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Tips, Tricks, and Traps for Advanced SMU DC Measurements

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In most applications, an SMU (source-measure unit or SourceMeter® instrument) simply gives an accurate answer all the time. Here's how to make sure it does every time.

AN SMU will normally, give an accurate measurement, but sometimes errors can creep in, and special methods are needed to overcome them. This article shows how to do some advanced measurements that may require more features than normally used. The measurement problems covered are common to all SMU users, but some of the solutions are unique to Keithley SMUs.

Understanding an SMU

An SMU is actually four instruments in one: a precision voltage source, a precision current source, a voltmeter, and an ammeter. SMUs are used in semiconductor device testing, optoelectronic test, materials research, and even as general lab instruments. In ***Figure 1*** the source block represents both the voltage source and current source capability. In reality, an SMU is always acting as both a voltage source and a current source.

The $V_{measure}$ circle represents the built-in voltmeter capability. Note that the voltmeter gives feedback to the source block, which means that it can be used to control it. The $I_{measure}$ circle represents the built-in ammeter, and it, too, can control the source block.

The voltage and current output go between the Force terminal and the Common terminal. By Kirchoff's loop rule, all current flowing out of the Force terminal must flow into the Common terminal. The return path is normally direct, although in some cases another SMU can act as the return path.

Note the Sense and Sense Lo terminals. These special high-impedance terminals are used to more accurately sense voltage at the DUT (device under test), and no current flows in them. They are used only where extreme accuracy is needed, or in some special applications.

Interpreting published specifications

It's important to understand both the source and measure specifications, because they have a large impact on many measurements. ***Table 1*** gives partial specifications for the Keithley model 4210-SMU found in the 4200-SCS Semiconductor Characterization System. Most of the examples in this article are affected by one or more of these specifications.

Note the 20V specification. The *Compliance* is 1A, which is the maximum current the instrument can supply on that range. The

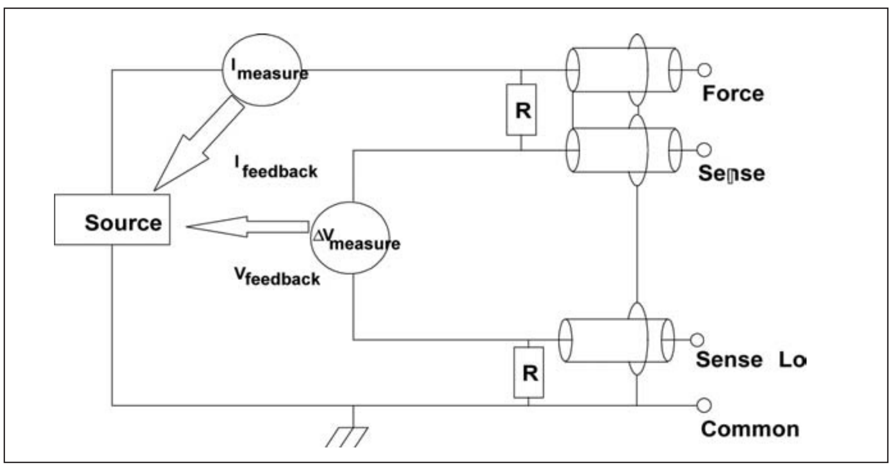

Figure. 1: An SMU includes a precision voltage source and a precision current source (shown here as one block), a voltmeter, and an ammeter.

Range	Compliance	Measure Resolution	Measure Accuracy	Source Resolution	Source Accuracy
20 V	1.05 A	20 µV	0.01% + 1 mV	500 µV	0.02% + 1.5 mV
1 A	21 V	1 µA	0.1% + 200 µA	50 µA	0.1% + 350 µA

Table 1: Typical Specifications for the SMUs in the Model 4200-SCS

Measure Resolution gives the smallest change the voltmeter can detect on the range stated—in this case, 20μV, or seven digits of resolution.

Measure Accuracy refers, again, to voltage measurement. The first number, 0.01% is the *gain* number; multiply it by the reading to get the error. For example, in measuring 20V the gain accuracy would give a 2mV uncertainly. The second number, offset, normally dominates when making measurements near zero. For example, measuring 0V on this range would give an uncertainty of 1mV.

The *Source Resolution* refers the instrument's ability to act as a voltage source. It's the smallest change that can be sourced out of the Force terminal. Note that the Source Resolution is 500μV, compared to the 20μV for Measure Resolution; as a general rule, an SMU can measure about ten times better than it can source. All sourcing resolution is limited by that 500μV resolution. For example, sourcing 2.80005V would not be a problem, but trying to source 2.80004V wouldn't work; it would be rounded to the nearest 500μV.

The *Source Accuracy* is related to how close to an exact real voltage can appear at the Force terminal. As with the Measure specification, the first number is called the gain number and is multiplied by the total output voltage. If we wanted to source, for example, 20V, we would have about a 4mV accuracy. The offset number has the greatest impact near zero volts. Setting the output to 0V on the 20V range, for example, could result in as much as 1.5mV at the output.

Looking at *Table 2*, if a user set an SMU to output 3.0005V, the actual output would be somewhere between the minimum and maximum specifications. If the user then set the SMU to output 3.001V, the output voltage would again be between the minimum and maximum specification. But since the step from 3.0005V to 3.001V is within the error band (the maximum specification for 3.0005V is more than the minimum specification for 3.001V), the output, instead of increasing by 500μV, could actually decrease by 3.7mV. In reality, this seldom happens, because offset, which creates this inaccuracy, is normally constant from one step to the next.

Table 2: The effect of SMU source accuracy

Desired Output (V)	Minimum Spec. (V)	Maximum Spec. (V)
3.0005	2.9984	3.0026
3.0010	2.9989	3.0031

Source accuracy example: MOSFET transconductance measurement

Figure 2 shows the effect of source accuracy. Here we use a Model 4200-SCS to determine the transconductance of a MOSFET by sweeping the gate voltage in 2mV steps while measuring the resulting drain current. The transconductance is derived by taking the differential of the drain current with respect to the gate voltage, dIdrain/dVgate. The differential calculation of transconductance is a very good test of an instrument, because it will magnify any errors and noise. Notice the periodic bumps in the transconductance (red) curve. Where did they come from? ***Figure 3*** shows the changes in drain current and gate voltage. The plot of changes in drain current contains small bumps, while gate voltage seems to be a perfect 2mV step. Why are there bumps in the drain current when there are none in the gate voltage?

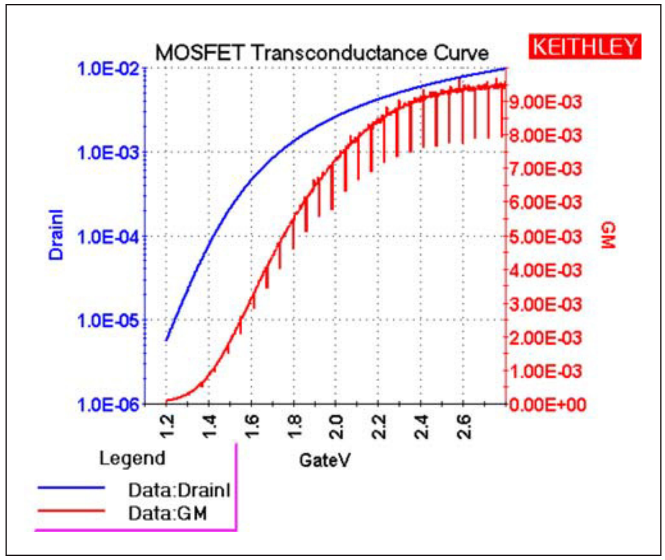

Figure 2: MOSFET drain current (blue) and transconductance (red) curves obtained by increasing the gate voltage in 2mV steps. Note the errors in the transconductance.

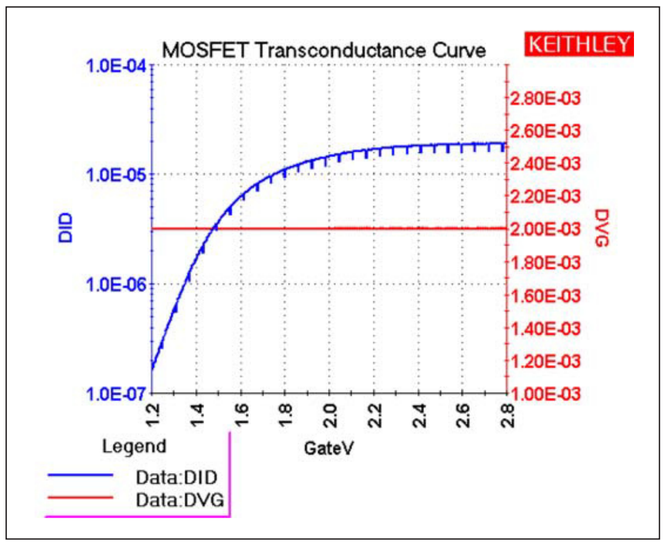

Figure 3: Looking at changes in drain current shows errors.

Figure 4 shows the same test again, but with the SMU set to measure the gate voltage. Remember the SMU can measure about ten times more accurately than it can source. Here we see 300μV bumps in the gate voltage, corresponding to the bumps in the drain current. This is more than 10× the source accuracy of the Model 4200-SCS, but by measuring we were able to detect it. If we now differentiate the drain current with respect to gate voltage, we get the curves in ***Figure 5***. With an accurate measurement of source voltage, we get a good and reliable transconductance measurement. To sum up: When you see an obviously strange measurement result on an SMU, review the instrument's specifications closely.

Floating SMU for more source accuracy

Another way to improve the source accuracy of an SMU is to use the Sense Lo terminal (***Figure 1***), which acts as a reference point for all voltage measurements and sourcing on the SMU. The SMU floats

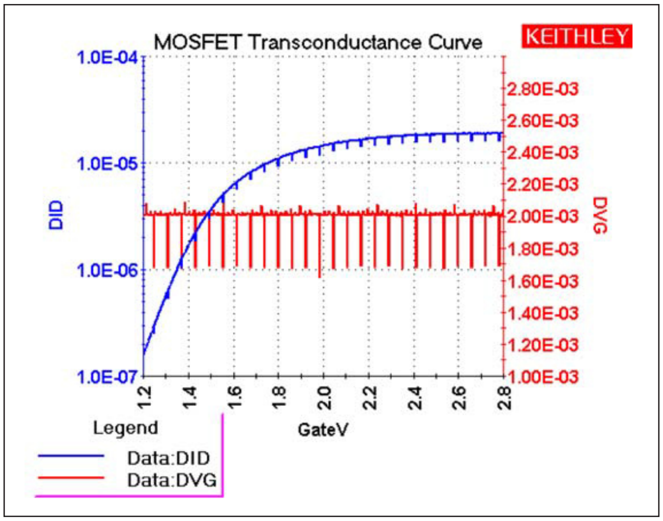

Figure 4: Measuring gate voltage with the SMU's voltmeter function reveals the cause of the problem: 300μV errors in the gate voltage.

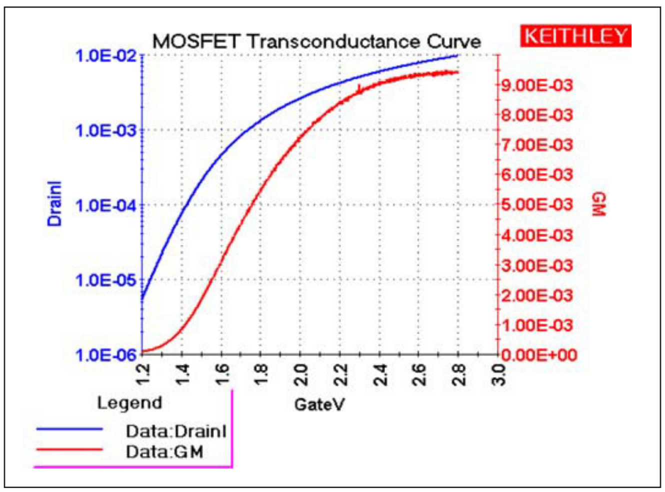

Figure 5: Differentiating the drain current with respect to the gate voltage gives an accurate result.

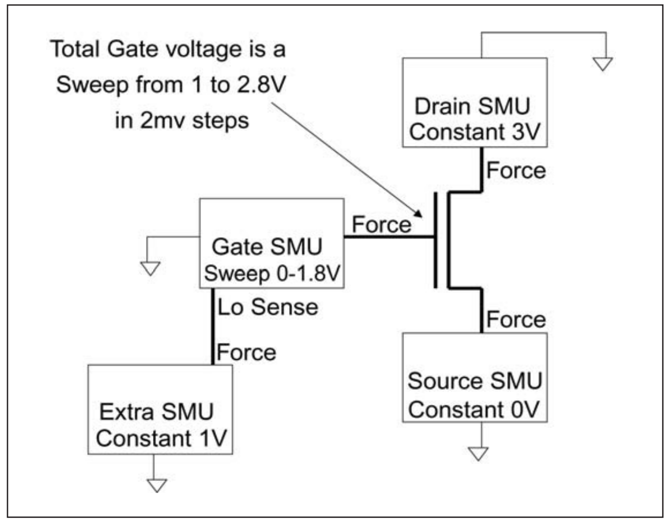

Figure 6: Using a second SMU to float the first SMU 1V above ground makes it possible to use the 2V range, cutting the 300mV gate voltage error to 50mV.

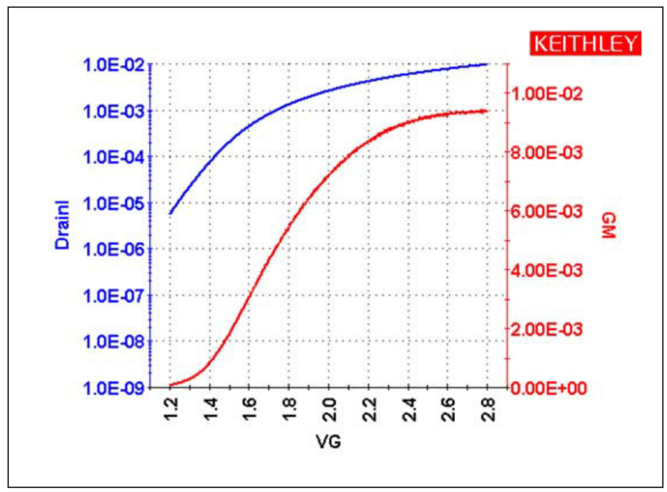

Figure 7: Floating the gate SMU on top of an extra SMU makes it possible to use the 2V range, reducing gate voltage error for error-free results.

on top of the Sense Lo terminal. This gives several opportunities. If, for example, one put a 1V battery between the Sense Lo terminal and Common, the entire SMU would float 1V above the Common—which leads to a way to get more accuracy. Remember in the previous examples, we were trying to make a 2mV step while the SMU was on a 20V range. We needed the 20V range because the highest voltage used in the application was 3V. If we could use the 2V range, we would have ten times the source resolution—50μV—and avoid the 300μV error. We do that by raising the Sense Lo terminal above the Common—not with a battery, but with another SMU set to 1V (***Figure 6***). Then we set the first SMU to sweep from 0 to 1.8V. The total sweep is still 1 to 2.8V in 2mV steps, but the gate SMU never needs to produce more than 2V, and the steps are very accurate. The resulting transconductance curves are shown in ***Figure 7***.

The SMU as an ideal voltmeter

An ideal voltmeter has infinite input impedance (defined as many orders of magnitude more than the impedance of what's being measured). It draws no current from the circuit being measured, and does not load it down.

To make an SMU into an ideal voltmeter, configure it as a current source, and set the current level to zero. No current can then flow into or out of the terminal, so it has effectively infinite impedance. In practice, the impedance is about 1 million divided by the full-scale current. For example, if the full scale current were set to 1μA, the unit's input impedance would be about $1\times10^{12}\Omega$. If full scale current were set at 1pA, the input impedance would be about $1\times10^{16}\Omega$. Another key characteristic of an ideal voltmeter is its offset current, which is the current the voltmeter itself generates. The example in ***Figure 8*** shows how both the input impedance and the offset current can cause a problem. ***Figure 8*** shows a high-impedance source: a 1V source in series with a 1GΩ resistance. Ideally, the SMU voltmeter should measure exactly 1V. Setting an SMU to act as a voltmeter normally causes it to act as a current source with zero amps output on

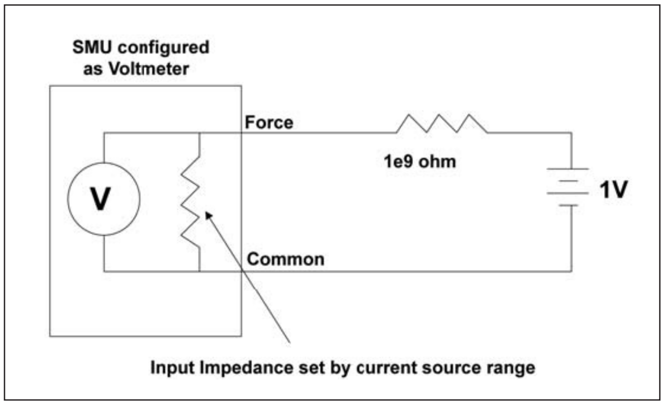

Figure 8: The input impedance of an SMU configured as a voltmeter is the reciprocal of the current range.

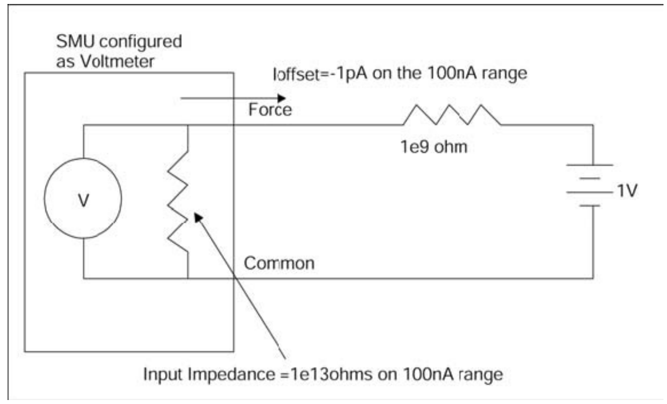

Figure 10: Setting the SMU correctly gives 10GΩ input impedance and –1pA offset current.

the 100nA range. For this example, however, we override the normal settings and put the SMU on the 1mA range (***Figure 9***). This gives an input impedance of 10^7Ω, which is two orders of magnitude less than the impedance of the source we want to measure and loads down the circuit to give a reading of 10mV instead of 1V.

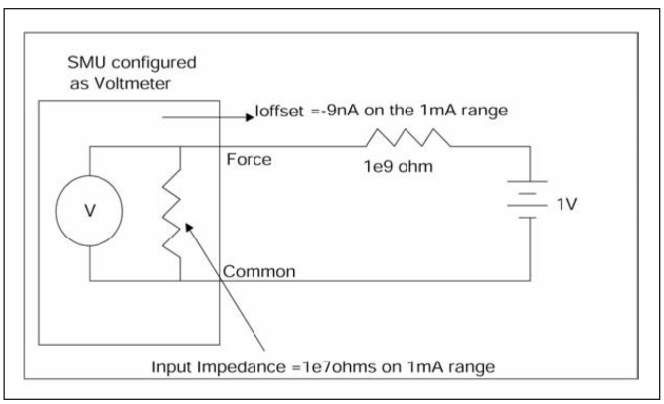

Figure 9: Mis-settting the current range to 1mA gives an input impedance of 10MΩ, which loads down the circuit under test. In addition, it allows a –9nA offset current.

But there's an even worse problem: the SMU's offset current. On the 1mA range the offset current specification for the Model 4200-SCS is 150nA. We measured it for this experiment, telling the SMU to measure its own offset current, and got –9nA, which is considerably better, but -9nA through a 1GΩ resistance gives about 8V, so the SMU terminal would attempt to float to 8V. In reality, the SMU floated to –2V, because of the range to which it was set, and clamped there.

Figure 10 shows the experiment repeated, this time letting the SMU set itself as it normally would: As a current source set to zero amps on the 100nA range. Now the input impedance is four orders of magnitude greater than that of the source, so we should get a good measurement without loading down the circuit. In addition, the offset current on the 100nA range is less than 1pA. So we get an accurate measurement of the battery voltage.

Floating differential voltmeter

An SMU can act as a floating differential voltmeter by making use of the Sense Lo terminal. A floating differential voltmeter can be five to ten times more accurate and more sensitive than a standard voltmeter. In addition, it can often take the place of two standard voltmeters and be easier to use as well.

In the previous example, we used the Source and Common terminals. Here we will use the Sense and Sense Lo terminals. ***Figure 11*** shows a string of three 20Ω resistors, with a 3V battery at the top and a 2V battery at the bottom, so the whole string is floating 2V above ground. We wish to measure the voltage across the resistors, but not change the current through them. A standard voltmeter, referenced to common, would not be suitable—we need a floating differential voltmeter. We set an SMU to be a voltmeter—a current source set to zero, on the 100nA range. We can set the SMU to the 2V range, whereas if we used a standard voltmeter we would have to use a 20V or 30V range, which would hurt accuracy and cause problems with offset current, as in the previous example.

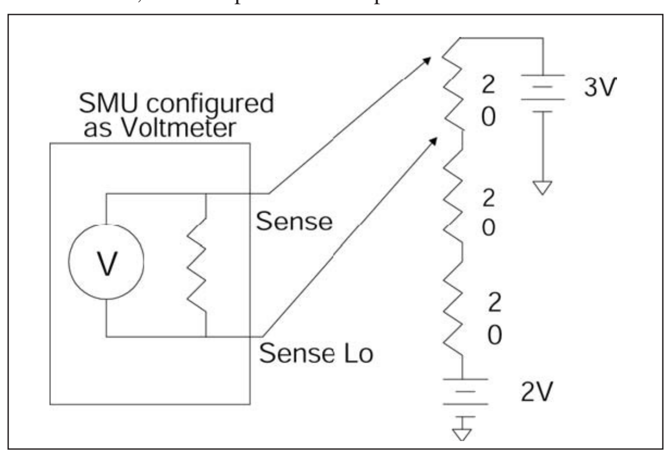

Figure 11: Measuring the voltages across these resistors is best done with a floating differential voltmeter

A word of warning here: The Sense Lo terminal on this particular SMU has about 100 kΩ of input impedance, and sometimes that affects the accuracy of the measurement.

Table 3 shows the result of the measurement. Notice it was possible to measure the actual resistor values with great accuracy because the instrument was on the 2V range and thus had an accuracy of better than 150μV.

Node	Voltage measured	Actual resistor value
Resistor 1	334.04mV	20.04 Ω
Resistor 2	334.75mV	20.08 Ω
Resistor 3	336.40mV	20.18 Ω

Table 3: Actual node voltages and resistance values measured

The SMU as an ideal ammeter

An ideal ammeter should have zero input impedance—or at least many orders of magnitude less than the circuit being measured. An SMU will act as an ideal ammeter if it is programmed to act as a voltage source set to zero volts. It will then try to hold zero volts at its terminals, and will measure all current that flows in or out. The input impedance of a Model 4200-SCS in this configuration is about 1 divided by the current range in µA. For example, on the 1µA range, the input impedance is about 1Ω.

An ideal ammeter has low offset voltage, which is voltage that the ammeter itself generates. An SMU can add or subtract voltages to compensate for any offset voltage. In fact, if we use the Sense terminal we can sense the voltage on the device and compensate for any voltage drop in the probes or test leads. ***Figure 12*** shows a large MOSFET; we want to measure the characteristics of the drain. We've added a 10Ω resistor in series with the source in order to simulate excessive test probe resistance. This resistor will add an extra voltage burden on the source terminal and allow the transistor to float a little above ground.

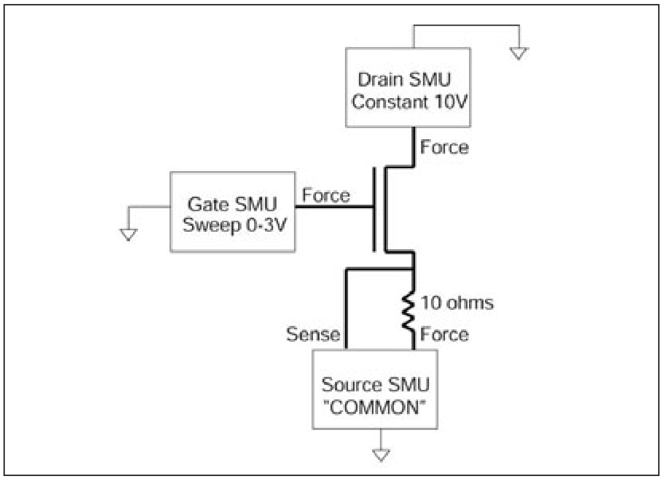

Figure 12: Connecting the SMU as shown can compensate for the drop across the source resistor.

We'll connect an SMU as an ammeter to the source terminal and measure the transfer characteristics of the transistor twice—once with the Sense terminal of the SMU disconnected (blue curve in ***Figure 13***), and once with it connected (red curve). The red curve shows more current flow, because the voltage on the source terminal rises above the common depending upon how much drain current is flowing, which reduces the gate-to-source voltage. The red curve, then, is accurate, while the blue is inaccurate.

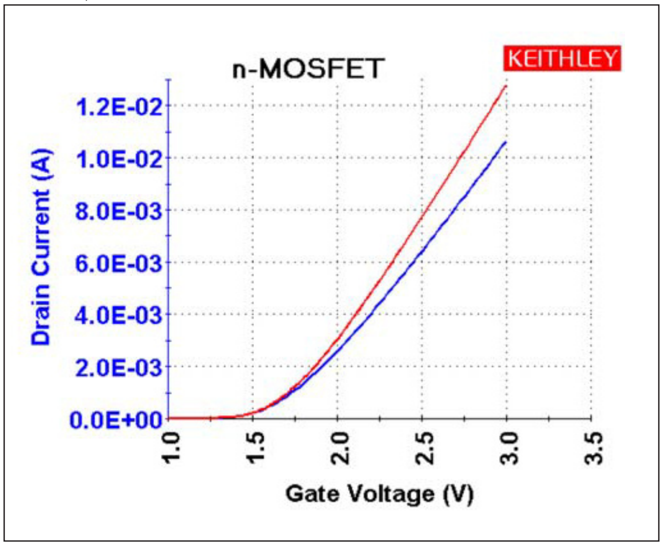

Figure 13: Connecting the SMU's Sense lead as shown in Figure 12 corrects the error.

Conclusions

There are many possible sources of error in precision measurement. By applying the methods outlined here, you should be able to avoid many of them. KEITHLEY

About the Author

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