

## **The Challenge of Integrating Three Critical Semiconductor Measurement Types into a Single Instrument Chassis**

Characterizing a semiconductor device, material, or process thoroughly requires the ability to make three types of measurements. The first two types are the most familiar: *precision DC I-V measurements* (typically made with high-precision Source-Measure Units or SMUs) and *AC impedance measurements* (in the semiconductor industry, often made with a capacitance-voltage or C-V meter). *Ultra-fast I-V* or *transient I-V measurements* represent the last, and most difficult to achieve, segment of this semiconductor characterization triangle. Until recently, semiconductor labs might have needed up to three different test systems to obtain all three measurement types. In addition to the expense of purchasing and maintaining multiple systems and training personnel to use them, this approach also made it difficult to combine different measurement types in a single application or to correlate the results from different types of measurements accurately when they were made at different times under varying test conditions and with different measurement instrumentation.

### **One Application, Multiple Measurement Types**

A growing number of semiconductor test applications require the use of more than one measurement type, which makes a single test system with multiple measurement capabilities highly desirable. For example, charge pumping (CP) is a well-known measurement technique for analyzing the semiconductor–dielectric interface of MOS structures. Important information about the quality and degradation of a device can be extracted from charge pumping current ( $I_{CP}$ ) measurement results, including the interface trap density and the mean capture cross section. Pulsing a gate voltage and measuring a DC substrate current

simultaneously is the basis for the various charge pumping methods, so both a pulse generator and sensitive DC ammeter are required to make these measurements.

Similarly, determining the electrical characteristics of photovoltaic (solar) cells often involves measuring the current and capacitance as a function of an applied DC voltage. The measurements are usually done at different light intensities and temperature conditions. Important device parameters can be extracted from the current-voltage (I-V) and capacitance-voltage (C-V) measurements, such as the output current, conversion efficiency, maximum power output, doping density, resistivity, etc. Electrical characterization is also important to determine losses in the photovoltaic cell in order to learn how to make the cells as efficient as possible with minimal losses.

Integrated parameter analyzers such as the Model 4200-SCS Semiconductor Characterization System can be configured to coordinate sourcing, measurement, and analysis involving multiple measurement types. The system's Keithley Test Environment Interactive (KTEI) operating software handles all three major measurement types in a single test environment and allows combining measurements made with different instrument types into a single test sequence.

The Model 4200-SCS's chassis-and-plug-in-modules design can be readily optimized to address specific applications or sets of applications. Just as important, as new application requirements evolve, this modular architecture allows for cost-effective system upgrades. System builders can choose from medium- and high-power Source-Measure Units for DC I-V measurements, an optional C-V meter for capacitance-voltage measurements, and an ultra-fast (pulsed) I-V module for high-speed pulse measurements. As a result, the Model 4200-SCS offers a complete solution for applications like charge pumping because it can be configured with the pulse generation and sensitive DC current measurement capabilities required, as well as the software needed to automate the measurements and analyze the results. It also includes predefined tests for making most of the common charge pumping tests, such as a pulsed base voltage sweep or a pulsed voltage amplitude sweep. For solar cell testing, the Model 4200-SCS's integrated I-V and C-V measurement capabilities make it well-suited for a wide range of applications, including capacitance-frequency (C-f), drive level capacitance profiling (DLCP), four-probe resistivity ( $\rho$ ,  $\sigma$ ), and Hall voltage ( $V_H$ ) measurements.

## **Source-Measure Units for DC I-V Measurements**

The basic Model 4200-SCS configuration includes two medium-power Source-Measure Units (SMUs). SMUs can source and measure both current and voltage. Two SMU models are available: a medium-power (100mA, 2W) version (Model 4200-SMU) and a high-power (1A, 20W) version (Model 4210-SMU). A chassis can contain up to nine SMUs in any combination of high- and medium-powered units.

The low current measurement capabilities of any SMU can be extended by adding an optional Remote PreAmp (Model 4200-PA), which provides 0.1fA resolution by effectively adding five current ranges to either SMU model. The PreAmp module is fully integrated with the system; to the user, the SMU simply appears to have additional measurement resolution available. The Remote PreAmp can be installed on the system's back panel for standard cabling to a prober, test fixture, or switch matrix. The Remote PreAmp can also be placed remotely (such as in a light-tight enclosure or on the prober platen) to minimize measurement problems due to long cables.

### **Integrated C-V Meter for Capacitance-Voltage Measurements**

The Model 4210-CVU is designed to make C-V measurements as easy to perform as I-V measurements. This optional capacitance-voltage instrument performs capacitance measurements from femtofarads (fF) to nanofarads (nF) at frequencies from 1kHz to 10MHz. It includes a new power package that supports high power C-V measurements up to 400V (200V per device terminal) for testing high power devices (MEMs, LDMOS devices, displays, etc.) and DC currents up to 300mA for measuring capacitance when a transistor is on. This module is provided with the broadest C-V test and analysis library available in any commercial C-V measurement solution. It allows configuring linear or custom C-V and C-f sweeps with up to 4096 data points. In addition, through the open environment of the Model 4200-SCS, users can modify any of the included tests, such as C-V, C-t, and C-f measurements and analysis of solar cells; high- and low- $\kappa$  structures; MOSFETs; BJTs; diodes; III-V compound devices; carbon nanotube (CNT) devices; doping profiles, TOX, and carrier lifetime tests; and junction, pin-to-pin, and interconnect capacitance measurements. The C-V instrument integrates directly into the Model 4200-SCS chassis. It can be incorporated into existing Model 4200-SCS systems or specified as an option for new systems.

### **A New Approach to Pulsed/High-Speed I-V Measurements**

Early implementations of high-speed (i.e., pulsed) I-V testing were developed to address applications such as characterizing high- $\kappa$  dielectrics and Silicon-On-Insulator (SOI) isothermal testing. When tested using traditional DC I-V techniques, their insulating substrates cause SOI devices to retain the self-heat generated by the test signal, skewing their measured characteristics; testing with pulsed signals reduces this effect.

Traditional high-speed-pulse/measure test systems typically involved an external pulse generator, a multi-channel oscilloscope, specially designed interconnect hardware, and software to integrate and control the instruments. Unfortunately, this approach tended to create latencies that complicated the coordination of signal source and measurement functions.

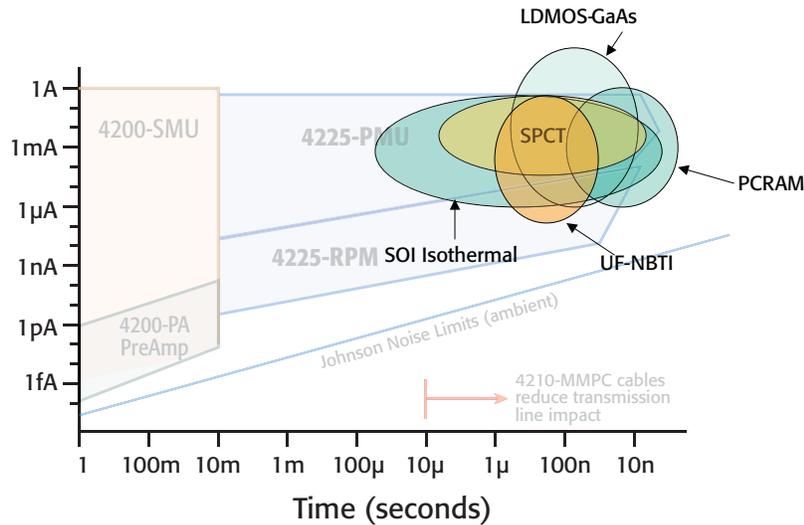
Depending on the instruments and how well they were integrated, it could also place limitations on how short the pulses and their duty cycle could be.

Despite these limitations, users of these early pulsed I-V test systems soon began applying them to a variety of other characterization tasks, including non-volatile memory testing, ultra-fast NBTI reliability testing, and many other applications. However, given their somewhat limited dynamic range, these systems remained something of a specialty technology.

In order to become a mainstream test technology, the next generation of ultra-fast I-V testing systems would have to provide a very broad source and measure dynamic range. That meant they had to be able to source sufficient voltage to characterize flash memory devices, as well as voltages low enough to handle the latest CMOS processes. For example, consider an embedded flash device in a CMOS process—the flash device might require up to 40V to program, but the CMOS process is running on 2.5V, so the test system used must be able to supply voltages for both requirements. It also needed to have a broad enough current range to handle the newest technologies, and fast enough rise times and long enough pulse widths to cover a wide range of applications. It had to be simple to use, and have an interconnect system that would allow the system to deliver accurate results reliably.

The development of the Model 4225-PMU Ultra-Fast I-V Module for the Model 4200-SCS makes it possible to integrate all three required measurement types into a single test system that's optimized for emerging lab applications like ultra-fast general-purpose I-V measurements; pulsed I-V and transient I-V measurements; flash, PCRAM, and other nonvolatile memory tests; isothermal testing of medium-sized power devices; materials testing for scaled CMOS, such as high- $\kappa$  dielectrics; and NBTI/PBTI reliability tests. (See Figure 1 for a graph that maps these new applications to the Model 4200's DC I-V and ultra-fast I-V sourcing and measurement ranges.)

## Current Measurements vs. Time Comparison of Various Keithley DC and Pulsed I-V Instruments



*Figure 1. The Model 4200-SCS's new ultra-fast I-V capability picks up where its DC I-V capability leaves off. Note how the traditional Model 4200-SMU can source and measure currents up to about 1A and down to about a picoamp. Although adding the optional remote preamplifier allows resolving signals as low as 0.1fA, its best speed is about 10 milliseconds. In contrast, the new Model 4225-PMU ultra-fast I-V module allows making measurements as fast as 10ns, which is critical for applications that involve characterizing device recovery. The optional remote amplifier/switch extends the current resolution of the module down to tens of picoamps, just slightly above the limit due to the Johnson noise produced by the devices under test.*

Many of the new ultra-fast I-V tests that lab users wish to perform, such as charge pumping and Negative Bias Temperature Instability (NBTI) testing, require greater current sensitivity than the Model 4225-PMU module provides. For these applications, the optional Model 4225-RPM Remote Amplifier/Switch offers additional low current ranges that extend the system's current sensitivity down to tens of picoamps. It also reduces cable capacitance effects and supports switching automatically between the Model 4225-PMU, the Model 4210-CVU C-V instrument, and the Model 4200-SMU/4210-SMU modules installed in the chassis. That makes it easy to use the most appropriate instrument for a particular measurement task, with no need to disconnect the module's wiring then reconnect it to a different instrument.

### Differing Cable Requirements for Different Measurement Types

One of the greatest challenges associated with integrating DC I-V, C-V, and ultra-fast I-V measurement capabilities into a single chassis is that the cabling required for each measurement type is fundamentally different. Although the cabling from the instrument to

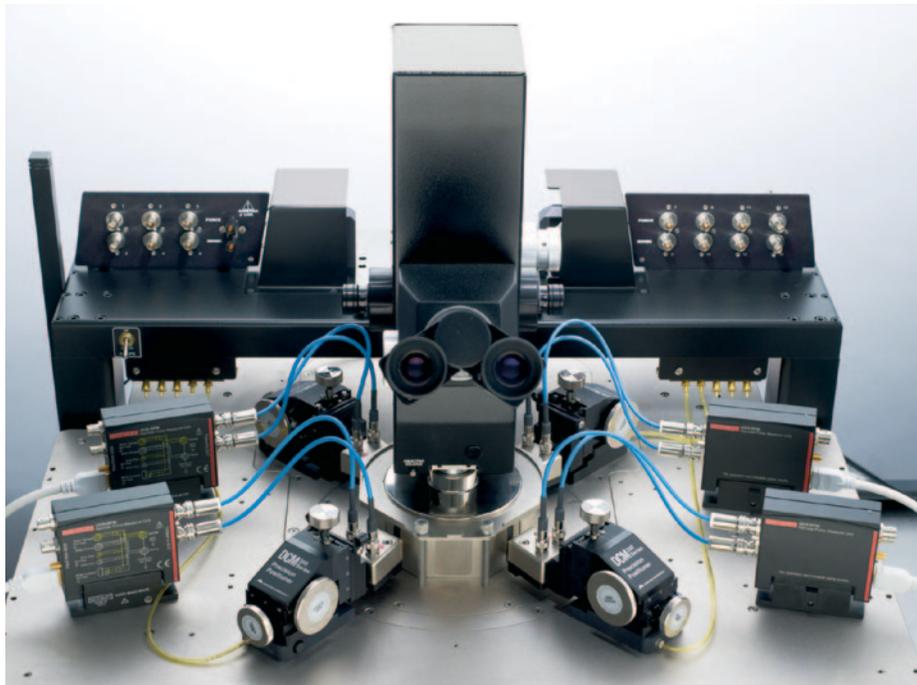
the probe station bulkhead and feed through is fairly straightforward, the cabling from the bulkhead to the probe tips can be confusing and difficult.

- *DC I-V measurements* are made using four triaxial cables. Guarding is necessary to achieve low current I-V measurements, which makes the use of triaxial cables necessary for these measurements. The measurement signal is carried on the center conductor, the inner shield is driven as a guard for the signal, and the outer shield is used for safety to shield the user from high voltages that may be applied to the guard and signal conductors. Four cables are necessary in order to achieve a remote sense, or Kelvin, connection to allow the instrument to sense the voltage at the device accurately.
- *C-V measurements* are made using four coaxial cables. The outer shells are connected together to control the characteristic impedance the signals see. All four cables' outer shells must be inter-connected near the DUT.
- *Ultra-fast I-V measurements* require the highest bandwidth of the three measurement types, so the cable must have a characteristic impedance that matches the source impedance to prevent reflections off the DUT from reflecting off the source. Ultra-fast I-V testing does not use a remote sense cable and is the only one of the three measurement types that connects the DUT to the outer shield of the cable.

<b>DC I-V measurements</b>	<ul style="list-style-type: none"> <li>• Triaxial cables</li> <li>• Kelvin connection</li> <li>• Isolated, driven guards</li> </ul>
<b>LCR/C-V measurements</b>	<ul style="list-style-type: none"> <li>• Coaxial cables</li> <li>• Kelvin connection</li> <li>• Shields connected at the probe tips</li> </ul>
<b>Ultra-Fast I-V measurements</b>	<ul style="list-style-type: none"> <li>• Coaxial cables</li> <li>• Non-Kelvin connection (single cable)</li> <li>• Shields connected at the probe tips</li> <li>• Shield optionally connected to a probe tip</li> </ul>

*Summary of differing cabling requirements for different measurement types*

To address the challenges created by these differing cabling requirements for different measurement types, Keithley has developed a high-performance multi-measurement cabling system that can support I-V, C-V and ultra-fast I-V measurements, reducing the burden on the system operator, who would otherwise be forced to go through the laborious process of re-cabling the connections from the test instrumentation to the prober every time a new measurement type was required. This kit (*Figure 2*) maximizes signal fidelity by eliminating the measurement errors that often result from cabling errors.



*Figure 2. The remote amplifier/switches and the multi-measurement performance cabling used to connect them to the probe manipulators on the wafer prober are critical to integrating accurate ultra-fast I-V, C-V, and precision DC I-V measurements into the same parametric analysis system.*

For more details on Keithley's multi-measurement performance cables, see Keithley's online white paper: [Labs' Demands for Greater Measurement Flexibility Require Cabling Systems Capable of Accommodating Multiple Measurement Types.](#)

## **Conclusion**

Ultra-fast I-V sourcing and measurement capabilities are just the latest examples of Keithley's ongoing commitment to provide a cost-effective system upgrade path to address new testing needs as they emerge. That means Model 4200-SCS users won't have to buy a new parametric analyzer because their old one is no longer supported. The Model 4200-SCS is engineered to adapt readily to the industry's changing test needs—making customers' capital investments stretch further and improving their ROI.

Specifications are subject to change without notice.  
All Keithley trademarks and trade names are the property of Keithley Instruments, Inc.  
All other trademarks and trade names are the property of their respective companies.

**KEITHLEY**

A G R E A T E R M E A S U R E O F C O N F I D E N C E

KEITHLEY INSTRUMENTS, INC. ■ 28775 AURORA RD. ■ CLEVELAND, OH 44139-1891 ■ 440-248-0400 ■ Fax: 440-248-6168 ■ 1-888-KEITHLEY ■ www.keithley.com

**BELGIUM**

Sint-Pieters-Leeuw  
Ph: 02-3630040  
Fax: 02-3630064  
info@keithley.nl  
www.keithley.nl

**CHINA**

Beijing  
Ph: 8610-82255010  
Fax: 8610-82255018  
china@keithley.com  
www.keithley.com.cn

**FRANCE**

Saint-Aubin  
Ph: 01-64532020  
Fax: 01-60117726  
info@keithley.fr  
www.keithley.fr

**GERMANY**

Germering  
Ph: 089-84930740  
Fax: 089-84930734  
info@keithley.de  
www.keithley.de

**INDIA**

Bangalore  
Ph: 080-26771071, -72, -73  
Fax: 080-26771076  
support\_india@keithley.com  
www.keithley.com

**ITALY**

Peschiera Borromeo (Mi)  
Ph: 02-5538421  
Fax: 02-55384228  
info@keithley.it  
www.keithley.it

**JAPAN**

Tokyo  
Ph: 81-3-5733-7555  
Fax: 81-3-5733-7556  
info.jp@keithley.com  
www.keithley.jp

**KOREA**

Seoul  
Ph: 82-2-574-7778  
Fax: 82-2-574-7838  
keithley@keithley.co.kr  
www.keithley.co.kr

**MALAYSIA**

Penang  
Ph: 60-4-643-9679  
Fax: 60-4-643-3794  
koh\_william@keithley.com  
www.keithley.com

**NETHERLANDS**

Gorinchem  
Ph: 0183-635333  
Fax: 0183-630821  
info@keithley.nl  
www.keithley.nl

**SINGAPORE**

Singapore  
Ph: 65-6747-9077  
Fax: 65-6747-2991  
koh\_william@keithley.com  
www.keithley.com

**SWITZERLAND**

Zürich  
Ph: 044-8219444  
Fax: 044-8203081  
info@keithley.ch  
www.keithley.ch

**TAIWAN**

Hsinchu  
Ph: 886-3-572-9077  
Fax: 886-3-572-9031  
info\_tw@keithley.com  
www.keithley.com.tw

**UNITED KINGDOM**

Theale  
Ph: 0118-9297500  
Fax: 0118-9297519  
info@keithley.co.uk  
www.keithley.co.uk