KEITHLEY
A Tektronix Company

Keithley's Guide to Understanding Electrical Test and Measurement

Essential Technical Articles and Advice

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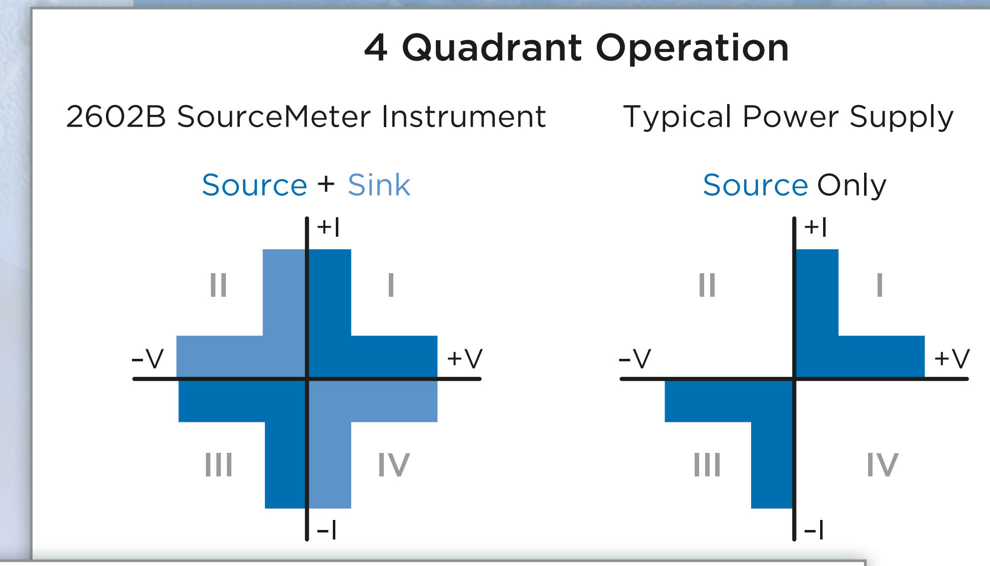
Introduction

Welcome to Keithley's Guide to ***Understanding Electrical Test and Measurement***. For over 60 years, Keithley test and measurement instruments have provided measurements ranging from the most basic to very complex. In all these applications, there is one common element—the best possible measurements need to be made. This library has been compiled to help you analyze your applications and the various types of bench top instruments that can solve your test and measurement needs.

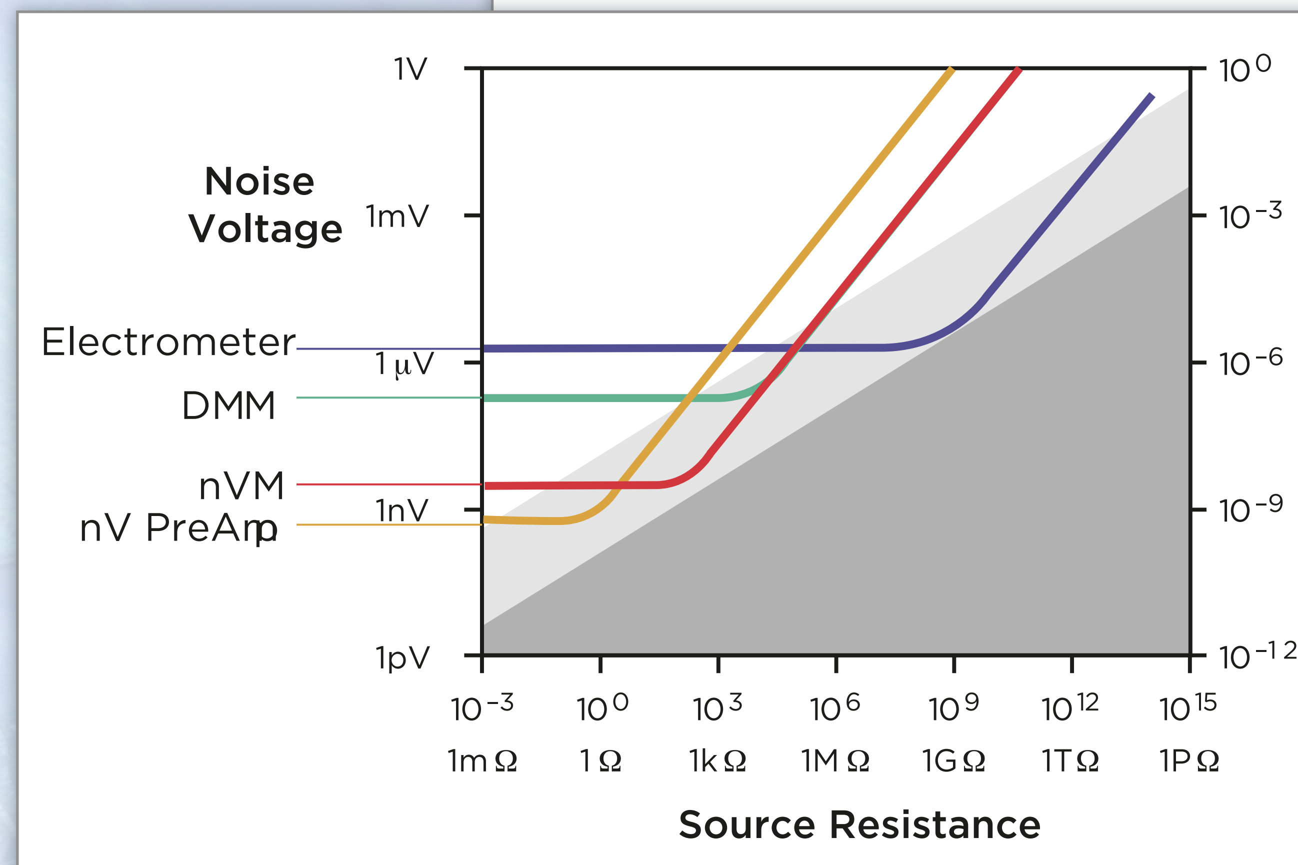


Technical Overviews

- Digital Multimeters and Systems
- DC Power Supplies
- Source Measurement Unit (SMU) Instrument

General Articles

- Choosing DMMs and More for High Performance Applications
- The Global Need for Low-Cost DMMs
- Choosing the Optimal Source Measurement Unit Instrument for Your Test and Measurement Application
- Rapidly Expanding Array of Test Applications Continues to Drive Source Measurement Unit Instrument Technology
- Understanding Linear Power Supply Specifications
- New Materials and Processes Call for New Test Techniques and Instrumentation
- The Right Bus for the Job
- Smart Instruments Keep Up with Changing R&D Needs
- The Test Bench Today: What Designers and Test Engineers Need from a Test-Bench Instrument



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Getting Back to the Basics of Electrical Measurements

Accurate measurements are central to virtually every scientific and engineering discipline, but all too often measurement science gets little attention in the undergraduate curriculum. Even those who received a thorough grounding in measurement fundamentals as undergraduates can be forgiven if they've forgotten some of the details. This white paper is intended to refresh those fading memories or to bring those who want to learn more about making good quality measurements up to speed.

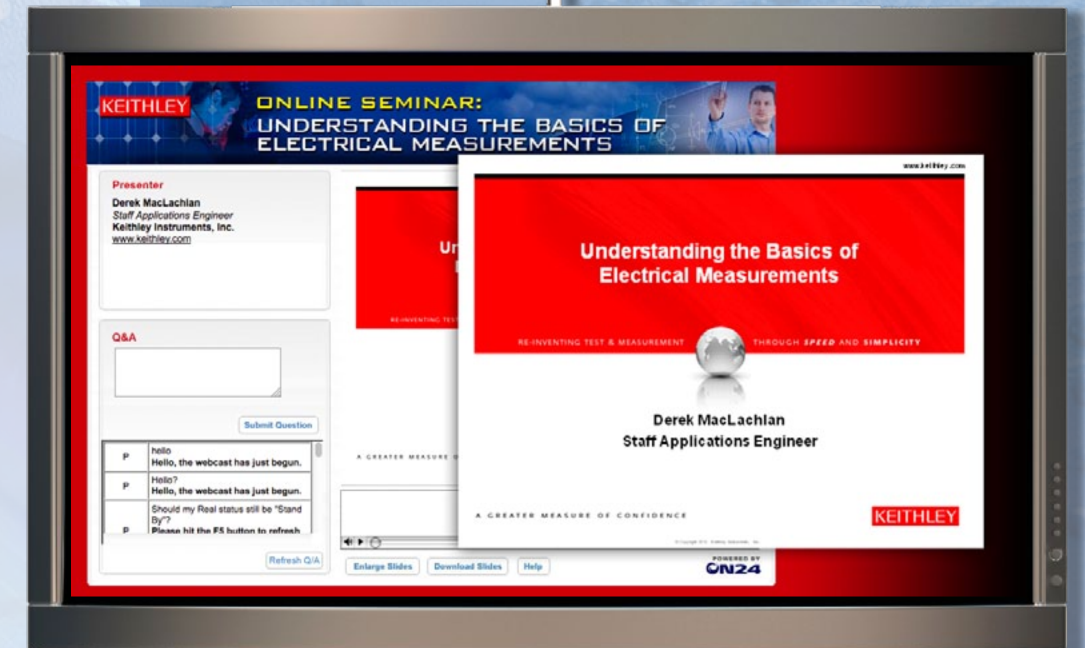
But what exactly does "good quality measurement" mean? Although it can mean a variety of things, one of the most important is the ability to create a test setup that's suitable for the purpose intended. Let's start with a typical test scenario that involves measuring some characteristics of a device or material. This can range from a very simple setup, such as using a benchtop digital multimeter (DMM) to measure resistance values, to more complex systems that involve fixturing, special cabling, etc. When determining the required performance of the system, that is, the required measurement accuracies, tolerances, speed, etc., one must include not only the performance of the measurement instrument but also the limitations imposed by and the effects of the cabling, connectors, test fixture, and even the environment under which tests will be carried out.

When considering a specific measurement instrument for an application, the specification or data sheet is the first place to look for information on its performance and how that will limit the results. However, data sheets are not always easy to interpret because they typically use specialized terminology.

Also, one can't always determine if a piece of test equipment will meet the requirements of the application simply by looking at its specifications. For example, the characteristics of the material or device under test may have a significant impact on measurement quality. The cabling, switching hardware, and the test fixture, if required, can also affect the test results.

The Four-Step Measurement Process

The process of designing and characterizing the performance of any test setup can be broken down into a four-step process. Following this process will greatly increase the chances of building a system that meets requirements and eliminates unpleasant and expensive surprises.



View the Webinar: Understanding the Basics of Measurement

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Step 1 | Define the System's Required Measurement Performance

The first step, before specifying a piece of equipment, is to define the system's required measurement performance. This is an essential prerequisite to designing, building, verifying, and ultimately using a test system that will meet the application's requirements. Defining the required level of performance involves understanding the specialized terminology like resolution, accuracy, repeatability, rise time, sensitivity, and many others.

Resolution is the smallest portion of the signal that can actually be observed. It is determined by the analog-to-digital (A/D) converter in the measurement device. There are several ways to characterize resolution—bits, digits, counts, etc. The more bits or digits there are, the greater the device's resolution. The resolution of most benchtop instruments is specified in digits, such as a 6½-digit DMM. Be aware that the *½ digit* terminology means that the most significant digit has less than a full range of 0 to 9. As a general rule, *½ digit* implies the most significant digit can have the values 0, 1, or 2. In contrast, data acquisition boards are often specified by the number of bits their A/D converters have.

- 12-bit A/D – 4096 counts – approx. 3½ digits
- 16-bit A/D – 65,536 counts – approx. 4½ digits
- 18-bit A/D – 262,144 counts – approx. 5½ digits
- 22-bit A/D – 4,194,304 counts – approx. 6½ digits
- 25-bit A/D – 33,554,304 counts – approx. 7½ digits
- 28 bit-A/D – 268,435,456 counts – approx. 8½ digits

Although the terms *sensitivity* and *accuracy* are often considered synonymous, they do not mean the same thing. Sensitivity refers to the smallest change in the measurement that can be detected and is specified in units of the measured value, such as volts, ohms, amps, degrees, etc. The sensitivity of an instrument is equal to its lowest range divided by the resolution. Therefore, the sensitivity of a 16-bit A/D based on a 2V scale is 2 divided by 65536 or 30 microvolts. A variety of instruments are optimized for making highly sensitive measurements, including nanovoltmeters, picoammeters, electrometers, and high-resolution DMMs. Here are some examples of how to calculate the sensitivity for A/Ds of varying levels of resolution:

- 3½ digits (2000) on 2V range = 1mV
- 4½ digits (20000) on 2Ω range = 100µΩ
- 16-bit (65536) A/D on 2V range = 30µV
- 8½ digits on 200mV range = 1nV

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Step 1 continued | Define the System's Required Measurement Performance

Now that we have a better understanding of sensitivity, what do we mean when describing the accuracy of an instrument? In fact, there are two types of accuracy to consider, namely *absolute accuracy* and *relative accuracy*. Absolute accuracy indicates the closeness of agreement between the result of a measurement and its true value, as traceable to an accepted national or international standard value. Devices are typically calibrated by comparing them to a known standard value. Most countries have their own standards institute where national standards are kept. The *drift* of an instrument refers to its ability to retain its calibration over time. Relative accuracy refers to the extent to which a measurement accurately reflects the relationship between an unknown and a locally established reference value.

The implications of these terms are demonstrated by the challenge of ensuring the absolute accuracy of a temperature measurement of 100.00°C to ±0.01° versus measuring a change in temperature of 0.01°C. Measuring the change is far easier than ensuring absolute accuracy to this tolerance, and often, that is all that an application requires. For example, in product testing, it is often important to measure the heat rise accurately (for example, in a power supply), but it really doesn't matter if it's at exactly 25.00°C ambient.

Repeatability is the ability to measure the same input to the same value over and over again. Ideally, the repeatability of measurements should be better than the accuracy. If repeatability is high, and the sources of error are known and quantified, then high resolution and repeatable measurements are often acceptable for many applications. Such measurements may have high relative accuracy with low absolute accuracy.

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Step 2 | Designing the Measurement System

The next step gets into the actual process of designing the measurement system, including the selection of equipment and fixtures, etc. As mentioned previously, interpreting a data sheet to determine which specifications are relevant to a system can be daunting, so let's look at some of the most important specs included:

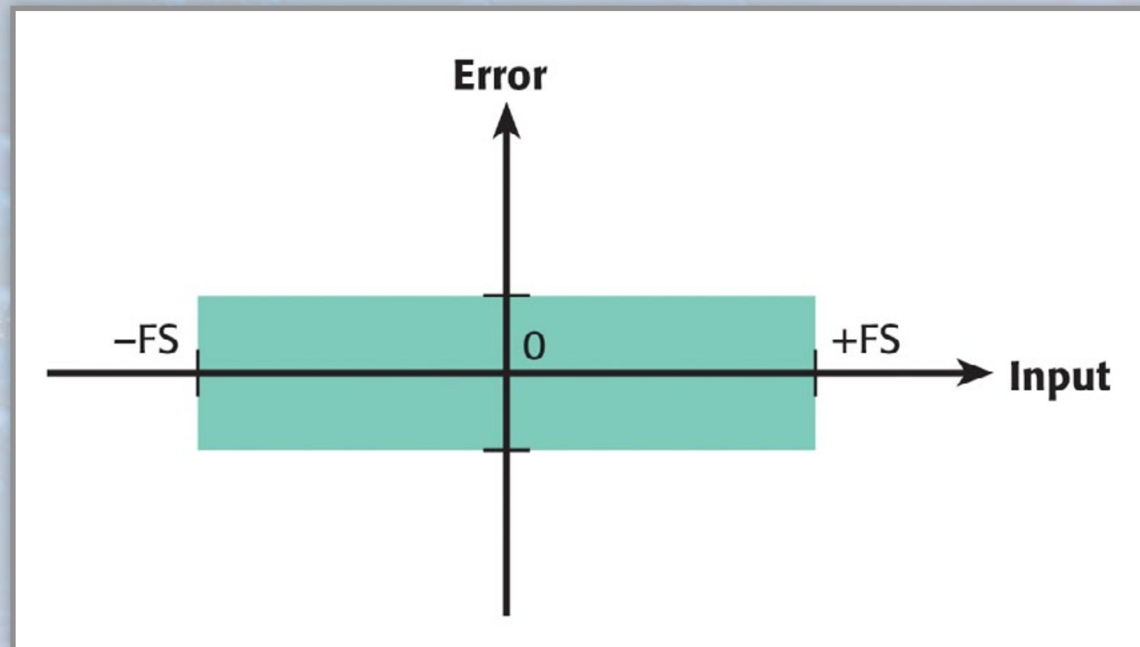

Figure 1

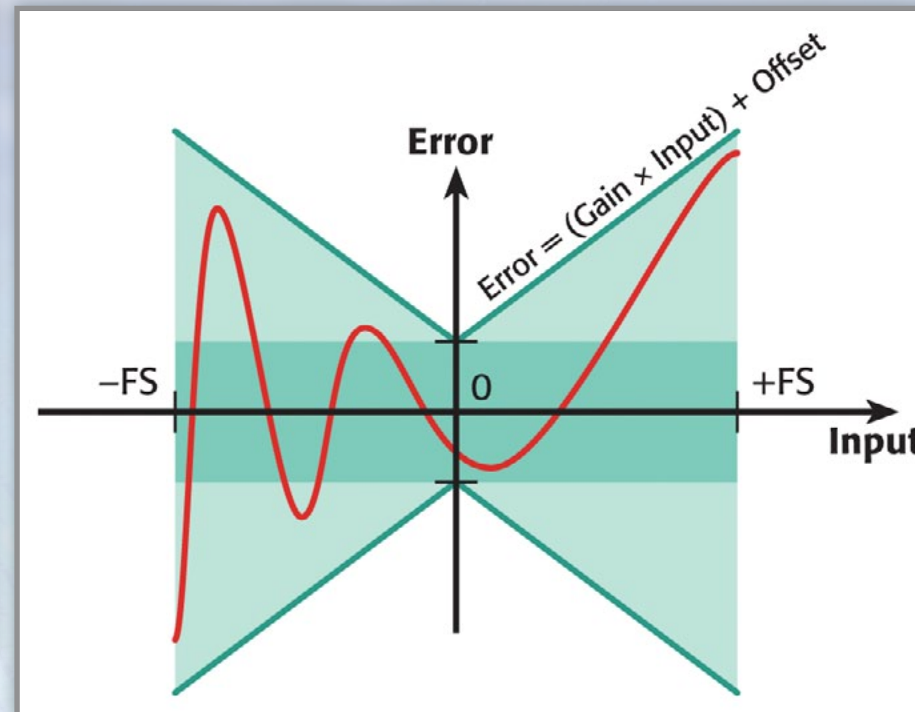

Figure 2

- **Accuracy.** Keithley normally expresses its accuracy specifications in two parts, namely as a proportion of the value being measured, and a proportion of the scale that the measurement is on, for example: ± (gain error + offset error). This can be expressed as ± (% reading + % range) or ± (ppm of reading + ppm of range). The range in ***Figure 1*** is represented by FS or "full scale." For example, the specification for Keithley's Model 2000 6½-digit multimeter, when measuring voltage on the 1V range, states an accuracy of 30ppm of the reading + 7ppm of range. The green box represents the offset error, which is expressed either as a percentage of the range or ppm of the range. ***Figure 2*** illustrates the gain error, which is expressed either as a % of the reading or ppm of the reading. When carrying out a reading, we can expect the error to be anywhere within the purple and green areas of the graph. Accuracy specs for high-quality measurement devices can be given for 24 hours, 90 days, one year, two years, or even five years from the time of last calibration. Basic accuracy specs often assume usage within 90 days of calibration.

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Step 2 continued | Designing the Measurement System

- **Temperature coefficient.** Accuracy specs are normally guaranteed within a specific temperature range; for example, the Model 2000 DMM's guaranteed range is 23°C, ±5°C. If carrying out measurements in an environment where temperatures are outside of this range, it's necessary to add a temperature-related error. This becomes especially difficult if the ambient temperatures vary considerably.
- **Instrumentation error.** Some measurement errors are a result of the instrument itself. As we have already discussed, instrument error or accuracy specifications always require two components: a proportion of the measured value, sometimes called gain error, and an offset value specified as a portion of full range. Let's look at the different instrument specifications for measuring the same value. In this example, we are trying to measure 0.5V on the 2V range, using a lesser quality DMM. Using the specifications, we can see that the uncertainty, or accuracy, will be ± 350μV. In abbreviated specs, frequently only the gain error is provided. The offset error, however, may be the most significant factor when measuring values at the low end of the range.

Accuracy = ±(% reading + % range)
= ±(gain error + offset error)

For example, DMM 2V range:
Accuracy = ±(0.03% of reading + 0.01% range)

For a 0.5V input:
Uncertainty = ±(0.03% × 0.5V + 0.01% × 2.0V)
= ±(0.00015V + 0.00020V)
= ±350μV

Reading = 0.49965 to 0.50035

In the next example, we have the same scenario, i.e., trying to measure 0.5V using the 2V range, but we are now using a better quality DMM. The example has better specifications on the 2V range, and the uncertainty is now just ±35μV.

DMM, 6½-digit, 2V range (2.000000)

Accuracy = ±(0.003% reading + 0.001% range)
= ±(30ppm readings + 10ppm range)
= ±(0.003% reading + 20 counts)

Uncertainty @ 0.5V = ±(0.000015 + 0.000020)
= ±0.000035V
= ±35μV

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Step 2 continued | Designing the Measurement System

Now if we look at performing the same measurement using a data acquisition board, note that 1 LSB offset error is range/4096 = 0.024% of range. On a 2V range, 1 LSB offset error is 0.488 millivolt. Note that the measurement accuracy is much poorer with this data acquisition card than when using the higher quality benchtop DMM.

Analog input board, 12 bit, 2V range

$$\text{Accuracy} = \pm(0.01\%\ \text{reading} + 1\ \text{LSB}) = \pm(100\text{ppm} + 1\ \text{bit})$$

$$\text{Uncertainty @ 05V} = \pm(0.000050 + \frac{2.0)}{4096}$$

$$= \pm(0.000050 + 0.000488)$$
$$= \pm 0.000538$$
$$= \pm 538\mu V$$

- **Sensitivity. Sensitivity,** the smallest observable change that can be detected by the instrument, may be limited either by noise or by the instrument's digital resolution. The level of instrument noise is often specified as a peak-to-peak or RMS value, sometimes within a certain bandwidth. It is important that the sensitivity figures from the data sheet will meet your requirements, but also consider the noise figures as these will especially affect low level measurements.
- **Timing.** What does the *timing* within a test setup mean? Obviously, an automated PC-controlled measurement setup allows making measurements far more quickly than manual testing. This is especially useful in a manufacturing environment, or where many measurements are required. However, it's critical to ensure that measurements are taken when the equipment has "settled" because there is always a tradeoff between the speed with which a measurement is made and its quality. The rise time of an analog instrument (or analog output) is generally defined as the time necessary for the output to rise from 10% to 90% of the final value when the input signal rises instantaneously from zero to some fixed value. Rise time affects the accuracy of the measurement when it's of the same order of magnitude as the period of the measurement. If the length of time allowed before taking the reading is equal to the rise time, an error of approximately 10% will result, because the signal will have reached only 90% of its final value. To reduce the error, more time must be allowed. To reduce the error to 1%, about two rise times must be allowed, while reducing the error to 0.1% would require roughly three rise times (or nearly seven time constants).

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Step 3 | Building and Verifying the Test System

This step addresses building the test system and verifying its performance, including a number of techniques that can be used to improve measurement quality.

Once a system builder has picked appropriate equipment, cables, and fixtures, and established that the equipment's specifications can meet the requirements, it's time to assemble it and verify its performance once step at a time. It is essential to check that each piece of test equipment has been calibrated within its specified calibration period, which is usually one year. If the instrument will be used for making voltage measurements, placing a short across the inputs of the meter will provide an indication of any offset errors. This can be directly compared to the specifications from the data sheet. If the instrument will be used for current measurements, then checking to see the current level with the ammeter open circuit will give an indication of offset current. Again, this can be directly compared to the specifications from the data sheet. Next, include the system cabling and repeat the tests, followed by the test fixture, then the device under test (DUT), repeating the tests after each addition. If the performance of the system does not meet the application's requirements, this "one step at a time" approach should help identify what is causing the problems.

Then, check the system timing to ensure there are sufficient delays to allow for settling time, and reassess it to make sure it satisfies the application's speed goals. Insufficient delay times between measurements can often create accuracy and repeatability problems. In fact, this is among the most common sources of error in test systems, and it's especially evident when running the test at speed produces a different result than when performing the test step by step or manually.

Although inductance can affect settling times, capacitance in the system is a more common problem. In a manual system, a delay of 0.25 to 0.5 seconds will seem to be instantaneous. But in an automated test system, steps are typically executed in a millisecond or less, and even the simplest systems may require delays of five to ten milliseconds after a change in stimulus to get accurate results.

Large systems with lots of cabling (and therefore, lots of cable capacitance, and/or those that measure high impedances ($\tau = RC$) may require even longer delays or special techniques like guarding. Coaxial cable typically has capacitance in the range of 30pF per foot. The common solution is to provide sufficient delays in the measurement process to allow bfor settling. Delays of several milliseconds are commonly needed, but some applications may require even longer delays. To address this need, most Keithley instruments include a programmable trigger delay.

Guarding is one technique for dealing with capacitance issues, reducing leakage errors and decreasing 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.

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Step 3 continued | Building and Verifying the Test System

Leading Sources of Measurement Error

Although all systems are unique, the following sources of error are among the most common:

- **Lead resistance.** For resistance measurements, especially at lower resistances, it is important to take into account the resistance of the test leads. In the example shown in ***Figure 3a***, the two-wire ohms method is being used to determine the resistance. A current source in the meter outputs a known and stable current, and the voltage drop is measured within the meter. This method works well if the resistance to be measured is very much greater than the lead resistance. However, what if the resistance to be measured is much closer to the lead resistance or even less? Using four-wire measurements (***Figure 3b***) will eliminate this problem. The voltage drop is now measured across the resistor, instead of across the resistor and leads. The input resistance of the voltmeter tends to be very high in comparison to the resistance to be measured; therefore, the lead resistances on the voltmeter path can be ignored. If, however, the resistance to be measured is very high, and approaching the resistance of the voltmeter, then an electrometer or specialized meter with extremely high input resistance may be required.

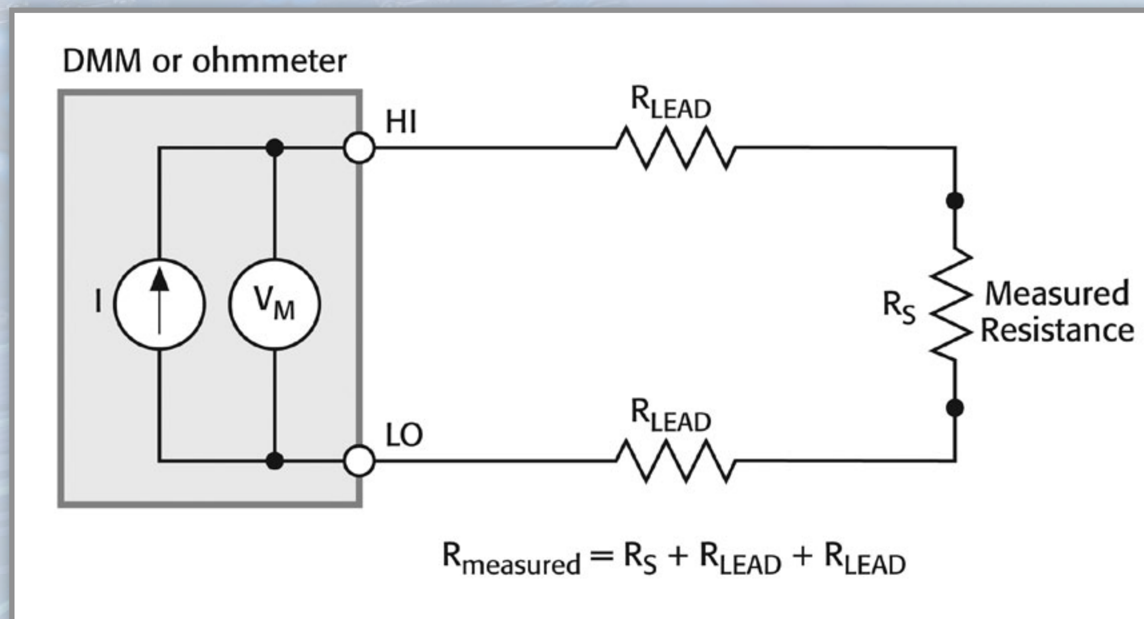

Figure 3a

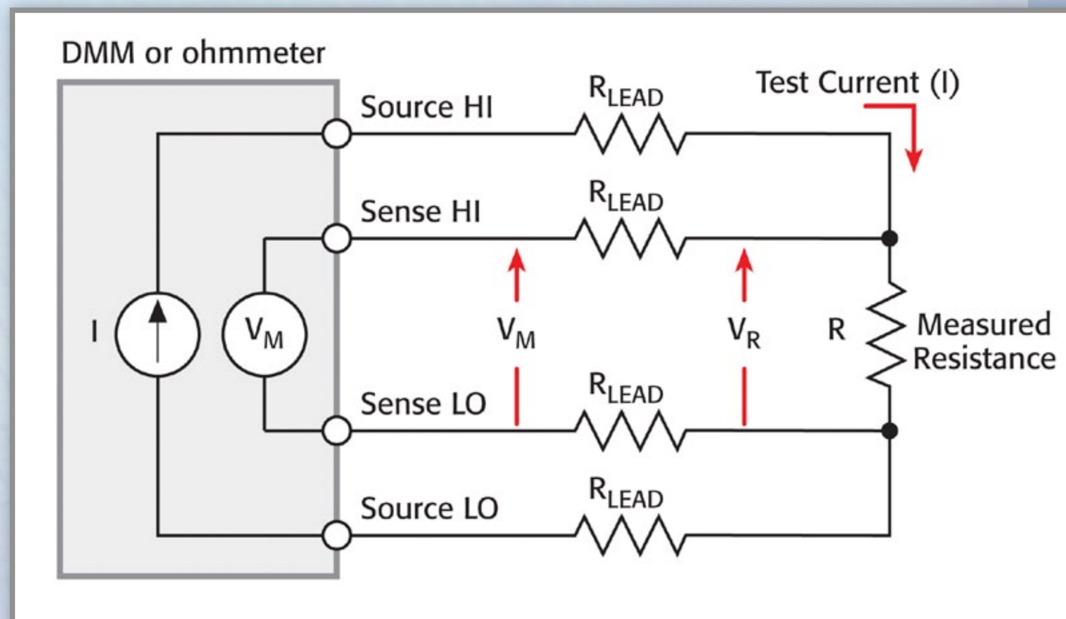

Figure 3b

- **Thermoelectric EMFs in connections.** In any measurement system, any connections made that are of dissimilar metals will produce a thermocouple. A thermocouple is essentially a device of two dissimilar metals that generates a voltage that varies with temperature. These qualities can be put to good use when using thermocouples to monitor temperature, but in standard test system, they result in the introduction of unwanted voltages. As temperatures vary, so does the magnitude of the unwanted voltages. ***Table 1*** lists some examples of the types of voltages that can be generated. Even when connecting copper to copper, there are typically enough differences in the composition of the two pieces of metal that voltages will be generated. If the magnitude of these errors is significant in comparison to the value to be measured, the offset compensated ohms technique can help eliminate the effect.

Materials	Potential
Cu – Cu	≤ 0.2QV/ºC
Cu – Ag	0.3QV/ºC
Cu – Au	0.3QV/ºC
Cu – Cd/Sn	0.3QV/ºC
Cu – Pb/Sn	1-3QV/ºC
Cu – Si	400QV/ºC
Cu – Kovar	40QV/ºC
Cu – CuO	1000QV/ºC

Table 1. Thermoelectric Potentials

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Step 3 continued | Building and Verifying the Test System

This offset-compensated ohms technique is built into many Keithley instruments. When this feature is enabled, the measurement cycle now consists of two parts (***Figure 4***): the first part is measuring the voltage with stimulus current switched on, the second part is to measure it with the stimulus current switched off. Subtracting the latter from the former will subtract out the errors due to thermoelectric EMFs. Therefore, this technique will effectively eliminate accuracy issues due to temperature drift.

- **External interference.** External interference introduces both AC and DC errors into signal measurements. The most common form of external noise "pick-up" is 50Hz or 60Hz line pick-up, depending on where in the world the measurements are being made. Picking up millivolts of noise is not uncommon, especially when measurements are made near fluorescent lights. The signal components of noise superimposed on a DC signal being measured may result in highly inaccurate and fluctuating measurements. As shown in ***Figure 5***, the measured value will very much depend on where the measurement is carried out in relation to the sine wave. Many modern instruments allow users to set the integration period in relation to the number of power line cycles. In other words, a setting of 1 NPLC will result in the measurement being integrated for 20 milliseconds (if 50Hz) and 16.67milliseconds (if 60Hz), which will eliminate any mains generated noise. The performance improvements this feature make possible are often dramatic.

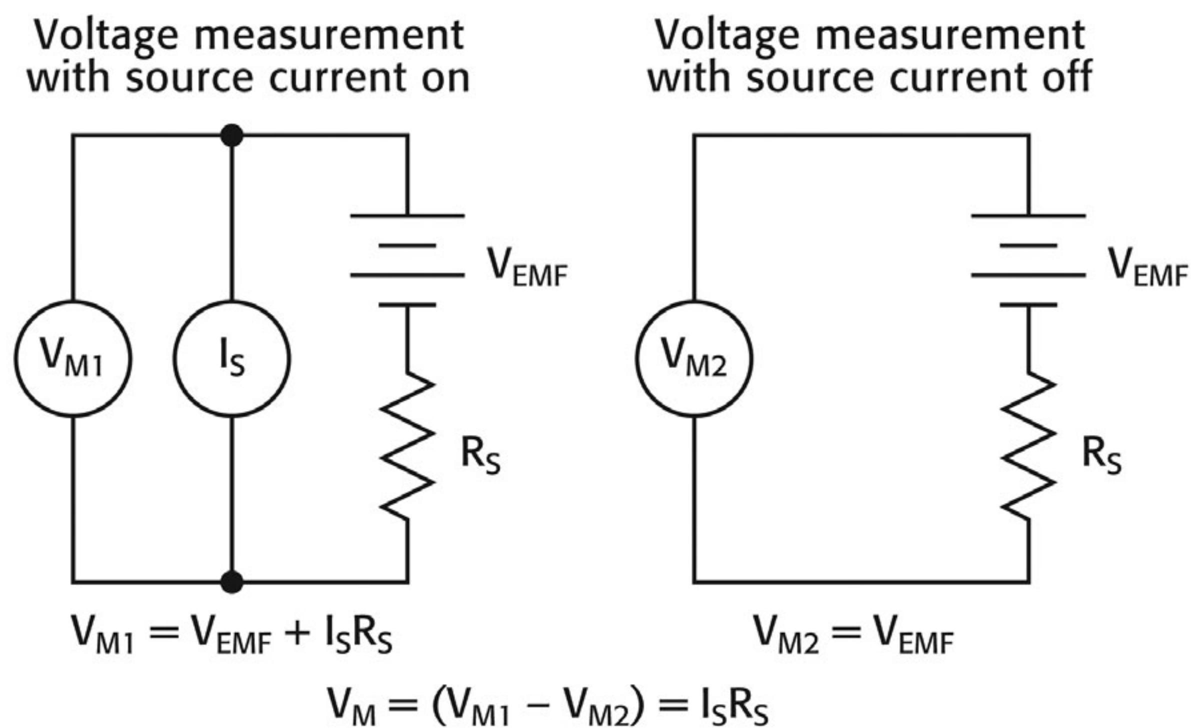

Figure 4

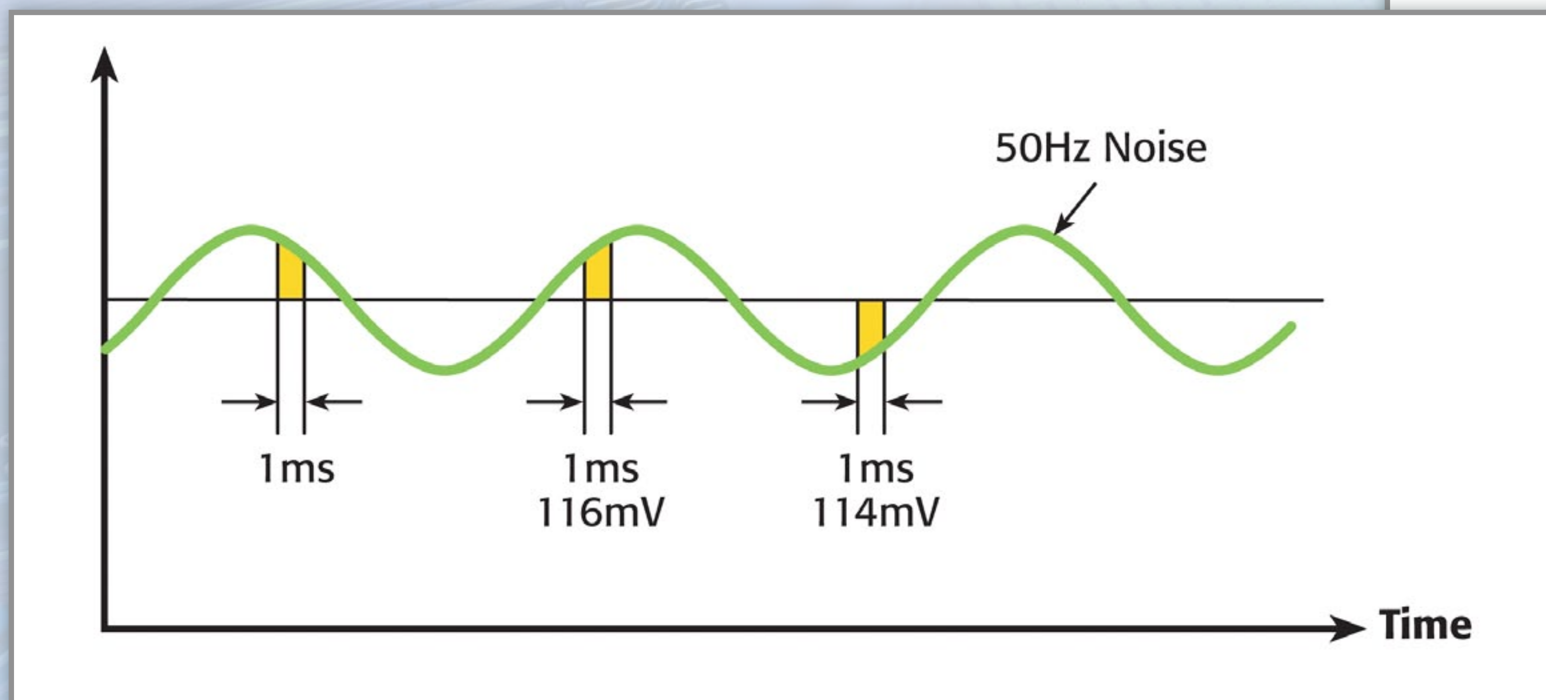

Figure 5

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Step 4 | Regular Calibration

- **Theoretical measurement limits.** The laws of physics provide a fundamental limit of how low a signal can be resolved because every system will generate some level of voltage and current noise. ***Figure 6*** identifies the levels of voltage that are impossible to measure, as well as the levels approaching the theoretical limits of voltage measurement.

Step 4

Once the test system has been built and verified, it's ready to begin making measurements in which users can have confidence. However, it's important to recheck the performance of any test setup on a regular basis. Because of component drift, the accuracy of an instrument will vary over time, so ensure that the instrumentation is calibrated regularly.

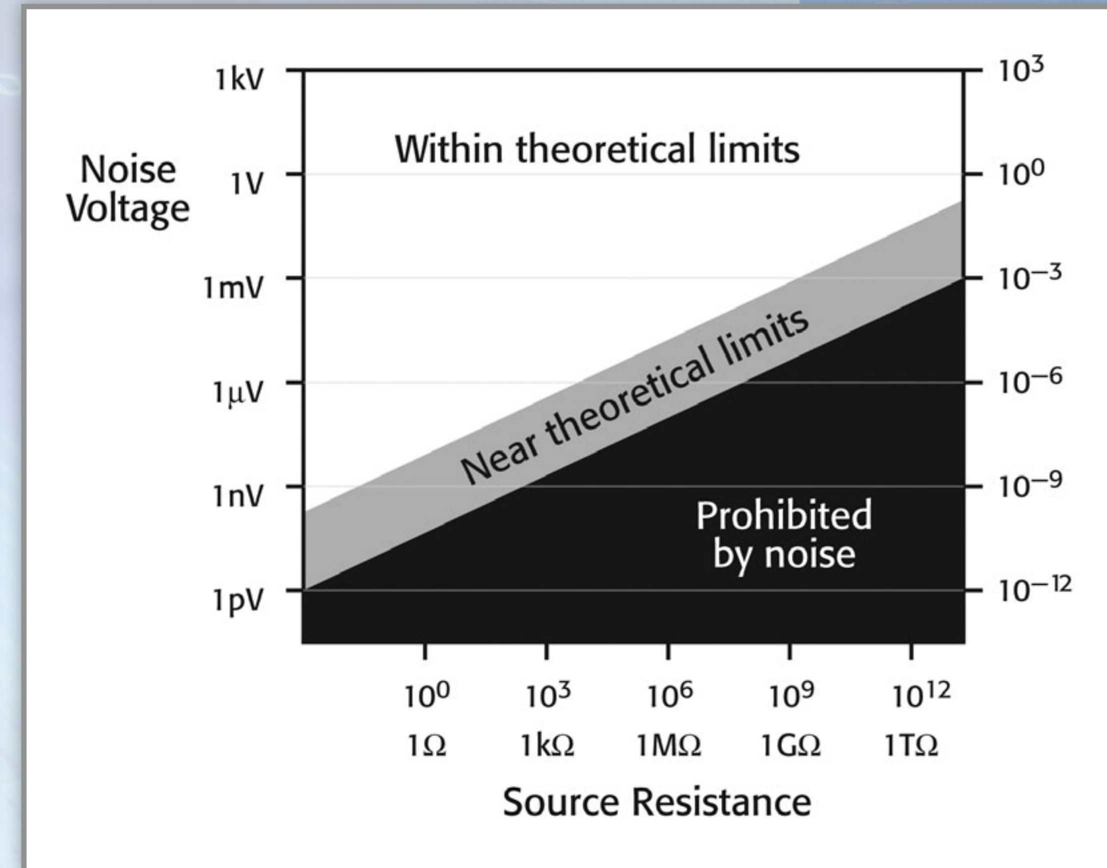

Figure 6

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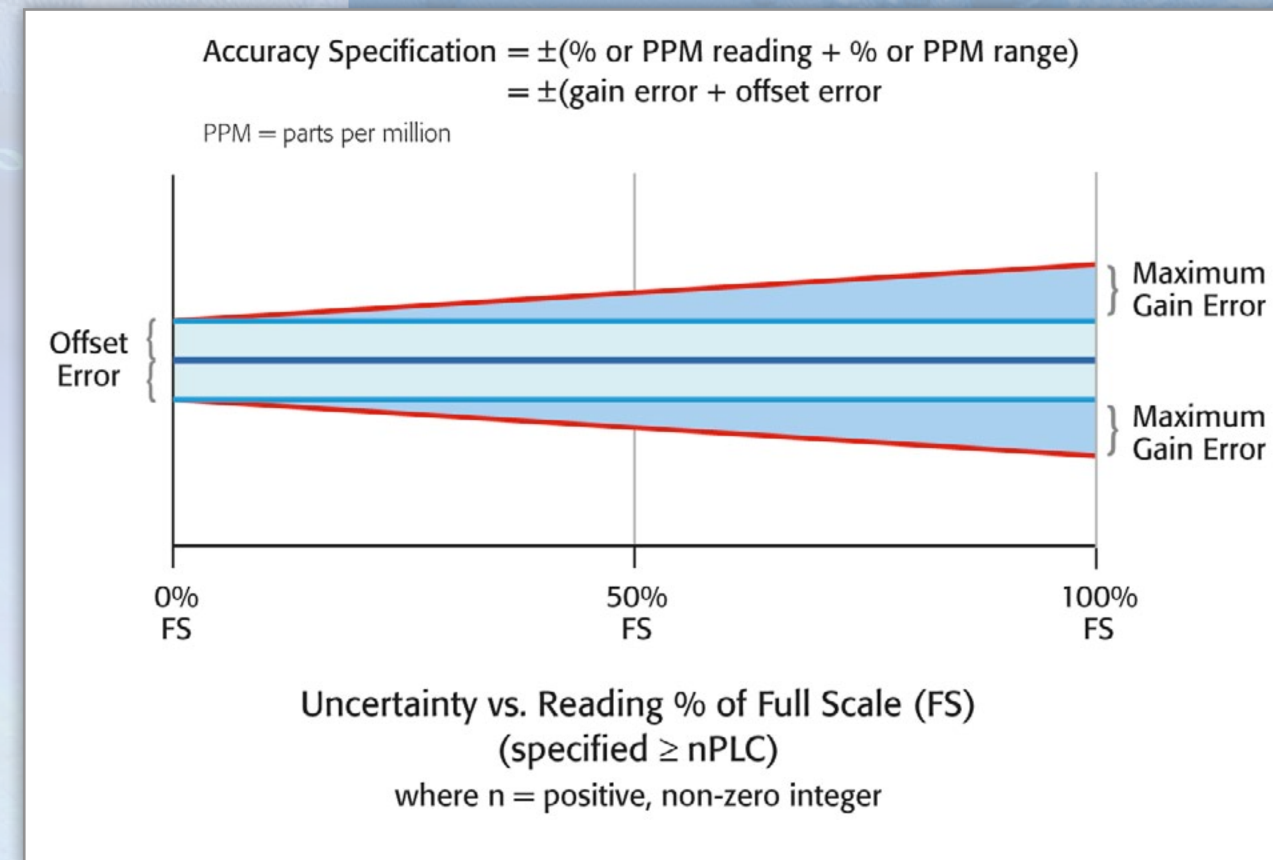
Instrument Options

Design Considerations for Maximizing Throughput and Accuracy in Switch/Measure Instrumentation

DMM and relay-based switching are the key building blocks for many test applications and the core elements of many ATE systems. Here we look at the speed vs. accuracy trade-offs involved in making multi-channel measurements with a digital multimeter (DMM) and relay switching in addition to the practical considerations involved in selecting the right type of DMM and switching hardware and best practices to optimize throughput. **Read Article…**



Speed and accuracy considerations

Cables

- Labs' Demands for Greater Measurement Flexibility Require Cabling Systems Capable of Accommodating Multiple Measurement Types
- Make Faster, Easier Prober Connections and Prevent Time-consuming Measurement Errors
- Need More Measurement Flexibility? Maybe You Need More Flexible Cabling

Data Acquisition with Ethernet

- Instrument-Grade Data Acquisition via Ethernet

IVI Drivers

- Using MATLAB® Software with Keithley Instruments through IVI Instrument Drivers

LXI

- Combining the Benefits of LXI and Scripting
- Exploring LXI's Advanced Capabilities

Pulse

- Getting More Out of Today's Pulse/Pattern Generators
- Introducing Pulsing into Reliability Tests for Advanced CMOS Technologies
- Pulse Testing for Nanoscale Devices
- Pulsed Characterization of Charge-trapping Behavior in High-κ Gate Dielectrics
- Pulsers Answer Emerging Testing Challenges
- Ultra-Fast I-V Applications for the Model 4225-PMU Ultra-Fast I-V Module

SCPI

- Converting a Series 2400 SourceMeter® SCPI Application to a Series 2600 System SourceMeter Script Application
- Converting a Series 2700 SCPI Application to a Series 3700 System Switch/Multimeter System Script Application

SRQ

- Using SRQ for Instrument Control over GPIB Bus

Switching

- Current Switching Demands Special Attention to Ensure Test System Accuracy
- Design Considerations for Maximizing Throughput and Accuracy in Switch/Measure Instrumentation
- Optimizing Switched Measurements with the Series 3700 System Switch/Multimeter and Series 2600 System SourceMeter Instruments Through the Use of TSP
- Optimizing Switch/Read Rates with Keithley Series 2000 DMMs and 7001/7002 Switch Systems
- Switching in Multipoint Testing

Test Sequencer

- Built-in Sequencer Accelerates Testing
- New Test Sequencing Instruments Lower Cost of Test for Device Manufacturers
- Shaving Milliseconds Off of Test Time

Test Script Processor (TSP®)Technology

- Optimizing Switched Measurements with the Series 3700 System Switch/Multimeter and Series 2600 System SourceMeter Instruments Through the Use of TSP
- Embedded Script Processors and Embedded Software Rank among the Most Significant T&M Instrument Design Trends of the Last Decade

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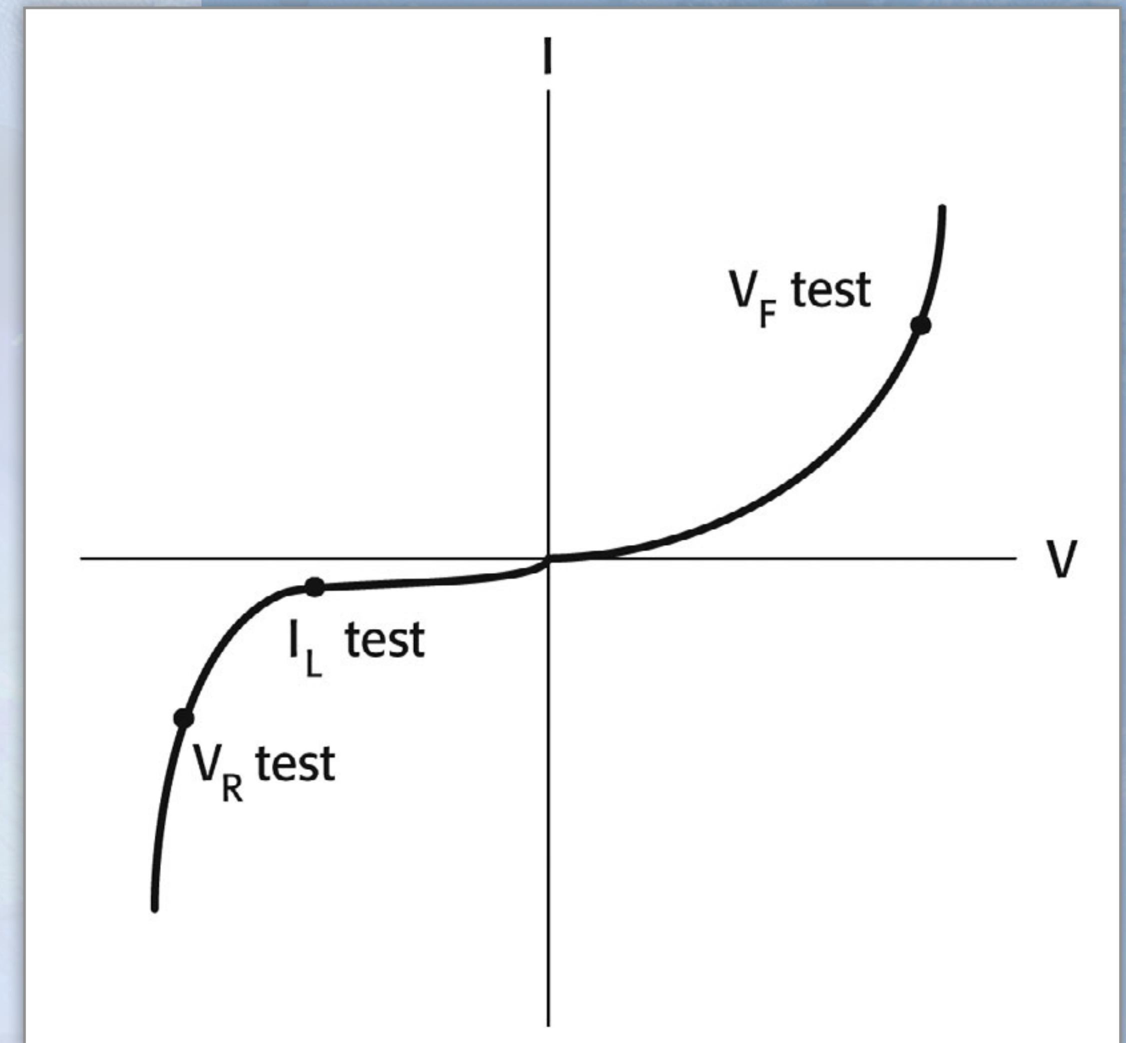
Applications

Production Testing of High Intensity, Visible LEDs using the Series 2600 System SourceMeter Instruments

Due to their long life and high reliability, visible light emitting diodes (LEDs) are finding their way into more and more applications. There is an ever-increasing need for cost-effective testing methods to ensure the reliability of the LED. This application note illustrates methods and issues related to creating production test system solutions that verify the performance of single and multiple (array) LED devices. **Learn more....**



Typical LED DC I-V Curve and Test Points (Not to Scale)

Accelerated Stress Testing: HALT/HASS Testing
- Burn-in Testing Techniques for Switching Power Supplies
- Fundamentals of HALT/HASS Testing
- Making AST/Burn-in Testing More Productive with Ethernet-based Instruments

Audio Analysis
- Achieving Quality Audio Tests for Mobile Phones
- The Basics of Through-the-Air Audio Quality Test System Characterization

Automotive Electrical Systems
- Switch to 42 Volt Automotive Systems Brings Challenges and Opportunities

Charge-Pumping Measurements
- Making Charge-Pumping Measurements with the Model 4200-SCS Semiconductor Characterization System and Series 3400 Pulse/Pattern Generator
- Performing Charge Pumping Measurements with the Model 4200-SCS Semiconductor Characterization System

Charge-Trapping Measurements
- Qualifying High Ð Gate Materials with Charge-Trapping Measurements

CMOS Devices
- I_{DDQ} Testing and Standby Current Testing with Series 2600 System SourceMeter Instruments
- On-The-Fly VTH Measurement for Bias Temperature Instability Characterization

Connectors
- Solutions for Production Testing of Connectors

Diodes
- Diode Production Testing with Series 2600 System SourceMeter Instruments
- High Throughput DC Production Testing of Laser Diode Modules and VCSELs with the Model 2602 System SourceMeter Instrument
- Production Testing of High Intensity, Visible LEDs using the Series 2600 System SourceMeter Instruments

Flat Panel Displays
- New Test Realities for Evolving FPD Technologies

Hall Effect Measurements
- Four-Probe Resistivity and Hall Voltage Measurements with the Model 4200-SCS
- Instrumentation and Techniques for Measuring High Resistivity and Hall Voltage of Semiconducting Materials

Higher Current
- Methods to Achieve Higher Currents from I-V Measurement Equipment

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

MOSFET Devices
- Evaluating Hot Carrier Induced Degradation of MOSFET Devices
- Evaluating Oxide Reliability Using V-Ramp and J-Ramp Techniques
- Performing Charge Pumping Measurements with the Model 4200-SCS Semiconductor Characterization System
- Monitoring Channel Hot Carrier (CHC) Degradation of MOSFET Devices using Keithley's Model 4200-SCS

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Applications

Multi-pin Devices

- Creating Scalable, Multipin, Multi-Function IC Test Systems Using the Model 2602 System SourceMeter Instrument
- Increasing Production Throughput of Multi-pin Devices with Keithley Series 2600 System SourceMeter Instruments

Nanotechnology Devices

- Electrical Measurements on Nanoscale Materials
- The Emerging Challenges of Nanotechnology Testing
- Improving Low Current Measurements on Nanoelectronic and Molecular Electronic Devices
- I-V Measurements of Nanoscale Wires and Tubes with the Model 4200-SCS and Zyvex S100 Nanomanipulator
- Nanoscale Device and Material Electrical Measurements
- Optimizing Low Current Measurements with the Model 4200-SCS Semiconductor Characterization System
- Pulse Testing for Nanoscale Devices
- Standards Will Help Ensure Order in Nano-Enabled Industries
- Test System is Key to Practical Applications of Nanotechnology
- Tips for Electrical Characterization of Carbon Nanotubes and Low Power Nanoscale Devices

Power Supplies

- Burn-in Testing Techniques for Switching Power Supplies
- High Reliability Power Supply Testing
- Ensuring that Power Supply Performance Meets Your Requirements
- Understanding Linear Power Supply Specifications

Semiconductor Devices

- C-V/I-V Testing Becomes Faster, Simpler, and More Economical
- Evolving Semiconductor Characterization and Parametric Test Solutions for the Evolving Semiconductor Industry
- Fundamentals of Semiconductor C-V Measurements
- Low Current SMU Models Open the Door to More Semi Applications and Lower Cost of Testing
- Optimizing Low Current Measurements with the Model 4200-SCS Semiconductor Characterization System
- Demand for Higher Power Semi Devices Will Require Pushing Instrumentation to New Extremes

Solar Cells

- Electrical Characterization of Photovoltaic Materials and Solar Cells with the Model 4200-SCS Semiconductor Characterization System
- Keithley Instruments' Solar Cell Test Survey - Keithley Survey Shows Differing Test Priorities and Methods for Testing Solar Cell/PV Devices
- Making I-V and C-V Measurements on Solar/Photovoltaic Cells Using the Model 4200-SCS Semiconductor Characterization System

Synchrotrons

- Synchrotron High Speed Magnetics Monitoring

Temperature Measurements

- How to Select the Right Temperature Sensor
- On-The-Fly VTH Measurement for Bias Temperature Instability Characterization
- Resistive Temperature Detectors: An Alternative to Thermocouples for Precise, Repeatable Temperature Measurements
- Using Forward Voltage to Measure Semiconductor Junction Temperature
- Making Temperature Measurements with the Model 2110

Wafer Level Reliability

- ACS Integrated Test System for High Throughput WLR Testing
- Evaluating Oxide Reliability Using V-Ramp and J-Ramp Techniques
- On-The-Fly Threshold Voltage Measurement for BTI Characterization
- New Challenges in WLR Testing
- Wafer Level Reliability Testing - A Critical Device and Process Development Step

Wireless Devices

- Achieving Quality Audio Tests for Mobile Phones
- The Basics of Through-the-Air Audio Quality Test System Characterization
- DC Electrical Characterization of RF Power Transistors
- Dual Channel Pulse Testing Simplifies RF Transistor Characterization

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System SourceMeter® SMU Instruments

Feature	2651A / 2657A High Current / High Voltage	2634B / 2635B / 2636B Low Current	2602B / 2612B Dual Channel	2601B / 2611B Single Channel	2604B / 2614B Dual Channel Benchtop
# of Channels	1 (optional expansion to 32 via TSP-Link®)	1 – 2 (optional expansion to 64 via TSP Link for 2635B/2363B)	2 (optional expansion to 64 via TSP-Link)	1 (optional expansion to 32 via TSP-Link)	2
Current Max / Min	2651A: 50A pulse/100fA 2657A: 120mA/1fA	2634B: 10A pulse/1fA 2636B, 2635B: 10A pulse/0.1fA	10A pulse/100fA	10A pulse/100fA	10A pulse/100 fA
Voltage Max / Min	2651A: 40V/100nV 2657A: 3,000V/100nV	200V/100nV	40V/100nV for 2602B 200V/100nV for 2612B	40V/100nV for 2601B 200V/100nV for 2611B	40V/100nV for 2604B 200V/100nV for 2614B
System-Level Automation	Digital I/O, TSP-Link, Contact Check	Digital I/O, TSP-Link, Contact Check (not available on 2634B)	Digital I/O, TSP-Link, Contact Check	Digital I/O, TSP-Link, Contact Check	N/A
Max readings / sec	38,500 1µSec/pt.,18-bit digitizer	20,000	20,000	20,000	20,000
Computer Interface	GPIB, LAN (LXI), RS-232	GPIB, LAN (LXI), RS-232, USB	GPIB, LAN (LXI), RS-232, USB	GPIB, LAN (LXI), RS-232, USB	GPIB, LAN (LXI), RS-232, USB
Connectors/Cabling	2651A: Screw terminal, adaptors for banana 2657A: HV triax, SHV	Triax	Screw terminal, adaptors for banana or triax	Screw terminal, adaptors for banana or triax	Screw terminal, adaptors for banana or triax

Feature	6430 Low I SourceMeter	2430 High Power SourceMeter Instrument	2410 High V SourceMeter Instrument	2420 / 2425 / 2440 High I SourceMeter Instruments	2400 / 2401 Low Power SourceMeter Instruments	2450 Touchscreen SourceMeter Instrument
Current Max / Min	105mA / 10aA	10.5A pulse / 100pA	1.05A / 10pA	5.25A/ 100pA	1.05A / 10pA	1.05A/10fA
Voltage Max / Min	200V / 1uV	200V / 1uV	1100V / 1uV	100V / 1uV	200V / 1uV	200V/10nV
Power	2W	1100W	22W	110W	22W	20W
Max readings / sec	256	2,000	2,000	2,000	2,000	3,100
Interface	GPIB, RS-232, Digital I/O, Trigger Link Trigger Bus	GPIB, RS-232, Digital I/O, Trigger Link Trigger Bus	GPIB, RS-232, Digital I/O, Trigger Link Trigger Bus	GPIB, RS-232, Digital I/O, Trigger Link Trigger Bus	GPIB, RS-232, Digital I/O, Trigger Link Trigger Bus	GPIB, USB, LAN/LXI, Digital I/O, TSP-Link
Connectors	Triax	Banana (front / rear)	Banana (front / rear)	Banana (front / rear)	Banana (front / rear)	Banana (front) Triax (rear)

Digital Multimeter Selector Guide

Feature	3706A	2002	2010 / 2001	2700 / 2701 / 2750	2100 / 2000	2110
Resolution (Digits)	7½ Digits	8½ Digits	7½ Digits	6½ Digits	6½ Digits	5½ Digits
Basic Accuracy	0.002%	0.0006%	0.0018%	0.002%	0.0038% (Model 2100) 0.0020% (Model 2000)	0.012%
Advanced Measure/ Functions	Temperature, 4-Wire Resistance, Low Ohms	Temperature, 4-Wire Resistance, Peak Detection, Low Ohms, Agilent 3458A emulation	Temperature, 4-Wire Resistance, Peak Detection, Low Ohms	Temperature, 4-Wire Resistance, Low Ohms (Model 2750)	Temperature, 4-Wire Resistance	Temperature, Thermocouple, Capacitance, 4-Wire Resistance
Optional Switch Features	Up to 576 Channels and 10 Card Options	10 Channel	10 Channel	Up to 200 Channels and 12 Card Options	10 Channel (Model 2000)	N/A
Interface	GPIB, LAN (LXI), USB-TMC, TSP-Link® Channel Expansion Bus	GPIB	GPIB, RS-232 (Model 2010) GPIB (Model 2001)	GPIB, RS-232 (Models 2700 and 2750) LAN, RS-232 (Model 2701)	USB-TMC (Models 2100 and 2110) GPIB, RS-232 (Model 2000)	USB-TMC GPIB (option)

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Printed in the U.S.A. 1.14