Accurate High Power Device Evaluation by Expanding Current Force/Measure Capability to 4 Amperes Using Agilent E5270A

Application Note E5270-1

- Maximum 4 A Current Force/Measure
- Short measurement time and pulsed output (1.5 ms)
- Easy to use, precise and flexible output control
- Effective for:
  - Model parameter extraction
  - Performance check of high-current and precision devices (High power devices, Laser diode, Solar cell)

Agilent E5270 Series of Parametric Measurement Solutions

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

Introduction

The continuing advances in integrated circuits are generating diverse semiconductor applications from low power consumption devices to high power devices. Although low power consumption / high speed semiconductor applications attract much attention these days, high power applications are still important and will be very important because of diversified application needs.

The maximum current of the High Power SMU (HPSMU) in the Agilent E5270 series is limited to one ampere (1 A). However, there are a few high power applications that require more than 1 A. High current itself can be obtained by using conventional DC power supply. However, this does not provide you with low current, low voltage, accuracy, speed, wide dynamic range bi-polar output and user friendliness that are required in the semiconductor applications; the SMU provides you with all of these capabilities. Therefore expanding the maximum current output range using SMUs is critical in high power applications.

The following are examples of such high power applications:

- Model parameter extraction of high power transistors used in the final stage of RF amplifiers that require wide dynamic range.
- Characterization of high power laser diode that is used for communication line.
- Solar cells or batteries that require both sink and source current capability in the same voltage polarity that is usually difficult to achieve with general DC power supply.
- Precise or stable measurements of power devices using a short measurement time or pulse by eliminating the parameter drift caused by the temperature rise from the self-Joule heating of the device.

Connecting SMUs in parallel is the most straightforward approach to increase the output current using SMUs. When SMUs are connected in parallel for increasing the maximum output current, the following limitations used to apply:

- Maximum current or power is limited by the mainframe and the available current or power is less than the total of the SMUs configured in the mainframe.

- Measured current is not accurate because the measurement timing is not simultaneous for the SMUs connected in parallel.
- When the SMU applies current to the device under test (DUT); measurement takes long time and the measured parameter drifts away owing to the self-heating of the DUT.

The E5270A Parametric Measurement Mainframe and HPSMUs can solve these limitations and provide accurate results up to 4 A with added flexibility and ease of use in measurements.

This application note provides information how to obtain these attractive advantages using the E5270A.

1. Agilent E5270A Features

The E5270A has the following features that are effective for high power applications:

- HPSMU: The maximum power is 20 watts (W) and 1 A output at +/- 20 V.
- The E5270A mainframe:
  - It has an eight channel plug-in slot and a maximum of four HPSMUs or eight MPSMUs can be installed.
  - The maximum power is 80W and full power of four HPSMUs or any combination of SMUs can be output.
- The Agilent E5270A GNDU: The ground unit can sink 4 A. It is equal to the total of four HPSMU maximum output currents. Therefore, the GNDU can sink full current of any combination of SMUs in the E5270A plug-in slot.
- Simultaneous outputs and measurements:
  The E5270A can output voltage or current simultaneously for any combination of SMUs.
  It also can make simultaneous measurements.
  Sweep measurements, spot pulsed measurements and spot output can be performed by using this feature.
  This feature is especially useful for high power measurements introduced in this application note.

Using these unique features of the E5270A, the maximum output can be expanded to 4 A in current and +/- 20 V in voltage using four HPSMUs connected in parallel. These features also enable user friendliness and accuracy for the high power measurements.

As an example, if you use three HPSMUs and two MPSMUs, then maximum 3.2 A (3 HPSMUs and one MPSMU) for the drain or the collector with one MPSMU for biasing the gate or the base can be easily configured.

2. High Power Measurement Techniques

Key technical points for achieving high accuracy in high-power and high-current measurements by connecting SMUs in parallel are discussed in this section.

The following points are keys to obtain the accurate measurements in high current applications;

- Use a Kelvin connection to eliminate voltage drop in the connection cable between the SMU and DUT.
- Perform measurements in a short period to eliminate a parameter drift caused by self-heating of the DUT. Pulsed measurements are preferable in many high current applications especially if the parameter is sensitive to device temperature.

Kelvin connection

Figure 1 shows Kelvin connection of an SMU with force and sense lines connected to the DUT using triaxial SMU cables.

Kelvin connection works as follows:

The voltage applied to the DUT from the SMU force is sensed at the close point of the DUT ("S" in Figure 1) and this voltage is fed

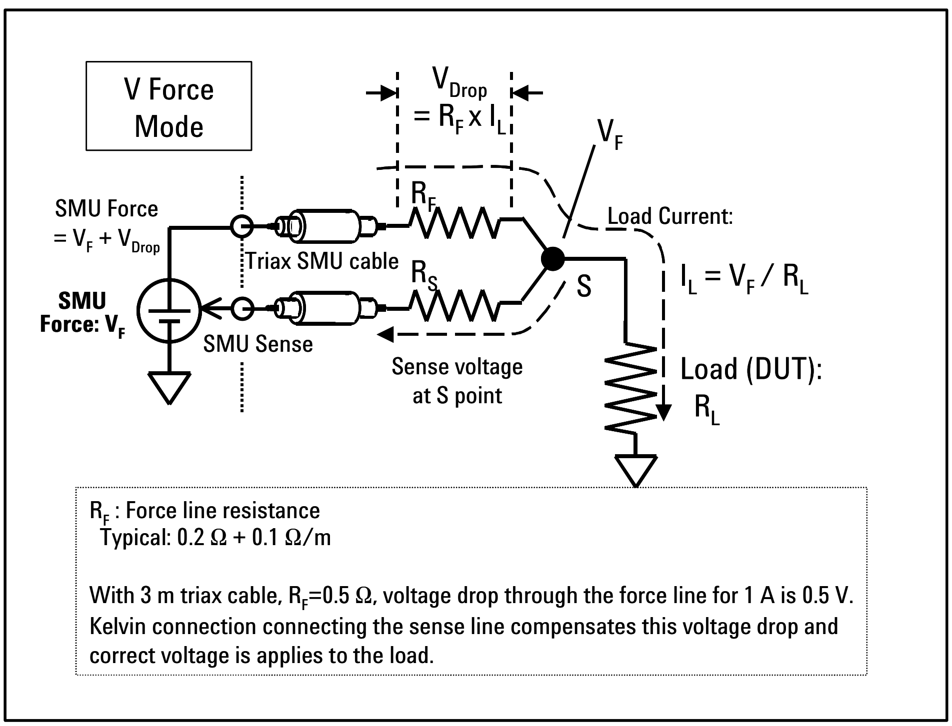


Figure 1. Kelvin connection using SMU Sense

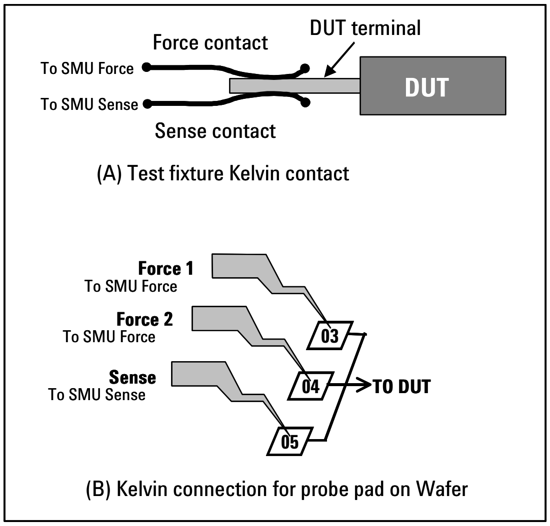


Figure 2. Kelvin contact

back to the SMU; then the output voltage of the SMU is adjusted by using analog feedback control of SMU so that the voltage in the sense input of SMU becomes the same as the programmed value. The impedance of the sense input of the SMU is very high and the exact voltage at the sense point of the DUT appears at the sense input of the SMU even when there is residual resistance at the point of contact to the DUT and in the connection cable. Therefore, by using Kelvin connection, the correct voltage always appears at the sense point of the DUT even if there is a voltage drop in the force line.

For example, typical resistance in the force line is $0.2\ \Omega + 0.1\ \Omega/m$ (where m is cable length in meters), and it is about $0.5\ \Omega$ with a 3 m triaxial cable. If 1 A current is forced to this line, about 0.5 volts voltage drop between the SMU and DUT is observed, and this is usually not an allowable voltage drop. If the sense line of the SMU is connected to the close point of the DUT, then this voltage drop in the force line is automatically compensated as described and correct voltage set to the SMU appears at the DUT.

If Kelvin connection is made to the DUT as shown in Figure 2 by using Kelvin contact, then a very stable connection eliminating the variation of the contact resistance can be established. Figure 2(A) is an example of Kelvin contact for a packaged device and Figure 2(B) is for on wafer.

Four ways for connecting SMUs in parallel

How you can satisfy above key requirements under parallel connection of SMUs

Figure 3 shows a typical basic configuration of SMUs connected in parallel to increase the output current in Kelvin and non-Kelvin connection.

Voltage force measurements are the most typical measurement mode in semiconductor applications. Figure 3(A) and (B) show voltage force and current measure mode (V Force, I Measure) with multi-SMUs connected in parallel, but the configuration is different in non-Kelvin connection (Figure 3(A), where two SMUs are used in voltage force mode) and Kelvin connection (Figure 3(B), where one SMU is used in Kelvin voltage force mode and the other SMU is used in current force mode).

The concept of Figure 3(A) is simple and easy to use. However, there are following two concerns in this configuration. One is measurement accuracy because it is not Kelvin connection and the voltage drop in the force line may not be ignored. The other is interference between the two SMUs because unexpected current may flow between the two voltage source SMUs. If these two issues are managed properly, this approach can be a solution with the features of ease-of-use and reasonable accuracy. The measurements can be controlled from standard software like the

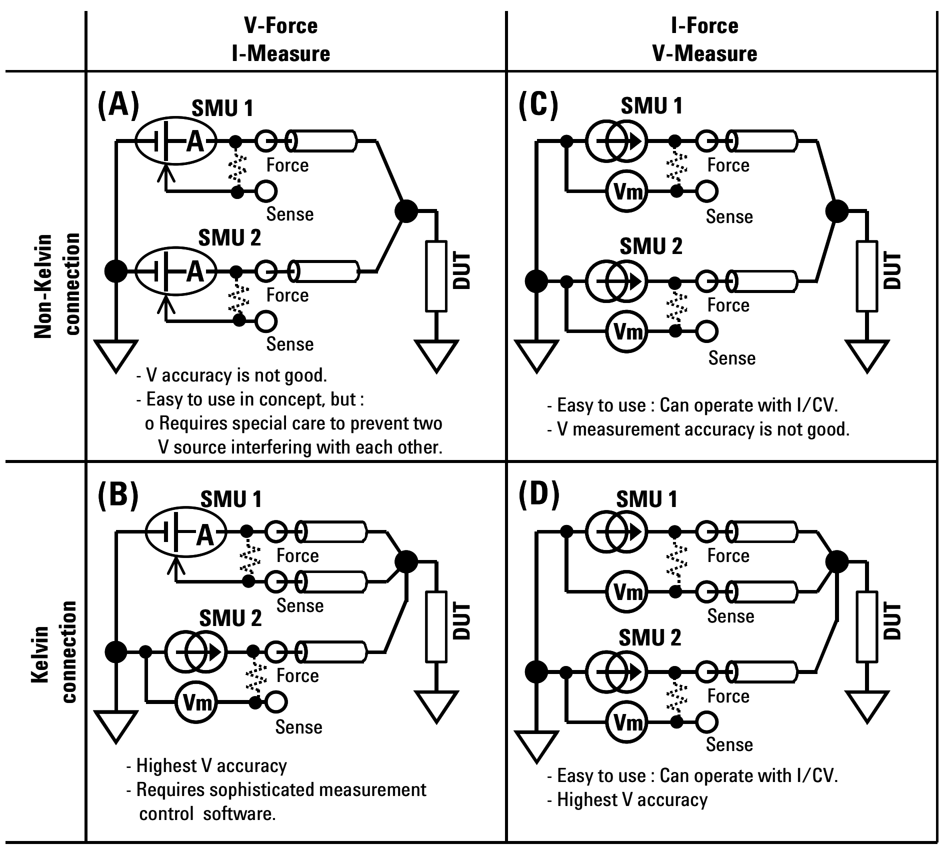


Figure 3. Basic configuration of parallel connected SMUs

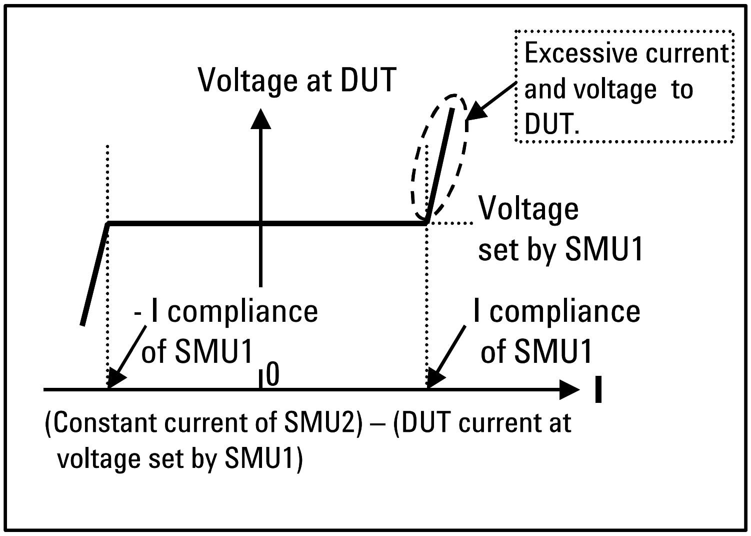


Figure 4. Constant current setting and DUT voltage

Agilent I/CV software without writing a special program code for ease of use.

Kelvin connection in Figure 3(B) provides the best accuracy in voltage force at the DUT, but it requires sophisticated control over the current output from SMU 2. SMU 2 infuses a constant current into the DUT in order to complement a current shortage from SMU 1. If the constant current from SMU 2 is larger than the compliance current of SMU 1 and if the constant current from SMU 2 minus the current flowing into the DUT at the voltage set by SMU 1 is larger than the current compliance of SMU 1, then the current from SMU 2 becomes excessive and flows into the DUT. This is the status where SMU 1 is driven into current force mode by exceeding the current compliance as illustrated in the circle of Figure 4. If excessive current flows to the DUT, then the voltage applied to the DUT exceeds the voltage set by SMU 1; this is not desirable. In order to avoid such a situation, a current from SMU 2 must be set intelligently to prevent excess current flowing into the DUT. For instance, a measurement control routine that has some prediction capability of the DUT current for setting the right constant current value and a feedback capability for adjusting the current source to a proper value is necessary.

The current force and voltage measure mode (I Force, V Measure) shown in Figures 3(C) and (D) are basically the same configuration for Kelvin or non-Kelvin configuration except for the point where the voltage sense is connected with the force line, i.e. inside a SMU (Figure 3(C) with high impedance resistor shown in dotted line) or at the DUT terminal (Figure 3(D) with sense cable from SMU 1). This is easier for controlling current force and voltage measurement mode than the other mode because you can set the current output from each SMU by halving the target current value.

Though the current source mode is easier for controlling the SMUs connected in parallel, it is less frequently used than voltage force mode. Therefore we'll discuss a little bit more about the behavior and the techniques of the voltage force mode when using multiple SMUs connected in parallel for providing better solution.

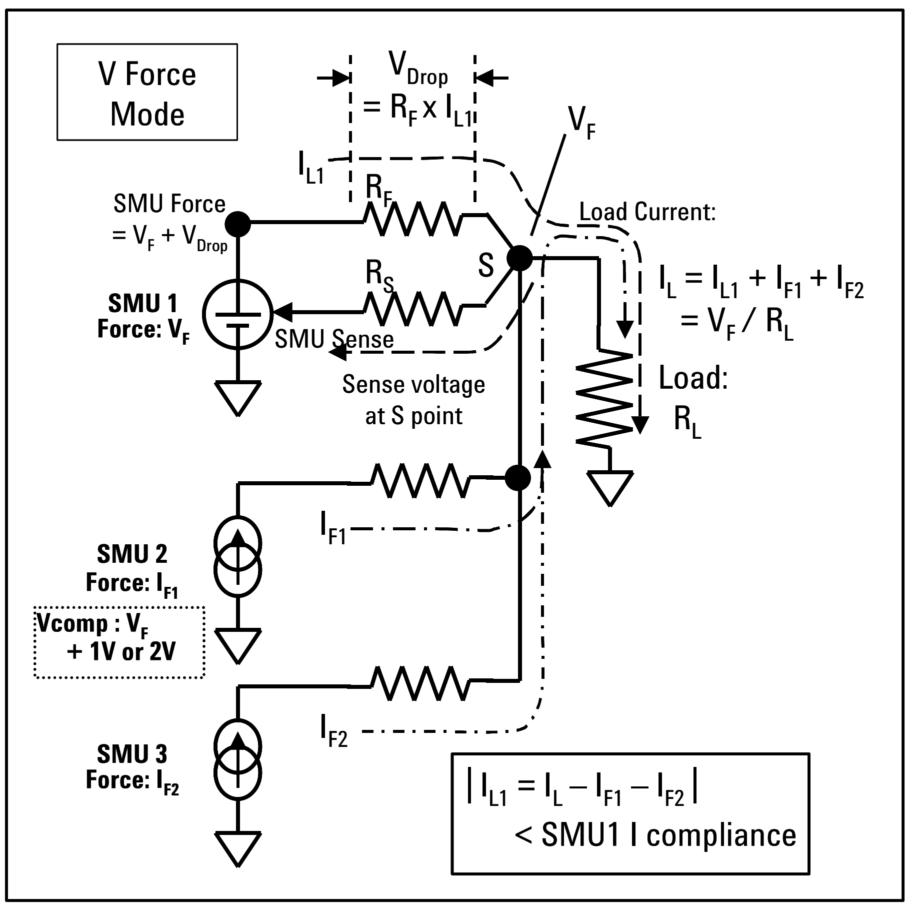


Figure 5. Parallel-SMU Force with Kelvin accuracy

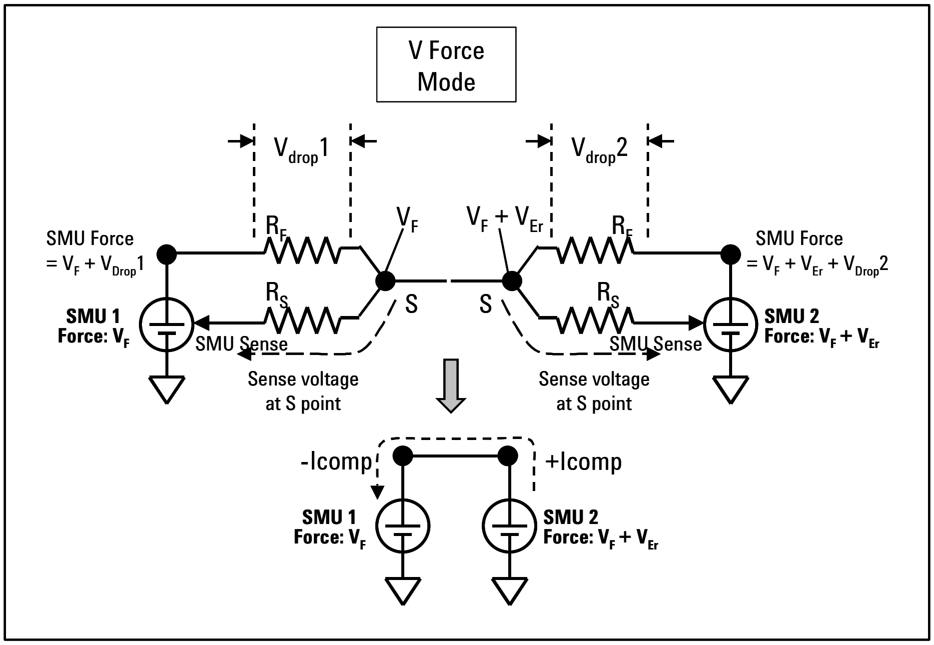


Figure 6. V-Force mode SMUs

Kelvin connection using Multi-SMUs in parallel under V force mode

Figure 5 is a more detailed breakdown schematic of Figure 3(B), in which three SMUs are connected in parallel. This approach provides the same voltage force accuracy of Kelvin connection shown in Figure 1 with increased current force and measuring capability. However the current source value must be set to satisfy the following relation:

$|I_{L1} = I_L - I_{F1} - I_{F2}| <$ "I compliance of SMU 1"

so that SMU 1 can complement or absorb any shortage or excessive current that is a difference between the current source from SMU 2, SMU 3 and the load current flowing to the DUT. Since the load current I_L varies by the force voltage applied to the DUT and the associated I-V characteristics of the DUT and the current is larger compared to the two SMU cases, this approach with three SMUs requires more care to set the right value for the current source of SMU 2 and SMU 3 than the two SMU case in Figure 3(B). The current source from two SMUs (or maximum three SMUs) easily drives SMU 1 in current compliance mode (refer Figure 4 by replacing "Constant current of SMU 2" to "Constant current of SMU 2 and SMU 3"); this must be avoided by using a control program.

The voltage applied to the DUT is set by SMU 1 while it operates in voltage mode. The voltage at the "S" point where the sense line is connected is fed back to SMU 1; SMU 1 provides just enough current to set the "S" point to the programmed voltage by handling all the factors of DUT current, current from the SMU 2, current from the SMU 3 and voltage drop by R_F x I_{L1} in the force line. There is no error associated with the residual resistance R_S in the sense line as already described.

It is advisable to set the voltage compliance of the current force SMUs to one or two volts above the V_F to avoid too high a voltage when SMU 1 is driven to current force mode, to prevent the DUT being damaged by excess voltage or power.

Why two voltage source SMUs cannot connect in parallel?

If two SMUs in voltage force mode with Kelvin connection could be connected easily in parallel as in the configuration in Figure 3(A), it would be beneficial for precision high current applications. However, they cannot be connected together.

Figure 6 shows such an example of connecting two SMUs together in voltage force mode with two sense lines connected at the DUT. The outputs of both SMUs are set to the same voltage V_F, but there is always a small difference in the output voltage; the error voltage is shown as V_{Er} in the example. Since the output resistance of the SMU in Kelvin connection is considered as zero ohm, when two outputs of SMUs are connected together as shown in the bottom view of Figure 6, a large current flows from one SMU to the other until one of the SMUs reaches its current compliance. This condition is unstable and it is not a desirable condition for SMUs. Therefore, the outputs of SMUs should not be connected in parallel in voltage force mode with Kelvin sense connection.

3. Parallel SMU Implementation using the Agilent E5270A

If used with the E5270A, the performance of voltage force mode shown in Figure 3(A) can be improved dramatically so that most semiconductor applications can be satisfied, i.e. high current force or sink capability of up to 4 amperes with reasonable accuracy and ease of use. The details of how to achieve this are introduced in this section.

Quasi-Kelvin Connection

As described, non-Kelvin connection results in a large voltage error in high current applications.

"Quasi-Kelvin connection" (Figure 7) combines the accuracy of Kelvin connection and the ease-of-use of non-Kelvin configuration.

- Accurate :
  As seen in the figure, the Kelvin connection is routed to a very close point to the load and then a small resistor R_Q is inserted between the load and the point where sense and force lines are connected. Since the exact voltage V_F is forced at the sense point that is very close to the load, and an accurate voltage V_F is applied through a very small resistor R_Q to the load, the voltage at the load is very accurate because of the very small voltage drop by R_Q.
- Simple :
  Since both SMUs operate in voltage mode, measurement is performed by setting both SMUs to the same voltage, measuring current at both SMUs and then adding them to get the total current. Therefore, no special care is required to control the measurements. Measurement can be done without special programming code and normal equipment control program such as the Agilent I/CV software can be used.

With the Agilent E5270A, this configuration provides easy measurements, good accuracy and short measurement time, with a small voltage drop at the DUT. If your application allows a voltage drop of about 10 mV at full current condition, then this Quasi-Kelvin connection is recommended.

With this approach, you can measure your device by simply using the Agilent I/CV software without any special program code.

The following describes the basic idea of quasi-Kelvin connection approach shown in Figure 7. In quasi-Kelvin connection, the triaxial SMU cables are routed to a very close point of the DUT, and the Kelvin sense connection is made that point. Then, a small resistance R_Q (R_{Q1} ,R_{Q2}) that limits an infinite current to flow (actually the current is limited by current compliance) between SMUs is added between the Kelvin sense point and the DUT. The series resistance R_Q is chosen to satisfy two conditions, (1) eliminating excessive current to flow, (2) not generating significant error.

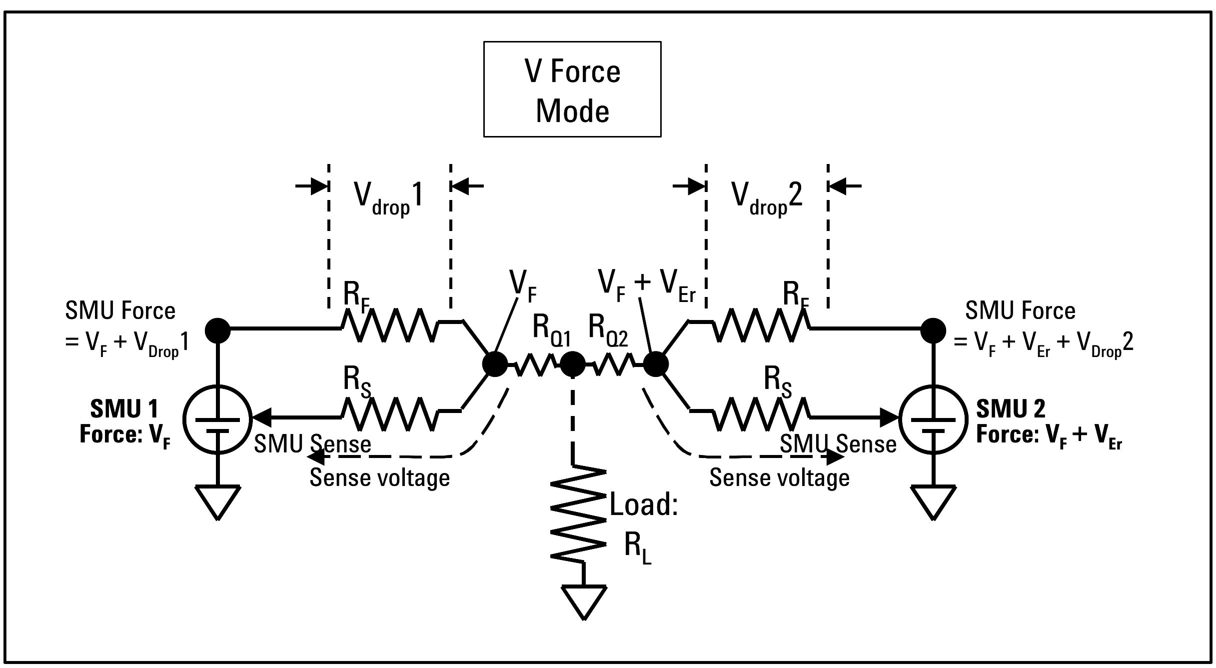


Figure 7. Quasi-Kelvin connection with two SMUs in parallel

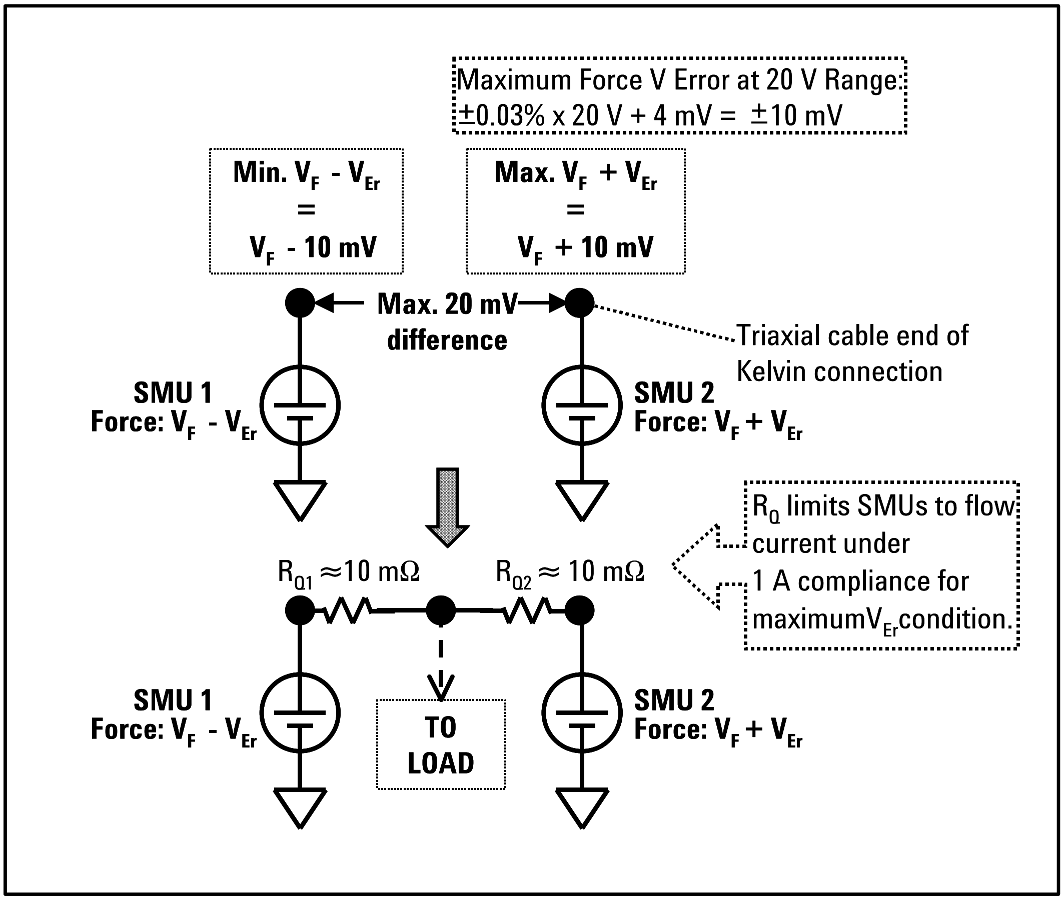


Figure 8. How to set R_Q in Quasi-Kelvin connection

How to set series resistance R_Q

Figure 8 shows how the series resistance R_Q is determined. In the example, a 20 V range is chosen because it is the maximum voltage range that can output 1 A current from the HPSMU. The maximum output voltage error in the 20 V range of the E5270A is within +/- 10 mV, and therefore the maximum difference in the output voltage between any SMU is within 20 mV if a same force voltage is set in the 2 V or 20 V range. Since the maximum output current of the SMU is 1 A, the series resistance between two SMUs can be chosen as 20 mΩ (= 20 mV/ 1 A) to limit the maximum current flowing between SMUs to less than the maximum current compliance of the HPSMU.

In the actual test environment, the offset voltage between any SMU can be considered less than 20 mV with enough margin if used under one Agilent E5270A mainframe. Therefore, 20 mΩ resistance is considered large enough to limit the maximum current flowing between the SMUs to less than 1 A compliance.

The R_Q value is 10 mΩ if two SMUs are connected in parallel as shown in the bottom of Figure 8. It becomes 13 mΩ for three SMUs and 15 mΩ for four SMUs parallel configuration if the worst-case resistance is calculated as described here, but 10 mΩ should be a good value for R_Q in the actual test environment. The resistance of a 10 cm wire is about 10 mΩ as shown in Figure 9, and this is the recommendation for inserting a 10 mΩ resistor in the measurement setup.

Error associated with Quasi-Kelvin connection

Figure 10 shows the error introduced by adding R_Q. V_F is a set voltage and V_L is the actual voltage that appears at the load terminal. Using the relation of V_F and V_L of the equation in the figure, the error $V_L/V_F=(1 - R_Q/2R_L)$ for two SMUs connected in parallel or $V_L/V_F=(1 - R_Q/n^*R_L)$, where n is the number of SMUs connected in parallel.

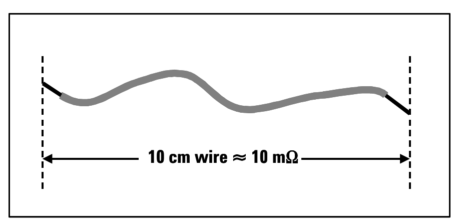
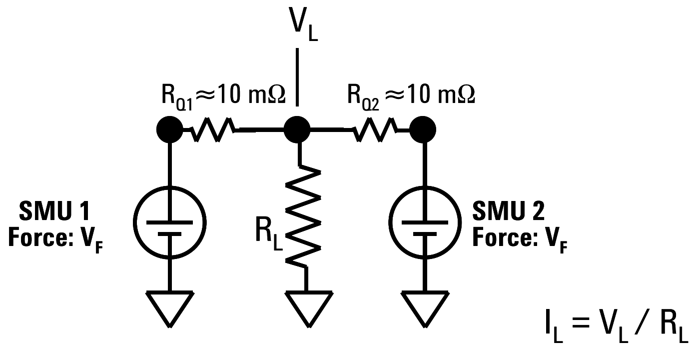


Figure 9. 10 mΩ resistance

For example if R_L>= 1 Ω and R_Q=10 mΩ, then about 0.5 % accuracy or better, or always less than 10 mV error can be achieved.



$$V_L = V_F \bullet \frac{1}{1 + \frac{R_{Q1} \bullet R_{Q2}}{R_L(R_{Q1} + R_{Q2})}}$$

Assuming $R_{Q1} = R_{Q2} = R_Q$

$$= V_F \bullet \frac{1}{1 + \frac{R_Q}{2 \bullet R_L}}$$

Assuming $R_Q << R_L$

$$\approx V_F \bullet \left(1 - \frac{R_Q}{2 \bullet R_L}\right)$$

Error is $R_Q/2R_L$ x 100 (%)

If R_L ≈1 Ω, then error is less than 0.5% (= 0.01/2 x 100) of V_f. This satisfies majority of accuracy requirements in high power applications.

Figure 10. Error introduced by R_Q in Quasi-Kelvin connection

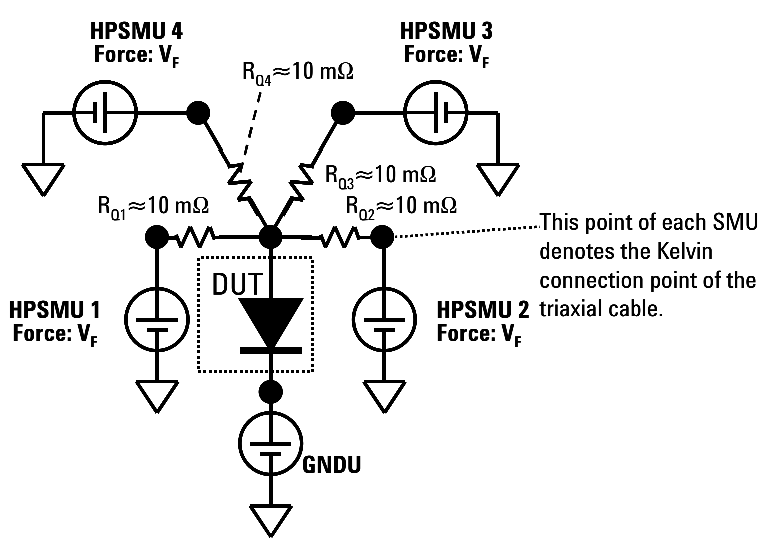


Figure 11. 4 A configuration of Quasi-Kelvin connection

Example results

Figure 11 is an example of 4 A configuration with four HPSMUs. The four force cables from the HPSMU output are routed to a close point of the DUT and each sense line is connected with the force line at the end of the triaxial cable in order to form the Kelvin connection to eliminate any residual resistance of the SMU and triaxial cable. Then a wire about 10 cm long, that is about 10 mΩ, from each Kelvin connection point to the DUT is used for connecting to the DUT as shown in the figure.

Figure 12 shows the current versus voltage curve of the power diode measured using the Agilent I/CV software with the configuration of Figure 11. The cursor reading shows 4.0001 A at 0.910 V on the measurement curve where the current reaches 4 A compliance.

The summation of the current of four HPSMUs is made using the transform editor of the Agilent I/CV software as shown in Figure 13.

4. Advanced Technique

Multi-channel sweep for Parallel SMU connection

This approach with SMUs connected in parallel is only possible if used with the multi-channel sweep and simultaneous measurement capability of the Agilent E5270 series instruments. The current measurements are made simultaneously at all SMU channels, and there is no error associated with the drift or noise of the DUT, HPSMU, Agilent E5270A mainframe or stability of the 10 mΩ resistor /wire which eliminates excessive current flowing between SMUs. If the current measurement is performed sequentially and there is any drift in the above components while the measurement is performed, then a relatively large drift current may appear between the SMUs in the measurements. This drift may appear as large noise or error after the summation of the measured current. In this case, the series resistance R_Q may need to be increased until the measurement becomes stable.

Each SMU in the E5270 series contains a high-speed analog to digital converter (HSADC) that measures current or voltage. If used with the HSADC and fixed range setting, then the measurement of each SMU in a sweep output is made synchronously and simultaneously as shown in Figure 14 for up to eight SMUs in one Agilent E5270A mainframe. Since measurements are performed simultaneously, the measurement can be a few times faster than the sequential measurement mode for applications that takes a long integration time such as more than one power line cycle (PLC) averaging mode.

Eliminate device heat-up and pulsed sweep

High power measurements easily heat up the DUT owing to the self Joule heating effect caused by the voltage and current applied from

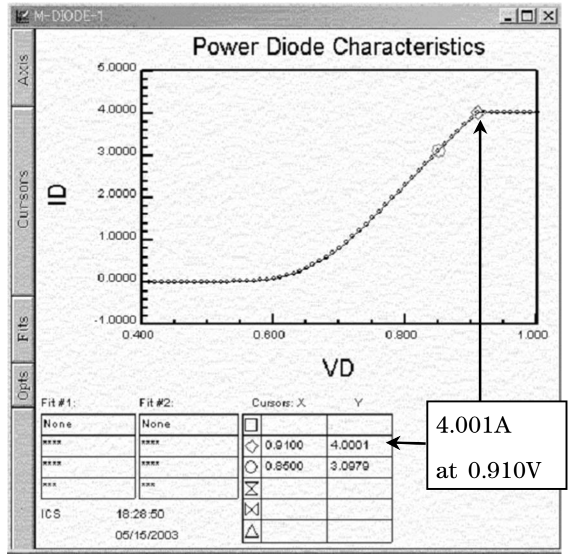


Figure 12. Power Diode measurements using the Agilent I/CV software

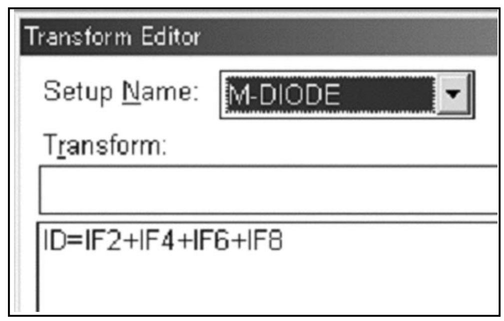


Figure 13. I/CV Transform Editor: Summation of current from four HPSMU

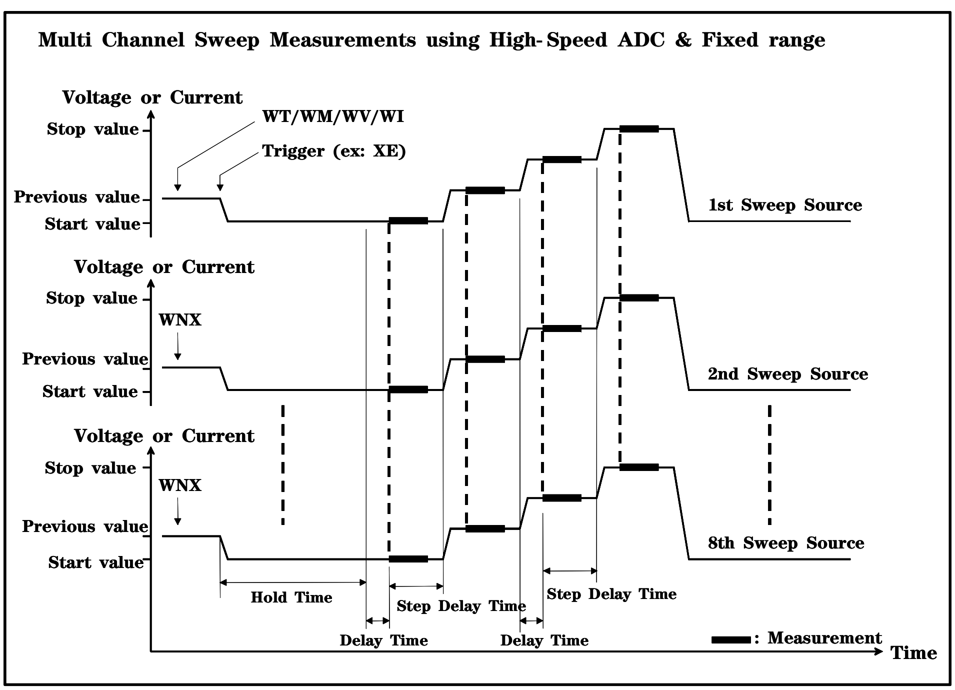


Figure 14. Multi channel simultaneous sweep measurements

the SMU, so measurement results may be different from the expected value. There are typically two approaches for reducing the heat-up of the device and consequently the associated error by self Joule heating. One is to finish the measurements in a short time, and the other is to use pulsed measurements. Pulsed measurements typically provide better results if the device parameter is highly sensitive to the device temperature, though it takes a longer total measurement time.

The multi-channel sweep with simultaneous measurement of the E5270A can minimize the measurement time and also reduce the heat-up of the DUT.

The E5270A can also output a multi-channel spot pulse and perform simultaneous measurements for up to eight channel SMUs. These measurements require a sophisticated test program if sweep measurements are to be made, but it provides accurate results by reducing the error caused by self-heating of the DUT. The minimum pulse width is about 1.5 milli-seconds in voltage force mode of the higher current range. An example wave shape of 10 V pulse of multi-channel pulse under three HPSMUs connected in parallel is shown in Figure 15. About 2 A currents from the three HPSMUs are measured simultaneously in the pulse period.

Example of results

Figure 16 shows the Vd versus Id curve of the power FET measured by using the Agilent I/CV software under Quasi-Kelvin connection. It connects three HPSMUs in parallel to drain, one MPSMU to gate and the GNDU to source. The drain voltage Vds is swept from 0 to 5 V and drain current Id is measured for each gate bias step. Maximum drain current is about three amperes.

Figure 17 is an example of a Gummel plot of a bipolar power transistor using the Quasi-Kelvin method. The measurement is made with three HPSMUs connected in parallel for a collector with a 1 A fixed range and one MPSMU connected to the base with Kelvin connection. The measurement was made using a program, but it also can be done using the Agilent I/CV software. Since it uses a 1 A fixed range, the minimum current resolution is limited to 50 μA. A special note in this example is that the minimum resolution of the 1 A range of the HPSMU is stably achieved even when three HPSMUs are connected in parallel; this is a good demonstration of the stability of the E5270A in this application.

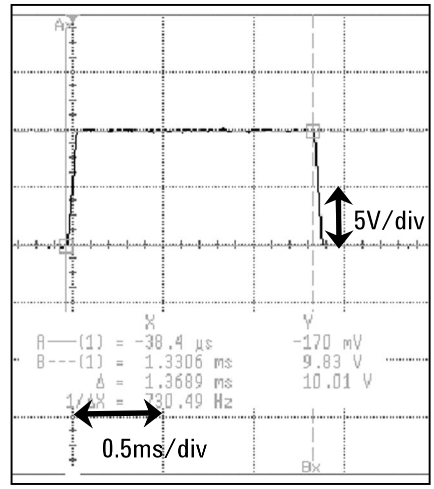
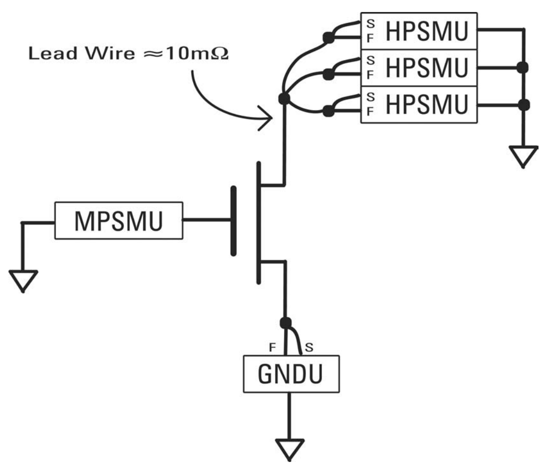


Figure 15. 10 V pulse shape in multi-channel pulsed measurements



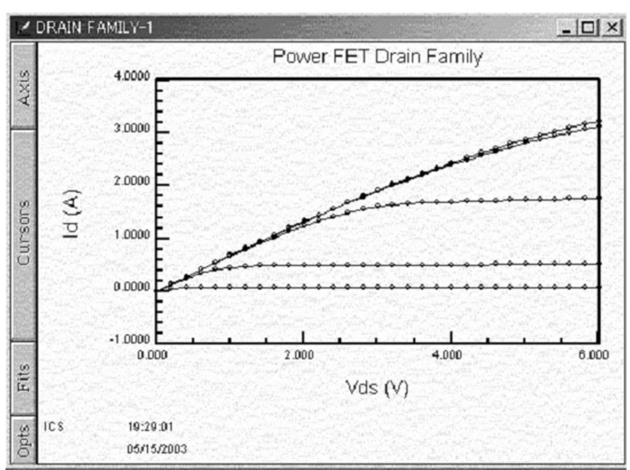


Figure 16. Power FET Id-Vg characteristics measured with Agilent I/CV software

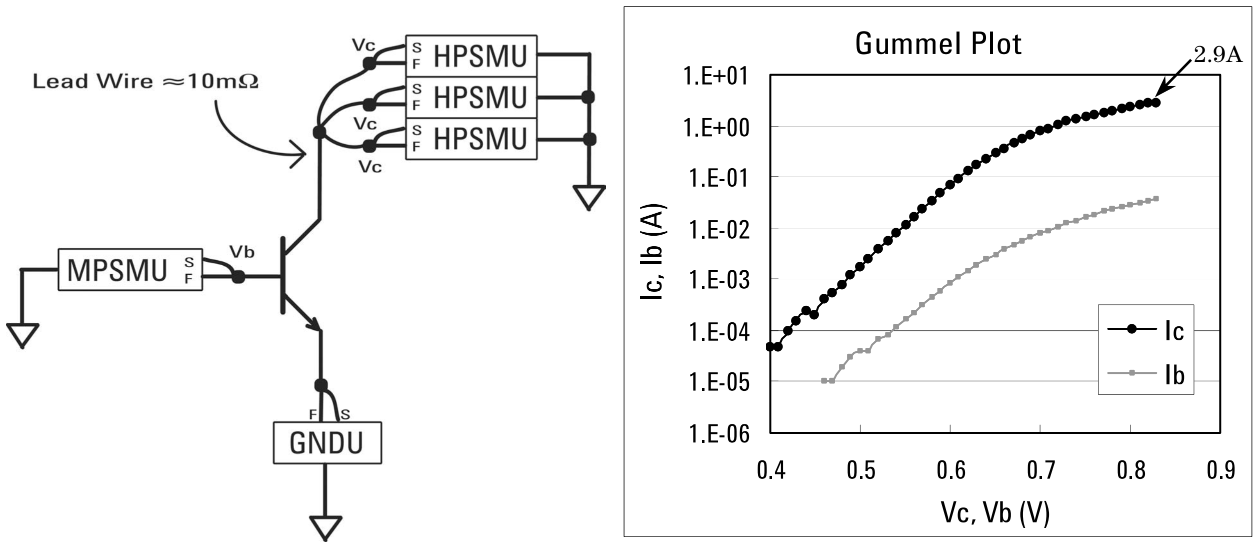


Figure 17. Gummel plot curve with Quasi-Kelvin connection

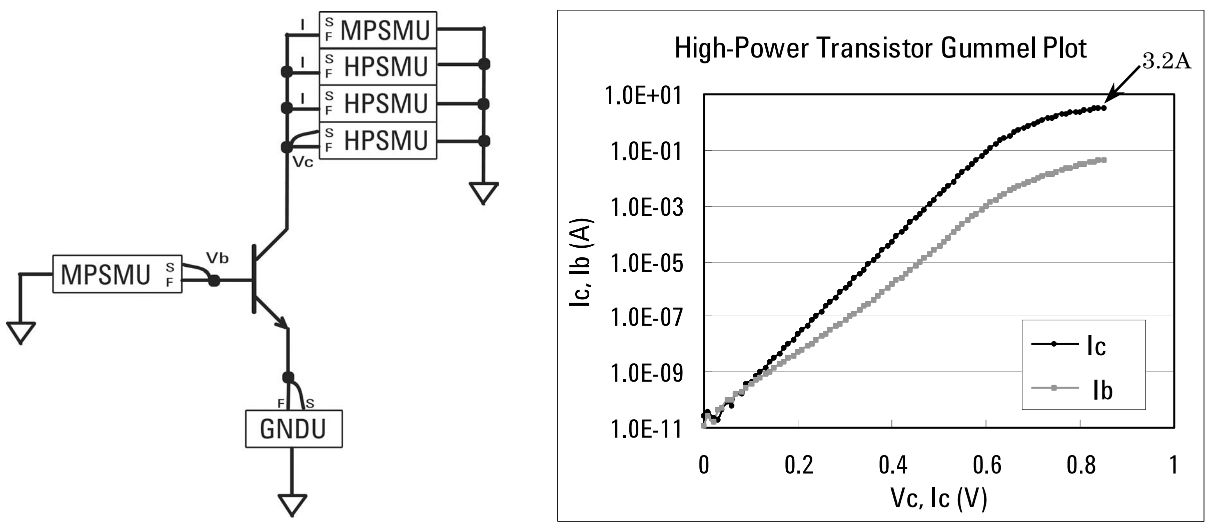


Figure 18. Pulsed Gummel plot measurements with Kelvin connection and current offset

Figure 18 is another example of a Gummel plot using the configuration of Figure 3(B), the parallel SMUs with Kelvin connection. The measurement was made using pulsed sweep by changing the configuration of the collector SMU from one SMU (V force mode, auto ranging) to four SMUs (three HPSMUs plus one MPSMU, and maximum drain current up to 3.2 A), and measurements are controlled by using a program.

The Gummel curve is measured in a wide range from 10 pA to 3.2 A in the example. The results indicate that the measurement is suitable for very accurate devise characterization. This example provides the E5270A's full accuracy from low current to high current with the voltage accuracy that meets the specification under the Kelvin connection. The pulse capability reduces the drift of the device parameter caused by Joule heating and enhances the total measurement accuracy. A simple program can easily expand the measurement range from low current to over 1 A high current using the E5270A's new capability.

Conclusion

For increasing SMU output current beyond the 1A limit by one SMU, connecting multiple SMUs in parallel is effective, and can increase the current output capability up to 4 A. In the most widely used V force measurements, there are two configurations for connecting SMUs in parallel while maintaining satisfactory accuracy.

One approach introduced is Quasi-Kelvin connection and the other method is Kelvin connection with constant current offset. The newly introduced Quasi-Kelvin connection can be safely achieved by using only the parallel measurement capability of the Agilent E5270A Parametric Measurement Mainframe.

The features of both methods are summarized next.

Common features:

- ❑ Agilent E5270A can expand maximum current output to 4 A using four HPSMUs.
- ❑ Accurate results can be obtained by the test performed in a short time using the multi-channel simultaneous measurements.
- ❑ Enhanced measurement accuracy using short pulse (1.5 ms) is possible by reducing parameter drift caused by devise heat-up due to self Joule heating.
  Pulsed sweep measurements require a test program.

Features of Quasi-Kelvin connection:

Pros	Cons
Ease of use :	Moderate accuracy:
- No programming required for measurements (i.e. measurement is made with the Agilent I/CV software)	- There is about 10 mV voltage drop per 1 A output /SMU, but this satisfies most accuracy requirements in semiconductor parametric applications.

Kelvin connection with constant current offset

Pros	Cons
Highest accuracy:	Control software:
- Accurate measurements by configuring Kelvin connection at the DUT terminal or socket can be achieved.	- Sophisticated control software is necessary for setting the proper current source value and for controlling the test sequence.

The sample setup file used for the Agilent I/CV software and sample program list for Gummel plot with Kelvin connection used in this application note are available from the following Agilent WEB site.

To find them, go to "http://www.agilent.com/see/parametric" and see “E5270 Series" and “Software, Firmware & Drivers”.

For more information about Agilent and its product, go to www.agilent.com.

For more information about Agilent Technologies semiconductor test products, applications, and services, visit our website: **www.agilent.com/go/semiconductor** or you can call one of the centers listed and ask to speak with a semiconductor test sales representative.

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