KEITHLEY

WHITE PAPER

The Evolution of Ultra-Fast I-V Measurement Techniques

Lee Stauffer
Senior Staff Technologist
Keithley Instruments, Inc.

Like DC current-voltage (I-V) and capacitance-voltage (C-V) measurements, the ability to make ultra-fast I-V measurements is becoming essential to anyone in a characterization lab responsible for developing new materials, devices, or processes. Making ultra-fast I-V measurements involves generating high-speed pulsed waveforms and measuring the resulting signals before the device under test has an opportunity to relax.

Early implementations of high-speed I-V testing, often referred to as pulsed I-V test systems, were developed to address applications such as characterizing high-k dielectrics and Silicon-On-Insulator (SOI) isothermal testing or to generate the short pulses necessary to characterize flash memory devices. Pulsed I-V measurement techniques are necessary because, when tested using traditional DC I-V techniques, their insulating substrates cause SOI devices to retain the heat self-generated by the test signal, skewing their measured characteristics; using pulsed test signals minimizes this effect.

In the past, high-speed-pulse/measure test systems typically were made up of a pulse generator, a multi-channel oscilloscope, interconnect hardware, and software to integrate and control the instruments. Unfortunately, these systems were plagued by latencies that complicated the coordination of signal source and measurement functions. Depending on the quality of the instruments and how well they were integrated, this approach 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 began looking for ways to apply

Keithley Instruments, Inc.
28775 Aurora Road
Cleveland, Ohio 44139
(440) 248-0400
Fax: (440) 248-6168
www.keithley.com

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 20V to program, but the CMOS process is running on 3V, 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.

Today, ultra-fast I-V source and measurement capabilities are being integrated into parametric analyzers for characterizing a growing range of device characteristics, particularly Negative Bias Temperature Instability (NBTI) and Positive Bias Temperature Instability (PBTI) degradation. By allowing researchers to make these device reliability measurements quickly and consistently, ultra-fast I-V measurement tools improve the accuracy of Designed-In Reliability (DIR) lifetime measurements, which support modeling for device and circuit design.

Until recently, some researchers have been forced to configure their own ultra-fast BTI test systems. These in-house-developed systems typically combine a pulse generator or arbitrary waveform generator with an oscilloscope equipped with current probes or some type of transimpedance amplifier to help measure low current. Although it is possible to build a BTI system that is suitable for a very specific set of electrical conditions if the instruments and interconnect are carefully selected, several major technical challenges remain:

- **Waveform generation.** Standard pulse generators and arbitrary waveform generators are designed to generate a waveform on a fixed recurring interval, rather than the Log(time) scale required for most reliability tests, including NBTI and PBTI testing.
- **Measurement timing and data storage.** Although oscilloscopes can be configured to trigger based on a waveform feature (such as a falling edge, for example), they are not designed to store samples selectively for specific portions of the waveform. This makes it necessary to store very large data sets for postprocessing. Only the most expensive oscilloscopes or those with costly memory expansion options can store enough data to compensate for these shortcomings.

- **Precision, accuracy, and sensitivity.** Bias temperature instability is a highly dynamic phenomenon that requires sensitive, high-speed measurements for accurate characterization. Assuming all other factors are constant, measurement physics largely defines the relationship between measurement speed and sensitivity. When making sub-millisecond measurements, all sources of noise must be taken into account; for sub-microsecond applications, even quantum effects can't be ignored. Oscilloscopes, current probes, and transimpedance amplifiers all have independently defined performance specifications and they are not necessarily optimized to work together. It is often very difficult to combine these components in a way that provides optimal performance across a wide dynamic range in order to achieve precision accurate measurements at high speeds.
- **Interconnect.** Systems built in house typically use splitters and bias tees, which limit the performance of the test setup. For example, a bias tee might limit bandwidth from 100ns to 10µs. Although this is suitable for high speed measurements, it prevents making any meaningful prestress and poststress DC measurements as part of the stress–measure sequence. It also prevents making measurements in the intermediate timing range of 10ms to DC.
- **Test control and data management.** Traditional oscilloscopes don't support data streaming, so results transfer must wait until the test ends. Once the test is complete, massive amounts of data must be transferred to the control computer for postprocessing, which requires parsing complex waveforms into individual test results, followed by further reduction of the data into actual measurements.
- **Test termination.** Given that the test results can't be analyzed until the data is transferred from the oscilloscope, the test duration must be determined prior to test initiation. This makes it impossible to terminate the test based on parametric shifts or to detect catastrophic failures in real time.
- **Automation.** Wafer- or cassette-level automation requires controlling both the test instruments and the wafer probe station, which systems built in house typically can't do. Also, incorporating sophisticated features like conditional test termination would add considerable complexity to the custom software necessary to run a system of this type.
- **Larger channel count.** Even if an in-house system works well when initially installed, system integrators may need to increase the channel or test system count to address evolving applications, which can be extremely complicated when attempting to upgrade a custom system. Typical test system maintenance issues such as calibration, operation, and correlation of these custom setups can also easily require a disproportionately high amount of technical resources, which are often in limited supply.

The latest generation of parameter analyzers can be configured to minimize or eliminate many of the shortfalls associated with BTI characterization systems built in house. Rather than a separate pulse or waveform generator and oscilloscope, they now combine these functions in high-speed source and measure modules that allow tight timing coordination. Because these modules are fully integrated with the parameter analyzer, they can make use of the system's data storage and automation capabilities. Chassis-based systems also make it uncomplicated to increase the number of high-speed channels simply by adding more modules.

The latest generation of parameter analyzers allows integrating ultra-fast I-V, DC I-V, and C-V measurements into the same test sequence. This is a particularly valuable capability for the growing number of applications that involve the use of multiple measurement types, such as charge pumping (CP), which typically involves pulsing a gate voltage and measuring a DC substrate current simultaneously, or determining the electrical characteristics of photovoltaic (solar) cells, which typically involves measuring current and capacitance as a function of an applied DC voltage.

Keithley's Model 4200-SCS Semiconductor Characterization System (***Figure 1***) has long supported precision DC I-V measurements (with integrated SMUs) and C-V measurements (with an optional C-V module). The recent introduction of the Model 4225-PMU Ultra-Fast I-V Module and Model 4225-RPM Remote Amplifier/Switch makes it possible to add ultra-high-speed sourcing and measurement to create a system that's also 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-κ dielectrics; and NBTI/PBTI reliability tests. (See ***Figure 2*** for a graph that maps many of these emerging applications to the Model 4200's DC I-V and ultra-fast I-V sourcing and measurement ranges.)

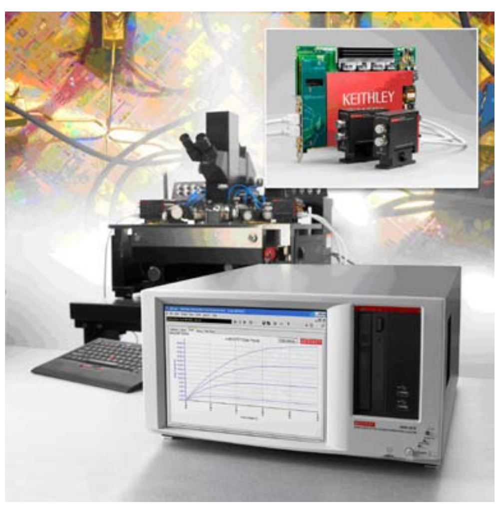

Figure 1. Model 4200-SCS parametric analyzer and ultra-fast I-V tools

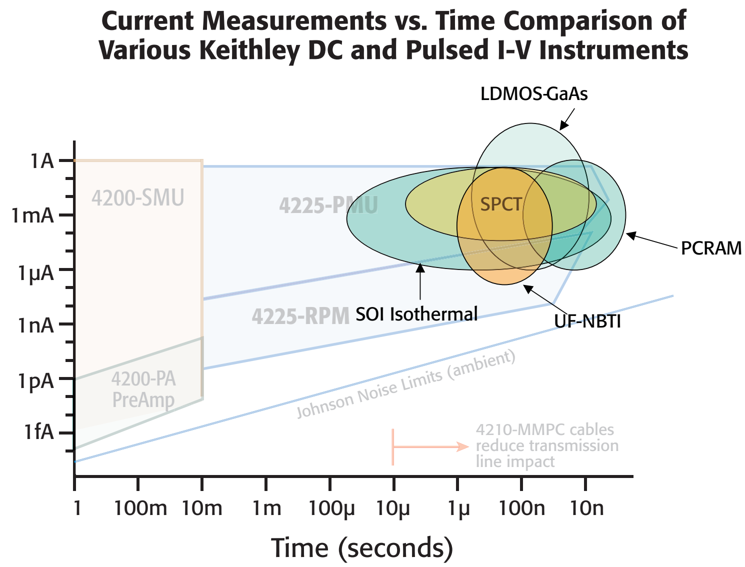

Figure 2. Ultra-fast I-V sourcing and measurement pick up where more traditional DC I-V capabilities leave off. Note how traditional SMU designs can source and measure currents up to about 1A and down to about a picoamp. Although adding a remote preamplifier allows resolving signals as low as 0.1fA, these DC-I-V-only configurations' best speed was about 10 milliseconds. In contrast, ultra-fast I-V solutions allow making measurements as fast as 10ns, which is critical for applications that involve characterizing device recovery. Optional remote amplifiers designed specifically for ultra-fast I-V testing extend the current resolution of these new solutions down to tens of picoamps, just slightly above the limit imposed by the Johnson noise produced by the devices under test. Systems that combine ultra-fast I-V source and measure instrumentation with remote amplifiers support a broader array of characterization applications than ever before available in a single chassis, including testing of phase change memory devices, single-pulse charge trapping/high-κ dielectric test, characterization of LDMOS or gallium arsenide medium-power amplifier devices, SOI isothermal test, ultra-fast negative bias temperature instability (NBTI) test, charge-based capacitance measurement (CBCM), MEMs capacitor test, and a growing list of others.

Figure 3 illustrates four sweep types available to support the growing array of ultra-fast I-V applications: transient I-V sweeps, in which voltage and/or current are continuously digitized; fast pulsed I-V, in which voltage and/or current are sampled after the pulse has settled; filtered pulse, which involves generating a variable pulse voltage while a DC SMU measures the resulting current; and pulse stress/DC measure, in which the voltage is pulsed, followed by a DC SMU measurement. In addition to these traditional sweep types, the Model 4225-PMU incorporates a full arbitrary waveform generation capability, as well as a Segment ARB® mode that simplifies creating, storing, and generating waveforms made up of up to 2048 user-defined lines segments. Each segment can have a different duration, which allows exceptional waveform generation flexibility.

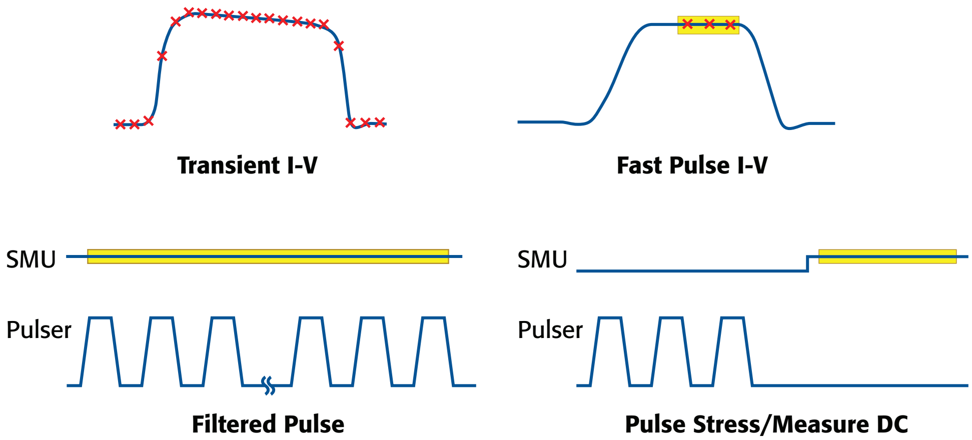

Figure 3. Ultra-fast I-V test setups.

Conclusion

As new devices and test applications emerge and the needs of semiconductor lab-based researchers continue to evolve, ultra-high-speed source/measure capabilities will become increasingly important. Test systems that offer the flexibility needed to adapt to these changing requirements cost-effectively will allow researchers to build on their previous work while keeping up with advances in measurement technology.

Author Note:

Lee Stauffer is Senior Staff Technologist for Keithley Instruments' Semiconductor Measurements Group, based in Cleveland, Ohio. Prior to joining Keithley, his career included designing satellite communication systems, as well as equipment and product engineering in semiconductor fabs.

KEITHLEY

A GREATER MEASURE OF CONFIDENCE

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: 86-10-8447-5556
Fax: 86-10-8225-5018
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
sea@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
sea@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

Printed in the U.S.A. No. 3108 01.24.11