KEITHLEY

Application Note Series

Number 2241

Making Ultra-Low Current Measurements with the Low-Noise Model 4200-SCS Semiconductor Characterization System

Introduction

Parametric characterization of semiconductor devices typically requires making extremely low current measurements. For MOSFET devices, the gate voltage controls the on/off of the MOSFET, in other words, the drain current flow. The off state current and the transition from the on state to the off state (the subthreshold current) are both of critical importance in the performance of a ULSI CMOS circuit. In modern, highly integrated circuits, the off state current is typically on the order of just femtoamps. Furthermore, there are a number of device phenomena that are of critical importance in device characterization, such as Gate Induced Drain Leakage (GIDL). Therefore, it is very important to have a tightly integrated parametric characterization system that is capable of making these ultra-low current measurements.

A typical semiconductor characterization system will include a DC characterization system such as the Keithley 4200-SCS, a switch matrix, a probe station, and cabling. Too often, however, when a semiconductor characterization system is configured, the system specifier will tend to concentrate on the DC parametric instrumentation while neglecting the rest of the system. In fact, the switch matrix and probe station chosen can have a significant impact on the system's overall measurement performance. In addition, even with a properly configured system, the system implementation itself can significantly affect measurement integrity.

This application note will discuss several important aspects of making low current measurements with the Model 4200-SCS, including grounding and shielding, noise in the measurement, and system settling time.

Grounding and Shielding Issues

Instrument Common vs. Chassis Ground

Before discussing grounding in detail, it is important to distinguish between the instrument common and the chassis ground. The Model 4200-SCS and similar instruments have two grounds available. One is called the common; the other is the power ground. (See ***Figure 1***.) When shipped from the factory, these two grounds are connected, but they are different. The common is the ground for the complete measurement circuit; it will affect the system's low-level measurement performance. In contrast, the chassis ground is connected to the power line ground and is mainly used for safety reasons. Usually, there are no problems associated with connecting these grounds together. Sometimes, however, the power line ground can be noisy. In other cases, a test fixture and probe station connected to the instrument may create a ground loop that generates additional noise. Due to these concerns, ensuring low-level measurement accuracy demands that the system grounding be thought out carefully.

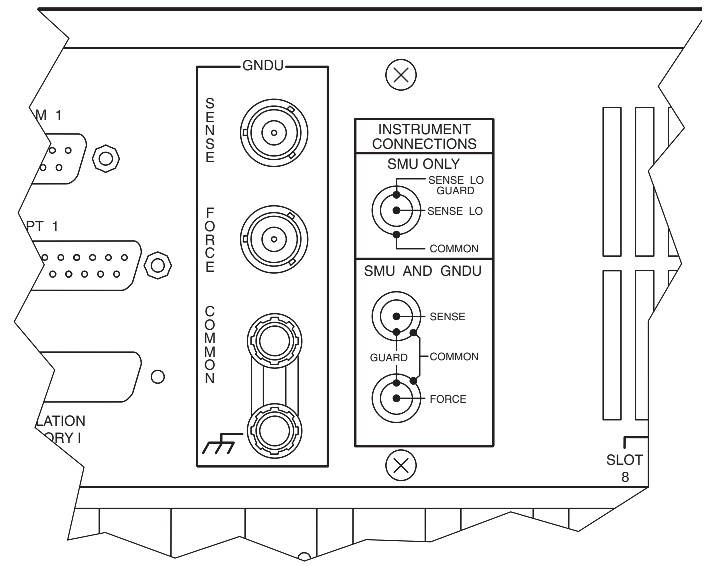

Figure 1. Common vs. Earth Ground (Chassis)

System Grounding and Shielding

Technically, although grounding and shielding are closely related, they are actually two different issues. In a test fixture or probe station, the device and probing are typically enclosed in soft metal shielding. This metal enclosure is used to eliminate interference from power lines and high frequency radiation (RF or microwave) and to reduce magnetic interference. Most semiconductor devices are also relatively light sensitive, so the enclosure also prevents light from striking the device under test, which could produce a low level current flow that would interfere with making accurate low current measurements.

This metal enclosure is normally grounded for safety reasons. However, when an instrument is connected to the probe station through triaxial cables, the point where ground connections are made is very important. The configuration in ***Figure 2a*** illustrates a common grounding design error.

Note that the instrument common and the chassis ground are connected. The probe station is also grounded to the power line locally. Even more significantly, the measurement

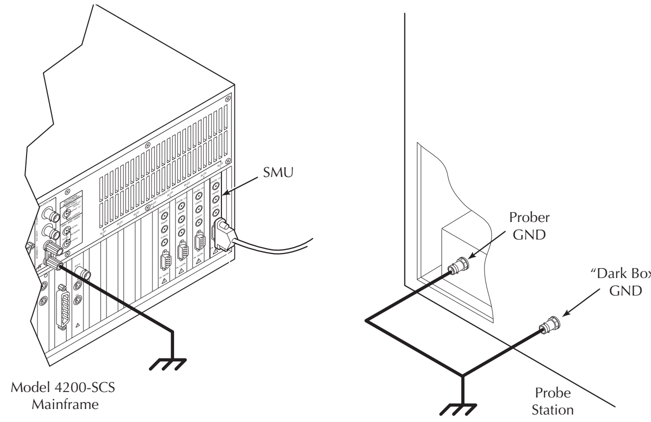

Figure 2a. Ground loops

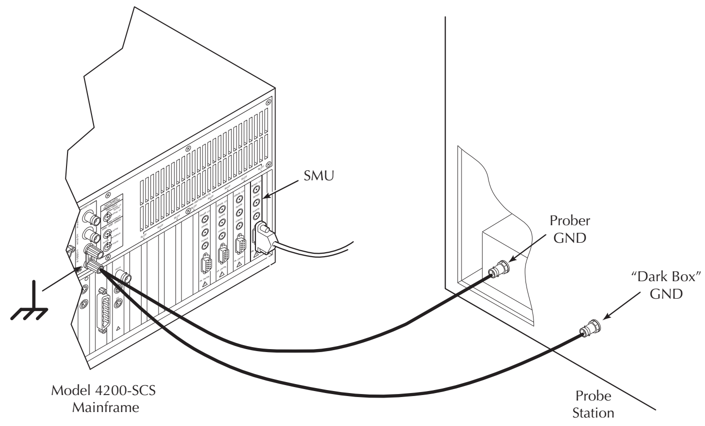

Figure 2b. Eliminating ground loops

instrument and the probe station are connected to different power outlets. The power line grounds of these two outlets may not be of the same level all the time. Therefore, a fluctuating current may flow between the instrument and the probe station. This creates what is known as a ground loop. To avoid ground loops, a single point ground must be used. ***Figure 2b*** illustrates a better grounding scheme when a probe station is used.

Techniques for Minimizing System Noise

Instrument Noise

Even assuming that a characterization system is properly shielded and grounded, it's still possible for noise to get incorporated unintentionally into the measurement results. Typically, measurement instruments like the Model 4200-SCS contribute very little noise to the overall error total. Its noise specification is only about 0.2% of the range, which means the p-p noise on the lowest range is just a few femtoamps. Noise can be further reduced with the use of proper signal averaging (through filtering and/or increasing the number of power line cycle integrations).

The most likely sources of noise are the other components of the system, such as long cables or switching hardware that is inappropriate for the application. Therefore, it is advisable to use the best switch matrix available, such as Keithley's 7174A ultra-low current switch, and to keep all connecting cables as short as possible.

Generally, system noise will have the greatest impact on measurement integrity when the signal to be measured is very small. That's because when the signal is amplified, the noise is also amplified. The key to low level measurement accuracy is increasing the signal-to-noise ratio. The Model 4200-SCS's Remote PreAmp increases the instrumentation's low current measurement capability. The PreAmp can be mounted remotely on a probe station platen so that the signal need only travel a very short distance (just the length of the probe needle) before it is amplified. When measuring extremely low currents, remote mounting of the PreAmp offers significant measurement accuracy advantages.

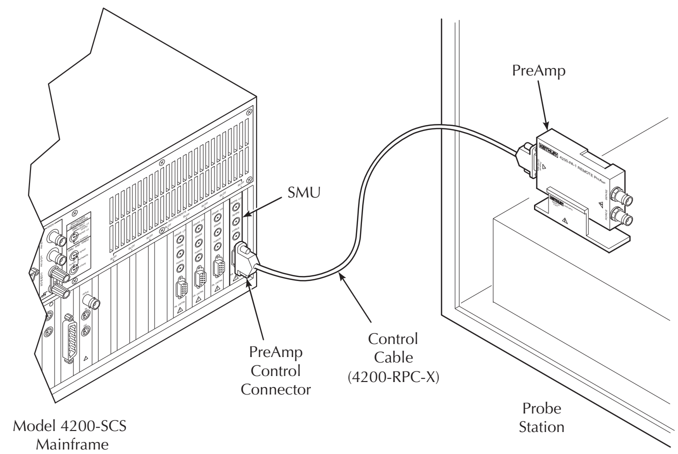

Figure 3. PreAmp mounted remotely on a probe station

Chuck Noise

Ambient temperature and thermal chucks are both commonly used in device characterization applications. Each type offers a choice of regular (coaxial) or guarded (triaxial) chuck designs, with coaxial chucks generally being less costly. However, coaxial chucks tend to have higher leakage and noise specifications than triaxial designs. Low current measurements require the use of guarded chucks. In this design, the guard of the chuck is connected to the inner shield (guard) of the triaxial cable. The inner shield is held at the center pin voltage by a unit gain buffer in the measurement instrument.

The heating element found in thermal chucks tends to add considerable noise to the measurement, especially if the heating element uses AC current. Whenever possible, a DC heater should be used to minimize the noise introduced into the measurement. To reduce noise still further, once the desired temperature has been reached, the heater can be switched off during the measurement. The drawback of this technique is that the temperature may drop slightly after the heater is turned off. However, if the measurement can be performed quickly, measurement accuracy should not suffer significantly.

Test System Settling Time

As mentioned previously, overall characterization system performance depends not only on the specifications of the measurement instrument itself, but in large part on the switch hardware, prober, and cabling. This is particularly true for high speed or low current measurements. Often, erroneous signals are measured that are unrelated to the real device parameters. It is important to note that measurement errors introduced by the settling current can not be eliminated by signal averaging.

Settling of the System

A step voltage test is typically used to characterize the problems associated with system settling. A 10V step is applied to the whole system under test, then current is monitored continuously. The resulting I-t (current vs. time) plot (***Figure 4***) can illustrate several important system characteristics.

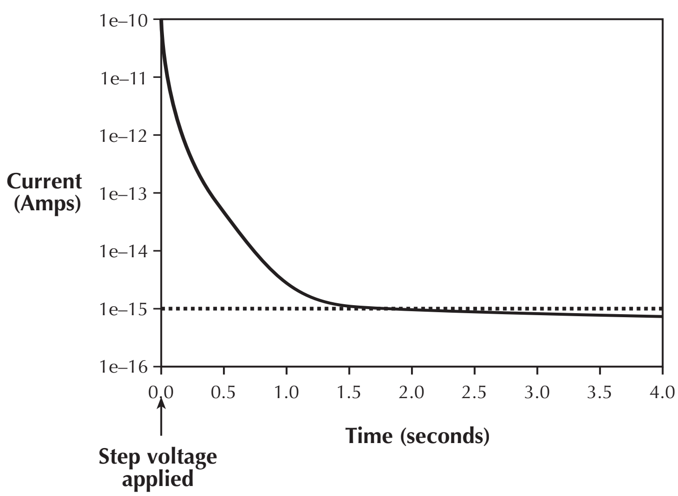

Figure 4. System settling time

There are two regions of interest on this I-t curve. Immediately after the voltage step, there is a transient current. This current will gradually decay to a steady value. The time this current requires to settle down to the steady value is the settling time. Typically, the time it takes to settle down to 1/e of the initial value is used as the time constant. This time constant can vary widely for different configurations or systems. Settling is mainly the result of the capacitance inherent in the switch relays, cables, etc. It may also be a function of the dielectric absorption of the insulating materials used in the system. If insulators with high dielectric absorption are used, the system settling time may be very long.

Extended settling times can have serious consequences in the measurement, such as when making a leakage current measurement on a high resistivity material. If the measurement speed is high, then a significant portion of the current measured is actually transient current, not the leakage current. This may lead the engineer to conclude erroneously that the material is leaky. Another potential problem is that because the current is transient, it may exhibit wide fluctuations. Sometimes, this phenomenon can be misinterpreted as the result of a noisy system.

Once the transient current has settled to its steady value, it corresponds to the system leakage current. Typically, leakage current is characterized as amp per volt (A/V). To determine the leakage current of the system, simply measure the steady-state current and divide by the voltage step. In a semiconductor test system, leakage current typically comes from the switch relays or the probe card. Most low-level characterization systems now use triaxial cables, so leakage current is rarely the result of the cabling.

There are two types of leakage associated with the switch or probe card:

- The Path-to-Ground leakage is the leakage path from the relay to the GND of the instrument or from the probe card pin to the ground.
- The Path-to-Path leakage is mostly the leakage between adjacent switch relays or probe card pins.

Determining the Proper Measurement Speed

For an SMU (Source Measure Unit) based instrument, the proper amount of delay must be added between the sourcing and measuring functions. In addition to the instrument-only delay, even more delay time may be needed to accommodate system settling. As discussed previously, the step voltage test can be used to determine the proper delay time.

From a measurement perspective, we are only concerned about the overall effect. Therefore, a step voltage test is the most convenient and rather simple test. The first step is to determine the tolerable measurement error. If a picoamp-level leakage current is tolerable, then the delay time can be set to the point that the transient current is at a sub-picoamp level. If the expected device current is in the tens of femtoamps, then the delay must be set so that the transient current is lower than the expected value.

It is important to note that there is a trade-off between the measurement speed and measurement level. If the current measurement level is low, then the delay between measurement steps must be longer, which means the measurement speed will be lower. On the other hand, if the user can tolerate a somewhat higher transient current, then a higher speed can be used.

Choosing the Proper System Configuration

Proper system configuration is the most critical aspect of avoiding measurement problems. A system of this type can only be as good as its worst-performing component. For instance, if a good instrument is configured with a poor performing switch or prober, then the switch or prober will determine the overall measurement performance, no matter how good the instrument is. The following examples illustrate the importance of proper component selection in ensuring system accuracy.

Switch Selection

The Model 4200-SCS has 100aA current resolution and 10fA current measurement accuracy. However, if the system is configured with a switch card with 100fA offset current (such as the Model 7072A Semiconductor Matrix Card), its measurement accuracy will be limited to approximately 100fA and extended settling times will be required. However, cards based on new technologies, such as the "air matrix" design used in the Model 7174A, offer significantly better leakage performance and faster settling times. In fact, the Model 7174A offers a 10fA offset current specification (typical) and a settling time of <2.5s to 400fA after application of 10V (typical).

Cable Selection

To reduce settling times, short cables should generally be used in the system. Reducing excessive cabling in the system will speed up the measurement. In addition, not all cables are the same, even though they may all be called triaxial cables. It is a good practice to order cables directly from the instrument vendor to ensure they all have been tested thoroughly.

Prober Card or Manipulator Selection

Not all prober cards and manipulators are created equal. While epoxy-based cards are suitable for many applications and are relatively economical, they have higher leakage current and longer settling time specifications than newer card designs can provide. For example, for ultra-low current measurement applications, high-performance, two-layer cards ensure low leakage and minimal dielectric absorption with Teflon®-insulated coaxial feed-throughs and ceramic blade needle mounts. Keithley offers both epoxy-based and high-performance card designs to simplify matching the card used to the requirements of the application.

If a manipulator is used, consider using a specially designed triaxial guarded manipulator. While a coaxial manipulator may be more economical or settle slightly faster, the low current performance of these manipulators typically can't compare with triaxial designs.

Conclusion

Making accurate low current measurements demands a thorough understanding of the factors that contribute to low level measurement errors. This understanding allows the system specifier to choose appropriate grounding and shielding techniques, chucks, switches, cabling, probe cards, etc., which will make the most of the capabilities inherent in modern device characterization systems.

KEITHLEY

A GREATER MEASURE OF CONFIDENCE

KEITHLEY INSTRUMENTS, INC. ■ 28775 AURORA ROAD ■ CLEVELAND, OHIO 44139-1891 ■ 440-248-0400 ■ Fax: 440-248-6168 ■ 1-888-KEITHLEY ■ www.keithley.com

BELGIUM
Sint-Pieters-Leeuw
Ph: 02-363 00 40
Fax: 02-363 00 64
www.keithley.nl

CHINA
Beijing
Ph: 8610-82255010
Fax: 8610-82255018
www.keithley.com.cn

FINLAND
Espoo
Ph: 09-88171661
Fax: 09-88171662
www.keithley.com

FRANCE
Saint-Aubin
Ph: 01-64 53 20 20
Fax: 01-60 11 77 26
www.keithley.fr

GERMANY
Germering
Ph: 089-84 93 07-40
Fax: 089-84 93 07-34
www.keithley.de

UNITED KINGDOM
Theale
Ph: 0118-929 75 00
Fax: 0118-929 75 19
www.keithley.co.uk

INDIA
Bangalore
Ph: 91-80-2677-1071/1072/1073
Fax: 91-80-2677-1076
www.keithley.com

ITALY
Milano
Ph: 02-553842.1
Fax: 02-55384228
www.keithley.it

JAPAN
Tokyo
Ph: 81-3-5733-7555
Fax: 81-3-5733-7556
www.keithley.jp

KOREA
Seoul
Ph: 82-2-574-7778
Fax: 82-2-574-7838
www.keithley.co.kr

MALAYSIA
Kuala Lumpur
Ph: 60-3-4041-0899
Fax: 60-3-4042-0899
www.keithley.com

NETHERLANDS
Gorinchem
Ph: 0183-63 53 33
Fax: 0183-63 08 21
www.keithley.nl

SINGAPORE
Singapore
Ph: 65-6747-9077
Fax: 65-6747-2991
www.keithley.com.sg

SWEDEN
Solna
Ph: 08-50 90 46 00
Fax: 08-655 26 10
www.keithley.com

TAIWAN
Hsinchu
Ph: 886-3-572-9077
Fax: 886-3-572-9031
www.keithley.com.tw

Printed in the U.S.A. No. 2241 11063KGW