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Choosing the Optimal Source Measurement Unit Instrument for Your Test and Measurement Application

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Stated in the simplest possible terms, a source measure unit (SMU) instrument integrates the capabilities of a precision power supply (PPS) with those of a high-performance digital multimeter (DMM) in a single instrument. For example, SMU instruments can simultaneously source or sink voltage while measuring current, and source or sink current while measuring voltage (***Figure 1***). They can be used as stand-alone constant voltage or constant current sources, as stand-alone voltmeters, ammeters, and ohmmeters, and as precision electronic loads. Their high performance architecture also allows using them as pulse generators, as waveform generators, and as automated current-voltage (I-V) characterization systems.

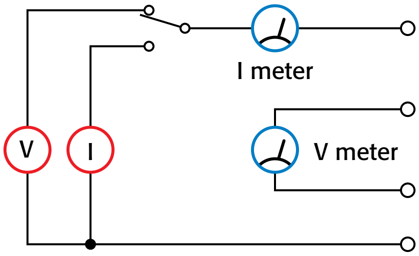

Figure 1. Basic SMU instrument topology.

The real benefit of SMU instruments for test and measurement applications comes from their ability to source and measure signals simultaneously. When compared with using separate instruments to handle each function, SMUs'

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simultaneous operation provides for faster test times, simplified connections, improved accuracy, less complex programming, and a lower cost of ownership (COO). Their tight integration lets them protect the device under test (DUT) from damage due to accidental overloads, thermal runaway, and other dangers. It also makes SMU instruments ideal for characterizing and testing semiconductors and other non-linear devices and materials.

SMU vs. Power Supply

Given that an SMU instrument integrates the functions of a power supply with a digital multimeter, how exactly does the performance of an SMU's source differ from that of a typical power supply?

- *Greater speed and precision:* SMUs are optimized for both speed and precision, so they can offer significantly faster rise times and much lower measurement uncertainty than power supplies. SMUs' settling times are measured in microseconds compared to the milliseconds that power supplies require to settle on their programmed value. Similarly, an SMU's measurement uncertainty is measured in nanoamps vs. microamps for typical power supplies.
- *Wider operating range and better resolution:* Because of their outstanding low current capability, SMUs typically offer much wider operating ranges with greater resolution than power supplies, so they are suitable for a wider range of test and measurement applications.
- *Four-quadrant rather than two-quadrant operation:* As illustrated in ***Figure 2***, a typical power supply can only source voltage and/or current. In other words, it provides only two-quadrant operation (in quadrants I and III), but an SMU can provide full four-quadrant operation because it's capable of sourcing and sinking power, acting as both power supply and an electronic load. During source or sink operation, the SMU can simultaneously measure voltage, current, and resistance. This operating flexibility can be especially valuable when characterizing batteries, solar cells, or other energy-generating devices.

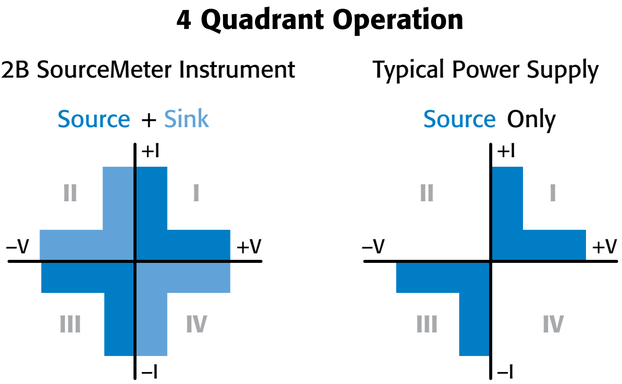


Figure 2. A power supply (right) offers only two-quadrant operation; an SMU instrument (left) can source and sink power in all four quadrants.

- *Built-in sweep capabilities:* The various sweep capabilities SMUs offer can simplify programming a test's source, delay, and measure characteristics, significantly boosting testing productivity. All sweeps can be configured for single-event or continuous operation to simplify the process of capturing the data needed to characterize and test a wide range of devices. Sweeps can also be used in conjunction with other throughput-enhancing features like Hi-Lo limit inspection and digital I/O control to create high speed production test systems.
    - A *fixed level sweep* outputs a single level of voltage or current with multiple measurements. This is typically done to bias or stress devices. Various types of fixed level sweeps can be generated, depending on the needs of the application.
    - *Linear/Log sweeps* are used to ramp up or ramp down a level of voltage or current from a starting level, changing in equal linear steps, or on a logarithmic scale until the stopping source level is reached. Linear sweeps are routinely used for testing devices like resistors, transistors, diodes, and much more.
    - *Pulsed sweeps* are often used to limit the amount of power that goes into a material sample or device over time and to minimize self-heating effects that could otherwise damage semiconductors and light emitting diodes (LEDs), experimental materials such as graphene, or other fragile nanotechnology-based devices.
    - *Custom sweeps* simplify creating application-specific waveforms.

SMU vs. DMM

Because of its built-in sourcing capabilities, an SMU can minimize overall measurement uncertainty in many applications. The first diagram in ***Figure 3*** shows the basic voltmeter configuration for the SMU. Here, the built-in current source can be used to offset or suppress any system-level leakage currents (such as cable noise) that could cause unwanted errors in voltage measurement applications.

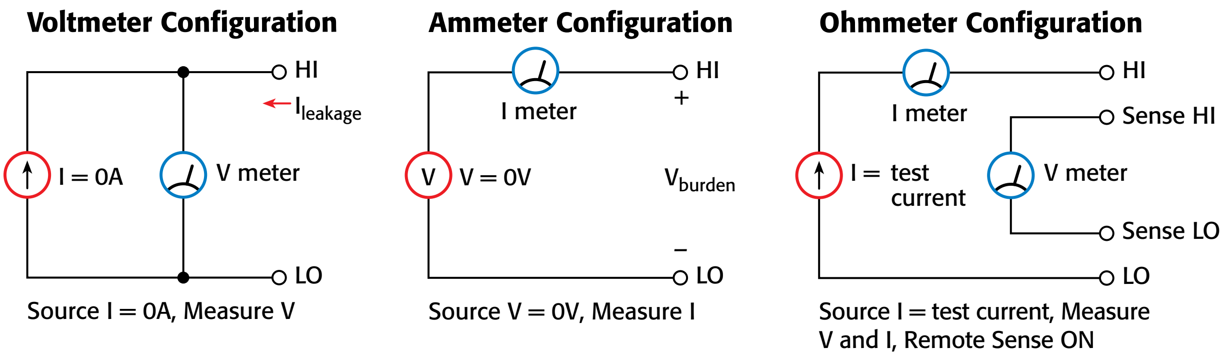


Figure 3. SMU voltmeter, ammeter, and ohmmeter configurations

For current measurements, the SMU's built-in source and "feedback ammeter" design work together to keep voltage burden low and enable low current measurements to sub-picoamp levels. DMMs do not have the built-in source and typically have "shunt ammeter" designs that typically limit low current capabilities to microamp or nanoamp levels.

Finally, for resistance measurements, the SMU architecture offers full flexibility over the amount of current or voltage sourced to the DUT. DMMs have fixed current source values that are dependent on the range being used to measure resistance. SMUs offer fully programmable source values for measuring resistance. This can be valuable for protecting DUTs or for measuring extra high or extra low resistances. For high resistance measurements, the source voltage method is preferred; for low resistance measurements, the source current method is best. Some SMUs have a six-wire ohms feature that "guards out" the effects of unwanted parallel resistance paths in the circuit.

SMU Measurement Terminology

One of the first considerations in choosing an SMU instrument must be the quality of the measurements it produces. Poor measurement integrity can cause those using the data produced to draw incorrect conclusions about the performance of a given DUT. In R&D, this can mean an imperfect understanding of a device's operating parameters, leading to unnecessary rework and costly time-to-market delays. In production test, inaccurate measurements can result in rejection of good parts (false failures) or acceptance of bad ones, either of which can cause poor yields, customer dissatisfaction, and other problems.

When considering an SMU instrument's measurement integrity, keep several key terms in mind: *accuracy*, *repeatability* or *stability*, *resolution*, *sensitivity*, and *integration time*.

Accuracy is defined as the closeness of agreement between the result of a measurement and its true value or accepted standard value. Imagine you are shooting arrows at a target: the accuracy of your shots would be defined by how close the arrows come to the bullseye.

Repeatability refers to the closeness of agreement between successive measurements carried out under the same conditions. Although repeatability is not typically specified on an instrument's data sheet, it can usually be easily determined during an instrument demonstration or evaluation. ***Figure 4*** illustrates the concepts of accuracy vs. repeatability.

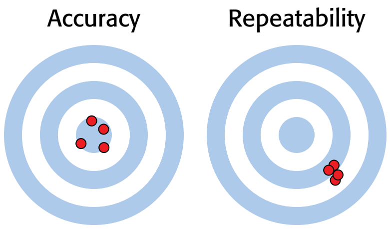


Figure 4. In the target on the left, the shooter had high accuracy but poor repeatability. The target on the right shows high repeatability but poor accuracy.

Resolution is defined as the smallest portion of the signal that can be observed. The resolution of an instrument is determined by the number of digits it can display on the front panel or send to a PC over the communication bus. This can often be changed by pressing a front panel button or by sending a programming command to the instrument. In ***Figure 5***, the user can select between 3, 4, 5, and 6 digits on the display.

Figure 5. Adjusting the Model 2450 SMU instrument's resolution.

An SMU instrument's usable maximum resolution depends on its overall accuracy and the resolution of its analog-to-digital converter (ADC). For example, no one would produce a 6½-digit instrument with an 8-bit ADC and 5% accuracy because most of the digits being displayed would be meaningless. In general, however, the higher the resolution is, the higher the bit count on the ADC and the higher the accuracy will be.

The *sensitivity* of a measurement is the smallest change in the measured signal that can be detected. The ultimate sensitivity of an instrument depends both on its maximum resolution and its lowest measurement range. For example, a 6½-digit SMU with a bottom range of 1µA would have 1pA sensitivity. However, depending on that instrument's accuracy, that sensitivity might not be particularly useful.

Measurement instruments employ either (or both) of two basic types of analog-to-digital converters: integrating ADCs and digitizing ADCs. In general, an integrating ADC will offer higher accuracy because it cancels out the unwanted effects of AC noise from the power line. The instrument's integration rate, which is specified in NPLC (Number of Power Line Cycles), is adjustable. To reject AC noise, the NPLC must be equal to or greater than 1. Integrating the measurement over multiple power line cycles will reject this noise still further and thereby provide a more accurate measurement. However, this noise rejection capability comes at the expense of reading speed; one power line cycle takes 16.7ms at 60Hz or 20ms at 50Hz. Setting the NPLC to a fraction of a line cycle will provide faster measurements at the expense of more noise or lower accuracy (***Figure 6***).

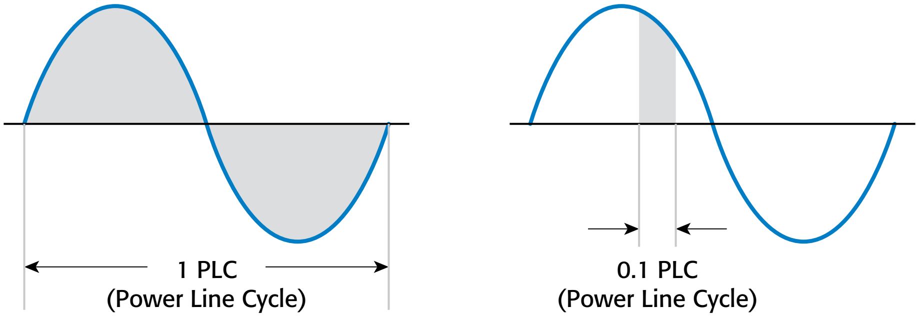


Figure 6. ADC integration time comparison (NPLC).

That means the reading rate and measurement speed of a highly accurate instrument like an SMU are determined by its NPLC setting. However, an ADC's reading rate is only one of many factors that affects an SMU instrument's true speed; other factors that can affect overall throughput include function and range change times, trigger in and out times, settling times, and program execution times.

Key Considerations for Selecting an SMU Instrument

When evaluating a specific SMU instrument for a specific application, it's essential to consider some key characteristics:

- Ease of use
- System-level speed/throughput
- Source resolution vs. stability
- Measurement settling time, offset error, noise
- Cabling and connections

Let's examine each of these characteristics in depth.

- *Ease of use*. In other words, how we interact with the instrument. Instrumentation users are accustomed to learning the front panel of their measurement tools through the use of plain text, buttons, and keys. Complex instruments could take from days to weeks to learn how to use the instrument in a way that best serves their application. Learning curves could be extensive, resulting in reduced productivity and efficiency, especially for those individuals who are not necessarily first time users of SMUs.

  With advances in touchscreen technology, capacitive touchscreen graphical user interfaces (GUI) on bench instrumentation can significantly reduce the learning curve. But above all, touchscreen GUIs significantly improve an instrument's ease of use for an instrument.

Figure 7. Advanced capacitive touchscreen GUI on Keithley's Model 2450 SourceMeter SMU Instrument.

The use of touchscreen technology is also beneficial in reducing the working space of the instrument, such that the display can provide larger numerical values, more details about the measurement, or even graphing capabilities, something that is difficult with single- or dual-line displays. Additionally, because GUI systems highly leverage software to define what is displayed, screens can be quickly changed as required for different applications.

Reaching out for what you want is an instinctive gesture. Using touch is just as simple: you simply point at what you want. Although with pushbutton-based instruments, some users may still hesitate to push a button if the front panel has too many buttons to push and it is unclear what the button will do. With a touchscreen approach, users feel comfortable that they cannot "do anything wrong"; they instinctively understand how to use the interface. Touchscreen systems make everyone an "expert user" from the first touch, whether a new instrument user or the most experienced user.

Touch technology is intuitive and highly learnable. Compared to traditional training methods, using touchscreens can drastically reduce training time, increase operator accuracy, and improve overall operational efficiencies. This helps to drive down costs.

- *System-level speed* or *throughput*. In other words, how quickly can you get a final measurement or set of measurements (such as a suite of current vs. voltage parameters) back to the PC controller? For example, let's consider a typical diode or LED test, which will consist of three measurements—forward voltage, reverse voltage, and reverse current—each of which is typically compared to upper and lower limits. The part is considered “bad” if any one parameter fails. The objective is to test this part as quickly as possible without sacrificing accuracy in order to minimize the cost of test.

  The challenge is that all the source and measure values are different. Although the readings/second specification is important, a range or function change must occur before a reading can be taken. This type of test isn't about taking multiple readings of the same value repeatedly; it's about taking single-point measurements at different source-measure levels. Therefore, the speed of the ADC (the NPLC spec) alone won't be a good indication of how quickly the instrument can test this part. One should also consider a variety of other operating parameters, including trigger in time, range change time, function change time, source settling time, trigger out time, and command transfer, processing, and execution time.

  Figure 8 shows a comparison of the actual test results from a Keithley Series 2600B System SourceMeter® instrument with that of another brand of SMU instrument. The data shows the number of diodes tested per second, so the higher the number the higher the speed. This is a true measure of test throughput.

	1 NPLC	0.1 NPLC	0.01 NPLC	0.001 NPLC	0.00048 NPLC
Non-Keithley SMU instrument	8.1	12.4	13.0	13.0	13.0
Keithley Series 2600B	13.3	33.2	37.8	38.2	N/A

Most accurate ←→ Least accurate

Figure 8. Test results: parts per second

Recall that the larger the NPLC is, the more accurate the measurement will be (corresponding to lower speed). Note how reducing the NPLC setting to less than 0.1 NPLC does not make a significant difference in overall test time per part. In typical applications in which multiple parameters are being tested, the speed of other characteristics, such as range or function change time, triggering time, bus communication time, or program execution time, start to dominate. Even at 1 NPLC, these other characteristics, if not optimized by the SMU instrument manufacturer, can have a big impact on overall test throughput. The Keithley Series 2600B System SourceMeter instrument in this example can test over 60% more parts per second at 1 NPLC and close to 3x more parts at the other NPLC settings.

Although range and function change times are important, it’s also possible to obtain major breakthroughs in system throughput by embedding then executing the majority of the test program within the SMU instrument itself. This eliminates most of the communications bus traffic, speeds up triggering, and optimizes command processing time. Using this type of feature is a major reason an SMU instrument running at 0.1 NPLC can be as much as four times faster and much more accurate than an SMU running at 0.00048 NPLC in real-world applications.

Keithley’s Series 2600B System SourceMeter and the Model 2450 Advanced Touchscreen SourceMeter instruments employ a feature known as Test Script Processing, or TSP® technology. TSP technology optimizes command transfer, command processing, and command execution times by embedding the actual test program (or script) into the instrument’s non-volatile memory. However, TSP technology goes far beyond simply storing and executing a sequence of standard SCPI commands. TSP technology is based on Lua, a powerful BASIC-like scripting language. Functions like “do” loops, variables, If-Then-Else statements, and more are all supported in Lua. Therefore, TSP scripts are just as powerful as traditional test programs residing in PCs but with the advantage of actually being embedded in the instrument to optimize overall test speed.

- An SMU instrument's *sourcing resolution* and *output stability* are also key to its overall performance. Let's look at the relationship between *source resolution* and *output stability.*

When evaluating the performance of an SMU instrument's source, it's important to look beyond the specification sheet and the instrument's source readback display. The source's actual output performance may be very different from its specified resolution or from its displayed value, which may require instrument specifiers to do their own testing to verify it.

Based solely on an SMU instrument's specification sheet, one might conclude that the SMU instrument with the greatest programming resolution is the most accurate. The programming resolution determines the output's "fineness" of adjustment. In ***Figure 9***, note that the non-Keithley SMU offers 50 times greater programming resolution than the Model 2450 SourceMeter instrument.

	Programming Resolution 20V Range
Non-Keithley 6½-digit SMU instrument	10 µV
Keithley Model 2450	500 µV

Figure 9. Programming resolution based on specification sheet.

Furthermore, based on the SMU's "source readback" value displayed on the front panel or over the bus (***Figure 10***), one might conclude that the SMU showing readback values closest to the programmed values is the most stable and therefore the better choice. In this example, note that the non-Keithley SMU shows 0µV of peak-to-peak variation when sourcing a 10.001V signal, while the Model 2450 shows 29.6µV.

Source Value = 10.001 V	**Source Readback Displayed Value (pk-pk of variation)**	**Actual Measured Value of Source Output (pk-pk of variation)**
Non-Keithley 6½-digit SMU instrument	0.0 µV	438.7 µV
Keithley Model 2450	29.6 µV	29.0 µV

Figure 10. Actual output stability.

However, the picture changes dramatically when we measure the actual source output using a separate instrument. To obtain the data in the right-most column of ***Figure 9***, we chose Keithley's Model 2002 8½-digit digital multimeter to measure the source output of each SMU directly. The Model 2002 is one of the most accurate

DMMs available on the market and is used by many calibration labs, which makes it a good choice for high accuracy applications of this type.

To view the stability of the source outputs, we made 100 measurements using the Model 2002 at 10 NPLC to ensure maximum accuracy. We observed that the non-Keithley 6½-digit SMU (***Figure 11a***) actually has almost 0.5mV peak-to-peak variation when sourcing a 10.001V signal. This is very different from the 0µV variation its source readback display indicates. In addition, this error is more than 40 times greater than the 10µV programming resolution. The Keithley Model 2450 SourceMeter Instrument (***Figure 11b***) actually has more than 15 times better output stability than the non-Keithley 6½-digit SMU (29.0µV vs. 438.7µV).

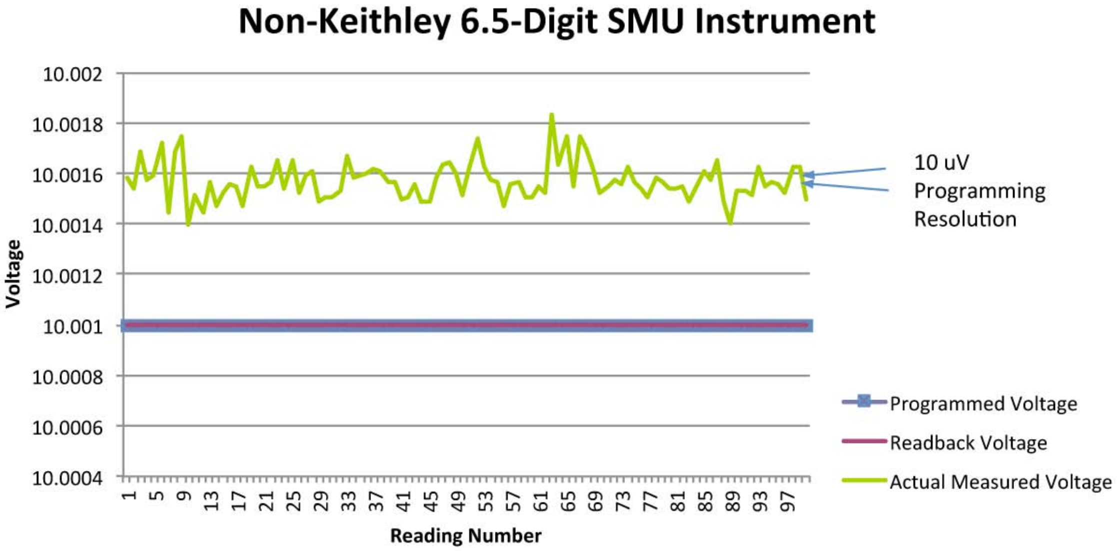


Figure 11a. Actual source performance: programming resolution vs. stability for non-Keithley 6½-digit SMU.

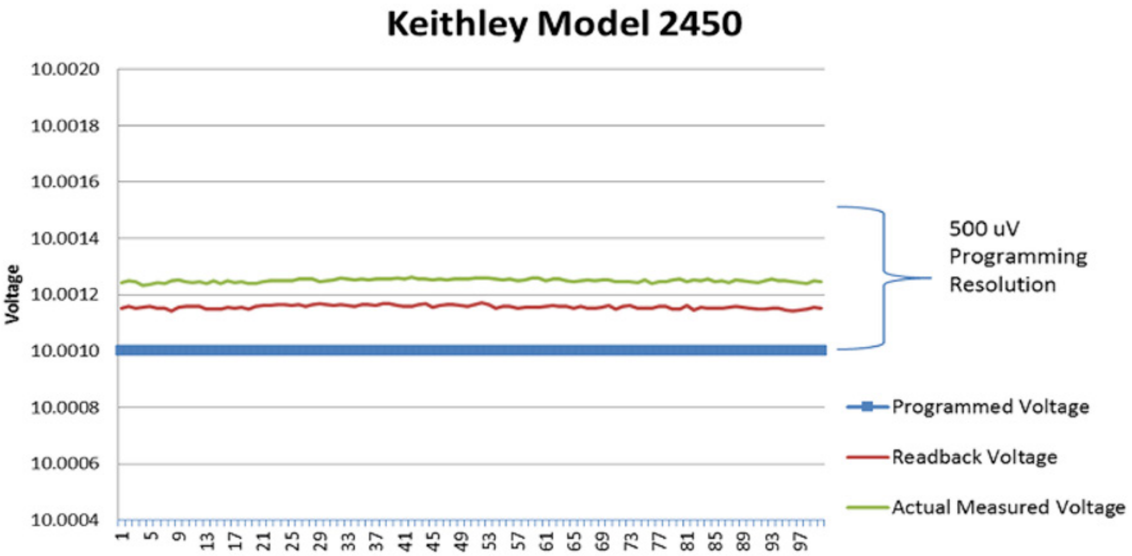


Figure 11b. Actual source performance: programming resolution vs. stability for Keithley Model 2450 SourceMeter instrument.

For the non-Keithley SMU, note that the readback voltage is exactly the same as the programmed voltage. However, the actual measured voltage is quite different from the readback voltage or the programmed voltage. The SMU readback indicates the output voltage to be exactly 10.001V; in reality, the output voltage is somewhere between 10.0014V and 10.0018V. This is a significant amount of error that the user would not normally see indicated on the SMU display. In addition, the fineness of adjustment of the programming resolution (10µV) is overwhelmed by the inherent error of the source, so this level of resolution is unrealizable.

In contrast, for the Keithley Model 2450 SourceMeter instrument, note that the readback voltage closely tracks the actual voltage measured at the output terminals. You'll also see that the readback voltage differs from the programmed voltage. One would expect to see a difference, given the source's accuracy specs. These kinds of results should give you confidence that the voltage actually being delivered to the DUT is that which is expected. In addition, with the Model 2450, the source error does not overwhelm the programming resolution, as it does for the non-Keithley SMU. That means users can have the confidence to take full advantage of the fineness of adjustment of the programming resolution.

As this comparison shows, an SMU instrument's programming resolution specification is not a good indication of its stability and overall performance. It also shows that the source readback results can be highly questionable. Therefore, when evaluating an SMU for your application, be sure to do some testing for yourself.

- *Measurement settling time, offset error,* and *noise* can have a big impact on an SMU instrument's performance, particularly in low current applications. The example illustrated in ***Figure 12*** shows the results of two SMU instruments sourcing 200V with nothing connected to the input terminals while measuring the resulting current using each instrument's built-in ammeter feature. This comparison offers a good indication of each instrument's fundamental low current performance, and it's an easy test to recreate on the test bench.

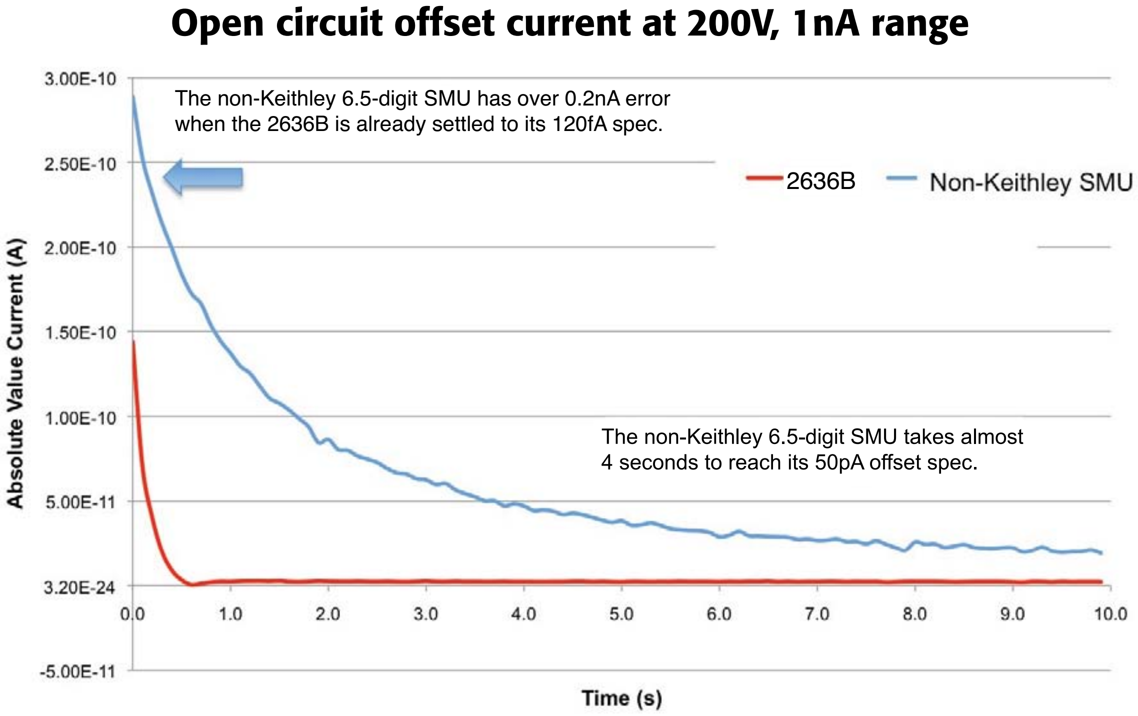


Figure 12. Comparison of measurement settling time, offset error, and noise.

Note that the non-Keithley 6½-digit SMU (the blue line) settles to its specified offset error of 50pA in about four seconds. The "bumpiness" of the data curve indicates measurement noise. In contrast, the Keithley Model 2636B (the red line) settles to its specified offset error of 0.12pA (120fA) in about half a second. The smooth data curve indicates a distinct lack of measurement noise. So, based on the data, it's obvious the Model 2636B will deliver a better measurement faster. In fact, at the point when the Model 2636B is settled and capable of providing in-spec sub-picoamp measurements, the non-Keithley SMU still has nanoamp-level errors. In addition, if you were to take a series of measurements over time, the Model 2636B would provide more consistent results due to its fast, flat, and noise-free settling.

Note that, in either case, when measuring low current, the settling times drive overall test time. This is due to R-C time constants inherent in the overall architectural design of any SMU instrument. Therefore, an ADC running at sub-line cycle integration (for example, at 0.001 NPLC) won't provide a faster measurement.

Low current performance is very important for many semiconductor and optoelectronic applications, as well as in materials research applications such as nanoscale devices, graphene, etc. To understand the true measurement performance of an SMU instrument, it's important to look beyond "headline" terms like *6½ digits* or *10fA resolution*. ***Figure 13*** offers another comparison of the low current performance of the Model 2636B with the non-Keithley 6½-digit SMU.

SMU	Lowest range	Total accuracy*	Resolution
Non-Keithley	10nA	±(0.10% + 50pA)	10fA
Keithley 2636B	100pA	±(0.15% + 120fA)	1fA

*Total accuracy = Gain accuracy (%) + Offset accuracy

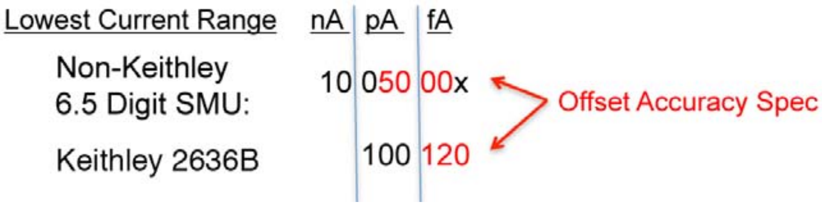


Figure 13. It's important to understand the difference between an SMU instrument's actual measurement performance and its "headline" specifications. The table lists specifications from the data sheet; the diagram explains the offset accuracy.

The non-Keithley SMU is specified as having 6½ digits and 10fA resolution. However, a closer look at the manufacturer's specs shows that its bottom current range is 10nA and its offset accuracy is 50pA. The total accuracy of most instruments is calculated as the gain accuracy plus offset accuracy. Gain accuracy is typically given in % of signal, and offset accuracy is usually a fixed amount.

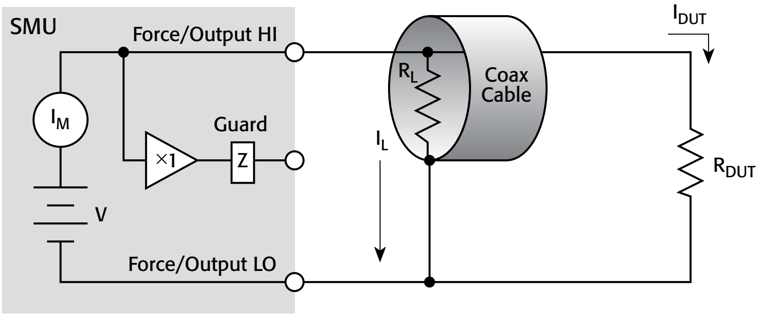
The Model 2636B is specified as having 1fA resolution. The spec table in ***Figure 13*** shows that it has a 100pA range and 120fA of offset accuracy. Obviously, although both the Keithley and non-Keithley SMU instruments can appear similar when looking at the "headline" specs, the Model 2636B actually has 400 times better offset accuracy, so it has much better sensitivity, and is capable of far more accurate low current measurements.

- *Cabling*. Using triaxial cables rather than the more common coaxial cables is essential to achieving optimal low current measurement performance. Triaxial cables have an extra shield that coaxial ones don't, which ensures lower current leakage, better R-C time constant response, and greater noise immunity. In addition, the better R-C response allows for faster settling when measuring higher levels of current.

Figure 14 illustrates how a triaxial cable works with the SMU instrument's driven guard to prevent the leakage resistance of the cable from degrading the low current measurements. In the circuit on the top, the leakage resistance of the coaxial cable is in parallel with the device under test, creating an unwanted leakage current. This leakage current will degrade low current measurements.

Coax Cable

a) Unguarded Circuit



R_L = Coax Cable Leakage Resistance

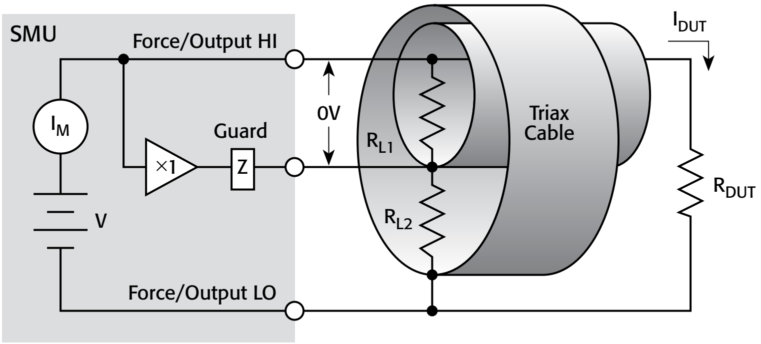
I_L = Leakage Current

R_{DUT} = Resistance of Device Under Test

$I_M = I_{DUT} + I_L$

Triax Cable

b) Guarded Circuit



R_{L1} = Triax Cable Inside Shield Leakage Resistance

R_{L2} = Leakage Resistance Between Shields

R_{DUT} = Resistance of Device Under Test

$I_M = I_{DUT}$

Figure 14. Cable and connection considerations.

In the circuit on the bottom, the inside shield of the triaxial cable is connected to the guard terminal of the SMU instrument. Now this shield is driven by the SMU's unity-gain, low impedance amplifier (Guard). The difference in potential between the Force/Output Hi terminal and the Guard terminal is nearly 0V, so the leakage current is eliminated.

Due to their high level of performance, triaxial cables can be expensive, so when specifying your final test configuration or comparing price quotations from various manufacturers, make certain they are included with the SMU instrument. If they are considered an optional accessory instead, you could be in for a costly surprise. In addition, some SMU instruments require optional adapters to convert more common input connectors, like banana jacks, to use triaxial cables. Again, be sure to understand and specify your cabling carefully, because it can easily add more than $2000 to the total cost of an SMU instrument.

Conclusion

The integrity of the measurements an SMU instrument produces must always be a primary selection consideration. Poor measurement integrity can produce costly errors in both R&D and production test applications, leading to expensive rework, time-to-market delays, poor yields, customer dissatisfaction, and other problems. A careful evaluation of an SMU's accuracy, repeatability, resolution, sensitivity, and integration time is critical. Other key considerations when selecting an SMU instrument include system-level throughput, source stability, measurement settling time, offset error, and noise, and finally, cabling and connection issues.

* * *

Biographical Notes

Mark A. Cejer is a marketing director for Keithley Instruments, Inc., which is part of the Tektronix test and measurement portfolio. He joined Keithley in 1991. During his tenure, he has served in a variety of positions, including marketing engineer, product/marketing manager, regional sales manager, and business manager. In his work, he has helped define and launch a number of Keithley's most popular instruments, including many of the company's SourceMeter® instruments, digital multimeters (DMMs), and datalogging products. Before joining Keithley, he served in several project management and electrical engineering positions in the electronics industry with emphasis on aerospace/defense. He holds a BSEE from the University of Akron (Akron, Ohio) and an MBA from Case Western Reserve University (Cleveland, Ohio.) His technical interests include compound semiconductors for power, LED, and energy efficiency applications, as well as optical devices, sensors, and discrete semiconductors.

Jonathan Tucker is a senior marketing and product manager for Keithley Instruments, which is part of the Tektronix test and measurement portfolio. He joined Keithley in 1987. During his tenure, he has served in a variety of positions, including manufacturing test engineer, applications engineer, applications manager, product manager, and business development manager. He holds a BSEE from Cleveland State University (Cleveland, Ohio) and an MBA from Kent State University (Kent, Ohio). He was a 2007 recipient of the Nano Science and Technology Institutes (NSTI) Fellow Award for outstanding contributions towards the advancement of the Nanotechnology, Microtechnology, and Biotechnology community. Jonathan is a Senior Member of IEEE and was recently the IEEE Nanotechnology Council Standards Committee Chairman. His technical interests include nanotechnology, LED and energy applications, software defined radio technology, and JAVA/HTML web programming.

Lishan Weng is an applications engineer at Keithley Instruments, Inc. in Cleveland, Ohio, which is part of the Tektronix test and measurement portfolio. Weng is interested in new measurement instruments/techniques related to graphene. She holds master's degrees in both electrical engineering and physics from Purdue University, where her research focused on graphene devices and p-type GaAs/AlGaAs heterostructures. Her previous research also includes carbon nanotube based nanolithography and tunable graphene oxidation, as well as quantum transport measurement and a specialization in AFM lithography.

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Printed in the U.S.A No. 3161 8.13.13

Technical Information

Source Measurement Unit (SMU) Instruments

All of Keithley's source measurement unit (SMU) instruments can source voltage while measuring current and source current while measuring voltage. Some also measure resistance. All are fully programmable instruments that can stand alone as complete source, measurement, and automation solutions. They are also easy to integrate into larger systems.

Keithley's SMU instruments are faster, easier to use, and more economical than using individual power supplies and measurement instruments that are harnessed together. Additionally, they provide more accurate and repeatable results. Keithley's SMU instruments are ideal for production and automation, yet precise and sensitive enough for laboratory applications.

Keithley's SMU instruments include our Series 2400 SourceMeter® instruments, Series 2600A System SourceMeter instruments, Model 237 High-Voltage Source-Measure unit, and Model 4200-SCS Semiconductor Characterization System.

How does an SMU instrument work?

SMU instruments can be used as stand-alone constant voltage or constant current sources and as stand-alone voltmeters or ammeters. However, their real strength is their ability to simultaneously source and measure—applying voltage to a device under test (load) and measuring the current flowing through it, or supplying current to a load and measuring the voltage drop across it.

The SMU instrument topology (**Figure 1**) protects the device under test (DUT) from damage due to accidental overloads, thermal runaway, and other problems. Both the current and voltage source are programmable with readback to maximize device measurement integrity. If the readback reaches a programmed compliance limit, then the source is clamped at the limit, providing fault protection.

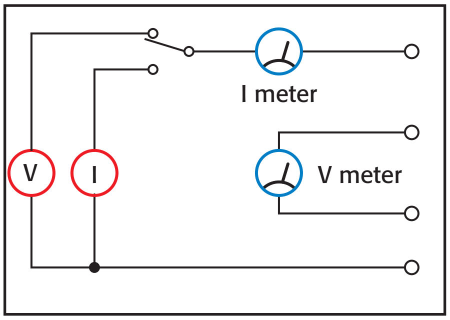
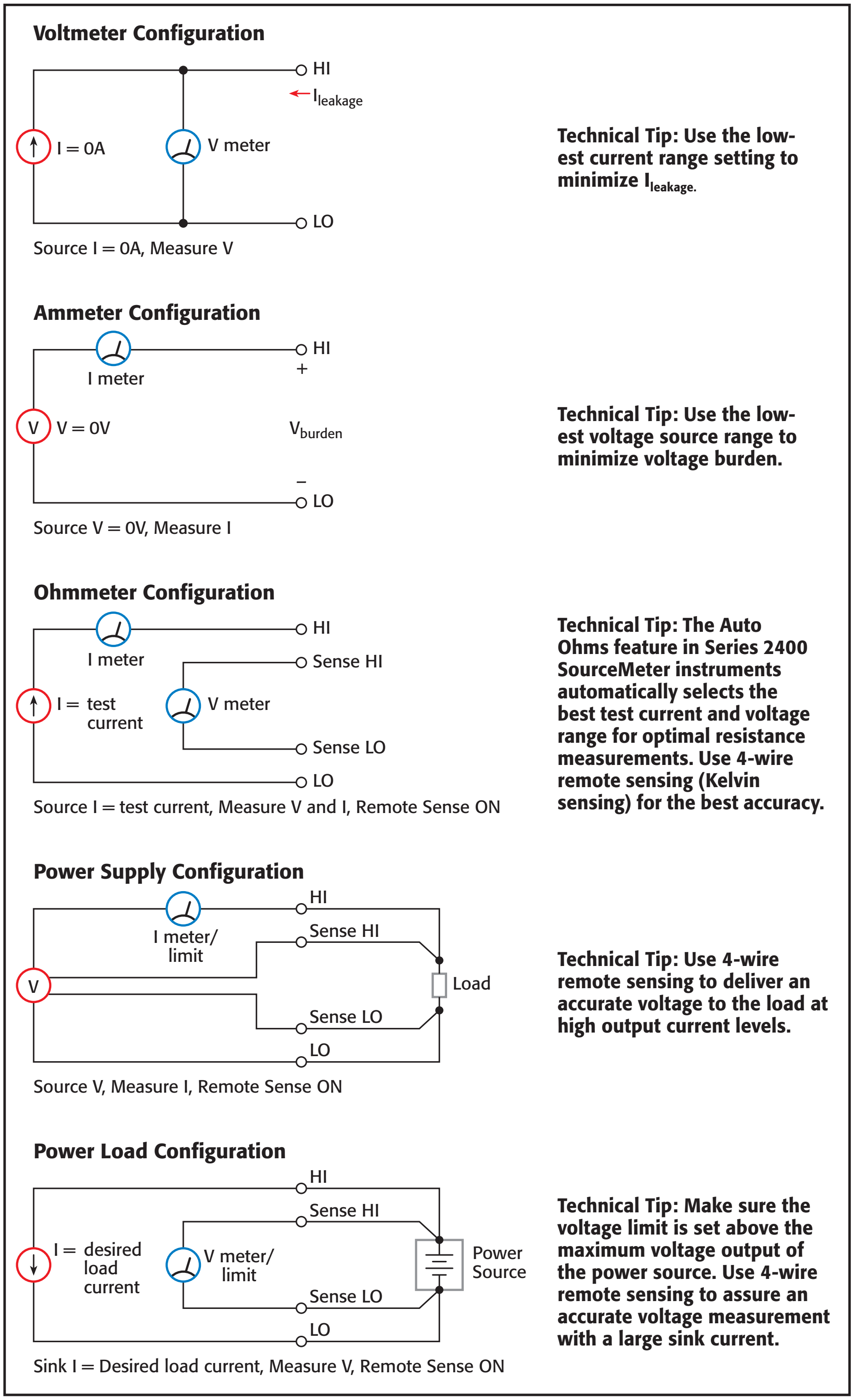


Figure 1. Basic SMU instrument topology



Technical Tip: Use the lowest current range setting to minimize $I_{leakage}$.

Technical Tip: Use the lowest voltage source range to minimize voltage burden.

Technical Tip: The Auto Ohms feature in Series 2400 SourceMeter instruments automatically selects the best test current and voltage range for optimal resistance measurements. Use 4-wire remote sensing (Kelvin sensing) for the best accuracy.

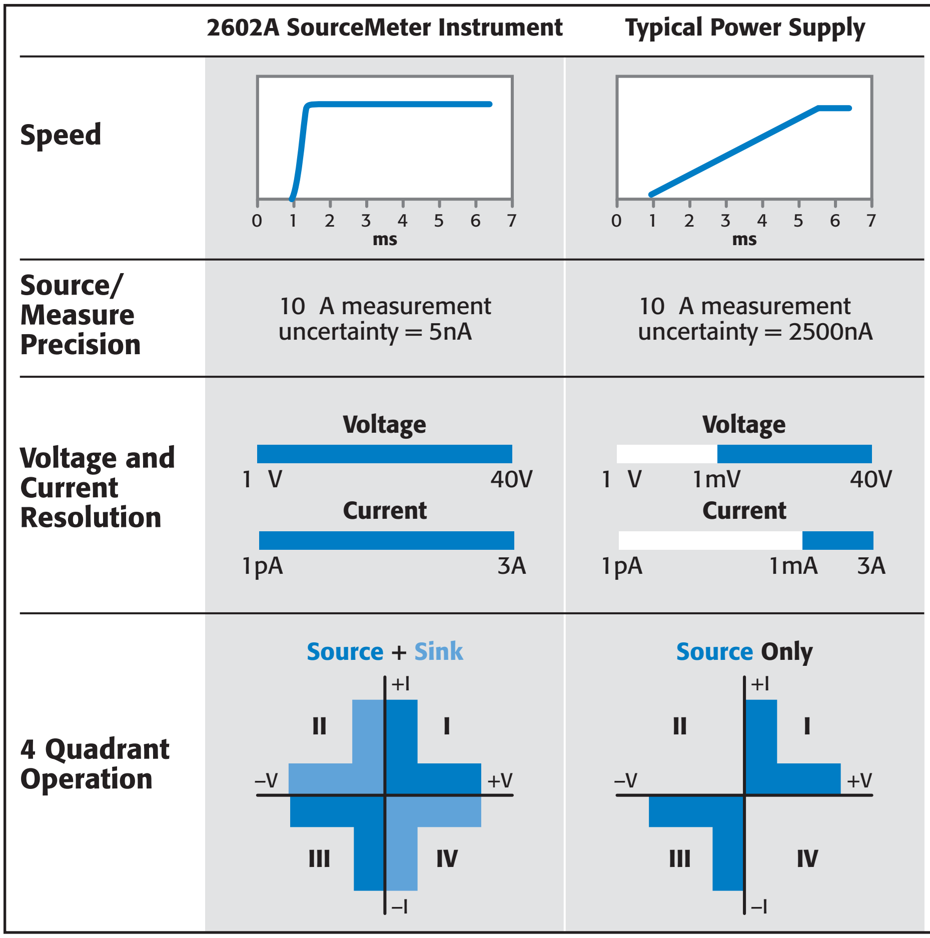
Technical Tip: Use 4-wire remote sensing to deliver an accurate voltage to the load at high output current levels.

Technical Tip: Make sure the voltage limit is set above the maximum voltage output of the power source. Use 4-wire remote sensing to assure an accurate voltage measurement with a large sink current.

Figure 2. SMU instrument configurations

Technical Information

Source Measurement Unit (SMU) Instruments



SMU instruments are optimized for speed and precision. In most models, both the source voltages and source currents settle to within 0.01% of the specified accuracy in as little as 50µs. This is 50 times faster than what a conventional power supply can provide.

SMU instruments offer a much broader range of voltage and current resolution than conventional power supplies. This allows you to use SMU instruments in many more types of applications.

A conventional power supply sources (supplies) voltage and/or current. An SMU instrument also sources power, but it can additionally sink (dissipate) power. It provides four-quadrant operation. In quadrants I and III it sources power to a load and in quadrants II and IV it sinks power from a load. (Voltage, current, and resistance can be measured during source or sink operations.) A conventional power supply only functions in quadrant IV.

Figure 3. Precision power supplies vs. SMUs

Advantages

Many advantages are achieved by combining source and measurement circuitry into a single unit:

- Supports faster test times with improved accuracy and repeatability
- Allows you to source voltage or current while making time-stamped voltage, current, and resistance measurements without changing connections
- Eliminates many of the complex synchronization, connection, and programming issues associated with using multiple instruments
- Minimizes the time required for test station development, setup, and maintenance
- Lowers the overall cost of system ownership

What are the most popular SMU instrument configurations?

The fully isolated, floating configuration of Keithley's SMU instruments provide maximum flexibility in configuring test setups. SMU instruments can be configured as many different instruments (**Figure 2**). This makes them invaluable tools in flexible product test racks and in R&D test bench tools.

How does an SMU instrument compare to a precision power supply?

The power supply capabilities of Keithley's SMU instruments surpass those provided by conventional power supplies. This is illustrated in **Figure 3**. In addition to the highly stable DC power source, low noise, and readback, Keithley's SMU instruments include other features not usually available on conventional power supplies. For example, most SMU instruments offer a Pulse mode, include programmable delays, and provide a test sequencer that allows you to set up and execute tests without PC intervention. **Figure 4** illustrates a typical precision power supply test that uses an SMU instrument.

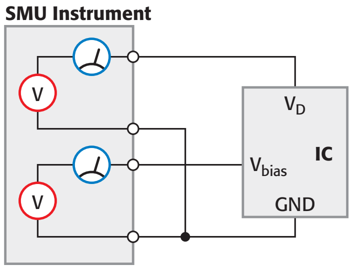
I-V characterization

Keithley's SMU instruments are core instruments for I-V characterization tests. Their ability to source voltage while simultaneously measuring current or source current while simultaneously measuring voltage can be combined with both DC and sweep operations to perform measurements such as forward voltage (V_F), reverse leakage, and reverse breakdown voltage (V_B) without changing a single connection to the device under test (**Figure 5**).

Built-in features allow multiple SMU instruments to be synchronized for parametric measure-

Technical Information

Source Measurement Unit (SMU) Instruments



Test	Description	Reading
Idd ON (5V)	Power supply current, V_D = 5V, device active	14.294 mA
Idd OFF (5V)	Power supply current, V_D = 5V, device in standby	50.361 nA
Idd ON (3.3V)	Power supply current, V_D = 3.3V, device active	12.871 mA
Idd ON (3.3V)	Power supply current, V_D = 3.3V, device in standby	42.198 nA
I_{IL}	Input leakage current	1.2358 μA

Figure 4. Typical precision power supply tests

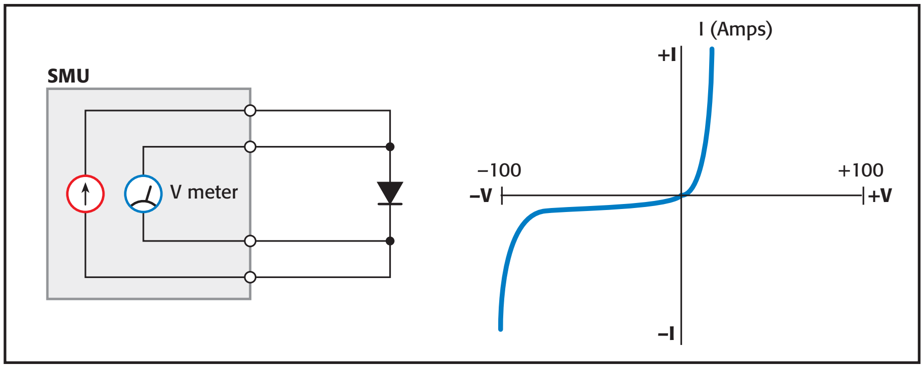


Figure 5. Typical diode characterization

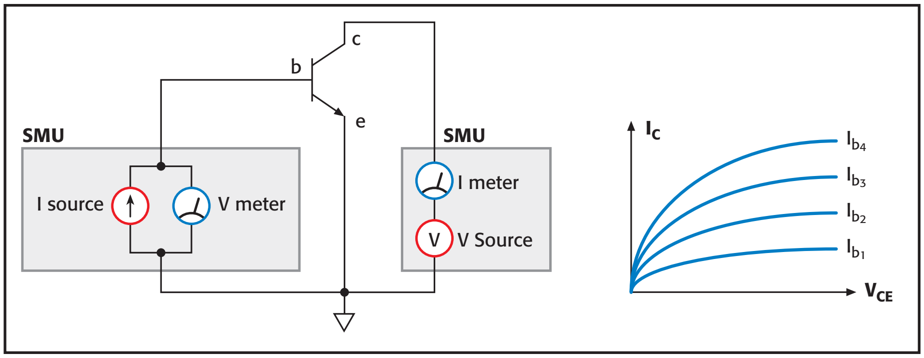


Figure 6. Typical family of curves for transistors

ments like threshold voltage, beta, and transconductance. Output interlocks provide controlled access to a test fixture, which is particularly important for the extended voltage range of the Model 237 (up to 1100V). Guarded 4-wire connections provide high quality measurements over a wide range (1fA to 10A).

A family of semiconductor curves can be obtained with just two SMU instruments (**Figure 6**). At each step of base current from SMU1, SMU2 sweeps V_{CE} and measures I_C. An SMU instrument can store data from a sweep in its buffer, thus reducing data transfer time to a computer. A family of curves could also be produced using pulse-sweeps to reduce power dissipation within a device.

Built-In Sweeps

Keithley's SMU instruments simplify capturing the data needed to characterize a wide range of devices with the SMU instruments' built-in pulsed and DC sweeps, including linear staircase, logarithmic staircase, and custom sweeps (**Figure 7**). Sweeps coupled with other throughput enhancements like built-in limit inspection, digital I/O, and a component handling interface are ideal for high speed, nonstop production environments. All sweep configurations can be programmed for single-event or continuous operation.

Instrumentation and software solutions for I-V characterization

Figure 8 illustrates various hardware and software solutions for I-V characterization. In the first example, Series 2400 SourceMeter instruments are connected to a PC.

In the second example, Series 2600A SourceMeter instruments are connected to a PC with TSP-Link® technology. TSP-Link technology seamlessly integrates multiple Series 2600A instruments into a single system that can be programmed and controlled as a single instrument through the master 2600A instrument or the PC.

The third example is the Model 4200-SCS Semiconductor Characterization System. This system includes an embedded PC, Windows® operating system, and mass storage. It is a complete DC characterization solution for semiconductor devices and test structures. It supports up to nine SMU modules and provides an array of Windows based software that is so intuitive that even a novice can use the system with ease. This point-and-click software supplies a full range of functionality, including: managing tests, generating reports, automating test sequencing, and creating user libraries. The Model 4200-SCS is a complete one box solution that combines sub-femtoamp resolution with real-time plotting and analysis. Key capabilities include instrument and prober drivers, interfaces to popular modeling/circuit simulation software, and WLR test capabilities.

High-Speed I-V Functional Testing

Keithley's SMU instruments are designed for maximum throughput on the production floor. Each SMU instrument provides high-speed measurements, an internal pass/fail comparator, programmable test sequencing, and digital I/O to control material handlers (**Figure 9**). Single- or multi-point pass/fail testing can be performed on a wide range of components, such as: network devices, circuit protection devices, active discrete devices, and sensors. The onboard pass/fail comparator simplifies high-speed pass/fail tests by avoiding the delay caused by computer and GPIB bus interaction. The buffer memory stores results, again avoiding the computer/GPIB bus interaction delay.

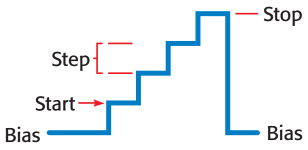
Technical Information

Source Measurement Unit (SMU) Instruments

Fixed Level

LEVEL, COUNT (number of DELAY-MEASURE cycles), DELAY, BIAS

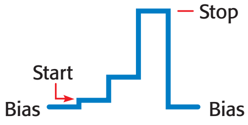
A fixed level sweep outputs a single level of voltage and current with multiple measurements to bias and/or stress devices.



Linear Stair

START, STOP, STEP, DELAY, BIAS

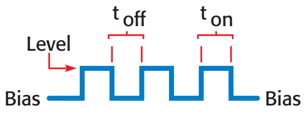
The linear staircase sweep goes from the start level to the stop level in equal linear steps.



Logarithmic Stair

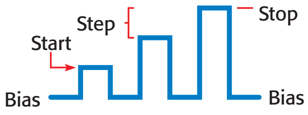
START, STOP, POINTS/DECADE (5, 10, 25, or 50), DELAY, BIAS

The logarithmic staircase sweep is similar to the linear staircase sweep, but it is done on a log scale with a specified number of steps per decade.



Pulse

LEVEL, COUNT, t_{on}, t_{off}, BIAS



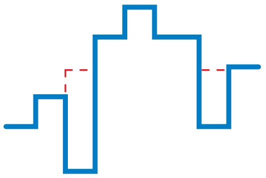
Linear Stair Pulse

START, STOP, STEP, t_{on}, t_{off}, BIAS

Pulsed sweeps greatly reduce the power dissipation within a device, so the effects of temperature (drift, device failure, etc.) are virtually eliminated.

Logarithmic Stair Pulse

START, STOP, POINTS/DECADE (5, 10, 25, or 50), t_{on}, t_{off}, BIAS



Custom

Custom sweeps allow the user to program individual steps to create waveforms

The custom sweep allows you to construct special sweeps by specifying the number of measurement points and the source level at each point.

Figure 7. Various sweeps supported by SMU instruments.

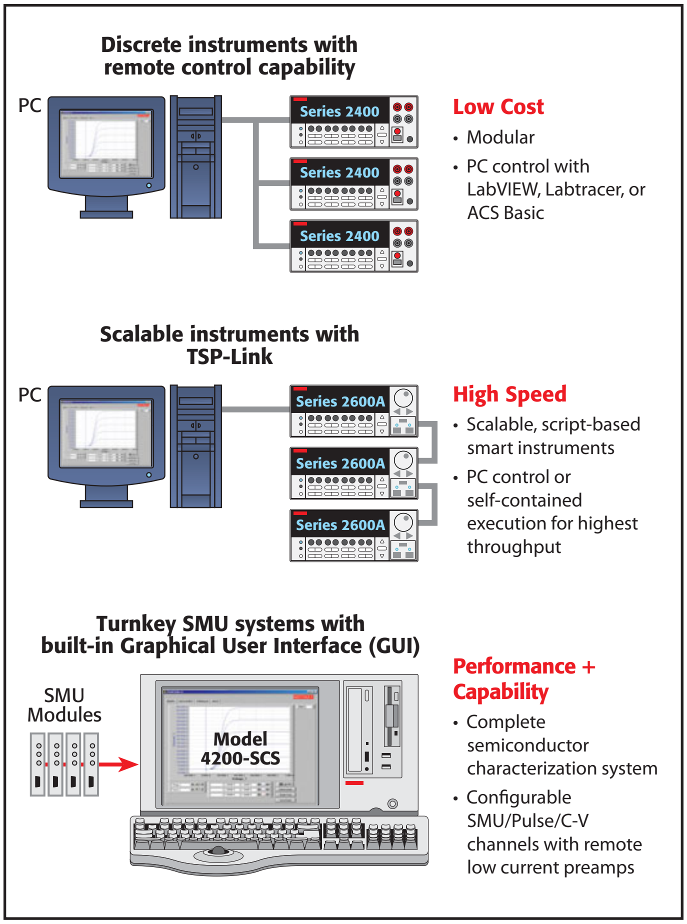


Figure 8. Examples of I-V characterization solutions

Need more test pins?

Keithley's new TSP-Link technology is a high speed interface for system expansion. It allows you to connect a virtually unlimited number of Series 2600A SourceMeter instruments in a master/slave configuration (**Figure 10**). All connected Series 2600A instruments can be programmed and operated under the control of the master instrument. TSP-Link technology provides an easy way to scale your system's channel count up or down to match changing application needs. There is no chassis involved.

In Series 2400 SourceMeter instruments, Trigger Link can be used to coordinate multiple instruments with hardware triggers.

Parallel test capability

Series 2600A instruments support true parallel testing. Each 2600A in a system can run its own test sequences, so the number of devices that can be tested in parallel is equivalent to the number of 2600A instruments in the system. Parallel testing coupled with the 20,000 rdgs/s of each 2600A creates a system that offers extremely high throughput.

Advanced automation for system throughput

Series 2600A TSP® Technology

Any Series 2600A instrument or 2600A-based system can run high speed, embedded test scripts with Test Script Processor (TSP) technology. The test sequence is processed and run on the embedded computer in the instrument, rather than from an external PC controller, so delays due to GPIB traffic congestion are eliminated (**Figure 11**). TSP test scripts allow throughput gains of up to 10x over equivalent PC-based programs controlling the same instruments via GPIB. TSP test scripts can be loaded and run from the front panel or over the system's GPIB interface. A single TSP test script, running on the master 2600A unit, can control all Series 2600A channels and acquire data from any Series 2600A instrument connected to the system with TSP-Link technology.

A Series 2600A-based system can stand alone as a complete measurement and automation solution for semiconductor device or component testing with the master 2600A unit controlling sourcing, measurements, pass/fail decisions, test sequence flow control, binning, the component handler, prober, and much more.

Series 2400 Source-Memory List

The Source-Memory List in Series 2400 SourceMeter instruments is a key feature for production testing. This programmable sequencer lets you set up a complete sequence of up to 100 tests. Each test can contain totally different test conditions, measurements, math, pass/fail, and binning criteria. The tests are executed sequentially without additional external commands. Conditional branching leads to different points on the test list, depending on the results.

The Source-Memory Sweep feature allows you to store up to 100 unique source and measure configurations in nonvolatile memory. This feature makes it possible to sweep through a group of source memory locations and execute a complete test sequence all at one time.

Digital I/O

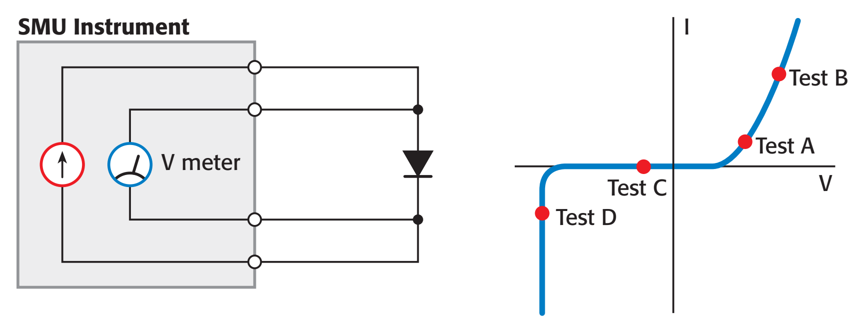
Digital communication is one of the most common requirements of a production test system because of the need to communicate with handlers, binning equipment, and user controls. The SMU instruments' digital I/O can also be used to interact with racks of instruments to trigger events, start readings, and collect results. Digital triggering and response enable fast and reliable results that are not dependent on the communication bus in use. (Digital I/O is not available on the Model 2401.)

Contact check

The optional Contact Check function eliminates measurement errors and false product failures by verifying good connections to the DUT quickly and easily before testing begins. In just 350μs (Series 2400) or 1ms (Series 2600A), this function's verification and notification routine ensures that you have good contact to a device before sending energy through it and spending time testing it (**Figure 12**). (The Contact Check function is not available on the Model 2401.)

Some of the problems this function can detect while verifying connector, fixture, and test harness integrity are contact fatigue, breakage, contamination, corrosion, loose or broken connections, and relay failures. If a bad contact is detected, it can abort the measurement, protecting the DUT. Three methods of fault notification are provided.

Source Measurement Unit (SMU) Instruments



	Pass/Fail Test	Description	Reading	Test Time	If Passes Test	If A Test Fails
Test A	Check Vf(A) at 100mA against pass/fail limits	Forward voltage test at 0.1A	0.6534 V	300 μs	Go to Test B	1. Bin part to bad bin. 2. Transmit data to computer while handler is placing new part. 3. Return to Test A.
Test B	Check Vf(B) at 1A against pass/fail limits	Forward voltage test at 1.0A	0.7268 V	300 μs	Go to Test C	
Test C	Check leakage current, Ir(C), at –10V and test against pass/fail limits	Reverse leakage current at –10V bias	10.122 nA	5 ms	Go to Test D	
Test D	Check Vbr(D)	Breakdown voltage	146.12 V	1 ms	1. Bin part to good bin. 2. Transmit readings to computer while handler is placing new part. 3. Return to Test A.	

Figure 9. Typical high speed I-V functional test

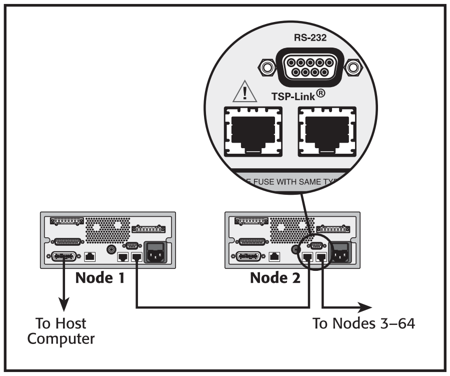


Figure 10. Series 2600A back panel

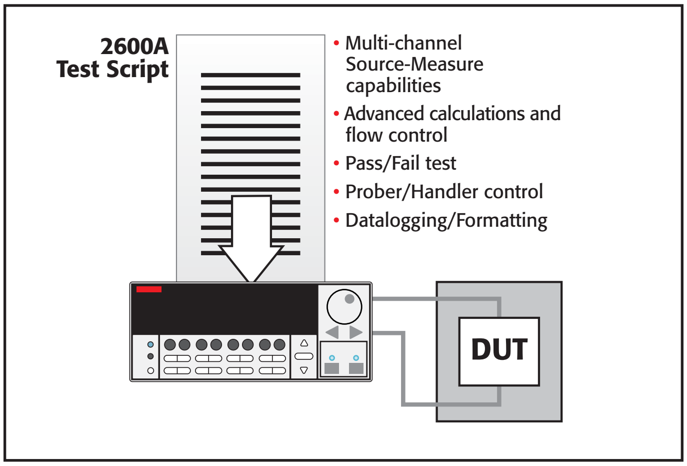


Figure 11. Series 2600A test script

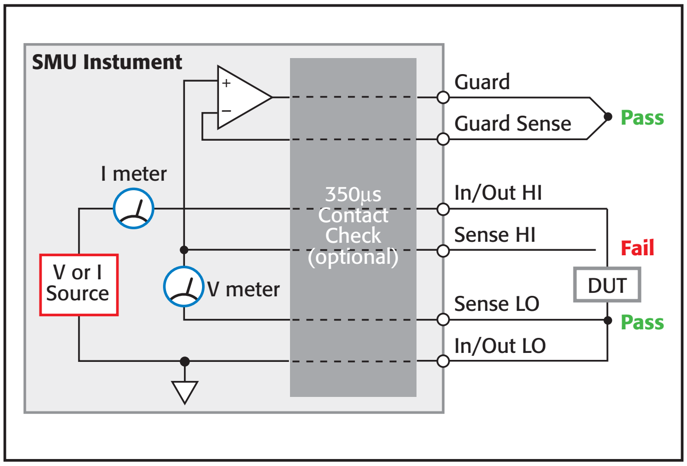


Figure 12. Series 2400 contact check

The Contact Check function was designed for high throughput 4-wire and 6-wire test applications. In Series 2400 SourceMeter instruments, three reference value choices (2Ω, 15Ω, and 50Ω) are supplied. If the resistance of good connections normally exceeds 50Ω, then the built-in contact check function is not suitable for that application and alternative approaches should be considered. Series 2600A instruments provide more flexibility with programmable values.