KEITHLEY BACKGROUNDER

Rapidly Expanding Array of Test Applications Continues to Drive Source Measurement Unit Instrument Technology

Since their introduction more than two decades ago, source measurement units (SMUs) have evolved into a category of multi-purpose instruments that are regularly called upon to address a rapidly expanding array of electronics industry applications:

- Semiconductor device fabrication, process development, and product research/design
- Production verification of electronic products such as portable wireless devices
- Production and development of new advanced materials for devices such as solar cells and HBLEDs
- Almost any electronic device test application

Before exploring the factors that define SMU technology, it may be helpful to define exactly what an SMU is (and what it isn't). Essentially, SMUs are fast-response, read-back voltage and current sources with high accuracy measurement capabilities, all tightly integrated in a single enclosure. They are designed for circuit and device evaluation where a DC signal must be applied to a device under test (DUT) and the response to that signal measured. They are capable of four-quadrant operation (***Figure 1***), acting as a positive or negative DC source or as a sink (load). They also provide highly repeatable measurements, typically with 5½- or 6½-digit resolution. SMUs can typically be used to perform sweeps of both current and voltage that can be used to determine the I-V characteristics of a device under test. As a result of these advantages, SMUs have been widely adopted in industry and are a common component of many automated test systems.

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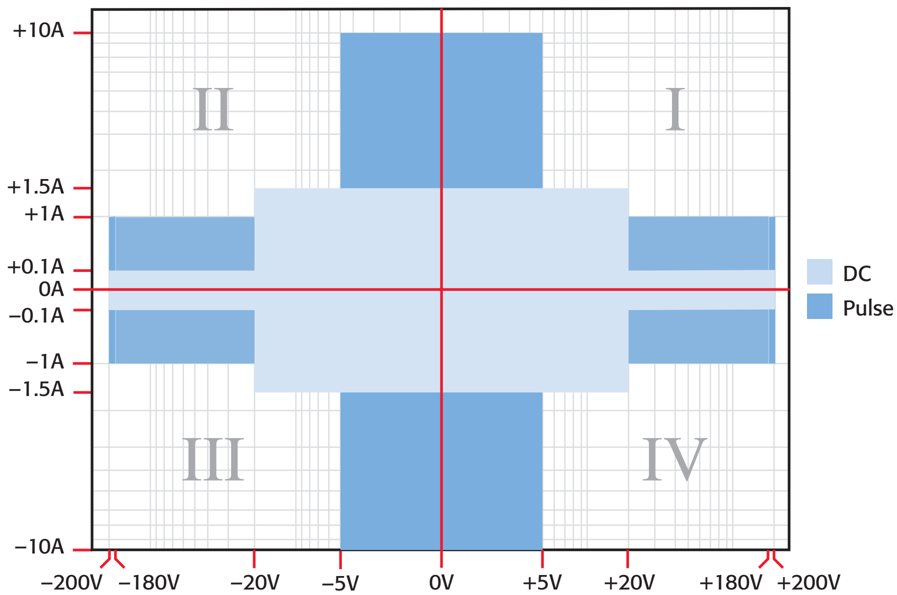

Figure 1: Four-quadrant SMU design.

Despite any claims to the contrary, traditional instrumentation remains a vital, growing part of the test and measurement industry. Although specific communication interfaces (GPIB, RS-232, etc.) may become obsolete over time, instrument-based SMUs, used either alone or integrated with other SMUs in a system, typically provide the fastest, most accurate, most flexible solutions for the widest range of demanding applications. "Component" SMUs often must compromise their performance to offer a specific form factor.

Widest Available Power and Signal Ranges

For testing many types of devices, it is desirable to have test equipment capable of operating with a wide range of signal levels. For example, devices such as power MOSFETs are designed to have very low resistance and handle very large currents when turned on but are also designed to have very high resistance and allow nearly zero current to flow when turned off. In the on state, this current is commonly as high as tens of amps; in the off state, this current may be less than nano-amps. Power diodes and high brightness LEDs have similar dynamic range requirements as well for full characterization. On these kinds of devices, when a forward bias voltage below the threshold value is applied, device currents are very low. As voltage is swept from 0V to the threshold, device current goes from the sub-nano-amp range up to milli-amps. As the bias voltage reaches and then exceeds the threshold, test currents increase very rapidly, reaching as high as tens to hundreds of amps depending on the device. Test equipment that is capable of taking accurate measurements over this wide range is desirable because it reduces the number of pieces of equipment required to test, thereby reducing both the complexity and the cost of the system.

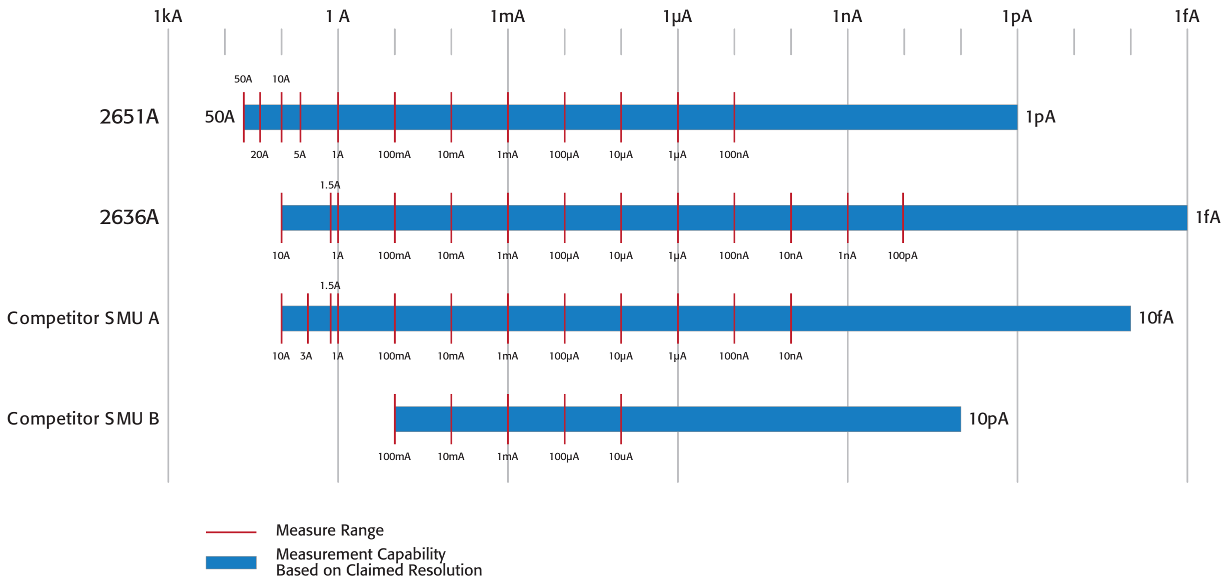

Figure 2: Dynamic range of Keithley SMUs vs. competitive offerings.

Keithley SourceMeter® instruments combine the most power with the widest range of signals available in a single instrument. The Model 2651A High Power SourceMeter instrument can deliver up to 200W of DC power and 2000W of pulsed power to a device. It can measure as much as 50A of current and is also capable of measuring with a maximum resolution of 1pA. The Model 2636A leads the industry in dynamic range with the ability to measure signals from 10A all the way down to 1fA, offering 16 decades of current resolution.

Some competitors' instrument-based SMUs claim nearly the same coverage of dynamic range as the Model 2636A Dual-channel System SourceMeter instrument, measuring from 10A all the way down to 10fA. However, when one compares the available measurement ranges from each SMU (***Figure 2***), it's obvious that the Model 2636A has current ranges for the next two orders of magnitude lower than the competition. What this means is that the Model 2636A doesn't have to rely on the least significant, least accurate digits of its measurement ranges to achieve a truly wide dynamic range. For instrument users, that provides far significantly greater confidence in the accuracy of their low current measurements.

Vendors of component SMUs also try to claim wide coverage. However, the form factor of these instruments limits them to a dynamic range several decades smaller than Keithley's instrument-based SMUs. On the high end of the range, they are limited by how much power the chassis can provide and most component SMUs will top out at 100mA. On the low end, the electromagnetic interference of all the circuitry designed into a small space with inadequate room for shielding creates too much electrical noise for any kind of low-level measurement to be practical; as a result, it is uncommon to see a component SMU with any current ranges lower than 10 micro-amps.

Fastest Analog-to-Digital Converters

Test equipment manufacturers are always pushing to wring more readings per second out of their SMUs. The digital engines behind the SMU get upgrades, the bandwidth of the communications channels are increased, but ultimately the most effective way to boost speed is to decrease the time it takes to acquire the measurement itself. Most SMUs use integrating analog-to-digital converters (ADCs) to take measurements due to their excellent ability to reject noise and produce incredibly accurate high resolution results. However, the quality of measurement from an integrating ADC is directly related to time, and the measurement degrades as it's forced to go faster.

An integrating ADC is able to produce outstanding results by turning the value of the input signal into a relationship between the time it takes to charge a capacitor with the input voltage level and the time it takes to discharge the capacitor with a reference voltage of the opposite polarity. In a standard dual-slope integrating ADC, this relationship is expressed by the equation $V_{in} = -V_{ref}\ (t_d/t_c)$, where V_{in} is the signal being measured, V_{ref} is the reference voltage, t_d is the time it took to discharge the capacitor, and t_c is the time it took to charge the capacitor. By charging a capacitor over time, noise spikes in the input signal are averaged out, thus minimizing noise in the measurement and improving accuracy. The time it takes to charge and discharge the capacitor is measured by counting the number of clock cycles of a fixed rate clock that pass during the charge and discharge cycles. Assuming then that t_c and t_d are represented by the number of clock cycles that have passed, by examining this equation, one can see that resolution is provided for by the time it takes to charge the capacitor (t_c). As more time is allowed to pass, the t_c count grows larger, increasing the number of steps into which the reference voltage (V_{ref}) will be broken. To put it simply, as the t_c count becomes larger, the resolution of the measurement increases.

Looking at this equation, one can see that the variable over which the instrument manufacturer has some control is the charge time (t_c). In order to speed up measurements, it's necessary to allow the integrating ADC less charge time, but doing so reduces the resolution of the measurements. Keithley SourceMeter instruments use integrating ADCs, but to combat loss of resolution due to speed, they employ an integrating ADC that uses an enhanced multi-slope rundown method instead of the more conventional dual-slope method. An enhanced multi-slope rundown integrating ADC uses a variety of innovative techniques to speed up the discharge time, allowing increased speed without reducing the charge time and thus the ultimate resolution of the measurement. Although the details of how this type of integrating ADC works are beyond the scope of this paper, a full description is available. Innovative techniques like the use of the multi-slope rundown method are what allow Keithley SMUs to produce the industry's fastest high resolution readings using integrating ADCs.

Keithley Series 2600A SourceMeter instruments are capable of reading rates as high as 20,000 readings per second using enhanced multi-slope rundown integrating ADCs. However, for applications that require still faster measurements, an integrating ADC quickly loses resolution and accuracy and a different type of ADC must be used. The Keithley Model 2651A

High Power SourceMeter instrument, which is capable of speeds of up to 1,000,000 readings per second, includes both an integrating ADC and an 18-bit high speed digitizing ADC. Using this high speed ADC, the Model 2651A has the highest reading rate of any SMU on the market while still maintaining high measurement resolution.

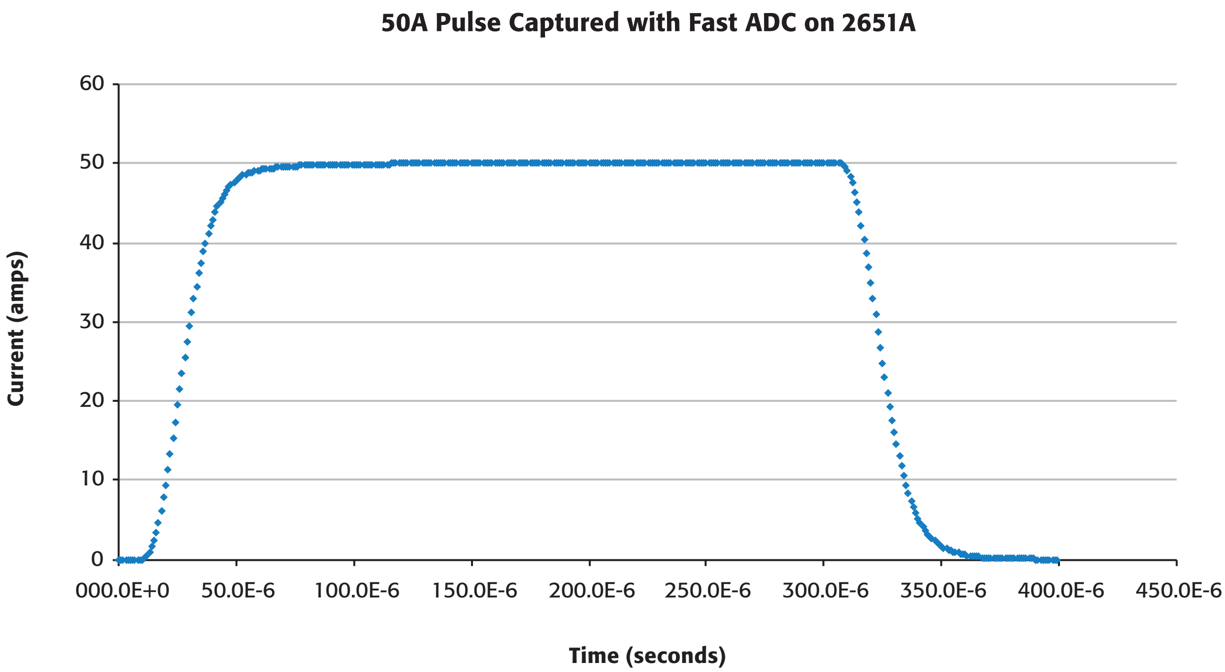

Figure 3: A 300-microsecond 50A pulse captured with the Model 2651A's 18-bit high speed digitizing ADC.

Figure 3 demonstrates the capability of the Model 2651A's high speed digitizing ADC. This ADC makes it possible to capture the entirety of a 300-microsecond 50A pulse using 400 samples and a one-microsecond interval. With this capability, the Model 2651A can capture device transients and thermal effects accurately without the need for additional test equipment.

Multi-Channel Scalability

No matter how fast an individual SMU may be, its merits are wasted if its performance slows to a crawl when it's integrated into a system. Component SMUs are inherently less affected by this issue thanks to their high speed, low latency connection to the host system through a PCI or PCIe backplane (133MB/s for PCI. 250MB/s for PCIe x1). In contrast, instrument-based SMUs communicate with a host system through an external bus such as GPIB, which has only a fraction of a backplane's speed (1.8MB/s standard). Keithley's engineers recognized this when they designed the Series 2600A SourceMeter instruments and built them to operate autonomously from the host system by using a Test Script Processor (TSP®) and to communicate and synchronize with one another via a high speed, low latency bus called TSP-Link® technology.

Traditional instrument-based SMUs require that each command be sent to them from the host one line at a time and, because all the instruments share the same bus, only one instrument can be addressed and talked to at a time. Given the slowness of the bus, a lot of time is spent sending commands and data across the bus to one instrument at a time while the remaining instruments often sit idle. TSP technology all but eliminates the time spent sending commands by allowing the instruments to run test scripts autonomously from the host system. Once a script has been loaded into a TSP-based SourceMeter instrument, an entire test sequence can be performed, with the host required to send only a single command that instructs the instrument to run the script.

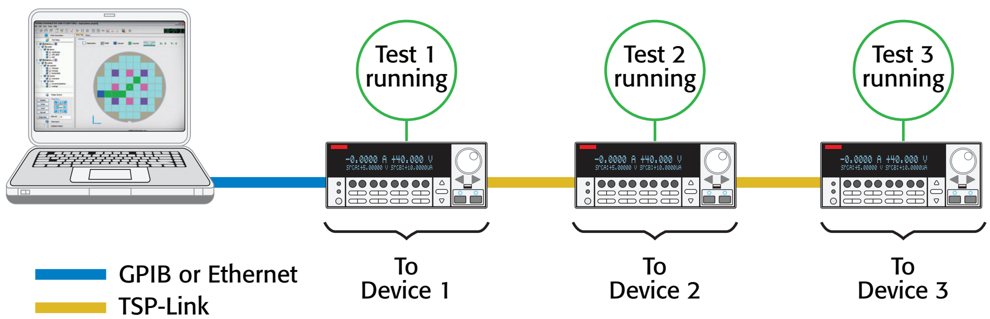

Figure 4: Example of a TSP-Link network with three SourceMeter instruments.

TSP-Link technology removes the need for multiple SourceMeter instruments to be attached to and individually addressed by the same bandwidth-limited GPIB bus. With TSP-Link technology, only one SourceMeter instrument is connected to the GPIB bus while the remaining SourceMeter instruments are connected to the first in a "daisy-chain" configuration using inexpensive CAT5e crossover cables. By connecting the additional SourceMeter instruments to the first via TSP-Link technology, the SMUs of these instruments appear as additional SMU channels on the first SourceMeter instrument and can be accessed quickly by a script running on the first SourceMeter instrument.

Unlike with component SMUs, channel expansion with TSP-Link technology is not limited to a handful of slots in a mainframe. TSP-Link technology's mainframe-less expansion allows connecting up to 32 instruments together, making it possible to create a system with as many as 64 SMU channels. Also, because the SMUs are instrument based, the amount of power available to them is not limited by what a chassis can provide to them. Even in high power component SMU-based systems, some models provide a maximum power output of only 84W. By connecting 32 Model 2651A High Power SourceMeter instruments together via TSP-Link interface, it is possible to create a system capable of delivering 6.4kW of DC power.

TSP-Link technology provides an elegant way to expand a system without the need for expensive GPIB adapters and cables and can boost system throughput by drastically reducing the amount of communication necessary between the instruments and the host. However, the real power of TSP-Link technology lies in its ability to increase throughput by running multiple tests in parallel. In traditional SMU systems, whether they are component-based SMUs in a chassis or instrument-based SMUs on a GPIB bus, access to the bus is limited and the host must send commands to each SMU one at a time. Adding more SMUs to the system means increasing the number of devices the host must address and to which it must send commands. Because commands cannot be sent to more than one SMU at a time in these systems, all tests must be performed sequentially.

In a system connected via a TSP-Link interface, instruments in the network can be divided into groups, with each group having its own Test Script Processor capable of running a script in parallel with every other group in the system. Groups may contain a single SourceMeter instrument or multiple SourceMeter instruments and are typically sized according to the number of SMU channels required to test a device. For example, if the device under test is a MOSFET with four terminals (Gate, Drain, Source, and Base) and the test is on wafer and requires one SMU per pin, then the group could be made from two dual-channel SourceMeter instruments, such as the Model 2636A Dual-channel System SourceMeter instrument. Once groups have been defined and each group has been given a script to run, the host can instruct all groups to begin execution in parallel with a single command. With the scripts for each group already in memory, the host can repeat the test simply by sending the command again.

Following the example of a four-terminal MOSFET on wafer, let's assume a TSP-Link network with one group and a complete test sequence with the following steps:

- The host sends the command to begin execution.
- The script runs and performs a complete set of tests on the device.
- The data is sent back to the host while the probe station simultaneously moves the probe needles to the next test site.

If this entire sequence takes a total of one second to complete, at that rate it would be possible to test 60 sites per minute. If another group is added to the TSP-Link network, the test would still take one second to complete. However, the addition of a second group makes it possible to test two parts in parallel so throughput is doubled to 120 sites per minute. Using TSP-Link technology, system throughput can be increased simply by adding more groups to the network.

I/O Connectors that Enable Maximum Performance

Keithley engineers choose the input/output connectors for SourceMeter instruments to provide maximum performance for the intended application. For mid-level signal ranges, banana connections work well to carry the signal and provide the greatest ease of use, which is why Series 2400 SourceMeter instruments provide this type of connection. However, for applications where the current is very high or very low, banana connections can't support the required levels of performance, so alternative connectors must be used.

For high current SourceMeter instruments like the Model 2651A High Power SourceMeter instrument, DC currents can be as high as 20A and pulsed currents can be as high as 50A.

Typical banana connectors are only rated up to 15A and have a contact resistance as high as 10mΩ. At 50A, this contact resistance would result in a 0.5V voltage drop in just the contact alone. Keithley chose to use a much higher performance Phoenix style connector that is rated for up to 76A DC. Not only does the connector have a current capacity rating high enough to meet the needs of the Model 2651A, but it maximizes performance by having a contact resistance low enough to avoid producing excessive voltage drops across the test leads, which can slow down rise and settling times. With a rated contact resistance of only 0.3mΩ, the voltage drop across the contact at 50A is only 15mV. Mating connectors with screw terminals are provided for making connections to the device to enhance ease of use.

For applications in which the current levels are less than one nano-amp, it's important to choose a connector that minimizes leakage current and supports the required voltage. That's why Keithley SourceMeter instruments with low current capability, such as the Model 237 High-voltage Source-measure unit, Model 2636A Dual-channel System SourceMeter instrument, and the Model 6430 Sub-femtoamp Remote SourceMeter instrument, all use triax connectors. Standard triax connections can safely handle up to 1500V and cover the output voltage capability of these instruments well. However, the greatest benefit of using triax is its ability to minimize leakage current, and in fact, all but eliminate it by guarding the test signal.

The simplest way to explain how a guarded triax connection eliminates leakage is to compare it to an unguarded coax connection. Coax connections are made up of a center conductor surrounded by a single shield with an insulator in between. The HI signal of the SMU is placed on the center conductor and the LO signal is placed on the shield, as shown in ***Figure 5***.

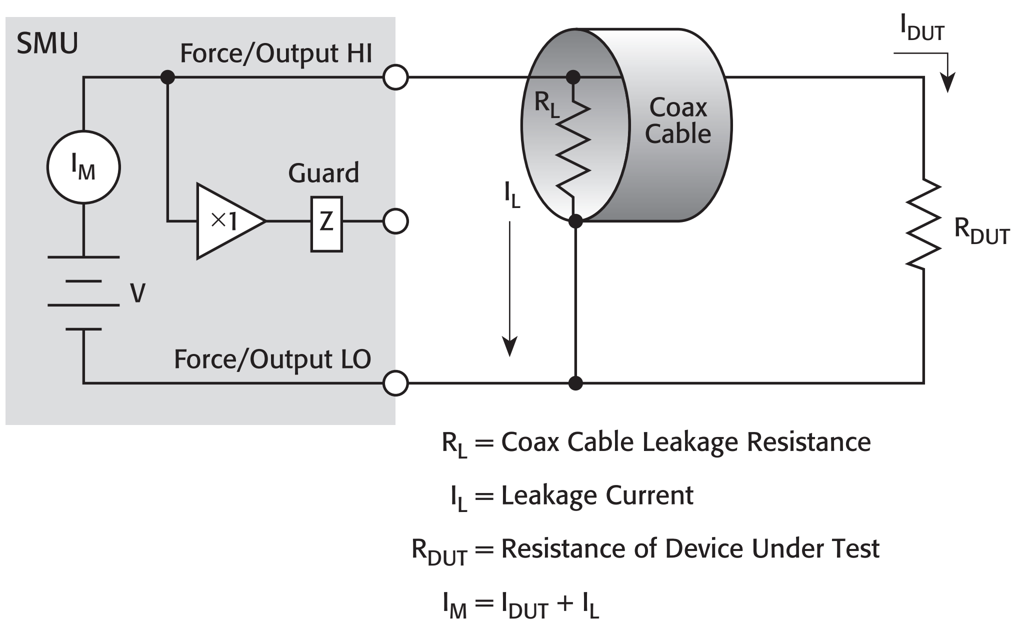

Figure 5: Unguarded coax connections.

In a coax connection, the insulator in between the center conductor and the shield creates a resistance path (R_L) that is connected in parallel with the device under (R_{DUT}). This extra current path results in a leakage current (I_L) that is added to the current through the device (I_{DUT}) to get the measured current (I_M).

Let's assume that R_{DUT} is 200GΩ and the test voltage is 200V. Ohm's Law tells us I = V/R, so the current one would expect to measure through the device is 200V/200GΩ = 1nA. The typical resistance of the insulator in a coaxial cable is approximately 2TΩ per meter, so assuming a cable length of one meter, the amount of current that would flow due to cable leakage would be 200V/2TΩ = 100pA. Given that the current measured is the sum of the current through the DUT and the leakage current, the measured current would be 1.1nA (1nA + 100pA = 1.1nA). This would result in a calculated resistance of 181.818GΩ (200V/1.1nA = 181.818GΩ), an error of 9.1% [(200GΩ – 181.818GΩ)/200GΩ * 100% = 9.1%]. As the cable length increases, the leakage resistance will get even smaller and the leakage current even greater; therefore, the error induced by leakage in the coax connection will be even larger.

In contrast, with a triax connection, the center conductor is surrounded by an inner shield and an outer shield. Like the coax connection, the center conductor carries the HI signal and the outer shield carries the LO signal. The inner shield, however, has a special purpose: to carry the guard signal.

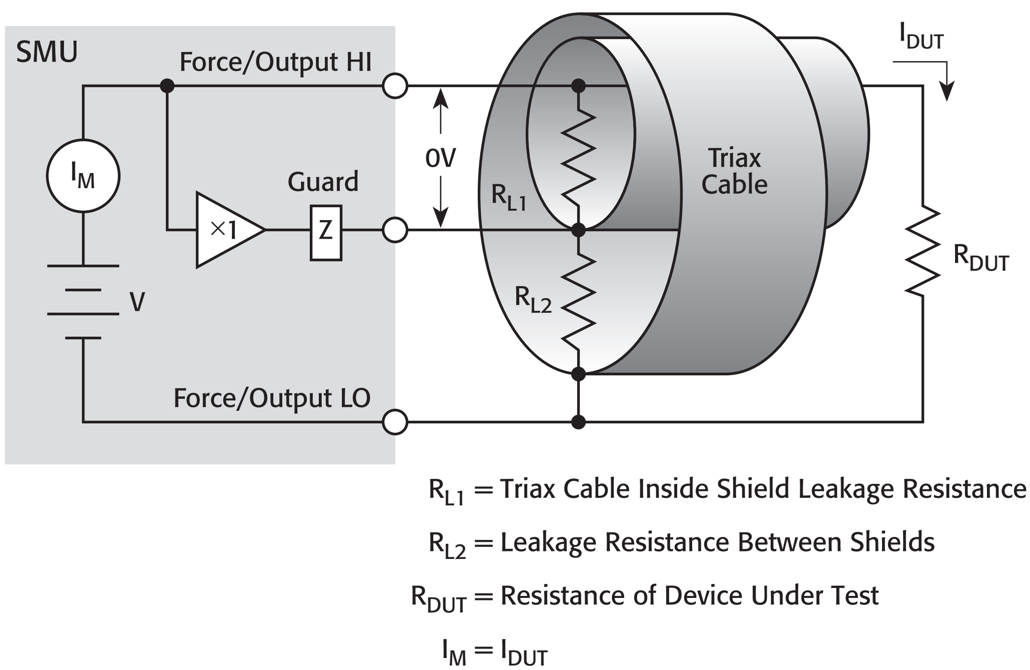

Figure 6: Guarded triax connections.

The guard signal is driven by a unity-gain, low impedance amplifier that follows the voltage of the HI signal. By driving the inner shield of the triax to the same voltage that is on the center conductor, the potential across the insulator between the center conductor and inner shield (R_{L1}) becomes 0V and the leakage current (I_L) is eliminated.

As the example shows, even very high resistance insulators can leak enough current to create very large errors in the measurement. Keithley SMUs with low current capability use triax natively to ensure that no path for leakage current can exist from the instrument to the end of the cable. Some SMUs use adapters to convert banana connections to triax. Although this is preferable to running individual leads straight from the instrument to the device under test, the connection path between the instrument and the adapter will still be unguarded, leaving a path for current to leak. This becomes an even more significant issue if the instrument and adapter are not cleaned regularly as oils from the operator's skin can form a relatively low resistance path between the terminals. By using triax natively, Keithley SourceMeter instruments ensure that these often-overlooked leakage paths cannot exist.

SMU Technology Leadership

Keithley's current SMU technology leadership position is the culmination of decades of instrument engineering design and development effort, beginning in the 1980s, which includes an extensive list of SMU-related patents:

- Range Changing Using N and P channel FETs (5,144,154)
- Control for Voltage/Current Source with Current/Voltage Limiting (5,039,934)
- High Voltage Solid-State Switch with Current Limit (5,146,100)
- Guarded Printed Circuit Board Islands (5,490,325)
- Test Contact Connection Checking Method and Circuit (5,886,530)
- Contact Check for Remote Sensed Measurement (5,999,002)
- Glitchless SMU Range Changing using Secondary Feedback
  (Source Measure Unit Having Secondary Feedback for Eliminating Transient During Range Changing) (6,262,670)
- Low Noise Power Transformer (7,009,486)
- Automatic Ranging Current Shunt (Self Config Current Sense) (7,276,893)
- Source Measure Circuit (Impedance Hider) 7,202,676
- High Capacitance Load Testing (7,800,380)
- Test Instrument Network (Dynamic TSP-Link Network Subdivision (DTNS)) (7,680,621)

Today, with four different classes of SMUs, Keithley has the test and measurement industry's most technically advanced line of instrument SMUs, designed for settings ranging from benchtop test to high throughput production test, with the broadest dynamic range available.

- **Model 237 High Voltage SMU** combines 10fA, 10-microvolt measurement sensitivity with the ability to source and measure up to 1100V. Although introduced in the late

1980s as part of the Series 230 family, the Model 237 is still addressing applications today in high voltage parametric testing for process control and reliability monitoring of Bipolar-CMOS-DMOS (BCD) technology.

- **Model 6430 Sub-Femtoamp Remote SourceMeter instrument** combines the voltage and current sourcing and measurement functions of an SMU with sensitivity, noise, and input resistance specifications superior to electrometers. Its 10aA sensitivity makes it invaluable for evaluating experimental components in test labs for low current, high resistance, or sensitive semiconductor measurements. Its low noise and drift also make it well suited for research studies in single electron devices, highly resistive nanowires and nanotubes, polymers, and other highly resistive nanomaterials.
- **Series 2400 SourceMeter instruments** are priced and designed to address bench (interactive) and lower-speed integrated systems. With the recent addition of the Model 2401 Low Voltage SourceMeter instrument, the Series 2400 line now offers researchers and system builders a choice of 8 different instrument-grade solutions to meet their dynamic range requirements. The wide range of choices eliminates the need to compromise on test requirements to accommodate the limitations of the instrumentation.
- **Series 2600A System SourceMeter instruments** offer the raw measurement speed, measurement integrity, and system-level throughput required to address high speed production test systems and PC-controlled bench applications. With the recent introduction of the Model 2651A, the product family now supports up to 200W DC and 2000W pulse test requirements.

Conclusion

Keithley is poised to continue to expand and grow its SMU leadership, giving customers the tools required to meet critical measurement needs across all leading DC characterization and measurement applications.

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