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Improving Low Current Measurements on Nanoelectronic and Molecular Electronic Devices

Jonathan L. Tucker
Keithley Instruments, Inc.

Nanotech Development

Moore's Law states that circuit density will double every 18 months. However, in order to maintain this rate of increase, there must be fundamental changes in the way circuits are formed. Over the past few years, there have been significant and exciting developments in nanotechnology, particularly in the areas of nanoelectronics and molecular electronic (also called moletronic) devices. The 2001 International Technology Roadmap for Semiconductors projects that by 2004, devices should shrink to 0.09 micron (90nm) structures, the upper end of the nanostructure size range. However, a few semiconductor companies that claim to be fabricating devices smaller than 100nm are already challenging that level.

Below a semiconductor scale of 100nm, the principles, fabrication methods, and ways to integrate silicon devices into systems are not fully developed, but apparently not impossible. Still, the increasing precision and quality control required for silicon devices smaller than 100nm will presumably require new fabrication equipment and facilities that may not be justified due to high cost. This cost barrier is likely to be reached within the next ten years. Even if cost were not a factor, silicon devices have physical size limitations that affect their performance. That means the race is on to develop nanodimensional and moletronic devices and associated production methods.

Keithley Instruments, Inc.
28775 Aurora Road
Cleveland, Ohio 44139
(440) 248-0400
Fax: (440) 248-6168
www.keithley.com

Carbon Nanotube and Organic Chain Devices

Two types of molecules that are being used as current carrying, nano-scale electronic devices are carbon nanotubes and polyphenylene-based chains. Researchers have already demonstrated carbon nanotube based FETs, nanotube based logic inverters, and organic-chain diodes, switches, and memory cells. All of these can lead to early stage logic devices for future computer architectures.

Carbon nanotubes (CNTs) have unique properties that make them good candidates for a variety of electronic devices. They can have either the electrical conductivity of metals, or act as a semiconductor. (Controlling CNT production processes to achieve the desired property is a major area of research.) CNT current carrying densities are as high as 10^9A/cm^2, whereas copper wire is limited to about 10^6A/cm^2. Besides acting as current conductors to interconnect other small-scale devices, CNTs can be used to construct a number of circuit devices. Researchers have experimented with CNTs in the fabrication of FETs, FET voltage inverters, low temperature single-electron transistors, intramolecular metal-semiconductor diodes, and intermolecular-crossed NT-NT diodes [1].

The CNT FET uses a nanotube that is laid across two gold contacts that serve as the source and drain, as shown in ***Figure 1a***. The nanotube essentially becomes the current carrying channel for the FET. DC characterization of this type of device is carried out just as with any other FET. An example is shown in ***Figure 1b***.

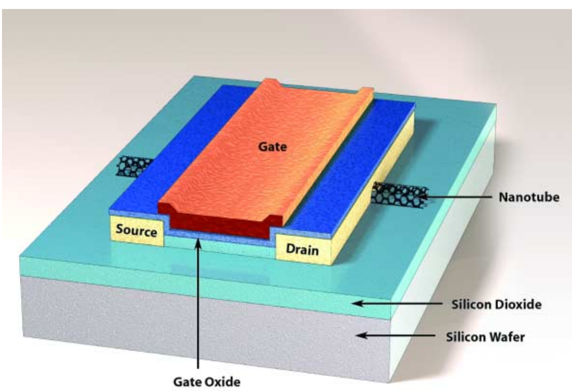

Figure 1a. ***Schematic cross-section of IBM's CNFET (carbon nanotube field effect transistor) [2] IBM Copyright.***

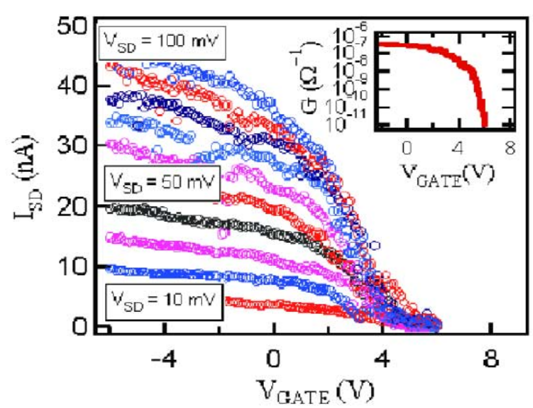

Figure 1b. ***I_{SD} versus V_G for an IBM nanotube FET [2]. The different color plots represent different source-drain voltages. IBM Copyright***

Figure 1b shows that the amount of current (I_{SD}) flowing through a nanotube channel can be changed by varying the voltage applied to the gate (V_G) [2]. Other tests typically performed on such devices include a transconductance curve (upper right corner of ***Figure***

1b), gate leakage, leakage current vs. temperature, substrate to drain leakage, and sub-threshold current. Since these types of devices are still in the research stage, measurements that provide insight into fundamental properties of conduction, such as transport mechanisms and I-V vs. temperature, are critical.

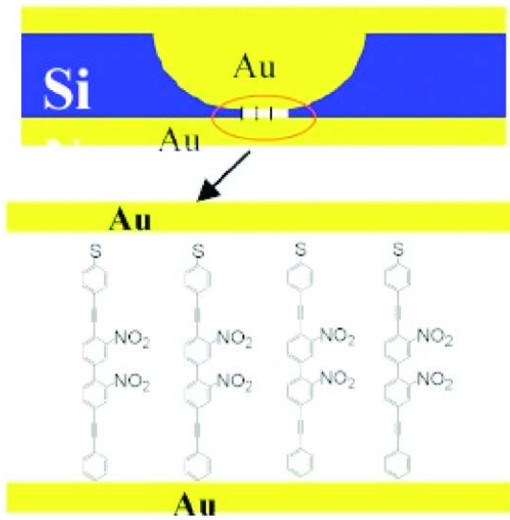

Figure 2. Nanopore structure [3]. Graphic courtesy of Mark A. Reed Research Group, Yale University.

Polyphenylene molecules are another approach to developing active electronic components. The nanopore test structure shown in ***Figure 2*** is based on polyphenylene molecules deposited between two gold electrodes on a silicon wafer. This structure serves as a probe pad, allowing a researcher to make probe connections for I-V characterization of nanoscale devices, such as molecular diodes (see ***Figure 3***).

With such I-V curves, researchers have determined that molecules can conduct small amounts of electrical current. Although I-V measurement methods are typical for device characterization, the levels of current measured are lower than those of many semiconductor devices fabricated today.

I-V characterization of moletronic devices requires low level current measurements in the nanoamp to femtoamp range. To complicate matters, these measurements are quite often made at cryogenic temperatures. Therefore, highly sensitive instruments are required, and appropriate measurement and connection techniques must be employed to avoid errors. Typically, nanoelectronic and moletronic devices are characterized with semiconductor test instruments and probe station systems, such as the one shown in ***Figure 4***.

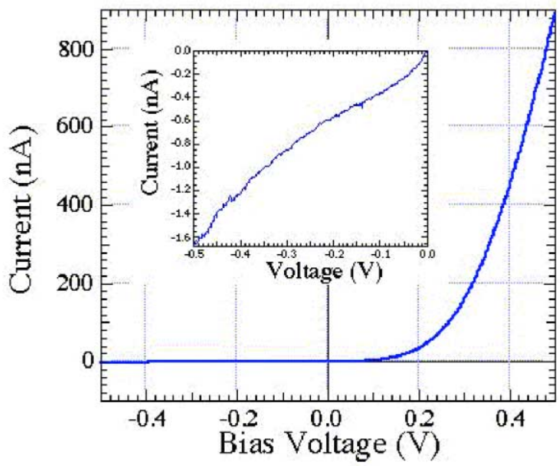

Figure 3. I-V curve for a molecular diode at room temperature [3]. Graphic courtesy of Mark A. Reed Research Group, Yale University.

Figure 4. Example of a Windows®-based semiconductor characterization system, the Keithley Model 4200-SCS.

Minimizing Sources of Measurement Error

As good as semiconductor characterization systems are, making ultra-low current measurements on nanoelectronic and moletronic devices is not trivial. Potential sources of measurement error must be understood and steps taken to reduce or eliminate them. Otherwise, a researcher will lack confidence in the characterization of materials and devices under test (DUTs). The following examples and techniques can improve low level current measurements.

Leakage Currents and Guarding. Low currents in the nanoamp to picoamp range must often be measured in nanoelectronic devices, so external leakage current error sources must be minimized, and instrument system leakage quantified. External leakage currents typically are generated between the measurement circuit and nearby voltage sources. These currents significantly degrade the accuracy of low current measurements. Techniques for minimizing leakage currents in a test circuit include the use of high quality insulators (Teflon, polyethylene, and sapphire), reducing the humidity of the test environment, and guarding.

Insulators absorb water vapor from the air, with the amount absorbed dependant on insulator material and humidity level. When the insulator contains ionic contaminants, spurious current generation can be especially troublesome in high humidity environments. The best insulator choice is one on which water vapor does not readily form a continuous film. However, this may be unavoidable if the DUT absorbs water easily. In that case, it's best to make the measurements in an environmentally controlled, low humidity room.

The use of guarding is a principal method of reducing leakage currents in a test circuit. A guard is a conductor connected to a low impedance point in the circuit that is at nearly the same potential as the high impedance lead being guarded (for example, In/Out Hi in ***Figure 5***). Guarding can isolate the high impedance input lead of an electrometer, picoammeter, or source-measure unit (SMU) from leakage current due to voltage sources. Guarding can also reduce the effect of shunt capacitance in the measurement circuit.

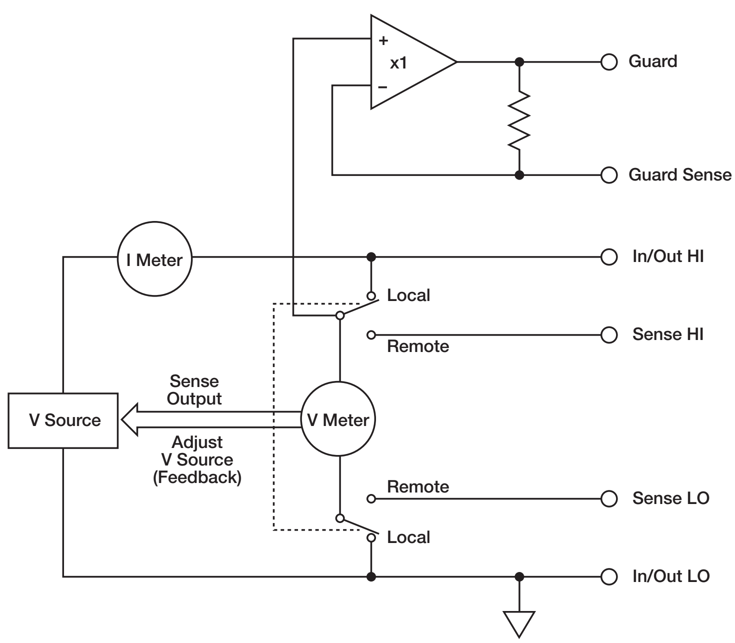

Figure 5. Simplified block diagram of a source-measure unit (SMU) configured to source voltage and measure current, showing guard connections.

Grounding and Shielding. It is important to distinguish between an instrument's common and chassis grounds. These two grounds 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. Accurate low level measurements require a comprehensive system grounding plan.

Although grounding and shielding are closely related, they are actually two different issues. In a test fixture or probe station, the DUT and probe typically are enclosed in soft metal shielding. The metal enclosure helps eliminate interference from power lines and high frequency radiation (RF or microwave), and reduces magnetic interference. The metal normally is grounded for safety reasons.

However, when an instrument is connected to a probe station through triaxial cables (the type used for guarded connections), physical grounding points are very important. The configuration in ***Figure 6a*** illustrates a common grounding 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 significant, the measurement instrument and the probe station are connected to different power outlets. The power line grounds of these two outlets may not be at the same electrical potential 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 6b*** illustrates a better grounding scheme for use with a probe station.

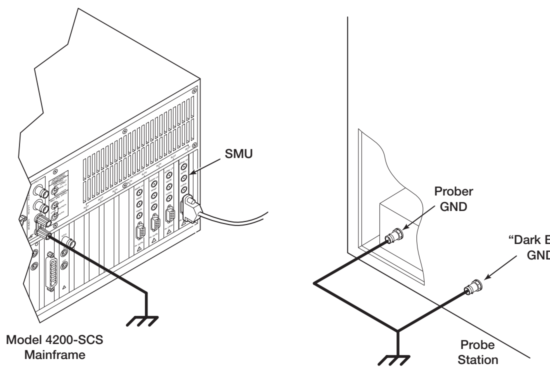

Figure 6a. Grounding connections that create ground loops.

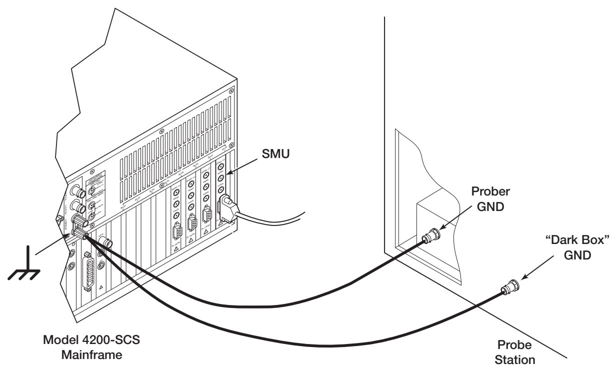

Figure 6b. Grounding connections that avoid ground loops.

Minimizing System and Instrument Noise. Even if a characterization system is properly shielded and grounded, it's still possible for noise to corrupt measurement results. Typically, instruments contribute very little to the total noise error in the measurements. For example, a good characterization system has a noise specification of about 0.2% of range, meaning the p-p noise on the lowest current range is just a few femtoamps. Noise can be further reduced with proper signal averaging (through filtering and/or increasing the measurement integration period, i.e., integrating over a larger number of power line cycles).

The most likely sources of noise are other test system components, such as long cables or switching hardware inappropriate for the application. Therefore, it is advisable to use the best switch matrix available, designed specifically for ultra-low current measurements. Then, keep all connecting cables as short as possible.

Generally, system noise has the greatest impact on measurement integrity when the DUT signal is very small (i.e., low signal-to-noise ratio). This leads to the classic problem of amplifying noise along with the signal. Clearly then, increasing the signal-to-noise ratio is key to low level measurement accuracy.

Some characterization systems offer a low noise pre-amplifier option that allows measurements down to the sub-femptoamp level. To get that level of sensitivity, it is best to mount the pre-amps remotely on a probe station platen. With this arrangement, the signal must travel only a very short distance (just the length of the probe needle) before it is amplified. Then, the amplified signal is routed through the cables and switch matrix into the measurement hardware.

Test System Settling Time. Fast, accurate low current measurements depend a great deal on the way system elements work together. Measuring instruments must be properly synchronized with the prober and switching matrix, if one is used. Improper synchronization and source-measure delay may lead to collection of signals unrelated to the real device parameters.

A step voltage test is typically used to characterize system settling time. A 10V step is applied across two open-circuit probe tips, and then current is monitored continuously for a period of time. The resulting current vs. time (I-t) curve **(Figure 7)** reveals several important system characteristics.

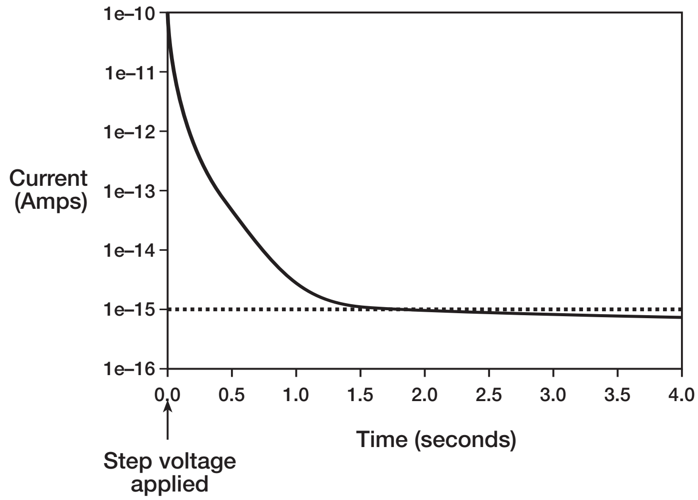

Figure 7. ***Use instrument settling time to set source-measure delays. Leakage current (in this case, 10^{-15}A) establishes the limit on basic instrument sensitivity.***

There are two regions of interest on the I-t curve: the transient segment and the steady current segment. Immediately after the voltage step, the transient current will gradually decay to a steady value. The time it takes to reach the steady value is the system settling time. Typically, the time needed to reach 1/e of the initial value is defined as the system time constant.

Settling time can vary widely for different systems, equipment, and cabling. It results mainly from capacitance inherent in switch relays, cables, etc., but may also be affected by dielectric absorption in the insulating materials of system components. High dielectric absorption can cause settling time to be quite long.

In most test situations, it is desirable to shorten test time to the minimum required for acceptable accuracy. This requires using the optimum source-measure delay, which is a function of the instrumentation source and measurement time, along with the system settling time. The latter usually is the dominant portion of source-measure delay time.

With the system leakage I-t curve in hand, the next step is to establish the acceptable measurement sensitivity or error. Suppose the task requires accurate DUT leakage measurements only at the picoamp level. Then, source-measure delay time can be established by a point on the transient portion of the system settling curve (***Figure 7***) where the leakage current is at a sub-picoamp level. If the expected DUT current is in the femtoamp range, then the delay time must be extended so that the transient current reaches a value lower than the expected reading before a measurement is taken.

Sources of Current Errors

System leakage current. Once the transient current has settled to its steady value, it corresponds to the system leakage current. Typically, system leakage current is expressed as amperes per volt. To determine its magnitude, simply measure the steady-state current and divide by the voltage step value. The magnitude of the system leakage current establishes the noise floor and overall sensitivity of the system. Usually, the largest leakage current contributors are the probe card and switching relays.

General error current model. Errors in current measuring instruments arise from extraneous currents flowing through various circuit elements. In the current measurement model of ***Figure 8***, the current indicated on the meter (M) is equal to the actual current through the meter (I_1), plus or minus inherent meter uncertainty. I_1 is the signal current (I_S), less the shunt current (I_{SH}) and the sum of all generated error currents (I_E).

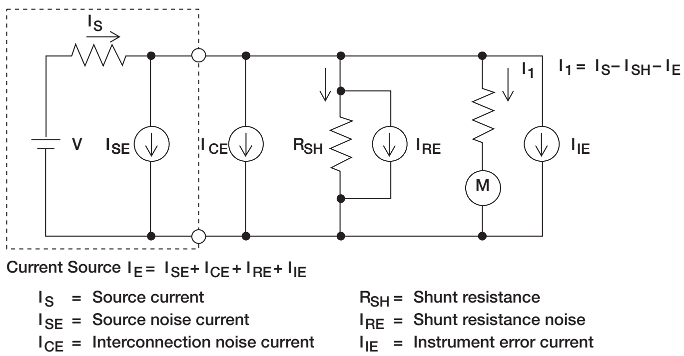

Figure 8. Sources of current error in a shunt type ammeter.

Figure 8 identifies the various noise and error currents generated during typical current measurements, which contribute to the error sum (I_E). The I_{SE} current generator represents noise currents produced within the DUT and its voltage source. These currents could arise due to the aforementioned leakage and dielectric absorption, or due to electrochemical, piezoelectric, and triboelectric effects. I_{CE} represents currents generated in the interconnection between the meter and the source/DUT circuit. I_{IE} represents the error current arising from all internal measuring instrument sources. I_{RE} is generated by the thermal activity of the shunt resistance. The rms value of this thermal noise current is given by:

$I_{RE} = (4kTf/R_{SH})^{1/2}$

where: k = Boltzman's constant (1.38×10^{-23}J/K)

T = absolute temperature in °K

f = noise bandwidth in Hz

R_{SH} = resistance in ohms

Making the Most of Instrumentation

Making accurate low current measurements on nanoelectronic and moletronic devices demands a thorough analysis of potential error sources, plus steps to reduce possible errors. These steps include selection of appropriate grounding and shielding techniques, cables, probe cards, switching matrices, etc. These efforts allow nanotechnology researchers to make the most of the capabilities inherent in modern device characterization systems.

Properly applied, these systems can speed up development of CNT and molecular electronic structures, which may ultimately redefine the processes used to fabricate semiconductor devices. By providing a means for economical, massive integration, such technology could pave the way for new computing architectures, 100× speed increases, significant reduction in power consumption, and other breakthroughs in performance.

Works Consulted

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About the Author

Jonathan Tucker is a Lead Industry Consultant at Keithley Instruments in Cleveland, Ohio, where he is responsible for new application test and measurement development in the Research and Education market segments. He received his Bachelor of Electrical Engineering degree from Cleveland State University and an MBA from Kent State University, and has 18 years of experience in test and measurement.

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Keithley Instruments, Inc. 28775 Aurora Road • Cleveland, Ohio 44139 • 440-248-0400 • Fax: 440-248-6168

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