A GREATER MEASURE OF CONFIDENCE

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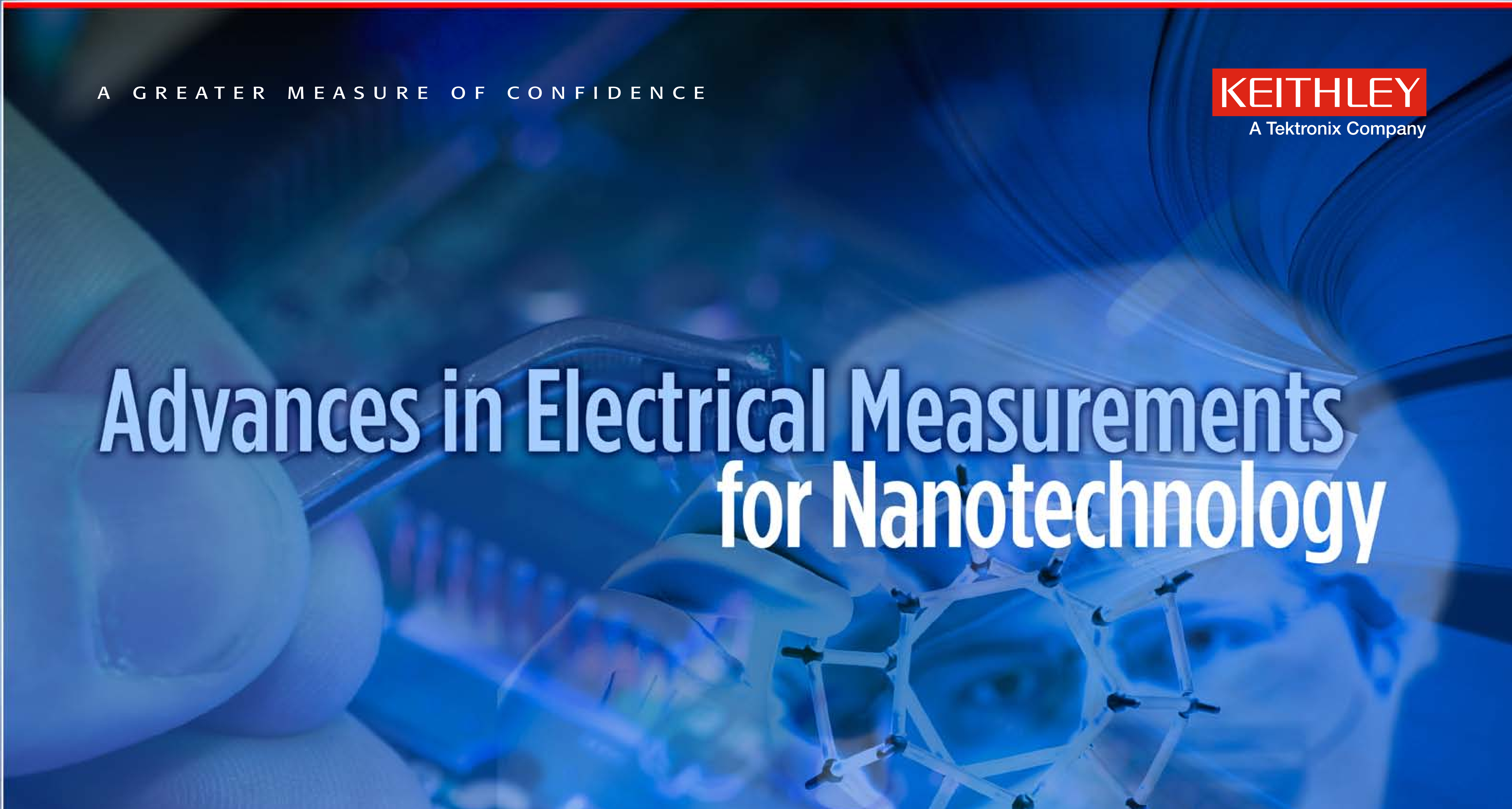

Advances in Electrical Measurements for Nanotechnology

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begin

Nanotech Testing Challenges

Introduction

Nanotechnology has the potential to improve our quality of life in diverse ways, such as faster electronics, huge memory/storage capacities for PCs, cheaper energy through more efficient energy conversion, and improved security through the development of nanoscale bio- and chemical-detection systems.

With nanoelectronic materials, sensitive electrical measurement tools are essential. They provide the data needed to understand the electrical properties of new materials fully and the electrical performance of new nanoelectronic devices and components. Instrument sensitivity must be much higher because electrical currents are much lower and many nanoscale materials exhibit significantly improved properties, such as conductivity. The magnitude of measured currents may be in the femtoamp range and resistances as low as micro-ohms. Therefore, measurement techniques and instruments must minimize noise and other sources of error that might interfere with the signal.

The nature of nanotech materials requires some novel testing techniques. Because these materials are built at the atomic or molecular level, quantum mechanics come into play. As a result of small particle sizes, the atoms and molecules of these new materials may bond differently than they might otherwise in bulk substances. There may be new electronic structures, crystalline shapes, and material behavior. Nanoparticles with these new properties can be used individually or as building blocks for bulk material. Although the discovery of bulk properties remains important, measurements also need to uncover the characteristics unique to nanoscale structures.

Particle size and structure have a major influence on the measurement techniques used to investigate a material. The material's chemical and electrical characteristics change as particle sizes are reduced to nanometer dimensions. This even applies to biological materials. Therefore, most of these materials require chemical and electrical testing to characterize them for practical product applications. For many of them, the actual quantity being measured is a low level current or voltage that was translated from another physical quantity.[1] Direct electrical measurements are possible on many substances with the probing instruments and nano-manipulators now available.

As a substance is reduced to nanoscopic dimensions, both the bandgap and the distance between adjacent energy levels within the material's electron energy bands are altered. These changes, along with a particle's nanoscopic size with respect to the material's mean free path (the average distance an electron travels between scattering events), directly affect the electrical resistance of a nanoparticle. More generally, a material's bandgap directly influences whether a particle is a conductor, an insulator, or a semiconductor. These influential electronic properties allow, for example, a carbon nanotube (CNT) to be used to create a transistor switch.[2] One way to do this is by connecting a semiconducting CNT between two electrodes that function as a drain and source. A third electrode (the gate) is placed directly under the entire length of the carbon nanotube channel. For a semiconducting CNT, the introduction of an electric field through the channel (via the insulated gate placed in proximity to the CNT channel) can be used to change the CNT from its semiconducting state to its insulating state by increasing the gate voltage. Decreasing the gate voltage will transition the device into a conducting state. This conduction mechanism is analogous to the operation of a silicon MOSFET transistor switch, which is created by doping silicon with either an electron acceptor or donor to alter the material's electronic conductivity in specific localities.

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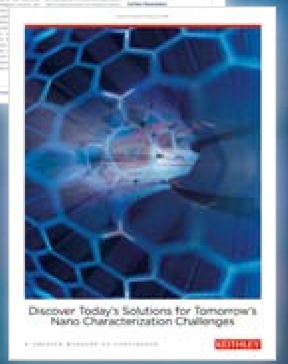

- Discover Today's Solutions for Tomorrow's Nano Characterization Challenges

Additional Resources

- The Emerging Challenges of Nanotechnology Testing
- Climbing the Commercialization Hill

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Nanotech Testing Challenges (continued)

For macroscopic particles, electrons take on discrete quanta of energy that lie within energy bands, with each band consisting of many energy levels that electrons can share through their thermal energies. For a conducting material, electrons can be thermally excited into the conduction band (i.e., electrons are present in the valence as well as in the conduction band). For an insulator (bandgap > thermal energy of the electron), enormous energy is required for an electron to transition from the valence to the conduction band separated by the material bandgap. If a suitable amount of energy is absorbed (> bandgap), then electrons can jump bands.

As a particle's size is reduced to nanoscopic dimensions, the allowable energies within the continuous bands separate into discrete levels (because there are far fewer atoms in the mix). This occurs when the separation between energy levels approaches the thermal energy of the electrons (*Figure 1*). With fewer energy levels within the specific energy band, the density of states of the material changes.

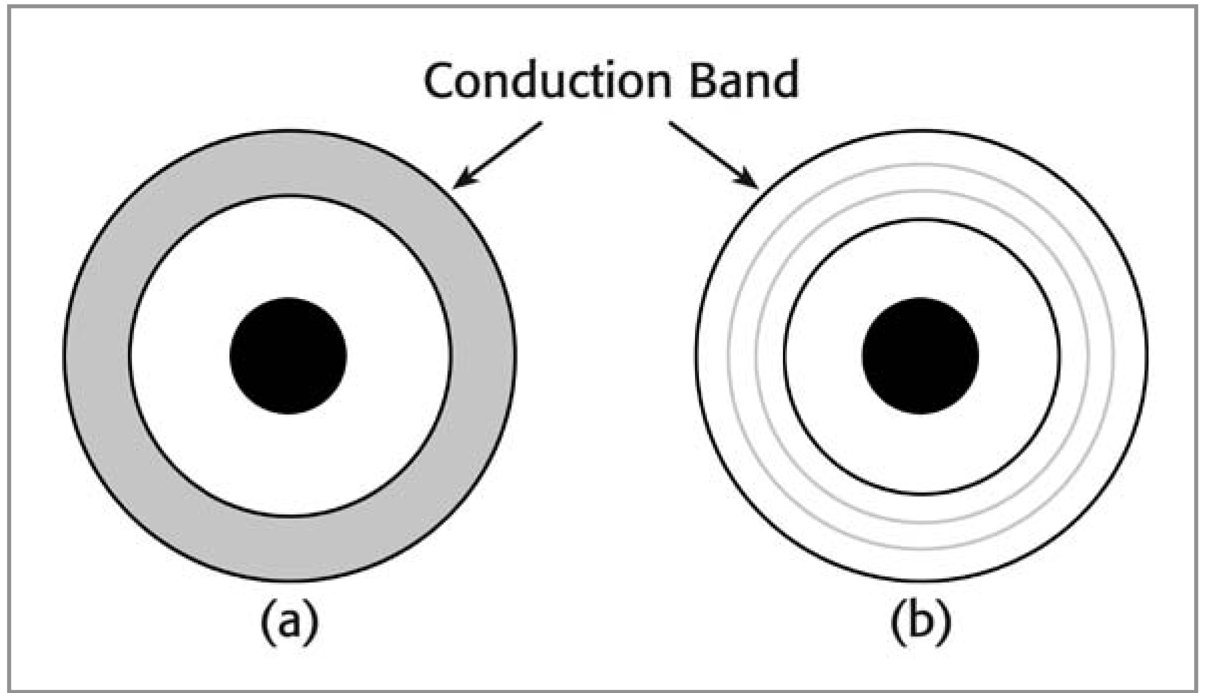

Figure 1. As material is reduced from macroscopic dimensions to nanoscopic size, its continuous energy bands (a) separate into discrete energy levels within the band (b) and the bandgap increases.

The density of states is a measure of 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. A corollary is that if the density of states is known, the size of the particle can be deduced.

Characterizing the density of states is a fundamental activity in nanoscopic material research. Density of states (3D dimensionality) as a function of energy can be expressed as:

$$\rho(E) = dn_s/dE = [\{4\pi(2m)^{3/2}\}/h^3][\sqrt{(E)}]$$

This represents the number of electron states per unit volume per unit energy at energy E, where:

m = the effective mass of the particle,
h = Planck's constant, and
E = the energy (electron orbital location) in electron volts.

Although the result is independent of volume (can be applied to any size particle), this equation is of limited value if the particle size/structure is unknown. However, other ways are available to determine the density of states experimentally, from which the particle size can be found.

Because the density of states can be used to predict the electrical behavior of materials, it is also possible to use electrical impedance measurements to derive density of states information. The density of states is found by plotting differential conductance vs. applied voltage. Differential conductance is simply (di/dv). When this conductance is plotted against voltage, the graph indicates the material's density of states. Highly conductive materials possess an abundance of free energy levels in the conduction band, i.e., greater density of states (more individual allowed energy levels per unit energy). Insulating materials have an electronic structure with a dearth of occupied energy levels in the conduction band. Because density of states corresponds to the density of these energy levels, a plot of conduction vs. voltage provides a direct measure of the electronic density of states at each energy level (voltage across the device).

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Nanotech Testing Challenges (continued)

One approach to this technique is to use a nano-manipulator that makes low resistance contacts to the nanoparticle. Such an arrangement allows charge transport and density of states measurements. This works well into the conduction region thanks to the low resistance direct connections of the nano-probes on the material (particle) being tested.

The nano-manipulator and its probes, along with a source-measure unit (SMU), are used to apply a current or voltage stimulus directly to the nanoparticle and measure its corresponding voltage or current response (***Figure 2***). The advantage of electrical source-measure testing is rooted in the fact that a specific SMU measurement mode (source current/measure voltage or vice versa) can be chosen based on the relative impedance of the material or device under test (DUT). Furthermore, the measurement mode can change dynamically as the impedance changes, such as occurs in CNTs acting as semiconductor switches. This allows a much wider dynamic range of voltage and current stimuli and measurements, thereby optimizing parametric test precision and accuracy. SMU voltage and current sensitivity can be as good as 1 microvolt and 100 atto-amps.

Photos courtesy of Zyvex Corporation

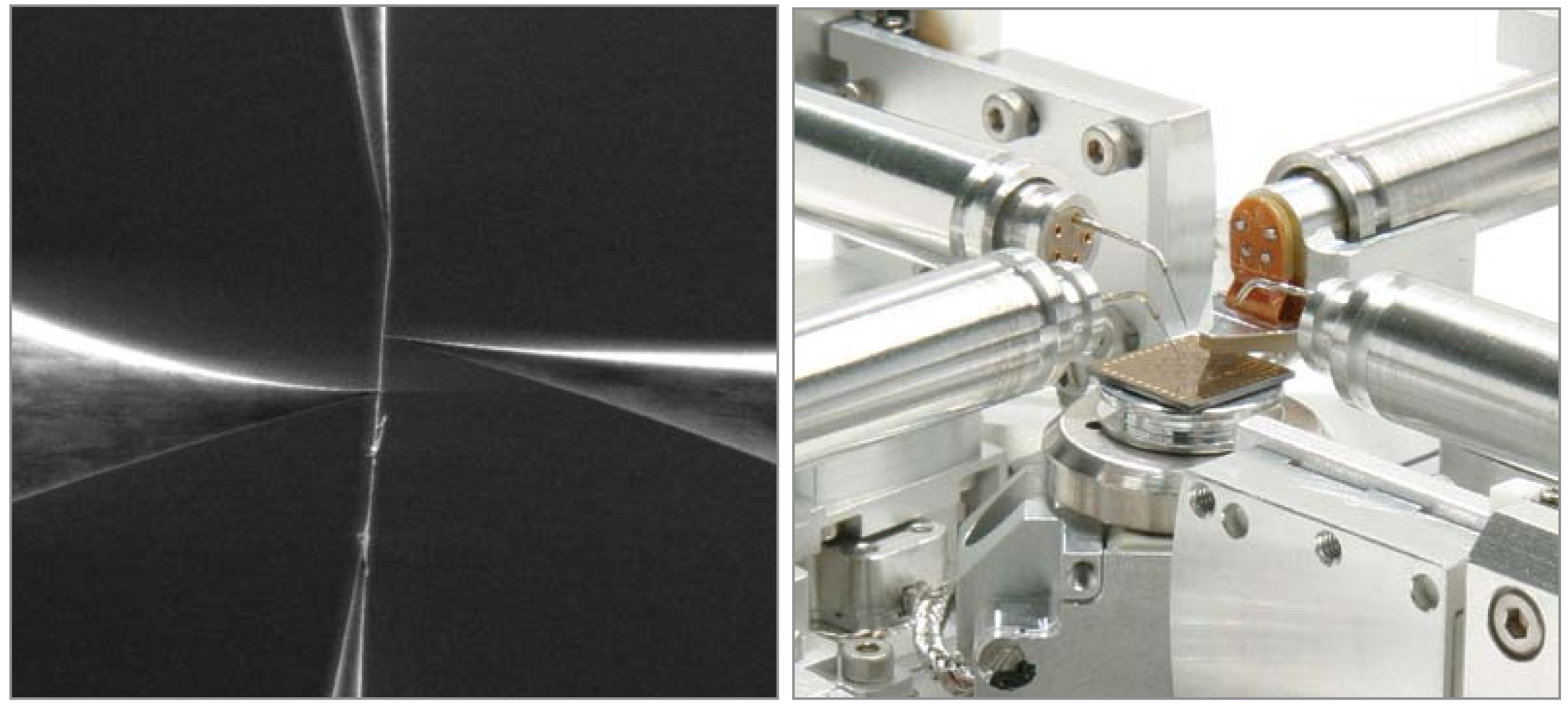

Figure 2. Nano-manipulator probing of nanoscale structures: Microscopic view of low impedance probe contact to a CNT for direct electrical measurements. Photo of a nano-manipulator head assembly.

Electrical measurements on nanoscopic materials place stringent requirements on the instrumentation. In order to measure conductivity, impedance, or other electrical properties, and relate those measurements to the density of states, a galvanic connection must be made to the nanoscopic DUT.[3] This represents one of the major hurdles to be overcome in the field of nanotechnology testing. There are only a few tools available and few device constructs that facilitate connections of this type.

Particle self-assembly can be accomplished from silicon to silicon, where conventional photolithographic techniques are used to make electrical connection pads for probing. Particles that are long enough to straddle such pads (for example, carbon nanowires) can be connected to the pads through externally generated electrostatic fields.

Although the properties of quantum wells, wires, and dots differ, it's possible that information about a particular material in the form of a quantum dot can be inferred by examining the same material fashioned as a quantum wire or well (nano-film). Nano-films are particularly easy to measure because only one dimension is small. Such a film might be deposited on a conductive substrate, allowing measurements through the volume as well as over the surface, using appropriately placed macroscopic test pads formed on the material surface. For conductive materials, separate pads for source and measure can be deposited to create a Kelvin (4-wire) connection.[4] This type of circuit eliminates test lead resistance from the measurement and improves accuracy. In any case, a quantum well (nano-film) can be tested like any other bulk material.

[1] Bioimpedance Bioelectricity Basics, Wiley 2003.

[2] Applied Physics Letters, Single and Multiwalled Carbon Nanotube Field Effect Transistors, volume 17, number 73, October 26, 1998, IBM Research Division.

[3] I-V Measurements of Nanoscale Wires and Tubes with the Model 4200-SCS and Zyvex S100 Nanomanipulator, Application Note #2481, Keithley Instruments, 2004.

[4] Four-Probe Resistivity and Hall Voltage Measurements with the Model 4200-SCS, Application Note #2475, Keithley Instruments, 2004.

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Jonathan Tucker

- **Electrical Characterization of Carbon Nanotube Transistors (CNT FETs) with the Model 4200-SCS**

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- **Nanoscale Device and Material Electrical Measurements**
- **Advanced Particle Beam Methods For Nano-characterization And Analysis**
- **Optimizing Low Current Measurements with the Model 4200-SCS Semiconductor Characterization System**
- **I-V Measurements of Nanoscale Wires and Tubes with the Model 4200-SCS and Zyvex S100 Nanomanipulator**
- **Tips for Electrical Characterization of Carbon Nanotubes and Low Power Nanoscale Devices**

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Electrical Measurement Considerations

Electrical measurements on passive devices (any device that is not a source of energy) are made by following a simple procedure: stimulate the sample in some way and measure its response to the stimulus. This method also works for devices that have both passive and active properties with linear or non-linear transfer functions. With appropriate techniques, a source-measure algorithm can be useful for characterizing sources of energy.

For nanoscopic particles, this general method takes the form of source-measure testing to quantify impedance, conductance, and resistance, which reveal critical material properties. This test methodology is useful even if the end application is not an electronic circuit.

Several considerations are important in the characterization of nanoscopic particles:

- Nanoscopic particles will not support the magnitude of currents that macroscopic device can carry (unless they are superconducting). This means that when a device is interrogated, the magnitude of a current stimulus must be carefully controlled.
- Nanoscopic particles will not hold off as much voltage from adjacent devices as a conventional electronic component or material (such as a transistor). This is because smaller devices can be and are placed closer together. Smaller devices also have less mass and may be affected by the forces associated with large fields. In addition, internal electric fields associated with nanoscopic particles can be very high, requiring careful attention to applied voltages.
- Given that nanoscopic devices are so small, they typically have lower parasitic (stray) inductance and capacitance. This is especially useful when they are used in an electronic circuit, enabling faster switching speeds and lower power consumption than comparable macroscopic devices. However, this also means that instrumentation for characterizing their I-V curves must measure low currents while tracking the short reaction time.

Because nanoscopic test applications often require low current sourcing and measurement, appropriate instrument selection and use is critical for accurate electrical characterization. In addition to being highly sensitive, the instrumentation must have a short response time (sometimes referred to as high bandwidth), which is related to a DUT's low capacitance and ability to change state rapidly at low currents.

The switching speed of a source-measure test circuit may be limited by the instrumentation used to follow the state of the device. This is especially true if a non-optimal measurement topology is used to observe the device. The two possible topologies are source current/measure voltage or source voltage/measure current.

When considering the measurement of low impedance (<1000 ohms) devices, the source current/measure voltage technique will generally yield the best results. Current sources are stable when applied to lower impedances, and a good signal-to-noise ratio can be achieved without great difficulty. This allows for accurate low voltage response measurements.

When measuring high impedance (>10,000 ohms) devices, the source voltage/measure current technique is best. Stable voltage sources to drive high impedances are easily constructed. When a well-designed voltage source is placed across a high impedance, it will quickly charge the stray capacitance of the DUT and test cables and rapidly settle to its final output value. The small current response of the DUT can be accurately measured with an appropriate ammeter.

Measuring Low and High Impedence: Model 6430 Sub-Femtoamp Remote SourceMeter® (SMU) instrument.

Measuring High Impedence: Model 6517B Electrometer/ High Resistance Meter

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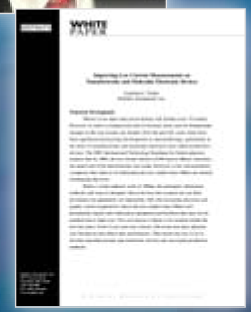
- Measurement Needs in Nano-Architectonics

Dr. Kang Wang
Director of the Center on Functional Engineered Nano Architectonics
University of California, Los Angeles



- Improving Low Current Measurements on Nanoelectronic and Molecular Electronic Devices

Additional Resources

- Electrical Measurements on Nanoscale Materials
- Four-Probe Resistivity and Hall Voltage Measurements with the Model 4200-SCS
- Guide to Measuring New Materials and Devices

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Electrical Noise

Measurement topology also has an impact on electrical noise, which is the ultimate limitation on measurement sensitivity and accuracy. For low impedance voltage measurements with a current source, the measurement circuits will be sensitive to DUT voltage noise and impedance. For macroscopic devices, such as a resistor, the Johnson noise voltage at room temperature (270K) is expressed as:

$$V_n = \sqrt{(4kTBR)}$$

where k = Boltzmann's constant

T = Absolute temperature of the source in degrees Kelvin

B = Noise bandwidth in Hertz

R = Resistance of the source in ohms

which can be further simplified to:

$$V_{\mathrm{n}} = 6.5 \times 10^{-10}[\sqrt{(BR)}]/R$$

This equation shows that as DUT resistance (R) decreases, the Johnson voltage noise generated by the DUT also decreases. Conversely, high impedance devices stimulated with a voltage source are limited by current measurement noise.

The Johnson current noise of a resistor at 270K is:

$$I_{\mathrm{n}} = 6.5 \times 10^{-10}[\sqrt{(BR)}]/R$$

indicating that the noise goes down as DUT resistance increases.

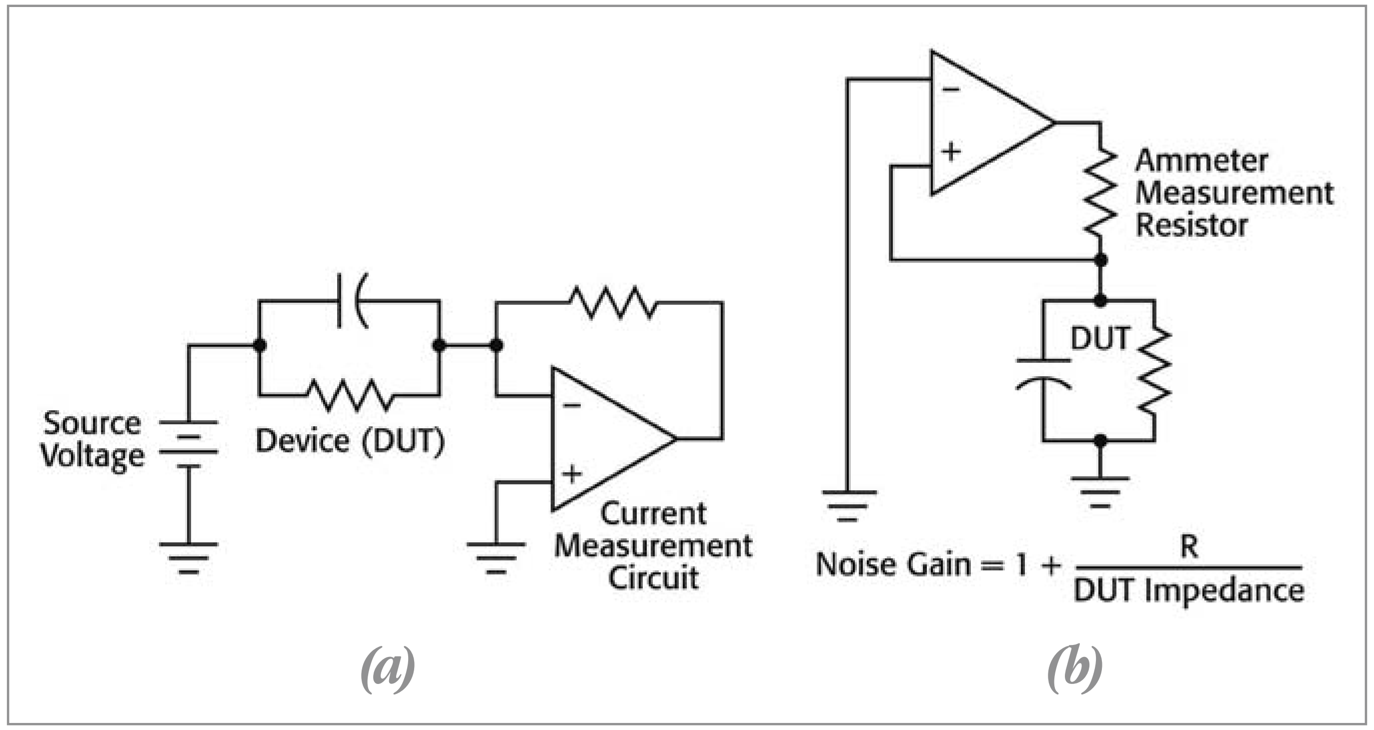

Figure 3. (a) Circuit model for the source voltage/measure current technique; (b) Modified model illustrating the noise gain (op-amp noise "gained up") when the DUT impedance is low compared to the measurement impedance.

For all particle sizes, in addition to Johnson noise, there could be a noise gain associated with the measurement topology chosen. Noise gain is a parasitic amplification of the noise of the measurement system that is not present when the correct measurement topology is chosen. For example, consider a source voltage/measure current topology. An operational amplifier is used in many current measurement (ammeter) circuits, as shown in ***Figure 3***.

To minimize noise gain, the ammeter circuit must operate at a low gain with respect to its non-inverting input terminal.

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- **Electronic Properties of Zinc-Blende Wurtzite Biphasic Gallium Nitride Nanowires and NanoFETs**

Dr. Virginia Ayers
Head, The Electronic and Biological Nanostructures Laboratory
Michigan State University

- **Making Ultra-Low Current Measurements with the Low-Noise Model 4200-SCS**

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- **Low Level Measurements Handbook**

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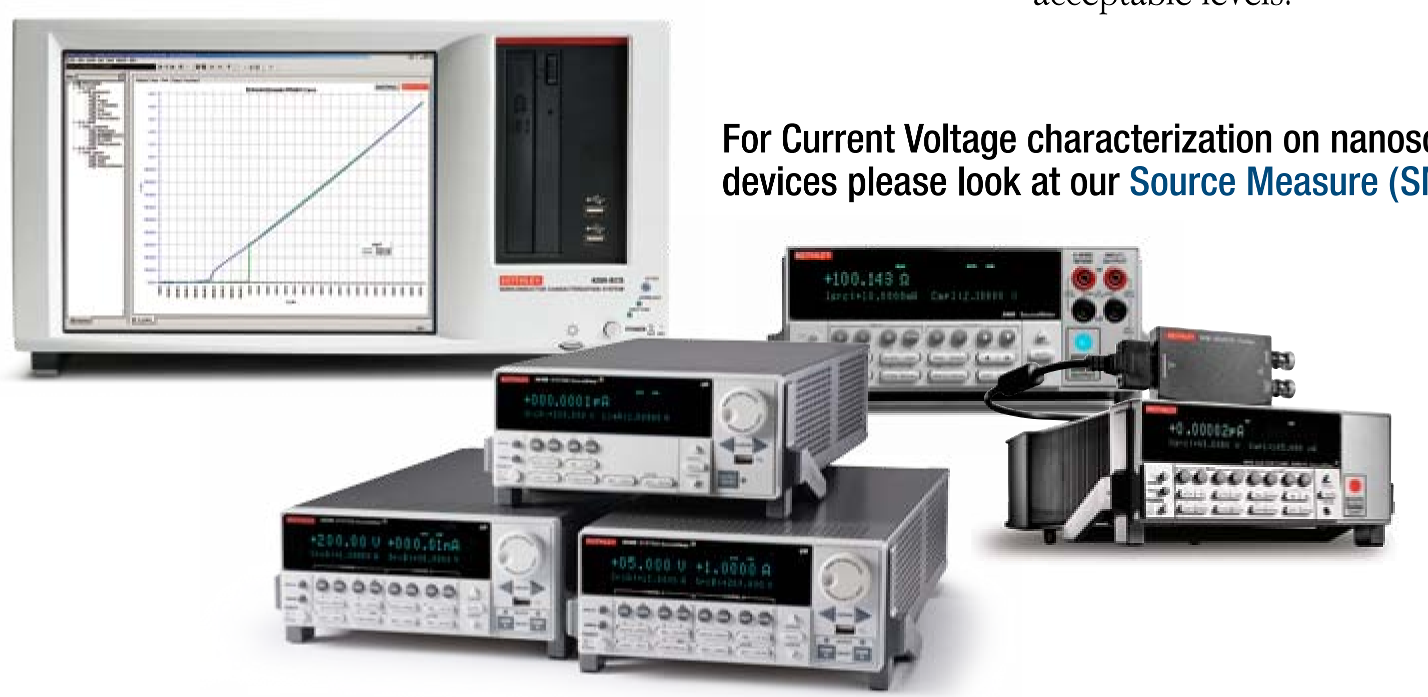
Source and Measure Unit (SMU) Instruments

A commercial DC source and measure unit (SMU) is a convenient test tool for many nanoscopic material and device measurements. SMUs change measurement topology automatically (that is, they can rapidly switch between sourcing voltage/measuring current and sourcing current/measuring voltage). This makes it easier to minimize measurement noise while maximizing measurement speed and accuracy.

Some nanoparticles can change state with the application of an external field. When investigating such materials, an SMU can be configured to source voltage and measure current for a nanoparticle in its high impedance state. When the material is in its low impedance state, more accurate results are achieved by sourcing current and measuring voltage. Furthermore, the SMU has a current compliance function that can automatically limit the DC current level to prevent damage to the material or device under test (DUT). Similarly, there is a voltage compliance function when voltage is being sourced.

When using the compliance function, an SMU will satisfy the source value unless the user's compliance value is exceeded. For example, when an SMU is configured to source voltage with a preset current compliance, if that compliance value is exceeded, the SMU automatically starts acting as a constant current source. Its output level then will be the compliance current value. Alternately, if the SMU is set to source current with a compliance voltage, it will automatically switch to sourcing voltage (the compliance voltage) if the DUT impedance and the current it draws begin to drive the voltage higher than the compliance value.

Although a nanoscopic device, such as a CNT switch, can change states rapidly, the change in instrument state is not instantaneous. Depending on the SMU model, the switching time can range from 100 nanoseconds to 100 microseconds. Although such switching speeds are not fast enough to track a nanoparticle as it changes state, the time is short enough to allow accurate measurements of both states while limiting DUT power dissipation to acceptable levels.



For Current Voltage characterization on nanoscale materials and next generation devices please look at our Source Measure (SMU) Instrument offerings.

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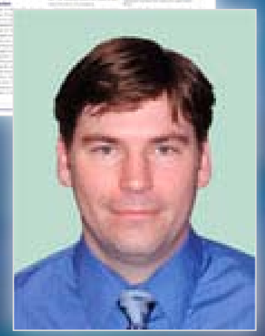
- Test System is Key to Practical Applications of Nanotechnology



- In-situ Correlation of Mechanical Properties, Deformation Behavior, and Electrical Characteristics of Materials Using Conductive Nanoindentation

Ryan Major
R&D Project Manager
Hysitron, Inc.

Additional Resources

- Model 4200-SCS Semiconductor Characterization System
- Series 2600A System SourceMeter® Instruments

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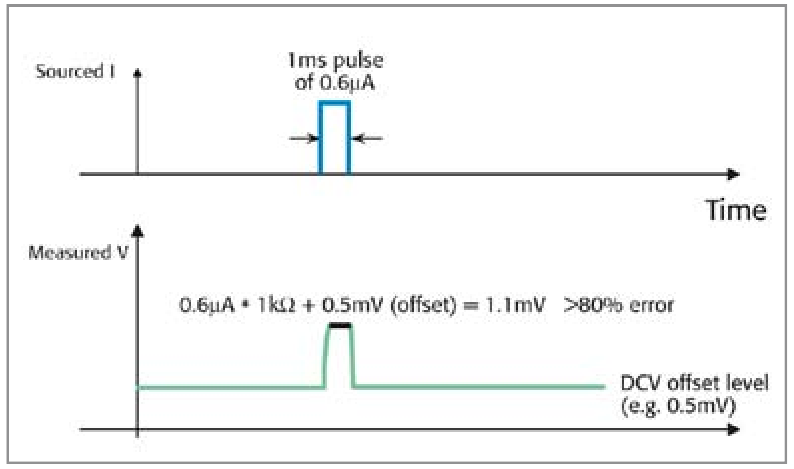
Pulsing Techniques

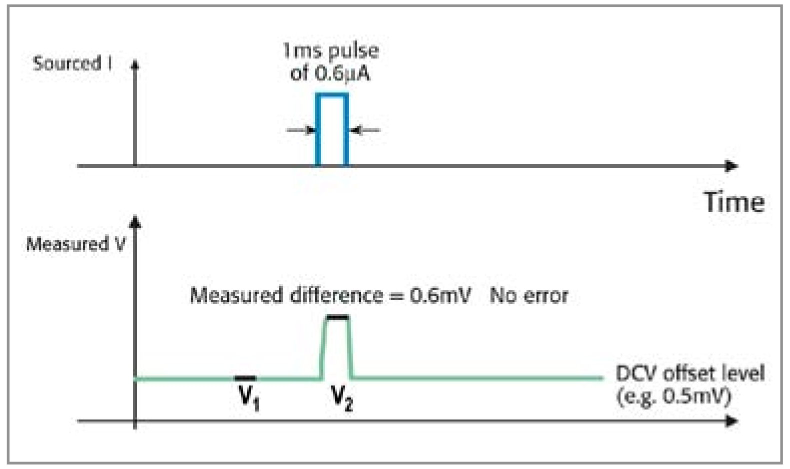
Choosing the correct measurement topology to improve measurement speed and minimize noise may still be insufficient to the test needs for some nanoscopic materials. For example, it appears that some CNTs can switch 1000 times faster than conventional CMOS transistor switches. This is too fast for the nano-amp ranges of commercial picoammeters. Demanding devices like these may require other techniques to improve the speed of impedance measurements.

Low power pulsing techniques may offer a partial solution to this problem and are available in some SMU designs. The idea is to use a much higher test current or test voltage and apply this large stimulus for a short sourcing cycle. The larger stimulus will lower the sourcing noise (by improving the signal-to-noise ratio) and improve the rise or settle time for a voltage pulse or current pulse, respectively. Quieter sources require less filtering and permit a shorter sourcing cycle time (narrower pulse width). A larger source stimulus also increases the response current or voltage so that higher instrument ranges can be used, further minimizing the effects of noise. Because there is less noise, the measurement acquisition time (integration period) can be shortened, allowing for faster measurements.

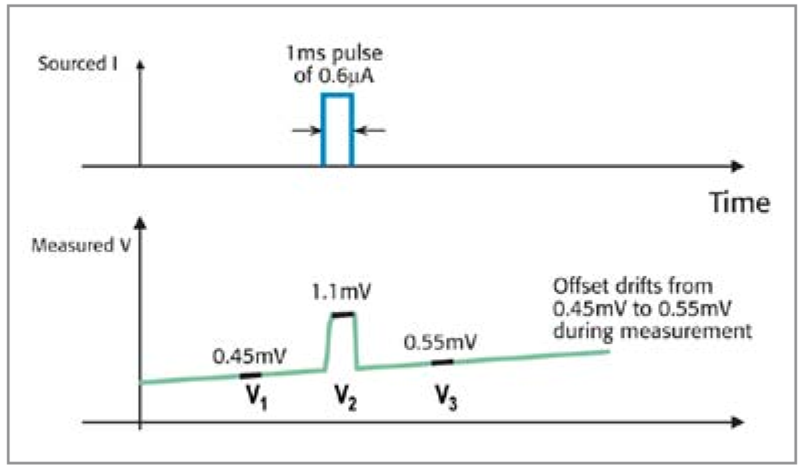
For Pulse and Low-Power Characterization check out our Model 4225-PMU Ultra Fast I-V Module, Model 6221 AC and DC Current Source, and the Model 2181A Nanovoltmeter



DC offsets due to thermal voltages and meter offsets can give significant errors in the measured voltage.



Performing a 2-point delta measurement cancels offset error. The measured delta voltage gives correct voltage response to the current pulse.



An optional third measurement point can help cancel moving offsets.

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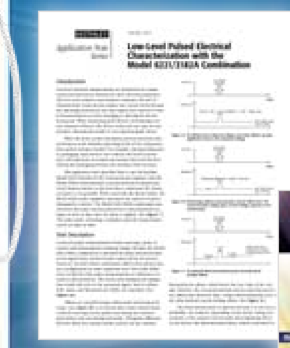

- Low-Level Pulsed Electrical Characterization with the Model 6221/2182A Combination

- Ultra-Fast I-V Applications for the Model 4225-PMU Ultra-Fast I-V Module

Additional Resources

- Pulse Testing for Nanoscale Devices
- Keithley Pulse Solutions

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Avoiding Self-Heating Problems

A possible source of error in nano research is self-heating due to excessive electrical current through the DUT. Such currents may even lead to catastrophic failure of the sample. Therefore, instrumentation must automatically limit source current during device testing. Programmable current and voltage compliance circuits are standard features of most SMU-based test systems with pulsed current capabilities and may be required to avoid self-heating of some low resistance structures.

When an elevated test current is required, it must be short enough so that it does not introduce enough energy to heat the DUT to destructive temperatures. (Nanoscopic devices tolerate very little heat, so the total energy dissipated in them must be maintained at low levels.) In addition, care must be taken that the magnitude of the test current is low enough that the DUT's nanoscopic channel does not become saturated. (For instance, a current channel that's 1.5 nanometers in diameter severely limits the number of electrons that can pass through it per unit of time.) Some nanoscopic devices can support only a few hundred nano-amps of current in their conductive state. Thus, a device's saturation current may define the maximum test current, even in pulsed applications.

The following equation illustrates how duty cycle and measurement time in pulse mode affect DUT power dissipation. To calculate power dissipation in pulse mode, multiply the apparent power dissipation (V·I) by the test stimulus time and divide by the test repetition rate:

$$P_p = P_a \times T_t / T_r$$

where: P_p = Pulse power dissipation
P_a = Apparent power (i.e., V·I)
T_t = Test time
T_r = Test repetition rate

Pulse mode is also useful for density of state measurements using a low impedance connection, such as through a nano-manipulator. Pulsing allows measurements at I/V locations that were previously uncharacterizable due to particle self-heating.

For nano/small scale semiconductor low power measurements check out the Model 6221 AC and DC Current Source, Model 2181A Nanovoltmeter and the Series 2600B SourceMeter® SMU Instruments

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- How to Avoid Self-Heating Effects on Nanoscale Devices

Jonathan Tucker
Senior Marketer, Nanotechnology
Keithley Instruments, Inc.

- AC versus DC Measurement Methods for Low-power Nanotech and Other Sensitive Devices

Mary Anne Tupta
Senior Staff Applications Engineer
Keithley Instruments, Inc.

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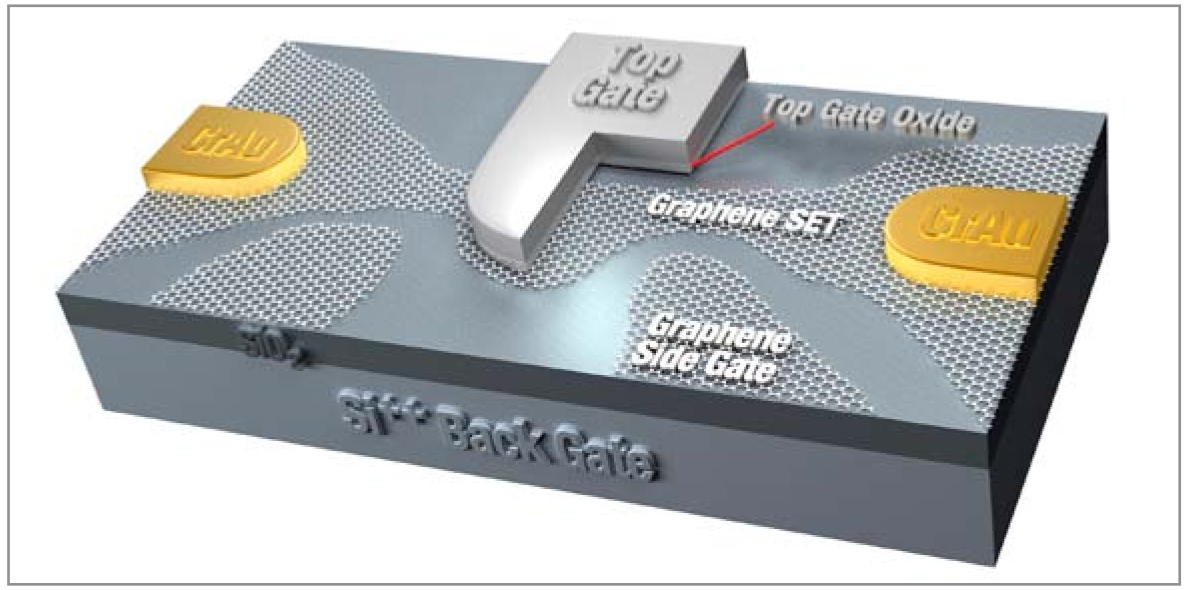
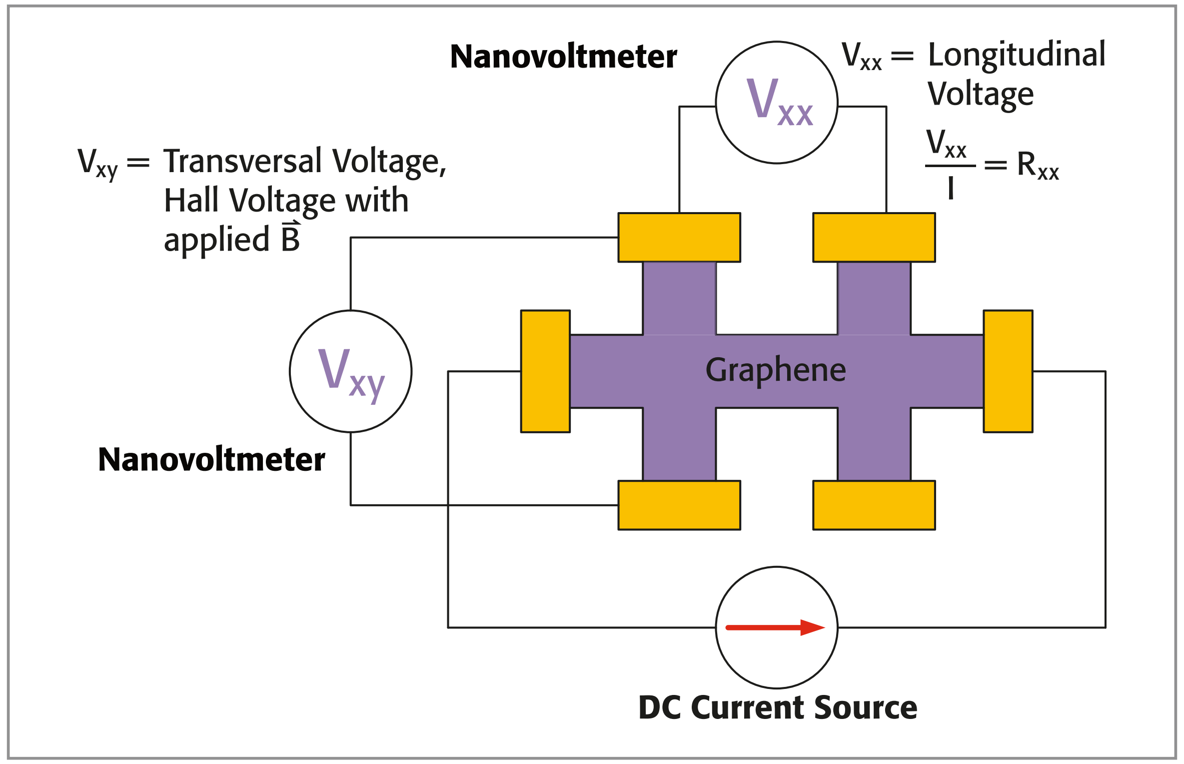
Graphene:
The Semiconductor Industry's Replacement for Silicon?

Graphene, the single-atom-thick crystal of carbon, has outstanding electrical conductivity. It also has extremely strong, yet flexible bonds. Its hardness is greater than the hardness of diamond. Until relatively recently, physicists did not believe that a solid crystal just a single atom thick could exist. Professors Novoselov and Geim proved otherwise with the discovery of graphene in 2004; for their achievement, they won the 2010 Nobel Prize in Physics.

For the semiconductor industry, the exciting thing about graphene is that electrons travel through it unimpeded, and these electrons behave according to quantum electrodynamic principles. Carrier mobilities through graphene are on the order of 10,000cm^2/V-s at room temperature, and mobility values as high as 200,000 cm^2/V-s on suspended samples of graphene have been reported. Graphene's high mobility has already led to the development of very high frequency (100GHz and higher) RF transistors. Unfortunately, graphene does not have a natural bandgap, so many researchers are investigating methods to create one so graphene's high speed properties and nano scale size could replace silicon in next-generation FETs for digital circuitry, thereby extending the life of Moore's Law.



A graphene single electron transistor (SET).



Configuration for simultaneous measurement of Hall effect voltage and longitudinal resistance of a graphene sample in a Hall bar configuration.

Researchers characterizing graphene and graphene-based materials use Hall effect measurements and study longitudinal resistance to assess carrier mobility and look for evidence of the quantum Hall effect, whereby longitudinal resistivity decreases to near 0Ω-cm. These measurements require very low current, precision sourcing, on the order of nano-amps. However, the most important aspect of tight control over sourcing is ensuring that excessive power does not develop across the graphene sample in order to avoid destroying it. Furthermore, at nano-amp source current levels, the resulting voltages developed across the sample are extremely small, on the order of ten to hundreds of nanovolts. These type of nanovolt-level measurements require special instrumentation with sufficient resolution and extremely high sensitivity.

In nanovolt-level measurements, thermoelectric voltages and noise sources can significantly impact measurement accuracy, so it's important to employ techniques designed to minimize these effects. For example, using a current source that allows reversing the polarity of its signal can eliminate measurement errors due to thermal voltage offsets. Furthermore, a current source that can output low duty cycle, narrow pulses will minimize measurement errors due to resistivity changes resulting from self-heating of the graphene sample.

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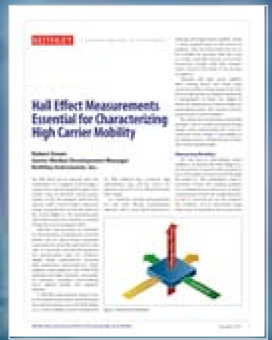
Want to Explore Further?

Featured Resources

- Mastering Low Power, Low Voltage, Low Resistance Measurement Techniques for Characterizing Graphene and Other Nano Materials

Robert Green

Additional Resources



- Hall Effect Measurements Essential for Characterizing High Carrier Mobility

For the latest insights on how scientists around the world are using Keithley instrumentation to explore graphene's potential, click here.

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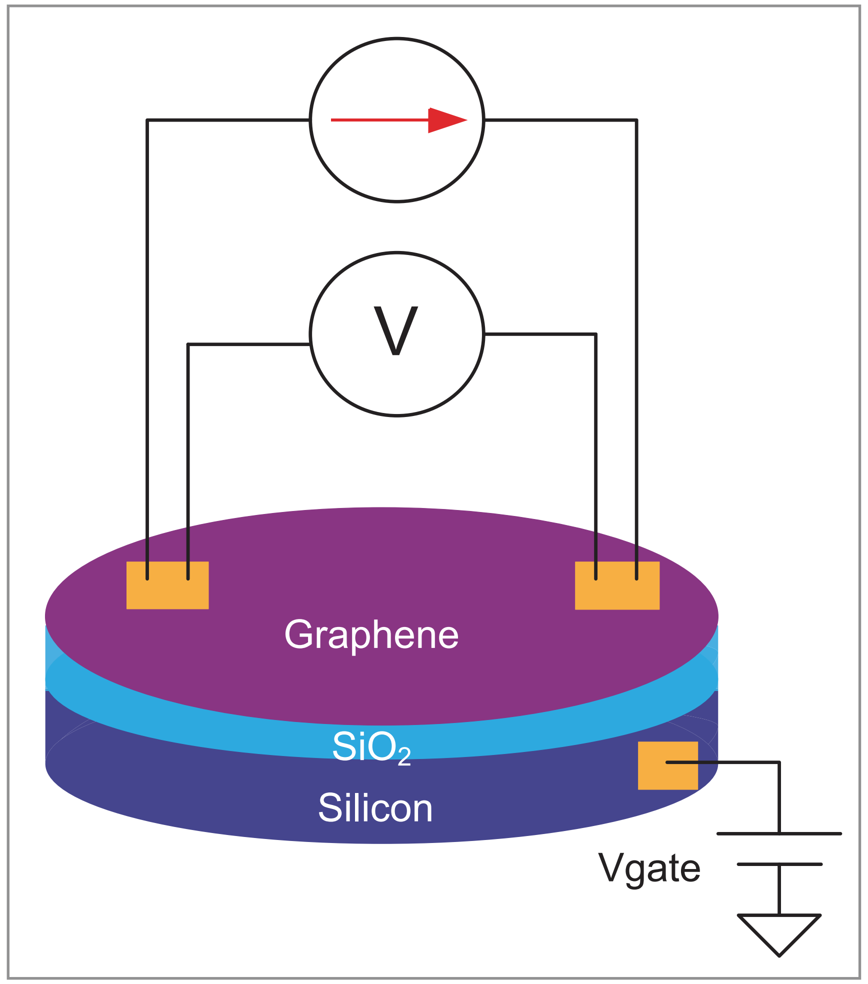
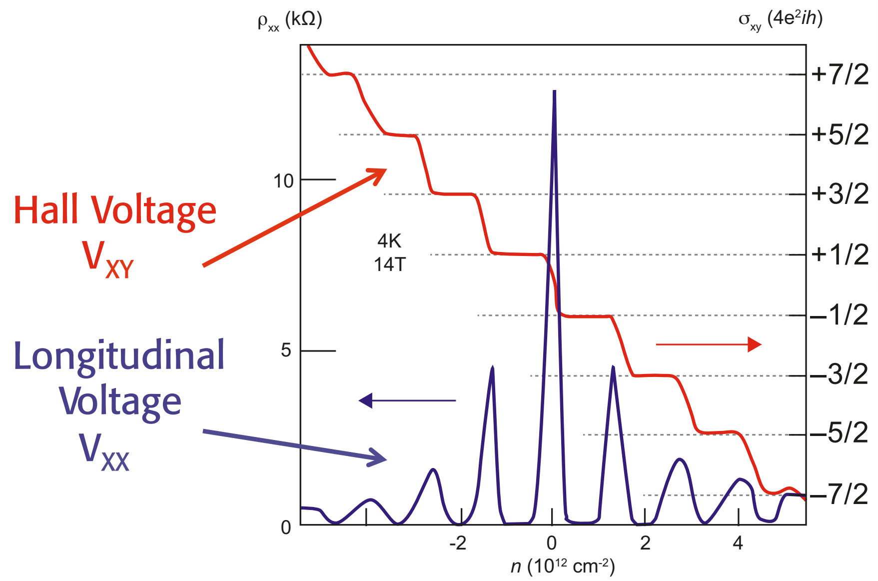
Graphene: The Semiconductor Industry's Replacement for Silicon? (continued)

Thus, using a current source and nanovoltmeter combination that can synchronize sourcing and measurement simplifies the elimination of the thermal offsets and the of averaging out noise signals.



Configuration of a measurement system for assessing the bandgap in graphene and graphene-based structures.

For graphene or a graphene-based material to replace silicon, it must have a bandgap so that a FET channel can be turned on and off. A precision SourceMeter® instrument is needed to modulate the substrate or "gate" voltage to characterize the sample's performance across a range of gate voltages. Again, a low level current source and a nanovoltmeter are required to provide low power, low level measurements.



Plot of Hall voltage and longitudinal voltage across a magnetic field of varying intensity. Note how the Hall Voltage is constant at specific points of magnetic field intensity; at those points, the longitudinal voltage drops to near 0, indicating extremely high conductivity. This demonstrates that graphene exhibits the quantum Hall effect.

Plot courtesy of Neto, Novoselov, Geim, et, al. The Electronic Properties of Graphene. Jan. 2009

For Hall Effect and Low-power Measurements check out the Model 6221 AC and DC Current Source, Model 2181A Nanovoltmeter, the Series 2400 SourceMeter® SMU Instruments, and the 4200-SCS Semiconductor Characterization System.

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- Take Advantage of Keithley's Expertise with Measurements on Graphene

Additional Resources

- Delta Mode Online Demo
- Achieving Accurate and Reliable Resistance Measurements in Low Power and Low Voltage Applications
- Hall Effects Fundamentals Webinar

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Summary

The electronic structure of nanoscopic particles is a reflection of the atomic electron energies and the distribution of orbitals for both molecularly shared and free electrons. This kind of information can be used to describe how such materials will interact in the presence of energy and other materials. The density of states in a material is directly related to its electronic structure and is useful in predicting or manipulating its properties.

It can be found through direct electrical measurements of differential conductance. Thus, the density of states can predict a material's electrical impedance and vice versa.

However, there is a right way and a wrong way to interrogate a nanoscopic material electrically, depending on its impedance. For a low impedance material, the source current/measure voltage method will result in the least electrical noise and allow the most accurate response measurement with the widest bandwidth. For a high impedance material, the source voltage/measure current method is more appropriate for similar reasons. At times, the appropriate measurement mode must be used in unison with yet another voltage or current source to activate or stimulate the device.

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Want to Explore Further?

Featured Resources


Characterizing Nanoscale Devices With Differential Conductance Measurements

- Characterizing Nanoscale Devices with Differential Conductance Measurements

Additional Resources

- Model 4200 Semiconductor Characterization Test System Product Intro
- Model 4200-SCS Semiconductor Characterization System

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Glossary

Absolute Accuracy. A measure of the closeness of agreement of an instrument reading compared to that of a primary standard having absolute traceability to a standard sanctioned by a recognized standards organization. Accuracy is often separated into gain and offset terms. *See also* **Relative Accuracy**.

A/D (Analog-to-Digital) Converter. A circuit used to convert an analog input signal into digital information. All digital meters use an A/D converter to convert the input signal into digital information.

Analog Output. An output that is directly proportional to the input signal.

Assembler. A molecular manufacturing device that can be used to guide chemical reactions by positioning molecules. An assembler can be programmed to build virtually any molecular structure or device from simpler chemical building blocks.

Auto-Ranging. The ability of an instrument to automatically switch among ranges to determine the range offering the highest resolution. The ranges are usually in decade steps.

Auto-Ranging Time. For instruments with auto-ranging capability, the time interval between application of a step input signal and its display, including the time for determining and changing to the correct range.

Bandwidth. The range of frequencies that can be conducted or amplified within certain limits. Bandwidth is usually specified by the –3dB (half-power) points.

Bias Voltage. A voltage applied to a circuit or device to establish a reference level or operating point of the device during testing.

Capacitance. In a capacitor or system of conductors and dielectrics, that property which permits the storage of electrically separated charges when potential differences exist between the conductors. Capacitance is related to the charge and voltage as follows: C = Q/V, where C is the capacitance in farads, Q is the charge in coulombs, and V is the voltage in volts.

Carbon Nanotube. A tube-shaped nanodevice formed from a sheet of single-layer carbon atoms that has novel electrical and tensile properties. These fibers may exhibit electrical conductivity as high as copper, thermal conductivity as high as diamond, strength 100 times greater than steel at one-sixth of steel's weight, and high strain to failure. They can be superconducting, insulating, semiconducting, or conducting (metallic). Non-carbon nanotubes, often called nanowires, are often created from boron nitride or silicon.

Channel (switching). One of several signal paths on a switching card. For scanner or multiplexer cards, the channel is used as a switched input in measuring circuits, or as a switched output in sourcing circuits. For switch cards, each channel's signals paths are independent of other channels. For matrix cards, a channel is established by the actuation of a relay at a row and column crosspoint.

Coaxial Cable. A cable formed from two or more coaxial cylindrical conductors insulated from each other. The outermost conductor is often earth grounded.

Common-Mode Rejection Ratio (CMRR). The ability of an instrument to reject interference from a common voltage at its input terminals with respect to ground. Usually expressed in decibels at a given frequency.

Common-Mode Current. The current that flows between the input low terminal and chassis ground of an instrument.

Common-Mode Voltage. A voltage between input low and earth ground of an instrument.

Contact Resistance. The resistance in ohms between the contacts of a relay or connector when the contacts are closed or in contact.

Contamination. Generally used to describe the unwanted material that adversely affects the physical, chemical, or electrical properties of a semiconductor or insulator.

D/A (Digital-to-Analog) Converter. A circuit used to convert digital information into an analog signal. D/A converters are used in many instruments to provide an isolated analog output.

Dielectric Absorption. The effect of residual charge storage after a previously charged capacitor has been discharged momentarily.

Digital Multimeter (DMM). An electronic instrument that measures voltage, current, resistance, or other electrical parameters by converting the analog signal to digital information and display. The typical five-function DMM measures DC volts, DC amps, AC volts, AC amps, and resistance.

Drift. A gradual change of a reading with no change in input signal or operating conditions.

Dry Circuit Testing. The process of measuring a device while keeping the voltage across the device below a certain level (e.g., <20mV) in order to prevent disturbance of oxidation or other degradation of the device being measured.

Electrochemical Effect. A phenomenon whereby currents are generated by galvanic battery action caused by contamination and humidity.

Electrometer. A highly refined DC multimeter. In comparison with a digital multimeter, an electrometer is characterized by higher input resistance and greater current sensitivity. It can also have functions not generally available on DMMs (e.g., measuring electric charge, sourcing voltage).

EMF. Electromotive force or voltage. EMF is generally used in context of a voltage difference caused by electromagnetic, electrochemical, or thermal effects.

Electrostatic Coupling. A phenomenon whereby a current is generated by a varying or moving voltage source near a conductor.

Error. The deviation (difference or ratio) of a measurement from its true value. True values are by their nature indeterminate. *See also* **Random Error** *and* **Systematic Error**.

Fall Time. The time required for a signal to change from a large percentage (usually 90%) to a small percentage (usually 10%) of its peak-to-peak value. See also Rise Time.

Faraday Cup. A Faraday cup (sometimes called a Faraday cage or icepail) is an enclosure made of sheet metal or mesh. It consists of two electrodes, one inside the other, separated by an insulator. While the inner electrode is connected to the electrometer, the outer electrode is connected to ground. When a charged object is placed inside the inner electrode, all the charge will flow into the measurement instrument. The electric field inside a closed, empty conductor is zero, so the cup shields the object placed inside it from any atmospheric or stray electric fields. This allows measuring the charge on the object accurately.

Feedback Picoammeter. A sensitive ammeter that uses an operational amplifier feedback configuration to convert an input current into voltage for measurement.

Floating. The condition where a common-mode voltage exists between an earth ground and the instrument or circuit of interest. (Circuit low is not tied to earth potential.)

Four-Point Probe. The four-point collinear probe resistivity measurement technique involves bringing four equally spaced probes in contact with the material of unknown resistance. The array is placed in the center of the material. A known current is passed through the two outside probes and the voltage is sensed at the two inside probes. The resistivity is calculated as follows:

$$\rho = \frac{\varpi}{ln2} \times \frac{V}{I} \times t \times k$$

where: V = the measured voltage in volts, I = the source current in amps, t = the wafer thickness in centimeters, and k = a correction factor based on the ratio of the probe to wafer diameter and on the ratio of wafer thickness to probe separation.

Four-Terminal Resistance Measurement. A measurement where two leads are used to supply a current to the unknown, and two different leads are used to sense the voltage drop across the resistance. The four-terminal configuration provides maximum benefits when measuring low resistances.

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Fullerene. Refers to C60, an approximately spherical, hollow, carbon molecule containing 60 carbon atoms arranged in interlocking hexagons and pentagons, reminiscent of the geodesic dome created by architect R. Buckminster Fuller. Sometimes called "buckminsterfullerene" or "buckyball."

Ground Loop. A situation resulting when two or more instruments are connected to different points on the ground bus and to earth or power line ground. Ground loops can develop undesired offset voltages or noise.

Guarding. A technique that reduces leakage errors and decreases response time. Guarding consists of a conductor driven by a low impedance source surrounding the lead of a high impedance signal. The guard voltage is kept at or near the potential of the signal voltage.

Hall Effect. The measurement of the transverse voltage across a conductor when placed in a magnetic field. With this measurement, it is possible to determine the type, concentration, and mobility of carriers in silicon.

High Impedance Terminal. A terminal where the source resistance times the expected stray current (for example, 1μA) exceeds the required voltage measurement sensitivity.

Input Bias Current. The current that flows at the instrument input due to internal instrument circuitry and bias voltage.

Input Impedance. The shunt resistance and capacitance (or inductance) as measured at the input terminals, not including effects of input bias or offset currents.

Input Offset Current. The difference between the two currents that must be supplied to the input measuring terminals of a differential instrument to reduce the output indication to zero (with zero input voltage and offset voltage). Sometimes informally used to refer to input bias current.

Input Offset Voltage. The voltage that must be applied directly between the input measuring terminals, with bias current supplied by a resistance path, to reduce the output indication to zero.

Input Resistance. The resistive component of input impedance.

Insulation Resistance. The ohmic resistance of insulation. Insulation resistance degrades quickly as humidity increases.

Johnson Noise. The noise in a resistor caused by the thermal motion of charge carriers. It has a white noise spectrum and is determined by the temperature, bandwidth, and resistance value.

Leakage Current. Error current that flows (leaks) through insulation resistance when a voltage is applied. Even high resistance paths between low current conductors and nearby voltage sources can generate significant leakage currents.

Long-Term Accuracy. The limit that errors will not exceed during a 90-day or longer time period. It is expressed as a percentage of reading (or sourced value) plus a number of counts over a specified temperature range.

Maximum Allowable Input. The maximum DC plus peak AC value (voltage or current) that can be applied between the high and low input measuring terminals without damaging the instrument.

MEMS. Microelectromechanical systems. Describes systems that can respond to a stimulus or create physical forces (sensors and actuators) and that have dimensions on the micrometer scale. They are typically manufactured using the same lithographic techniques used to make silicon-based ICs.

Micro-ohmmeter. An ohmmeter that is optimized for low resistance measurements. The typical micro-ohmmeter uses the four-terminal measurement method and has special features for optimum low level measurement accuracy.

Molecular Electronics. Any system with atomically precise electronic devices of nanometer dimensions, especially if made of discrete molecular parts, rather than the continuous materials found in today's semiconductor devices.

Molecular Manipulator. A device combining a proximal-probe mechanism for atomically precise positioning with a molecule binding site on the tip; can serve as the basis for building complex structures by positional synthesis.

Molecular Manufacturing. Manufacturing using molecular machinery, giving molecule-by-molecule control of products and by-products via positional chemical synthesis.

Molecular Nanotechnology. Thorough, inexpensive control of the structure of matter based on molecule-by-molecule control of products and by-products; the products and processes of molecular manufacturing, including molecular machinery.

MOSFET. A metal oxide field effect transistor. A unipolar device characterized by extremely high input resistance.

Nano-. A prefix meaning one billionth (1/1,000,000,000).

Nanoelectronics. Electronics on a nanometer scale. Includes both molecular electronics and nanoscale devices that resemble current semiconductor devices.

Nanotechnology. Fabrication of devices with atomic or molecular scale precision. Devices with minimum feature sizes less than 100 nanometers (nm) are considered products of nanotechnology. A nanometer [one-billionth of a meter (10^{-9}m)] is the unit of length generally most appropriate for describing the size of single molecules.

Nanovoltmeter. A voltmeter optimized to provide nanovolt sensitivity (generally uses low thermoelectric EMF connectors, offset compensation, etc.).

Noise. Any unwanted signal imposed on a desired signal.

Normal-Mode Rejection Ratio (NMRR). The ability of an instrument to reject interference across its input terminals. Usually expressed in decibels at a specific frequency such as that of the AC power line.

Normal-Mode Voltage. A voltage applied between the high and low input terminals of an instrument.

Offset Current. A current generated by a circuit even though no signals are applied. Offset currents are generated by triboelectric, piezoelectric, or electrochemical effects present in the circuit.

Overload Protection. A circuit that protects the instrument from excessive current or voltage at the input terminals.

Picoammeter. An ammeter optimized for the precise measurement of small currents. Generally, a feedback ammeter.

Piezoelectric Effect. A term used to describe currents generated when mechanical stress is applied to certain types of insulators.

Precision. Refers to the freedom of uncertainty in the measurement. It is often applied in the context of repeatability or reproducibility and should not be used in place of accuracy. See also Uncertainty.

Quantum Dot. A nanoscale object (usually a semiconductor island) that can confine a single electron (or a few) and in which the electrons occupy discrete energy states, just as they would in an atom. Quantum dots have been called "artificial atoms."

Random Error. The mean of a large number of measurements influenced by random error matches the true value. *See also* **Systematic Error**.

Range. A continuous band of signal values that can be measured or sourced. In bipolar instruments, range includes positive and negative values.

Reading. The displayed number that represents the characteristic of the input signal.

Reading Rate. The rate at which the reading number is updated. The reading rate is the reciprocal of the time between readings.

Relative Accuracy. The accuracy of a measuring instrument in reference to a secondary standard. *See also* **Absolute Accuracy**.

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Repeatability. The closeness of agreement between successive measurements carried out under the same conditions.

Reproducibility. The closeness of agreement between measurements of the same quantity carried out with a stated change in conditions.

Resolution. The smallest portion of the input (or output) signal that can be measured (or sourced) and displayed.

Response Time. For a measuring instrument, the time between application of a step input signal and the indication of its magnitude within a rated accuracy. For a sourcing instrument, the time between a programmed change and the availability of the value at its output terminals. Also known as **Settling Time**.

Rise Time. The time required for a signal to change from a small percentage (usually 10%) to a large percentage (usually 90%) of its peak-to-peak amplitude. *See also* **Fall Time**.

Sensitivity. The smallest quantity that can be measured and displayed.

Settling Time. For a measuring instrument, the time between application of a step input signal and the indication of its magnitude within a rated accuracy. For a sourcing instrument, the time between a programmed change and the availability of the value at its output terminals. Also known as **Response Time**.

Shielding. A metal enclosure around the circuit being measured, or a metal sleeve surrounding the wire conductors (coax or triax cable) to lessen interference, interaction, or leakage. The shield is usually grounded or connected to input LO.

Shunt Ammeter. A type of ammeter that measures current by converting the input current into a voltage by means of shunt resistance. Shunt ammeters have higher voltage burden and lower sensitivity than do feedback ammeters.

Shunt Capacitance Loading. The effect on a measurement of the capacitance across the input terminals, such as from cables or fixtures. Shunt capacitance increases both rise time and settling time.

Short-Term Accuracy. The limit that errors will not exceed during a short, specified time period (such as 24 hours) of continuous operation. Unless specified, no zeroing or adjustment of any kind are permitted. It is expressed as percentage of reading (or sourced value) plus a number of counts over a specified temperature range.

Single Electron Transistor. A switching device that uses controlled electron tunneling to amplify current. An SET is made from two tunnel junctions that share a common electrode. A tunnel junction consists of two pieces of metal separated by a very thin (~1nm) insulator. The only way for electrons in one of the metal electrodes to travel to the other electrode is to tunnel through the insulator. Tunneling is a discrete process, so the electric charge that flows through the tunnel junction flows in multiples of e, the charge of a single electron.

Source Impedance. The combination of resistance and capacitive or inductive reactance the source presents to the input terminals of a measuring instrument.

Source-Measure Unit (SMU). An electronic instrument that sources and measures DC voltage and current. Generally, SMUs have two modes of operation: source voltage and measure current, or source current and measure voltage. Also known as source-monitor unit or stimulus-measurement unit.

SourceMeter. A SourceMeter® instrument is very similar to the source-measure unit in many ways, including its ability to source and measure both current and voltage and to perform sweeps. In addition, a SourceMeter instrument can display the measurements directly in resistance, as well as voltage and current. It is designed for general-purpose, high speed production test applications. It can also be used as a source for moderate to low level measurements and for research applications.

Source Resistance. The resistive component of source impedance. *See also* **Thevenin Equivalent Circuit**.

Spintronics. Electronics that take advantage of the spin of an electron in some way, rather than just its charge.

Standard Cell. An electrochemical cell used as a voltage reference in laboratories.

Superconductor. A conductor that has zero resistance. Such materials usually become superconducting only at very low temperatures.

Switch Card. A type of card with independent and isolated relays for switching inputs and outputs on each channel.

Switching Mainframe. A switching instrument that connects signals among sourcing and measuring instruments and devices under test. A mainframe is also referred to as a scanner, multiplexer, matrix, or programmable switch.

Systematic Error. The mean of a large number of measurements influenced by systematic error deviates from the true value. *See also* **Random Error.**

Temperature Coefficient. A measure of the change in reading (or sourced value) with a change in temperature. It is expressed as a percentage of reading (or sourced value), plus a number of counts per degree change in temperature.

Temperature Coefficient of Resistance. The change of resistance of a material or device per degree of temperature change, usually expressed in ppm/°C.

Thermoelectric EMFs. Voltages resulting from temperature differences within a measuring circuit or when conductors of dissimilar materials are joined together.

Thevenin Equivalent Circuit. A circuit used to simplify analysis of complex, two-terminal linear networks. The Thevenin equivalent voltage is the open-circuit voltage and the Thevenin equivalent resistance equals the open-circuit voltage divided by the short-circuit current.

Transfer Accuracy. A comparison of two nearly equal measurements over a limited temperature range and time period. It is expressed in ppm. *See also* **Relative Accuracy**, **Short-Term Accuracy**.

Triboelectric Effect. A phenomenon whereby currents are generated by charges created by friction between a conductor and an insulator.

Trigger. An external stimulus that initiates one or more instrument functions. Trigger stimuli include: an input signal, the front panel, an external trigger pulse, and IEEE-488 bus X, talk, and GET triggers.

Two-Terminal Resistance Measurement. A measurement where the source current and sense voltage are applied through the same set of test leads.

Uncertainty. An estimate of the possible error in a measurement; in other words, the estimated possible deviation from its actual value.

van der Pauw Measurement. A measurement technique used to measure the resistivity of arbitrarily shaped samples.

Voltage Burden. The voltage drop across the input terminals of an ammeter.

Voltage Coefficient. The change in resistance value with applied voltage. Usually expressed in percent/V or in ppm/V.

Warm-up Time. The time required after power is applied to an instrument to achieve rated accuracy at reference conditions.

Zero Offset. The reading that occurs when the input terminals of a measuring instrument are shorted (voltmeter) or open-circuited (ammeter).

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Which Keithley nanotechnology solution is best for your sourcing or measurement application?

Keithley instrumentation is being used in a growing list of nanotechnology research and production test settings. The applications shown here are only a sampling of the nanotechnology test and measurement tasks for which our instruments and systems are suitable. If your tests require sourcing or measuring low level signals, Keithley instrumentation can help you perform them more accurately and cost-effectively.

Want low current measurements without the high price tag?

With <200µV burden voltage, the cost-effective **Model 6485 Picoammeter** ensures accurate low current measurements, even in circuits with very low source voltages. The **Model 6487 Picoammeter/Voltage Source** adds a 500V bias source for high resistance and resistivity measurements. The **Model 6482 Dual-Channel Picoammeter/Voltage Source** gives you two channels in one instrument to save rack space.

Trying to characterize high resistance nanomaterials?

The **Model 6517B Electrometer/High Resistance Meter's** built-in 1kV source, 200TΩ input resistance, and low current sensitivity make it an ideal solution.

Want seamless control over current pulse sourcing and measurement?

When linked together, the **Model 6221 AC+DC Current Source** and **Model 2182A Nanovoltmeter** are designed to operate like a single instrument to make high speed pulse mode measurements.

Studying highly resistive nanowires?

The **Model 6430 Sub-Femtoamp Remote SourceMeter®** instrument's low noise and drift performance make it ideal. It measures currents with 400aA (400×10^{-18}A) sensitivity.

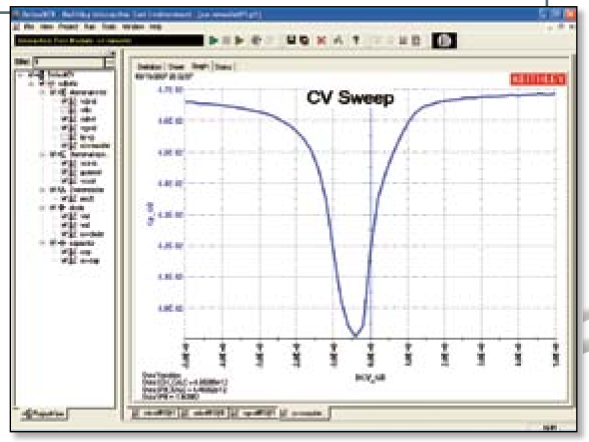
Application	Requirements
Polymer Nanofibers/ Nanowires	High R/Low I, 1MΩ to 10^{14}Ω
Semiconductor Nanowires	Low Power, R <10MΩ, Pulse
Carbon Nanotubes and Graphene	Low Power, R < 100kΩ
Single Electron Devices/Transistors	Low I, Low V
Carbon Nanotube Field Effect Transistors	Low I, Pulse
Nanobatteries	Low I, Low Power
Nanophotonics	Low I, Pulse
Synthesized Molecular Electronics/Wires	Low I, Low Power
Nanosensors & Arrays	Low I, Low V
Thermal Transport	Low I, Low Power, Pulse

Want multiple channels of sourcing and measurement?

The fully integrated **Model 4200 Semiconductor Characterization System** brings together all three core measurement types, DC-IV, AC impedence and transient I-V, in one easy-to-operate package. It's used in many phases of nano research, development, characterization, and production.

Need to characterize mobility, carrier density, and device speed?

The **Model 4210-CVU Option** takes the guesswork out of obtaining valid capacitance-voltage (C-V) measurements quickly and easily, with intuitive point-and-click setup, complete cabling, and built-in element models.



Troubled by overheating problems?

The **Model 4225-PMU** option for the Model 4200-SCS performs pulsed I-V testing on a variety of devices for many different purposes, including preventing device self-heating by using narrow pulses and/or low duty cycle pulses rather than DC signals.

Testing lots of devices?

Series 2600B System SourceMeter® instruments let you make precision DC, pulse, and low frequency AC source-measure tests quickly, easily, and economically. They offer virtually unlimited flexibility to scale the system's channel count up or down to match changing application needs.

Looking for just a single channel?

Each **Series 2400 SourceMeter instrument** is a complete, single-channel DC parametric tester. Choose from a variety of ranges and functions to suit specific application needs. The Model 2430 can be programmed to produce individual pulses or pulse trains up to 5ms wide.

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For More Information

Nanotechnology Measurement Handbook:** A Guide to Electrical Measurements for Nano-science Application* is one of the resources Keithley offers to help you learn how to test nanoscale materials and devices more effectively. It offers practical assistance in making precision low level DC and pulse measurements on nanomaterials and devices. This 130+-page handbook is useful both as a reference and as an aid to understanding low level phenomena observed in the lab. It provides an overview of the theoretical and practical considerations involved in measuring low currents, high resistances, low voltages, and low resistances. ***Click here to request a downloadable copy of the handbook *(Adobe Reader required).*

Other Sources of Information on Nanotechnology

TryNano.org is a resource for students, their parents, their teachers and their school counselors. It was created jointly by IEEE, IBM, and the New York Hall of Science for the benefit of the public. TryNano.org is an initiative led by the IEEE Nanotechnology Council and the IEEE Educational Activities Board with funding from the IEEE New Initiatives Committee.

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Printed in the U.S.A. No. 3114 3.15.13