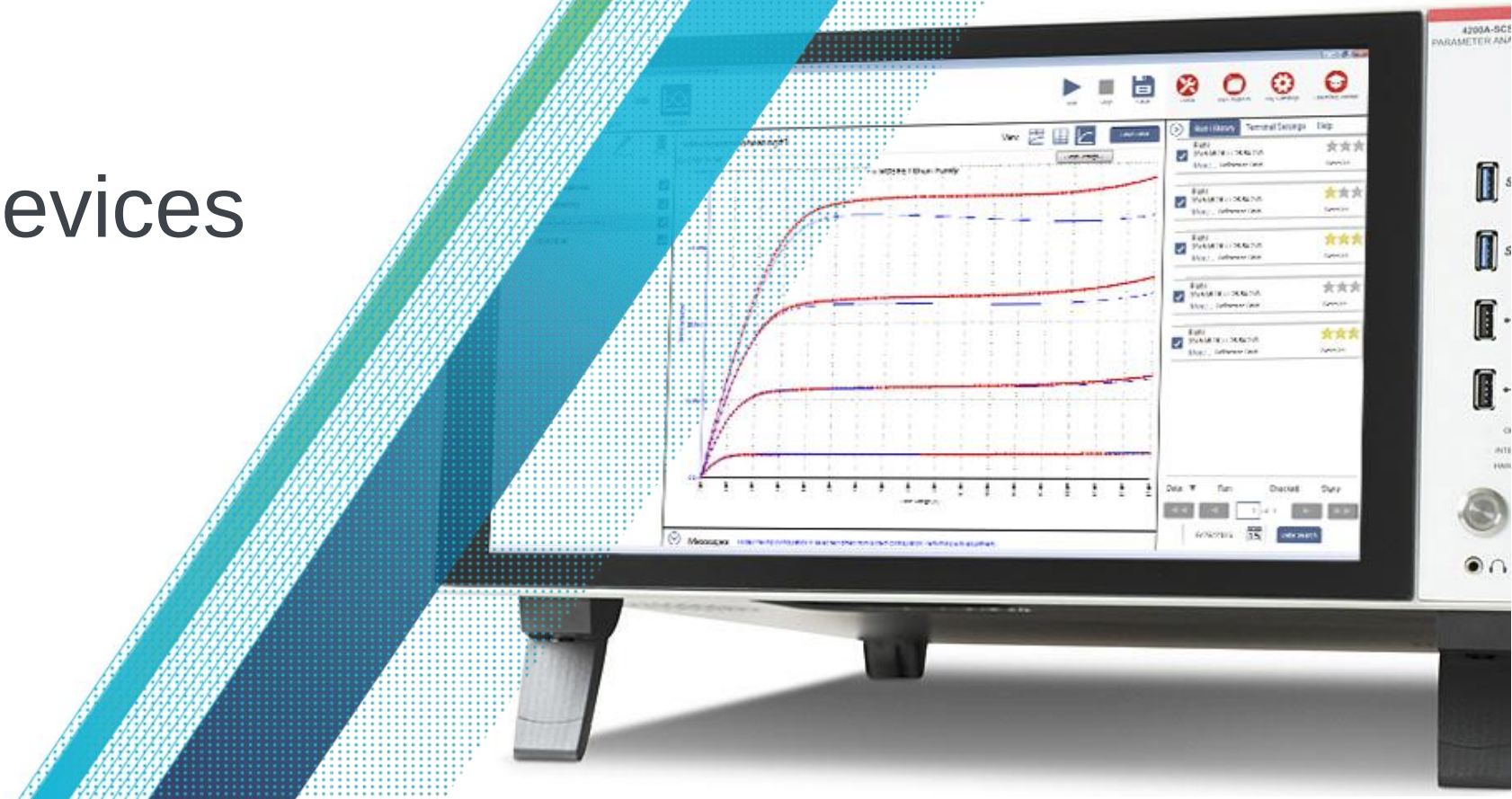
Tektronix

Characterizing Semiconductor Devices and Materials

19 AUGUST 2016

KEITHLEY
A Tektronix Company



Semiconductor Trends

NEW MARKETS AND APPLICATIONS DRIVE DEMAND

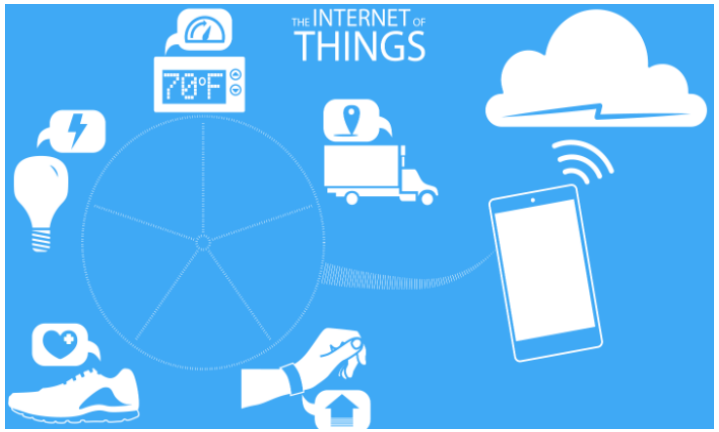
Internet of Things (IoT) – personal devices and machine-to-machine connections.

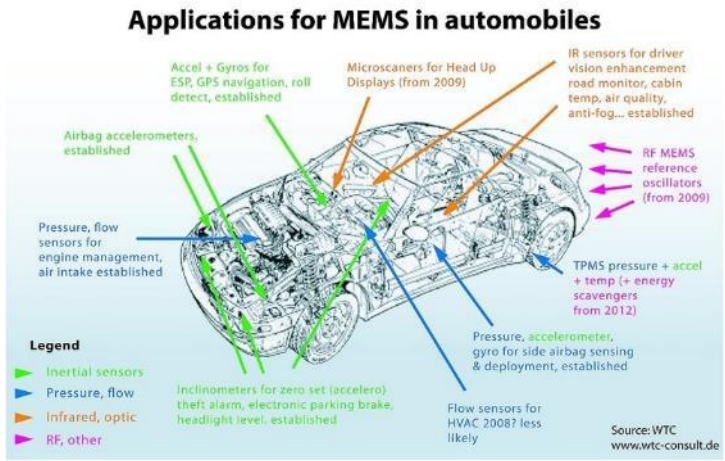
Automotive – higher energy efficiency, reduced emissions, and increased safety, comfort and convenience drive the need for improved semiconductors

Cloud computing - denser, energy efficient and secure data centers

Communications, Space, Military, Industrial, Medical

Lower or higher power, higher functioning, more reliable, less weight demand new devices and materials.

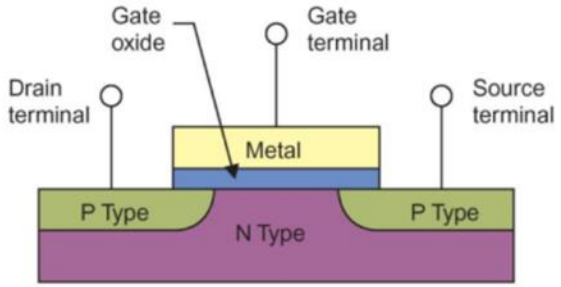


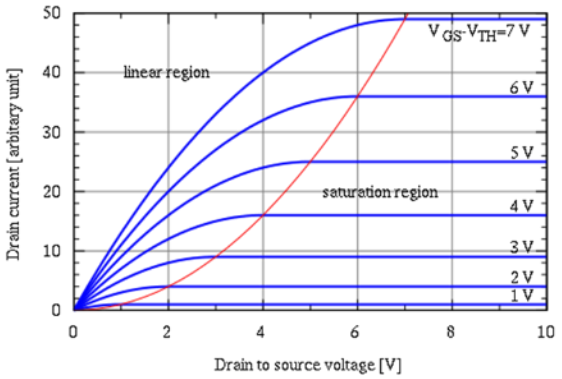


Characterization

WHAT IS IT AND WHY DO IT?

- Performance of semiconductor devices depends on fundamental electrical parameters.
- Provides a method of understanding a material or device's fundamental properties
  - Other methods are optical, chemical, physical etc.
- Provides the ability to control and to design applications that take maximum advantage of a material or device's performance.
- Involves testing of four main types of devices:
  - Resistors, Diodes, Transistors, Capacitors





Semiconductor Device Workflow

Materials & Device Research

- Experimental research leading to an increased understanding of the DUT.
- Universities, National Labs, Flat Panel Displays, Integrated Devices, Industry Labs

"When I get unexpected results, I have to stop my testing and determine if the bad data is due to the device or the test equipment or probe station. This is frustrating and delays my research."

Semiconductor Device Workflow

Materials & Device Research	Device Development & Characterization
• Experimental research leading to an increased understanding of the DUT.	• Developing device architecture which meets technology performance, reliability and yield goals
• Universities, National Labs, Flat Panel Display MFG. Integrated Device Mfg., Industry Labs	• Integrated Device Mfg., Flat Panel Display Mfg., Fabs/Foundries

"I don't use test equipment daily. When I get unexpected results, I don't know if the data is due to the device or the test equipment or probe station. This is frustrating and delays my research."

Semiconductor Device Workflow

Materials & Device Research	Device Development & Characterization	Modelling
• Experimental research leading to an increased understanding of the DUT. • Universities, National Labs, Flat Panel Displays. Integrated Devices, Industry Labs	• Developing device architecture which meets technology performance, reliability and yield goals • Integrated Device Mfg., Flat Panel Display Mfg., Fabs/Foundries	• Create device behavior models based on fundamental physics. The models are then used to simulate electrical behavior. • Integrated Device Mfg., Flat Panel Display Mfg., Fabs/Foundries

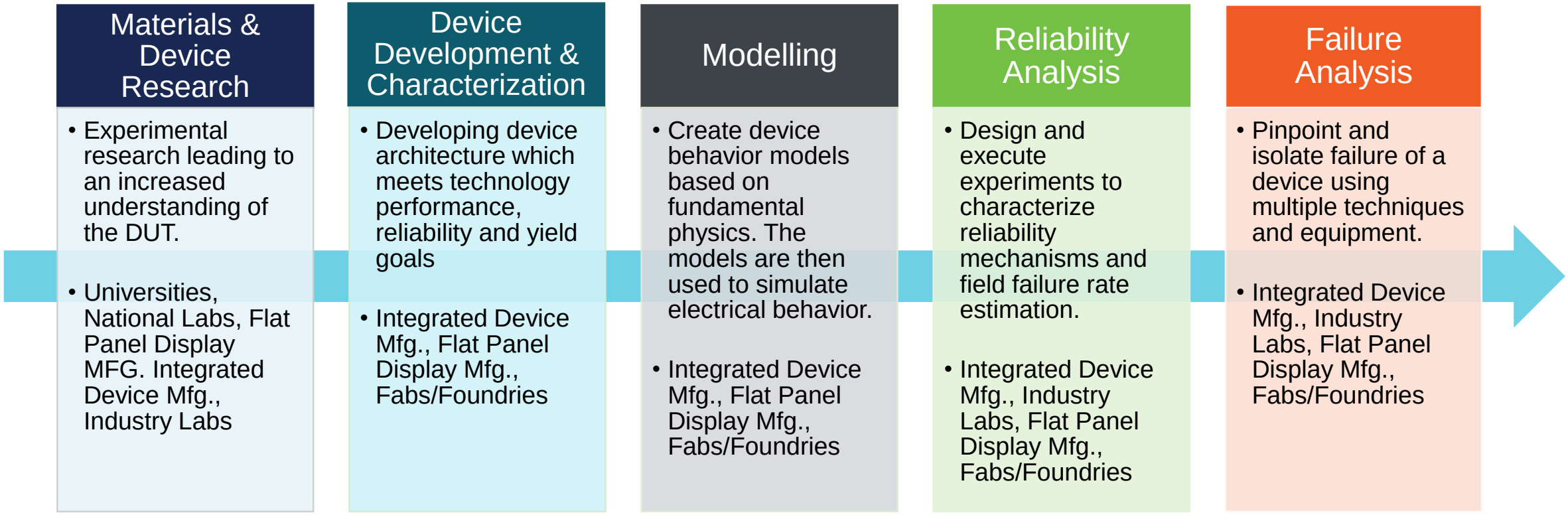
"When I get unexpected results, I have to stop my testing and determine if the bad data is due to the device or the test equipment or probe station. This is frustrating and delays my research."

Semiconductor Device Workflow

Materials & Device Research	Device Development & Characterization	Modelling	Reliability Analysis
• Experimental research leading to an increased understanding of the DUT. • Universities, National Labs, Flat Panel Display MFG. Integrated Device Mfg., Industry Labs	• Developing device architecture which meets technology performance, reliability and yield goals • Integrated Device Mfg., Flat Panel Display Mfg., Fabs/Foundries	• Create device behavior models based on fundamental physics. The models are then used to simulate electrical behavior. • Integrated Device Mfg., Flat Panel Display Mfg., Fabs/Foundries	• Design and execute experiments to characterize reliability mechanisms and field failure rate estimation. • Integrated Device Mfg., Industry Labs, Flat Panel Display Mfg., Fabs/Foundries

"I always want more data and faster insight into my reliability analysis. There is always pressure to move the device to production quickly. I worry that I haven't collected enough data."

Semiconductor Device Workflow

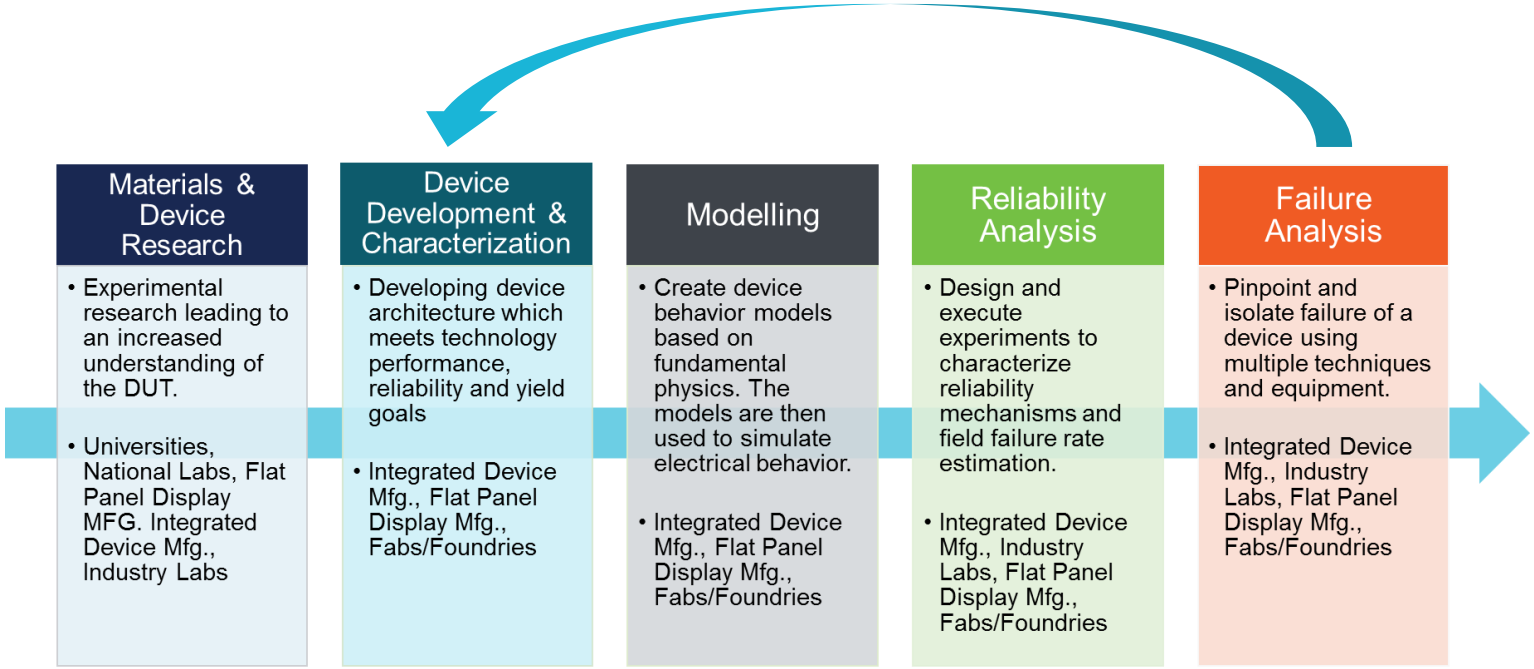


"I need to quickly determine the device failure to prevent a safety problem and stop field failures. My analysis has to be correct because I may have to shut down the production line."

Characterization Trends

FA AND RELIABILITY TECHNIQUES

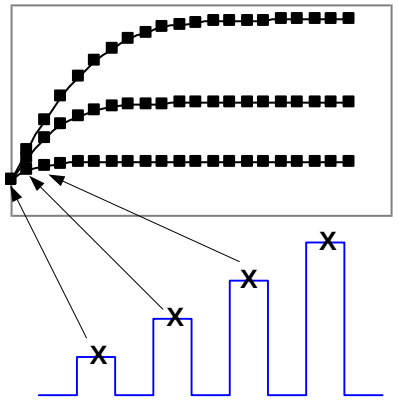
- Failure Analysis is no longer ***only*** performed after a device has been produced.
- Failure Analysis is used often during the device development phase.



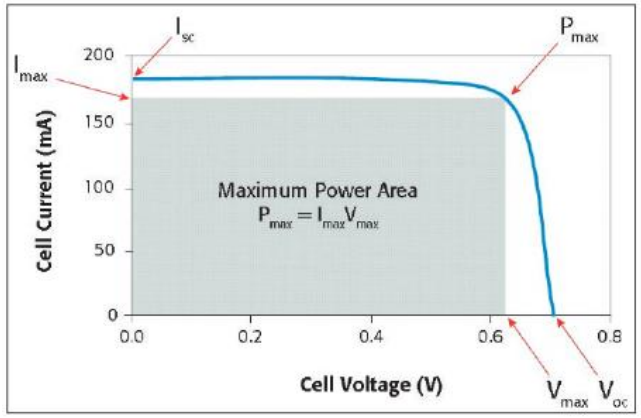
Characterization Trends

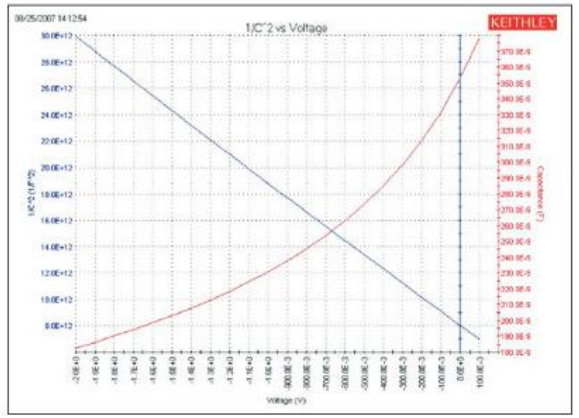
MEASUREMENTS

- Growing trend to use Pulsed I-V measurements to minimize the self-heating effects often seen with a DC I-V measurement.
- Use waveform capture (oscilloscope) to identify transient behaviors
- In-depth characterization requires I-V and C-V measurements.

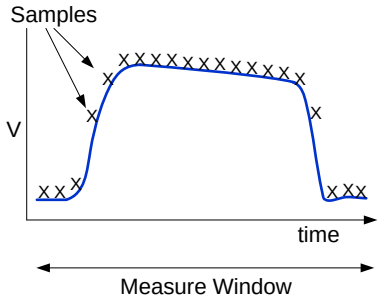


Forward biased I-V of Solar cell





Doping density of Si solar cell derived from C-V sweep



Characterization Trends

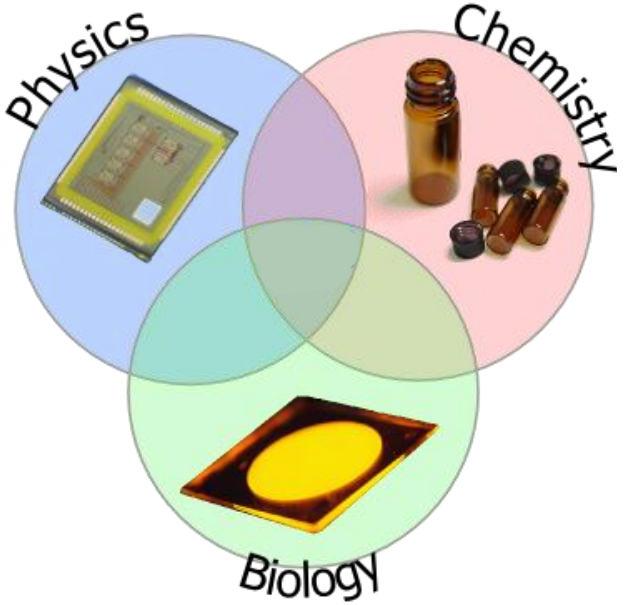
NO LONGER FOR GRADUATE LEVEL STUDENTS

- Increasingly, universities in the USA are moving in-depth semiconductor coursework and research projects to the undergraduate level (year 3 and 4 in a Bachelors degree program).
- Gives students a unique immersive perspective on semiconductors/nanotechnology and prepares them earlier in their careers for concepts in the future.

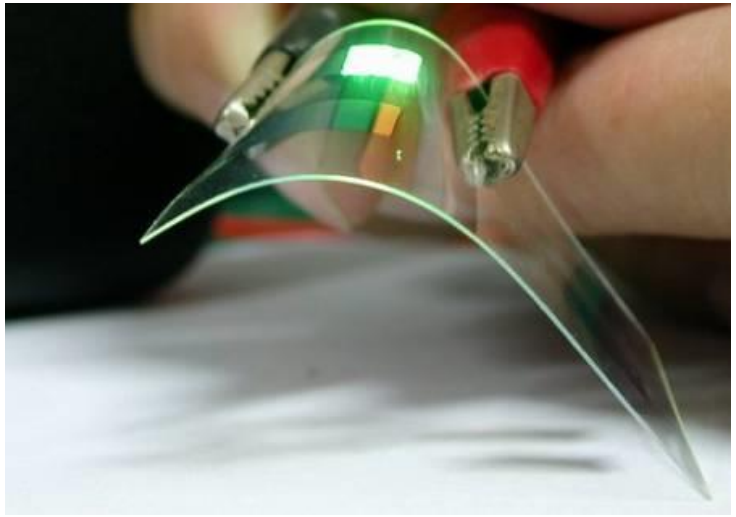
University of Illinois Urbana-Champaign

Characterization Trends

INTERDISCIPLINARY RESEARCH



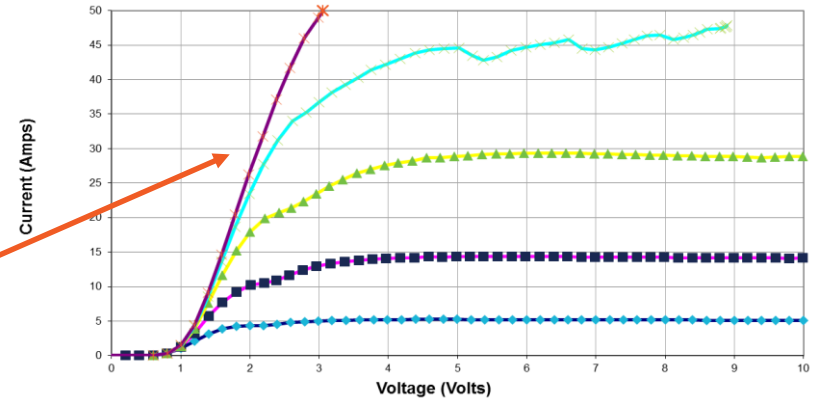
- Organic materials are an important new class of semiconductors as they combine the virtues of plastics, which can be easily shaped, with those of semiconductors which are the basis of all microelectronics.
- These novel materials can be used to make lightweight flexible optoelectronic devices such as displays, solar cells and lasers.
- Characterization often requires electrical and chemical techniques



Characterization is Complicated!

SEMICONDUCTOR DEVICE, MATERIALS & PROCESS DEVELOPMENT

- Often connections to probers, test equipment and the device under test is complicated.
- Sorting through and understanding the assortment of test parameters complicates the test plan and delays testing.
- Often, a parameter analyzer is used sporadically. Users must relearn how to operate equipment.
- Unexpected results occur and delays the research.
  - Determine if incorrect data is due to instrumentation, probe station or device under test.



How is Keithley Instruments addressing these trends?

- Insert 4200A promo video here

4200A-SCS Parameter Analyzer

ACCELERATING INSIGHT

- Integrated parameter analyzer that reduces characterization complexity, troubleshooting and test set-up time.
- Fully characterize a device, material or process
  - DC I-V Source Measure Units (SMU)
  - AC Impedance Capacitance-Voltage Unit (CVU)
  - Pulsed I-V Pulse Measure Unit (PMU)
- Industry's easiest methods to switch between I-V, C-V and Pulsed I-V measurements
- Jumpstart testing with over 250 user-modifiable, searchable application tests
  - No complex programming required
- Industry's first instrument with built-in measurement videos
  - "YouTube-like" experience
  - Get answers faster and investigate unexpected results more quickly

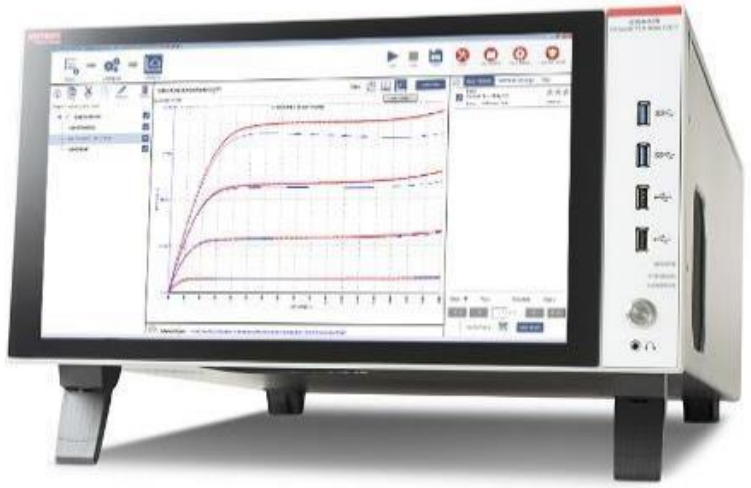
4200A-SCS Parameter Analyzer

4200A-CVIV Multi-Switch

More Viewing Area for Interactive Testing

4200A-SCS PARAMETER ANALYZER

- Industry's largest display
  - 15.6" LCD widescreen
  - Capacitive touchscreen
    - Ability to turn off touchscreen capability
  - 1920x1080 HD display
  - Same 5U chassis height as the 4200-SCS
  - Version without display also available
- Other Benefits
  - Solid-state hard drive for fast boot-up and data storage
  - Runs Microsoft's Windows 7, the established standard in industry and business



Semiconductor Devices, Materials, Processes

WIDE RANGE OF APPLICATIONS

- Semiconductor device and process development
- Reliability and lifetime testing
- Failure analysis
- MOSFET, BJT, and III-V device characterizatic
- Nanotechnology and MEMs research
- Advanced Non-volatile Memory testing
- Organic electronics characterization
- Device modeling
- Solar cell/photovoltaic device characterization

A Complete Solution from DC to Pulse

4200A-SCS Parameter Analyzer			
System Software	Clarius™ with >250 application tests/projects/devices		
I-V Measurements	Medium Power SMU 210V, 100mA	High Power SMU 210V, 1A	Remote Pre-amplifier 0.1 fA resolution
Pulse I-V/Transient	Pulse Measure Unit	Pulse Generator Unit	
C-V Measurements	Capacitance-Voltage Unit 1kHz to 1MHz	Ramp-Rate (Quasi Static) C-V	Very Low Frequency VLF C-V
Switching	IV/CV Multi-Switch Module	Remote Preamplifier/Switch Module	Ultra Low Current Switch Matrices
Drivers for probe stations, temp. controllers, external equipment			

New User Experience

Clear, Uncomplicated Analysis

Simplifying Parameter Analysis

CLARIUS SOFTWARE

- Easy for expert users and sporadic users to begin testing

Select from over 250 Tests, Projects, and Devices from the library to jumpstart testing.

Configure tests with minimal keystrokes using the new “All Parameters” view or graphical view.

Analyze and organize results. Never worry about losing data!

Develop Test Plans Quickly

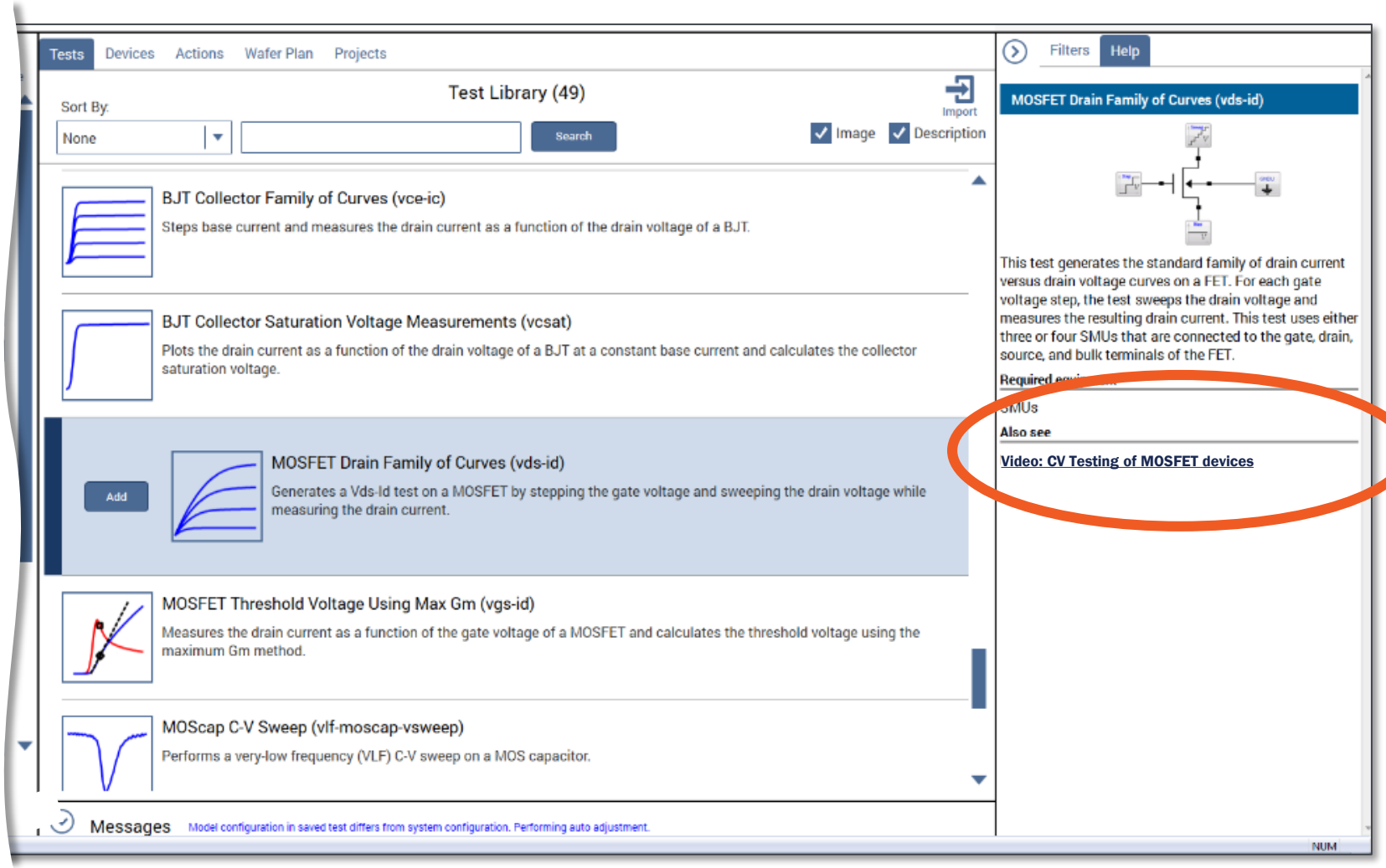
Library of Tests, Projects, Devices, Prober commands and more

Drag and drop tests to build your test plan

Perform test sequencing with a mouse click

Filter library for quick selection

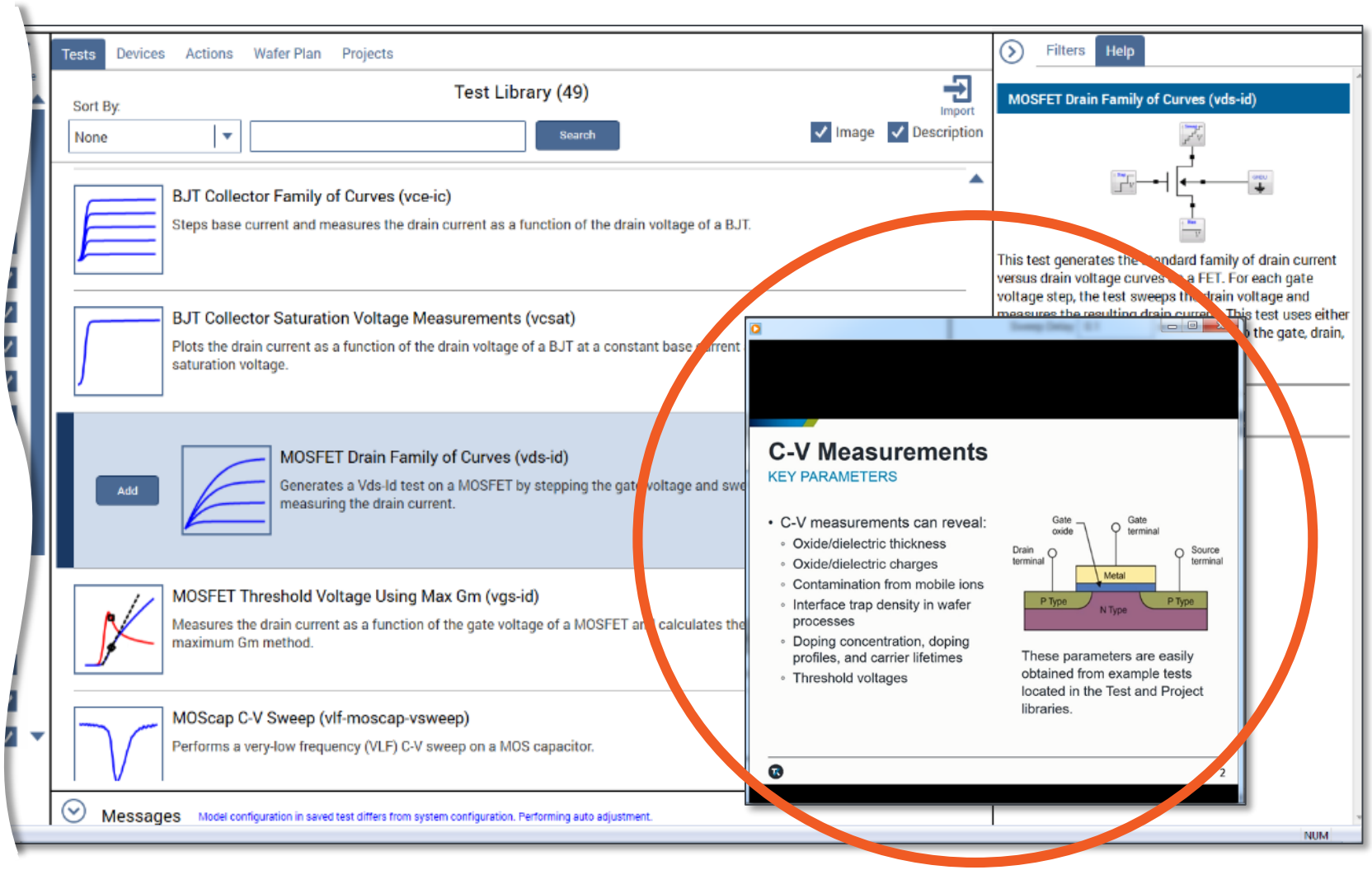
Select Screen – Faster Test Development



- Faster test development and reduced learning curve:
  - Comprehensive test descriptions
  - Schematic view of test
  - Associated videos and application notes available

- Insert Help video in Japanese here

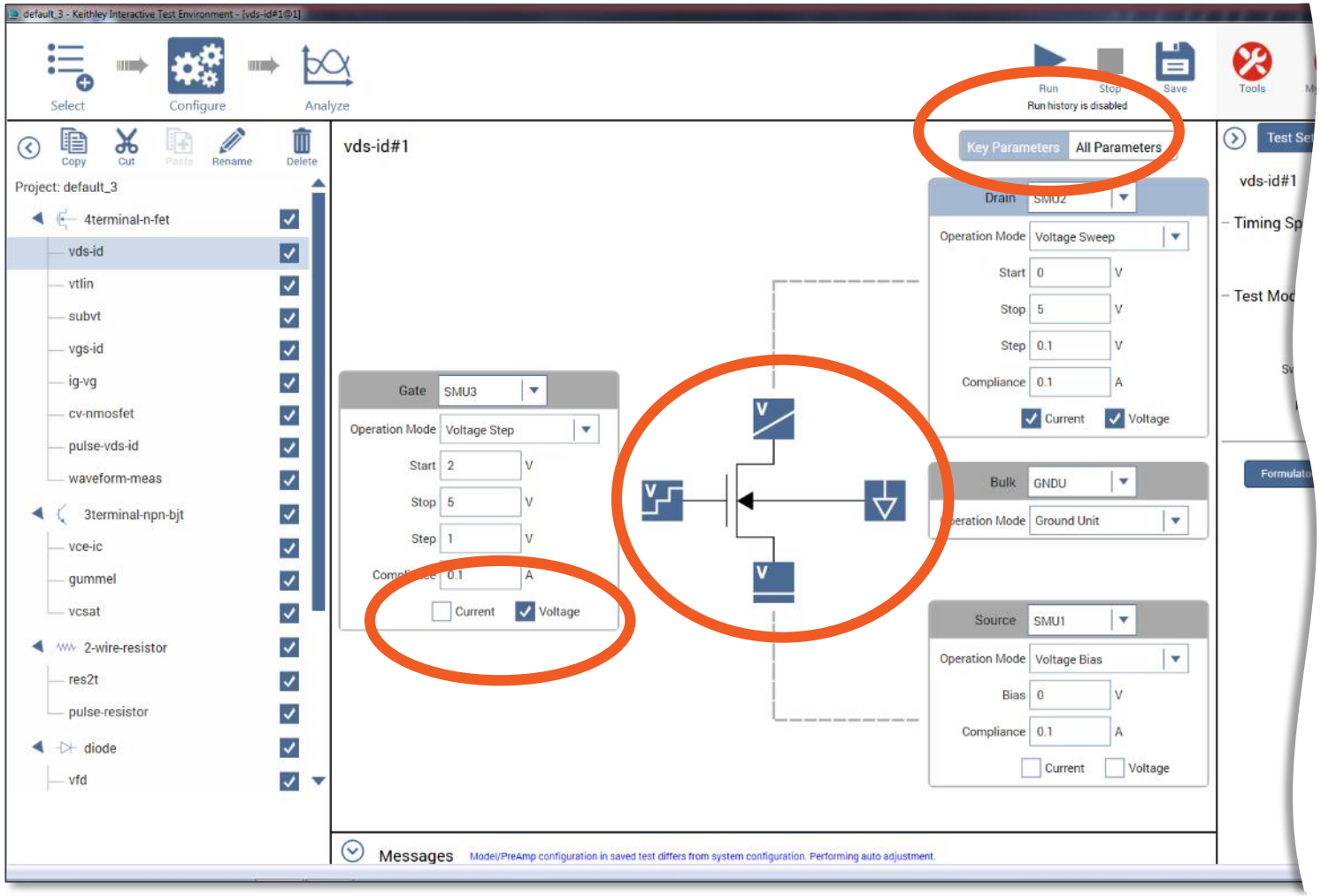
Select Screen – Reduce Learning Curve



- 4-5 minute videos provide concise information
- Multiple languages available
  - Chinese
  - English
  - Japanese
  - Korean

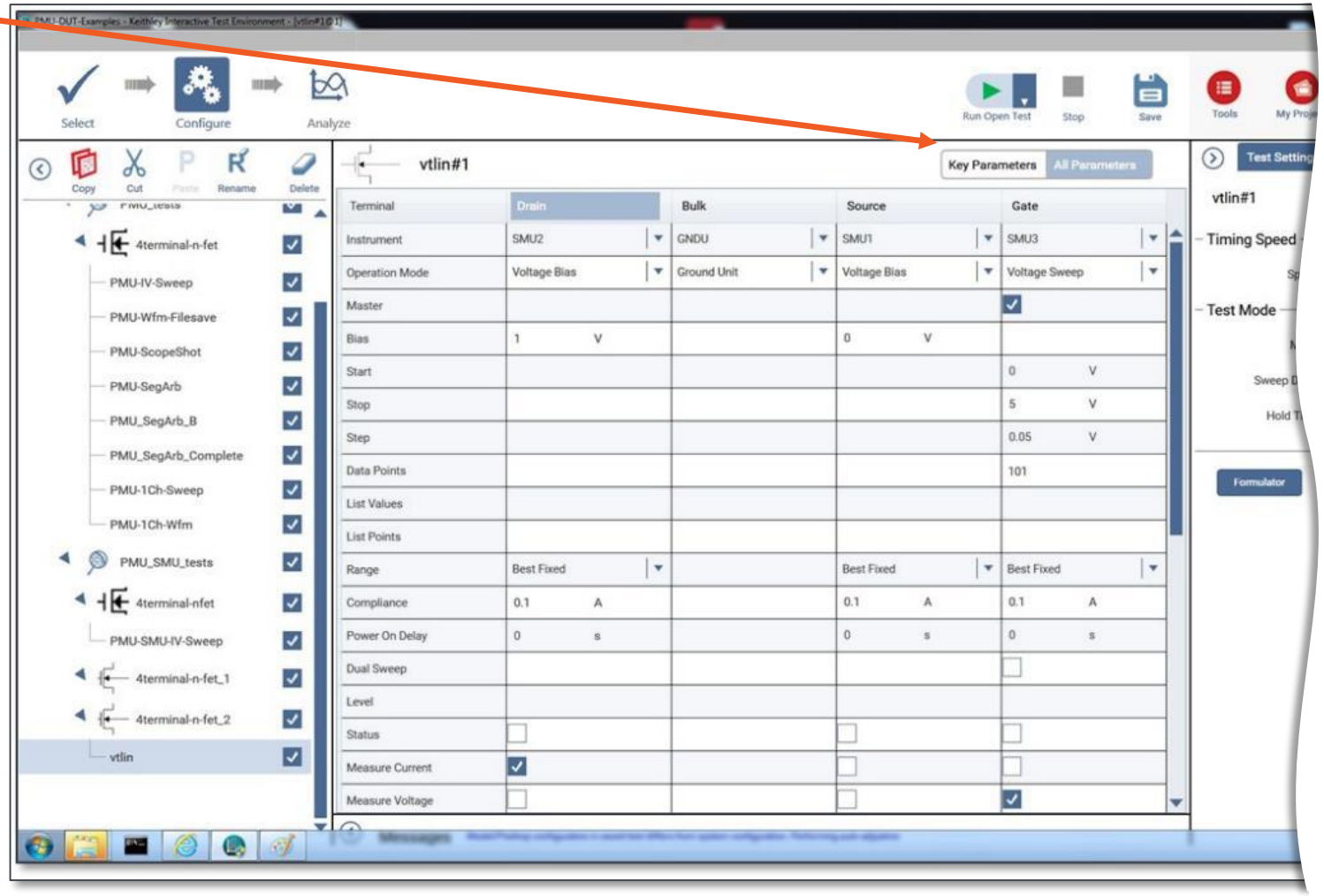
Configure your tests with confidence

- Toggle between Key and All Parameters view for easy test configuration
- At a glance, confirm the testing parameters at each terminal
- Flattened menus
  - Common parameters are configured on primary screen
  - Easy to select measure Current or Voltage



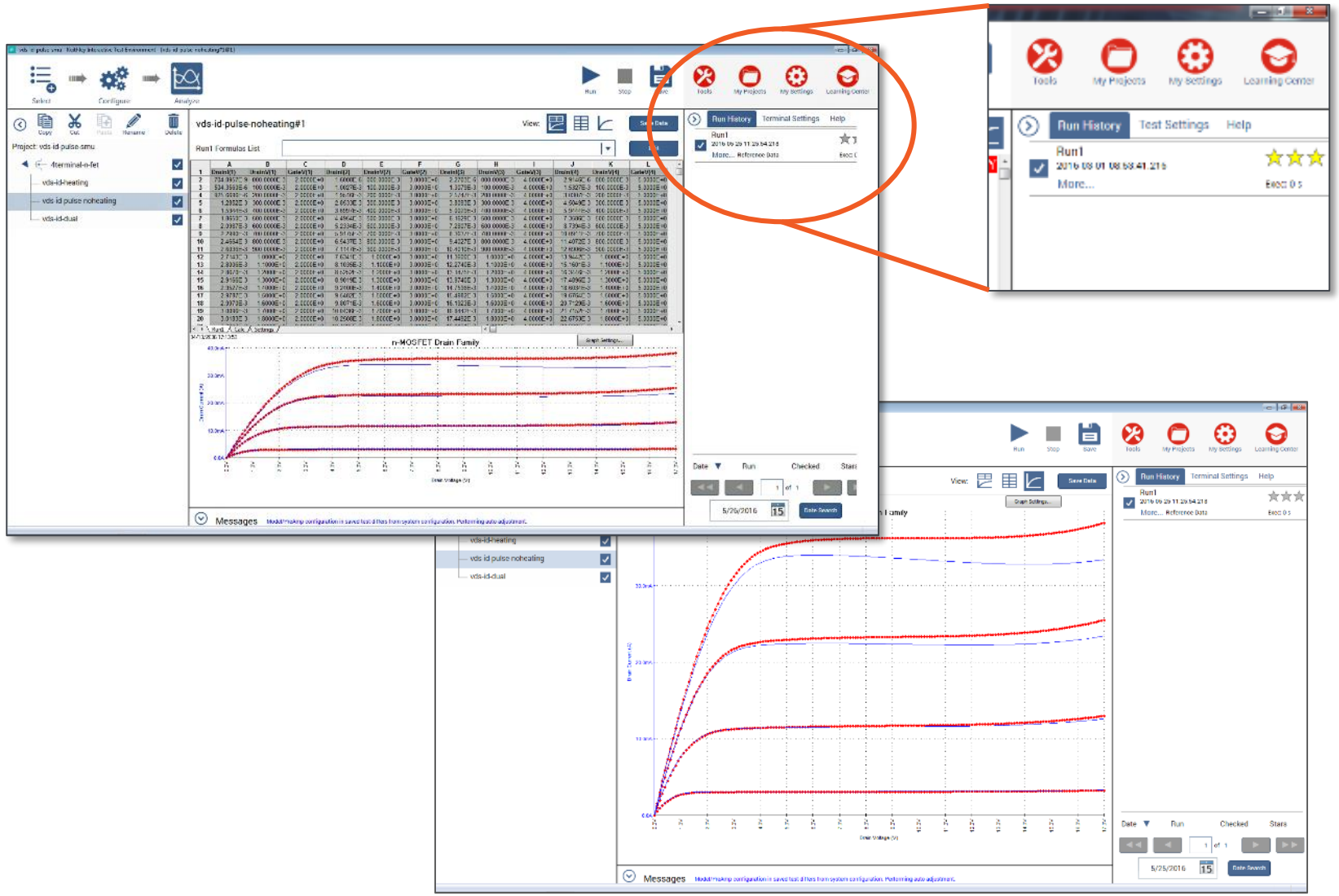
Configure screen – All Parameters view

- Toggle between Key Parameters and All Parameters view
- Key Parameters view is ideal for users that just want to enter the test parameters.



Analyze your results

- All test history is saved
  - Never overwrite or lose test data!
- Tag good, bad, and questionable results for easy identification
- Filter test data for analysis



How does this address the market trends?

CASE STUDY – TRAINING STUDENTS

- University of Illinois Urbana-Champaign engages undergraduate and graduate students in the fabrication and testing process of semiconductor devices
- ISO Certification is required to attract external paying customers to use the lab
- Achieving ISO level of standards can be difficult when teaching and training students
- Embedded measurement videos in the 4200A helps the teaching staff provide consistent training which is required for ISO certification.
- The university can also add their own videos to the 4200A for further training.

How does this address the market trends?

CASE STUDY – INTERDISCIPLINARY RESEARCH

- University of Akron, Ohio characterizes organic semiconductor devices.
  - Cyclic voltammetry techniques (chemistry) and DC I-V (electrical) measurement techniques are needed for this application.
  - Test equipment needed is a potentiostat for chemistry measurements and a parameter analyzer for the semiconductor measurements.
- Having both a potentiostat and a parameter analyzer is expensive, more equipment to maintain and calibrate.
- 4200A-SCS can perform both electrochemistry and DC electrical test techniques and the built-in measurement guidance enables either discipline to quickly begin testing.
  - Speak the language of chemistry and physics

Switching Between Measurements

The Challenge

SWITCHING BETWEEN MEASUREMENTS

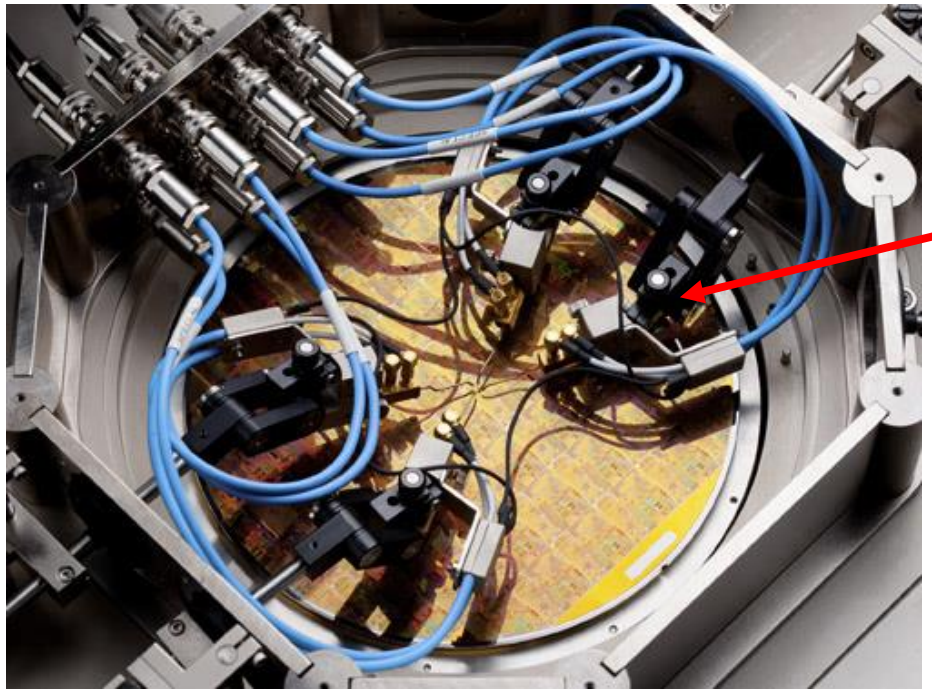
- Three key measurement types required for complete characterization picture
  - DC I-V, AC Impedance (C-V) and Ultra-fast Pulsed I-V
- However, the optimized cabling is very different for each measurement type

Precision DC I-V	AC Impedance (C-V)	Ultra-Fast Pulsed I-V
Triaxial cables	Coaxial cables	Coaxial cables
Kelvin connection	Kelvin connection	Non-Kelvin connections
Isolated, driven guard	Guards connected at probes	Shields connected at probes

Challenge inside the prober system

- Very time consuming, training intensive, possible damage to DUT
- Probe pins must be pulled up off the wafer to change the cabling
- Difficult to reposition the probe exactly the same location

Cables to Instruments

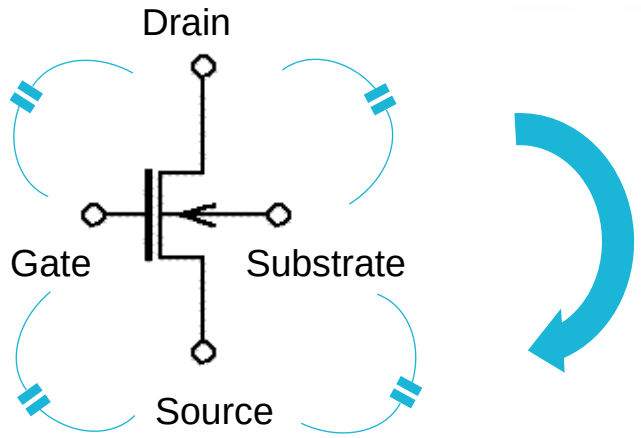


Each different test requires changing the cables attached to the manipulator!

4 Channel IV/CV Multi-switch

4200A-CVIV

- Automatically switch between IV and CV measurements - save time!
  - Keep the same test set-up, cables etc.
  - Keep prober tips on wafer to maintain same impedance
- Walk-around the device with CV measurements without re-cabling or moving the prober tips.
- Full CV compensation out to the DUT



Clear Information Where Needed

CV/IV SWITCHING

- Industry's first integrated remote display is ideal for set-up and troubleshooting
- View real-time test status
- Personalize output naming convention via Clarius user interface
- Rubber bumper allows for multiple orientations on the probe station
  - Turn display information with "rotate" button
- Turn off display to reduce light near DUT

Maximum Flexibility

4 CHANNEL IV/CV MULTI-SWITCH

- Provides maximum flexibility and control over test setup. Configure 1-4 channels, as needed, for testing.
- Set up any channel with extra low-current resolution using customer-installable preamplifiers
- Use Pass-Thru modules for channels that don’t require low current resolution … saves cost!
- Full 4-wire Kelvin inputs and outputs for low level measurements

Inputs

SMU and CVU inputs

Outputs

Triaxial outputs to device under test

Remote Preamplifier/Switch Module

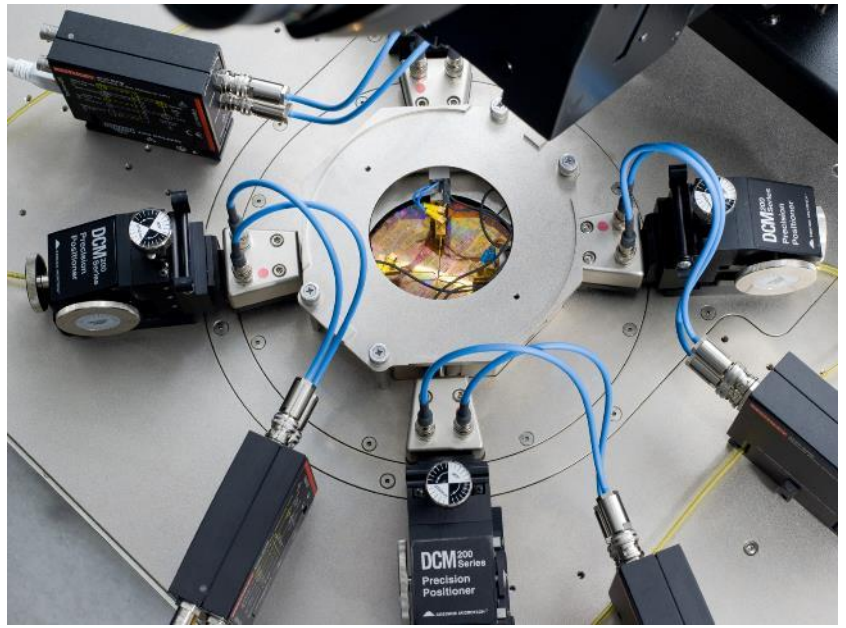
4225-RPM

- Single channel module simplifies connections to DUT and extends current range of PMU
- Automatic switching between I-V, C-V and Ultra-fast Pulsed I-V measurements
  - No changing test setup or cables
- Extends the current range of the 4225-PMU
  - Provides current sensitivity down to tens of pico-amps
  - Reduces cable capacitance effects
- Magnetic and vacuum base available for easy installation on prober platen

How does this address the market trends

USE CASE – LAB WITH DUPLICATE PROBE STATIONS

- Multiple measurements can be made with ease without the worry of re-configuring your test set-up.
- Save time and stay focused on the research
- Minimize set-up errors
- Save budget



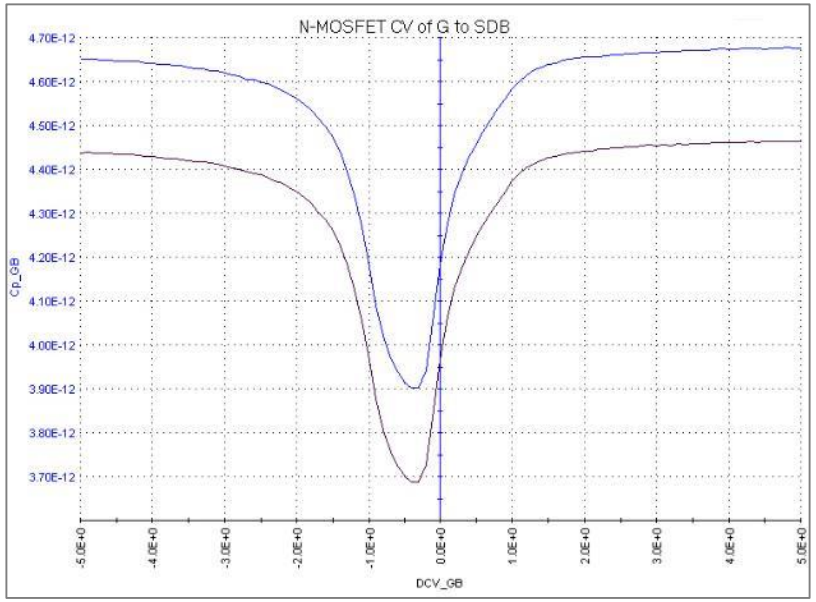
Capacitance-Voltage Unit (CVU)

4210-CVU

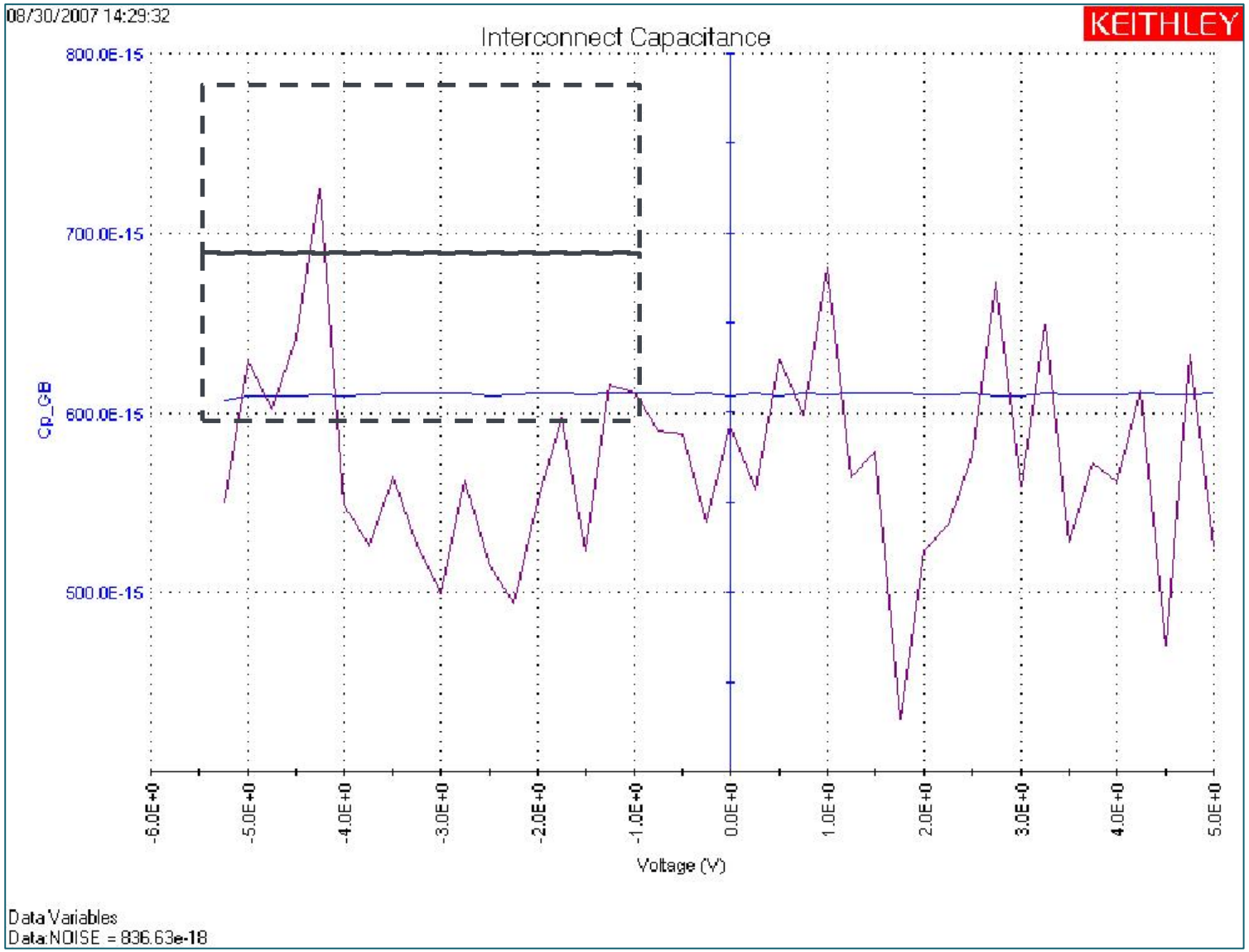
Multi-frequency AC Impedance

4210-CVU CAPACITANCE-VOLTAGE

- Measures from femto-farads (fF) to nano-farads (nF)
- Test frequencies from 1kHz to 10MHz
- DC source (sweep) +/-30 V (60 V differential) internal
- External DC bias up to +/- 200V (400V differential) using SMUs
- Extensive sample programs in Clarius library
- Parameter extraction examples

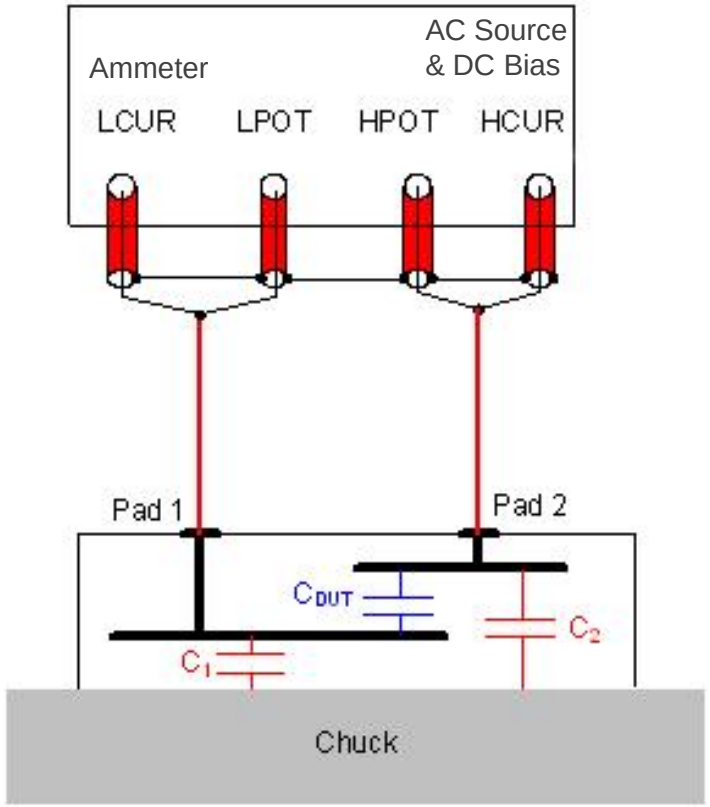


Exam

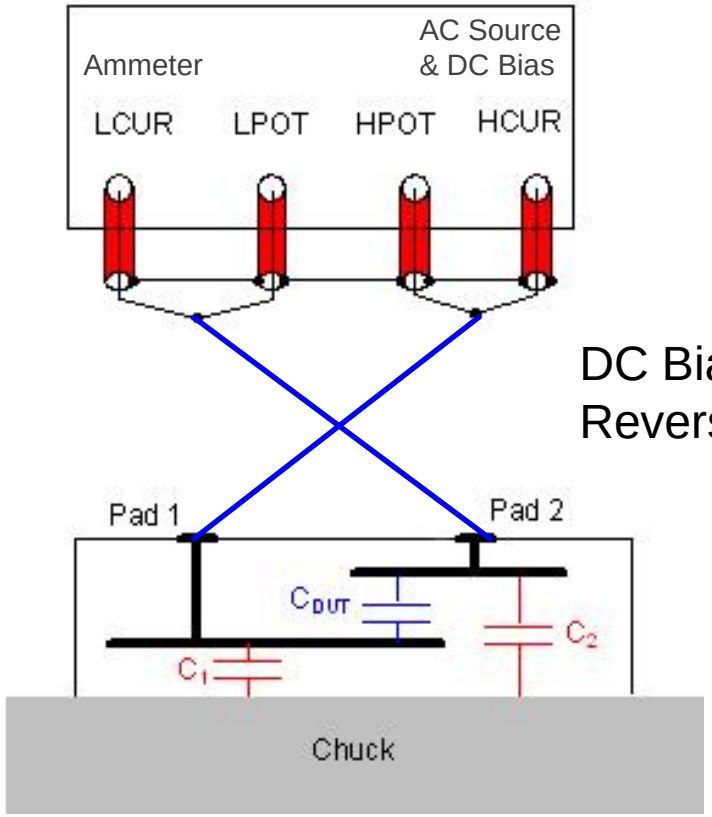

08/30/2007 14:29:32
Interconnect Capacitance
KEITHLEY
800.0E-15
700.0E-15
600.0E-15
500.0E-15
Cp_GB
-6.0E+0
-5.0E+0
-4.0E+0
-3.0E+0
-2.0E+0
-1.0E+0
0.0E+0
1.0E+0
2.0E+0
3.0E+0
4.0E+0
5.0E+0
Voltage (V)
Data:Variables
Data:NOISE = 836.63e-18

Switch High and Lo Leads

Noisy measurement connection scheme



Terminal connections switched

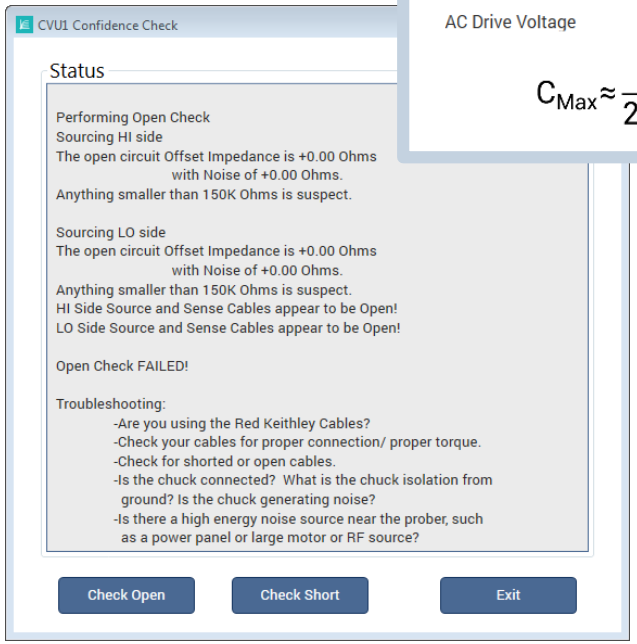


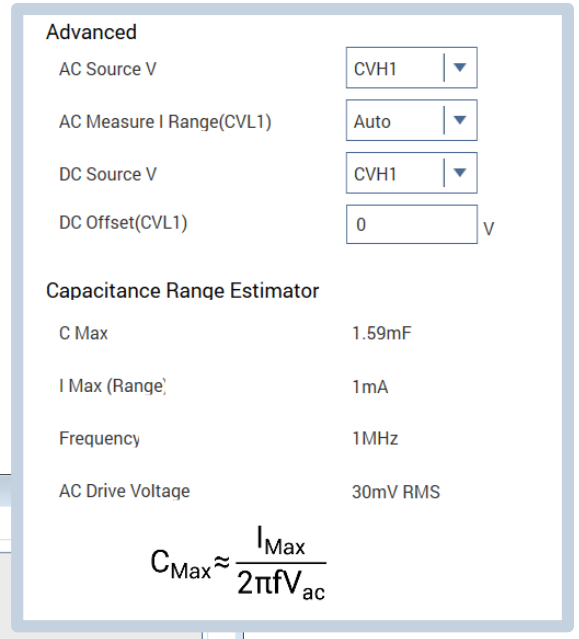
DC Bias Reversed!

Simplified C-V Measurements

UNIQUE TOOLS

- Move the AC measurement and DC Bias to least noisy terminal with just a mouse click
  - No re-cabling or changing the test setup
  - Faster research and time to answer
- Real time capacitance measurements
  - Check your switch matrix, prober connections before beginning a test
- Confidence Check
  - Reveals problems before you begin C-V test
  - Provides troubleshooting tips

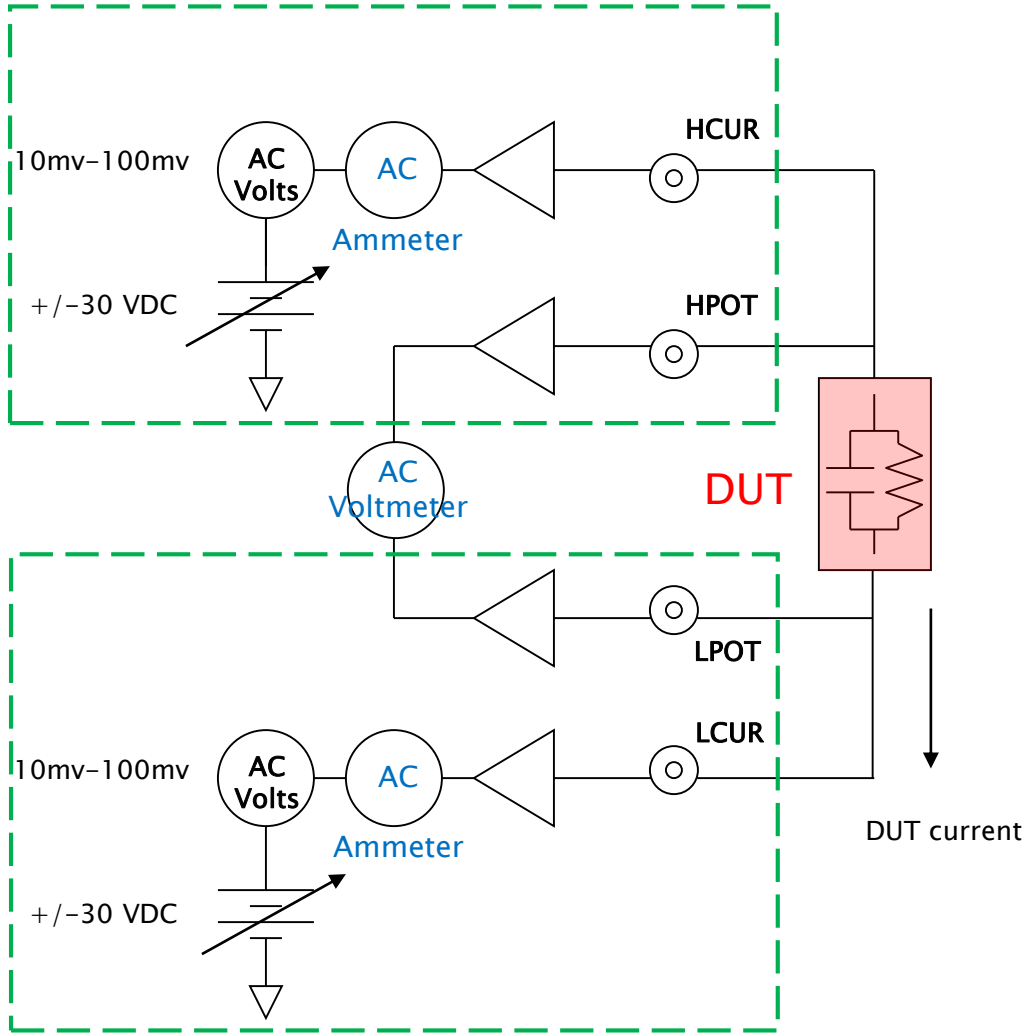




Symmetrical Circuitry

4210-CVU INSTRUMENT CARD

- Unique than most LCR meters, symmetrical circuitry enables easy switching of AC ammeter and DC bias.
- Clarius software enables easy switching in software
- Helps researchers understand quickly the behavior of the DUT

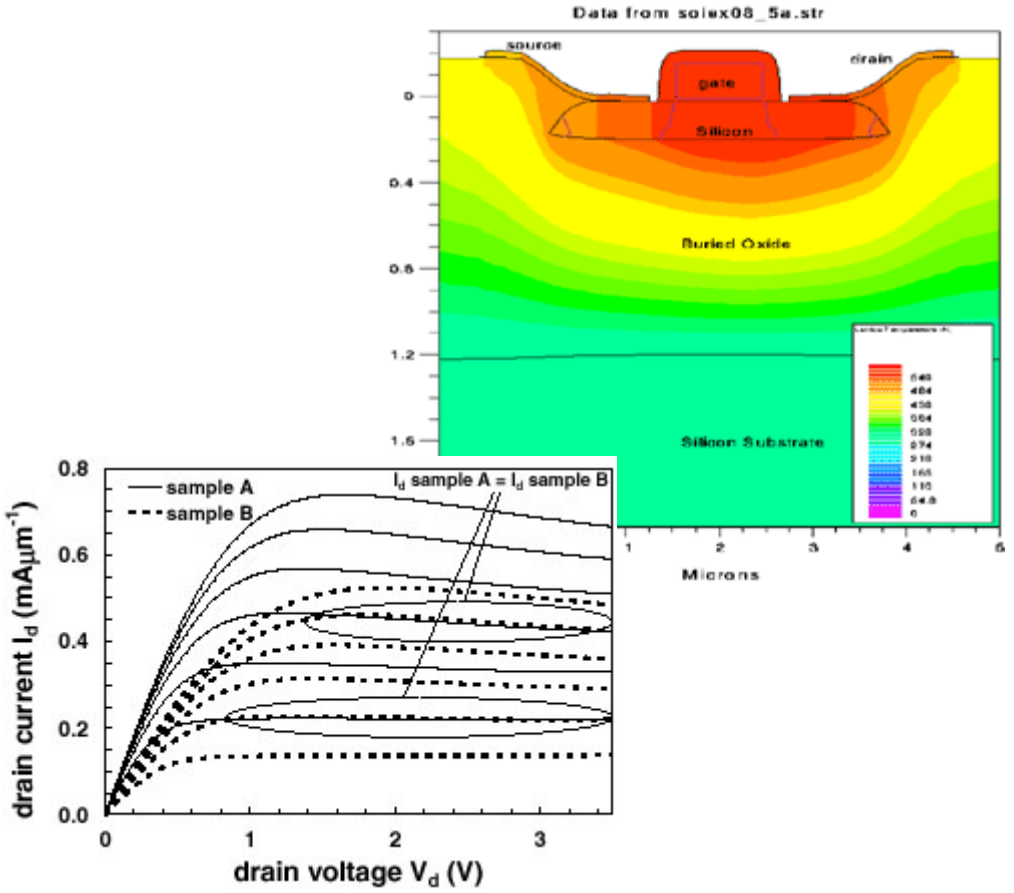


Ultra-fast Pulse Measure Unit

4225-PMU and 4225-RPM

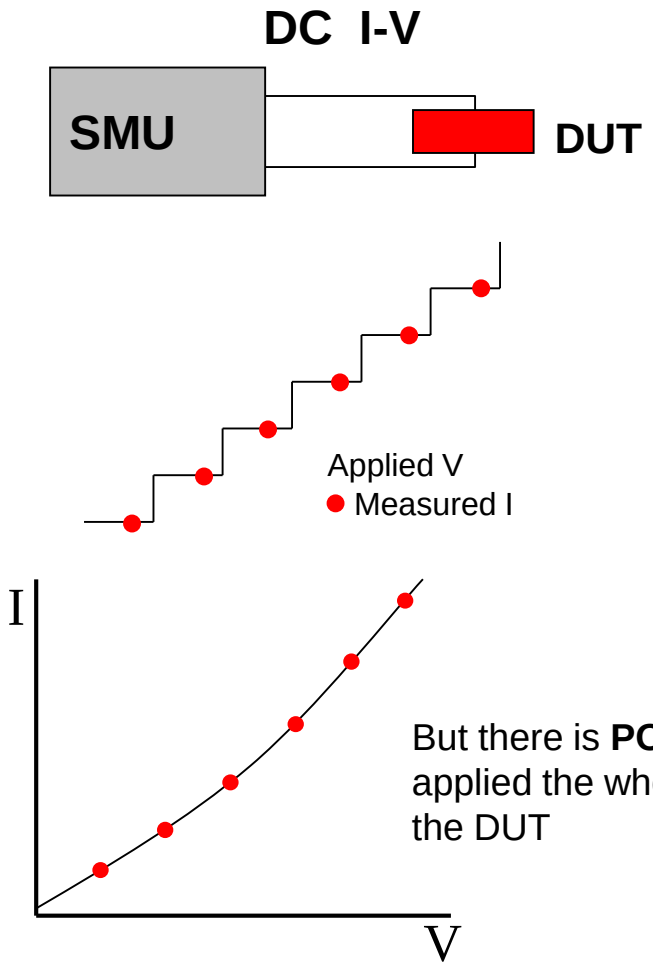
Why do we need Pulse I-V Testing?

- Increasingly common requirement due to:
  - Lower power consumption devices
  - Advanced processes utilizing exotic materials
  - Minimizing self-heating effects of devices
  - Non-volatile memory program/erase testing
  - Reliability cycle testing
  - Minimize current drift of the device
  - Reduce degradation in measurements due to trapped charge.

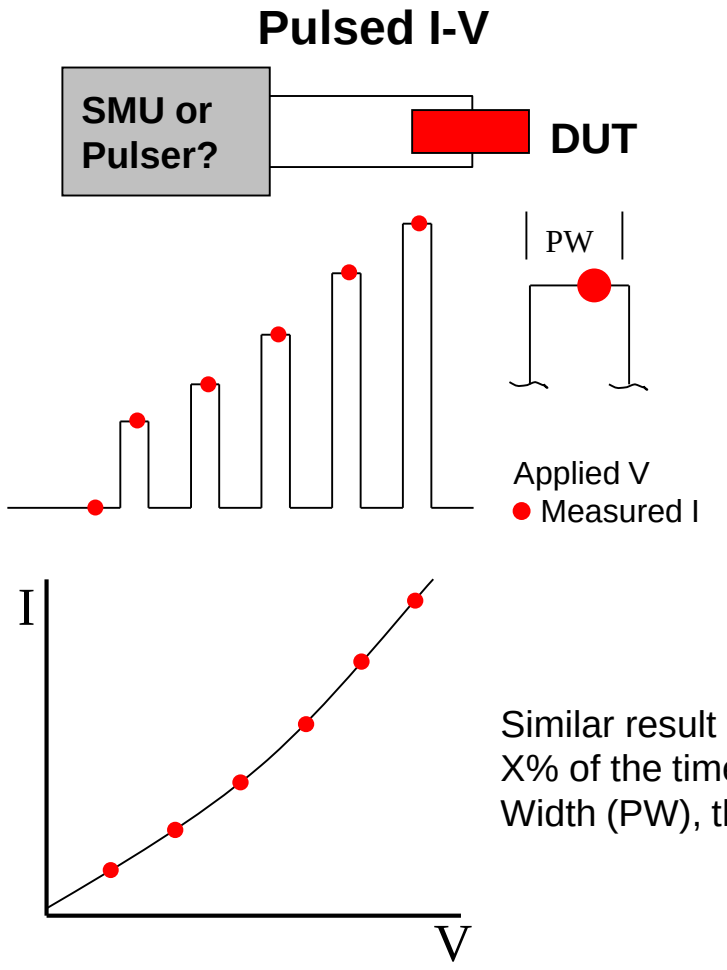


Pulsed I-V provides same results as DC I-V

DC-LIKE RESULTS



But there is **POWER** applied the whole time to the DUT



Similar result but power is applied only X% of the time. The narrower the Pulse Width (PW), the less the DUT heats up.

Ultra-Fast Pulse Measure Unit

4225-PMU

- Dual channel pulse source
  - 50 MHz, <10 ns to 1 sec pulse width, +/- 10 V
  - 10 MHz, <100 ns to 1 sec pulse width, +/- 40V
  - 256k ARB, 1024 Segment ARB
- Measures I & V simultaneously
  - Measures I & V over full range of pulse widths
  - Current sensitivity to 10's of pA
  - Current noise of <200pA in 100 usec
  - Sources and Measures up to 800 mA (40 V@50 Ohms)
- Up to 6 cards per chassis
  - 12 channels per chassis, all synchronized

4225-PMU shown with 4225-RPM Remote Preamplifier/Switch Module

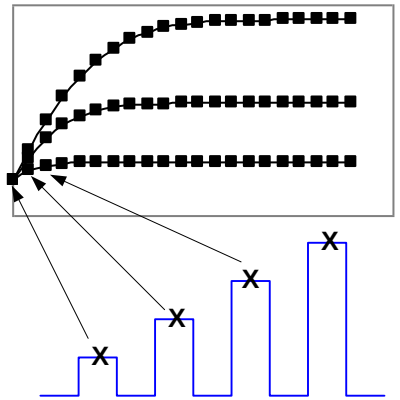
R&D 100 2011

Remote Preamplifier/Switch Module

4225-RPM

- Single channel module simplifies connections to DUT and extends current range of PMU
- Automatic switching between I-V, C-V and Ultra-fast Pulsed I-V measurements
  - No changing test setup or cables
- Extends the current range of the 4225-PMU
  - Provides current sensitivity down to tens of pico-amps
  - Reduces cable capacitance effects
- Magnetic and vacuum base available for easy installation on prober platen

Operating Modes of 4225-PMU

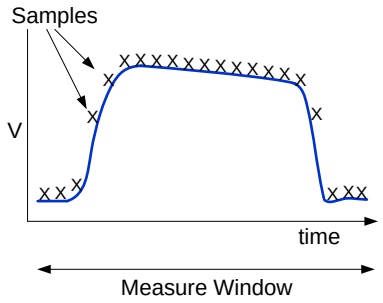


Pulsed I-V

- Pulse and measure with DC-like results
- Step, sweep, pulse train and DC outputs

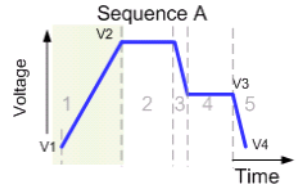
Transient I-V

- waveform capture
- time-based current and voltage measurements



Pulsed Sourcing

- Two-level or multi-level pulsing
- Arbitrary Waveform Generator
- Segment ARB

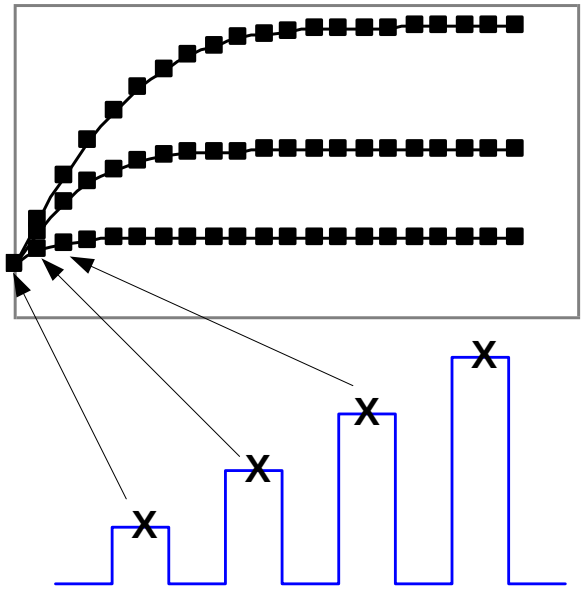


Sequence A Definition			
Segment	Start V	Stop V	Duration
1	V1	V2	T1
2	V2	V2	T2
3	V2	V3	T3
4	V3	V3	T4
5	V3	V4	T5

Pulsed I-V Mode

425-PMU PULSED I-V

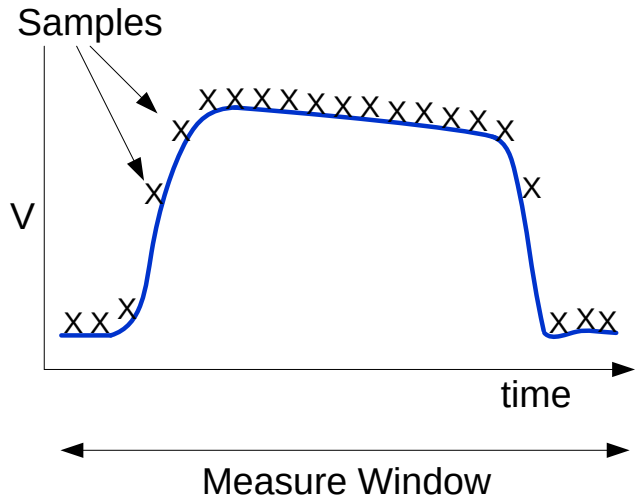
- Pulsed source and a corresponding high speed, time-based measurement that provides DC like results.
- For each pulse an average of readings are taken in a predefined window – called “spot mean”.
- User defines the parameters include:
  - Pulse width
  - Duty cycle
  - Rise/fall times
  - Amplitude



Transient I-V Mode

4225-PMU WAVEFORM CAPTURE MODE

- Transient I-V is also known as Waveform Capture similar to an oscilloscope
- Time-based current and/or voltage measurement that captures the pulsed waveform.
- Used to evaluate a dynamic test circuit or
- Used as a diagnostic tool for choosing the appropriate pulse settings in the pulse I-V mode.



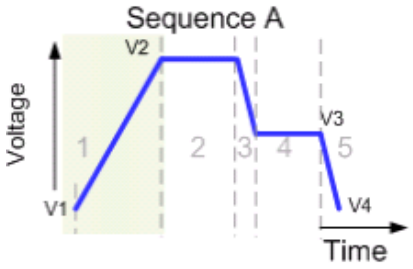
Pulsed Sourcing

4225-PMU SEGMENT ARBITRARY WAVEFORM

- **Two-level pulsing**: user inputs a high and low value of the pulse. Can choose to measure the “spot mean” at both the high and low values.

- **Multi-level pulsing with Segment Arb**: user inputs individual segments of the desired pulse. This mode allows measuring.

- **Arbitrary Waveform Generator** (KPULSE): user creates the arbitrary waveform in KPULSE and then implements the waveform in a UTM. This mode does not allow measuring.



Sequence A Definition			
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1	V1	V2	T1
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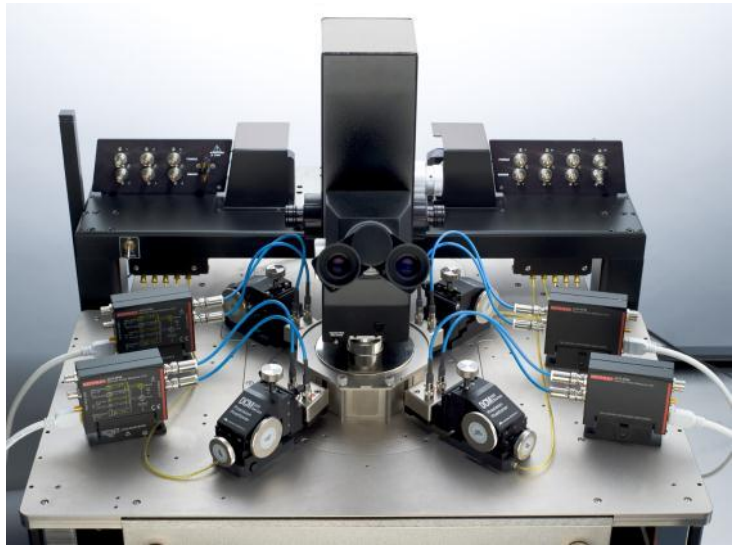
3	V2	V3	T3
4	V3	V3	T4
5	V3	V4	T5

Segment Arb

Ultra-fast NBTI using 4200-BTI-A

TARGET APPLICATION

Stress device and then measure recovery effect as quickly as possible after stress is removed

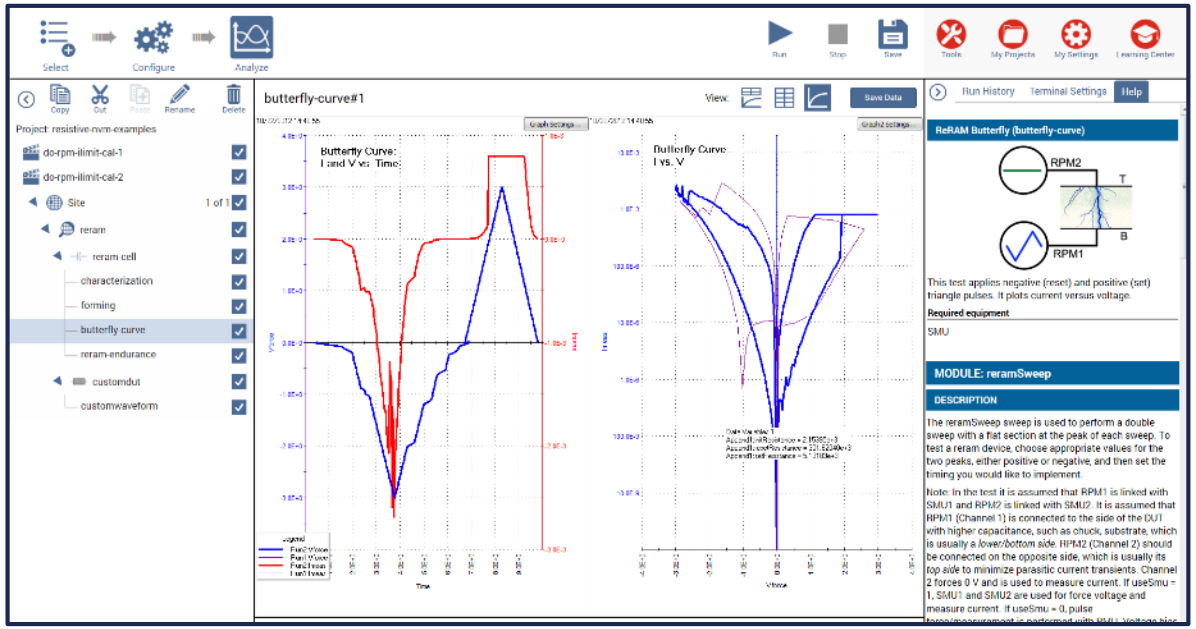


- Best-in-class test speed allows faster, more complete device characterization
  - 10x faster than nearest competing solution
  - 2x more sensitive than nearest competing solution
- Begin measuring BTI degradation as soon as 30ns after stress is removed
- Measure transistor VT in less than 1µs using I_D–V_G sweep method

Non-Volatile Memory Testing

TARGET APPLICATION WITH 4225-PMU

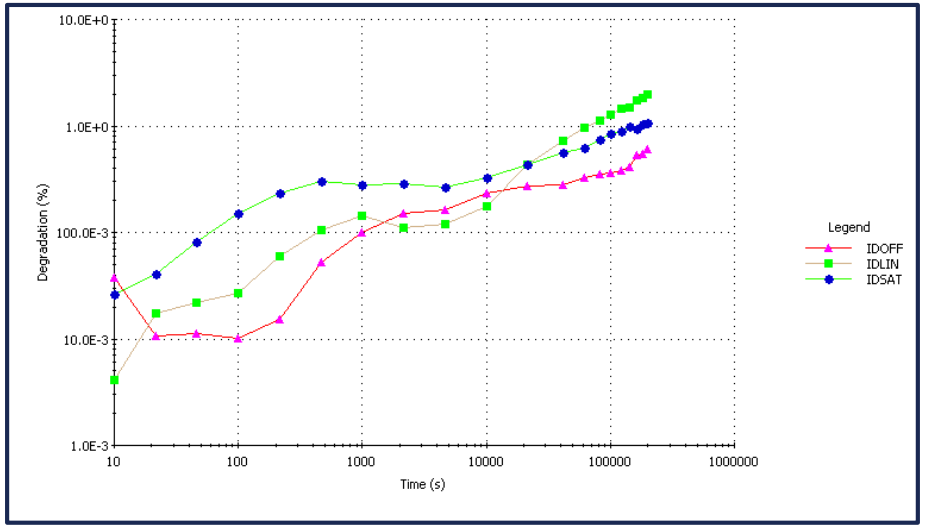
- Meet demanding NVM technologies testing:
  - Flash, PRAM, FeRAM, RRAM, MRAM
  - Easily adapt to other types of NVM
- Precise measurements of both V and I simultaneously over a wider range and with shorter pulses
- Flexible waveform generation and fast transient analysis



Wafer Level and Packaged Reliability

STRESS AND MEASURE TARGET APPLICATION

- Easy setup of stress conditions and patterns
- Real time graphing for monitoring lengthy tests
- User programmable compliance exit conditions
- Easy and flexible test development
- Enhanced stress looping
- PMU for AC stress
- PMU+RPM for Ultra-Fast BTI



Failure Analysis

TARGET APPLICATION

Packaged devices

- Measure overall performance
  - Iddq, power-up state
- Identify failing pins
  - Curve trace every pin
- Compare failing device to known good device
  - Switch between pins, measure and compare
- Package development

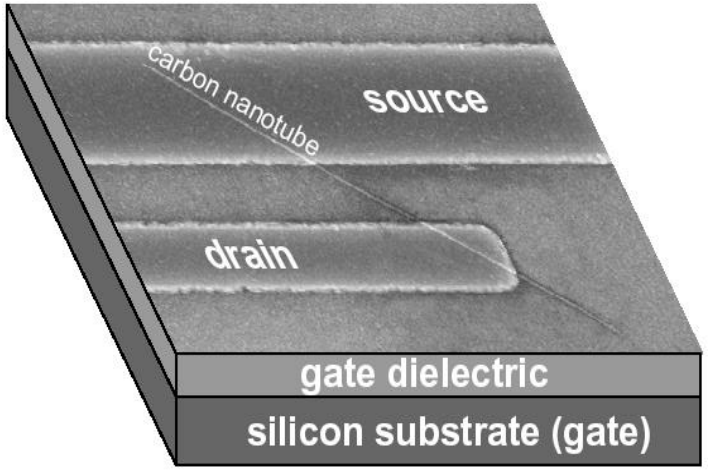
Wafer level or de-lidded devices

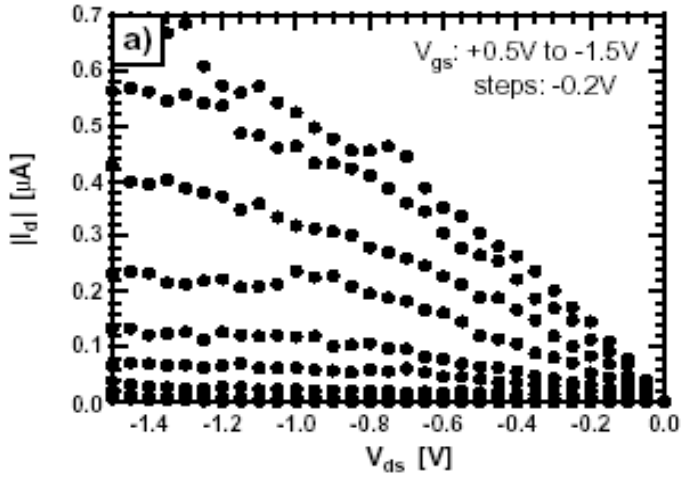
- Drop pins with a prober or nanoprober
- Characterize specific devices or test structures
- Standard tests are included with 4200A-SCS to minimize test development burden

Nanotechnology Devices

4225-PMU TARGET APPLICATION

- Low-level measurements ideal for the device scale
- Ultra-fast Pulse I-V to minimize self-heating in devices and materials
- Nanotech toolkit (included) provides sample tests and quick startup
- Specific Applications
  - Single Electron Transistors
  - Carbon Nanotube Transistors
  - Quantum-Well/Quantum-Dot devices

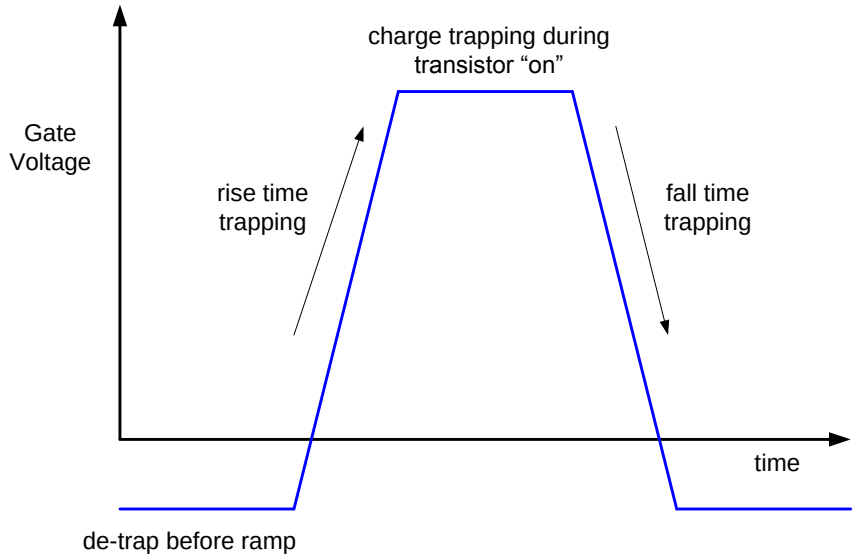


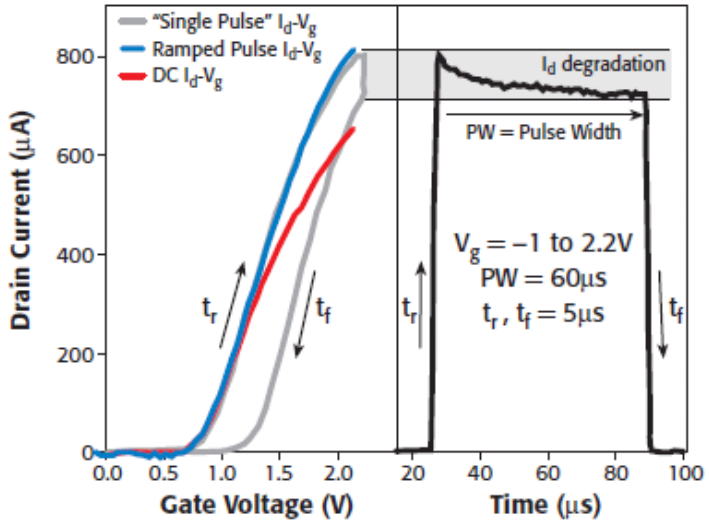


Charge Trapping

4225-PMU TARGET APPLICATION

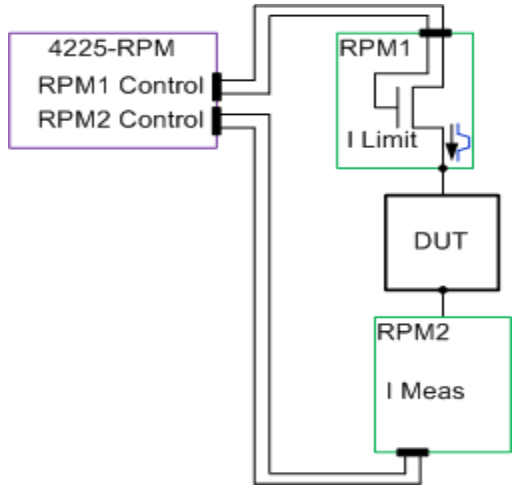
- Charge trapping method involves:
  - Apply a single gate voltage pulse while measuring the resulting drain current.
- Application project using the 4225-PMU is included in Clarius library which minimizes test plan development and time to start testing.
- Charge trapping project enables the user to trap and de-trap the device on rising and falling edges of pulse



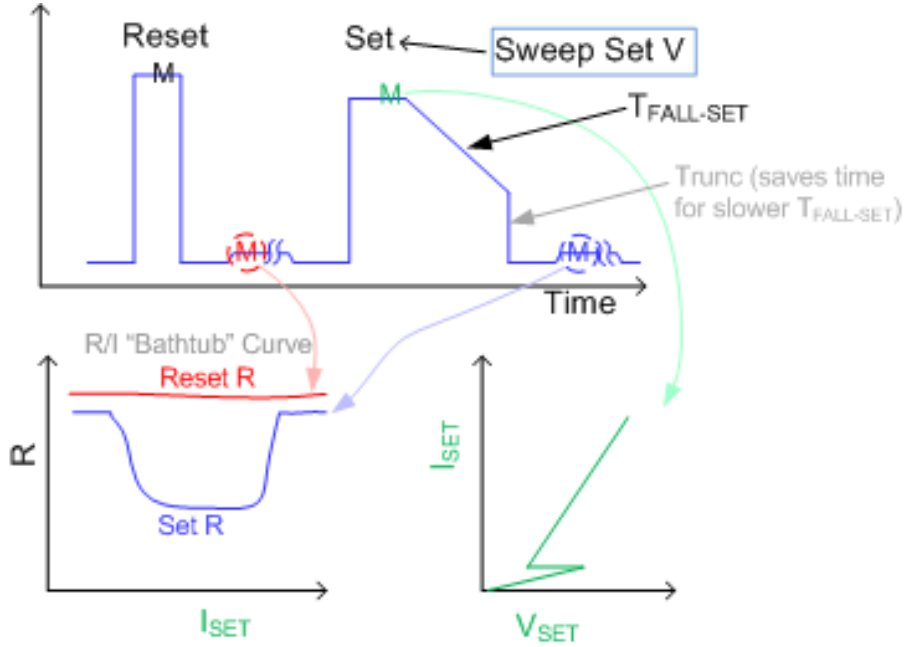


Phase Change Memory

4225-PMU TARGET APPLICATION



- Phase Change Memory has a high and low resistance state.
- A pulse is applied to change states.
- The material changes states in a few 10's of nanoseconds
- Due to the high and low resistance states, a 4225-RPM is needed to measure the small currents.
- The PMU/RPM combination *replaces* a dual channel pulse card, an oscilloscope, and a SMU



Rethinking Parameter Analysis!

ACCELERATING INSIGHT

- ***Complete characterization*** with DC I-V, C-V and Pulsed I-V instrumentation
- ***Industry's easiest*** method to switch between measurements with new IV/CV Multi-Switch
- ***50% reduction*** in characterization complexity and test setup with new ***Clarius*** user interface
- ***Industry's first*** instrument with built-in measurement videos easily accessible via "YouTube-like" experience
- ***Industry's largest*** display on a Parameter Analyzer

4200A-SCS Parameter Analyzer

4200A-CVIV Multi-Switch

Thank you

DC I-V Source Measure Units (SMU)

4200-SMU and 4210-SMU

DC Current-Voltage Measurements

SOURCE MEASURE UNIT (SMU)

- **4200-SMU Medium Power SMU**
  - +/- 210 V, +/- 100 mA, 100 fA resolution
- **4210-SMU High Power SMU**
  - +/- 210 V, +/- 1 A, 100 fA resolution
- **4200-PA optional pre-amplifier**
  - Extends SMU current range and supports 0.1 fA resolution
- 6 ½ digit A/D per SMU for parallel, simultaneous, high-precision measurements
- *All* slots in the 4200-SCS can be configured with any SMU

Additional SMU capabilities

AC IMPEDANCE

- Using two SMUs with preamplifiers, the following techniques can be performed:
  - Quasi-static, ramp-rate C-V
  - Very Low Frequency C-V (10 mHz – 10 Hz)