

Evaluation of High Voltage Characteristics of Semiconductor Processes and Devices by expanding Force Voltage Capability to 400 V using Agilent E5270A

Application Note E5270-3

- Maximum 400 V Force/Measure
- Minimum 100 μ V Force, 2 μ V Measure
 - Useful for:
 - High voltage process evaluation
 - High voltage device characterization

Agilent E5270A 8 slot Parametric Measurement Mainframe with 4 SMU plug-in modules

Introduction

Generally, the operating voltage of state of the art high-density integrated circuits (ICs) is decreasing as the IC design rule shrinks. The voltage required for characterizing these devices is also decreasing, but the voltage required for testing the semiconductor processes such as checking the inter-level insulation layer still remains relatively high. The low-K insulator and cupper inter-connect systems that are widely used under the 0.13 μ m process technologies also require high voltage for evaluating the copper process integrity.

In addition to the state of the art technologies, the parametric test system is widely used for covering several generations of technologies (design rules) or even across several groups of technologies, for example memory, logic and driver devices. Therefore the output voltage range of parametric test systems or test instruments must encompass a relatively wide voltage range as shown in Figure 1, which illustrates the operating voltage and current by grouping typical device categories in a simple format.

When considering the output voltage, current and power of the measurement instruments or testers that are available in the market place, the devices can be grouped into two types from the viewpoint of parametric measurement applications. As illustrated in Figure 1, one type of power device is measured using a power device tester or curve tracer, and the other power device is measured using a parametric tester. As can be seen from the figure, the break point of the two groups is a few hundred volts and a few amperes, though there is



Agilent E5270 Series of Parametric Measurement Solutions



Figure 1. Simplified operating voltage and current of semiconductor devices



Figure 2. Differential SMU connection

certainly a relatively wide gray zone between the two groups. Although most of applications are moving in the lower voltage direction, but high voltage is occasionally required such as for low-K and cupper interconnect, so it is important to maintain a certain level of high voltage measurement capability even the boundary of high voltage depends on a specific application.

It is very convenient and beneficial if the output voltage of the SMU can be expanded for those applications that the normal SMU cannot cover. This also keeps the high performance of the SMU, while saving cost, space and maintenance effort that would be necessary if a standalone high voltage instrument is added to the test system. Adding a high voltage instrument tends to complicates both the software and hardware settings for switching between the SMU and high voltage instrument.

This easily degrades the SMU performance in low voltage and low current applications; a specially designed low leakage and high voltage switch and a guard technique would be required to keep a certain standard of low level performance.

This application note introduces a technique for expanding the output voltage using the SMU of the Agilent E5270A 8-slot Parametric Measurement Mainframe.

Techniques for Increasing Output Voltage

Two-terminal DUT

The most commonly used technique for increasing the output voltage using the SMU is to apply a voltage differentially using two SMUs as shown in Figure 2.

If the output voltage of one SMU is set to +200 V and the other SMU to -200 V as shown in the figure, then 400 V is applied differentially to the device under test (DUT). This connection is possible only if the DUT can be considered a real two-terminal device. The output voltage from each SMU is swept as shown in Figure 3 (A), and the resultant differential voltage appears at the DUT as in Figure 3 (B). The voltage shape in Figure 3 (B) is as expected and it can be understood that this approach effectively expands the output voltage of the SMU without any potential problem.

Multi-terminal DUT

How about the case of a multiterminal DUT? Figure 4 shows an example connection of a multi-terminal DUT. Figure 4 (A) shows the case of



Figure 4. Multi-terminal DUT

a three-terminal DUT connected with three SMUs. The dotted line indicates the connection of a four-terminal case. Figures 4 (B) and 4 (C) are examples of typical multiterminal devices, a threeterminal transistor example in Figure 4 (B) and a fourterminal FET example in Figure 4 (C).

Can these devices be measured using the same approach? No, the method shown in Figure 3 cannot be used for multiterminal devices, if each SMU is swept in a different timing.

If the base, gate or substrate is swept sequentially to the reference voltage of measurement start point V_{F2} in different timing, then the large V_{F2} voltage appears at one of the terminals, damaging the base, gate or substrate. To prevent damaging the device, the base, gate and substrate must be swept simultaneously to the V_{F2} point as shown in Figure 5. In Figure 5 (A), three SMU outputs $V_{\rm F1},~V_{\rm F2}$ and $V_{\rm F3}$ are swept together simultaneously to the reference start point V_{F1} , and then $V_{\rm F2}$ and $V_{\rm F3}$ are set sequentially for starting real measurements. Figure 5 (B) shows the differential output voltage that is the voltage applied to each DUT terminal referenced to V_{F1} , it is exactly the same as the standard non-differential measurements.

At the end of the measurement, the three SMU outputs V_{F1} , V_{F2} and V_{F3} must sweep simultaneously to zero volts.

Technical requirement for differential voltage source

As can be seen from Figure 5, this approach relies on the



Figure 5. Voltage shape of multi-terminal DUT

simultaneous sweep of multi-SMUs when all the SMU outputs are set to the reference voltage before the start of actual measurements, and then the voltage is returned to zero volts all at once after the measurements are finished. Since the purpose of the sweep made before and after the measurements is to minimize the voltage difference between the SMUs, thus preventing any high voltage applied between the DUT terminals and damage to the DUT when sweeping to the reference start voltage or returning to zero volts, the voltage difference between the SMUs in each sweep step must be small enough to not damage the DUT. The sweep voltage in each step is enlarged in the magnifier of Figure 5. The

sweep becomes smoother and the difference between the SMUs becomes smaller with the decrease in the sweep step voltage, but it takes more time to settle to the target voltage if the voltage step for sweep is set too small.

When applying this technique, the following two key issues must be considered.

- How to implement simultaneous sweep?
- Is the time for simultaneous sweep acceptably short?

If the simultaneous sweep is necessary in only one or two SMUs, then it can be done using the built-in sweep function of any of the Agilent 415X series Semiconductor Parameter Analyzer, Agilent 4142B DC Source Monitor or Agilent E5270 Series Parametric Measurement Solutions. But three or more SMUs, then the choice is limited to the Agilent E5270A 8-slot Parametric Measurement Mainframe.

If the built-in simultaneous sweep cannot be used, then the equivalent sweep of the simultaneous sweep has to be generated by writing a PC program code. Suppose the sweep voltage is 200 V and each step is 0.5 V for three SMUs. The total voltage steps would be 1,200 {= (200 V / 0.5 V) x 3 SMUs} steps. If one step takes 10 ms per SMU, as is typical in older instruments, then it takes 12 seconds (=1,200 x 10 ms) for only going to the start voltage before doing the intended high-voltage measurements. Then after the measurement that would be done possibly within a second, returning to zero volts for finishing the measurements takes another 12 seconds. Therefore the total measurement time is about 25 seconds at best if each step of the sweep is controlled from a PC. The 25 seconds for single measurement is too long for many applications, and this approach can only be used on special occasions if each step of the simultaneous sweep is generated by a PC program.

You can implement this technique with greater flexibility and fewer limitations if you use the Agilent E5270A that can simultaneously sweep up to eight SMU channels without sacrificing the measurement time.

Agilent E5270A Solutions

Agilent E5270A features

The Agilent E5270A has the following attractive features that are effective for implementing the differential voltage output and expanding the output voltage range:

- Multi-channel simultaneous sweep measurements:
 - The Agilent E5270A can

perform multi-channel sweep measurements for up to eight SMUs as shown in Figure 6. You can sweep any combination of SMUs in different start, stop and step voltages by synchronizing each step of the sweep. This sweep mode is useful both when setting the initial reference voltage before the start of measurements and returning to zero volts after the end of measurements.



Figure 6. Multi-channel sweep measurements



Figure 7. Output voltage and time stamp plot

• High speed sweep and measurements:

- The Agilent E5270A is faster in sweep and spot measurements compared to other Agilent parametric analyzers or instruments. In addition to its high speed, it has a small overhead in sweep time by increasing the number of SMUs used in the built-in multi-channel sweep; this results in a sufficiently short time for settling to the initial measurement start voltage and returning to zero volts at the end of the test and justifies this test approach. The output voltage versus time stamp plot is shown in Figure 7; the sweep time from zero volts to -200 volts in 0.5 volt steps is about 1.3 seconds for three SMUs sweeping together.

• Configurable SMU: - You can configure the High Power SMU (HPSMU) that provides 200 V maximum (occupies two E5270A plug-in slots) and Medium Power SMU (MPSMU) that provides 100 V maximum (occupies one E5270A plug-in slot) in any combination for up to eight slots of the Agilent E5270A Parametric Measurement Mainframe. For example, if your measurement requires both many SMU channels and high voltage output, then you can configure for standard four-terminal device with three MPSMUs and one HPSMU that occupy five slots of the E5270A mainframe. This configuration can output 300 volts maximum and is illustrated in Figure 8 (A). There still remains three slots SMU space in the E5270A mainframe for any



Figure 8. SMU configuration example



Figure 9. Implementation example

additional SMU requirements. Figure 8 (B) shows another example of a four HPSMU configuration that supports 400 V maximum for four-terminal MOSFET. These examples indicate the great freedom in configuring the SMU depending on the voltage required in the application.

Implementation example

Figure 9 shows a measurement example of Id-Vd

characteristics of a power MOSFET from zero to 400 volts sweep. The gate is set for 3.0 V and 3.1 V for each Vd sweep.

Figure 10 shows the actual output waveform measured

using an oscilloscope. "SMU OUTPUT" in the lower half screen shows the output of each SMU. In the center of the time scale, two saw tooth waves are observed; that is drain voltage sweep corresponding to the two Id -Vd sweep measurements shown in Figure 9. It first sweeps all the SMUs from 0 to -200 V for source, drain and gate. Then, the gate is biased from -200 V to -197 V, that is actually a 3 V gate bias relative to the source voltage. Next, the drain is swept from -200 V to 200 V, that is equivalent to a 0 to 400 V sweep relative to the source. The second drain sweep is repeated for 3.1 V relative gate voltage, and then all the SMUs



Figure 10. Output voltage waveform



Figure 11. SMU outputs in each step V

are swept back together to zero volts to finish the measurements.

The upper half screen shows the drain sweep voltage that is relative to the source measured by an oscilloscope using a differential mode, the drain SMU channel minus the source SMU channel. It clearly shows that the output voltage is exactly the same as the case of the normal Id versus Vd sweep measurements.

Finally the output voltage waveform of each SMU in the initial sweep period is shown in Figure 11. It can be seen that there is a small difference in the step timing of each SMU as already illustrated in Figure 5. Because of this minor timing difference between the SMUs, the step voltage sweeping to the measurement start voltage and returning to zero volts must be so small that does not apply any stress to the device.

If you maintain this sweep step voltage to a reasonable range, so that a smaller value takes more time and larger voltage is faster but places more stress on the DUT, you can safely implement the differential high voltage measurements. The example verifies the effectiveness of the approach.

VXIplug&play program example

This approach requires a user written program.

VXIplug&play driver of the Agilent E5270 series simplifies the development work of the user program.

The VXIplug&play driver can be run under Microsoft Windows applications; for example, Microsoft Visual Basic, Microsoft Visual C++ or Borland C++ Builder. It can be also run under Microsoft Visual Basic for Application (VBA) of Microsoft Excel and it can further reduce the datahandling task after the measurement data is taken.

Figure 12 (A) shows a sample user setup window created using Excel. The measurement data can be listed in a different worksheet by using the Excel VBA function as shown in Figure 12 (B).

The sample program used in

this application note can be downloaded from the Agilent web site.

www.agilent.com/see/parametric

Start V (Var 1) 0 Stop V (Var 1) 400 Var 1 # of Step 81 Var 1 I comp 4E-2	Measure Total time : 3.796875 sec ADC Averaging 16 Meas. Item : 1 1 = Id-Vd with Vg (Var2) 2 = Id-Vd (2ch), 3=Q pulsed Breakdown (2ch)
Base Offset V -200 Cal. S & G SMU ch.	Record time data
var 2 Step V 0.1	
Var 2 # of Step 2	Start I : -0.035514 mA
Var 2 I comp 1E-3	Stop I at 81 : 0.2584 mA
SMU Configuration (Slot number) Drain Ch 4 Source Ch. (HPSMU) 8 Gate Ch. 6	

Figure 12. (A) Sample measurement setup window using Microsoft Excel

	В	С	D	E	F	G	Н	I	J	K	L	М		
10	1	Voltage (V)	Current 1 (A)	Current 2 (A)	Current 3 (A)	Current 4 (A)	Current 5 (A)							
11	1	0	-0.000018402	-3.5514E-05										
12	2	5	0.00010664	0.00023146			Ī							
13	3	10	0.00010716	0.00023288										
14	4	15	0.00010756	0.00023386										
15	5	20	0.00010784	0.0002346										
16	6	25	0.00010808	0.00023536										
17	7	30	0.00010832	0.0002357					19.0404					
18	8	35	0.00010828	0.0002359		Id-Vd Characteristics								
19	9	40	0.00010846	0.00023614										
20	10	45	0.00010842	0.00023648		0.0003 r								
21	11	50	0.00010854	0.00023674										
22	12	55	0.00010862	0.00023722	0	.00025		and the second division of the second divisio						
23	13	60	0.00010864	0.0002368										
24	14	65	0.0001087	0.00023698		0.0002								
25	15	70	0.00010884	0.00023704		00015				-+	- Current 1 (A	9		
26	16	75	0.0001088	0.0002372		.00015					- Current 2 (A	4)		
27	17	80	0.00010876	0.00023744	E E	0.0001					Current 3 (A			
28	18	85	0.00010894	0.00023734	므						Cumont 4 ()	31		
29	19	90	0.00010888	0.00023754	0	.00005 🛏					Current 4 (A	<u> </u>		
30	20	95	0.00010918	0.00023772						-*-	- Current 5 (A	9		
31	21	100	0.000109	0.00023808		U 🔶	I	·						
32	22	105	0.00010894	0.0002377	0	00005	100 20)0 300	400	500				
33	23	110	0.00010922	0.0002383	-0	.00005								
34	24	115	0.0001092	0.00023876		0.0001 L								
35	25	120	0.00010938	0.00023902				V. ///						
36	26	125	0.00010936	0.0002388				va (v)						
37	27	130	0.00010922	0.00023884										
38	28	135	0.0001094	0.00023852										
39	29	140	0.0001096	0.0002392										
40	30	145	0.00010962	0.00023936										
	21 Meas Se	150 etup/Swpdata	n nnn1nog M swp data (T	A1 21 150 0 00012088. ↓ Neas Setur (Swm data / Miseri data / ↓										

Figure 12. (B) Sample measurement data window of Microsoft Excel

Advanced Information

Offset voltage between SMUs

When this technique is used on a device that has a control input like the gate of the FET, the difference of the output voltage between the source SMU and the gate SMU may have to be examined. For example, the large common mode differential voltage applied to the FET's source and gate, as shown in Figure 13, generates a small offset voltage because the output voltage from each SMU varies within the limit of the accuracy specification.

As an example, consider a case where the gate and the source of the FET are biased to - 200 V. In Table 1. the SMU specification of voltage accuracy in 200 V range is shown, and the resultant maximum force voltage error (= output voltage x % error + offset) at 200 V output is +/- 120 mV. If the errors of each SMU's output voltage are independent of each other, then the worst case voltage difference of source and gate SMU becomes twice the 120 mV, that is +/- 240 mV when -200 V is applied as the common mode differential voltage to the source and the gate.

If the +/- 240 mV difference is large for the application, then each SMU can be calibrated by using high resolution central ADC (HR ADC) and the difference can be reduced to +/- 160 mV, which is double +/- 80 mV shown in the "V Measure" column of Table 1.

If the voltage difference between the source SMU and the gate SMU has to be further



Figure 13. Common mode offset voltage error

				Max. error
	% Error	Offset err or	Resolution	(at 200 V)
V Force	+/-0.045%	+/- 30 mV	10 mV	+/-120 mV
V Measure	+/-0.035%	+/-10 mV	0.2 mV	+/-80 mV

Table 1. Voltage specification and maximum error in 200 V range

reduced, this can be achieved by calibrating each SMU by using the high resolution central ADC. The procedure is, first, measure the same voltage from one SMU by connecting both SMUs' output together, second, calibrate the voltage monitor circuit of each SMU using the same monitor voltage and one central precision ADC, then third, calibrate the DAC of each SMU using the calibrated ADC. This approach can minimize the offset voltage of two (or more) SMUs.

By calibrating the output of the gate SMU relative to the source SMU, the relative error could be reduced to a few 10s mV, thus satisfying most of the requirements in high voltage device application.

Quasi-pulsed spot measurements for breakdown characterization

Quasi-pulsed spot measurements are useful for measuring high-voltage breakdown characteristics with the following features: (1) The stress applied to the DUT is minimized by reducing the breakdown time while the breakdown current flows, and (2) The measurement time is minimized by reducing unnecessary wait time. Figure 14 shows typical examples of measuring the breakdown voltage when not using the quasi-pulsed spot measurements. The voltage is gradually applied to the DUT with the slew rate determined by the current compliance of the SMU and the capacitive load of the DUT; the time to reach breakdown varies by the breakdown voltage. Figure 14 (A) is a case where the



Figure 14. Breakdown measurements



Figure 15. Quasi-pulsed spot breakdown measurements

breakdown voltage varies over a relatively wide range and a fixed wait time that is needed for measuring the BV2 breakdown is inserted. In the VB1 case, the measurement could be done at point t1 just after breakdown occurs, but the actual measurement has to wait until t2 timing; resulting in higher stress to the DUT because it is kept longer in the breakdown status. Now, take a case where the voltage swings from 0 V to 400 V and the slew rate is 5 V/ms. It takes 80 ms for slewing 400 V (=400/5) and the wait time may need to be set around 100 ms with a margin for detecting all the breakdown if there is any voltage between 0 to 400 V. If the breakdown voltage is known to be greater than, say 300 V, then the measurement can be made between 300 V and 400 V, but it is still necessary to wait more than 20 ms (=100/5) before starting the measurement.

Figure 14 (B) shows a case where mainly the slew rate changes. In this case, the wait time has to be set for the slowest slew rate. This also adds more stress to the DUT in the case of higher slew rate because the breakdown becomes longer than for the lower slew rate case.

The measurement sequence of breakdown measurements using the quasi-pulsed spot measurement is shown in Figure 15. The quasi-pulsed spot measurements measure the voltage of the DUT by the user specified current at the timing so that the DUT voltage has stabilized by waiting for the user specified delay time after the detection of the

change in slew rate; usually this point is very close to the breakdown of the DUT. Since this measurement mode automatically detects the breakdown without affecting the difference of the actual breakdown voltage nor the difference of slew rate and measures the breakdown voltage just after the breakdown occurs as in Figure 15, it minimizes the stress applied to the DUT. After the breakdown voltage is measured, the voltage returns to start voltage or zero volts and minimizes the measurement time. You can easily measure the breakdown voltage quickly without considering the wait time that is determined by the slew rate and the breakdown voltage by using the quasi-pulsed spot measurements.

Current compliance of reference SMU

The current compliance of the reference SMU should be set larger than the sum of the compliance setting of other SMUs. If the current compliance is set as described. then the reference SMU, for example a source SMU in FET measurements, always behaves as expected by the program even if the DUT fails. The output of the other SMU operates relative to the reference SMU output, and is similar, as the reference SMU is set to the GNDU. If the current compliance of the drain SMU, for example, is set to the largest current, then the source voltage is pulled towards the drain voltage if the source SMU hits the current compliance,

resulting in damage to the device.

Safety consideration

Since this technique drives the reference measurement terminal of the DUT to a high voltage that is usually set to zero volts, a safety mechanism must be implemented to protect the operator from exposure to any hazardous voltage.

The operator or any engineer who may access the DUT, regardless of the system status (idle, measuring or malfunctioning), must be insulated from the DUT and any conductor that is electrically connected to the DUT because hazardous voltage may appear on the surface of the conductor. For example, the DUT, fixture, manipulator and any conductors that are electrically connected to the SMU should be surrounded by a ground level shield box. The interlock protection mechanism must be implemented so that hazardous SMU output voltage is automatically turned off when anyone accesses to the DUT.

If this differential approach is used on the wafer prober application, the wafer chuck may have to apply a high voltage. In this case, the chuck and the related conductor parts connected to the chuck must be enclosed by a ground level shield, and an interlock system must be implemented to provide protection from hazardous voltage on any occasion.

Conclusion

The measurement voltage of the SMU can be doubled by applying voltage differentially to the DUT using two or more SMUs. However, three or more terminal devices require a multi-channel sweep measurement capability to avoid damaging the DUT.

The Agilent E5270A 8-slot Parametric Measurement Mainframe and SMUs can provide satisfactory measurement capability for high-voltage characterization of semiconductor devices or processes that require more than 200 V and up to 400 V voltage range.

The high-speed sweep capability and built-in multi-channel sweep measurements mode of the Agilent E5270A are suitable for covering these high voltage measurements without adding much overhead in measurement setup and measurement speed.

The quasi-pulsed spot measurement mode is suitable for high-voltage breakdown measurement, and it provides accuracy, ease of use and fast measurement results.

Finally, this solution demands extra safety considerations because the measurement reference point that is usually ground level is biased to a high voltage. For more information about Agilent and its product, go to www.agilent.com.

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