Applications Overview

- Galvanic Cycling of Rechargeable Batteries
- I-V Characterization of Solar Cells and Panels
- Making Low Resistance Measurements Using High Current
- DC I-V Characterization of Transistors

Model 2460 High Current SourceMeter® Source Measure Unit (SMU) Instrument

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Galvanic Cycling of Rechargeable Batteries

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Application Overview:
Galvanic Cycling of Rechargeable Batteries

Why is it necessary to test rechargeable batteries?
Rechargeable, or secondary, batteries are commonly used in place of disposable batteries in electronic devices such as laptops, video game controllers, mobile phones, digital cameras, and remote controls. In an effort to improve upon or replace existing battery technologies, researchers are studying ways to increase battery life and, at the same time, decrease the cost of rechargeable batteries.

What are some rechargeable battery types?
Common types of rechargeable batteries include Lithium Ion (Li-ion,) Nickel Metal Hydride (Ni-MH,) and Nickel Cadmiun (NiCd.)

How are rechargeable batteries characterized?
The characteristics of a rechargeable battery are commonly tested using discharge and charge (Galvanic) cycling. Cycle tests provide information about the battery such as its internal chemistry, capacity, number of useable cycles, and lifetime. In production testing, a discharge/charge cycle is often performed to verify battery specifications and to ensure that it's not defective.

Key criteria for rechargeable batteries
1. Constant current charging and discharging
   a) Defined in terms of the battery's capacity
   b) Capacity is the amount of electrical charge that the battery can store
2. Battery Storage Capacity
   a) Specified in milliampere-hours (mAH) available.
   b) Normally expressed in terms of discharge, or load current
3. Rate of Discharge
   a) The rate at which the discharge current will discharge the entire battery in one hour is known as the **C-rate**.
   b) Example
      i. A battery rated at 1000mAh will output 1000mA for one hour if discharged at 1C
      ii. If a 500mAh cell is discharged at 50mA, then it is discharged 0.1C, can source 50mA for ten hours.

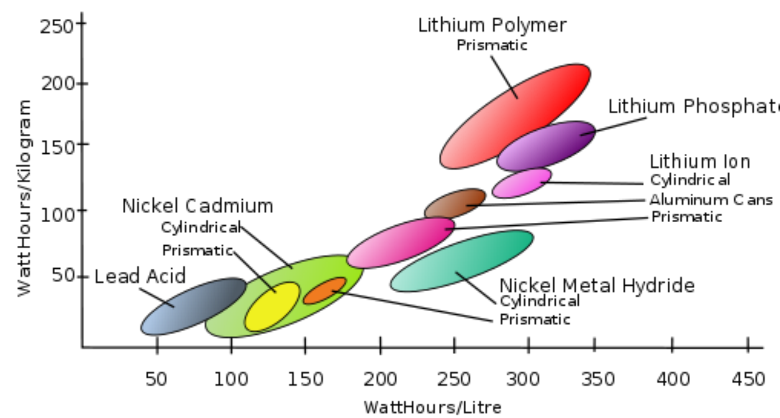

Figure 1. Secondary cell energy densities (src: Wikimedia Commons.)

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Application Overview:
Galvanic Cycling of Rechargeable Batteries

How is a rechargeable battery tested?

Charge Cycle

A battery is typically charged using a constant current. A source measure unit (SMU) instrument is used as a voltage source set to the voltage rating of the battery with the desired charging current set as the current limit. At the start of the test, the battery voltage is less than the voltage output setting of the SMU instrument. As a result, this voltage difference drives a current that is immediately limited to the user-defined current limit. When in current limit, the SMU instrument is acting as a constant current source until it reaches the programmed voltage level. As the battery becomes fully charged, the current will decrease until it reaches zero or near zero.

Test Criteria (Refer to Figure 2)

- SMU instrument in source mode
- $V_S > V_B$
- SMU instrument functions as a power supply
- Charge current (I) is positive

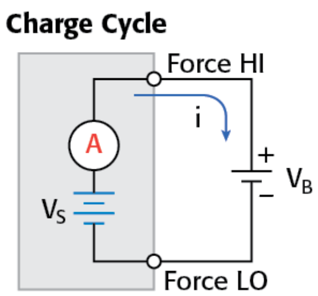

Figure 2. Charge circuit diagrams.

Discharge Cycle

When discharging a battery, the SMU instrument operates as a sink or electronic load because it 's dissipating power rather than sourcing it. The voltage source of the SMU instrument is set to a lower level than the battery voltage. The current limit sets the discharge rate. When the output is enabled, the current from the battery flows into the HI terminal of the SMU instrument. As a result, the current readings will be negative. The discharge current should stay constant until the battery voltage decreases to the voltage source setting of the SMU instrument.

Test Criteria (Refer to Figure 3)

- SMU instrument in sink mode
- $V_S < V_B$
- SMU instrument functions as an electronic load
- Discharge current (I) is negative

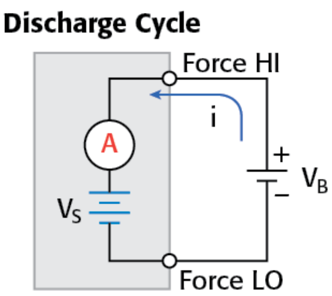

Figure 3. Discharge circuit diagrams.

Application Overview:
Galvanic Cycling of Rechargeable Batteries

What is a SourceMeter® SMU Instrument?
A SourceMeter Source Measure Unit (SMU) Instrument can source and measure simultaneously to a device under test (DUT.) The typical SMU instrument can source voltage, source current, measure current, measure voltage, and measure resistance. These instruments can source and measure over a wide range of currents and voltages. In most cases, the functions are combined to simultaneously source voltage and measure current or simultaneously source current and measure voltage. For low resistance measurements at high currents, the SourceMeter Instrument is a good fit since it provides 4-wire measurements and built-in offset-compensated ohms measurement capability.

Viewing the test data on a graphical SMU instrument
A graphical SMU instrument can display the results on the front panel (Figure 3) or the data can be exported to Excel for graphing, as well (Figure 4.)

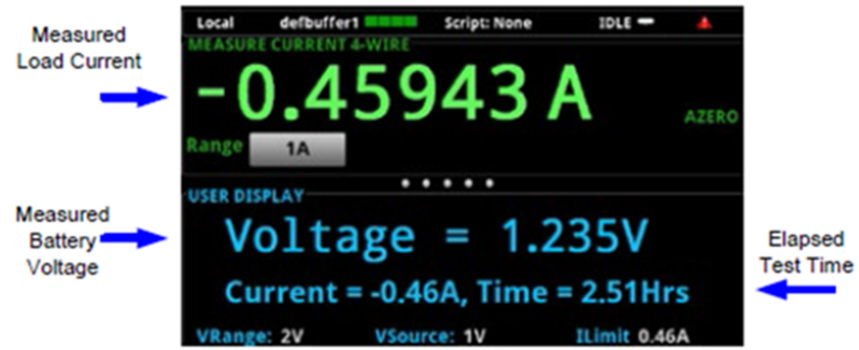

Figure 3. A graphical SMU instrument can display the load current, Battery voltage, and elapsed time for charging or discharging a battery.

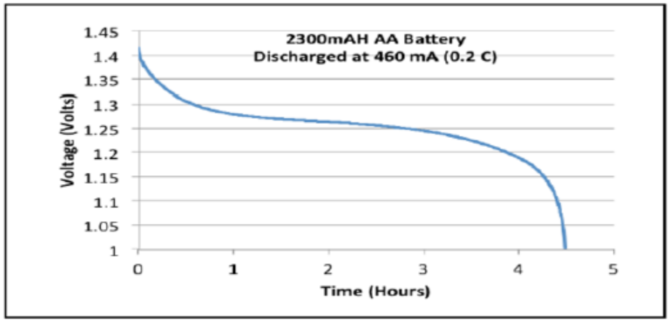

Figure 4. Discharge characteristics of a 2500mAH D cell rechargeable battery.

For additional information on galvanic cycling of rechargeable batteries, please visit www.keithley.com.

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I-V Characterization of Solar Cells and Panels

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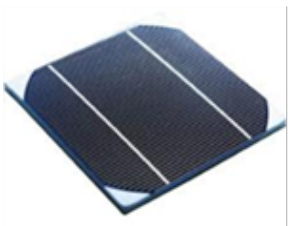
Application Overview
I-V Characterization of Solar Cells and Panels

I-V Characterization of Solar Cells
Solar or photovoltaic (PV) cells are devices that absorb photons from a light source and then release electrons, causing an electric current to flow when the cell is connected to a load. Researchers and manufacturers of PV cells strive to achieve the highest possible efficiency with minimal losses. As a result, electrical characterization of the cell as well as PV materials is performed as part of research and development and during the manufacturing process. The current-voltage (I-V) characterization of the cell is performed to derive important parameters about the cell's performance, including its maximum current (I_{max}) and voltage (V_{max}), open circuit voltage (V_{OC}), short circuit current (I_{SC}), and its efficiency (η) .



Common measurements made in I-V characterization of solar cells & panels
Open circuit voltage (V_{OC}) - The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell; this occurs at zero current.

Short circuit current (I_{SC}) - The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited.) The short circuit current is shown with I-V curve in Figure 1.

Other Common Measurements
- Shunt resistance (R_{SH})
- Conversion efficiency (η)
- Maximum power output (P_{max})
- Voltage at Pmax (V_{max})
- Resistivity
- Fill factor (ff)
- Series resistance (R_s)

The three parameters that are used to characterize a solar cell, the maximum power point (P_{max}), the short circuit current (I_{SC}), and the open circuit voltage (V_{OC}), are illustrated in Figure 1, which shows a typical forward bias I-V curve of an illuminated solar cell. The maximum power point (P_{max}) is the product of the maximum cell current (I_{max}) and the voltage (V_{max})where the power output of the cell is greatest. This point is located at the "knee" of the curve.

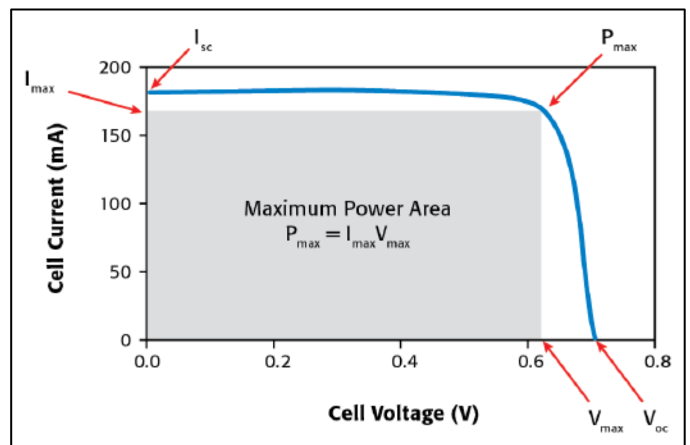


Figure 1. Typical forward bias I-V characteristics of a solar cell.

Application Overview

I-V Characterization of Solar Cells and Panels

Testing a solar cell or solar panel

Solar cell researchers and users are very focused on improving cell efficiency and maximizing energy extraction, requiring I-V measurements to characterize solar cell performance. Source measure unit (SMU) instruments are the industry standard for photovoltaic I-V characterization and are ideal for solar cell testing because they:

- Provide the industry's widest dynamic range, having high and low current capability
- Have the ability to act as a high precision electronic load with the ability to sink high currents
- Offer a range of power ranges from 20 to 100 watts
- Can handle high load impedances, including capacitive loads like solar cells

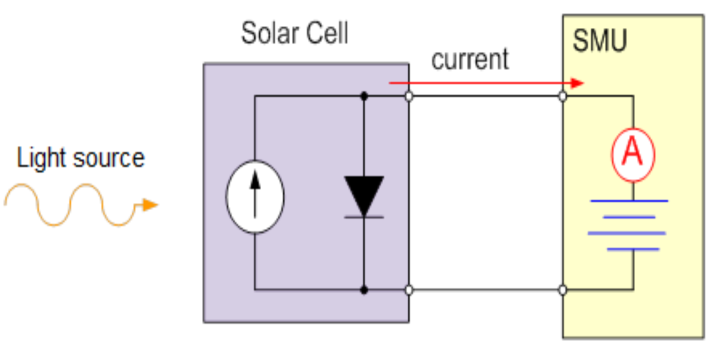


Figure 2. Circuit diagram showing a SMU instrument in use for I-V characterization of a solar cell.

Viewing the solar cell or solar panel data on a graphical SMU instrument

A graphical SMU instrument can display both the I-V curve of a forward bias solar cell or solar panel and the three parameters used to characterize a cell or panel as shown in Figure 3.

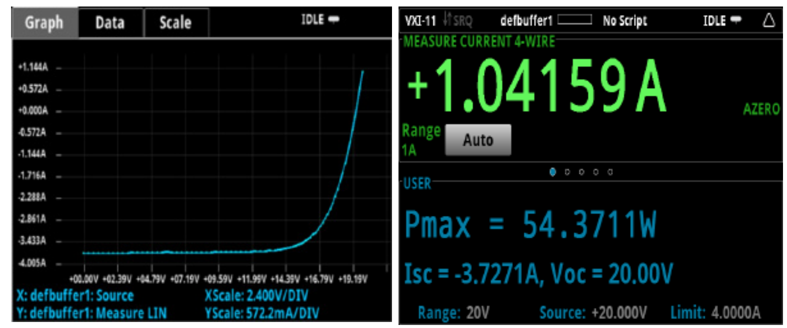


Figure 3. A graphical SMU instrument can display an I-V curve of a solar cell and can indicate maximum power (Pmax,) short circuit current (Isc,) and open circuit voltage (Voc.)

What is a SourceMeter® SMU Instrument?

A SourceMeter SMU Instrument is a type of test equipment capable of both sourcing and measuring simultaneously to a device under test (DUT). The typical SMU instrument can source voltage, source current, measure current, measure voltage, and measure resistance. These instruments can source and measure over a wide range of currents and voltages. In most cases, the functions are combined to simultaneously source voltage and measure current or simultaneously source current and measure voltage.

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Making Low Resistance Measurements Using High Current

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Application Overview:
Making Low Resistance Measurements Using High Current

Why are low resistance measurements necessary?

Measuring low resistance can identify resistance elements that have changed over time and if they have increased over acceptable values. Quite often, it's common to measure a low resistance initially and then measure the resistance at a later time to determine if degradation of a device or material has been affected by the environment, heat, fatigue, corrosion, vibration, or other conditions that may occur. Low resistance measurements using high current are often made on high power resistors, circuit breakers, switches, bus bars, cables ,and connectors. Low resistance measurements are also made on materials such as superconductors.

How are these measurements made?

To make low resistance measurements (<100W) with high current, a current (I) is forced, and the resulting voltage drop (V_M) is measured (Figure 1.) Source measure unit (SMU) instruments have the ability to automatically calculate the resistance. The measured voltage across the unknown resistance will vary depending on the amount of current supplied and the resistance value.

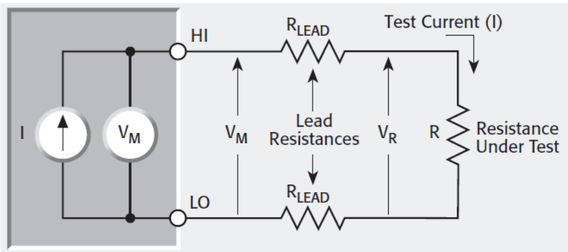

Figure 1: Typical two-wire resistance measurement using an SMU instrument.

What measurement problems can occur?

Low resistance measurements are subject to error sources, including lead resistance, thermoelectric voltages, and device heating.

- <u>Lead Resistance</u>: As shown in Figure 1, all test leads have some level of resistance, as much has 100s of milliohms. This can result in an incorrect measurement if the lead resistance is high enough.
- <u>Thermoelectric Voltages</u>: Thermoelectric EMFs or voltages are generated when different parts of a circuit are at different temperatures and when conductors made of dissimilar materials are joined together. A few microvolts of thermal voltages can be generated by temperature gradients in the test circuit caused by fluctuating temperatures in the lab or draft near the sensitive circuitry.
- <u>Device Heating</u>: The test currents used for low resistance measurements are often much higher than the currents used for high resistance measurements, so power dissipation in the device can be a consideration if it is high enough to cause the device's resistance value to change. Power dissipation in a resistor is given by $P = I^2R$. Power dissipated in a device increases by a factor of four each time the current doubles.

Use the Four-Wire Method to Make Successful Low R, High I Measurements

The Four-wire (Kelvin) Connection Method (Figure 2) is generally preferred for low resistance measurements for eliminating lead resistances.

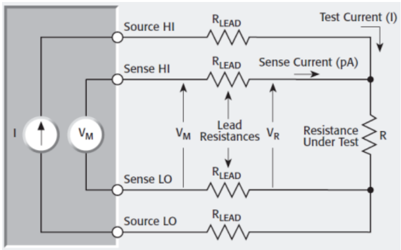

Figure 2: Four-wire Kelvin connection method.

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Application Overview:
Making Low Resistance Measurements Using High Current

With the Four-wire Method, the test current (I) is forced through the test resistance (R) through one set of test leads, while the voltage (V_M) across the DUT is measured through a second set of leads called sense leads. Although some small current may flow through the sense leads, it's usually negligible and can generally be ignored for all practical purposes. The voltage drop across the sense leads is negligible, so the voltage measured by the meter (V_M) is essentially the same as the voltage (V_R) across the resistance (R). The resistance value can be determined much more accurately than with the Two-wire Method.

Use Offset-Compensated Ohms Method

Offset-compensated Ohms Method is a technique used to minimize thermoelectric EMFs. As shown in Figure 3a, the source current is applied to the resistance being measured during only part of the cycle. When the source current is on, the total voltage measured by the instrument (Figure 3b) includes the voltage drop across the resistor as well as any thermoelectric EMFs. During the second halfof the measurement cycle, the source current is set to zero amps, and the only voltage measured by the meter (Figure 3c) is any thermoelectric EMF present in the circuit. Given that V_{EMF} is accurately measured during the second half of the cycle, it can be subtracted from the voltage measurement made during the first half of the cycle, so the offset-compensated voltage measurement becomes:

$$V_M = V_{M1} - V_{M2}$$
$$V_M = (V_{EMF} + IR) - V_{EMF}$$
$$V_M = IR$$
$$\text{and, } R = V_M / I$$

Again, note that the measurement process cancels the thermoelectric EMF term (V_{EMF}).

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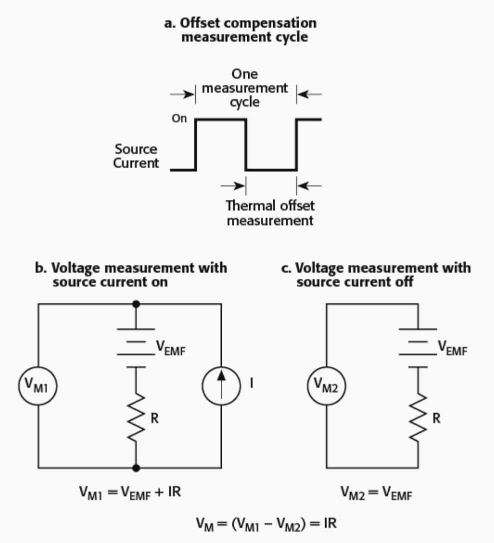

Figure 3. Offset-Compensated Ohms Method.

Figure 4. A graphical SMU instrument can display both the source current and four-wire resistance measurement with high accuracy.

For additional information on making low resistance measurements using high current, please visit www.keithley.com.

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DC I-V Characterization of Transistors

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DC I-V Characterization of Transistors

DC Characterizing Transistors

Semiconductor devices (e.g., transistors) are the foundation of electronic products. Most devices need to be electrically characterized in various settings of the research and development process: research labs, fabs, universities, device manufacturers, etc. Some of the countless applications for transistors include amplifiers, memory devices, switches, voltage regulators, logic devices, sensors, RF power amplifiers, and much more.

One industry that has witnessed tremendous growth recently in the use of transistors is the communications industry. The demands for greater bandwidth and mobility are the main drivers of innovation in this industry. For most wireless networks geared to transmitting and receiving data, the ability to amplify signals at high frequency is critical. This task is commonly achieved with a Radio Frequency (RF) power amplifier and low noise amplifier.

What are Some Types of Transistors?

The two most common transistors are the bipolar junction transistor (BJT) and the field effect transistor (FET). A BJT is a type of transistor that relies on both minority and majority carriers for its operation. The FET is a majority charge-carrier device in which the current-carrying capability is varied by an applied electric field. The many types of FETs include the MOSFET (metal-oxidesemiconductor), MESFET (metal-semiconductor), JFET (junction), OFET (organic), GNRFET (graphene nano-ribbon), and CNTFET (carbon nanotube). These FETs differ in the design of their channels.

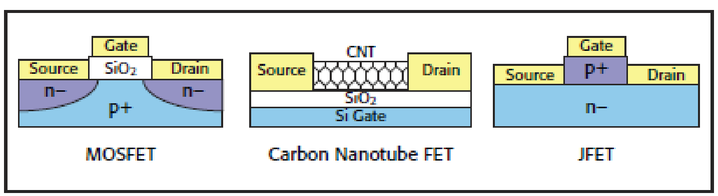

Figure 1. illustrates the MOSFET, CNTFET, and JFET.

Testing a MOSFET Transistor

There are several possible ways to characterize the electrical properties of a transistor. Typical systems for characterizing transistor include multiple instruments for sourcing and measuring current and voltage. A Source-Measure Unit (SMU) can be used to achieve greater flexibility and simplicity in the measurement configuration. Testing devices that have more than two terminals usually requires more than one SMU.

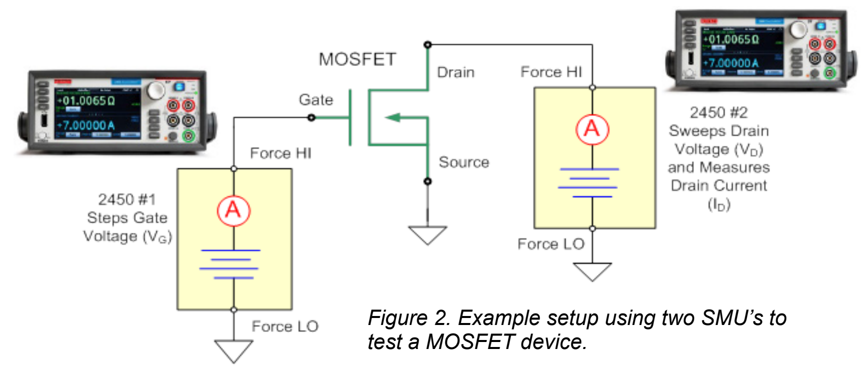

Figure 2. Example setup using two SMU's to test a MOSFET device.

Common Measurements Made in I-V Characterization of FET Transistors

- <u>Drain Voltage</u> (V_D) - The voltage appearing at the drain terminal of a field-effect transistor is called the drain voltage.
- <u>Drain Current</u> (I_D) - The current taken from the voltage source by the drain terminal is called the drain current. Drain current can yield a lot of insight on the device's operation and efficiency.
- <u>Other common measurements include</u>:
  - Gate Voltage (V_G)
  - Breakdown Voltage (V_B)
  - Gate Leakage (I_L)
  - Threshold Voltage (V_{TH})

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DC I-V Characterization of Transistors

MOSFET Family of Curves

A typical MOSFET family of collector curves generated by a software tool using two SMUs is shown in Figure 3.

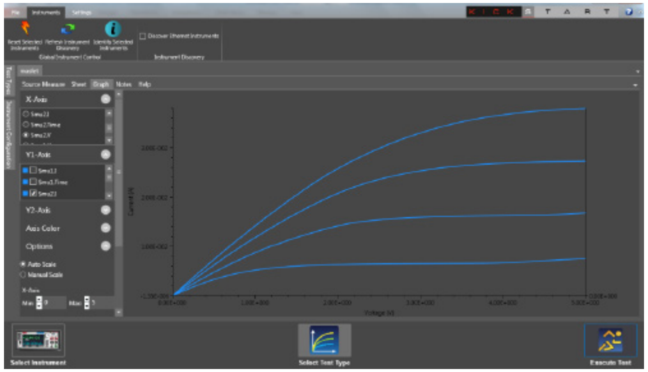

Figure 3. Family of curves using Keithley's KickStart software controlling two interactive SMUs

Typical Measurement Setup for a HBT Transistor

A type of transistor used in the telecommunications industry is an HBT or Heterojunction Bipolar Transistor. The HBT is a type of bipolar junction transistor (BJT) which uses differing semiconductor materials for the emitter and base regions, thus creating a heterojunction. The HBT improves on the BJT in that it can handle signals of very high frequencies, up to several hundred GHz, which is commonly used in the telecommunications industry. It is commonly used in applications requiring a high power efficiency, such as RF power amplifiers in cellular phones.

Figure 4 shows two SMU instruments connected to the device. The first SMU instrument is connected between the HBT base and the emitter. The second SMU instrument is connected between the collector and the emitter. To acquire the collector family curves from the HBT, the base SMU instrument is set to output current and measure voltage. The collector SMU instrument is set to sweep voltage and measure current. After the first base current is set, the collector voltage is swept while the collector current is measured.

Then, the base current is stepped up and the collector voltage is swept again while collector current is measured. This process is repeated until all the collectorI-V curves at the different base current levels are acquired.

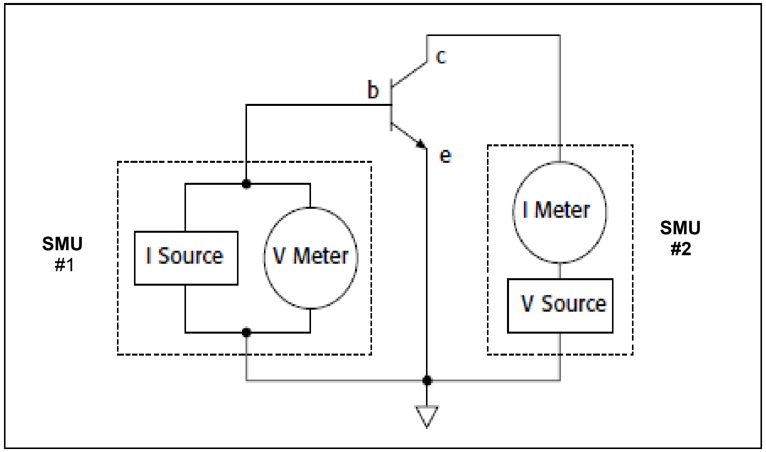

Figure 4. Instrument setup to measure HBT collector family I-V curves

What is a SourceMeter SMU Instrument?

A SourceMeter, which can also be referred to as a source-measure unit (SMU), is a type of test equipment capable of both sourcing and measuring simultaneously to a Device Under Test (DUT). The typical SMU provides the following five functions: source voltage, source current, measure current, measure voltage, measure resistance. These instruments can source and measure over a wide range of currents and voltages. In most cases the functions are used together in the following combinations: simultaneously source voltage and measure current or simultaneously source current and measure voltage.

For additional information, please refer to the website www.keithley.com for detailed specifications of the Model 2450 and 2460 Interactive SMU's

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