Next generation semiconductor devices and applications

(차세대 반도체 소자 및 응용)

장소: 공과대학 6호관 510호

시간: 화 (6-A, 6-B, 7-A, 7-B, 8-A, 8-B)

3. Semiconductor parameter analyzer

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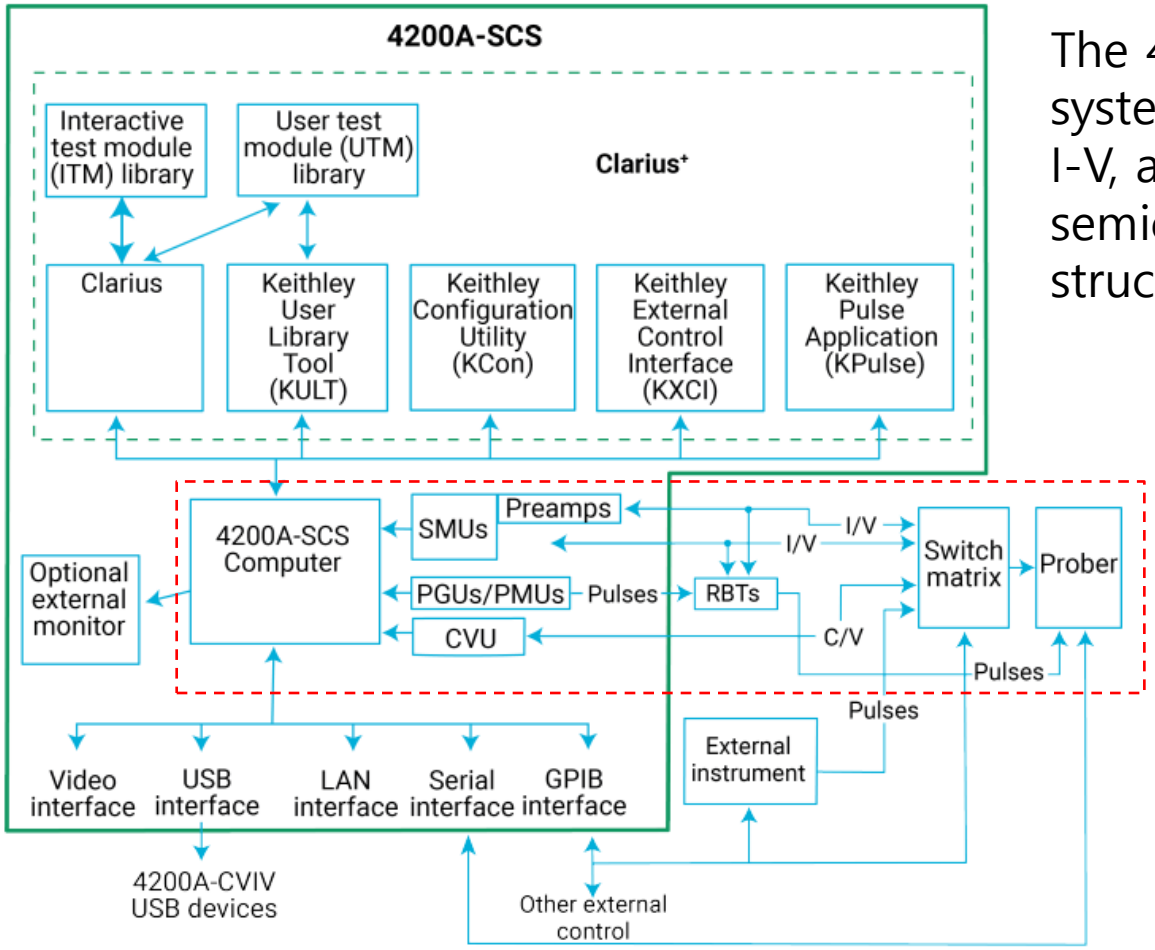
Figure 1: 4200A-SCS summary



The 4200A-SCS is an automated system that provides I-V, pulsed I-V, and C-V characterization of semiconductor devices and test structures

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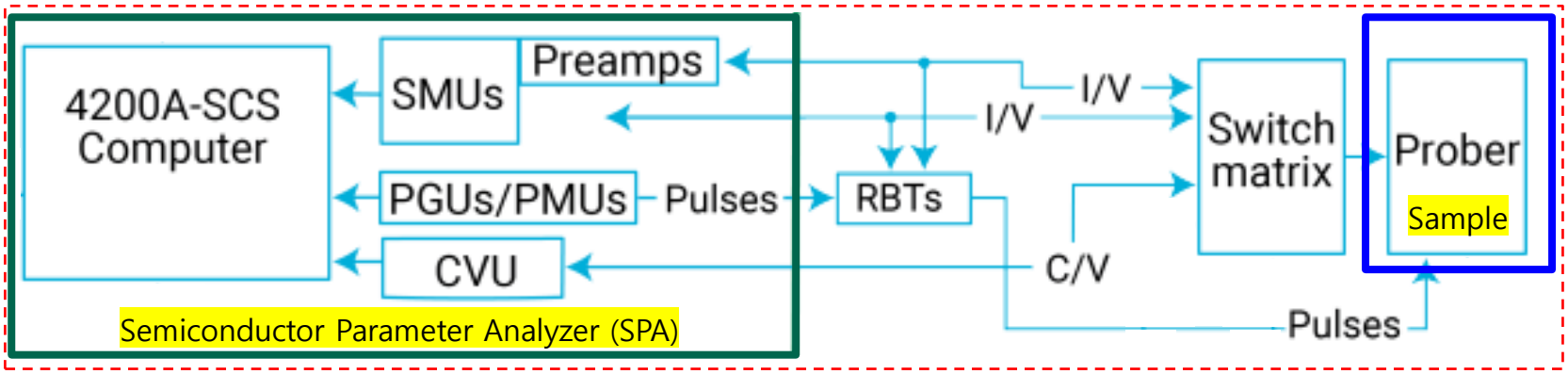
Measurement Configuration



- Source-measure unit (SMU)
- Ground unit (GNDU)
- Preamplifier
- Pulse source-measure hardware (PMU+RPM)
- Capacitance-Voltage Unit (CVU)

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Measurement Configuration detail

Source-measure unit (SMU)

The fundamental instrument module used by the 4200A-SCS is the source-measure unit (SMU). The basic function of a SMU is to perform one of the following source-measure operations

- Source voltage and measure current or voltage
- Source current and measure voltage or current

The source of the SMU can be configured to sweep or step voltages or currents, or to output a constant bias voltage or current.

There are medium-power and high-power source-measure units available.
The 2 W medium-power SMUs are models 4200-SMU and 4201-SMU.
The 20 W high-power SMUs are models 4210-SMU and 4211-SMU. The following table lists the maximum limits of the SMUs

Source-measure units

Model	Maximum voltage	Maximum current	Maximum power
4200-SMU 4201-SMU	210 V	105 mA	2.2 W
4210-SMU 4211-SMU	210 V	1.05 A	22 W

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Measurement Configuration detail

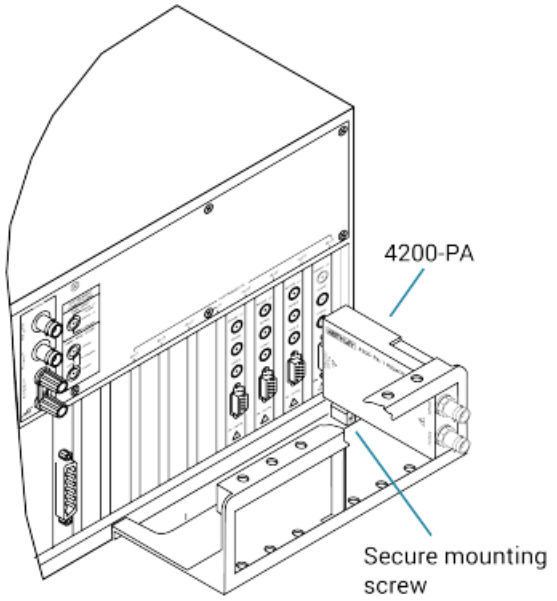
Preamplifier

A 4200-PA preamplifier adds five low-current source-measure ranges to a SMU. Without a preamplifier, the 100 nA range (100 fA resolution) is the lowest current source-measure range for a SMU.

With a preamplifier installed, the 10 nA, 1 nA, 100 pA, 10 pA, and 1 pA source-measure ranges are added.
is connected.

The preamplifiers can be removed from the rear panel and mounted remotely to reduce the effects of long cables on measurement quality (long cables can add noise to low current measurements and can cause oscillation with some devices).
An installed preamplifier is matched to the SMU to which it is connected.

Figure 11: Preamplifier rear-panel mounting



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Measurement Configuration detail

Ground unit (GNDU)

The ground unit on the rear panel of the 4200A-SCS provides a convenient method of making ground connections. This eliminates the need to use a SMU for this purpose

Capacitance-Voltage Unit (CVU)

Capacitance-voltage (C-V) measurements are often used to characterize the gate oxide thickness, oxide defect density, and doping profile of MOSFETs.
In these measurements, as the gate voltage varies, the capacitance of the gate to the drain and source changes. Capacitance measurements are typically made using an ac technique.
The CVUs measure ac impedance by applying a dc bias voltage and sourcing an ac voltage across the device under test (DUT) and then measuring the resultant ac current and phase angle.
The 4210-CVU operates from 1 kHz to 10 MHz. The ac test signal (10 mVRMS to 100 mVRMS) can be dc voltage biased from −30 V to +30 V.
The 4215-CVU operates from 1 kHz to 10 MHz at 1 kHz resolution. The ac test signal (10 mV to 1 VRMS) can be dc voltage biased from −30 V to +30 V

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Measurement Configuration detail

Pulse source-measure hardware

The 4220-PGU High Voltage Pulse Generator Unit and 4225-PMU Ultra-Fast Pulse Measure Unit are high-speed pulse-generator cards for the 4200A-SCS.

The 4220-PGU provides pulse output only. The 4225-PMU provides both pulse output and pulse measurement.
The PGU and PMU have similar pulse output characteristics.

The 4225-PMU can be paired one or two 4225-RPM Remote Preamplifier/Switch Modules.

When the RPM is used as a preamplifier for the PMU, it provides additional low-current measurement ranges. When the RPM is used as a switch, it switches between the PMU, SMUs, and CVUs

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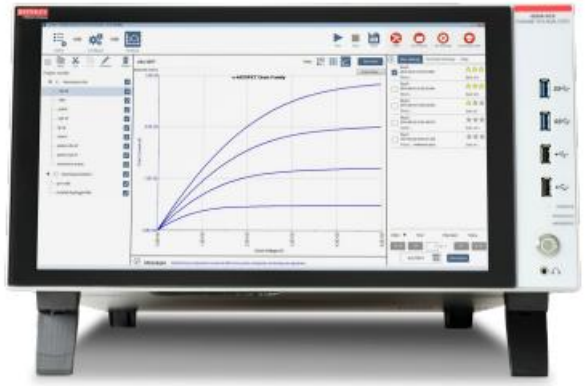
Performance Specifications



I-V Source Measure Units (SMUs)

- ±210 V/100 mA or ±210 V/1 A modules
- 100 fA measure resolution
- 10 aA measure resolution with optional preamp
- 10 mHz – 10 Hz very low frequency capacitance measurements
- 100 µF load capacitance
- 4-quadrant operation
- 2 or 4-wire connections

C-V Multi-frequency Capacitance Units (CVUs)

- AC impedance measurements (C-V, C-f, C-t)
- 1 kHz – 10 MHz frequency range
- ±30 V (60 V differential) built-in DC bias, expandable to ±210 V (420 V differential)
- Simple switching between I-V and C-V measurements with the optional CVIV Multi-Switch

Pulsed I-V Ultra-fast Pulse Measure Unit (PMU)

- Two independent or synchronized channels of high-speed pulsed I-V source and measure
- 200 MS/s, 5 ns sampling rate
- ±40 V (80 V_{p-p}), ±800 mA
- Transient waveform capture mode
- Arbitrary waveform generator for multi-level pulse waveform with 10 ns programmable resolution

High Voltage Pulse Generator Unit (PGU)

- Two channels of high-speed pulsed V source
- ±40 V (80 V_{p-p}), ±800 mA
- Arbitrary waveform generator Segment ARB® mode for multi-level pulse waveform with 10 ns programmable resolution

I-V/C-V Multi-Switch Module (CVIV)

- Easily switch between I-V and C-V measurements without re-cabling or lifting prober needles
- Move the C-V measurement to any terminal without re-cabling or lifting prober needles
- ±210 V DC bias capable

Remote Preamplifier/Switch Module (RPM)

- Automatically switches between I-V, C-V, and ultra-fast pulsed I-V measurements
- Extends current sensitivity of the 4225-PMU to tens of picoamps
- Reduces cable capacitance effects

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Performance Specifications

The Ultimate Parameter Analyzer for Materials, Semiconductor Devices and Process Development

Perform I-V, C-V and pulsed I-V characterization with speed, clarity and confidence with the powerful Clarius software.

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Performance Specifications

4200A-SCS Instruments and Modules

Model	Description	Key Measurements	Range	Measure Resolution
4200-SMU	Medium Power Source-Measure Unit	• DC I-V • Very Low Frequency C-V • QSCV	±100 mA, ±210 V	0.2 µV, 100 fA
4201-SMU	Medium Power SMU with increased low I stability			
4210-SMU	High Power Source-Measure Unit		±1 A, ±210 V	
4211-SMU	High Power SMU with increased low I stability			
4200-PA	Remote Preamplifier Module		Extends current ranges for all SMUs	0.2 µV, 10 aA
4210-CVU	Capacitance-Voltage Unit	• AC Impedance • C-V, C-f, C-t	• 1 kHz – 10 MHz • ±30 V built-in DC bias (60 V differential) • ±210 V DC bias with SMUs • 100 mV AC drive	1 aF, 1 nS, 0.001 degree
4215-CVU	High Resolution Capacitance-Voltage Unit	• AC Impedance • C-V, C-f, C-t	• 1 kHz – 10 MHz • ±30 V built in DC bias (60 V differential) • ±210 V DC bias with SMUs • 1 V AC drive	1 kHz 1 aF, 1 nS, 0.001 degree
4200A-CVIV	I-V/C-V Multi-Switch Module	DC I-V and C-V with Automatic Switching	–	–
4225-PMU	Ultra-Fast Pulse Measure Unit	• Pulsed I-V • SegmentARB® Multi-level Pulsing • Transient Waveform Capture	• ±40 V (80 V_{p-p}), ±800 mA • 200 MS/s simultaneous I and V measure • 2048 unique segments • 20 ns PW source only • 60 ns PW source/measure	75 nA
4225-RPM	Remote Preamplifier/ Switch Module	• Enables automatic switching between SMU, CVU and PMU	Extends current range of 4225-PMU unit	200 pA
4220-PGU	High Voltage Pulse Generator Unit	• Pulsed Voltage Source • SegmentARB® Multi-level Pulsing	• ±40 V (80 V_{p-p}) • 2048 unique segments	–
Ground Unit	Built-in, Low Noise Ground Unit	–	• Triaxial connection: 2.6 A • Binding post: 9.5 A	–

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Performance Specifications

Example List of Extracted or Measured Parameters

CMOS transistor	Id-Vg, Id-Vd, Ig-Vg, Vth, Vtlin, Sub-Vt, Rds-on, breakdown, capacitance, QSCV, Low-frequency CV, self-heating reduction and more
BJT	Ic-Vc, Vcsat, Gummel plot, capacitance, βF, αF
Non-volatile Memory	Vth, endurance test, capacitance
Nanoscale	Resistance, Id-Vg, Id-Vd, Ic-Vc
Discrete components	Id-Vg, Id-Vd, Ic-Vc, V_{fdiode}, V_{rdiode}, capacitance
Materials	Van der Pauw, 4-point collinear resistivity, Hall Effect
Photovoltaics	$I_{forward}$, $I_{reverse}$, HiR, LoR
Power device	Pulsed Id-Vg, pulsed Id-Vd, breakdown
Reliability	NBTI/PBTI, charge pumping, hot carrier injection, V-Ramp, J-Ramp, TDDB

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Source Measure Units (SMU)

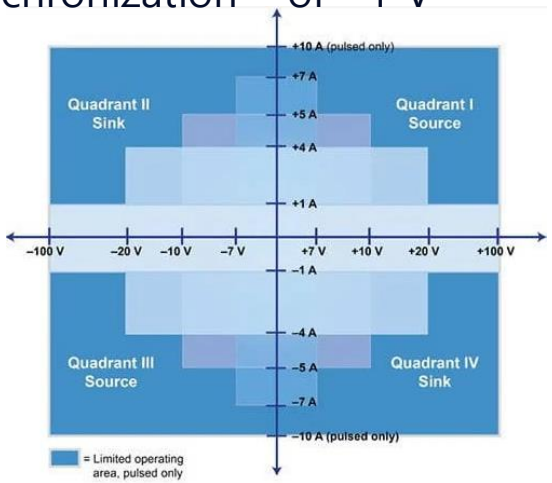
What is Source Measure Units (SMU)?

A source measure unit (SMU) is an instrument that combines a sourcing function and a measurement function on the same pin or connector. It can source voltage or current and simultaneously measure voltage and/or current.

For 4200A-SCS Parameter Analyzer

- A source measure unit can source either voltage or current and can simultaneously measure both voltage and current with high resolution and accuracy.
- The SMU integrates the voltage source, current source, ammeter and voltmeter in one instrument card for tight synchronization of I-V measurements.

- A source measure unit has four-quadrant capability, which means it can not only source but also sinks current, as when taking current from a device under test (DUT), such as a charged capacitor or solar cell.



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Source Measure Units (SMU)

Basic source-measure connections

How to connect the source-measure units (SMUs) to the device under test (DUT).

- The SMU can be connected directly to the device under test (DUT) with triaxial cables using either local or remote sensing

Cables for electrical measurement

COAXIAL VS. TRIAXIAL CABLE: WHAT'S THE DIFFERENCE?

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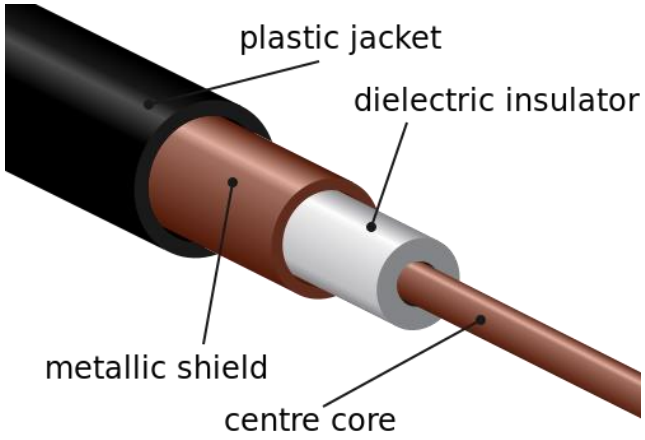
Source Measure Units (SMU)

COAXIAL CABLE

-A **coaxial cable** consists of two concentric conductors, an inner conductor and a tubular outer conductor, which is used simultaneously for the return of the signal. This is called an unbalanced line.

The distance between **outer conductor** (sheath) and **inner conductor** is kept constant by a **solid insulation** (dielectric) made of high polymer plastics.
Due to the shielding effect of the outer sheath, the coaxial cable does not emit the frequency (signal) to be transmitted to the environment.



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Source Measure Units (SMU)

TRIAXIAL CABLE

- A triaxial cable is a special form of the coaxial cable, that consists of three concentrical conductors. The latter are separated by a dielectric medium and a shielding

Structure of a triaxial cable:

1 = Inner conductor (completion as massive wire or litz wire (1b))
2 = Dielectric medium / Insulation
3 = Shield braiding or foil
4 = Dielectric medium / Insulation
5 = Shield braiding or foil
6 = Outer sheath

-Application fields are video technology and electronical metrology.
- In electrical metrology femtoampere currents can be measured with a suitable construction using Triaxial cables.
- Due to the higher production costs, the triaxial cables are more expensive than coaxial cables.

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Source Measure Units (SMU)

Triaxial cables for 4200A-SCS Parameter Analyzer

Model number	Cable length (m)
4200-TRX-0.3	0.3
4200-TRX-0.75	0.75
4200-TRX-1	1.0
4200-TRX-2	2.0
4200-TRX-3	3.0

Electrical specifications

Electrical impedance: 50 Ω

Frequency range: 0 Hz to 4 GHz

Working voltage:

- **Inner shield to outer shield:** 250 VDC
- **Center conductor to outer shield:** 250 VDC
- **Center conductor to inner shield:** < 100 V

Insulation resistance: 1×10^{13} Ω minimum

Operating environment: 0 °C to 50 °C, up to 70 percent relative humidity at ≤ 35 °C

Center conductor resistance: < 0.1 Ω per foot

Figure 1: Triaxial cable 4200-TRX-X

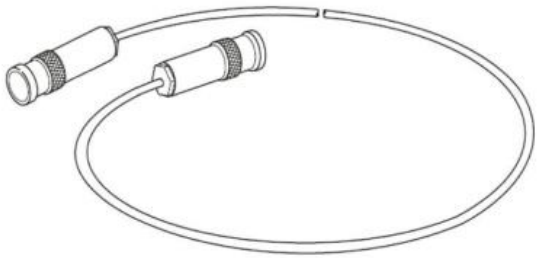
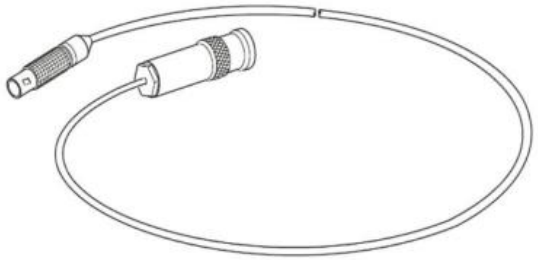


Figure 2: Triaxial cable 4200-MTRX-X



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Source Measure Units (SMU)

SMU local sense connections

The simplest method to connect SMUs to the device under test (DUT) is to use one SMU for each terminal of the device.

<When setting up a test>

① The FORCE terminal (center conductor) of the SMU is used to apply voltage or current to the device.

② The FORCE terminal or ground unit can also be used to connect the device terminal to the COMMON circuit.

Figure 3: SMU local sense connections

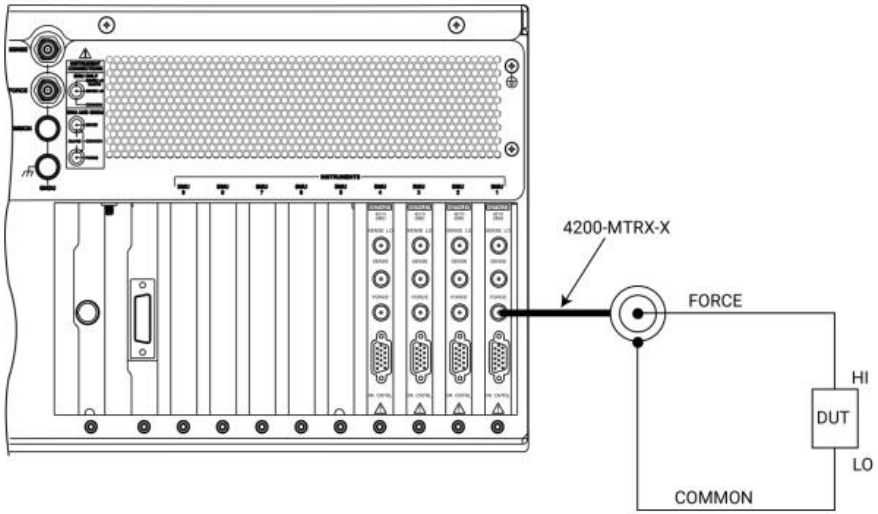
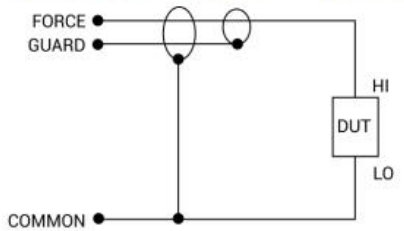


Figure 4: SMU local sense connections - equivalent circuit



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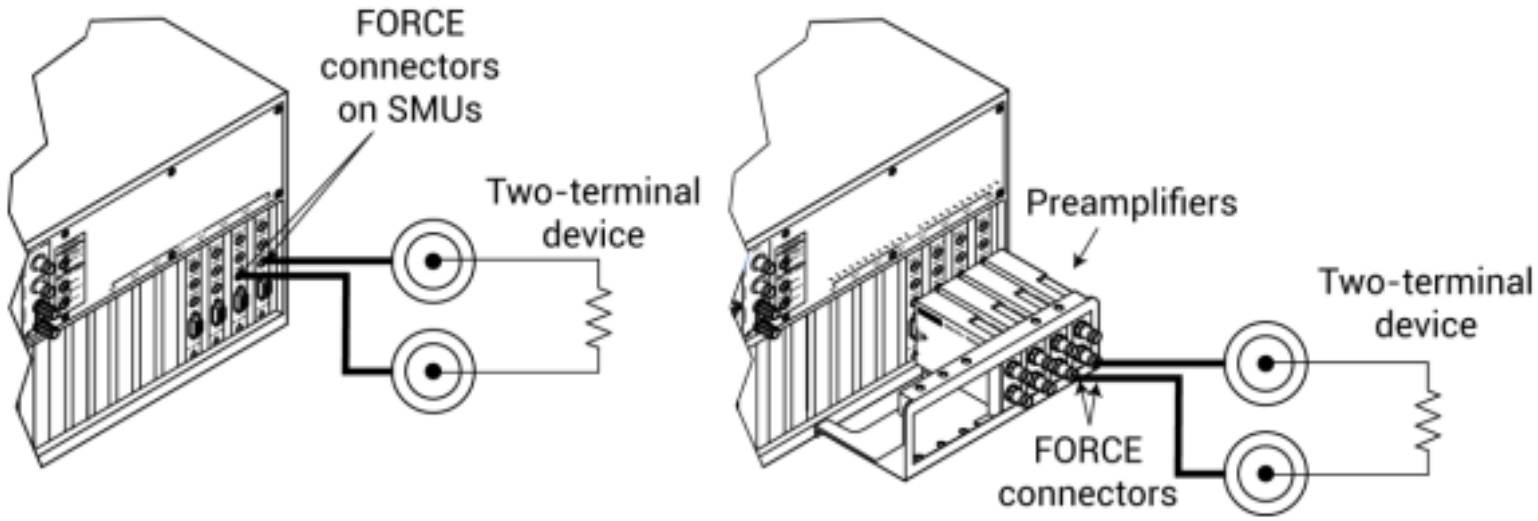
Source Measure Units (SMU)

Basic device connections for SMUs

The following figures show the basic connections to 2-terminal devices.
Notice that only the FORCE HI terminal of each SMU is connected to the device terminal. FORCE HI is the center conductor of the triaxial cable.



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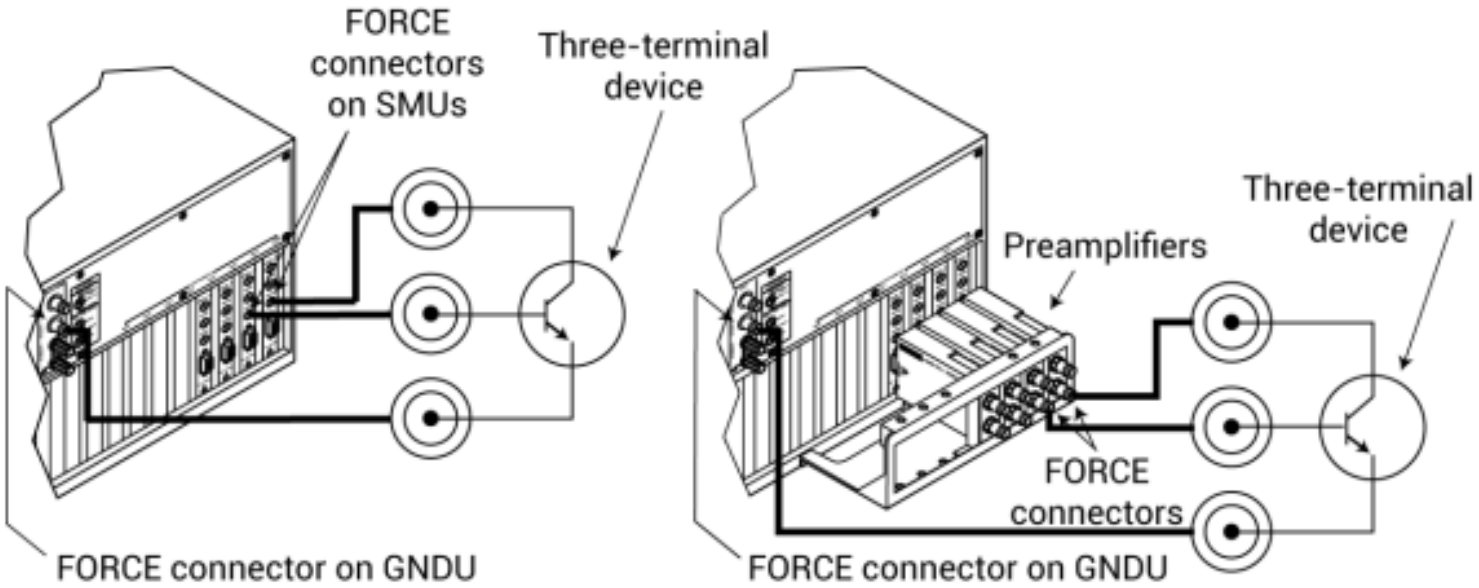
Source Measure Units (SMU)

Basic device connections for SMUs

The following figures show the basic connections to 3-terminal devices.
Notice that only the FORCE HI terminal of each SMU is connected to the device terminal. FORCE HI is the center conductor of the triaxial cable.



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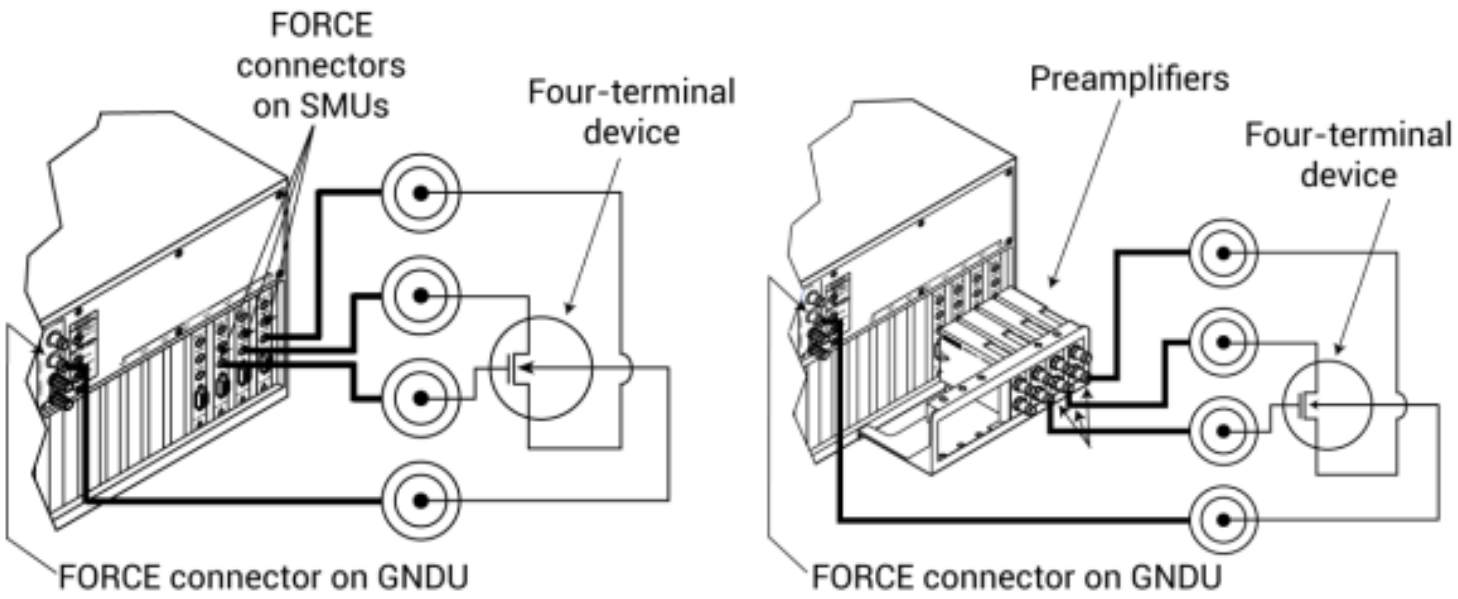
Source Measure Units (SMU)

Basic device connections for SMUs

The following figures show the basic connections to 4-terminal devices.
Notice that only the FORCE HI terminal of each SMU is connected to the device terminal. FORCE HI is the center conductor of the triaxial cable.



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Source Measure Units (SMU)

Shielding and guarding

Many test situations require that the device under test (DUT) be shielded or guarded (or both) to avoid detrimental effects caused by electrostatic interference, parasitic capacitance, system leakage currents, and so forth.

➡ To shield, but not guard, the device, connect the DUT shield to COMMON

Figure 8: Device shielding

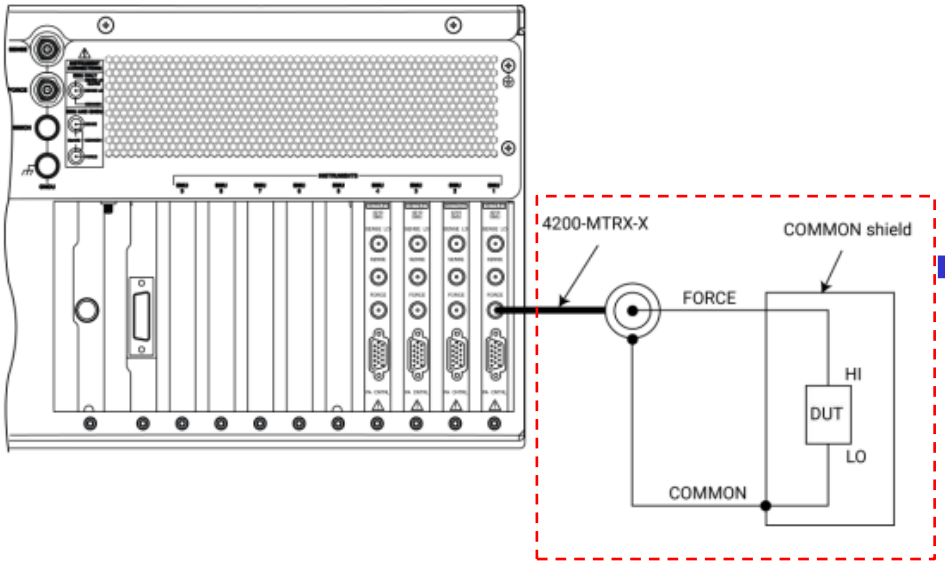
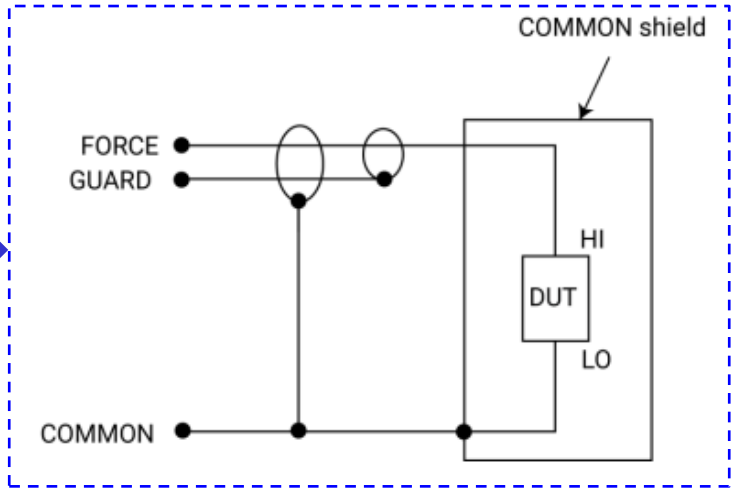


Figure 9: Device shielding basic circuit



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Source Measure Units (SMU)

Shielding and guarding

Many test situations require that the device under test (DUT) be shielded or guarded (or both) to avoid detrimental effects caused by electrostatic interference, parasitic capacitance, system leakage currents, and so forth.

➡ To guard the device, connect the DUT shield to GUARD. GUARD is the inner shield of triaxial cable

Figure 10: Device guarding

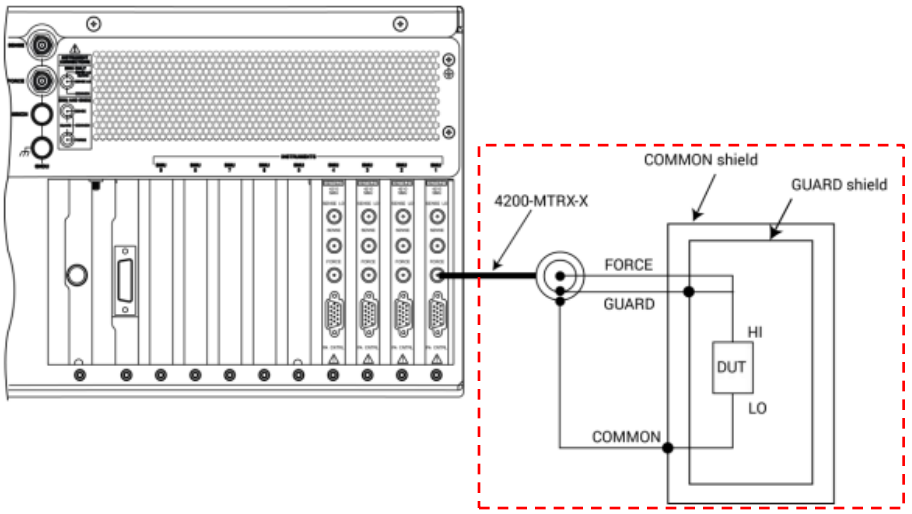
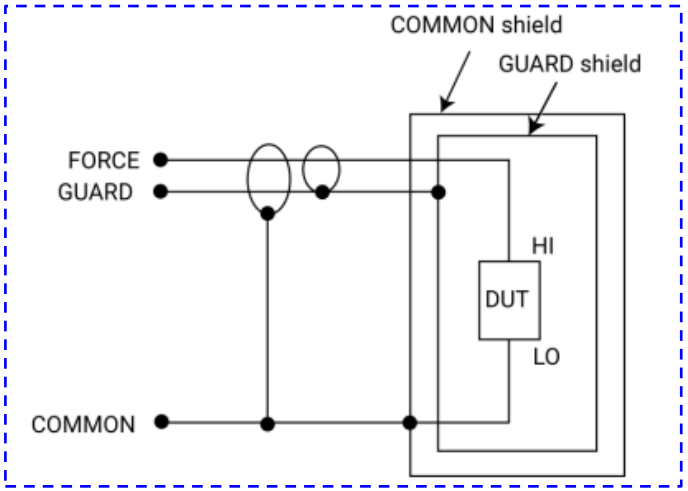


Figure 11: Device guarding basic circuit



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Source Measure Units (SMU)

Signal integrity(신호 무결성)

To maintain signal integrity, especially at low current levels, consider the following when making signal connections between the 4200A-SCS instrumentation and the device under test (DUT)

- Use only low-noise triaxial cables such as those provided with the SMU (4200-MTRX-X) and preamplifier (4200-TRX-X).
- Keep connecting cables as short as possible.
- Avoid flexing or vibrating connecting cables while making measurements.
- Do not touch connector insulators. Be sure to keep all connector insulators clean to minimize contamination-induced leakage currents.
- Avoid stresses in cables. Do not allow large portions to hang under their own weight.
- Place on a table or flat surface if possible. Avoid tight bends in the cables.

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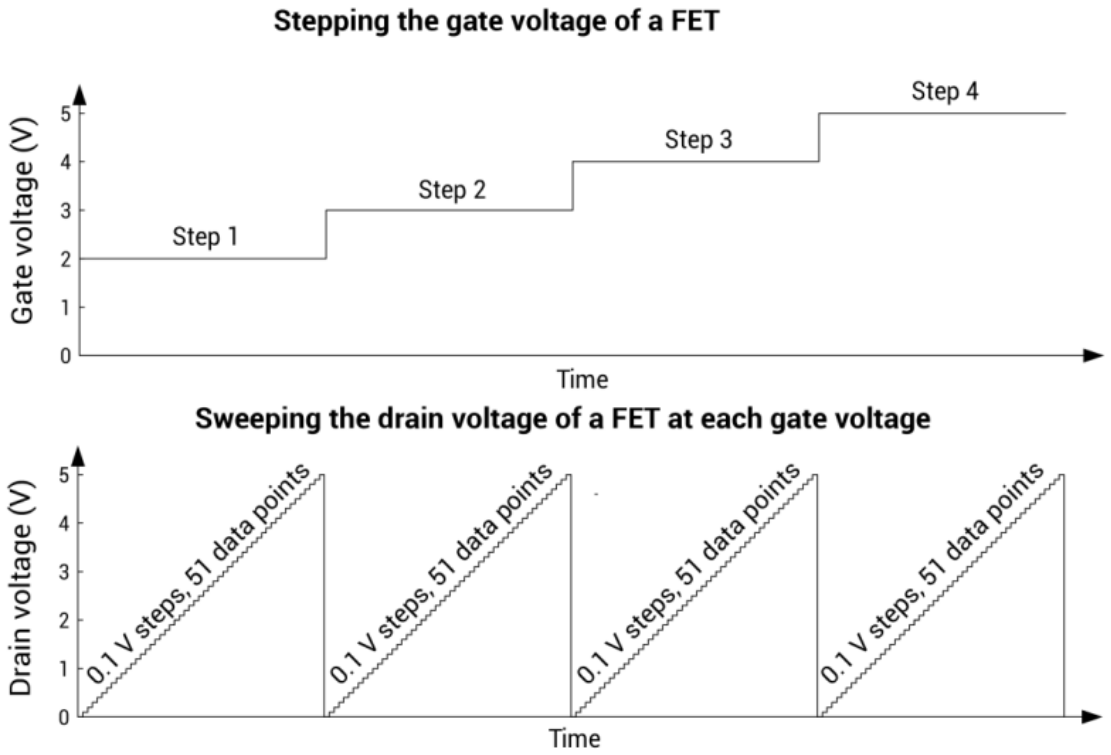
Operation Mode (SMU)

The operation mode determines what type of test is run on the terminal.

Selecting the appropriate mode sets the most common settings for that operation, which simplifies terminal and test configuration.



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Operation Mode (SMU)

The operation mode determines what type of test is run on the terminal.

Open operation mode

- Open operation mode maintains a zero current state at the terminal, subject to the maximum voltage compliance of the connected SMU. You cannot set any parameters when the Open operation mode is selected.

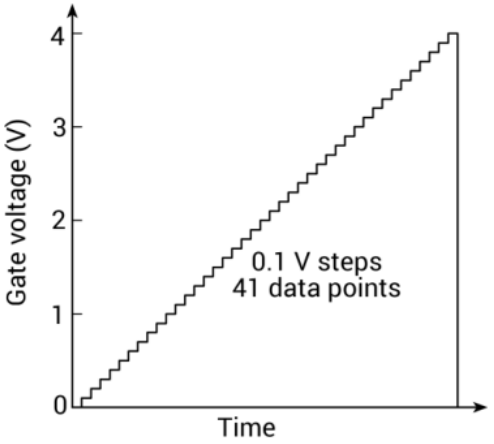
Voltage Bias operation mode

- The Voltage Bias operation mode maintains a selected constant-voltage state at the terminal, subject to a user-specified current compliance of the connected SMU

Voltage Linear Sweep operation mode

- he test increments through a series of constant voltage steps. You define the start and stop voltages and the voltage size between each step. An example is shown in the next figure.

Figure 37: Example linear sweep



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Operation Mode (SMU)

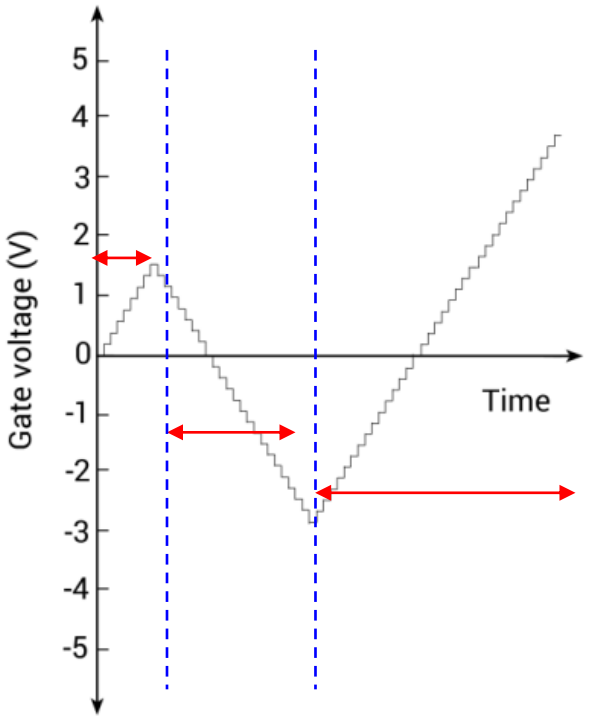
The operation mode determines what type of test is run on the terminal.

Voltage Segment Sweep operation mode

- The test increments through a series of constant voltage steps. You can define the starting voltage and up to four stop voltage points and four step voltage points.

- An example of a three-segment voltage sweep is shown in the following figure

Figure 38: Example multi-segment voltage sweep



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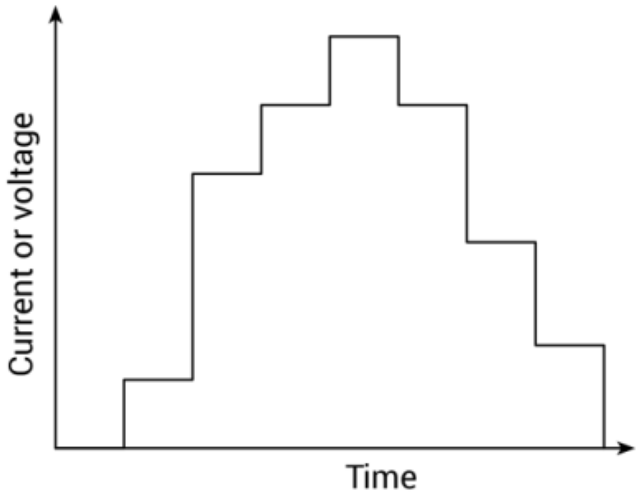
Operation Mode (SMU)

The operation mode determines what type of test is run on the terminal.

Voltage List Sweep operation mode

- The Voltage List Sweep operation mode allows you to customize the voltage values for each step of the sweep
- It allow you to skip unimportant measurement points or to synthesize a custom sweep that is based on a special mathematical equation
- Use list sweeps to make **pulsed measurements** to avoid overheating of sensitive devices

Figure 39: Example list sweep



3. Semiconductor parameter analyzer

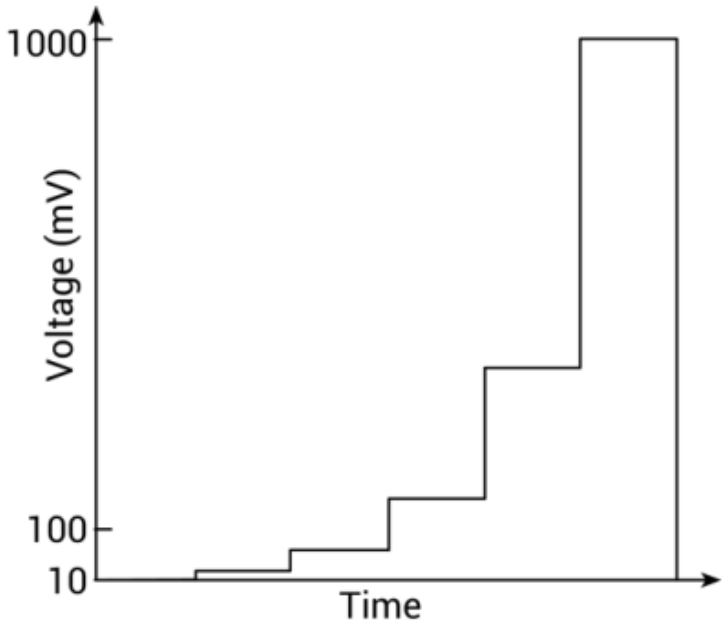
Operation Mode (SMU)

The operation mode determines what type of test is run on the terminal.

Voltage Log Sweep operation mode

- The Voltage Log Sweep operation mode allows you to sweep over a large range and plot the measurements on a logarithmic scale
- A linear sweep is typically unsatisfactory for such applications, because the first increment can miss several of the lower decades. For example, the first ~0.1 V step of a 101-point linear sweep from 0.001 V to 10 V misses the two decades between 0.001 V and 0.1 V.

Figure 40: Example logarithmic sweep



3. Semiconductor parameter analyzer

SMU - all terminal parameters

Parameter descriptions are provided in the following topics

Base Current

Available when Pulse Mode is selected. The current level that the instrument sources when the pulse output is off. The level that you can set depends on the present source range.

Base Voltage

Available when Pulse Mode is selected. The voltage level that the instrument sources when the pulse
output is off. The level that you can set depends on the present source range.

Bias

The bias is the amount of voltage or current to be forced

3. Semiconductor parameter analyzer

SMU - all terminal parameters

Parameter descriptions are provided in the following topics

Compliance

- One can set a limit that stops a SMU from sourcing a current or voltage that is more than that limit
- This limit is called compliance and helps prevent damage to the device under test (DUT)
- The SMU will not exceed the maximum limit set for compliance
- The current is clamped at the compliance value when the SMU is acting as a voltage source

➡ When a SMU reaches compliance, it continues to make measurements. However, the measurement stays at the value it was at when compliance occurred.

For example, if you are sourcing voltage and the compliance is set to 100 mA, it continues to measure 100 mA after compliance is reached.

One can stop the test if the source reaches compliance

3. Semiconductor parameter analyzer

SMU - all terminal parameters

Parameter descriptions are provided in the following topics

Dual Sweep

End of Slide