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 measurement 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.
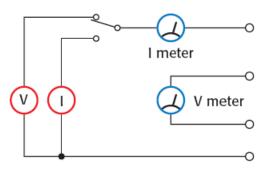

Figure 1. Basic SMU instrument topology.

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' 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.

4 Quadrant Operation

2602A SourceMeter Instrument

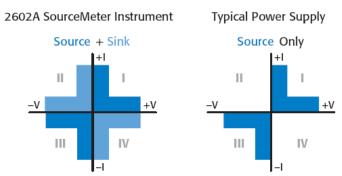Source + Sink

Typical Power Supply

Source Only

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.

  o 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.

  o *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.

  o *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.

Voltmeter Configuration

Source I = 0A, Measure V

Ammeter Configuration

Source V = 0V, Measure I

Ohmmeter Configuration

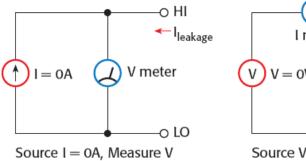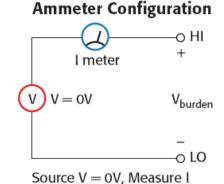Source I = test current, Measure V and I, Remote Sense ON

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.
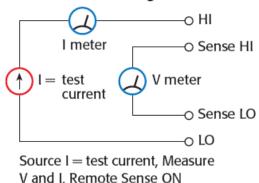
This can be valuable for protecting DUTs or for measuring extra high or extra low resistances. For high resistance measurements, the source voltage method is preferred; for low resistance measurements, the source current method is best. Some SMUs have a six-wire ohms feature that "guards out" the effects 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 bull's-eye.

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 datasheet, it can usually be easily determined during an instrument demonstration or evaluation. Figure 4 illustrates the concepts of accuracy vs. repeatability.
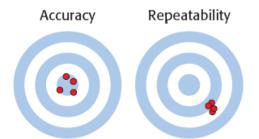

Figure 4. In the target on the left, the shooter had high accuracy but poor repeatability. The target on the right shows high repeatability but poor accuracy.

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 is toggling between 4½, 5½, and 6½ digits on the display and has just selected the 6½-digit display.

Figure 5. Adjusting an 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).
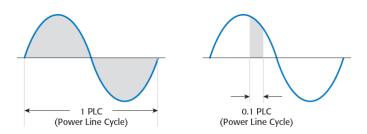

Figure 6. ADC integration time comparison (NPLC).

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:

- 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.

- *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 spec 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 7 shows a comparison of the actual test results from a Keithley Series 2600A 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	6.1	8.1	8.2	8.2	8.2
Keithley Series 2600A	13.3	33.2	37.8	38.2	N/A

Most accurate ←——————————————————→ Least accurate

Figure 7. 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 2600A System SourceMeter instrument in this example can test more than twice as many parts per second at 1 NPLC; therefore, it has more than 100% faster

throughput than the other SMU instrument while maintaining optimum accuracy.

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 2600A System 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 have 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 spec 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 spec 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 8*, note that the non-Keithley SMU offers 50 times greater programming resolution than the Model 2400 SourceMeter instrument.

	Programming Resolution 20V Range
Non-Keithley 6½-digit SMU instrument	10 µV
Keithley Series 2400	500 µV

Figure 8. 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 9*), 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 2400 shows 30µV.

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 Series 2400	30.0 µV	42.9 µV

Figure 9. 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 10a*) 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 2400 SourceMeter instrument (*Figure 10b*) actually has more than 10 times better output stability than the non-Keithley 6½-digit SMU (42.9µV vs. 438.7µV).

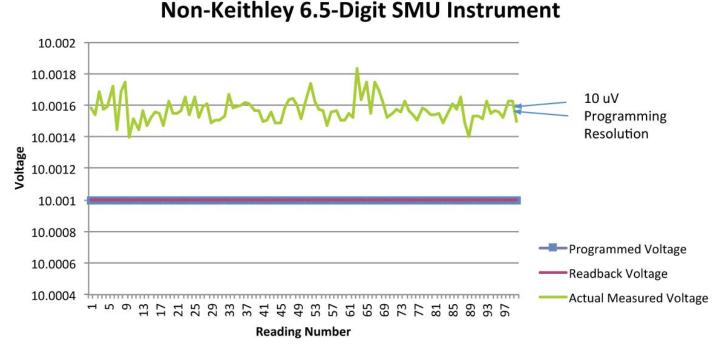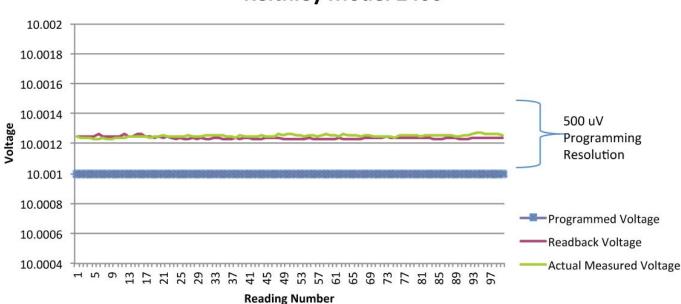## Non-Keithley 6.5-Digit SMU Instrument

Figure 10a. Actual source performance: programming resolution vs. stability for non-Keithley 6½-digit SMU.

Keithley Model 2400

Figure 10b. Actual source performance: programming resolution vs. stability for Keithley Model 2400 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 2400 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 2400, 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 11* 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 11. 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 2636A (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 2636A will deliver a better measurement faster. In fact, at the point when the Model 2636A 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 2636A 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 12* offers another comparison of the low current performance of the Model 2636A with the non-Keithley 6½-digit SMU.

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

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

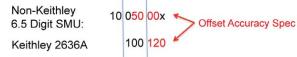| Lowest Current Range	nA	pA	fA	
Non-Keithley 6.5 Digit SMU:	10	050	00x	← Offset Accuracy Spec
Keithley 2636A		100	120	←

Figure 12. 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.
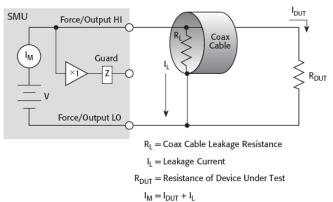
The Model 2636A is specified as having 1fA resolution. The spec table in *Figure 12* shows that it has a 100pA range and 120fA of offset accuracy. Obviously, although both the Keithley and non-Keithley SMU instruments can appear similar when looking at the "headline" specs, the Model 2636A actually has 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.
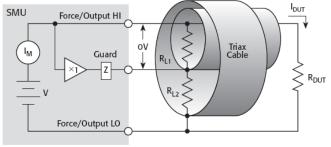
Figure 13 illustrates how a triaxial cable works with the SMU instrument's driven guard to prevent the leakage resistance of the cable from degrading the low current measurements. In the circuit on the top, the leakage resistance of the coaxial cable is in parallel with the device under test, creating 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 13. 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.

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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.

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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