

Optimizing Low-Current Measurements and Instruments

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Characterizing devices at low current levels requires knowledge, skill, and the right test equipment. Even with all three, achieving accuracy at low current levels can be a challenge because the level of the current is often at or below the noise level of the test setup. To ensure success in low-level current measurements, it is important to know the type of test equipment to use, the different sources of measurement error, and the appropriate techniques to minimize these errors. Examining several test examples, such as characterization of a field-effect transistor (FET) and a carbon nanotube, can help in the learning process.

How low is low? The term *low current* is relative, of course. A current level considered low for one application, such as 1mA, may be high for a device operating at 10nA. In general, an instrument's noise level will establish its low-level sensitivity, with low-current measurements referring to those made near an instrument's noise level. Trends in portable and remote electronic devices, along with advances in semiconductors and nanotechnology, are requiring greater use of low-current measurements. Small-geometry devices, photovoltaic devices, and carbon nanotubes are a few examples of devices designed to operate at extremely low current levels, and all of these devices must be characterized in terms of their current-voltage (I-V) characteristics.

A number of instruments are available for low-current measurements, depending upon the type of device under test (DUT) and the level of current to be measured. Perhaps the most ubiquitous tool on production lines and in field service is the digital multimeter (DMM), which typically provides capabilities

for measuring current, voltage, resistance, and temperature. The range of commercial products is wide, from low-cost units with 3½-digit readout resolution to rack-mount and benchtop high-precision laboratory units. The most sensitive DMMs available can measure current levels as low as about 10pA.

When greater precision is needed, various forms of ammeters are available to measure current, ranging from simple devices that measure the flow of current through a coil by the deflection of that coil in a magnetic field to newer digital ammeters that use an analog-to-digital converter (ADC) to measure the voltage across a shunt resistor and then determine and display the current from that reading. The shunt resistor usually has a low value to minimize the voltage drop across it. That voltage is often referred to as the *voltage burden*, because it can impact low-level measurements. Ammeters, which can also be realized using a feedback resistor, are referred to as *picoammeters* when designed specifically for low-current measurements. Picoammeters are available in various configurations, including high-speed models and logarithmic units capable of displaying a wide current range.

A simple feedback ammeter can be modeled by means of a small number of parameters (*Figure 1*), including the source resistance (R_S) and source capacitance (C_S), source voltage (V_S), and noise voltage (V_{NOISE}) of the ammeter. Additional parameters are the feedback resistance (R_F) and the feedback capacitance (C_F) of the ammeter. Using this model and its parameters, the noise gain of the ammeter circuit can be found from

$$\text{Output } V_{NOISE} = \text{Input } V_{NOISE} (1 + R_F/R_S)$$

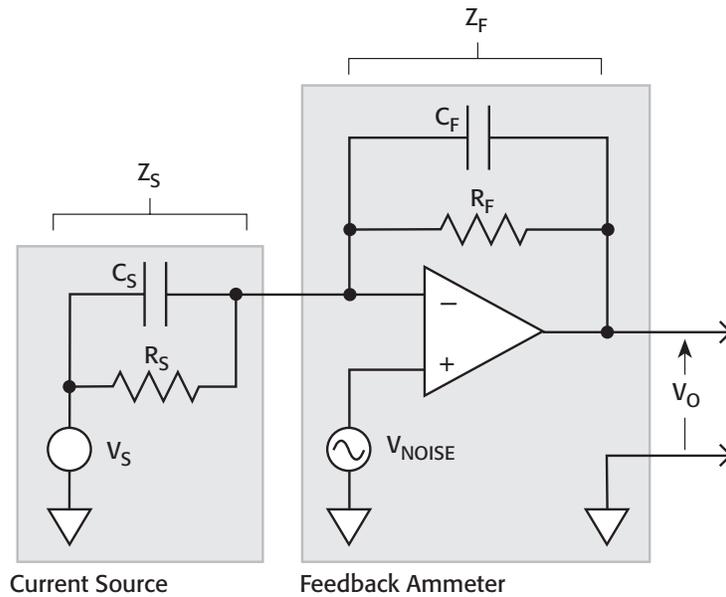


Figure 1. This diagram shows a simple model for a feedback ammeter for measuring low current levels.

As the source resistance decreases in value, the output noise increases. When $R_F = R_S$, the input noise is multiplied by a factor of 2. If the source resistance is too low, it can have a detrimental effect on the noise performance of the measurement system. The optimum source resistance is a function of required measurement range for an ammeter, with a minimum value of $1M\Omega$ to measure nanoamps of current compared to a minimum value of $1G\Omega$ to measure picoamps of current. The source capacitance can also affect the noise performance of a low-current measurement instrument.

A DUT's source capacitance can affect the noise performance of a feedback ammeter. In general, as the source capacitance increases, the noise gain also increases. Modifying the equation for output voltage noise by substituting the feedback impedance (Z_F) for the feedback resistance (R_F) and the source impedance (Z_S) for the source resistance (R_S) yields:

$$\text{Output } V_{\text{NOISE}} = \text{Input } V_{\text{NOISE}} (1 + Z_F/Z_S)$$

The feedback impedance can be found from its relationship to the feedback resistance and feedback capacitance, as

$$Z_F = \frac{R_F}{\sqrt{(2\omega f R_F C_F)^2 + 1}}$$

and the source impedance can be found from its relationship to the source resistance and source capacitance, as

$$Z_S = \frac{R_S}{\sqrt{(2\omega f R_S C_S)^2 + 1}}$$

As the source capacitance (C_S) increases, the source impedance (Z_S) decreases in value, with a corresponding increase in noise gain.

Additional current-measurement instruments include electrometers and source-measure units (SMUs). An electrometer is essentially a voltmeter with a high input impedance ($1T\Omega$ and higher) that can be used to measure low current levels. It can be used as an ammeter to measure low current levels even at low voltages, and can also be used as a voltmeter to make voltage measurements with minimal effect on the circuit being measured. As an ammeter, an electrometer can measure currents as low as the instrument's input offset current, as low as $1fA$ in some cases. As a voltmeter, an electrometer can measure the voltage on a capacitor without significantly discharging the device, and can measure the potential of piezoelectric crystals and high-impedance pH electrodes.

The SMU (*Figure 2*) is an innovation for making low-current measurements. It combines precision current and voltage sources with sensitive detection circuitry for measuring both current and voltage. An SMU can simultaneously provide a source of current and measure voltage or provide a source of voltage and measure current. A well-equipped SMU may

include a voltage source, current source, ammeter, voltmeter, and ohmmeter and is also programmable for use in automatic-test-equipment (ATE) systems.



Figure 2. A source-measure unit (SMU) combines current and voltage sources with detection circuitry for measuring current and voltage.

Minimizing Noise

All of these measuring instruments are effective tools for measuring current, although their sensitivity to low levels of current will be limited mainly by sources of noise, both within and external to the test instrument. The DUT also plays a part in the level of current that can be detected with a given instrument, because the DUT's source resistance (R_S) establishes the level of Johnson current noise (I_J), which is low-level noise caused by temperature effects on electrons in a conductor. Johnson noise, which can be expressed in terms of either current or voltage, is essentially the voltage noise of a device divided by the device resistance:

$$\begin{aligned} I_J &= V_J/R_S \\ &= \frac{\sqrt{(4kTBR_S)}}{R_S} \\ &= \sqrt{(4kTB/R_S)} \end{aligned}$$

where k = Boltzmann's constant (1.38×10^{-23} J/K),
 T = Absolute temperature of the source (in °K),
 B = the noise bandwidth (in Hz), and
 R_S = the resistance of the source (in ohms).

Both temperature and noise bandwidth affect the Johnson current noise. A reduction in either parameter will also reduce the Johnson current noise. Cryogenic cooling, for example, is

often used to reduce noise in amplifiers and other circuits but adds cost and complexity. The noise bandwidth can be reduced by filtering, but this will result in slowing the measurement speed. The Johnson current noise also decreases as the DUT's source resistance decreases, but this is not often a practical or even possible option (*Figure 3*).

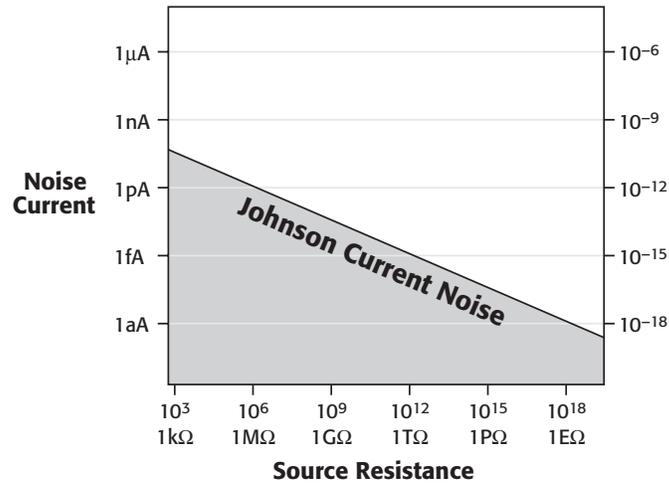


Figure 3. Johnson current noise is dependent upon many factors, including the source resistance of the DUT.

In an ideal case, the current measured for a DUT would be that of the known current source. Current noise comes from several unwanted sources, however, and it is these additional currents that can make it difficult to read low levels of current from the desired current source. One of these unwanted sources is part of the measurement system itself: the coaxial cables used to interconnect test instruments to each other or to the DUT. Typical test cables can generate as much as tens of nanoamps of current as a result of the triboelectric effect. This occurs when the outer shield of a coaxial test cable rubs against the cable's insulation when the cable is flexed. As a result, electrons are stripped from the insulation, and added to the current total. In some applications, such as nanotechnology and semiconductor research, the current generated by this effect may exceed the level of current to be measured from the DUT.

The triboelectric effect can be minimized by using low-noise cable, with an inner insulator of polyethylene coated with graphite underneath the outer shield. The graphite reduces friction, and provides a path for the displaced electrons to return to their original locations, eliminating random electron motion and their contribution to the additional noise level. Excess current flow from the triboelectric effect can also be minimized by reducing the length of the test cables as much as possible. The test setup should be isolated from vibration to minimize unwanted movement of the test cables, by positioning test cables on top of vibration-absorbing

material, such as foam rubber. Test cable movement can also be minimized by taping the cables to a stable surface, such as the test bench.

The piezoelectric effect is another source of measurement error in low-current measurements, current generated by mechanical stress on susceptible materials. The effect varies by material although some materials commonly used in electronic systems, such as polytetrafluoroethylene (PTFE) dielectrics, can produce a relatively large amount of current for a given amount of stress and vibration. Ceramic materials are less affected by piezoelectric effects and produce lower current levels. To minimize current generated by this effect, it is critical to minimize mechanical stress on insulators and construct any low-current test system using insulating materials with minimal piezoelectric properties.

Insulators can also degrade low-current measurement accuracy by means of dielectric absorption. The phenomenon occurs when a high-enough voltage across an insulator causes positive and negative charges to polarize. When the voltage is removed from the insulator, it gives up the separated charges as a decaying current, which is added to the total amount measured during a test. The decay time for the current from dielectric absorption to dissipate can be from minutes to hours. The effect can be minimized by applying only low-voltage levels to insulators used for low-current measurements.

Insulators can also contribute to degrading low-current measurement accuracy due to contamination from salt, moisture, oil, or even fingerprints on the surface of the insulator. Contamination effects can also plague printed circuit boards in a test fixture or in the test setup when, for example, excessive flux is used when soldering. On an insulator, the contamination acts to form a low-current battery at a sensitive current node within the insulator, generating noise currents that can be on the order of nanoamps, or at the level of noise currents caused by the triboelectric effect. To minimize measurement errors from insulator contamination, an operator should wear gloves when handling insulators or simply avoid touching them. The use of solder should be minimized, and solder areas should be cleaned with an appropriate solvent, such as isopropyl alcohol. A clean cotton swab should be used for every cleaning, and cotton swabs should never be reused or dipped into the cleaning solution after having been used for cleaning.

It is critical to make low-current measurements in the absence of magnetic fields, because such fields can induce the flow of current. A magnetic field with intensity changing over time can cause the flow of current in nearby conductors, as can the motion of a conductor within a magnetic field. Both cases should be avoided to maintain the accuracy of low-level current measurements, and any measuring instrument or system should be properly shielded from magnetic fields to avoid false readings.

An instrument used for low-current measurements should show a zero reading when its input terminals are left in an open-circuit condition. Unfortunately, this is rarely the case due to a small current known as the input offset current. It is caused by bias currents of active devices used in the measuring instrument, as well as leakage current through insulators in instrument or test system. Most instrument manufacturers specify the input offset current on their products' data sheets for comparison purposes, and this small amount of current must be taken into account in any low-current measurement. Because of the input offset current, any current measured by a test instrument (I_M) is actually the sum of the current from the source (I_S) and the offset current (I_{OFFSET}):

$$I_M = I_S + I_{\text{OFFSET}}$$

The input offset current can be found by capping the input connector and selecting the lowest current range available on the measuring instrument. The reading shown by the instrument, after it has properly settled to a stable value, should be within the specification shown on the instrument's data sheet. On some instruments, a current-suppression function can partially null input offset current.

Another way to subtract input offset current from a low-current measurement is to use a relative function found on some measuring equipment, such as ammeters. The relative function stores the reading of whatever residual offset current is being measured when the input terminals left in an open-circuit condition; this reading is treated as the zero point for subsequent readings.

Some examples of practical low-current measurements include characterization of field-effect transistors (FETs) and carbon nanotube (CNT) devices. A more common FET test involves evaluation of a device's common-source characteristics. Even at low current levels, the drain current can be studied using a simple test setup with two SMU channels (*Figure 4*). In this example, a two-channel Series 2600B System SourceMeter instrument from Keithley Instruments (www.keithley.com) was used, because these instruments provide the capability to source current or voltage and measure current or voltage at the same time. In order to characterize the FET, it is mounted in a test fixture that allows secure ground and bias connections. One of the SMU channels supplies a swept gate-source voltage (V_{GS}) to the fixtured FET while the other supplies a swept drain-source voltage (V_{DS}) to the DUT while also measuring the device's drain current (I_D). This simple test setup allows testing drain currents of 10nA or less.

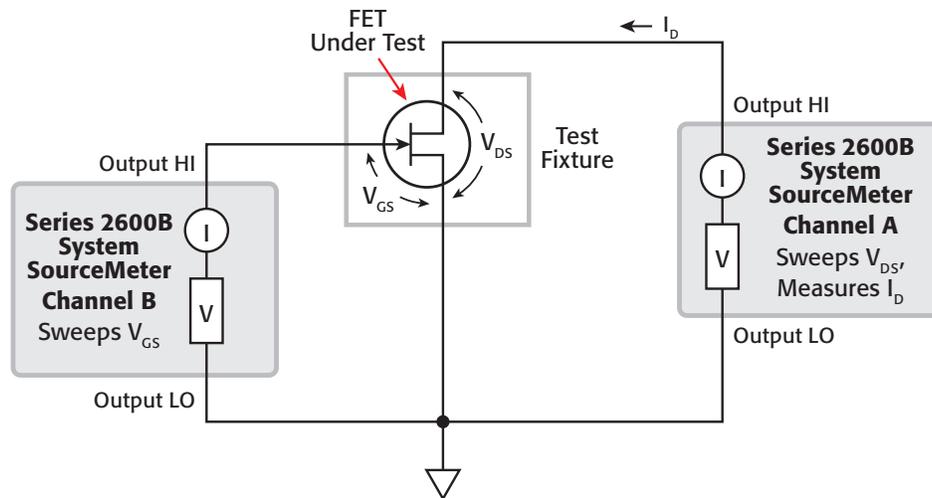


Figure 4. Two SMU channels can be used for evaluating swept I-V characteristics of FETs and other semiconductor devices.

Electronic materials such as photovoltaic wafers and CNT sheets are typically characterized in terms of their current density—how much current they can generate for a given area of material. Researchers from South Korea’s Seoul National University, for example, used a Keithley Model 6517B electrometer to evaluate multi-walled carbon nanotube (MWNT) devices fabricated on an arc-discharge CNT substrate.¹ In the studies, current densities as low as $10^{-4}/\text{cm}^2$ were measured at applied electric fields of $5\text{V}/\mu\text{m}$ and less. Practical analysis of the I-V characteristics of CNT-based electronics can be performed in a manner similar to that for the FET by using a pair of SMUs to sweep drain and gate voltages while measuring and plotting the drain current as a function of gate voltage.

The required resolution and accuracy of low-current measurements will dictate the type of measurement tool used. When accuracy is less of an issue, a basic DMM may suffice. But for more demanding requirements, a precision electrometer or SMU may be needed. As an example, the Models 2635B and 2636B SMUs are optimized for low-current measurements, providing measurement resolution to 1fA .

References

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2. Joeong Hahn, Jae-Eun Yoo, Jaeik Han, Hyok Bo Kwon, and Jung Sang Suh, “Field emission from the film of the finely dispersed arc discharge black core material,” *Carbon*, Vol. 43, 2005, pp. 937-943.

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