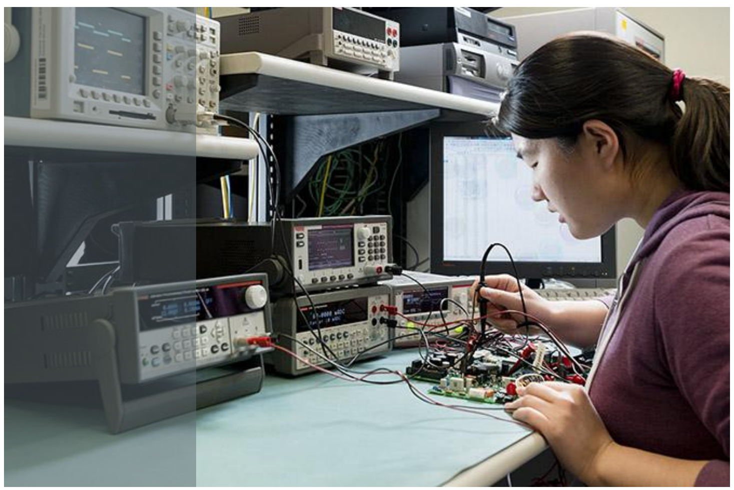
SMU Application

(Keithley 2450 & 2460)



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Agenda

- Introduction
  - *SMU*

- Applications and Tests
  - *Resistivity Test*
  - *LED*
  - *Solar Panel (Battery)*
  - *MOSFET*

What is a Source Measure Unit (SMU)?

- SMUs are precision instruments for sourcing current or voltage and simultaneously measuring current, voltage and/or resistance with high speed and accuracy.

Precision DMM

Source Measure Unit (**SMU)**

Precision Power Supply

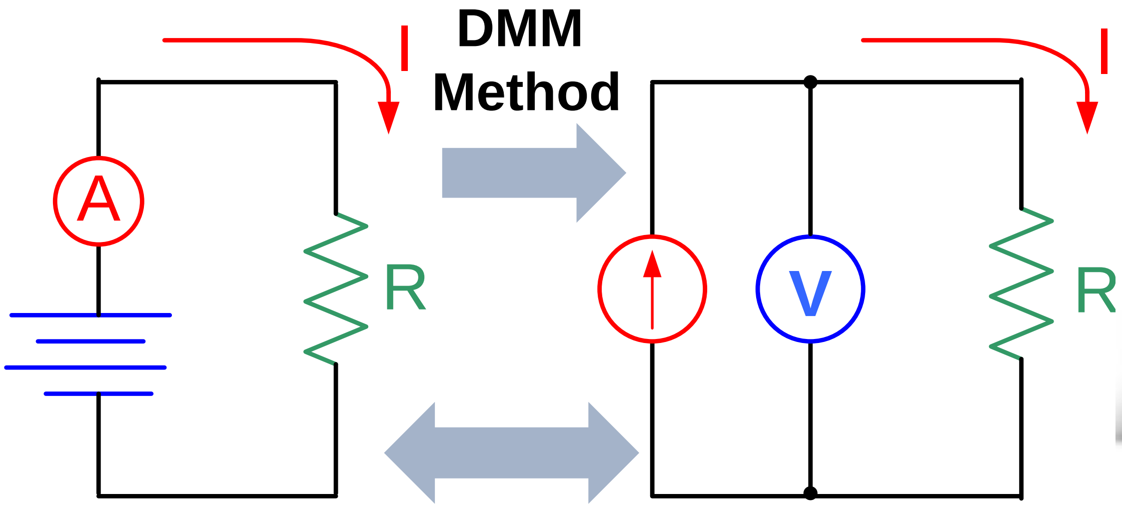
True Current Source

Electronic Load

What is a Source Measure Unit (SMU)?

SMU Compared to DMM: *Resistance Measurements*

User can chose which method to use based on DUT and tests:



Force-V
Measure -I

SMU
Both
Methods

Force-I
Measure-V

Best for High Resistances	Best for Low Resistances

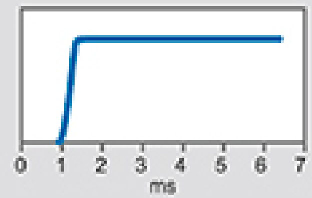
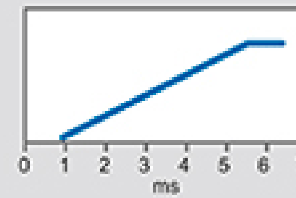
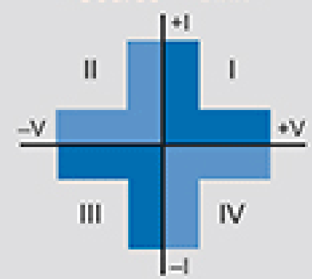
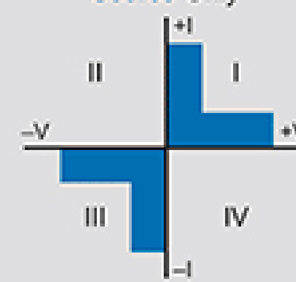
What is a Source Measure Unit (SMU)?

SMU Compared to Power Supply: *What are the differences?*

Power Supply

Versus

Source Measure Unit (**SMU**)

	SMU Instrument	Typical Power Supply
Speed		
Source/ Measure Precision	10µA measurement uncertainty = 5nA	10µA measurement uncertainty = 2500nA
Voltage and Current Resolution (Typical)	Voltage: 1µV – 200V Current: 1pA – 3A	Voltage: 1µV, 1mV – 200V Current: 1pA, 1mA – 3A
4 Quadrant Operation	Source + Sink 	Source Only 

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Application

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SMU Applications Span Electronics R&D and Industries


LED's, Lights


Solar Panels & Cells


OLED Displays

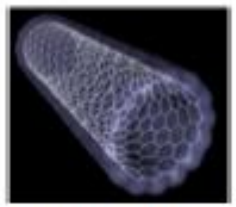

Laser Diode Modules


Power Semi


Transistors and other Discrete Semi Devices


Implantable Medical Devices


Electro-Chemistry


Nano-materials, nano-electronics


Printed / Flexible Electronic


Electronic components, sensors


Batteries

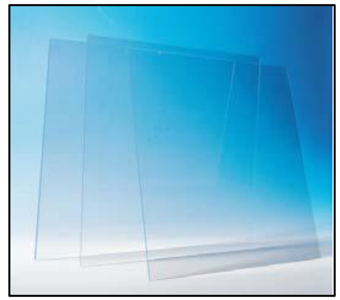
Research, Design Validation, Characterization, Performance Testing

Versatile!

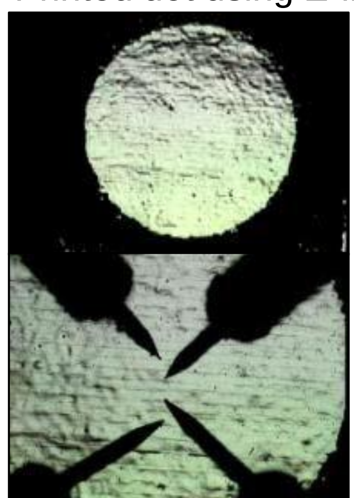
Resistivity Measurement

The Model 2450 or 2460 can be used to measure the resistivity of a wide range of materials including conductive coatings, semiconductor wafers, solar cell materials, e-Inks, etc.

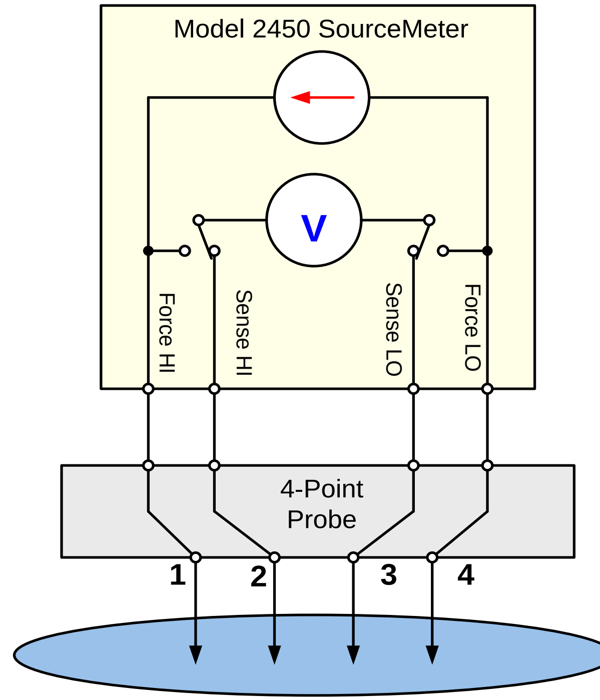
Indium Tin Oxide



Printed dot using E-ink



Probing the dot



Semiconductor Wafer

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Four-Point Measurement

-The four-point collinear probe resistivity measurement technique involves bringing four equally spaced probes in contact with the material of unknown resistance. The probe array is placed in the center of the material.

- A known current is passed through the two outside probes and the voltage is sensed at the two inside probes. The resistivity is calculated as follows:

$$\rho = \frac{\pi}{\ln 2} \times \frac{V}{I} \times t \times k$$

where: ρ = the volume resistivity (Ω-cm)

V = the measured voltage (volts)

I = the source current (amps)

t = the wafer thickness (cm)

k = a correction factor based on the ratio of the probe to wafer diameter and on the ratio of wafer thickness to probe separation

$$\sigma = \frac{\pi}{\ln 2} \times \frac{V}{I} \times k$$

where: σ = the sheet resistance (Ω/square or just Ω)

Four-Point Measurement

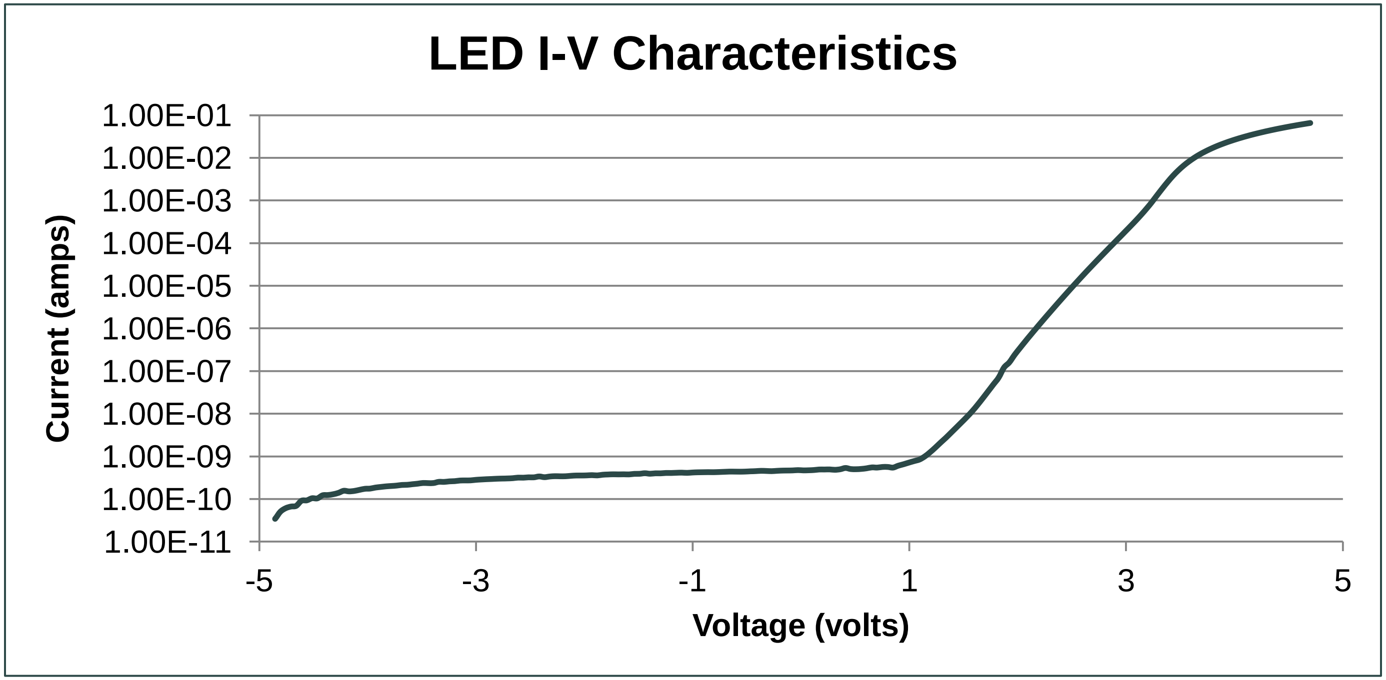
A correction factor (K)

d/s	Correction
3	0.5
3.448	0.5734
4	0.6462
5	0.7419
6.061	0.8089
7.5	0.8665
8.696	0.8972
10	0.9204
12.5	0.9475
15	0.9628
20	0.9788
28.57	0.9895
40	0.9945
100	0.9991
infinite	1

- The table shown directly below pertains to sheet resistance measurements made in the center of a circular slice.
- d/s = diameter of sample divided by probe spacing (probe spacing being the distance between any two adjacent probes).
- For example, a 4mm diameter sample probed with a four point probe with 1mm tip spacing would have a correction factor of 0.6462.
- A 100mm wafer measured with a four point probe head that has 1mm tip spacing would have a correction factor of 0.9991.
- Source: SEMI MF84-02 -Test Method for Measuring Resistivity of Silicon Wafers With an In-Line Four-Point Probe.

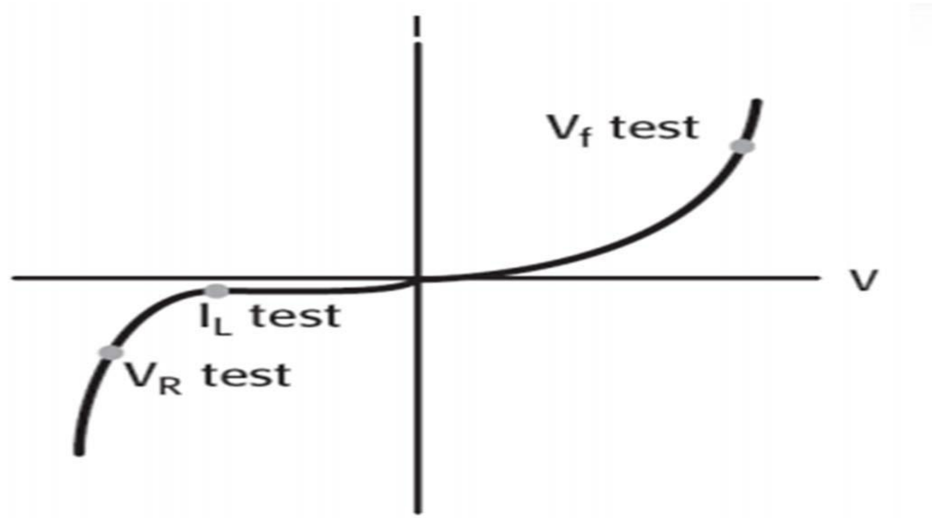
LED I-V Characterization

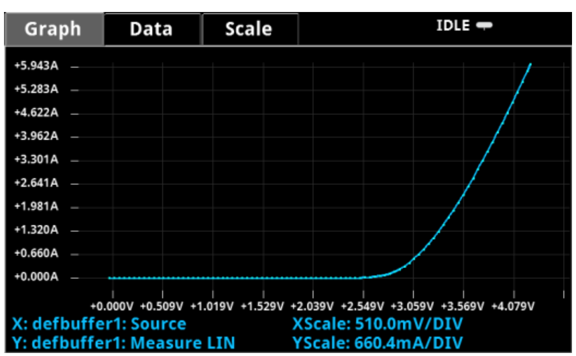
With the ability to source and measure current and voltage all in one unit, the SMU is an ideal tool for testing optoelectronic devices such as LED I-V characterization.

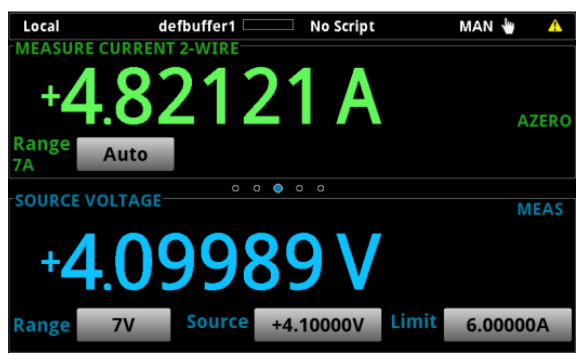


LED, HBLED Characterization

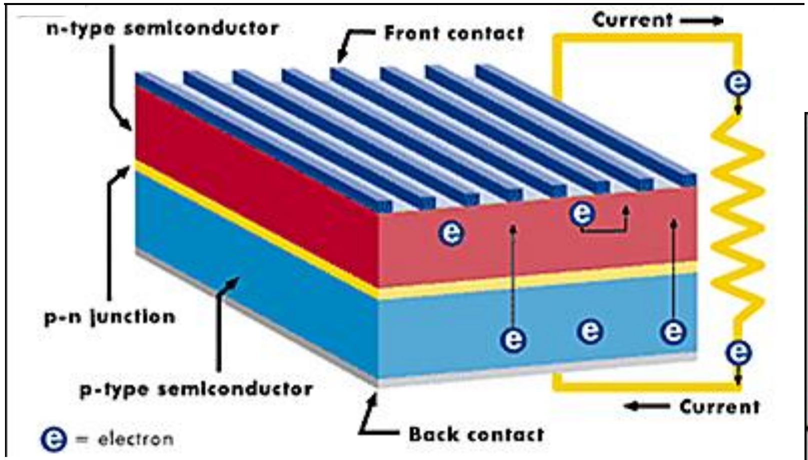
- **Common measurements made in I/V characterization of HBLED's**
  - Forward Voltage (V_f)
  - Reverse Leakage Current (I_L)
  - Reverse Breakdown Voltage (V_R)

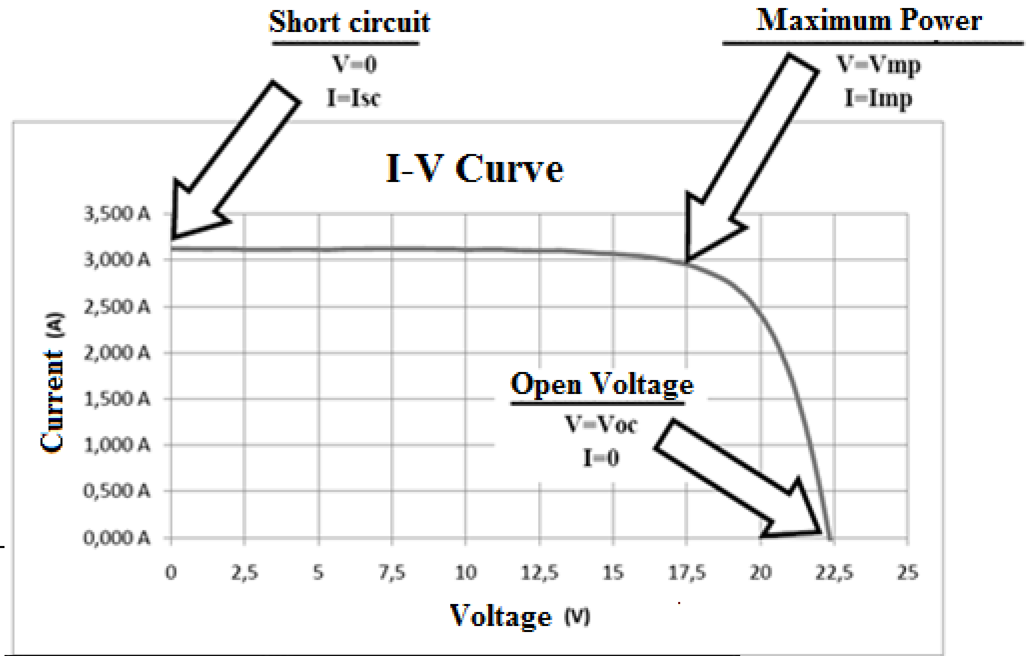


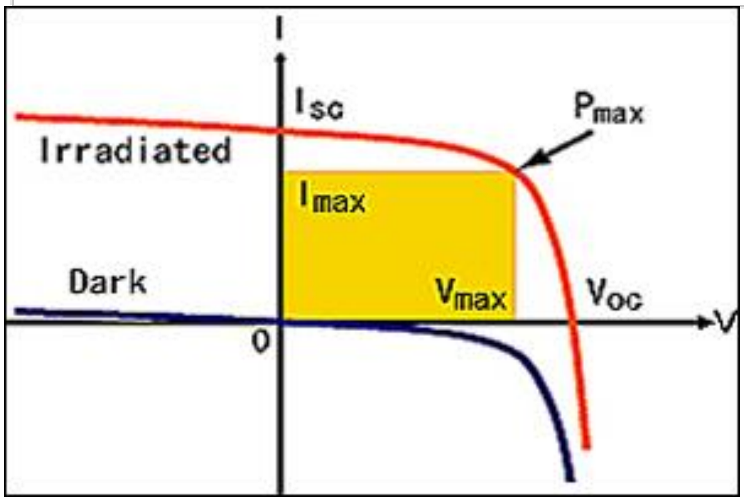




Photovoltaic Solar Cells (PV Diodes) – Source & Sink







When lit a PV cell creates voltage/current so SMU acts as a settable active load

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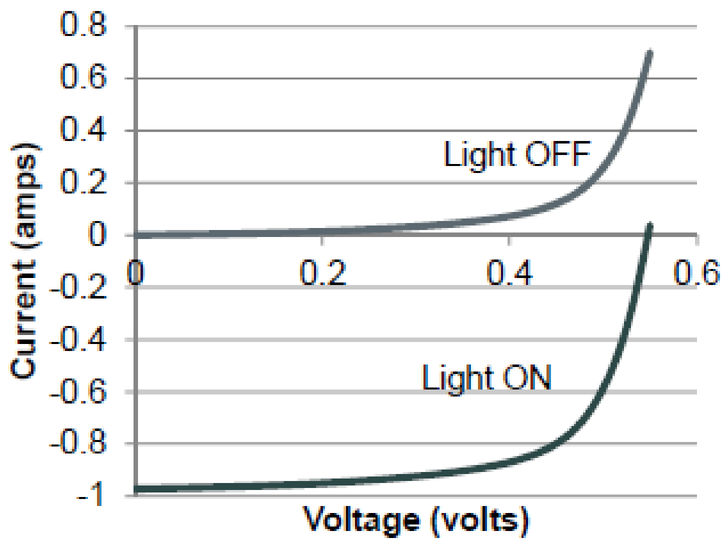
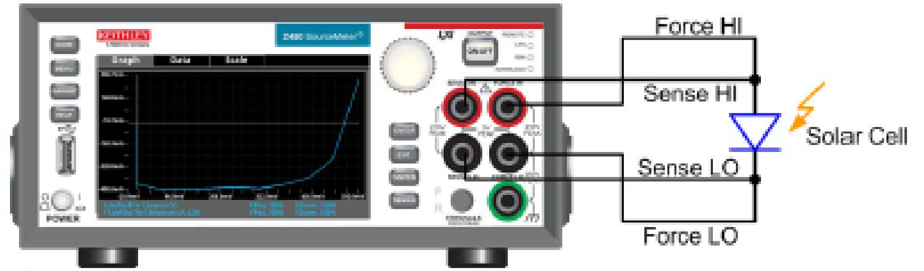
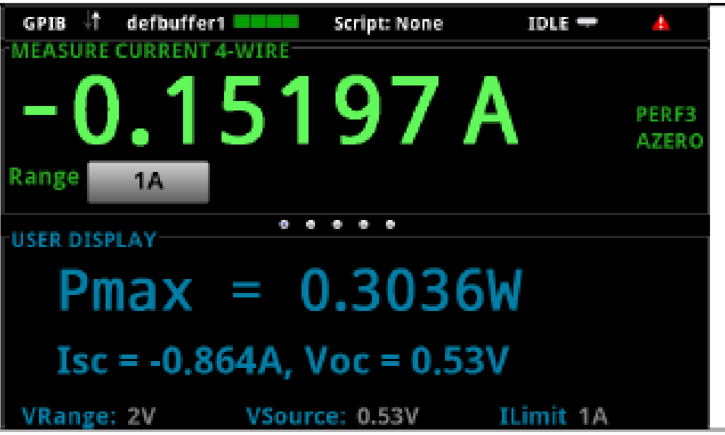
Solar Panel Testing Using the Model 2450



I-V Sweeps of solar cell taken with the cell in the dark and with the cell illuminated.



Solar cell graphs can be generated over the bus or on the front panel user interface of the Model 2450



Large user interface can display derived solar cell I-V parameters such as the maximum power, short circuit current, and the open circuit voltage.

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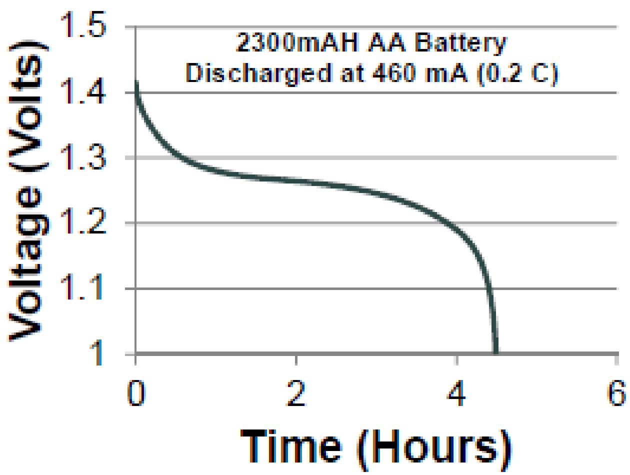
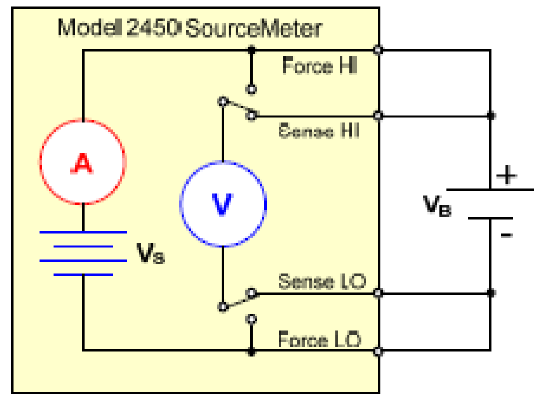
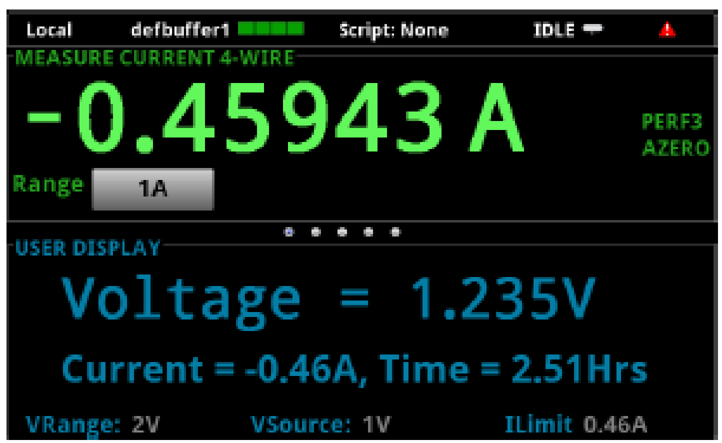
Battery Discharge Test Using the Model 2450





Model 2450 Configured for Charging/Discharging a Battery



Model 2450 Touchscreen Display can be programmed to provide updated test data to user such as battery voltage, load current, and elapsed test time.

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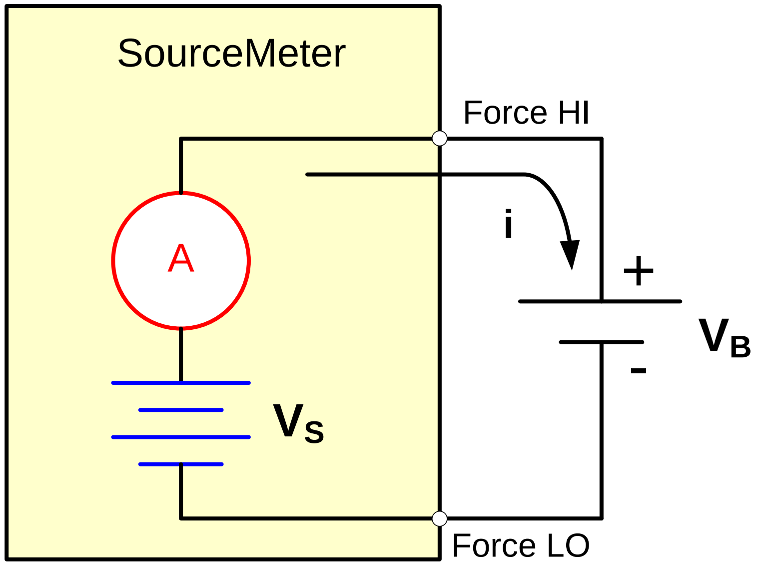
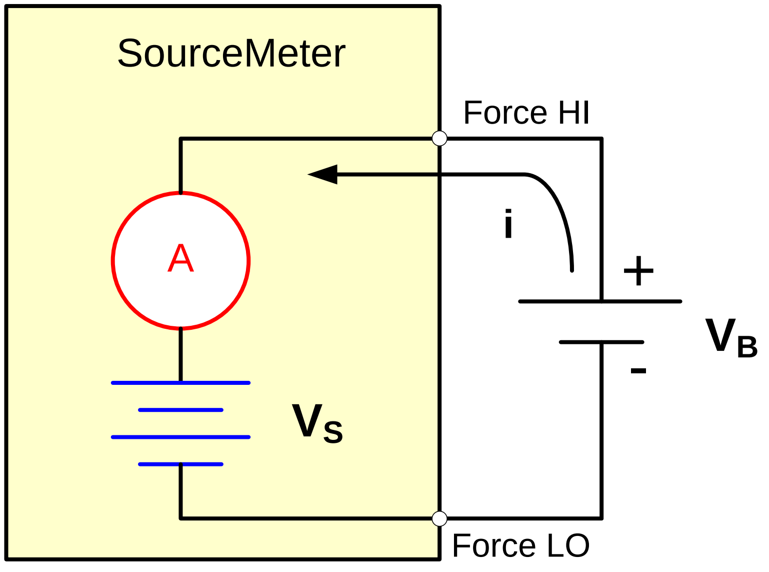
Battery Charge/Discharge

Charge Cycle



SourceMeter in Source Mode
$V_S > V_B$
SourceMeter Functions as Power Supply
Charge Current (i) is Positive

Discharge Cycle



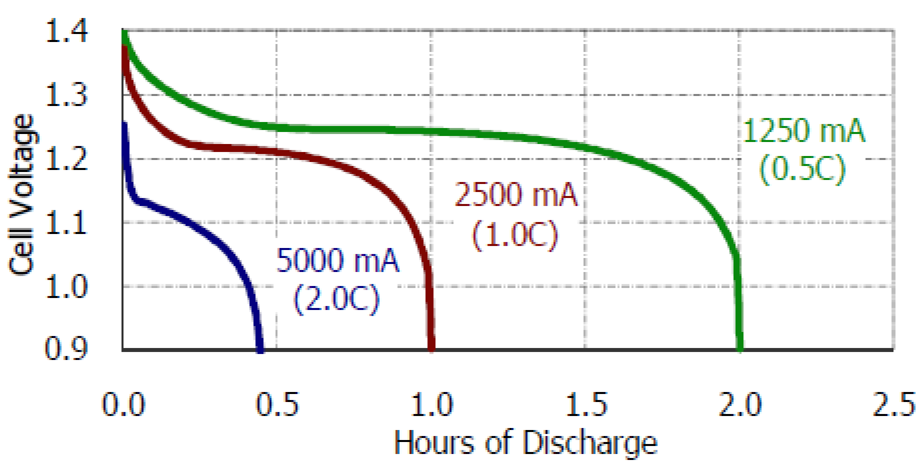
SourceMeter in Sink Mode
$V_S < V_B$
SourceMeter Functions as Electronic Load
Discharge Current (i) is Negative

Battery Discharge Test

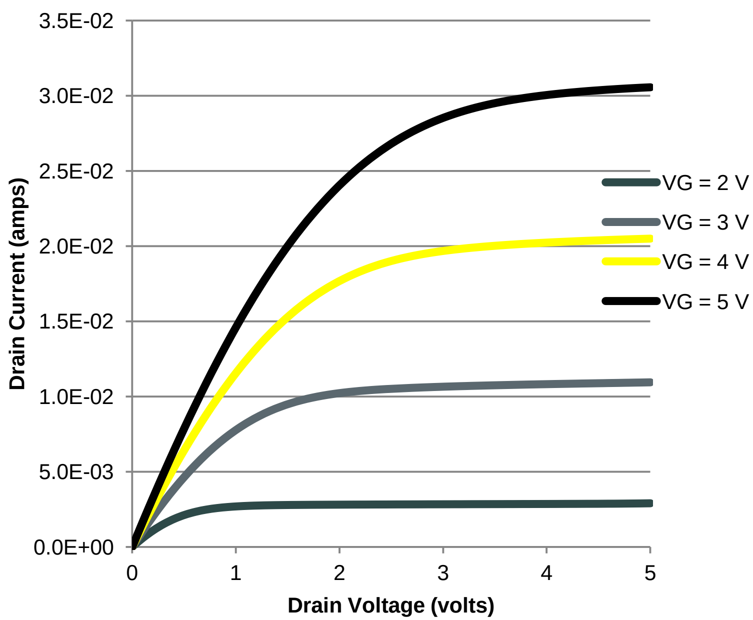
ENERGIZER NH50-2500

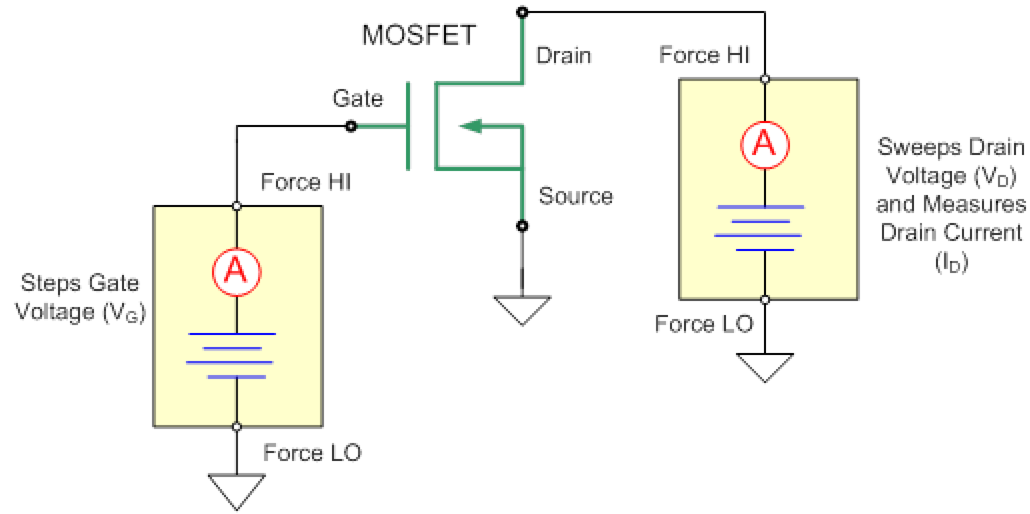
Specifications

Classification:	Rechargeable
Chemical System:	Nickel-Metal Hydride (NiMH)
Designation:	ANSI-1.2H4
Nominal Voltage:	1.2 Volts
Rated Capacity:	2500 mAh* at 21°C (70°F)

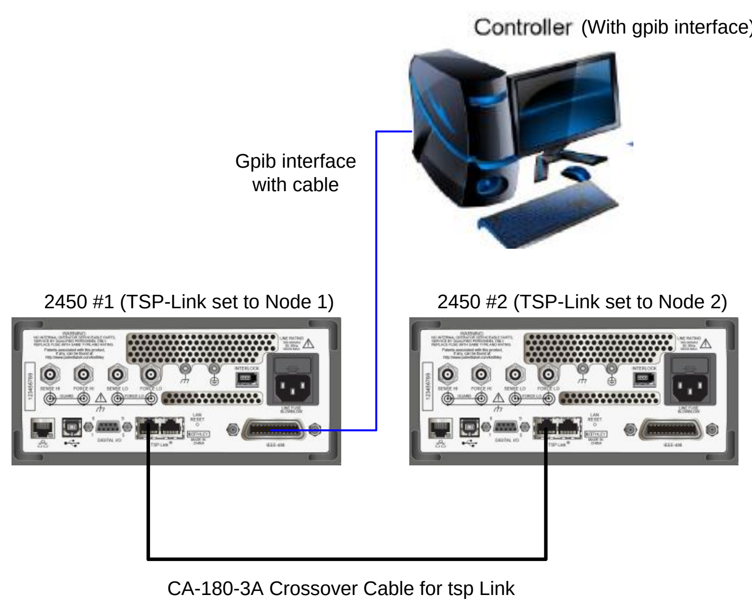


FET Test Using Two Model 2450's or 2460's or both





Anyone recognize these???



TSP-Link is used to synchronize the gate voltage stepping and drain voltage sweeping of the two units.

App Note Available to Support Model 2450 or 2460 Resistivity Measurement and Battery Cycling

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Application Note Series

Number 3247

Resistivity Measurements Using the Model 2450 SourceMeter® SMU Instrument and a Four-Point Collinear Probe

Introduction

Electrical resistivity is a basic material property that quantifies a material's opposition to current flow; it is the reciprocal of conductivity. The resistivity of a material depends upon several factors, including the material doping, processing, and environmental factors such as temperature and humidity. The resistivity of the material can affect the characteristics of a device of which it's made, such as the series resistance, threshold voltage, capacitance, and other parameters.

Determining the resistivity of a material is common in both research and fabrication environments. There are many methods for determining the resistivity of a material, but the technique may vary depending upon the type of material, magnitude of the resistance, shape, and thickness of the material. One of the most common ways of measuring the resistivity of some thin, flat materials, such as semiconductors or conductive coatings, uses a four-point collinear probe. The four-point probe technique involves bringing four equally spaced probes in contact with a material of unknown resistance. A DC current is forced between the outer two probes, and a voltmeter measures the voltage difference between the inner two probes. The resistivity is calculated from geometric factors, the source current, and the voltage measurement. The instrumentation used for this test includes a DC current source, a sensitive voltmeter, and a four-point collinear probe.

To simplify measurements, a single instrument, the Model 2450 SourceMeter® Source Measure Unit (SMU) Instrument, can be used. This instrument can source and measure both current and voltage and can be configured to display resistance or resistivity. The Model 2450 enables the user to choose a test current over many decades (from picoamps to amps), as well as measure voltage with resolution in the microvolt range. The Model 2450 is pictured in *Figure 1* connected to a Signatone four-point collinear probe. This configuration is set up to measure the resistivity of a semiconductor wafer.

Figure 1. Model 2450 SourceMeter SMU Instrument with the Lucas/Signatone Corporation (Gilroy, CA) Model SP4 4-Point Probe Head and S-302 Test Stand measuring the resistivity of a sample.

This application note explains how to perform resistivity measurements on materials using the Model 2450 and a four-point collinear probe.

The Four-Point Collinear Probe Method

The four-point collinear probe technique involves bringing four equally spaced probes in contact with a material of unknown resistance. The probes, mounted into a probe head, are gently placed in the center of the wafer as shown in the resistivity test circuit in *Figure 2*.

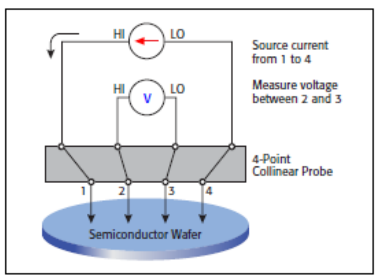

Figure 2. Four-point probe resistivity test circuit.

The two outer probes, 1 and 4, are used for sourcing current. The two inner probes, 2 and 3, are used for measuring the resulting voltage drop across the surface of the sample.

The volume or bulk resistivity (ρ) is calculated as follows:

$$\rho = \frac{\pi}{\ln 2}\,\frac{V}{I}\,t\,k = 4.532\,\frac{V}{I}\,t\,k$$

where:

ρ = the volume resistivity (Ω-cm)

V = the voltage measured between probes 2 and 3 (voltage)

I = the magnitude of the source current (amps)

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Application Note Series

Number 3221

Rechargeable Battery Charge/Discharge (Galvanic) Cycling Using the Keithley Model 2450 or Model 2460 SourceMeter® SMU Instrument

Introduction

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. Common types of rechargeable batteries include Li-ion (Lithium Ion), Ni-MH (Nickel Metal Hydride), and NiCd (Nickel Cadmium). The characteristics of a rechargeable battery are commonly tested using discharge and charge 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 it is not defective.

A typical battery discharge/charge test setup often includes a programmable power supply, an electronic load, a voltmeter, and an ammeter. Battery testing can be simplified by using a single instrument, the Model 2450 or Model 2460 SourceMeter Source Measure Unit (SMU) Instrument, that has the flexibility to source/sink current as well as measure voltage and current. By using the Model 2450 or 2460, the user only needs to set up a single unit instead of an entire rack full of equipment. As a result, the SourceMeter can charge up the battery by sourcing current, discharge the battery by dissipating power, and monitor the battery's voltage and load current.

Model	2450	2460
Output	±21 V @ ±1.05 A ±210 V @ ±105 mA	±100 V @ ±1.05 A ±20 V @ ±4 A ±10 V @ ±5 A ±7 V @ ±7 A

Figure 1 illustrates a typical system for charge/discharge cycling using the Model 2450 or 2460.

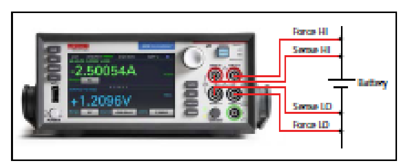

Figure 1. Model 2450 SourceMeter SMU Instrument shows results of testing a AAA battery.

Battery Charging/Discharging

Rates for constant current charging and discharging are defined in terms of the battery's capacity, which is the amount of electrical charge that the battery can store. The capacity is specified in milliampere-hours (mAH) available and should be expressed in terms of a discharge, or load, current. The rate at which the discharge current will discharge the entire battery in one hour is known as the C-rate. For example, a battery rated at 1000mAH will output 1000mA for one hour if discharged at 1C. If a 500mAH cell is discharged at 50mA, then it is discharged at one-tenth the C-rate (0.1C) and therefore can source 50mA for ten hours.

Test Description

For both the charging and discharging cycles, the Model 2450 or Model 2460 SourceMeter SMU Instrument is configured to source voltage and measure current. A simplified circuit diagram of both the charge and discharge cycles is shown in *Figure 2*.

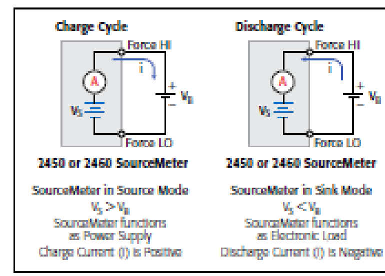

Figure 2. Charge and discharge circuit diagrams.

A battery is usually charged using a constant current. This is accomplished using the SourceMeter 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 volta ge output setting of the SourceMeter. As a result, this voltage difference drives a current that is immediately limited to the user-defined current limit. When in current limit, the SourceMeter 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

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App Note Available to Support Model 2450 or 2460 Photovoltaic Cells and Characterization of Diodes

KEITHLEY
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Application Note Series

Number 3234

I-V Characterization of Photovoltaic Cells and Panels Using the Keithley Model 2450 or Model 2460 SourceMeter® SMU Instrument

Introduction

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. Solar panels are just a collection of solar cells connected in series and parallel that provide more power than just a single, smaller cell. Researchers and manufacturers of PV cells and panels 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).

These I-V characteristics can easily be generated using a Keithley Model 2450 or Model 2460 SourceMeter SMU Instrument, which can source and measure both current and voltage. Because both SourceMeter instruments have four-quadrant source capability, they can sink the cell current as a function of an applied voltage. ***Table 1*** shows the power envelope of both the Models 2450 and 2460.

Model	2450	2460
Output*	±210 V @ ±105 mA ±21 V @ ±1.05 A	±100 V @ ±1.05 A ±20 V @ ±4 A ±10 V @ ±5 A ±7 V @ ±7 A

* To sink higher current levels, use Keithley Model 2651A High Power System SourceMeter Instrument, which can sink up to 20A at 10VDC.

Table 1. Power Envelopes of Model 2450 and Model 2460 SourceMeter instruments

This application note explains how to simplify I-V characterization of solar cells and panels by using the Model 2450 or 2460, shown in ***Figure 1***. In particular, this application note explains how to perform I-V testing from the front panel of the instrument, including how to generate graphs and save data to a USB drive. It also details how to automate the measurements over a communication bus.

The Solar Cell

The solar cell may be represented by the equivalent circuit model shown in ***Figure 2***, which consists of a light-induced current source (I_L), a diode that generates a saturation current [$I_S(e^{qV/kT} - 1)$], series resistance (r_s), and shunt resistance (r_{sh}). The series resistance is due to the resistance of the metal contacts, ohmic losses in the front surface of the cell, impurity

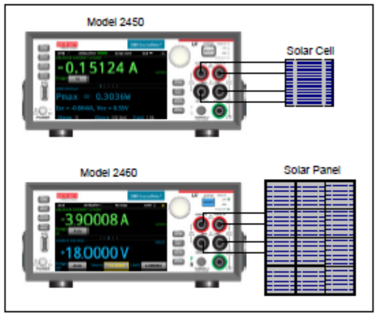

Figure 1. Models 2450 and 2460 making I-V measurements on a solar cell and a solar panel.

concentrations, and junction depth. The series resistance is an important parameter because it reduces both the cell's short-circuit current and its maximum power output. Ideally, the series resistance should be zero ohms. The shunt resistance represents the loss due to surface leakage along the edge of the cell or to crystal defects. Ideally, the shunt resistance should be infinite.

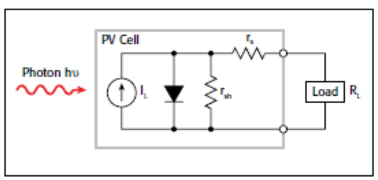

Figure 2. Idealized equivalent circuit of a photovoltaic cell.

If a load resistor (R_L) is connected to an illuminated solar cell, then the total current becomes:

$$I = I_S(e^{qV/kT} - 1) - I_L$$

where: I_S = current due to diode saturation
I_L = current due to optical generation

Several parameters are used to characterize the efficiency of the solar cell, including the maximum power point (P_{max}),

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Number 3225

Easy I-V Characterization of Diodes Using the Model 2450 SourceMeter® SMU Instrument

Introduction

Diodes are two-terminal electronic devices that typically enable current to flow in one direction (forward bias) and block the current from flowing (reverse bias) in the opposite direction. However, there are many types of diodes that perform various functions such as Zener, light emitting (LEDs), organic light emitting (OLEDs), Shockley, avalanche, photodiode, etc. Each of these specific types of diodes can be differentiated by their current-voltage (I-V) characteristics. I-V testing of diodes is performed in research labs as well as in a production environment on packaged devices or on a wafer.

I-V characterization of a diode typically requires a sensitive ammeter, voltmeter, voltage source, and current source. Being able to program, synchronize, and connect all these separate instruments can be cumbersome and time consuming, as well as require a considerable amount of rack or bench space. To simplify testing and reduce rack space, a single unit, such as Keithley's Model 2450 SourceMeter SMU Instrument, is ideal for diode characterization because it can source and measure both current and voltage. The Model 2450 can sweep the source voltage and measure current over many decades (10^{-11}A to 1A), which is required for diode testing. These measurements can be generated automatically over the bus or just as easily via the large touchscreen, which enables the user to set up tests and graph them on the screen. The Model 2450 is pictured in ***Figure 1*** sourcing voltage and measuring current on a red LED that is connected to its inputs in a four-wire configuration.

Figure 1. Model 2450 SourceMeter SMU Instrument measuring the I-V characteristics of a red LED.

This application note explains how to perform I-V characterization on diodes easily using the Model 2450 SourceMeter SMU Instrument. In particular, it describes how to take, graph, and store measurements using the front panel user interface, as well as how to automate the measurements over the bus.

Diode I-V Tests

In general, the parameter testing of diodes typically involves being able to source and measure both current and voltage over a wide range. For example, while sweeping a forward voltage from 0V to about 1V, the resulting measured current can range from 10^{-12}A to 1A. However, the actual magnitudes, the types of I-V tests, and the parameters extracted are dependent on the particular diodes to be tested. To test an LED, the user will want to measure the luminous intensity as a function of an applied current, whereas an engineer testing a Zener diode will want to know the "clamped" or Zener voltage at a particular test current. However, there are many common tests among the various types of diodes.

A typical diode I-V curve is shown in ***Figure 2*** indicating the forward, reverse, and breakdown regions, as well as common test points, the forward voltage (V_F), leakage current (I_R), and the breakdown voltage (V_R). The forward voltage test (V_F) involves sourcing a specified forward bias current within the normal operating range of the diode, then measuring the resulting voltage drop. The leakage current test (I_R) determines the low level of current that leaks across the diode under reverse voltage conditions. This test is performed by sourcing a specified reverse voltage, then measuring the resulting leakage current. In the reverse breakdown voltage test (V_R), a specified reverse current bias is sourced and the resulting voltage drop across the diode is measured.

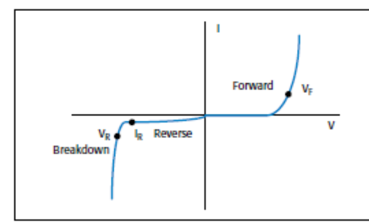

Figure 2. Current-voltage curve of a typical diode showing the forward, reverse, and breakdown regions.

Making Connections from the Diode to the Model 2450

The diode is connected to the Model 2450 as shown in ***Figure 3***. A four-wire connection is made to eliminate the effects of lead

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