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New dG Measurement Methods Reveal Nanodevice Characteristics Faster, at Lower Cost

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Ohm's Law May Not Be Relevant

The demand for smaller, lower power electronic devices is fueling nanotechnology development. Researchers are striving to understand the quantum level structure and behavior of nanoscale devices and how these affect electrical properties. This makes it possible, for example, to observe or predict when tunneling occurs, calculate a device's density of states, understand conduction phenomenon in cryogenic environments, and create artificial atoms in which energy quantization can be modified based on material structure and geometry.

In the macroscopic world, conductors may have obeyed Ohm's Law. In the realm of nanotechnology, Ohm's definition of resistance is often irrelevant. The slope of the I-V curve for a nanoscale device may not be a fundamental constant of the material. Therefore, measurements of an I-V curve's slope at a large number of points are needed to study nanodevices. This plot of differential conductance (dG = dI/dV) is one of the most important measurements made on nanoscale devices, but it presents a unique set of challenges. Fortunately, new measurement techniques are making this type of study much easier.

Applications for Differential Conductance Measurements

Differential conductance measurements are performed in many applications but may have a number of aliases. These include:

- Electron Energy Spectroscopy – studies of the electron energy structure of quantum dots, nanoparticles, and artificial atoms
- Scanning Tunneling Spectroscopy – non-contact surface characteristics of nanoscale materials and devices
- Density of States – electronic properties of ultra-small semiconductors and nanotubes
- Differential Conductance (dG = dI/dV) – I-V characteristics, such as conduction at room and cryogenic temperatures, tunneling phenomena, etc.

Since differential conductance (dI/dV) is directly proportional to the density of states, it is the most direct measurement of this phenomenon. Such measurements can identify conditions under which conductance reaches a maximum, i.e., the electron energies (eV) where nanoscale material electrons are the most active. This allows researchers to characterize the number of energy options available to an electron as it falls into a lower energy level by giving up energy or as it ascends to a higher energy level after absorbing energy. Thus, knowing the density of states allows researchers to select and manipulate materials to create useful devices.

Differential Conductance Techniques

Currently, no standard exists for collecting dG data, but the following two methods are the most common:

DC I-V Technique – This technique uses a current-voltage sweep to collect a large number of data points, generates an I-V curve

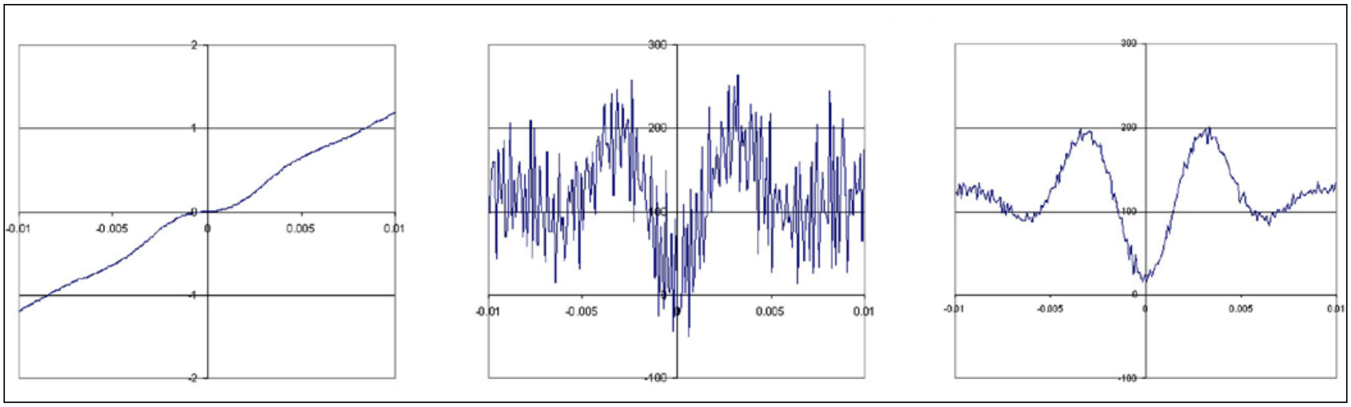


Figure 1a. I-V curve generated from a DC source-measure sweep.

Figure 1b. Differentiated I-V curve created from $\Sigma(I_{n+1}-I_n)/(V_{n+1}-V_n)$.

Figure 1c. 100 curves, averaged curve together.

(Figure 1a), and takes the mathematical derivative of the curve between each pair of data points. This has the advantage of being easy to set up and operate. It requires only one source and one measurement instrument, making it relatively easy to coordinate and control them. The fundamental problem is that noise is amplified when the measurements are differentiated (Figure 1b).

Because of the small differences between adjacent data points, a small amount of noise in either the voltage or current causes a large uncertainty in the conductance, which is unacceptable for most uses. To reduce this noise, the I-V curve and its derivative can be measured repeatedly and the data averaged. Averaging reduces the noise by a factor that is the $\sqrt{N}$, where N is the number of times the curve is measured. While this could eventually produce a clean data set, researchers are usually forced to accept higher noise levels, because of the amount of time required to reduce the noise to very low values. Figure 1c demonstrates a differentiated I-V curve and the result when 100 such curves are averaged, which would result in a reduction in the noise by a factor of 10.

AC Technique – This methodology applies a low amplitude sinusoidal signal superimposed on a stepped DC bias (Figure 2) to the device under test (DUT). Traditionally, a lock-in amplifier has been used to obtain the AC voltage across the DUT and the AC current through it. The problem with this method is that, while it provides a small improvement in noise over the DC I-V technique, it results in a more complex test system.

There is no single product that is widely accepted for the task of combining the AC signal and DC bias. Often, six to eight instruments are assembled to meet this requirement. The instrumentation may include a lock-in amplifier, AC voltage source or function generator, DC bias source, DC ammeter, and coupling capacitor/circuitry to combine AC source and DC bias (Figure 3). Measurements require precise coordination and computer control of the instruments, and the test setup is susceptible to problems of ground loops and common mode current noise, which can erode the low noise benefits of the AC method.

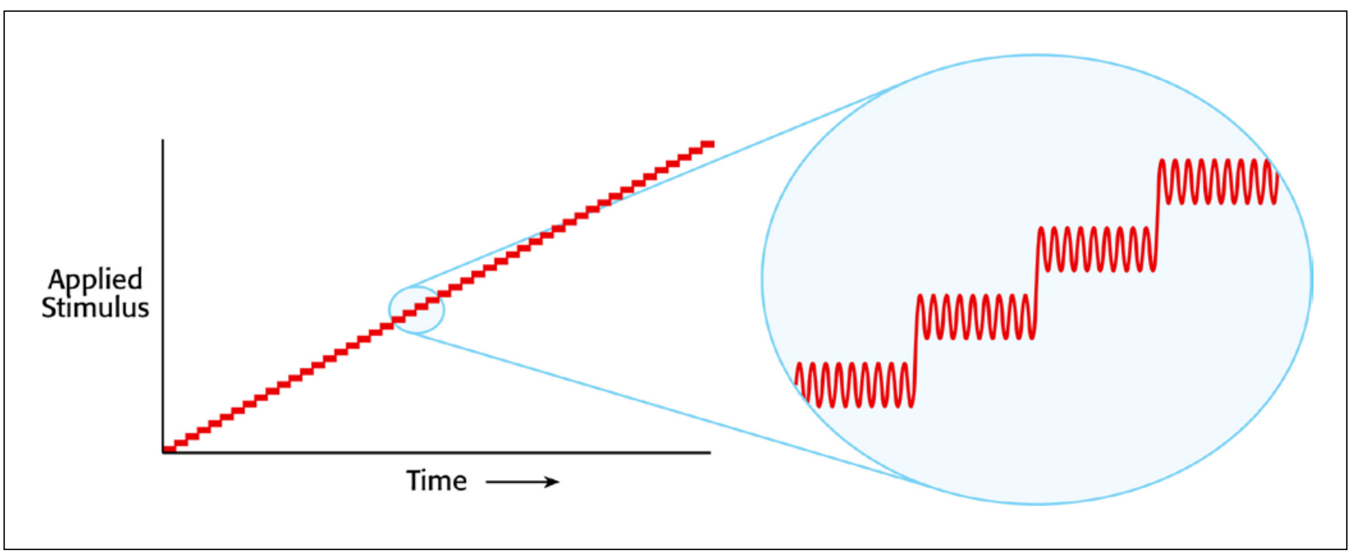


Figure 2. The AC technique measures the response to a sine stimulus while sweeping the DC bias through the DUT's operating range.

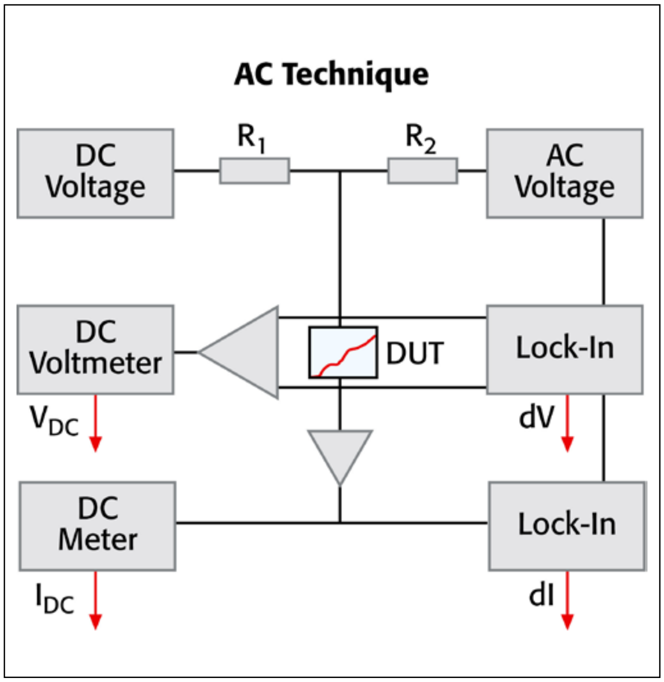


Figure 3. Block diagram of the AC technique, which reduces noise but is complex and expensive.

Mixing the AC and DC signals may be done with series resistors or with blocking capacitors. In either case, there is a significant technical challenge. After mixing, the current through the DUT and the voltage across it are not calibrated, so both the AC and DC components of the current and voltage must be measured (note AC and DC meters in Figure 3).

Another complication is the AC measurement frequency, which should be as high as possible to take advantage of the lock-in amplifier's low noise operating region. Unfortunately, a nanoscale DUT's response frequency is usually limited to about 10–100Hz , out of the low noise (1/f) operating region of the lock-in amp.

If a study can best be done by sourcing a current, then the researcher might create an AC source using a function generator and a series resistor. An ideal current source, however, requires a high output impedance with respect to the load impedance. In this case, the load resistance is unknown until the measurement is made. This forces the researcher to use trial and error to optimize the series resistance required for the test system, which is generally why an additional instrument, an ammeter, is required to know exactly how much current is being sourced to the DUT. All these steps challenge time and resources.

Improved AC Technique

While the I-V technique is simple but noisy, the existing AC technique is complex and provides only slightly lower noise. Fortunately, there is a new technique that is not only simple and low noise, it also provides improvements in speed and accuracy when characterizing nanoscale materials and devices. This technique uses a current source that combines the DC and AC source components (stimulus), and a sensitive nanovoltmeter for the response measurements. To further improve results, a four-wire (Kelvin) source-measure configuration is used. The test set-up is shown in Figure 4.

The amplitude of the alternating portion of the source current is the differential current, dI (Figure 5), which is held constant throughout the test. The current source is synchronized with the nanovoltmeter via the Trigger Link cable. After measuring the voltage at each current step, the nanovoltmeter calculates the delta voltage between consecutive steps. Each delta voltage is averaged with the previous delta voltage to calculate the differential voltage, dV, and ultimately, dG (Ref. 1).

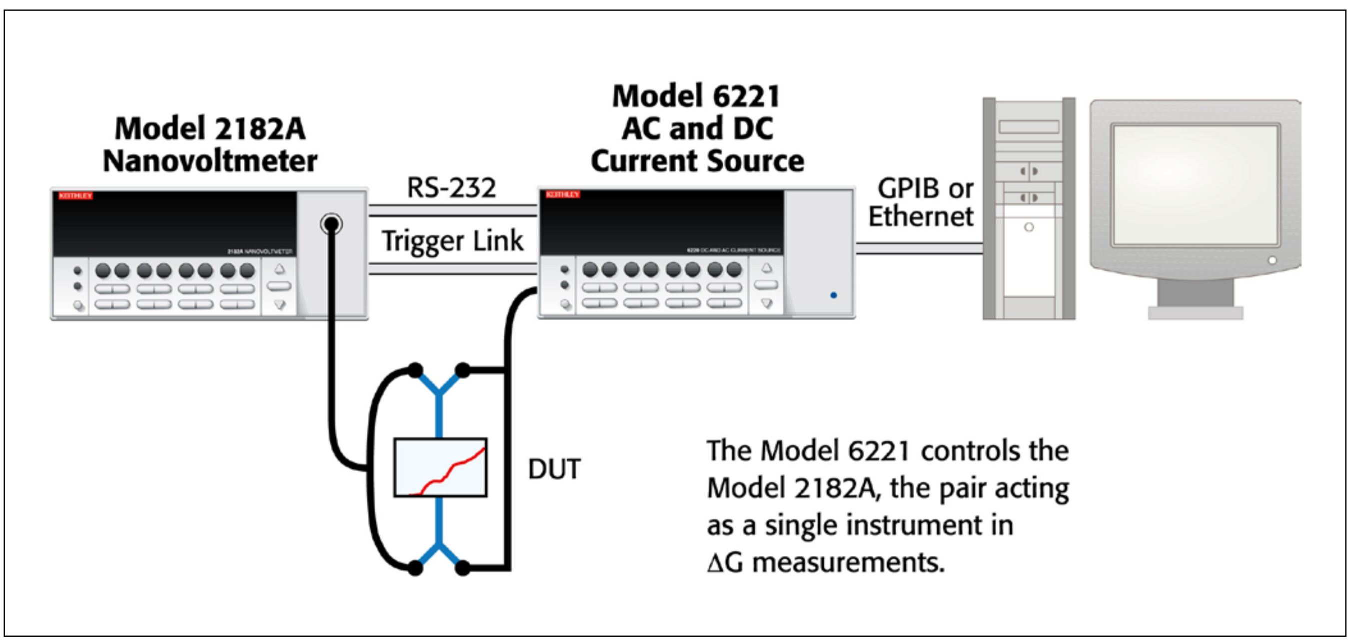


Figure 4. Improved AC test technique configuration (instruments supplied by Keithley).

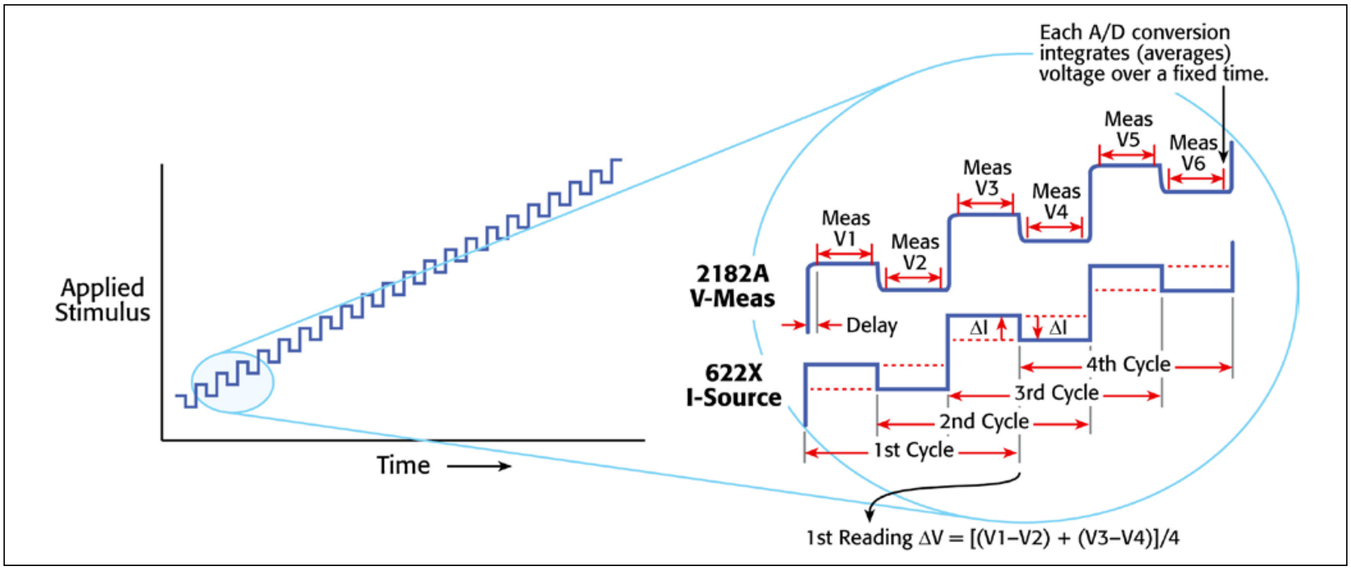


Figure 5a. Applied current for the dG test set-up in Figure 4.

Figure 5b. Detail of applied current and measured DUT voltage.

More Benefits

The improved AC technique provides low noise results at least ten times faster than previous methods. Only two instruments are required (Figure 4), instead of six to eight in the old method, plus their external circuitry. Use of the true current source shown in Figure 4 is unmatched by any user-constructed system in terms of accuracy and noise. It can source current accurately to well below 10pA, with output impedance as high as 10^{14} ohms.

Whether or not the current levels are low, the measured voltage levels are almost always low. The nanovoltmeter's sensitivity and low noise are better than lock-in amplifiers, and its ability to compensate for offsets and drift make it a superior solution for dG measurements.

The four-wire connections of the improved method (DUT connections in Figure 4), are desirable because they eliminate voltage errors due to measurement lead and contact resistance. This is especially worrisome when a nanoscale device has regions of low or moderate impedance, because lead resistance may be significant compared to the actual resistance of the DUT. In a four-wire configuration, there is no current flowing through the sense leads and thus no voltage drop. Essentially, the nanovoltmeter is placed directly across the DUT.

Another key benefit is achieved by sourcing the sweep in equal current steps. With this source-current/measure-voltage approach, more data points are collected in the region of highest conductance, thereby providing more detail in areas of greatest interest to researchers. Because of its inherently low noise, the improved AC technique requires far fewer measurements to get clean results compared to the DC I-V method and its data averaging approach. The new method requires only one sweep, shortening hours of data collection to a few minutes.

With only two instruments and less cabling, spurious capacitance is less of a problem. The fundamental system RC time constant is determined by device impedance (R) and cable capacitance (C), and the AC stimulus cannot be applied to the DUT at a frequency faster than this time constant. The two instruments used for the new technique also allow guarded measurements (Ref. 2), which eliminate the slowing effects of cable capacitance by reducing DC leakage. This greatly improves the test system's measurement settling time, resulting in higher speed and greater accuracy.

Special Usage Cases

Some nanoscale devices have non-monotonic I-V curves. This behavior, often described as negative differential conductance (NDC), can be classified in two categories:

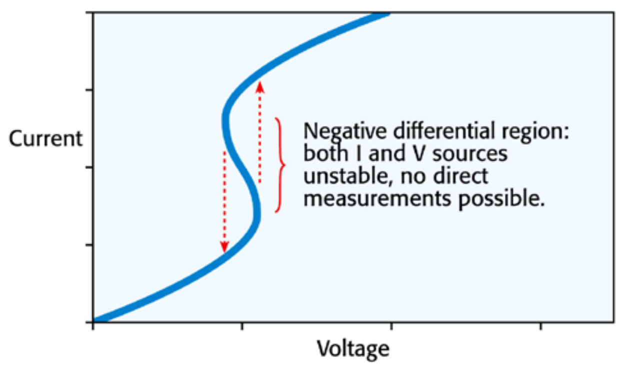
(1) a given voltage may correlate to more than one possible current

(2) a given current may correlate to more than one possible voltage

For description purposes, Case 1 will be referred to as Current Hop and is illustrated in Figure 6. Case 2 will be referred to as Multi-voltage NDC, illustrated by Figure 7. Since neither voltage nor current sources are stable over NDC regions, some modifications to the new AC measurement technique just described are required.

Current Hop – A regulated voltage source is a poor choice when testing a nanoscale device that has an I-V curve with multiple current values for a given applied voltage (Figure 6a). This is manifested as a hysteresis curve that is uncharacteristic of the NDC region (dashed lines in Figure 6a), and is due to the regulated voltage source being unstable into a negative resistance load.

While a current source has similar problems, it can be used with a series resistor added into the HI lead of the instrument. The resistor value must be equal to or greater than the largest negative resistance



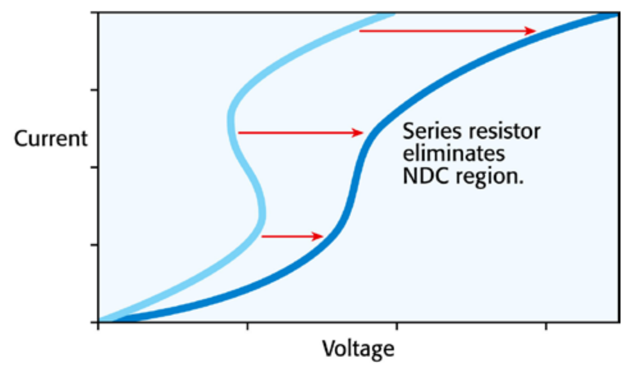


Figure 6a. DUT's with negative differential conductance, as shown here, require a minor modification to the test set-up.

Figure 6b. The purple curve is the conductance seen by the AC current source when an appropriate series resistor is placed in its output lead. No NDC is apparent and the source remains stable.

throughout the DUT's NDC region. With such a resistor, the current source 'sees' a composite load that does not appear to have an NDC region, so the source remains stable. For each current value, voltage is measured across only the DUT; this generates the correct I-V curve, including the NDC region.

When this technique is used with the Keithley Model 6221 AC Source and Model 2182A Nanovoltmeter, no other setup change is required. Again, note the advantage of a four-wire test configuration, which provides the highest accuracy by eliminating lead resistance from the measurements. With this lead arrangement (Figure 4), the nanovoltmeter is connected directly across the DUT, not the series resistor, whose IR voltage drop is rejected along with that of other lead resistance. Thus, the entire dG curve can be directly measured.

Note that lead resistance, which is normally considered a problem, can actually facilitate full characterization of nanoscale DUTs exhibiting NDC. In addition, the instruments shown in Figure 4 are designed to work together and provide a direct readout of dG. Other methods require separate measurements of DUT current and voltage in NDC cases and then calculation of dG.

Multi-voltage NDC (Figure 7a) – As in the case of current hop, neither voltage nor current sources are stable over a multi-voltage NDC region. However, a current source may be used for applying a stimulus to the DUT if a parallel resistor is placed across its output. The value of this resistor must be smaller than the smallest negative resistance throughout the NDC region of the DUT. This ensures that the slope of the resistor's I-V curve exceeds the maximum slope of the negative resistance region of the DUT's curve. Thus, the slope of the combined I-V response remains monotonic (Figure 7b). Since the desired measurement is the differential conductance, dG, of the DUT, the conductance of the parallel resistor (1/R) can be simply subtracted from every measurement in the sweep.

Conclusion

AC current sources are now available that can quickly characterize the differential conductance of nanoscale devices, including those that exhibit negative dG. When combined with a sensitive nanovoltmeter, these two instruments eliminate the need for homegrown current sources and complex test arrangements of up to eight different instruments. An added benefit is significantly lower capital cost.

In addition, the latest AC sources have much lower noise, better accuracy, and higher throughput over a broader range of measurements due to faster device settling times. Measurement speed is further enhanced by the fact that these new instruments require only one measurement sweep for a complete dG curve, instead of the thousands needed previously. This shortens hours of data collection to only a few minutes.

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About the Author

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