WHITE PAPER

Selecting the Right SMU

Which SMU best meets your needs?

KEYSIGHT

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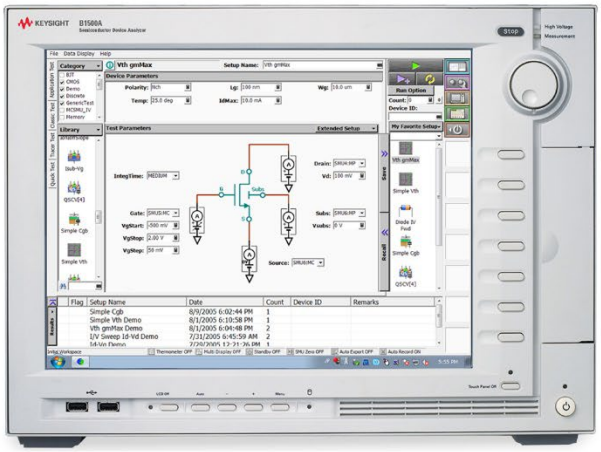
SMU Categories

Source/measure units (SMUs) come in many form factors, and selecting the correct type to optimize performance for a given application is not always a simple task. You can loosely classify SMUs into one of three categories:

- SMUs available as options for a modular benchtop instrument
- Stand-alone benchtop SMUs
- PXI-based SMUs functioning as building blocks for PXI-based systems

This whitepaper will explain the basic operation and applications of SMUs before discussing the pros and cons of these different SMU categories.











What is an SMU?

As its name implies, an SMU can force voltage or current and simultaneously measure voltage and/or current. The diagram below shows a simplified SMU equivalent circuit:

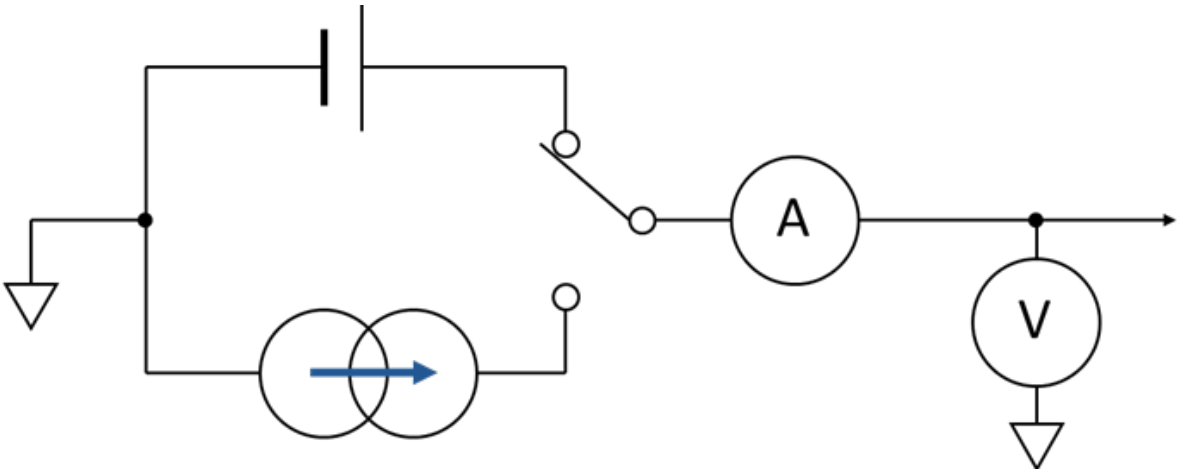


Figure 1. The conceptual circuit schematic for an SMU.

While all SMUs share this basic configuration, most SMUs have specific characteristics that aid them in achieving a given task. For example, SMUs designed for battery characterization only need to operate in two of the IV plane quadrants (positive voltage and plus or minus current) since the voltage across a battery is never negative. These types of SMUs typically have extremely accurate time-sampling capabilities coupled with the ability to collect data over long periods (features necessary for precise battery drain analysis). In contrast, SMU designed for semiconductor device characterization must operate in all four quadrants of the IV plane (positive and negative voltage and plus or minus current), since semiconductor devices require characterization in both forward and reverse operation. These types of SMUs also need extremely precise low-current measurement resolution (down to the sub-femtoamp range), which necessitates guarded (triaxial) connectors rather than standard BNC connectors. Finally, for all types of SMUs it is important that they support remote (aka 4-wire or Kelvin) sensing to eliminate the effects of resistive voltage drop through the wires connecting them to the DUT.

SMUs Available As Options For A Modular Benchtop Instrument

Benchtop instruments focused on certain applications (such as multi-channel precision bias sources, DC power analysis, or semiconductor parametric tests) typically include one or more types of SMUs as module options. In these cases, you can only select SMUs compatible with the instrument under consideration, so it is important to understand both the modular instrument's overall features and the SMUs that it supports.

Using SMUs as multi-channel precision bias sources

In high-tech applications such as data centers, silicon photonics, RF Power Amplifiers (PA) / Front-End-Module (FEM), quantum computing, and so on, multi-channel SMUs are used as precision bias sources because the Device Under Test (DUT) is highly integrated and has multiple bias ports. These applications require bias sources with tight synchronization between channels and the ability to monitor each channel's current and voltage fluctuations precisely. One of the key challenges for these applications is space constraints, so minimizing the physical footprint of test equipment is crucial. A typical test setup consisting of benchtop SMUs would make the system size huge.

The Keysight PZ2100 Series High Channel Density Precision SMUs provide an effective solution with a compact footprint. Up to 20 channels can be integrated into a 1U rack space, integrating high-resolution current and voltage measurement capabilities. This compact design optimizes space usage, enhances precision, and maintains the stability of multi-channel bias sources for advanced technological applications.

The PZ2100A mainframe uncompromisingly integrates up to 20 SMU channels into an efficient 1U height full-width rack space and supports several flexible high-performance module options. It supports a variety of resources such as the PZ2110A High-Resolution SMU, PZ2120/21A High-Speed SMUs, and PZ2130/31A High-Channel Density SMUs with multiple functions such as pulser and digitizer, as well as precise voltage/current sourcing and measuring to adapt to a wide range of application requirements.

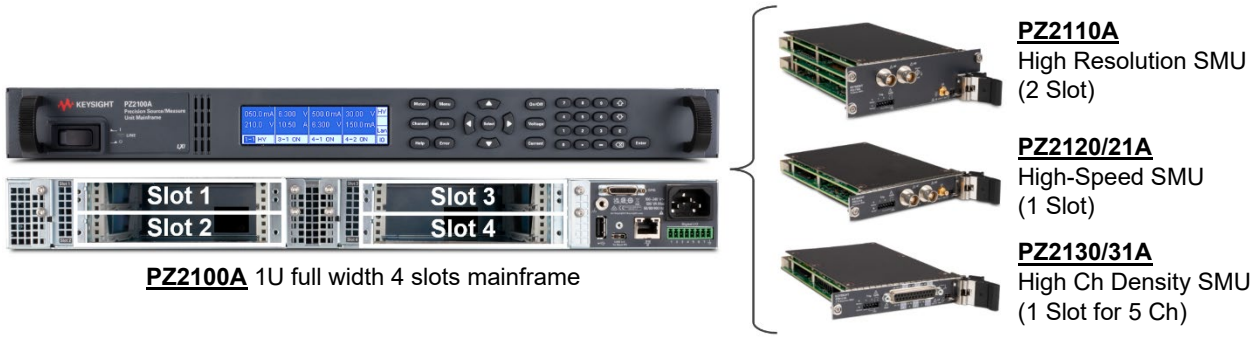


Figure 2. The PZ2100 series High Channel Density Precision SMUs

The following table summarizes the PZ2100 series' SMU module capabilities.

	High-resolution	High-speed		High-channel density	
Model	**PZ2110A**	**PZ2120A**	**PZ2121A**	**PZ2130A**	**PZ2131A**
Density	1 ch / 2 slot	1 ch / slot		5 ch / slot	
Max. output range	210 V / 315 mA	60 V / 3.5 A DC / 10.5 A pulse		30 V / 500 mA[1]	
Min. resolution	0.5 µV / 10 fA	6 µV / 100 fA		6 µV / 100 pA	6 µV / 10 pA
Max. sampling rate	1.25 MSa/s	1 MSa/s	15 MSa/s	250 kSa/s	500 kS/s
Min. pulse width	20 µs	50 µs	10 µs	No pulse	100 µs

1: Max. DC current of Ch 1-2: +750 mA / -500 mA, Ch 3-5: ± 500 mA

The PZ2100 series also ensures precise synchronization of the PZ2100A mainframe channels (within 50 ns of each other) without additional cabling. Furthermore, the external trigger ports on the mainframe and modules allow it to synchronize with any external equipment flexibly and accurately.

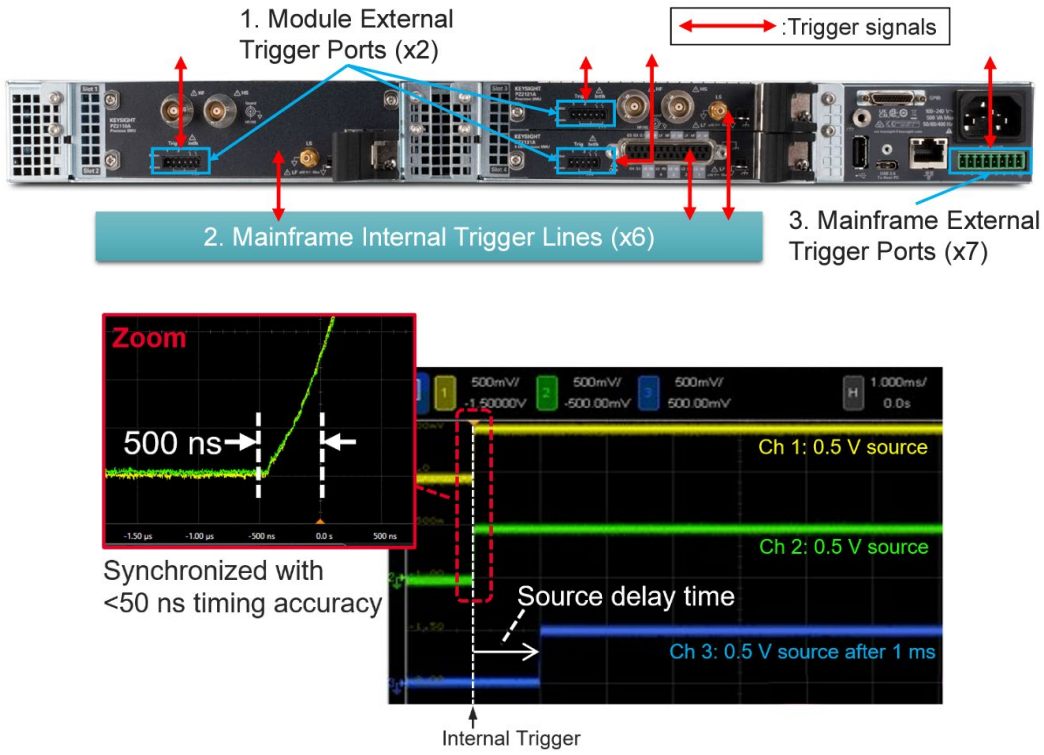


Figure 3. Internal trigger lines and external trigger ports (above) and power supply sequence example (below)

By integrating 4x high channel density SMUs, the PZ2100A condenses 20 channels into a single 1U rack space. As shown in Figure 4, compared to traditional solutions using benchtop 2-channel SMUs, it occupies only one-tenth of the space. This provides a significant advantage in saving valuable rack space and minimizing the test system footprint.

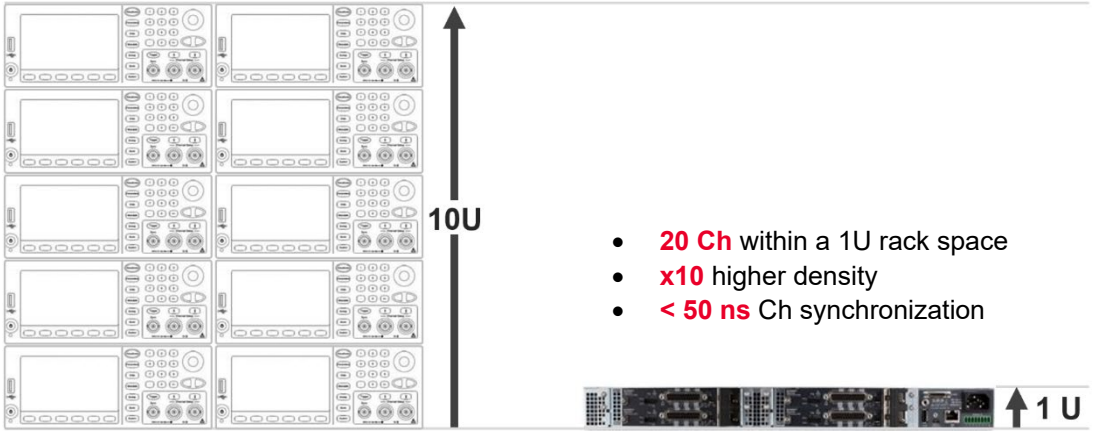


Figure 4. Example of 20 channels SMU bias source solution

Two software options are available to control the PZ2100 series SMUs from an external PC. The PW9251A PathWave IV Curve is a powerful GUI software designed to simplify and accelerate the process of performing synchronous current-voltage (IV) measurements controlling up to four mainframes (up to 40 channels). The BV0003B PathWave BenchVue Power Supply Control App offers easy control of the PZ2100 series up to 20 channels, allowing you to monitor and record source outputs to assess the impact of power draw for specific events.

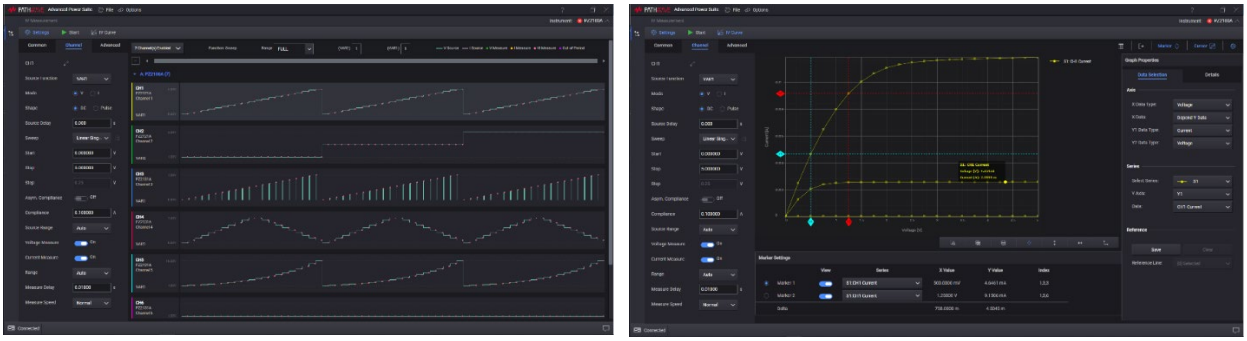


Figure 5. PW9251A PathWave IV Curve Software (Left: Setting page example. Right: Id-Vd test result example.)

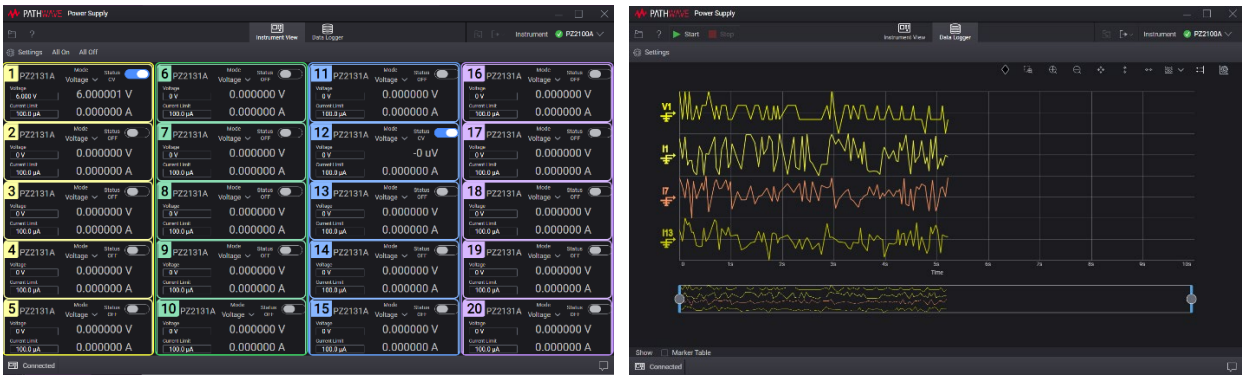


Figure 6. BV0003B PathWave BenchVue Power Supply Control (Left: Meter view mode. Right: Data logger mode.)

For more information on multi-channel precision bias sources

- High Channel Density Precision Bias Solution for Optical Device Testing in Data Center
- High-Channel Density Precision IV Test Solution for LED
- Overcoming DC Bias Supply Challenges in Quantum Computing Development
- Keysight Learn: Source Measure Units

SMUs for DC power analysis

As previously mentioned, SMUs used for DC power analysis focus on precision measurement over time. This makes them ideal for performing tasks such as characterizing secondary (rechargeable) batteries since they can discharge and charge a battery under test while recording both current and voltage. Using this information, it is possible to create a battery model showing voltage and internal resistance versus State-of-Charge (SoC). Another use of SMUs in DC power analyzers is DC-to-DC converter characterization. Connecting an SMU to the input and an electronic load module to the output of a DC-to-DC converter makes it easy to evaluate all relevant parameters.

The Keysight N6700 Modular Power System family, which consists of the N6700C and N6705C mainframes, supports two- and four-quadrant SMU modules.



Figure 7. The N6700C and N6705C modular power system family.

The following table summarizes the N6700 family's SMU module voltage, current, and power output capabilities.

	N6781A / N6782A	N6784A	N6785A / N6786A
Maximum voltage	20 V / 6 V	± 20 V / ± 6 V	20 V / 15 V / 10 V / 6 V
Maximum current	± 1 A / ± 3 A	± 1 A / ± 3 A	± 4 A / ± 5 A / ± 6.7 A / ± 8 A
Maximum power	20 W	20 W	80 W

A typical measurement application for the N678xA SMUs is measuring voltage or current versus time, such as monitoring the current draw of a battery-powered device during various operation modes. The N678xA SMUs can datalog up to 90 minutes of data at 50 kSa/s using N6700 internal memory (or infinite time if using an external PC). The N678xA SMU also possesses seamless measurement ranging, allowing them to make fast dynamic measurements from 100 nanoamps up to 3 Amps.

Seamless measurement ranging is important when measuring the current draw of IoT devices for the following reasons. Battery-powered mobile devices alternate between several different modes during their operation (i.e., active, idle, and sleep), which means that the current they draw at any point in time can vary from milliamps to nanoamps, as shown in the following figure.

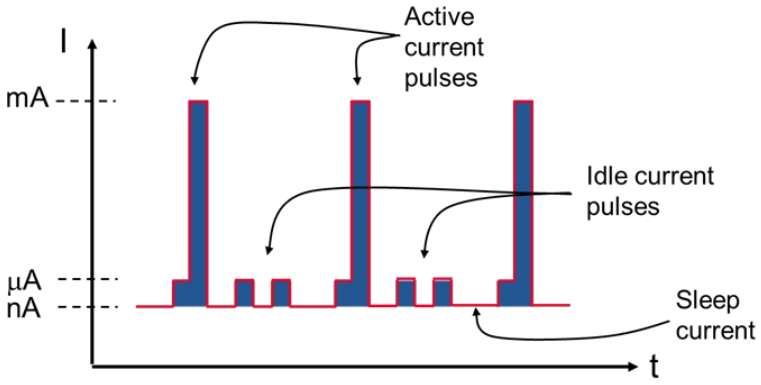


Figure 8. A typical IoT device operates in several different states with widely different current requirements during each state.

This makes current measurement difficult for the following reasons:

- Measurement equipment must have an extremely wide dynamic range
- Device modes change very rapidly
- The current draw changes randomly depending on what tasks the device is doing
- Traditional test tools cannot make these difficult measurements due to ranging limitations

Traditional SMU circuitry must switch in and out (using relays) different resistor values to handle the maximum expected current or voltage value based on the measurement range specified by the user. These SMUs cannot change ranges rapidly enough to keep up with the device state changes, so you lose current measurement accuracy and resolution. Seamless measurement ranging is a patented technique that allows the SMU to change ranges rapidly with no delay or data loss, as shown in the following figure.

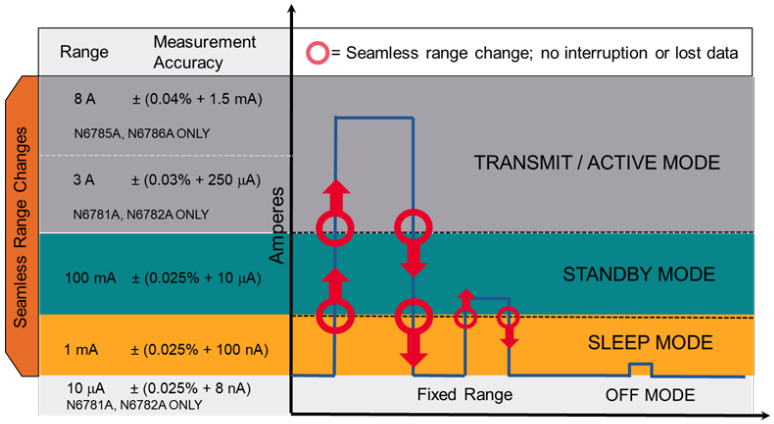


Figure 9. Graphics showing how seamless measurement ranging can prevent data loss as the instrument moves between different measurement ranges.

The following screen captures demonstrate the significant difference in measurement performance; it compares measurement measurements made using fixed ranging with those made using seamless measurement ranging.



Figure 10. Comparing the results of measuring cell phone current draw using fixed measurement ranging with those obtained using seamless measurement ranging.

For more information on power analysis

If you want a “one-stop-shop” for basic information on power-related topics, Keysight’s Power Handbook can provide the answers for you.

SMUs used for semiconductor parametric test

SMUs used to make semiconductor parametric measurements excel in their ability to make precise current-voltage (IV) measurements across all four quadrants of the IV plane. Since most semiconductor devices are voltage-controlled, in parametric tests, the x-axis (independent variable) represents voltage, and the y-axis (dependent variable) represents current. Because parametric tests often require current measurements below one nanoamp, SMUs designed for this purpose use triaxial connections rather than BNC connections.

Consider the case below, where you apply 10 V to the center conductor of a BNC cable with an effective signal wire to ground shield resistance of 1 Giga Ohm.

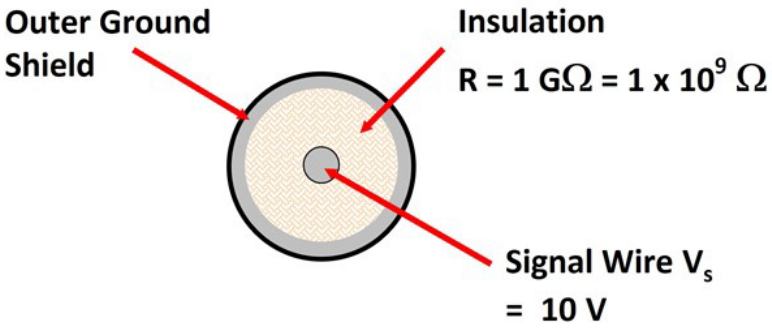


Figure 11. Cross section of BNC cable

A simple calculation shows us how much leakage current this creates:

$$I = \frac{10\ V}{1\ G\Omega} = 10\ nA$$

Obviously, you cannot measure currents down into the femtoamp range if the cables are leaking nanoamps of current. Triaxial cables and fixturing resolve this issue by introducing a third conductor between the signal wire and the outer ground shield. Buffer circuitry within the SMU maintains the center conductor at the same voltage potential as the signal wire to at least within one part in a million (and usually better than that). The following figure shows the results when you apply 10 V to a triaxial cable.

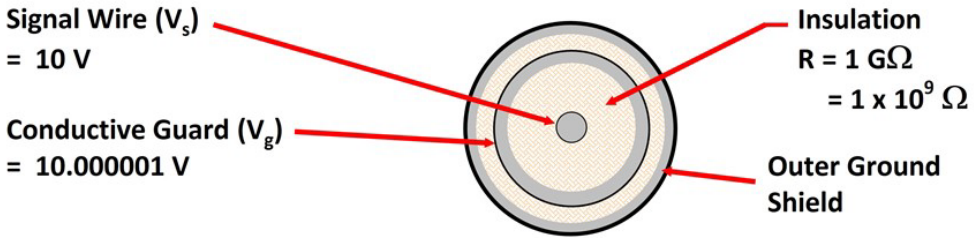


Figure 12. Cross section of triaxial cable

You can now calculate the leakage current as follows:

$$I = \frac{10.000001 - 10\ V}{1\ G\Omega} = 1\ fA$$

It is for this reason that all parametric test SMUs have triaxial outputs.

Keysight's B1500A Semiconductor Device Analyzer supports a variety of SMUs suitable for low-power semiconductor parametric tests. It is a PC-based, ten-slot modular instrument that includes Keysight's EasyEXPERT group+ software.

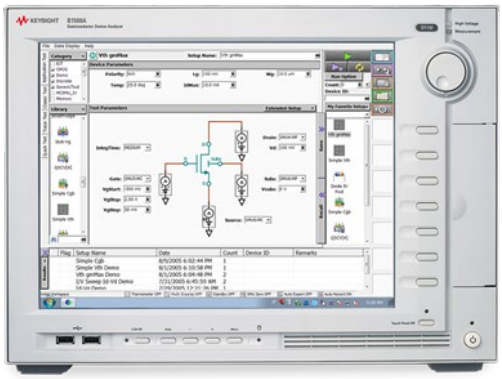


Figure 13. The B1500A Semiconductor Device Analyzer with EasyEXPERT software

EasyEXPERT includes hundreds of pre-defined, user-modifiable application tests that make it easy to use the B1500A's SMUs to make various parametric measurements. The following graph shows a B1500A application test that determines the threshold voltage of a MOSFET:

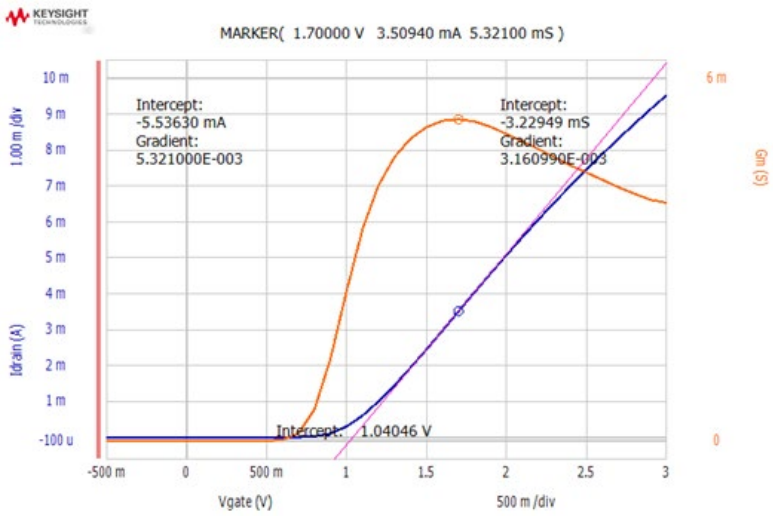


Figure 14. B1500A application test to determine MOSFET threshold voltage (Vth).

This application test derives the Vth by first performing a numerical differentiation on the MOSFET's measured Id versus Vgs graph and plotting the device transconductance (Gm) curve, determining the value of Vgs where the maximum value of Gm occurs, drawing a tangent line on the Id curve where Gm is a maximum, and finally locating where the tangent line intersects the Vgs axis to determine the value of Vth.

The B1500A has a module to perform capacitance (CV) measurements, and you can use its SMUs with the capacitance module to supply a DC bias of up to 100 V. In addition, the B1500A supports modules with high-voltage pulsing and fast IV sampling capabilities, and when using these modules, you can use the B1500A's SMUs as bias sources. As you can see, the tight integration between the B1500A mainframe, its supported SMUs, and the EasyEXPERT software makes this an ideal solution for using SMUs to perform parametric testing.

Keysight offers two solutions for using SMUs to test power semiconductor devices: the B1505A Power Device Analyzer/Curve Tracer and the B1506A Power Device Analyzer for Circuit Design. Both products support SMUs designed for power device testing but have different focuses.

The B1505A has numerous capabilities to meet the needs of power device manufacturers and R&D engineers, and it supports both on-wafer and packaged device measurements. However, because it has many available options, configuring a solution is not simple and certain choices do not allow for easy upgrade paths later. Therefore, if you plan to purchase a B1505A you need to carefully consider both your current and future measurement needs in close consultation with a Keysight expert.



Figure 15. The B1505A Power Device Analyzer / Curve tracer (with 10 kV and high-voltage/medium current options)

The B1506A focuses on the needs of power device users, and it can automatically generate a customized power device data sheet in a few minutes. The B1506A also has the advantage of being completely upgradable. You can start with a basic configuration to make IV measurements at up to 20 A and 3 kV and later upgrade this configuration to make IV measurements at up to 1500 A and both IV and CV measurements at up to 3 kV. However, the B1506A has some measurement limitations that the B1505A does not, so before purchasing a B1506A, you need to ensure it can meet all your expected needs.



Figure 16. The B1506A Power Device Analyzer for Circuit Design

The following table encapsulates the best applications for these two benchtop instruments.

B1505A power device analyzer / Curve tracer	B1506A power device analyzer for circuit design
Best for:	**Best for:**
• Advanced device research	• Turnkey packaged device testing
• Users requiring specific capabilities (SOA, 10 kV, etc.)	• Users with limited test experience
• Users who need to perform on-wafer testing	• Users who need easy upgrade paths

The B1505A and B1506A mainframes do not have sufficient power to meet the needs of all high-power device tests. Therefore, external units are necessary for measurements requiring ultra-high current (up to 1500 A), ultra-high voltage (up to 10 kV), and safe operating area (SOA) measurements. When using these options, SMUs in the B1505A and B1506A mainframes act as control units for the external modules. Only the MCSMU and HCSMU modules can act as control units, and two are necessary for each module (one for voltage control and one for current control).

The following table summarizes the SMUs available for the B1500A, B1505A, and B1506A mainframes and their key specifications:

SMU type	Part #	Supported mainframes	Key specs
High-Power SMU (HPSMU)	B1510A	B1500A, B1505A	Max Current: ± 1 A Max Voltage: ± 200 V Current Resolution: 10 fA Voltage Resolution: 2 mV
Medium Power SMU (MPSMU)	B1511B	B1500A, B1505A, B1506A	Max Current: ± 100 mA Max Voltage: ± 100 V Current Resolution: 10 fA (0.1 fA with ASU) Voltage Resolution: 0.5 mV
High Current SMU (HCSMU)	B1512A	B1505A, B1506A	Max Current: ± 1 A (DC); ± 20 A (Pulsed) Max Voltage: ± 40 V (DC); ± 20 V (Pulsed) Current Resolution: 10 pA Voltage Resolution: 200 nV
High Voltage SMU (HVSMU)	B1513C	B1505A, B1506A	Max Current: ± 8 mA / ± 4 mA Max Voltage: ± 1500 V / ± 3000 V Current Resolution: 10 fA Voltage Resolution: 200 mV
Medium Current SMU (MCSMU)	B1514A	B1500A, B1505A, B1506A	Max Current: ± 100 mA (DC); ± 1 A (Pulsed) Max Voltage: ± 30 V Current Resolution: 10 pA Voltage Resolution: 200 nV
High-Resolution SMU (HRSMU)	B1517A	B1500A	Max Current: ± 100 mA Max Voltage: ± 100 V Current Resolution: 1 fA (0.1 fA with ASU) Voltage Resolution: 0.5 mV

For More Information on Parametric Test

If you want more information on using SMUs in parametric test applications, download the latest Parametric Measurement Handbook.

Standalone Benchtop SMUs

The Keysight B2900 Series of SMUs are standalone benchtop instruments focused on device and material characterization. All the B2900 SMUs support four quadrant operation and have a front panel interface. In addition, the higher-performance models can achieve measurement resolution down to 10 femtoamps. The “BL” models are single-channel, and the “B” models are available in both one- and two-channel versions. The following table summarizes the key specifications of these SMUs.

	B2901BL	B2910BL	B2901B/02B	B2911B/12B
Maximum voltage (DC)	21 V	210 V	210 V	210 V
Maximum current (DC)	1.5 A	1.5 A	3 A	3 A
Maximum current (Pulsed)	---	---	10.5 A	10.5 A
Current measurement resolution	1 pA	10 fA	100 fA	10 fA



Figure 17. Front view of the B2900B SMU

While Keysight’s benchtop SMUs support front-panel control similar to larger modular products, however, their smaller form factor limits their menu structure and display size.

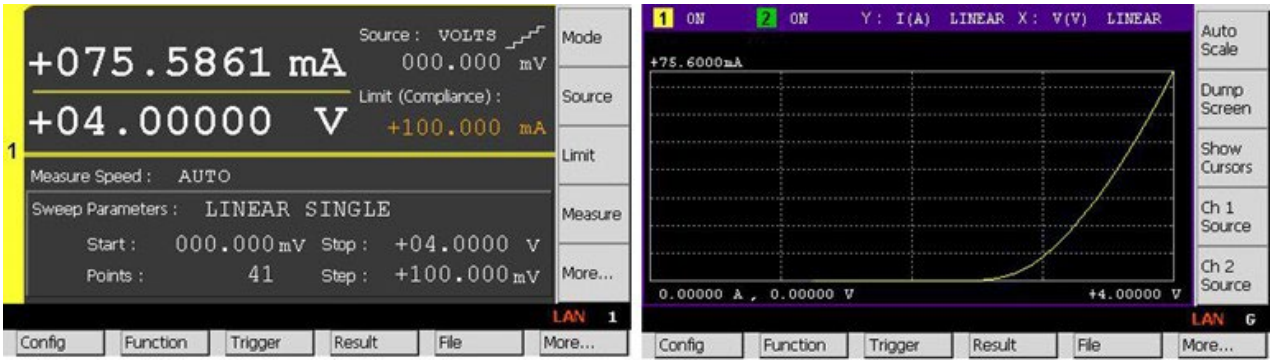


Figure 18. Front panel interface of the B2900B SMUs and example graph (diode characteristic).

Multiple software options are available to control the B2900B SMUs from an external PC. The PW9251A PathWave IV Curve Software allows you to control up to four B2900B SMU channels. It allows you to export graphs and tabular data into other PC-based applications easily, and it also permits you to perform basic mathematical operations on measurement data.

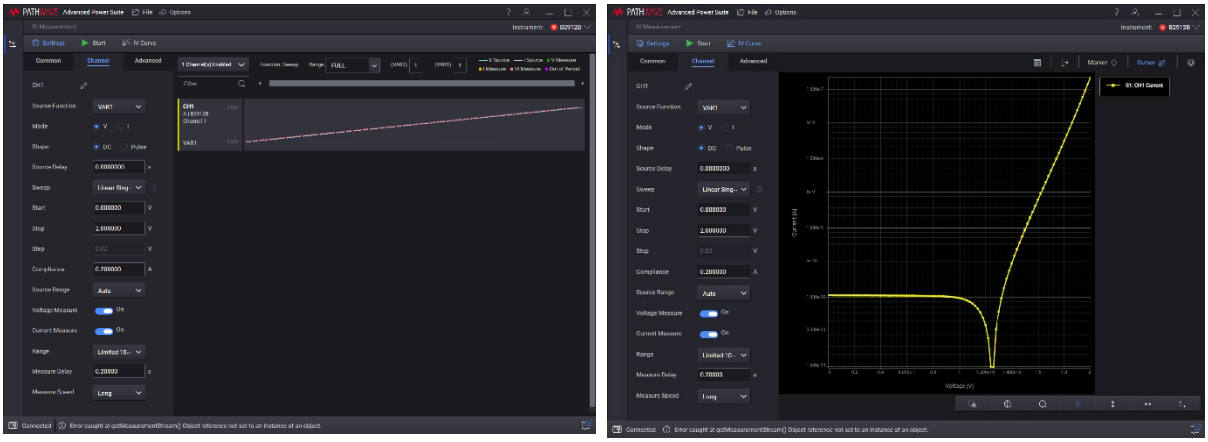


Figure 19. Example of a diode sweep measurement on the B2900B SMU using PW9251A Software

You can also use the B2900B SMUs to perform semiconductor parametric measurements similar to those performed by the B1500A. However, since the default B2900B outputs are banana jacks, you need triaxial adapters to make sub-nanoamp measurements. Keysight can supply banana jack to triaxial adapters for the B2900B SMUs that support both two-wire (non-Kelvin) and four-wire (Kelvin) measurements.



Figure 20. The N1297A (two-wire) and N1297B (four-wire) banana jack to triaxial adapters for the B2900B SMUs

If you plan to make extensive parametric measurements using the B2900B SMUs, then the best choice for PC-based software is EasyEXPERT group+. This is the same software that runs on the B150xA products, and it has the same capabilities. You can use EasyEXPERT to control up to four B2900B SMUs or up to eight channels (if all four B2900B units are two-channel units). Since synchronization of SMU

channels is critical for semiconductor parametric measurements, using EasyEXPERT to control multiple B2900B SMUs requires the N1294A-032 Digital I/O Trigger Cable for Multiple Unit Control. You can create a “poor man’s” B1500A with this cable.



Figure 21. The N1294A-032 Digital I/O Trigger Cable for Multiple Unit Control ensures synchronization of up to four B2900B units.

Although EasyEXPERT supports up to eight B2900B SMU channels, you can perform many parametric tests using only two SMUs. Even tests that might need four SMUs (such as the Id-Vg characterization of a MOSFET) are possible using two SMUs if the source and substrate connections are grounded. Therefore, EasyEXPERT supports B2900 libraries for parametric tests using only two SMUs. The following figure shows an application test that can extract MOSFET threshold voltage using only two SMUs.

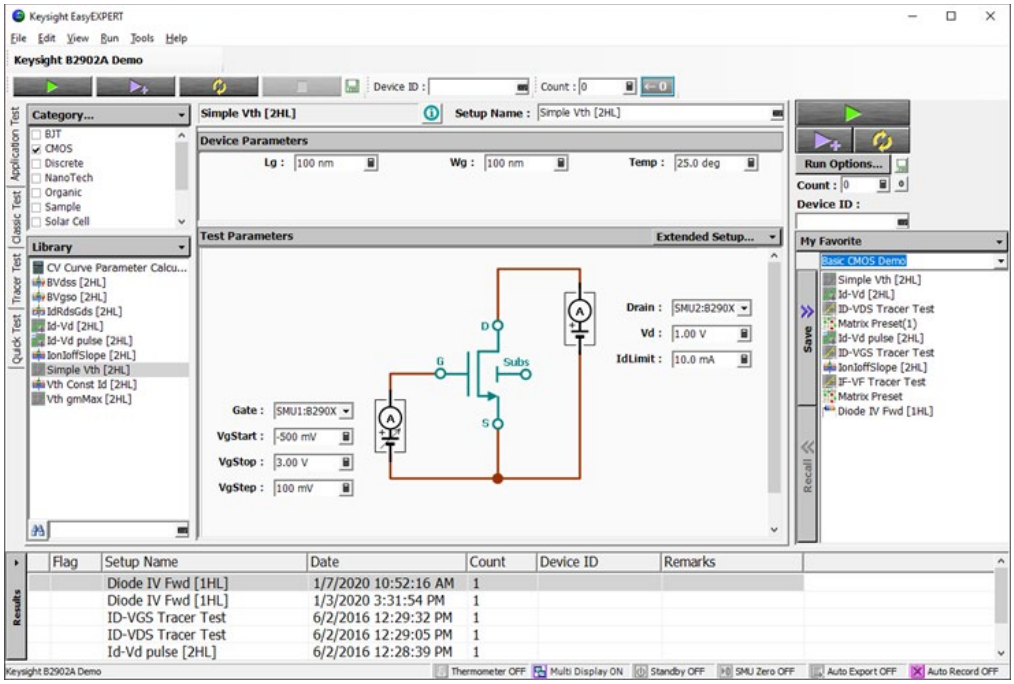


Figure 22. The EasyEXPERT screen shows application tests supporting two-channel SMU measurements.

PXI SMUs Used in PXI-based systems

PXI (PCI eXtensions for Instrumentation) systems utilize the compact version of the PCI (Peripheral Component Interconnect) standard, which originated in the early 1990s to enable the easy addition of internal components to desktop computers. Besides providing a small form factor, a nice feature of PXI is that an industry consortium defines its hardware, electrical, software, power, and cooling standards to ensure interoperability between components from different companies.



Figure 23. Example of an embedded PXI chassis controller and 10-slot PXI chassis.

Keysight has a family of PXI SMUs that support many different application needs. The following table summarizes the capabilities of these SMUs.

	M9111A	M9601A	M9602A/03A	M9614A/15A
Quadrants	2	4	4	4
Channels per Card	1	1	1	5
Maximum Voltage (DC)	13 V/6 V	± 210 V	± 60 V	± 30 V
Maximum Current (DC)	± 1 A/± 3 A	± 315 mA	+ 3.5 A, - 0.13 A	± 500 mA
Maximum Current (Pulsed)	NA	± 315 mA	± 10.5 A	± 500 mA
Minimum. Pulse Width	NA	20 µs	10 µs	100 µs
Maximum Sample Rate	200 kSa/s	1.25 MSa/s	15 MSa/s	500 kSa/s
Current Meas. Resolution	1.4 nA	10 fA	100 fA	10 pA

It is critical to point out that the M9111A SMU focuses on applications such as power amplifiers and front-end module testing since these tasks require a bias source with fast voltage recovery. In contrast, the other PXI SMUs focus more on device and material characterization in R&D and manufacturing. The M9111A also has only two output voltage/current ranges, whereas the other PXI SMUs have multiple output voltage/current ranges (however, they cannot simultaneously output the maximum voltages and currents shown in the table).



Figure 24. The M9601A, M9602A/03A and M9614A/15A PXI SMUs.

An important consideration when using PXI SMUs (or any PXI module) is the power limitations of the mainframe you are using with them. You need to consider the maximum current output of the PXI chassis' 12 V rail, the maximum power of the user slots, and the overall maximum power output of the chassis. In general, the maximum current output of the PXI chassis' 12 V rail determines the maximum current output of any SMUs installed in it. For example, the 12 V rail on Keysight's M9046A 18-slot PXI chassis can supply up to 6 A for certain PXI modules (including the M9614A and M9615A), and this type of capability is necessary to get full output current from them.

Different members of the M96xxA family of PXI SMUs possess capabilities optimized for distinct purposes, so knowing when to use each is vital. It is also important to understand that the M96xxA family of PXI SMUs does not support auto measurement ranging; instead, they use fixed measurement ranging combined with (in some cases) seamless measurement ranging. When making current versus voltage (IV) semiconductor device measurements with the M96xxA family of PXI SMUs, you need to take this limitation into consideration. To aid you in developing measurements for these products, Keysight has the PX0109A Quick I/V Measurement Software for PXI Precision SMUs available for purchase.

The M9601A SMU possesses the highest current measurement resolution (10 fA) of any member of the M96xxA family of PXI SMUs. This makes it an ideal choice for applications such as measuring low-level leakage currents or the insulation resistance of semiconductors, electronic components, and ICs. However, since the M9601A only supports fixed ranging, you must carefully select the appropriate measurement range when performing these types of tests.

The M9602A/03A SMUs support specialized capabilities ideal for applications such as vertical cavity surface emitting laser (VCSEL) and integrated circuit (IC) production tests. Both of these SMUs can sample data at up to 15 Mega-samples per second (15 MSa/s) and generate very short current pulses (down to 10 microseconds). This current pulsing capability is unmatched by any other SMU currently available in the marketplace (see graph below). The M9602A/03A SMUs support fixed measurement ranging and seamless measurement ranging (the same as that previously described for the N6705C SMUs). This gives the M9602A/03 SMUs the ability to measure DUT currents accurately and dynamically across a wide range of currents.

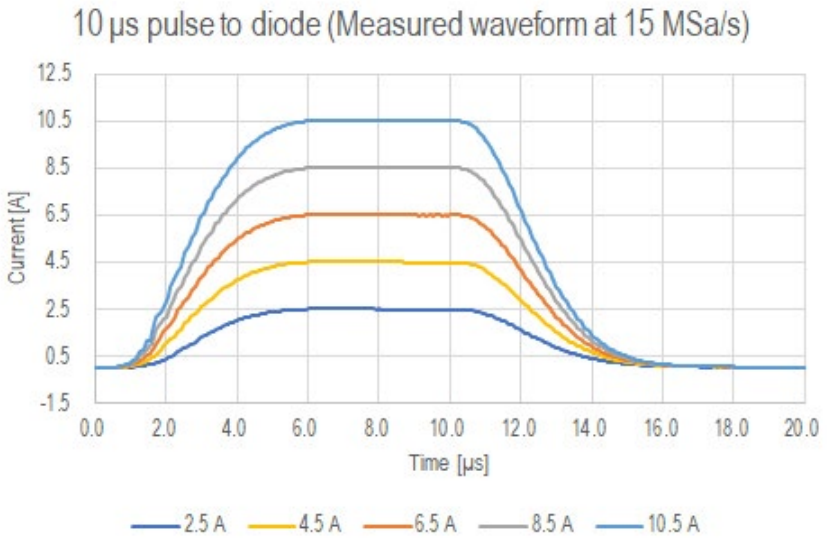


Figure 25. Graph showing the fast pulsing (10 µs) and fast sampling (15 MSa/s) capabilities of the M9602A and M9603A PXI SMUs.

The M9614A/15A PXI SMU cards provide five independent SMU channels in a single-slot module, supplying the lowest cost per channel of any Keysight SMU. This makes them ideal for applications requiring multiple channels, such as parallel reliability tests and burn-in, quantum computing, and optical device tests. Similar to the M9602A/03A, the M9614A/15A SMUs support both fixed and seamless measurement ranging.

Conclusion

Selecting the right SMU for a given undertaking requires many considerations (some of which may be at odds with one another). However, you often have a better chance of achieving your required goals if you consider the optimal SMU form factor for your desired task before defining the needed SMU performance specifications. To aid you in this task, the following table summarizes the key points regarding each of the three SMU form factors discussed in this white paper.

Summary of SMU Pros and Cons

SMU type	Pros	Cons
Modular benchtop instrument SMU	• Save valuable rack space and minimize the test system footprint. • SMUs have specialized capabilities aligned with the modular instrument's primary functions. • SMUs automatically synchronized with each other. (and other instrument resources) • Typically, the cost per SMU channel is lower if the number of channels is high. • SMUs do not require an external controller.	• Available SMU types may not meet all test needs. • Number of SMUs limited by mainframe.
Standalone benchtop SMU	• Take up a small benchtop area. • Typically, a lower cost per SMU channel if the number of channels is low. (as compared to modular benchtop instruments)	• SMU synchronization between multiple units is not automatic. • Not space efficient for racked solutions with many SMUs. • Requires external PC for software control.
PXI SMU	• Form factor permits high densities. • Effectively, there is no limit on the number of SMUs available. • Multiple SMU types available to meet specialized needs. • Typically, the cost per SMU channel is lower if the number of channels is high. (excluding chassis and controller costs)	• Maximum power output limited by chassis. • Requires external PC or PC in chassis for control. • Not cost-effective unless the PXI chassis is densely populated.

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