
<td>A</td>
<td>6.71×10⁻¹⁶</td>
</tr>
<tr>
<td>Tamb</td>
<td>ambient temperature of measurement and model parameter extraction</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>Cje</td>
<td>base-emitter zero-bias depletion capacitance (Cje, Vje, and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Vje</td>
<td>base-emitter junction built-in potential (Cje, Vje, and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)</td>
<td>V</td>
<td>0.75</td>
</tr>
<tr>
<td>Mje</td>
<td>base-emitter junction exponential factor (Cje, Vje, and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Cjc</td>
<td>base-collector zero-bias depletion capacitance (Cjc, Vjc, and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Vjc</td>
<td>base-collector junction built-in potential (Cjc, Vjc, and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)</td>
<td>V</td>
<td>0.75</td>
</tr>
<tr>
<td>Mjc</td>
<td>base-collector junction exponential factor (Cjc, Vjc, and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Rb</td>
<td>base resistance</td>
<td>ohms</td>
<td>10⁻⁴</td>
</tr>
</tbody>
</table>

† A value of 0.0 is interpreted as infinity

Table 2-2. EE_BJT T2_Model Parameters (continued)
Notes/Equations/References

1. This model specifies values for BJT_NPN or BJT_PNP devices.

2. EEBJT2 is the second generation BJT model designed by HP EEsof. The model has been created specifically for automatic parameter extraction from measured data including dc and S-parameter measurements. The goal of this model is to overcome some of the problems associated with EEBJT1 or Gummel-Poon models’ limited accuracy and parameter extraction difficulty with regard to silicon rf/microwave transistors. EEBJT2 is not generally equivalent or compatible with the Gummel-Poon or EEBJT1 models. EEBJT2 can provide a reasonably accurate reproduction of transistor behavior, including dc bias solution, bias-dependent S-parameters including the effects of package parasitics, and true nonlinear harmonic output power. The model is quasi-static, analytical, and isothermal. The model does not scale with area since parameters are intended to be extracted directly from measured data and

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>emitter resistance</td>
<td>ohms</td>
<td>10^-4</td>
</tr>
<tr>
<td>Rc</td>
<td>collector resistance</td>
<td>ohms</td>
<td>10^-4</td>
</tr>
<tr>
<td>Fc</td>
<td>forward-bias depletion capacitance coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>wVsubfwd</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvsub</td>
<td>substrate junction reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvbe</td>
<td>base-emitter reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvbc</td>
<td>base-collector reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wVbcfwd</td>
<td>base-collector forward bias (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wIbmax</td>
<td>maximum base current (warning)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wIcmax</td>
<td>maximum collector current (warning)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>AllParams</td>
<td>name of DataAccessComponent for file-based model</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† A value of 0.0 is interpreted as infinity
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not from layout considerations. Default values of some parameters are chosen from an average of the first EEBJ T2 library model parameters.

3. To prevent numerical problems, the setting of some model parameters is trapped by the simulator. The parameter values are changed internally:
   • $M_{jc}$ and $M_{je}$ must be $\leq 0.99$
   • $F_c$ must be $\leq 0.9999$
   • $R_b$, $R_c$, and $R_e$ must be $\geq 10^{-4}$

4. The Temp parameter is only used to calculate the noise performance of this device. Temperature scaling of model parameters is not performed for this device.

5. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.

6. This device has no default artwork associated with it.

Equations

Base-Emitter and Base-Collector Current

The base-emitter current in the BJT has been changed significantly from the Gummel-Poon and other earlier models. These models assume that the non-leakage base-emitter current is related to the collector-emitter current by a simple constant, known as beta. Observation of base-emitter current in both silicon and AlGaAs devices has shown that this assumption is incorrect. Difficulties with this method of modeling base current have been observed for many years. A large, very bias-dependent base resistance in the modified Gummel-Poon model in Berkeley SPICE has been used to attempt to correct the problem with the base-emitter current expressions. This base resistance value and its variation is often extracted from dc data only, with the result that the behavior of the device over frequency is often poorly modeled. This problem is then solved by assigning some fraction of the base-collector capacitance to either side of the base in a distributed manner.

HP EEsos's experience with EEBJ T2 has shown that properly modeled base-emitter current and conductance renders both the large bias-dependent base resistance and distributed base-collector capacitance unnecessary and greatly improves both the dc and ac accuracy of the resulting model.
EE_BJT2 models the base-emitter current with two non-ideal exponential expressions, one for the bulk recombination current (usually dominant in silicon devices), and one for other recombination currents (usually attributed to surface leakage).

\[
I_{be} = \left(I_{bif}\left\{\exp\left(\frac{V_{be}}{N_{bf}V_T}\right) - 1.0\right\}\right) + \left(I_{se}\left(\exp\left(\frac{V_{be}}{(N_e \times V_T)}\right) - 1.0\right)\right)
\]

where

\[
V_T = \frac{k \times T_{amb}}{q}
\]

where

\( k \) is Boltzmann's constant, and \( q \) is deviceary charge.

Note that \( N_{bf} \) is not necessarily 1.0, which is effectively the case in the Gummel-Poon model.

The base-collector current is similarly modeled:

\[
I_{bc} = \left(I_{bir}\left\{\exp\left(\frac{V_{bc}}{N_{br}V_T}\right) - 1.0\right\}\right) + \left(I_{sc}\left(\exp\left(\frac{V_{bc}}{(N_c \times V_T)}\right) - 1.0\right)\right)
\]

Virtually all silicon rf/microwave transistors are vertical planar devices, so the second current term containing \( I_{sc} \) and \( N_c \) is usually negligible.

The total base current \( I_b \) is the sum of \( I_{be} \) and \( I_{bc} \). Note that this method of modeling base current obsoletes the concept of a constant beta.

**Collector-Emitter Current**

The forward and reverse components of the collector-emitter current are modeled in a manner similar to the Gummel-Poon model, but with more flexibility. Observation of collector-emitter current behavior has shown that the forward and reverse components do not necessarily share identical saturation currents, as in the Gummel-Poon model. The basic expressions in EE_BJT2, not including high-level injection effects and Early effects, are:

\[
I_{cf} = I_{sf} \times \left(\exp\left(\frac{V_{be}}{(N_f \times V_T)}\right) - 1.0\right)
\]

\[
I_{cr} = I_{sr} \times \left(\exp\left(\frac{V_{bc}}{(N_r \times V_T)}\right) - 1.0\right)
\]
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where Isf and Isr are not exactly equal but are usually very close. Nf and Nr are not necessarily equal or 1.0, but are usually very close. Careful control of ambient temperature during device measurement is required for precise extraction of all of the saturation currents and emission coefficients in the model.

The effects of high-level injection and bias-dependent base charge storage are modeled via a normalized base charge, similar to the Gummel-Poon model:

\[
I_{ce} = \frac{(I_{cf} - I_{cr})}{Q_b}
\]

where

\[
Q_b = \left(\frac{Q_1}{2.0}\right) \times (1.0 + \sqrt{1.0 + (4.0 \times Q_2)})
\]

and

\[
Q_1 = \frac{1.0}{1.0 - \left(\frac{V_{bc}}{V_{af}} \right) - \left(\frac{V_{be}}{V_{ar}}\right)}
\]

\[
Q_2 = \left(\frac{I_{sf}}{I_{kf}}\right) \times \left(\exp\left(\frac{V_{be}}{(N_f \times V_T)}\right) - 1.0\right) + \left(\frac{I_{sf}}{I_{kf}}\right) \times \left(\exp\left(\frac{V_{bc}}{(N_r \times V_T)}\right) - 1.0\right)
\]

Note: All computations of the exponential expressions used in the model are linearized to prevent numerical overflow or underflow at large forward or reverse bias conditions, respectively.

Base-Emitter and Base-Collector Capacitances

Diffusion and depletion capacitances are modeled for both junctions of the transistor model in a manner very similar to the Gummel-Poon model.

for \(V_{bc} \leq F_c \times V_{jc}\)

\[
C_{bc} = C_{bc_{diffusion}} + C_{bc_{depletion}}
\]

where

2-30 Multiplicity (\(M\)) Parameter
\[
C_{bc_{\text{diffusion}}} = \frac{T_r \times I_r}{N_r \times V_T}
\]

and
\[
C_{bc_{\text{depletion}}} = \frac{C_{jc}}{(1.0 - \left(\frac{V_{bc}}{V_{jc}}\right)^{M_{jc}})}
\]

for \( V_{bc} > F_c \times V_{jc} \)

\[
C_{bc_{\text{depletion}}} = \left(\frac{C_{jc}}{(1.0 - F_c)^{M_{jc}}}\right) \times \left(1.0 + \left(\frac{M_{jc}(V_{bc} - F_c \times V_{jc})}{V_{jc}(1.0 - F_c)}\right)\right)
\]

for \( V_{be} \leq F_c \times V_{je} \)

\[
C_{be} = C_{be_{\text{diffusion}}} + C_{be_{\text{depletion}}}
\]

where
\[
C_{be_{\text{depletion}}} = \frac{C_{je}}{(1.0 - \left(\frac{V_{be}}{V_{je}}\right)^{M_{je}})}
\]

for \( V_{be} > F_c \times V_{je} \)

\[
C_{be_{\text{depletion}}} = \left(\frac{C_{je}}{(1.0 - F_c)^{M_{je}}}\right) \times \left(1.0 + \left(\frac{M_{je}(V_{be} - (F_c \times V_{je}))}{V_{je}(1.0 - F_c)}\right)\right)
\]

The diffusion capacitance for \( C_{be} \) is somewhat differently formulated vs. that of \( C_{bc} \). The transit time is not a constant for the diffusion capacitance for \( C_{be} \), but is a function of both junction voltages, formulated in a manner similar to the modified Gummel-Poon model. The total base-emitter charge is equal to the sum of the base-emitter depletion charge (which is a function of \( V_{be} \) only) and the so-called transit charge (which is a function of both \( V_{be} \) and \( V_{bc} \)).

\[
Q_{\text{transit}} = T_{ff} \times \left(\frac{I_{cf}}{Q_b}\right)
\]

where
\[
T_{ff} = T_f \times \left(1.0 + X_{tf} \left(\frac{1.0 - F_t}{1.0 + F_t}\right)^{2.0} \times \exp\left(\frac{V_{bc}}{1.44 \times V_{gf}}\right)\right)
\]
Noise Model

Thermal noise generated by resistors $R_b$, $R_c$, and $R_e$ is characterized by the following spectral density:

$$\frac{<i^2>}{\Delta f} = \frac{4kT}{R}$$

Shot noise generated by each of the dc currents flowing from base to emitter, base to collector, and collector to emitter is characterized by the following spectral density:

$$\frac{<i^2>}{\Delta f} = 2qI_{DC}$$

In the previous expressions, $k$ is Boltzmann’s constant, $T$ is the operating temperature in Kelvin, $q$ is the electron charge, and $\Delta f$ is the noise bandwidth.

Flicker and burst noise for this device is not modeled in this version of the simulator. However, the bias-dependent noise sources $I_{NoiseBD}$ and $V_{NoiseBD}$ can be connected external to the device to model flicker or burst noise.
References:


Equivalent Circuit
Devices and Models, BJT

![Intrinsic Model Diagram]

- $V_{bc}$
- $I_{bc}$
- $I_{be}$
- $V_{be}$
- $C_{bc}$
- $C_{be}$
- $I_{cb}$
- $I_{ce}$
- $I_{cf}$
- $I_{le}$

2-34 Multiplicity ($\_M$) Parameter
## MEXTRAM_Model (MEXTRAM Model)

### Symbol

![Symbol](image)

### Parameters

Model parameters must be specified in SI units.

**Table 2-3. MEXTRAM_Model Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPN</td>
<td>NPN model type</td>
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<tr>
<td>PNP</td>
<td>PNP model type</td>
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<tr>
<td>Release</td>
<td>model level</td>
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<td>Exmod</td>
<td>flag for extended modelling of reverse current gain</td>
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</tr>
<tr>
<td>Exphi</td>
<td>flag for distributed high-frequency effects in transient</td>
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<tr>
<td>Exavl</td>
<td>flag for extended modelling of avalanche currents</td>
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</tr>
<tr>
<td>Is</td>
<td>collector-emitter saturation current</td>
<td>A/m²</td>
<td>9.6369×10⁻¹⁸</td>
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<tr>
<td>Bf</td>
<td>ideal forward current gain</td>
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<td>138.9</td>
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<tr>
<td>Xibi</td>
<td>fraction of ideal base current that belongs to sidewall</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Ibf</td>
<td>saturation current of non-ideal forward base current</td>
<td>A/m²</td>
<td>2.7223×10⁻¹⁵</td>
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<tr>
<td>Vlf</td>
<td>crossover voltage of non-ideal forward base current</td>
<td>V</td>
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<tr>
<td>Ik</td>
<td>high-injection knee current</td>
<td>A/m²</td>
<td>1.5×10⁻¹⁵</td>
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<td>Bri</td>
<td>ideal reverse current gain</td>
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<td>6.243</td>
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<tr>
<td>Ibr</td>
<td>saturation current of non-ideal reverse base current</td>
<td>A</td>
<td>4.6066×10⁻¹⁴</td>
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<tr>
<td>Vlr</td>
<td>crossover voltage of non-ideal reverse base current</td>
<td>V</td>
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<tr>
<td>Xext</td>
<td>part of $I_{EX}$, $Q_{EX}$, $Q_{TEX}$ and $I_{SUB}$ that depends on base-collector voltage $V_{BC1}$</td>
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<td>Description</td>
<td>Unit</td>
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<td>------------------------</td>
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<tr>
<td>Qb0</td>
<td>base charge at zero bias</td>
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<tr>
<td>Eta</td>
<td>factor of built-in field of base (=η).</td>
<td>4.8</td>
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<td>weak avalanche parameter</td>
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<tr>
<td>Efi</td>
<td>electric field intercept (with Exavl=1)</td>
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<td>critical current for hot carriers</td>
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<td>Rcc</td>
<td>constant part of collector resistance</td>
<td>Ω/m²</td>
<td>11.09</td>
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<tr>
<td>Rcv</td>
<td>resistance of unmodulated epilayer</td>
<td>Ω/m²</td>
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<td>Sccv</td>
<td>space charge resistance of epilayer</td>
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<td>current spreading factor epilayer</td>
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<td>Rbc</td>
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<td>Rbv</td>
<td>variable part of base resistance at zero bias</td>
<td>Ω/m²</td>
<td>307.7</td>
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<td>Re</td>
<td>emitter series resistance</td>
<td>Ω/m²</td>
<td>1.696</td>
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<td>Taune</td>
<td>minimum delay time of neutral and emitter charge</td>
<td>sec</td>
<td>6.6626×10^{-12}</td>
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<td>Mtau</td>
<td>non-ideality factor of the neutral and emitter charge</td>
<td>S</td>
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<td>Cje</td>
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<td>F/m²</td>
<td>4.9094×10^{-14}</td>
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<tr>
<td>Vde</td>
<td>base-emitter diffusion voltage</td>
<td>V</td>
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<tr>
<td>Pe</td>
<td>base-emitter grading coefficient</td>
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</tr>
<tr>
<td>Xcje</td>
<td>fraction of base-emitter depletion capacitance that belongs to sidewall</td>
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<td>0.26</td>
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<tr>
<td>Cjc</td>
<td>zero bias base-collector depletion capacitance</td>
<td>F/m²</td>
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<tr>
<td>Vdc</td>
<td>base-collector diffusion voltage</td>
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<td>Pc</td>
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<td>constant part of Cjc</td>
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<td>Mc</td>
<td>collector current modulation coefficient</td>
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<td>Xcjc</td>
<td>fraction of base-collector depletion capacitance under emitter area</td>
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<td>Parameter</td>
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<tr>
<td>$T_{ref}$</td>
<td>reference temperature</td>
<td>°C</td>
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<tr>
<td>$D_{ta}$</td>
<td>difference of device temperature to ambient temperature ($T_{Device}=T_{Ambient}+D_{ta}$)</td>
<td>°C</td>
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</tr>
<tr>
<td>$V_{ge}$</td>
<td>emitter bandgap voltage</td>
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<td>1.129</td>
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<tr>
<td>$V_{gb}$</td>
<td>base bandgap voltage</td>
<td>V</td>
<td>1.206</td>
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<td>$V_{gc}$</td>
<td>collector bandgap voltage</td>
<td>V</td>
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<tr>
<td>$V_{gj}$</td>
<td>emitter-base junction band-gap voltage</td>
<td>V</td>
<td>1.129</td>
</tr>
<tr>
<td>$V_{i}$</td>
<td>ionization voltage base dope</td>
<td>V</td>
<td>$2.1 \times 10^{-2}$</td>
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<tr>
<td>$N_{a}$</td>
<td>maximum base dope concentration</td>
<td>cm$^{-3}$</td>
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</tr>
<tr>
<td>$E_{r}$</td>
<td>temperature coefficient of $V_{lf}$ and $V_{lr}$</td>
<td></td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$A_{b}$</td>
<td>temperature coefficient resistivity base</td>
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<td>1.0</td>
</tr>
<tr>
<td>$A_{e pi}$</td>
<td>temperature coefficient resistivity of the epilayer</td>
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<td>1.9</td>
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<tr>
<td>$A_{e x}$</td>
<td>temperature coefficient resistivity of the extrinsic base</td>
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<tr>
<td>$A_{c}$</td>
<td>temperature coefficient resistivity of the buried layer</td>
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</tr>
<tr>
<td>$K_{f}$</td>
<td>flicker noise coefficient ideal base current</td>
<td></td>
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<tr>
<td>$K_{fn}$</td>
<td>flicker noise coefficient non-ideal base current</td>
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</tr>
<tr>
<td>$A_{f}$</td>
<td>flicker noise exponent</td>
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</tr>
<tr>
<td>$I_{ss}$</td>
<td>base-substrate saturation current</td>
<td>A/m$^2$</td>
<td>$5.8602 \times 10^{17}$</td>
</tr>
<tr>
<td>$I_{ks}$</td>
<td>knee current of the substrate</td>
<td>A/m$^2$</td>
<td>$6.7099 \times 10^{-6}$</td>
</tr>
<tr>
<td>$C_{js}$</td>
<td>zero bias collector-substrate depletion capacitance</td>
<td>F/m$^2$</td>
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<td>$V_{ds}$</td>
<td>collector-substrate diffusion voltage</td>
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<td>$P_{s}$</td>
<td>collector-substrate grading coefficient</td>
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</tr>
<tr>
<td>$V_{gs}$</td>
<td>substrate bandgap voltage</td>
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<td>1.12</td>
</tr>
<tr>
<td>$A_{s}$</td>
<td>for closed buried or an open buried layer</td>
<td></td>
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</tr>
<tr>
<td>$wV_{subfwd}$</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-3. MEXTRAM_Model Parameters (continued)
Devices and Models, BJT

### Notes/Equations/References

1. This model (version 503) supplies values for BJT\_NPN, BJT\_PNP, BJT4\_NPN, and BJT4\_PNP devices.

2. For the MEXTRAM bipolar transistor model, model equations are explicit functions of internal branch voltages; therefore, no internal quantities are solved iteratively. Transistor parameters are discussed where relevant; most parameters can be extracted from capacitance, dc, and $f_T$ measurements, and are process and transistor layout (geometry) dependent. Initial/predictive parameter sets can be computed from process and layout data. This model does not contain extensive geometrical or process scaling rules (only multiplication factors to put transistors in parallel). The extended modeling of reverse behavior, the increase of the avalanche current when the current density in the epilayer exceeds the doping level, and the distributed high-frequency effect are optional and can be switched on by setting flags. Besides the NPN transistor a PNP model description is available, both with and without substrate (discrete transistors) modeling.

3. The Philips model uses the MULT parameter as a scaling factor. In ADS, MULT is implemented as AREA, which has the same mathematical effect. Because the Philips model uses MULT as the multiplier/scaling, the values are in measurements such as Amps. However, in ADS, units of area are m$^2$, so they

---

**Table 2-3. MEXTRAM Model Parameters (continued)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>wBvsub</td>
<td>substrate junction reverse breakdown voltage</td>
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<tr>
<td></td>
<td>(warning)</td>
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</tr>
<tr>
<td>wBvbe</td>
<td>base-emitter reverse breakdown voltage</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(warning)</td>
<td></td>
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</tr>
<tr>
<td>wBvbc</td>
<td>base-collector reverse breakdown voltage</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(warning)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wVbcfwd</td>
<td>base-collector forward bias</td>
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<tr>
<td></td>
<td>(warning)</td>
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<td>wIbmax</td>
<td>maximum base current</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(warning)</td>
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<tr>
<td>wIcmax</td>
<td>maximum collector current</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(warning)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation</td>
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<tr>
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<td>AllParams</td>
<td>name of DataAccessComponent for file-based</td>
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<tr>
<td></td>
<td>model parameter values</td>
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</tbody>
</table>

---

2-38 Multiplicity (\(M\)) Parameter
are listed accordingly. This accounts for differences in reporting of some units in the Phillips documentation.

4. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams.

Survey of Modeled Effects

- Temperature effects
- Charge storage effects
- Substrate effects and parasitic PNP
- High-injection effects
- Built-in electric field in base region
- Bias-dependent Early effect
- Low-level non-ideal base currents
- Hard and quasi-saturation
- Weak avalanche
- Hot carrier effects in the collector epilayer
- Explicit modeling of inactive regions
- Split base-collector depletion capacitance
- Current crowding and conductivity modulation for base resistance
- First-order approximation of distributed high-frequency effects in the intrinsic base (high-frequency current crowding and excess phase-shift).

Active Transistor

Main Current

In the MEXTRAM model the Moll-Ross relation is used to take into account the depletion and diffusion charges:

\[
I_n = \frac{(I_f - I_r)}{1 + (Q_{t_e} + Q_{t_c} + Q_{b_e} + Q_{b_c})/Q_b0}
\]
Devices and Models, BJT

\[ Q_{be} = f_1(n_o) \]
\[ Q_{bc} = f_2(n_b) \]

The depletion charges are represented by \( Q_{te} \) and \( Q_{tc} \). The computation of the diffusion charges \( Q_{be} \) and \( Q_{bc} \) is based directly on the solution of the differential equation for the majority carriers in the neutral base region and relates the charges to the injected minority carrier concentrations at the emitter (no) and collector edges (nb). These concentrations, in turn, depend on the internal junction voltages \( V_{b2e1} \) and \( V_{b2c} \) by considering the p-n product at both junctions. In this way high injection, bias-dependent current gain, a current-dependent transit time, and the effect of the built-in electric field are included. The ideal forward and reverse current are given by:

\[ I_f - I_r = I_s \times (\exp(V_{b2e1}/V_t) - \exp(V_{b2c}/V_t)) \]

where \( V_t \) is the thermal voltage.

The parameters are:

- \( I_s \) = extracted from Gummel plot at low \( V_{be} \)
- \( Q_{b0} \) = integral of base charge extracted from reverse Early effect
- \( X_{jc} \) = fraction of \( C_{jc} \) underneath emitter; obtained from forward Early effect
- \( I_k \) = from gain fall-off: only one knee current
- \( \eta \) = built-in field in the base due to the doping profile. This parameter is normally between 3 and 6. It is difficult to obtain from direct measurements, and has a weak influence on computed currents and charges.

**Ideal Forward Base Current**

The ideal forward base current is defined in the usual way. The total base current has a bottom and a sidewall contribution. The separation is given by the factor \( X_{1b1} \). This factor can be determined by analyzing the maximum current gain of transistors with different geometries.

\[ I_{b1} = (1 - X_{bi}) \times \frac{I_s}{B_f} (\exp(V_{b2e1}/V_t) - 1) \]

The parameters are:

---

2-40 Multiplicity \(_M\) Parameter
\( B_f = \) ideal forward current gain
\( X_{ibi} = \) fraction of ideal base current that belongs to the sidewall

**Non-Ideal Forward Base Current**

The non-ideal base current originates from the recombination in the depleted base-emitter region:

\[
I_{b2} = I_{bf} \times \frac{\exp(V_{b2e1}/V_t) - 1}{\exp(V_{b2e1}/(2 \times V_t)) + \exp(V_{lf}/(2 \times V_t))}
\]

Formulation of the non-ideal base current differs from the Gummel-Poon model. The MEXTRAM formulation is less flexible than the Gummel-Poon model. The formulation is the same when in the MEXTRAM model \( V_{lf} \) is small (<0.4V), and when in the Gummel-Poon model parameter \( n_e = 2 \). The parameters are:

- \( V_{lf} = \) crossover voltage of the non-ideal forward base current
- \( I_{bf} = \) saturation current of the non-ideal forward base current

**Base-Emitter Depletion Charge**

The base-emitter depletion charge is modeled in the classical way using a grading coefficient. The depletion charge is partitioned in a bottom and a sidewall component by the parameter \( X_{cje} \).

\[
C_{te} = (1 - X_{cje}) \times \frac{C_{je}}{1 - (V_{b2e1}/V_{de})^{P_e}}
\]

The capacitance becomes infinity at \( V_{b2e1} = V_{de} \). Therefore in the model the integral of equation is slightly modified and consequently \( C_{te} \). The capacitance now has a maximum at the base-emitter diffusion voltage \( V_{de} \) and is symmetrical around the diffusion voltage. The maximum capacitance is determined by the value of \( K \) and the grading coefficient \( P_e \). The value of \( K \) is a model constant and is taken equal to 0.01. When \( P_e = 0.4 \), the maximum is approximately three times the capacitance at zero bias. The parameters are:

- \( C_{jc} = \) zone bias base-emitter depletion capacitance
- \( V_{de} = \) base-emitter diffusion voltage
- \( P_e = \) base-emitter grading coefficient
Base-Collector Depletion Charge

The base-collector depletion capacitance underneath the emitter $Q_{tc}$ takes into account the finite thickness of the epilayer and current modulation:

$$C_{tc} = X_{cjc} C_{jc} \times \left( \frac{(1 - X_p) \times f(V_{c1} C_2)}{1 - \left( (V_{B2} \times C_2)/(V_{dc}) \right)^{P_c} + X_p} \right)$$

$$f(V_{c1} \times C_2) = \left( 1 - \frac{V_{C1} C_2}{V_{C1} C_2 + Ih_c \times R_{cv}} \right)^{M_c}$$

The function $f(V_{c1} C_2)$ equals one when $I_{c1} C_2 = V_{c1} C_2 = 0$, and becomes zero when the current density in the epilayer exceeds the doping level ($V_{c1} C_2 > Ih_c \times R_{cv}$). The parameters are:

- $C_{jc}$ = zero bias base-collector depletion capacitance
- $X_{cjc}$ = part of $C_{jc}$ underneath emitter
- $V_{dc}$ = base-collector diffusion voltage
- $P_c$ = base-collector grading coefficient
- $X_p$ = depletion layer thickness at zero bias divided by epilayer thickness
- $M_c$ = collector current modulation coefficient ($0.3 < m_c < 0.5$)

$C_{jc}$, $P_c$ and $X_p$ is obtained from CV measurements; $V_{dc}$ must be extracted from the quasi-saturation regime; $X_{cjc}$ is obtained from the forward Early-effect.

Neutral Base and Emitter Diffusion Charge

The neutral base-emitter diffusion charge ($Q_n$) is given by:

$$Q_n = Q_{n0} \times \exp \left( \frac{V_{b2} e_1}{M_{tau} \times V_{t}} - 1 \right)$$

The charge $Q_{n0}$ is calculated from the transit time $T_{aune}$ and $M_{tau}$. The parameters (extracted from the maximum value of the cut-off frequency, $f_T$) are:

- $T_{aune}$ = minimum delay time of neutral and emitter charge
- $M_{tau}$ = non-ideality factor of the neutral and emitter charge; in most cases $M_{tau} = 1$
Base-Charge Partitioning

Distributed high-frequency effects are modeled, in first order approximation, both in lateral direction (current crowding) and in vertical direction (excess phase-shift). The distributed effects are an optional feature of the MEXTRAM model, and can be switched on and off by flag Exphi (on: Exphi - 1; off: Exphi = 0). In vertical direction (excess phase-shift), base charge partitioning is used; for simplicity, it is implemented for forward base charge ($Q_{be}$) and low-level injection only. No additional parameters.

\[
Q'_{be} = (1 - q_c(Eta)) \times Q_{be}
\]
\[
Q'_{bc} = Q_{bc} + q_c(Eta) \times Q_{be}
\]

Modeling of Epilayer Current Charges

The epilayer resistance depends on the supplied collector voltage and current, imposed primarily by base-emitter voltage. The effective resistance of the epilayer is strongly voltage- and current-dependent because:

- In the forward mode of operation, the internal base charge junction voltage ($V_{b2c2}$) may become forward-biased at high collector currents (quasi-saturation). When this happens, the region in the collector near the base is injected by carriers from the base, causing the region to become low resistive.

- In the reverse mode of operation, both the external and internal base charge junction voltages are forward biased, flooding the whole epitaxial layer with carriers, which causes it to become low resistive.

- The current flow in the highly-resistive region is ohmic if the carrier density ($n$) is low ($n \ll N_{epi}$), and space-charge-limited if the carrier density exceeds the doping level ($N_{epi}$).

- Current spreading in the epilayer reduces the resistance and is of special importance if the carrier density exceeds $N_{epi}$. In the latter case, the carriers move with the saturated drift velocity, $V_{sat}$ (hot-carrier current-flow).

A compact modal formulation of quasi-saturation is given by Kull et al [1]. The Kull model is valid only if the collector current density is below the critical current density ($J_{hc}$) for hot carriers:

\[
J_{hc} = q \times N_{epi} \times V_{sat}
\]
The Kull formulation has served as a basis for the epilayer model in MEXTRAM.

**Collector Resistance Model**

The Kull model is based on charge neutrality \((p + N_{\text{epi}} = n)\) and gives the current through the epilayer \((I_{c1}c_2)\) as a function of the internal and external b.c. junction voltage. These voltages are given by the solution vector of the circuit simulator. The final equations of the Kull formulation [1] are:

\[
I_{c1}c_2 = \frac{E_c + V_{b2}c_2 - V_{b1}c_1}{R_{cv}}
\]

\[
E_c = V_t \times \left[ K_0 - K_w \ln \left( \frac{K_0 + 1}{K_w + 1} \right) \right]
\]

\[
K_0 = \sqrt{1 + 4 \times \exp \left[ \left( V_{b2}c_2 - V_{d1}c_2 \right) / V_t \right]}
\]

\[
K_w = \sqrt{1 + 4 \times \exp \left[ \left( V_{b1}c_1 - V_{d1}c_2 \right) / V_t \right]}
\]

\[
V_t = k \times \frac{T}{q}
\]

Voltage source \((E_c)\) takes into account the decrease in resistance due to carriers injected from the base into the collector epilayer. If both junctions are reverse biased \((V_{b2}c_1 - V_{d1}c_2 \text{ and } V_{b2}c_2 - V_{d1}c_2 \text{ are negative})\), \(E_c\) is zero and we have a simple constant resistance \((R_{cv})\). Because of this, this model does not take into account the hot-carrier behavior (carriers moving with the saturated drift-velocity) in the lightly-doped collector epilayer. The model is valid if the transistor operates in the reverse mode (reverse-biased b.e. junction, forward-biased b.c. junction). Then the entire epilayer is filled with carriers and a space-charge region does not exist. The derivation of the MEXTRAM epilayer resistance model is published in de Graaff and Kloosterman [2]. In the end, the following equations are found:

\[
\frac{X_i}{W_{\text{epi}}} = \frac{E_c}{I_{c1}c_2 \times R_{cv}}
\]

\[
I_{\text{low}} = \frac{I_{hc} \times V_{c1}c_2}{V_{c1}c_2 + I_{hc} \times R_{cv} \times (1 - X_i / W_{\text{epi}})}
\]
where \( X_i/W_{\text{epi}} \) is the thickness of the injected region of the epilayer.

Substitution of equations and into equation gives a cubic equation. The epilayer current \((I_{c_1}c_2)\) is computed by solving the cubic equation. The complex computation can be done with real variables. Summarizing, the epilayer resistance model takes into account:

- Ohmic current flow at low current densities
- Decrease in resistance due to carriers injected from the base if only the internal base-collector junction is forward biased (quasi-saturation), and if both the internal and external base-collector junctions are forward biased (reverse mode of operation)
- Space charge limited current flow at high current densities
- Current spreading in the epilayer

The model parameters are:

\[
I_{hc} = \frac{q \times N_{\text{epi}} \times A_{\text{em}} \times v_{\text{sat}} \times \frac{1 + Sf_l}{\alpha_{cf}}}{V_{c_1}c_2 - I_{low} \times R_{cv} \times \left(1 - \frac{X_i}{W_{\text{epi}}}\right)}
\]

\[
R_{cv} = \frac{W_{\text{epi}}}{q \times N_{\text{epi}} \times \mu \times A_{\text{em}}} \times \frac{\alpha_{cf}}{1 + Sf_l}
\]

\[
S_{rcv} = \frac{W^2_{\text{epi}}}{2 \times \varepsilon \times v_{\text{sat}} \times A_{\text{em}}} \times \frac{\alpha_{cf}}{1 + Sf_h}
\]

\[
V_{dc} = V_t \times \ln \left( \frac{(N_{\text{epi}}/n_i)^2}{\frac{1}{H_e} + \frac{1}{L_e}} \right)
\]

\[
S_{fh} = \frac{2}{3} \times \tan(\alpha_h) \times W_{\text{epi}} \times \left(\frac{1}{H_e} + \frac{1}{L_e}\right)
\]

where

\[
A_{\text{em}} = H_e \times L_e,
\]
Devices and Models, BJT

\[ S_f = \tan(\alpha_h) \times W_{\text{epi}} \times \left( \frac{1}{H_e} + \frac{1}{L_e} \right) \]

- \( \alpha_l \): the spreading angle at low current levels \( (I_{c1c2} < I_{hc}) \)
- \( \alpha_h \): the spreading angle at high current levels \( (I_{c1c2} > I_{hc}) \)
- \( \alpha_{cf} \): the fraction of \( I_{c1c2} \) flowing through the emitter floor area
- \( L_e \): the length of the emitter stripe.

The turnover from equations and in the forward mode to equation in the reverse mode does not give discontinuities in the first and second derivative. The third derivative is discontinuous. Parameter \( S_f \) depends on transistor geometry and the decrease in gain and cutoff frequency will be affected by this parameter. \( S_f \) is included in \( R_{cv} \) and \( I_{hc} \), and not needed as a separate parameter. In most cases, \( V_{dc} \) is computed directly from the doping level. \( R_{cv}, I_{hc}, \) and \( S_{rvcv} \) are extracted from the quasi-saturation regime at low values of \( V_{ce} \).

**Diffusion Charge of the Epilayer**

The diffusion charge of the epilayer can be easily derived by applying the Moll-Ross relation to the base + collector region (from node \( e_1 \) to node \( c_1 \)):

\[
I_n = I_{c1c2} = \frac{1}{s} \times \left\{ \frac{\exp(Vb_2e_1/V_t) - \exp(Vb_2c_1/V_t)}{Q_{te} + Q_{tc} + Q_{be} + Q_{bc} + Q_{epi}} \right\}
\]

Subtracting equation , the expression for \( Q_{epi} \) becomes:

\[
Q_{epi} = \frac{1}{s} \times Q_{b0} \times \left\{ \frac{\exp(Vb_2c_1/V_t) - \exp(Vb_2c_1/V_t)}{I_{c1c2}} \right\}
\]

In the transition from forward to reverse mode, \( I_{c1c2} \) passes zero and numerical problems can be expected. Substitution of equation into equation leads in the case where \( Vb_2c_2 = Vb_2c_1 \) to the following expression for \( Q_{epi} \):

\[
p_0 = \frac{2 \times \exp\{(Vb_2c_2 - V_{dc})/V_t\}}{1 + K_{0}}
\]

\[
p_w = \frac{2 \times \exp\{(Vb_2c_1 - V_{dc})/V_t\}}{1 + K_{w}}
\]
Avalanche Multiplication Model

Due to the high-electric field in the space-charge region, avalanche currents are generated; this generation strongly depends on the maximum electric field. The maximum electric field may reside at the base charge junction or at the buried layer. The generation of avalanche current in Kloosterman and de Graaff [3] is only a function of the electric field at the internal base charge junction. Therefore, the validity of this model is restricted to low current levels ($I_{c1} < I_{hc}$).

Current spreading in the collector region changes the electric-field distribution and decreases the maximum electric field. Because the generation of avalanche current is sensitive with respect to the maximum electric-field, it is difficult to set up an accurate and still simple model for high collector current densities. Because this operating area (high voltages, high current levels) is not of practical interest (due to power dissipation) and, more importantly, the convergency behavior of the model degrades, we must carefully consider the extension of the avalanche model to the high current regime.

At low current densities ($I_{c1} < I_{hc}$), the model is essentially the same as in Kloosterman and de Graaff [3]. As an optional feature, the model is extended to current levels exceeding $I_{hc}$ (negative output resistance: snap-back behavior). Due to negative output resistance, serious convergency problems are imaginable. Without this feature, output resistance can be very small, but is always positive.

The generation of avalanche current is based on Chynoweth's empirical law for the ionization coefficient [4]:

$$P_n = \alpha_n \times \exp\left(\frac{-b_n}{|E|}\right)$$

Because only weak avalanche multiplication is considered, the generated avalanche current is proportional with the main current ($I_n$):

$$I_g = I_n \times \int_{x=0}^{X_d} \alpha_n \times \exp\left(\frac{-b_n}{|E(x)|}\right) \times dx$$

$X_d =$ the boundary of the space-charge region.
To calculate the avalanche current, we must evaluate the integral of equation in the space-charge region. This integral is determined by the maximum electric field. We make a suitable approximation around the maximum electric field:

$$E(x) = E_m \times \left(1 - \frac{x}{\lambda}\right) \approx \frac{E_m}{1 + x/\lambda}$$

$$\lambda = \text{the point where the extrapolated electric-field is zero.}$$

Then the generated avalanche current becomes:

$$\frac{I_g}{I_n} = \frac{\alpha_n \times E_m \times \lambda \times \left\{ \exp\left(-\frac{b_n}{E_m}\right) - \exp\left(-\frac{b_n}{E_m} \times \left(1 + \frac{X_d}{\lambda}\right)\right) \right\}}{\exp\left(-\frac{b_n}{E_m} \times \left(1 + \frac{X_d}{\lambda}\right)\right)}$$

The maximum electric field ($E_m$), the depletion layer thickness ($X_d$), and the intersection point ($\lambda$) are calculated using the charge model of $Q_{tc}$ and the collector resistance model. The model parameters are:

- $Avl = \frac{b_n \times \sqrt{\frac{2 \times \varepsilon \times V_{dc}}{q \times N_{epi}}}}{\sqrt{1 + 2 \times Sf_l} \times 2 + Sf_l + 2 \times Sfh}$$

- $F_i = 2 \times \frac{1 + 2 \times Sf_l}{1 + 2 \times Sfh \times 2 + 3 \times Sfh} \times (-1)$

$Avl$ = obtained from the decrease of $I_b$ at high $V_{cb}$ and low $I_c$ values

$Sfh$ = equation

$Sf_l$ = equation

$Efi$ = used in extended avalanche model only

Sfh and Efi are extracted from the output characteristics at high $V_{ce}$ and high $I_c$. Because most devices are heated due to power dissipation in this operation regime, parameter extraction is cumbersome. Calculating Efi and Sfh is often a good alternative.

**Extrinsic Regions**

**Reverse Base Current**

The reverse base current is affected by high injection and partitioned over the two external base-collector branches:

---

2-48  Multiplicity (M) Parameter
The current $I_{\text{ex}}$ is computed in a similar way using the voltage $V_{bc1}$. Because the computing time to evaluate the extrinsic regions is doubled due to this partitioning, it is an optional feature. The parameters are:

- $B_{ri}$ = ideal reverse current gain
- $X_{\text{ext}}$ = partitioning factor

**Non-Ideal Reverse Base Current**

The non-ideal reverse base current ($I_{b3}$) is modeled in the same way as the forward non-ideal base current. The parameters are:

- $I_{br}$ = saturation current of the non-ideal reverse base current
- $V_{lr}$ = crossover voltage of the non-ideal reverse base current

**Extrinsic Base-Collector Depletion Capacitance**

The base-collector depletion capacitance of the extrinsic region is divided over the external-base node $b_1$ (part: $Q_{\text{tc}}$). The model formulation is obtained by omitting the current modulation term in the formulation of $Q_{\text{tc}}$ (equation).

$$C_{\text{tc ex}} = (1 - X_{\text{ext}}) \times (1 - X_{cj c}) \times C_{jc} \times \left( \frac{1 - X_p}{1 - (V_{b1}c_1/V_{dc})^{p_c}} + X_p \right)$$

\[ah_b = 2 \times \left( \frac{1 - \exp(-Eta)}{Eta} \right)\]
\[al_b = \exp(-Eta)\]
\[4 \times l_s \times ah_b^2 \times \exp\left( \frac{V_{b1}c_1}{V_t} \right)\]
\[g_l = \frac{I_k \times a_l^2}{al_b} \]
\[n_{b_{ex}} = a_l b \times \frac{g_l}{2 \times (1 + \sqrt{1 + g_l})} \]
\[I_{ex} = \frac{(1 - X_{\text{ext}}) \times (ah_b + n_{b_{ex}} \times l_s)}{ak \times ah_b \times n_{b_{ex}} - l_s} \]
2-50 Multiplicity (_M) Parameter

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\[ X_{ctc_{ex}} = X_{ext} \times (1 - X_{cjc}) \times C_{jc} \times \left( \frac{1 - X_p}{1 - \left( V_{bc1} / (V_{dc}) \right)^P} + X_p \right) \]

Parameter \( X_{ext} \) is partitioning factor for the extrinsic region. This partitioning factor is important for the output conductance \( Y_{12} \) at high frequencies.

**Diffusion Charge of the Extrinsic Region**

These charges are formulated in the same way as \( Q_{bc} \) and \( Q_{epi} \), now using voltages \( V_{c1b1} \) and \( V_{bc1} \), and the appropriate area \( (1 - X_{cjc}) / X_{cjc} \).

No additional parameters.

**Parasitic PNP**

The substrate current of the PNP takes into account high injection. The parameters are:

- \( I_{ss} \) = substrate saturation current
- \( I_{ks} \) = knee in the substrate current; when the value of \( I_{ks} \) is low, the reverse current gain increases at medium reverse current levels

When the collector-substrate junction becomes forward biased, only a signal current \( I_{sf} \) is present in the model.

\[ I_{sf} = I_{ss} \times \exp \left( \frac{(V_{sc1})}{(V_t)} - 1 \right) \]

No additional parameters.

**Collector-Substrate Depletion Capacitance**

The collector-substrate charge \( Q_{ts} \) is modeled in the usual way:

\[ C_{ts} = \frac{C_{js}}{1 - \left( V_{sc1} / (V_{ds}) \right)^P} \]

Parameters \( C_{js} \), \( V_{ds} \), and \( P \) are obtained from collector-substrate CV measurement.

**Base-Emitter Sidewall**

Base-emitter sidewall base current \( S_{ib1} \):

---

2-50 Multiplicity (_M) Parameter
Parameter $X_{ibi}$ obtained from geometrical scaling of the current gain.

Base-emitter sidewall depletion capacitance $S_{Q_{te}}$:

$$S_{Q_{te}} = \frac{X_{cj} \times C_{je}}{1 - (V_{b_1e}/V_{de})^P_{e}}$$

Parameter $X_{cj}$ obtained from geometrical scaling of the capacitances.

**Variable Base Resistance**

The base resistance is divided in a variable part ($R_{bv}$) and a constant part ($R_{bc}$). The variable part is modulated by the base width variation (depletion charges at the junctions $Q_{te}$ and $Q_{tc}$) and at high current densities it decreases because of the diffusion charges $Q_{be}$ and $Q_{bc}$. The parameter $R_{bv}$ is the resistance at zero base-emitter and base-collector voltage. The resistance model also considers DC current crowding. The resistance decreases at high base currents when $V_{b_1b_2}$ is positive, and it increases when $V_{b_1b_2}$ is negative (reversal of the base $e$ current).

Charge modulation:

$$R_b = \frac{R_{bv}}{1 + (Q_{te} + Q_{tc} + Q_{be} + Q_{bc})/(Q_{b0})}$$

DC current crowding:

$$I_{b_1b_2} = \frac{2 \times V_t}{3 \times R_b} \times (\exp(V_{b_1b_2}/V_t) - 1) + \frac{V_{b_1b_2}}{3 \times R_b}$$

Ac current crowding is an optional feature of the model ($\text{Exphi}=1$):

$$Q_{b_1b_2} = V_{b_1b_2} \times (C_{te} + C_{be} + C_n)/5$$

**Constant Series Resistances**

The model contains three constant series resistors at the base, emitter, and collector terminals ($R_{bc}$, $R_e$, $R_{cc}$). (Substrate resistance is not incorporated in the model.)
Temperature Scaling Rules
Temperature scaling rules are applied to these parameters.

- Resistances: $R_{bc}$, $R_{bv}$, $R_{e}$, and $R_{cc}$
- Capacitances: $C_{je}$, $V_{de}$, $C_{jc}$, $V_{dc}$, $X_{p}$, $C_{js}$, $V_{ds}$, $Q_{bo}$, $Q_{n_{0}}$, and $M_{tau}$
- Saturation Currents: $I_s$ and $I_{ss}$
- Gain Modeling: $B_f$, $I_{bf}$, $V_{if}$, $B_{ri}$, $I_{br}$, $V_{lr}$, $I_k$, and $I_{ks}$
- Avalanche: $A_v$

These parameters are used in the temperature scaling rules:

- Bandgap Voltages: $V_{ge}$, $V_{gb}$, $V_{gc}$, $V_{gs}$, and $V_{gj}$
- Mobility Exponents: $A_b$, $A_{epi}$, $A_{ex}$, $A_c$, and $A_s$
- $Q_{b0}$: $V_i$ and $N_a$
- $V_{lf}$ and $V_{lr}$: $E_r$

Noise Model

- Thermal Noise: Resistances $R_{bc}$, $R_{bv}$, $R_{e}$, and $R_{cc}$
- Shot Noise: $I_n$, $I_{b1}$, $S_{ib1}$, $I_{b2}$, $I_{b3}$, $I_{ex}$, and $X_{Iex}$
- $1/F$ noise: $I_{b1}$, $S_{Ib1}$, $I_{b2}$, and $I_{b3}$
- $1/F$ noise parameters: $K_f$, $K_{fn}$, and $A_f$
Figure 2-1. Equivalent Circuit for Vertical NPN Transistor
Figure 2-2. Small Signal Equivalent Circuit for Vertical NPN Transistor

References


**STBJT_Model (ST Bipolar Transistor Model)**

**Symbol**

![Symbol](image)

**Parameters**

Model parameters must be specified in SI units/

<table>
<thead>
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<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
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† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.
## Table 2-4. STBJT Model Parameters (continued)

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<td>0.0†††</td>
</tr>
<tr>
<td>Rbm</td>
<td>minimum base resistance at high current (0 means Rb)</td>
<td>Ohm</td>
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<td>Re</td>
<td>emitter resistance</td>
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<tr>
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<td>collector resistance under the emitter</td>
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<tr>
<td>Rcs</td>
<td>collector resistance in saturation</td>
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<tr>
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<td>B-E zero-bias depletion capacitance</td>
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<td>B-E junction built-in potential</td>
<td>V</td>
<td>0.75</td>
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† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.
Table 2-4. STBJ T_Model Parameters (continued)

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<td>Cjc</td>
<td>B-C zero-bias depletion gap</td>
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<td>Vjc</td>
<td>B-C junction built-in potential</td>
<td>V</td>
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<td>junction grading coefficient</td>
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<td>Xjbc</td>
<td>fraction of Cjc connected to B int node</td>
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<td>zero-bias collector substrate (ground) cap</td>
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<td>Vjs</td>
<td>C-s (B-S) built-in potential</td>
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<td>C-s (B-S) grading coefficient</td>
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<td>voltage dependence of Tf on B-C voltage (0 means infinity)</td>
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<td>fixed to infinity</td>
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† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.
### Table 2-4. STBJT Model Parameters (continued)

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<td>Kelvin</td>
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<td>Trb2</td>
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<td>Tre1</td>
<td>linear temperature coefficient for Re</td>
<td>Kelvin</td>
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<td>Tre2</td>
<td>quadratic temperature coefficient for Re</td>
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<td>linear temperature coefficient for Rc</td>
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<td>Trc2</td>
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<td>Trcs2</td>
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<td>forward I_k (0 means infinity)</td>
<td>A</td>
<td>set to infinity</td>
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<tr>
<td>Ikr</td>
<td>reverse I_k (0 means infinity)</td>
<td>A</td>
<td>set to infinity</td>
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<td>minimum conductance</td>
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<td>name of DataAccessComponent for file-based model parameter values</td>
<td>...</td>
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</tbody>
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† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.
## VBIC_Model (VBIC Model)

### Parameters

Table 2-5. VBIC_Model Parameters

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<thead>
<tr>
<th>Parameter</th>
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<td>extrinsic collector resistance</td>
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<tr>
<td>Rci†</td>
<td>intrinsic collector resistance</td>
<td>Ω</td>
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<td>epi drift saturation voltage</td>
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† This parameter value varies with temperature based on model Tnom and device Temp.
Table 2-5. VBIC_Model Parameters (continued)

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<tr>
<th>Parameter</th>
<th>Definition</th>
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<td>extrinsic base-collector overlap capacitance</td>
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<td>Cjc†</td>
<td>base-collector zero-bias capacitance</td>
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<td>collector charge at zero bias</td>
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† This parameter value varies with temperature based on model Tnom and device Temp.
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<th>Definition</th>
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<th>Default</th>
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<td>ideal parasitic base-collector emission coefficient</td>
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*† This parameter value varies with temperature based on model Tnom and device Temp.
Table 2-5. VBIC_Model Parameters (continued)

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<tr>
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<th>Default</th>
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<td>Eaie</td>
<td>activation energy for Ibei</td>
<td>eV 1.12</td>
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<td>eV 1.12</td>
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<td>base-collector reverse breakdown voltage (warning)</td>
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<tr>
<td>wBvcfwd</td>
<td>base-collector forward bias (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wIbmax</td>
<td>maximum base current (warning)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wIcmax</td>
<td>maximum collector current (warning)</td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
Notes/Equations/References

1. This model (version 1.1.4) supplies values for a VBIC device.

2. The VBIC vertical BJT model was developed specifically as a replacement for the SPICE Gummel-Poon model by representatives of the IC and CAD industries.

VBIC includes improved modeling of the Early effect (output conductance), substrate current, quasi-saturation, and behavior over temperature—information necessary for accurate modeling of current state-of-the-art devices. However, it has additionally been defined so that, with default parameters, the model will simplify to be as similar as possible to the Gummel-Poon model.

- Advantages of VBIC over the Gummel-Poon model include:
  - An Early effect model based on the junction depletion charges
  - A modified Kull model for quasi-saturation valid into the Kirk regime (the high-injection effect at the collector)
  - Inclusion of the parasitic substrate transistor
  - An improved single-piece junction capacitance model for all 3 junction capacitances
  - Improved static temperature scaling
  - First-order modeling of distributed base and emitter ac and dc crowding
  - Overall improved high-level diffusion capacitance modeling (including quasi-saturation charge)
  - Inclusion of parasitic overlap capacitances; inclusion of the onset of weak avalanche current for the base-collector junction.
  - High-order continuity (infinite) in equations. A noise model similar to that of the Gummel-Poon model, with shot, thermal, and 1/f components

Table 2-5. VBIC_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>AllParams</td>
<td>name of DataAccessComponent for file-based model parameter values</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.

4. Colin McAndrew, AT&T/Motorola; Jerry Seitchik, Texas Instruments; Derek Bowers, Analog Devices; Mark Dunn, Hewlett Packard; Mark Foisy, Motorola; Ian Getreu, Analogy; Marc McSwain, MetaSoftware; Shahriar Moinian, AT&T Bell Laboratories; James Parker, National Semiconductor; Paul van Wijnen, Intel/Philips; Larry Wagner, IBM, VBIC95: An Improved Vertical, IC Bipolar Transistor Model.


VBIC (Nonlinear Bipolar Transistors)

VBIC_NPN, (VBIC Nonlinear Bipolar Transistor, NPN)
VBIC_PNP, (VBIC Nonlinear Bipolar Transistor, PNP)

Symbol

Parameters

Model = name of a VBIC_Model
Scale = scaling factor (default: 1)
Region = dc operating region: 0 = off, 1 = on, 2 = rev, 3 = sat (default: on)
Temp = device operating temperature, in °C (default: 25)
Mode = simulation mode for this device: nonlinear, linear (default: nonlinear)
_M = number of devices in parallel (default: 1)

Range of Usage
N/A

Notes/Equations/References

1. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated VBIC_Model) certain model parameters are scaled such that the device is simulated at its operating temperature.

2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.

3. This device has no default artwork associated with it.
Chapter 3: Devices and Models, GaAs

Bin Model
The BinModel in the GaAs library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

For information on the use of the binning feature, refer to the section “Bin Model (Bin Model for Automatic Model Selection).” This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.

Multiplicity (_M) Parameter
For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section “Multiplicity.” This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.
Curtice2_Model (Curtice-Quadratic GaAsFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 3-1. Curtice2_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFET</td>
<td>N-channel model</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>PFET</td>
<td>P-channel model</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Idsmod</td>
<td>Ids model</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Vto†</td>
<td>threshold voltage</td>
<td>V</td>
<td>−2</td>
</tr>
<tr>
<td>Beta†, ††</td>
<td>transconductance</td>
<td>A/V²</td>
<td>10⁻⁴</td>
</tr>
<tr>
<td>Lambda</td>
<td>channel length modulation</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Alpha</td>
<td>hyperbolic tangent function</td>
<td>1/V</td>
<td>2.0</td>
</tr>
<tr>
<td>Tau</td>
<td>transit time under gate</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Tnom</td>
<td>nominal ambient temperature at which these</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>model parameters were derived</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idstc</td>
<td>Ids temperature coefficient</td>
<td>A/Temp°C</td>
<td>0</td>
</tr>
<tr>
<td>Vtotc</td>
<td>Vto temperature coefficient</td>
<td>V/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>Betatce</td>
<td>drain current exponential temperature coefficient</td>
<td>%/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>Rin ††††</td>
<td>channel resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
</tbody>
</table>

†This parameter value varies with temperature based on model Tnom and device Temp.
††This parameter value scales with Area.
†††† This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rf†††</td>
<td>gate-source effective forward- bias resistance</td>
<td>ohms</td>
<td>infinity‡</td>
</tr>
<tr>
<td>Gscap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Cgs†† ††</td>
<td>zero bias gate-source junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgd †, ††</td>
<td>zero bias gate-drain junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Rgd†††</td>
<td>gate drain resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Gdcap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Fc</td>
<td>coefficient for forward bias depletion capacitance (diode model)</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Rd†††</td>
<td>drain ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rg</td>
<td>gate resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rs†††</td>
<td>source ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Ld</td>
<td>drain inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Lg</td>
<td>gate inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Ls</td>
<td>source inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Cds††</td>
<td>drain-source capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Rc†††</td>
<td>used with Crf to model frequency dependent output conductance</td>
<td>ohms</td>
<td>infinity‡</td>
</tr>
<tr>
<td>Crf†††</td>
<td>used with Rc to model frequency dependent output conductance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Gsfwd</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Gsrev</td>
<td>0=none, 1=linear, 2=diode</td>
<td>none</td>
<td></td>
</tr>
</tbody>
</table>

†This parameter value varies with temperature based on model Tnom and device Temp.
††This parameter value scales with Area.
††† This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
### Table 3-1. Curtice2_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gdfwd</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Gdrev</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>R1†††</td>
<td>approximate breakdown resistance</td>
<td>ohms</td>
<td>infinity‡</td>
</tr>
<tr>
<td>R2†††</td>
<td>resistance relating breakdown voltage to channel current</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Vbi†</td>
<td>built-in gate potential</td>
<td>V</td>
<td>0.85</td>
</tr>
<tr>
<td>Vbr</td>
<td>gate-drain junction reverse bias breakdown voltage (gate-source junction</td>
<td>V</td>
<td>10^-10</td>
</tr>
<tr>
<td></td>
<td>reverse bias breakdown voltage with Vds &lt; 0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iₙₜ, †</td>
<td>gate junction saturation current (diode model)</td>
<td>A</td>
<td>10^-14</td>
</tr>
<tr>
<td>Ir</td>
<td>gate reverse saturation current</td>
<td>A</td>
<td>10^-14</td>
</tr>
<tr>
<td>Iₘₜ</td>
<td>explosion current</td>
<td>A</td>
<td>1.6</td>
</tr>
<tr>
<td>Xₜi</td>
<td>temperature exponent for saturation current</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Eₜg</td>
<td>energy gap for temperature effect on Iₙ</td>
<td>eV</td>
<td>1.11</td>
</tr>
<tr>
<td>N</td>
<td>gate junction emission coefficient (diode model)</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Fnc</td>
<td>flicker noise corner frequency</td>
<td>Hz</td>
<td>0</td>
</tr>
<tr>
<td>R</td>
<td>gate noise coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>P</td>
<td>drain noise coefficient</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>gate-drain noise correlation coefficient</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Taumdl</td>
<td>second order Bessel polynomial to model tau</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>wVgfwd</td>
<td>gate junction forward bias warning</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage warning</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

†This parameter value varies with temperature based on model Tnom and device Temp.
††This parameter value scales with Area.
†††This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
Notes/Equations/References

1. This model supplies values for a GaAsFET device.

2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

3. Drain-source current

The drain current in the Curtice quadratic model is based on the work of W. R. Curtice [1].

The quadratic dependence of the drain current with respect to the gate voltage is computed with the following expression in the region $V_{ds} \geq 0.0V$.

$$I_{ds} = \beta \times (V_{gs} - V_{to})^2 \times (1 + \lambda \times V_{ds}) \times \tanh(\alpha \times V_{ds}).$$

Assuming symmetry, in the reverse region, the drain and source swap roles and the expression becomes:

$$I_{ds} = \beta \times (V_{gd} - V_{to})^2 \times (1 - \lambda \times V_{ds}) \times \tanh(\alpha \times V_{ds}).$$

The drain current is set to zero in either case if the junction voltage ($V_{gs}$ or $V_{gd}$) drops below the threshold voltage $V_{to}$.
4. Junction charge (capacitance)

You are provided with two options in modeling the junction capacitance of a
device. The first is to model the junction as a linear component (a constant
capacitance). The second is to model the junction using a diode depletion
model. If a non-zero value of Cgs is specified and Gscap is set to 1
linear), the gate-source junction will be modeled as a linear component.
Similarly, specifying a non-zero value for Cgd and Gdcap = 1 result in a linear
gate-drain model. A non-zero value for either Cgs or Cgd together with Gscap
= 2 (junction) or Gdcap = 2 will force the use of the diode depletion capacitance
model for that particular junction. Note, that each junction is modeled
independent of the other and hence, it is possible to model one junction as a
linear component while the other is treated nonlinearly. The junction depletion
charge and capacitance equations are summarized below.

**Gate-source junction**

For \( V_{gc} < Fc \times V_{bi} \)

\[
Q_{gs} = 2 \times V_{bi} \times Cgs \left[ 1 - \sqrt{1 - \frac{V_{gc}}{V_{bi}}} \right]
\]

\[
C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gc}} = \frac{Cgs}{\sqrt{1 - \frac{V_{gc}}{V_{bi}}}}
\]

For \( V_{gc} \geq Fc \times V_{bi} \)

\[
Q_{gs} = 2 \times V_{bi} \times Cgs \left[ 1 - \sqrt{1 - Fc} \right] + \frac{Cgs}{(1 - Fc)^{3/2}}
\]

\[
\times \left( 1 - \frac{3 \times Fc}{2} \right) \times (V_{gc} - Fc \times V_{bi}) + \frac{V_{gc}^2 - (Fc \times V_{bi})^2}{4 \times V_{bi}}
\]

\[
C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gc}} = \frac{Cgs}{(1 - Fc)^{3/2}} \times \left[ 1 - \frac{3 \times Fc}{2} + \frac{V_{gc}}{2 \times V_{bi}} \right]
\]

**Gate-drain junction**

For \( V_{gd} < Fc \times V_{bi} \)
For $V_{gd} \geq Fc \times V_{bi}$

\[
Q_{gd} = 2 \times V_{bi} \times C_{gd} \times \left[ 1 - \sqrt{1 - \frac{V_{gd}}{V_{bi}}} \right]
\]

\[
C_{gd} = \frac{\partial Q_{gd}}{\partial V_{gd}} = \frac{C_{gd}}{\sqrt{1 - \frac{V_{gd}}{V_{bi}}}}
\]

5. Gate forward conduction and breakdown

Agilent’s implementation of the Curtice quadratic model provides a few options for modeling gate conduction current between the gate-source and gate-drain junctions. The simplest model is that proposed by Curtice for his cubic polynomial model (see Curtice3). This model assumes an effective value of forward bias resistance $R_f$ and an approximate breakdown resistance $R_1$. With model parameters $Gsfwd = 1$ (linear) and $R_f$ reset to non-zero, gate-source forward conduction current is given by:

\[
I_{gs} = \frac{(V_{gs} - V_{bi})}{R_f} \quad \text{when } V_{gs} > V_{bi}
\]

\[
= 0 \quad \text{when } V_{gs} \leq V_{bi}.
\]

If $Gsfwd = 2$ (diode), the preceding expression for $I_{gs}$ is replaced with the following diode expression:

\[
I_{gs} = I_s \times \left[ \exp\left( \frac{V_{gs}}{N \times V_T} \right) - 1 \right]
\]
Similarly, with parameter Gdfwd = 1 (linear) and Rf set to non-zero, gate-drain forward conduction current is given by:

\[
I_{gd} = \frac{(V_{gd} - V_{bi})}{Rf} \quad \text{when } V_{gd} > V_{bi}
\]

\[
= 0 \quad \text{when } V_{gd} \leq V_{bi}.
\]

If Gdfwd is set to 2 (diode), the preceding expression for \(I_{gd}\) is replaced with a diode expression:

\[
I_{gd} = I_s \times \left[ \exp \left( \frac{V_{gd}}{N \times v_t} \right) - 1 \right]
\]

The reverse breakdown current \((I_{dg})\) is given by the following expression if \(R1\) is set non-zero and Gdrev = 1 (linear):

\[
I_{gd} = \frac{V_{dg} - V_b}{R1} \quad \text{when } V_{dg} \geq V_b \text{ and } V_b > 0
\]

\[
= 0 \quad \text{when } V_{dg} < V_b \text{ or } V_b \leq 0
\]

\[
V_b = V_{br} + R2 \times I_{ds}
\]

If Gdrev is set to 2, the preceding \(I_{gd}\) expression is replaced with a diode expression:

\[
I_{gd} = -I_r \times \left[ \exp \left( \frac{V_{dg} - V_b}{V_j r} \right) - 1 \right]
\]

With Gsrev = 1 (linear) and \(R1\) set to non-zero, the gate-source reverse breakdown current \(I_{gs}\) is given by the following expression:

\[
I_{gs} = \frac{(V_{sg} - V_b)}{R1} \quad \text{when } V_{sg} \geq V_{bi} \text{ and } V_b > 0
\]

\[
= 0 \quad \text{when } V_{sg} \leq V_{bi} \text{ or } V_b \leq 0
\]

If Gsrev is set to 2, the preceding \(I_{gs}\) expression is replaced with a diode expression:

\[
I_{gs} = -I_r \times \left[ \exp \left( \frac{V_{sg} - V_b}{V_j r} \right) - 1 \right]
\]

When the diode equations are both enabled, the dc model is symmetric with respect to the drain and source terminals. The ac model will also be symmetric if, in addition to the latter, \(C_{gs} = C_{gd}\).

6. Time delay

---

3-8 Curtice2_Model (Curtice-Quadratic GaAsFET Model)
This implementation models the delay as an ideal time delay. In the time domain, the drain source current for the ideal delay is given by:

\[ I_{ds}(t) = I_{ds}(V_j(t - \tau), V_{ds}(t)) \]

where \( V_j = V_{gs} \) or \( V_j = V_{gd} \) (depending on whether \( V_{ds} \) is positive or negative). In the frequency domain, only the transconductance is impacted by this delay and the familiar expression for transconductance is obtained

\[ y_m = g_m \times \exp(-j \times \omega \times \tau) \]

7. High-frequency output conductance

The series-RC network in Figure 3-1 is comprised of the parameters Crf and Rc and is included to provide a correction to the ac output conductance at a specific bias condition. At a frequency high enough such that CRF is an effective short, the output conductance of the device can be increased by the factor \( 1/R_c \). (For more on this, see [2].)

![Figure 3-1. Curtice2_Model Schematic](image)

8. Temperature Scaling

The model specifies \( T_{nom} \), the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than \( T_{nom} \), several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)
The saturation current $I_s$ scales as:

$$I_s^{\text{NEW}} = I_s \times \exp\left(\frac{T_{\text{Temp}}}{T_{\text{nom}}} - 1\right) \frac{q \times E_g}{k \times N \times T_{\text{Temp}}} + \frac{X \times \ln\left(\frac{T_{\text{Temp}}}{T_{\text{nom}}}\right)}{N}$$

The gate depletion capacitances $C_{gs}$ and $C_{gd}$ vary as:

$$C_{gs}^{\text{NEW}} = C_{gs} \left[1 + 0.5 \left[4 \times 10^{-4} (T_{\text{Temp}} - T_{\text{REF}}) - \gamma T_{\text{Temp}}\right]\right]$$

$$C_{gd}^{\text{NEW}} = C_{gd} \left[1 + 0.5 \left[4 \times 10^{-4} (T_{\text{Temp}} - T_{\text{REF}}) - \gamma T_{\text{Temp}}\right]\right]$$

where $\gamma$ is a function of the junction potential and the energy gap variation with temperature.

The gate junction potential $V_{bi}$ varies as:

$$V_{bi}^{\text{NEW}} = \frac{T_{\text{Temp}}}{T_{\text{nom}}} V_{bi} + \frac{2kT_{\text{Temp}}}{q} \ln\left(\frac{n_i}{n_i T_{\text{Temp}}}\right)$$

where $n_i$ is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

The threshold voltage $V_{to}$ varies as:

$$V_{to}^{\text{NEW}} = V_{to} + V_{totc}(T_{\text{Temp}} - T_{\text{nom}})$$

The transconductance Beta varies as:

$$\beta^{\text{NEW}} = \beta \times 1.01^{\beta_{\text{atc}}(T_{\text{Temp}} - T_{\text{nom}})}$$

If $\beta_{\text{atc}} = 0$ and $I_{ds}^{\text{NEW}} \neq 0$

$$I_{ds}^{\text{NEW}} = I_{ds} \times (1 + I_{ds}^{\text{NEW}} \times (T_{\text{Temp}} - T_{\text{nom}}))$$

9. Noise Model

Thermal noise generated by resistors $R_g$, $R_s$, and $R_d$ is characterized by the following spectral density:
\[
\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}
\]

Parameters P, R, and C model drain and gate noise sources.

\[
\frac{\langle i_d^2 \rangle}{\Delta f} = 4kT g_m P(1 + f_{NC}/f)
\]

\[
\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT C^2 \frac{\omega^2 R}{g_m}
\]

\[
\frac{\langle i_g i_d^* \rangle}{\Delta f} = 4kT j C g_s \omega \sqrt{PR} C
\]

References


Advanced_Curtice2_Model (Advanced Curtice-Quadratic GaAsFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 3-2. Advanced_Curtice2_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFET</td>
<td>N-channel model</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>PFET</td>
<td>P-channel model</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Idsmod</td>
<td>Ids model</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Vto†</td>
<td>threshold voltage</td>
<td>V</td>
<td>−2</td>
</tr>
<tr>
<td>Beta†, ††</td>
<td>transconductance</td>
<td>A/V²</td>
<td>10⁻⁴</td>
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<tr>
<td>Lambda</td>
<td>channel length modulation</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Alpha</td>
<td>hyperbolic tangent function</td>
<td>1/V</td>
<td>2.0</td>
</tr>
<tr>
<td>Tau</td>
<td>transit time under gate</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Taumdl</td>
<td>second order Bessel polynomial to model Tau effect in transient simulation</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Tnom</td>
<td>nominal ambient temperature at which these model parameters were derived</td>
<td>°C</td>
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<tr>
<td>Idstc</td>
<td>Ids temperature coefficient</td>
<td>A/Temp°C</td>
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<td>Ucrit</td>
<td>critical field for mobility degradation</td>
<td></td>
<td>0</td>
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<tr>
<td>Vgexp</td>
<td>Vgs – Vto exponent</td>
<td></td>
<td>2</td>
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<tr>
<td>Gamds</td>
<td>effective pinch-off combined with Vds</td>
<td></td>
<td>−0.01</td>
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</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area.
††† This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{t_0}ctc )</td>
<td>( V_0 ) temperature coefficient</td>
<td>V/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>( \beta_{t_0}tce )</td>
<td>drain current exponential temperature coefficient</td>
<td>%/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>( R_{gs}^{†††} )</td>
<td>gate-source resistance</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>( R_{ft}^{†††} )</td>
<td>gate-source effective forward-bias resistance</td>
<td>ohms</td>
<td>infinity‡</td>
</tr>
<tr>
<td>( G_{scap} )</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>( C_{gs}^{‡, ††} )</td>
<td>zero bias gate-source junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>( C_{gd}^{†, ††} )</td>
<td>zero bias gate-drain junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>( G_{dcap} )</td>
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<td>( F_c )</td>
<td>coefficient for forward bias depletion capacitance (diode model)</td>
<td></td>
<td>0.5</td>
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<tr>
<td>( R_{gd}^{†††} )</td>
<td>gate drain resistance</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>( R_d^{†††} )</td>
<td>drain ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>( R_g )</td>
<td>gate resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>( R_{S}^{†††} )</td>
<td>source ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>( L_d )</td>
<td>drain inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>( L_g )</td>
<td>gate inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>( L_s )</td>
<td>source inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>( C_{ds}^{††} )</td>
<td>drain-source capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>( R_{C}^{†††} )</td>
<td>used with ( C_{rf} ) to model frequency dependent output conductance</td>
<td>ohms</td>
<td>infinity‡</td>
</tr>
<tr>
<td>( C_{rf}^{†††} )</td>
<td>used with ( R_c ) to model frequency dependent output conductance</td>
<td>F</td>
<td>0.0</td>
</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
‡ This parameter value scales with Area.
‡‡ This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
### Table 3-2. Advanced_Curtice2_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gsfwd</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Gsrev</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Gdfwd</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Gdrev</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>R1†††</td>
<td>approximate breakdown resistance</td>
<td>ohms</td>
<td>infinity‡</td>
</tr>
<tr>
<td>R2†††</td>
<td>resistance relating breakdown voltage to channel current</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Vbi†</td>
<td>built-in gate potential</td>
<td>V</td>
<td>0.85</td>
</tr>
<tr>
<td>Vbr</td>
<td>gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with V&lt;sub&gt;ds&lt;/sub&gt;&lt;0)</td>
<td>V</td>
<td>10^100</td>
</tr>
<tr>
<td>Vjr</td>
<td>breakdown junction potential</td>
<td>V</td>
<td>1</td>
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<tr>
<td>I&lt;sub&gt;st&lt;/sub&gt;††</td>
<td>gate junction rev. saturation current (diode model)</td>
<td>A</td>
<td>10^-14</td>
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<tr>
<td>I&lt;sub&gt;r&lt;/sub&gt;</td>
<td>gate reverse saturation current</td>
<td>A</td>
<td>10^-14</td>
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<td>explosion current</td>
<td>A</td>
<td>1.6</td>
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<td>X&lt;sub&gt;ti&lt;/sub&gt;</td>
<td>temperature exponent for saturation current</td>
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<td>3.0</td>
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<tr>
<td>E&lt;sub&gt;g&lt;/sub&gt;</td>
<td>energy gap for temperature effect on I&lt;sub&gt;s&lt;/sub&gt;</td>
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<td>1.11</td>
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<td>gate junction emission coefficient (diode model)</td>
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<td>Fnc</td>
<td>flicker noise corner frequency</td>
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<tr>
<td>R</td>
<td>gate noise coefficient</td>
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<tr>
<td>P</td>
<td>drain noise coefficient</td>
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<td>1</td>
</tr>
<tr>
<td>C</td>
<td>gate-drain noise correlation coefficient</td>
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<td>0.9</td>
</tr>
<tr>
<td>wVgfwd</td>
<td>gate junction forward bias (warning)</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model T<sub>nom</sub> and device T<sub>emp</sub>.
†† This parameter value scales with Area.
††† This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
Table 3-2. Advanced_Curtice2_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgd</td>
<td>gate-drain reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent for file-based model parameter values</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area.
††† This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.

Notes/Equations/References

1. This model supplies values for a GaAsFET device.

\[
\frac{\langle i_d^2 \rangle}{\Delta f} = 4kT g_m P (1 + f_{NC}/f)
\]

\[
\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT C^2 g_s^2 \omega^2 R/g_m
\]

\[
\frac{\langle i_g i_d \rangle}{\Delta f} = 4kT j C g_s \omega/R
\]

Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

3. Drain-source current
The drain current in the Advanced Curtice quadratic model is based on the work of W. R. Curtice [1].

The quadratic dependence of the drain current with respect to the gate voltage is computed with the following expression in the region $V_{ds} \geq 0.0V$.

$$I_{ds} = \beta_{NEW} \times (V_{gs} - V_{toNEW})^{V_{gs}exp} \times (1 + \lambda \times V_{ds}) \times \tanh(\alpha \times V_{ds})$$

where

$$V_{toNEW} = V_{to} + Gainds \times V_{ds}$$

$$\beta_{NEW} = \beta_{NEW} / (1 + (V_{gs} - V_{toNEW} \times U_{crit})$$

Assuming symmetry, in the reverse region, the drain and source swap roles and the expression becomes:

$$I_{ds} = \beta_{NEW} \times (V_{gd} - V_{toNEW})^{V_{gd}exp} \times (1 - \lambda \times V_{ds}) \times \tanh(\alpha \times V_{ds})$$

where

$$I_{ds} = \beta_{NEW} \times (V_{gd} - V_{toNEW})^{V_{gd}exp} \times (1 + \lambda \times V_{ds}) \times \tanh(\alpha \times V_{ds})$$

where

$$V_{toNEW} = V_{to} + Gainds \times V_{ds}$$

$$\beta_{NEW} = \beta_{NEW} / (1 + (V_{gd} - V_{toNEW} \times U_{crit})$$

The drain current is set to zero in either case if the junction voltage ($V_{gs}$ or $V_{gd}$) drops below the threshold voltage $V_{to}$.

If $U_{crit}$ is not equal to 0, the temperature coefficients $V_{totc}$ and $Betatc$ are disabled.

### Curtice3_Model (Curtice-Cubic GaAsFET Model)

**Symbol**

![Symbol Image]

**Parameters**

Model parameters must be specified in SI units.

Table 3-3. Curtice3_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFET</td>
<td>N-channel model</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>PFET</td>
<td>P-channel model</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Idsmod</td>
<td>I&lt;sub&gt;ds&lt;/sub&gt; model</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Beta2</td>
<td>coefficient for pinch-off change with respect to V&lt;sub&gt;ds&lt;/sub&gt;</td>
<td>1/V</td>
<td>10&lt;sup&gt;-4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Rds0&lt;sup&gt;†††&lt;/sup&gt;</td>
<td>dc conductance at V&lt;sub&gt;gs&lt;/sub&gt;=0</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>Vout0</td>
<td>output voltage (V&lt;sub&gt;ds&lt;/sub&gt;) at which A0, A1, A2, A3 were evaluated</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Vdsdc</td>
<td>V&lt;sub&gt;ds&lt;/sub&gt; at Rds0 measured bias</td>
<td>V</td>
<td>0</td>
</tr>
<tr>
<td>Tau</td>
<td>transit time under gate</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Gamma</td>
<td>current saturation</td>
<td>1/V</td>
<td>2.0</td>
</tr>
<tr>
<td>Tnom</td>
<td>nominal ambient temperature at which these model parameters were derived</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>Idstc</td>
<td>I&lt;sub&gt;ds&lt;/sub&gt; temperature coefficient</td>
<td>A/Temp&lt;sup&gt;°&lt;/sup&gt;C</td>
<td>0</td>
</tr>
<tr>
<td>A0&lt;sup&gt;††&lt;/sup&gt;</td>
<td>cubic polynomial I&lt;sub&gt;ds&lt;/sub&gt; equation coefficient 1</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>A1&lt;sup&gt;††&lt;/sup&gt;</td>
<td>cubic polynomial I&lt;sub&gt;ds&lt;/sub&gt; equation coefficient 2</td>
<td>A/V</td>
<td>0.0</td>
</tr>
<tr>
<td>A2&lt;sup&gt;††&lt;/sup&gt;</td>
<td>cubic polynomial I&lt;sub&gt;ds&lt;/sub&gt; equation coefficient 3</td>
<td>A/V&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.0</td>
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</tbody>
</table>

† This parameter value varies with temperature based on model T<sub>nom</sub> and device Temp.

†† This parameter value scales with Area.

††† This parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_3$††</td>
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<td>A/V$^3$</td>
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<tr>
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<td>A0, A1, A2, A3 temperature coefficient</td>
<td>V/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>Betatce</td>
<td>drain current exponential temperature coefficient</td>
<td>%/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>Rin†††</td>
<td>channel resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rf†††</td>
<td>gate-source effective forward-bias resistance</td>
<td>ohms</td>
<td>infinity‡</td>
</tr>
<tr>
<td>Fc</td>
<td>forward-bias depletion capacitance coefficient (diode model)</td>
<td>F</td>
<td>0.5</td>
</tr>
<tr>
<td>Gscap</td>
<td>0=none,1=linear,2=junction,3=Statz charge,5=Statz cap</td>
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</tr>
<tr>
<td>Cgs††</td>
<td>zero-bias gate-source capacitance</td>
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<td>0.0</td>
</tr>
<tr>
<td>Cgd††</td>
<td>zero-bias gate-drain capacitance</td>
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<td>Rgd†††</td>
<td>gate drain resistance</td>
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<td>Gdcap</td>
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<td>Rd††</td>
<td>drain ohmic resistance</td>
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<td>gate resistance</td>
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<td>Rs†††</td>
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<tr>
<td>Lg</td>
<td>gate inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Ls</td>
<td>source inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Cds††</td>
<td>drain-source capacitance</td>
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<tr>
<td>Crf††</td>
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<tr>
<td>Rds†††</td>
<td>additional output resistance for RF operation</td>
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<td>infinity‡</td>
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</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area.
††† This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
Table 3-3. Curtice3_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gsfwd</td>
<td>0=none, 1=linear, 2=diode</td>
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</tr>
<tr>
<td>Gsrev</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Gdfwd</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Gdrev</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>R1†††</td>
<td>approximate breakdown resistance</td>
<td>ohms</td>
<td>infinity‡</td>
</tr>
<tr>
<td>R2†††</td>
<td>resistance relating breakdown voltage to channel current</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Vbi†</td>
<td>built-in gate potential</td>
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<td>0.85</td>
</tr>
<tr>
<td>Vbr</td>
<td>gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with (V_{ds} &lt; 0))</td>
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<td>10^{100}</td>
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<td>10^{-14}</td>
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<td>temperature exponent for saturation current</td>
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<td>flicker noise corner frequency</td>
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<td>P</td>
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† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area.
††† This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
Table 3-3. Curtice3_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>gate-drain noise correlation coefficient</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>wVgfwd</td>
<td>gate junction forward bias (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgd</td>
<td>gate-drain reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
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<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td></td>
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<td>AllParams</td>
<td>.DataAccessComponent for file-based model parameter values</td>
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</tr>
</tbody>
</table>

† This parameter value varies with temperature based on model Tnom and device Temp.
‖ This parameter value scales with Area.
‖‖ This parameter value scales inversely with Area.
§ A value of 0.0 is interpreted as infinity.

Notes/Equations/References

1. This model supplies values for a GaAsFET device.

2. The Curtice cubic model is based on the work of Curtice and Ettenberg. Curtice3_Model contains most of the features described in Curtice's original paper plus some additional features that may be turned off. The following subsections review the highlights of the model. Refer to Curtice's paper [1] for more information.

3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.
Equations/Discussion:

Drain-Source Current

The drain current in Curric3_Model is computed with the following expression:

\[ I_{ds} = I_{ds0} \times \tanh(\Gamma \times V_{ds}), \quad \text{Tau}_{NEW} = \text{Tau} + A5 \times V_{ds} \]

where

\[ I_{ds0} = [A0 + A1 \times V_1 + A2 \times V_1^2 + A3 \times V_1^3] + (V_{ds} - V_{ds_c})/R_{ds0} \]

\[ V_1 = V_{g}\left(t - \text{Tau}_{NEW}\right) \times (1 + \beta_2 \geq (V_{out0} - V_{ds})), \text{ when } V_{ds} \geq 0.0 \text{ V} \]

\[ V_1 = V_{gd}\left(t - \text{Tau}_{NEW}\right) \times (1 + \beta_2 \geq (V_{out0} + V_{ds})), \text{ when } V_{ds} < 0.0 \text{ V} \]

The latter results in a symmetrical drain-source current that is continuous at \( V_{ds} = 0.0 \text{ V} \). For values of \( V_1 \) below the internal computed maximum pinchoff voltage \( V_{pmax} \), which is the voltage at the local minimum of the function

\[ A0 + A1 \times V_1 + A2 \times V_1^2 + A3 \times V_1^3 \]

\( I_{ds0} \) is replaced with the following expression:

\[ I_{ds0} = [A0 + A1 \times \max + A2 \times V_{pmax}^2 + A3 \times V_{pmax}^3] + (V_{ds} - V_{ds_c})/R_{ds0} \]

If the \( I_{ds0} \) value is negative (for \( V_{ds} > 0.0 \text{V} \)), current is set to 0.

This implementation models the delay as an ideal time delay.

Junction Charge (Capacitance)

You are provided with two options in modeling the junction capacitance of a device. The first is to model the junction as a linear component (a constant capacitance). The second is to model the junction using a diode depletion capacitance model. If a non-zero value of \( C_{gs} \) is specified and \( G_{scap} \) is set to 1 (linear), the gate-source junction will be modeled as a linear component. Similarly, specifying a non-zero value for \( C_{gd} \) and \( G_{dcap} = 1 \) results in a linear gate-drain model. A non-zero value for either \( C_{gs} \) or \( C_{gd} \) together with \( G_{scap} = 2 \) (junction) or \( G_{dcap} = 2 \) will force the use of the diode depletion capacitance model for that particular junction. Note, that each junction is modeled independent of the other and hence, it is possible to model one junction as a linear component while the other is treated nonlinearly. The junction depletion charge and capacitance equations are summarized below.

Gate-Source Junction

For \( V_{gc} < F_c \times V_{bi} \)
$Q_{gs} = 2 \times V_{bi} \times C_{gs} \times \left[ 1 - \sqrt{1 - \frac{V_{gc}}{V_{bi}}} \right]$ 

$C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gc}} = \frac{C_{gs}}{\sqrt{1 - \frac{V_{gc}}{V_{bi}}}}$

For $V_{gc} \geq Fc \times V_{bi}$

$Q_{gs} = 2 \times V_{bi} \times C_{gs} \times \left[ 1 - \sqrt{1 - \frac{Fc}{V_{bi}}} \right] + \frac{C_{gs}}{(1 - Fc)^{3/2}} \times \left[ \left(1 - \frac{3 \times Fc}{2}\right) \times (V_{gc} - Fc \times V_{bi}) \left(\frac{V_{gc} - (Fc \times V_{bi})^2}{4 \times V_{bi}}\right)\right]$ 

$C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gc}} = \frac{C_{gs}}{(1 - Fc)^{3/2}} \times \left[ 1 - \frac{3 \times Fc}{2} \right] + \frac{V_{gc}}{2 \times V_{bi}}$

Gate-Drain Junction

For $V_{gd} < Fc \times V_{bi}$

$Q_{gd} = 2 \times V_{bi} \times C_{gd} \times \left[ 1 - \sqrt{1 - \frac{V_{gd}}{V_{bi}}} \right]$ 

$C_{gd} = \frac{\partial Q_{gd}}{\partial V_{gd}} = \frac{C_{gd}}{\sqrt{1 - \frac{V_{gd}}{V_{bi}}}}$

For $V_{gd} \geq Fc \times V_{bi}$

$Q_{gd} = 2 \times V_{bi} \times C_{gd} \times \left( 1 - \sqrt{1 - \frac{Fc}{V_{bi}}} \right) + \frac{C_{gd}}{(1 - Fc)^{3/2}} \times \left( 1 - \frac{3 \times Fc}{2} \right) \times \left( V_{gd} - Fc \times V_{bi} \right) + \frac{V_{gd}^2 - (Fc \times V_{bi})^2}{4 \times V_{bi}}$
Gate Forward Conduction and Breakdown

Agilent’s implementation of the Curtice quadratic model provides a few options for modeling gate conduction current between the gate-source and gate-drain junctions. The simplest model is that proposed by Curtice for his cubic polynomial model (see Curtice3). This model assumes an effective value of forward bias resistance $R_f$ and an approximate breakdown resistance $R_1$. With model parameters $G_{sfwd} = 1$ (linear) and $R_f$ reset to non-zero, gate-source forward conduction current is given by:

$$I_{gs} = \frac{(V_{gs} - V_{bi})}{R_f} \text{ when } V_{gs} > V_{bi}$$

$$= 0 \text{ when } V_{gs} \leq V_{bi}.$$  

If $G_{sfwd} = 2$ (diode), the preceding expression for $I_{gs}$ is replaced with the following diode expression:

$$I_{gs} = I_s \times \left[ \exp\left(\frac{V_{gs}}{N \times V_t}\right) - 1 \right]$$

Similarly, with parameter $G_{dfwd} = 1$ (linear) and $R_f$ set to non-zero, gate-drain forward conduction current is given by:

$$I_{gd} = \frac{(V_{gd} - V_{bi})}{R_f} \text{ when } V_{gd} > V_{bi}$$

$$= 0 \text{ when } V_{gd} \leq V_{bi}.$$  

If $G_{dfwd}$ is set to 2 (diode), the preceding expression for $I_{gd}$ is replaced with a diode expression:

$$I_{gd} = I_s \times \left[ \exp\left(\frac{V_{gd}}{N \times V_t}\right) - 1 \right]$$

The reverse breakdown current ($I_{gd}$) is given by the following expression if $R_1$ is set non-zero and $G_{drev} = 1$ (linear):

$$I_{gd} = \frac{V_{gd} - V_b}{R_1} \text{ when } V_{gd} \geq V_b \text{ and } V_b > 0$$

$$= 0 \text{ when } V_{gd} < V_b \text{ or } V_b \leq 0.$$  

$$V_b = V_{br} + 2 \times I_{ds}$$
If \( G_{drev} \) is set to 2, the preceding \( I_{gd} \) expression is replaced with a diode expression:

\[
I_{gd} = -I_r \times \left[ \exp \left( \frac{V_{dg} - V_b}{V_{jr}} \right) - 1 \right].
\]

With \( G_{srev} = 1 \) (linear) and \( R_1 \) set to non-zero, the gate-source reverse breakdown current \( I_{gs} \) is given by the following expression:

\[
I_{gs} = \frac{(V_{sg} - V_b)}{R_1} \quad \text{when } V_{sg} \geq V_{bi} \text{ and } V_b > 0
\]

\[
= 0 \quad \text{when } V_{sg} \leq V_{bi} \text{ or } V_b \leq 0
\]

If \( G_{srev} \) is set to 2, the preceding \( I_{gs} \) expression is replaced with a diode expression:

\[
I_{gs} = -I_r \times \left[ \exp \left( \frac{V_{sg} - V_b}{V_{jr}} \right) - 1 \right]
\]

When the diode equations are both enabled, the dc model is symmetric with respect to the drain and source terminals. The ac model will also be symmetric if, in addition to the latter, \( C_{gs} = C_{gd} \).

**High-Frequency Output Conductance**

Curtice3 Model provides the user with two methods of modeling the high frequency output conductance. The series-RC network dispersion model (Figure 3-2) is comprised of the parameters \( C_{rf} \) and \( R_{ds} \) and is included to provide a correction to the ac output conductance at a specific bias condition. At a frequency high enough such that \( C_{rf} \) is an effective short, the output conductance of the device can be increased by the factor \( 1/R_{ds} \). (Also see [2]).
Temperature Scaling

The model specifies T_{nom}, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than T_{nom}, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation current I_s scales as:

\[ I_s^{NEW} = I_s \times \exp \left( \frac{T_{\text{temp}}}{T_{\text{nom}}} - 1 \right) \]  
\[ \times \frac{q \times E_g}{k \times N \times T_{\text{temp}}} + \frac{X_{ti}}{N} \times \ln \left( \frac{T_{\text{temp}}}{T_{\text{nom}}} \right) \]

The gate depletion capacitances C_{gso} and C_{gdo} vary as:

\[ C_{gs}^{NEW} = C_{gs} \frac{1 + 0.5 \times 4 \times 10^{-4} (T_{\text{temp}} - T_{\text{REF}}) - \gamma^{T_{\text{temp}}} \gamma^{T_{\text{REF}}}}{1 + 0.5 \times 4 \times 10^{-4} (T_{\text{nom}} - T_{\text{REF}}) - \gamma^{T_{\text{nom}}}} \]

\[ C_{gd}^{NEW} = C_{gd} \frac{1 + 0.5 \times 4 \times 10^{-4} (T_{\text{temp}} - T_{\text{REF}}) - \gamma^{T_{\text{temp}}} \gamma^{T_{\text{REF}}}}{1 + 0.5 \times 4 \times 10^{-4} (T_{\text{nom}} - T_{\text{REF}}) - \gamma^{T_{\text{nom}}}} \]

where \( \gamma \) is a function of junction potential and energy gap variation with temperature.

The gate junction potential V_{bi} varies as:

\[ V_{bi}^{NEW} = V_{bi} \times \exp \left( \frac{T_{\text{temp}}}{T_{\text{nom}}} - 1 \right) \]  
\[ \times \frac{q \times E_g}{k \times N \times T_{\text{temp}}} + \frac{X_{ti}}{N} \times \ln \left( \frac{T_{\text{temp}}}{T_{\text{nom}}} \right) \]
The cubic polynomial coefficients $A_0$, $A_1$, $A_2$, and $A_3$ vary as:

\[
\begin{align*}
\Delta &= V_{\text{totc}}(\text{Temp} - T_{\text{nom}}) \\
A_0^{\text{NEW}} &= (A_0 - \Delta \times A_1 + \Delta^2 \times A_2 - \Delta^3 \times A_3) \times 1.01^{\text{Betac}(\text{Temp} - T_{\text{nom}})} \\
A_1^{\text{NEW}} &= (A_1 - 2\Delta \times A_2 + 3\Delta^2 \times A_3 - \Delta^3 \times A_3) \times 1.01^{\text{Betac}(\text{Temp} - T_{\text{nom}})} \\
A_2^{\text{NEW}} &= (A_2 - 3\Delta \times A_3) \times 1.01^{\text{Betac}(\text{Temp} - T_{\text{nom}})} \\
A_3^{\text{NEW}} &= (A_3) \times 1.01^{\text{Betac}(\text{Temp} - T_{\text{nom}})}
\end{align*}
\]

**Noise Model**

Thermal noise generated by resistors $R_g$, $R_s$ and $R_d$ is characterized by the spectral density:

\[
\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}
\]

Parameters $P$, $R$, and $C$ model drain and gate noise sources.

\[
\begin{align*}
\frac{\langle i_d^2 \rangle}{\Delta f} &= 4kT g_m \frac{P(1 + f_{NC}/f)}{g_m} \\
\frac{\langle i_d^2 \rangle}{\Delta f} &= 4kT C^2 g_s \frac{\omega^2}{g_m} R \frac{C}{g_m} \\
\frac{\langle i_g, i_d^* \rangle}{\Delta f} &= 4kT j C g_s \omega \frac{C}{R} \frac{C}{g_m}
\end{align*}
\]

**Computation of Vto Parameter**

The $V_{\text{to}}$ parameter is not used in this model. Instead, it is computed internally to avoid the discontinuous or non-physical characteristic in $i_d$ versus $v_{gs}$ if $A_0$, $A_1$, $A_2$, $A_3$ are not properly extracted.
For a given set of A's, ADS will try to find the maximum cut off voltage (Vpmax), which satisfies the following conditions:

\[ V_{pmax} < 0 \]
\[ f(V_{pmax}) = A_0 + A_1 \cdot V_{pmax} + A_2 \cdot V_{pmax}^2 + A_3 \cdot V_{pmax}^3 \leq 0 \]

first derivative of \( f(V_{pmax}) = 0 \) (inflection point)
second derivative of \( f(V_{pmax}) > 0 \) (this is a minimum)

If \( V_{pmax} \) can't be found, a warning message appears, stating that the cubic model does not pinch off.

During analysis, the following are computed:

\[ v_c = v_{gs} \cdot (1 + \text{Beta} \cdot (V_{out0} - v_{ds})) \]
\[ i_{ds} = \left((A_0 + A_1 \cdot v_c + A_2 \cdot v_c^2 + A_3 \cdot v_c^3) + \frac{(v_{ds} - V_{dsdc})}{R_{ds0}}\right) \cdot \tanh(\Gamma \cdot v_{ds}) \]

If \( i_{ds} < 0 \) then set \( i_{ds} = 0 \).
If \( i_{ds} > 0 \) and \( V_c \leq V_{pmax} \) then compute \( i_{vc} \) as follows:

\[ i_{vc} = (f(V_{pmax}) + \frac{(v_{ds} - V_{dsdc})}{R_{ds0}} \cdot \tanh(\Gamma \cdot v_{ds})) \]

If \( i_{vc} > 0 \) then set \( i_{ds} = i_{vc} \) and give a warning message stating that cubic mode does not pinch off
else set \( i_{ds} = 0 \)

To ensure the model is physical and continuous, it is important to obtain a meaningful set of A's that \( V_{pmax} \) can be found.
Devices and Models, GaAs

References


EE_FET3 (EEsof Scalable Nonlinear GaAsFet, Second Generation)

Symbol

Parameters
Model = name of an EE_FET3_Model
Ugw = unit gate width, in length units (default: 0)
N = number of gate fingers (default: 1)
Temp = device operating temperature (default: 25)
_M = number of devices in parallel (default: 1)

Range of Usage
Ugw > 0
N > 0

Notes/Equations/References
1. Ugw and N are used for scaling device instance; refer to the model for these descriptions.
**EE_FET3_Model (EEsof Scalable Nonlinear GaAsFet Model)**

**Symbol**

![Symbol Image]

**Parameters**

Model parameters must be specified in SI units.

**Table 3-4. EE_FET_3 Model Parameters**

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vto</td>
<td>zero bias threshold</td>
<td>V</td>
<td>-1.5</td>
</tr>
<tr>
<td>Gamma</td>
<td>Vds dependent threshold</td>
<td>1/V</td>
<td>0.05</td>
</tr>
<tr>
<td>Vgo</td>
<td>gate-source voltage where transconductance is a maximum</td>
<td>V</td>
<td>-0.5</td>
</tr>
<tr>
<td>Vdelt</td>
<td>controls linearization point for transconductance characteristic</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Vch</td>
<td>gate-source voltage where Gamma no longer affects I-V curves</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Gmmax</td>
<td>peak transconductance</td>
<td>S</td>
<td>$70 \times 10^{-3}$</td>
</tr>
<tr>
<td>Vdso</td>
<td>output voltage where Vds dependence disappears from equations</td>
<td>V</td>
<td>2.0</td>
</tr>
<tr>
<td>Vsat</td>
<td>drain-source current saturation</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Kapa</td>
<td>output conductance</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Peff</td>
<td>channel to backside self-heating</td>
<td>W</td>
<td>2.0</td>
</tr>
<tr>
<td>Vtso</td>
<td>subthreshold onset voltage</td>
<td>V</td>
<td>-10.0</td>
</tr>
<tr>
<td>Is</td>
<td>gate junction reverse saturation current</td>
<td>A</td>
<td>$10^{-20}$</td>
</tr>
<tr>
<td>N</td>
<td>gate junction ideality factor</td>
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<td>1.0</td>
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<tr>
<td>Ris</td>
<td>source end channel resistance</td>
<td>ohms</td>
<td>2.0</td>
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<td>Rid</td>
<td>drain end channel resistance</td>
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Table 3-4. EE_FET_3 Model Parameters (continued)

<table>
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<th>Name</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>Tau</td>
<td>gate transit time delay</td>
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<tr>
<td>Cdso</td>
<td>drain-source inter-electrode capacitance</td>
<td>F</td>
<td>$80 \times 10^{-15}$</td>
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<td>Rdb</td>
<td>dispersion source output impedance</td>
<td>ohms</td>
<td>$10^9$</td>
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<tr>
<td>Cbs</td>
<td>trapping-state capacitance</td>
<td>F</td>
<td>$1.6 \times 10^{-13}$</td>
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<tr>
<td>Vtoac</td>
<td>zero bias threshold (ac)</td>
<td>V</td>
<td>$-1.5$</td>
</tr>
<tr>
<td>Vtoactc</td>
<td>linear temperature coefficient for Vtoac</td>
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<tr>
<td>Gammaac</td>
<td>Vds dependent threshold (ac)</td>
<td>1/V</td>
<td>0.05</td>
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<td>Vdeltac</td>
<td>controls linearization point for transconductance</td>
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<td>linear temperature coefficient for Gmmax</td>
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<tr>
<td>Kapaac</td>
<td>output conductance (ac)</td>
<td>1/V</td>
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</tr>
<tr>
<td>Peffac</td>
<td>channel to backside self-heating (ac)</td>
<td>W</td>
<td>10.0</td>
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<td>Vtsoac</td>
<td>subthreshold onset voltage (ac)</td>
<td>V</td>
<td>$-10.0$</td>
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<td>Gdbm</td>
<td>additional d-b branch conductance at Vds = Vdsm</td>
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<td>0.0</td>
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<tr>
<td>Kdb</td>
<td>controls Vds dependence of additional d-b branch</td>
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<td>Vdsm</td>
<td>voltage where additional d-b branch conductance</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>C11o</td>
<td>maximum input capacitance for Vds = Vdso and Vdso &gt; Deltads</td>
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<td>$0.3 \times 10^{-12}$</td>
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<td>C11th</td>
<td>minimum (threshold) input capacitance for Vds = Vdso</td>
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<td>Vinfl</td>
<td>inflection point in C11-Vgs characteristic</td>
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### Table 3-4. EE_FET_3 Model Parameters (continued)

<table>
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<td>Deltds</td>
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<td>Lambda</td>
<td>C11-Vds characteristic slope</td>
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<td>breakdown current coefficient at threshold</td>
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<td>drain-gate voltage where breakdown source begins conducting</td>
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<td>breakdown current exponent</td>
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<td>number of device gate fingers</td>
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<tr>
<td>Tnom</td>
<td>parameter measurement temperature</td>
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<tr>
<td>Rgtc</td>
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<td>Rdtc</td>
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<td>Rstc</td>
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<td>Vtotc</td>
<td>linear temperature coefficient for pinchoff voltage</td>
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<td>Gmmaxtc</td>
<td>linear temperature coefficient for Gmmax</td>
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<td>Xti</td>
<td>saturation current temperature exponent</td>
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<td>wVgfwd</td>
<td>gate junction forward bias warning</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage warning</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgd</td>
<td>gate-drain reverse breakdown voltage warning</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage warning</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>
Notes/Equations/References

1. This model supplies values for an EE_FET3 device.

2. To prevent numerical problems, the setting of some model parameters to 0 is trapped by the simulator. The parameter values are changed:

   \[ \begin{align*}
   R_d &= 10^{-4} \\
   R_s &= 10^{-4} \\
   R_g &= 10^{-4} \\
   R_{is} &= 10^{-4} \\
   R_{id} &= 10^{-4} \\
   V_{sat} &= 0.1 \\
   P_{eff} &= 10^{-6} \\
   P_{effac} &= 10^{-6} \\
   Delt_{ds} &= 0.1 \\
   Delt_{gs} &= 0.1 \\
   I_{dsoc} &= 0.1 \\
   I_s &= 10^{-50}
   \end{align*} \]

3. The Temp parameter is only used to calculate the noise performance of this device. Temperature scaling of model parameters is not performed for this device.

4. Model parameters such as Ls, Ld, and Lg (as well as other package related parameters that are included as part of the output from the EEFET3 IC-CAP model file) are not used by the EE_FET3 device in the simulator. Only those parameters listed in Tables 3-4 are part of the EE_FET3 device. Any extrinsic devices must be added externally by the user.

Table 3-4. EE_FET_3 Model Parameters (continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
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<tr>
<td>wIdsmax</td>
<td>maximum drain-source current warning</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation warning</td>
<td>W</td>
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<tr>
<td>AllParams</td>
<td>DataAccessComponent for file-based model parameter values</td>
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</table>
Equations/Discussion

EE_FET3 is an empirical analytic model that was developed by HP EEsof for the express purpose of fitting measured electrical behavior of GaAs FETs. The model represents a complete redesign of the previous generation model EEFET1-2 and includes the following features:

- Accurate isothermal drain-source current model fits virtually all processes.
- Self-heating correction for drain-source current.
- Improved charge model more accurately tracks measured capacitance values.
- Dispersion model that permits simultaneous fitting of high-frequency conductances and dc characteristics.
- Improved breakdown model describes gate-drain current as a function of both $V_{gs}$ and $V_{ds}$.
- Well-behaved (non-polynomial) expressions permit accurate extrapolations outside of the measurement range used to extract the model.

The model equations were developed concurrently with parameter extraction techniques to ensure the model would contain only parameters that were extractable from measured data. Although the model is amenable to automated parameter extraction techniques, it was designed to consist of parameters that are easily estimated (visually) from measured data such as $g_m$-$V_{gs}$ plots. The increased number of model parameters is commensurate with the improvement in accuracy as compared with other popular empirical models. Since the model equations are all well-behaved analytic expressions, EE_FET3 possesses no inherent limitations with respect to its usable power range. HP EEsof's IC-CAP program provides the user with the capability of extracting EEFET3 models from measured data.

Drain-Source Current

The drain-source current model in EE_FET3 is comprised of various analytic expressions that were developed through examination of $g_m$ vs. bias plots on a wide class of devices from various manufacturers. The expressions below are given for $V_{ds} > 0.0$ V although the model is equally valid for $V_{ds} < 0.0$ V. The model assumes the device is symmetrical, and one need only replace $V_{gs}$ with $V_{gd}$ and $V_{ds}$ with $-V_{ds}$ in order to obtain the reverse region ($V_{ds} < 0.0$ V) equations. The $g_m$, $g_{ds}$ and $I_{ds}$ equations take on four different forms depending on the value of $V_{gs}$. 

---

3-34  Multiplicity ($M$) Parameter
relative to some of the model parameters. The $I_{ds}$ expression is continuous through at least the second derivative everywhere.

if $V_{gs} \geq V_g$ and $V_{delt} \leq 0.0$

\[ g_{mo} = Gmmax\{1 + \text{Gamma}(V_{dso} - V_{ds})\} \]

\[ I_{dso} = Gmmax\left\{V_x(V_{gs}) - \frac{(V_{go} + V_{to})}{2} + V_{ch}\right\} \]

\[ g_{dso} = -Gmmax(\text{Gamma}(V_{gs} - V_{ch})) \]

else if $V_{Delt} > 0.0$ and $V_{gs} > V_{gb}$

\[ g_{mo} = g_{mm}(V_{gb}) + m_{g_{mm}} \times (V_{gs} - V_{gb}) \]

\[ I_{dso} = g_{mm}(V_{gb}) \times (V_{gs} - V_{gb}) + \frac{m_{g_{mm}}}{2} (V_{gs} - V_{gb})^2 + I_{dsm}(V_{gb}) \]

\[ g_{dso} = \frac{\partial(g_{mm}(V_{gb}))}{\partial V_{ds}}(V_{gs} - V_{gb}) + \frac{1}{2}(V_{gs} - V_{gb})^2 \times \frac{\partial m_{g_{mm}}}{\partial V_{ds}} - \frac{\partial V_{gb}}{\partial V_{ds}} g_{mo} \]

else if $V_{gs} \leq V_t$

\[ g_{mo} = 0.0 \]

\[ I_{dso} = 0.0 \]

\[ g_{dso} = 0.0 \]

else

\[ g_{mo} = g_{mm}(V_{gs}) \]

\[ I_{dso} = I_{dsm}(V_{gs}) \]

\[ g_{dso} = \frac{Gmmax}{2} \text{Gamma}(V_{gs} - V_{ch}) \times \left\{\cos\left[\pi \times \frac{V_x(V_{gs}) - (V_{go} - V_{ch})}{V_{to} - V_{go}}\right] + 1\right\} \]
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where

\[ g_{mm}(V) = \frac{Gmmax}{2} \left[ 1 + \text{Gamma}(Vdso - V_{ds}) \right] \]

\[ \times \left\{ \cos \left[ \pi \times \frac{V_x(V) - (Vgo - Vch)}{V_{to} - Vgo} \right] + 1 \right\} \]

\[ I_{dsm}(V) = \frac{Gmmax}{2} \left[ ((Vto - Vgo)/\pi) \sin \left[ \pi \times \frac{V_x(V) - (Vgo - Vch)}{V_{to} - Vgo} \right] \right. \]

\[ + V_x(V) - (Vto - Vch) \]

\[ V_x(V) = (V - Vch) \left[ 1 + \text{Gamma}(Vdso - V_{ds}) \right] \]

\[ V_g = \frac{Vgo - Vch}{1 + \text{Gamma}(Vdso - V_{ds})} + Vch \]

\[ V_t = \frac{Vto - Vch}{1 + \text{Gamma}(Vdso - V_{ds})} + Vch \]

\[ V_{gb} = \frac{(Vgo - Vdel_t) - Vch}{1 + \text{Gamma}(Vdso - V_{ds})} + Vch \]

\[ m_{g_{mm}} = \frac{\partial g_{mm}}{\partial V} \bigg|_{V = V_{gb}} \]

\[ = -\frac{Gmmax \pi}{2(Vto - Vgo)} \left[ 1 + \text{Gamma}(Vdso - V_{ds}) \right]^2 \]

\[ \times \sin \left[ -\pi \times \frac{Vdel_t}{V_{to} - Vgo} \right] \]

\[ g_{mm}(V_{gb}) = \frac{Gmmax}{2} \left[ 1 + \text{Gamma}(Vdso - V_{ds}) \right] \]

\[ \times \left\{ \cos \left[ -\pi \times \frac{Vdel_t}{V_{to} - Vgo} \right] + 1 \right\} \]
The preceding relations for \( I_{ds}, g_{mo} \) and \( g_{dso} \) can now be substituted in the following equations that model the current saturation and output conductance. This portion of the model can be recognized from the work of Curtice [1].

These expressions do an excellent job of fitting GaAs FET I-V characteristics in regions of low power dissipation; they will also fit pulsed (isothermal) I-V characteristics. In order to model negative conductance effects due to self-heating, the thermal model of Canfield was incorporated [2]. With this final enhancement, the dc expressions for \( I_{ds} \) and associated conductances become:

\[
I_{ds}(V_{gb}) = \frac{G_{max}}{2} \left( \frac{(V_{to} - V_{go})}{\pi} \right) \sin \left[ -\pi \times \frac{V_{del} - V_{to}}{V_{to} - V_{go}} \right] + (V_{go} - V_{del} - V_{to})
\]

\[
\frac{\partial (g_{mm}(V_{gb}))}{\partial V_{ds}} = -\frac{G_{max}}{2} \text{Gamma} \left\{ \cos \left[ -\pi \times \frac{V_{del} - V_{to}}{V_{to} - V_{go}} \right] + 1 \right\}
\]

\[
\frac{\partial m_{gm}}{\partial V_{ds}} = \frac{G_{max} \pi}{(V_{to} - V_{go})} \left( \text{Gamma} \right) [1 + \text{Ganna}(V_{dso} - V_{ds})] \times \sin \left[ -\pi \times \frac{V_{del} - V_{to}}{V_{to} - V_{go}} \right]
\]

\[
\frac{\partial V_{gb}}{\partial V_{ds}} = \frac{(V_{go} - V_{del}) - V_{ch}}{[1 + \text{Gamma}(V_{dso} - V_{ds})]^2} \times \text{Gamma}
\]
Qualitatively, operation of the drain-source model can be described as follows. The $V_{ds}$ dependence of the equations is dominated by the parameters $V_{sat}$, Gamma, Kapa, and Peff. Isothermal output conductance is controlled by Gamma and Kapa. The impact of Gamma on output conductance is more significant near threshold. At $V_{gs}=V_{ch}$, the output conductance is controlled only by Kapa. The parameter Peff provides a correction to the isothermal model for modeling the self-heating effects manifested as a negative resistance on the I-V curves. The parameter $V_{sat}$ represents the drain-source voltage at which the current saturates and output conductance becomes a constant (approximately).

The overall impact of $V_{ch}$ on the I-V characteristics is second order at best, and many different values of $V_{ch}$ will provide good fits to I-V plots. For most applications encountered, it is our experience that the default value of 1.0V is an adequate value for $V_{ch}$. Similar to $V_{ch}$, $V_{dso}$ is a parameter that should be set rather than optimized. At $V_{ds}=V_{dso}$, the drain-source model collapses to a single voltage dependency in $V_{gs}$. It is recommended that the user set $V_{dso}$ to a typical $V_{ds}$ operating point in saturation. At this point, many of the parameters can be extracted right off a $I_{ds}$-$V_{gs}$ plot for $V_{ds}=V_{dso}$ or preferably, a $g_m$($dc$)-$V_{gs}$ plot at $V_{ds}=V_{dso}$.

When $V_{ds}=V_{dso}$ and Peff is set large (to disable the self-heating model), the significance of the parameters $V_{to}$, $V_{g0}$, $V_{delt}$, $G_{mmax}$ are easily understood from
a plot of $g_m^{(dc)}-V_{gs}$. $G_{m_{\text{max}}}$ is the peak constant transconductance of the model that occurs at $V_{gs}=V_{go}$. The parameter $V_{to}$ represents the gate-source voltage where $g_m$ goes to zero. If $V_{\Delta l}$ is set to a positive value, then it causes the transconductance to become linear at $V_{gs}=V_{go}-V_{\Delta l}$ with a slope equal to that of the underlying cosine function at this voltage. The parameter definitions are illustrated in Figure 3-3.

**Figure 3-3. EEFET3 $g_m-V_{gs}$ Parameters**

**Dispersion Current ($I_{db}$)**

Dispersion in a GaAs MESFET drain-source current is evidenced by the observation that the output conductance and transconductance beyond some transition frequency is higher than that inferred by the dc measurements. A physical explanation often attributed to this phenomenon is that the channel carriers are subject to being trapped in the channel-substrate and channel-surface interfaces. Under slowly varying signal conditions, the rate at which electrons are trapped in these sites is equal to the rate at which they are emitted back into the channel. Under rapidly varying signals, the traps cannot follow the applied signal and the high-frequency output conductance results.

The circuit used to model conductance dispersion consists of the devices $R_{db}$, $C_{bs}$ (these linear devices are also parameters) and the nonlinear source $I_{db}(V_{gs}, V_{ds})$. The model is a large-signal generalization of the dispersion model proposed by Golio et al. [3]. At dc, the drain-source current is just the current $I_{ds}$. At high
frequency (well above transition frequency), drain source current will be equal to
\( I_{ds}(high\ frequency) = I_{ds}(dc) + I_{db} \). Linearization of the drain-source model yields
the following expressions for \( y_{21} \) and \( y_{22} \) of the intrinsic EE\_FET3 model.

\[
y_{21} = g_{dsgs} + g_{dbgs} - \frac{g_{dbgs}}{1 + j\omega \times C_{bs}(R_{db})}
\]

\[
y_{22} = g_{dssds} + g_{dbdss} + \frac{1}{R_{db}} - \frac{\left(g_{dbds} + \frac{1}{R_{db}}\right)}{1 + j\omega \times C_{bs}(R_{db})}
\]

where

\[ g_{dsgs} = \frac{\partial I_{ds}}{\partial V_{gs}} \]
\[ g_{dssds} = \frac{\partial I_{ds}}{\partial V_{ds}} \]
\[ g_{dbgs} = \frac{\partial I_{db}}{\partial V_{gs}} \]
\[ g_{dbdss} = \frac{\partial I_{db}}{\partial V_{ds}} \]

Evaluating these expressions at the frequencies \( \omega = 0 \) and \( \omega = \infty \) produces the
following results for transconductance and output conductance:

for \( \omega = 0 \),

\[ \text{Re}\{y_{21}\} = g_m = g_{dsgs} \]
\[ \text{Re}\{y_{22}\} = g_{ds} = g_{dssds} \]

for \( \omega = \infty \),

\[ \text{Re}\{y_{21}\} = g_m = g_{dsgs} + g_{dbgs} \]
\[ \text{Re}\{y_{22}\} = g_{ds} = g_{dssds} + g_{dbdss} + \frac{1}{R_{db}} \]

Between these two extremes, the conductances make a smooth transition, the
abruptness of which is governed by the time constant \( \tau_{disp} = R_{db} \times C_{bs} \). The
frequency \( f_0 \) at which the conductances are midway between these two extremes is
defined as
The parameter Rdb should be set large enough so that its contribution to the output conductance is negligible. Unless the user is specifically interested in simulating the device near \( f_0 \), the default values of Rdb and Cbs specified in Table 3-4 will be adequate for most microwave applications.

The EE_FET3 \( I_{ds} \) model can be extracted to fit either dc or ac characteristics. In order to simultaneously fit both dc I-V and ac conductances, EE_FET3 uses a simple scheme for modeling the \( I_{db} \) current source whereby different values of the same parameters can be used in the \( I_{ds} \) equations. The dc and ac drain-source currents can be expressed as follows:

\[
I_{ds}^{dc}(\text{Voltages, Parameters}) = I_{ds}(\text{Voltages, Gmmax, Vdelt, Vto, Gamma, Kapa, Peff, Vtso, Vgo, Vch, Vdso, Vsat})
\]

\[
I_{ds}^{ac}(\text{Voltages, Parameters}) = I_{ds}(\text{Voltages, Gmmaxac, Vdeltac, Vtoac, Gammaac, Kappaac, Peффac, Vtsoac, Vgo, Vch, Vdso, Vsat})
\]

Parameters such as Vgo that do not have an ac counterpart (there is no Vgoac parameter) have been found not to vary significantly between extractions using dc measurements versus those using ac measurements. The difference between the ac and dc values of \( I_{ds} \) plus an additional term that is a function of \( V_{ds} \) only, gives the value of \( I_{db} \) for the dispersion model

\[
I_{db}(V_{gs}, V_{ds}) = I_{ds}^{ac}(V_{gs}, V_{ds}) - I_{ds}^{dc}(V_{gs}, V_{ds}) + I_{dbp}(V_{ds})
\]

where \( I_{dbp} \) and its associated conductance are given by:

for \( V_{ds} > V_{dsm} \) and \( K_{db} \neq 0 \):

\[
I_{dbp} = \frac{G_{dbm}}{K_{db}} \tan^{-1} \left( \frac{(V_{ds} - V_{dsm})}{\sqrt{K_{db}(G_{dbm})}} \right) + G_{dbm}(V_{dsm})
\]

\[
G_{dbp} = \frac{G_{dbm}}{(K_{db}(G_{dbm}(V_{ds} - V_{dsm})^2 + 1))}
\]
For $V_{ds} < -V_{dsm}$ and $Kdb \neq 0$:

$$I_{dbp} = \frac{G_{dbm}}{Kdb} \tan^{-1} \left(\frac{(V_{ds} + V_{dsm})}{Kdb(G_{dbm})} - G_{dbm} \times V_{dsm}\right)$$

$$g_{dbp} = \frac{G_{dbm}}{(Kdb(\frac{V_{ds} + V_{dsm}}{2} + 1))}$$

For $-V_{dsm} \leq V_{ds} \leq V_{dsm}$ or $Kdb = 0$:

$$I_{dbp} = G_{dbm} \times V_{ds}$$

$$g_{dbp} = G_{dbm}$$

By setting the 7 high-frequency parameters equal to their dc counterparts, the dispersion model reduces to $I_{db} = I_{dbp}$. Examination of the $I_{dbp}$ expression reveals that the additional setting of $G_{dbm}$ to 0 disables the dispersion model entirely. The $I_{dbp}$ current is a function of $V_{ds}$ only, and will impact output conductance only. However, the current function $I_{ds}^{ac}$ will impact $g_m$ and $g_{ds}$. Therefore, the model is primarily intended to use $g_m$ data as a means for tuning $I_{ds}^{ac}$. Once this fitting is accomplished, $G_{dbm}$, $Kdb$ and $V_{dsm}$ can be tuned to optimize the $g_{ds}$ fit.

Gate Charge Model

The EE_FET3 gate charge model was developed through careful examination of extracted device capacitances over bias. The model consists of simple closed form charge expressions whose derivatives fit observed bias dependencies in capacitance data. This capacitances data can be obtained directly from measured Y-parameter data.

$$C_{11} = \frac{\text{im}[y_{11}]}{\omega} = \frac{\partial q_g}{\partial V_{gs}}$$

$$C_{12} = \frac{\text{im}[y_{12}]}{\omega} = \frac{\partial q_g}{\partial V_{ds}}$$

The capacitance data is remarkably self-consistent. In other words, a single $q_g$ function's derivatives will fit both $C_{11}$ data and $C_{12}$ data. The EE_FET3 gate charge expression is:
where

\[ g(V_j) = V_j - V_{infl} + \frac{\Delta t_{ds}}{3} \log \left( \cosh \left( \frac{3}{\Delta t_{ds}} (V_j - V_{infl}) \right) \right) \]

This expression is valid for both positive and negative \( V_{ds} \). Symmetry is forced through the following smoothing functions proposed by Statz [4]:

\[ V_j = \frac{1}{2} \left( 2V_{gs} - V_{ds} + \sqrt{V_{ds}^2 + \Delta t_{ds}^2} \right) \]
\[ V_o = \sqrt{V_{ds}^2 + \Delta t_{ds}^2} \]

Differentiating the gate charge expression \( g(V_j) \) with respect to \( V_{gs} \) yields the following expression for the gate capacitance \( C_{11} \):

\[ C_{11}(V_j, V_o) = \left( \frac{(C_{11o} - C_{11th})}{2} \times g(V_j) + C_{11th} \right) \times [1 + \Lambda (V_o - V_{dso})] - C_{11sat} \times V_o \]

where

\[ g(V_j) = \frac{dg(V_j)}{dV_j} = 1 + \tanh \left( \frac{3}{\Delta t_{ds}} (V_j - V_{infl}) \right) \]

The gate transcapacitance \( C_{12} \) is defined as:
The EE_FET3 topology requires that the gate charge be subdivided between the respective charge sources \( q_{gc} \) and \( q_{gy} \). Although simulation could be performed directly from the nodal gate charge \( q_g \), division of the charge into branches permits the inclusion of the resistances \( R_{is} \) and \( R_{id} \) that model charging delay between the depletion region and the channel. EE_FET3 assumes the following form for the gate-drain charge in saturation:

\[
C_{12}(V_j, V_o) = \frac{\partial q_g}{\partial V_{ds}} = \frac{\partial q_g}{\partial V_j} \frac{\partial V_j}{\partial V_{ds}} + \frac{\partial q_g}{\partial V_o} \frac{\partial V_o}{\partial V_{ds}}
\]

\[
= C_{11}(V_j, V_o) \times \left[ \frac{V_{ds}}{\sqrt{V_{ds}^2 + \Delta t_d s^2}} - 1 \right]
\]

\[
+ \left[ g(V_j) + C_{11}th(V_j - Vinfl) \right] \times \text{Lambda}(\text{-C12sat})
\]

\[
\times \frac{V_{ds}}{\sqrt{V_{ds}^2 + \Delta t_d s^2}}
\]

The EE_FET3 topology requires that the gate charge be subdivided between the respective charge sources \( q_{gc} \) and \( q_{gy} \). Although simulation could be performed directly from the nodal gate charge \( q_g \), division of the charge into branches permits the inclusion of the resistances \( R_{is} \) and \( R_{id} \) that model charging delay between the depletion region and the channel. EE_FET3 assumes the following form for the gate-drain charge in saturation:

\[
q_{gy}(V_{gy}) = C_{gdsat}(V_{gy} + q_{gyo})
\]

which gives rise to a constant gate-drain capacitance in saturation. The gate-source charge \( q_{gc} \) can now be obtained by subtracting the latter from the gate charge equation. Smoothing functions can then be applied to these expressions in saturation in order to extend the model’s applicable bias range to all \( V_{ds} \) values.

These smoothing functions force symmetry on the \( q_{gy} \) and \( q_{gc} \) charges such that

\[
q_{gy} = q_{gc} = \frac{q_g}{2}
\]

at \( V_{gc} = V_{gy} \). Under large negative \( V_{ds} \) (saturation at the source end of the device), \( q_{gy} \) and \( q_{gc} \) swap roles:

\[
q_{gc}(V_{gc}) = C_{gdsat}(V_{gc} + q_{gco})
\]

The following continuous charge equations satisfy these constraints and are specified in terms of the gate charge:
where $f_1$ and $f_2$ are smoothing functions defined by

$$f_1 = \frac{1}{2} \left[ 1 + \tanh \left( \frac{3}{\Delta \text{E} \Delta t \Delta s} (V_{gc} - V_{gy}) \right) \right]$$

and

$$f_2 = \frac{1}{2} \left[ 1 - \tanh \left( \frac{3}{\Delta \text{E} \Delta t \Delta s} (V_{gc} - V_{gy}) \right) \right]$$

The capacitances associated with these branch charge sources can be obtained through differentiation of the $q_{gc}$ and $q_{gy}$ equations and by application of the chain rule to capacitances $C_{11}$ and $C_{12}$. The gate charge derivatives re-formulated in terms of $V_{gc}$ and $V_{gy}$ are:

$$C_{ggy} = \frac{\partial q_g}{\partial V_{gy}} = -C_{12}(V_{gc} - V_{gy})$$

$$C_{ggc} = \frac{\partial q_g}{\partial V_{gc}} = C_{11}(V_{gc} - V_{gy}) + C_{12}(V_{gc} - V_{gy})$$

The branch charge derivatives are:

$$C_{gygy} = \frac{\partial q_{gy}}{\partial V_{gy}} = \{ q_g(V_{gc} - V_{gy}) - C_{gdsat} \times V_{gc} \} \times \frac{\partial f_2}{\partial V_{gy}}$$

$$+ f_2 \times C_{ggy} + C_{gdsat} \times \left[ V_{gy} \times \frac{\partial f_1}{\partial V_{gy}} + f_1 \right]$$

$$C_{gygc} = \frac{\partial q_{gy}}{\partial V_{gc}} = \{ q_g(V_{gc} - V_{gy}) - C_{gdsat} \times V_{gc} \} \times \frac{\partial f_2}{\partial V_{gc}}$$

$$+ f_2 \times [C_{ggc} - C_{gdsat}] + C_{gdsat} \times V_{gy} \times \frac{\partial f_1}{\partial V_{gc}}$$
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\[
C_{gcgc} = \frac{\partial q_{gc}}{\partial V_{gc}} = \{q_g(V_{gc} - V_{gy}) - C_{gsat} \times V_{gy}\} \times \frac{\partial f_1}{\partial V_{gc}}
\]

\[+ f_1 \times C_{ggc} + C_{gsat} \times \left[ V_{gc} \times \frac{\partial f_2}{\partial V_{gc}} + f_2 \right] \]

\[
C_{gcgy} = \frac{\partial q_{gc}}{\partial V_{gy}} = \{q_g(V_{gc} - V_{gy}) - C_{gsat} \times V_{gy}\} \times \frac{\partial f_1}{\partial V_{gy}}
\]

\[+ f_1 \times [C_{ggg} - C_{gsat}] + C_{gsat} \times V_{gc} \times \frac{\partial f_2}{\partial V_{gy}} \]

where

\[
\frac{\partial f_1}{\partial V_{gc}} = \frac{3}{2 \times \Delta t_{ds}} \times \text{sech} \left( \frac{2 \times (V_{gc} - V_{gy})}{3 \Delta t_{ds}} \right)
\]

\[
\frac{\partial f_1}{\partial V_{gy}} = -\frac{\partial f_1}{\partial V_{gc}}
\]

\[
\frac{\partial f_2}{\partial V_{gc}} = -\frac{\partial f_1}{\partial V_{gc}}
\]

\[
\frac{\partial f_2}{\partial V_{gy}} = \frac{\partial f_1}{\partial V_{gc}}
\]

When \(V_{gs}=V_{dso}\) and \(V_{dso}>>\Delta t_{ds}\), the gate capacitance \(C_{11}\) reduces to a single voltage dependency in \(V_{gs}\). Similar to the \(I_{ds}\) model then, the majority of the important gate charge parameters can be estimated from a single trace of a plot. In this case, the plot of interest is \(C_{11}-V_{gs}\) at \(V_{ds}=V_{dso}\).

The parameter definitions are illustrated in Figure 3-4. The parameter \(\Delta t_{ds}\) models the gate capacitance transition from the linear region of the device into
saturation. Lambda models the slope of the $C_{11}-V_{ds}$ characteristic in saturation. $C_{12\text{sat}}$ is used to fit the gate transcapacitance ($C_{12}$) in saturation.

**Output Charge and Delay**

EE_FET3 uses a constant output capacitance specified with the parameter $C_{dso}$. This gives rise to a drain-source charge term of the form

$$q_{ds}(V_{ds}) = C_{dso} \times V_{ds}$$

The drain-source current previously described in this section is delayed with the parameter $\tau$ according to the following equation:

$$I_{ds}(t) = I_{ds}(V_{gs}(t-Tau), V_{ds}(t))$$

In the frequency domain, only the transconductance is impacted by this delay and the familiar expression for transconductance is obtained:

$$y_m = g_m \times \exp(-j \times \omega \times Tau)$$

**Gate Forward Conduction and Breakdown**

Forward conduction in the gate junction is modeled using a standard 2-parameter diode expression. The current for this gate-source current is:

$$I_{gs}(V_{gs}) = I_s \times \left[ e^{\frac{qV_{gs}}{nkT}} - 1 \right]$$
where \( q \) is the charge on an electron, \( k \) is Boltzmann’s constant and \( T \) is the junction temperature.

The EE_FET3 breakdown model was developed from measured dc breakdown data and includes the voltage dependency of both gate-drain and gate-source junctions. EE_FET3 models breakdown for \( V_{ds} > 0 \text{V} \) only, breakdown in the \( V_{ds} < 0 \text{V} \) region is not handled. The model consists of 4 parameters that are easily optimized to measured data. The breakdown current is given by:

\[
I_{gd}(V_{gd}, V_{gs}) = -K_{bk}\left(1 - \frac{I_{ds}(V_{gs}, V_{ds})}{I_{dsoc}}\right) \times (-V_{gd} - V_{br})^{N_{br}}
\]

for \(-V_{gd} > V_{br}\)

\[
I_{gd}(V_{gd}, V_{gs}) = 0
\]

for \(-V_{gd} \leq V_{br}\)

\(I_{dsoc}\) should be set to the maximum value attainable by \( I_{ds}\) to preclude the possibility of the gate-drain current flowing in the wrong direction.

**Scaling Relations**

Scaling of EE_FET3 model parameters is accomplished through the use of the model parameters \( U_{gw} \) and \( N_{gf} \) (see Table 3-4) and the device parameters \( U_{gw} \) (same name as the model parameter) and \( N \). From these four parameters, the following scaling relations can be defined:

\[
\begin{align*}
  sf &= \frac{U_{gw}^{new} \times N}{U_{gw}(N_{gf})} \\
  sfg &= \frac{U_{gw} \times N}{U_{gw}^{new} \times N_{gf}}
\end{align*}
\]

where \( U_{gw}^{new} \) represents the device parameter \( U_{gw} \), the new unit gate width.

Scaling will be disabled if any of the 4 scaling parameters are set to 0. The new EE_FET3 parameters are computed internally by the simulator according to the following equations:
\[ \begin{align*}
\text{Ris}^{\text{new}}_{\text{sf}} &= \text{Ris}_{\text{sf}} \\
\text{Rid}^{\text{new}}_{\text{sf}} &= \text{Rid}_{\text{sf}} \\
\text{Gmmax}^{\text{new}}_{\text{sf}} &= \text{Gmmax}(\text{sf}) \\
\text{Gmmaxac}^{\text{new}}_{\text{sf}} &= \text{Gmmaxac}(\text{sf}) \\
\text{Peff}^{\text{new}}_{\text{sf}} &= \text{Peff} \times \text{sf} \\
\text{Peffac}^{\text{new}}_{\text{sf}} &= \text{Peffac}(\text{sf}) \\
\text{Rdb}^{\text{new}}_{\text{sf}} &= \text{Rdb}_{\text{sf}} \\
\text{Gdbm}^{\text{new}}_{\text{sf}} &= \text{Gdbm}(\text{sf}) \\
\text{Kdb}^{\text{new}}_{\text{sf}} &= \text{Kdb}_{\text{sf}} \\
\text{I}_s^{\text{new}}_{\text{sf}} &= \text{I}_s \times \text{sf} \\
\text{Kbk}^{\text{new}}_{\text{sf}} &= \text{Kbk}(\text{sf}) \\
\text{Idsoc}^{\text{new}}_{\text{sf}} &= \text{Idsoc}(\text{sf}) \\
\text{Rg}^{\text{new}}_{\text{sf}} &= \text{Rg}_{\text{sf}} \\
\text{Rd}^{\text{new}}_{\text{sf}} &= \text{Rd}_{\text{sf}} \\
\text{Rs}^{\text{new}}_{\text{sf}} &= \text{Rs}_{\text{sf}} \\
\text{Cbs}^{\text{new}}_{\text{sf}} &= \text{Cbs} \times \text{sf} \\
\text{C}_{11}^{\text{new}}_{\text{sf}} &= \text{C}_{11} \times \text{sf} \\
\text{C}_{11\text{th}}^{\text{new}}_{\text{sf}} &= \text{C}_{11\text{th}} \times \text{sf} \\
\text{C}_{12\text{sat}}^{\text{new}}_{\text{sf}} &= \text{C}_{12\text{sat}} \times \text{sf} \\
\text{Cgdsat}^{\text{new}}_{\text{sf}} &= \text{Cgdsat} \times \text{sf} \\
\text{Cdso}^{\text{new}}_{\text{sf}} &= \text{Cdso} \times \text{sf}
\end{align*} \]
Temperature Scaling

The model specifies $T_{nom}$, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than $T_{nom}$, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation current $I_s$ scales as:

$$I_s^{NEW} = I_s \times \exp\left[\frac{\left(\frac{T_{temp}}{T_{nom}} - 1\right)}{k \times N \times T_{temp}} + \frac{X_{ti}}{N} \ln\left(\frac{T_{temp}}{T_{nom}}\right)\right]$$

The threshold voltage $V_{to}$ varies as:

$$V_{to}^{NEW} = V_{to} + V_{tots}(T_{temp} - T_{nom})$$

Following are additional equations for the temperature scaling parameters:

$$R_G^{NEW} = R_g((1 + R_{gtc})(T_{temp} - T_{nom}))$$

$$R_D^{NEW} = R_d((1 + R_{d tc})(T_{temp} - T_{nom}))$$

$$R_S^{NEW} = R_s((1 + R_{stc})(T_{temp} - T_{nom}))$$

$$V_{TOAC}^{NEW} = V_{toac} + V_{toactc}(T_{temp} - T_{nom})$$

$$V_{TSO}^{NEW} = V_{tso} + V_{tots}(T_{temp} - T_{nom})$$

$$V_{TSOAC}^{NEW} = V_{tsoac} + V_{tostc}(T_{temp} - T_{nom})$$

$$\Gamma^{NEW} = \Gamma (\left[\frac{T_{temp}}{T_{nom}}\right]^{\Gamma_{MAC}})$$

$$\Gamma^{MAC}^{NEW} = \Gamma^{MAC} (\left[\frac{T_{temp}}{T_{nom}}\right]^{\Gamma_{MACCTC}})$$

$$G_{MAX}^{NEW} = G_{MAX} + G_{MAXTC}(T_{temp} - T_{nom})$$

$$G_{MAXAC}^{NEW} = G_{MAXAC} + G_{MAXACTC}(T_{temp} - T_{nom})$$
\[ V_{\text{INFL}}^{\text{NEW}} = V_{\text{INFL}} + V_{\text{INFLtc}}(\text{Temp} - \text{T}_{\text{nom}}) \]

**Noise Model**

Thermal noise generated by resistors \( R_g, R_s, R_d, R_{is}, R_{id}, \) and \( R_{db} \) is characterized by the following spectral density:

\[ \frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R} \]

Channel noise generated by the dc transconductance \( g_m \) is characterized by the following spectral density:

\[ \frac{\langle i_{ds}^2 \rangle}{\Delta f} = \frac{8kTg_m}{3} \]

In these expressions, \( k \) is Boltzmann's constant, \( T \) is the operating temperature in Kelvin, \( q \) is the electron charge, and \( \Delta f \) is the noise bandwidth.

Flicker noise for this device is not modeled in this version of the simulator. However, the bias-dependent noise sources \( I_{\text{NoiseBD}} \) and \( V_{\text{NoiseBD}} \) can be connected external to the device to model flicker noise.

**Equivalent Circuit**

![Equivalent Circuit Diagram]

**Device Operating Point Data**

This model generates device operating point data during a DC simulation. The procedure for viewing device operating point data for a component is in the Circuit Simulation manual. The data that is displayed for the EE_FET3_Model (and EE_HEMT1_model) is:

\[ \begin{align*}
\text{VINFL} & \quad \text{Vinfl} \\
\text{VINFLtc} & \quad \text{Vinfltc} \\
\text{TEMP} & \quad \text{Temp} \\
\text{T}_{\text{nom}} & \quad \text{T}_{\text{nom}}
\end{align*} \]
Devices and Models, GaAs

EE_FET3       X1.A1

Id 0.167708
Ig -9.99941e-015
Is -0.167708
Power 0.838539
Gm 0.119883
Gds 0.0109841
GmAc 0.0487499
GdsAc 0.00342116
Ggs 2.31388e-017
Ggd 0
dIgd_dVgs 0
Cgc 1.40818e-012
dQgc_dVgy -2.28547e-013
Cgy 5e-014
dQgy_dVgc -4.57459e-025
Vgs -0.25
Vds 5

I. Conductance Model:
The detailed operating point analysis returns information on the internal computations of EEfet3. Since the model accounts for dynamic affects found in conductance and transconductance of GaAs devices both “dc” and “ac” operation are reported for Gm and Gds.

Gm, Gds     DC transconductance, output conductance
GmAc, GdsAC High frequency transconductance and output conductance
dIgd_dVgs  The transconductance effects of the gate-drain voltage.

References


Devices and Models, GaAs

**EE_HEMT1 (EEsof Scalable Nonlinear HEMT)**

**Symbol**

![Symbol Diagram]

**Parameters**

- Model = name of an EE_HEMT1_Model
- \( \text{Ugw} \) = new unit gate width, in length units
- \( \text{N} \) = new number of gate fingers
- \( \_M \) = number of devices in parallel (default: 1)

**Range of Usage**

- \( \text{Ugw} > 0 \)
- \( \text{N} > 0 \)

**Notes/Equations/References**

1. \( \text{Ugw} \) and \( \text{N} \) are used for scaling device instance; refer to the model for these descriptions.
EE_HEMT1_Model (EEsof Scalable Nonlinear HEMT Model)

Symbol

Parameters

Model Data parameters must be specified in SI units.

Table 3-5. EE_HEMT1_Model Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vto</td>
<td>zero bias threshold</td>
<td>V</td>
<td>−1.5</td>
</tr>
<tr>
<td>Gamma</td>
<td>Vds dependent threshold</td>
<td>1/V</td>
<td>0.05</td>
</tr>
<tr>
<td>Vgo</td>
<td>gate-source voltage where transconductance is a maximum</td>
<td>V</td>
<td>−0.5</td>
</tr>
<tr>
<td>Vdelt</td>
<td>not used</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Vch</td>
<td>gate-source voltage where Gamma no longer affects I-V curves</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Gmmax</td>
<td>peak transconductance</td>
<td>S</td>
<td>70×10⁻³</td>
</tr>
<tr>
<td>Vdso</td>
<td>output voltage where Vo dependence disappears from equations</td>
<td>V</td>
<td>2.0</td>
</tr>
<tr>
<td>Vsat</td>
<td>drain-source current saturation</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Kapa</td>
<td>output conductance</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Peff</td>
<td>channel to backside self-heating</td>
<td>W</td>
<td>2.0</td>
</tr>
<tr>
<td>Vtso</td>
<td>subthreshold onset voltage</td>
<td>V</td>
<td>−10.0</td>
</tr>
<tr>
<td>Is</td>
<td>gate junction reverse saturation current</td>
<td>A</td>
<td>10⁻²⁰</td>
</tr>
<tr>
<td>N</td>
<td>gate junction ideality factor</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Ris</td>
<td>source end channel resistance</td>
<td>ohms</td>
<td>2.0</td>
</tr>
<tr>
<td>Rid</td>
<td>drain end channel resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
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</table>
### Table 3-5. EE_HEMT1_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tau</td>
<td>gate transit time delay</td>
<td>sec</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>Cds0</td>
<td>drain-source inter-electrode capacitance</td>
<td>F</td>
<td>$80 \times 10^{-15}$</td>
</tr>
<tr>
<td>Rdb</td>
<td>dispersion source output impedance</td>
<td>ohms</td>
<td>$10^9$</td>
</tr>
<tr>
<td>Cbs</td>
<td>trapping-state capacitance</td>
<td>F</td>
<td>$1.6 \times 10^{-13}$</td>
</tr>
<tr>
<td>Vtoac</td>
<td>zero bias threshold (ac)</td>
<td>V</td>
<td>$-1.5$</td>
</tr>
<tr>
<td>Gammaac</td>
<td>V0 dependent threshold (ac)</td>
<td>s</td>
<td>$0.05$</td>
</tr>
<tr>
<td>Vdelta</td>
<td>not used</td>
<td>V</td>
<td>$0.0$</td>
</tr>
<tr>
<td>Gmmaxac</td>
<td>peak transconductance (ac)</td>
<td>S</td>
<td>$600 \times 10^{-3}$</td>
</tr>
<tr>
<td>Kapaac</td>
<td>output conductance (ac)</td>
<td>1/V</td>
<td>$0.0$</td>
</tr>
<tr>
<td>Peffac</td>
<td>channel to backside self-heating (ac)</td>
<td>W</td>
<td>$10.0$</td>
</tr>
<tr>
<td>Vtsoac</td>
<td>subthreshold onset voltage (ac)</td>
<td>V</td>
<td>$-10.0$</td>
</tr>
<tr>
<td>Gdbsm</td>
<td>additional d-b branch conductance at Vo = VDSM</td>
<td>S</td>
<td>$0.0$</td>
</tr>
<tr>
<td>Kdb</td>
<td>controls Vds dependence of additional d-b branch conductance.</td>
<td></td>
<td>$0.0$</td>
</tr>
<tr>
<td>Vdsm</td>
<td>voltage where additional d-b branch conductance becomes constant</td>
<td>V</td>
<td>$1.0$</td>
</tr>
<tr>
<td>C11o</td>
<td>maximum input capacitance for Vds=Vdso and Vdso&gt;Deltds</td>
<td>F</td>
<td>$0.3 \times 10^{-12}$</td>
</tr>
<tr>
<td>C11th</td>
<td>minimum (threshold) input capacitance for Vds=Vdso</td>
<td>F</td>
<td>$0.03 \times 10^{-12}$</td>
</tr>
<tr>
<td>Vinfl</td>
<td>inflection point in C11-Vgs characteristic</td>
<td>V</td>
<td>$-1.0$</td>
</tr>
<tr>
<td>Deltgs</td>
<td>C11th to C11o transition voltage</td>
<td>V</td>
<td>$0.5$</td>
</tr>
<tr>
<td>Deltlds</td>
<td>linear region to saturation region transition</td>
<td>V</td>
<td>$1.0$</td>
</tr>
<tr>
<td>Lambda</td>
<td>C11-Vds characteristic slope</td>
<td>1/V</td>
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</tr>
<tr>
<td>C12sat</td>
<td>input transcapacitance for Vgs=Vinfl and Vds&gt;Deltls</td>
<td>F</td>
<td>$0.03 \times 10^{-12}$</td>
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<tr>
<td>Cgdsat</td>
<td>gate drain capacitance for Vds&gt;Deltlds</td>
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</tr>
<tr>
<td>Name</td>
<td>Description</td>
<td>Unit</td>
<td>Default</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>-----------</td>
<td>---------------</td>
</tr>
<tr>
<td>Kbk</td>
<td>breakdown current coefficient at threshold</td>
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<tr>
<td>Vbr</td>
<td>drain-gate voltage where breakdown source begins conducting</td>
<td>V</td>
<td>15.0</td>
</tr>
<tr>
<td>Nbr</td>
<td>breakdown current exponent</td>
<td>-</td>
<td>2.0</td>
</tr>
<tr>
<td>Idsoc</td>
<td>open channel (maximum) value of Ids</td>
<td>A</td>
<td>$10010^{-3}$</td>
</tr>
<tr>
<td>Rd</td>
<td>drain contact resistance</td>
<td>ohms</td>
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<td>Rs</td>
<td>source contact resistance</td>
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<tr>
<td>Rg</td>
<td>gate metallization resistance</td>
<td>ohms</td>
<td>1.0</td>
</tr>
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<td>Ugw</td>
<td>unit gate width of device</td>
<td>M</td>
<td>0.0</td>
</tr>
<tr>
<td>Ngf</td>
<td>number of device gate fingers</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Vco</td>
<td>voltage where transconductance compression begins for Vds=Vdso</td>
<td>V</td>
<td>10.0</td>
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<tr>
<td>Vba</td>
<td>transconductance compression tail-off</td>
<td>V</td>
<td>1.0</td>
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<tr>
<td>Vbc</td>
<td>transconductance roll-off to tail-off transition voltage</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Mu</td>
<td>adds Vds dependence to transconductance compression onset</td>
<td></td>
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<td>Deltgm</td>
<td>slope of transconductance compression characteristic</td>
<td>S/V</td>
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<tr>
<td>Deltgmac</td>
<td>slope of transconductance compression characteristic (ac)</td>
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<td>Alpha</td>
<td>transconductance saturation to compression transition</td>
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<td>K.mod</td>
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<td>K.ver</td>
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<tr>
<td>wVgfwd</td>
<td>gate junction forward bias warning</td>
<td>V</td>
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<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage warning</td>
<td>V</td>
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<td>gate-drain reverse breakdown voltage warning</td>
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<td>wBvds</td>
<td>drain-source breakdown voltage warning</td>
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### Table 3-5. EE_HEMT1_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current warning</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation warning</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Rgutc</td>
<td>linear temperature coefficient for RG 1/degC</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Rdutc</td>
<td>linear temperature coefficient for RD 1/degC</td>
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<td></td>
</tr>
<tr>
<td>Rstc</td>
<td>linear temperature coefficient for RS 1/degC</td>
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<tr>
<td>Vtotc</td>
<td>linear temperature coefficient for pinchoff voltage</td>
<td>V/deg. C</td>
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<tr>
<td>Gmmaxtc</td>
<td>linear temperature coefficient for Gmmax</td>
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<td>Xti</td>
<td>saturation current temperature exponent</td>
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<tr>
<td>Vinfltc</td>
<td>linear temperature coefficient for Vinfl</td>
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<td>Gammatc</td>
<td>linear temperature coefficient for Gamma</td>
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<td>linear temperature coefficient for Vtoac</td>
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<td>linear temperature coefficient for Gmmaxac</td>
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<tr>
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<td>linear temperature coefficient for Gammaac</td>
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<td>Tnom</td>
<td>parameter measurement temperature</td>
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<tr>
<td>AllParams</td>
<td>DataAccessComponent for file-based model parameter values</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Notes/Equations/References

1. This model supplies values for an EE_HEMT1 device.

2. Model parameters such as Ls, Ld, and Lg (as well as other package related parameters that are included as part of the output from the EE_HEMT1 IC-CAP model file) are not used by the EE_HEMT1 component in the simulator. Only those parameters listed in Table 3-5 are part of the EE_HEMT1 component. Any extrinsic components must be added externally by the user.

3. In order to prevent numerical problems, the setting of some model parameters to 0 is trapped by the simulator. The parameter values are changed internally as follows:
   \[ Rd = 10^{-4} \]
   \[ Rs = 10^{-4} \]
   \[ Rg = 10^{-4} \]
   \[ Ris = 10^{-4} \]
   \[ Rid = 10^{-4} \]
   \[ Vsat = 0.1 \]
   \[ Peff = 10^{-6} \]
   \[ Peffac = 10^{-6} \]
   \[ Deltds = 0.1 \]
   \[ Deltgs = 0.1 \]
   \[ Idsoc = 0.1 \]
   \[ Is = 10^{-50} \]

4. Temp parameter is used to calculate the noise performance for this model.

5. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.
Equations/Discussion

EE_HEMT1 is an empirical analytic model that was developed by HP EEsof for the express purpose of fitting measured electrical behavior of HEMTs. The model includes the following features:

- Accurate isothermal drain-source current model fits virtually all processes
- Flexible transconductance formulation permits accurate fitting of \( g_m \) compression found in HEMTs
- Self-heating correction for drain-source current
- Charge model that accurately tracks measured capacitance values
- Dispersion model that permits simultaneous fitting of high-frequency conductances and dc characteristics
- Accurate breakdown model describes gate-drain current as a function of both \( V_{gs} \) and \( V_{ds} \)
- Well-behaved (non-polynomial) expressions permit accurate extrapolations outside of the measurement range used to extract the model.

The model equations were developed concurrently with parameter extraction techniques to ensure the model would contain only parameters that were extractable from measured data. Although the model is amenable to automated parameter extraction techniques, it was designed to consist of parameters that are easily estimated (visually) from measured data such as \( g_m-V_{gs} \) plots. The increased number of model parameters is commensurate with the improvement in accuracy as compared with other popular empirical models. Since the model equations are all well behaved analytic expressions, EE_HEMT1 possesses no inherent limitations with respect to its usable power range. With the parameters \( V_{delt} \) and \( V_{deltac} \) set to zero, EE_FET3 becomes a subset of EE_HEMT1. The linear transconductance region modeled with the parameter \( V_{delt} \) in EE_FET3 is omitted from EE_HEMT1 and replaced with a series of parameters designed to model transconductance compression. HP EEsof’s IC-CAP program provides the user with the capability of extracting EE_HEMT1 models from measured data.

Drain-Source Current

The drain-source current model in EE_HEMT1 is comprised of various analytic expressions that were developed through examination of \( g_m \) versus bias plots on a wide class of devices from various manufacturers. The expressions below are given for \( V_{ds} > 0.0V \) although the model is equally valid for \( V_{ds} < 0.0V \). The model
assumes the device is symmetrical, and one need only replace $V_{gs}$ with $V_{gd}$ and $V_{ds}$ with $-V_{ds}$ in order to obtain the reverse region ($V_{ds} < 0.0V$) equations. The $g_m$, $g_{ds}$ and $I_{ds}$ equations take on four different forms depending on the value of $V_{gs}$ relative to some of the model parameters. The $I_{ds}$ expression is continuous through at least the second derivative everywhere.

if $V_{gs} \geq V_g$

$$g_{mo} = G_{m_{max}}(1 + \Gamma(V_{ds} - V_{ds}))$$

$$I_{ds} = G_{m_{max}} \left\{ V_x(V_{gs}) - \frac{(V_{go} + V_{to})}{2} + V_{ch} \right\}$$

$$g_{ds} = -G_{m_{max}} \times \Gamma(V_{gs} - V_{ch})$$

else if $V_{gs} \leq V_t$

$$g_{mo} = 0.0$$

$$I_{ds} = 0.0$$

$$g_{ds} = 0.0$$

else

$$g_{mo} = g_{mm}(V_{gs})$$

$$I_{ds} = I_{ds_{m}}(V_{gs})$$

$$g_{ds} = \frac{-G_{m_{max}}}{2} \Gamma(V_{gs} - V_{ch})$$

$$\times \left\{ \cos \left[ \pi \times \frac{V_{ch} - (V_{gs}) - (V_{go} - V_{ch})}{V_{to} - V_{go}} \right] + 1 \right\}$$

where
The following voltages define regions of operation that are used in the $g_m$ compression terms:

\[ V_c = V_{co} + Mu \times (V_{dso} - V_{ds}) \]
\[ V_b = V_{bc} + V_c \]
\[ V_a = V_b - V_{ba} \]

For $V_{gs} > V_c$, the basic $I_{ds}$, $g_m$, and $g_{dso}$ relations are modified as follows:

For $V_{gs} < V_b$,

\[ g_{mo}^{\text{comp}} = g_{mo} - g_{mv}(V_{gs}, V_{ds}) \]
\[ I_{dso}^{\text{comp}} = I_{dso} - I_{dsv}(V_{gs}, V_{ds}) \]
\[ g_{dso}^{\text{comp}} = g_{dso} - g_{dsv}(V_{gs}, V_{ds}) \]

for $V_{gs} \geq V_b$ and $b \neq -1$. 

\[ g_{mm}(V) = \frac{G_{m_{max}}}{2} \left[ 1 + \text{Gamma}(V_{dso} - V_{ds}) \right] \]

\[ \times \left\{ \cos \left[ \pi \times \frac{V_x(V) - (V_{go} - V_{ch})}{V_{to} - V_{go}} \right] + 1 \right\} \]

\[ I_{dsm}(V) = \frac{G_{m_{max}}}{2} \left[ (V_{to} - V_{go}) \sin \left[ \pi \times \frac{V_x(V) - (V_{go} - V_{ch})}{V_{to} - V_{go}} \right] \right. \]

\[ + V_x'(V) - (V_{to} - V_{ch}) \left. \right] \]

\[ V_x(V) = (V - V_{ch}) \left[ 1 + \text{Gamma}(V_{dso} - V_{ds}) \right] \]

\[ V_g = \frac{V_{go} - V_{ch}}{1 + \text{Gamma}(V_{dso} - V_{ds})} + V_{ch} \]

\[ V_t = \frac{V_{to} - V_{ch}}{1 + \text{Gamma}(V_{dso} - V_{ds})} + V_{ch}. \]
\( g_{mo}^{\text{comp}} = g_{mo} - [a(V_{gs} - V_a)^b + g_{moff}] \)

\( I_{dso}^{\text{comp}} = I_{dso} - \frac{a}{b + 1}[V_{gs} - V_a]^{b + 1} - V_{ba}^{b + 1} - g_{moff} \times (V_{gs} - V_b) \)

\(-I_{dsv}(V_{b} - V_{ds})\)

\( g_{dso}^{\text{comp}} = g_{dso} - M \mu a(V_{gs} - V_a)^b + g_{moff} \) - \( g_{dsv}(V_{b} - V_{ds}) \)

for \( V_{gs} \geq V_b \) and \( b = -1 \),

\( g_{mo}^{\text{comp}} = g_{mo} - [a(V_{gs} - V_a)^b + g_{moff}] \)

\( I_{dso}^{\text{comp}} = I_{dso} - a[\log(V_{gs} - V_a) - \log(V_{ba})] - g_{moff} \times (V_{gs} - V_b) \)

\(-I_{dsv}(V_{b} - V_{ds})\)

\( g_{dso}^{\text{comp}} = g_{dso} - \frac{M\mu a(V_{gs} - V_a)^b}{(V_{gs} - V_a)} - M \mu \times g_{moff} - g_{dsv}(V_{b} - V_{ds}) \)

where

\( a = \frac{g_{mv}(V_{b} - V_{ds}) - g_{moff}}{V_{ba}^b} \)

\( b = \frac{s_{vb} \times V_{ba}}{g_{mv}(V_{b} - V_{ds}) - g_{moff}} \)

\( s_{vb} = \Delta \text{lgm} \times \frac{V_{bc}}{\sqrt{\text{Alpha}^2 + V_{bc}^2}} \)

\( g_{mv}(V_{b} - V_{ds}) = \Delta \text{lgm} \times \left[ \frac{1}{2} \right] \left[ \frac{\text{Alpha}^2 + (V - V_c)^2}{\text{Alpha}^2 + (V - V_c)^2} - \text{Alpha} \right] \)

\( I_{dsv}(V_{b} - V_{ds}) = \Delta \text{lgm} \times \left[ \frac{1}{2} \right] \left[ (V - V_c) \sqrt{\text{Alpha}^2 + (V - V_c)^2} \right] \)
- $\alpha^2 \times \log \left[ \frac{(V - V_c) + \sqrt{\alpha^2 + (V - V_c)^2}}{\alpha} \right]$

- $\alpha \times (V - V_c)^2$

$$g_{dsV}(V, V_{ds}) = \Delta \text{tg} \times \mu \left[ \frac{1}{2} \left( \frac{2(V - V_c)^2 + \alpha^2}{\sqrt{\alpha^2 + (V - V_c)^2}} \right) \right]$$

$$+ \frac{\alpha^2}{(V - V_c) + \sqrt{\alpha^2 + (V - V_c)^2}}$$

$$\times \left[ 1 + \frac{(V - V_c)}{\sqrt{\alpha^2 + (V - V_c)^2}} \right] - \alpha$$

$g_{m0} = g_{m0}(V_{co}, V_{dso})$

To prevent $g_m$ from becoming negative at high gate-source biases, the following restriction is placed on the parameter $\Delta \text{tg}$:

$$\Delta \text{tg} < \frac{g_{m0}}{\sqrt{\alpha^2 + V_{bc}^2} - \alpha}$$

The preceding relations for $g_{dsV}^\text{comp}$, $g_{mo}^\text{comp}$ and $g_{dso}^\text{comp}$ can now be substituted in the following equations that model current saturation and output conductance. This portion of the model can be recognized from the work of Curtice [1].

$$g_m = g_{mo}^\text{comp} (1 + \kappa a \times V_{ds}) \tanh \frac{3V_{ds}}{V_{sat}}$$

$$I_{ds} = I_{dso}^\text{comp} (1 + \kappa a \times V_{ds}) \tanh \frac{3V_{ds}}{V_{sat}}$$
These expressions do an excellent job of fitting HEMT I-V characteristics in regions of low power dissipation. They will also fit pulsed (isothermal) I-V characteristics. To model negative conductance effects due to self-heating, the thermal model of Canfield was incorporated [2]. With this final enhancement, the dc expressions for $I_{ds}$ and its associated conductances become:

$$g_{ds} = \left\{ g_{ds0}^\text{comp} (1 + K\text{apa} \times V_{ds}) + I_{ds0}^\text{comp} K\text{apa} \right\} \tanh \left( \frac{3V_{ds}}{V_{sat}}\right)$$

$$+ I_{ds0}^\text{comp} \times \frac{3(1 + K\text{apa} \times V_{ds})}{V_{sat}} \sech \left( \frac{3V_{ds}}{V_{sat}}\right)$$

These expressions do an excellent job of fitting HEMT I-V characteristics in regions of low power dissipation. They will also fit pulsed (isothermal) I-V characteristics. To model negative conductance effects due to self-heating, the thermal model of Canfield was incorporated [2]. With this final enhancement, the dc expressions for $I_{ds}$ and its associated conductances become:

$$I_{ds} = \frac{l_{ds}^\text{'}p_{\text{diss}}}{1 + P_{\text{diss}}/P_{\text{eff}}}$$

$$g_{m} = \left\{ \frac{g_{m}^{\text{'}p_{\text{diss}}^{2}}}{1 + P_{\text{diss}}^{2}/P_{\text{eff}}} \right\}$$

$$g_{ds} = \frac{g_{ds}^\text{'}l_{ds}^2}{1 + P_{\text{diss}}^{2}/P_{\text{eff}}}$$

where

$$P_{\text{diss}} = l_{ds}^\text{'}V_{ds}$$

Qualitatively, the operation of the drain-source model can be described as follows. The $V_{ds}$ dependence of the equations is dominated by the parameters $V_{sat}$, Gamma, Kapa, and $P_{eff}$. Isothermal output conductance is controlled by Gamma and Kapa. The impact of Gamma on output conductance is more significant near threshold. At $V_{gs}=V_{ch}$, the output conductance is controlled only by Kapa. $P_{eff}$ provides a correction to the isothermal model for modeling the self-heating effects manifested as a negative resistance on the I-V curves. $V_{sat}$ represents the drain-source voltage at which the current saturates and output conductance becomes a constant (approximately). Mu also impacts the I-V curves in the $g_{m}$
compression region, but its effect is second order. In most cases, the $g_m$ fit is more sensitive to the parameter $M_u$.

The overall impact of $V_{ch}$ on the I-V characteristics is second order at best, and many different values of $V_{ch}$ will provide good fits to I-V plots. For most applications encountered, the default value of 1.0V is an adequate value for $V_{ch}$.

Similar to $V_{ch}$, $V_{dso}$ is a parameter that should be set rather than optimized. At $V_{ds}=V_{dso}$, the drain-source model collapses to a single voltage dependency in $V_{gs}$. It is recommended that the user set $V_{dso}$ to a typical $V_{ds}$ operating point in saturation. At this point, many of the parameters can be extracted from a $I_{ds}-V_{gs}$ plot for $V_{ds}=V_{dso}$ or, preferably, a $g_m(dc)-V_{gs}$ plot at $V_{ds}=V_{dso}$.

When $V_{ds}=V_{dso}$ and $P_{eff}$ is set large (to disable the self-heating model), the significance of $V_{to}$, $V_{gmax}$, $V_{co}$, $V_{ba}$, $V_{bc}$, $Deltgm$ and $Alpha$ are easily understood from a plot of $g_m(dc)-V_{gs}$. $Gmmax$ is the peak transconductance of the model that occurs at $V_{gs}=V_{gmax}$. $V_{to}$ represents the gate-source voltage where $g_m$ goes to zero. Transconductance compression begins at $V_{gs}=V_{co}$. $Alpha$ controls the abruptness of this transition while $Deltgm$ controls the slope of the $g_m$ characteristic in compression. At $V_{gs}=V_{co}+V_{bc}$, the linear $g_m$ slope begins to tail-off and asymptotically approach zero. The shape of this tail-off region is controlled by $V_{ba}$. The parameter definitions are illustrated in Figure 3-5.

![Figure 3-5. EE.HEMT1 gm-Vgs Parameters](image)

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3-66  Multiplicity (_M) Parameter
Dispersion Current (Idb)

Dispersion in a GaAs MESFET or HEMT drain-source current is evidenced by the observation that the output conductance and transconductance beyond some transition frequency is higher than that inferred by the dc measurements. A physical explanation often attributed to this phenomenon is that the channel carriers are subject to being trapped in the channel-substrate and channel-surface interfaces. Under slowly varying signal conditions, the rate at which electrons are trapped in these sites is equal to the rate at which they are emitted back into the channel. Under rapidly varying signals, the traps cannot follow the applied signal and the high-frequency output conductance results.

The circuit used to model conductance dispersion consists of the Rdb, Cbs (these linear components are also parameters) and the nonlinear source Idb(Vgs, Vds). The model is a large-signal generalization of the dispersion model proposed by Golio et al. [3]. At dc, the drain-source current is just the current Ids. At high frequency (well above the transition frequency), the drain source current will be equal to Ids(high frequency) = Ids(dc) + Idb. Linearization of the drain-source model yields the following expressions for y21 and y22 of the intrinsic EE_HEMT1 model:

\[
y_{21} = g_{ds} + g_{ds} - \frac{g_{dbs}}{1 + j\omega \times C_{bs}(R_{db})}
\]

\[
y_{22} = g_{ds} + g_{db} + \frac{1}{R_{db}} - \left( \frac{g_{dbs}}{1 + j\omega \times C_{bs}(R_{db})} \right)
\]

where

\[
g_{ds} = \frac{\partial I_{ds}}{\partial V_{gs}}
\]

\[
g_{ds} = \frac{\partial I_{ds}}{\partial V_{ds}}
\]

\[
g_{db} = \frac{\partial I_{db}}{\partial V_{gs}}
\]

\[
g_{db} = \frac{\partial I_{db}}{\partial V_{ds}}
\]
Evaluating these expressions at the frequencies $\omega=0$ and $\omega=\infty$, produces the following results for transconductance and output conductance:

for $\omega=0$,

\[ \text{Re}\{y_{21}\} = g_m = g_{\text{ds}\text{gs}} \]
\[ \text{Re}\{y_{22}\} = g_d = g_{\text{dsd}s} \]

for $\omega=\infty$,

\[ \text{Re}\{y_{21}\} = g_m = g_{\text{ds\text{gs}}\text{gs}} + g_{\text{dbs}} \]
\[ \text{Re}\{y_{22}\} = g_d = g_{\text{dss}\text{ds}} + g_{\text{dsbds}} + \frac{1}{R_{\text{db}}} \]

Between these two extremes, the conductances make a smooth transition, the abruptness of which is governed by the time constant $\tau_{\text{disp}} = R_{\text{db}} \times C_{\text{bs}}$. The frequency $f_0$ at which the conductances are midway between these two extremes is defined as

\[ f_0 = \frac{1}{2\pi\tau_{\text{disp}}} \]

The parameter $R_{\text{db}}$ should be set large enough so that its contribution to the output conductance is negligible. Unless the user is specifically interested in simulating the device near $f_0$, the default values of $R_{\text{db}}$ and $C_{\text{bs}}$ will be adequate for most microwave applications.

The EE_HEMT1 $I_{ds}$ model can be extracted to fit either dc or ac characteristics. In order to simultaneously fit both dc $I$-$V$ characteristics and ac conductances, EE_HEMT1 uses a simple scheme for modeling the $I_{db}$ current source whereby different values of the same parameters can be used in the $I_{ds}$ equations. The dc and ac drain-source currents can be expressed as follows:

\[ I_{ds}^{\text{dc}} (\text{Voltages, Parameters}) = I_{ds} (\text{Voltages, Gmmax, Vdelt, Vto, Gamma, Kapa, Peff, Vtso, Deltgm, Vgo, Vdso, Vsat} \]
\[ I_{ds}^{\text{ac}} (\text{Voltages, Parameters}) = I_{ds} (\text{Voltages, Gmmaxac, Vdeltac, Vto, Gammaac, Kapaac, Peffac, Vtsoac, Deltgmac, Vgo, Vch, Vdso, Vsat} \]
Parameters such as Vgo that do not have an ac counterpart (there is no Vgoac parameter) have been found not to vary significantly between extractions utilizing dc measurements versus those using ac measurements. The difference between the ac and dc values of Ids, plus an additional term that is a function of Vds only, gives the value of Id for the dispersion model

\[ I_{db}(V_{gs}, V_{ds}) = I_{ds}^{ac}(V_{gs}, V_{ds}) - I_{ds}^{dc}(V_{gs}, V_{ds}) + I_{dbp}(V_{ds}) \]

where \( I_{dbp} \) and its associated conductance are given by:

for \( V_{ds} > V_{dsm} \) and \( K_{db} \neq 0 \):

\[ I_{dbp} = \frac{G_{dbm}}{K_{db}} \tan^{-1} \left( (V_{ds} - V_{dsm}) \sqrt{K_{db}(G_{dbm})} + G_{dbm} \times V_{dsm} \right) \]

\[ g_{dbp} = \frac{G_{dbm}}{(K_{db}(G_{dbm}(V_{ds} - V_{dsm})^2 + 1))} \]

for \( V_{ds} \leq V_{dsm} \) and \( K_{db} \neq 0 \):

\[ I_{dbp} = \frac{G_{dbm}}{K_{db}} \tan^{-1} \left( (V_{ds} + V_{dsm}) \sqrt{K_{db}(G_{dbm})} - G_{dsm} \times V_{dsn} \right) \]

\[ g_{dbp} = \frac{(G_{dbm})}{(K_{db}(G_{dbm}(V_{ds} + V_{dsm})^2 + 1))} \]

for \( -V_{dsm} \leq V_{ds} \leq V_{dsm} \) or \( K_{db} = 0 \):

\[ I_{ds} = G_{dbm} \times V_{ds} \]

\[ g_{dbm} = G_{dbm} \]

By setting the eight high-frequency parameters equal to their dc counterparts, the dispersion model reduces to \( I_{db} = I_{dbp} \). Examination of the \( I_{dbp} \) expression reveals that the additional setting of Gdbm to zero disables the dispersion model entirely. Since the \( I_{dbp} \) current is a function of \( V_{ds} \) only, it will impact output conductance only. However, the current function

\[ I_{ds}^{AC} \]
will impact both $g_m$ and $g_{ds}$. For this reason, the model is primarily intended to utilize $g_m$ data as a means for tuning

\[
\frac{AC}{ds}
\]

Once this fitting is accomplished, the parameters $G$dbm, $K$db and $V$ds$m$ can be tuned to optimize the $g_{ds}$ fit.

**Gate Charge Model**

The EE_HEMT1 gate charge model was developed through careful examination of extracted device capacitances over bias. The model consists of simple closed form charge expressions whose derivatives fit observed bias dependencies in capacitance data. This capacitance data can be obtained directly from measured $Y$-parameter data:

\[
C_{11} = \frac{\text{im}[y_{11}]}{\omega} = \frac{\partial q_g}{\partial V_{gs}}
\]

\[
C_{12} = \frac{\text{im}[y_{12}]}{\omega} = \frac{\partial q_g}{\partial V_{ds}}
\]

The capacitance data is remarkably self-consistent. In other words, a single $q_g$ function's derivatives will fit both $C_{11}$ data and $C_{12}$ data. The EE_HEMT1 gate charge expression is:

\[
q_g(V_j, V_o) = \left[ \frac{C_{11o} - C_{11th}}{2} g(V_j) + C_{11th}(V_j - V_{infl}) \right]
\]

\[\times [1 + \Lambda mbda(V_o - Vdso)] - C_{12sat} \times V_o \]

where

\[
g(V_j) = V_j - V_{infl} + \frac{\Delta lgs}{3} \ln \left( \cosh \left( \frac{3}{\Delta lgs} (V_j - V_{infl}) \right) \right)
\]

This expression is valid for both positive and negative $V_{ds}$. Symmetry is forced through the following smoothing functions proposed by Statz [4]:

3-70  Multiplicity (_M) Parameter
\[
V_j = \frac{1}{2} \left( 2V_{gs} - V_{ds} + \sqrt{V_{ds}^2 + \Delta t d_{ds}^2} \right)
\]
\[
V_o = \sqrt{V_{ds}^2 + \Delta t d_{ds}^2}
\]

Differentiating the gate charge expression wrt \( V_{gs} \) yields the following expression for the gate capacitance \( C_{11} \):

\[
C_{11}(V_j, V_o) = \left[ \frac{C_{11o} - C_{11th}}{2} g(V_j) + C_{11th} \right] \times [1 + \text{Lambda}(V_o - V_{ds0})]
\]

where

\[
g(V_j) = \frac{\partial g(V_j)}{\partial V_j} = 1 + \tanh \left[ \frac{3}{\Delta t d_{gs}} (V_j - V_{infl}) \right]
\]

The gate transcapacitance \( C_{12} \) is defined as:

\[
C_{12}(V_j, V_o) = \frac{\partial q_g}{\partial V_{ds}} = \frac{\partial q_g}{\partial V_j} \frac{\partial V_j}{\partial V_{ds}} + \frac{\partial q_g}{\partial V_o} \frac{\partial V_o}{\partial V_{ds}}
\]

\[
= C_{11}(V_j, V_o) \times \frac{1}{2} \left[ \frac{V_{ds}}{\sqrt{V_{ds}^2 + \Delta t d_{ds}^2}} - 1 \right]
\]

\[
+ \left[ \frac{C_{11o} - C_{11th}}{2} g(V_j - V_{infl}) \right]
\]

\[
\times \text{Lambda} - C_{12sat} \times \frac{V_{ds}}{\sqrt{V_{ds}^2 + \Delta t d_{ds}^2}}
\]

The EE_HEMT1 topology requires that the gate charge be subdivided between the respective charge sources \( q_{gc} \) and \( q_{gy} \). Although simulation could be performed directly from the nodal gate charge \( q_g \), division of the charge into branches permits the inclusion of the resistances \( R_{is} \) and \( R_{id} \) that model charging delay between the depletion region and the channel. EE_HEMT1 assumes the following form for the gate-drain charge in saturation:

\[
q_{gy}(V_{gy}) = C_{gdsat} \times (V_{gy} + q_{gyo})
\]
which gives rise to a constant gate-drain capacitance in saturation.

The gate-source charge \( q_{gs} \) can now be obtained by subtracting the latter from the gate charge equation. Smoothing functions can then be applied to these expressions in saturation in order to extend the model’s applicable bias range to all \( V_{ds} \) values. These smoothing functions force symmetry on the \( q_{gy} \) and \( q_{gc} \) charges such that

\[
q_{gy} = q_{gc} = \frac{q_g}{2}
\]

at \( V_{gc} = V_{gy} \). Under large negative \( V_{ds} \) (saturation at the source end of the device), \( q_{gy} \) and \( q_{gc} \) swap roles, i.e:

\[
q_{gc}(V_{gc}) = C_{gdsat} \times (V_{gc} + q_{gco})
\]

The following continuous charge equations satisfy these constraints and are specified in terms of the gate charge:

\[
q_{gy}(V_{gc}, V_{gy}) = (q_g(V_{gc} - V_{gy}) - C_{gdsat} \times V_{gc}) \times f_2 + C_{gdsat} \times V_{gy} \times f_1
\]

\[
q_{gc}(V_{gc}, V_{gy}) = (q_g(V_{gc} - V_{gy}) - C_{gdsat} \times V_{gy}) \times f_1 + C(G_{gdsat}) \times V_{gc} \times f_2
\]

where \( f_1 \) and \( f_2 \) are smoothing functions defined by

\[
f_1 = \frac{1}{2} \left[ 1 + \tanh \left( -\frac{3}{\Delta V_{ds}} (V_{gc} - V_{gy}) \right) \right]
\]

and

\[
f_2 = \frac{1}{2} \left[ 1 - \tanh \left( -\frac{3}{\Delta V_{ds}} (V_{gc} - V_{gy}) \right) \right]
\]

The capacitances associated with these branch charge sources can be obtained through differentiation of the \( q_{gc} \) and \( q_{gy} \) equations and by application of the chain rule to the capacitances \( C_{11} \) and \( C_{12} \). The gate charge derivatives re-formulated in terms of \( V_{gc} \) and \( V_{gy} \) are:
The branch charge derivatives are:

\[ C_{gy} = \frac{\partial q_g}{\partial V_{gy}} = -C_{12}(V_{gc} - V_{gy}) \]
\[ C_{gc} = \frac{\partial q_g}{\partial V_{gc}} = C_{11}(V_{gc} - V_{gy}) + C_{12}(V_{gc} - V_{gy}) \]

The branch charge derivatives are:

\[ C_{gy} = \frac{\partial q_g}{\partial V_{gy}} = \{q_g(V_{gc} - V_{gy}) - C_{gdsat} \times V_{gc}\} \times \frac{\partial f_2}{\partial V_{gy}} + f_2 \times C_{gy} + C_{gdsat} \times \left[V_{gy} \times \frac{\partial f_1}{\partial V_{gy}} + f_1\right] \]

\[ C_{gc} = \frac{\partial q_g}{\partial V_{gc}} = \{q_g(V_{gc} - V_{gy}) - C_{gdsat} \times V_{gc}\} \times \frac{\partial f_2}{\partial V_{gc}} + f_2 \times [C_{gc} - C_{gdsat}] + C_{gdsat} \times V_{gy} \times \frac{\partial f_1}{\partial V_{gc}} \]

\[ C_{gc} = \frac{\partial q_g}{\partial V_{gc}} = \{q_g(V_{gc} - V_{gy}) - C_{gdsat} \times V_{gc}\} \times \frac{\partial f_1}{\partial V_{gc}} + f_1 \times C_{gc} + C_{gdsat} \times V_{gc} \times \frac{\partial f_2}{\partial V_{gc}} + f_2\]
When $V_{ds} = V_{dso}$ and $V_{dso} \gg \Delta t_{ds}$, the gate capacitance $C_{11}$ reduces to a single voltage dependency in $V_{gs}$. Similar to the $I_{ds}$ model, the majority of the important gate charge parameters can then be estimated from a single trace of a plot. In this case, the plot of interest is $C_{11}$-$V_{gs}$ at $V_{ds} = V_{dso}$. The parameter definitions are illustrated in Figure 3-6.

The parameter $\Delta t_{ds}$ models the gate capacitance transition from the linear region of the device into saturation. Lambda models the slope of the $C_{11}$-$V_{ds}$ characteristic in saturation. $C_{12\text{sat}}$ is used to fit the gate transcapacitance ($C_{12}$) in saturation.

$$
\frac{\partial f_1}{\partial V_{gc}} = \frac{3}{2 \times \Delta t_{ds}} \text{sech} \left( \frac{3(V_{gc} - V_{gy})}{\Delta t_{ds}} \right)
$$

Output Charge and Delay

$EE\_HEMT1$ uses a constant output capacitance specified with the parameter $C_{dso}$. This gives rise to a drain-source charge term of the form
The drain-source current described previously, is delayed with the parameter TAU according to the following equation:
\[ I_{ds}(t) = I_{ds}(V_{gs}(t - TAU), V_{ds}(t)) \]

In the frequency domain, only the transconductance is impacted by this delay and the familiar expression for transconductance is obtained
\[ y_m = g_m \times \exp(-j \times \omega \times Tau) \]

**Gate Forward Conduction and Breakdown**

Forward conduction in the gate junction is modeled using a standard 2-parameter diode expression. The current for this gate-source current is:
\[ I_{gs}(V_{gs}) = I_S \times \left[ \frac{qV_{gs}}{nkT} \right] - 1 \]

where \( q \) is the charge on an electron, \( k \) is Boltzmann’s constant, and \( T \) is the junction temperature.

The EE_HEMT1 breakdown model was developed from measured dc breakdown data and includes the voltage dependency of both gate-drain and gate-source junctions. EE_HEMT1 models breakdown for \( V_{ds} > 0V \) only, breakdown in the \( V_{ds} < 0V \) region is not handled. The model consists of four parameters that are easily optimized to measured data. The breakdown current is given by:

for \( -V_{gd} > V_{br} \)
\[ I_{gd}(V_{gd}, V_{gs}) = -Kb_k \left[ I - \frac{I_{ds}(V_{gs}, V_{ds})}{I_{dsoc}} \right] \times (-V_{gd} - V_{br})^{N_{br}} \]

for \( -V_{gd} \leq V_{br} \)
\[ I_{gd}(V_{gd}, V_{gs}) = 0 \]

Some care must be exercised in setting \( I_{dsoc} \). This parameter should be set to the maximum value attainable by \( I_{ds} \). This precludes the possibility of the gate-drain current flowing in the wrong direction.
Scaling Relations

Scaling of EE_HEMT1 model parameters is accomplished through model parameters $U_{gw}$ and $N_{gf}$ and device parameters $U_{gw}$ (same name as the model parameter) and $N$. From these four parameters, the following scaling relations can be defined:

$$s_f = \frac{U_{gw}^{new} \times N}{U_{gw} \times N_{gf}}$$

$$s_{fg} = \frac{U_{gw} \times N}{U_{gw}^{new} \times N_{gf}}$$

where $U_{gw^{new}}$ represents the device parameter $U_{gw}$, the new unit gate width.

Scaling will be disabled if any of the four scaling parameters are set to 0. The new EE_HEMT1 parameters are computed internally by the simulator according to the following equations:

$$R_{is}^{new} = \frac{R_{is}}{s_f}$$

$$R_{id}^{new} = \frac{R_{id}}{s_f}$$

$$G_{mmmax}^{new} = G_{mmmax} \times s_f$$

$$G_{mmmaxac}^{new} = G_{mmmaxac} \times s_f$$

$$D_{tgm}^{new} = D_{tgm} \times s_f$$

$$D_{tgmac}^{new} = D_{tgmac} \times s_f$$

$$P_{eff}^{new} = P_{eff} \times s_f$$

$$P_{effac}^{new} = P_{effac} \times s_f$$

$$R_{db}^{new} = \frac{R_{db}}{s_f}$$

$$G_{dbm}^{new} = G_{dbm} \times s_f$$

$$K_{db}^{new} = \frac{K_{db}}{s_f}$$

$$I_{s}^{new} = I_{s} \times s_f$$

---

3-76 Multiplicity (_M) Parameter
Thermal noise generated by resistors $R_g$, $R_s$, $R_d$, $R_{is}$, $R_{id}$, and $R_{db}$ is characterized by the following spectral density.

$$\frac{<i^2_i>}{\Delta f} = \frac{4kT}{R}$$

Channel noise generated by the dc transconductance $g_m$ is characterized by the following spectral density:

$$\frac{<i^2_{ds}>}{\Delta f} = \frac{8kT g_m}{3}$$

In the preceding expressions, $k$ is Boltzmann's constant, $T$ is the operating temperature in Kelvin, $q$ is the electron charge, and $\Delta f$ is the noise bandwidth.

Flicker noise for this device is not modeled in this version of the simulator. However, the bias-dependent noise sources $I_{\text{NoiseBD}}$ and $V_{\text{NoiseBD}}$ can be connected external to the device to model flicker noise.
The model specifies $T_{nom}$, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than $T_{nom}$, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation current $I_s$ scales as:

$$I_s^{\text{NEW}} = I_s \times \exp \left[ \frac{T_{\text{Temp}}}{T_{\text{Nom}}} - 1 \right] \frac{q \times E_g}{k \times N \times T_{\text{Temp}}} + \frac{Xt_i}{N} \times \ln \left( \frac{T_{\text{Temp}}}{T_{\text{Nom}}} \right)$$

The threshold voltage $V_{to}$ varies as:

$$V_{to}^{\text{NEW}} = V_{to} + V_{tocc}(\text{Temp} - T_{\text{nom}})$$

Following are additional equations for the temperature scaling parameters:

$$R_G^{\text{NEW}} = R_g((1 + R_{gtc})(\text{Temp} - T_{\text{nom}}))$$

$$R_D^{\text{NEW}} = R_d((1 + R_{d tc})(\text{Temp} - T_{\text{nom}}))$$

$$R_S^{\text{NEW}} = R_s((1 + R_{stc})(\text{Temp} - T_{\text{nom}}))$$

$$V_{T\text{OAC}}^{\text{NEW}} = V_{toac} + V_{tocc}(\text{Temp} - T_{\text{nom}})$$

$$V_{T\text{SO}}^{\text{NEW}} = V_{tso} + V_{tocc}(\text{Temp} - T_{\text{nom}})$$

$$V_{T\text{SOAC}}^{\text{NEW}} = V_{tsoac} + V_{tocc}(\text{Temp} - T_{\text{nom}})$$

$$\Gamma_{\text{MA}}^{\text{NEW}} = \Gamma_{\text{MA}} \left( \frac{T_{\text{Temp}}}{T_{\text{Nom}}} \right)$$

$$\Gamma_{\text{MAAC}}^{\text{NEW}} = \Gamma_{\text{MAAC}} \left( \frac{T_{\text{Temp}}}{T_{\text{Nom}}} \right)$$

$$\Gamma_{\text{MAX}}^{\text{NEW}} = \Gamma_{\text{MAX}} + \Gamma_{\text{MAXTC}}(\text{Temp} - T_{\text{nom}})$$

$$\Gamma_{\text{MAXAC}}^{\text{NEW}} = \Gamma_{\text{MAXAC}} + \Gamma_{\text{MAXACTC}}(\text{Temp} - T_{\text{nom}})$$
\[ \text{VINFL}^{\text{NEW}} = \text{Vinfl} + \text{Vinfltc}(\text{Temp} - \text{Tnom}) \]

**Equivalent Circuit**

![Equivalent Circuit Diagram]

**References**


**GaAsFET (Nonlinear Gallium Arsenide FET)**

**Symbol**

![GaAsFET Symbol](image)

**Parameters**

- **Model** = name of a GaAsFET model
- **Area** = scaling factor that scales certain parameter values of the associated model item (default: 1.0)
- **Temp** = device operating temperature, in °C (default: 25)
- **Mode** = simulation mode for this device: linear; nonlinear (default: nonlinear) (refer to Note 3)
- **M** = number of devices in parallel (default: 1)

**Range of Usage**

Area > 0

**Notes/Equations/References**

1. Advanced_Curtice2_Model, Curtice2_Model, Curtice3_Model, Materka_Model, Modified_Materka_Model, Statz_Model, and Tajima_Model are the nonlinear model items that define the GaAsFET.

2. The Area parameter permits changes to a specific semiconductor because semiconductors may share the same model.
   - Parameters scaled proportionally to Area: A0, A1, A2, A3, Beta, Cgs, Cgd, Cgs, Cds, Ios.
   - Resistive parameters scaled inversely proportional to Area: Rd, Rg, Rs. For example, Model = Curtice2 and Area=3 use the following computations:
These computations have the same effect as placing three devices in parallel to simulate a larger device and are much more efficient.

3. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.

4. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated model item) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to the appropriate model to see which parameter values are scaled.

5. This device has no default artwork associated with it.
HP_FET (HP_Root FET)

Symbol

Parameters
Model = name of an HP_FET model
Wtot = total device gate width, in length units (default: 10^-4)
N = number of device gate fingers (default: 1)
_M = number of devices in parallel (default: 1)

Range of Usage
N/A

Notes/Equations/References
1. If Wtot or N is specified as Rawfile value or zero, the default gate width as
   specified in the model file is used. For other values, these values can be used to
   scale the extracted model for different geometries. The scaling remains valid for
   ratios up to 5:1.
2. Wtot is the total gate width—not the width per finger; the parameter N is the
   number of fingers; therefore, the width per finger is Wtot/N.
3. Currents and capacitances scale linearly with gate width
   \[ I = I_0 \times \frac{W_{\text{tot}}}{W_0} \]
   \[ C = C_0 \times \frac{W_{\text{tot}}}{W_0} \]
   
   The parasitic resistances scale as:
   \[ R_g = R_{G0} \frac{W_{\text{tot}}}{W_0} \left( \frac{N_0}{N} \right)^2 \]
   \[ R_d = R_{D0} \times \frac{W_0}{W_{\text{tot}}} \]
\[ R_s = R_{S0} \times \frac{W_0}{W_{tot}} \]

where \( W_{tot} \) and \( N \) are the user-specified values and \( W_0 \) and \( N_0 \) are the extracted values given in HP_FET_Model. The parasitic inductances do not scale.

4. Care should be taken when using the transistor outside of the region at which the model measurements were taken. Extrapolation of the measured data may occur without warning during dc, harmonic balance, and time-domain analyses. This extrapolated data may produce unreliable results.

5. HP_FET currents can be measured with the standard current measurements, except that pins must be specified by number instead of name; for example, 1=G, 2=D, 3=S.

6. The HP_FET cannot be temperature scaled and is noiseless.
HP_FET_Model (HP Root Model GaAsFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 3-6. HP_FET_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>File</td>
<td>name of file containing measured data</td>
<td></td>
<td>rawfile value</td>
</tr>
<tr>
<td>Rs</td>
<td>source resistance (overrides extracted value)</td>
<td>ohms</td>
<td>rawfile value</td>
</tr>
<tr>
<td>Rg</td>
<td>gate resistance (overrides extracted value)</td>
<td>ohms</td>
<td>rawfile value</td>
</tr>
<tr>
<td>Rd</td>
<td>drain resistance (overrides extracted value)</td>
<td>ohms</td>
<td>rawfile value</td>
</tr>
<tr>
<td>Ls</td>
<td>source inductance (overrides extracted value)</td>
<td>H</td>
<td>rawfile value</td>
</tr>
<tr>
<td>Lg</td>
<td>gate inductance (overrides extracted value)</td>
<td>H</td>
<td>rawfile value</td>
</tr>
<tr>
<td>Ld</td>
<td>drain inductance (overrides extracted value)</td>
<td>H</td>
<td>rawfile value</td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent for file-based model parameter values</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes/Equations/References

1. This model supplies values for an HP_FET device.
2. The default extension for the model file is .raw. This file should be in the same format as HP Root model data.
3. If Rs, Rg, Rd, Ls, Lg, or Ld is specified as rawfile value or zero, the default parasitic value is taken from the extracted values stored in the data file named by File parameter. Generally, rawfile value should be used.
4. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.
5. Because this model is measurement-based, extrapolation warning messages may occur if the Newton iteration exceeds the measurement range. If these messages occur frequently, check that the measurement data is within the simulation range.

6. For a list of HP Root Model references, refer to “HP_Diode_Model (HP_Root Diode Model)” on page 1-12.
Materka Model (Materka GaAsFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 3-7. Materka Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFET</td>
<td>N-channel model</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>PFET</td>
<td>P-channel model</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Idsmod</td>
<td>Ids model</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Idss</td>
<td>saturation drain current</td>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>Vto†</td>
<td>threshold voltage</td>
<td>V</td>
<td>−2</td>
</tr>
<tr>
<td>Alpha</td>
<td>hyperbolic tangent function</td>
<td>V</td>
<td>2</td>
</tr>
<tr>
<td>Beta2</td>
<td>coefficient for pinch-off change with respect to Vds</td>
<td>1/V</td>
<td>0</td>
</tr>
<tr>
<td>Tau</td>
<td>transit time under gate</td>
<td>sec</td>
<td>0</td>
</tr>
<tr>
<td>Lambda</td>
<td>channel length modulation</td>
<td>1/V</td>
<td>0</td>
</tr>
<tr>
<td>Rin</td>
<td>channel resistance</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>Fc</td>
<td>coefficient for forward bias depletion capacitance (diode model)</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Gscap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td>linear</td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
‡ Parameter value scales with Area.
‡‡ Parameter value scales inversely with Area.
‡‡‡ A value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cgs</td>
<td>zero bias gate-source junction capacitance</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>Gd-cap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Cgd</td>
<td>zero bias gate-drain junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Rd</td>
<td>drain ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rg</td>
<td>gate resistance</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Rs</td>
<td>source resistance</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Ld</td>
<td>drain inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Lg</td>
<td>gate inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Ls</td>
<td>source inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Gs-fw</td>
<td>0-none, 1=linear, 2=diode</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Gs-rev</td>
<td>0-none, 1=linear, 2=diode</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Gd-fw</td>
<td>0-none, 1=linear, 2=diode</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Gd-rev</td>
<td>0-none, 1=linear, 2=diode</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Vbi</td>
<td>built-in gate potential</td>
<td>V</td>
<td>0.85</td>
</tr>
<tr>
<td>Vjr</td>
<td>gate-drain junction reverse bias breakdown voltage ( (\text{gate-source junction reverse bias breakdown voltage with } V_{ds} &lt; 0) )</td>
<td>V</td>
<td>0.025</td>
</tr>
<tr>
<td>Is</td>
<td>gate junction reverse saturation current (diode model)</td>
<td>A</td>
<td>(10^{-14})</td>
</tr>
<tr>
<td>Ir</td>
<td>gate reverse saturation current</td>
<td>A</td>
<td>(10^{-14})</td>
</tr>
<tr>
<td>Imax</td>
<td>explosion current</td>
<td>A</td>
<td>1.6</td>
</tr>
<tr>
<td>N</td>
<td>gate junction ideality factor (diode model)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vbr</td>
<td>gate junction reverse bias breakdown voltage</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
‡‡ Parameter value scales with Area.
‡‡‡ Parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
### Table 3-7. Materka_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fnc</td>
<td>flicker noise corner frequency</td>
<td>Hz</td>
<td>$10^{100}$</td>
</tr>
<tr>
<td>R</td>
<td>gate noise coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>P</td>
<td>drain noise coefficient</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>gate-drain noise correlation coefficient</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Taumdl</td>
<td>second order Bessel polynomial to model tau effect in transient simulation</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Tnom</td>
<td>nominal ambient temperature at which these model parameters were derived</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>wVgfwd</td>
<td>gate junction forward bias (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgd</td>
<td>gate-drain reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent for file-based model parameter values</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
†† Parameter value scales with Area.
††† Parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.

### Notes/Equations/References

1. This model supplies values for a GaAsFET device.

\[
\frac{\langle i_d^2 \rangle}{\Delta f} = 4kT g_m P (1 + f_{NC}/f)
\]

\[
\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT g_s^2 \omega^2 R / g_m
\]
3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

4. The drain current in Materka_Model is computed with the following expression:
   \[
   V_p = V_{to} + \text{Beta2} \times V_{ds}
   \]
   if \((V_{fc} - V_p \leq 0 \text{ or } V_p \geq 0)\)
   else
   \[
   T_I = \text{ABS (Alpha} \times V_{ds})
   \]
   \[
   \text{TanhF} = \text{tanh} (T_I/(V_{gc} - V_p))
   \]
   \[
   I_{ds} = I_{dss} \times \left(\frac{V_{gc}}{V_p} - 1\right)^2 \times \text{TanhF} \times (1 + \text{Lambda} \times V_{ds})
   \]


\[
\frac{\langle i_g, i_d^* \rangle}{\Delta f} = 4kT_j \ C_{gs} \ \omega_{\omega} / \sqrt{PR} \ C
\]
**Mesfet_Form (Symbolic MESFET Model)**

**Symbol**

![Symbol](image)

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFET</td>
<td>N-channel model</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>PFET</td>
<td>P-channel model</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Idsmod</td>
<td>Ids model</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Ids</td>
<td>user-defined equation for drain-source current</td>
<td></td>
<td>See Notes</td>
</tr>
<tr>
<td>Qgs</td>
<td>user-defined equation for gate-source charge</td>
<td>V</td>
<td>See Notes</td>
</tr>
<tr>
<td>Qgd</td>
<td>user-defined equation for gate-drain charge</td>
<td>1/V</td>
<td>See Notes</td>
</tr>
<tr>
<td>Igd</td>
<td>user-defined equation for gate-drain current</td>
<td>1/V</td>
<td>See Notes</td>
</tr>
<tr>
<td>Igs</td>
<td>user-defined equation for gate-source current</td>
<td>1/V</td>
<td>See Notes</td>
</tr>
<tr>
<td>Beta</td>
<td>transconductance</td>
<td>A/V^2</td>
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</tr>
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<td>Lambda</td>
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<td>doping tail extending</td>
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<td>nominal ambient temperature</td>
<td>ohms</td>
<td>25</td>
</tr>
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<td>Idstc</td>
<td>IDS temperature coefficient</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>Vbi</td>
<td>built-in gate potential</td>
<td>V</td>
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</tr>
<tr>
<td>Tau</td>
<td>transit time under gate</td>
<td>S</td>
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</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Unit</td>
<td>Default</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>------</td>
<td>---------</td>
</tr>
<tr>
<td>Rds0</td>
<td>DC conductance at $V_{gs} = 0$</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Betatce</td>
<td>BETA exponential temperature coefficient</td>
<td>%/deg. C</td>
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</tr>
<tr>
<td>Delta1</td>
<td>capacitance transition voltage</td>
<td>V</td>
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</tr>
<tr>
<td>Delta2</td>
<td>capacitance threshold transition voltage</td>
<td>V</td>
<td>0.2</td>
</tr>
<tr>
<td>Gscap</td>
<td>$0 = \text{none}, 1 = \text{linear}, 2 = \text{junction}, 3 = \text{Statz Charge}, 4 = \text{Symbolic}, 5 = \text{Statz Cap}$</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Gdcap</td>
<td>$0 = \text{none}, 1 = \text{linear}, 2 = \text{junction}, 3 = \text{Statz Charge}, 4 = \text{Symbolic}, 5 = \text{Statz Cap}$</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Cgs</td>
<td>zero-bias G-S junction cap</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgd</td>
<td>zero-bias G-D junction cap</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Rgs</td>
<td>G-S resistance</td>
<td>Ohm</td>
<td>0.0</td>
</tr>
<tr>
<td>Rgd</td>
<td>gate drain resistance</td>
<td>Ohm</td>
<td>0.0</td>
</tr>
<tr>
<td>Rf</td>
<td>G-S effective forward-bias resistance ($0 = \infty$)</td>
<td>Ohm</td>
<td>0.0</td>
</tr>
<tr>
<td>Tqm</td>
<td>temperature coefficient for triquint junction capacitance</td>
<td>Ohm</td>
<td>0.2</td>
</tr>
<tr>
<td>Vmax</td>
<td>maximum junction voltage before capacitance limiting</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Fc</td>
<td>coefficient for forward-bias depletion cap</td>
<td>Ohm</td>
<td>fixed at 0</td>
</tr>
<tr>
<td>Rd</td>
<td>drain ohmic resistance</td>
<td>Ohm</td>
<td>fixed at 0</td>
</tr>
<tr>
<td>Rg</td>
<td>gate resistance</td>
<td>Ohm</td>
<td>fixed at 0</td>
</tr>
<tr>
<td>Rs</td>
<td>Source ohmic resistance</td>
<td>Ohm</td>
<td>fixed at 0</td>
</tr>
<tr>
<td>Ld</td>
<td>drain inductance</td>
<td>H</td>
<td>fixed at 0</td>
</tr>
<tr>
<td>Lg</td>
<td>gate inductance</td>
<td>H</td>
<td>fixed at 0</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Unit</td>
<td>Default</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>------</td>
<td>---------</td>
</tr>
<tr>
<td>LS</td>
<td>source inductance</td>
<td>H</td>
<td>fixed at 0</td>
</tr>
<tr>
<td>CDs</td>
<td>drain-source cap</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>CRf</td>
<td>used with RC to model frequency-dependent output conductance</td>
<td>F</td>
<td>$10^{100}$</td>
</tr>
<tr>
<td>Rc</td>
<td>used with CRC to model frequency-dependent output conductance ($0 = \infty$)</td>
<td>Ohm</td>
<td>0.5</td>
</tr>
<tr>
<td>Gsfwd</td>
<td>$0 = \text{none}, 1 = \text{linear}, 2 = \text{diode}$</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Gdfwd</td>
<td>$0 = \text{none}, 1 = \text{linear}, 2 = \text{diode}$</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Gsrev</td>
<td>$0 = \text{none}, 1 = \text{linear}, 2 = \text{diode}, 3 = \text{custom}$</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Gdrev</td>
<td>gate junction forward bias warning</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Vjr</td>
<td>breakdown junction potential</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>IS</td>
<td>gate-junction saturation current</td>
<td>A</td>
<td>1.0e-14</td>
</tr>
<tr>
<td>Ir</td>
<td>gate rev saturation current</td>
<td>A</td>
<td>1.0e-14</td>
</tr>
<tr>
<td>Imax</td>
<td>expression current</td>
<td>A</td>
<td>1.6</td>
</tr>
<tr>
<td>Xti</td>
<td>saturation current temperature exponent</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>gate junction emission coefficient</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Eg</td>
<td>energy tap for temperature effect on IS</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>Vbr</td>
<td>gate junction reverse bias breakdown voltage ($0 = \infty$)</td>
<td>V</td>
<td>1e100</td>
</tr>
<tr>
<td>Vt0tc</td>
<td>VTO temperature coefficient</td>
<td>V/deg. C</td>
<td>0.0</td>
</tr>
<tr>
<td>Rin</td>
<td>channel resistance</td>
<td>Ohm</td>
<td>0.0</td>
</tr>
<tr>
<td>Taumdl</td>
<td>use 2nd order Bessel polynomial to model tau effect in transient</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Fnc</td>
<td>flicker noise corner frequency</td>
<td>Hertz</td>
<td>0.0</td>
</tr>
<tr>
<td>R</td>
<td>gate noise coefficient</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>gate-drain noise correlation coefficient</td>
<td>0.9</td>
<td></td>
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<tr>
<td>P</td>
<td>drain noise coefficient</td>
<td>1.0</td>
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Table 3-8. Mesfet_Form Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>wVgfwd</td>
<td>gate junction forward bias (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgd</td>
<td>gate-drain reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvd</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent for file-based model parameter values</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes/Equations References

1. The following equations are the default settings for some of the parameters:

   \[ I_{ds} = (100ma)^{((1+\_v2)^2)\text{tanh}(\_v1)} \]
   \[ Q_{gs} = (1pf)^{\_v1} - (1pf) \times ((\_v2) - (\_v1))^{(\_v1)} \]
   \[ Q_{gd} = (1prf)^{\_v1} - ((\_v2) - (\_v1))^{(\_v1)} \]
   \[ I_{gd} = \text{ramp} \left( (10 + (\_v1)) / 10 \right) \]
   \[ I_{gs} = \text{ramp} \left( (10 + (\_v1)) / 10 \right) \]
Modified_Materka_Model (Modified Materka GaAsFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 3-9. Modified_Materka_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFET</td>
<td>N-channel model</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>PFET</td>
<td>P-channel model</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Idsmod</td>
<td>Ids model</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Idss</td>
<td>saturation drain current</td>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>Vto</td>
<td>threshold voltage</td>
<td>V</td>
<td>-2</td>
</tr>
<tr>
<td>Beta2</td>
<td>coefficient for pinch-off change with respect to Vds</td>
<td>1/V</td>
<td>2</td>
</tr>
<tr>
<td>Ee</td>
<td>exponent defining dependence of saturation current</td>
<td>1/V</td>
<td>2</td>
</tr>
<tr>
<td>Ke</td>
<td>description of dependence on gate voltage</td>
<td>1/V</td>
<td>0</td>
</tr>
<tr>
<td>Kg</td>
<td>dependence on Vgs of drain slope in linear region</td>
<td>1/V</td>
<td>0</td>
</tr>
<tr>
<td>SI</td>
<td>linear region slope of Vgs-0 drain characteristic</td>
<td>S</td>
<td>1</td>
</tr>
<tr>
<td>Ss</td>
<td>saturation region drain slope characteristic at vgs=0</td>
<td>S</td>
<td>0</td>
</tr>
<tr>
<td>Tau</td>
<td>transit time under gate</td>
<td>sec</td>
<td>0</td>
</tr>
<tr>
<td>Rgs</td>
<td>channel resistance</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>Rgd</td>
<td>gate drain resistance</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>Fc</td>
<td>coefficient for forward bias depletion capacitance (diode model)</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
‡ Parameter value scales with Area.
‡‡ Parameter value scales inversely with Area.
‡‡‡ Parameter value varies with temperature based on model Tnom and device Temp.
‡ A value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gscap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cgs</td>
<td>zero bias gate-source junction capacitance</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>Gdcap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cgd</td>
<td>zero bias gate-drain junction capacitance</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>Rd</td>
<td>drain ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rg</td>
<td>gate resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rs</td>
<td>source ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Ld</td>
<td>drain inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Lg</td>
<td>gate inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Ls</td>
<td>source inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Cds</td>
<td>drain-source capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Gsfwd</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gsrev</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gdfwd</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gdrev</td>
<td>0=none, 1=linear, 2=diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vbi†</td>
<td>built-in gate potential</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Vjr</td>
<td>gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with V_{ds} &lt; 0)</td>
<td>V</td>
<td>0.025</td>
</tr>
<tr>
<td>Is</td>
<td>gate junction saturation current (diode model)</td>
<td>A</td>
<td>10^{-14}</td>
</tr>
<tr>
<td>Ir</td>
<td>gate reverse saturation current</td>
<td>A</td>
<td>10^{-14}</td>
</tr>
<tr>
<td>Imax</td>
<td>explosion current</td>
<td>A</td>
<td>1.6</td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model T_{nom} and device Temp.  
 †† Parameter value scales with Area.  
 ††† Parameter value scales inversely with Area.  
‡ A value of 0.0 is interpreted as infinity.
### Notes/Equations/References

1. This model supplies values for a GaAsFET device.

\[
\frac{\langle i_d^2 \rangle}{\Delta f} = 4 kT g_m P (1 + f_{NC} / f)
\]
3. The drain current in Modified_Materka_Model is computed with the following expression:

\[ V_p = V_{to} + \text{Beta2} \times V_{ds} \]

if (V_{fc} - V_p \leq 0 or V_p \geq 0)

and \( I_{ds} = 0 \)

else

\[ \text{power0} = \left( 1 - \frac{V_{gc}}{V_p} \right) \left( E + K \times V_{gc} \right) \]

\[ f_i = I_{dss} \times \text{power0} \]

\[ g_i = \tanh \left( S \times V_{ds} / (I_{dss} \times (1 - K \times V_{gc})) \right) \]

\[ h_i = 1 + S \times V_{ds} / I_{dss} \]

\[ I_{ds} = f_i \times g_i \times h_i \]

4. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

**Statz_Model (Statz Raytheon GaAsFET Model)**

**Symbol**

![Symbol Image]

**Parameters**

Model parameters must be specified in SI units.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFET</td>
<td>N-channel type</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>PFET</td>
<td>P-channel type</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Idsmod</td>
<td>Statz model</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Vto††</td>
<td>threshold voltage</td>
<td>V</td>
<td>–2</td>
</tr>
<tr>
<td>Beta†, ††</td>
<td>transconductance</td>
<td>A/V²</td>
<td>10⁻⁴</td>
</tr>
<tr>
<td>Lambda</td>
<td>output conductance</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Alpha</td>
<td>current saturation</td>
<td>1/V</td>
<td>2.0</td>
</tr>
<tr>
<td>B</td>
<td>controls $I_{ds}-V_{gs}$ characteristic transition from quadratic to linear behavior (b in Statz’s paper)</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Tnom</td>
<td>nominal ambient temperature at which these model parameters were derived</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>Idstc</td>
<td>$I_{ds}$ temperature coefficient</td>
<td>A/Temp°C</td>
<td>0</td>
</tr>
<tr>
<td>Vbi††</td>
<td>built-in gate potential</td>
<td>V</td>
<td>0.85</td>
</tr>
<tr>
<td>Tau</td>
<td>transit time under gate</td>
<td>sec</td>
<td>0.0</td>
</tr>
</tbody>
</table>

† Parameter value scales with Area.
†† Parameter value varies with temperature based on model Tnom and device Temp.
††† Value of 0.0 is interpreted as infinity.
‡ Parameter value scales inversely with Area.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>BetaTce</td>
<td>drain current exponential temperature coefficient</td>
<td>%/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>Delta1</td>
<td>capacitance saturation transition voltage</td>
<td>V</td>
<td>0.3</td>
</tr>
<tr>
<td>Delta2</td>
<td>capacitance threshold transition voltage</td>
<td>V</td>
<td>0.2</td>
</tr>
<tr>
<td>Gscap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>GdCap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Cgs†, ††</td>
<td>zero bias gate-source junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>GdCap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Cgd†, ††</td>
<td>zero bias gate-drain junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Rgd‡</td>
<td>gate drain resistance</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>Tqm</td>
<td>junction capacitance temperature coefficient</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>Vmax</td>
<td>maximum junction voltage before capacitance limiting</td>
<td>V</td>
<td>0.5</td>
</tr>
<tr>
<td>Fc</td>
<td>coefficient for forward bias depletion capacitance (diode model)</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Rd ‡</td>
<td>drain ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rg</td>
<td>gate resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rs‡</td>
<td>source ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Ld</td>
<td>drain inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Lg</td>
<td>gate inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Ls</td>
<td>source inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>Cds†</td>
<td>drain-source capacitance</td>
<td>F</td>
<td>0</td>
</tr>
</tbody>
</table>

† Parameter value scales with Area.
†† Parameter value varies with temperature based on model Tnom and device Temp.
††† Value of 0.0 is interpreted as infinity.
‡ Parameter value scales inversely with Area.
### Table 3-10. Statz_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crf†</td>
<td>used with Rc to model frequency dependent output conductance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Rc‡</td>
<td>used with Crf to model frequency dependent output conductance</td>
<td>ohms</td>
<td>infinity†††</td>
</tr>
<tr>
<td>Gsfwd</td>
<td>0-none, 1=linear, 2=diode</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Gsrev</td>
<td>0-none, 1=linear, 2=diode</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Gdfwd</td>
<td>0-none, 1=linear, 2=diode</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Gdrev</td>
<td>0-none, 1=linear, 2=diode</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>Vjr</td>
<td>breakdown junction potential</td>
<td>V</td>
<td>0.025</td>
</tr>
<tr>
<td>Is†</td>
<td>gate junction saturation current (diode model)</td>
<td>A</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Ir†</td>
<td>gate reverse saturation current</td>
<td>A</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Imax</td>
<td>explosion current</td>
<td>A</td>
<td>1.6</td>
</tr>
<tr>
<td>Xti</td>
<td>temperature exponent for saturation current</td>
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</tr>
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<td>N</td>
<td>gate junction emission coefficient</td>
<td></td>
<td>1</td>
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<td>Eg</td>
<td>energy gap for temperature effect on Is</td>
<td>eV</td>
<td>1.11</td>
</tr>
<tr>
<td>Vbr</td>
<td>gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with $V_{ds}&lt;0$)</td>
<td>V</td>
<td>$10^{100}$</td>
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<tr>
<td>Vtotc</td>
<td>Vto temperature coefficient</td>
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<td>Rin‡</td>
<td>channel resistance</td>
<td>ohms</td>
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<tr>
<td>Taumdl</td>
<td>second order Bessel polynomial to model tau effect in transient</td>
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<td>no</td>
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<td>Fnc</td>
<td>flicker noise corner frequency</td>
<td>Hz</td>
<td>0</td>
</tr>
<tr>
<td>R</td>
<td>gate noise coefficient</td>
<td></td>
<td>0.5</td>
</tr>
</tbody>
</table>

† Parameter value scales with Area.
†† Parameter value varies with temperature based on model Tnom and device Temp.
††† Value of 0.0 is interpreted as infinity.
‡ Parameter value scales inversely with Area.
Table 3-10. Statz_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>gate-drain noise correlation coefficient</td>
<td></td>
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</tr>
<tr>
<td>P</td>
<td>drain noise coefficient</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>wVgfwd</td>
<td>gate junction forward bias warning</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage warning</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgd</td>
<td>gate-drain reverse breakdown voltage warning</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage warning</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wIdmax</td>
<td>maximum drain-source current warning</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation warning</td>
<td>W</td>
<td></td>
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<tr>
<td>AllParams</td>
<td>DataAccessComponent for file-based model parameter values</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value scales with Area.
†† Parameter value varies with temperature based on model Tnom and device Temp.
††† Value of 0.0 is interpreted as infinity.
‡ Parameter value scales inversely with Area.
Notes/Equations/References
1. This model supplies values for a GaAsFET device.
2. Statz_Model implementation is based on the work of Statz et al [1]. In particular, the expressions for drain source current and gate charge are implemented exactly as published in [1]. The Statz model also includes a number of features that (although not described in the Statz article) are generally accepted to be important features of a GaAsFET model. These include a gate delay factor (Tau), an input charging resistance (Ri), gate junction forward conduction and breakdown.
3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

Equations/Discussion
Drain-Source Current
Statz_Model dc drain-source current is given by these expressions:
For $0 < V_{ds} < 3 / \alpha$

$$I_{ds} = \frac{\beta(V_{gs} - V_{to})^2}{1 + \beta(V_{gs} - V_{to})} \left[ 1 - \left( 1 - \frac{\alpha V_{ds}}{3} \right)^3 \right] (1 + \lambda V_{ds})$$

where $\alpha$ is Alpha, $\beta$ is Beta, $\Theta$ is B.
For $V_{ds} \geq 3/\alpha$

$$I_{ds} = \frac{\beta(V_{gs} - V_{to})^2}{1 + \beta(V_{gs} - V_{to})} (1 + \lambda V_{ds})$$

The current is set to zero for $V_{gs} < V_{to}$.
where $\alpha$ is Alpha, $\beta$ is Beta, $\Theta$ is B.

Gate Charge
You are provided with two options in modeling the junction capacitance of a device. The first is to model the junction as a linear component (a constant capacitance). The second is to model the junction using a diode depletion capacitance model. If a
non-zero value of $C_{gs}$ is specified and $G_{scap}$ is set to 1 (linear), the gate-source junction will be modeled as a linear component. Similarly, specifying a non-zero value for $C_{gd}$ and $G_{dcap} = 1$ result in a linear gate-drain model. A non-zero value for either $C_{gs}$ or $C_{gd}$ together with $G_{scap} = 2$ (junction) or $G_{dcap} = 2$ will force the use of the diode depletion capacitance model for that particular junction. Note, that each junction is modeled independent of the other and hence, it is possible to model one junction as a linear component while the other is treated nonlinearly. The junction depletion charge and capacitance equations are summarized below.

The gate charge in Statz Model is given by,

For $V_{new} > V_{\text{max}}$,

$$Q_g = C_{gs} \left( 2 \times V_{bi} \left( 1 - \sqrt{1 - \frac{V_{\text{max}}}{V_{bi}}} \right) + \frac{V_{new} - V_{\text{max}}}{\sqrt{1 - \frac{V_{\text{max}}}{V_{bi}}}^2} \right) + C_{gd} \times V_{eff_2}$$

For $V_{new} \leq V_{\text{max}}$

$$Q_g = C_{gs} \times 2 \times V_{bi} \left( 1 - \sqrt{1 - \frac{V_{new}}{V_{bi}}} \right) + C_{gd} \times V_{eff_2}$$

where

$$V_{\text{max}} = \min (F_c \times V_{bi}, V_{\text{max}})$$

$$V_{new} = \frac{1}{2} \left( V_{eff_1} + V_{to} + \sqrt{(V_{eff_1} - V_{to})^2 + \Delta t a_2^2} \right)$$

$$V_{eff_1} = \frac{1}{2} \left( V_{gc} + V_{gd} + \sqrt{(V_{gc} - V_{gd})^2 + \Delta t a_1^2} \right)$$

and

$$V_{eff_2} = \frac{1}{2} \left( V_{gc} + V_{gd} - \sqrt{(V_{gc} - V_{gd})^2 + \Delta t a_1^2} \right)$$

The inclusion of $R_i$ requires that one of the controlling voltages be switched from $V_{gs}$ to $V_{gc}$. This results in a symmetry between the d-c nodes instead of the d-s nodal...
symmetry described in the Statz paper (of course, if Ri is set to zero, the model reduces to the exact representation in the Statz paper).

To implement this model in a simulator, the gate charge must be partitioned between the g-c and g-d branches. Implementation of the Statz model partitions the gate charge according to the work of Divekar [2]. Under this partitioning scheme, the gate-source charge is given by:

\[
\begin{align*}
Q_{gs} &= C_{gs} \left[ 2 \times V_{bi} \left( 1 - \sqrt{1 - \frac{V_{max}}{V_{bi}}} \right) + \frac{V_{new} - V_{max}}{\sqrt{1 - \frac{V_{max}}{V_{bi}}}} \right] \\
&\quad \text{for } V_{new} > V_{max}, \\
Q_{gs} &= C_{gs} \times 2 \times V_{bi} \left( 1 - \sqrt{1 - \frac{V_{new}}{V_{bi}}} \right) \\
&\quad \text{for } V_{new} \leq V_{max}
\end{align*}
\]

while the gate-drain charge is

\[
Q_{gd} = C_{gd} \times V_{eff2}
\]

The small-signal capacitances (equations 16 and 17 in the Statz paper) are related to the charge partial derivatives through the following expressions:

\[
\begin{align*}
C_{gs} &= \frac{\partial Q_{gs}}{\partial V_{gc}} + \frac{\partial Q_{gd}}{\partial V_{gc}} \\
C_{gd} &= \frac{\partial Q_{gs}}{\partial V_{gd}} + \frac{\partial Q_{gd}}{\partial V_{gd}}
\end{align*}
\]

Although the drain-source current model and the gate-conduction model (next section) are well behaved for negative \(V_{ds}\) (as well as the zero crossing), the charge model may cause convergence problems in the region \(V_{ds} < 0.0\) V. The reason for this is that the charge partitioning is somewhat artificial in that \(Q_{gs}\) and \(Q_{gd}\) should swap roles for negative \(V_{ds}\) but don't. It is recommended that this model be used for positive \(V_{ds}\) only.
Gate forward conduction and breakdown

Implementation of Statz_Model places a diode model in both the gate-source and gate-drain junctions to model forward conduction current and reverse breakdown current. These currents are computed with these expressions:

**Gate-Source Current**

- for \( V_{gs} > -10 \times N \times v_t \)
  
  \[ I_{gs} = I_s \times \left[ \exp \left( \frac{V_{gs}}{N \times v_t} \right) - 1 \right] \]

- for \(-V_{br} + 50 \times v_t < V_{gs} \leq -10 \times N \times v_t\)
  
  \[ I_{gs} = I_s \times [\exp(-10) - 1] + g_{gs} \times (V_{gs} - 10 \times N \times v_t) \]
  
  where
  
  \[ g_{gs} = I_s \times \frac{\exp(-10)}{N \times v_t} \]

- for \( V_{gs} \leq -V_{br} + 50 \times v_t \)
  
  \[ I_{gs} = -I_s \times \exp \left( \frac{-V_{br} + V_{gs}}{N \times v_t} \right) + I_s \times [\exp(-10) - 1] + g_{gs} \times (V_{gs} - 10 \times N \times v_t) \]

**Gate-Drain Current**

- for \( V_{gd} > -10 \times N \times v_t \)
  
  \[ I_{gd} = I_s \times \left[ \exp \left( \frac{V_{gd}}{N \times v_t} \right) - 1 \right] \]

- for \(-V_{br} + 50 \times v_t < V_{gd} \leq -10 \times N \times v_t\)
  
  \[ I_{gd} = I_s \times [\exp(-10) - 1] + g_{gd} \times (V_{gd} - 10 \times N \times v_t) \]
  
  where
  
  \[ g_{gd} = I_s \times \frac{\exp(-10)}{N \times v_t} \]
for $V_{gd} \leq -V_{br} + 50 \times v_t$

$$I_{gd} = -I_s \times \exp \left( \frac{-(V_{br} + V_{gd})}{N \times v_t} \right) \times [\exp(-10) - 1] + g_{gd} \times (V_{gd} - 10 \times N \times v_t)$$

**Time Delay**

Like Curtice2_Model and Curtice3_Model, Statz_Model uses an ideal time delay to model transit time effects under the gate. In the time domain, the drain source current for the ideal delay is given by:

$$I_{ds}(t) = I_{ds}(V_j(t-Tau), V_{ds}(t))$$

where $V_j = V_{gs}$ or $V_j = V_{gd}$ (depending on whether $V_{ds}$ is positive or negative). In the frequency domain, only the transconductance is impacted by this delay and the familiar expression for transconductance is obtained

$$y_m = g_{m} \times \exp(-j \times \omega \times Tau)$$

**High-Frequency Output Conductance**

The series-RC network, Figure 3-7, is comprised of the parameters $C_{rf}$ and $R_c$ and is included to provide a correction to the ac output conductance at a specific bias condition. At a frequency high enough such that $C_{rf}$ is an effective short, the output conductance of the device can be increased by the factor $1/R_c$. (Also see [3].)

![Figure 3-7. Statz_Model Schematic](image-url)
Temperature Scaling

The model specifies T_{nom}, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than T_{nom}, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation current I_s scales as:

\[ I_s^{\text{NEW}} = I_s \times \exp \left[ \frac{\left( T_{\text{Temp}} - T_{\text{Nom}} \right) q \times E_g}{k \times N \times T_{\text{Temp}}} + \frac{X_{ti} \times \ln \left( \frac{T_{\text{Temp}}}{T_{\text{Nom}}} \right)}{N} \right] \]

The gate depletion capacitances C_{gs} and C_{gd} vary as:

\[ C_{gs}^{\text{NEW}} = C_{gs} \frac{1 + 0.5 \left[ 4 \times 10^{-4} \left( T_{\text{Temp}} - T_{\text{REF}} \right) - \gamma T_{\text{Temp}} \right]}{1 + 0.5 \left[ 4 \times 10^{-4} \left( T_{\text{Nom}} - T_{\text{REF}} \right) - \gamma T_{\text{Nom}} \right]} \]

\[ C_{gd}^{\text{NEW}} = C_{gd} \frac{1 + 0.5 \left[ 4 \times 10^{-4} \left( T_{\text{Temp}} - T_{\text{REF}} \right) - \gamma T_{\text{Temp}} \right]}{1 + 0.5 \left[ 4 \times 10^{-4} \left( T_{\text{Nom}} - T_{\text{REF}} \right) - \gamma T_{\text{Nom}} \right]} \]

where \( \gamma \) is a function of junction potential and energy gap variation with temperature.

The gate junction potential V_{bi} varies as:

\[ V_{bi}^{\text{NEW}} = \frac{T_{\text{Temp}}}{T_{\text{Nom}}} \times V_{bi} + \frac{2k \times T_{\text{Temp}}}{q} \ln \left( \frac{n_i T_{\text{Nom}}}{n_i T_{\text{Temp}}} \right) \]

where \( n_i \) is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

The threshold voltage V_{to} varies as:

\[ V_{to}^{\text{NEW}} = V_{to} + V_{totc} \left( T_{\text{Temp}} - T_{\text{Nom}} \right) \]

The transconductance \( \beta \) varies as:

\[ \beta^{\text{NEW}} = \beta \times 1.01^{\beta_{\text{atc}} \left( T_{\text{Temp}} - T_{\text{Nom}} \right)} \]
Noise Model

Thermal noise generated by resistors $R_g, R_s, R_d$ and $R_i$ is characterized by the spectral density:

$$\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}$$

Parameters $P, R,$ and $C$ model drain and gate noise sources.

$$\frac{\langle i_d^2 \rangle}{\Delta f} = 4kTg_m P(1 + f_{NC}/f)$$

$$\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT C_{gs}^2 \frac{\omega^2 R}{g_m}$$

$$\frac{\langle i_g i_d^* \rangle}{\Delta f} = 4kT j C_{gs} \omega / PR C$$

References


Tajima_Model (Tajima GaAsFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 3-11. Tajima_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
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<tr>
<td>NFET</td>
<td>N-channel model</td>
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<tr>
<td>PFET</td>
<td>P-channel model</td>
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<td>Idsmod</td>
<td>Ids model</td>
<td>5</td>
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<td>Vdss</td>
<td>drain current saturation voltage of this model</td>
<td>V</td>
<td>1</td>
</tr>
<tr>
<td>Vto</td>
<td>value of V1 below which Ids = Ids(V1=VT0,Vds)</td>
<td>V</td>
<td>−2</td>
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<tr>
<td>Beta2</td>
<td>coefficient for pinch-off change with respect to Vds</td>
<td>1/V</td>
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<tr>
<td>Ta</td>
<td>model 5: ‘a’ coefficient</td>
<td></td>
<td>−0.2</td>
</tr>
<tr>
<td>Tb</td>
<td>model 5: ‘b’ coefficient</td>
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<td>0.6</td>
</tr>
<tr>
<td>Tm</td>
<td>model 5: ‘m’ coefficient</td>
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<td>3.0</td>
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<tr>
<td>Idss</td>
<td>saturation drain current</td>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>Rin††</td>
<td>channel resistance</td>
<td>ohms</td>
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</tr>
<tr>
<td>Fc</td>
<td>coefficient for forward bias depletion capacitance (diode model)</td>
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</tr>
<tr>
<td>Gscap</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td>linear</td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
†† Parameter value scales with Area.
††† Parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{gs}^{\dagger \dagger} )</td>
<td>zero bias gate-source junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>( G_{dcap} )</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td>linear</td>
</tr>
<tr>
<td>( C_{gd}^{\dagger \dagger} )</td>
<td>zero bias gate-drain junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>( R_d )</td>
<td>drain ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>( R_g )</td>
<td>gate resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>( R_s )</td>
<td>source ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>( L_d )</td>
<td>drain inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>( L_g )</td>
<td>gate inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>( L_s )</td>
<td>source inductance</td>
<td>henry</td>
<td>0.0</td>
</tr>
<tr>
<td>( C_{ds}^{\dagger \dagger} )</td>
<td>drain-source capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>( C_{rf}^{\dagger \dagger} )</td>
<td>used to model frequency-dependent output conductance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>( R_c^{\dagger \dagger \dagger} )</td>
<td>output resistance for RF operation</td>
<td>ohms</td>
<td>infinity‡</td>
</tr>
<tr>
<td>( G_{sfwd} )</td>
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<td></td>
<td>linear</td>
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<tr>
<td>( G_{srev} )</td>
<td>0=none, 1=linear, 2=diode</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>( G_{dfwd} )</td>
<td>0=none, 1=linear, 2=diode</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>( G_{drev} )</td>
<td>0=none, 1=linear, 2=diode</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>( V_{bi}^{\dagger} )</td>
<td>built-in gate potential</td>
<td>V</td>
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<td>( I_s )</td>
<td>gate junction reverse saturation current (diode model)</td>
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<td>( 10^{-14} )</td>
</tr>
<tr>
<td>( I_{max} )</td>
<td>explosion current</td>
<td>A</td>
<td>1.6</td>
</tr>
<tr>
<td>( N )</td>
<td>gate junction emission coefficient (diode model)</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>( F_{nc} )</td>
<td>flicker noise corner frequency</td>
<td>Hz</td>
<td>0</td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
†† Parameter value scales with Area.
††† Parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.

Table 3-11. Tajima_Model Parameters (continued)
1. This model supplies values for a GaAsFET device.


\[
\frac{\langle i_d^2 \rangle}{\Delta f} = 4kTg_m P(1 + f_{NC}/f) \tag{3-1}
\]

\[
\frac{\langle i_g^2 \rangle}{\Delta f} = 4kTC_g^2 \omega^2 R/g_m \tag{3-2}
\]

\[
\frac{\langle i_g i_d^* \rangle}{\Delta f} = 4kTj C_g \omega \sqrt{PR} C \tag{3-3}
\]
3. Following are additional parameter equations:

\[ \nu_p = V_{to} - \text{Beta}^2 \cdot V_{ds} - V_{bi} \]  
\[ (3-4) \]

\[ \nu_c = (\nu_{gs} - V_{bi} - \nu_p) / \nu_p \]  
\[ (3-5) \]

If \( \nu_p \geq 0 \) or \( \nu_c \geq 0 \), then \( i_d = 0 \)  
\[ (3-6) \]

else

\[ i_{d1} = \left[ \frac{\exp(\text{Tm} \cdot \nu_c)}{\text{Tm}} - \nu_c \right] \left[ 1 - \frac{1 - \exp(-\text{Tm})}{\text{Tm}} \right] \]  
\[ (3-7) \]

\[ i_{d2} = \text{Id}_{ss} \cdot \left[ 1 - \exp \left( \frac{\nu_{ds}}{\text{Vd}_{ss}} \right) - \text{Ta} \left( \frac{\nu_{ds}}{\text{Vd}_{ss}} \right)^2 - \text{Tb} \left( \frac{\nu_{ds}}{\text{Vd}_{ss}} \right)^3 \right] \]  
\[ (3-8) \]

\[ i_d = i_{d1} \cdot i_{d2} \]  
\[ (3-9) \]

4. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

TOM (TriQuint Scalable Nonlinear GaAsFET)

Symbol

Parameters
Model = name of a TOM_Model
W = new unit gate width, in length units (default 1.0)
N = new number of gate fingers (default: 1)
Temp = device operating temperature, in °C (default: 25)
Mode = simulation mode for this device: linear or nonlinear (refer to Note 2)
_M = number of devices in parallel (default: 1)

Range of Usage
W > 0
N > 0

Notes/Equations/References
1. W and N are used for scaling device instance; refer to the model for these descriptions.
2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.
3. This device has no default artwork associated with it.
TOM_Model (TriQuint Scalable Nonlinear GaAsFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 3-12. TOM_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idsmod</td>
<td>I&lt;sub&gt;ds&lt;/sub&gt; model</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>V&lt;sub&gt;t0&lt;/sub&gt;</td>
<td>nonscalable portion of threshold voltage</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>V&lt;sub&gt;to&lt;/sub&gt;</td>
<td>scalable portion of threshold voltage</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Alpha</td>
<td>saturation voltage coefficient</td>
<td>1/V</td>
<td>2.0</td>
</tr>
<tr>
<td>Beta&lt;sup&gt;†††&lt;/sup&gt;</td>
<td>transconductance coefficient</td>
<td>A/V&lt;sup&gt;2&lt;/sup&gt;</td>
<td>10&lt;sup&gt;-4&lt;/sup&gt;</td>
</tr>
<tr>
<td>T&lt;sub&gt;qdelta&lt;/sub&gt;</td>
<td>output feedback coefficient</td>
<td>1/W</td>
<td>0</td>
</tr>
<tr>
<td>T&lt;sub&gt;qgamma&lt;/sub&gt;</td>
<td>dc drain pull coefficient</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>T&lt;sub&gt;qgammaAc&lt;/sub&gt;</td>
<td>AC pinchoff change with vds</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>T&lt;sub&gt;nom&lt;/sub&gt;</td>
<td>nominal ambient temperature at which these</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>Q</td>
<td>power law exponent</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Tau</td>
<td>gate transit time delay</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>V&lt;sub&gt;t0c&lt;/sub&gt;</td>
<td>V&lt;sub&gt;to&lt;/sub&gt; temperature coefficient</td>
<td>V/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>Betatce</td>
<td>drain current exponential temperature coefficient</td>
<td>%/°C</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<sup>†</sup> Parameter value varies with temperature based on model T<sub>nom</sub> and device Temp.

<sup>††</sup> Parameter value scales inversely with Area.

<sup>†††</sup> Parameter value scales with Area.

<sup‡</sup> Value of 0.0 is interpreted as infinity.

<sup‡‡</sup> Total gate resistance is R<sub>g</sub> + R<sub>gmet</sub>.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cgs†††</td>
<td>zero-bias gate-source capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgd†††</td>
<td>zero-bias gate-drain capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Vbi</td>
<td>gate diode built-in potential</td>
<td>V</td>
<td>0.85</td>
</tr>
<tr>
<td>Tqm</td>
<td>temperature coefficient for TriQuint junction capacitance</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>Vmax</td>
<td>maximum junction voltage before capacitance limiting</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Fc</td>
<td>coefficient for forward bias depletion capacitance (diode model)</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Delta1</td>
<td>capacitance saturation transition voltage</td>
<td>V</td>
<td>0.3</td>
</tr>
<tr>
<td>Delta2</td>
<td>capacitance threshold transition voltage</td>
<td>V</td>
<td>0.2</td>
</tr>
<tr>
<td>M</td>
<td>grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Is†††</td>
<td>gate diode saturation current (diode model)</td>
<td>A</td>
<td>10^{-14}</td>
</tr>
<tr>
<td>N</td>
<td>gate diode emission coefficient (diode model)</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Eg</td>
<td>energy gap for temperature effect on Is</td>
<td>eV</td>
<td>1.11</td>
</tr>
<tr>
<td>Xti</td>
<td>temperature exponent for saturation current</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Vbr</td>
<td>gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with $V_{ds} = 0$)</td>
<td>V</td>
<td>infinity‡</td>
</tr>
<tr>
<td>Rg‡‡</td>
<td>gate resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rd‡</td>
<td>drain contact resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rs†</td>
<td>source contact resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Trg1</td>
<td>linear temperature coefficient for Rg</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Trd1</td>
<td>linear temperature coefficient for Rd</td>
<td>1/°C</td>
<td>0</td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
‡‡ Total gate resistance is Rg + Rgmet.
†† Parameter value scales inversely with Area.
††† Parameter value scales with Area.
‡ Value of 0.0 is interpreted as infinity.
Table 3-12. TOM_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trs1</td>
<td>linear temperature coefficient for $R_s$</td>
<td>$1/°C$</td>
<td>0</td>
</tr>
<tr>
<td>Cds†††</td>
<td>drain source capacitance</td>
<td>$F$</td>
<td>0.0</td>
</tr>
<tr>
<td>Rdb</td>
<td>$R$ for frequency-dependent output conductance</td>
<td>$\text{Ohms}$</td>
<td>0.0</td>
</tr>
<tr>
<td>Cbs</td>
<td>$C$ for frequency-dependent output capacitance</td>
<td>$F$</td>
<td>0.0</td>
</tr>
<tr>
<td>Rgmet‡‡</td>
<td>gate metal resistance</td>
<td>$\text{ohms}$</td>
<td>0.0</td>
</tr>
<tr>
<td>Ris††</td>
<td>source end channel resistance</td>
<td>$\text{ohms}$</td>
<td>0.0</td>
</tr>
<tr>
<td>Rid††</td>
<td>drain end channel resistance</td>
<td>$\text{ohms}$</td>
<td>0.0</td>
</tr>
<tr>
<td>Vgr</td>
<td>$V_g$ (s,d) c includes voltage across $R_g$ (s,d)</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>I_max</td>
<td>explosion current</td>
<td>$A$</td>
<td>1.6</td>
</tr>
<tr>
<td>Fnc</td>
<td>flicker noise corner efficiency</td>
<td>$\text{Hz}$</td>
<td>0</td>
</tr>
<tr>
<td>R</td>
<td>gate noise coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>P</td>
<td>drain noise coefficient</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>gate drain noise correlation coefficient</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Taumdl</td>
<td>second order Bessel polynomial to model tau effect in transient simulation</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Ugw</td>
<td>unit gate width of device</td>
<td>$\text{meter}$</td>
<td>1e-6</td>
</tr>
<tr>
<td>Ngf</td>
<td>number of device gate fingers</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>wVgfwd</td>
<td>gate junction forward bias warning</td>
<td>$V$</td>
<td></td>
</tr>
<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage warning</td>
<td>$V$</td>
<td></td>
</tr>
<tr>
<td>wBvgd</td>
<td>gate-drain reverse breakdown voltage warning</td>
<td>$V$</td>
<td></td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage warning</td>
<td>$V$</td>
<td></td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current warning</td>
<td>$A$</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation warning</td>
<td>$W$</td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model $T_{nom}$ and device $T_{emp}$.
†† Parameter value scales inversely with Area.
††† Parameter value scales with Area.
‡ Value of 0.0 is interpreted as infinity.
‡‡ Total gate resistance is $R_g + R_{gmet}$. 
1. This model supplies values for a TOM device.

2. Model parameters such as $L_s$, $L_d$, $L_g$ are not used by the TOM device in the simulator. Only those parameters listed in Table 3-12 are part of the TOM device. Extrinsic devices must be added externally by the user.

3. To prevent numerical problems, the setting of some model parameters to 0 is trapped by the simulator. The parameter values are changed internally:

   $$R_d = 10^{-4} \quad R_{is} = 10^{-4}$$
   $$R_s = 10^{-4} \quad R_{id} = 10^{-4}$$
   $$R_g = 10^{-4} \quad R_{gmet} = 10^{-4}$$

Other parameters are restricted to values $>0$. If the user violates this restriction, the parameters will be internally fixed by the simulator:

   $$V_{bi} = 0.1$$
   $$N = 1.0$$
   $$T_{qdelta} = 0.0$$

**Dimensional Scaling Relations**

Scaling of TOM _Model_ parameters is accomplished through the use of the model parameters $U_{gw}$ and $N_{gf}$ (see Table 3-12) and the device parameters $U_{gw}$ (same

---

Table 3-12. TOM _Model_ Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{scap}$</td>
<td>0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap</td>
<td></td>
<td>Statz</td>
</tr>
<tr>
<td>$G_{sfwd}$</td>
<td>0=none, 1=linear, 2=dioide</td>
<td></td>
<td>dioide</td>
</tr>
</tbody>
</table>

$\dagger$ Parameter value varies with temperature based on model $T_{nom}$ and device $T_{emp}$.

$\dagger\dagger$ Parameter value scales inversely with Area.

$\dagger\dagger\dagger$ Parameter value scales with Area.

$\dagger$ Value of 0.0 is interpreted as infinity.

$\dagger\dagger$ Total gate resistance is $R_g + R_{gmet}$. 
name as the model parameter) and N. From these four parameters, the following scaling relations can be defined:

\[ sf = \frac{W \times N}{U_{gw} \times N_{gf}} \]
\[ sfg = \frac{U_{gw} \times N}{W \times N_{gf}} \]

where \( W \) represents the device parameter \( U_{gw} \), the new unit gate width.

Scaling will be disabled if \( N \) is not specified. The new parameters are computed internally by the simulator according to the following equations:

\[ \beta_{new} = \beta \times sf \]
\[ T_{qdelta,new} = \frac{T_{qdelta}}{sf} \]
\[ V_{tosc,new} = \frac{V_{tosc}}{sf} \]
\[ I_s,new = I_s \times sf \]
\[ R_{is,new} = \frac{R_{is}}{sf} \]
\[ R_{id,new} = \frac{R_{id}}{sf} \]

**Temperature Scaling Relations**

TOM_Model uses an extensive set of temperature scaling relations that permit the analysis of drain current, gate current, capacitances and even parasitic resistances over ambient temperature changes. The scaling relations assume the unscaled (nominal) parameters were extracted at \( T_{nom} \). The parameters are scaled to an arbitrary operating ambient temperature \( (Temp) \) through the temperature scaling relations. Note that the user must specify the temperatures \( Temp \) and \( T_{nom} \) in °C—the program converts these temperatures to units of Kelvin. The equations that follow use temperature in Kelvin.

\[ V_{bi}(Temp) = V_{bi} \times \left( \frac{Temp}{T_{nom}} \right) - 3V_{t} \log\left( \frac{Temp}{T_{nom}} \right) \]
\[ - E_{g}(T_{nom}) \times \left( \frac{Temp}{T_{nom}} \right) + E_{g}(Temp) \]
\[
\beta(T_{\text{Temp}}) = \beta_{1.01} \times (T_{\text{Temp}} - T_{\text{nom}})
\]
\[
V_{\text{to}}(T_{\text{Temp}}) = V_{\text{to}} + V_{\text{t0c}} \times (T_{\text{Temp}} - T_{\text{nom}})
\]
\[
I_s(T_{\text{Temp}}) = \exp \left[ \frac{T_{\text{Temp}}}{T_{\text{nom}}} - 1 \right] \times \frac{E_g}{V_t} \times I_s \left( \frac{T_{\text{Temp}}}{T_{\text{nom}}} \right) \times \frac{\xi_t}{N}
\]
\[
R_d(T_{\text{Temp}}) = R_d \times \left( 1 + T_{\text{rd1}} \times (T_{\text{Temp}} - T_{\text{nom}}) \right)
\]
\[
R_s(T_{\text{Temp}}) = R_s \times \left( 1 + T_{\text{rs1}} \times (T_{\text{Temp}} - T_{\text{nom}}) \right)
\]
\[
C_{gs}(T_{\text{Temp}}) = C_{gs} \left[ 1 + T_{qm} \times \left( 4.0 \times 10^{-4} (T_{\text{Temp}} - T_{\text{nom}}) + 1 - \frac{V_{\text{bi}}(T_{\text{Temp}})}{V_{\text{bi}}} \right) \right]
\]
\[
C_{gd}(T_{\text{Temp}}) = C_{gd} \left[ 1 + T_{qm} \times \left( 4.0 \times 10^{-4} \times \left( (T_{\text{Temp}} - T_{\text{nom}}) + 1 - \frac{V_{\text{bi}}(T_{\text{Temp}})}{V_{\text{bi}}} \right) \right) \right]
\]
where
\[
V_t = \frac{V \times T_{\text{Temp}}}{q}
\]
\[
E_g(T) = \frac{1.519 - 5.405 \times 10^{-4} T^2}{T + 204}
\]
where
\[
K = \text{Boltzmann's constant} = 8.62 \times 10^{-5} \text{eV K}^{-1}
\]
\[
q = \text{electron charge} = 1.602 \times 10^{-19} \text{C}
\]

**Noise Model**

Thermal noise generated by resistors $R_g$, $R_s$ and $R_d$ is characterized by the following spectral density.
\[
\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}
\]
Parameters $P$, $R$, and $C$ model drain and gate noise sources.
In this circuit illustration, Rdb and Cbs are shown. They are not available at the time of the initial release of this product version, but will be added in a future product patch or release.

References

Chapter 4: Devices and Models, JFET

Bin Model

The BinModel in the JFET library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

For information on the use of the binning feature, refer to the section “Bin Model (Bin Model for Automatic Model Selection).” This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section “Multiplicity.” This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.
JFET_Model (Junction FET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFET</td>
<td>N-channel model</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>PFET</td>
<td>P-channel model</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Vto†</td>
<td>zero-bias threshold voltage</td>
<td>V</td>
<td>-2.0</td>
</tr>
<tr>
<td>Beta†, ††</td>
<td>transconductance parameter</td>
<td>A/V^2</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>Lambda</td>
<td>channel-length modulation parameter</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Rd††</td>
<td>drain ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rs††</td>
<td>source ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Is†, ††</td>
<td>gate-junction saturation current</td>
<td>A</td>
<td>10^{-14}</td>
</tr>
<tr>
<td>Cgs†</td>
<td>zero-bias gate-source junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgd†</td>
<td>zero-bias gate-drain junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Pb†</td>
<td>gate-junction potential</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Fc</td>
<td>forward-bias junction capacitance coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Tnom</td>
<td>nominal ambient temperature at which these model parameters were derived</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>Kf</td>
<td>flicker-noise coefficient</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Af</td>
<td>flicker-noise exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Imax</td>
<td>explosion current</td>
<td>A</td>
<td>1.6</td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
†† Parameter value is scaled with Area specified with the JFET device.
1. This model supplies values for a JFET device.
2. JFET_Model equations are based on the FET model of Shichman and Hodges. For more information on JFET_Model, its parameters and equations, see [1].
3. The dc characteristics of a JFET_Model are defined by:
   - Vto and Beta: determine variation in drain current with respect to gate voltage.
   - Lambda: determines the output conductances
   - Is: saturation current of the two gate junctions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>gate P-N emission coefficient</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Isr†</td>
<td>gate P-N recombination current parameter</td>
<td>A</td>
<td>0.0</td>
</tr>
<tr>
<td>Nr</td>
<td>Isr emission coefficient</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Alpha</td>
<td>ionization coefficient</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Vk</td>
<td>ionization knee voltage</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>M</td>
<td>gate P-N grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Vtotc</td>
<td>Vto temperature coefficient</td>
<td>V/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>Betatce</td>
<td>Beta exponential temperature coefficient</td>
<td>%/°C</td>
<td>0.0</td>
</tr>
<tr>
<td>Xti</td>
<td>temperature coefficient</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Fe</td>
<td>flicker noise frequency exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>wBvgs</td>
<td>gate-source reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvgd</td>
<td>gate-drain reverse breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent-based parameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
†† Parameter value is scaled with Area specified with the JFET device.
4. Charge storage is modeled by nonlinear depletion layer capacitance for both gate junctions. These capacitances vary as 1/Sqrt(Junction Voltage) and are defined by Cgs, Cgd and Pb.

5. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams.

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation currents Is and Isr scale as:

\[
Is^{\text{NEW}} = Is \times \exp \left[ \left( \frac{Temp}{Tnom} - 1 \right) \frac{q \times Eg}{k \times N \times Temp} + \frac{Xti}{N} \times \ln \left( \frac{Temp}{Tnom} \right) \right]
\]

\[
Isr^{\text{NEW}} = Isr \times \exp \left[ \left( \frac{Temp}{Tnom} - 1 \right) \frac{q \times Eg}{k \times Nr \times Temp} + \frac{Xti}{Nr} \times \ln \left( \frac{Temp}{Tnom} \right) \right]
\]

The depletion capacitances Cgs and Cgd vary as:

\[
Cgs^{\text{NEW}} = Cgs \left[ \frac{1 + M \left[ 4 \times 10^{-4} \left( Temp - T_{REF} \right) - \gamma_{Temp} \right]}{1 + M \left[ 4 \times 10^{-4} \left( Tnom - T_{REF} \right) - \gamma_{Temp} \right]} \right]
\]

\[
Cgd^{\text{NEW}} = Cgd \left[ \frac{1 + M \left[ 4 \times 10^{-4} \left( Temp - T_{REF} \right) - \gamma_{Temp} \right]}{1 + M \left[ 4 \times 10^{-4} \left( Tnom - T_{REF} \right) - \gamma_{Temp} \right]} \right]
\]

where \( \gamma \) is a function of the junction potential and the energy gap variation with temperature.

The gate junction potential Pb varies as:

\[
Pb^{\text{NEW}} = \frac{Temp}{Tnom} \times Pb + \frac{2k \times Temp}{q} \ln \left( \frac{n_i^{Tnom}}{n_i^{Temp}} \right)
\]
where \( n_i \) is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

The threshold voltage \( V_{to} \) varies as:

\[
V_{to}^{\text{NEW}} = V_{to} + V_{totc}(\text{Temp} - \text{Tnom})
\]

The transconductance \( \beta \) varies as:

\[
\beta^{\text{NEW}} = \beta \times 1.01^{\text{Betatc}(\text{Temp} - \text{Tnom})}
\]

**Noise Model**

Thermal noise generated by resistors \( R_s \) and \( R_d \) is characterized by the following spectral density:

\[
\frac{<i^2>}{\Delta f} = \frac{4kT}{R}
\]

Channel noise and flicker noise (\( K_f, A_f, F_{fe} \)) generated by the dc transconductance \( g_m \) and current flow from drain to source is characterized by the following spectral density:

\[
\frac{<I_{ds}^2>}{\Delta f} = \frac{8kTg_m}{3} + k_f \frac{I_{DS}}{f_{fe}}
\]

In the above expressions, \( k \) is Boltzmann’s constant, \( T \) is the operating temperature in Kelvin, \( q \) is the electron charge, \( k_f, a_f, \) and \( f_{fe} \) are model parameters, \( f \) is the simulation frequency, and \( \Delta f \) is the noise bandwidth.

**References**

Devices and Models, JFET

Equivalent Circuit

\[ \text{Diagram showing the JFET model with symbols for } G, D, S, C_{gd}, C_{gs}, R_d, R_s, I_G, I_d \]
JFET (Nonlinear Junction Field-Effect Transistors)

JFET_NFET (Nonlinear Junction Field-Effect Transistor, N-Channel)
JFET_PFET (Nonlinear Junction Field-Effect Transistor, P-Channel)

Parameters

Model = name of a JFET_Model
Area = scaling factor that scales certain parameter values of the JFET_Model (default: 1)
Region = d.c. operating region: off, on, rev, ohmic (default: on)
Temp = device operating temperature, in °C (default: 25)
Mode = simulation mode for this device: linear or nonlinear (refer to Note 2) (default: nonlinear)
_M = number of devices in parallel (default: 1)

Range of Usage
N/A

Notes/Equations/References

1. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated JFET_Model) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to JFET_Model to see which parameter values are scaled.

2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in
their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.

3. This device has no default artwork associated with it.

References


Chapter 5: Devices and Models, MOS

Bin Model

The BinModel in the MOS library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

For information on the use of the binning feature, refer to the section "Bin Model (Bin Model for Automatic Model Selection.)" This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section "Multiplicity." This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.

Use of MOSFET Parameter Nlev

The MOSFET noise model is controlled by the model parameter Nlev. Table 5-1 shows which noise equations are used for each value of Nlev. These equations are always used for the BSIM1, BSIM2, LEVEL1, LEVEL2, LEVEL3 and LEVEL3_MOD models. For a BSIM3, these equations can be used to override the standard BSIM3v3 noise equations only when Nlev ≥ 1.

<table>
<thead>
<tr>
<th>Nlev Value</th>
<th>Channel Noise</th>
<th>Flicker Noise</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>8/3k T g_m</td>
<td>K_f | I_{DS}</td>
<td>AF \f^FTE</td>
</tr>
<tr>
<td>0</td>
<td>8/3k T g_m</td>
<td>K_f | I_{DS}</td>
<td>AF \f^FTE C_{OX} L^2 E_{ff}</td>
</tr>
</tbody>
</table>
Table 5-1. Equations Used for Nlev parameter (continued)

<table>
<thead>
<tr>
<th>Nlev Value</th>
<th>Channel Noise</th>
<th>Flicker Noise</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{8}{3}kTg_m$</td>
<td>$K_f I_{DS} \frac{A_f}{f F_r C_{OX} W_{Eff} L_{Eff}}$</td>
<td>Hspice Nlev=1</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{8}{3}kTg_m$</td>
<td>$K_f g_m^2 \frac{f F_r C_{OX} W_{Eff} L_{Eff}}{L_{ef}}$</td>
<td>Hspice Nlev=2</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{8}{3}kT B \left(V_{GS} - V_T\right)^{1+a} A_B^2 \frac{G_{dsnoi}}{1+a}$</td>
<td>$K_f g_m^2 \frac{f F_r C_{OX} W_{Eff} L_{eff}}{L_{eff}}$</td>
<td>Hspice Nlev=3</td>
</tr>
</tbody>
</table>

1 (pinchoff)

$a = 1 - V_{DS}/V_{DSAT}$ (linear)

0 (saturation)
BSIM1_Model (BSIM1 MOSFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 5-2. BSIM1_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOS</td>
<td>N-channel type model</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>PMOS</td>
<td>P-channel type model</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Idsmod</td>
<td>I'ds model</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Rsh</td>
<td>drain and source diffusion sheet resistance</td>
<td>ohms/sq</td>
<td>0.0</td>
</tr>
<tr>
<td>Jd</td>
<td>bulk junction area saturation current</td>
<td>A/m²</td>
<td>0.0</td>
</tr>
<tr>
<td>Temp</td>
<td>parameter measurement temperature</td>
<td>ºC</td>
<td>25</td>
</tr>
<tr>
<td>Muz</td>
<td>zero-bias surface mobility</td>
<td>cm²/N/sec</td>
<td>600</td>
</tr>
<tr>
<td>DI</td>
<td>shortening of channel</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Dw</td>
<td>narrowing of channel</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Vdd</td>
<td>measurement drain bias range</td>
<td>V</td>
<td>5.0</td>
</tr>
<tr>
<td>Vfb</td>
<td>flat-band voltage</td>
<td>V</td>
<td>-0.3</td>
</tr>
<tr>
<td>Phi</td>
<td>surface potential at strong inversion</td>
<td>V</td>
<td>0.6</td>
</tr>
<tr>
<td>K1</td>
<td>body effect coefficient</td>
<td>√V</td>
<td>0.5</td>
</tr>
<tr>
<td>K2</td>
<td>drain/source depletion charge sharing coefficient</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Eta</td>
<td>drain-induced barrier lowering coefficient</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>U0</td>
<td>transverse field mobility degradation coefficient</td>
<td>1/V</td>
<td>670.0</td>
</tr>
<tr>
<td>U1</td>
<td>zero-bias velocity saturation coefficient</td>
<td>µm/V</td>
<td>0.0</td>
</tr>
<tr>
<td>X2mz</td>
<td>sensitivity of mobility to substrate bias</td>
<td>cm²/V²</td>
<td>0.0</td>
</tr>
<tr>
<td>X2e</td>
<td>sensitivity of barrier lowering cf to substrate bias</td>
<td>1/V</td>
<td>-0.07</td>
</tr>
</tbody>
</table>
Table 5-2. BSIM1_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>X3e</td>
<td>sensitivity of barrier lowering cf to drain bias</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>X2u0</td>
<td>sensitivity of transverse field cf to substrate bias</td>
<td>1/V^2</td>
<td>0.0</td>
</tr>
<tr>
<td>X2u1</td>
<td>sensitivity of velocity saturation to substrate bias</td>
<td>(\mu m/V^2)</td>
<td>0.0</td>
</tr>
<tr>
<td>X3u1</td>
<td>sensitivity of velocity saturation to drain bias</td>
<td>(\mu m/V^2)</td>
<td>0.0</td>
</tr>
<tr>
<td>Mus</td>
<td>mobility at zero substrate bias at Vds=Vdd</td>
<td>cm^2/Vs</td>
<td>1082</td>
</tr>
<tr>
<td>X2ms</td>
<td>sensitivity of mobility to substrate bias</td>
<td>cm^2/V^2s</td>
<td>0.0</td>
</tr>
<tr>
<td>X3ms</td>
<td>sensitivity of mobility to drain bias at Vds=Vdd</td>
<td>cm^2/V^2s</td>
<td>0.0</td>
</tr>
<tr>
<td>N0</td>
<td>zero-bias subthreshold slope coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Nb</td>
<td>sensitivity of subthreshold slope to substrate bias</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Nd</td>
<td>sensitivity of subthreshold slope to drain bias</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Tox</td>
<td>oxide thickness</td>
<td>(\mu m)</td>
<td>10^{-7}</td>
</tr>
<tr>
<td>Cj</td>
<td>zero-bias bulk junction bottom capacitance</td>
<td>F/m^2</td>
<td>0.0</td>
</tr>
<tr>
<td>Mj</td>
<td>bulk junction bottom grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Cjsw</td>
<td>zero-bias bulk junction sidewall capacitance</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Mjsw</td>
<td>bulk junction sidewall grading coefficient</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Pb</td>
<td>bulk junction potential</td>
<td>V</td>
<td>0.8</td>
</tr>
<tr>
<td>Pbsw</td>
<td>built-in potential of source drain junction sidewall</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Cgso</td>
<td>gate-source overlap capacitance, per channel width</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgdo</td>
<td>gate-drain overlap capacitance, per channel width</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgbo</td>
<td>gate-bulk overlap capacitance, per channel width</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Xpart</td>
<td>coefficient of channel charge share</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Nlev</td>
<td>Noise model level</td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>Gdwnoi</td>
<td>Drain noise parameters for Nlev=3</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Kf</td>
<td>flicker noise coefficient</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Af</td>
<td>flicker noise exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Ffe</td>
<td>flicker noise frequency exponent</td>
<td></td>
<td>1.0</td>
</tr>
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</table>
Table 5-2. BSIM1_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{g}$</td>
<td>gate resistance</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>$N$</td>
<td>bulk P-N emission coefficient</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>$I_{\text{max}}$</td>
<td>explosion current</td>
<td>A</td>
<td>10.0</td>
</tr>
<tr>
<td>wVsubfwd</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvsub</td>
<td>substrate junction reverse breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvg</td>
<td>gate oxide breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td>infinite</td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td>infinite</td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent-based parameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes/Equations/References

1. This model supplies values for a MOSFET device.

2. BSIM1, BSIM2, and BSIM3 MOSFET models use the same parameters and parameter definitions as the BSIM models in SPICE3 (University of California-Berkeley).

3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.
BSIM2 Model (BSIM2 MOSFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 5-3. BSIM2_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOS</td>
<td>N-channel type model</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>PMOS</td>
<td>P-channel type model</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Idsmod</td>
<td>Ids model</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Rsh</td>
<td>drain and source diffusion sheet resistance</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Js</td>
<td>bulk junction saturation current, per junction area</td>
<td>A/m²</td>
<td>0.0</td>
</tr>
<tr>
<td>Mu0</td>
<td>zero-bias surface mobility</td>
<td>cm²/V·s</td>
<td>600</td>
</tr>
<tr>
<td>Dl</td>
<td>shortening of channel, in</td>
<td>µm</td>
<td>0.0</td>
</tr>
<tr>
<td>Dw</td>
<td>Narrowing of channel, in</td>
<td>µm</td>
<td>0.0</td>
</tr>
<tr>
<td>Vdd</td>
<td>measurement drain bias range</td>
<td>V</td>
<td>5.0</td>
</tr>
<tr>
<td>Vgg</td>
<td>measurement gate bias range</td>
<td>V</td>
<td>5.0</td>
</tr>
<tr>
<td>Vbb</td>
<td>measurement bulk bias range</td>
<td>V</td>
<td>-5.0</td>
</tr>
<tr>
<td>Temp</td>
<td>measurement temperature</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>Tox</td>
<td>oxide thickness</td>
<td>µm</td>
<td>10⁻⁷</td>
</tr>
<tr>
<td>Cj</td>
<td>zero-bias bulk junction bottom capacitance</td>
<td>F/m²</td>
<td>5.0</td>
</tr>
<tr>
<td>Mj</td>
<td>bulk junction bottom grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Cjsw</td>
<td>zero-bias bulk junction sidewall capacitance</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Mjsw</td>
<td>bulk junction sidewall grading coefficient</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Pb</td>
<td>bulk junction potential</td>
<td>V</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Table 5-3. BSIM2_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pbsw</td>
<td>built-in potential of source drain junction sidewall</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Cgso</td>
<td>gate-source overlap capacitance, per channel width</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgdo</td>
<td>gate-drain overlap capacitance, per channel width</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgbo</td>
<td>gate-bulk overlap capacitance, per channel width</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Xpart</td>
<td>coefficient of channel charge share</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Vfb</td>
<td>flat-band voltage</td>
<td>V</td>
<td>-0.1</td>
</tr>
<tr>
<td>Phi</td>
<td>surface potential at strong inversion</td>
<td>V</td>
<td>0.6</td>
</tr>
<tr>
<td>K1</td>
<td>body effect coefficient</td>
<td>√V</td>
<td>0.5</td>
</tr>
<tr>
<td>K2</td>
<td>drain/source depletion charge sharing coefficient</td>
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<td>0.0</td>
</tr>
<tr>
<td>Eta0</td>
<td>zero-bias drain-induced barrier lowering coefficient</td>
<td></td>
<td>0.08</td>
</tr>
<tr>
<td>Ua0</td>
<td>transverse field mobility degradation coefficient</td>
<td>1/V</td>
<td>670.0</td>
</tr>
<tr>
<td>U10</td>
<td>zero-bias velocity saturation coefficient</td>
<td>μm/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Mu0b</td>
<td>sensitivity of mobility to substrate bias</td>
<td>cm²/N²s</td>
<td>0.0</td>
</tr>
<tr>
<td>Etab</td>
<td>sensitivity of barrier lowering cf to substrate bias</td>
<td>1/V</td>
<td>-0.07</td>
</tr>
<tr>
<td>Uab</td>
<td>sensitivity of transverse field cf to substrate bias</td>
<td>1/V²</td>
<td>0.0</td>
</tr>
<tr>
<td>U1b</td>
<td>sensitivity of velocity saturation to substrate bias</td>
<td>μm/V²</td>
<td>0.0</td>
</tr>
<tr>
<td>U1d</td>
<td>sensitivity of velocity saturation to drain bias</td>
<td>μm/V²</td>
<td>0.0</td>
</tr>
<tr>
<td>Mus0</td>
<td>mobility at zero substrate bias at Vds=Vdd</td>
<td>cm²/Ns</td>
<td>600.0</td>
</tr>
<tr>
<td>Musb</td>
<td>sensitivity of mobility to substrate bias</td>
<td>cm²/N²s</td>
<td>0.0</td>
</tr>
<tr>
<td>N0</td>
<td>zero-bias subthreshold slope coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Nb</td>
<td>sensitivity of subthreshold slope to substrate bias</td>
<td>1/V</td>
<td>1.0</td>
</tr>
<tr>
<td>Nd</td>
<td>sensitivity of subthreshold slope to drain bias</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Mu20</td>
<td>empirical parameter in beta 0 expression</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Mu2b</td>
<td>sensitivity of Mu2 to Vbs</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Mu2g</td>
<td>sensitivity of Mu2 to Vgs</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Mu30</td>
<td>linear empirical parameter in beta 0 exp</td>
<td>cm²/N²s</td>
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</table>
Table 5-3. BSIM2_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mu3b</td>
<td>sensitivity of Mu3 to Vbs</td>
<td>cm²/V³s</td>
<td>0.0</td>
</tr>
<tr>
<td>Mu3g</td>
<td>sensitivity of Mu3 to Vgs</td>
<td>cm²/V³s</td>
<td>0.0</td>
</tr>
<tr>
<td>Mu40</td>
<td>quadratic empirical parameter in beta0 exp</td>
<td>cm²/V³s</td>
<td>0.0</td>
</tr>
<tr>
<td>Mu4b</td>
<td>sensitivity of Mu4 to Vbs</td>
<td>cm²/V⁴s</td>
<td>0.0</td>
</tr>
<tr>
<td>Ub0</td>
<td>mobility reduction to vertical field at Vbs=0</td>
<td>1/V²</td>
<td>0.0</td>
</tr>
<tr>
<td>Ubb</td>
<td>sensitivity of mobility reduction to Vbs</td>
<td>1/V³</td>
<td>0.0</td>
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<tr>
<td>Vof0</td>
<td>threshold voltage offset in the subthreshold region</td>
<td>V</td>
<td>0.0</td>
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<tr>
<td>Vofb</td>
<td>sensitivity of Vof to Vbs</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Vofd</td>
<td>sensitivity of Vof to Vds</td>
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<td>0.0</td>
</tr>
<tr>
<td>Ai0</td>
<td>pre-factor of hot-electron effect</td>
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<td>Aib</td>
<td>sensitivity of Ai to Vbs</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Bi0</td>
<td>exponential factor of hot-electron effect</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Bib</td>
<td>sensitivity of Bi to Vbs</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Vghigh</td>
<td>upper bound for the transition region</td>
<td>V</td>
<td>0.0</td>
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<tr>
<td>Vglow</td>
<td>lower bound for the transition region</td>
<td>V</td>
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<tr>
<td>Lvglow</td>
<td>length dependence of Vglow</td>
<td>um*V</td>
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<tr>
<td>Wvglow</td>
<td>length dependence of Vglow</td>
<td>um*V</td>
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<td>Nlev</td>
<td>Noise model level</td>
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<td>Gdwnoi</td>
<td>Drain noise parameters for Nlev=3</td>
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<tr>
<td>Kf</td>
<td>flicker noise coefficient</td>
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<td>Af</td>
<td>flicker noise exponent</td>
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<td>Ffe</td>
<td>flicker noise frequency exponent</td>
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<td>1.0</td>
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<tr>
<td>Rg</td>
<td>gate resistance</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>N</td>
<td>bulk P-N emission coefficient</td>
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<td>1.0</td>
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<tr>
<td>Imax</td>
<td>explosion current</td>
<td>A</td>
<td>10.0</td>
</tr>
<tr>
<td>wVsubfwd</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
</tbody>
</table>
Notes/Equations/References

1. This model supplies values for a MOSFET device.

2. BSIM1, BSIM2, and BSIM3 MOSFET models use the same parameters and parameter definitions as the BSIM models in SPICE3 (University of California-Berkeley).

3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
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</thead>
<tbody>
<tr>
<td>wBvsub</td>
<td>substrate junction reverse breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
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<tr>
<td>wBvg</td>
<td>gate oxide breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td>infinite</td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td>infinite</td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent-based parameters</td>
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<td></td>
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BSIM3_Model (BSIM3 MOSFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 5-4. BSIM3_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
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<tr>
<td>NMOS</td>
<td>N-channel type model</td>
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<tr>
<td>PMOS</td>
<td>P-channel type model</td>
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<td>no</td>
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<tr>
<td>Idsmod</td>
<td>Ids model</td>
<td></td>
<td>8</td>
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<tr>
<td>Version</td>
<td>model version</td>
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<td>3.22</td>
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<td>Mobmod</td>
<td>mobility model selector</td>
<td></td>
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<tr>
<td>Capmod</td>
<td>capacitance model selector</td>
<td></td>
<td>1</td>
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<tr>
<td>Noimod</td>
<td>noise model selector</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Paramchk</td>
<td>model parameter checking selector</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Binunit</td>
<td>bin unit selector</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Rg</td>
<td>gate resistance</td>
<td>ohms</td>
<td>0</td>
</tr>
<tr>
<td>Rsh</td>
<td>drain and source diffusion sheet resistance</td>
<td>ohms/sq</td>
<td>0.0</td>
</tr>
<tr>
<td>Nj</td>
<td>bulk P-N emission coefficient</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Xti</td>
<td>junction current temp. exponent</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Js</td>
<td>gate saturation current</td>
<td>A/m^2</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>Jsw</td>
<td>sidewall junction reverse saturation current</td>
<td>A/m^2</td>
<td>0.0</td>
</tr>
<tr>
<td>Lint</td>
<td>length offset fitting parameter (binning parameter; see Note 4)</td>
<td>m</td>
<td>0.0</td>
</tr>
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</table>

† Calculated parameter
Table 5-4. BSIM3_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
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</thead>
<tbody>
<tr>
<td>L1</td>
<td>coefficient of length dependence for length offset</td>
<td>m&lt;sup&gt;L1n&lt;/sup&gt;</td>
<td>0.0</td>
</tr>
<tr>
<td>L1n</td>
<td>power of length dependence of length offset</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Lw</td>
<td>coefficient of width dependence for length offset</td>
<td>m&lt;sup&gt;Lwn&lt;/sup&gt;</td>
<td>0.0</td>
</tr>
<tr>
<td>Lwn</td>
<td>power of width dependence of length offset</td>
<td>m&lt;sup&gt;(Lwn+Lln)&lt;/sup&gt;</td>
<td>0.0</td>
</tr>
<tr>
<td>W1</td>
<td>coefficient of length dependence for width offset</td>
<td>m&lt;sup&gt;W1n&lt;/sup&gt;</td>
<td>0.0</td>
</tr>
<tr>
<td>W1n</td>
<td>power of length dependence of width offset</td>
<td>m&lt;sup&gt;W1n&lt;/sup&gt;</td>
<td>1.0</td>
</tr>
<tr>
<td>Ww</td>
<td>coefficient of width dependence for width offset</td>
<td>m&lt;sup&gt;Wwn&lt;/sup&gt;</td>
<td>0.0</td>
</tr>
<tr>
<td>Wwn</td>
<td>power of width dependence of width offset</td>
<td>m&lt;sup&gt;(Wwn+Wln)&lt;/sup&gt;</td>
<td>1.0</td>
</tr>
<tr>
<td>Wwl</td>
<td>coefficient of length and width cross term for length offset</td>
<td>m&lt;sup&gt;(Wwn+Wln)&lt;/sup&gt;</td>
<td>0.0</td>
</tr>
<tr>
<td>Tnom</td>
<td>parameter measurement temp.</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>Tox</td>
<td>oxide thickness</td>
<td>m</td>
<td>1.5 × 10&lt;sup&gt;-8&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cj</td>
<td>zero-bias bulk junction bottom capacitance</td>
<td>F/m&lt;sup&gt;2&lt;/sup&gt;</td>
<td>5.0 × 10&lt;sup&gt;-4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mj</td>
<td>bulk junction bottom grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Cjsw</td>
<td>zero-bias bulk junction sidewall capacitance</td>
<td>F/m</td>
<td>5.0 × 10&lt;sup&gt;-10&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mjsw</td>
<td>bulk junction sidewall grading coefficient</td>
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† Calculated parameter.
Table 5-4. BSIM3_Model Parameters (continued)

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<th>Parameter</th>
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<tbody>
<tr>
<td>Pb</td>
<td>bulk junction potential</td>
<td>V</td>
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<tr>
<td>Pbsw</td>
<td>sidewall junction potential</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Xt</td>
<td>doping depth</td>
<td>m</td>
<td>$1.55 \times 10^{-7}$</td>
</tr>
<tr>
<td>Vbm</td>
<td>maximum applied body bias</td>
<td>V</td>
<td>−5.0</td>
</tr>
<tr>
<td>Vbx</td>
<td>Vth transition body voltage</td>
<td>V</td>
<td>†</td>
</tr>
<tr>
<td>Xj</td>
<td>metallurgical junction depth</td>
<td>m</td>
<td>$1.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>Dwg</td>
<td>coefficient of Weff's gate dependence</td>
<td>m/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Dwb</td>
<td>coefficient of Weff's body dependence</td>
<td>m/V$^{(1/2)}$</td>
<td>0.0</td>
</tr>
<tr>
<td>Nch</td>
<td>channel doping concentration</td>
<td>1/cm$^3$</td>
<td>$1.7 \times 10^{17}$</td>
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<tr>
<td>Nsub</td>
<td>substrate doping concentration</td>
<td>1/cm$^3$</td>
<td>$6.0 \times 10^{16}$</td>
</tr>
<tr>
<td>Ngate</td>
<td>poly-gate doping concentration</td>
<td>1/cm$^3$</td>
<td>†</td>
</tr>
<tr>
<td>Gamma1</td>
<td>body effect coefficient near interface</td>
<td>V$^{(1/2)}$</td>
<td>†</td>
</tr>
<tr>
<td>Gamma2</td>
<td>body effect coefficient in the bulk</td>
<td>V$^{(1/2)}$</td>
<td>†</td>
</tr>
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<td>1st parameter of impact ionization current</td>
<td>m/V</td>
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<tr>
<td>Beta0</td>
<td>2nd parameter of impact ionization current</td>
<td>V</td>
<td>30.0</td>
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<td>Vth0</td>
<td>zero-bias threshold voltage</td>
<td>V</td>
<td>†</td>
</tr>
<tr>
<td>K1</td>
<td>first order body effect coefficient</td>
<td>V$^{(1/2)}$</td>
<td>†</td>
</tr>
<tr>
<td>K2</td>
<td>second order body effect coefficient</td>
<td>V$^{(1/2)}$</td>
<td>†</td>
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<td>K3</td>
<td>narrow width effect coefficient</td>
<td>V$^{(1/2)}$</td>
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<td>K3b</td>
<td>body effect coefficient of K3</td>
<td>1/V</td>
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† Calculated parameter
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
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<tbody>
<tr>
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<td>narrow width effect W offset (binning parameter; see Note 4)</td>
<td>m</td>
<td>$2.5 \times 10^{-6}$</td>
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<tr>
<td>Nlx</td>
<td>lateral non-uniform doping effect (binning parameter; see Note 4)</td>
<td>m</td>
<td>$1.74 \times 10^{-7}$</td>
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<td>Dvt0</td>
<td>short channel effect coefficient 0 (binning parameter; see Note 4)</td>
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<tr>
<td>Dvt1</td>
<td>short channel effect coefficient 1 (binning parameter; see Note 4)</td>
<td>-</td>
<td>0.53</td>
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<tr>
<td>Dvt2</td>
<td>short channel effect coefficient 2 (binning parameter; see Note 4)</td>
<td>1/V</td>
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<tr>
<td>Dvt0w</td>
<td>narrow width effect coefficient 0 (binning parameter; see Note 4)</td>
<td>1/m</td>
<td>0.0</td>
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<tr>
<td>Dvt1w</td>
<td>narrow width effect coefficient 1 (binning parameter; see Note 4)</td>
<td>1/m</td>
<td>$5.3 \times 10^{6}$</td>
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<tr>
<td>Dvt2w</td>
<td>narrow width effect coefficient 2 (binning parameter; see Note 4)</td>
<td>1/V</td>
<td>−0.032</td>
</tr>
<tr>
<td>Cgso</td>
<td>gate-source overlap capacitance, per channel width</td>
<td>F/m</td>
<td>†</td>
</tr>
<tr>
<td>Cgdo</td>
<td>gate-drain overlap capacitance, per channel width</td>
<td>F/m</td>
<td>†</td>
</tr>
<tr>
<td>Cgbo</td>
<td>gate-bulk overlap capacitance, per channel length</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Xpart</td>
<td>flag for channel charge partition</td>
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<tr>
<td>Drout</td>
<td>DIBL effect on Rout coefficient binning parameter; see Note 4)</td>
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<tr>
<td>Dsub</td>
<td>DIBL effect coefficient in subthreshold region binning parameter; see Note 4</td>
<td>-</td>
<td>(fixed by Drout)</td>
</tr>
<tr>
<td>Ua</td>
<td>linear Vgs dependence of mobility (binning parameter; see Note 4)</td>
<td>m/V</td>
<td>$2.25 \times 10^{-9}$</td>
</tr>
<tr>
<td>Ua1</td>
<td>temperature coefficient of Ua</td>
<td>m/V</td>
<td>$4.31 \times 10^{-9}$</td>
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† Calculated parameter
Table 5-4. BSIM3 Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
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<tbody>
<tr>
<td>Ub1</td>
<td>temperature coefficient of Ub</td>
<td>(m/V)^2</td>
<td>$-7.61 \times 10^{-18}$</td>
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<tr>
<td>Ub</td>
<td>quadratic Vgs dependence of mobility (binning parameter; see Note 4)</td>
<td>(m/V)^2</td>
<td>$5.87 \times 10^{-19}$</td>
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<tr>
<td>Uc</td>
<td>body-bias dependence of mobility (binning parameter; see Note 4)</td>
<td>m/V^2 1/V</td>
<td>$-4.65 \times 10^{-11}$ Mobmod = 1,2 − 0.0465 Mobmod = 3</td>
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<tr>
<td>Uc1</td>
<td>temperature coefficient of Uc</td>
<td>m/V^2 1/V</td>
<td>$-5.6 \times 10^{-11}$ Mobmod = 1,2 − 0.056 Mobmod = 3</td>
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<tr>
<td>U0</td>
<td>low-field mobility at T=Tnom (binning parameter; see Note 4)</td>
<td>cm^2/Vs</td>
<td>670.0 NMOS 250.0 PMOS</td>
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<tr>
<td>Ute</td>
<td>temperature coefficient of mobility</td>
<td>0/V</td>
<td>−1.5</td>
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<tr>
<td>Rdsw</td>
<td>source drain resistance per width (binning parameter; see Note 4)</td>
<td>ohms × µm^Wr</td>
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<td>Prwg</td>
<td>gate bias effect coefficient of Rdsw (binning parameter; see Note 4)</td>
<td>1/V</td>
<td>0.0</td>
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<tr>
<td>Prwb</td>
<td>body effect coefficient of Rdsw (binning parameter; see Note 4)</td>
<td>1/V</td>
<td>0.0</td>
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<tr>
<td>Wr</td>
<td>width dependence of Rds (binning parameter; see Note 4)</td>
<td>1/V</td>
<td>1.0</td>
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<tr>
<td>Prt</td>
<td>temperature coefficient of Rdsw</td>
<td>ohms × µm</td>
<td>0.0</td>
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<tr>
<td>Vsat</td>
<td>saturation velocity at T=Tnom (binning parameter; see Note 4)</td>
<td>m/s</td>
<td>$8.0 \times 10^4$</td>
</tr>
<tr>
<td>At</td>
<td>temperature coefficient of Vsat</td>
<td>m/s</td>
<td>$3.3 \times 10^4$</td>
</tr>
<tr>
<td>A0</td>
<td>bulk charge effect coefficient for channel length (binning parameter; see Note 4)</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Keta</td>
<td>body-bias coefficient of bulk charge (binning parameter; see Note 4)</td>
<td>1/V</td>
<td>−0.047</td>
</tr>
<tr>
<td>Ags</td>
<td>gate bias coefficient of Abulk (binning parameter; see Note 4)</td>
<td>1/V</td>
<td>0.0</td>
</tr>
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† Calculated parameter
Table 5-4. BSIM3_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>first non-saturation factor for PMOS (binning parameter; see Note 4)</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>A2</td>
<td>second non-saturation factor for PMOS (binning parameter; see Note 4)</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>B0</td>
<td>bulk charge effect coefficient for channel width (binning parameter; see Note 4)</td>
<td>m</td>
<td>0.0</td>
</tr>
<tr>
<td>B1</td>
<td>bulk charge effect width offset (binning parameter; see Note 4)</td>
<td>m</td>
<td>0.0</td>
</tr>
<tr>
<td>Voff</td>
<td>threshold voltage offset (binning parameter; see Note 4)</td>
<td>V</td>
<td>-0.08</td>
</tr>
<tr>
<td>Nfactor</td>
<td>subthreshold swing factor (binning parameter; see Note 4)</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Cdsc</td>
<td>D/S and channel coupling capacitance (binning parameter; see Note 4)</td>
<td>F/m²</td>
<td>2.4 × 10⁻⁴</td>
</tr>
<tr>
<td>Cdscb</td>
<td>body-bias dependence of Cdsc (binning parameter; see Note 4)</td>
<td>F/V/m²</td>
<td>0.0</td>
</tr>
<tr>
<td>Cdscd</td>
<td>drain-bias dependence of Cdsc (binning parameter; see Note 4)</td>
<td>F/V/m²</td>
<td>0.0</td>
</tr>
<tr>
<td>Cit</td>
<td>interface state capacitance (binning parameter; see Note 4)</td>
<td>F/m²</td>
<td>0.0</td>
</tr>
<tr>
<td>Eta0</td>
<td>subthreshold region DIBL coefficient (binning parameter; see Note 4)</td>
<td></td>
<td>0.08</td>
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<tr>
<td>Etab</td>
<td>body-bias coefficient for DIBL effect (binning parameter; see Note 4)</td>
<td>1/V</td>
<td>-0.07</td>
</tr>
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<td>Pclm</td>
<td>channel-length modulation coefficient (binning parameter; see Note 4)</td>
<td></td>
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<tr>
<td>Pdiblc1</td>
<td>first Rout DIBL effect coefficient</td>
<td></td>
<td>0.39</td>
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<tr>
<td>Pdiblc2</td>
<td>second Rout DIBL effect coefficient</td>
<td></td>
<td>0.0086</td>
</tr>
<tr>
<td>Pdiblcb</td>
<td>body effect coefficient of DIBL correction parameters</td>
<td>1/V</td>
<td>0</td>
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† Calculated parameter
<table>
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<tr>
<td>Pscbe1</td>
<td>first substrate current body effect</td>
<td>V/m</td>
<td>$4.24 \times 10^8$</td>
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<tr>
<td>Pscbe2</td>
<td>second substrate current body effect</td>
<td>m/V</td>
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<tr>
<td>Pvag</td>
<td>Vg dependence of Rout coefficient (binning parameter; see Note 4)</td>
<td>V</td>
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<tr>
<td>Delta</td>
<td>effective Vds parameter (binning parameter; see Note 4)</td>
<td>V</td>
<td>0.01</td>
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<td>Kt1</td>
<td>temperature coefficient of Vth</td>
<td>V</td>
<td>−0.11</td>
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<tr>
<td>Kt1l</td>
<td>channel length sensitivity of Kt1</td>
<td>Vxm</td>
<td>0.0</td>
</tr>
<tr>
<td>Kt2</td>
<td>body bias coefficient of Kt1</td>
<td></td>
<td>0.022</td>
</tr>
<tr>
<td>Cgsl</td>
<td>light doped source-gate region overlap capacitance</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgdl</td>
<td>light doped drain-gate region overlap capacitance</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Ckappa</td>
<td>coefficient for lightly doped region overlap capacitance</td>
<td>F/m</td>
<td>0.6</td>
</tr>
<tr>
<td>Cf</td>
<td>fringing field capacitance</td>
<td>F/m</td>
<td></td>
</tr>
<tr>
<td>Clc</td>
<td>constant term for short channel model</td>
<td>m</td>
<td>$0.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>Cle</td>
<td>exponential term for short channel</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>Dlc</td>
<td>length offset fitting parameter from C-V</td>
<td>m</td>
<td>Lint</td>
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<tr>
<td>Dwc</td>
<td>width offset fitting parameter from C-V</td>
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<td>Wint</td>
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<td>Nlev</td>
<td>Noise model level</td>
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<td>Gdwnoi</td>
<td>Drain noise parameters for Nlev=3</td>
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<tr>
<td>Kf</td>
<td>flicker (1/f) noise coefficient</td>
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<td>0.0</td>
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<tr>
<td>Af</td>
<td>flicker (1/f) noise exponent</td>
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<td>Noia</td>
<td>noise parameter A</td>
<td></td>
<td>$1.0 \times 10^{20}$ NMOS $9.9 \times 10^{18}$ PMOS</td>
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† Calculated parameter
### Table 5-4. BSIM3_Model Parameters (continued)

<table>
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<td></td>
<td></td>
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<tr>
<td>Noic</td>
<td>noise parameter C</td>
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<td>$-1.4 \times 10^{-12}$ NMOS</td>
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<td></td>
<td></td>
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<td>$1.4 \times 10^{12}$ PMOS</td>
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<td>Imax</td>
<td>explosion current</td>
<td>A</td>
<td>10.0</td>
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<tr>
<td>wVsubfwd</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvsub</td>
<td>substrate junction reverse breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvg</td>
<td>gate oxide breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
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<tr>
<td>wdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td>infinite</td>
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<tr>
<td>Toxm</td>
<td>gate oxide thickness tox value at which parameters are extracted</td>
<td>m</td>
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<tr>
<td>Vfb</td>
<td>DC flat-band voltage</td>
<td>V</td>
<td>†</td>
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<td>Noff</td>
<td>CV parameter in VgsteffCV for weak-to-strong inversion region</td>
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<td>Voffcv</td>
<td>CV parameter in VgsteffCV for weak-to-strong inversion region</td>
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<tr>
<td>Ijth</td>
<td>diode limiting current</td>
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<td>†</td>
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<td>Alpha1</td>
<td>substrate current parameter</td>
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<td>exponential coefficient for charge thickness in the accumulation and depletion regions (binning parameter; see Note 4)</td>
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<td>temperature coefficient of pb</td>
<td>V/K</td>
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<tr>
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<td>temperature coefficient of pbsw</td>
<td>V/K</td>
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<tr>
<td>Tpbswg</td>
<td>temperature coefficient of pbswg</td>
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† Calculated parameter
Table 5-4. BSIM3_Model Parameters (continued)

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<td>Tcjsw</td>
<td>temperature coefficient of cjsw</td>
<td>1/K</td>
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<tr>
<td>Tcjswg</td>
<td>temperature coefficient of cjswg</td>
<td>1/K</td>
<td>0.0</td>
</tr>
<tr>
<td>Llc</td>
<td>coefficient of length dependence for CV channel length offset</td>
<td>$m_{L l n}$</td>
<td>DC $L_l$</td>
</tr>
<tr>
<td>Lwc</td>
<td>coefficient of width dependence for CV channel length offset</td>
<td>$m_{L w n}$</td>
<td>DC $L_w$</td>
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<tr>
<td>Lwlc</td>
<td>coefficient of length and width cross-term for CV channel length offset</td>
<td>$m_{L w n + L l n}$</td>
<td>DC $L_w l$</td>
</tr>
<tr>
<td>Wlc</td>
<td>coefficient of length dependence for CV channel width offset</td>
<td>$m_{W l n}$</td>
<td>DC $W_l$</td>
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<tr>
<td>Wwc</td>
<td>coefficient of width dependence for CV channel width offset</td>
<td>$m_{W w n}$</td>
<td>DC $W_w$</td>
</tr>
<tr>
<td>Wwlc</td>
<td>coefficient of length and width cross-term for CV channel width offset</td>
<td>$m_{W l n + W w n}$</td>
<td>DC $W_w l$</td>
</tr>
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<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td>infinite</td>
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<td>area calculation method</td>
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<td>Calcacm</td>
<td>flag to use Acm when Acm=12</td>
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<td>Hdif</td>
<td>length of heavily doped diffusion (ACM=2,3 only)</td>
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<td>Ldif</td>
<td>length of lightly doped diffusion adjacent to gate (ACM=1,2)</td>
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<td>width diffusion layer shrink reduction factor</td>
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<td>Xw</td>
<td>accounts for masking and etching effects</td>
<td>m</td>
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</tr>
<tr>
<td>Xi</td>
<td>accounts for masking and etching effects</td>
<td>m</td>
<td>0</td>
</tr>
<tr>
<td>Rdc</td>
<td>additional drain resistance due to contact resistance</td>
<td>Ohms</td>
<td>0</td>
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† Calculated parameter
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rsc</td>
<td>additional source resistance due to contact resistance</td>
<td>Ohms</td>
<td>0</td>
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<tr>
<td>Vfbcv</td>
<td>flat-band voltage parameter for cap-mod=0 only</td>
<td>F/m</td>
<td>-1.0</td>
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<tr>
<td>B3qmod</td>
<td>BSIM3 charge model (0 for Berkeley, 1 for Hspice Capmod = 0)</td>
<td>...</td>
<td>0</td>
</tr>
<tr>
<td>Cjswg</td>
<td>S/D (gate side) sidewall junction capacitance</td>
<td>F/m</td>
<td>Cjsw</td>
</tr>
<tr>
<td>Pbswg</td>
<td>S/D (gate side) sidewall junction built in potential</td>
<td>V</td>
<td>Mjsw</td>
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<td>Mjswg</td>
<td>S/D (gate side) sidewall junction grading coefficient</td>
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<td>non-quasi-static Elmore constant parameter</td>
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<tr>
<td>Rs</td>
<td>source resistance</td>
<td>Ohms</td>
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<td>flicker noise model selector</td>
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<td>temperature equation selector for capacitance (0/1/2/3)</td>
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<tr>
<td>Gap2</td>
<td>energy gap temperature coefficient beta</td>
<td>K</td>
<td>1108</td>
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<td>Cta</td>
<td>Cj linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
<tr>
<td>Ctp</td>
<td>Cjsw linear temperature coefficient</td>
<td>1/°C</td>
<td>0</td>
</tr>
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<td>Pta</td>
<td>Vj linear temperature coefficient</td>
<td>1/°C</td>
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† Calculated parameter
Table 5-4. BSIM3_Model Parameters (continued)

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<td>Ptp</td>
<td>Vjsw linear temperature coefficient</td>
<td>$1/\degree C$</td>
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<tr>
<td>Trd</td>
<td>Rd linear temperature coefficient</td>
<td>$1/\degree C$</td>
<td>0</td>
</tr>
<tr>
<td>Trs</td>
<td>Rs linear temperature coefficient</td>
<td>$1/\degree C$</td>
<td>0</td>
</tr>
<tr>
<td>Wmin</td>
<td>binning minimum width (not used for binning; use BinModel)</td>
<td>m</td>
<td>0</td>
</tr>
<tr>
<td>Wmax</td>
<td>binning maximum width (not used for binning; use BinModel)</td>
<td>m</td>
<td>1</td>
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<tr>
<td>Lmin</td>
<td>binning minimum length (not used for binning; use BinModel)</td>
<td>m</td>
<td>0</td>
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<tr>
<td>Lmax</td>
<td>binning maximum length (not used for binning; use BinModel)</td>
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<tr>
<td>AllParams</td>
<td>.DataAccessComponent-based parameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Calculated parameter

Notes/Equations/References

1. Nqsmod is also supported as an instance parameter. For simulation, only the Nqsmod instance parameter is used; the Nqsmod model parameter is not used. This is the way Berkeley defined Nqsmod in BSIM3v3.2. Hspice supports Nqsmod only as a model parameter.

2. This model supplies values for a MOSFET device. The default Version is 3.22. The previous version can be used by setting the Version parameter to 3.0, 3.1, 3.2, or 3.21.

3. BSIM1, BSIM2, and BSIM3 MOSFET models use the same parameters and parameter definitions as the BSIM models in SPICE3 (University of California-Berkeley).

4. Several DC, AC, and capacitance parameters can be binned. They are identified in the Description column of Table 5-4. All of these parameters follow this implementation:

$$P = P_0 + \frac{P_L}{W_{eff}} + \frac{P_w}{L_{eff}} + \frac{P_d}{L_{eff} \times W_{eff}}$$  \hspace{1cm} (5-1)
For example, for the parameter $k_1$, the following relationships exist: $P_0 = k_1$, $P_L = l_1$, $P_W = w_1$, $P_P = p_1$. The Binunit parameter is a binning unit selector. If $\text{Binunit} = 1$, the units of $L_{\text{eff}}$ and $W_{\text{eff}}$, used in the preceding binning equation have the units of microns, otherwise in meters. For example, for a device with $L_{\text{eff}} = 0.5\mu\text{m}$ and $W_{\text{eff}} = 10\mu\text{m}$, if $\text{Binunit} = 1$, the parameter values for $v_{\text{sat}}$ are $1\times10^5$, $1\times10^4$, $2\times10^4$, and $3\times10^4$ for $v_{\text{sat}}$, $l_{\text{vsat}}$, $w_{\text{vsat}}$, and $p_{\text{vsat}}$, respectively. Therefore, the effective value of $v_{\text{sat}}$ for this device is:

$$v_{\text{sat}} = 1\times10^5 + 1\times10^4/0.5 + 2\times10^4/10 + 3\times10^4/(0.5\times10) = 1.28\times10^5$$

To get the same effective value of $v_{\text{sat}}$ for $\text{Binunit} = 0$, the values of $v_{\text{sat}}$, $l_{\text{vsat}}$, $w_{\text{vsat}}$, and $p_{\text{vsat}}$ would be $1\times10^5$, $1\times10^{-2}$, $2\times10^{-2}$, $3\times10^{-8}$, respectively. Thus:

$$v_{\text{sat}} = 1\times10^5 + 1\times10^{-2}/0.5\times10^{-6} + 2\times10^{-2}/10\times10^{-6} + 3\times10^{-8}/(0.5\times10^{-6} \times 10\times10^{-6}) = 1.28\times10^5$$

5. The nonquasi-static (NQS) charge model is supported in versions 3.2 and later.

6. Model parameter $U_0$ can be entered in meters or centimeters. $U_0$ is converted to $m^2/V\sec$ as follows: if $U_0 > 1$, it is multiplied by $10^{-4}$.

7. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

8. DC operating point data is generated for this model. If a DC simulation is performed, device operating point data can be viewed for a component. The procedure for doing this is described in the Circuit Simulation manual. The device operating point information that is displayed for the BSIM3 model is:

- $G_{mb}$: Small-signal $V_{bs}$ to $I_{ds}$ transconductance, in Siemens
- $G_{ds}$: Small-signal drain source conductance, in Siemens
- $V_{dsat}$: Saturation voltage, in Volts
- $C_{apbd}$: Small-signal bulk drain capacitance, in Farads
- $C_{apbs}$: Small-signal bulk source capacitance, in Farads
- $C_{gd}$: Small-signal gate drain Meyer capacitance, in Farads
- $C_{gb}$: Small-signal gate bulk Meyer capacitance, in Farads
- $C_{gs}$: Small-signal gate source Meyer capacitance, in Farads
- $D_{qg}$: Small-signal transcapacitance $dQ_{g}/dV_{g}$, in Farads
Devices and Models, MOS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>DqwDvdb</td>
<td>Small-signal transcapacitance dQg/dVd, in Farads</td>
</tr>
<tr>
<td>DqwDvsb</td>
<td>Small-signal transcapacitance dQg/dVs, in Farads</td>
</tr>
<tr>
<td>DqbdDvgb</td>
<td>Small-signal transcapacitance dQb/dVg, in Farads</td>
</tr>
<tr>
<td>DqbdDvdb</td>
<td>Small-signal transcapacitance dQb/dVd, in Farads</td>
</tr>
<tr>
<td>DqbdDvsb</td>
<td>Small-signal transcapacitance dQb/dVs, in Farads</td>
</tr>
<tr>
<td>DqdbDvgb</td>
<td>Small-signal transcapacitance dQd/dVg, in Farads</td>
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<tr>
<td>DqdbDvsb</td>
<td>Small-signal transcapacitance dQd/dVs, in Farads</td>
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</table>
BSIM3SOI_Model (BSIM3 Silicon On Insulator MOSFET Model)

Symbol

![Symbol Image]

**Parameters**

Model parameters must be specified in SI units. In some cases, parameters that are simply geometric variations of a listed parameter, such as L, W, or P, are not listed in this table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
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<tbody>
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<td>Noimod</td>
<td>noise model selector</td>
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<td>1</td>
</tr>
<tr>
<td>Shmod</td>
<td>self-heating mode selector; 0 = no self-heating, 1 = self-heating</td>
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<td>Ddmod</td>
<td>dynamic depletion mode selector</td>
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<td>Igmod</td>
<td>gate current model selector</td>
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<td>drain bias dependence of Cdsc</td>
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† Calculated parameter
Table 5-5. BSIM3SOI Parameters (continued)

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<td>saturation velocity at temp, m/s (binning parameter; see Note 3)</td>
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<td>gate bulk coefficient of Abulk (binning parameter; see Note 3)</td>
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<td>A2</td>
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<td>body-bias coefficient of the bulk charge effect (binning parameter; see Note 3)</td>
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<td>substrate doping concentration with polarity</td>
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<td>Nch</td>
<td>Channel doping concentration</td>
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<td>Ngate</td>
<td>poly-gate doping concentration</td>
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<td>V^(1/2)†</td>
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<td>body-effect coefficient in the bulk</td>
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<td>Vth transition body voltage</td>
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<td>maximum body voltage</td>
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<td>$K_{3b}$</td>
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<td>$W_O$</td>
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<td>$N_{1x}$</td>
<td>lateral non-uniform doping coefficient (binning parameter; see Note 3)</td>
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<td>$D_{rout}$</td>
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*Calculated parameter*
Table 5-5. BSIM3SOI Parameters (continued)

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<td>first-order mobility degradation coefficient (binning parameter; see Note 3)</td>
<td>m/V</td>
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<td>m/V</td>
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<td>second-order mobility degradation coefficient (binning parameter; see Note 3)</td>
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<td>low-field mobility at T=Tnom (binning parameter; see Note 3)</td>
<td>m^2/(V*s)</td>
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<td>temperature coefficient of mobility</td>
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<td>Voff</td>
<td>Offset voltage in sub-threshold region (binning parameter; see Note 3)</td>
<td>V</td>
<td>0.08</td>
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<td>measurement temperature</td>
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<td>G-D overlap capacitance per meter channel width</td>
<td>F/m</td>
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<td>gate bias effect on parasitic resistance (binning parameter; see Note 3)</td>
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† Calculated parameter
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<td>temperature coefficient of parasitic resistance</td>
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<td>second non-saturation factor for PMOS</td>
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<td>channel-length modulation effect coefficient</td>
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<td>silicon-on-insulator thickness</td>
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† Calculated parameter
### Table 5-5. BSIM3SOI Parameters (continued)

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<td>V</td>
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<td>S/D (gate side) sidewall junction grading coefficient</td>
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<td>S/D (gate side) sidewall junction capacitance</td>
<td>( m )</td>
<td>1.0( \times )10^{-10}</td>
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<td>Lin</td>
<td>power of length dependence of length offset</td>
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<td>coefficient of length and width cross term length offset</td>
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<td>( m/V )</td>
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† Calculated parameter
### Table 5-5. BSIM3SOI Parameters (continued)

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<td>coefficient of length and width cross term width of offset</td>
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<td>fringing field capacitance</td>
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† Calculated parameter
Table 5-5. BSIM3SOI Parameters (continued)

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<td>Ketas</td>
<td>surface potential adjustment for bulk charge effect (binning parameter; see Note 3)</td>
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Table 5-5. BSIM3SOI Parameters (continued)

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<tr>
<td>Sii1</td>
<td>second $V_{gs}$ dependent parameter for impact ionization current (binning parameter; see Note 3)</td>
<td>$V^{-1}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Sii2</td>
<td>third $V_{gs}$ dependent parameter for impact ionization current (binning parameter; see Note 3)</td>
<td>$V^{-1}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Siid</td>
<td>$V_{gs}$ dependent parameter for impact ionization current (binning parameter; see Note 3)</td>
<td>$V^{-1}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Fbjtii</td>
<td>fraction of bipolar current affecting the impact ionization</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Esatii</td>
<td>saturation electric field for impact ionization (binning parameter; see Note 3)</td>
<td>$V/m$</td>
<td>1.0e7</td>
</tr>
<tr>
<td>Ntun</td>
<td>reverse tunneling new-ideality factor (binning parameter; see Note 3)</td>
<td></td>
<td>10.0</td>
</tr>
<tr>
<td>Nrecf0</td>
<td>recombination non-ideality factor at forward bias (binning parameter; see Note 3)</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Nrecro</td>
<td>recombination non-ideality factor at reversed bias (binning parameter; see Note 3)</td>
<td></td>
<td>10.0</td>
</tr>
<tr>
<td>Isbjt</td>
<td>BJT injection saturation current (binning parameter; see Note 3)</td>
<td>$A/m^2$</td>
<td>1.0e-6</td>
</tr>
<tr>
<td>Isdif</td>
<td>Body to source/drain injection saturation current (binning parameter; see Note 3)</td>
<td>$A/m^2$</td>
<td>0.0</td>
</tr>
<tr>
<td>Isrec</td>
<td>recombination in depletion saturation current (binning parameter; see Note 3)</td>
<td>$A/m^2$</td>
<td>1.0e-6</td>
</tr>
<tr>
<td>Istun</td>
<td>reverse tunneling saturation current (binning parameter; see Note 3)</td>
<td>$A/m^2$</td>
<td>0.0</td>
</tr>
<tr>
<td>Ln</td>
<td>electron/hole diffusion length</td>
<td>$m$</td>
<td>2.0e-6</td>
</tr>
</tbody>
</table>

† Calculated parameter
Table 5-5. BSIM3SOI Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vrec0</td>
<td>voltage dependent parameter for recombination current (binning parameter; see Note 3)</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Vtun0</td>
<td>voltage dependent parameter for tunneling current (binning parameter; see Note 3)</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Nbjt</td>
<td>power coefficient of channel length dependency for bipolar current (binning parameter; see Note 3)</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Lbjt0</td>
<td>channel length for bipolar current (binning parameter; see Note 3)</td>
<td>m</td>
<td>0.2e-6</td>
</tr>
<tr>
<td>Ldif0</td>
<td>channel length dependency coefficient of diffusion cap</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Vabjt</td>
<td>early voltage for bipolar current (binning parameter; see Note 3)</td>
<td>V</td>
<td>10.0</td>
</tr>
<tr>
<td>Aely</td>
<td>channel length dependency of early voltage for bipolar current (binning parameter; see Note 3)</td>
<td>V/m</td>
<td>10.0</td>
</tr>
<tr>
<td>Ahli</td>
<td>high level injection parameter for bipolar current (binning parameter; see Note 3)</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Rbody</td>
<td>intrinsic body sheet resistance</td>
<td>Ohm/m^2</td>
<td>0.0</td>
</tr>
<tr>
<td>Rbsh</td>
<td>extrinsic body sheet resistance</td>
<td>Ohm/m^2</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgeo</td>
<td>capacitance per unit channel length</td>
<td>F/m</td>
<td>0/0</td>
</tr>
<tr>
<td>Tt</td>
<td>diffusion capacitance transit time coefficient</td>
<td>s</td>
<td>1.0e-12</td>
</tr>
<tr>
<td>Ndif</td>
<td>power coefficient of channel length dependency for diffusion capacitance</td>
<td></td>
<td>-1.0</td>
</tr>
<tr>
<td>Vsdfb</td>
<td>capacitance flatband voltage (binning parameter; see Note 3)</td>
<td>V</td>
<td>†</td>
</tr>
<tr>
<td>Vsdtb</td>
<td>capacitance threshold voltage (binning parameter; see Note 3)</td>
<td>V</td>
<td>†</td>
</tr>
</tbody>
</table>

† Calculated parameter
### Table 5-5. BSIM3SOI Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Csdmin</td>
<td>source/drain bottom diffusion minimum capacitance</td>
<td>F</td>
<td>†</td>
</tr>
<tr>
<td>Asd</td>
<td>source/drain bottom diffusion smoothing parameter</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Cdesw</td>
<td>source/drain sidewall fringing capacitance per unit channel length</td>
<td>F/m</td>
<td>0/0</td>
</tr>
<tr>
<td>Ntrefc</td>
<td>temperature coefficient for Ncref</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Ntrecr</td>
<td>temperature coefficient for Ncrer</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Dlcb</td>
<td>length offset fitting parameter for body charge</td>
<td>m</td>
<td>Lint</td>
</tr>
<tr>
<td>Fbody</td>
<td>scaling factor for body charge</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Tcjswg</td>
<td>temperature coefficient of Cjswg</td>
<td>K^-1</td>
<td>0.0</td>
</tr>
<tr>
<td>Tpbswg</td>
<td>temperature coefficient of Pbswg</td>
<td>V/K</td>
<td>0.0</td>
</tr>
<tr>
<td>Acde</td>
<td>exponential coefficient for finite charge thickness (binning parameter; see Note 3)</td>
<td>m/V</td>
<td>1.0</td>
</tr>
<tr>
<td>Moin</td>
<td>coefficient for gate-bias dependent surface potential (binning parameter; see Note 3)</td>
<td>V^*(1/2)</td>
<td>15.0</td>
</tr>
<tr>
<td>Delvt</td>
<td>threshold voltage adjust for CV, V (binning parameter; see Note 3)</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Kb1</td>
<td>coefficient of Vbs0 dependency on Ves (binning parameter; see Note 3)</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Dlbg</td>
<td>length offset fitting parameter for backgate charge</td>
<td>m</td>
<td>0.0</td>
</tr>
<tr>
<td>Toxqm</td>
<td>effective oxide thickness considering quantum effect</td>
<td>m</td>
<td>Tox</td>
</tr>
<tr>
<td>Wh0</td>
<td>minimum width for thermal resistance calculation</td>
<td>m</td>
<td>0.0</td>
</tr>
<tr>
<td>Rhalo</td>
<td>Body halo sheet resistance</td>
<td>Ohms</td>
<td>1.0e15</td>
</tr>
<tr>
<td>Ntox</td>
<td>power term of gate current</td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>

† Calculated parameter
1. In the current ADS program version, this model is named BISIM3SOI, which is equivalent to the Berkeley model named BSIMSOI, a deep submicron, silicon-on-insulator MOSFET device model for SPICE engines. It was developed by the BSIM Group under the direction of Professor Chenming Hu in the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley. BSIMSOI is closely related to the industry standard bulk MOSFET model, BSIM.
2. BSIMDP2.2, used for this ADS release, is the new version of the Partial Depletion SOI MOSFET model, BSIMP SOI. The gate-body tunneling (substrate current) is added in this release to enhance the model accuracy. BSIMDP2.2 information can be found on the BSIMSOI website (http://www-device.eecs.berkeley.edu/~bsimsoi).

3. Several DC, AC, and capacitance parameters can be binned. They are identified in the Description column of Table 5-5. All of these parameters follow this implementation:

\[
P = P_0 + \frac{P_L}{L_{eff}} + \frac{P_W}{W_{eff}} + \frac{P_P}{L_{eff} \times W_{eff}}
\]  

(5-2)

For example, for the parameter \( k_1 \), the following relationships exist: \( P_0 = k_1 \), \( P_L = l_k l \), \( P_W = w_k l \), \( P_P = p_k l \). The Binunit parameter is a binning unit selector. If Binunit = 1, the units of \( L_{eff} \) and \( W_{eff} \) used in the preceding binning equation have the units of microns, otherwise in meters. For example, for a device with \( L_{eff} = 0.5 \mu m \) and \( W_{eff} = 10 \mu m \), if Binunit = 1, the parameter values for \( v_{sat} \) are 1e5, 1e4, 2e4, and 3e4 for \( v_{sat} \), \( l_{vsat} \), \( w_{vsat} \), and \( p_{vsat} \), respectively. Therefore, the effective value of \( v_{sat} \) for this device is:

\[
v_{sat} = 1e5 + 1e4/0.5 + 2e4/10 + 3e4/(0.5*10) = 1.28e5
\]

To get the same effective value of \( v_{sat} \) for Binunit = 0, the values of \( v_{sat} \), \( l_{vsat} \), \( w_{vsat} \), and \( p_{vsat} \) would be 1e5, 1e–2, 2e–2, 3e–8, respectively. Thus:

\[
v_{sat} = 1e5 + 1e-2/0.5e6 + 2e-2/10e-6 + 3e-8/(0.5e-6 * 10e-6) = 1.28e5
\]
BSIM3 Silicon On Insulator Transistor, Floating Body (NMOS and PMOS)

BSIM3SOI_NMOS (BSIM3 SOI Transistor (Floating Body), NMOS
BSIM3SOI_PMOS (BSIM3 SOI Transistor (Floating Body), PMOS)

Symbol

Parameters

Model parameters must be specified in SI units

Model = model instance name

Length = channel length in um, mm, cm, meter, mil, or in (default: 5.0e-6)

Width = channel width in um, mm, cm, meter, mil, or in (default: 5.0e-6)

Ad = area of drain diffusion, in m^2 (default: 0.0)

As = area of source diffusion, in m^2 (default: 0.0)

Pd = perimeter of the drain junction, in m (default: 0.0)

Ps = perimeter of the source diffusion, in m (default: 0.0)

Nrd = number of squares of the drain diffusion (default: 1.0)

Nrs = number of squares of the source diffusion (default: 1.0)

Nrb = number of squares in body (default: 1.0)

Bjtoff = BJT on/off flag (yes = 1, no = 0; default: no)

Rth0 = instance thermal resistance in Ohms (default: model Rth0)

Cth0 = instance thermal resistance in F (default: model Cth0)

Nbc = number of body contact insulation edge (default: 0.0)

Nseg = number of segments for width partitioning (default: 1.0)

Pdbcp = perimeter length for bc parasitics at drain side (default: 0.0)

Psbcp = perimeter length for bc parasitics at source side (default: 0.0)
Agbc = gate to body overlap area for bc parasitics, in m^2 (default: 0.0)
Aebcp = substrate to body overlap area for bc parasitics, in m^2 (default: 0.0)
Vbsusr = Vbs specified by the user, in V (default: Vbs)
Temp = device operating temperature, Celsius (default: 25.0)
Mode = simulation mode for this device (default: nonlinear)
Noise = noise generation option (yes = 1, no = 0; default: yes)
_M = number of devices in parallel (default: 1)
BSIM3 Silicon On Insulator Transistor with 5th Terminal, External Body Contact (NMOS and PMOS)

BSIM3SOI5_NMOS (BSIM3 SOI Transistor with 5th Terminal, NMOS)
BSIM3SOI5_PMOS (BSIM3 SOI Transistor with 5th Terminal, NMOS)

Symbol

Parameters
Model parameters must be specified in SI units
Model = model instance name
Length = channel length in um, mm, cm, meter, mil, or in (default: 5.0e-6)
Width = channel width in um, mm, cm, meter, mil, or in (default: 5.0e-6)
Ad = area of drain diffusion, in m^2 (default: 0.0)
As = area of source diffusion, in m^2 (default: 0.0)
Pd = perimeter of the drain junction, in m (default: 0.0)
Ps = perimeter of the drain junction, in m (default: 0.0)
Nrd = number of squares of the drain diffusion (default: 1.0)
Nrs = number of squares of the source diffusion (default: 1.0)
Nrb = number of squares in body (default: 1.0)
Bjtoff = BJT on/off flag (yes = 1, no = 0; default: no)
Rth0 = instance thermal resistance in Ohms (default: model Rth0)
Cth0 = instance thermal resistance in F (default: model Cth0)
Nbc = number of body contact insulation edge (default: 0.0)
Nseg = number of segments for width partitioning (default: 1.0)
Pdbcp = perimter length for bc parasitics at drain side (default: 0.0)
Psbcp = perimter length for bc parasitics at source side (default: 0.0)
Agbcps = gate to body overlap area for bc parasitics, in m^2 (default: 0.0)
Aebcps = substrate to body overlap area for bc parasitics, in m^2 (default: 0.0)
Vbsusr = Vbs specified by the user, in V (default: Vbs)
Temp = device operating temperature, Celsius (default: 25.0)
Mode = simulation mode for this device (default: nonlinear)
Noise = noise generation option (yes = 1, no = 0; default: yes)
_M = number of devices in parallel (default: 1)
EE_MOS (EEsof Nonlinear MOSFET)

EE_MOS1 (EEsof Nonlinear MOSFET, N-Channel)
EE_MOS1P (EEsof Nonlinear MOSFET, P-Chanel)

Symbol

Parameters
Model = name of an EE_MOS1_Model
Temp = device operating temperature, in °C (default: 25)
Noise = noise generation (yes=1; default) (no =0)
_M = number of devices in parallel (default: 1)
**EE_MOS1_Model (EEsof Nonlinear MOSFET Model)**

**Symbol**

![Symbol](image)

**Parameters**

Table 5-6. EE_MOS1_Model Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is</td>
<td>reverse saturation current</td>
<td>A</td>
<td>10^-14</td>
</tr>
<tr>
<td>N</td>
<td>junction ideality factor</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Cdso</td>
<td>zero-bias output capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Vbi</td>
<td>diode built-in potential</td>
<td>V</td>
<td>0.7</td>
</tr>
<tr>
<td>Mj</td>
<td>junction grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Fc</td>
<td>depletion capacitance linearization point</td>
<td></td>
<td>10^-4</td>
</tr>
<tr>
<td>Vbr</td>
<td>drain-source voltage where breakdown current begins conducting</td>
<td>V</td>
<td>10^-4</td>
</tr>
<tr>
<td>Kbo</td>
<td>breakdown current coefficient</td>
<td></td>
<td>10^-4</td>
</tr>
<tr>
<td>Nbr</td>
<td>breakdown current exponent</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Vinfl</td>
<td>inflection point in Cgs-Vgs characteristic</td>
<td>V</td>
<td>5.0</td>
</tr>
<tr>
<td>Deltds</td>
<td>linear region to saturation region transition</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Deltgs</td>
<td>Cgs-Vgs transition voltage</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Cgsmax</td>
<td>maximum value of Cgs</td>
<td>F</td>
<td>10^-12</td>
</tr>
<tr>
<td>Cgso</td>
<td>constant portion of gate-source capacitance</td>
<td>F</td>
<td>10^-13</td>
</tr>
<tr>
<td>Cgdo</td>
<td>constant portion of gate-drain capacitance</td>
<td>F</td>
<td>10^-13</td>
</tr>
<tr>
<td>Vgo</td>
<td>gate-source voltage where transconductance is a maximum</td>
<td>V</td>
<td>7.0</td>
</tr>
<tr>
<td>Vto</td>
<td>zero bias threshold voltage</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Gamma</td>
<td>vds dependent threshold</td>
<td>1/V</td>
<td>0.0</td>
</tr>
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</table>
### Table 5-6. EE_MOS1_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gmmax</td>
<td>peak transconductance</td>
<td>S</td>
<td>$10 \times 10^{-3}$</td>
</tr>
<tr>
<td>Delta</td>
<td>transconductance tail-off rate</td>
<td>V</td>
<td>2.0</td>
</tr>
<tr>
<td>Vbreak</td>
<td>voltage where transconductance tail-off begins</td>
<td>V</td>
<td>4.0</td>
</tr>
<tr>
<td>Lambda</td>
<td>output conductance parameter</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Vsatm</td>
<td>maximum value of saturation voltage</td>
<td>V</td>
<td>10.0</td>
</tr>
<tr>
<td>Vgm</td>
<td>gate-source voltage where saturation voltage is Vsatm</td>
<td>V</td>
<td>5.0</td>
</tr>
<tr>
<td>Rdb</td>
<td>dispersion source output impedance</td>
<td>ohms</td>
<td>10^9</td>
</tr>
<tr>
<td>Cbs</td>
<td>dispersion source capacitance</td>
<td>F</td>
<td>$1.6 \times 10^{-13}$</td>
</tr>
<tr>
<td>Gmmaxac</td>
<td>ac value of Gmmax</td>
<td>S</td>
<td>$60 \times 10^{-3}$</td>
</tr>
<tr>
<td>Del tac</td>
<td>ac value of Delta</td>
<td>V</td>
<td>2.0</td>
</tr>
<tr>
<td>Vbreakac</td>
<td>ac value of Vbreak</td>
<td>V</td>
<td>4.0</td>
</tr>
<tr>
<td>Vgoac</td>
<td>ac value of Vgo</td>
<td>V</td>
<td>7</td>
</tr>
<tr>
<td>Lambdaac</td>
<td>ac value of Lambda</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Vsatmac</td>
<td>maximum value of saturation voltage (ac)</td>
<td>V</td>
<td>10.0</td>
</tr>
<tr>
<td>Vgmac</td>
<td>gate-source voltage where saturation voltage is Vsatm (ac)</td>
<td>V</td>
<td>5.0</td>
</tr>
<tr>
<td>Gdbm</td>
<td>additional d-b branch conductance at Vdsm</td>
<td>S</td>
<td>0.0</td>
</tr>
<tr>
<td>Kdb</td>
<td>controls Vds dependence of D-B branch conductance</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Vdsm</td>
<td>voltage where D-B branch conductance becomes constant</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Rd</td>
<td>drain contact resistance</td>
<td>ohms</td>
<td>1.0</td>
</tr>
<tr>
<td>Rs</td>
<td>source contact resistance</td>
<td>ohms</td>
<td>1.0</td>
</tr>
<tr>
<td>Rg</td>
<td>gate metallization resistance</td>
<td>ohms</td>
<td>1.0</td>
</tr>
<tr>
<td>Ris</td>
<td>source end channel resistance</td>
<td>ohms</td>
<td>1.0</td>
</tr>
<tr>
<td>Rid</td>
<td>drain end channel resistance</td>
<td>ohms</td>
<td>1.0</td>
</tr>
<tr>
<td>wBvg</td>
<td>gate oxide breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
</tbody>
</table>
Notes/Equations/References

1. This model supplies values for an EE_MOS device.
2. Model parameters such as Ls, Ld, Lg (as well as other package-related parameters that are included as part of the model file output from the EEMOS1 IC-CAP kernel) are not used by EE_MOS in the simulator. Only those parameters listed in Table 5-6 are part of EE_MOS. Any extrinsic devices must be added externally by the user.
3. To prevent numerical problems, the setting of some model parameters to 0 is trapped by the simulator. The parameter values are changed internally:
   
   \[ \begin{align*}
   R_d &= 10^{-4} \\
   R_s &= 10^{-4} \\
   R_g &= 10^{-4} \\
   R_{is} &= 10^{-4} \\
   R_{id} &= 10^{-4} \\
   V_{gm} &= 0.1 \\
   V_{gmac} &= 0.1 \\
   V_{satm} &= 0.1 \\
   V_{satmac} &= 0.1 \\
   \Delta t_{ds} &= 0.1 \\
   \end{align*} \]

4. TEMP parameter is only used to calculate the noise performance of this model. Temperature scaling of model parameters is not performed.
5. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are

---

Table 5-6. EE_MOS1_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td>infinite</td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td>infinite</td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent-based parameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

6. This device has no default artwork associated with it.

Equations/Discussion:

EEMOS1 is an empirical analytic model that was developed by HP EEsof for the express purpose of fitting measured electrical behavior of 3-terminal n-channel MOSFETs intended for high-frequency analog applications. Unlike most physics-based MOSFET models found in SPICE programs, EEMOS1 contains no process or physical parameters. It does, however, accurately fit those electrical quantities that have direct bearing on the RF predictive abilities of the model, namely $g_m$ vs. bias, $g_{ds}$ vs. bias and, to a lesser degree, input and output capacitances vs. bias. The model includes the following features:

- Accurate drain-source current model fits measured current over gate and drain bias variations.
- Flexible transconductance formulation permits accurate fitting of $g_m$ compression found in MOSFETs.
- Charge model that accurately tracks measured capacitance values.
- Dispersion model that permits simultaneous fitting of high-frequency conductances and dc characteristics.
- Well-behaved analytic expressions permit accurate extrapolations outside of the measurement range used to extract the model.

The model equations were developed concurrently with parameter extraction techniques to ensure the model would contain only parameters that were extractable from measured data. Although the model is amenable to automated parameter extraction techniques, it was designed to consist of parameters that are easily estimated (visually) from measured data such as $g_m$-$V_{gs}$ plots. Because the model equations are all well-behaved analytic expressions, EEMOS1 possesses no inherent limitations with respect to its usable power range. HP EEsof's IC-CAP program provides the user with the capability of extracting EEMOS1 models from measured data.
Channel Current

The channel current model in EEMOS1 is comprised of empirically derived analytic expressions and requires the specification of 9 parameter values. Because EEMOS1 is intended for large-signal analog applications, no attempt is made to characterize this channel current in the subthreshold or weak inversion region. The channel current expression is intended for use above $V_t$ only. The equations were developed through examination of $I_{ds}$ vs. bias and $g_m$ vs. bias plots on a number of DMOS devices from various manufacturers. The equations are sufficiently flexible enough to handle either enhancement or depletion mode devices. The expressions below are given for $V_{ds}>0.0V$ although the model is equally valid for $V_{ds}<0.0V$. The model assumes the device is symmetrical; simply replace $V_{gs}$ with $V_{gd}$ and $V_{ds}$ with $-V_{ds}$ to obtain the reverse region ($V_{ds}<0.0V$) equations. The $g_m$, $g_{ds}$ and $I_{ds}$ equations take on two different forms depending on the value of $V_{gs}$ relative to some of the model parameters. The $I_{ds}$ expression is continuous through at least the second derivative everywhere except at $V_t$, where the second derivative is discontinuous.

The following voltages define regions of operation that are used in the current definitions:

\[ V_t = V_{to} - \gamma \times V_{ds} \]

\[ V_{gst} = V_{gs} - V_t, \]

for $V_{gst} \leq 0$

\[ g_{mo} = 0.0 \]

\[ I_{dso} = 0.0 \]

\[ g_{dso} = 0.0 \]

for $V_{gst} \geq 0$ and $V_{gs} \leq V_{break}$

\[ g_{mo} = g_{mm}(V_{gs}, V_{ds}) \]

\[ I_{dso} = I_{dsm}(V_{gs}, V_{ds}) \]

\[ g_{dso} = g_{dsm}(V_{gs}, V_{ds}) \]

for $V_{gst} \geq 0$ and $V_{gs} > V_{break}$
Devices and Models, MOS

\[ g_{mo} = a(V_{gs} - V_{asym})^b \]

\[ I_{dso} = I_{dsm}(V_{break}, V_{ds}) + \frac{a}{b+1} [(V_{gs} - V_{asym})^{b+1} - \Delta t^{b+1}] \]

\[ g_{dso} = g_{dsm}(V_{break}, V_{ds}) \]

where:

\[ g_{mm}(V, V_{ds}) = G_{mmax} \left[ 1 - \left( \frac{V - V_{go}}{V_t - V_{go}} \right)^2 \right] \]

\[ I_{dsm}(V, V_{ds}) = \left( G_{mmax} \times \left[ (V - V_{go}) \left( 1 - \frac{1}{3} \left( \frac{V - V_{go}}{V_t - V_{go}} \right)^2 \right)^{\frac{2}{3}} \right] \right) \]

\[ g_{dsm}(V, V_{ds}) = G_{mmax} \times \left[ \frac{2 \times \Gamma}{3} \left( 1 - \left( \frac{V - V_{go}}{V_t - V_{go}} \right)^3 \right) \right] \]

\[ m_{g_{mm}} = \frac{\partial g_{mm}}{\partial V} \bigg|_{V = V_{break}} = \frac{2 \times G_{mmax} \sqrt{V_{break} - V_{go}}}{V_t - V_{go} \left( \frac{V_t - V_{go}}{V_t - V_{go}} \right)} \]

\[ V_{asym} = V_{break} - \Delta t \]

\[ b = \frac{m_{g_{mm}} \times \Delta t}{g_{mm}(V_{break}, V_{ds})} \]

\[ a = \frac{g_{mm}(V_{break}, V_{ds})}{\Delta t^b} \]

If \( b = -1 \), then the integral of \( g_{mo} (I_{dso}) \) is comprised of natural log functions:

\[ I_{dso} = I_{dsm}(V_{break}, V_{ds}) + a \log(V_{gs} - V_{asym}) - \log(\Delta t) \]

The current saturation mechanism in EEMOS1 is described empirically through the parameters \( V_{gm} \) and \( V_{satm} \). The drain voltage where the channel current saturates is dependent on \( V_{gs} \) through the following relation:
\[ V_{sat} = V_{satm} \times \tanh \left( \frac{3(V_{gs} - V_t)}{V_{gm}} \right) \]

The preceding relations for \( I_{dso}, g_m, \) and \( g_{do} \) can now be substituted in the following equations that model the current saturation and output conductance. This portion of the model is similar to an approach described by Curtice for modeling MESFETs [1].

\[
I_{ds} = I_{dso} (1 + \Lambda \text{ambda} \times V_{ds}) \tanh \left( \frac{3V_{ds}}{V_{sat}} \right)
\]

\[
g_m = \left[ g_{mo} \tanh \left( \frac{3V_{ds}}{V_{sat}} \right) - I_{dso} \sech^2 \left( \frac{3V_{ds}}{V_{sat}} \right) \right] \times (1 + \Lambda \text{ambda} \times V_{ds})
\]

\[
g_{ds} = \left\{ g_{dso} (1 + \Lambda \text{ambda} \times V_{ds}) + I_{dso} \Lambda \text{ambda} \right\} \tanh \left( \frac{3V_{ds}}{V_{sat}} \right)
\]

\[
+ I_{dso} \times \frac{3(V_{sat} - V_{ds} \partial V_{sat} / \partial V_{ds}) (1 + \Lambda \text{ambda} \times V_{ds})}{V_{sat}^2} \sech^2 \left( \frac{3V_{ds}}{V_{sat}} \right)
\]

where

\[
\frac{\partial V_{sat}}{\partial V_{gs}} = \frac{3 \times V_{satm}}{V_{gm}} \sech \left( \frac{2/3(V_{gs} - V_t)}{V_{gm}} \right)
\]

\[
\frac{\partial V_{sat}}{\partial V_{ds}} = \frac{3 \times V_{satm} \times \Gamma aamma}{V_{gm}} \sech \left( \frac{2/3(V_{gs} - V_t)}{V_{gm}} \right)
\]

Qualitatively, the operation of the channel current model can be described as follows. The \( V_{ds} \) dependence of the equations is dominated by the parameters \( V_{satm}, V_{gm}, \) Gamma, and Lambda. Output conductance is controlled by Gamma and Lambda. The parameter \( V_{satm} \) represents the maximum drain-source voltage where the drain current saturates. \( V_{gm} \) is the gate voltage corresponding to the I-V trace where \( V_{sat} = V_{satm} \).
When Gamma = 0, Vsatm=0 and Lambda=0, EEMOS1 becomes dependent on Vgs only. Under these simplified conditions, the parameters describing the $g_m-V_{gs}$ dependence of the model are easily explained. $V_{to}$ is the $V_{gs}$ value where $g_m$ becomes zero. The transconductance peaks at $V_{gs}=V_{GO}$ with a value of $G_{m\text{max}}$. At $V_{gs}=V_{break}$, the model breaks from its quadratic $g_m$ dependence and follows a hyperbolic dependence. The parameter Delt controls the voltage asymptote of this hyperbola. The shape of this tail-off region can be altered by tuning on the parameter Delt. EEMOS1 constrains the hyperbola to match the derivative of the quadratic function at $V_{gs}=V_{break}$. This ensures a continuous transition between the respective modeling regions for simulation. The parameter definitions are illustrated in Figure 5-1.

**Disperssion Current (Idb)**

The circuit used to model conductance dispersion consists of the elements $R_{db}$, $C_{bs}$ (these linear elements are also parameters) and the nonlinear source $I_{db}(V_{gs}, V_{ds})$. The model is a large-signal generalization of the dispersion model proposed by Golio et al. for MESFETs [2]. At dc, the drain-source current is just the current $I_{ds}$. At high frequency (well above the transition frequency), the drain source current will be equal to $I_{ds\text{ (high frequency)}} = I_{ds\text{ (dc)}} + I_{db}$.

Linearization of the drain-source model yields the following expressions for $y_{21}$ and $y_{22}$ of the intrinsic EEMOS1 model:

---

5-48  EE_MOS1_Model (EEsof Nonlinear MOSFET Model)
Evaluating these expressions at the frequencies $\omega = 0$ and $\omega = \infty$, produces the following results for transconductance and output conductance:

For $\omega = 0$,

\[
\text{Re}[y_{21}] = g_m = g_{dsgs}
\]

\[
\text{Re}[y_{22}] = g_{ds} = g_{dssd}
\]

For $\omega = \infty$,

\[
\text{Re}[y_{21}] = g_m = g_{dsgs} + g_{dbgs}
\]

\[
\text{Re}[y_{22}] = g_{ds} = g_{dssd} + g_{dbds} + \frac{1}{Rdb}
\]

Between these two extremes, the conductances make a smooth transition, the abruptness of that is governed by the time constant $\tau_{\text{disp}} = Rdb \times Cbs$. The frequency $f_0$ at which the conductances are midway between these two extremes is defined as
The parameter Rdb should be set large enough so that its contribution to the output conductance is negligible. Unless the user is specifically interested in simulating the device near f0, the default values of Rdb and Cbs specified in Table 5-6 will be adequate for most RF applications.

The EEMOS1 Ids model can be extracted to fit either dc or ac characteristics. In order to simultaneously fit both dc I-Vs and ac conductances, EEMOS1 uses a simple scheme for modeling the Idb current source whereby different values of the same parameters can be used in the Ids equations. The dc and ac drain-source currents can be expressed as follows:

\[
I_{ds}^{\text{dc}}(\text{Voltages Parameters}) = I_{ds}(\text{Voltages,Vto,\Gamma,\text{Vgo,\text{Gmmax, Delt, \text{Vbreak, L\text{ambda, \text{Vsatm,\text{Vgm}})}}})
\]

\[
I_{ds}^{\text{ac}}(\text{Voltages Parameters}) = I_{ds}(\text{Voltages,Vto,\Gamma,\text{Vgoac, \text{Gmmaxac, Deltac, \text{Vbreakac, L\text{ambdaac, \text{Vsatmac, \text{Vgmac}}}})}})
\]

Parameters such as Vto that do not have an ac counterpart (there is no Vtoac parameter), have been found not to vary significantly between extractions using dc measurements versus those using ac measurements. The difference between the ac and dc values of Ids plus an additional term that is a function of Vds only gives the value of Idb for the dispersion model

\[
I_{db}(V_{gs},V_{ds}) = I_{ds}^{\text{ac}}(V_{gs},V_{ds}) - I_{ds}^{\text{dc}}(V_{gs},V_{ds}) + I_{dbp}(V_{ds})
\]

where I_{dbp} and its associated conductance are given by:

for \(V_{ds} > V_{dsm}\) and \(Kdb \neq 0:\)

\[
I_{dbp} = G_{dbm} \tan^{-1}\left((V_{ds} - V_{dsm})/(Kdb \times G_{dbm})\right) + G_{dbm} \times V_{dsm}
\]
For \( V_{ds} < -V_{dsm} \) and \( K_{db} \neq 0 \):

\[
I_{dp} = \frac{G_{dbm}}{K_{db}} \tan^{-1}\left(\frac{V_{ds} + V_{dsm}}{\sqrt{K_{db} \times G_{dbm} - G_{dbm} \times V_{dsm}}}\right)
\]

\[
g_{dbp} = \frac{G_{dbm}}{K_{db} \times G_{dbm} \times (V_{ds} + V_{dsm})^2 + 1)
\]

For \(-V_{dsm} \leq V_{ds} \leq V_{dsm}\) or \(K_{db} = 0\):

\[
I_{ds} = G_{dbm} \times V_{ds}
\]

\[
g_{dbm} = G_{dbm}
\]

By setting the seven high-frequency parameters equal to their dc counterparts, the dispersion model reduces to \( I_{dp} = I_{dpb} \). Examination of the \( I_{dpb} \) expression reveals that the additional setting of \( G_{dbm} \) to zero disables the dispersion model entirely. Because the \( I_{dpb} \) current is a function of \( V_{ds} \) only, it will impact output conductance only. However, the current function \( I_{ds}^{ac} \) will impact both \( g_m \) and \( g_{ds} \). For this reason, the model is primarily intended to use \( g_m \) data as a means for tuning \( I_{ds}^{ac} \). Once this fitting is accomplished, the parameters \( G_{dbm}, K_{db}, \) and \( V_{dsm} \) can be tuned to optimize the \( g_{ds} \) fit.

**Charge Model**

The EEMOS1 charge model consists of three separate charge sources that model channel charge and charge associated with the substrate (output) diode. The channel charge is partitioned between the two charge sources \( q_{gc} \) and \( q_{gy} \) such that symmetry is maintained relative to \( V_{ds} = 0 \). These expressions were empirically developed by HP EEsof such that their derivatives would fit measured capacitance data. The channel charge expressions are:

\[
q_{gc} = \frac{C_{gmsmax}}{4} \left[ V_{gc} - V_{infl} + \sqrt{(V_{gc} - V_{infl})^2 + \Delta tgs^2}\right]
\]
Devices and Models, MOS

\[ \times \left[ 1 + \tanh \left( \frac{3(V_{gc} - V_{gy})}{\Delta t_{ds}} \right) \right] + C_{gso} \times V_{gc} \]

\[ q_{gy} = \frac{C_{gmsa}}{4} \times \left[ V_{gy} - V_{infl} + \sqrt{(V_{gy} - V_{infl})^2 + \Delta t_{gs}^2} \right] \times \left[ 1 - \tanh \left( \frac{3(V_{gy} - V_{gc})}{\Delta t_{ds}} \right) \right] + C_{gdo} \times V_{gy} \]

The output charge and its derivative are modeled using the standard junction diode depletion formula:

For \(-V_{ds} < F \times V_{bi}\)

\[ q_{ds} = \frac{C_{ds} \times V_{bi}}{1 - M_j} \times \left[ 1 - \left( 1 + \frac{V_{ds}}{V_{bi}} \right)^{1 - M_j} \right] \]

\[ C_{dsds} = \frac{\partial q_{ds}}{\partial V_{ds}} = \frac{C_{ds} \times V_{bi}}{1 + \frac{V_{ds}^{M_j}}{V_{bi}}} \]

For \(-V_{ds} < -F \times V_{bi}\)

the capacitance is extrapolated linearly from its value at \(F \times V_{bi}\) according to the standard SPICE equation for a junction diode [3]. The charge derivatives are related to the small-signal capacitances through the following expressions:

\[ C_{gs} = C_{gcgc} + C_{gygc} \]

\[ C_{gd} = C_{gcgy} + C_{gygy} \]

\[ C_{ds} = C_{dsds} - C_{gcgy} \]

where

\[ C_{gcgc} = \frac{\partial q_{gc}}{\partial V_{gc}} \]

\[ C_{gcgy} = \frac{\partial q_{gc}}{\partial V_{gy}} \]
Substrate Diode and Breakdown

When the drain-source voltage is reverse-biased, the substrate diode conducts according to the standard diode relation:

\[
I_{\text{for}}(V_{ds}) = I_s \times \left[ \frac{-qV_{ds}}{e^{\frac{qV_{ds}}{nkT}} - 1} \right]
\]

where \( q \) is the charge on an electron, \( k \) is Boltzmann's constant, and \( T \) is the junction temperature.

The EEMOS1 breakdown model is based on a simple power law expression. The model consists of three parameters that are easily optimized to measured data. The breakdown current is given by:

For \( V_{ds} > V_{br} \),

\[
I_{\text{bkdn}}(V_{ds}) = K_{bo}(V_{ds} - V_{br})^{N_{br}}
\]

For \( V_{ds} \leq V_{br} \)

\[
I_{\text{bkdn}}(V_{ds}) = 0
\]

Total current flowing through the substrate (body) diode from source to drain is given by:

\[
I_{\text{sub}}(V_{ds}) = I_{\text{for}}(V_{ds}) - I_{\text{bkdn}}(V_d)
\]

Noise Model

Thermal noise generated by resistors \( R_g, R_s, R_d, R_{is}, R_{id}, \) and \( R_{db} \) is characterized by the following spectral density.
Channel noise generated by the dc transconductance $g_m$ is characterized by the following spectral density:

$$\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}$$

In the preceding expressions, $k$ is Boltzmann's constant, $T$ is the operating temperature in Kelvin, $q$ is the electron charge, and $\Delta f$ is the noise bandwidth.

Flicker noise for this device is not modeled in this simulator version. However, the bias-dependent noise sources I_NoiseBD and V_NoiseBD (from the Sources library) can be connected external to the device to model flicker noise.

**Equivalent Circuit**

![Equivalent Circuit Diagram]

**References**


HP_MOS (HP_Root MOS Transistor)

Symbol

Parameters

Model = name of an EE_MOS_Model

Wtot = total gate width, in length units (default: 10⁻⁴)

N = number of gate fingers (default: 1)

_M = number of devices in parallel (default: 1)

Notes/Equations/References

1. Wtot and N are optional scaling parameters that make it possible to scale the extracted model for different geometries.

2. Wtot is the total gate width—not the width per finger; N is the number of fingers. Therefore, the width per finger is Wtot / N. The scaling remains valid for ratios up to 5:1.

3. The parameters Ggs, Gds, Gmr, dQg_dVgs, and the rest are the small-signal parameters of the device evaluated at the dc operating point. To be displayed, they must be listed among the OUTPUT_VARS in the analysis component.
HP_MOS_Model (HP_Root MOS Transistor Model)

Symbol

Parameters

- File = name of rawfile
- Rs = source resistance
- Rg = gate resistance
- Rd = drain resistance
- Ls = source inductance
- Lg = gate inductance
- Ld = drain inductance
- AllParams = DataAccessComponent-based parameters

Notes/Equations/References

1. The values of Rs, Rg, Rd, Ls, Lg, and Ld are meant to override the extracted values stored in the data file named in the File parameter. Generally, these parameters should not be used.

2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

3. Because this model is measurement-based, extrapolation warning messages may occur if the Newton iteration exceeds the measurement range. If these messages occur frequently, check that the measurement data is within the simulation range.

4. For a list of HP Root Model references, refer to “HP_Diode_Model (HP_Root Diode Model)” on page 1-12.
LEVEL1_Model (MOSFET Level-1 Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 5-7. LEVEL1_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOS</td>
<td>N-channel model</td>
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<tr>
<td>PMOS</td>
<td>P-channel model</td>
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<td>capacitance model selector</td>
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<td>Vto†</td>
<td>zero-bias threshold voltage</td>
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<td>transconductance coefficient</td>
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<td>Gamma</td>
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<td>Phi†</td>
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<td>Cbd†</td>
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<td>Cgso</td>
<td>gate-source overlap capacitance per meter of channel width</td>
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</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
†† Value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
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</thead>
<tbody>
<tr>
<td>Cgdo</td>
<td>gate-drain overlap capacitance per meter of channel width</td>
<td>F/m</td>
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<tr>
<td>Cgbo</td>
<td>gate-bulk overlap capacitance per meter of channel length</td>
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<td>Rsh</td>
<td>drain and source diffusion sheet resistance</td>
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<td>Cj†</td>
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<td>Mj</td>
<td>bulk junction bottom grading coefficient</td>
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<td>Cjsw†</td>
<td>zero-bias bulk junction periphery capacitance per meter of junction perimeter</td>
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<td>bulk junction periphery grading coefficient</td>
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<td>bulk junction saturation current per square meter of junction area</td>
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<td>Nss</td>
<td>surface state density</td>
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</tr>
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<td>Tpg</td>
<td>gate material type: 0 = aluminum; -1 = same as bulk; 1 = opposite to bulk</td>
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<tr>
<td>Af</td>
<td>flicker-noise exponent</td>
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<tr>
<td>Fc</td>
<td>bulk junction forward-bias depletion capacitance coefficient</td>
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<tr>
<td>Rg</td>
<td>gate ohmic resistance</td>
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</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.  
†† Value of 0.0 is interpreted as infinity.
Notes/Equations:

1. The simulator provides three MOSFET device models that differ in formulation of I-V characteristics. MOSFET Level1_Model is Shichman-Hodges model derived from [1].

2. Vto, Kp, Gamma, Phi, and Lambda determine the dc characteristics of a MOSFET device. The program will compute these parameters (except Lambda) if instead of specifying them, you specify the process parameters Tox, Uo, Nsub, and Nss.

3. Vto is positive (negative) for enhancement mode and negative (positive) for depletion mode N-channel (P-channel) devices.

Table 5-7. LEVEL1_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rds</td>
<td>drain-source shunt resistance</td>
<td>ohms</td>
<td>infinity††</td>
</tr>
<tr>
<td>Tnom</td>
<td>nominal ambient temp. at which model parameters were derived</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>N</td>
<td>bulk P-N emission coefficient</td>
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<td>1.0</td>
</tr>
<tr>
<td>Tt</td>
<td>bulk P-N transit time</td>
<td>sec</td>
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</tr>
<tr>
<td>Ffe</td>
<td>flicker noise frequency exponent</td>
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<tr>
<td>lmax</td>
<td>explosion current</td>
<td>A</td>
<td>10.0</td>
</tr>
<tr>
<td>wVsubfwd</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvsub</td>
<td>substrate junction reverse breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvg</td>
<td>gate oxide breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td>infinite</td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td>infinite</td>
</tr>
<tr>
<td>AllParams</td>
<td>.DataAccessComponent-based parameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on model Tnom and device Temp.
†† Value of 0.0 is interpreted as infinity.
4. The p-n junctions between the bulk and the drain and the bulk and the source are modeled by parasitic diodes. Each bottom junction is modeled by a diode and each periphery junction is modeled by a depletion capacitance.

5. Diode parameters for the bottom junctions can be specified as absolute values ($I_s$, $C_{bd}$ and $C_{bs}$) or as per unit junction area values ($I_s$ and $C_j$).

   - If $C_{bd} = 0.0$ and $C_{bs} = 0.0$, then $C_{bd}$ and $C_{bs}$ will be computed:
     \[ C_{bd} = C_j \times A_d, \quad C_{bs} = C_j \times A_s \]
   - If $I_s > 0.0$ and $A_d > 0.0$ and $A_s > 0.0$, then $I_s$ for drain and source will be computed:
     \[ I_s(\text{drain}) = I_s \times A_d, \quad I_s(\text{source}) = I_s \times A_s \]

6. Drain and source ohmic resistances can be specified as absolute values ($R_d$, $R_s$) or as per unit square value ($R_{sh}$).

   - If $N_{rd} \neq 0.0$ or $N_{rs} \neq 0.0$, $R_d$ and $R_s$ will be computed:
     \[ R_d = R_{sh} \times N_{rd}, \quad R_s = R_{sh} \times N_{rs} \]

7. Charge storage in the MOSFET consists of capacitances associated with parasitics and intrinsic device.

   - Parasitic capacitances consist of three constant overlap capacitances ($C_{gdo}$, $C_{gso}$, $C_{gbo}$) and the depletion layer capacitances for both substrate junctions (divided into bottom and periphery), that vary as $M_j$ and $M_{jsw}$ power of junction voltage, respectively, and are determined by the parameters $C_{bd}$, $C_{bs}$, $C_j$, $C_{jsw}$, $M_j$, $M_{jsw}$, $P_b$ and $F_c$.

   - The intrinsic capacitances consist of the nonlinear thin-oxide capacitance, which is distributed among the gate, drain, source, and bulk regions.

8. Charge storage is modeled by fixed and nonlinear gate and junction capacitances. MOS gate capacitances, as a nonlinear function of terminal voltages, are modeled by Meyer’s piece-wise linear model for levels 1, 2, and 3. The Ward charge conservation model is also available for levels 2 and 3, by specifying the XQC parameter to a value smaller than or equal to 0.5. For Level 1, the model parameter $TOX$ must be specified to invoke the Meyer model when $\text{Capmod} = 1$ (default value). If $\text{Capmod} = 0$, no gate capacitances will be computed. If $\text{Capmod} = 2$, a smooth version of the Meyer model is used. If $\text{Capmod} = 3$, the charge conserving first-order MOS charge model [2] that was used in Libra is used.
9. To include the thin-oxide charge storage effect, model parameter Tox must be > 0.0.

10. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

**Temperature Scaling**

The model specifies T\text{nom}, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than T\text{nom}, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The depletion capacitances C\text{bd}, C\text{bs}, C\text{j}, and C\text{jsw} vary as:

\[
\text{Cbd}^{\text{NEW}} = \text{Cbd} \left[ \frac{1 + Mj[4 \times 10^{-4}(\text{Temp} - \text{T}_{\text{REF}}) - \gamma^\text{Temp}]}{1 + Mj[4 \times 10^{-4}(\text{T}_{\text{nom}} - \text{T}_{\text{REF}}) - \gamma^\text{Temp}]} \right]
\]

\[
\text{Cbs}^{\text{NEW}} = \text{Cbs} \left[ \frac{1 + Mj[4 \times 10^{-4}(\text{Temp} - \text{T}_{\text{REF}}) - \gamma^\text{Temp}]}{1 + Mj[4 \times 10^{-4}(\text{T}_{\text{nom}} - \text{T}_{\text{REF}}) - \gamma^\text{Temp}]} \right]
\]

\[
\text{Cj}^{\text{NEW}} = \text{Cj} \left[ \frac{1 + Mj[4 \times 10^{-4}(\text{Temp} - \text{T}_{\text{REF}}) - \gamma^\text{Temp}]}{1 + Mj[4 \times 10^{-4}(\text{T}_{\text{nom}} - \text{T}_{\text{REF}}) - \gamma^\text{Temp}]} \right]
\]

\[
\text{Cjsw}^{\text{NEW}} = \text{Cjsw} \left[ \frac{1 + Mjsw[4 \times 10^{-4}(\text{Temp} - \text{T}_{\text{REF}}) - \gamma^\text{Temp}]}{1 + Mjsw[4 \times 10^{-4}(\text{T}_{\text{nom}} - \text{T}_{\text{REF}}) - \gamma^\text{Temp}]} \right]
\]

where \gamma is a function of the junction potential and the energy gap variation with temperature.

The surface potential \Phi and the bulk junction potential \text{Pb} vary as:
The transconductance $K_p$ and mobility $U_o$ vary as:

$$K_p^{\text{NEW}} = K_p\left(\frac{\text{Temp}}{T_{\text{nom}}}\right)^{3/2}$$

$$U_o^{\text{NEW}} = U_o\left(\frac{\text{Temp}}{T_{\text{nom}}}\right)^{3/2}$$

The source and drain to substrate leakage currents $I_s$ and $J_s$ vary as:

$$I_s^{\text{NEW}} = I_s \times \exp\left(\frac{q \times E_G^{T_{\text{nom}}}}{k \times T_{\text{nom}}} - \frac{q \times E_G^{\text{Temp}}}{k \times \text{Temp}}\right)$$

$$J_s^{\text{NEW}} = J_s \times \exp\left(\frac{q \times E_G^{T_{\text{nom}}}}{k \times T_{\text{nom}}} - \frac{q \times E_G^{\text{Temp}}}{k \times \text{Temp}}\right)$$

where $E_G$ is the silicon bandgap energy as a function of temperature.

The MOSFET threshold voltage variation with temperature is given by:

$$V_{to}^{\text{NEW}} = V_{to} + \gamma\left(\sqrt{\Phi^{\text{NEW}}} - \sqrt{\Phi}\right) + \frac{\Phi^{\text{NEW}} - \Phi}{2} - \frac{E_G^{\text{Temp}} - E_G^{T_{\text{nom}}}}{2}$$

**Noise Model**

Thermal noise generated by resistor $R_g$, $R_s$, $R_d$, and $R_{ds}$ is characterized by the following spectral density:

$$\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}$$
Channel and flicker noise (Kf, Af, Ffe) generated by dc transconductance g_m and current flow from drain to source is characterized by spectral density:

\[
\frac{<i_{ds}^2>}{\Delta f} = \frac{8kT g_m}{3} + k_f \frac{I_{DS}^{2 f}}{f_{fe}}
\]

In the preceding expressions, \( k \) is Boltzmann's constant, \( T \) is operating temperature in Kelvin, \( q \) is electron charge, \( K_f, A_f, \) and \( f_{fe} \) are model parameters, \( f \) is simulation frequency, and \( \Delta f \) is noise bandwidth.

References


Equivalent Circuit
LEVEL2_Model (MOSFET Level-2 Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 5-8. LEVEL2_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOS</td>
<td>N-channel model</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>PMOS</td>
<td>P-channel model</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Idsmod</td>
<td>IDS model</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Capmod</td>
<td>capacitance model selector</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Vto†</td>
<td>zero-bias threshold voltage</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Kp†</td>
<td>transconductance coefficient</td>
<td>A/V²</td>
<td>2 × 10⁻⁵</td>
</tr>
<tr>
<td>Gamma</td>
<td>bulk threshold parameter</td>
<td>V</td>
<td>0.0</td>
</tr>
<tr>
<td>Phi†</td>
<td>surface potential</td>
<td>√V</td>
<td>0.6</td>
</tr>
<tr>
<td>Lambda</td>
<td>channel-length modulation parameter</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Rd</td>
<td>drain ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rs</td>
<td>source ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Cbd†</td>
<td>zero-bias bulk-drain junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Cbs†</td>
<td>zero-bias bulk-source junction capacitance</td>
<td>F</td>
<td>0.0</td>
</tr>
<tr>
<td>Is</td>
<td>bulk junction saturation current</td>
<td>A</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Pb†</td>
<td>bulk junction potential</td>
<td>V</td>
<td>0.8</td>
</tr>
<tr>
<td>Cgso</td>
<td>gate-source overlap capacitance per meter of</td>
<td>F/m</td>
<td>0.0</td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on Tnom of the model and Temp of the device.
†† A value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cgdo</td>
<td>gate-drain overlap capacitance per meter of channel width</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgbo</td>
<td>gate-bulk overlap capacitance per meter of channel length</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Rsh</td>
<td>drain and source diffusion sheet resistance</td>
<td>ohms/sq</td>
<td>0.0</td>
</tr>
<tr>
<td>Cj†</td>
<td>zero-bias bulk junction bottom capacitance per square meter of junction area</td>
<td>F/m²</td>
<td>0.0††</td>
</tr>
<tr>
<td>Mj</td>
<td>bulk junction bottom grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Cjsw†</td>
<td>zero-bias bulk junction periphery capacitance per meter of junction perimeter</td>
<td>F/m</td>
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</tr>
<tr>
<td>Mjsw</td>
<td>bulk junction periphery grading coefficient</td>
<td></td>
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</tr>
<tr>
<td>Js†</td>
<td>bulk junction saturation current per square meter of junction area</td>
<td>A/m²</td>
<td>0.0</td>
</tr>
<tr>
<td>Tox</td>
<td>oxide thickness</td>
<td>m</td>
<td>10⁻⁷</td>
</tr>
<tr>
<td>Nsub</td>
<td>substrate (bulk) doping density</td>
<td>1/Cm³</td>
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</tr>
<tr>
<td>Nss</td>
<td>surface state density</td>
<td>1/Cm²</td>
<td>0.0</td>
</tr>
<tr>
<td>Nfs</td>
<td>fast surface state density</td>
<td>1/Cm²</td>
<td>0.0</td>
</tr>
<tr>
<td>Tpg</td>
<td>gate material type: 0 = aluminum; -1 = same as bulk; 1 = opposite to bulk</td>
<td></td>
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</tr>
<tr>
<td>Xj</td>
<td>metallurgical junction depth</td>
<td>m</td>
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<tr>
<td>Ld</td>
<td>lateral diffusion length</td>
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<td>0.0</td>
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<tr>
<td>Uo†</td>
<td>surface mobility</td>
<td>Cm²/(V×s)</td>
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<tr>
<td>Ucrit</td>
<td>critical field for mobility degradation</td>
<td>V/Cm</td>
<td>10⁴</td>
</tr>
<tr>
<td>Uexp</td>
<td>critical field exponent in mobility degradation</td>
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</tr>
<tr>
<td>Vmax</td>
<td>carriers maximum drift velocity</td>
<td>m/s</td>
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</tr>
<tr>
<td>Neff</td>
<td>total channel charge coefficient</td>
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</table>

† Parameter value varies with temperature based on Tnom of the model and Temp of the device.
†† A value of 0.0 is interpreted as infinity.
Table 5-8. LEVEL2_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
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<tbody>
<tr>
<td>Xqc</td>
<td>fraction of channel charge attributed to drain</td>
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<td>Nlev</td>
<td>Noise model level</td>
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<tr>
<td>Gdwnoi</td>
<td>Drain noise parameters for Nlev=3</td>
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<tr>
<td>Kf</td>
<td>flicker noise coefficient</td>
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<td>0.0</td>
</tr>
<tr>
<td>Af</td>
<td>flicker noise exponent</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Fc</td>
<td>bulk junction forward-bias depletion capacitance coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Delta</td>
<td>width effect on threshold voltage</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Rg</td>
<td>gate ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Rds</td>
<td>drain-source shunt resistance</td>
<td>ohms</td>
<td>infinity††</td>
</tr>
<tr>
<td>Tnom</td>
<td>nominal ambient temperature at which these model parameters were derived</td>
<td>°C</td>
<td>25</td>
</tr>
<tr>
<td>N</td>
<td>bulk P-N emission coefficient</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Tt</td>
<td>bulk P-N transit time</td>
<td>sec</td>
<td>0.0</td>
</tr>
<tr>
<td>Ffe</td>
<td>flicker noise frequency exponent</td>
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<td>Imax</td>
<td>explosion current</td>
<td>A</td>
<td>10.0</td>
</tr>
<tr>
<td>wVsubfwd</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvsub</td>
<td>substrate junction reverse breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvg</td>
<td>gate oxide breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wIdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td>infinite</td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td>infinite</td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent-based parameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Parameter value varies with temperature based on Tnom of the model and Temp of the device.
†† A value of 0.0 is interpreted as infinity.

Notes/Equations/References
1. The simulator provides three MOSFET device models that differ in formulation of I-V characteristics. LEVEL2_Model is a geometry-based, analytical model derived from [1].

2. LEVEL2_Model includes second order effects such as threshold voltage shift, mobility reduction, velocity saturation, channel length modulation, and subthreshold conduction.

3. Parameters Vto, Kp, Gamma, Phi, and Lambda determine the dc characteristics of a MOSFET device. The program will compute these parameters (except Lambda) if, instead of specifying them, you specify the process parameters Tox, Uo, Nsub, and Nss.

4. Vto is positive (negative) for enhancement mode and negative (positive) for depletion mode N-channel (P-channel) devices.

5. The p-n junctions between the bulk and the drain and the bulk and the source are modeled by parasitic diodes. Each bottom junction is modeled by a diode and each periphery junction is modeled by a depletion capacitance.

6. The diode parameters for the bottom junctions can be specified as absolute values (Is, Cbd and Cbs) or as per unit junction area values (Js and Cj).

   If Cbd = 0.0 and Cbs = 0.0, then Cbd and Cbs will be computed:
   \[ \text{Cbd} = Cj \times Ad, \quad \text{Cbs} = Cj \times As \]

   If Js > 0.0 and Ad > 0.0 and As > 0.0, then Is for drain and source will be computed:
   \[ \text{Is(drain)} = Js \times Ad, \quad \text{Is(source)} = Js \times As \]

7. Drain and source ohmic resistances can be specified as absolute values (Rd, Rs) or as per unit square value (Rsh).

   If Nrd \neq 0.0 or Nrs \neq 0.0, Rd and Rs will be computed:
   \[ \text{Rd} = Rsh \times Nrd, \quad \text{Rs} = Rsh \times Nrs \]

8. Charge storage is modeled by fixed and nonlinear gate and junction capacitances. MOS gate capacitances, as a nonlinear function of terminal voltages, are modeled by Meyer's piece-wise linear model for levels 1, 2, and 3. The Ward charge conservation model is also available for levels 2 and 3, by specifying the XQC parameter to a value smaller than or equal to 0.5. For Level 1, the model parameter TOX must be specified to invoke the Meyer model when Capmod is equal to 1 (default value). If Capmod = 0, no gate capacitances will
be computed. If Capmod = 2, a smooth version of the Meyer model is used. If Capmod = 3, the charge conserving first-order MOS charge model [2] that was used in Libra is used.

9. The simulator uses Ward and Dutton [2] charge-controlled capacitance model if Xqc ≤ 0.5. If Xqc > 0.5, the charge-conserving first-order MOS charge model is used.

10. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The depletion capacitances Cbd, Cbs, Cj, and Cjsw vary as:

\[
Cbd_{\text{NEW}} = Cbd \left[ \frac{1 + M_j[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + M_j[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]} \right]
\]

\[
Cbs_{\text{NEW}} = Cbs \left[ \frac{1 + M_j[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + M_j[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]} \right]
\]

\[
C_j_{\text{NEW}} = C_j \left[ \frac{1 + M_j[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + M_j[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]} \right]
\]

\[
Cjsw_{\text{NEW}} = Cjsw \left[ \frac{1 + M_{jsw}[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + M_{jsw}[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]} \right]
\]
where \( \gamma \) is a function of the junction potential and the energy gap variation with temperature.

The surface potential \( \Phi \) and the bulk junction potential \( P_b \) vary as:

\[
\Phi_{\text{NEW}}^{\text{Temp}} = \frac{T_{\text{Temp}}}{T_{\text{Nom}}} \times \Phi_{\text{Nom}} + \frac{2kT_{\text{Temp}}}{q} \ln \left( \frac{n_i_{\text{Temp}}}{n_i_{\text{Nom}}} \right)
\]

\[
P_{b\text{NEW}}^{\text{Temp}} = \frac{T_{\text{Temp}}}{T_{\text{Nom}}} \times P_{b\text{Nom}} + \frac{2kT_{\text{Temp}}}{q} \ln \left( \frac{n_i_{\text{Temp}}}{n_i_{\text{Nom}}} \right)
\]

The transconductance \( K_p \) and mobility \( U_0 \) vary as:

\[
K_{p\text{NEW}}^{\text{Temp}} = K_p \left( \frac{T_{\text{Temp}}}{T_{\text{Nom}}} \right)^{3/2}
\]

\[
U_{0\text{NEW}}^{\text{Temp}} = U_0 \left( \frac{T_{\text{Temp}}}{T_{\text{Nom}}} \right)^{3/2}
\]

The source and drain to substrate leakage currents \( I_s \) and \( J_s \) vary as:

\[
I_{s\text{NEW}}^{\text{Temp}} = I_s \exp \left( \frac{q \times E_G^{\text{Nom}}}{k \times T_{\text{Nom}}} - \frac{q \times E_G^{\text{Temp}}}{k \times T_{\text{Temp}}} \right)
\]

\[
J_{s\text{NEW}}^{\text{Temp}} = J_s \exp \left( \frac{q \times E_G^{\text{Nom}}}{k \times T_{\text{Nom}}} - \frac{q \times E_G^{\text{Temp}}}{k \times T_{\text{Temp}}} \right)
\]

where \( E_G \) is the silicon bandgap energy as a function of temperature.

The MOSFET threshold voltage variation with temperature is given by:

\[
V_{t0\text{NEW}}^{\text{Temp}} = V_{t0} + \gamma \left( \sqrt{\Phi_{\text{NEW}}^{\text{Temp}} - \Phi_{\text{Nom}}} \right) + \frac{\Phi_{\text{NEW}}^{\text{Temp}} - \Phi_{\text{Nom}}}{2} - \frac{E_G^{\text{Temp}} - E_G^{\text{Nom}}}{2}
\]
Noise Model

Thermal noise generated by resistor $R_g$, $R_s$, $R_d$, and $R_{ds}$ is characterized by the following spectral density:

$$\frac{<i^2>}{\Delta f} = \frac{4kT}{R}$$

Channel noise and flicker noise ($K_f$, $A_f$, $F_{fe}$) generated by the dc transconductance $g_m$ and current flow from drain to source is characterized by the following spectral density:

$$\frac{<i^2_{ds}>}{\Delta f} = \frac{8kTg_m}{3} + \frac{k_f I_{DS}}{f_{fe}}$$

In the preceding expressions, $k$ is Boltzmann’s constant, $T$ is the operating temperature in Kelvin, $q$ is the electron charge, $k_f$, $a_f$, and $F_{fe}$ are model parameters, $f$ is the simulation frequency, and $\Delta f$ is the noise bandwidth.

References:


LEVEL3_Model (MOSFET Level-3 Model)

Symbol

![MOSFET Symbol]

Parameters

Model parameters must be specified in SI units.

Table 5-9. LEVEL3_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
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<tbody>
<tr>
<td>NMOS</td>
<td>N-channel model</td>
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<tr>
<td>PMOS</td>
<td>P-channel model</td>
<td></td>
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<td>IDS model</td>
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<td>capacitance model selector</td>
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<td>Vto†</td>
<td>zero-bias threshold voltage</td>
<td>V</td>
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</tr>
<tr>
<td>Kp†</td>
<td>transconductance coefficient</td>
<td>A/V²</td>
<td>2×10⁻⁵</td>
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<tr>
<td>Gamma</td>
<td>bulk threshold</td>
<td>√V</td>
<td>0.0</td>
</tr>
<tr>
<td>Phi†</td>
<td>surface potential</td>
<td>V</td>
<td>0.6</td>
</tr>
<tr>
<td>Rd</td>
<td>drain ohmic resistance</td>
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<td>Rs</td>
<td>source ohmic resistance</td>
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<td>Cbd†</td>
<td>zero-bias bulk-drain junction capacitance</td>
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<td>Cbs†</td>
<td>zero-bias bulk-source junction capacitance</td>
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<tr>
<td>Is†</td>
<td>bulk junction saturation current</td>
<td>A</td>
<td>10⁻¹⁴</td>
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<td>Pb†</td>
<td>bulk junction potential</td>
<td>V</td>
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<tr>
<td>Cgso</td>
<td>gate-source overlap capacitance per meter of channel width</td>
<td>F/m</td>
<td>0.0</td>
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</table>

† Parameter value varies with temperature based on Tnom of model and Temp of device.
†† Value of 0.0 is interpreted as infinity.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
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</thead>
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<tr>
<td>Cgdo</td>
<td>gate-drain overlap capacitance per meter of channel width</td>
<td>F/m</td>
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<tr>
<td>Cgbo</td>
<td>gate-bulk overlap capacitance per meter of channel length</td>
<td>F/m</td>
<td>0.0</td>
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<td>Rsh</td>
<td>drain and source diffusion sheet resistance</td>
<td>ohms/sq</td>
<td>0.0</td>
</tr>
<tr>
<td>Cj†</td>
<td>zero-bias bulk junction bottom capacitance per square meter of junction area</td>
<td>F/m²</td>
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<td>Mj</td>
<td>bulk junction bottom grading coefficient</td>
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<tr>
<td>Cjsw†</td>
<td>zero-bias bulk junction periphery capacitance per meter of junction perimeter</td>
<td>F/m</td>
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<td>Mjsw</td>
<td>bulk junction periphery grading coefficient</td>
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<td>bulk junction saturation current per square meter of junction area</td>
<td>A/m²</td>
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<td>oxide thickness</td>
<td>m</td>
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<td>substrate (bulk) doping density</td>
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<td>Nss</td>
<td>surface state density</td>
<td>1/cm²</td>
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<td>Nfs</td>
<td>fast surface state density</td>
<td>1/cm²</td>
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<td>metallurgical junction depth</td>
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<td>lateral diffusion length</td>
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<td>Uo†</td>
<td>surface mobility</td>
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<td>Vmax</td>
<td>carriers maximum drift velocity</td>
<td>m/s</td>
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<td>Xqc</td>
<td>coefficient of channel charge share</td>
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<td>Noise model level</td>
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† Parameter value varies with temperature based on Tnom of model and Temp of device.
†† Value of 0.0 is interpreted as infinity.
Table 5-9. LEVEL3_Model Parameters (continued)

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<td>Fc</td>
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<td>Delta</td>
<td>width effect on threshold voltage</td>
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<td>Theta</td>
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<td>Rds</td>
<td>drain-source shunt resistance</td>
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<td>wBvg</td>
<td>gate oxide breakdown voltage (warning)</td>
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</tbody>
</table>

† Parameter value varies with temperature based on Tnom of model and Temp of device.
†† Value of 0.0 is interpreted as infinity.
1. The simulator provides three MOSFET device models that differ in formulation of I-V characteristics. LEVEL3_Model is a semi-empirical model derived from [1].

2. LEVEL3_Model includes second order effects such as threshold voltage shift, mobility reduction, velocity saturation, channel length modulation, and subthreshold conduction.

3. Parameters Vto, Kp, Gamma, Phi, and Lambda determine the dc characteristics of a MOSFET device. Program will compute these parameters (except Lambda) if, instead of specifying them, you specify the process parameters Tox, Uo, Nsub, and Nss.

4. Vto is positive (negative) for enhancement mode and negative (positive) for depletion mode N-channel (P-channel) devices.

5. The p-n junctions between the bulk and the drain and the bulk and the source are modeled by parasitic diodes. Each bottom junction is modeled by a diode and each periphery junction is modeled by a depletion capacitance.

6. The diode parameters for the bottom junctions can be specified as absolute values (Is, Cbd and Cbs) or as per unit junction area values (Js and Cj).

   If Cbd=0.0 and Cbs=0.0, Cbd and Cbs will be computed:
   
   $$\text{Cbd} = \text{Cj} \times \text{Ad} \quad \text{Cbs} = \text{Cj} \times \text{As}$$

   If Js>0.0 and Ad>0.0 and As>0.0, Js for drain and source will be computed:
   
   $$\text{Js(drain)} = J_s \times \text{Ad} \quad \text{Js(source)} = J_s \times \text{As}$$

   Drain and source ohmic resistances can be specified as absolute values (Rd, Rs) or as per unit square value (Rsh).

   If Nrd≠0.0 or Nrs≠0.0, Rd and Rs will be computed:
   
   $$\text{Rd} = \text{Rsh} \times \text{Nrd} \quad \text{Rs} = \text{Rsh} \times \text{Nrs}$$

7. Charge storage in the MOSFET consists of capacitances associated with parasitics and intrinsic device.

   The parasitic capacitances consist of three constant overlap capacitances (Cgdo, Cgso, Cgbo) and the depletion layer capacitances for both substrate junctions (divided into bottom and periphery) that vary as Mj and Mjsw power of junction.

---

LEVEL3_Model (MOSFET Level-3 Model)
voltage, respectively, and are determined by the parameters Cbd, Cbs, Cj, Cjsw, Mj, Mjsw, Pb and Fc.

The intrinsic capacitances consist of the nonlinear thin-oxide capacitance, which is distributed among the gate, drain, source, and bulk regions.

8. Charge storage is modeled by fixed and nonlinear gate and junction capacitances. MOS gate capacitances, as a nonlinear function of terminal voltages, are modeled by Meyer’s piece-wise linear model for levels 1, 2, and 3. The Ward charge conservation model is also available for levels 2 and 3, by specifying the XQC parameter to a value smaller than or equal to 0.5. For Level 1, the model parameter TOX must be specified to invoke the Meyer model when Capmod is equal to 1 (default value). If Capmod = 0, no gate capacitances will be computed. If Capmod = 2, a smooth version of the Meyer model is used. If Capmod = 3, the charge conserving first-order MOS charge model [2] that was used in Libra is used.

9. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

**Temperature Scaling**

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The depletion capacitances Cbd, Cbs, Cj, and Cjsw vary as:

\[
\text{Cbd}^{\text{NEW}} = \text{Cbd} \frac{1 + Mj[4 \times 10^{-4}(\text{Temp} - T_{\text{REF}}) - \gamma^{\text{Temp}}]}{1 + Mj[4 \times 10^{-4}(\text{Tnom} - T_{\text{REF}}) - \gamma^{\text{Temp}}]}
\]

\[
\text{Cbs}^{\text{NEW}} = \text{Cbs} \frac{1 + Mj[4 \times 10^{-4}(\text{Temp} - T_{\text{REF}}) - \gamma^{\text{Temp}}]}{1 + Mj[4 \times 10^{-4}(\text{Tnom} - T_{\text{REF}}) - \gamma^{\text{Temp}}]}
\]
where $\gamma$ is a function of the junction potential and the energy gap variation with temperature.

The surface potential $\Phi$ and the bulk junction potential $P_b$ vary as:

$$\Phi^{NEW} = \Phi + \frac{2k \times \text{Temp}}{q} \ln \left( \frac{n_i^{T_{nom}}}{n_i^{\text{Temp}}} \right)$$

$$P_b^{NEW} = P_b + \frac{2k \times \text{Temp}}{q} \ln \left( \frac{n_i^{T_{nom}}}{n_i^{\text{Temp}}} \right)$$

The transconductance $K_p$ and mobility $U_o$ vary as:

$$K_p^{NEW} = K_p \left( \frac{\text{Temp}}{T_{nom}} \right)^{3/2}$$

$$U_o^{NEW} = U_o \left( \frac{\text{Temp}}{T_{nom}} \right)^{3/2}$$

The source and drain to substrate leakage currents $I_s$ and $J_s$ vary as:

$$I_s^{NEW} = I_s \times \exp \left( \frac{q \times E_G^{T_{nom}}}{k \times T_{nom}} - \frac{q \times E_G^{\text{Temp}}}{k \times \text{Temp}} \right)$$

$$J_s^{NEW} = J_s \times \exp \left( \frac{q \times E_G^{T_{nom}}}{k \times T_{nom}} - \frac{q \times E_G^{\text{Temp}}}{k \times \text{Temp}} \right)$$

where $E_G$ is the silicon bandgap energy as a function of temperature.
The MOSFET threshold voltage variation with temperature is given by:

\[
V_{\text{to}}^{\text{NEW}} = V_{\text{to}} + \gamma \left( \sqrt{\Phi^{\text{NEW}}} - \sqrt{\Phi} \right) + \frac{\Phi^{\text{NEW}} - \Phi}{2} - \frac{E_G^{\text{Temp}} - E_G^{\text{Tnom}}}{2}
\]

**Noise Model**

Thermal noise generated by resistor \( R_g, R_s, R_d, \) and \( R_{ds} \) is characterized by the following spectral density:

\[
\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}
\]

Channel noise and flicker noise (\( K_f, A_f, F_{fe} \)) generated by dc transconductance \( g_m \) and current flow from drain to source is characterized by the spectral density:

\[
\frac{\langle i_{ds}^2 \rangle}{\Delta f} = \frac{8kT g_m}{3} + k_f \frac{I_{DS}}{f_{fe}}
\]

In the preceding expressions, \( k \) is Boltzmann’s constant, \( T \) is the operating temperature in Kelvin, \( q \) is the electron charge, \( k_f, A_f, \) and \( F_{fe} \) are model parameters, \( f \) is the simulation frequency, and \( \Delta f \) is the noise bandwidth.

**References**


Devices and Models, MOS

Equivalent Circuit
LEVEL3_MOD_Model (LEVEL 3 NMOD MOSFET Model)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 5-10. LEVEL3_MOD_Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOS</td>
<td>N-channel model</td>
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<tr>
<td>PMOS</td>
<td>P-channel model</td>
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<td>zero-bias threshold voltage</td>
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<td>Kp†</td>
<td>transconductance coefficient</td>
<td>A/V²</td>
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<td>Gamma</td>
<td>bulk threshold parameter</td>
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</tr>
<tr>
<td>Rd</td>
<td>drain ohmic resistance</td>
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</tr>
<tr>
<td>Rs</td>
<td>source ohmic resistance</td>
<td>ohms</td>
<td>0.0</td>
</tr>
<tr>
<td>Cbd†</td>
<td>zero-bias bulk-drain junction capacitance</td>
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<td>Cbs†</td>
<td>zero-bias bulk-source junction capacitance</td>
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<tr>
<td>Is†</td>
<td>bulk junction saturation current</td>
<td>A</td>
<td>10⁻¹⁴</td>
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<tr>
<td>Pb†</td>
<td>bulk junction potential</td>
<td>V</td>
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</table>

† Parameter value varies with temperature based on Tnom of model and Temp of device.
†† Value of 0.0 is interpreted as infinity.
### Table 5-10. LEVEL3_MOD_Model Parameters (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Default</th>
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<tbody>
<tr>
<td>Cgso</td>
<td>gate-source overlap cap. per meter of channel width</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgdo</td>
<td>gate-drain overlap cap. per meter of channel width</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Cgbo</td>
<td>gate-bulk overlap cap. per meter of channel length</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Rsh</td>
<td>drain and source diffusion sheet resistance</td>
<td>ohms/sq.</td>
<td>0.0</td>
</tr>
<tr>
<td>Cj†</td>
<td>zero-bias bulk junction bottom capacitance per square meter of junction area</td>
<td>F/m²</td>
<td>0.0</td>
</tr>
<tr>
<td>Mj</td>
<td>bulk junction bottom grading coefficient</td>
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<td>0.5</td>
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<tr>
<td>Cjsw†</td>
<td>zero-bias bulk junction periphery capacitance per meter of junction perimeter</td>
<td>F/m</td>
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<tr>
<td>Mjsw</td>
<td>bulk junction periphery grading coefficient</td>
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<td>bulk junction saturation current per square meter of junction area</td>
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<td>0.0</td>
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<tr>
<td>Tox</td>
<td>oxide thickness</td>
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<td>substrate (bulk) doping density</td>
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<td>surface state density</td>
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<td>fast surface state density</td>
<td>1/cm²</td>
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<td>Tpg</td>
<td>gate material type: 0=aluminum; -1=same as substrate; 1=opposite substrate</td>
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<td>Xj</td>
<td>metallurgical junction depth</td>
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<td>lateral diffusion length</td>
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† Parameter value varies with temperature based on Tnom of model and Temp of device.

†† Value of 0.0 is interpreted as infinity.
Table 5-10. LEVEL3_MOD_Model Parameters (continued)

<table>
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<tr>
<th>Parameter</th>
<th>Description</th>
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<td>$A_f$</td>
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<td>mobility modulation</td>
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<tr>
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<td>gate resistance</td>
<td>ohms</td>
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<tr>
<td>$R_{ds}$</td>
<td>drain-source shunt resistance</td>
<td>ohms</td>
<td>infinity††</td>
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<tr>
<td>Tnom</td>
<td>nominal ambient temperature at which these model parameters were derived</td>
<td>C</td>
<td>25</td>
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<td>N</td>
<td>bulk P-N emission coefficient</td>
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<td>bulk P-N transit time</td>
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<td>$F_{fe}$</td>
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<td>$I_{max}$</td>
<td>explosion current</td>
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<td>$w_{V_{subfwd}}$</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
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<tr>
<td>$w_{B_{vsub}}$</td>
<td>substrate junction reverse breakdown voltage (warning)</td>
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<td>infinite</td>
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<tr>
<td>$w_{B_{vg}}$</td>
<td>gate oxide breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
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<td>$w_{Bvds}$</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
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<td>$w_{ldsmax}$</td>
<td>maximum drain-source current (warning)</td>
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<td>$w_{P_{max}}$</td>
<td>maximum power dissipation (warning)</td>
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<tr>
<td>AllParams</td>
<td>DataAccessComponent-based parameters</td>
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† Parameter value varies with temperature based on Tnom of model and Temp of device.
†† Value of 0.0 is interpreted as infinity.
Notes/Equations/References

1. LEVEL3_MOD_Model is an enhanced version of the SPICE level 3 model. It exhibits smooth and continuous transitions in the weak to strong inversion region, and in the region between linear and saturation modes of device operation.

2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.
MM9 (Philips MOS Model 9)

MM9_NMOS (Philips MOS Model 9, NMOS)
MM9_PMOS (Philips MOS Model 9, PMOS)

Symbol

Parameters
Model = name of a MOS_Model9
Length = channel length, in length units (default: 10^-4)
Width = channel width, in length units (default: 10^-4)
Ab = diffusion area (default: 10^-12)
Ls = length of sidewall not under gate, in length units (default: 10^-4)
Lg = length of sidewall under gate, in length units (default: 10^-4)
Region = dc operating region: off, on, rev, sat (default: on)
Temp = device operating temperature, in °C (default: 300.15)
Mult = number of devices in parallel (default: 1)
Mode = device simulation mode: nonlinear, linear (default: nonlinear)
_M = number of devices in parallel (default: 1)

Notes/Equations/References
1. MOS Model 9 (version 902) is a compact MOS-transistor model intended for the simulation of circuit behavior with emphasis on analog applications. The model gives a complete description of all transistor action related quantities: nodal currents and charges, noise-power spectral densities and weak-avalanche currents. The equations describing these quantities are based on the gradual-channel approximation with a number of first-order corrections for
small-size effects. The consistency is maintained by using the same carrier-density and electrical-field expressions in the calculation of all model quantities. Model 9 provides a model for the intrinsic transistor only; junction charges and leakage currents are not included.

2. More information about the model can be obtained from:
MM30_Model (Philips MOS Model 30)

Symbol

Parameters
NMOS = NMOS Model Type; YES, NO (default: YES)
PMOS = PMOS Model Type; YES, NO (default: YES)
Ron = Ohmic resistance at zero-bias, Ohm (default: 1.0)
Rsat = space charge resistance at zero-bias in Ohms (default: 1.0)
Vsat = critical drain-source voltage for hot carrier, V (default: 10.0)
Psat = velocity saturation coefficient (default: 1.0)
Vp = pinch off voltage at zero gate and substrate voltages, V (default: -1.0)
Tox = gate oxide thickness, cm (default: -1.0)
Dch = doping level channel, cm$^{-3}$ (default: 1.0e+15)
Dsub = doping level substrate, cm$^{-3}$ (default: 1.0e+15)
Vsub = substrate diffusion voltage, V (default: 0.6)
Cgate = gate capacitance at zero-bias, F (default: 0.0)
Csub = substrate capacitance at zero-bias, F (default: 0.0)
Tausc = space charge transit time of the channel, F (default: 0.0)
Tref = reference temperature on Celsius (default: 25.0)
Vgap = bandgap voltage channel, V (default: 1.2)
Ach = temperature coefficient resistivity of the channel (default: 0.0)
Kf = flicker noise coefficient (default: 0.0)
Af = flicker noise exponent (default: 1.0)
AllParams = Data Access Component (DAC) based parameters
Notes/Equations/References

1. The Junction-Field-Effect Transistor (JFET) and the depletion mode Metal-Oxide (MOSFET) are semiconductor devices whose operation is achieved by depleting an already existing channel via a voltage controlled p-n junction (JFET) or a gate controlled surface depletion (MOSFET). These devices are often used as a load in high voltage MOS devices. This long channel JFET/MOSFET model is specially developed to describe the drift region of LDMOS, EPMOS and VDMOS devices. Please refer to the Philips report The MOS model, level 3002. The pdf file MOSModel 30.02 is downloadable at the following web site:

http://www-us.semiconductors.com/Philips_Models/documentation/add_models/
Philips MOS Model 30 (NMOS and PMOS)

MM30_NMOS (Philips MOS Model 30, NMOS)
MM30_PMOS (Philips MOS Model 30, PMOS)

Symbol

Parameters

Model = Model instance name (can be file-based)
Temp = temperature in Celsius (default: 25.0)
Mult_ = Multiplication factor (default: 1.0)
_M = Number of devices in parallel (default: 1)
**MOS_Model9_Process (Philips MOS Model 9, Process Based)**

**Symbol**

![MOS_Model9_Process symbol]

**Parameters**

Model parameters must be specified in SI units.

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<th>Parameter</th>
<th>Description</th>
<th>Units</th>
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<td>PMOS</td>
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<td>Type</td>
<td>process-based model type</td>
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<td>Ler</td>
<td>effective channel length of reference transistor</td>
<td>m</td>
<td>$10^{-4}$</td>
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<tr>
<td>Wer</td>
<td>effective channel width of reference transistor</td>
<td>m</td>
<td>$10^{-4}$</td>
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<td>difference between actual and programmed poly-silicon gate length</td>
<td>m</td>
<td>0.0</td>
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<td>effective channel length reduction per side due to lateral diffusion of source/drain dopant ions</td>
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<tr>
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<tr>
<td>Tr</td>
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<td>300.15</td>
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<tr>
<td>Vtor</td>
<td>threshold voltage at zero back-bias</td>
<td>V</td>
<td>0.87505</td>
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<tr>
<td>Stvto</td>
<td>coefficient of temperature dependence of Vto</td>
<td>V/K</td>
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</tr>
<tr>
<td>Slvto</td>
<td>coefficient of length dependence of Vto</td>
<td>V×m</td>
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<td>Parameter</td>
<td>Description</td>
<td>Units</td>
<td>Default</td>
</tr>
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<td>$\sqrt{V} \times m$</td>
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<tr>
<td>$K_{or}$</td>
<td>low back-bias body factor</td>
<td>$\sqrt{V}$</td>
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<td>$Slko$</td>
<td>coefficient of length dependence of $K_o$</td>
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<td>surface potential at strong inversion</td>
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<td>transition voltage for dual-k factor model</td>
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<td>$Betsq$</td>
<td>gain factor</td>
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<td>$The1r$</td>
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<td>0.99507x10^{-01}</td>
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<tr>
<td>$Slthe1r$</td>
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<td>$m/V$</td>
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<td>$m/V$</td>
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<td>$Wdog$</td>
<td>characteristic drain gate width below which dogboning appears</td>
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<td>coefficient describing the width dependence of $The1$ for $W &lt; Wdog$</td>
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<tr>
<td>$The2r$</td>
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<td>$\sqrt{V}$</td>
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Table 5-11. MOS_Model9_Process (continued)

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<td>$St\text{the2}r$</td>
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<td>$Sl\text{the2}r$</td>
<td>coefficient of length dependence of (\text{The}_2)</td>
<td>(m\sqrt{\text{V}})</td>
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<td>(m\sqrt{\text{V/K}})</td>
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<tr>
<td>$Sw\text{the2}$</td>
<td>coefficient of width dependence of (\text{The}_2)</td>
<td>(m\sqrt{\text{V}})</td>
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<tr>
<td>$\text{The3}r$</td>
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<tr>
<td>$St\text{the3}r$</td>
<td>coefficient of temperature dependence of (\text{The}_3)</td>
<td>(1/\text{V/K})</td>
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<td>$\text{Gam1}r$</td>
<td>coefficient for drain-induced threshold shift for large gate drive</td>
<td>(V(1 - \text{Etabs}))</td>
<td>(0.38096 \times 10^{-2})</td>
</tr>
<tr>
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<td>(V(1 - \text{Etabs})m)</td>
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<tr>
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<td>(V(1 - \text{Etabs})m)</td>
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<td>factor of channel-length modulation</td>
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<tr>
<td>$Sl\text{alp}$</td>
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<td>(m(\text{Etaalp}))</td>
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<td>characteristic voltage of channel length modulation</td>
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<td>(0.67876 \times 10^{1})</td>
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<td>$\text{Gamoor}$</td>
<td>coefficient of drain-induced threshold shift at zero gate drive</td>
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<td>(0.29702 \times 10^{-4})</td>
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<td>Parameter</td>
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<td>Units</td>
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<td>( \mu )</td>
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<tr>
<td>( Z_{\text{er}} )</td>
<td>weak-inversion correction factor</td>
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<tr>
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<td>exponent of length dependence of ( Z_{\text{er}} )</td>
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<td>coefficient of length dependence of ( Z_{\text{er}} )</td>
<td>( m(E_{\text{zr}}) )</td>
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<tr>
<td>( V_{sbtr} )</td>
<td>limiting voltage of VSB dependence of ( \mu ) and ( \Gamma_{\text{mo}} )</td>
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<td>0.61268 ( \times 10^1 )</td>
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<td>( m )</td>
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<td>thickness of oxide layer</td>
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<td>( C_{ol} )</td>
<td>gate overlap per unit channel width</td>
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<td>( N_{fr} )</td>
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<tr>
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<td>voltage at which junction parameters have been determined</td>
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<td>Parameter</td>
<td>Description</td>
<td>Units</td>
<td>Default</td>
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<td>-----------</td>
<td>---------</td>
</tr>
<tr>
<td>Jsgbr</td>
<td>bottom saturation current density due to electron-hole generation at V=Vr</td>
<td>A/m²</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Jsdbr</td>
<td>bottom saturation current density due to diffusion from back contact</td>
<td>A/m²</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Jsgsr</td>
<td>sidewall saturation current density due to electron-hole generation at V=Vr</td>
<td>A/m</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Jsdsr</td>
<td>sidewall saturation current density due to diffusion from back contact</td>
<td>A/m</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Jsggr</td>
<td>gate edge saturation current density due to electron-hole generation at V=Vr</td>
<td>A/m</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Jsdgr</td>
<td>gate edge saturation current density due to diffusion from back contact</td>
<td>A/m</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Cjbr</td>
<td>bottom junction capacitance at V=Vr</td>
<td>F/m²</td>
<td>0.0</td>
</tr>
<tr>
<td>Cjsr</td>
<td>sidewall junction capacitance at V=Vr</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Cjgr</td>
<td>gate edge junction capacitance at V=Vr</td>
<td>F/m</td>
<td>0.0</td>
</tr>
<tr>
<td>Vdbr</td>
<td>diffusion voltage of bottom junction at V=Vr</td>
<td>V</td>
<td>0.8</td>
</tr>
<tr>
<td>Vdssr</td>
<td>diffusion voltage of sidewall junction at V=Vr</td>
<td>V</td>
<td>0.8</td>
</tr>
<tr>
<td>Vdgr</td>
<td>diffusion voltage of gate edge junction at V=Vr</td>
<td>V</td>
<td>0.8</td>
</tr>
<tr>
<td>Pb</td>
<td>bottom-junction grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Ps</td>
<td>sidewall-junction grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Pg</td>
<td>gate-edge-junction grading coefficient</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Nb</td>
<td>emission coefficient of bottom forward current</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Ns</td>
<td>emission coefficient of sidewall forward current</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Ng</td>
<td>emission coefficient of gate-edge forward current</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent-based parameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Notes/Equations/References

1. This model supplies values for an MM9 device.

2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.
MOS_Model9_Single (Philips MOS Model 9, Single Device)

Symbol

Parameters

Model parameters must be specified in SI units.

Table 5-12. MOS_Model9_Single Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOS</td>
<td>N-channel type MOSFET</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>PMOS</td>
<td>P-channel type MOSFET</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Type</td>
<td>single device type</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Vto</td>
<td>threshold voltage at zero back-bias</td>
<td>V</td>
<td>0.87505</td>
</tr>
<tr>
<td>Ko</td>
<td>low-back-bias body factor</td>
<td>V(1/2)</td>
<td>0.74368</td>
</tr>
<tr>
<td>K</td>
<td>high-back-bias body factor</td>
<td>V(1/2)</td>
<td>0.55237</td>
</tr>
<tr>
<td>Phib</td>
<td>surface potential at strong inversion</td>
<td>V</td>
<td>0.65</td>
</tr>
<tr>
<td>Vsbx</td>
<td>transition voltage for dual-k factor model</td>
<td>V</td>
<td>0.63304</td>
</tr>
<tr>
<td>Bet</td>
<td>gain factor</td>
<td>A/V^2</td>
<td>0.12069×10^{-3}</td>
</tr>
<tr>
<td>The1</td>
<td>coefficient of mobility reduction due to gate-induced field</td>
<td>1/V</td>
<td>0.99507×10^{-1}</td>
</tr>
<tr>
<td>The2</td>
<td>coefficient of mobility reduction due to back-bias</td>
<td>V(1/2)</td>
<td>0.43225×10^{-1}</td>
</tr>
<tr>
<td>The3</td>
<td>coefficient of mobility reduction due to lateral field</td>
<td>1/V</td>
<td>0.0</td>
</tr>
<tr>
<td>Gam1</td>
<td>coefficient for drain-induced threshold shift for large gate drive</td>
<td>V(1-Etads)</td>
<td>0.38096×10^{-2}</td>
</tr>
<tr>
<td>Etads</td>
<td>exponent of VDS dependence of Gam1</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>Alp</td>
<td>factor of channel-length modulation</td>
<td></td>
<td>0.1×10^{-1}</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Units</td>
<td>Default</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------------------------------------------</td>
<td>---------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Vp</td>
<td>characteristic voltage of channel length modulation</td>
<td>V</td>
<td>0.67876×10(^{1})</td>
</tr>
<tr>
<td>Gamoo</td>
<td>coefficient of drain-induced threshold shift at zero gate drive</td>
<td></td>
<td>0.29702×10(^{-4})</td>
</tr>
<tr>
<td>Etagam</td>
<td>exponent of back-bias dependence of Gamo</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Mo</td>
<td>factor of subthreshold slope</td>
<td></td>
<td>0.44</td>
</tr>
<tr>
<td>Etam</td>
<td>exponent of back-bias dependence of M</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Zet1</td>
<td>weak-inversion correction factor</td>
<td></td>
<td>0.20153×10(^{1})</td>
</tr>
<tr>
<td>Vsbt</td>
<td>limiting voltage of vsb dependence of M and Gamo</td>
<td>V</td>
<td>0.61268×10(^{+1})</td>
</tr>
<tr>
<td>A1</td>
<td>factor of weak-avalanche current</td>
<td></td>
<td>0.20348×10(^{2})</td>
</tr>
<tr>
<td>A2</td>
<td>exponent of weak-avalanche current</td>
<td>V</td>
<td>0.33932×10(^{2})</td>
</tr>
<tr>
<td>A3</td>
<td>factor of drain-source voltage above which weak-avalanche occurs</td>
<td></td>
<td>0.10078×10(^{1})</td>
</tr>
<tr>
<td>Cox</td>
<td>gate-to-channel capacitance</td>
<td>F</td>
<td>10(^{-12})</td>
</tr>
<tr>
<td>Cgso</td>
<td>gate-source overlap capacitance</td>
<td>F</td>
<td>10(^{-12})</td>
</tr>
<tr>
<td>Cgdo</td>
<td>gate-drain overlap capacitance</td>
<td>F</td>
<td>10(^{-12})</td>
</tr>
<tr>
<td>Nt</td>
<td>coefficient of thermal noise</td>
<td>J</td>
<td>0.0</td>
</tr>
<tr>
<td>Nf</td>
<td>coefficient of flicker noise</td>
<td>V(^{2})</td>
<td>0.0</td>
</tr>
<tr>
<td>Isgb</td>
<td>generation saturation current of bottom area AB</td>
<td>A</td>
<td>10(^{-14})</td>
</tr>
<tr>
<td>Isdb</td>
<td>diffusion saturation current of bottom area AB</td>
<td>A</td>
<td>10(^{-14})</td>
</tr>
<tr>
<td>Isgs</td>
<td>generation saturation current of locos-edge LS</td>
<td>A</td>
<td>10(^{-14})</td>
</tr>
<tr>
<td>Isds</td>
<td>diffusion saturation current of locos-edge LS</td>
<td>A</td>
<td>10(^{-14})</td>
</tr>
<tr>
<td>Isgg</td>
<td>generation saturation current of gate-edge LG</td>
<td>A</td>
<td>10(^{-14})</td>
</tr>
<tr>
<td>Isdg</td>
<td>diffusion saturation current of gate-edge LG</td>
<td>A</td>
<td>10(^{-14})</td>
</tr>
</tbody>
</table>
### Table 5-12. MOS_Model9_Single Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cjb</td>
<td>bottom junction capacitance</td>
<td>F</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Cjs</td>
<td>sidewall junction capacitance</td>
<td>F</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Cjg</td>
<td>gate edge junction capacitance</td>
<td>F</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Vdb</td>
<td>diffusion voltage of bottom area Ab</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Vds</td>
<td>diffusion voltage of Locos-edge Ls</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Vdg</td>
<td>diffusion voltage of gate edge Lg</td>
<td>V</td>
<td>1.0</td>
</tr>
<tr>
<td>Pb</td>
<td>bottom-junction grading coefficient</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>Ps</td>
<td>sidewall-junction grading coefficient</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>Pg</td>
<td>gate-edge-junction grading coefficient</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>Nb</td>
<td>emission coefficient of bottom forward current</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Ns</td>
<td>emission coefficient of sidewall forward current</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Ng</td>
<td>emission coefficient of gate-edge forward current</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>wVsubfwd</td>
<td>substrate junction forward bias (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvsub</td>
<td>substrate junction reverse breakdown voltage</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvg</td>
<td>gate oxide breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wBvds</td>
<td>drain-source breakdown voltage (warning)</td>
<td>V</td>
<td>infinite</td>
</tr>
<tr>
<td>wdsmax</td>
<td>maximum drain-source current (warning)</td>
<td>A</td>
<td>infinite</td>
</tr>
<tr>
<td>wPmax</td>
<td>maximum power dissipation (warning)</td>
<td>W</td>
<td>infinite</td>
</tr>
<tr>
<td>AllParams</td>
<td>DataAccessComponent-based parameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Notes/Equations/References

1. This model supplies values for an MM9 device.

2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.
MOSFET (Nonlinear, N-Channel and P-Channel)

MOSFET_NMOS (Nonlinear MOSFET, N-Channel)
MOSFET_PMOS (Nonlinear MOSFET, P-Channel)

Symbol

Parameters

Model = name of BSIM1_Model, BSIM2_Model, BSIM3_Model, LEVEL1_Model, LEVEL2_Model, LEVEL3_Model, or LEVEL3_MOD_Model

Length = channel length: um, mm, cm, meter, mil, in (default: 10^-4 m)

Width = channel width: um, mm, cm, meter, mil, in (default: 10^-4 m)

Ad = drain diffusion area, m^2 (default: 0.0)

As = source diffusion area, m^2 (default: 0.0)

Pd = drain junction perimeter: um, mm, cm, meter, mil, in (default: 0.0 m)

Ps = source junction perimeter: um, mm, cm, meter, mil, in (default: 0.0 m)

Nrd = number of equivalent squares in drain diffusion region (default: 1); Nrd is multiplied by Rsh (sheet resistance factor specified in Model) to get parasitic series drain resistance.

Nrs = number of equivalent squares in source diffusion region (default: 1) Nrs is multiplied by Rsh (sheet resistance factor specified in Model) to get parasitic series source resistance.

Region = dc operating region: off, on, rev, sat (default: on)

Temp = device operating temperature (refer to Note 1), in °C, (default: 25)

Mode = simulation mode for this device: nonlinear or linear (default: nonlinear) (refer to Note 3)
Nqslmod = turns on(1) or off(0) the Non-Quasi static charge model option
_M = number of devices in parallel (default:1)

Range of Usage
Length, Width, Ad, As, Pd, Ps > 0

Notes
1. The Temp parameter specifies the physical (operating) temperature of the
device. If this is different than the temperature at which the model parameters
are valid or extracted (specified by the Tnom parameter of the associated model)
certain model parameters are scaled such that the device is simulated at its
operating temperature. Refer to the appropriate model to see which parameter
values are scaled.

2. The_M parameter affects MOSFET channel width, diode leakage, capacitors,
and resistors in the following manner.
Width: Mult × Weff
Areas and perimeters:
   Mult × Ad
   Mult × As
   Mult × Pd
   Mult × Ps
Diode leakage:
   if (Js == 0), then Is = Mult × Is
Capacitors:
   if (CJ == 0), then Cbd = Mult × Cbd, Cbs = Mult × Cbs
Resistors:
   if (Nrs × Rsh == 0), then Rs = Rs/Mult; else Rs = (Nrs × Rsh)/Mult
   if (Nrd × Rsh == 0), then Rd = Rd/Mult; else Rd = (Nrd × Rsh)/Mult
Due to second-order effects in some models (BSIM3 for example), the use of the
Mult parameter is not exactly equivalent to parallel multiple devices.

3. The Mode parameter is used only during harmonic balance, oscillator, or
large-signal S-parameter analysis. By identifying devices that are operating in
their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.

4. This device has no default artwork associated with it.

References


Devices and Models, MOS

5-100 Use of MOSFET Parameter Nlev
Chapter 6: Linear Devices
**BIP (Bipolar Transistor)**

**Symbol**

---

**Parameters**

- \( A = \) magnitude of current gain (alpha) at dc
- \( T = \) time delay associated with current gain, in seconds
- \( F = -3 \) dB frequency for current gain, in hertz
- \( C_c = \) collector capacitance, in farads
- \( G_c = \) collector conductance, in Siemens
- \( R_b = \) base resistance, in ohms
- \( L_b = \) base inductance, in henries
- \( C_e = \) emitter capacitance, in farads
- \( R_e = \) emitter resistance, in ohms
- \( L_e = \) emitter inductance, in henrie

**Range of Usage**

\( 0 < A < 1.0 \)

**Notes/Equations/References**

1. \( A(f) = A \times e^{-(\frac{f}{F})} \) (for \( F > 0 \))

2. \( A(f) = A \times e^{-\left(\frac{j 2 \pi f T}{F}\right)} \) (for \( F = 0 \))

where \( f = \) simulation frequency


\[ F = \text{reference frequency} \]

2. For time-domain analysis, the frequency-domain analytical model is used.

3. This component is assumed to be noiseless.

4. This component has no default artwork associated with it.

**Equivalent Circuit**

![Equivalent Circuit Diagram]
**BIPB (Bipolar Transistor, β Control)**

**Symbol**

![Symbol Diagram]

**Parameters**

- $B =$ magnitude of current gain (Beta) at dc
- $A =$ phase offset of current gain
- $T =$ time delay associated with current gain, in seconds
- $C_c =$ collector capacitance, in farads
- $G_c =$ collector conductance, in Siemens
- $R_b =$ base resistance, in ohms
- $L_b =$ base inductance, in henries
- $C_e =$ emitter capacitance, in farads
- $R_e =$ emitter resistance, in ohms
- $L_e =$ emitter lead inductance, in henries
- $R_{el} =$ emitter lead resistance, in ohms

**Range of Usage**

$B > 0$

**Notes/Equations/References**

1. $\beta(f) = B \times e^{-j(2\pi f T_{sec} - A_{radians})}$
   where
   $f =$ simulation frequency in hertz
2. For time-domain analysis, the frequency-domain analytical model is used.
3. This component is assumed to be noiseless.

---

6-4  BIPB (Bipolar Transistor, β Control)
4. This component has no default artwork associated with it.

Equivalent Circuit

\[ I_c = \beta(f) \times I_b \]
DFET (Dual-Gate Field Effect Transistor)

Symbol

Parameters

- $G_{m1}$ = dc transconductance - gate 1, in Siemens
- $T_1$ = time delay of $G_{m1}$, in seconds
- $F_1$ = $-3$ dB frequency for $G_{m1}$
- $C_{gs1}$ = gate-to-source capacitance - gate 1, in farads
- $R_{i1}$ = input resistance - gate 1, in ohms
- $C_{dg1}$ = drain-to-gate capacitance - gate 1, in farads
- $C_{ds1}$ = drain-to-source capacitance - gate 1, in farads
- $R_{ds1}$ = drain-to-source resistance - gate 1, in ohms
- $R_{g1}$ = gate 1 resistance, in ohms
- $L_{g1}$ = gate 1 inductance, in henries
- $G_{m2}$ = dc transconductance - gate 2, in Siemens
- $T_2$ = time delay of $G_{m2}$, in seconds
- $F_2$ = $-3$ dB frequency for $G_{m2}$
- $C_{gs2}$ = gate-to-source capacitance - gate 2, in farads
- $R_{i2}$ = input resistance - gate 2, in ohms
- $C_{dg2}$ = drain-to-gate capacitance - gate 2, in farads
- $C_{ds2}$ = drain-to-source capacitance - gate 2, in farads
- $R_{ds2}$ = drain-to-source resistance - gate 2, in ohms
- $R_{g2}$ = gate 2 resistance, in ohms
Lg2 = gate 2 inductance, in henries
Rd = drain resistance, in ohms
Ld = drain inductance, in henries
Rs = source resistance, in ohms
Ls = source inductance, in henries
Cgls = gate1-to-source capacitance, in farads
Cgl2 = gate1-to-gate2 capacitance, in farads
CgLd = gate1-to-drain capacitance, in farads
Cg2d = gate2-to-drain capacitance, in farads
Cds = drain-to-source capacitance, in farads
R12 = resistance representing composite of resistance of drain 1 and source 2, in ohms

Range of Usage
N/A

Notes/Equations/References
1. For time-domain analysis, the frequency-domain analytical model is used.
2. This component is assumed to be noiseless.
3. This component has no default artwork associated with it.
Linear Devices

**Equivalent Circuit**

![Equivalent Circuit Diagram]

6-8 DFET (Dual-Gate Field Effect Transistor)
FET (Field Effect Transistor)

Symbol

Parameters

- \(G\) = magnitude of transconductance at dc, in Siemens
- \(T\) = time delay associated with transconductance, in seconds
- \(F\) = transconductance roll-off frequency, in frequency units
- \(C_{gs}\) = gate-to-source capacitance, in farads
- \(G_{gs}\) = gate-to-source conductance, in Siemens
- \(R_i\) = channel resistance, in ohms
- \(C_{dg}\) = drain-to-gate capacitance, in farads
- \(C_{dc}\) = dipole layer capacitance, in farads
- \(C_{ds}\) = drain-to-source capacitance, in farads
- \(R_{ds}\) = drain-to-source resistance, in ohms

Range of Usage

N/A

Notes/Equations/References

1. Setting \(F\) equal to zero gives constant transconductance magnitude with respect to frequency:

   \[
   \text{Transconductance} = G(f) = G \times \left(\frac{e^{\left(j2\pi f T\right)}}{1 + j f / T}\right) \quad (\text{for } F > 0)
   \]

   \[
   \text{Transconductance} = G(f) = G \times e^{-\left(j2\pi T\right)} \quad (\text{for } F = 0)
   \]

   where
Linear Devices

\[
\begin{align*}
\text{f} &= \text{simulation frequency, in hertz} \\
\text{F} &= \text{reference frequency, in hertz} \\
\text{T} &= \text{time delay, in seconds}
\end{align*}
\]

2. For time-domain analysis, the frequency-domain analytical model is used.

3. This component is assumed to be noiseless.

4. This component has no default artwork associated with it.

**Equivalent Circuit**
FET2 (Field Effect Transistor with Source Resistance)

Symbol

Parameters

- \( G \) = magnitude of transconductance at dc, in Siemens
- \( T \) = time delay associated with transconductance, in seconds
- \( F \) = transconductance roll-off frequency, in frequency units
- \( C_{gs} \) = gate-to-source capacitance, in farads
- \( G_{gs} \) = gate-to-source conductance, in Siemens
- \( R_{i} \) = channel resistance, in ohms
- \( C_{dg} \) = drain-to-gate capacitance, in farads
- \( C_{dc} \) = dipole layer capacitance, in farads
- \( C_{ds} \) = drain-to-source capacitance, in farads
- \( R_{ds} \) = drain-to-source resistance, in ohms
- \( R_{s} \) = source resistance, in ohms

Range of Usage

N/A

Notes/Equations/References

1. Setting \( F \) equal to zero gives constant transconductance magnitude with respect to frequency:

\[
\text{Transconductance} = G(f) = G \times \frac{e^{-j(2\pi fT)}}{1 + j\frac{T}{F}} \quad (\text{for } F > 0)
\]

\[
\text{Transconductance} = G(f) = G \times e^{-j(2\pi fT)} \quad (\text{for } F = 0)
\]

where
Linear Devices

\[ f = \text{simulation frequency, in hertz} \]
\[ F = \text{reference frequency, in hertz} \]
\[ T = \text{time delay, in seconds} \]

2. For time-domain analysis, the frequency-domain analytical model is used.
3. This component is assumed to be noiseless.
4. This component has no default artwork associated with it.

**Equivalent Circuit**
FETN1 (FET Noise Model (Van der Ziel))

Symbol

Parameters

- **G**: magnitude of transconductance, in Siemens
- **T**: time delay associated with transconductance, in seconds
- **Cgs**: gate-to-source capacitance, in farads
- **Ri**: channel resistance, in ohms
- **Rds**: drain-to-source resistance, in ohms
- **P**: noise parameter P (see references)
- **R**: noise parameter R (see references)
- **C**: noise parameter C (see references)

Range of Usage

N/A

Notes/Equations

1. This component provides a linear bias-independent FET noise model (by A. Van der Ziel) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.

2. The effect of feedback or parasitics on the noise performance of FETN1 is determined by connecting appropriate circuit components externally to FETN1.

3. For time-domain analysis, the frequency-domain analytical model is used.

4. This component has no default artwork associated with it.

References


**Equivalent Circuit**

![Equivalent Circuit Diagram]

---

6-14  FETN1 (FET Noise Model (Van der Ziel))
FETN2 (FET Noise Model (Statz, et al))

Symbol

Parameters

$G =$ magnitude of transconductance, in Siemens

$T =$ time delay associated with transconductance, in seconds

$C_{gs} =$ gate-to-source capacitance, in farads

$R_i =$ channel resistance, in ohms

$R_s =$ drain-to-source resistance, in ohms

$R_g =$ gate resistance, in ohms

$K_r =$ noise parameter $K_r$ (see references)

$K_c =$ noise parameter $K_c$ (see references)

$K_g =$ noise parameter $K_g$ (see references)

Range of Usage

N/A

Notes/Equations

1. This component provides a linear bias-independent FET noise model (by Statz, et al.) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.

2. The effect of feedback or parasitics on the noise performance of FETN2 is determined by connecting appropriate circuit components externally to FETN2.

3. For time-domain analysis, the frequency-domain analytical model is used.

4. This component has no default artwork associated with it.

References


**Equivalent Circuit**

![Equivalent Circuit Diagram]

---

6-16  FETN2 (FET Noise Model (Statz, et al))
FETN3 (FET Noise Model (Fukui))

Symbol

Parameters
G = magnitude of transconductance, in Siemens
T = time delay associated with transconductance, in seconds
Cgs = gate-to-source capacitance, in farads
Ri = channel resistance, in ohms
Rs = source resistance, in ohms
Rg = gate resistance, in ohms
K1 = noise parameter K1 (see references)
K2 = noise parameter K2 (see references)
K3 = noise parameter K3 (see references)
K4 = noise parameter K4 (see references)

Range of Usage
N/A

Notes/Equations
1. This component provides a linear bias-independent FET noise model (by Fukui) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.
2. The effect of feedback or parasitics on the noise performance of FETN3 is determined by connecting appropriate circuit components externally to FETN3.
3. The expressions that relate the noise parameters to the model components (G, Cgs, for example) and the K1-K4 parameters use the model components in specific units. The values of K1-K4 should conform to these units of the model components. (See references.)
4. For time-domain analysis, the frequency-domain analytical model is used.

5. This component has no default artwork associated with it.

References


Equivalent Circuit
**FETN4 (FET Noise Model (Podell))**

**Symbol**

![Symbol](image)

**Parameters**

- \( G \) = magnitude of transconductance, in Siemens
- \( T \) = time delay associated with transconductance, in seconds
- \( C_{gs} \) = gate-to-source capacitance, in farads
- \( R_{i} \) = channel resistance, in ohms
- \( R_{s} \) = source resistance, in ohms
- \( R_{g} \) = gate resistance, in ohms
- \( N_{F_{\text{min}}} \) = minimum noise figure, in dB
- \( F_{\text{Ref}} \) = frequency at which \( N_{F_{\text{min}}} \) is measured, in hertz

**Range of Usage**

N/A

**Notes/Equations/References**

1. This component provides a linear bias-independent FET noise model (by Podell) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.

2. The effect of feedback or parasitics on the noise performance of FETN4 is determined by connecting appropriate circuit components externally to FETN4.

3. For time-domain analysis, the frequency-domain analytical model is used.

4. This component has no default artwork associated with it.

Linear Devices

Equivalent Circuit

![Equivalent Circuit Diagram]

6-20  FETN4 (FET Noise Model (Podell))
**FETN4a (FET Noise Model (Podell))**

**Symbol**

![Symbol Diagram]

**Parameters**
- G = magnitude of transconductance, in Siemens
- T = time delay associated with transconductance, in seconds
- Cgs = gate-to-source capacitance, in farads
- Ri = channel resistance, in ohms
- Rs = source resistance, in ohms
- Rg = gate resistance, in ohms
- K = parameter related to the noise performance of this model (see references)

**Range of Usage**

N/A

**Notes/Equations**

1. This component provides a linear bias-independent FET noise model (by Podell) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.

2. This model is the same as FETN4 except that the input parameter related to the noise performance for FETN4a is K, whereas those for FETN4 are NFMin and FRef. Specifying K instead of NFMin and FRef is an alternate way to describe the same model.

3. The effect of feedback or parasitics on the noise performance of FETN4a is determined by connecting appropriate circuit components externally to FETN4a.

4. For time-domain analysis, the frequency-domain analytical model is used.

5. This component has no default artwork associated with it.
References


Equivalent Circuit
FETN5 FET Noise Model (Gupta, et al.)

Symbol

Parameters

\( G \) = magnitude of transconductance, in Siemens

\( T \) = time delay associated with transconductance, in seconds

\( C_{gs} \) = gate-to-source capacitance, in farads

\( R_{i} \) = channel resistance, in ohms

\( R_{ds} \) = drain-to-source resistance, in ohms

\( R_{s} \) = source resistance, in ohms

\( R_{g} \) = gate resistance, in ohms

\( S_{io} \) = power spectral density of output noise current, in picoamperes squared per hertz (see references)

Range of Usage

N/A

Notes/Equations

1. This component provides a linear bias-independent FET noise model (by Gupta, et al.) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.

2. The effect of feedback or parasitics on the noise performance of FETN5 is determined by connecting appropriate circuit components externally to FETN5.

3. For time-domain analysis, the frequency-domain analytical model is used.

4. This component has no default artwork associated with it.

References


**Equivalent Circuit**

![Equivalent Circuit Diagram](image-url)
HYBPI (Hybrid-Pi Bipolar Transistor)

Symbol

Parameters
- G = transconductance, in Siemens
- T = transit time, in seconds
- C_{pi} = base-emitter (pi) capacitance, in farads
- R_{pi} = base-emitter (pi) resistance, in ohms
- C_{mu} = base-collector (mu) capacitance, in farads
- R_{mu} = base-collector (mu) resistance, in ohms
- R_{b} = base resistance, in ohms
- R_{c} = collector resistance, in ohms
- R_{e} = emitter resistance, in ohms

Range of Usage
- R_{pi} > 0
- R_{mu} > 0

Notes/Equations/References
1. For time-domain analysis, the frequency-domain analytical model is used.
2. This component is assumed to be noiseless.
3. This component has no default artwork associated with it.
Linear Devices

Equivalent Circuit
PIN (PIN Diode, Chip Model)

Symbol

Parameters

- $C_j =$ junction capacitance, in farads
- $R_j =$ junction resistance, in ohms
- $R_s =$ diode series resistance, in ohms
- $L_s =$ bond wire inductance, in henries
- $C_b =$ by-pass capacitance, in farads
- $C_g =$ capacitance of gap across which diode is connected, in farads

Range of Usage

N/A

Notes/Equations/References

1. This component is assumed to be noiseless.
2. This component has no default artwork associated with it.

Equivalent Circuit
PIN2 (PIN Diode, Packaged Model)

Symbol

Parameters
Cj = junction capacitance, in farads
Rj = junction resistance, in ohms
Rs = series resistance, in ohms
Ls = series inductance, in henries
Cp = package capacitance, in farads

Range of Usage
N/A

Notes/Equations/References
1. This component is assumed to be noiseless.
2. This component has no default artwork associated with it.

Equivalent Circuit
Chapter 7: Equation-Based Non-Linear Components

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section “Multiplicity.” This section appears in Chapter 1, Introduction, of Circuit Components: Introduction and Simulation Components.
Equation-Based Non-Linear Components

FDD1P to FDD 10P (1- to 10-Port Frequency-Domain Defined Device)

Symbol

Parameters

$I[i, j]$ = current equation that describes spectral current. $i$ refers to the port number. $j$ refers to a frequency index.

$V[i, j]$ = voltage equation that describes spectral voltage. $i$ refers to the port number. $j$ refers to a frequency index.

Freq[$k$] = carrier frequency, in hertz

Trig[$k$] = trigger event

Ce[$k$] = clock enable definition

Range of Usage

$0 \leq i \leq 10$

Notes/Equations/References

1. The frequency-domain defined device (FDD) enables you to create equation-based, user-defined, nonlinear components. The FDD is a multi-port
device that describes current and voltage spectral values in terms of algebraic relationships of other voltage and current spectral values. It is for developing nonlinear, behavioral models that are more easily defined in the frequency domain.

For complete information on how to use these devices and application examples, refer to Circuit Simulation.

2. Equations that relate the port spectral voltages and currents are described in the frequency domain. The two basic types of equations are current equations and voltage equations. Their format is:

$I[\text{port, findex}] = f(_\text{sv}(), _\text{sv}_d(), _\text{si}(), _\text{si}_d())$

$V[\text{port, findex}] = f(_\text{sv}(), _\text{sv}_d(), _\text{si}(), _\text{si}_d())$

where port is the port number and findex is a frequency index.

The equations can be listed in any order, and more than one equation can be used for a single port, but each port must have at least one equation.

The variables of interest at a given port are the port spectral voltages and port spectral currents. Spectral voltages and currents can be obtained using the functions _sv(), _si(), _sv_d(), and _si_d().

3. The freq parameter enables you to define one or more carrier frequencies.

4. The FDD enables you to define up to 31 trigger events. Anytime the value of the trigger expression is equal to a number other than zero, a trigger event is declared for the corresponding trigger.

5. Clock enables specify that the output of a given port can change only when a specified trigger, or a set of specified triggers, occurs.
Equation-Based Non-Linear Components

NonlinC (Nonlinear Capacitor)

Symbol

Parameters

\[
\text{Coeff} = \text{list of coefficients that describe a polynomial that defines capacitance as a function of voltage } v \text{ across the capacitor where}
\]

\[
\text{cap} = \text{Coeff}[0] + \text{Coeff}[1] \times v + \text{Coeff}[2] \times v^2 + \ldots + \text{Coeff}[n] \times v^n
\]

and coefficients are entered using the list function

\[
\text{Coeff} = \text{list} \left( \text{Coeff}[0], \text{Coeff}[1], \text{Coeff}[2], \ldots, \text{Coeff}[n] \right)
\]

Range of Usage

N/A

Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line.

2. Units of Coeff[0] = farads
   units of Coeff[1] = farads/volt
   units of Coeff[2] = farads/volt^2

   Coefficients are entered using the list function. For example, if
   \[ C = 5V^2 + 4V^4 \]
   the parameter entry is
   \[ \text{Coeff} = \text{list}(0,0,5,0,4) \]

3. The controlling voltage \( v \) is the voltage across the capacitor, with pin 1 (the one with the slash) being positive and pin 2 being negative.

4. This component has no default artwork associated with it.
NonlinCCCS (Nonlinear Current-Controlled Current Source)

Symbol

Illustration

Parameters

Coeff = list of coefficients that describe a polynomial that defines output current \( I_2 \) as a function of input current \( I_1 \):

if only one coefficient is specified

\[ I_2 = \text{Coeff}[0] \times I_1 \]

the coefficient is entered using the list function

\[ \text{Coeff} = \text{list}(\text{Coeff}[0]) \]

otherwise

\[ I_2 = \text{Coeff}[0] + \text{Coeff}[1] \times I_1 + \text{Coeff}[2] \times I_1^2 + \ldots + \text{Coeff}[n] \times I_1^n \]

and coefficients are entered as

\[ \text{Coeff} = \text{list} (\text{Coeff}[0], \text{Coeff}[1], \text{Coeff}[2], \ldots, \text{Coeff}[n]) \]

Range of Usage

N/A
Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line using the list function. For example, if

\[ I_2 = 3 - 2I_1^2 + 5I_1^6 \]

the parameter entry is

\[ \text{Coeff} = \text{list}(3,0,-2,0,0,0,5) \]

If \( I_2 = 5I_1 \), then \( \text{Coeff} = \text{list}(5) \)

If \( I_2 = 5 \), then \( \text{Coeff} = \text{list}(5,0) \)

2. This component has no default artwork associated with it.

3. Output current is in Amperes.
NonlinCCVS (Nonlinear Current-Controlled Voltage Source)

Symbol

Illustration

Parameters

Coeff = a list of coefficients that describe a polynomial that defines output voltage $V_2$ as a function of input current $I_1$:

- if only one coefficient is specified
  
  \[ V_2 = \text{Coeff}[0] \times I_1 \]

  the coefficient is entered using the list function

  \[ \text{Coeff} = \text{list} (\text{Coeff}[0]) \]

- otherwise

  \[ V_2 = \text{Coeff}[0] + \text{Coeff}[1] \times I_1 + \text{Coeff}[2] \times I_1^2 + \ldots + \text{Coeff}[n] \times I_1^n \]

  and coefficients are entered as

  \[ \text{Coeff} = \text{list} (\text{Coeff}[0], \text{Coeff}[1], \text{Coeff}[2], \ldots, \text{Coeff}[n]) \]

Range of Usage

N/A
Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line. For example, if
   \[ V_2 = 3 - 2I_1^2 + 5I_1^6 \]
   the parameter entry is
   `Coeff = list(3,0,-2,0,0,5)`
   If \( V_2 = 5I_1 \), then `Coeff = list(5)`
   If \( V_2 = 5 \), then `Coeff = list(5,0)`

2. This component has no default artwork associated with it.

3. Output voltage is in Volts.
NonlinL (Nonlinear Inductor)

Symbol

Parameters

Coeff = a list of coefficients that describe a polynomial that defines inductance as a function of current through the inductor:

\[ L = \text{Coeff}[0] + \text{Coeff}[1] \times I + \text{Coeff}[2] \times I^2 + \ldots + \text{Coeff}[n] \times I^n \]

and coefficients are entered using the list function

\[ \text{Coeff} = \text{list}(\text{Coeff}[0], \text{Coeff}[1], \text{Coeff}[2], \ldots, \text{Coeff}[n]) \]

Range of Usage

N/A

Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line.

   - units of Coeff[0] = henries
   - units of Coeff[1] = henries/amp
   - units of Coeff[2] = henries/amp^2

   Coefficients are entered using the list function. For example, if
   \[ L = 5I^2 + 4I^4 \]
   the parameter entry is
   \[ \text{Coeff} = \text{list}(0, 0, 5, 0, 4) \]

2. The controlling circuit i is the current flowing from pin 1 (the one with the slash) to pin 2.

3. This component has no default artwork associated with it.
NonlinVCCS (Nonlinear Voltage-Controlled Current Source)

Symbol

Illustration

Parameters

\[ I_2 = \text{Coeff}[0] \times V_1 \]

if only one coefficient is specified

the coefficient is entered using the list function

\[ \text{Coeff} = \text{list(Coeff[0])} \]

otherwise

\[ I_2 = \text{Coeff}[0] + \text{Coeff}[1] \times V_1 + \text{Coeff}[2] \times V_1^2 + \ldots + \text{Coeff}[n] \times V_1^n \]

and coefficients are entered as

\[ \text{Coeff} = \text{list(Coeff[0], Coeff[1], Coeff[2], \ldots, Coeff[n])} \]

Range of Usage

N/A
Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line. Enter values for each coefficient in a single line using the list function. For example, if

\[ I_2 = 3 - 2V_1^2 + 5V_1^6 \]

the parameter entry is

\[ \text{Coeff} = \text{list}(3,0,-2,0,0,5) \]

If \( I_2 = 5V_1 \), then \( \text{Coeff} = \text{list}(5) \)

If \( I_2 = 5 \), then \( \text{Coeff} = \text{list}(5,0) \)

2. This component has no default artwork associated with it.

3. Output current is in Amperes.
Equation-Based Non-Linear Components

**NonlinVCVS (Nonlinear Voltage-Controlled Voltage Source)**

**Symbol**

```
+   +
\_\_\_
  \_\_\_
  +
  +
+   +
  3
  -
  4
```

**Illustration**

```
+   +
\_\_\_
  \_\_\_
  +
  +
+   +
  3
  -
  4
```

**Parameters**

\( \text{Coeff} = \text{a list of coefficients that describe a polynomial that defines output voltage } V_2 \text{ as a function of input voltage } V_1: \)

If only one coefficient is specified

\[ V_2 = \text{Coeff}[0] \times V_1 \]

the coefficient is entered using the list function

\( \text{Coeff} = \text{list(Coeff[0])} \)

otherwise,

\[ V_2 = \text{Coeff}[0] + \text{Coeff}[1] \times V_1 + \text{Coeff}[2] \times V_1^2 + \ldots + \text{Coeff}[n] \times V_1^n \]

and coefficients are entered as

\( \text{Coeff} = \text{list(Coeff[0], Coeff[1], Coeff[2], \ldots, Coeff[n])} \)

**Range of Usage**

N/A
Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line. Enter values for each coefficient in a single line using the list function. For example, if

   \[ V_2 = 3 - 2V_1^2 + 5V_1^6 \]

   the parameter entry is

   \[ \text{Coeff} = \text{list}(3,0,-2,0,0,0,5) \]

   If \( V_2 = 5V_1 \), then \( \text{Coeff} = \text{list}(5) \)

   If \( V_2 = 5 \), then \( \text{Coeff} = \text{list}(5,0) \)

2. This component has no default artwork associated with it.

3. Output voltage is in Volts.
Equation-Based Non-Linear Components

SDD1P to SDD14P (Symbolically Defined Device, 1-12 or 14 or 16 Ports)

Symbol

Parameters

\[ I[i, j] = \text{explicit equation that describes port current in terms of voltage. } i \text{ refers to the port number. } j \text{ refers to the weighting function (0,1, or user defined).} \]

\[ F[i,j] = \text{implicit equation defining a nonlinear relationship of port voltages and port currents (or the currents of certain other devices) that is equal to 0. } i \text{ refers to the port number. } j \text{ refers to the weighting function (0,1, or user defined).} \]

\[ H[k] = \text{user-defined weighting function} \]

\[ C[l] = \text{controlling current} \]

\[ I_n[i,j] = \text{equation that specifies the noise current squared. } i \text{ refers to the port number. } j \text{ refers to the weighting function (0,1, or user defined).} \]

\[ N_c[i,j] = \text{complex noise correlation coefficient between ports } i \text{ and } j. \]

Range of Usage

\[ 0 \leq i \leq 10 \]

\[ 0 \leq j \]
\[ 2 \leq k \leq l \]

**Notes/Equations/References**

1. The symbolically-defined device (SDD) enables you to create equation based, user-defined, nonlinear components. The SDD is a multi-port device which is defined by specifying algebraic relationships that relate the port voltages, currents, and their derivatives, plus currents from certain other devices.

2. Devices SDD1P through SDD10P are available from the component palette and library browser. Two additional devices, SDD12P and SDD14P are only available by typing their exact names into the Component History box, pressing Enter, and moving the cursor to the drawing error to place the components.

3. Port variables, \_in and \_vn, contain the current and voltage values of a port, respectively. \( n \) specifies the port number, for example, the current and voltage variables for port one are \_i1 and \_v1, respectively.

4. The equations that relate port currents and port voltages are specified in the time domain. These constitutive relationships may be specified in either explicit or implicit representations.

   With the explicit representation, the current at port \( k \) is specified as a function of port voltages:
   \[ i_k = f(v_1, v_2, ... v_n) \]

   The implicit representation uses an implicit relationship between any of the port currents and any of the port voltages:
   \[ f_k(v_1, v_2, ... v_n, i_1, i_2, ... i_n) = 0 \]

   Using the implicit representation, you can also reference current flowing in another device, by using controlling currents.

   Different types of expressions cannot be mixed—that is, a single port must be described by either implicit or explicit expressions. Every port must have at least one equation.

   By convention, a positive port current flows into the terminal marked +.

5. A weighting function is a frequency-dependent expression used to scale the spectrum of a port current. Weighting functions are evaluated in the frequency domain.
There are two predefined weighting functions. Weighting function 0 is defined to be identically one. It is used when no weighting is desired. Weighting function 1 is defined as $jw$ and is used when a time derivative is desired. You can define other weighting functions, starting with 2.

6. An SDD can also be set up to reference the current flowing in another device. The devices that can be referenced are limited to either voltage sources or current probes in the same network. To specify a current as a control current, you enter the instance name of the device in the $C[k]$ parameter of the SDD. These currents can then be referred to using the variable $c[k]$ for the $k$th referenced current. These variables $c[k]$ may be used in the SDD equations along with the SDD port voltages $v[n]$ and port currents $i[n]$.

7. $\text{In}[\cdot]$ and $\text{Nc}[\cdot]$ are used to specify the noise behavior of the SDD. $\text{In}[i,j]$ specifies

$$\left(i_i, i_i^*\right)$$

the short-circuit noise current squared, in units of amperes squared at port $i$, with weighting function $j$.

$\text{Nc}[i,j]$ specifies the complex noise correlation coefficient between ports $i$ and $j$. It should be a complex number with a magnitude less than or equal to one, $\text{Nc}[i,j]$ and $\text{Nc}[j,i]$ should be complex conjugates of each other.

$$\text{Nc}[i,j] = \frac{i_i i_j^*}{\sqrt{(i_i i_i^*)(i_j i_j^*)}}$$

8. For more information on how to use these devices and application examples, refer to Circuit Simulation.
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