Tektronix®

kickstart

KickStart Software Suite and Specialty Apps

APPLICATIONS GUIDE

Introduction

KickStart Software eliminates the need for complex programming by providing an intuitive, app-based environment for test configuration, execution, and data visualization. This applications guide features a collection of application notes that highlight specific KickStart Apps to demonstrate how engineers can configure tests, visualize measurements in real time, and export results seamlessly for deeper analysis. Whether you're characterizing semiconductor devices, performing pulsed I-V measurements, testing wide bandgap (WBG) materials, analyzing battery performance, or running long-term reliability studies, there's a KickStart app to gather insights faster and make decisions with confidence.

Contents

How to Test a Resistor with a Multimeter and the KickStart DMM App

APPLICATION NOTE

Introduction

The practical limitations of cost-effective device manufacture require that resistors be assigned a tolerance range by their manufacturers. As such, digital multimeters are often used to confirm whether a given resistor falls within its specified tolerance range. When testing many resistors, it is helpful to use an instrument that can automatically check if a resistor is within its tolerance specifications and record this data. This can be done through custom code development, but code creation is an expensive and time-consuming investment. KickStart Software offers an easy, no-code solution to testing resistor tolerances using its DMM App. In this application note, we will go over how to test resistor tolerances using a Keithley DMM6500 6.5-digit Digital Multimeter with KickStart Software and how to access and interpret the data.

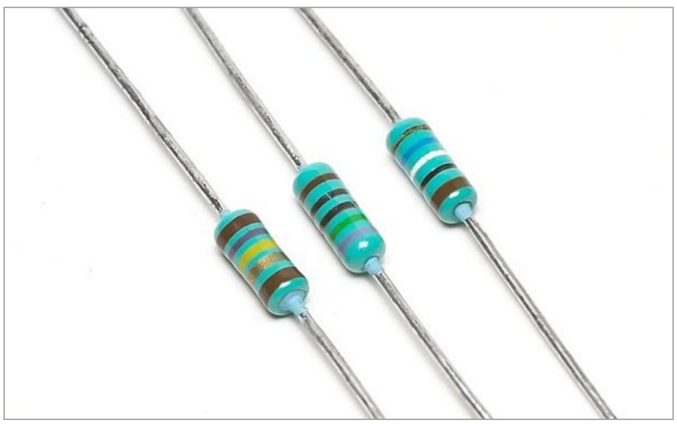

Figure 1: Basic resistors typically used in circuit design.

What is Resistor Tolerance?

A resistor's tolerance is the percentage of error in its nominal resistance, or the acceptable range of variance in a resistor's measured resistance as compared to its nominal value. Tolerance is expressed as a plus or minus percentage measured under no load at a specific temperature, typically 25 degrees Celsius. Depending on the type of resistor, these tolerances can vary from as loose as ±20% to as tight as ±0.005%.

How can one test a resistor with a multimeter? The DMM6500 and KickStart Software can do simple pass-or-fail testing, as well as grading. Grading resistors is a common application that is done by monitoring multiple limits until the first failure.

Using the KickStart DMM App to Test a Resistor

To test a resistor with a multimeter, the KickStart DMM App allows you to remotely configure your DMM6500 settings and analyze test data from the convenience of your PC.

The settings of importance for this application include the measurement function, which you will set to either two-wire or four-wire resistance. Four-wire sense will help negate lead resistance in measurements and is more accurate, especially for measuring low-resistance devices.

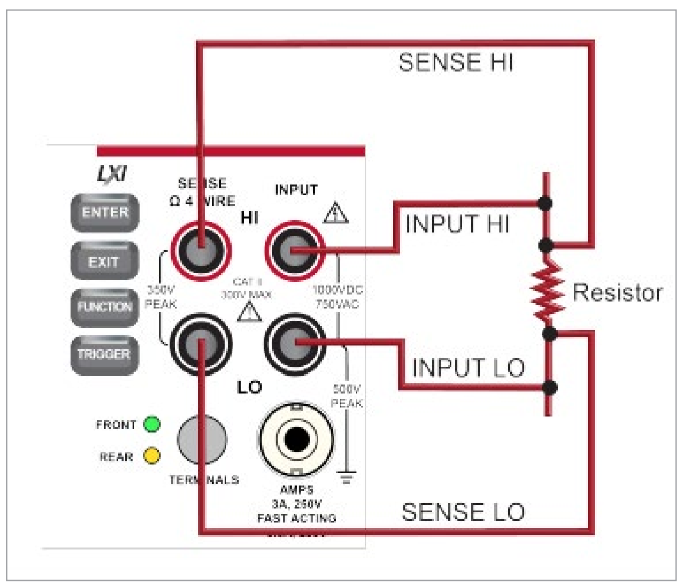

Figure 2: Front-panel connections for four-wire resistance measurements.

You will also want to ensure that Offset Compensation is enabled, as this setting will further improve resistance measurement accuracy by removing thermal offsets.

Additional settings such as Range, NPLC and Auto Zero can also be adjusted to further improve measurement accuracy.

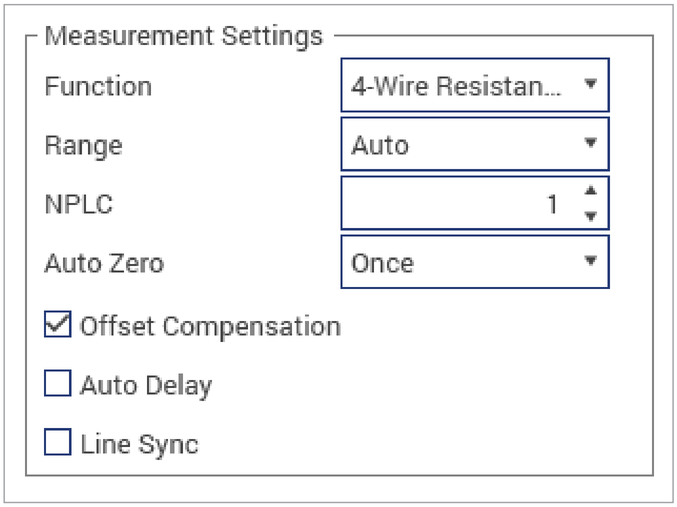

Figure 3: KickStart DMM App measurement settings.

The Acquistion settings include controls for Measure Delay and Measure Count. Measure Count should be set to the amount of resistors that will be tested.

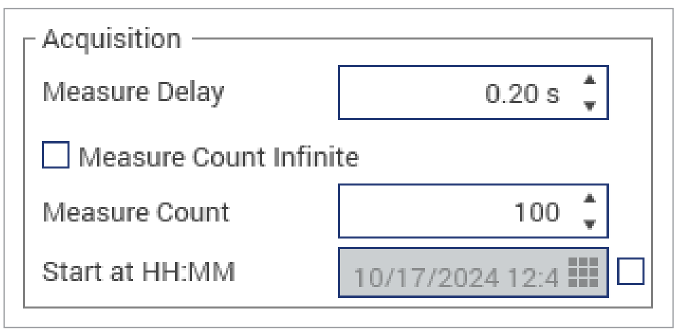

Figure 4: KickStart DMM App Aquisition settings.

Finding the Limits

To test resistor tolerance with KickStart, we will need to use the limits. Start by enabling Limit 1.

Figure 5: KickStart DMM App Limit 1 settings enabled.

Next, we need to find the upper and lower limits of our target resistance measurement. We can do so with the following formulas:

$$\text{Upper Limit} = R + RT$$

$$\text{Lower Limit} = R - RT$$

where R is the rated resistance of the resistor and T is the resistor's tolerance range. For example, a 100 ohm resistor with a tolerance of ±20% would use the following limits:

$$\text{Upper Limit} = 100\ \Omega + 100\ \Omega(20\%) = 120\ \Omega$$

$$\text{Lower Limit} = 100\ \Omega - 100\ \Omega(20\%) = 80\ \Omega$$

To grade resistors, you can also enable Limit 2. This will cause KickStart to test Limit 1 first, and, if the measurement falls within the limit, the software will then test that reading against Limit 2.

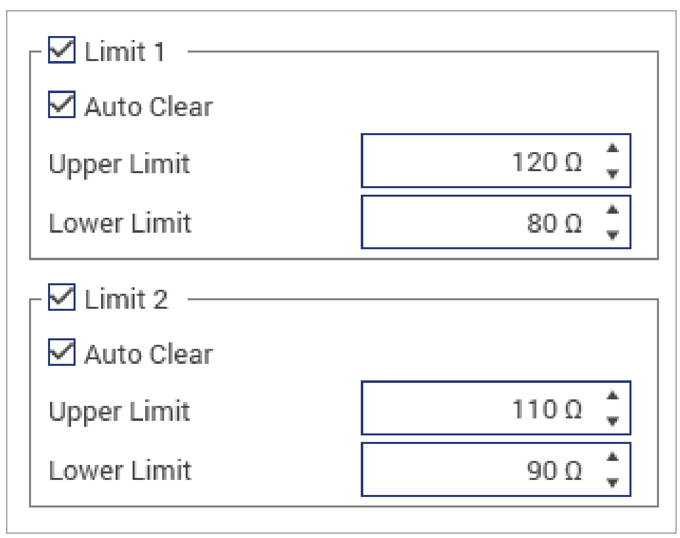

Figure 6: KickStart DMM App Limit 1 and Limit 2 settings enabled.

Connecting a Foot Pedal

A convenient way to ensure ample time to connect each new resistor between readings is to use a generic momentary switch or foot pedal to manually trigger measurements. Switches that are normally open or normally closed will both work, as will a momentary switch of the kind used for musical keyboards.

The coaxial External_Trigger_IN on the back of the DMM6500 can be connected directly to a switch. A convenient way to connect a foot pedal is to use a pedal with a quarter-inch jack connector (such as is used for electric pianos) and a quarter-inch jack to coaxial adapter.

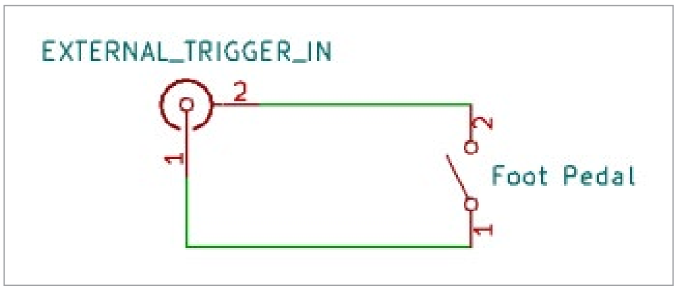

Figure 7: Foot Pedal connection for DMM6500.

The trigger can be configured within KickStart by setting the Trigger Mode to External:

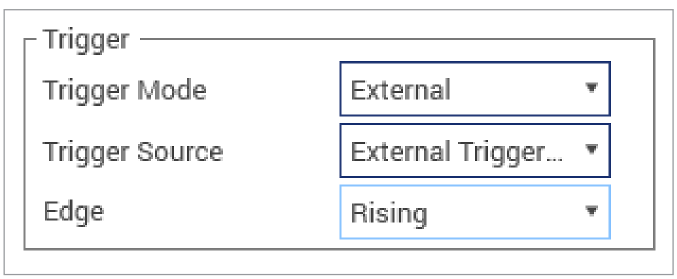

Figure 8: KickStart DMM App Trigger settings.

Interpreting the Data

Measurements that fall outside of the set limits and, thus, the resistor's rated tolerance will appear highlighted in the KickStart Table tab. If Limit 1 fails, the Resistance value will be highlighted in yellow and will not be checked against Limit 2. If Limit 1 passes but Limit 2 fails, the Resistance value will be highlighted in orange. If both limits pass, the Resistance value will not be highlighted. This is how KickStart allows you to determine resistor grading at a glance.

DMM-1

Settings | Table | Graph

	DMM-1	
	Time (s)	Resistance (Ω)
1	0.000000	104.7332
2	30.072115	124.6466
3	60.143157	114.9933
4	90.214189	124.6458
5	120.357139	104.8369

Figure 9: Failed resistor measurements highlighted in the KickStart Table tab.

Conclusion

When you need to test a resistor using a multimeter, KickStart Software offers an easy, no-code solution using its DMM App. KickStart's user-friendly interface makes the required settings easy to find and adjust as necessary for any test. You even have the choice of running a fully-automated test or the ability to trigger measurements manually based on your specific test needs.

The data visualization tools included with KickStart Software provide the convenience of having the resultant data directly at your fingertips. These visualization tools, such as the Table tab, offer a solution to resistor grading and limit testing by making failed measurements that fall outside of the desired limits highly visible, showing you which devices to bin at a glance.

Visit tek.com/kickstart to download and install Kickstart Software today.

Simplifying Long-Term Reliability Testing with the KickStart Data Logger App

APPLICATION NOTE

Introduction

Data Acquisition (DAQ), or data logging, is a process of gathering and analyzing data from various physical phenomena. It plays a crucial role in engineering, scientific research, and industrial settings, enabling real-time monitoring and control of parameters such as temperature, pressure, and voltage. Data acquisition is essential for quality control, process optimization, and troubleshooting.

Data acquisition systems play a key role in reliability testing, allowing different stress conditions like temperature, salt spray, or vibration and their effects on a device to be monitored long term, making it possible to analyze any trends that form over time.

Software is an essential component to long-term datalogging. Because tests involving data acquisition can typically run for weeks, using software to automate the instrumentation and data collection is a necessity. The Kickstart Data Logger App makes automating long term data acquisition and analysis easy.

KickStart Software is compatible with the following Tektronix data acquisition systems: DAQ6510, 3706A, and 2750.

Figure 1: Tektronix DAQ System models 3706A, DAQ6510, and compatible switch cards.

Easy Data Acquisition with the KickStart Data Logger App

The KickStart Software Data Logger App allows you to quickly and easily set up data logging for reliability testing, as well as view, analyze, and export the resulting data from a single user interface without the need to code.

Figure 2: A Tektronix DAQ6510 monitoring components inside an environmental test chamber.

The following example application utilizes a DAQ6510 equipped with a 7700 Multiplexer Card to track the temperatures of different electrical components exposed to stressors within an environmental test chamber.

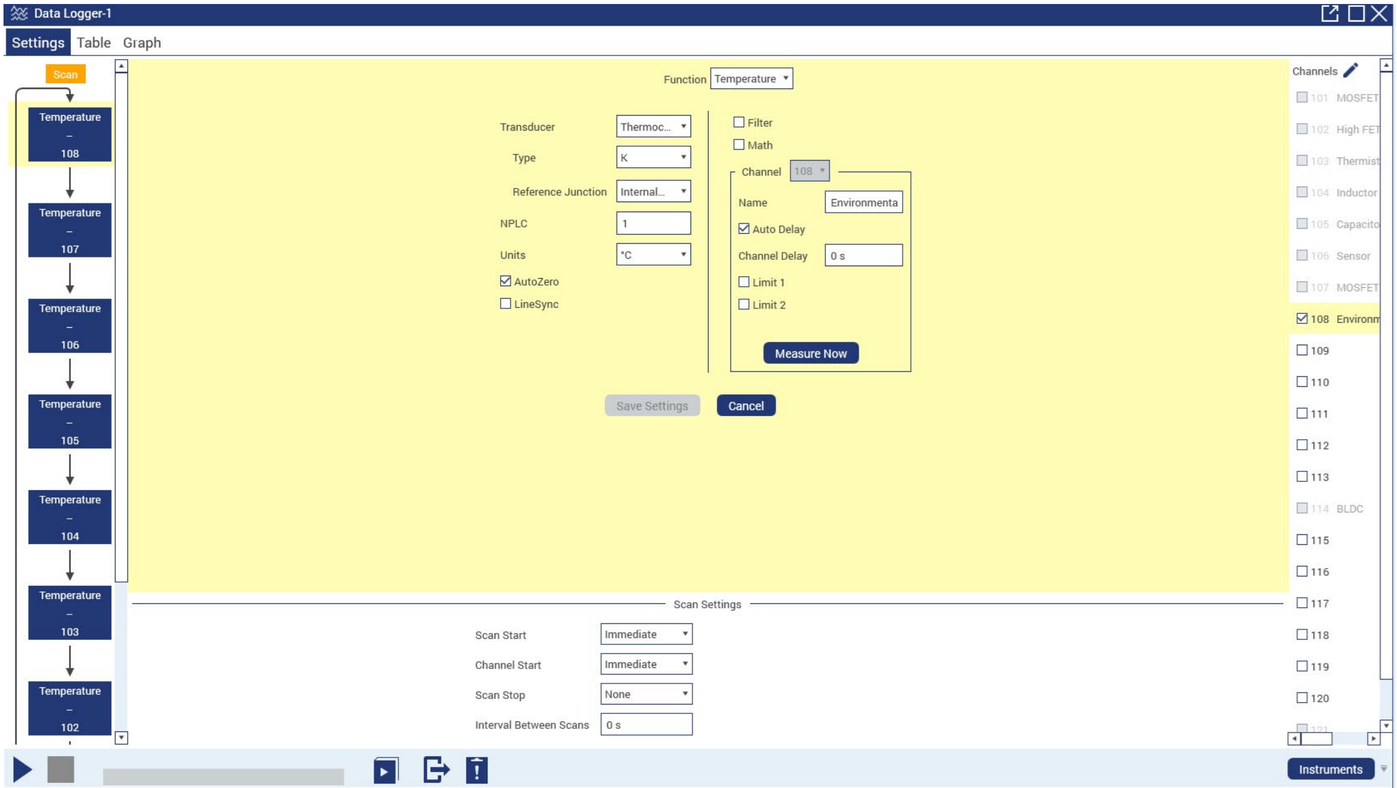

Figure 3: The KickStart Datalogger App Settings tab, configured to take infinite scans of eight channels taking temperature measurements.

Figure 3 shows the KickStart Data Logger App Settings tab configured for a temperature scan of multiple different components over time, including MOSFETs, capacitors, inductors, and sensors, as well as monitoring the temperature of the environmental test chamber itself. Each device is assigned to its own channel that is labeled accordingly. For the purposes of this test, the "Scan Stop" setting has been set to None, so that the test runs infinitely. The intention of setting an infinite scan is so that the test can be stopped manually via the stop button as opposed to setting a specific timeframe for the test to end.

Once the Run button is clicked and the test begins, the DAQ6510 will automatically begin to take measurements and KickStart Software will collect the resulting data. This data can be monitored in the Table tab or Graph tab. **Figure 4** showcases the results of the temperature scan, where it is shown that the temperature of the devices under test rises as the temperature of the environmental chamber levels off after the initial heating phase.

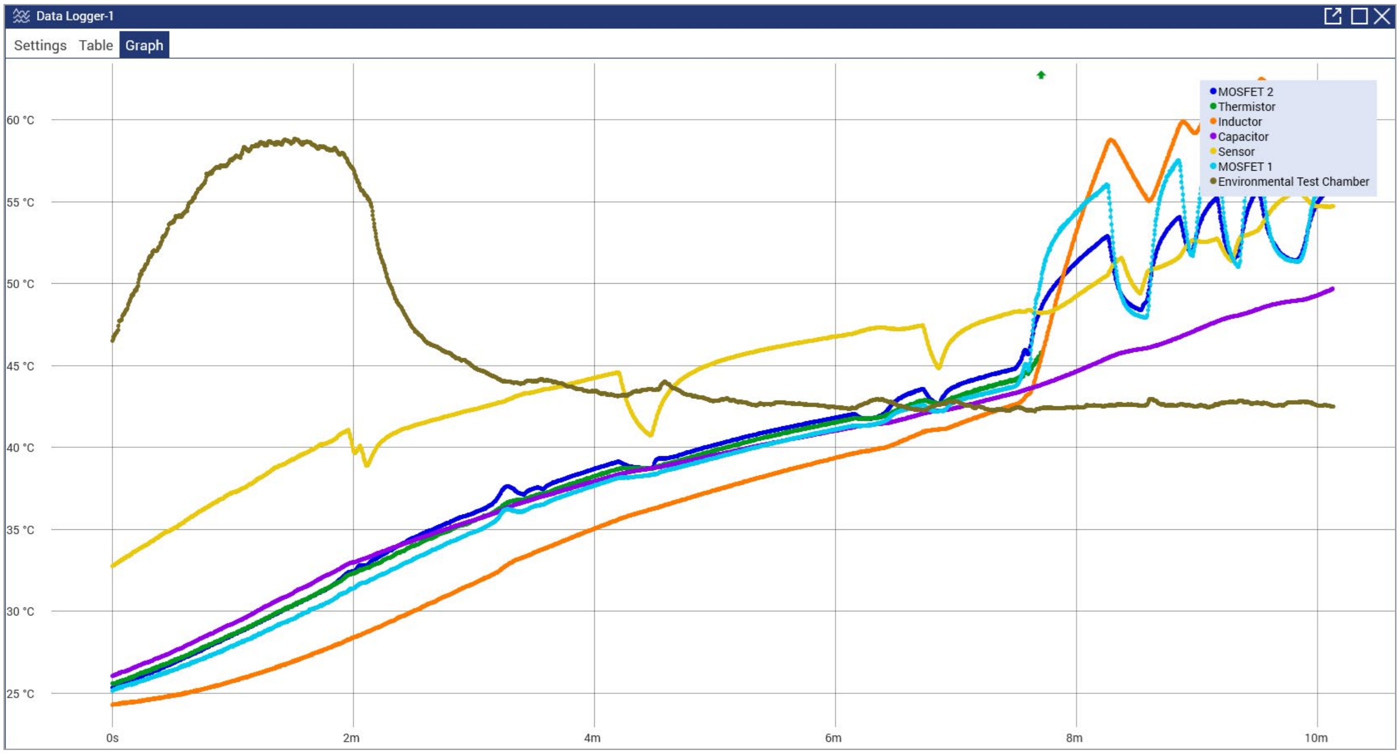

Figure 4: The KickStart Software Graph tab, showcasing the resultant data.

Tips and Tricks

Select Multiple Channels

Hold down the shift key while selecting the first and last channel of the group to quickly select a group of channels so that the same settings can be applied to the entire group.

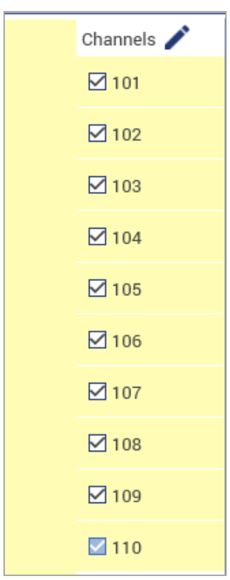

Figure 5: A group of scan channels that will all share the same measurement settings. Channels 101 and 110 were both selected while pressing the shift key, causing all channels between 101 and 110 to be selected.

Edit Table Columns

Columns in the Table tab can be customized for readability and presentation. By expanding the arrow on the left side of the column label, channels in the Table tab can be renamed, hidden, or expanded to show the channel's specific timestamps.

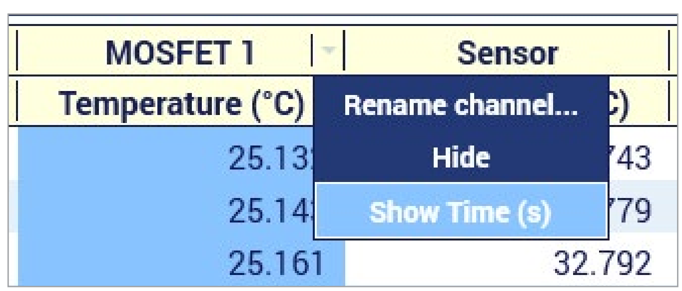

Figure 6: The KickStart Software Table tab with the column settings expanded.

By expanding the arrow on the left side of any Time column, the timestamp format can be changed to absolute time, relative time in seconds, or relative time in day/hour/minute/seconds format.

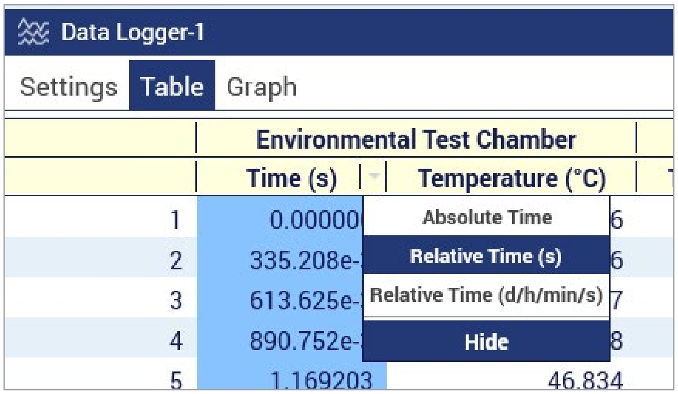

Figure 7: The KickStart Software Table tab with the time column settings expanded.

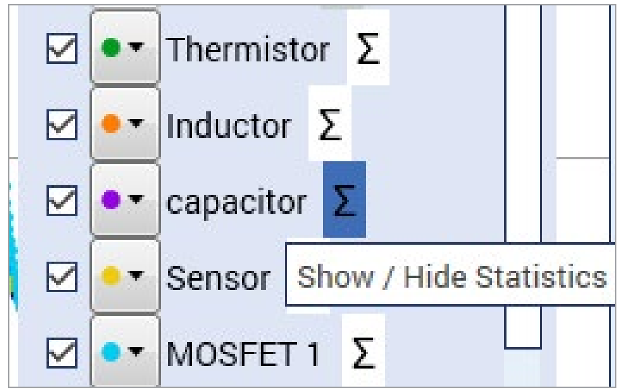

Figure 8: The show and hide statistics option within the KickStart Software graph legend.

View Statistics

Statistics such as area under the curve and standard deviation can be viewed in the graph by mousing over the legend and clicking on the sigma symbol next to the selected trace.

Once statistics have been applied to a trace, they will appear in a box overlaid on the graph. The area beneath the selected trace will be filled in, representing the area under the curve measurement. By right-clicking on the graph, cursors can be applied, and any calculated statistics will instead be measured between those cursors.

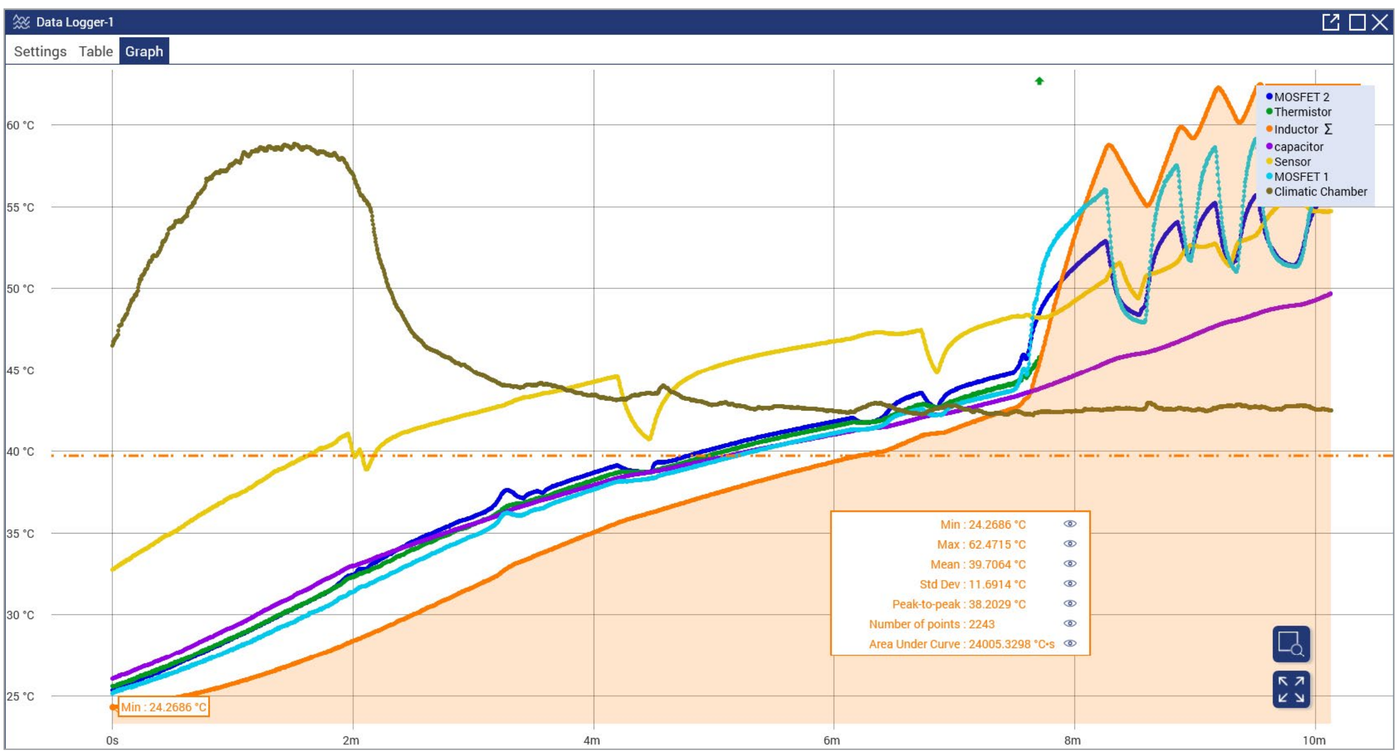

Figure 9: The graph with statistics applied to the Inductor trace.

Best Practices

When using the KickStart Data Logger App long term, there are several best practices that improve the software's performance and ensure that tests will run for days or weeks.

Turn Off Instrument Auto Discovery

To turn off instrument auto discovery, select the Instruments Tab and press the F12 key. This will cause the instrument auto discovery control to appear. Simply deselect the checkbox and KickStart Software will no longer automatically discover instruments on the network.

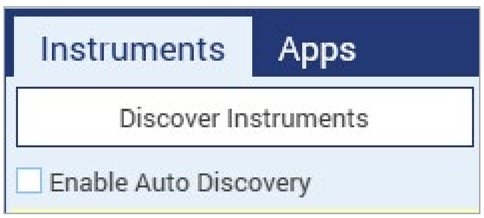

Figure 10: **The KickStart Software Instrument Auto Discovery enablement checkbox that can be accessed by pressing the F12 key while viewing the Instruments Tab.**

Turning off instrument auto discovery improves KickStart's long term performance by limiting the number of interactions between the instrument and the software. After closing the software, instrument auto discovery will be enabled again the next time KickStart is opened.

Turn On Auto Export

Auto export is a useful setting contained in the export data menu. When enabled, collected data will be automatically exported to a *.csv or *.xlsx file when a run has been completed. As of KickStart Software version 2.11.4, an additional "split files" setting can be enabled if auto export is turned on. This setting allows for data to be automatically exported after a specified period while the test is running.

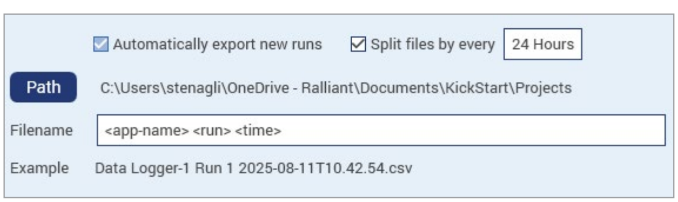

Figure 11: **The KickStart Software data export menu with Auto Export and file splitting enabled.**

Splitting the incoming data into separate files to be exported hourly, daily, or weekly is quite useful for long term data logging applications. This method allows for better organization of data and avoids the creation of unreasonably large files.

Slow Down the Test

When datalogging over a period of days or weeks, be mindful of how much data you want to generate in that timespan. Test speed has the greatest impact on memory usage. This is because continuously generating large amounts of data within a very short timeframe can create an imbalance between new data generation and old data discard, leading to data accumulation. Therefore, consider adding delays or increasing the interval between channel closures or scans to ensure that readings are taken at a reasonable rate.

Avoid Viewing the Graph Until the Test is Complete

Making sure to remain on the Settings Tab while a long-term test is running may improve performance for PCs with less processing power or RAM. Peaking at the Graph or Table Tab temporarily is permissible with some considerations.

The Table Tab operates in two states. One is with AutoScroll enabled, which continuously scrolls to display the latest data. The other is with AutoScroll disabled. Users can stop scrolling by clicking any data row, or switching to another tab will also disable AutoScroll. Disabling AutoScroll consumes less memory, but enabling auto-scroll should not cause significant issues. Of course, for long-term tests, the best practice is to switch to the Table Tab only when viewing data is necessary and return to the Settings Tab otherwise.

Regarding the Graph Tab, it also has two modes: a scrolling X-Axis mode, where the x-axis scrolls or remains static to display data within a specific time window, and an infinite X-Axis mode, where the x-axis displays all values starting from time zero. The scrolling X-Axis mode consumes less memory. Therefore, for long-running tests, the best practice is to only switch to the Graph Tab when viewing the data is necessary and to avoid staying in infinite X-Axis mode for very long periods. Whenever possible, use the scrolling X-Axis mode; the smaller the time window, the less memory it consumes. After viewing, switch back to the Settings Tab.

Conclusion

The KickStart Data Logger App streamlines the process of setting up, running, and analyzing long term reliability tests by providing a simple yet powerful interface for data acquisition. By automating measurement collection, enabling flexible configuration, and offering intuitive tools for data visualization and export, the software removes many of the barriers traditionally associated with long term datalogging. When combined with best practices such as optimizing performance settings, engineers and researchers alike can ensure reliable, continuous operation for days or even weeks. The KickStart Data Logger App empowers users to focus less on managing instrumentation and more on gaining meaningful insights from their data.

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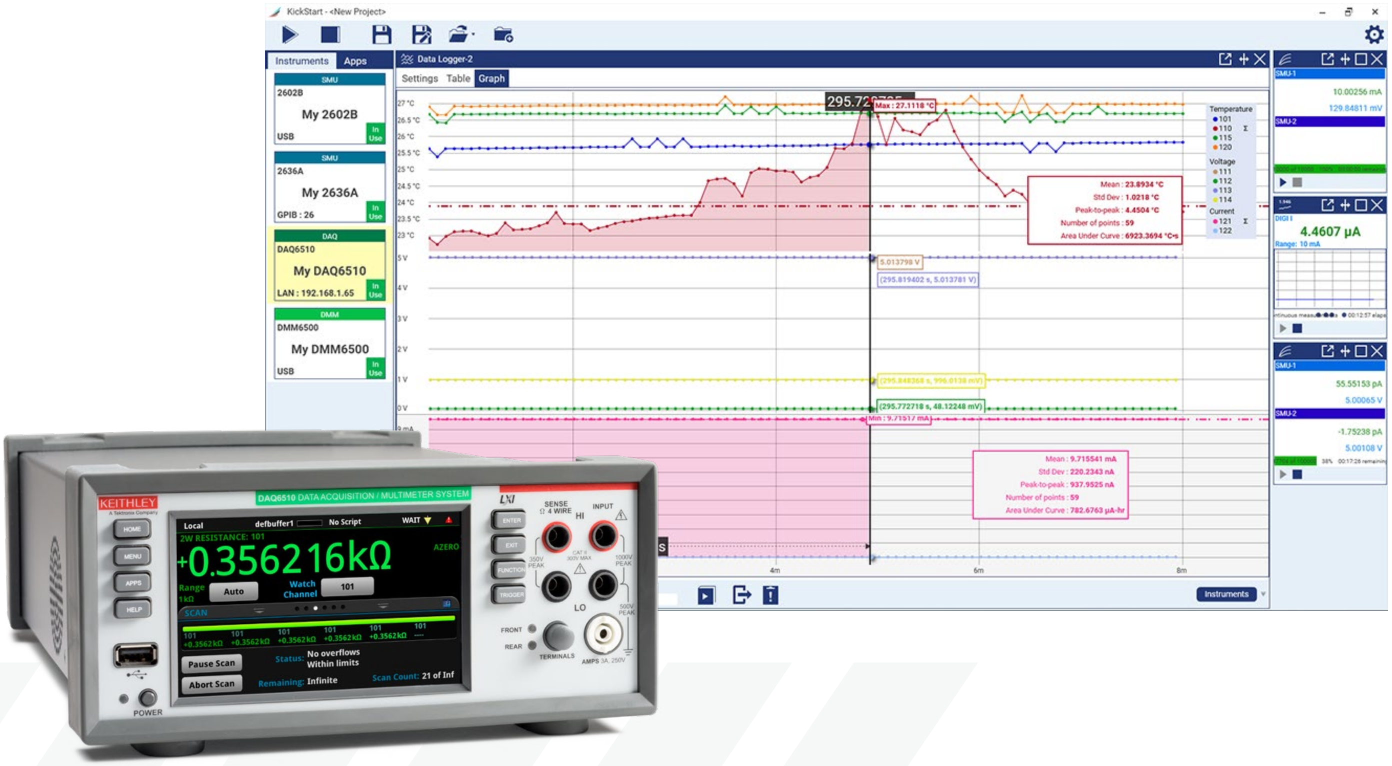
Performing Strain Gauge Measurements with the Keithley DAQ6510 Data Acquisition and Logging Multimeter System and KickStart Software

APPLICATION NOTE



Introduction

A strain gauge is a resistive device that is used to monitor changes in force. As the object on which the strain gauge is mounted is deformed or displaced, so too is the strain gauge, converting mechanical properties into an electrically measurable stimulus.

Strain sensors are useful in several applications:

- Studying torque measurements in electric vehicle drive systems that have a substantially higher power density compared to their combustion engine counterparts. Electric drives have higher rotational speeds, and their torque forces will increase with hauling vehicles as we see the electrification of truck types, from passenger all the way up to Class 8 (heavy duty).
- Stress analysis of building structures can lead to early detection of structural damage in buildings, possibly helping us to better understand climate change and environmental effects.
- Strain gauges can be installed on load-bearing parts used in aerospace to help determine changes during flight.
- Pressure can be monitored in railway systems to promote the warning of excess conditions, thereby assisting maintenance crews in identifying and addressing problem spots before they get out of hand.

This application note will focus on defining some basic strain measurement principals and a means for obtaining these measurements with greater ease. Moreover, we share how you can use the Keithley DAQ6510 Data Acquisition and Logging Multimeter System in concert with the KickStart software to acquire strain measurements through our proposed simplified method.

Simplifying Strain Gauge Measurement

Strain measurements typically do not fluctuate more than a few millistrain – which is equivalent to resistance changes ranging in milliohms – and a popular means for obtaining them is to use a Wheatstone bridge configuration like the one shown in **Figure 1**. The resistors are selected such that when the values are balanced the ratio R_1/R_2 will be equivalent to R_4/R_3 to achieve an output voltage (V_0) of zero. The equation for calculating V_0 for the Wheatstone bridge is as follows, in this case, balanced with $R_2 = R_3 = 100\ \Omega$ and $R_1 = R_4 = 200\ \Omega$:

$$V_O = \left[\left(\frac{R_3}{R_3 + R_4}\right) - \left(\frac{R_2}{R_2 + R_1}\right)\right] * V_{EX}$$

$$V_O = \left[\left(\frac{100}{100 + 200}\right) - \left(\frac{100}{100 + 200}\right)\right] * V_{EX}$$

$$V_O = \left[\frac{1}{3} - \frac{1}{3}\right] * V_{EX} = 0 * V_{EX} = 0\ V$$

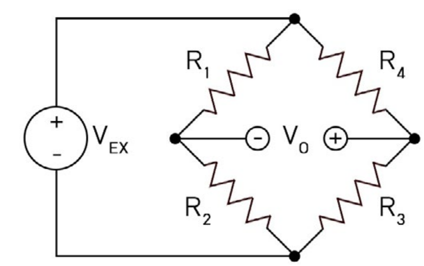


Figure 1: Wheatstone bridge configuration for use in strain measurement.

While we could go through the effort of replacing R_4 in the Wheatstone bridge with a strain gauge (so that the changes in its resistance will result in non-zero values for V_0), this setup can be complicated, requiring a voltage source, two separate voltage measurement devices, and multiple precision resistors to accurately compute a resultant strain value. Also, with so many components, it may be necessary to additionally apply some form of bridge balancing, offset nulling, or other conditioning circuitry. Instead, we will consider implementing a simpler, more cost-effective means using a precision digital multimeter (DMM) and resistance measurements applied directly to the strain gauge.

A 6½-digit DMM can provide a great deal of accuracy and resolution when measuring low-resistance devices. When values are less than 100 ohms, the four-wire (Kelvin) method can be applied to eliminate offsets due to test lead resistance. The primary disadvantage is that when numerous devices are monitored by way of a multiplexer, the number of channels required for the measurement is double that of the traditional two-wire resistance method. However, strain gauge manufacturers are producing some higher resistance device options that will better accommodate the use of the two-wire measurement and help promote greater channel availability in the switching system.

Figure 2 shows how strain (represented as ε) may be calculated as the ratio of the change in length to the known, unstrained length.

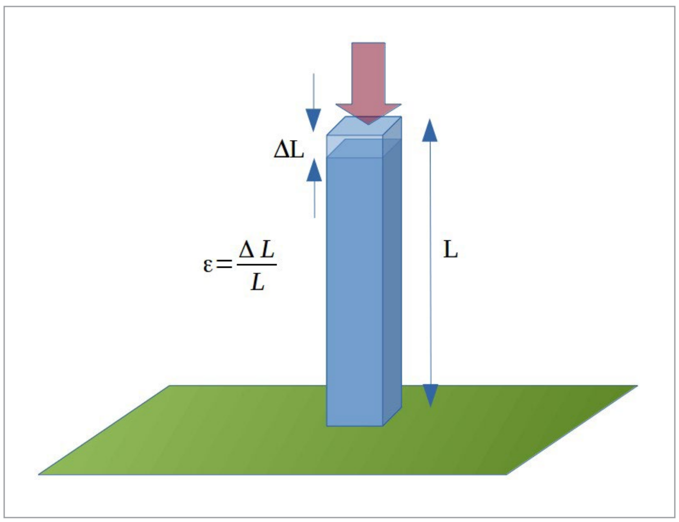


Figure 2: Strain computed from compressed device state in comparison to its quiescent state.

Manufacturers specify a gauge factor (GF) for their devices, which is an expression of the sensitivity to strain, using the formula below, where R is the resistance:

$$GF = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} = \frac{\frac{\Delta R}{R}}{\varepsilon}$$

To solve for strain, the equation is converted as such:

$$\varepsilon = \frac{\frac{\Delta R}{R}}{GF}$$

$$\varepsilon = \Delta R * \frac{1}{GF * R}$$

Since the device's GF is known and the quiescent state resistance can be obtained by way of a simple initial measurement, you can apply the slope intercept formula to each strained resistance measurement to help determine a strain value. For the y-intercept component (*b*), we will use the negative inverse of the GF:

$$y = m * x + b$$

$$m = 1/(GF * R)$$

$$b = -1/(GF)$$

Performing the Strain Measurement

Let us consider performing the measurement using the Keithley DAQ6510 6½-Digit Data Acquisition and Logging Multimeter System along with KickStart Software. Let's also consider a case where you will use a pre-wired strain gauge – whose nominal, listed resistance is 350 Ω and whose GF is specified as 1.93 – connected to channel 101 of your multiplexer card.

After the DAQ6510 is connected to your PC and KickStart Software is running, open an instance of the Data Logger App and opt for the DAQ6510 as the instrument of interest.

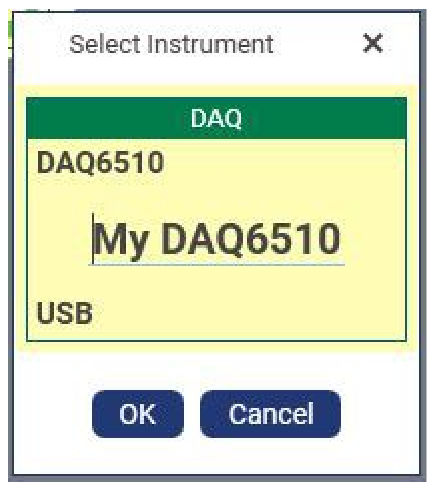


Figure 3: Launch the Data Logger app.

Choose the **2-Wire Resistance** option from the Function list control then select the channel (101) to which your strain gauge is connected. In the "Channel" group area (see **Figure 4**), click on the **Measure Now** button to obtain the strain gauge's quiescent resistance value.

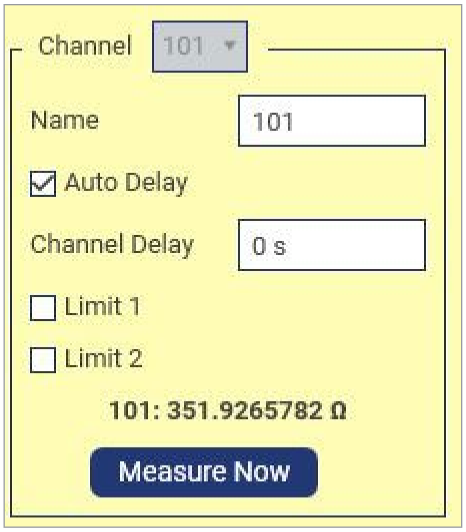


Figure 4: Measuring the device in its unstrained state will give us one of our known factors to be used in computing strain.

Using our measured value and our manufacturer-specified GF, compute the slope-intercept coefficients as:

$$m = \frac{1}{1.93 * 351.9265782} = 0.00147228$$

$$b = -\frac{1}{1.93} = -0.518135$$

Apply the check to the **Math** control to expose the options, choosing **mX+b** for the Function and applying the coefficients calculated above to their designated input fields. Note, too, that you can apply a custom Unit to the calculation. Using your computer's numeric keypad and the **Alt+238** key combination you can generate the lower-case epsilon character that represents the strain unit.

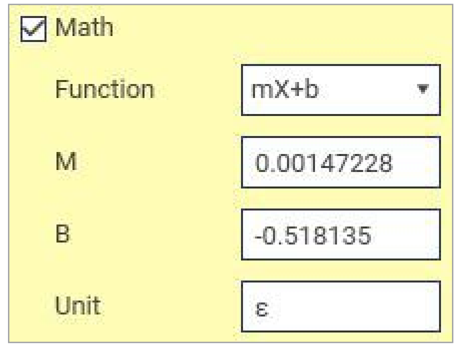


Figure 5: Applying math coefficients and user-specified units.

With the settings applied you will then click **Save Settings**.

To obtain a fast series of measurements, change the Interval Between Scans value to **0.25 s**. Click on the Run button.

In changing to the **Graph** view, you can see that, as you apply tension and compression to the surface on which the strain gauge is mounted, the plot updates as expected with the Y-axis representing the measurements at microstrain (με) levels.

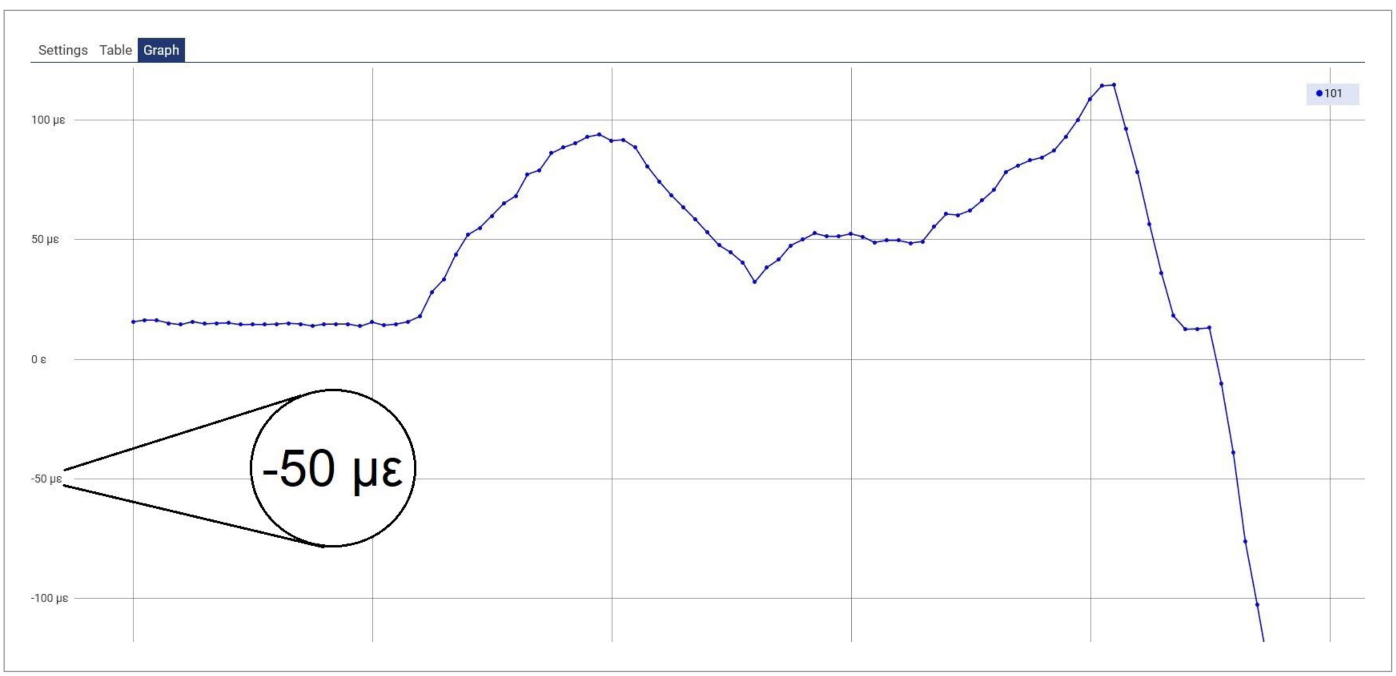


Figure 6: Graphing strain measurements.

Summary

Keithley KickStart Software can be used to quickly automate your strain measurements by way of per-channel math functionality and the ability to apply custom units. Further, while the Keithley DAQ6510 6½-Digit Data Acquisition and Logging Multimeter System can measure micro-ohm changes in your resistive devices on up to 80 channels for two-wire devices, so too can the Keithley Series 3706A Systems Switch and Multiplexer but with increased accuracy on up to 576 channels for two-wire devices.

While the Wheatstone bridge method may be popular, direct resistance measurements made by way of a precision digital multimeter with switching capabilities can greatly simplify your setup. Four-wire resistance measurements can be used when the strain gauge is less than 100 Ω but will require more wiring complexity and yield less channel capability with respect to switching. Two-wire resistance measurements promote greater channel bandwidth and are optimal when the strain device has a higher resistance.

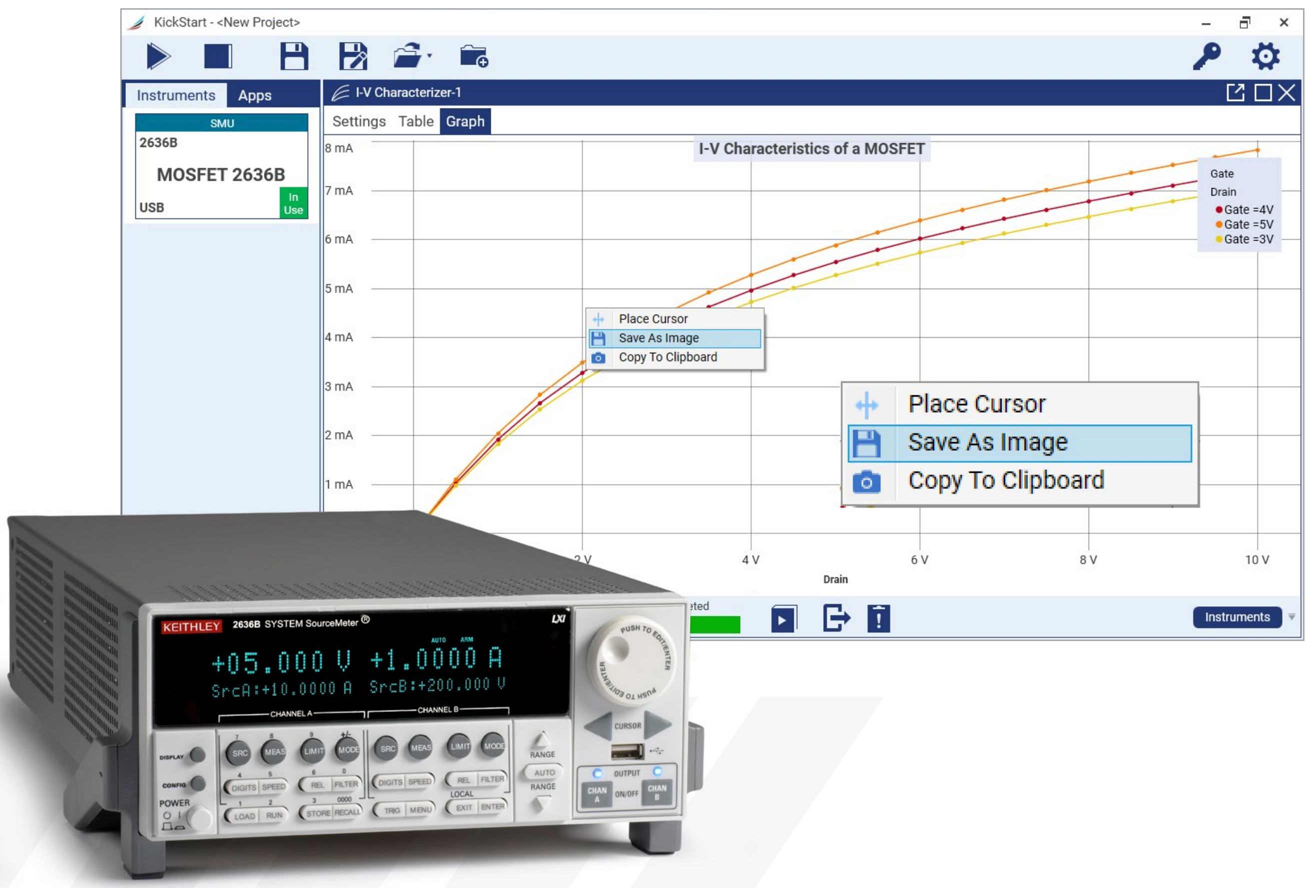
For more information about four-wire versus two-wire resistance measurements, refer to the *Keithley Low Level Measurements Handbook* (section 3.3, "Low Resistance Measurements") found on tek.com.

To learn more about the DAQ6510 and other options, visit Keithley Switching and Data Acquisition Systems.

To learn more about KickStart Software apps and licensing options, visit tek.com/keithley-kickstart.

Pulsed I-V Characterization of MOSFETs Using KickStart Software

APPLICATION NOTE



Introduction

Manufacturers of transistor devices tend to start their design prototype evaluations to yield characteristic information, while still working in their research and design labs. While straight DC testing is the norm in most cases, some of these devices are expected to be operated with a pulsed or briefly-on (switched) stimulus to yield a certain behavior or outcome. The test setups may seem simple on the surface but learning and understanding how to use the instrumentation involved in said tests can often require a steep learning curve. Even after learning to physically operate the equipment, generating the code to automate the testing process can also come with its own challenges as well as a time investment. Ideally, there would be some sort of existing software that can intuitively simplify as much of the testing and automation process as possible.

This document will first introduce the reasons why pulse-based testing might be beneficial for a semiconductor device. Further details are supplied that specifically indicate the application of pulsed test for MOSFET transistors. Additionally, specifics are provided to help guide the reader in using the Keithley KickStart Software to establish automated tests for these devices and generate both tabular and graphical representations of their data.

Benefits of Pulse Testing

The most common reason for using pulsed measurements is to reduce joule heating (i.e., device self-heating). When a test signal is applied to a device under test (DUT), the device consumes power and turns it into heat, increasing the device's temperature. The longer that power is applied, the hotter the device becomes, which affects its electrical characteristics. If a DUT's temperature can't be kept constant, it can't be characterized accurately. However, with pulsed testing, power is only applied to the DUT briefly, minimizing self-heating. Duty cycles of one percent or less are recommended to reduce the average power dissipated by the device over time. Pulsed measurements are designed to minimize the power applied to the device so much that its internal temperature rise is nearly zero, so heating will have little or no effect on the measurements.

Because they minimize joule heating, pulsed measurements are widely used in nanotechnology research, where it is necessary to characterize delicate materials and structures like CNT FETs, semiconductor nanowires, graphene-based devices, molecular-based electronics, and MEMs structures. The heat produced with traditional DC measurement techniques could easily alter or destroy them.

To survive high levels of continuous DC power, devices like MOSFETs and IGBTs require packaging with a solid metal backing and even heat-sinking. However, during the early stages of device development, packaging these experimental devices would be much too costly and time consuming, so early testing is performed at the wafer level. Because pulsed testing minimizes the power applied to a device, it allows for complete characterization of these devices on the probe station, reducing the cost of test.

The reduction in joule heating that pulsed testing allows also simplifies the process of characterizing devices at varying temperatures.

Semiconductor devices are typically so small that it is impossible to measure their temperature directly with a probe. With pulsed measurements, however, the self-heating of the device can be made so insignificant that its internal temperature can be assumed to be equal to the surrounding ambient temperature. To characterize the device at a specific temperature, simply change the surrounding ambient temperature with a thermal chamber or temperature-controlled heat sink. Once the device has reached thermal equilibrium at the new ambient temperature, repeat the pulsed measurements to characterize the device at the new temperature.

Pulsed measurements are also useful for extending instruments' operating boundaries. A growing number of power semiconductor devices are capable of operating at 100 A or higher but building an instrument capable of sourcing this much DC current would be prohibitive. However, when delivering pulse mode power, these high-power outputs are only needed for very short intervals, which can be done by storing the required energy from a smaller power supply within capacitors and delivering it all in one short burst. This allows instruments like a high-power source measure unit (SMU) to source high current (or voltage) levels with precision current and voltage measurements.

Measuring I-V Curves of a MOSFET

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. Keithley is the industry leader in I-V characterization of transistors. Using SMU instruments for semiconductor characterization is ideal because of their ability to both source and measure, especially low currents. Testing devices that have more than two terminals usually requires more than one SMU.

However, a two-channel SMU can perform most characterizations on a single field effect transistor (FET).

Figure 1 shows two SMUs in use for I-V characterization of a MOSFET.

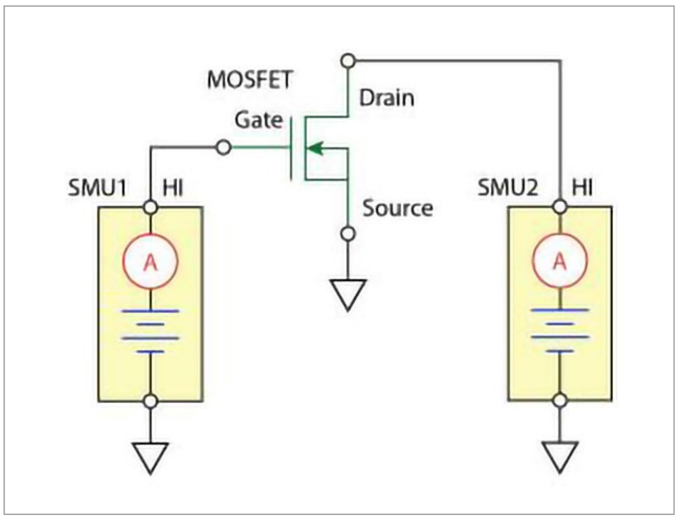


Figure 1: Circuit diagram showing a two-channel SMU in use for I-V characterization of a MOSFET.

Examples of common measurements made in I-V characterization of transistors are as follows:

- Drain Voltage (V_D) - The voltage appearing at the drain terminal of a FET is called the drain voltage.
- Drain Current (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.

Other common measurements include:

- Gate Voltage (V_G)
- Gate Current (I_G)
- Threshold Voltage (V_{TH})

Figure 2 shows a MOSFET drain family of curves generated by using a dual-channel Keithley SourceMeter® SMU instrument.

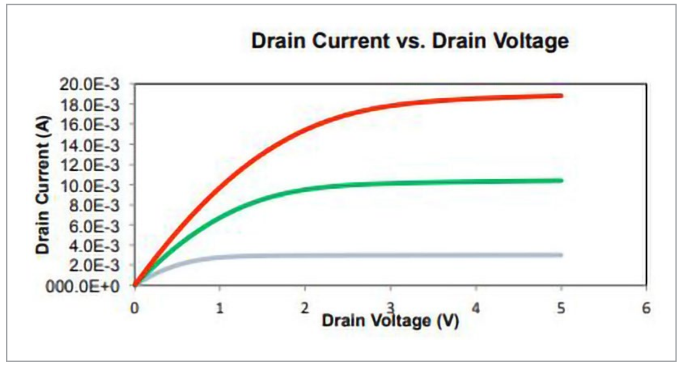


Figure 2: I-V curve of a MOSFET.

Pulsed I-V characterization (as alluded to previously, wherein voltages and currents are applied for a very short time and at a limited duty cycle) is another common way to measure I-V curves and can be accomplished using the KickStart Software. Pulsed I-V measurements can reduce test times and allow for MOSFET characterization without exceeding its safe operating area or causing the device to self-heat and its parameters to shift.

Two pulsed I-V channels are typically used to measure these MOSFET I-V curves with one channel connected to the gate and the other to the drain. The ground of each channel is connected to the MOSFET source pin.

To construct the transistor curves, the gate channel first applies voltage to the gate, then the drain channel sweeps V_{DS} through a range of values, measuring the resulting current at each point. Next, the gate channel applies a different voltage to the gate and the process repeats, constructing the next MOSFET I-V curve in the set.

A SMU can simplify this process with built-in pulsed and DC sweeps, including linear staircase, logarithmic staircase, and custom sweeps (**Figure 3**). All sweep configurations can be programmed for single-event or continuous operation.

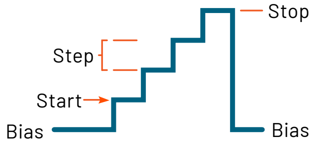
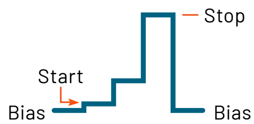
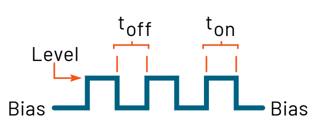
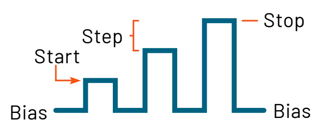
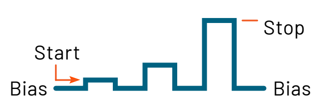
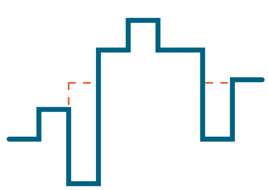
 **Fixed Level**	LEVEL, COUNT (number of DELAY-MEASURE cycles), DELAY, BIAS	**A fixed level sweep outputs a single level of voltage and current with multiple measurements to bias and/or stress devices.**
 **Linear Stair**	START, STOP, STEP, DELAY, BIAS	**The linear staircase sweep goes from the start level to the stop level in equal linear steps.**
 **Logarithmic Stair**	START, STOP, POINTS/DECADE (5, 10, 25, or 50), DELAY, BIAS	**The logarithmic staircase sweep is similar to the linear staircase sweep, but it is done on a log scale with a specified number of steps per decade.**
 **Pulse**	LEVEL, COUNT, t_{on}, t_{off}, BIAS	
 **Linear Stair Pulse**	START, STOP, STEP, t_{on}, t_{off}, BIAS	**Pulsed sweeps greatly reduce the power dissipation within a device, so the effects of temperature (drift, device failure, etc.) are virtually eliminated.**
 **Logarithmic Stair Pulse**	START, STOP, POINTS/DECADE (5, 10, 25, or 50), t_{on}, t_{off}, BIAS	
 **Custom**	Custom sweeps allow the user to program individual steps to create waveforms	**The custom sweep allows you to construct special sweeps by specifying the number of measurement points and the source level at each point.**

Figure 3: Examples of DC and pulsed sweeps.

Measuring Pulsed I-V Characteristics of FETs in KickStart

This example application demonstrates how to use a Series 2636B SMU instrument to perform pulsed I-V characterization of FETs. The 2636B is a good choice for semiconductor device testing because it can quickly and accurately source and measure both current and voltage.

Determining the I-V parameters of FETs helps you ensure that they function properly in their intended applications, and that they meet specifications. There are many I-V tests that you can perform with the 2636B, including gate leakage, breakdown voltage, threshold voltage, transfer characteristics, and drain current. The number of 2636B instruments required for testing depends on the number of FET terminals that must be biased and measured.

This application shows you how to perform a drain family of curves (Vds-Id) on a three-terminal MOSFET. The MOSFET is the most commonly used FET because it is the basis for digital integrated circuits.

Equipment and Software Required

- One 2636B SourceMeter SMU Instrument
- Keithley KickStart Startup Software version 2.6.0 or later, installed on your computer; you can download the KickStart software from tek.com/keithley-kickstart.
- Four triaxial cables (Keithley 7078-TRX-10)
- A metal-shielded test fixture or probe station with female triaxial connectors
- A triaxial tee connector (Keithley 237-TRX-T)
- Use one GPIB cable, one USB cable, or one ethernet cable

Set up Remote Connections

This application is configured to run remotely. You can run this application from any of the supported communication interfaces for the instrument (GPIB, USB, or ethernet).

Figure 4 shows the rear-panel connection locations for the remote communication interfaces.

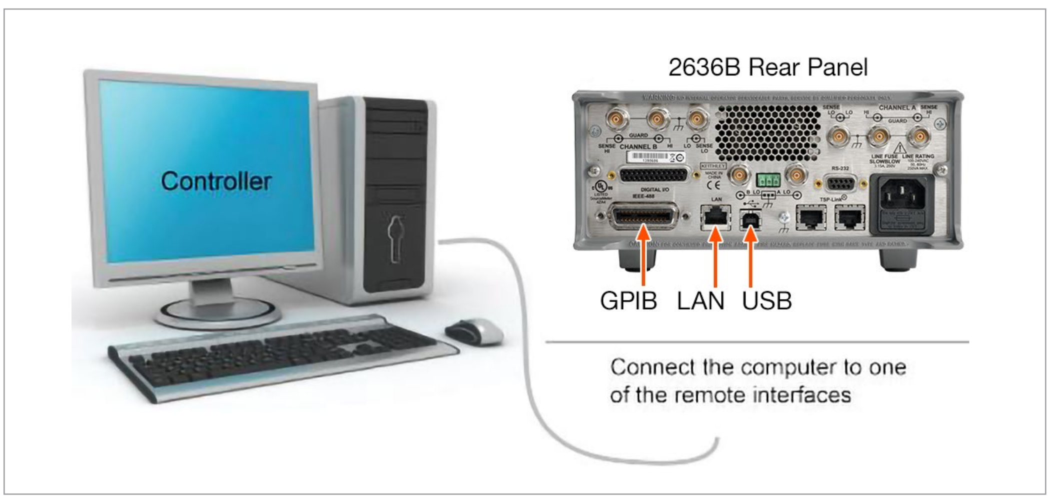


Figure 4: 2636B remote interface connections.

Device Connections

To perform a drain family of curves, configure both instruments to source voltage and measure current.

In this circuit, you connect the Force HI terminal of 2636B SMUB to the gate of the MOSFET and connect the Force HI terminal of 2636B SMUA to the drain.

You connect the source terminal of the MOSFET to the Force LO terminals of both 2636B channels. You need a second 2636B (or a 2635B single channel SMU) if you want to source and measure from all three terminals.

Figure 5 shows an I-V test configuration for a MOSFET using the two 2636B instrument channels.

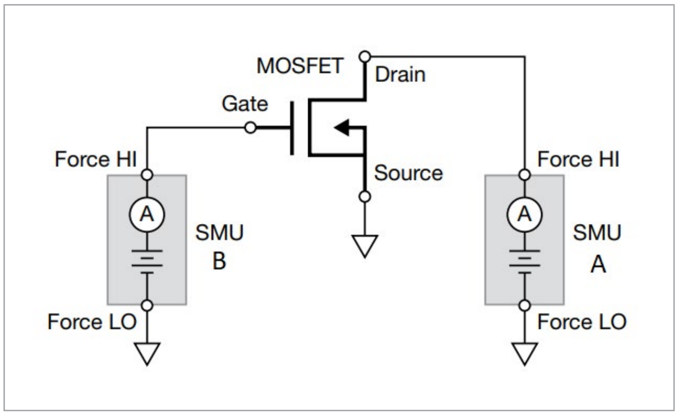


Figure 5: Three-terminal I-V test configuration for a MOSFET.

Figure 6 shows the connections from the rear-panel terminals of the 2636B channels to the MOSFET.

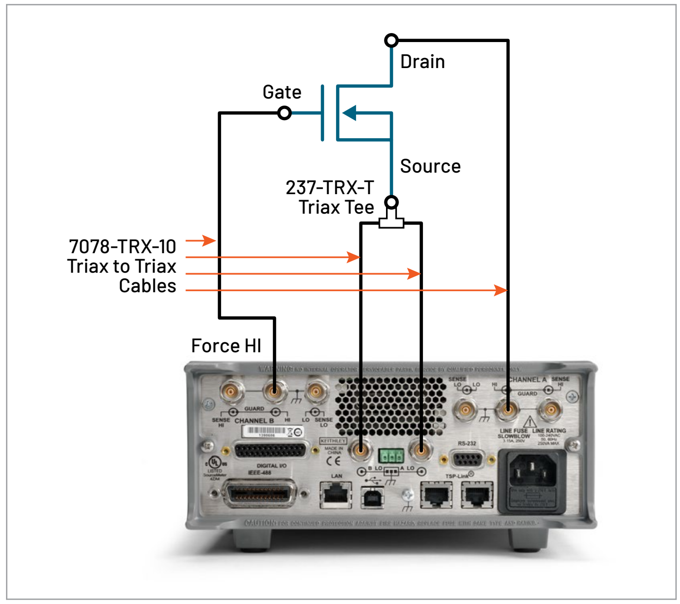


Figure 6: Two 2636B channels configured to test a three-terminal MOSFET.

For this application, connect four triaxial cables (7078-TRX-10) from the 2636B rear-panel female triaxial connectors to the MOSFET device. Mount the MOSFET device in a metal-shielded test fixture with female triaxial connectors. Connect the Force LO terminals of both 2636B channels to the Source terminal of the MOSFET using a triaxial tee connector (237-TRX-T).

Launch KickStart and Set Up the Test

Once the communication cable is connected between the computer and the 2636B, you are ready to launch the KickStart software.

To create the test project:

1. Launch the KickStart software. The startup screen is displayed, as shown in **Figure 7**.

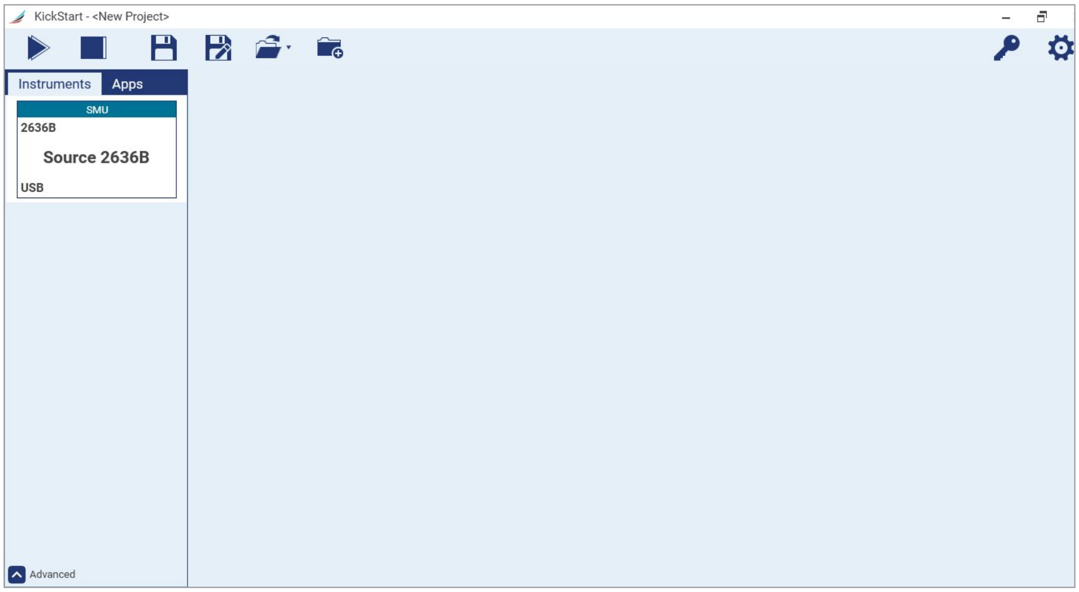


Figure 7: KickStart software startup page.

2. In the instrument instance, click on the centered label to rename to "MOSFET 2636B". Note that this is not a mandatory step but a means to show how you might apply customized names to your instruments in the event that you have several SMUs or other instruments to choose from in the KickStart user interface.

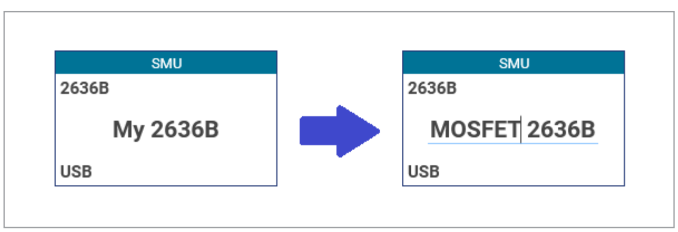


Figure 8: The user can rename instrument instances.

3. Either double-click or drag the MOSFET 2636B instrument into the main app staging area then select **I-V Characterizer**.

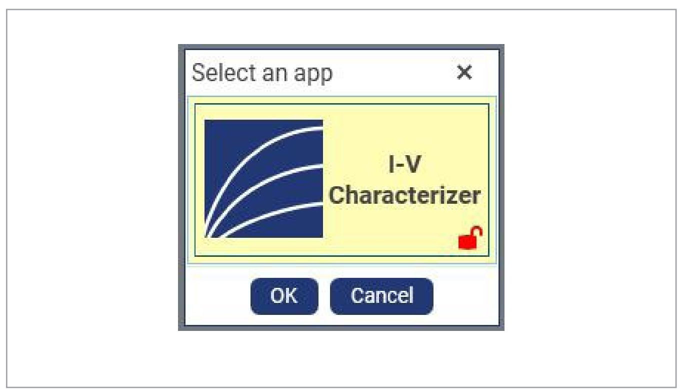


Figure 9: Select the I-V Characterizer App.

4. Navigate to the SMU-1 channel settings tab and modify the channel label to read "Drain".

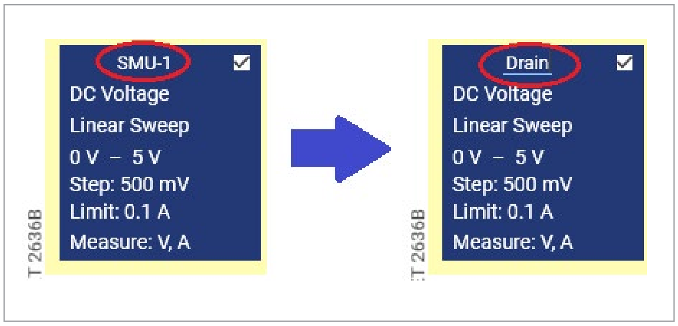


Figure 10: Renaming the SMU channel.

5. Apply the following drain source changes (illustrated in **Figure 11**):
   a. Set the Type to **Pulse**.
   a. Set the Function to **Voltage**.
   a. Set the Mode to **Sweep**.
   a. Set the Start level to **0 V**.
   a. Set the Stop level to **10 V**.

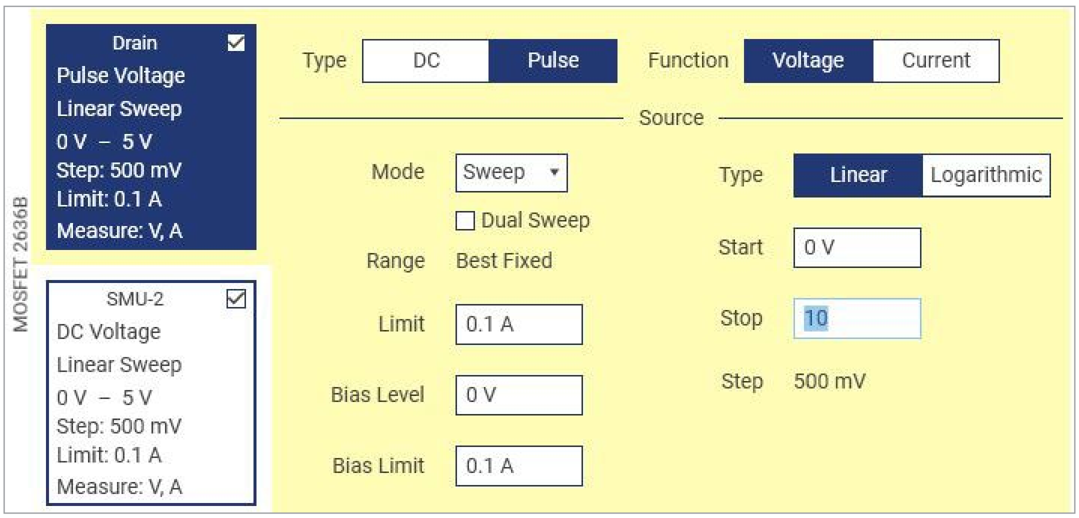


Figure 11: Apply drain source type and output settings.

2. Navigate to the SMU-2 settings tab and modify the channel label to read "Gate".

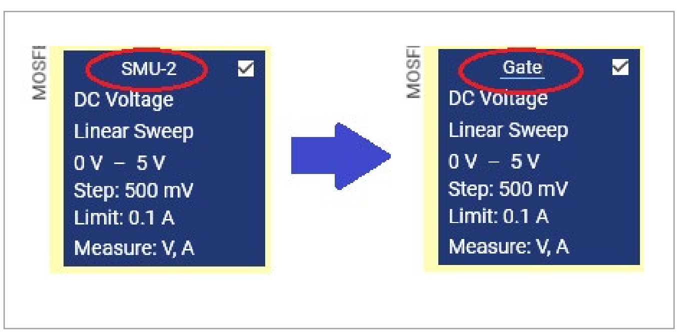


Figure 12: Renaming the SMU channel.

3. Apply the following Gate source changes (illustrated in **Figure 13**):
   a. Set the Type to **Pulse**.
   a. Set the Function to **Voltage**.
   a. Set the Mode to **Sweep**.
   a. Set the Start level to **3 V**.
   a. Set the Stop level to **5 V**.
   a. Set the Limit to **10 mA**.

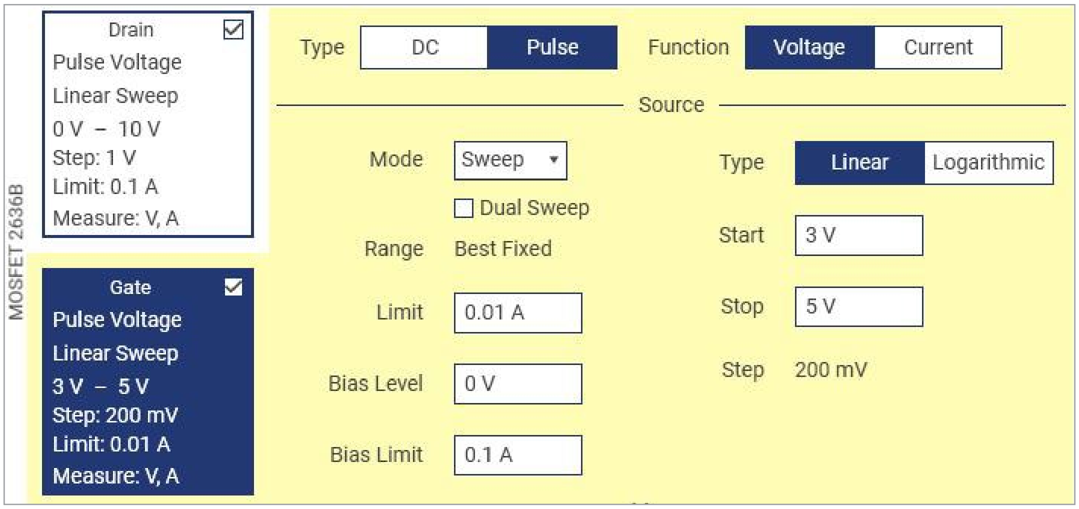


Figure 13: Apply gate source type and output settings.

8. In the Measure settings area, change the Range to **10 mA**.
9. Navigate to the Common Settings pane and apply the following settings:
   a. Set the Source/Sweep Points to **21**.
   b. Set the Source to Measure Delay to **5e-4 s**.
   c. Set the Width to 10 ms.
   d. Set the Off Time to 100 ms.
   e. Set the Stepper to Gate.
   f. Set the Stepper Points to **3**.

Note, too, how the Waveform Viewer pane updates to show the output of each SMU channel, with the Gate stepper (SMU-2) applying a set level for each of its defined steps and the Drain sweeper (SMU-1) performing a sweep at each of the gate step levels.

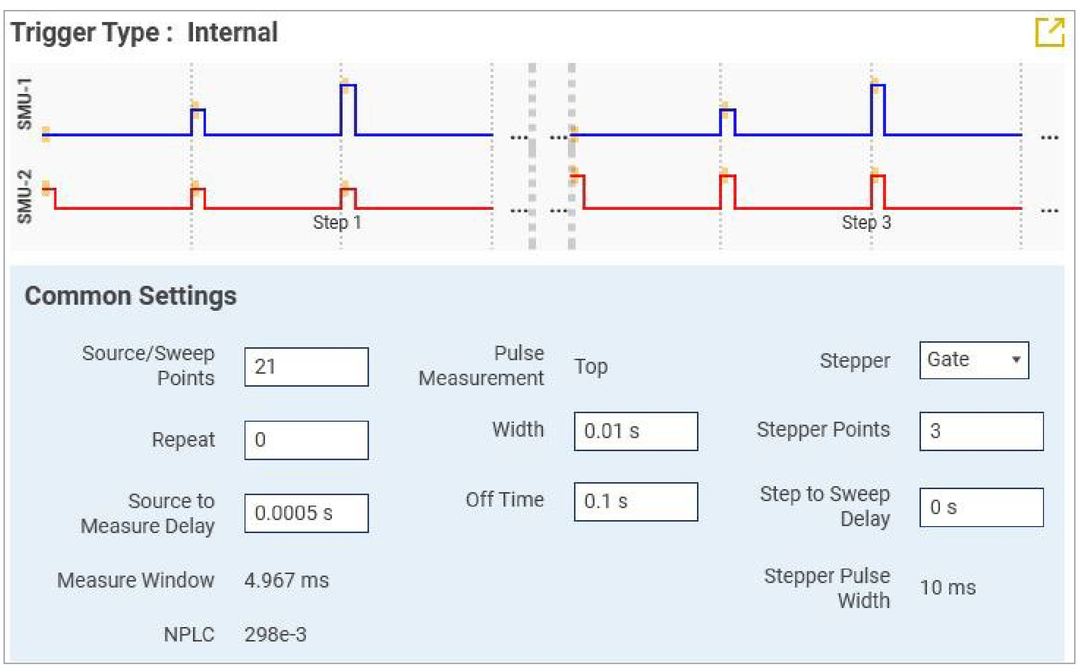


Figure 14: Apply the Common Settings.

10. Click on the **Run** button to execute the test.
11. Click on the **Graph** tab at the top of the KickStart user interface.
12. Hover your mouse cursor above the legend and de-select the Current data for the Gate.

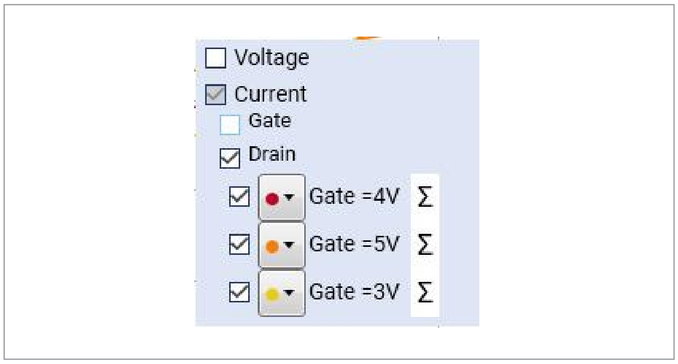


Figure 15: Update the legend settings to plot only Drain current on the y-axis.

13. Hover your mouse cursor in the top center area of the graph to reveal the title entry field and provide a title of your choosing to your graph.

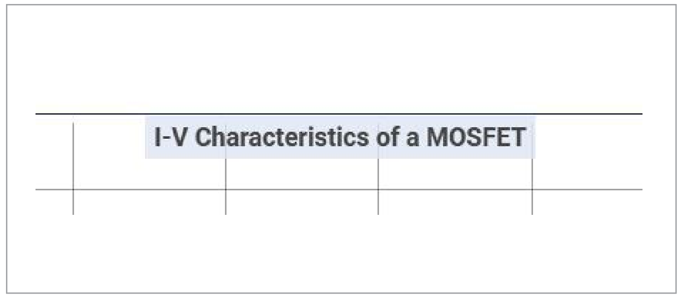


Figure 16: Provide your test data a title.

14. You have immediate visualization of your data but also have the option to save the graph image as a *.png file or copy to the clipboard for immediate pasting into messages or reports.

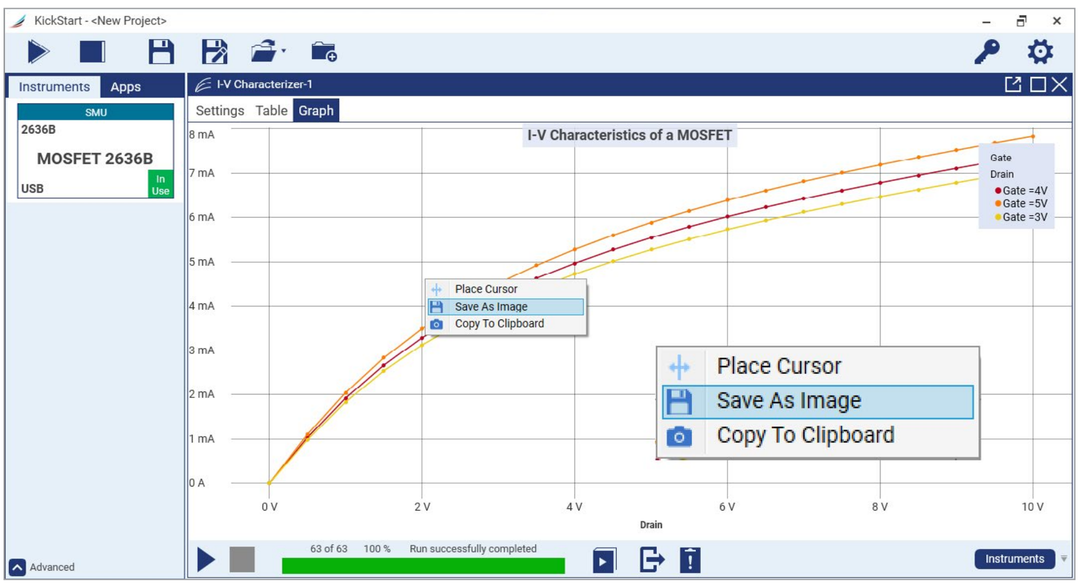


Figure 17: Pulse width modulated output data presented graphically.

Summary

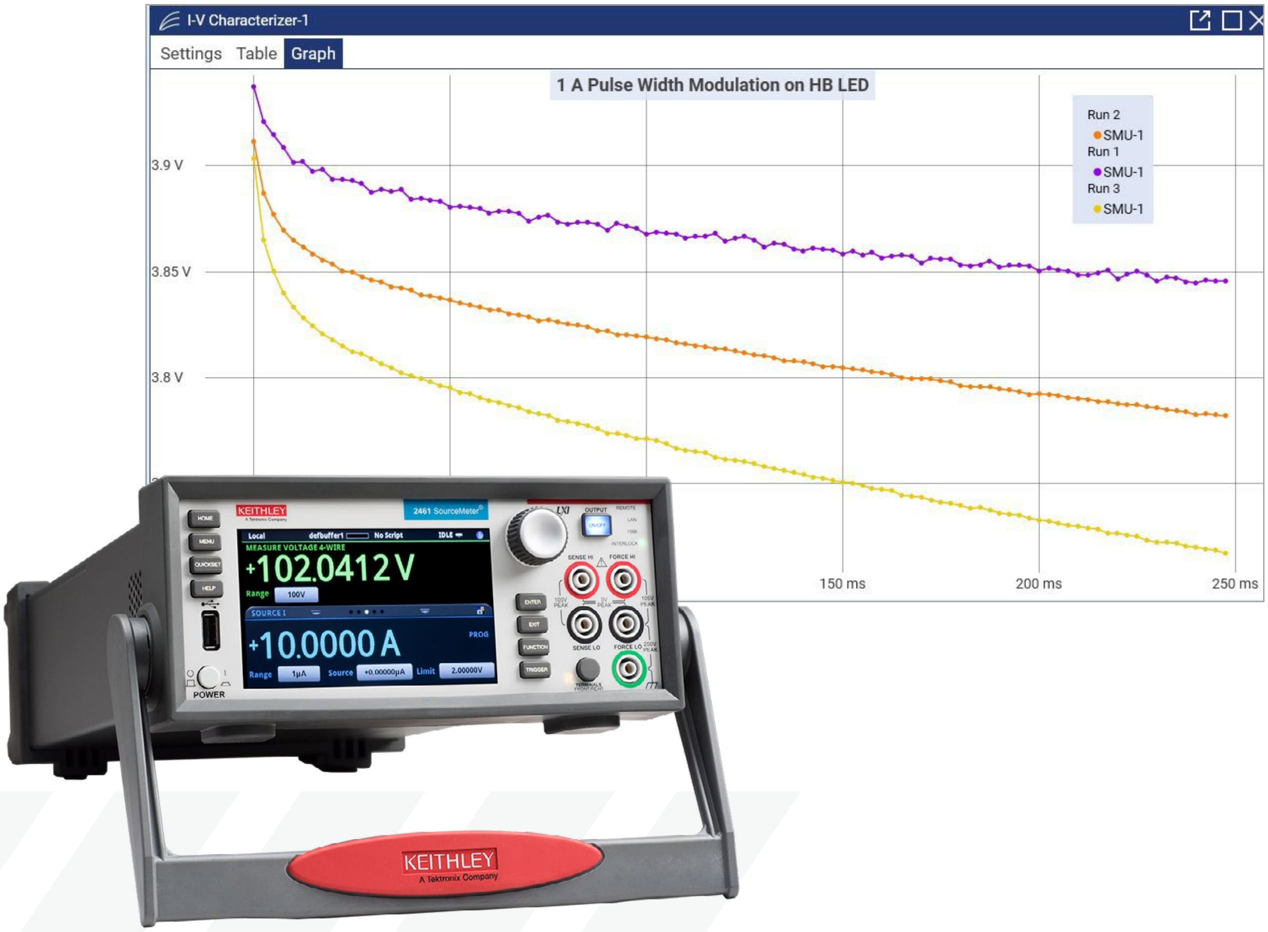
The primary reason for pulse testing is to reduce device self-heating that happens when the device is activated – especially at its maximum operating potential – for increasing periods of time. Early device designs where proper packaging or heat sinking are not yet in place are the perfect stage at which to employ pulse testing. For IGBTs and power MOSFETs this can help yield early insights into device performance, potentially leading to flaw detection and design modifications.

Whatever your pulse-based testing needs, Keithley source measure units and KickStart software are an ideal pairing to help quickly establish your test setups, collect data, and share tabular and graphical insights with your colleagues. The KickStart examples shared within this document use the Series 2636B SMU that are capable of achieving 10 A, 50 W in its pulse operating region. However, keep in mind that KickStart also supports the 2651A (for higher current up to 50 A) and 2657A (for higher voltages up to 3000 V) SMUs.

Tektronix®

Pulsed Characterization of HBLEDs Using Keithley KickStart Software

APPLICATION NOTE



Introduction

Manufacturers of devices like high-brightness light-emitting diodes (HBLEDs) tend to start their design prototype evaluations to yield characteristic information, while still working in their research and design labs. While straight DC testing is the norm in most cases, some of these devices are expected to be operated with a pulsed or briefly-on (switched) stimulus to yield a certain behavior or outcome. The test setups may seem simple on the surface but learning and understanding how to use the instrumentation involved in said tests can often require a steep learning curve. Even after learning to physically operate the equipment, generating the code to automate the testing process can also come with its own challenges as well as a time investment. Ideally, there would be some sort of existing software that can intuitively simplify as much of the testing and automation process as possible.

This application note will first introduce the reasons why pulse-based testing might be beneficial for a semiconductor device. Further details are supplied that specifically indicate the application of pulsed test for high-brightness LEDs. Additionally, specifics are provided to help guide the reader in using the Keithley KickStart Software to establish automated tests and generate both tabular and graphical representations of their data.

Benefits of Pulse Testing

The most common reason for using pulsed measurements is to reduce joule heating (i.e., device self-heating). When a test signal is applied to a device under test (DUT), the device consumes power and turns it into heat, increasing the device's temperature. The longer that power is applied, the hotter the device becomes, which affects its electrical characteristics. If a DUT's temperature can't be kept constant, it can't be characterized accurately. However, with pulsed testing, power is only applied to the DUT briefly, minimizing self-heating. Duty cycles of one percent or less are recommended to reduce the average power dissipated by the device over time. Pulsed measurements are designed to minimize the power applied to the device so much that its internal temperature rise is nearly zero, so heating will have little or no effect on the measurements.

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Pulsed measurements are also useful for extending instruments' operating boundaries. A growing number of power semiconductor devices are capable of operating at 100 A or higher but building an instrument capable of sourcing this much DC current would be prohibitive. However, when delivering pulse mode power, these high-power outputs are only needed for very short intervals, which can be done by storing the required energy from a smaller power supply within capacitors and delivering it all in one short burst. This allows instruments like a high-power source measure unit (SMU) to source high current (or voltage) levels with precision current and voltage measurements.

HBLED Testing – Forward Voltage and Pulse Width Modulation

Visible LEDs have gained a reputation for high efficiency and long lifetimes, which has led to their use in a growing list of applications, including automotive displays and exterior lights, backlighting for televisions and video monitors, streetlights, outdoor signs, and interior lighting. Extensive research and development efforts by LED manufacturers have led to the creation of LEDs with higher luminous flux, longer lifetimes, greater chromaticity, and more lumens per watt, which has driven demand and encouraged an even wider array of applications. To ensure the reliability and quality of these devices, accurate and cost-effective testing is critical.

LED testing involves different types of test sequences at various stages of production, such as during design research and development, on-wafer measurements during production, and final tests of packaged parts. While concrete testing "recipes" often include a multitude of steps intended to verify product lifetime or extract data on specific performance characteristics, they are beyond the scope of this application note. This section of the document is intended to provide solid information on some elementary "ingredients" for these recipes—basic tests that illustrate how to probe for the diodes' characteristics and example test setups.

Testing LEDs typically involves both electrical and optical measurements. Here we focus on electrical characterization. **Figure 1** illustrates the electrical I-V curve of a typical diode. A complete test could include a multitude of voltage values versus current operating points, but a limited sample of points is generally sufficient to probe for the figures of merit.

Some tests require sourcing a known current and measuring a voltage, while others require sourcing a voltage and measuring the resulting current. A SMU instrument is ideal for these types of tests because it can be configured to source voltages or currents and can also measure each of these signal types simultaneously.

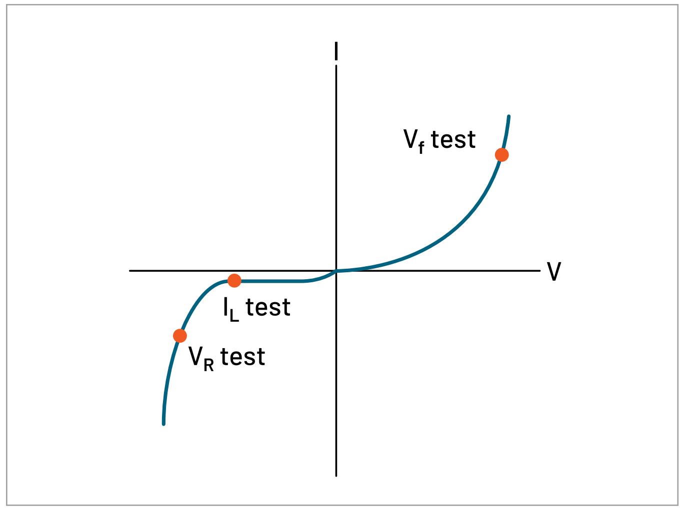


Figure 1: Typical LED DC I-V curve and test points (not to scale).

The V_F test verifies the forward operating voltage of the visible LED. When a forward current is applied to the diode, it begins to conduct. During the initial low current source values, the voltage drop across the diode increases rapidly, but the slope begins to level off as drive currents increase. The diode normally operates in this region of relatively constant voltage. It is also quite useful to test the diode under these operating conditions. The forward voltage test (V_F) is performed by sourcing a known current and measuring the resulting voltage drop across the diode. Typical test currents range from tens of milliamps to amps, while the resulting voltage measurement is typically in the range of few volts. The results of this test are usually used by manufacturers for binning purposes as the forward voltage is directly related to the chromaticity of the LED.

While the traditional process for this testing involves applying constant direct current (DC) stimulus, changes in technology warrant changes in methodology. While voltage levels across LEDs have not shown a dramatic shift, HBLEDs are subject to higher currents and, therefore, higher power. Device designers have developed different means to operate and test them.

Pulse width modulation is a common method of controlling the brightness of LEDs. When using this technique, the current through the LED is pulsed at a constant frequency with a constant pulse level, but the width of the pulse is varied (**Figure 2**). Varying the width of the pulse changes the amount of time the LED is in the ON state, as well as the perceived level of brightness. In this drive scheme, the LED is actually flashing, but the frequency of the flashing is so high that it's indistinguishable to the human eye from a constant light level. Although it's possible to control the brightness of an LED simply by lowering the forward drive current, pulse width modulation is the preferable technique for a number of reasons.

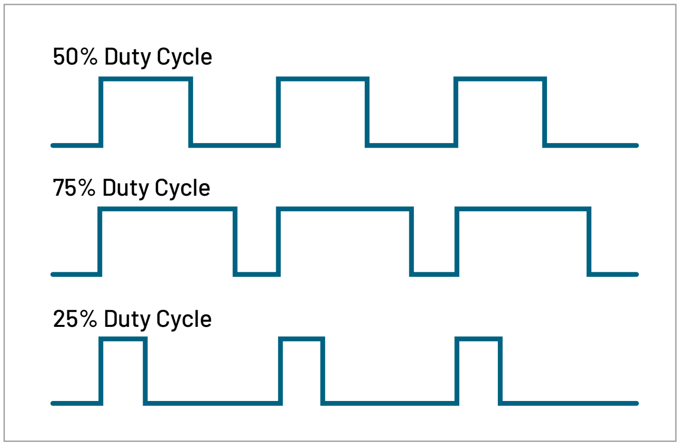


Figure 2: In pulse width modulation, the pulse level and frequency remain constant, but the duty cycle is varied.

Arguably, the most important reason for using pulse width modulation is to maintain consistency of the color of the light as the LED's brightness is reduced. In an LED, the color of the light it emits is related to the forward voltage at which it operates. Although the forward voltage of an LED will remain relatively constant as the forward current is changed, it actually does vary by as much as tens to even hundreds of millivolts. This occurs especially at lower current levels (**Figure 3**). This slight variation in forward voltage equates to a slight variation in light color, which is undesirable for the end user. If heating effects are ignored, in the pulse width modulation technique, the LED is pulsed using exactly the same current level on every pulse, so the forward voltage is the same for every pulse; therefore, the color of the light emitted will not vary.

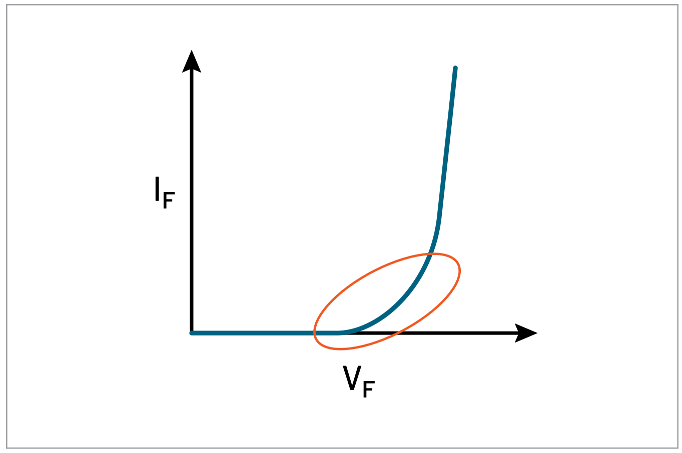


Figure 3: Forward voltage changes significantly when the forward current is low and becomes constant as forward current increases.

Another important reason pulse width modulation is preferable is because this technique provides linear control over brightness. The amount of light an LED emits is not linearly related to the amount of current used to drive it. In other words, reducing the drive current by 50% will not cut the light output by 50%; instead, it will drop by some other amount. This would make a dimming scheme based on varying current difficult to apply because it would be necessary to characterize each LED's light output vs. forward current then calibrate the drive scheme to that curve. Using pulse width modulation is a much simpler way to get linear control over brightness. With pulse width modulation, all that's necessary to make the LEDs output 50% as much light is to reduce the duty cycle by 50%. If the LEDs are only ON for half as long, only half as much light will be produced.

Power efficiency is another advantage of the pulse width modulation approach. Because pulse width modulation uses a constant current level for each pulse, it's possible to select a pulse level where the LED operates most efficiently, that is, where the lumen output per watt is the greatest. That means the LED is operating at maximum efficiency no matter what brightness level is used. Another way in which pulse width modulation enhances efficiency is that LEDs will actually output more light for a given drive current when pulsed rather than at DC. Many manufacturers' datasheets include a graph of forward current vs. luminous flux. If the manufacturer has characterized the LED under both pulsed and DC drive currents, one can observe that the pulsed characterization curve lies above the DC characterization curve. This is due to the reduced self-heating that the pulsed drive current produces. Finally, pulse width modulation enhances power efficiency even in the circuitry that drives it. The switching circuitry used in pulsed width modulation wastes very little power. When the switch circuitry is turned off, virtually no current flows and virtually zero power is being used. When the switch is turned on, due to the very low ON-state resistances, nearly all the power is delivered to the LED and very little is consumed by the switch. In a variable current drive scheme, power to the LED is often reduced by consuming the excess power elsewhere in the circuit.

Generating a Pulse Modulated Output on an LED in KickStart

This example application demonstrates how to generate a pulsed current train on a high-brightness LED using the Keithley KickStart Startup Software and a 2461 High Current SourceMeter® SMU Instrument. KickStart allows you to set up your instrument and run a test quickly without writing any code. The data generated by KickStart can be plotted on a graph or viewed in a table. The measurements can also be saved to a file in .csv or .xlsx file format.

In this example, you will use the KickStart software to configure the 2461 to output various pulsed current train waveforms for an expected period and with a different duty cycle applied in each instance. The voltage versus time will be plotted on the graph, and all run instances will be selected for simultaneous comparison.

Equipment and Software Required

- One 2461 High-Current Graphical Touchscreen SourceMeter SMU Instrument.
- Keithley KickStart Startup Software version 2.6.0 or later, installed on your computer; you can download KickStart from https://www.tek.com/keithley-kickstart.
- For front-panel connections, use four insulated banana cables such as the Keithley 8608 High-Performance Clip Lead Set (one set included with the 2461; you will need another set).
- For rear-panel connections, use one 2460-KIT Screw-Terminal Connector Kit (provided with the 2461), or you can use one set of 2460-BAN Banana Test Leads/ Adapter Cables (with appropriate connections to the device).
- One GPIB, USB, or ethernet cable to connect the 2461 to a computer.
- One high-brightness LED.

Set up Remote Connections

This application is configured to run remotely. You can run this application from any of the supported communication interfaces for the instrument (GPIB, USB, or ethernet).

Figure 4 shows the rear-panel connection locations for the remote communication interfaces.

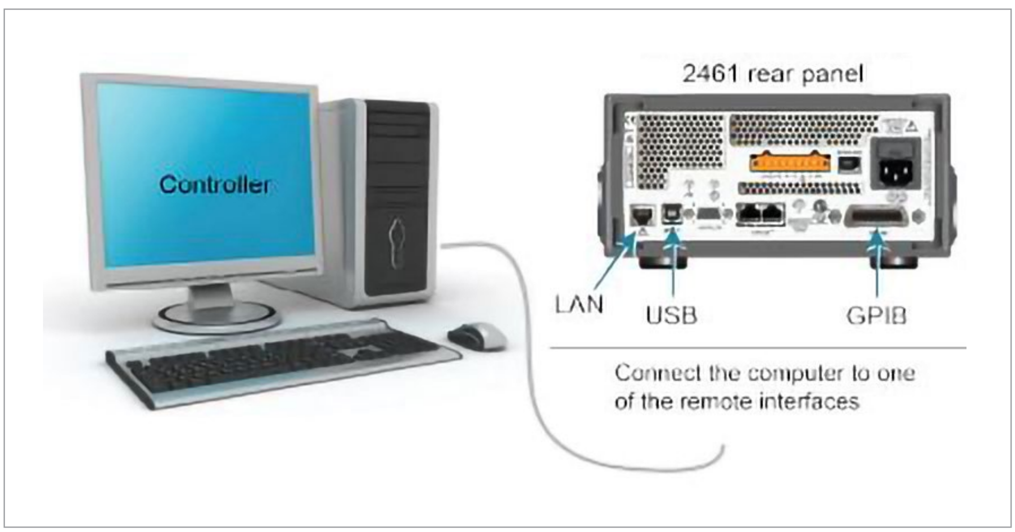


Figure 4: 2461 remote interface connections.

Device Connections

For best measurement accuracy and to eliminate the effects of test lead resistance when sourcing high current, connect the 2461 to the device under test (DUT) using the four-wire sense method.

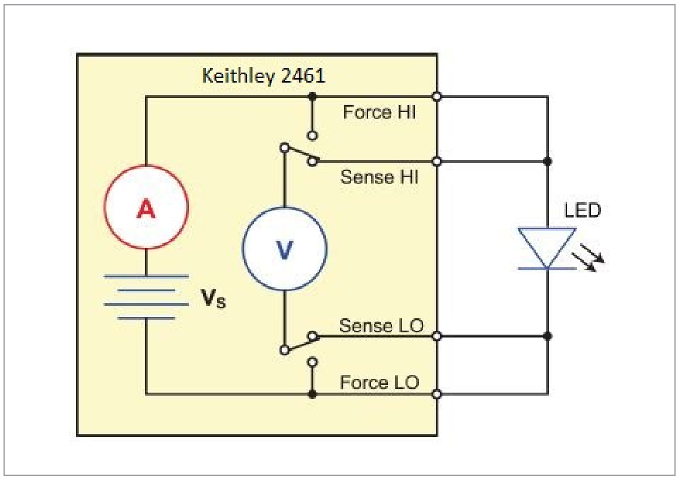


Figure 5: 2461 four-wire connections to an LED.

To use the four-wire sense connection method:

- Connect the FORCE HI and SENSE HI leads to the anode terminal of the LED.
- Connect the FORCE LO and SENSE LO leads to the cathode terminal of the LED.
- Make the connections as close to the DUT as possible to exclude the test-lead resistance from the measurement.

Figures 6 and 7 show the physical connections for the front and rear panels. Note that you must use either the front-panel terminals or rear-panel terminals — you cannot mix connections.

Figure 6 shows the front-panel connections. You can make these connections with four insulated banana cables that are rated to the maximum current (7 A) such as two sets of the Keithley 8608 High-Performance Clip Lead Set.

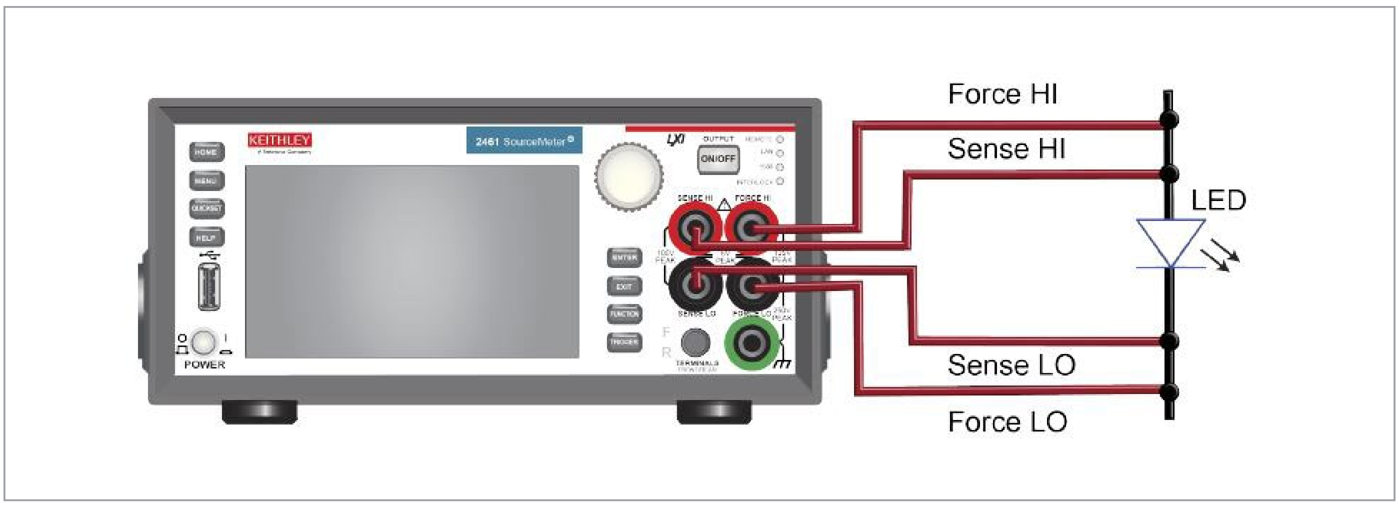


Figure 6: 2461 front panel 4-wire connections to an LED.

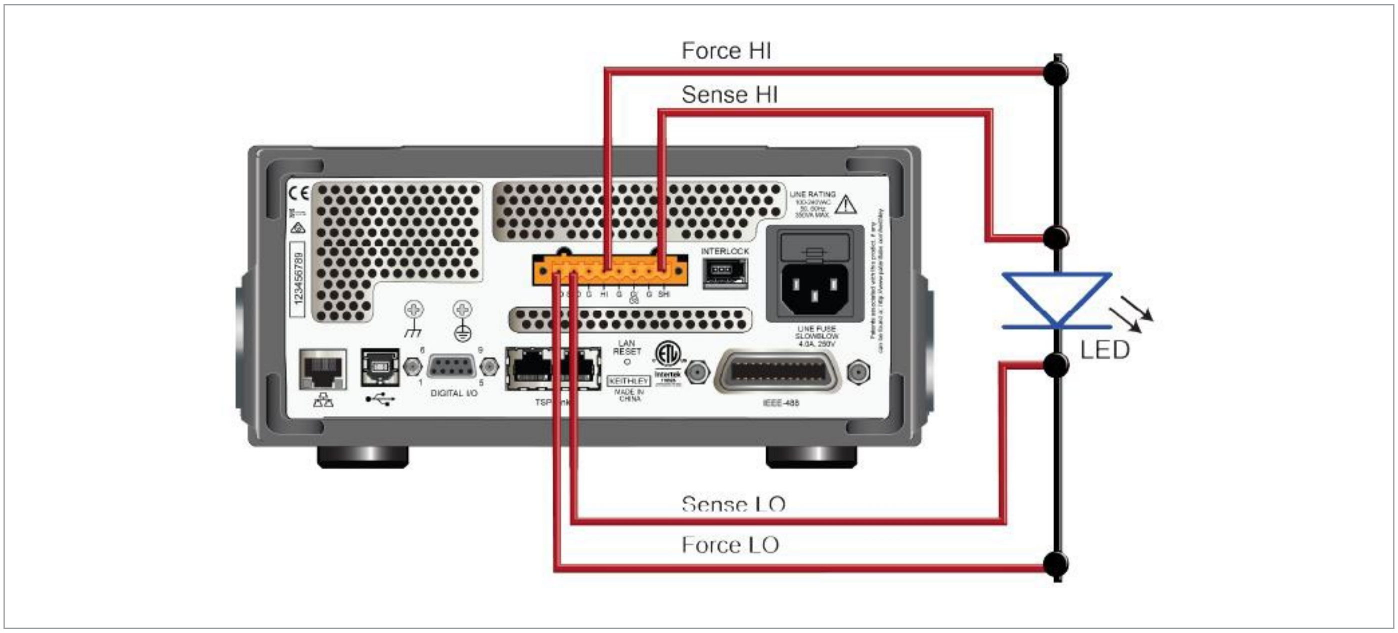


Figure 7: 2461 rear panel 4-wire connections to an LED.

Figure 7 shows the rear-panel connections. You can make these connections with either the 2460-KIT Screw-Terminal Connector Kit (included with the 2461) or a 2460-BAN Banana Test Leads/Adapter Cable with appropriate cabling.

Configure the 2461 to Use the KickStart Software

The 2461 must be set to use the Test Script Processor (TSP®) command set before you can use the KickStart software. By default, the 2461 is configured to use the SCPI command set. You must select the TSP command set before using KickStart.

To enable TSP commands:

1. Press the **MENU** key.
2. Under System, select **Settings**.
3. For Command Set, select **TSP**.
4. At the prompt to reboot, select **Yes**.

Launch KickStart and Set Up the Test

Once the communication cable is connected to the computer and the TSP command set is enabled, you are ready to launch the KickStart software.

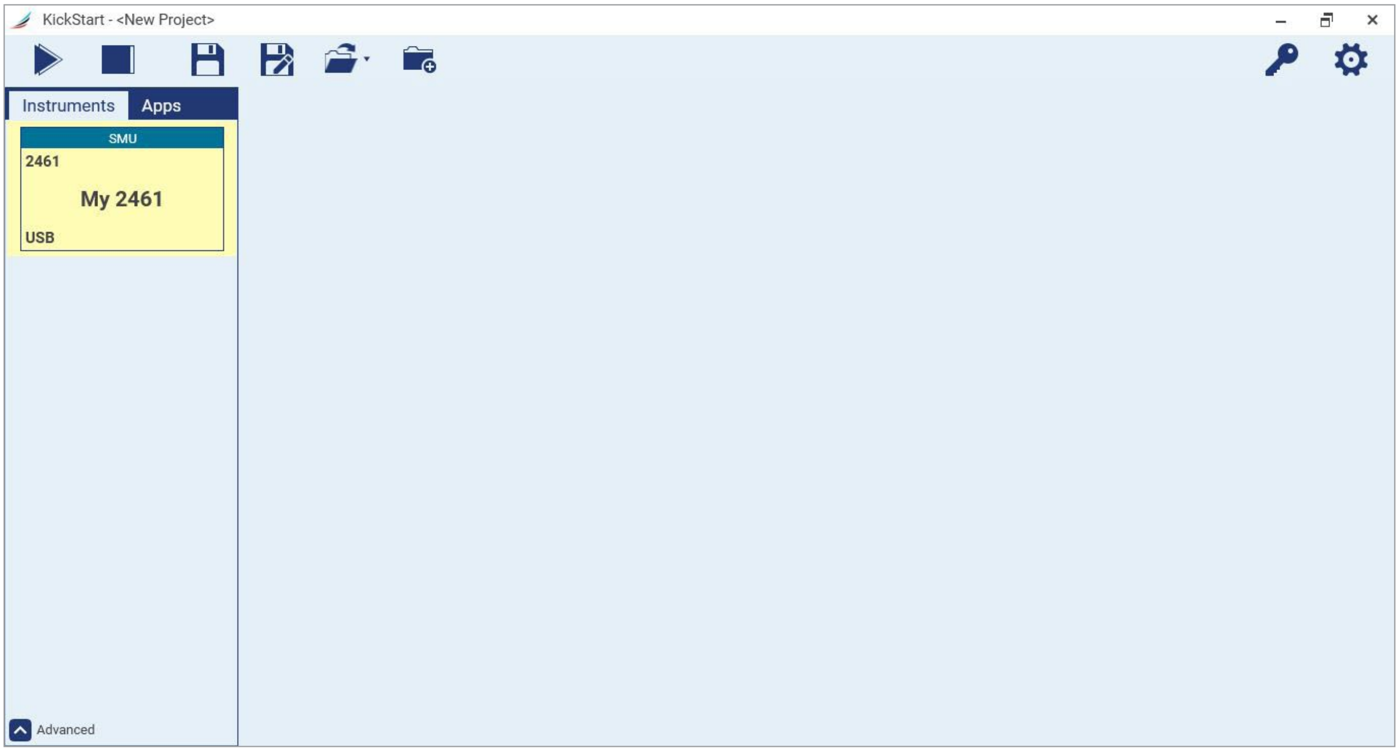


Figure 8: KickStart software startup page.

To create the test project:

1. Launch the KickStart software. The startup screen is displayed, as shown in the **Figure 8**.
2. Either double-click or drag the 2461 instrument into the main app staging area then select **I-V Characterizer.**

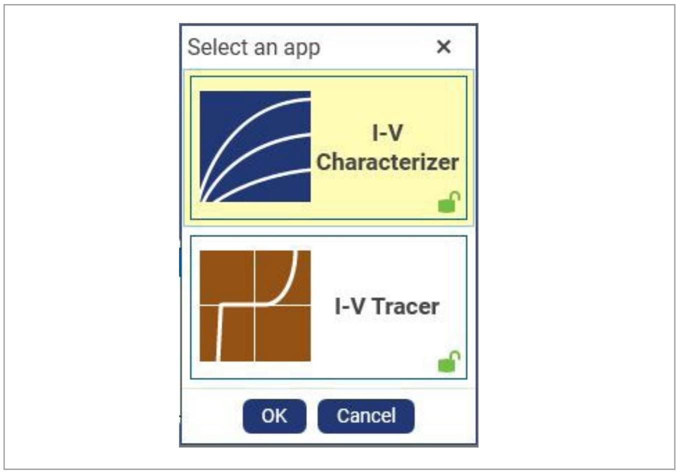


Figure 9: Select the I-V Characterizer App.

3. Navigate to the SMU-1 settings tab and apply the following source changes (illustrated **Figure 10**):
   a. Set the Type to **Pulse**.
   a. Set the Function to **Current**.
   a. Set the Mode to **Train**.
   a. Set the Level to **1 A**.

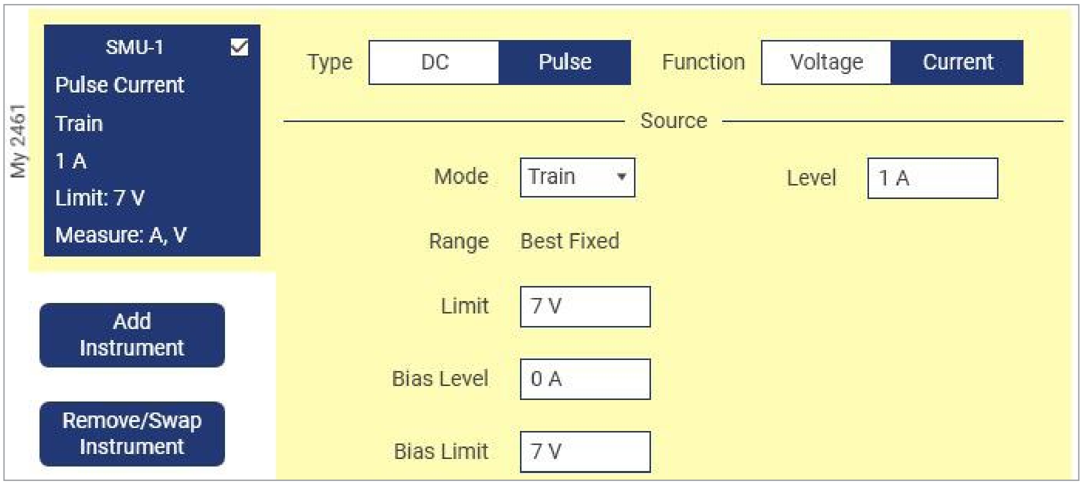


Figure 10: Apply source type and output settings.

4. Scroll to the Instrument Settings and set the Sense to **4-Wire**.

Figure 11: Apply Instrument Settings.

5. Navigate to the Common Settings pane. In this section you will apply a series of pulse width and off times that are defined for a given period of **2.5 ms** (or 400 Hz). The three test run cases are shown in the following table.

Table 1: Pulse definition settings.

Width	Off Time
625 µs	1.875 ms
1.25 ms	1.25 ms
1.875 ms	625 µs

For the first test case, apply the following settings:

- Set the Source/Sweep Points to **100** (note that this defines the number of pulses).
- Set the Source to Measure Delay to **5e-5 s**.
- Set the Width to **625 µs**.
- Set the Off Time to **1.875 ms**.

Note, too, how the Waveform Viewer pane updates to show that the output of the SMU can be expected to be of a pulse type with a duty cycle of 25%.

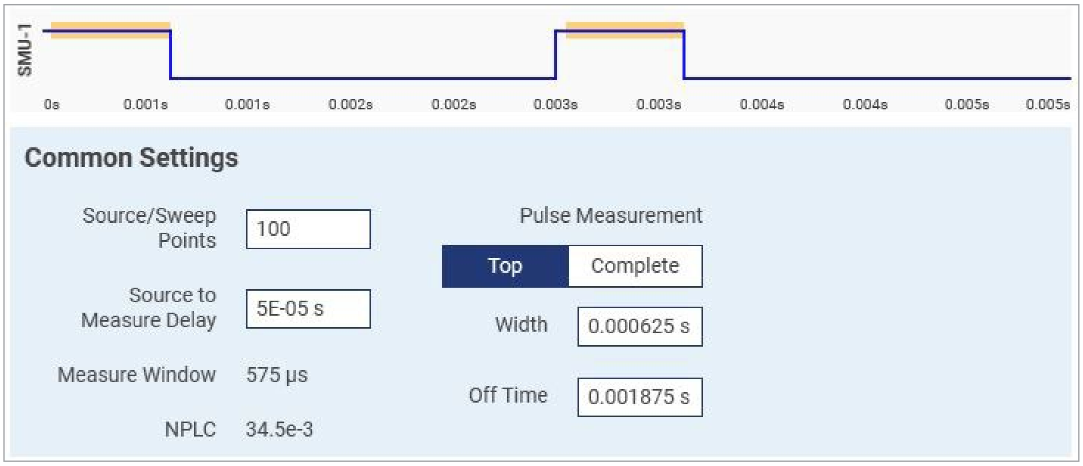


Figure 12: Common Settings and Waveform Viewer updated.

6. Click on the **Run** button to execute the test.
7. Upon completion, modify the Pulse Measurement attributes in the Common Settings pane such that both the Width and Off Time are set to **1.25 ms** (duty cycle of 50%).

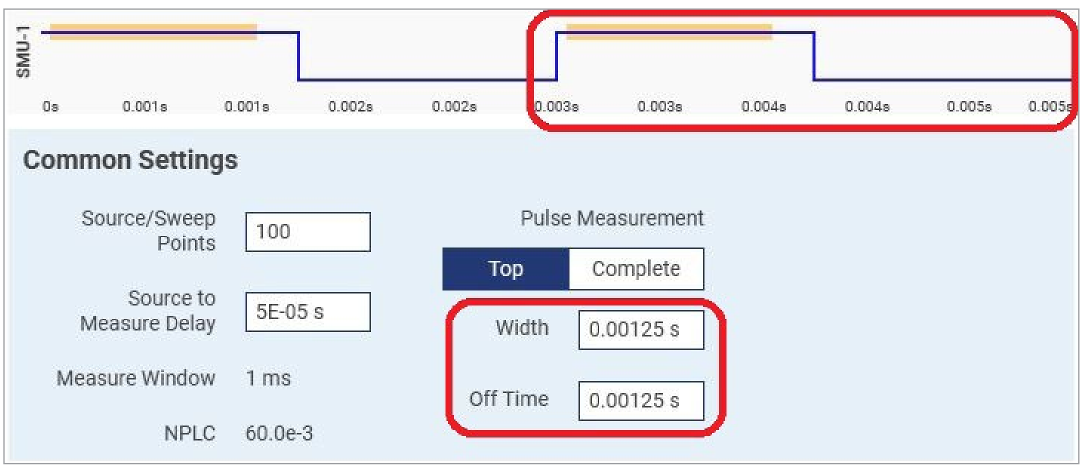


Figure 13: Common Settings and Waveform Viewer updated.

8. Click on the **Run** button to execute the test.
9. Upon completion, modify the Pulse Measurement attributes in the Common Settings pane and set the Width to **1.875 ms** and the Off Time to **625 µs** (duty cycle of 75%).

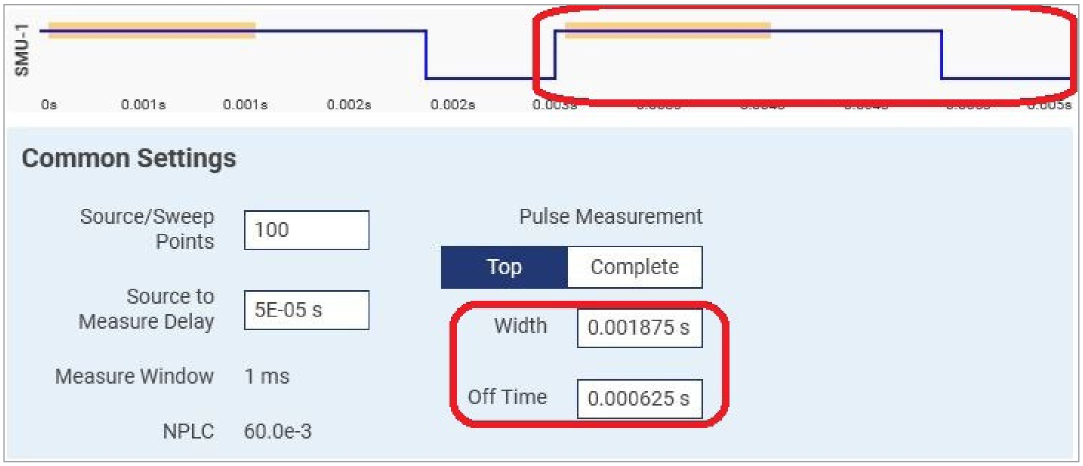


Figure 14: Common Settings and Waveform Viewer updated.

10. Click on the **Run** button to execute the test.
11. Click on the **Run History** button to expose the three app runs you just conducted.
12. Select each of the individual runs and update the area reading "Enter a run description here" to provide a general description of the test configuration run (see **Figure 15** for an example).

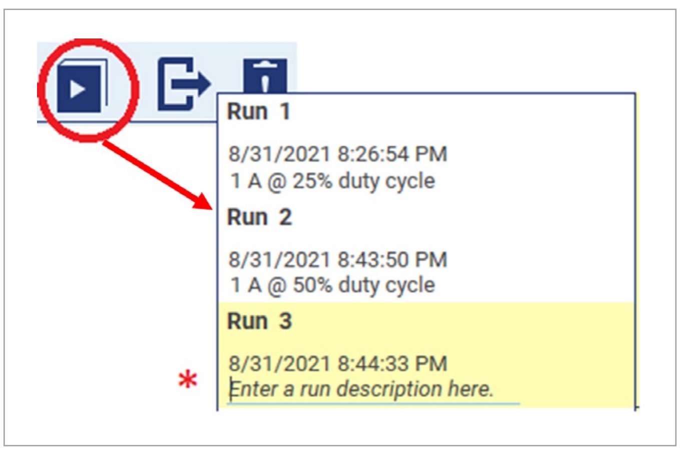


Figure 15: Use the Run History to help document changes to the app configuration.

13. Use the **Shift** or **Ctrl** keys on your keyboard (along with mouse clicks) to select all three runs for comparison.
14. Click on the **Graph** tab at the top of the KickStart user interface.
15. Hover your mouse cursor above the x-axis title to reveal the configuration options then change the Source to **Time**.
16. Hover your mouse cursor above the legend and select to plot **Voltage** then de-select current.

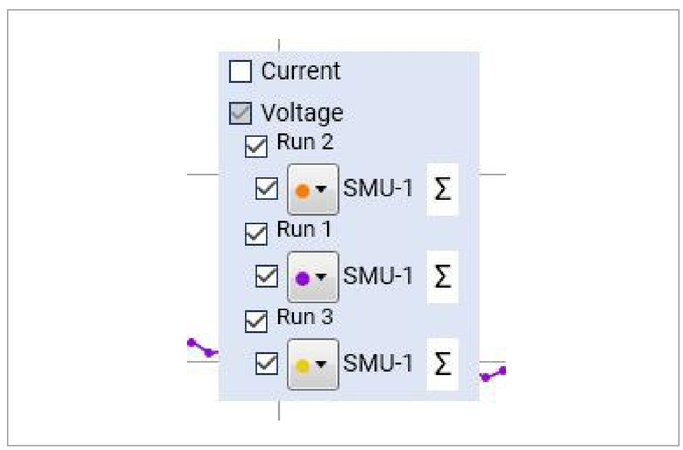


Figure 16: Update the legend settings to plot Voltage on the y-axis.

17. Hover your mouse cursor in the top center area of the graph to reveal the title entry field and provide a title of your choosing to your graph.

Figure 17: Provide your test data a title.

18. Your final plotted output should look similar to the **Figure 18**.

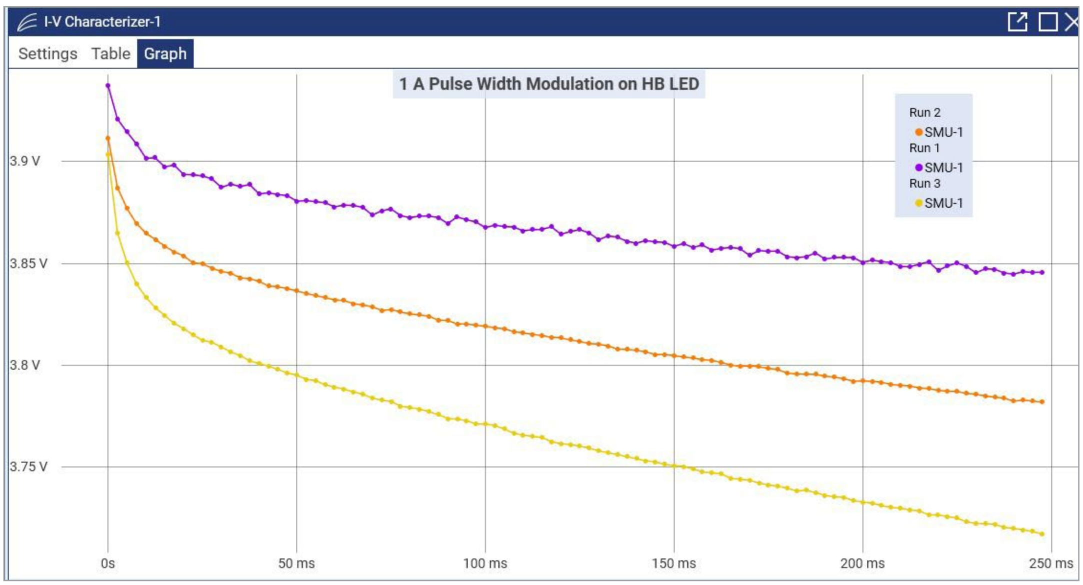


Figure 18: Pulse width modulated output data presented graphically.

Summary

The primary reason for pulse testing is to reduce device self-heating that happens when the device is activated – especially at its maximum operating potential – for increasing periods of time.

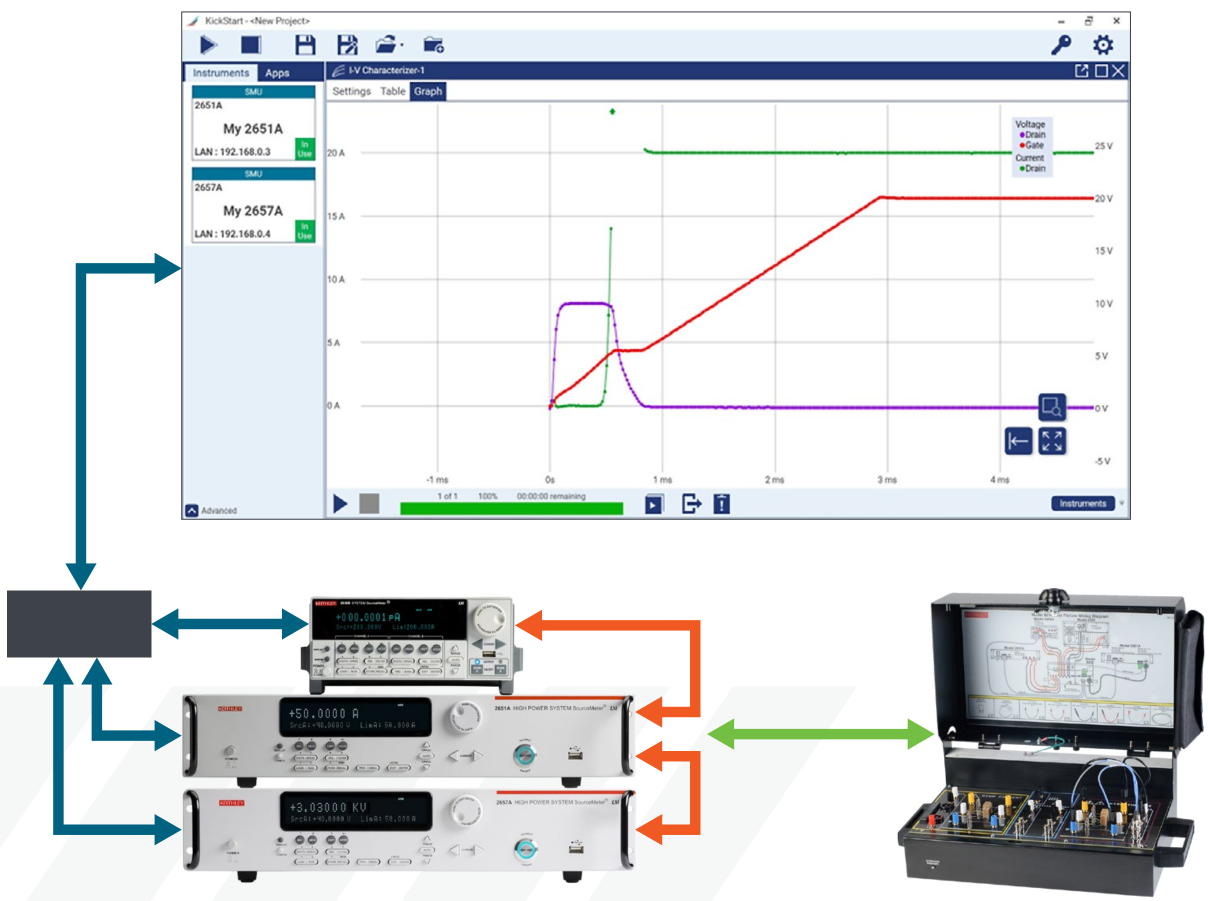
Pulse width modulation is applied to high-brightness LEDs to control their light intensity during regular operation. The longer the pulse width (or higher the duty cycle), the stronger the luminosity. These LEDs are also PWM driven to help ensure color quality while a consistent forward current level is applied. Having the LED on for only a fraction of the time improves the efficiency of the device and helps to extend its lifespan.

Whatever your pulse-based testing needs are, Keithley source measure unit (SMU) instruments and KickStart Software are an ideal pairing to help quickly establish your test setups, collect data, and share tabular and graphical insights with your colleagues. The KickStart examples shared within this application note can use either the 2450 or 2461 SMU instruments, which are capable of achieving 1 A, 20 W and 10 A, 1000 W, respectively, in their pulse operating regions. However, keep in mind that KickStart also supports the Keithley 2651A (for higher current up to 50 A) and 2657A (for higher voltages up to 3000 V) SMU instruments.

Tektronix®

Power MOSFET Device I-V Characterization in KickStart

APPLICATION NOTE



Introduction

As electrical power consumption continues to evolve in our industries, more power is required to be effectively converted in different ways. The power MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is a key component in power conversion technology due to being well suited for very high voltage, high current, and high speed switching applications. These advantages promote further development in structure and material of new conversion technologies. A lot of materials and structures have been introduced to push existing boundaries in support of greater power and speed. Wide band gap materials silicon carbide (SiC) and gallium nitride (GaN) have been used prevalently in power MOSFET device technologies, and work in tandem with Keithley's variety of high power source measure units (SMUs) to characterize the power MOSFET. The 2657A High Power System SourceMeter® Instrument covers 3 kV, and the 2651A — another high-power system SourceMeter® instrument — covers 50 A in pulse. The KickStart software offers the I-V Characterizer app that is used to establish automated setups and execution of I-V characterization tests for power MOSFET devices. This application note will provide details for how the power MOSFET I-V characterization is performed with a combination of the 2651A, 2657A, and 2636B System SourceMeter® Instruments and the KickStart Instrument Control Software.

Wide Band Gap Materials

The electron is a key factor of electrical mobility and allows currents to flow – every individual material in this world has some energy level for electrons. As atoms are combined in solid state, the energy levels shown start to present as distinct ranges. The energy band of the electrons in the valence shell is called the valence band and these electrons cannot contribute to the current flow because they are bound to the valence band. However, if these electrons get some energy, electrically or thermally, they become excited and may shift to the conduction band where they are free to move and contribute to the current generation. The energy between the valence band and the conduction band is called the energy band gap.

Figure 1 shows if any material has a band gap of 1 eV to 3 eV that can move to the conduction band from valence band, those materials can be defined as semiconductors. If the material is higher than 5 eV, it is an insulator that prevents or severely minimizes electrical conductivity. Conductors can also be defined as two overlapped bands in which free electrons are always present even without acquiring any energy. Silicon has about a 1 eV band gap. When the band gap is larger than 2 eV, it is generally deemed a wide band gap device. SiC and GaN commonly use these wide band devices that have slightly more than 3eV band gap. Both materials have a high electric field so that they can block the larger voltages that regular silicon cannot. The electron in the n-type MOSFET is a majority carrier, and power MOSFETs utilize the advantage of these majority carriers to a conduct higher current. These wide bandgap materials also have advantages in thermal characteristics and electron mobility.

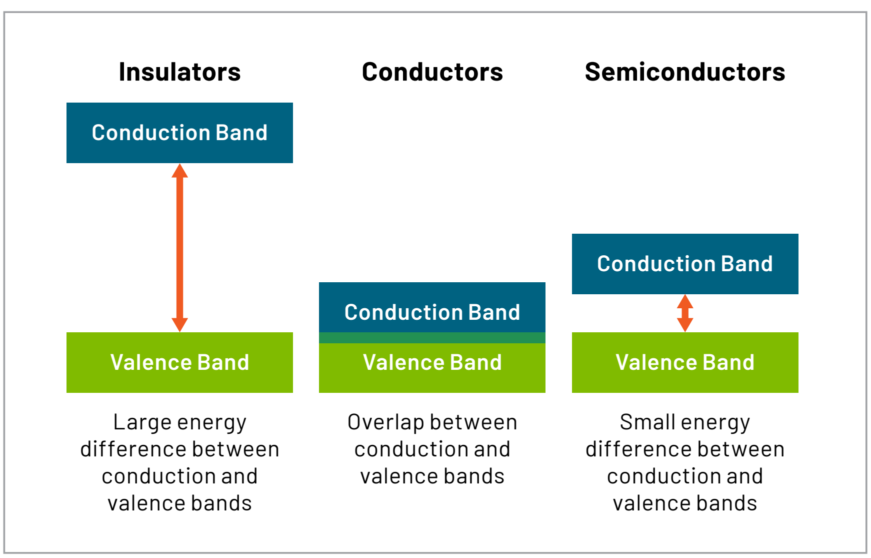


Figure 1. Energy Band Gap

Power MOSFET Device Structures

Figure 2 shows the basic device structure of a high power MOSFET. The drain is in the bottom of the wafer and the source on the top of it, making for a vertical structure. There are two p-n junctions in the left and right side. These junctions develop depletion layers so that in an off-state mode, the depletion layer expands in the drift region. This expanded layer can block very high voltage from the p well channel all the way to the drift layer.

In on-state mode, the channel region is formed by the gate voltage higher than the threshold value. It creates an inversion channel under the gate oxide that supports current flow from the drain to the source. Most regular low power MOSFET devices use some part of minority carriers, diminishing the device performance. When the channel is opened, the drift layer works as JFET (junction field emission transistor) so that a vest of majority carriers can move through the drift layer. This structure can have a very high current when in the on-state, and high voltage when in the off-state with high speed in switching either of these two states.

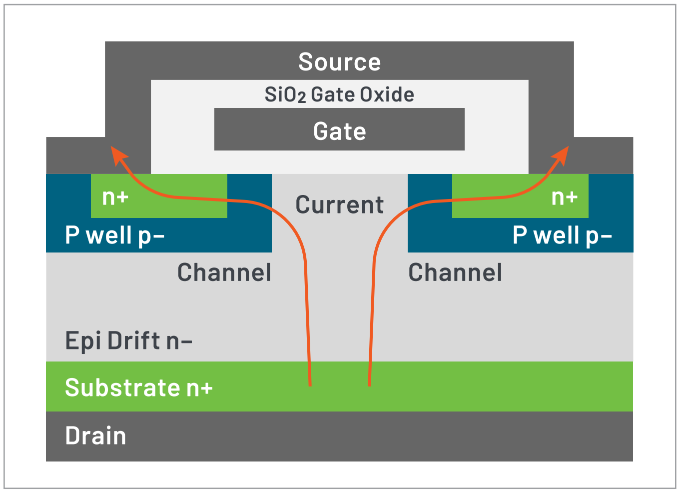


Figure 2. Basic Power MOSFET Structure

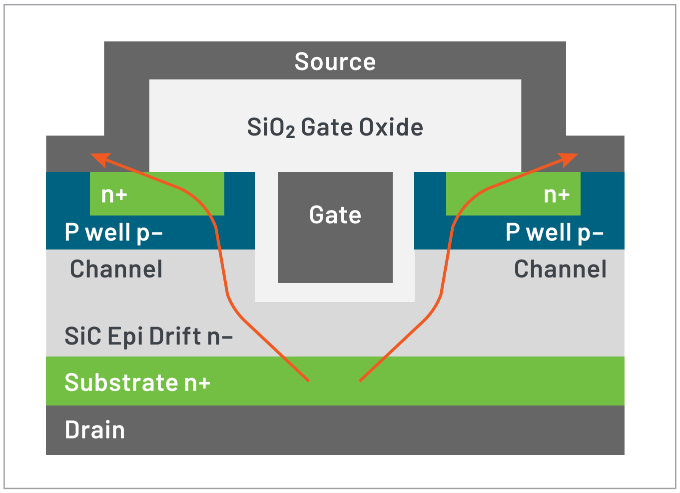


Figure 3. Power MOSFET Trench Structure

Other technologies have been introduced to improve device performance. **Figure 3** shows one of these advanced structures: a trench MOSFET. There is a trench in the wafer hosting, the gate terminal and, the channel in the p well is formed vertically. There are some people who would prefer the drift layer thickness to increase to achieve a higher blocking voltage, however, the on-state resistance would then also increase with the thicker drift layer. Keeping the distance from the channel, to the drain short helps to keep the on-state resistance low. The trench structure MOSFET has very low on-state resistance — on the order of single-digit milliohm levels — due to the short drift layer.

Power MOSFET Test Setup

The 2657A High Power System SourceMeter® Instrument can support high voltage of up to 3 kV with a maximum current 120 mA. The 2657A is fit for the off-state measurement of power MOSFET devices in tests such as breakdown voltage and leakage current. The alternate High Power System SourceMeter® Instrument 2651A can support high current of up to 50 A at the maximum pulse level. It is good for on-state measurement tests like on-state resistance, conductance, output characteristic test, body diode, and transfer characteristic testing. The 8010 High Power Device Test Fixture is highly recommended for safe and reliable connections to the MOSFET under test. The KickStart software supports both High Power System SourceMeters 2657A and 2651A, as well as the 2636B. Each SMU should be connected to the control PC so the KickStart software can recognize each individual instrument. All three SMUs should be tethered together using the TSP-Link interface to enable the most efficient pulse testing through tight hardware triggering.

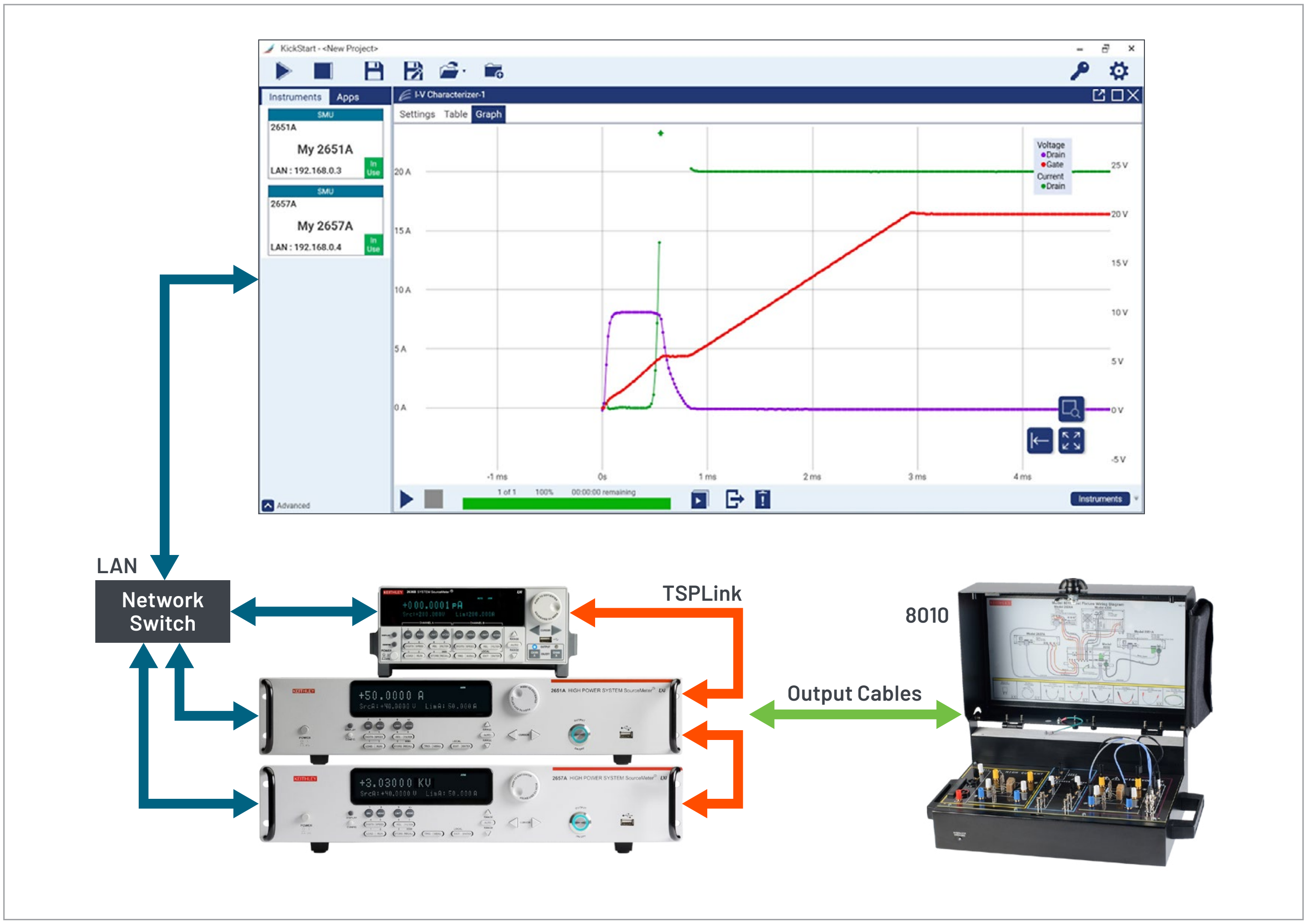


Figure 4. Power MOSFET Test Configuration with 8010 High Power Device Test Fixture.

On-State Characterization

The on-state resistance (Rdson) is a key determinant of the conduction loss of a power MOSFET. As **Figure 4** shows, its value can range from a few milliohms to tens of milliohms. The resistance of the drift layer contributes to the on-state resistance, and the thickness of the layer can affect the on-state resistance and breakdown voltage: the thinner the layer, the smaller the on-state resistance and the lower the breakdown voltage. The trench structure is helpful in reducing the on-state resistance, but it presents a tradeoff because a reduction in the breakdown voltage will likely lead to an increase in the on-state resistance. The test condition of the on-state resistance is usually defined as a resistance measured at a specific current level of the drain and specific voltage bias of the gate. **Figure 4** shows the on-resistance measurements with some drain current steps from 10 A to 50 A while sweeping the gate voltage from 10 V to 20 V. The on-state resistance is about 14 mΩ with the device drain pulsed at 50 A of current with 20 V applied to the gate. The 2651A SourceMeter supports 1ms maximum pulse width in the 50 A range at 10 V. If the higher voltage ranges of 20 V or 40 V are required, then the maximum pulse width will reduce to 330 µs and 300 µs, respectively. KickStart will provide a pulse or output signal preview for each terminal (**Figure 5**).

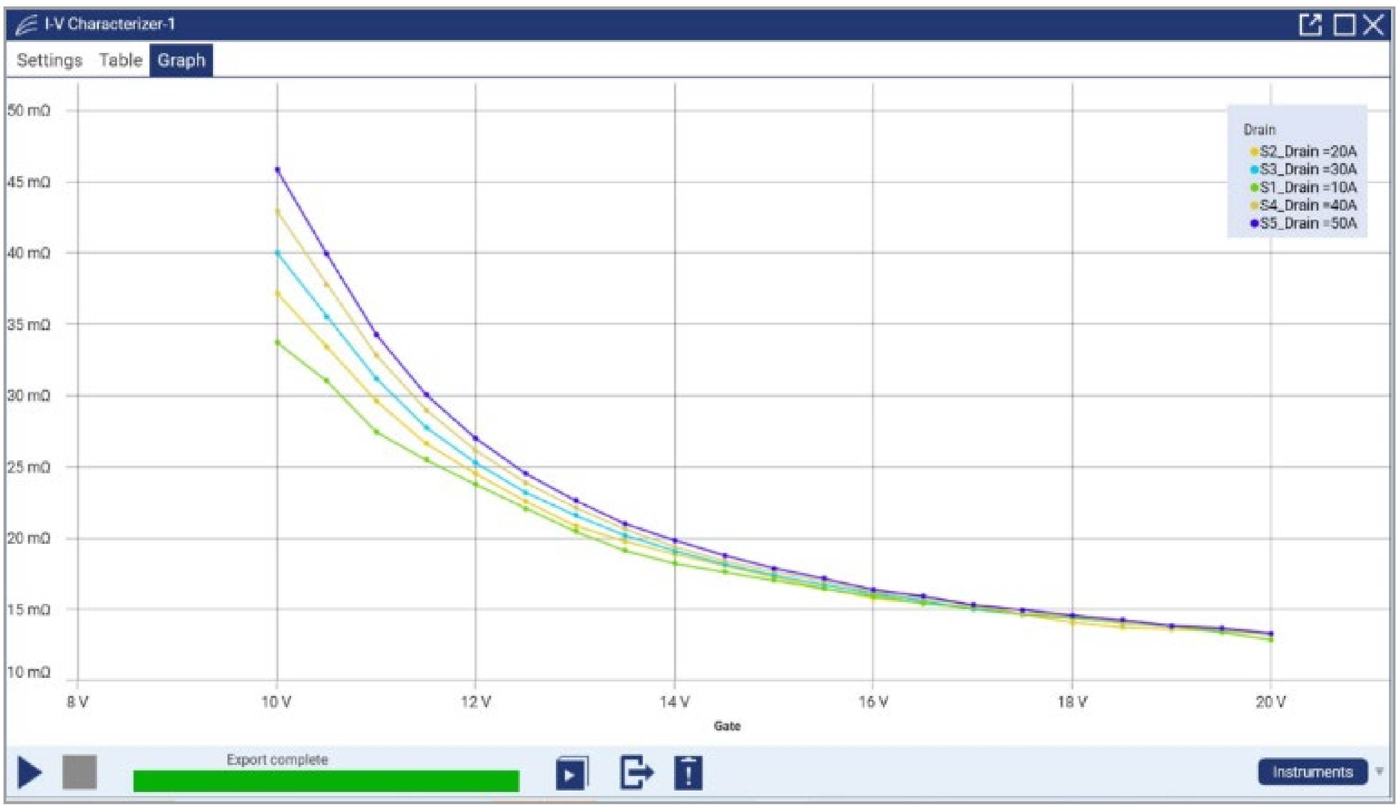


Figure 4. On-State Resistance Measurement (Rdson).

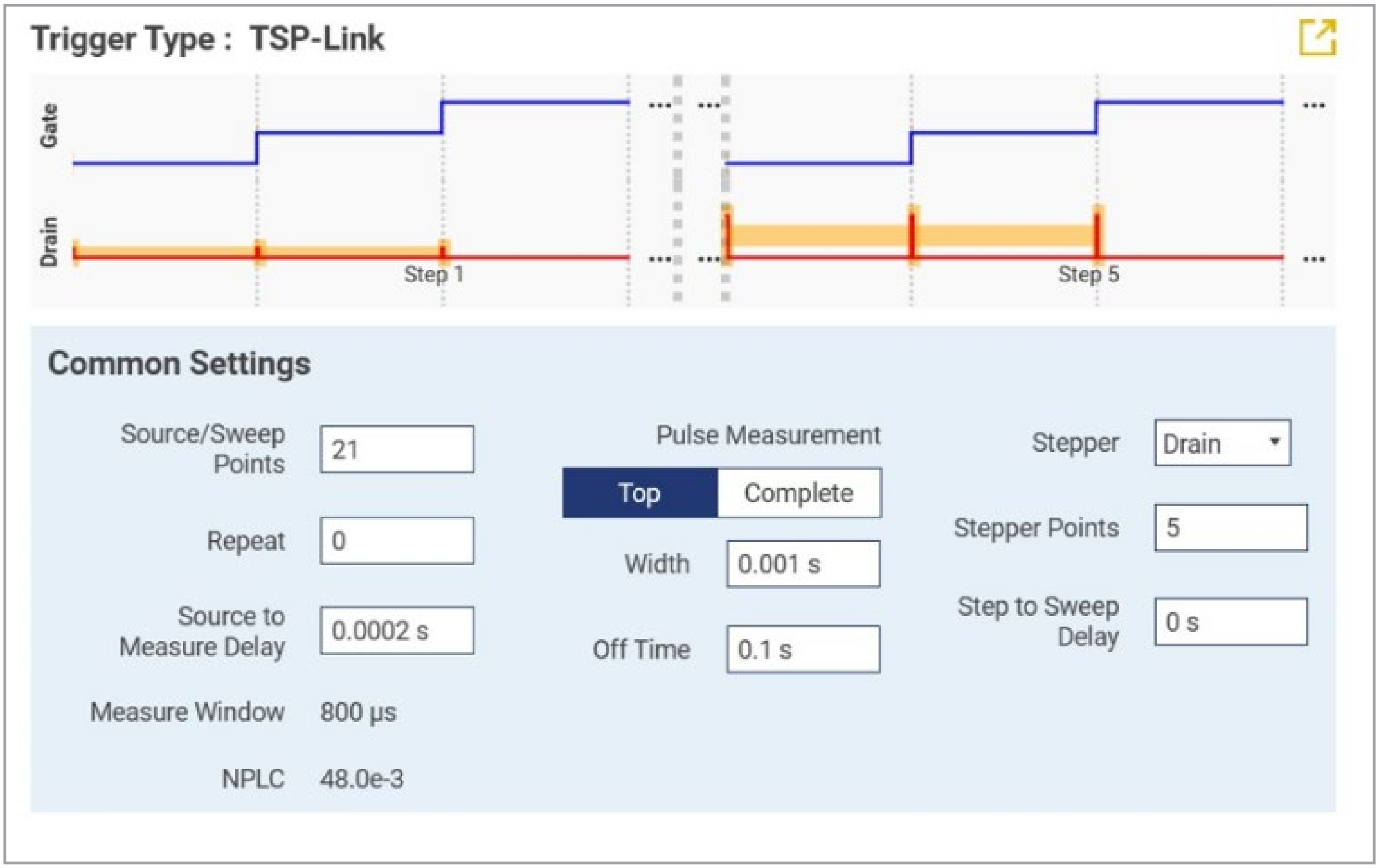


Figure 5. Pulse Setting for On-State Resistance.

Another important test in the on-state is the output characterization as shown in **Figure 6**. This test sweeps the drain voltage from 0 V to 10 V with the gate stepping from 6 V to 10 V in 1V increments. This high current test must be done with as short a pulse width as possible to avoid thermal heating.

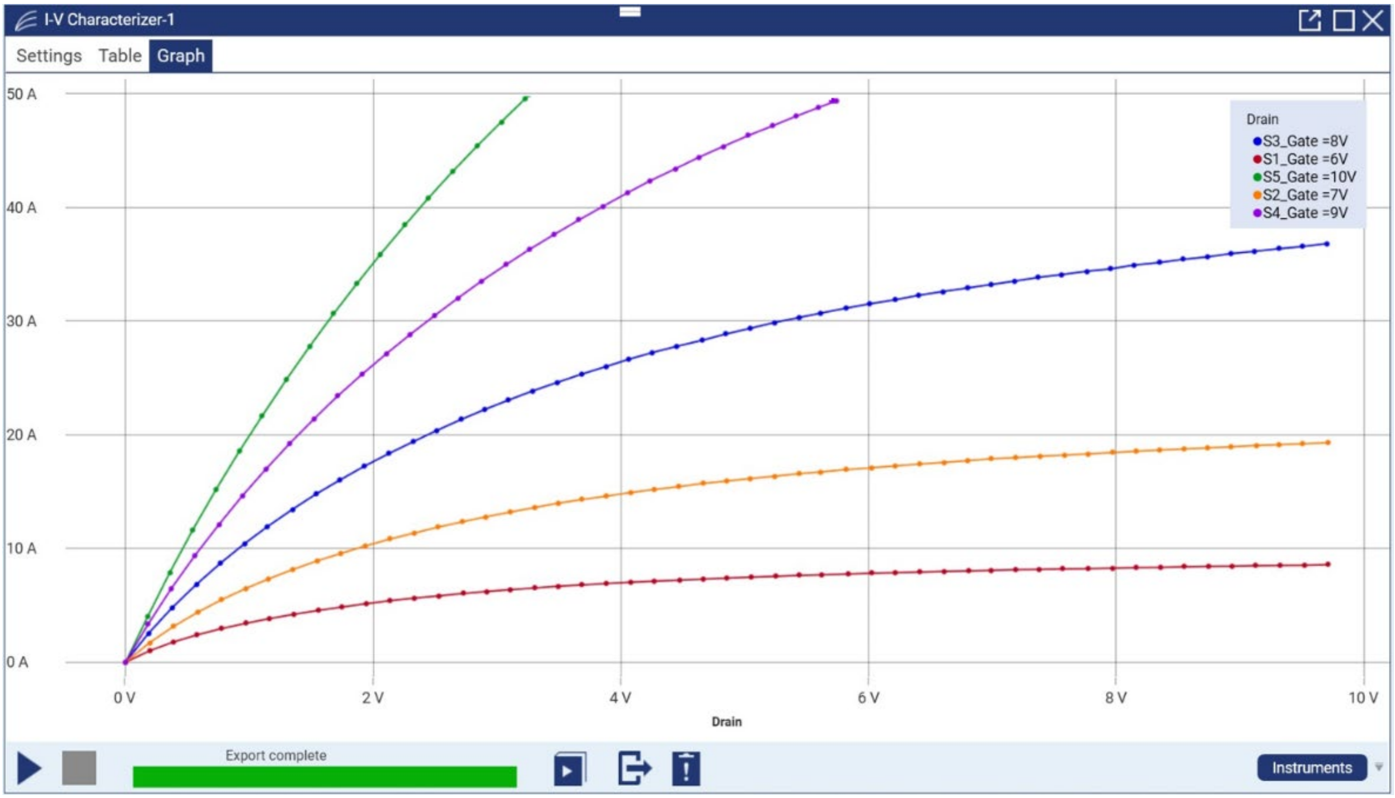


Figure 6. Output Characteristic Curve

Off-State Characterization

The off-state breakdown voltage (BVDSS) is another important parameter of the power device, helping to determine the maximum voltage that can be applied to it. If the p well channel is closed, the device is like a p-n junction, where positive drain voltage becomes the reverse bias to the p-n junction creating more voltage and drift layer depth to maintain the blocking of the voltage levels. The BVDSS is usually defined as the drain to source voltage when the leakage current is set to approximately 100 µA while the gate bias is 0 V. The BVDSS measurement can be performed by measuring voltage while sourcing current at a specified leakage level. Another method is to sweep the voltage across the drain using a current compliance set to the leakage level. In either test method, the gate bias is 0 V to ensure the device is in its off state. At the point where the current hits the compliance level, the corresponding voltage is interpreted as the breakdown voltage. **Figure 7** shows the result sweeping from 0 V to the 1.5 kV. The current hits the 100 µA compliance at 1.08 kV, therefore, the breakdown voltage BVdss is said to be 1.08 kV.

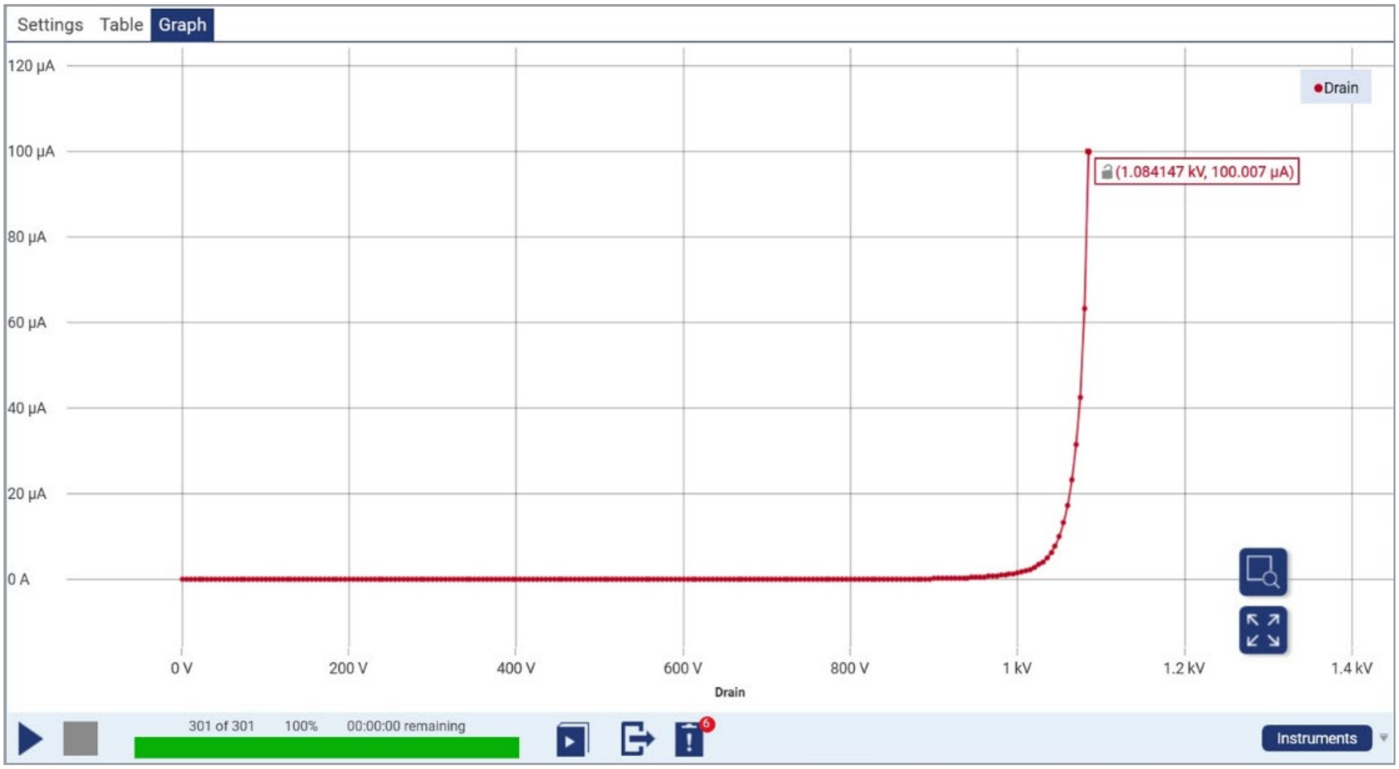


Figure 7. Breakdown Voltage (BVDSS) Test in Sweeping the Drain Voltage.

Body Diode Characterization

There is a body diode characteristic in some power MOSFET datasheets. The p-type layer is shorted to the source, and it faces the n-type drift layer so that a p-n diode is formed between the source and the drain (as shown in **Figure 2**), causing current to flow in the reverse direction. This is not the expectation for the power MOSFET design, but this feature can be used in some analog circuits. **Figure 8** shows that KickStart can make the body diode measurement by sweeping the drain voltage from 0 V to –5 V with the gate voltage biased to –5 V.

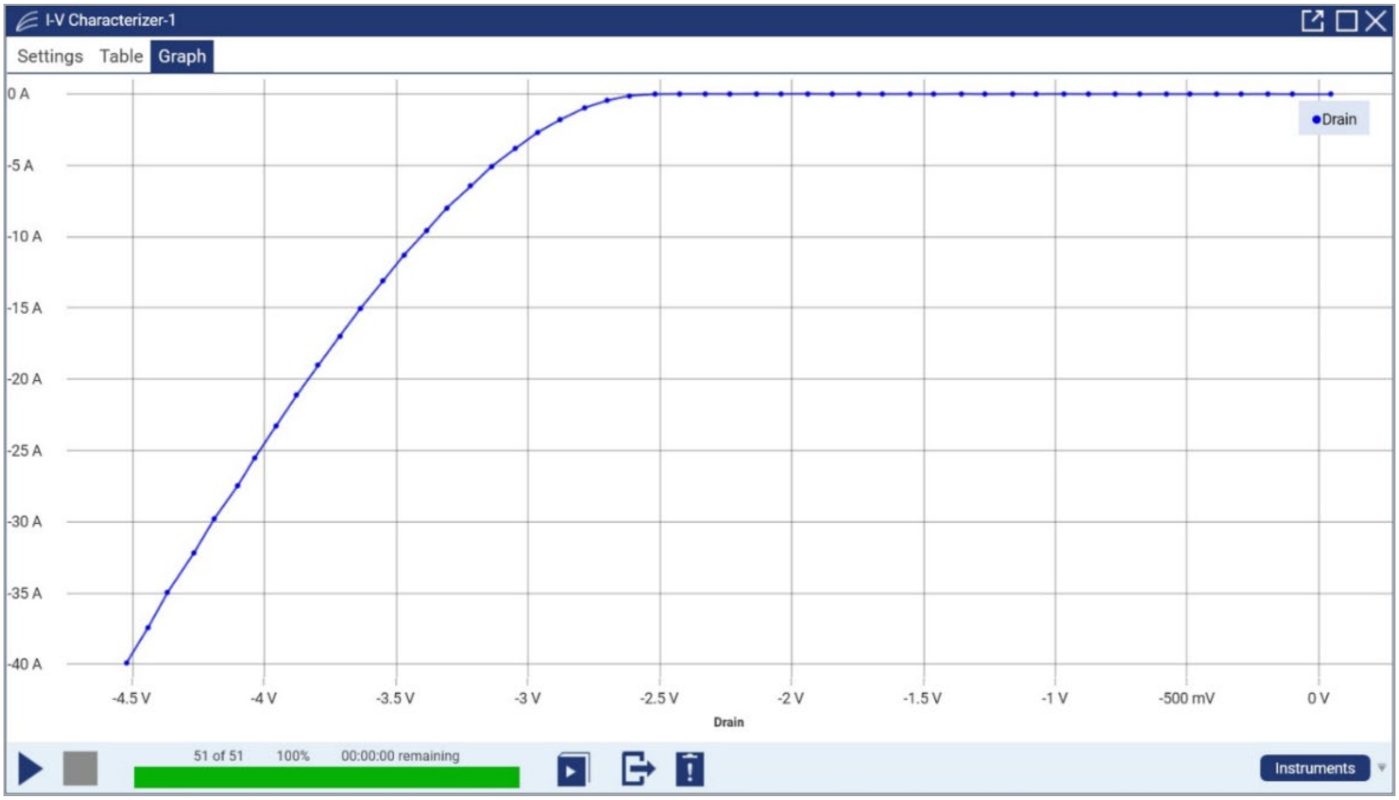


Figure 8. Body Diode Test in the Third Quadrant Operation.

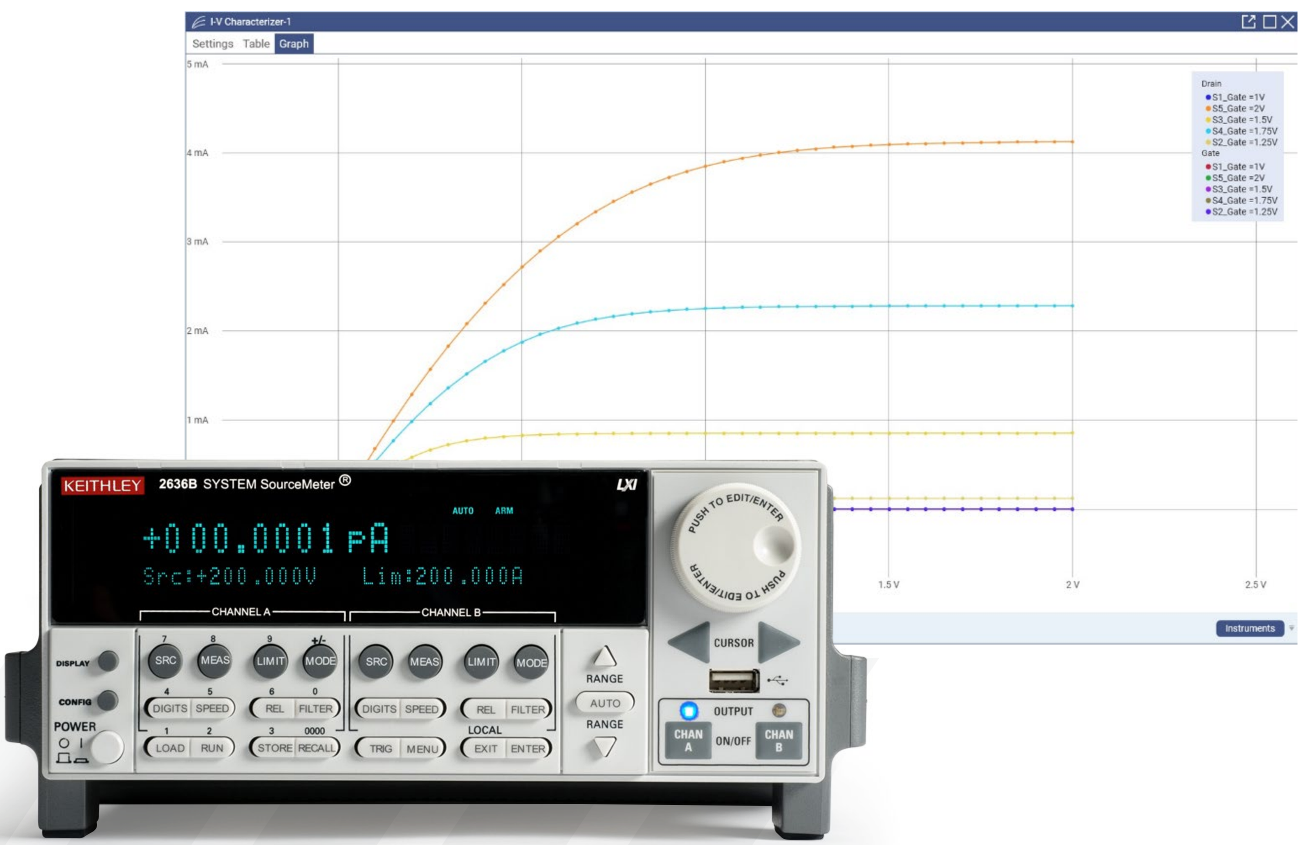
Conclusion

Power MOSFET devices have different technologies depending on device structure, materials, and operation principle, and as any of these characteristics change, DC I-V characterization will need to be done. The two most critical power MOSFET parameters are the on-state resistance and off-state breakdown voltage. The Keithley High Power System SourceMeter® Instruments and the Keithley KickStart software are great solutions that allow users to achieve the DC characterization of their devices quickly and easily.

Tektronix®

DC I-V Characterization of MOSFET Devices Using KickStart Software

APPLICATION NOTE



Introduction

The MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is one of the most common transistor devices in modern electronic circuit designs. There are a wide variety of materials and structures being introduced to specific applications, but the MOSFET structure and its working principle exhibit continuous widespread adaptation. They have been primarily used for switching and power amplifier applications. MOSFETs have excellent performance in electrical switching circuits because the devices have two opposing electrical characteristics which control very low current in the off-state and some amount of current in the on-state. MOSFETs can be worked as an amplifier itself with some other devices or used as a part of operational amplifiers which are common devices in analog circuits. Source measure units (SMUs) are the instruments best suited to conduct the DC I-V characterization of MOSFET devices because SMUs can cover a broad range of source and measurement needs. Keithley provides various SMU models and software to characterize the MOSFET devices. Specifically, the Series 2636B/35B/34B System SourceMeter® Instrument covers low current down to a 100 pA range and 0.1 fA resolution. The KickStart software features the I-V Characterizer app to be able to test the behaviors of different discrete components. This note is to focus on showing how the DC I-V characterization of the MOSFET can be accomplished using the 2636B System SourceMeter® Instrument and the KickStart Instrument Control Software.

MOSFET Device

The MOSFET device is a silicon-based semiconductor and shown in **Figure 1**. There is an oxide layer grown on the silicon semiconductor layer and the metal layer is placed on the top of the oxide as the gate. From top to bottom, the structure should be metal, oxide, and semiconductor and, therefore, identifiable as a MOS structure. There are three electrodes in the MOSFET — gate , drain, and source — to operate the device. In the case of an n-type MOSFET, the semiconductor layer must be a p-type silicon substrate created by doping an impurity on the silicon to ensure the holes are the majority carriers. The hole in the atomic structure of the silicon is intended to lose an electron when the impurity material is added on the generic silicon so that the more holes can make more positive charges. The oxide is a very thin layer produced by combining oxygen with silicon (SiO_2). It works as an insulator to prevent any current flow from the gate to the semiconductor area. The impurity implanted semiconductor can act as a conductor or an insulator depending on the gate, drain, and source bias conditions. The MOS (Metal Oxide Semiconductor) portion of the term "MOSFET" is indicative of the structure of the device.

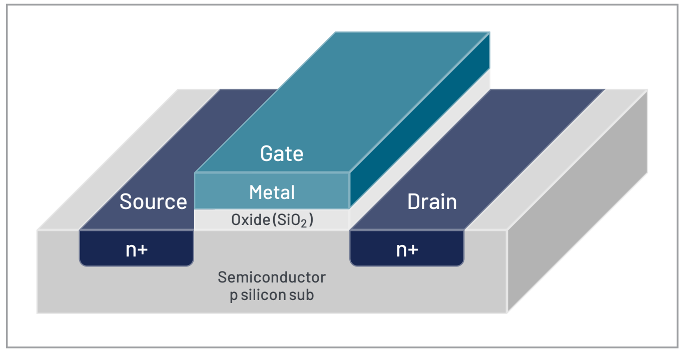


Figure 1. N type MOSFET structure.

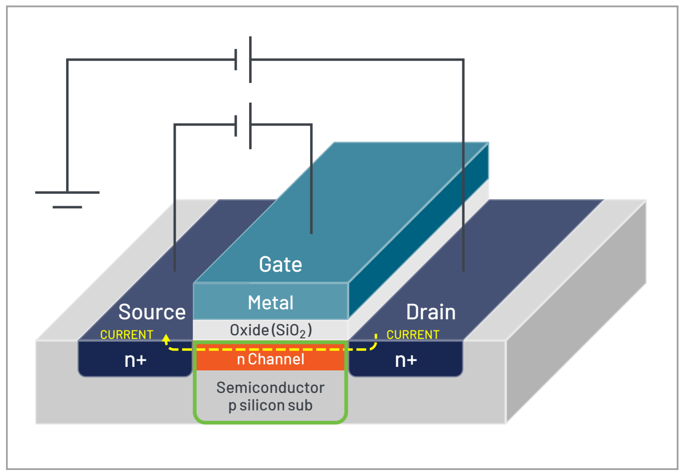


Figure 2. N type MOSFET operation.

The typical gate current flowing to the substrate and to the source may be less than 1 pA. When a positive voltage higher than the threshold voltage is applied on the gate, then the majority carriers move away from the oxide and the minority carriers which are free electrons move underneath the oxide in **Figure 2**. This electric field is called a channel and the current can flow through the channel from the drain to the source working as a conductor. When no gate voltage bias or any negative bias is applied then the device works as an insulator and no current can flow. The FET (Field Effect Transistor) implies the operation principle of the MOSFET device.

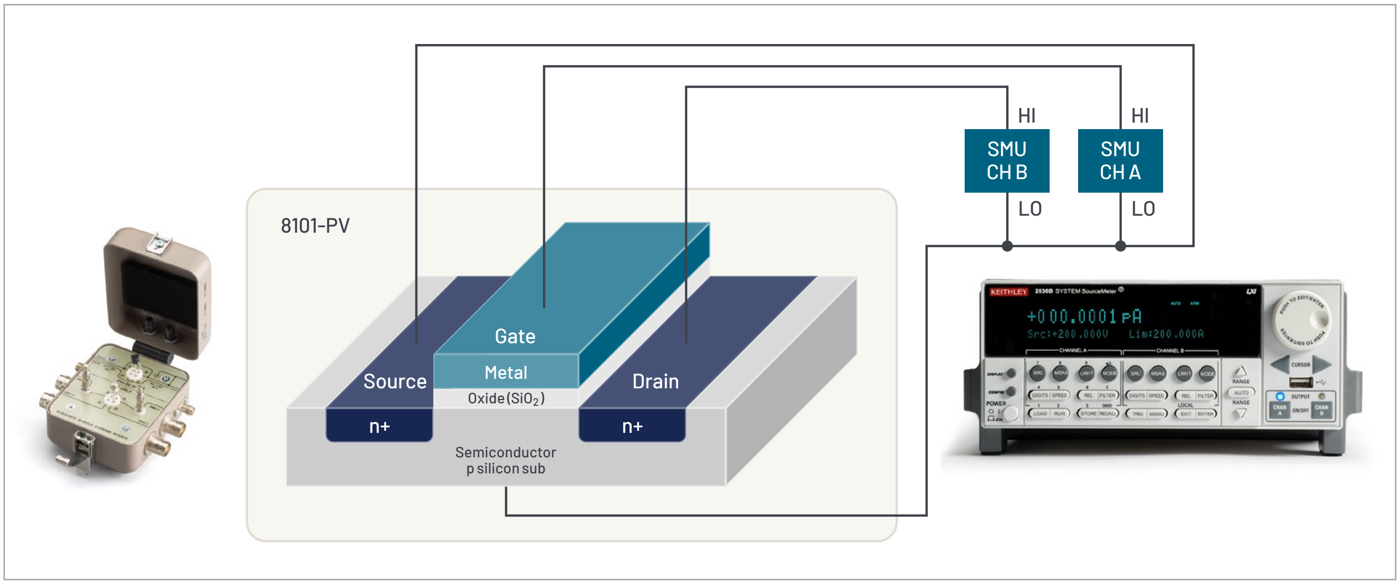


Figure 3. Test setup for MOSFET.

Instrument Connection for MOSFET Test

Two SMU channels are required for these tests and a dual-channel instrument from the Series 2600B System SourceMeter line is recommended. The 8101-PIV fixture is recommended for connections to the FET under test when the voltage does not exceed 42 VDC. If lethal voltages may be exposed when the test fixture lid is open, a safety interlock circuit must be connected before use to avoid a possible shock hazard. Triaxial cables are recommended to make connections to the fixture from instrument.

MOSFET Transfer Characteristic

The transfer characteristic of MOSFET devices is a measure of the drain current as output versus the gate voltage as input. This is referred to as a Vgs-Ids test because it shows the drain current characteristic with respect to changes in the gate voltage. Typically for this transfer test, a fixed voltage is applied to the drain while the voltage sweeps at the gate from slightly negative to some amount of positive bias for an n-type MOSFET. **Figure 4** shows settings for this test case, with the voltage for the gate sweeping from –0.5 V to 3 V with 101 points and the drain at a fixed bias of 0.05 V. Note that the measure settings for the drain use auto range so that the SMU channel can cover current measurement from the lowest level to the maximum level of the device. If the device may be capable of high power and high current, the 4-Wire Sense mode is recommended for the drain.

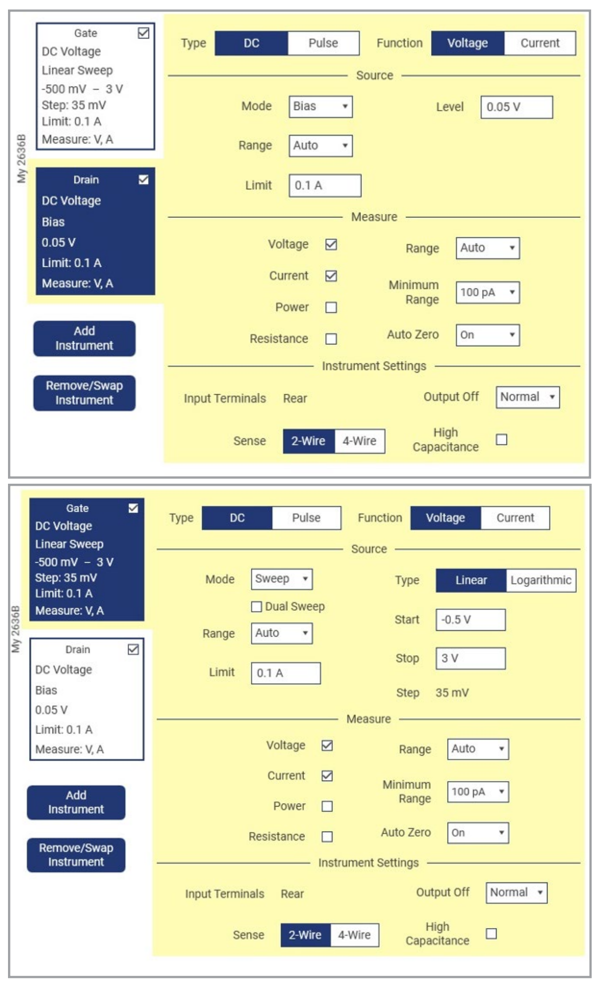


Figure 4. Drain (top) and gate (bottom) settings for transfer measurement in KickStart.

Figure 5 shows the transfer characteristic results for the demo device in linear scale. The x-axis is the gate voltage sweeping from –0.5 V to 3 V as the input source to the device and the y-axis is the current measurement at the drain. The drain current is shown to be about 0 A as the gate voltage approaches 1 V and steadily increases thereafter. The area beyond the 1 V point where some quantity of current flows is identified as the on-state of the device.

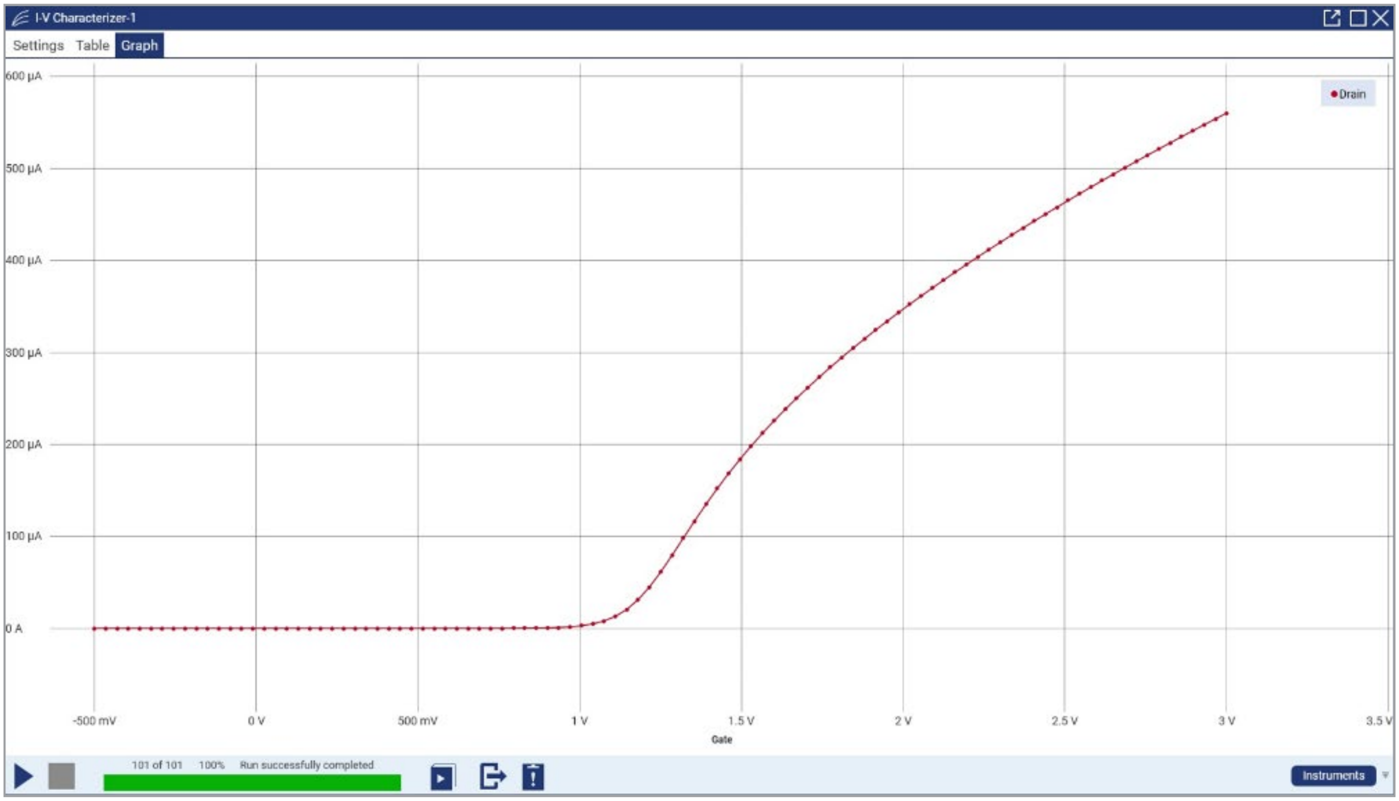


Figure 5. Transfer curve in linear scale shown in the KickStart I-V Characterizer App.

For detailed analysis, the transfer curve is usually displayed using a logarithmic scale as shown in **Figure 6** to better help visually identify low level activity in the drain current prior to and through the point at which it starts to substantially conduct over each individual gate bias sweep point. From the gate voltage 0 V to 1 V, there is still some current flowing. While the gate voltage remains below 0 V no drain current flows and the device is completely shut off. This is referred to as the device off-state. The leakage current of the off-state device is an item of serious concern because a higher leakage can contribute to unprecedented power loss in the application circuits. In this case, the leakage current is less than 60 fA when the gate bias is below 0 V. A Keithley Series 2636B/35B/34B SMU will support below 1 pA leakage current measurement.

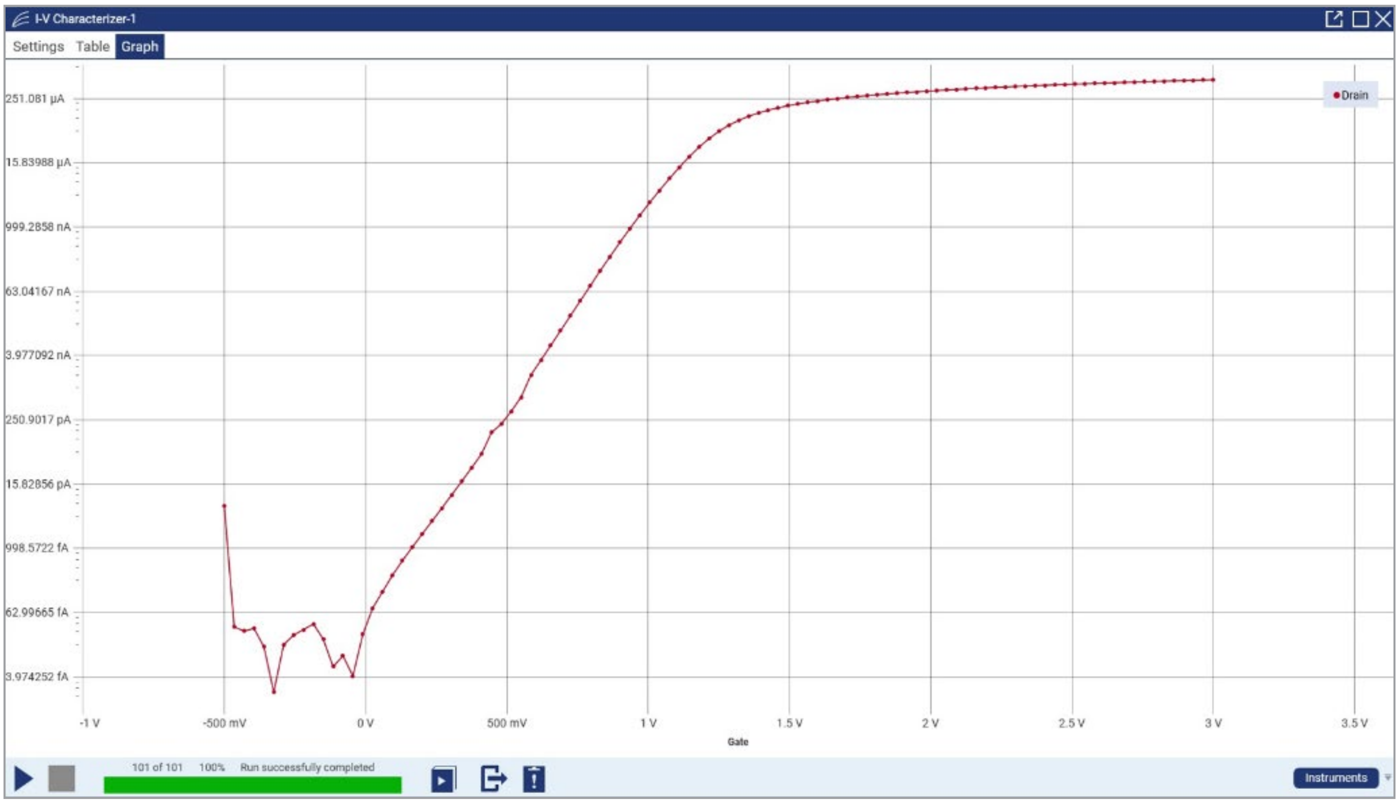


Figure 6. Transfer curve in logarithmic scale shown in the KickStart I-V Characterizer App.

Another benefit of the transfer characteristic is to be able to figure out the transconductance curve and the threshold voltage of the device. The KickStart software provides all the raw data inclusive of test settings and measurements. This data can be exported to a spreadsheet program such as Microsoft Excel. The transconductance (Gm) can be plotted and the Vth can be calculated as shown in **Figure 7**.

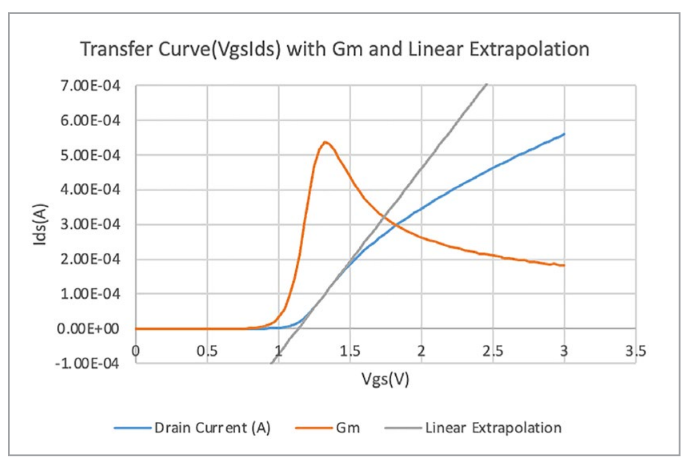


Figure 7. Transfer curve with transconductance and tangent.

The transconductance is the derivative of the transfer curve which is the slope of each measurement point, and it is described as:

$$Gm = \frac{\Delta Ids}{\Delta Vgs}$$

Many methods have been introduced to calculate the threshold voltage. The linear extrapolation method is the most widely used to extract the threshold voltage. It must first be determined that the gate voltage axis intercepts at the 0 A drain current of the linear extrapolation where the transfer curve is at the maximum transconductance point. Then the threshold voltage is calculated by adding half the drain voltage. The Vth calculation in this case is 1.16 V using the linear extrapolation method.

MOSFET Output Characteristic

The output characteristic is obtained by sweeping the gate voltage across the desired range of values in specific increments. A voltage is applied at the device gate, the drain voltage is then swept through the required range, once again at the desired increments, with the drain current measured at each of the corresponding drain voltage points. Plots can then be made from this data to show Vds-Ids with curves corresponding to each of the specified gate voltage levels. **Figure 8** shows a specific example of the output characteristic test setup for the demo DUT. The drain is swept from 0 V to 2 V in 50 mV increments. The gate is incremented from 1 V to 2 V using 0.25 V steps and should be enabled as a stepper in the common settings. This will generate five drain family curves.

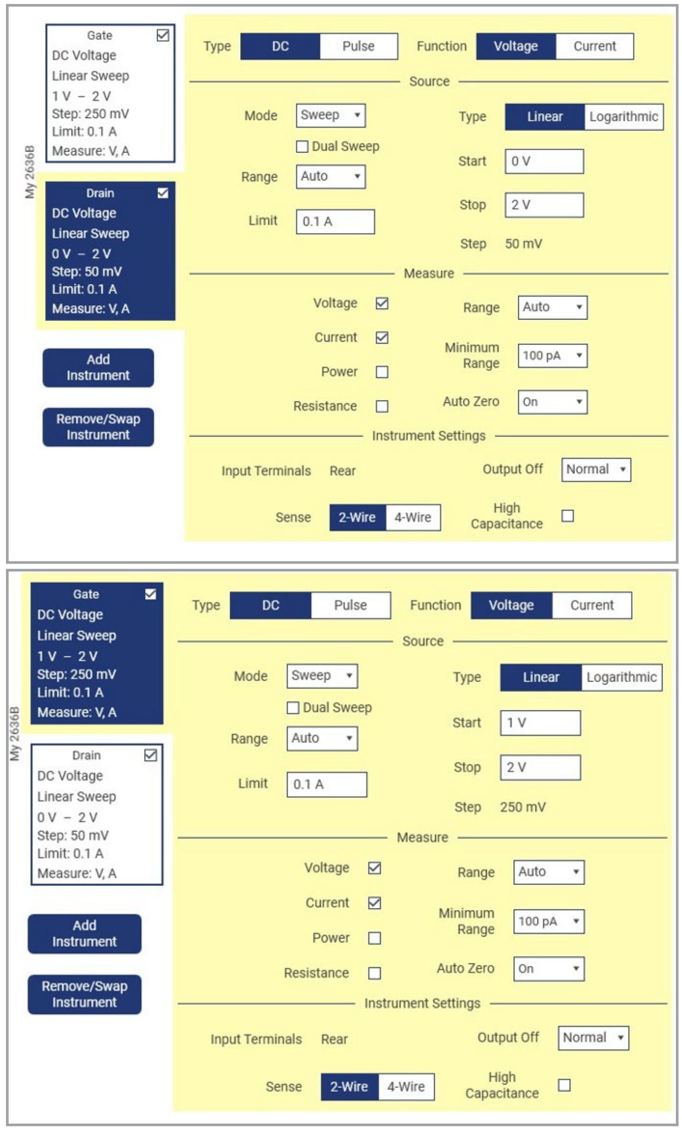


Figure 8. Drain (top) and gate (bottom) settings for output measurement in KickStart.

Figure 9 shows the result of the output characteristic test using a linear scale. As the drain voltage increases, the drain current grows and saturates with some level of current. Note how the current ceases to increase beyond some level of drain voltage. This area where the current plateaus is called the saturation region. The interval over which the current increases is called the linear or ohmic region. The drain voltage point that identifies the transition between these two regions is the pinch-off voltage. After the pinch-off voltage has been reached, the drain current levels of the saturation are importantly considered in the device characterization for the power amplifier circuit applications. Gate voltage settings less than the threshold voltage are not necessary for determining the output characteristics because the drain output current would be too low and not clearly shown. Note, in this case, that the output drain current (when the applied gate voltage is 1 V) is almost 0 A all the way to the maximum drain voltage.

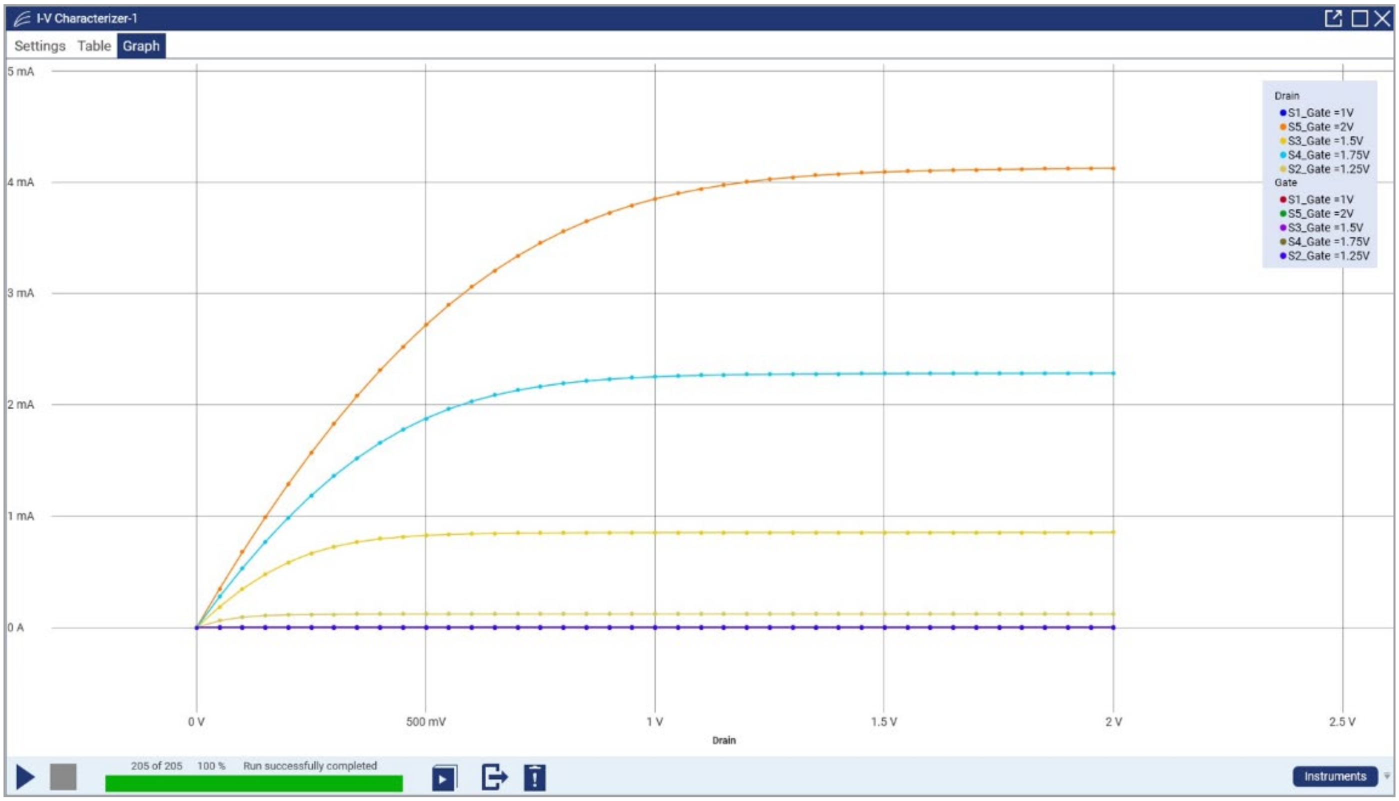


Figure 9. Output curve shown in the KickStart I-V Characterizer App.

There are other possible DC I-V characterizations of MOSFET devices with SMU instruments using the KickStart software. The breakdown voltage test is one of the important off-state characteristics. Using the same device connections, the gate and source voltages are biased at 0 V while the drain voltage is swept. At the extreme end of the drain sweep, the device will no longer be able to impede the flow of current and will start to conduct, and the current level at this transition point is defined as a breakdown current. The voltage read at this same point is deemed to be the breakdown voltage for the device. The leakage current of the drain at the off-state and the drain current at the specific condition can be easily tested using the KickStart software.

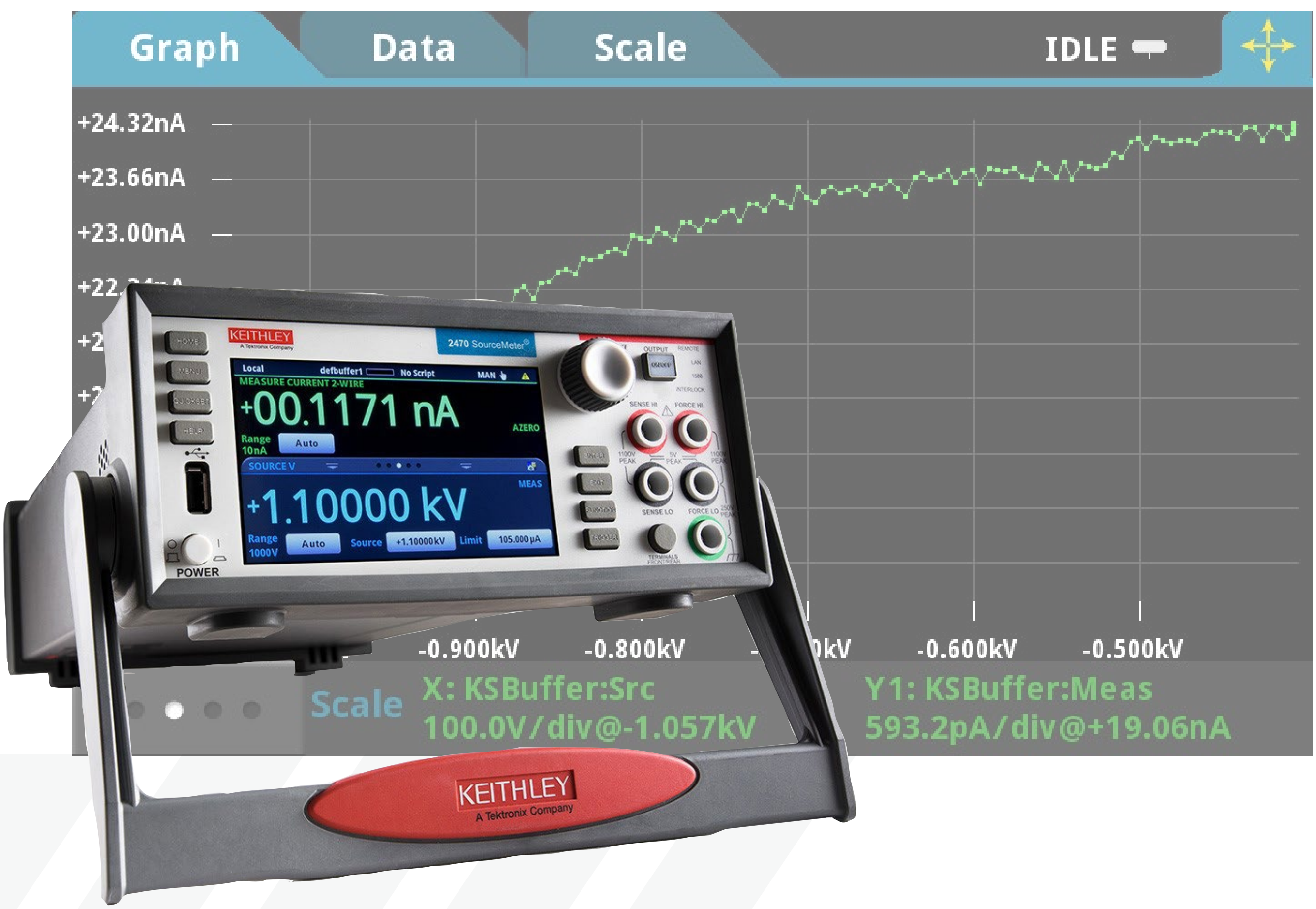
Conclusion

MOSFET devices continue to be used in switching circuits and power amplifier circuit applications, and DC I-V is still common and necessary for basic characterization of a MOSFET device. Keithley's KickStart software and Series 2636B/35B/34B SMUs make for a great solution that allows users to achieve the transfer, output, and other device characteristics.

Please visit the KickStart Software product page to learn more.

Breakdown and Leakage Current Measurements on High Voltage Semiconductor Devices Using the Keithley 2470 SourceMeter® Source Measure Unit (SMU) Instrument and KickStart Software

APPLICATION NOTE



Introduction

After years of research and design, Silicon Carbide (SiC) and Gallium Nitride (GaN) power devices are becoming more viable. The shift to SiC and GaN is driving new designs from the ground up. SiC, with its capability of driving high power at high voltages for high power applications, and GaN, with its super high-power density for medium to low power applications, are pushing the limits of what is possible with silicon-based designs in efficiency and power density. For example, SiC is finding applications in higher power, higher voltage designs such as motor drives in automobiles, locomotives, and PV inverters. GaN technology is also shaking up the world of RF power amplifiers, thanks to many of the same attributes that make it well-suited for power conversion. GaN is carving its niche in data-center power, wireless power, consumer power supplies, and automotive and military/government power electronics.

These devices, though high performance, come with challenges. Setting cost and reliability aside, these power devices are not drop-in replacements for their silicon counterparts. Semiconductor R&D engineers are working to validate and characterize new components. Driver manufacturers are developing new gate drivers to withstand the demands of faster switching, EMI management, and more sophisticated topologies. Manufacturing engineers in these companies are dealing with wafer testing challenges – having to thoroughly test smaller devices over wider voltage and current ranges than ever. Manually characterizing wafer and package-part level devices for electrical performance requires learning new techniques, equipment, and probing infrastructure for low level measurement (e.g., pA of leakage current measurement in the presence of high breakdown voltage).

Some of the biggest challenges working with SiC and GaN devices are the gate drive requirements. SiC requires much higher gate voltage (V_{gs}) with a negative bias for turn off. GaN, on the other hand, has much lower threshold voltage (V_{th}), requiring tight gate drive designs. Wide band gap (WBG) devices, by the nature of their physics, also have a higher body diode voltage drop that requires much tighter control of dead-time and turn-on/turn-off transitions. Solving these challenges are not trivial. It's critical that you have accurate electrical source and measure testing when characterizing these high voltage devices so that the right design decisions can be made in a timely fashion. Increasing design margins and overdesigning will only drive costs up and bring performance down. And, due to the high voltages involved - usually >200 V, keeping the scientist and engineer safe from harmful voltage is very important.

Keithley has long had a strong presence in high power semiconductor device test. Most recently, Keithley introduced the 2470 1.1kV Graphical SourceMeter® Source Measure Unit (**Figure 1**) to address challenging measurements for SiC and GaN device testing. This application note considers the application of this new source measure unit with Keithley's KickStart software for high voltage semiconductor device testing.

Figure 1: Keithley's high voltage 2470 Graphical SMU

High Voltage Device Tests

Basic characterization of high voltage semiconductor devices typically involves a study of the breakdown voltage and leakage current. These two parameters help the device designer to quickly determine whether the device was correctly manufactured and whether it can be effectively used in the target application.

Breakdown Voltage Measurements

Measuring breakdown voltage is done by applying an increasing reverse voltage to the device until a certain test current is reached that indicates that the device is in breakdown. **Figure 2** depicts a breakdown measurement on a high voltage diode using a source measure unit like the 2470. Note how the SMU is connected to the diode's cathode to apply a reverse voltage.

In qualifying breakdown voltage, measurements are typically made well beyond the expected rating of the device to ensure that the device is robust and reliable. The 2470's 1100-volt sourcing capability is typically high enough to test many SiC and GaN devices today and future device designs.

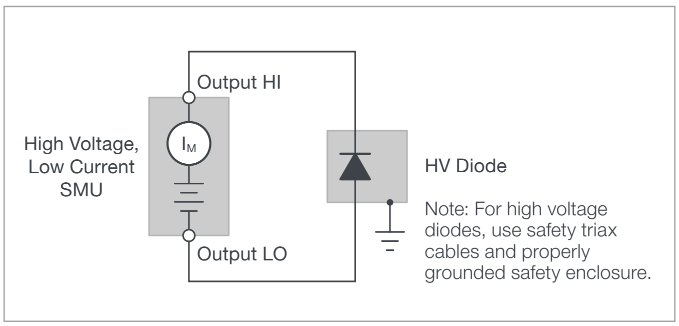


Figure 2. Typical breakdown voltage measurement of a high voltage diode using the 2470 High Voltage SMU.

Safety Considerations

When testing at high voltage, safety is of utmost concern. The 2470 SMU can generate voltage voltage up to 1.1 kV, so precautions must be taken to ensure that the operator is not exposed to unsafe voltage:

- Enclose the device under test (DUT) and any exposed connections in a properly grounded fixture such as the fixture shown in **Figure 3**.
- Use the safety interlock provided on the rear panel of the 2470 SMU as shown in **Figure 4**. The 2470 is fully interlocked so that the high voltage output is turned off if the interlock is not engaged. The interlock circuit of the SMU should be connected to a normally-open switch that closes only when the user access point in the system is closed to ensure that operators cannot meet a high voltage connection to the DUT. For example, opening the lid of the test fixture should open the switch/relay that disengages the interlock of the 2470 SMU.
- Use cables and connectors rated to the maximum voltage in the system. Keithley's TRX-1100V-* high voltage triax cables are designed for the 2470 which meet today's high voltage safety standards.
- Always use the proper safety gloves when working with high voltages on energized components as shown in **Figure 5**.

Figure 3: Properly grounded testing fixture

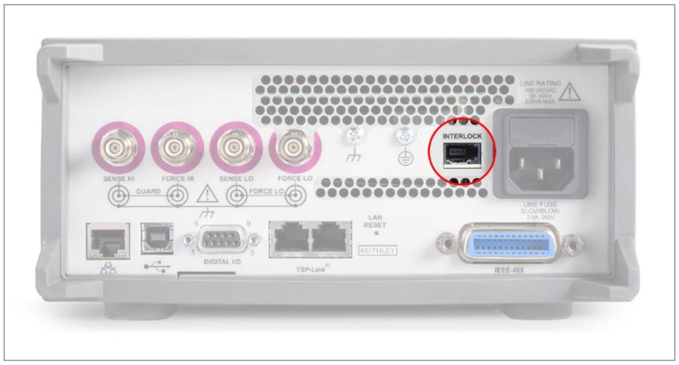


Figure 4: Location of safety interlock connection on rear panel of 2470 SMU

Figure 5. Using proper safety gloves when working with high voltages on energized components.

Leakage Current Measurements

In a typical power conversion application, the semiconductor device is used as a switch. Leakage current measurements indicate how closely the semiconductor performs to an ideal switch. Also, when measuring the reliability of the device, leakage current measurements are used to indicate device degradation and to make predictions of device lifetime.

Semiconductor researchers are finding materials to make higher quality switches and produce high power devices with very small leakage currents. SMUs like the 2470 offers precision low current measurement capabilities with measurement resolution as low as 10 fA.

To prevent unwanted measurement error when measuring currents less than 1 µA, use triaxial cables and electrostatic shielding. Triaxial cables are essential in part because they permit carrying the guard terminal from the current measurement instrument. Guarding eliminates the effect of system leakage currents by routing them away from the measurement terminal. Use an electrostatic shield to shunt electrostatic charges away from the measurement terminal. An electrostatic shield is a metal enclosure that surrounds the circuit and any exposed connections. The safe test enclosure may serve as an electrostatic shield. For more tips on optimizing low current measurements, refer to Keithley's *Low Level Measurements Handbook*.

Characterizing a SiC Power Diode with KickStart Software

Keithley's KickStart software can be used to quickly run breakdown and reverse leakage current testing with the 2470. KickStart simplifies what you need to know about the instrument so that in just minutes you can take the instrument out of the box and get real data on your device. By plotting data immediately and offering quick statistical summaries of the data in the reading table, KickStart allows you to gather insights faster and make the decisions you need to move on to the next stage of device development. The software saves you time by facilitating quick replication of tests and comparison of results using convenient export features.

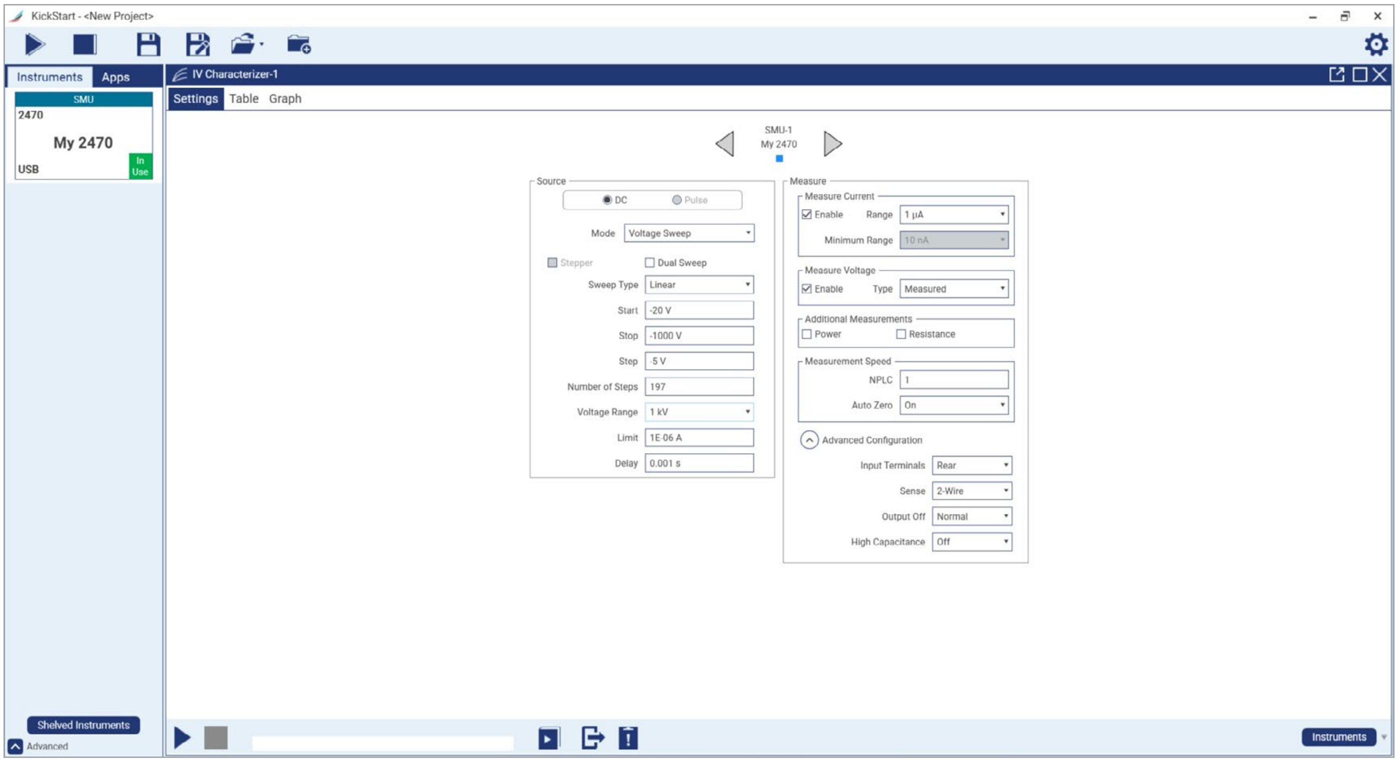


Figure 6. KickStart software and IV Characterizer App

For this example, we will measure the leakage current on a high voltage ultrafast soft recovery silicon carbide rectifier diode. The diode has a maximum specified reverse current of 100 μA when 1000 V of reverse voltage is applied at room temperature. To set up the test, the diode is inserted into a test fixture as shown in **Figure 7**. The test fixture also incorporates a safety interlock using a magnetic relay switch to ensure that if the top cover is off the fixture, the SMU output turns off to prevent someone from coming in contact with high voltages.

Figure 7. Test Fixture for testing the high voltage diode which includes a safety interlock relay system.

The key test parameters are as follows:

- Linear Sweep
- Start Point: –20 V
- Stop Point –1000 V
- Step: –5 V
- Current Limit: 1 μA
- Measure Current Range: 1 μA
- Source Voltage Range: 1 kV
- Measurement Speed: 1 NPLC
- Auto Zero: On

The 2470's rear inputs will be used since the test required the use of high voltage triax connections. The test parameters are set up as shown in **Figure 8**.

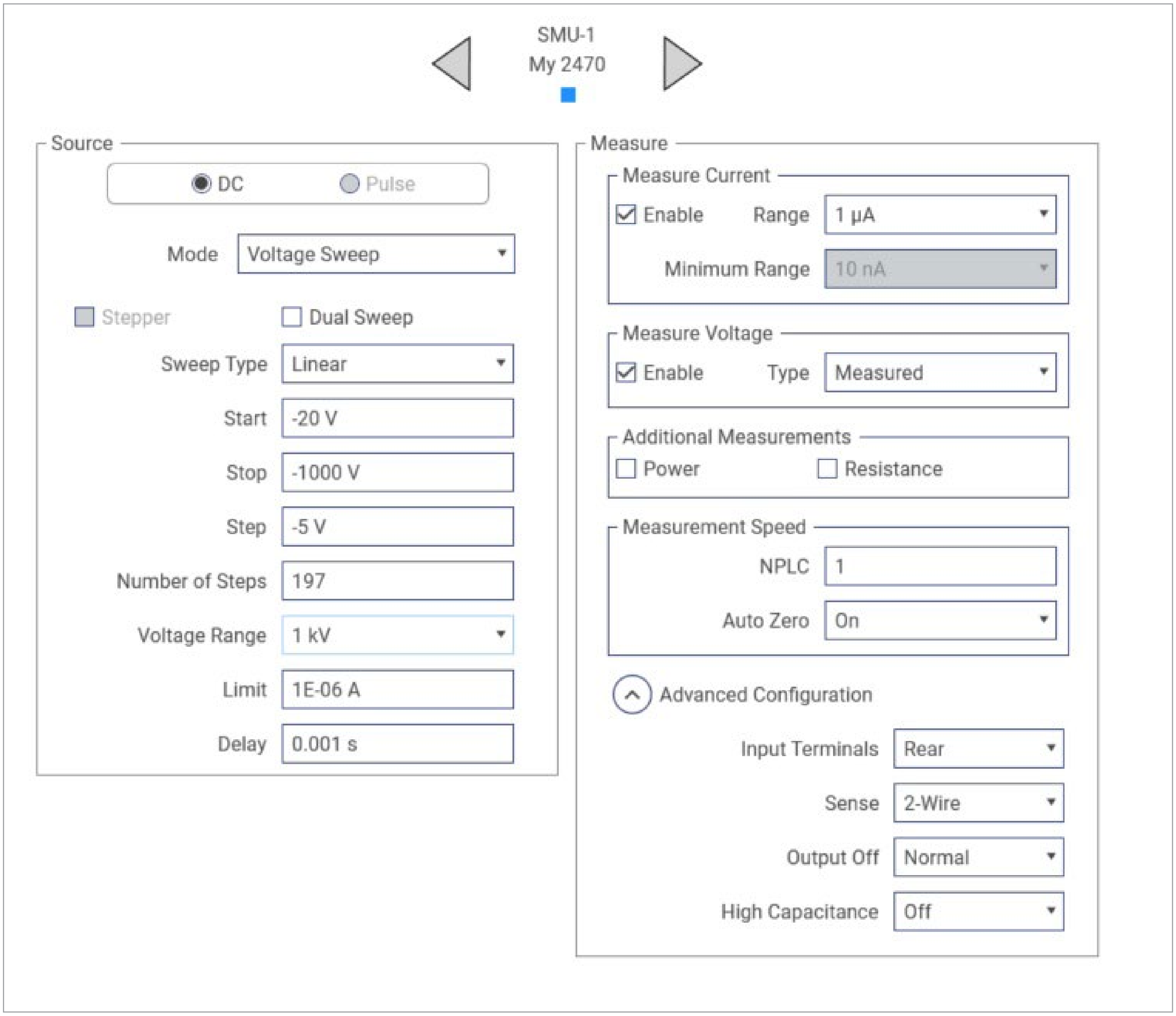


Figure 8: Test setup using Kickstart.

The KickStart test can now be initiated and viewed on the Graph Screen. The results of the test are shown in **Figure 9**.

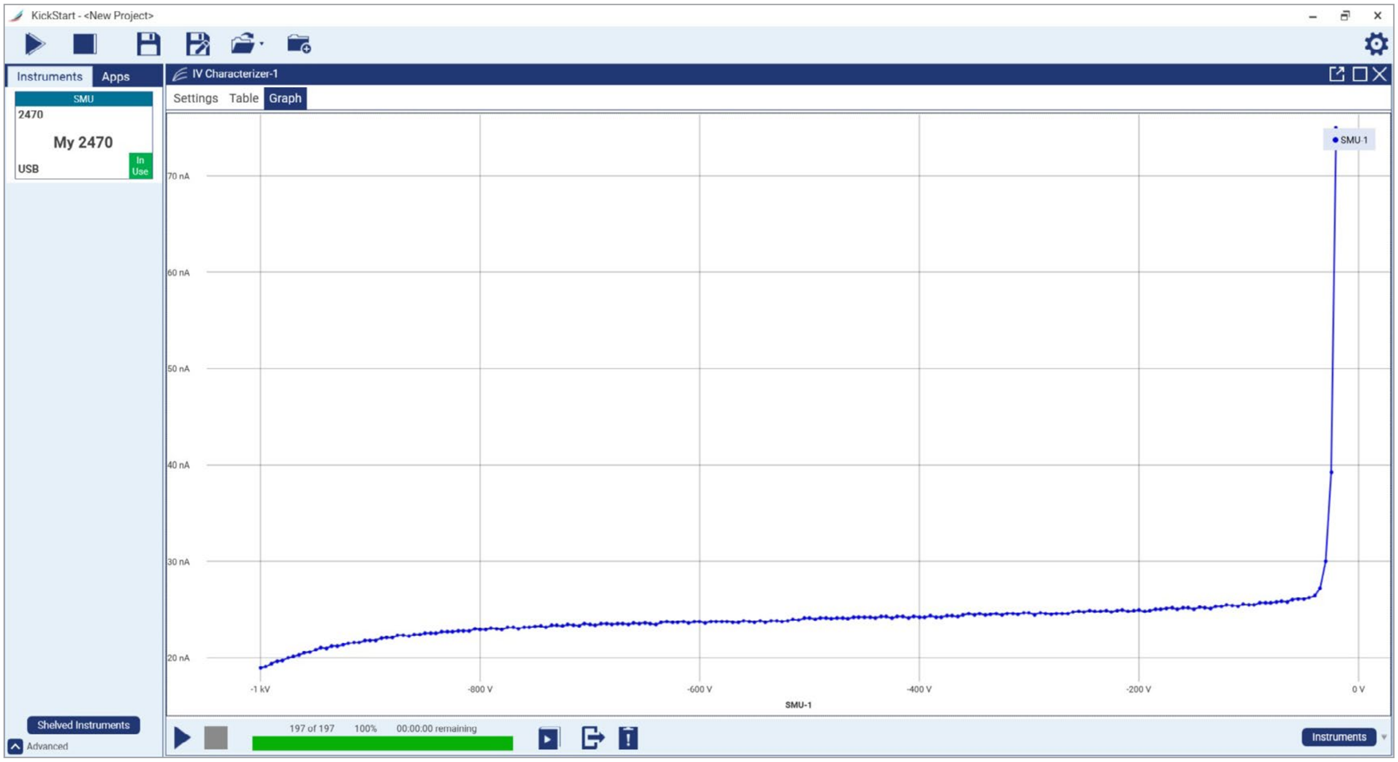


Figure 9: Leakage current results of High Voltage Diode using 2470 and KickStart

The results show that the diode meets its specification. The reverse current grows at a faster rate as the reverse voltage increases, indicating that the diode is approaching breakdown. With KickStart, we can zoom in on the area of the chart to show the reverse current growing fast as the test voltage increases as shown in **Figure 10**.

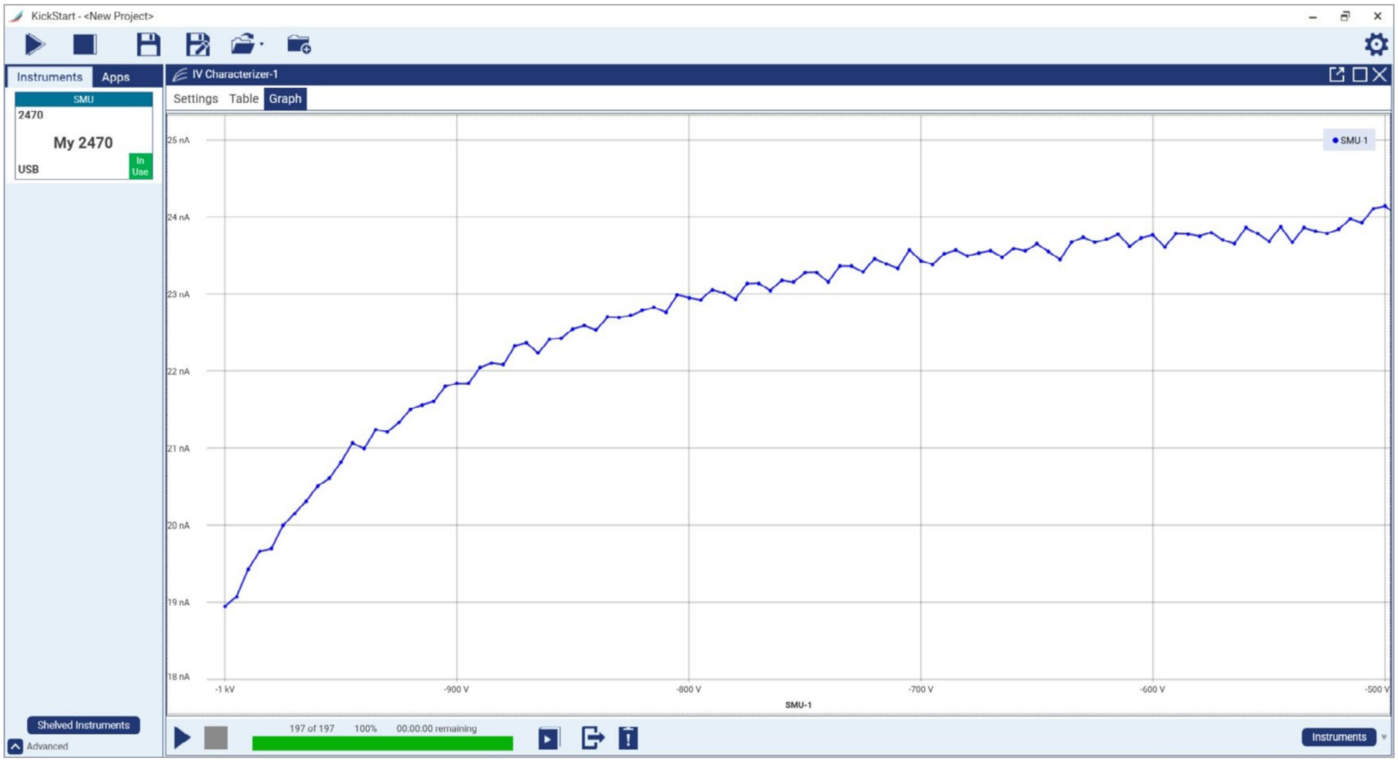


Figure 10: Zooming in with Kickstart.

The 2470 can also plot the results in real time and screen shot capture the plot. The results of the test as graphed and zoomed in on the 2470 are shown in **Figure 11**.

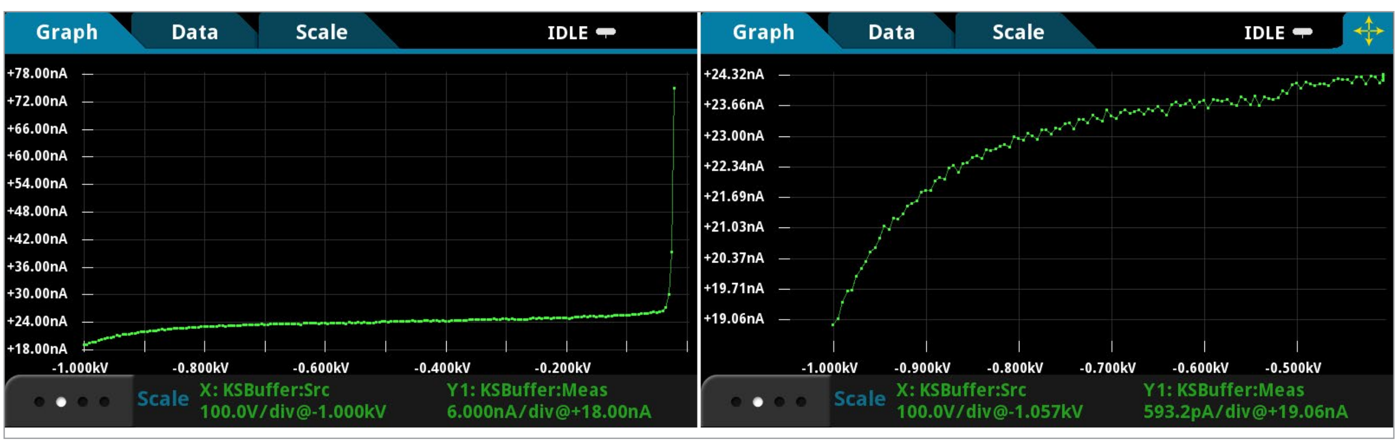


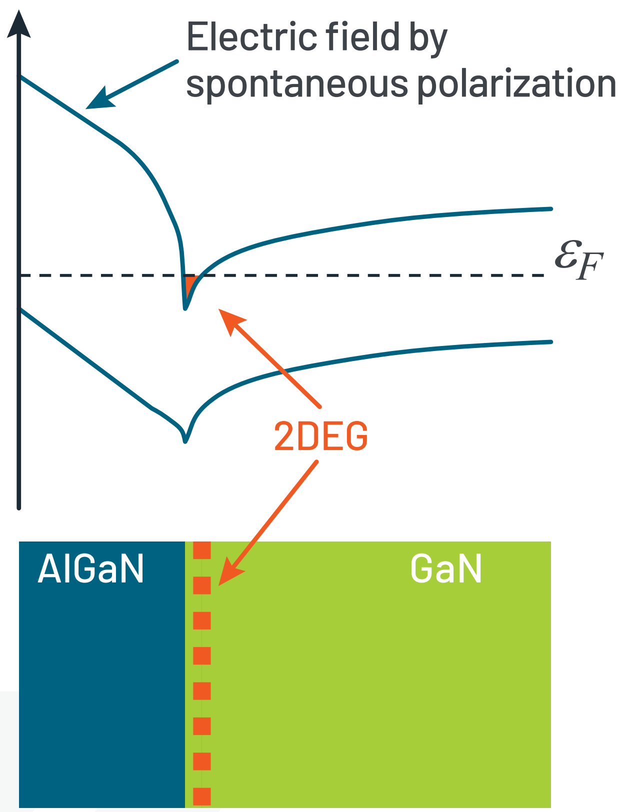
Figure 11: Screen captures from the 2470.

Conclusion

Testing new silicon carbide and gallium nitride high voltage, high power semiconductor devices involves a consideration of test system safety, wide voltage range, and accurate current measurement. Coupling a Keithley SourceMeter SMU instrument like the 2470, KickStart software, and their associated accessories meets all these needs and further facilitates research of high voltage materials and semiconductor devices.

Challenges in GaN HEMT Power Device DC Characterization

APPLICATION NOTE



Introduction

Power electronics technologies have been rapidly changing to meet new requirements. CO_2 reduction, higher efficiency with low power consumption, and system downsizing have been main drivers of new technologies in power electronics applications. Wide bandgap (WBG) semiconductors are widely adapted to convert power in the power electronics. Specifically, Gallium Nitride (GaN) devices have been prevalently leveraged in high-speed applications inclusive of consumer products to high power use cases due to the GaN devices operating very fast and with high efficiency while also housed within a small structure. Still, there are some remaining challenges in DC I-V characterization. This application note will provide details regarding oscillation of GaN HEMT devices during DC characterization and propose better ways to mitigate said oscillation.

Keithley provides a variety of High Power SourceMeter® source measure units (SMUs) to characterize components such as the power MOSFET. The 2657A High Power System SourceMeter Instrument is capable of sourcing 3 kV, and the 2651A — another high-power system SourceMeter instrument — is 50 A capable in pulse mode operation. The 8010 Test Fixture can be used with either SourceMeter SMU to hold and shield your power device. The ACS and KickStart software packages offer a means to establish automated setups and perform execution of I-V characterization tests for power MOSFET devices.

GaN HEMT Structure

GaN HEMT devices have a mainly lateral structure as shown in **Figure 1**. This device utilizes the benefit of a hetero junction characteristic at the interface of the GaN and the AlGaN materials where a deep valley of 2DEG (Dimension Electron Gas) conduction energy level is formed, allowing a large quantity of electrons to enter it. These particular electrons can have higher mobility than in other regular states, and this high mobility aids in increasing the current from drain to source. This type of device structure is called a high electron mobility transistor or HEMT. An inconvenience of this device is that it is normally turned on, which is not desired in most applications. This normally on-state GaN HEMT device is called a depletion mode GaN (or D-mode GaN for short). To turn the GaN HEMT device off, some level of negative gate bias is required to deactivate the 2DEG. For readers interested in the normally on-state GaN HEMT device characterization, an application note entitled "Power Sequence for GaN HEMT Characterization" can be found on tek.com.

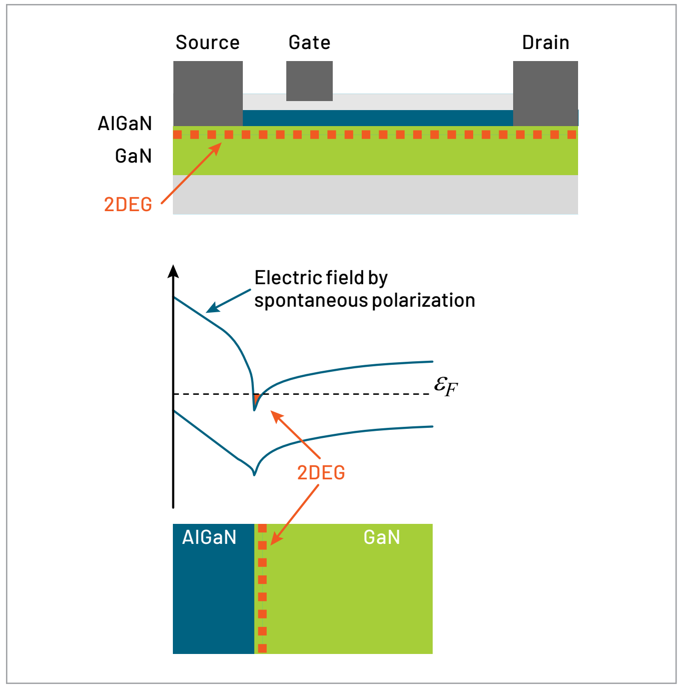


Figure 1. Typical GaN HEMT device.

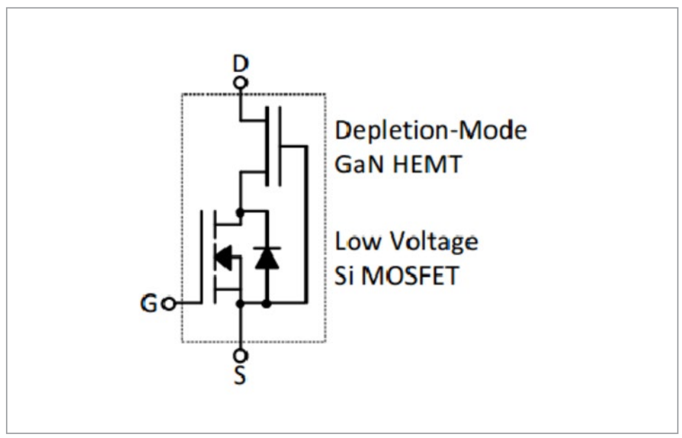


Figure 2. Cascode of GaN HEMT device.

Enhancement mode GaN HEMTs (E-Mode GaNs for short) have been introduced to enable a normally off device state by adding a p-type doped GaN layer between the AlGaN and the gate metal. This p-type doped GaN layer acts as a normal positive bias to prevent the 2DEG from being formed. When the gate bias is present, the majority carriers move away from the AlGaN interface so the 2DEG can be formed at the gate bias. The Cascode structure in **Figure 2** is another technology that has been introduced to ensure the normally off device state. In the Cascode, a regular Si MOSFET is added to a HEMT to invert the on state of the device to the off state. The presence of a gate bias at the Si MOSFET can switch the device state on.

High Speed of GaN HEMT Device

The GaN HEMT is well known as a device that supports high frequency switching. With respect to use as a high power device, the electrons driven by a voltage bias will cause the drift current, resulting in some collisions and scattering as the electrons move through the semiconductor materials. This scattering can disrupt and limit drift current. However, this carrier scattering is minimized in the 2DEG of the HEMT such that electron mobility is multiple times higher than the mobility of other technologies.

With all MOSFET devices, input capacitance (Ciss) — inclusive of the capacitance between gate and source (Cgs) and the capacitance between gate and drain (Cgd) — will affect the switching speed at the gate, slowing it down and reducing its efficiency. To reduce its impact and promote maximum output power at the drain, the input capacitance should be charged up quickly by first applying a bias to the gate. The GaN device is less impacted by capacitance of the gate. In comparison to other high power MOSFET devices, the GaN HEMT input capacitance is usually about ten times lower allowing the device to have faster state switching and resulting in less power loss.

Most high power vertical device MOSFETs have a body diode for third quadrant operation shown in **Figure 3**. Many power conversion applications utilize the third quadrant operation. When the device is off state, the body diode can still make current flow for opposite current in the third quadrant. When the device is switched off completely with the body diode, the drain voltage ramps up and the drain falls down to zero. The problem is that the body diode needs some time to recover (the reverse recovery time or T_{rr}) and that negatively impacts the switching speed, because some charges accumulated during third quadrant operation make reverse current. This is illustrated in **Figure 4**. The device needs the Trr to recover from the effects of charging (or Q_{rr} — reverse recovery charge). In contrast, the GaN HEMT device has no inherent body diode in its structure, and the T_{rr} and Q_{rr} are minimized or eliminated altogether thus accelerating its switching speed. Note, though, that there is still body diode in the cascode type of GaN device because of the regular Si MOSFET.

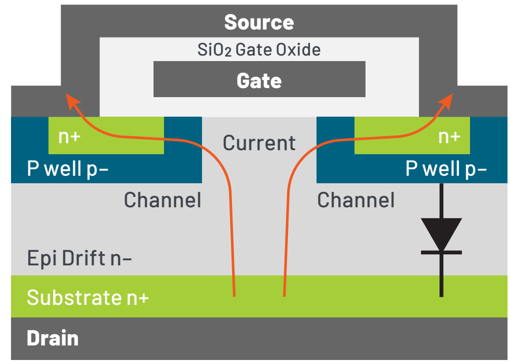


Figure 3. Typical high power MOSFET with body diode.

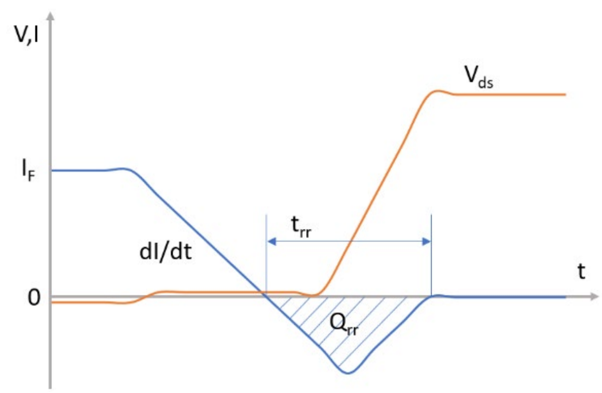


Figure 4. Reverse recovery timing example.

Oscillation in GaN HEMT DC Characterization

The lateral structure limits current delivery but promotes a speed advantage. Additionally, high-speed GaN devices may introduce another challenge in DC characterization causing frustration for test engineers and circuit designers alike: oscillation. The remainder of this application note focuses just on oscillation in DC characterization. When the devices are in the off state and only leakage level current is flowing, there is almost zero oscillation. It is the on state where several complicated oscillation issues might occur. One such case can arise when your test instruments use a feedback control loop technology to generate an output voltage and current with some amount of bandwidth. The oscillation can occur if the instrument band couldn't over the load band in the high capacitive load or inductive load.

If the capacitance of a device gate is high enough, then this could also promote oscillation. A remedy to suppress this might be to include some amount of series resistance at the gate; this series resistance may be effective but not work out perfectly. The capacitance of a GaN HEMT device is usually ten times lower than other types of power MOSFET devices. The oscillation can also originate in the drain terminal of the GaN HEMT device at very high frequencies, transferring over or coupling to the gate terminal via the capacitance between them.

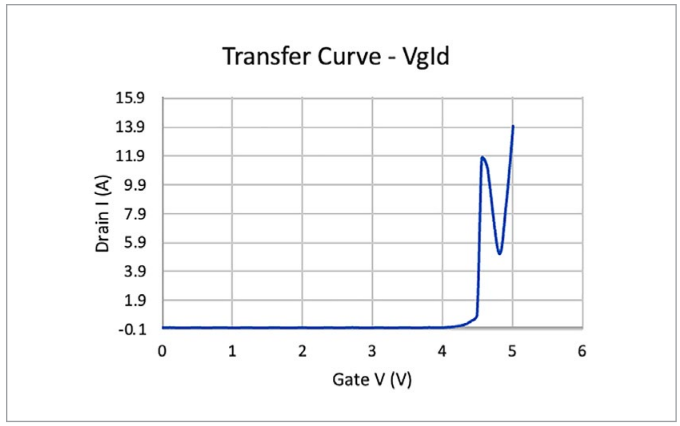


Figure 5. Transfer curve (VgId) with oscillation.

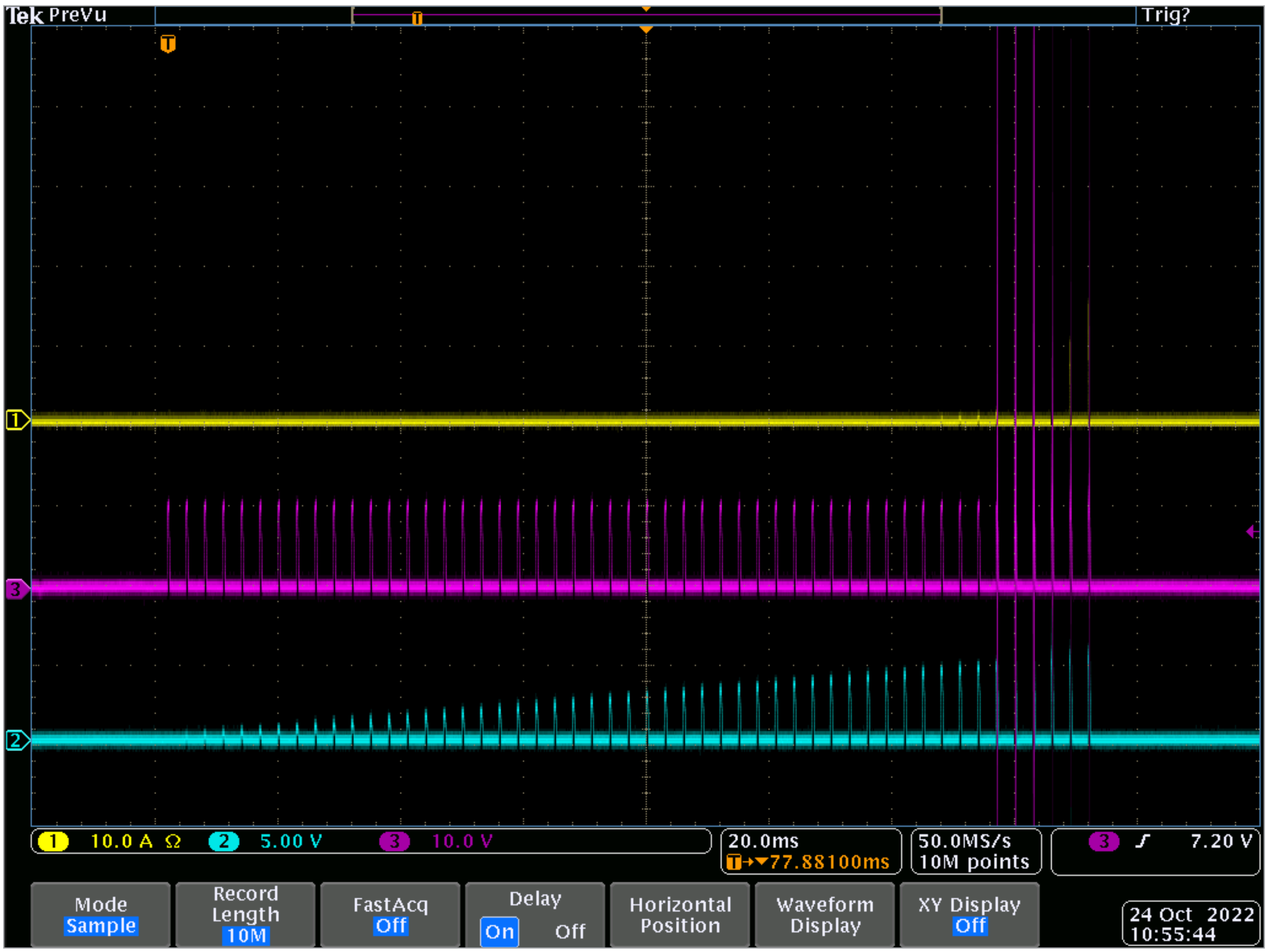


Figure 6. Oscilloscope waveforms of the Vg-Id test (yellow – drain I, magenta – drain V, blue – gate V).

Figure 5 shows an oscillation in the Vg-Id characterization. Oscillations are present in the threshold voltage region in this case, but this can occur any time the device is in the on-state. The example is of the cascode type, which has a higher threshold voltage than the pure HEMT type due to the integrated Si MOSFET (as noted earlier), and pure HEMT devices have a lower threshold voltage than other device structures. **Figure 6** shows the oscilloscope waveform of the I-V characterization where oscillations are observed in the signals of drain current, drain voltage, and gate voltage each. **Figure 7** shows the single waveform of the sweep measurement, while **Figure 8** magnifies the oscillation with a frequency higher than 3 MHz for this GaN HEMT device, well beyond DC instrument band.

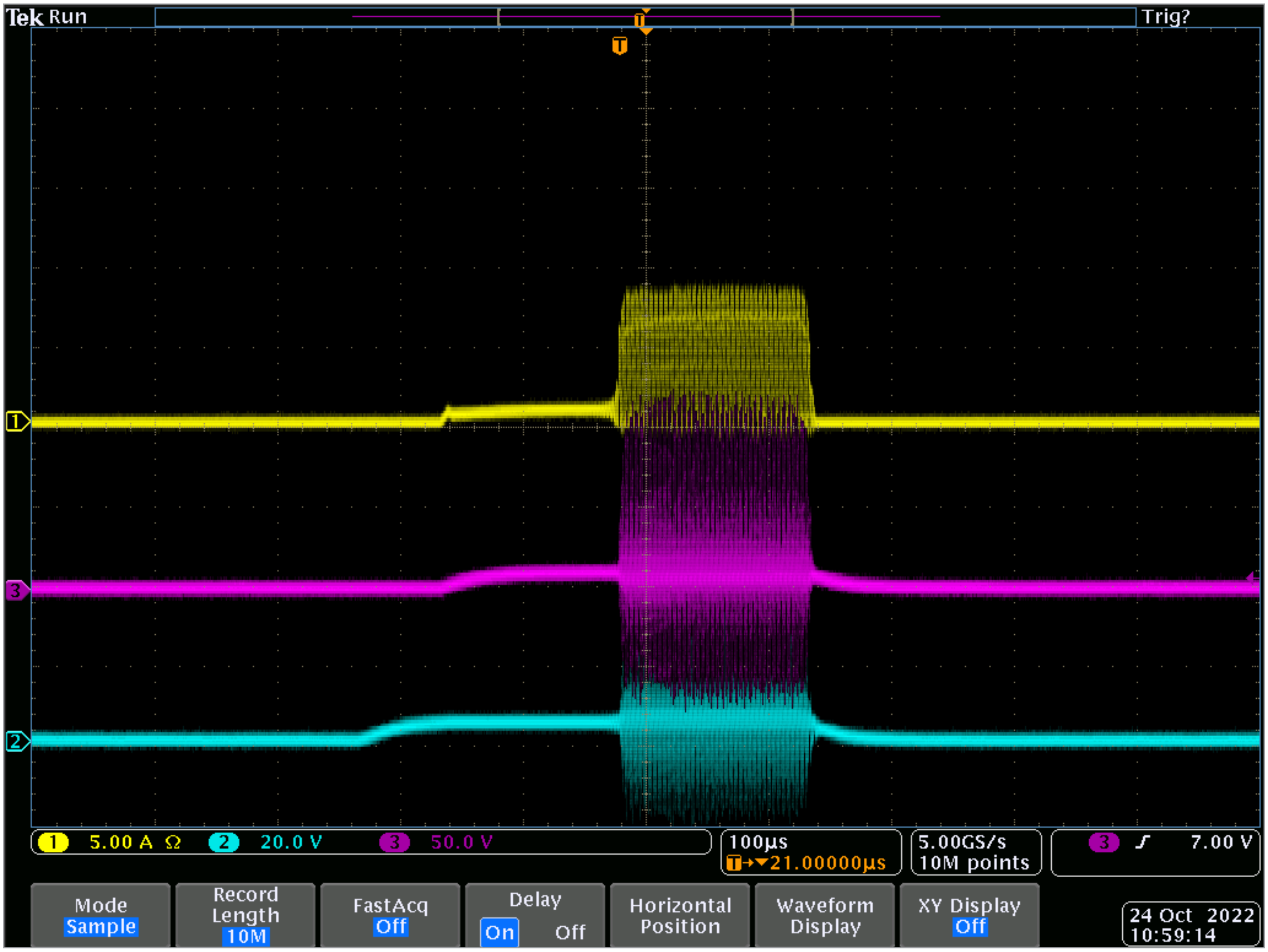


Figure 7. Single waveform capture of the sweep measurement (yellow – drain I, magenta – drain V, blue – gate V).

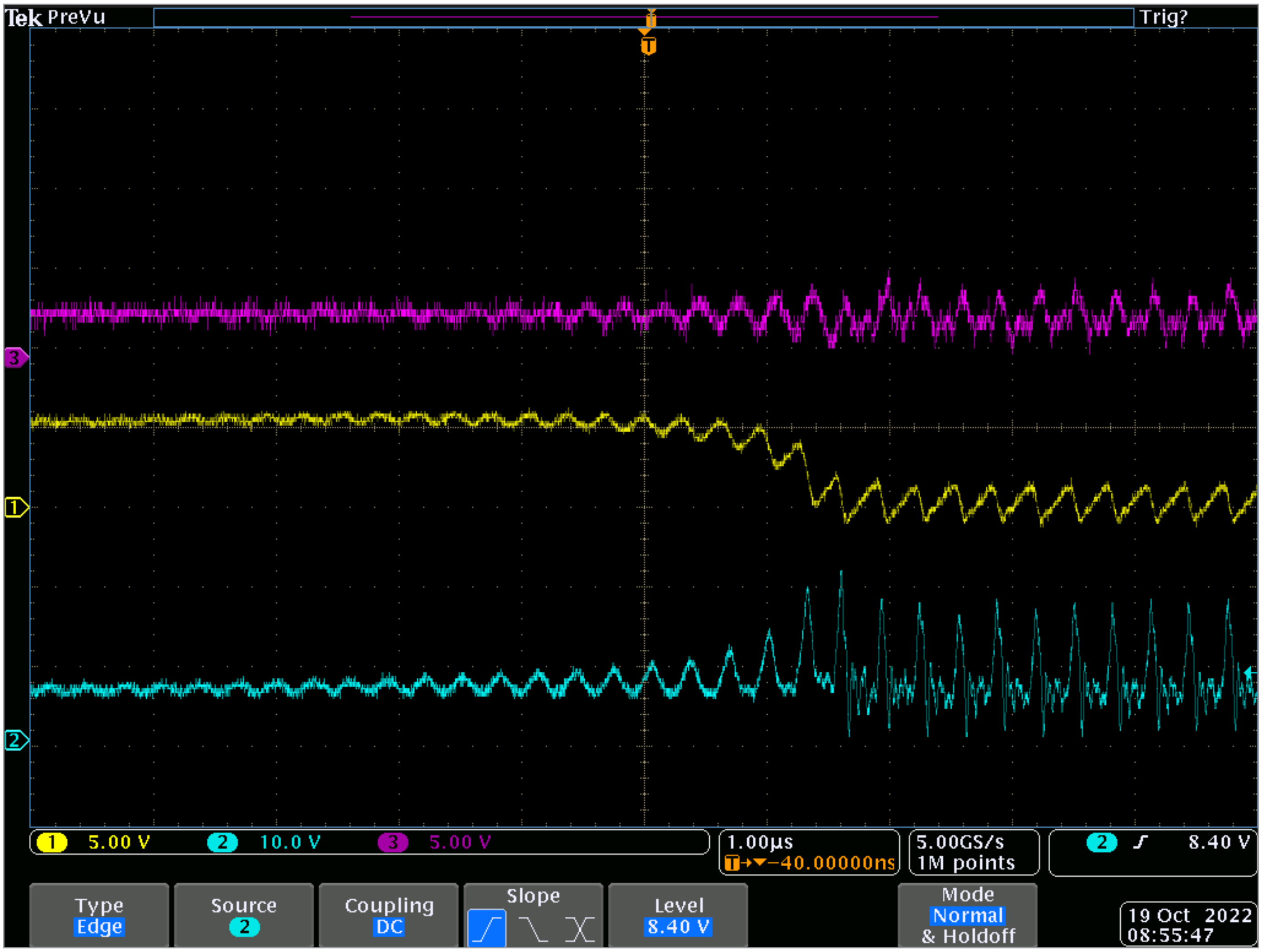


Figure 8. Zoom-in on the high frequency oscillation (yellow – drain I, magenta – gate V, blue – drain V).

Inductance in the Connection Setup

Addressing cable inductance is critical to avoid the oscillation when performing DC characterization of a high speed GaN HEMT device. Keithley offers a low inductance cable (2651A-KIT in **Figure 9**) designed to be used with the 2651A High Current SourceMeter SMU. The one-meter-long cable has a mere 195 nH inductance at 100 kHz, far less than that of a regular BNC cable. Triaxial cables typically have about double the inductance of standard coaxial cable and are not recommended for high frequency device testing.

Figure 9. 2651A-KIT cable for use with the 2651A.

Additionally, Keithley provides the 8010 High Power Device Test Fixture in **Figure 10,** which is excellent for GaN device test and includes a built-in safety interlock. Note, too, that even when using a triaxial cable to connect a 2636B

SourceMeter SMU to the gate (via the triaxial terminal interface), the fixture uses the inner shield of triaxial cable in the low side, which aids in reducing the cable inductance.

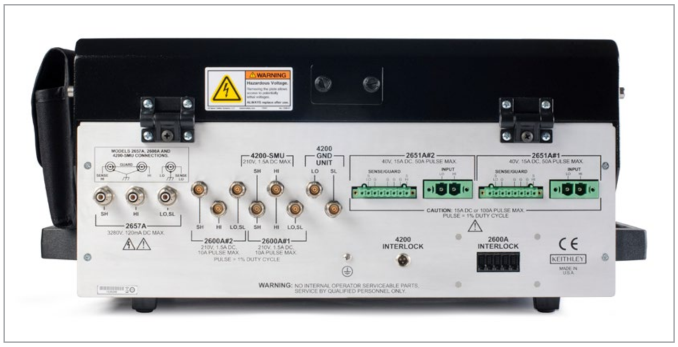


Figure 10. 8010 High Power Device Test Fixture rear view.

Figure 11 offers the transfer curve test comparison using the 8010 High Power Test Fixture (with the triaxial cable in the gate connection) and shows that the oscillation (from **Figure 5**) is no longer evident. If oscillation persists when using the triaxial cable with the 8010 fixture, lower inductance can be achieved using coaxial cable. The coaxial cables can be connected directly to the devices through the rear access port of the 8010 fixture. Keithley offers a blue, lower inductance coaxial cable (SC-182) that has better inductance performance than a standard coaxial cable. A 2601B-PULSE-CA3 is the blue lower inductance coax cable terminated by BNC. These lower inductance cables are great when interfacing with a probe station for low power GaN HEMT device test.

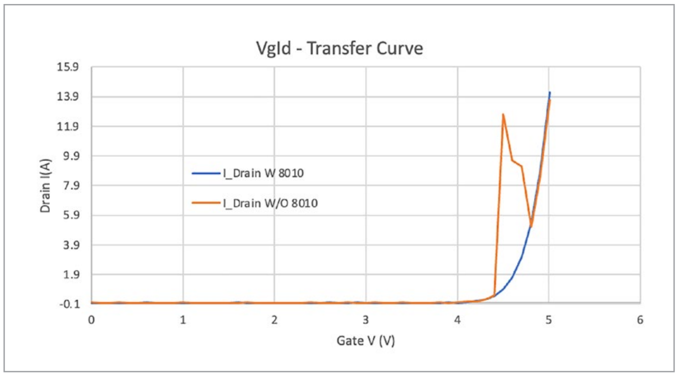


Figure 11. Vgld curve (transfer curve) with the 8010 fixture.

Ferrite Bead on Drain

In most cases, oscillation can be solved in proper cabling to the test fixture. However, the oscillation may persist in cases where long cables are used in connection to a probe station, among other reasons. The basic characteristics of ferrite beads are similar to inductors, though their high frequency impedance characteristics are different from those of inductors. In comparison to inductors, ferrite beads have a high resistance (R) component and low quality factor (Q), pushing them to act more like resistors at high frequency and eliminating energy storage - characteristics commonly utilized for suppressing high frequency oscillation and noise. **Figure 12** shows the ferrite beads at work (added on the drain terminal and as close to the device as possible) effectively eliminating the oscillation presented in the earlier example shared in **Figure 7**. Placing the bead on drain is much more effective than on gate terminal.

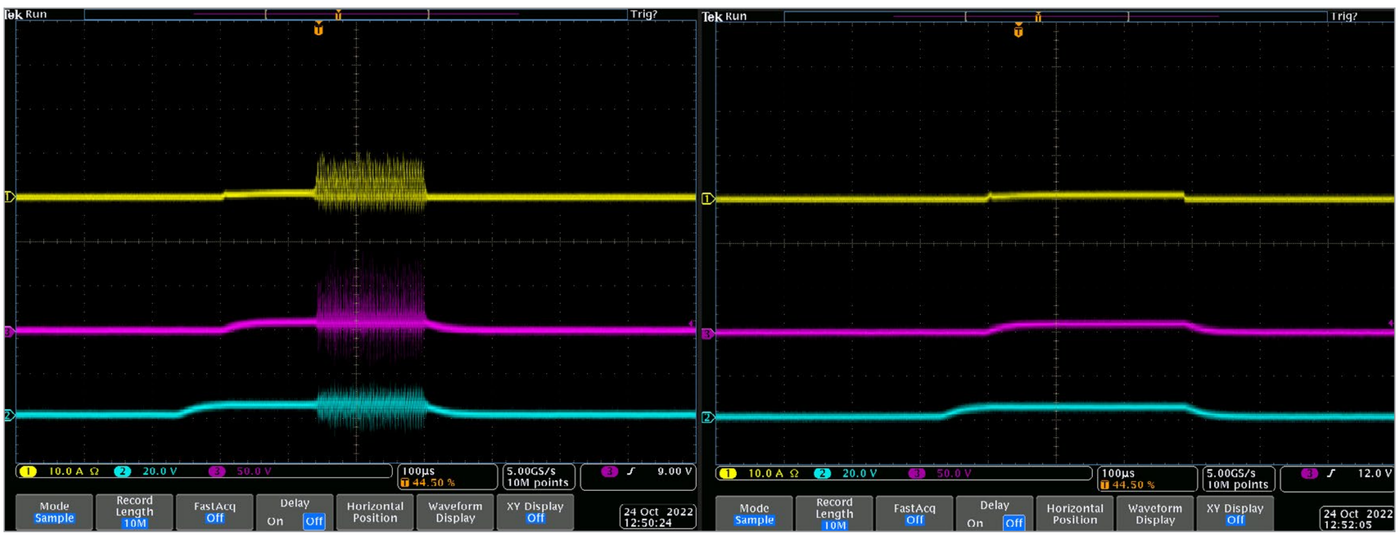


Figure 12. Ferrite bead effectiveness on drain (left - without ferrite bead, right - with ferrite bead) (yellow - drain I, magenta - gate V, blue - drain V).

Capacitor on Drain

Most GaN HEMT devices have very low output capacitance (Coss), typically lower than 1 nF. Adding a capacitor between the drain and source can absorb the high frequency oscillation and noise. At the DUT circuit board design level where GaN HEMPT devices are employed, an RC snubber circuit is commonly used to suppress oscillation. Capacitors alone or capacitors with resistors are an effective means to minimize the oscillation. **Figure 13** is the waveform capture for when 10 nF capacitor is placed at the drain terminal of the device as close as possible. It is effective to put it as close as possible to the device.

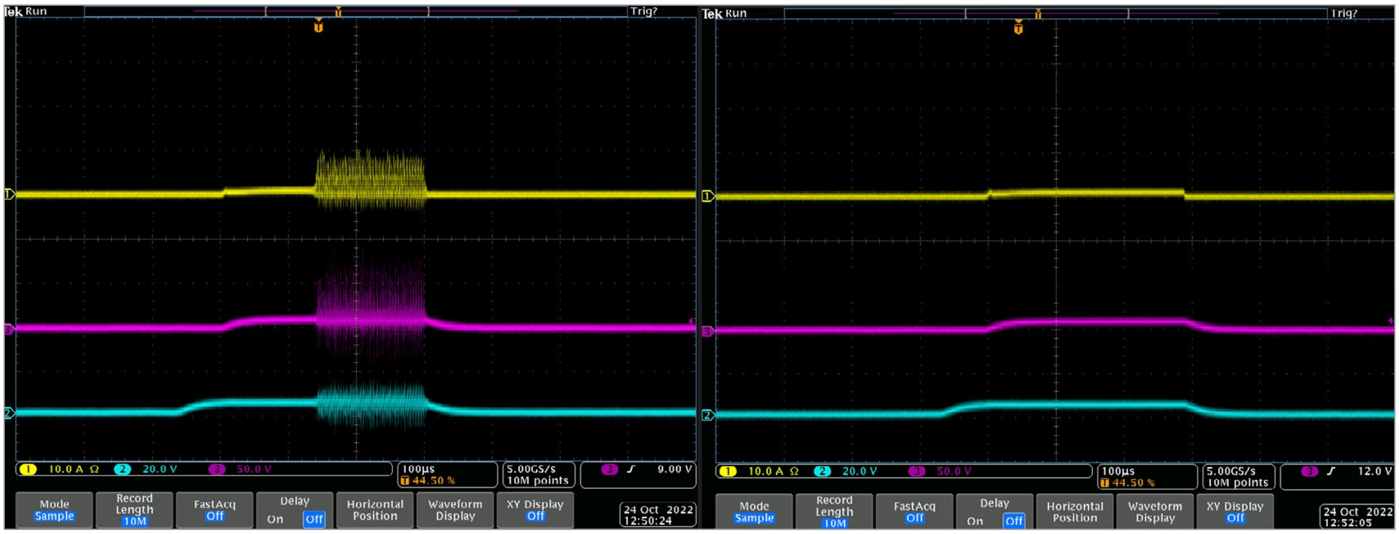


Figure 13. Capacitor effectiveness on drain (left - without capacitor, right – with capacitor).

Conclusion

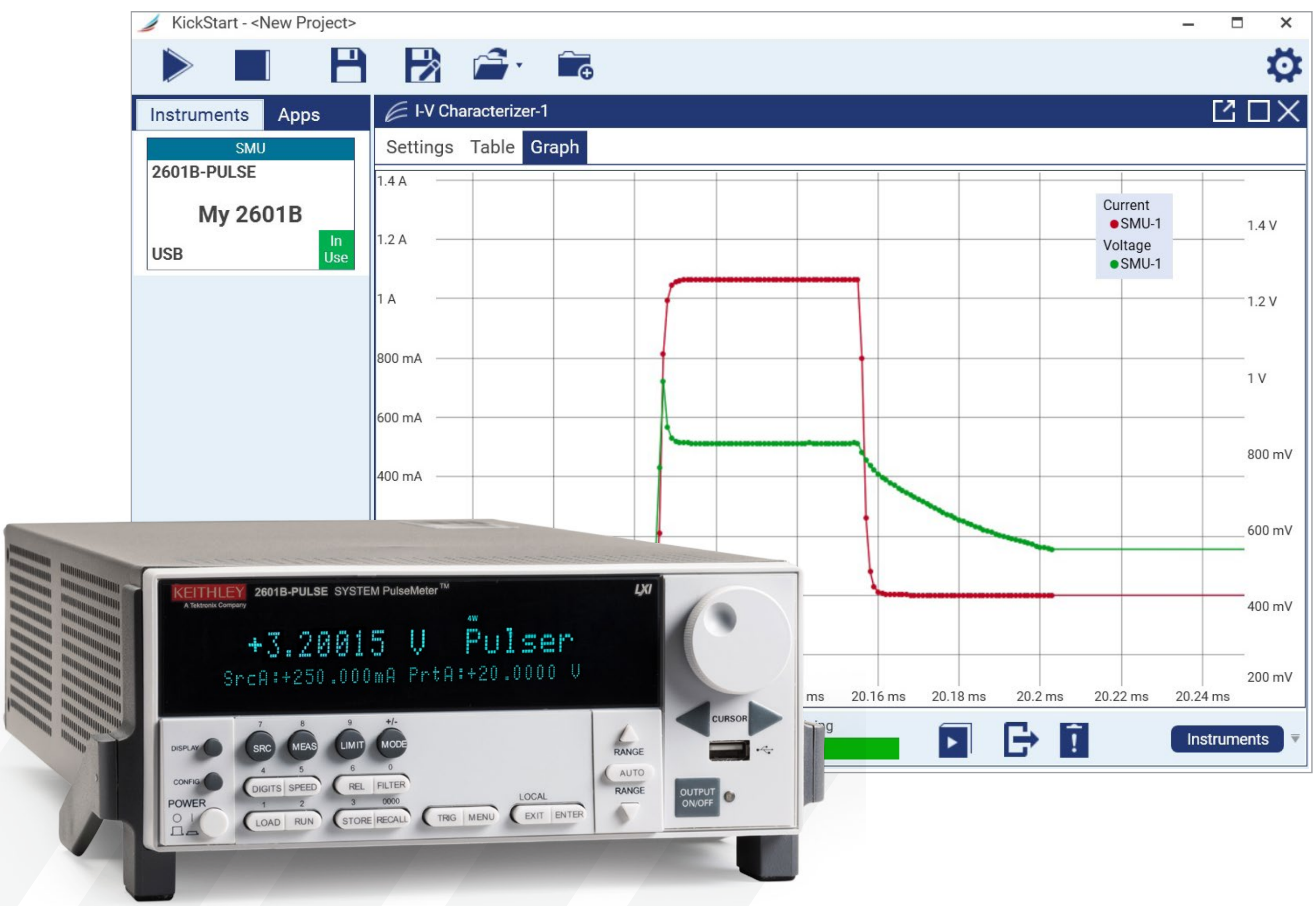
GaN HEMT devices are very fast and efficient and have a unique structure and performance, but oscillation is one of the primary challenges with high frequency devices during the DC characterization. This application note discussed the oscillation challenges and offered best practices (optimized cabling and connection, adding ferrites or capacitance, and other) to best address the need to minimize or eliminate the different oscillation contributors. Keithley high power SourceMeter SMU options (both the 2651A and 2657A) and the 8010 High Power Device Test Fixture are a great combination for GaN HEMT device test. Additionally, Keithley software options such as ACS Basic and KickStart both support GaN HEMT DC characterization.

For more information on high power device testing or the instruments and software mentioned above, visit tek.com.

Tektronix®

Testing Laser Diode Modules and VCSELs with the 2601B-PULSE System SourceMeter® Instrument and KickStart Instrument Control Software

APPLICATION NOTE



Introduction

Laser diodes (LDs) and VCSELs (Vertical Cavity Surface Emitting Lasers) are the primary components used in optical communications, spectroscopy, 3D sensing and imaging, and a host of other important applications. As the demand for these applications grows, so does the need for the basic components themselves. This demand requires greater emphasis on developing accurate, cost-effective test strategies.

A typical LD module consists of a laser diode and a back facet monitor photodiode. Temperature-controlled LD modules also include a thermoelectric controller (TEC) and a thermistor to facilitate precise regulation of the LD's operating temperature, as illustrated in **Figure 1**. (High speed LD modules may also carry an integrated modulator chip that's not shown in **Figure 1**.)

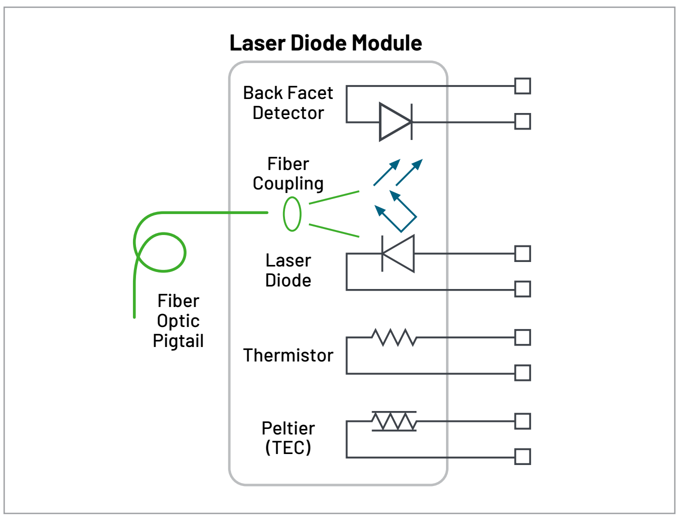


Figure 1: Typical laser diode module.

A VCSEL has a more complicated semiconductor structure than a standard laser diode, but typically a less complicated package. A classic cross-section of a VCSEL is shown in **Figure 2**. Unlike edge-emitting laser diodes, the VCSEL can be tested on wafer. This presents new opportunities and challenges in testing that will be addressed later in this application note.

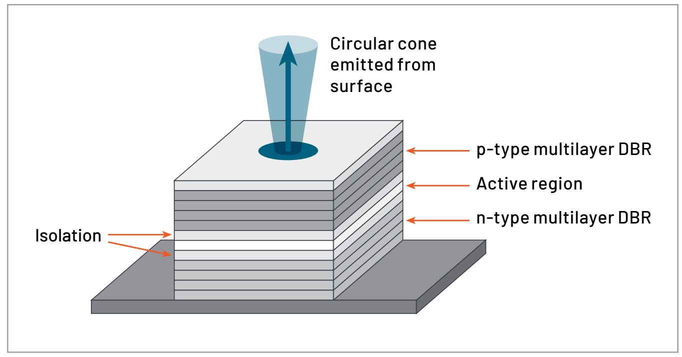


Figure 2: A Simplified VCSEL Structure.

It's important to remember that, with either device type, there are many testing steps taken in the value stream from R&D to manufacturing process. R&D involves lots of testing and measuring to achieve a breakthrough or the development of new intellectual property. The tools used in R&D are designed for flexibility—allowing you to adjust testing requirements and explore "what if" scenarios. The nature of manufacturing requires testing each component prior to the next step in assembly. For example, the cost of scrapping a complete laser module due to a failed back facet monitor photodiode is much greater than the cost of providing 100% testing of the photodiode component prior to the assembly step. High speed, flexible test solutions are essential to minimize the cost of the test.

This app note looks at both hardware and software tools that provide the results required in today's R&D labs.

Test Descriptions

During DC testing, the characteristics of interest for the LD or VCSEL module include:

- Laser forward voltage
- Kink test or slope efficiency (dL/dI)
- Threshold current
- Monitor (back facet) reverse-bias voltage
- Monitor (back facet) current
- Monitor (back facet) dark current
- Optical output power

The most common subset of the characteristics can be measured in a test known as the LIV test sweep. In R&D, this test helps the researcher and engineer identify key characteristics of their designs which may have the potential for commercialization. In manufacturing, this test identifies failed assemblies early in the test process, so expensive non-DC domain test systems are more cost-effective when testing the remaining higher yield components. **Figure 3** shows a common instrument configuration used to perform the LIV test sweep.

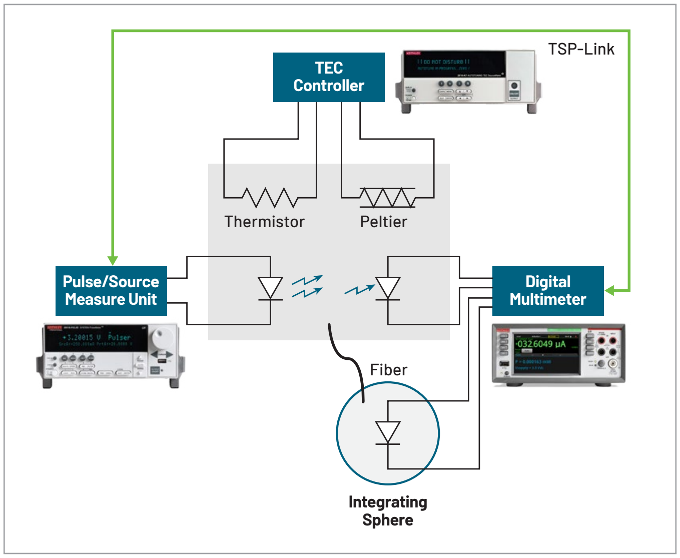


Figure 3: Typical block diagram of LIV instrumentation.

LIV Test Sweep

Forward Voltage Test

The forward voltage (V_F) test verifies the forward DC characteristics of the LD. Current (I_F) is swept and voltage drop across the LD is measured.

Some high powered LDs may require current (I_F) sweeps up to 2–3 A, usually in increments of 1 mA. Most need sweeps up to 1 A with 0.5 mA or 0.25 mA steps. Time per test sweep should be in the range of a few milliseconds for DC sweeps. The typical measurement range is 0–10 V and microvolt-level resolution is often required.

VCSELs have typically been lower powered devices requiring current (I_F) sweeps up 30 mA, with current steps of 1 μA. But that has changed as higher power VCSELs and arrays are being used in applications like LIDAR – light detection and ranging, for automotive and ADAS vehicle systems. Unfortunately, higher current runs the risk of device self-heating that could damage if not destroy the device. Thus, short pulse width sweeps, as short as 10 μs are used to test the VCSELs to minimize device heating and enable accurate measurements.

For the pulse test, we can use the 2601B-PULSE System SourceMeter 10 μs Pulser/SMU instrument to source pulsed current to the laser and measure the corresponding voltage drop.

Light Intensity Measurement

Light intensity (L) measurements verify the light output of the LD. Light output power increases as drive current is increased and the output of this test is usually displayed in milliwatts.

For light measurements, photodiode or photodetector is exposed to the output of the laser diode. This radiation is absorbed, and a current is produced by the detector. This resulting current is measured with a picoammeter, electrometer (a highly refined DC multimeter), or a precision digital multimeter. Typically, a measurement range of 100 nA is more than adequate for many lasers.

The returned photocurrent can then be used to determine the optical power of the device under test. Optical power measurements require a calibrated detector or integrating sphere. The calibration information, or responsivity (R), is a wavelength-dependent value determined during the calibration process. To calculate the optical power from a photocurrent, use the following equation:

$L = I_p / R$

where:

L = Optical power of the light source (watts)

I_p = Current from the detector. Commonly called photo-current (amps)

R = Responsivity of the detector at the wavelength of choice (amps/watt)*.

* The responsivity curve is provided when the detector or sphere/detector assembly has been calibrated.

The current measured by the detector is divided by the responsivity of the detector at the wavelength of interest. The result is the optical power impinging on the detector.

Lasing Threshold Current Test

The threshold current is the current at which the LD starts lasing. One technique for threshold determination is the second derivative technique. The threshold for this method is defined as the first maxima of the second derivative of the light output and is a calculation based on the light measurement (L). This is highlighted in **Figure 4**.

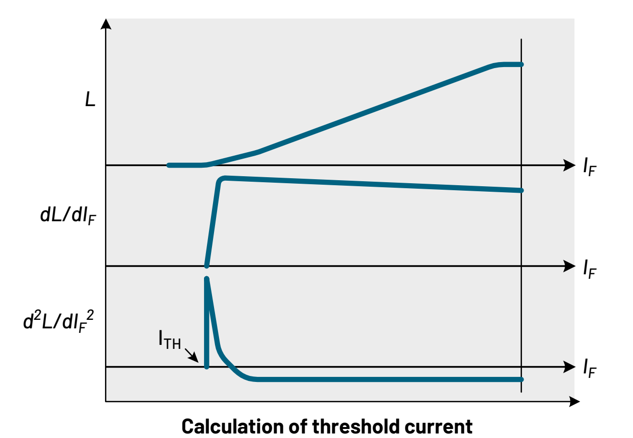


Figure 4: Graphical Calculation of Threshold Current.

Back Facet Monitor Diode (BFMD) Test

This test verifies the response of the back facet detector photodiode (also reverse-biased) to increase light output of the LD as the drive current is increased. Typical current measurement range is 0–100 mA and the required resolution is 0.1 mA. This measurement is typically performed with a picoammeter, electrometer or precision digital multimeter as long as it offers an acceptable low current measurement range. Typically, a measurement range of 100 nA is more than adequate for low powered optical devices.

Kink Test/Slope Efficiency

This test verifies the proportionality of the relationship between the drive current (I_F) and the light output (L) as depicted in **Figure 5**.

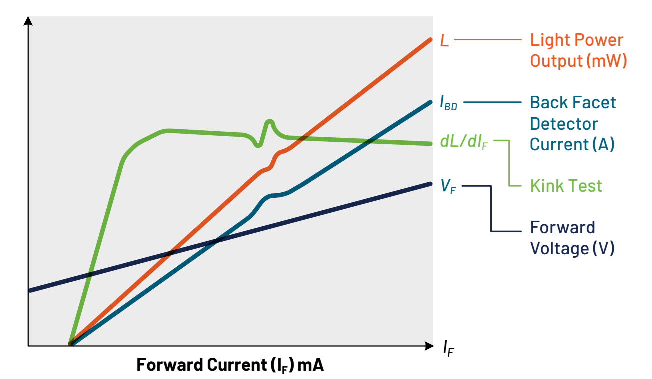


Figure 5. Typical Suite of LIV Curves.

The relationship between the drive current (I_F) and the light output power (L) should be linear about the nominal operating range. If the relationship is truly linear over the tested range, the first derivative of the curve will be a nearly horizontal line. This is graphed as dL/dI_F. The first derivative will tend to amplify any bumps or kinks in the light/current (L-I) curve. If this curve has any significant "kinks" or, in other words, is not smooth, the laser is considered defective. If operated at the I_F value corresponding to the "kink," the light output will not be proportional. The maximum value of the second derivative of the L vs. I_F curve can be used to calculate the threshold current, which is the value of the drive current at which the LD starts "lasing" or outputting significant light.

The kink and slope efficiency of a particular device are also calculations based on the analysis of the light measurement (L).

Temperature Testing

The LIV test is often performed at more than one laser diode temperature. In some cases, the LD is tested at both the nominal temperature and the extremes of the device specification, such as –40°C, 25°C and 85°C. Another common strategy is to perform the LIV test at several temperatures, such as 5°C, 10°C, 15°C, 20°C, 25°C, 30°C and 35°C. Then, these families of LIV curves are analyzed to ensure the device meets the specification.

Test System Configuration

As shown in **Figure 6**, a DC and Pulsed LIV test system includes a 2601B-PULSE Pulser/SMU, a 2510-AT Autotuning TEC SourceMeter instrument, a DMM7510 Digital Multimeter and a PC equipped with a GPIB interface card.

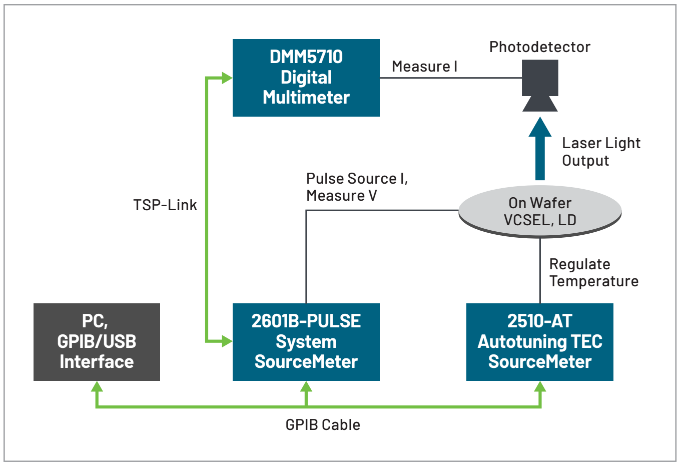


Figure 6: Typical LIV Test Setup for an LD Module. The 2601B-PULSE is used to characterize the laser diode or VCSEL. The DMM7510 monitor's the light output while the 2510-AT is controlling the LD module temperature. Can also be used to test VCSELs without the TEC controller.

VCSELs are the only type of lasers that lend themselves to testing at the wafer level. For production testing, a wafer prober makes the electrical connection to each device through a probe card. The prober station also positions the optical detector directly over the devices. The characterization can then be performed using a single 2601B-PULSE SourceMeter instrument.

If the probe card can connect to many devices simultaneously, then a system designed for multi-point testing should be constructed to test all of the devices each time the probe card makes contacts to the wafer. Due to the high number of devices on a wafer, a scanning approach to testing multiple devices may be too time consuming. Using many pairs of instruments to test multiple devices in parallel is often the optimum solution for applications that require high throughput.

The 2601B-PULSE System SourceMeter is an industry-leading high current/high speed pulser with measure plus the full functionality of a traditional SMU. The instrument offers leading 10 A current pulse output at 10 V with a pulse width minimum of 10 µs, perfect for testing vertical cavity surface emitting lasers (VCSEL) used in LIDAR and facial recognition, LEDs for lighting and displays, semiconductor device characterization, surge protection testing, and so much more. An example output pulse is shown in **Figure 7**.

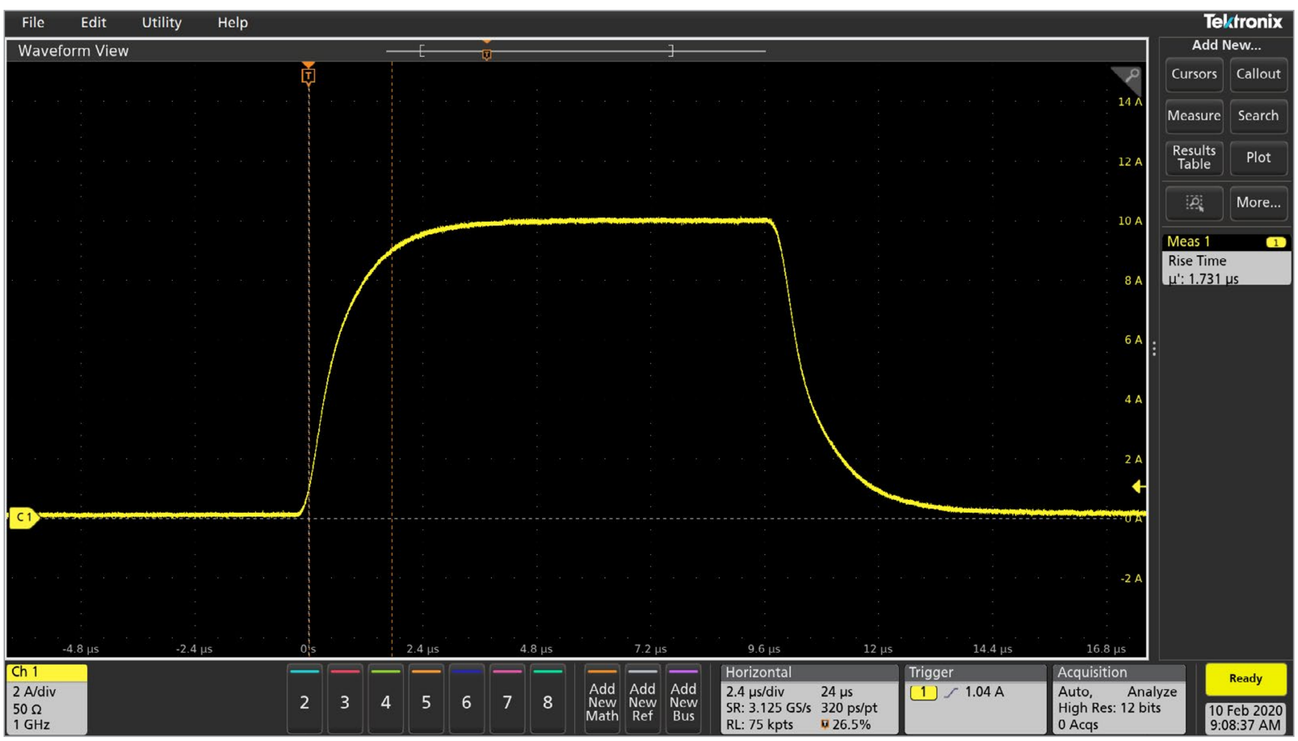


Figure 7: 10 A @ 10 V at 10 µs pulse width with 1.7 µs rise time.

The pulser's built-in dual 1 Megasample/second (MS/s), 18-bit digitizers make it possible to acquire both pulse current and voltage waveforms simultaneously without the need to use a separate instrument. For automated system applications, the 2601B-PULSE's Test Script Processor (TSP®) runs complete test programs from inside the instrument for industry-best throughput. In larger, multi-channel applications, the Keithley TSP-Link® technology works together with TSP technology to enable high-speed, pulser/SMU-per-pin parallel testing.

The 2510-AT Autotuning TEC SourceMeter controls the TEC element and maintains stable module temperature while the DMM7510 Digital Multimeter measures the output current from the photodetector. The DMM7510 also offers Keithley's TSP technology, allowing it to be connected to the 2601B-PULSE for test script control and triggering.

The PC programs the controls of the 2510-AT and can be used to upload test scripts to the 2601B-PULSE and the DMM7510, enabling complete coordination of test execution, data collection and later analysis of the measurement results using popular software tools or Keithley's KickStart Instrument Control software.

Utilizing Test Script Processor

With many instruments, the PC controls all aspects of the test. In each element of a test sequence, the instruments must be configured for each test, perform the desired action, and then return the data to the controlling PC (**Figure 8**).

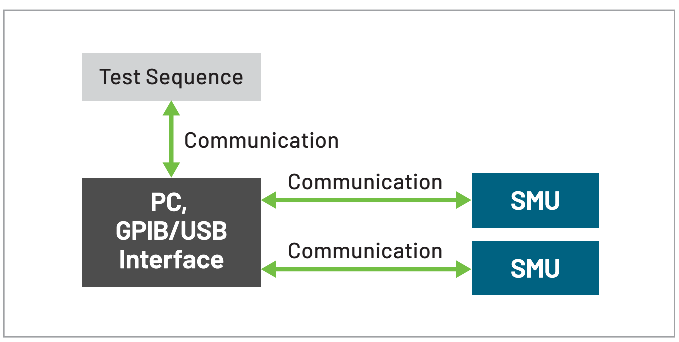


Figure 8: PC control of standard instruments.

The controlling PC then must collect the data, provide the appropriate analysis information, and for production tests, evaluate the pass/fail criteria and perform the appropriate action for binning the device under test. Each command sent and executed consumes precious production time and lowers throughput.

Obviously, a large percentage of this test sequence is consumed by communicating information to and from the PC. Series 2600B instruments, like the 2601B-PULSE and even the DMM7510 offer the unique ability to increase the throughput of complicated test sequences dramatically by decreasing the amount of traffic over the communications bus. In these instruments, the majority of the test sequence is embedded in instrument. The Test Script Processor (TSP) is a full-featured test sequence engine that allows control of the test sequence, with internal pass/fail criteria, math, calculations, and control of digital I/O (see **Figure 9**). TSP can store a user-defined test sequence in memory and execute it on command. This limits the "set-up" and configuration time for each step in the test sequence and increases throughput by lessening the amount of communications to and from the instrument and PC.

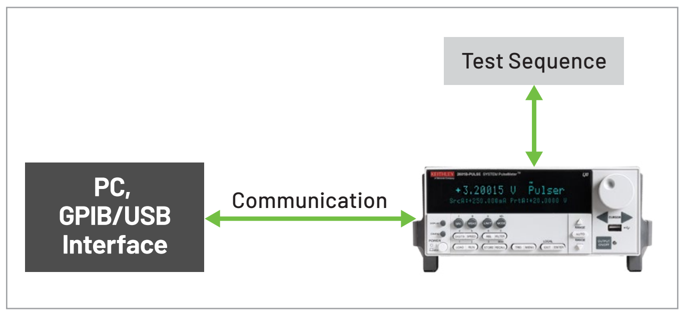


Figure 9: Use of the embedded Test Script Processor (TSP) to store the test sequence. Note decreased communications traffic.

For example, here is a simple step-by-step process for programming the 2601B-PULSE:

1. Create the script.
2. Download the script to the instrument.
3. Call the script to run.

The 2601B-PULSE script can be written/downloaded using Keithley's Test Script Builder Software or downloaded to the instrument using another program such as Visual Studio or LabVIEW. See the 2601B-PULSE's User's Manual for more information on programming the 2601B-PULSE.

Using KickStart Software to Prototype Tests

A fast and convenient way to perform R&D tests on VCSELs or LDs is to use Keithley's KickStart software. KickStart simplifies what you need to know about the instrument so that in just minutes you can take the instrument out of the box and get real data on your device. By plotting data immediately and offering quick statistical summaries of the data in the reading table, KickStart allows you to gather insights faster and make the decisions you need to move on to the next stage of device development. The software saves you time by facilitating quick replication of tests and comparison of results using convenient export features. KickStart enables you to focus your time on interpreting the test results so that your team can meet its innovation goals.

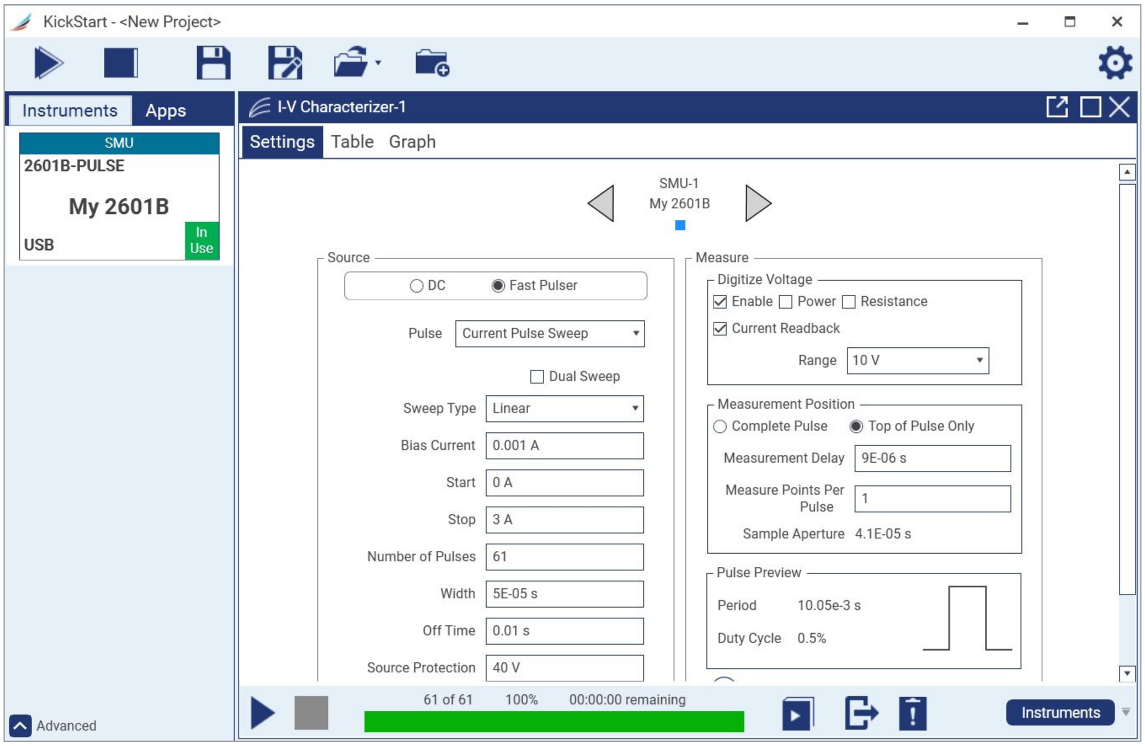


Figure 10: KickStart Instrument Control Software.

To create a simple current sweep pulse train to test on a VCSEL, for example, the following settings can be applied:

- Source:
- Fast Pulser
- Pulse: Current Pulse Sweep
- Sweep Type: Linear
- Bias Current: 0.001 A
- Start: 0 A
- Stop: 3 A
- Number of Pulses: 61
- Width: 5E-05 s (50 μs)
- Off Time: 0.01 s
- Source Protection: 40 V
- Measure / Digitize
- Measure:
- Digitize Voltage:
  - Enable
  - Current Readback
  - Range: 10 V
- Measurement Position:
  - Top of Pulse Only
  - Measurement Delay: 9E-06 s (9 μs)
  - Measure Points Per Pulse: 1

After running the test on a VCSEL, you can review the results in KickStart either in tabular form or in a graph as shown in **Figures 11 and 12**.

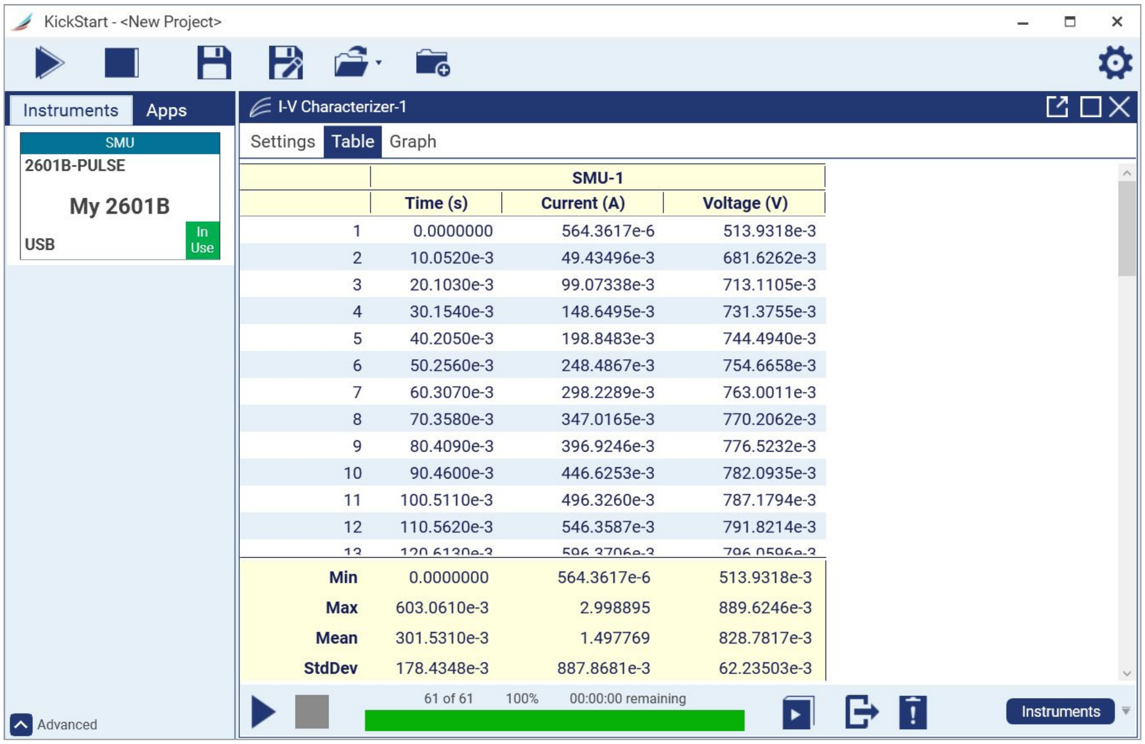


Figure 11: Tabular view of results in KickStart.

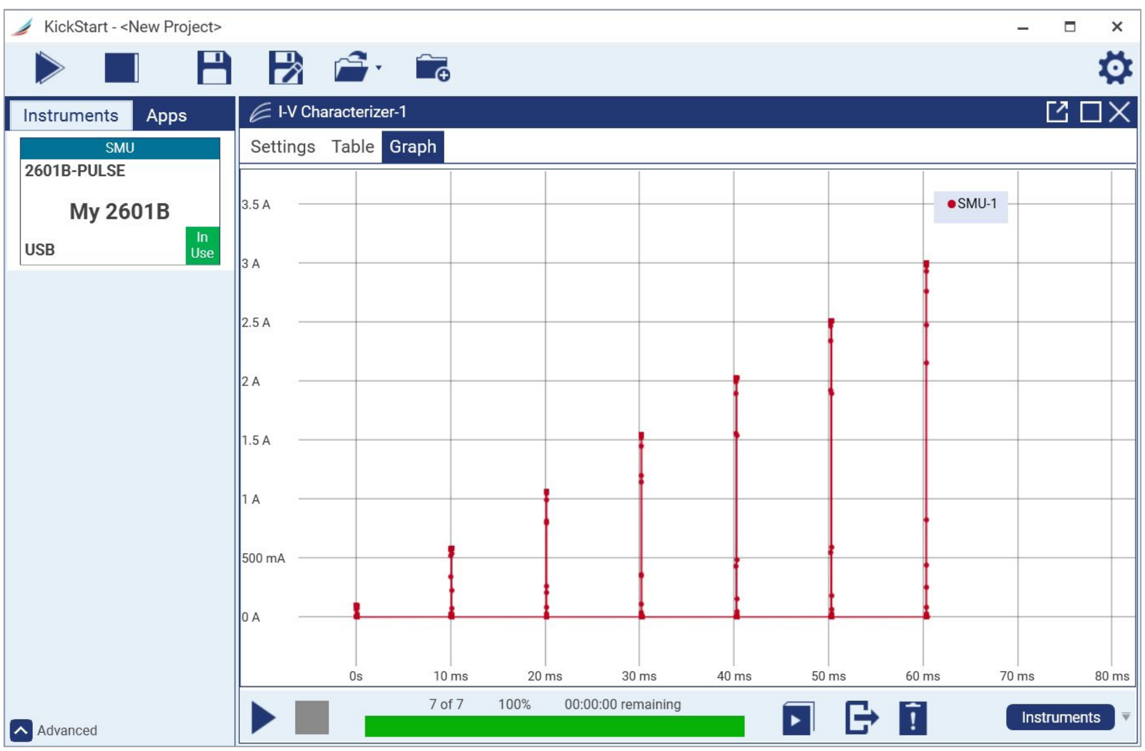


Figure 12: Graph view of results from a VCSEL current pulse sweep.

KickStart offers the ability to zoom into a particular pulse so you can review the current source as well as the measured voltage using the built-in dual 1 Megasample/second (MS/s), 18-bit digitizers. An example is shown in **Figure 13** from the test ran on the VCSEL.

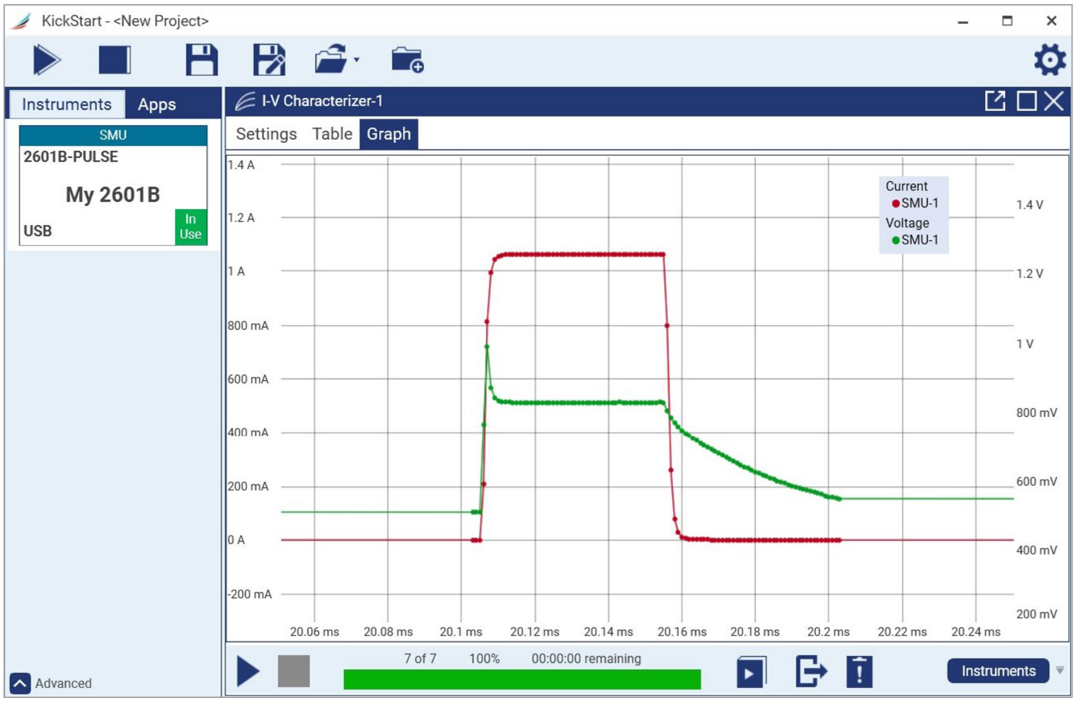


Figure 13: Graph zoomed on a particular pulse output.

KickStart also provides analysis tools, such as cursors and statistics so you can review the results further as shown in **Figure 14**.

Figure 14: Analysis example of a pulse within KickStart.

Methods and Techniques

Cabling

Cabling must be optimized for accuracy and test speed. High quality, low noise cable is required for all measurements. The cable characteristics for the LD and VCSEL drive signal are much different from those of the photodiode signals. Cable inductance can also be a factor and could result in pulse outputs that have overshoot and undershoots as shown in **Figure 15**.

Figure 15: Pulse outputs that have overshoots and undershoots due to cable inductances.

The photodiode signal is generated by sourcing several volts and measuring the current flow in the nanoampere range. At such low currents, it is critical to use a low noise shielded cable to optimize the signal-to-noise ratio. Using the shortest length of cable will also improve the signal-to-noise ratio by reducing leakage and induced currents, as well as minimizing capacitance.

The slew rate (dV/dt) of the LD drive signal, if testing LD's, is a function of the semiconductor junction. The junction voltage will change only a few millivolts for a current change of tens of milliamps. As a result of the low slew rate requirements, the capacitance of the LD drive signal cable is not as critical to the application as the voltage drop across the cable as it carries up to 3 A. A large gauge cable will help reduce the voltage drop over the length of the cable while having minimal impact on the speed of the test.

In all cases, the cabling must be shielded and as short as possible to reduce noise and capacitance. Lower noise means less integration time is required for each measurement and the test sweep will be faster.

Typical Sources of Error

Junction Self-Heating

As test times get longer, the semiconductor junction of the VCSEL will tend to get increasingly hot. The forward voltage test tends to be susceptible to junction self-heating. As the junction heats, the voltage will drop or, more importantly, the leakage current will increase during the constant voltage test.

Therefore, it is important to keep the test time as short as possible without sacrificing measurement accuracy or stability. The instruments in the SourceMeter® family allow users to configure the device soak time before the measurement, as well as the amount of time the input signal is acquired. The soak time allows any circuit capacitance to settle before the measurement begins. The measurement integration time is determined by the number of power line cycles (NPLC). If the input power is at 60 Hz, a 1 NPLC measurement would require 1/60 seconds, or 16.667 ms. The integration time defines how long the analog-to-digital converter (ADC) acquires the input signal. Usually, the integration time chosen represents a trade-off between speed and accuracy.

Typical DC soak times for the V_F test can range from 1 ms to 5 ms, and 5 ms to 20 ms for the light/current (L-I) test. These short test times help reduce errors due to junction self-heating. It's possible to characterize the junction heating characteristics by performing a series of tests and varying only the soak time with each repetition of the test. Pulse testing on the other hand further reduces junction heating while applying higher currents when the pulse widths are typically <50 µs.

Leakage Currents

In addition to the nominal leakage characteristics of the cabling and DUT fixturing, conductive contamination of the fixture will increase over time, producing leakage currents. Techniques to minimize leakage may be required when measuring low currents or when using low current photodiodes.

One technique for minimizing leakage current is to use a guarded fixture. In a guarded fixture, the region near the DUT is held at the same potential as the Output HI signal. This reduces the potential difference between the DUT and the leakage paths.

Electrostatic Interference

High resistance measurements, like those made using photodiodes, may be affected by electrostatic interference from charged objects. It may be necessary to use an electrostatic shield (Faraday cup) to eliminate electrostatic effects. For more information, see the section titled "Low Current Measurements" in the sixth edition of Keithley's *Low Level Measurements Handbook*.

- Double insulate all electrical connections that an operator could touch. Double insulation ensures the operator is still protected, even if one insulation layer fails.
- Use high reliability, fail-safe interlock switches to disconnect power sources when a test fixture cover is opened.
- Where possible, use automated handlers so operators do not require access to the inside of the test fixture or have a need to open guards.
- Provide proper training to all users of the system so they understand all potential hazards and know how to protect themselves from injury.
- It is the responsibility of the test system designers, integrators, and installers to make sure operator and maintenance personnel protection is in place and effective.

Light Interference

Stray light entering the optical fibers, or the integrating sphere will skew the test results. Take care to ensure that all components are properly shielded at all wavelengths that could affect the conductance of the semiconductor junctions. This is especially critical for dark current measurements of the photodiode.

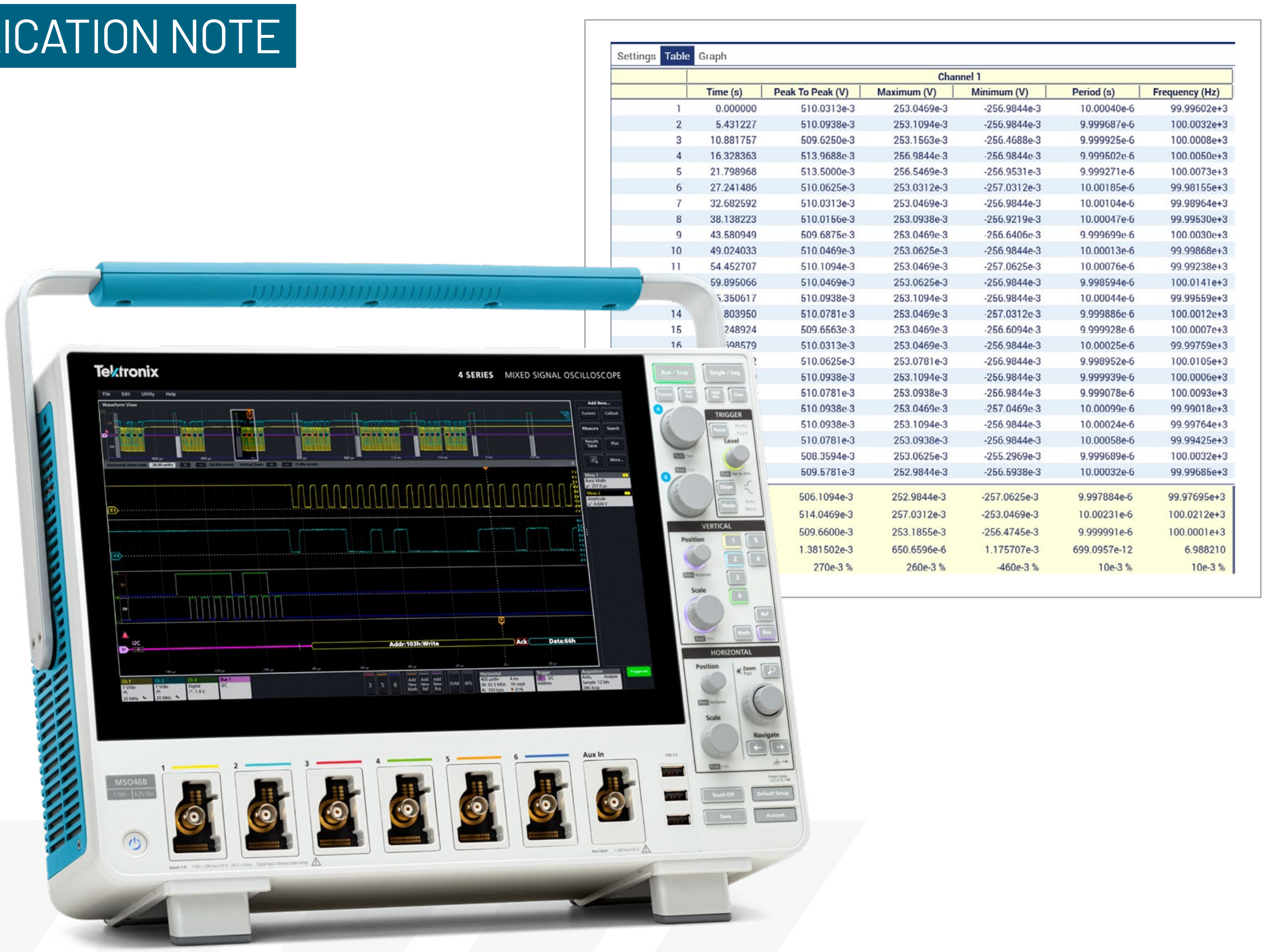
Conclusion

Not only does DC and Pulse testing of LD modules and VCSELs drive innovation in the R&D lab as well as reduce manufacturing cost by identifying failed components early in the manufacturing process, it can also play a critical role in accelerated lifecycle testing. Many LD and VCSEL manufacturers offer high reliability LD and VCSEL parts that have successfully endured days of LIV type testing at elevated operating temperature to identify unstable parts prior to incorporation in subsystems destined for unique environments including for undersea operations and automotive/ADAS vehicle LIDAR systems.

Tektronix®

Measurement Data Logging with the 4 Series B MSO Mixed Signal Oscilloscope and KickStart Software

APPLICATION NOTE



Introduction

Oscilloscopes are highly versatile and powerful instruments for collecting precise measurements with an outstanding range of analysis tools. The Tektronix 4 Series B MSO Mixed Signal Oscilloscope, the latest digital oscilloscope from Tektronix, is now also supported by KickStart Software as of version 2.11.3.

Figure 1: The Tektronix 4 Series B MSO.

Digital oscilloscopes have functions that make waveform measurements easy. They have front-panel buttons and screen-based menus from which you can select automated measurements. These automated measurements appear as on-screen alphanumeric readouts.

However, getting these measurements off the oscilloscope and onto a PC for further analysis and disaggregation typically requires the use of a physical USB drive, programming or software.

The KickStart Software Scope App can be used to configure and capture these measurements and gather screenshots from the convenience of your PC, while also providing easy to use data visualization and analysis tools.

What is Measurement Data Logging?

Data logging can be separated into three different categories: seamless data logging, triggered data logging and measurement data logging. For the purposes of this application note, we will be focusing on measurement data logging, but it is important to define the other categories to distinguish between them.

Seamless Data Logging

Seamless data logging is when data points are taken at consistent intervals over a long period of time. At the end of the test, the full set of data can then be analyzed for anomalies or long-term trends. This type of data logging is commonly performed by dedicated datalogger instrumentation and software such as the DAQ6510 6½-digit Data Acquisition and Multimeter System with the KickStart Data Logger App. Seamless datalogging is used when it is imperative that there be no gaps larger than the sample intervals in the data. Oscilloscopes are triggered devices and, as such, are unable to perform seamless data logging.

Figure 2: Dedicated switching and datalogging instrumentation used for seamless data logging.

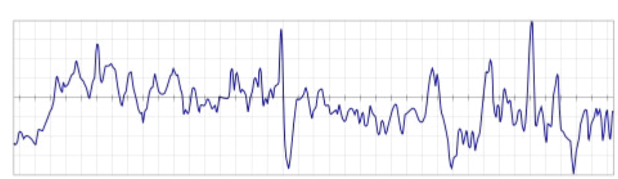


Figure 3: An example of seamless data logging. There are no gaps in the captured data.

Triggered Data Logging

Triggered data logging is when an event known as a "trigger" is defined, and the data recording does not begin until the trigger requirements are fulfilled. This results in taking "snapshots" of data that are centered on the trigger point. This is useful for detecting and recording certain events over a period for analysis, especially if you don't want to collect the data in between these events.

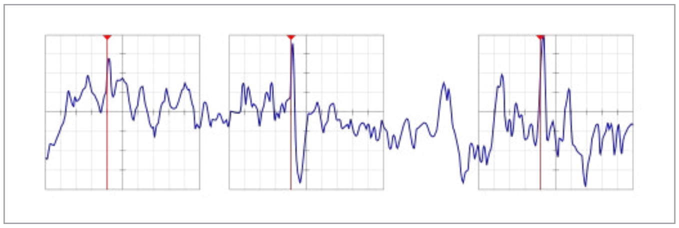


Figure 4: Triggered datalogging will have gaps in the captured data. The red vertical line indicates the trigger point.

Measurement Data Logging

Measurement data logging is similar to triggered data logging, where the goal is to detect and record an event, but is used when the only important parameter to log is a measurement, such as a peak-to-peak measurement, or a rise time measurement. During measurement data logging, a measurement is made on each oscilloscope acquisition and saved. This means that there is less data to sort through, and it takes less time to transfer the measurement data then waveform data, so the repeat rate can be much faster.

Measurement data logging is useful for event monitoring, ensuring that an event never exceeds a certain value, such as when monitoring the power output of a transmitter.

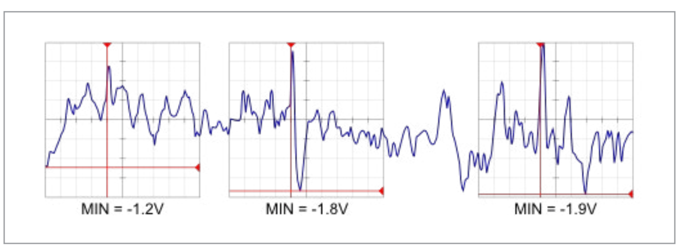


Figure 5: Measurement datalogging will make a measurement on each triggered acquisition. These measurements can then be collected and graphed to visualize trends in the data.

Using the KickStart Software Scope App for Logging Measurements

The KickStart Scope app can be used for the datalogging of measurements via its Measurements Mode. Measurements Mode allows a user to select up to eight measurements to retrieve from the scope. The measurements are made by the oscilloscope and logged into the KickStart Table. The user can then use the Graph tab in KickStart to view the measurement data and easily note trends or spot anomalies.

To start, connect the scope to a PC via LAN or USB, attach the probes to the device under test and set up the oscilloscope's acquisition settings from the front panel. The main settings of interest are the record length, sample rate and trigger type.

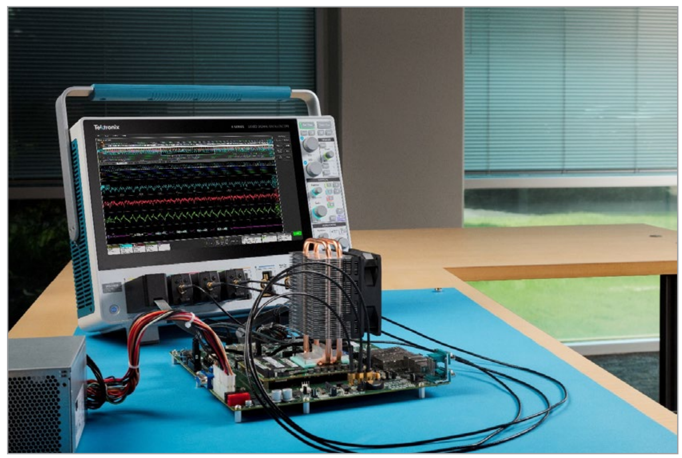


Figure 6: A 4 Series B MSO used on a bench setup for power integrity testing.

Once the oscilloscope acquisition settings are configured on the front panel, KickStart Software can be used to acquire and log measurements.

Launch KickStart Software and connect to the 4 Series B MSO.

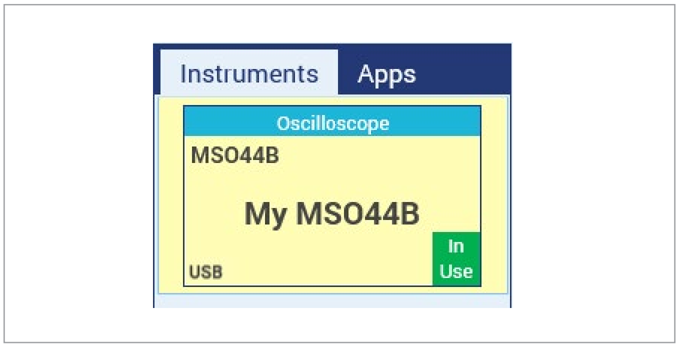


Figure 7: A connected 4 Series B MSO appearing in the KickStart Software Instruments tab.

Select the Measurements mode and use the Add A Measurement button to add up to eight measurements to be logged.

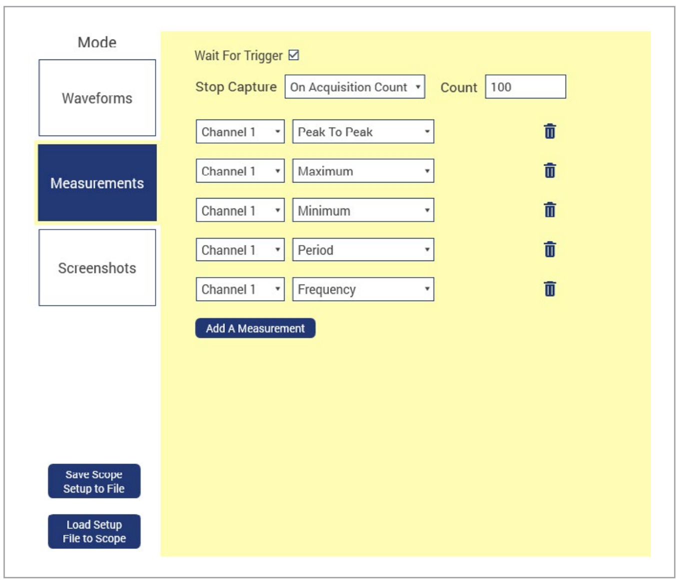


Figure 8: The KickStart Scope App Measurement Mode settings screen.

The measurements that can be logged by the KickStart Scope app include:

- AC RMS
- Amplitude
- Area
- Base
- Burst Width
- Data Rate
- Delay
- Duration N-Periods
- Falling Slew Rate
- Fall Time
- Frequency
- High Time
- Hold Time
- Maximum
- Mean
- Minimum
- Negative Duty Cycle
- Negative Overshoot
- Negative Pulse Width
- Positive Duty Cycle
- Period
- Phase
- Peak to Peak
- Positive Overshoot
- Positive Pulse Width
- Rise Time
- Rising Slew Rate
- RMS
- Skew
- Setup Time
- Time Outside Level
- Top
- Unit Interval

Measurement logging can be configured to end after a specified number of acquisitions, after a specified duration of time or to be taken continuously.

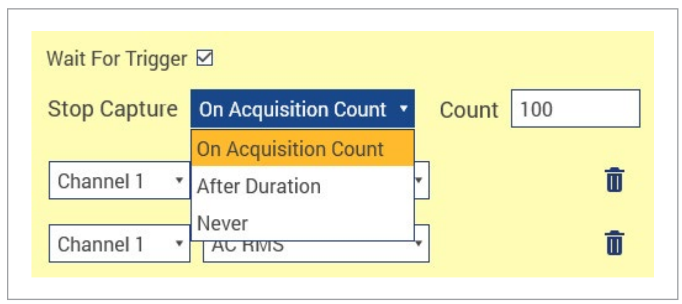


Figure 9: The KickStart Scope App Stop Capture options.

To start measurement logging, simply press the run button at the bottom left of the app window.

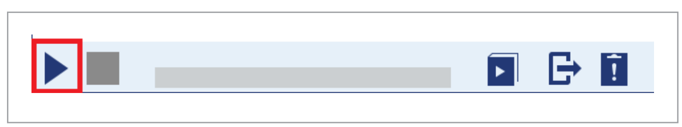


Figure 10: The KickStart Scope App run button is in the toolbar at the bottom of the app window.

Retrieving the Data

When the test is finished, the data can be viewed in the Table tab or the Graph tab.

The KickStart Software Table tab comes equipped with built in statistics to highlight key trends and assist users in coming to conclusions more quickly.

Settings Table Graph

	Channel 1					
	Time (s)	Peak To Peak (V)	Maximum (V)	Minimum (V)	Period (s)	Frequency (Hz)
1	0.000000	510.0313e-3	253.0469e-3	-256.9844e-3	10.00040e-6	99.99602e+3
2	5.431227	510.0938e-3	253.1094e-3	-256.9844e-3	9.999687e-6	100.0032e+3
3	10.881757	509.6250e-3	253.1563e-3	-256.4688e-3	9.999925e-6	100.0008e+3
4	16.328363	513.9688e-3	256.9844e-3	-256.9844e-3	9.999502e-6	100.0050e+3
5	21.798968	513.5000e-3	256.5469e-3	-256.9531e-3	9.999271e-6	100.0073e+3
6	27.241486	510.0625e-3	253.0312e-3	-257.0312e-3	10.00185e-6	99.98155e+3
7	32.682592	510.0313e-3	253.0469e-3	-256.9844e-3	10.00104e-6	99.98964e+3
8	38.138223	510.0156e-3	253.0938e-3	-256.9219e-3	10.00047e-6	99.99530e+3
9	43.580949	509.6875e-3	253.0469e-3	-256.6406e-3	9.999699e-6	100.0030e+3
10	49.024033	510.0469e-3	253.0625e-3	-256.9844e-3	10.00013e-6	99.99868e+3
11	54.452707	510.1094e-3	253.0469e-3	-257.0625e-3	10.00076e-6	99.99238e+3
12	59.895066	510.0469e-3	253.0625e-3	-256.9844e-3	9.998594e-6	100.0141e+3
13	65.350617	510.0938e-3	253.1094e-3	-256.9844e-3	10.00044e-6	99.99559e+3
14	70.803950	510.0781e-3	253.0469e-3	-257.0312e-3	9.999886e-6	100.0012e+3
15	76.248924	509.6563e-3	253.0469e-3	-256.6094e-3	9.999928e-6	100.0007e+3
16	81.698579	510.0313e-3	253.0469e-3	-256.9844e-3	10.00025e-6	99.99759e+3
17	87.149362	510.0625e-3	253.0781e-3	-256.9844e-3	9.998952e-6	100.0105e+3
18	92.593620	510.0938e-3	253.1094e-3	-256.9844e-3	9.999939e-6	100.0006e+3
19	98.047004	510.0781e-3	253.0938e-3	-256.9844e-3	9.999078e-6	100.0093e+3
20	103.495883	510.0938e-3	253.0469e-3	-257.0469e-3	10.00099e-6	99.99018e+3
21	108.940113	510.0938e-3	253.1094e-3	-256.9844e-3	10.00024e-6	99.99764e+3
22	114.384609	510.0781e-3	253.0938e-3	-256.9844e-3	10.00058e-6	99.99425e+3
23	119.832121	508.3594e-3	253.0625e-3	-255.2969e-3	9.999689e-6	100.0032e+3
24	125.273099	509.5781e-3	252.9844e-3	-256.5938e-3	10.00032e-6	99.99685e+3
Min	0.000000	506.1094e-3	252.9844e-3	-257.0625e-3	9.997884e-6	99.97695e+3
Max	539.203157	514.0469e-3	257.0312e-3	-253.0469e-3	10.00231e-6	100.0212e+3
Mean	269.643141	509.6600e-3	253.1855e-3	-256.4745e-3	9.999991e-6	100.0001e+3
StdDev	158.030254	1.381502e-3	650.6596e-6	1.175707e-3	699.0957e-12	6.988210
CV	58.61 %	270e-3 %	260e-3 %	-460e-3 %	10e-3 %	10e-3 %

Figure 11:The KickStart Software Table tab.

The KickStart Software Graph tab can be used to visualize the data collected by the KickStart Scope App. The graph includes several tools to assist with data analysis, including cursors, statistics and a run comparison feature.

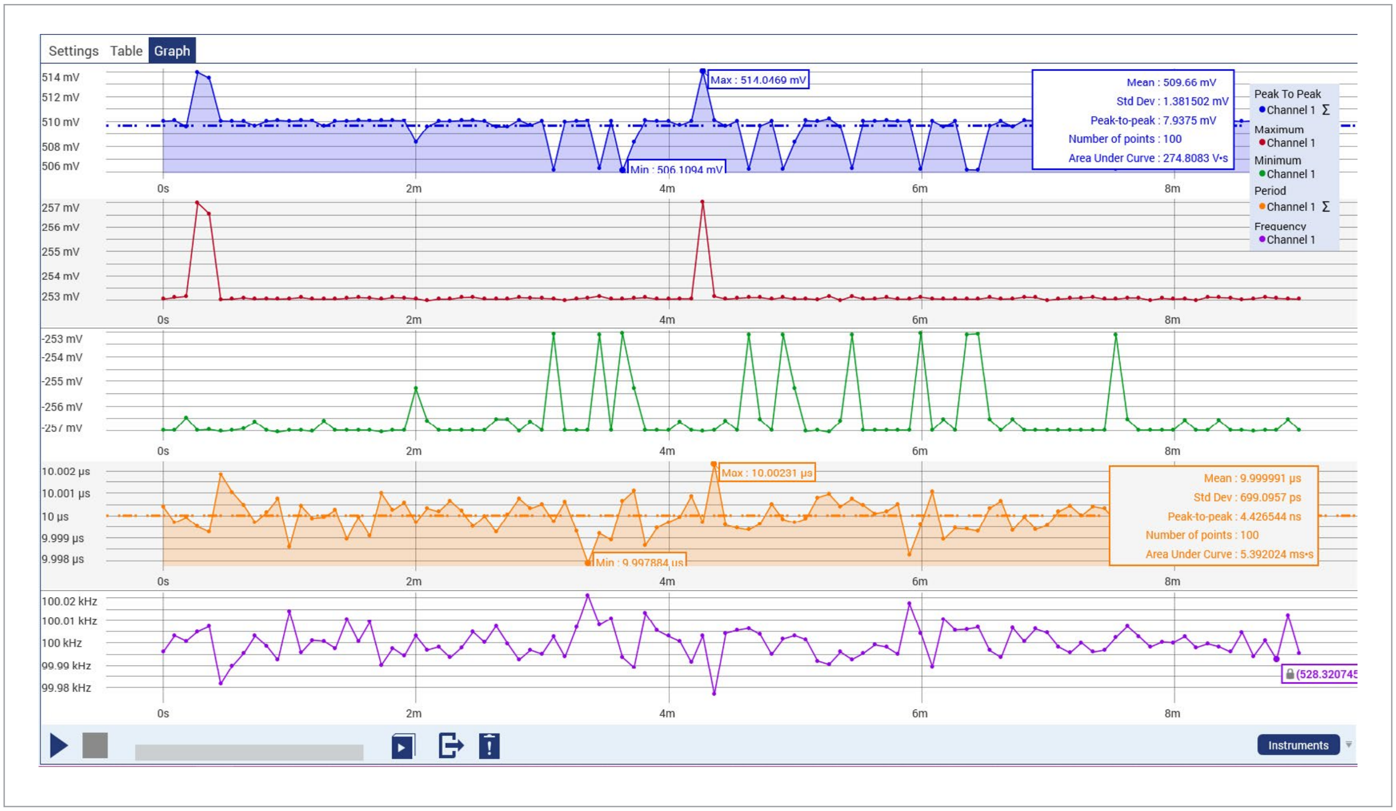


Figure 12: The KickStart Software Graph tab showing the logged data of five different measurement types with statistics applied to the period and peak to peak measurements.

KickStart Software also allows for easy data export, enabling users to take the data collected by the software and use it elsewhere, such as for further analysis and computing or for generating reports.

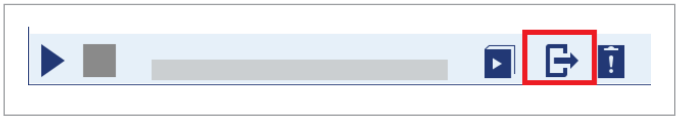


Figure 13: The KickStart Software Data Export button is in the toolbar at the bottom of the app window.

The data table contents can be exported in a *.csv or *.xlsx formats and the graph can be exported as a *.png at multiple different image resolutions. The Export Data menu can even be configured to automatically export new data at the completion of each run, saving time and ensuring that data is never lost.

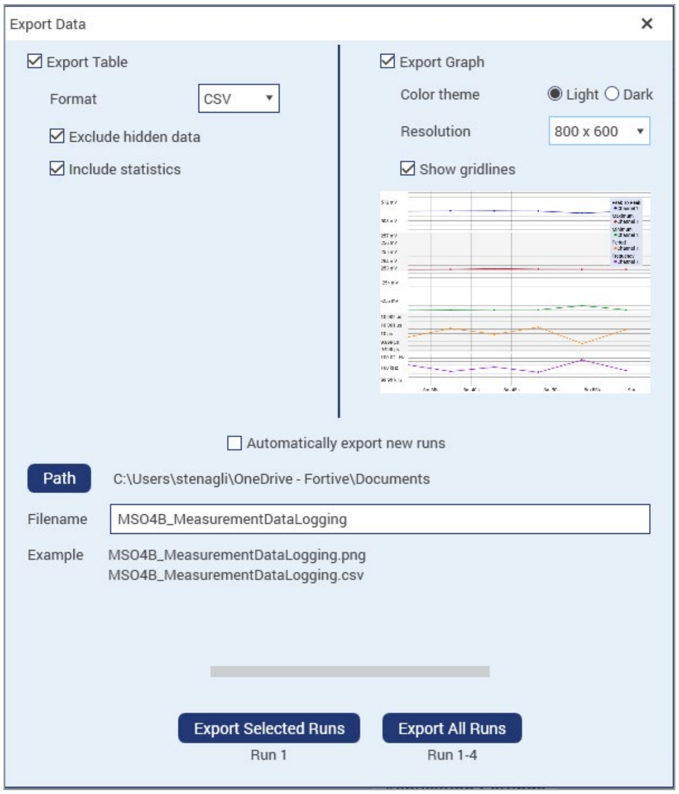


Figure 14: The KickStart Software Data Export menu.

Conclusion

Measurement data logging comes in handy when specific parameters and events need to be tracked over a period of time. However, getting these measurements off the oscilloscope and onto a PC to use in reporting or further analysis can be a hassle, particularly for sites where security is a concern.

The KickStart Software Scope App can be used to configure and capture these measurements, while also providing easy to use data visualization and analysis tools, and data export options all from the convenience of a PC.

As of KickStart Software version 2.11.3, the Tektronix 4 Series B MSO Mixed Signal Oscilloscope is now supported by KickStart Software and can utilize all of the productivity and convenience features it provides.

To learn more about KickStart Software, visit tek.com/KickStart.

Tektronix®

Using Keithley's All-In-One Battery Test Solution to Characterize, Optimize, and Exercise IoT Home Security Products

APPLICATION NOTE

Introduction

With the increasing prevalence of wireless technology and IoT devices, the need for rechargeable batteries that perform consistently over multiple charge cycles has grown exponentially. Consumers want to be certain that IoT controlled thermostats, lighting, security systems, and other appliances will continue operating long term and not degrade significantly over time. Thus, supplying safe, stable batteries to power these devices and meet the increasing demand is paramount.

One of the ways that batteries are exercised to determine reliability and lifespan is via battery cycle testing. Battery cycling involves charging and discharging a battery repeatedly for a specified number of cycles to determine its performance over time and after heavy usage.

This app note will discuss some of the features available starting in version 2.11.0 of the KickStart Software Battery Simulator App. This version of the Battery Simulator App introduces the new battery cycling functionality, and source measure unit (SMU) support allowing for both battery simulation and model generation in a one-box solution. In addition to discussing these new features, we will demonstrate the Battery Simulator App's ability to test batteries and generate and simulate battery models using a wireless Ring Video Doorbell and Ring Security Camera.

The Previous Solution

In a previous application note on this topic, Battery Optimization using Keithley 2281S and 2380 and KickStart Battery Simulator App, we discussed how to determine battery performance through discharge curve analysis and battery simulation. The discharge curve generated during battery model generation can give significant insight into a battery's performance under different environmental conditions. Meanwhile, the simulation of these battery models allows for precise, repeatable test conditions. This can then be used to gauge the consistency of a device's behavior as seen in **Figure 1**.

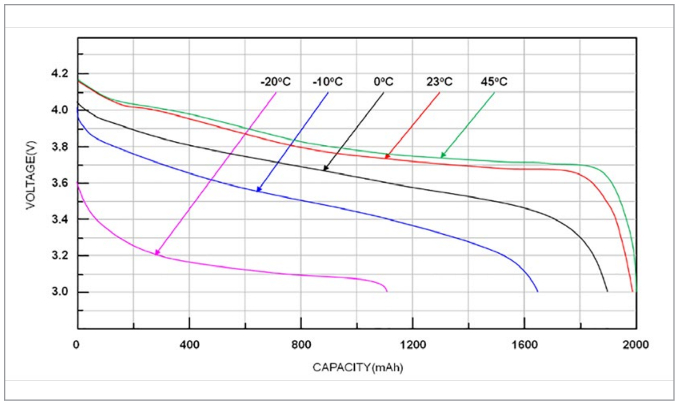


Figure 1: Li-Ion Discharge Curve and Temperature

The previous solution offered by the KickStart Software Battery Simulator App involved generating a battery model using a 2380 Series Electronic Load and then simulating that model using a 2281S Battery Simulator.

Figure 2: 2380 and Kalinco Fitness Tracker Battery

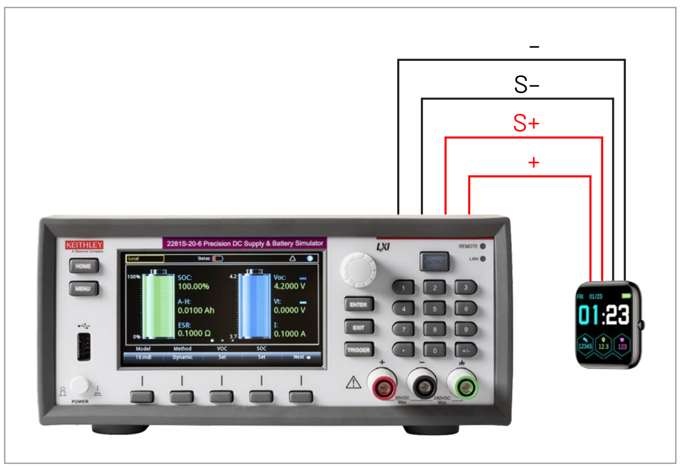


Figure 3: 2281S and Kalinco Fitness Tracker

This setup gets the job done but requires access to two separate instruments and does not offer functionality beyond battery model generation and battery simulation. However, if a SMU were to be used, then model generation, battery simulation, and battery cycle testing functionalities could all be accessed with a single instrument.

The New Solution

Along with battery model generation and battery simulation capabilities, version 2.11.0 of the KickStart Software Battery Simulator App introduces the ability to perform battery cycling tests using 2400 Graphical Touchscreen and 2600B series SMUs. This can be either as a full charge and discharge cycle, or as just the charge or discharge portions alone.

Battery Simulation	Battery Discharge Model Generation	Battery Cycle Testing
2281S Battery Simulator	2380 Series Electronic Loads	–
TTI Graphical Series SMUs	TTI Graphical Series SMUs	TTI Graphical Series SMUs
2600B Series SMUs	2600B Series SMUs	2600B Series SMUs
KickStart Battery Simulator App		

Figure 4: Chart explaining which instruments can perform which operations with the Battery Simulator App

In a battery cycling test, the objective is to exercise a battery by charging and discharging it repeatedly to determine when the battery's total capacity begins to degrade. Thus, battery lifetime can be discerned through a long-term battery cycle test.

Batteries can be charged or discharged in a few different ways. A charge or discharge cycle may employ a constant current (CC) or constant voltage (CV) method. The CC method simply applies a current bias to the battery to prevent overcurrent charge conditions, while the CV method applies a voltage bias with a steadily decreasing charge current. A hybrid CC + CV method is also available for charge cycles. Hybrid Charge Mode is typically defined by a constant current charge followed by a constant voltage charge. The SMU is placed in a current source mode and supplies a bias to the battery. The battery is charged up to a voltage specified by the Max Operating Voltage/Threshold Voltage parameter, which is where the Source V limit is set. Once the Max Operating Voltage is reached, the SMU operates in compliance mode, and we see the sourced current start to drop. When the sourced current drops to the Threshold Current, the charge is done.

It is also important to consider how long a charge/discharge cycle should be. If the charging or discharging time drastically differs from what is rated, then significant damage to a battery can be done. Discharging a battery too deeply can crystalize, often permanently, the internal structure of the battery. This, as well as other stresses, cause a decrease in capacity. Conversely, overcharging batteries greatly increases the chance of failure in the form of overheating, bloating, or even thermal runaway and explosion. So, if a cycle does not complete before the Max Charging Time or Max Discharging Time parameters are met, the test will end with a resulting failure message.

As previously stated, a battery is aged via undergoing multiple charge and discharge cycles. The goal is for the total battery capacity to not degrade excessively once aged. Furthermore, an excessive decrease in rated capacity indicates that the battery is damaged or is nearing the end of its lifecycle. This damage increases the chance of battery failure and thermal runaway. The Capacity Target % parameter allows the user to set the percentage of the starting battery capacity which should remain by the end of the test. If the measured battery capacity is lower than the (rated capacity * capacity target %) then the test fails.

Which Solution is Right for My Application?

With so many instrumentation options available, it might be difficult to determine which solution will deliver the best results for your battery test and simulation applications. Each instrument family, or model therein, offers its own advantages due to differences in ranges, accuracy, speed, and noise levels. For example, while the 2400 graphical series SMUs, 2600B series SMUs and the 2281S can source, sink, and measure, all offer the same 6.5-digit resolution, and all offer the same sample interval within KickStart Software, they do have differences in how much voltage, current, or power they can sink. See **Figures 5, 6, 7, and 8** for helpful charts listing suggested instrumentation for different battery modeling applications and their specifications.

CC Discharge	Battery Type	2450 Graphical SMU	246x Graphical SMUs	2470 Graphical SMU	2600B Series SMUs	2380 DC Electronic Load
≤10mA	Coin cell	✓	✓	✓	✓	✗
Sleep Modes	Any	✓	✓	✓	✓	✗
5A	Li-Ion/Li-Po	✗	✓	✗	✗	✓
1 A		✓	✓	✓	✓	✓

Figure 5: Table outlining the capabilities of different instrumentation options for model generation

Charge Current	Battery Type	2450 Graphical SMU	246x Graphical SMUs	2470 Graphical SMU	2600B Series SMUs	2281S Battery Simulator
≤10mA	Coin cell	✓	✓	✓	✓	✓
5A	Li-Ion/Li-Po	✗	✓	✗	✗	✓
1 A		✓	✓	✓	✓	✓

Figure 6: Table outlining the capabilities of different instrumentation options for model simulation

Specifications	2461 Graphical SMU	2281S Battery Simulator
Sourcing	100 V; 7A (10A Pulse)	20V; 6A
Sinking	100V; 7A (10A Pulse)	20V; 1A (Uncontrolled)
Voltage Setting Accuracy	±(0.015% + 200 µV)	±(0.02% + 3 mV)
Current Setting Accuracy	±(0.025% + 1 nA)	±(0.05% + 5 mA)
Voltage Measurement Accuracy	±(0.012% + 200 µV)	±(0.02% + 2 mV)
Current Measurement Accuracy	±(0.025% + 700 pA)	±(0.04% + 10 µA)
Setting Accuracy Resolution	5 µV and 50 pA	1 mV and 0.1 mA
Measurement Accuracy Resolution	100 nV and 1 pA	0.1 mV and 10 nA
Noise Levels	1 µV (RMS) and 40 pA (RMS)	<1 mV RMS, <6 mV p-p, and <3 mA RMS
Load Regulations	± (0.01% + 100 µV), ± (0.01% + 100 pA)	±(0.01% + 2 mV), ±(0.01% + 0.25 mA)
Line Regulations	(0.01%)	±(0.01% + 1 mV), ±(0.01% ± 0.25 mA)

Figure 7: Table outlining the specifications of the 2461 Graphical SMU and the 2281S Battery Simulator

2450	2460	2470
200 V; 1A	105 V; 7A (7A Pulse) (100 W)	1100 V; 1A (20 W)
200 V; 1A	105 V; 7A (7A Pulse) (100 W)	1100 V; 1A (20 W)
±(0.100% + 200 µV)	±(0.015% + 200 µV)	±(0.015% + 200 µV)
±(0.100% + 100 pA)	±(0.025% + 1 nA)	±(0.100% + 200 pA)
±(0.100% + 150 µV)	±(0.012% + 200 µV)	±(0.012% + 200 µV)
±(0.100% + 50 pA)	±(0.025% + 700 pA)	±(0.10% + 250 pA)
500 nV and 500 fA	5 µV and 50 pA	5 µV and 500 fA
10 nV and 10 fA	100 nV and 1 pA	100 nV and 10 fA
1 µV and 500 fA (RMS) (<10 Hz)	1 µV and 40 pA (RMS) (<10Hz)	2 µV and 500 fA (RMS) (<10Hz)
±(0.01%+100 µV), ±(0.01%+100 pA.)	±(0.01%+100 µV), ±(0.01%+100 pA.)	±(0.01%+100 µV), ±(0.01%+100 pA.)
(0.01%)	(0.01%)	(0.01%)

Figure 8: Table outlining the specifications of the 2450, 2460, and 2470 Graphical SMUs

One of the most significant differences between the 2400 graphical series SMUs and the 2281S is the higher ESR range supported by the 2461 and other SMUs. This higher ESR range allows the SMUs to simulate a greater range of batteries.

Testing an IoT Device with a SMU and Kickstart Software

To demonstrate the capabilities of the enhanced KickStart Software Battery Simulator App, as well as of the 2400 graphical series SMUs, a ring wireless security camera was chosen to act as a DUT. First, to begin the characterization and optimization process, a model of the device's battery needs to be made. To do so, access to the battery cells themselves is needed. Fortunately, the wireless Ring Security Camera uses removeable battery packs.

After carefully removing the outer casing of the battery pack, shown in **Figure 9**, two 18650 lithium-ion batteries, in parallel, along with a battery management system (BMS) board can be seen. The BMS is displayed in **Figure 10**, while the batteries are shown in **Figure 11**. Next, the battery is disconnected from the BMS board. From here, a 2450 was connected to the pair of batteries in a four-wire sense connection, similar to that in **Figure 3**.

Figure 9: Ring Wireless Security Camera Battery Pack

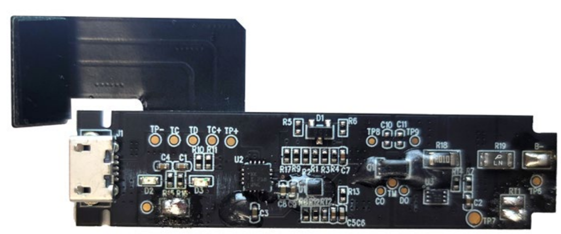


Figure 10: Ring Battery Pack BMS

Figure 11: 18650 Cells from Ring Battery Pack

Now that the 2450 is properly connected to the battery, a battery discharge model of the two Li-ion batteries in parallel can be created in a few mouse clicks. From within KickStart Software, clicking the 2450 SMU and then the Battery Simulator App will open the simulate battery window. From here, click on "generate discharge model" to begin entering your model generation settings. As the two 18650 cells are each rated for 3180mAh, the total capacity of the batteries in parallel is 6360 mAh. The settings shown in **Figure 12** were chosen for the model generation.

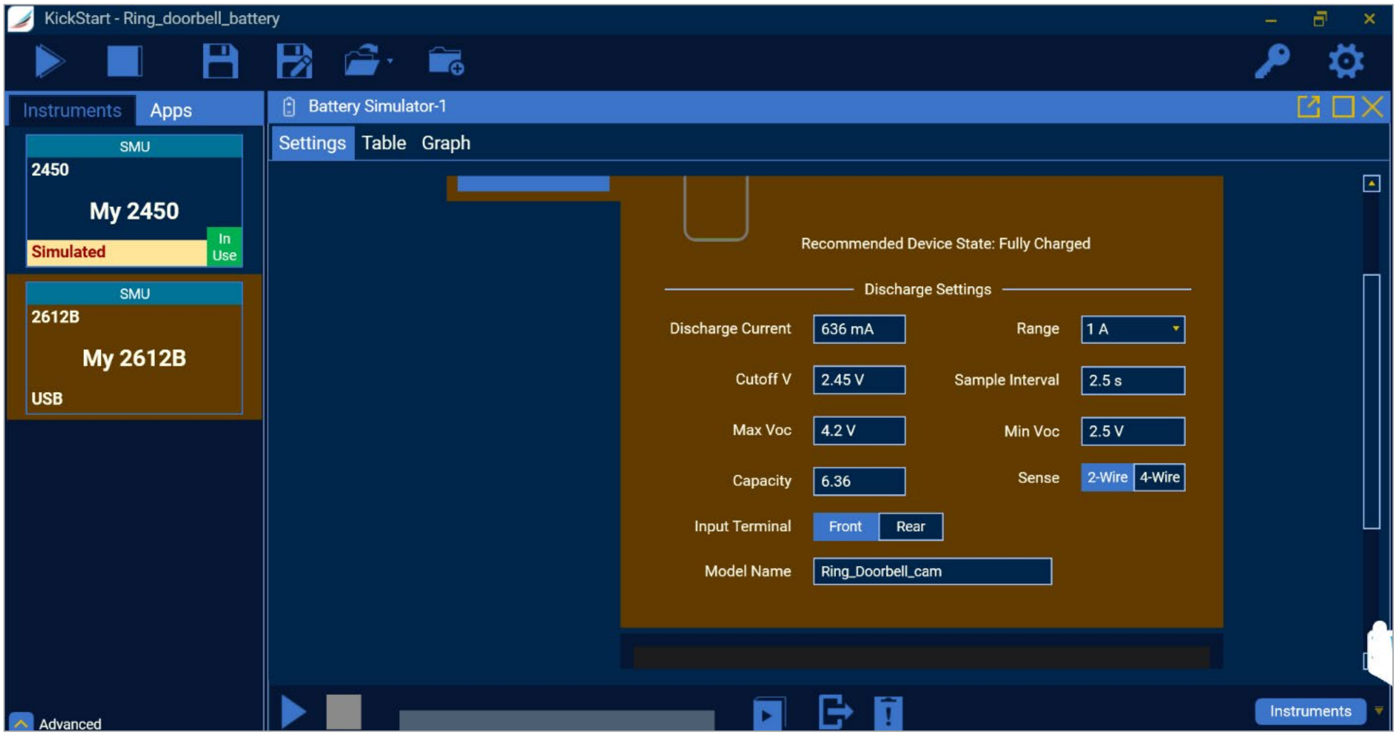


Figure 12: Generate Discharge Model Settings

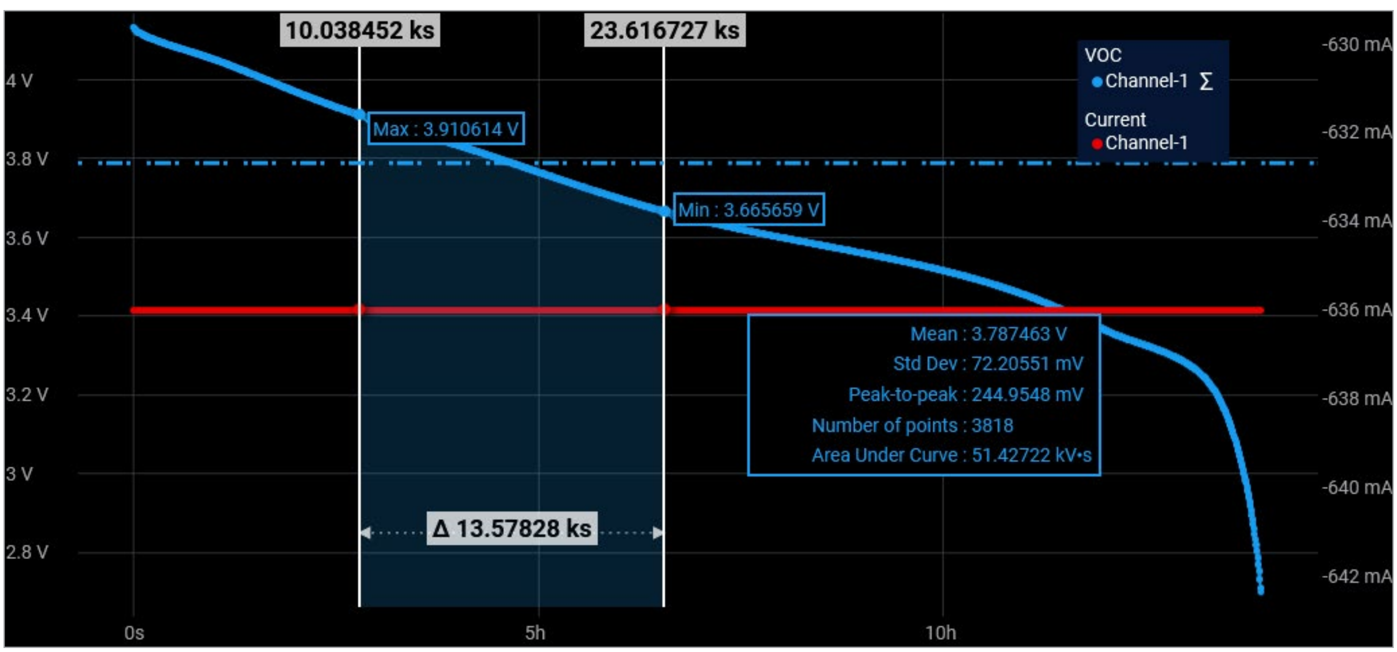


Figure 13: Battery Discharge and Graphing Tools

After clicking the run button, the discharge will begin and continue until the Cutoff V parameter is reached. During this time, you can click on the table tab to see a table of every measurement taken by the 2450, as well as some statistics such as the maximum, average, and standard deviation. Next, clicking on the graph tab reveals plots for VOC, ESR, and current. Within the legend you can also see a sigma icon that is used to show or hide statistics. Clicking this button will reveal statistics such as number of points and area under the curve. Cursors can also be added to the graph to easily view timestamps and determine the time between two specified samples. The battery discharge curve and these analysis tools can be seen in **Figure 13**. The resulting 101-point model can be seen in **Figure 14**.

Figure 14: 101-point Ring Battery Pack Demo

PW_MODEL_PW2281S_20_6		
Capacity = 6.36 AH		
SOC (%)	Open Voltage (V)	ESR (ohm)
0	2.5	0.389
1	2.929	0.386
2	3.057	0.385
3	3.144	0.383
4	3.204	0.381
5	3.242	0.379
6	3.268	0.377
7	3.286	0.376
8	3.3	0.373
9	3.312	0.371
10	3.323	0.369
11	3.332	0.366
12	3.342	0.363
13	3.352	0.36
14	3.365	0.358
15	3.379	0.356
16	3.392	0.355
17	3.405	0.354
18	3.418	0.353
19	3.43	0.351
20	3.441	0.351
21	3.452	0.35
22	3.462	0.35
23	3.471	0.35
24	3.48	0.35
25	3.489	0.349
26	3.497	0.349
27	3.505	0.349
28	3.512	0.349
29	3.519	0.349
30	3.525	0.349
31	3.532	0.348
32	3.538	0.348
33	3.544	0.348

PW_MODEL_PW2281S_20_6		
Capacity = 6.36 AH		
SOC (%)	Open Voltage (V)	ESR (ohm)
34	3.55	0.348
35	3.555	0.349
36	3.561	0.348
37	3.567	0.348
38	3.572	0.347
39	3.577	0.347
40	3.583	0.347
41	3.588	0.347
42	3.594	0.347
43	3.599	0.347
44	3.605	0.348
45	3.61	0.348
46	3.616	0.348
47	3.622	0.348
48	3.628	0.348
49	3.634	0.347
50	3.641	0.347
51	3.647	0.347
52	3.654	0.348
53	3.661	0.348
54	3.669	0.348
55	3.676	0.347
56	3.684	0.347
57	3.693	0.347
58	3.701	0.347
59	3.71	0.347
60	3.719	0.347
61	3.728	0.347
62	3.737	0.348
63	3.747	0.348
64	3.756	0.347
65	3.766	0.347
66	3.776	0.347
67	3.785	0.347

PW_MODEL_PW2281S_20_6		
Capacity = 6.36 AH		
SOC (%)	Open Voltage (V)	ESR (ohm)
68	3.795	0.347
69	3.804	0.347
70	3.814	0.347
71	3.823	0.347
72	3.832	0.348
73	3.841	0.348
74	3.849	0.348
75	3.858	0.348
76	3.866	0.348
77	3.875	0.348
78	3.883	0.348
79	3.892	0.348
80	3.901	0.348
81	3.91	0.348
82	3.919	0.349
83	3.929	0.349
84	3.939	0.35
85	3.95	0.35
86	3.96	0.35
87	3.972	0.35
88	3.983	0.35
89	3.995	0.349
90	4.006	0.35
91	4.018	0.35
92	4.029	0.35
93	4.04	0.35
94	4.05	0.351
95	4.06	0.352
96	4.069	0.353
97	4.078	0.353
98	4.087	0.353
99	4.096	0.354
100	4.2	0.355

Once the model has been generated, the battery pack can be simulated by the 2450 SMU, allowing it to act in place of the batteries to power the wireless Ring security camera. However, during testing it was discovered that the battery packs included with the Ring security camera come with anti-tamper protections preventing the battery pack from working after being reassembled. To get around this issue, a wired Ring security camera, normally powered by micro-USB, was substituted. The micro-USB cable that plugs into the back of the Ring security camera was cut to reveal the positive and negative power wires. The 2450 was then connected to these exposed wires in a four-wire sense connection similar to what's shown in **Figure 3**. From here, the "simulate" tab in the Battery Simulator App was opened, the previously generated battery model, "ring_Doorbell_cam.csv" was chosen, and the settings shown in **Figure 15** were applied.

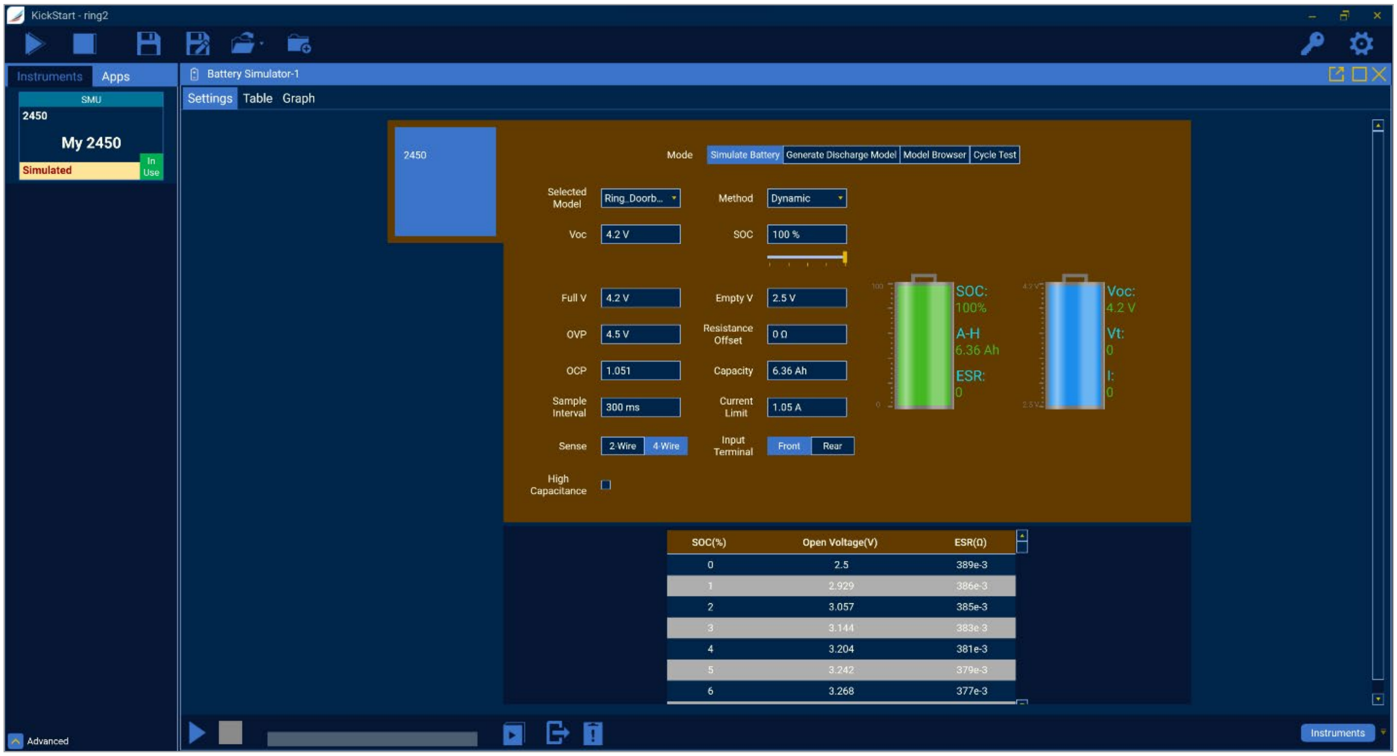


Figure 15: Battery Simulation Settings

If a battery model is being used and wasn't generated using KickStart Software, the Model Browser tab allows users to select a model and import it to their local Kickstart Software repository. The model browser also allows for quick modifications to the selected battery model. An example of the model browser tab can be seen in **Figure 16**. After pressing the run button, the 2450 will begin to simulate the Ring security camera's battery and power on the device. Just as with the generate discharge model tab, KickStart Software will start to record measurements while simultaneously visualizing this data in the table and graph tabs. However, the graph for battery simulation also allows the user to plot SoC and capacity. The discharge curve of the simulated battery is shown in **Figure 17**.

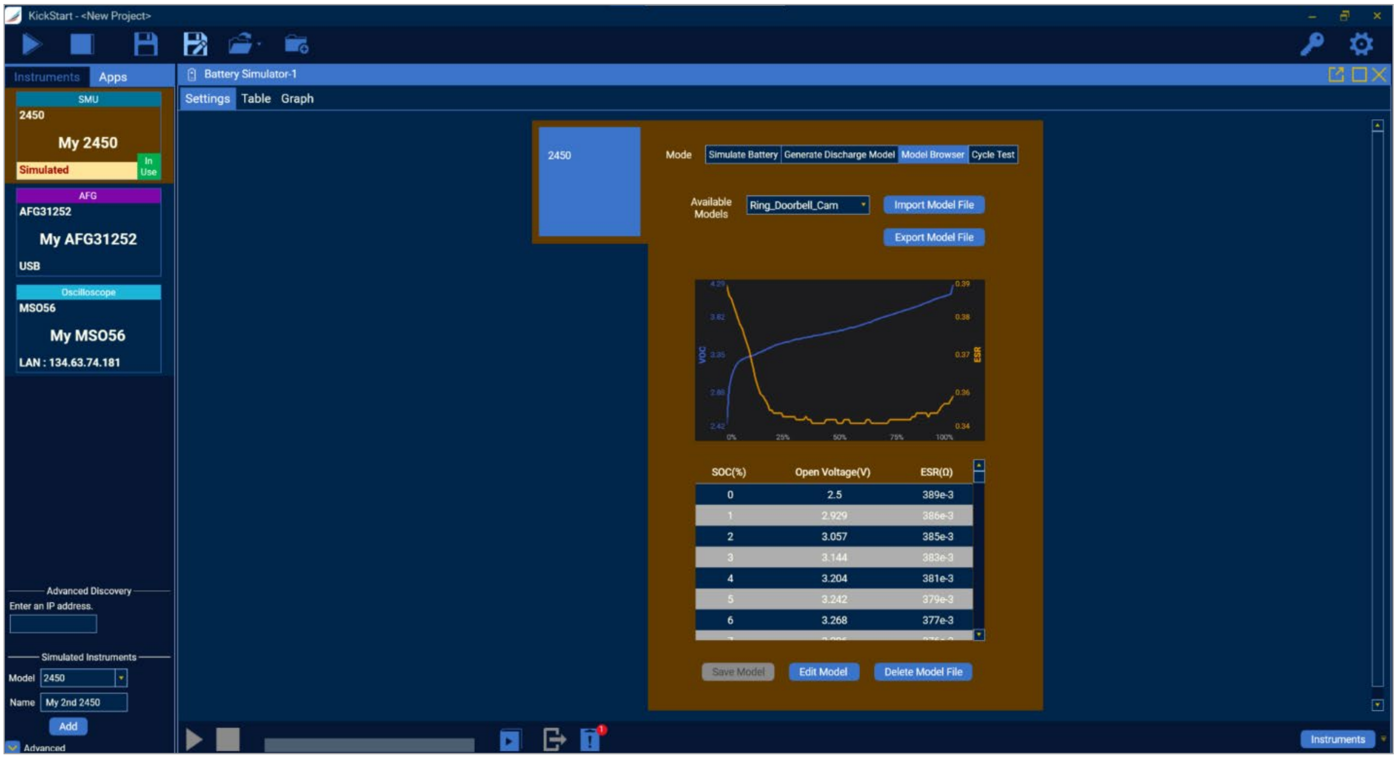


Figure 16: Model Browser

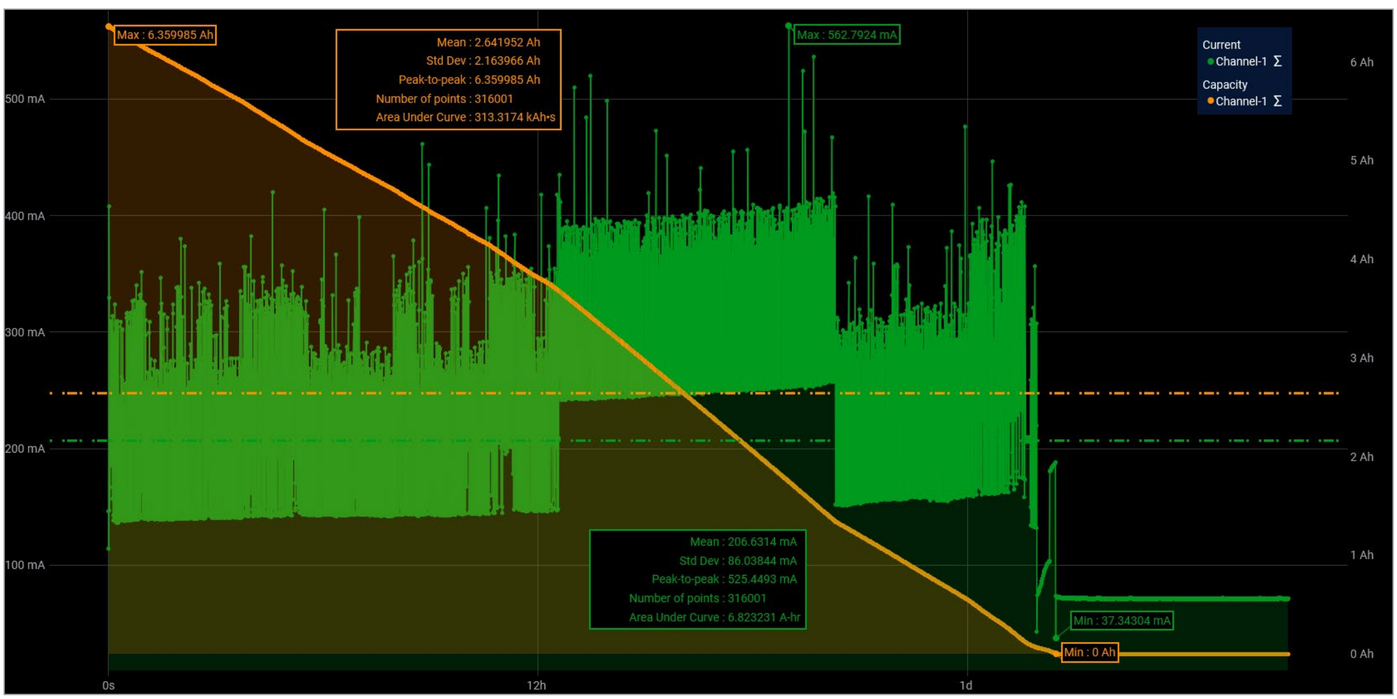


Figure 17: Battery Simulation Results

Figure 17 illustrates that the current draw increases dramatically when accessing the camera from the Ring App. The section of the graph starting at about 12 hours shows the current draw when manually accessing the camera, while the other spikes show the automatic motion detection function. Also shown in this graph are statistic windows displaying information about each plot. Cursors can also be added to limit the range the statistics window focuses on. These tools make it easier to analyze information such as power usage of DUTs and area under the curve.

To determine how the Ring Video Doorbell's battery lifespan degrades across multiple charge and discharge cycles as the battery is depleted and recharged overtime as it is used, the battery pack can be cycle tested using KickStart Software. In the battery cycle test tab, users will set their charge and discharge settings according to their battery specifications. Users will also set parameters such as number of cycles, and capacity target. An example of the battery cycle settings for the Ring battery pack is shown in **Figure 18**, and the plot of the resulting data is seen in **Figure 19**.

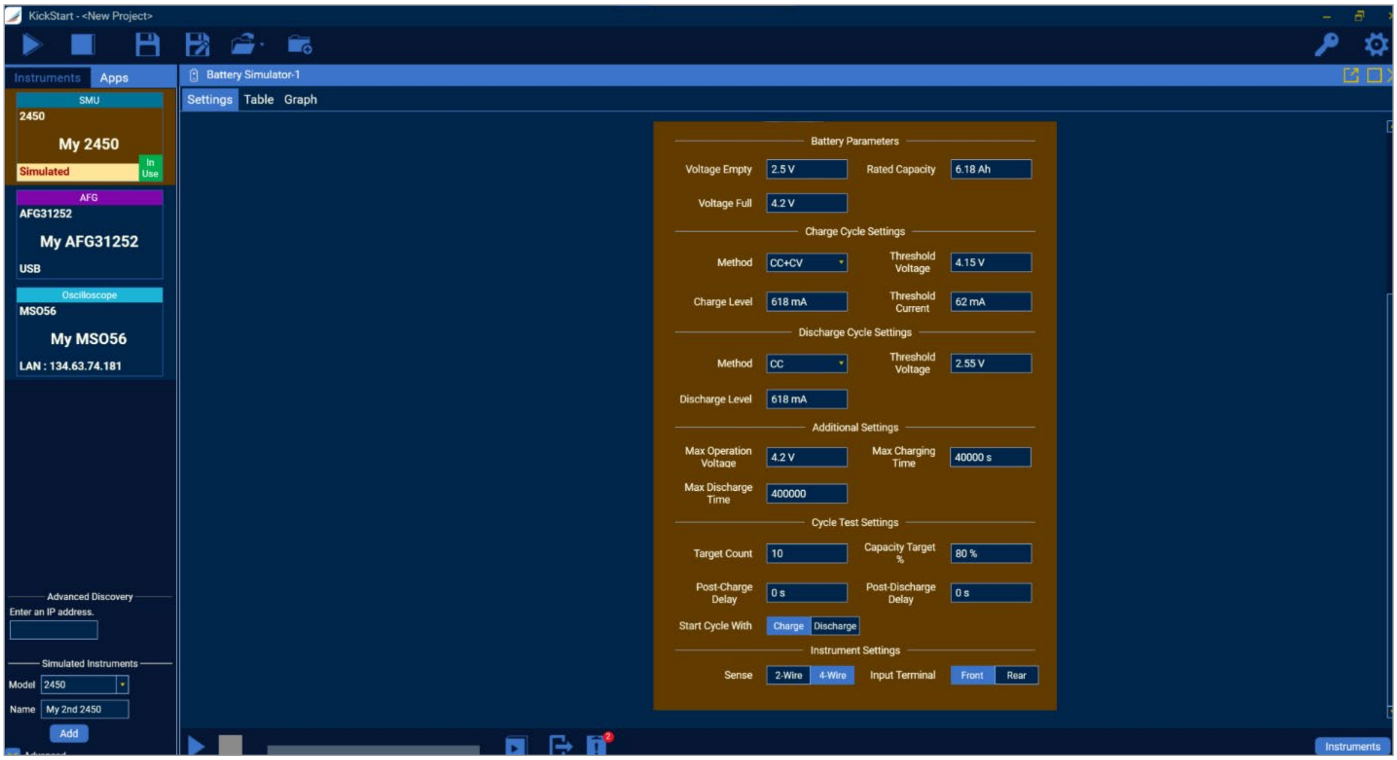


Figure 18: Battery Cycle Test Settings

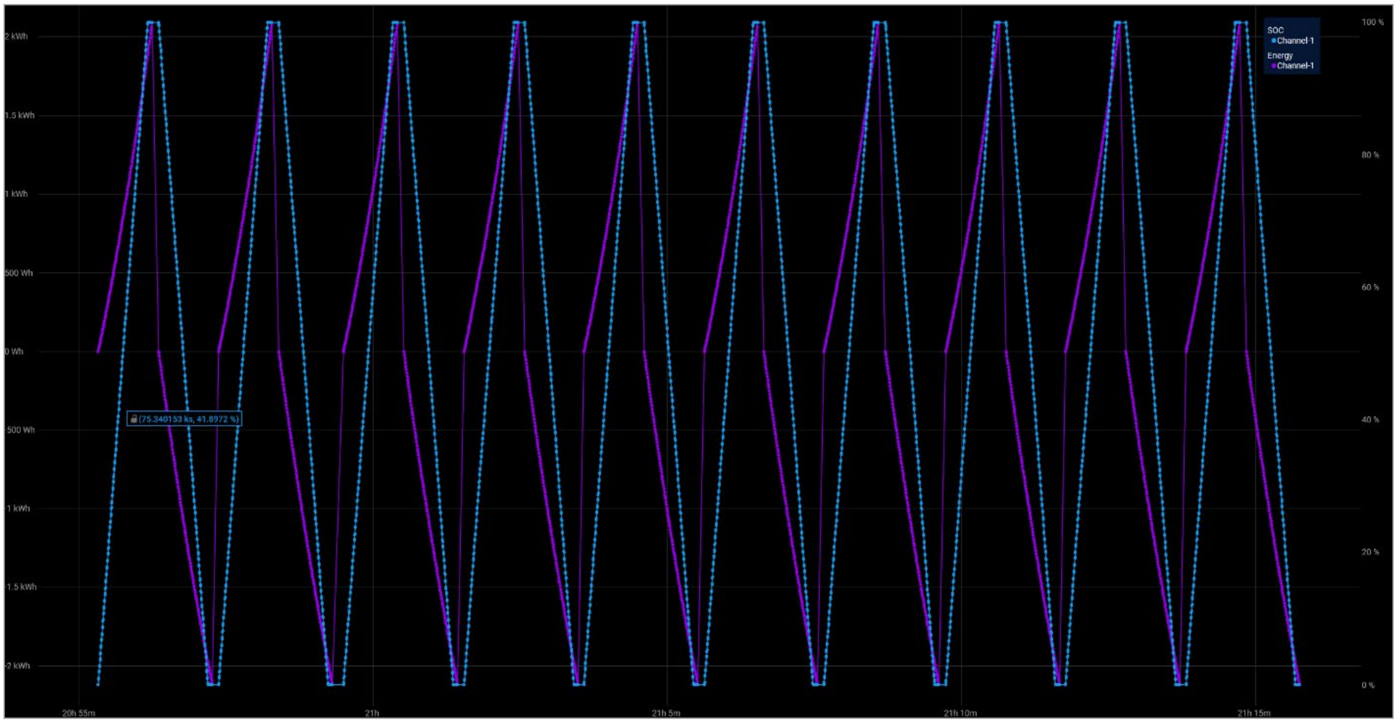


Figure 19: Battery Cycle Test Results

The battery cycle test mode also includes a table and graph tab to visualize data. If the battery being tested is in-between a full and empty charge, or if the user wants to ensure they are testing from a fully charged or fully depleted battery, a "Charge Only" or "Discharge Only" battery cycle can be run. An example of these settings can be seen in **Figures 20 and 21**.

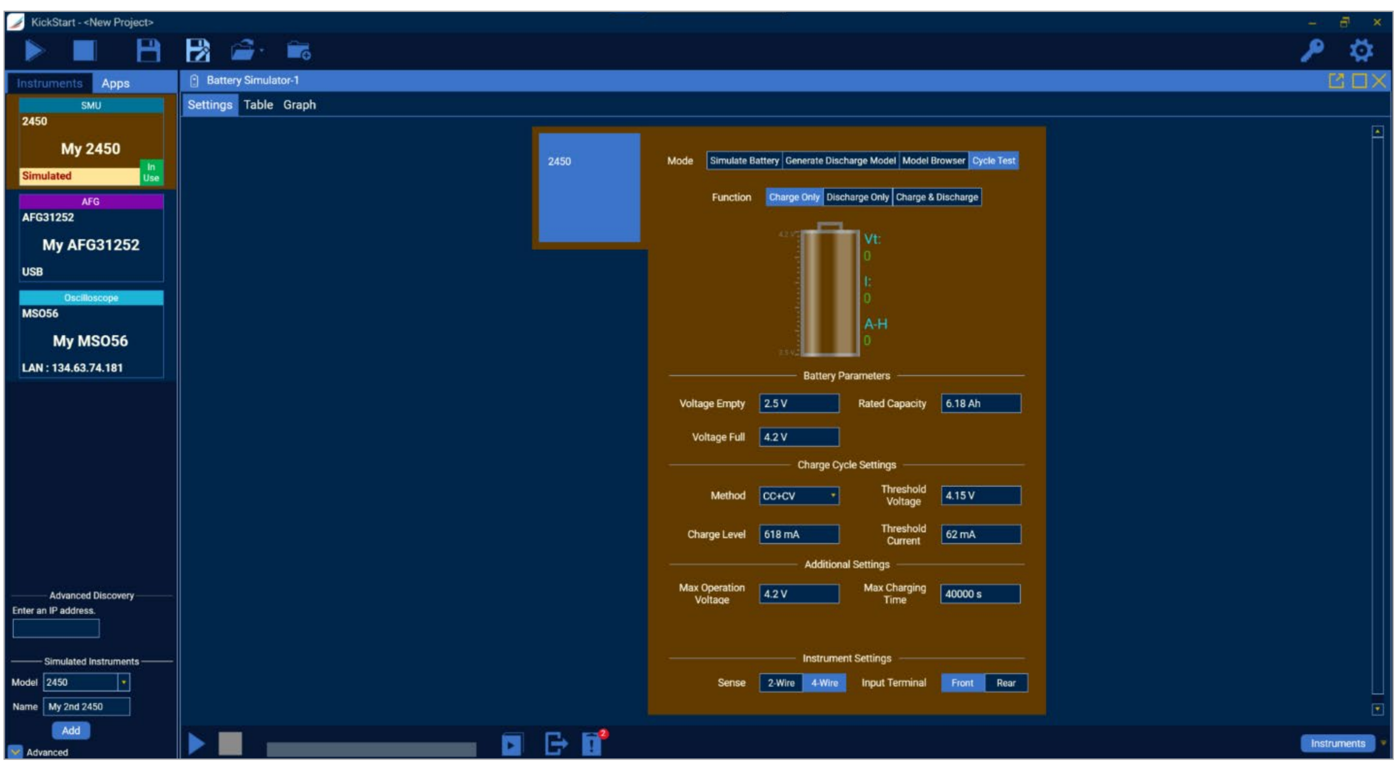


Figure 20: Battery Cycle – Charge Only Settings

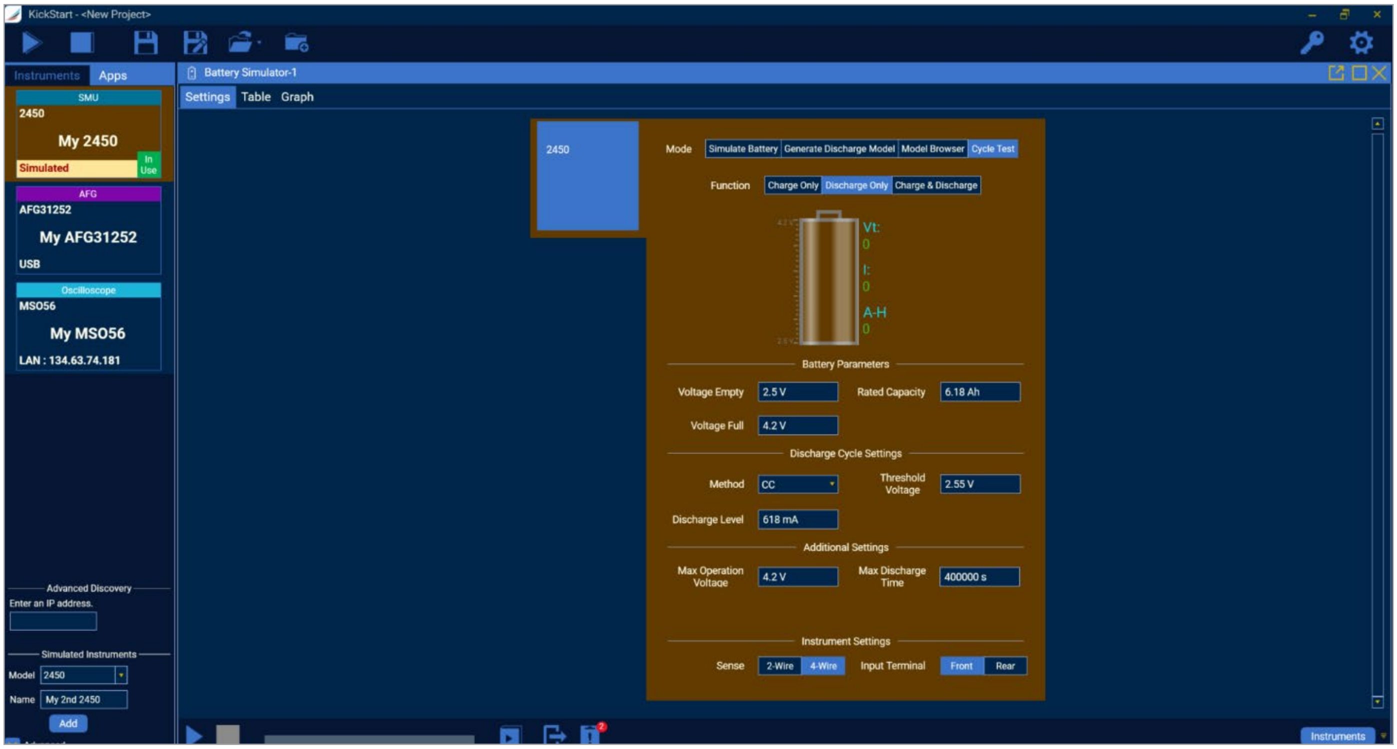


Figure 21: Battery Cycle – Discharge Only Settings

Conclusion

The addition of SMUs to the KickStart Software Battery Simulator App broadens the scope of batteries which can be tested alongside a powerful "one-box" solution. KickStart Software enables easy repetition of tests under various conditions and allows for a simple method to generate battery models for simulation. The same SMU can be used to simulate the models and the inclusion of battery charge/discharge and cycle testing extends the functionality of the app even further, allowing users to test battery longevity alongside device optimization and overall performance. The simplicity afforded by a total software plus instrumentation solution means that it is possible for anyone to set up and run tests quickly and efficiently — from students to technicians to design engineers.

Battery Optimization using the Keithley Series 2281S and 2380 and KickStart Software's Battery Simulator App

APPLICATION NOTE

Introduction

As battery-powered devices have become a staple of everyday life, battery performance has become a critical factor in device design. Single use, or primary, disposable batteries remain ubiquitous in their usage, often used to power remote controllers, flashlights, and radios. These are most often seen in the form of alkaline batteries or the older zinc-carbon batteries. However, rechargeable, or secondary, batteries are commonly and increasingly used in place of disposable batteries in electronic devices such as laptops, mobile phones, and digital cameras. Common types of rechargeable batteries include Li-ion (Lithium Ion) and Ni-MH (Nickel Metal Hydride). Because of the criticality of battery performance to everyday life, and the wide range of battery types, test and design engineers working with battery powered devices need a way to optimize their device's performance and battery life.

When optimizing a device for battery life, it may be important to analyze the performance of a given battery type over one charge cycle. This is done through a discharge curve which shows the battery's change in voltage over time when connected to a load. A battery's performance over one charge cycle varies greatly with many different factors including size, temperature, material, and discharge current. A battery's performance is also heavily dependent on the Equivalent Series Resistance, ESR, of the battery. The ESR of a battery is the inherent internal resistance, depicted as the resistor in a battery's Thevenin equivalent circuit. Examples of discharge curves, as well as this variance in performance, can be seen in **Figure 1**, where a lower temperature increases the ESR, which in turn increases the battery's discharge rate. This behavior can also be observed in **Figure 2**, where a higher load current also leads to an increase in discharge rate.

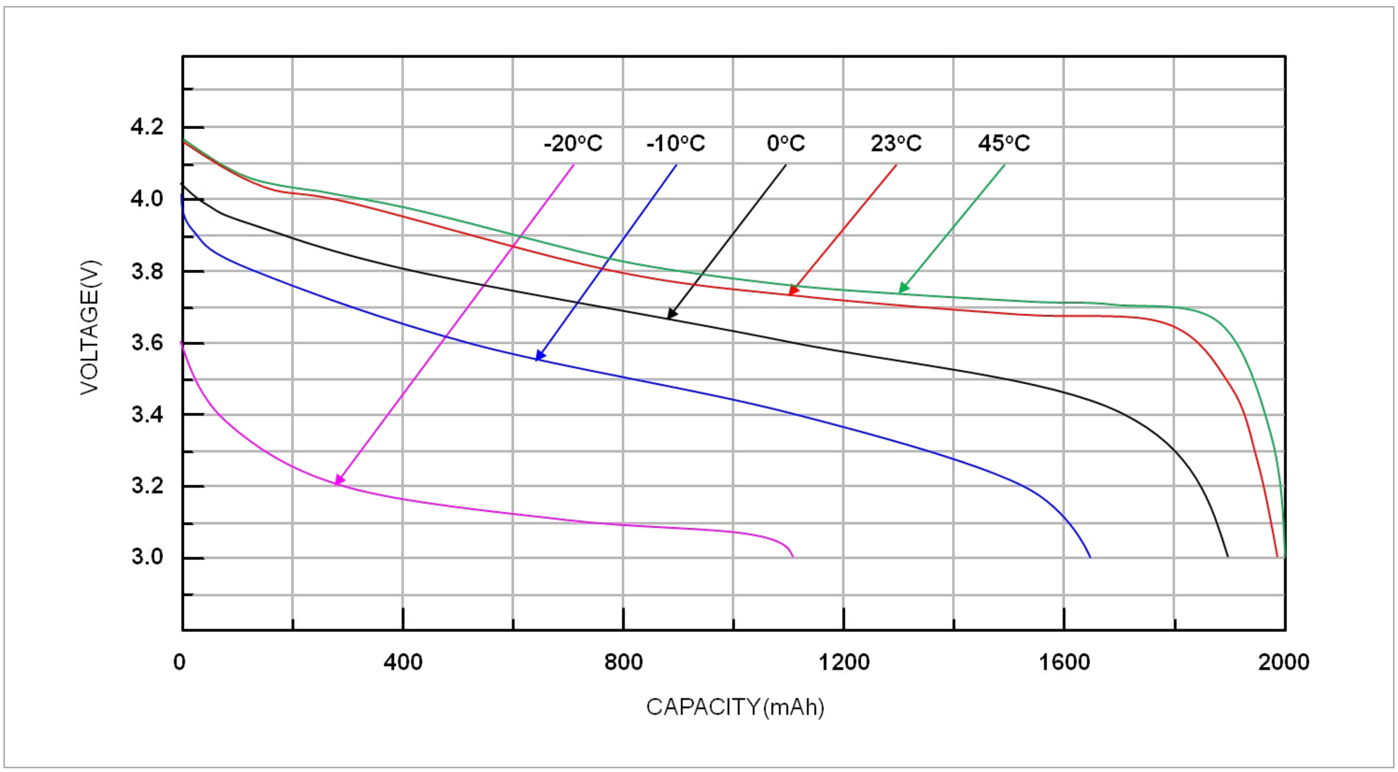


Figure 1: Li-Ion Discharge Curve and Temperature

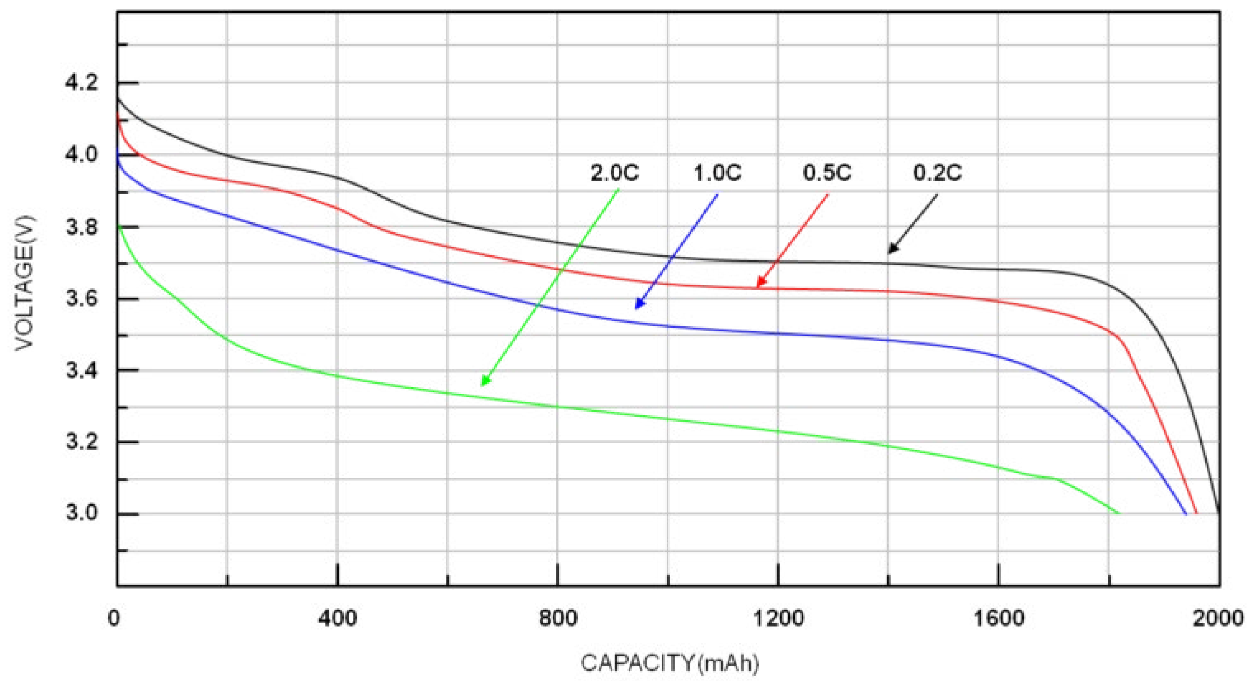


Figure 2: Li-Ion Discharge Curve and Discharge Rate

When Keithley's KickStart Software, and the KickStart Battery Simulator App, is paired with the 2281S model generation becomes simple. KickStart Software's intuitive interface, model editing abilities, and battery model repository allow the test or design engineer to create battery models at different conditions and test their device against these various models quickly.

To optimize the battery life of a device, it may be useful to test the device's performance at different "States of Charge", SOC, and "Open Circuit Voltage", VOC For instance, a lithium polymer battery typically operates over a range of 4.2 V fully charged to 3 V. Design and test engineers will want to ensure their device operates properly at all voltages or shuts down before low power causes instability. Keithley's KickStart Software makes this easy, allowing the user to set the SOC of their simulated battery, even during simulation. The KickStart Software also allows for dynamic and static battery models, where the simulated battery's SOC can decrease in real time according to the applied load, or where the model stays at the exact SOC and VOC set by the user. Because of these powerful data collection tools, easy to use interface, and the "all-in-one" nature of Keithley's KickStart Software, the KickStart Battery Simulator App offers unprecedented value and simplicity in quickly simulating various battery models for device testing.

Application

The objective of this app note is to demonstrate the abilities of KickStart software's Battery Simulator App, and the 2281S through analyzing the battery performance of a smart, wearable medical device.

Recently, Smart or Internet of Things (IoT) wearables have seen a marked uptick in adoption. Smart wearables, with their ability to monitor the user's vitals, offer new ways of tracking patient health and worker safety. These devices are intended to collect data over long periods of time and, as such, there is a need to test them to optimize both battery life and efficiency. The Battery Simulator App within KickStart software makes this testing quick and simple. However, before the device's performance can be optimized, models of the battery must be made. Battery models can be generated in KickStart software by discharging a battery using a Keithley Series 2380 DC Electronic Load. This app note will focus on the KALINCO Smart Fitness Tracker and its built-in battery. The fitness tracker is displayed in **Figures 3–5**.

Figure 3: Kalinco Fitness Tracker

Figure 4: 180 mAh Li-Po battery

Figure 5: Deconstructed View

Creating a model with the 2380 Electronic Load

Figure 6 shows the configuration used in the KickStart software to create a discharge model of the fitness tracker's battery using the Keithley Series 2380 DC Electronic Load. To start model generation, open the KickStart Software. The 2380 should be detected automatically and displayed in the instruments tab on the left-hand side of the screen. Double click or drag the 2380 icon into the center of the screen. This will launch a new window asking for your desired app. Select Battery Simulator and edit the parameters to reflect the qualities of the device under test. When a model is generated using a Series 2380 instrument, the device being modeled must be in a fully charged state. An example of the Generate Discharge Model screen and its relevant parameters are shown in **Figure 7**.

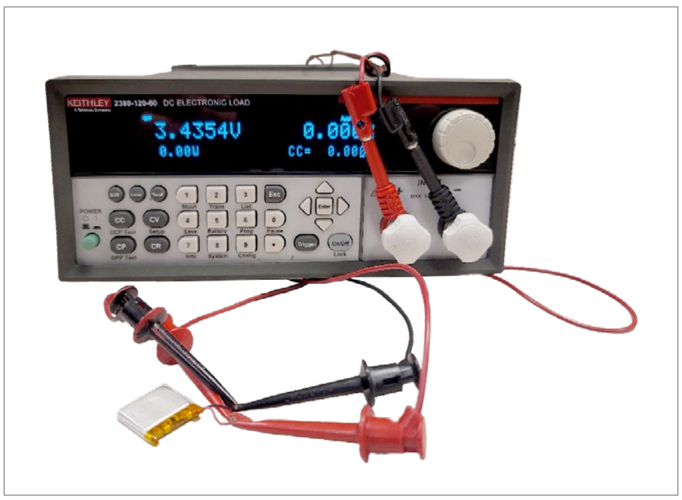


Figure 6: 2380 and Kalinco Fitness Tracker Battery

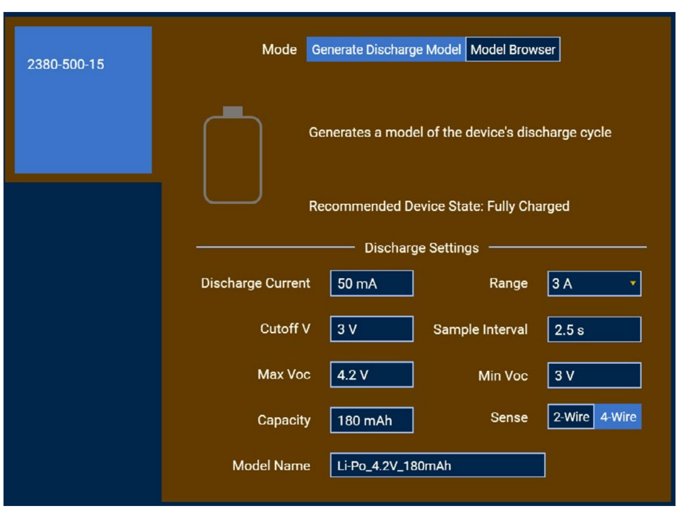


Figure 7: Generate Discharge Model in KickStart Software

When generating a discharge model, the specific parameters corresponding to your battery as outlined by the battery's datasheet must be used. The discharge current is the maximum amount of current that will be drawn from the battery during the test. Because this discharge model operates in constant current mode, this current will be present throughout the duration of model generation. For this example, discharge current will be set to 50 mA. Next, the range was set at the low range option. For the 2380-120-60 this is 6 A and for the 2380-500-15 and 2380-500-30 this is 3 A. Next, the "Cutoff V" is the end voltage condition for generating discharge models. Once the battery voltage reaches this level the data collection is complete. For this example, the Cutoff voltage was set to 3 V. The sample interval is the time between data measurements. This was left as 2.5 seconds. The Max and Min VOC values are the maximum and minimum open circuit voltages of the battery model after generation. These were set for 4.2 V and 3.0 V respectively. The capacity is the total energy in the battery, measured in Amp hours. For the battery included with the Kalinco Smart Fitness Tracker, the capacity is listed as 180 mAh.

The "Sense" setting corresponds to the use of either 2-wire or 4-wire sense for taking measurements. When measuring voltage or resistance within a circuit, an instrument will generally source a current, measure the voltage, and calculate the resistance. In a 2-wire sense setup the current source and voltage measurement happen at the same leads, while a 4-wire sense uses separate leads for the current source and the voltage measurement. Because of this, 2-wire measurements will introduce lead resistance into the measurement. For DUTs with high resistances, the added resistance from the test leads may not lead to significant error. However, in cases where resistance is 1 kΩ or less test lead resistance may lead to significant error. Therefore, for the best accuracy, this was set to 4-Wire. Lastly, after these parameters are set a model name can be chosen and the blue play button can be pressed to begin the data collection. As the voltage at the battery terminals, Vt, decreases, the progress bar will fill up at the bottom of the KickStart Battery Simulator App screen.

Once data collection has completed, the file will be automatically exported to the following directory: "C:\Users\%userprofile%\AppData\Local\Keithley\KickStart\BatterySimulator\ImportedModels". For the purposes of this demonstration, another discharge model is generated with the battery enclosed in a temperature-controlled environment at about 5°C.

Simulating the Model with the 2281S Battery Simulator

After the battery models have been generated using the 2380, simulation and analysis can begin. **Figure 8** shows a 4-wire sense connection between the Keithley 2281S, connected to KickStart Software's Battery Simulator, and the Kalinco fitness tracker. However, the model that was generated using the 2380 must first be transferred to the 2281S. To do so you must import a new battery model by navigating to the Model Browser tab. An example of this screen is shown in **Figure 9**. In addition to any user-generated models, the KickStart Battery Simulator App comes pre-loaded with several models of common batteries, which can be seen in the "available models" drop-down menu. Next, click "Import Model File." The software will prompt for a *.csv file. Simply select the preferred file of the appropriate type and the new model will be added to the list of available models stored in the app. After selecting the model, you'll see the graph and table on this screen populated with data. Custom battery models can also be edited or deleted within the Model Browser.

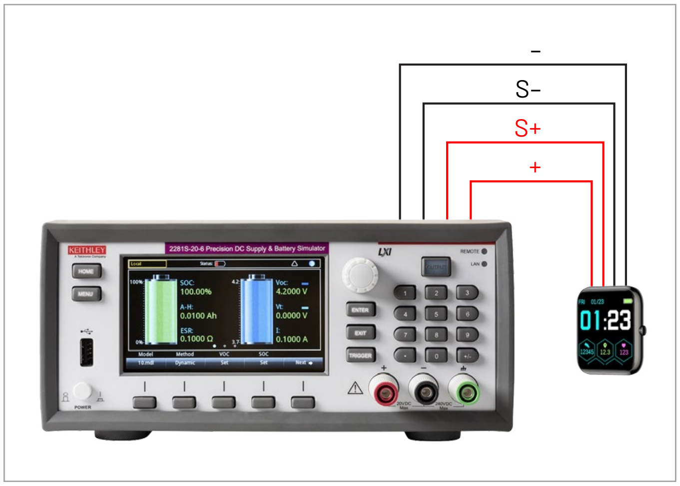


Figure 8: 2281S and Kalinco Fitness Tracker

Figure 9: Import Model File

To edit a model, select the preferred model from the "Available Models" dropdown menu and navigate towards the bottom of the window. Click "Edit Model." This will allow you to interact with the model table and change the Open Voltage and ESR values by double clicking on any individual cell. To keep the edits, click the "Save Model" button. To dismiss the changes, click "Cancel Edit." Once the model is imported, and the model entries are confirmed to be as desired, switch the view to the Simulate Battery tab. Next select the desired model from the "Selected Model" drop-down. Lastly, ensure SOC is set to 100% and all simulation parameters are as desired. An example of this view with simulation parameters is shown in **Figure 10**.

Figure 10: Simulate Battery in KickStart Software

The KickStart Battery Simulator app offers two methods of simulation: "dynamic" and "static". A dynamic model will simulate the discharge of battery, lowering its capacity and VOC as a load is applied, while a static model holds one SOC constant. A slider is also located underneath SOC to easily slide through battery percentages. For the purposes of this example, this should be set to dynamic. There are additionally three protection parameters which should be set before starting the simulation. The first two are "Over-Voltage Protection", OVP, and "Over-Current Protection", OCP. These two settings will stop the simulation if the voltage or current of the simulated battery exceeds this value. For this example, these were left at the default value of 21 V for OVP and 1 A for OCP. The third setting is the "Current Limit". This is the maximum value the simulated battery will output. This was set at 500 mA. An additional setting, "Resistance Offset", allows for adjustments to the ESR value by adding a positive or negative offset. This was left at 0 Ω. With these settings now in place, you can start the model simulation and data collection by pressing the blue play button at the bottom of the KickStart Software screen.

Once the run button is pressed, the smart watch is powered, and data will begin filling the table and graph. The battery icons featured in the simulation settings view allow the user to monitor the state of the simulated battery in a visual format. These indicators update in real time and allow for the visualization of key parameters such as SOC, capacity, ESR, VOC, voltage at the terminal (Vt), and current. From here, the battery usage of the smart watch in various conditions can be determined. For the purposes of this application two conditions were determined. The first was an exercise mode which tracks fitness information such as heart rate, steps, and time. The second was a timer mode which forces the screen to stay on. These two conditions were then run for one hour each, using both the room temperature, about 20°C, battery model and the 5°C, cold model.

Results and Added Value

To see the simulation data or model data in a larger tabular or graphical view, select the "Table" or "Graph" tabs. In the table tab, columns can be renamed or hidden, and statistics such as minimum, maximum, mean, standard deviation, and coefficient of variation can be viewed. Under the graph tab, the VOC, current, and ESR can be viewed. The graph tools allow for viewing additional statistics under the curve, zooming in to see areas of interest, and changing the axes from linear scale to logarithmic.

In addition to the data collected with the KickStart Software, the behavior of the device at low SOC can be characterized. For instance, while the Kalinco Fitness Tracker stayed powered on the end of the charge around 3 V, the screen was visibly dimmer, the device was noticeably slower, and, when powered off, would not power back on. **Figure 11** shows examples the table and graph tabs within the KickStart Software, after data has been collected.

	Channel-1					
	Time (s)	VOC (V)	ESR (Ω)	Current (A)	SOC (%)	Capacity (Ah)
1	0.0000	4.198	300.0e-3	4.339e-3	99.99	180.0e-3
2	34.3e-3	4.198	300.0e-3	5.077e-3	99.99	180.0e-3
3	68.5e-3	4.198	300.0e-3	6.399e-3	99.99	180.0e-3
4	102.7e-3	4.198	300.0e-3	8.066e-3	99.99	180.0e-3
5	136.9e-3	4.198	300.0e-3	8.439e-3	99.99	180.0e-3
6	171.7e-3	4.198	300.0e-3	13.25e-3	99.99	180.0e-3
7	206.0e-3	4.198	300.0e-3	13.61e-3	99.99	180.0e-3
8	240.2e-3	4.198	300.0e-3	14.13e-3	99.99	180.0e-3
9	274.4e-3	4.198	300.0e-3	13.49e-3	99.99	180.0e-3
10	308.5e-3	4.198	300.0e-3	13.40e-3	99.99	180.0e-3
11	342.8e-3	4.198	300.0e-3	13.69e-3	99.99	180.0e-3
12	377.1e-3	4.198	300.0e-3	19.33e-3	99.99	180.0e-3
13	411.3e-3	4.198	300.0e-3	13.49e-3	99.99	180.0e-3
14	445.5e-3	4.198	300.0e-3	13.76e-3	99.99	180.0e-3
15	479.7e-3	4.198	300.0e-3	18.01e-3	99.99	180.0e-3
16	513.9e-3	4.198	300.0e-3	13.34e-3	99.99	180.0e-3
17	548.0e-3	4.198	300.0e-3	14.89e-3	99.99	180.0e-3
18	582.2e-3	4.198	300.0e-3	16.85e-3	99.99	180.0e-3
19	616.4e-3	4.198	300.0e-3	13.37e-3	99.99	180.0e-3
20	650.6e-3	4.198	300.0e-3	16.06e-3	99.99	180.0e-3
21	684.7e-3	4.198	300.0e-3	15.65e-3	99.99	180.0e-3
22	718.9e-3	4.198	300.0e-3	13.43e-3	99.99	180.0e-3
23	753.1e-3	4.198	300.0e-3	17.43e-3	99.99	180.0e-3
24	787.2e-3	4.198	300.0e-3	14.52e-3	99.99	180.0e-3
25	821.4e-3	4.198	300.0e-3	13.53e-3	99.99	180.0e-3
26	855.6e-3	4.198	300.0e-3	13.19e-3	99.99	180.0e-3
27	889.8e-3	4.198	300.0e-3	13.69e-3	99.99	180.0e-3
Min	0.0000	4.177	250.0e-3	40.43e-6	89.23	160.6e-3
Max	3.6299222e+3	4.198	300.0e-3	120.2e-3	99.99	180.0e-3
Mean	1.9722812e+3	4.184	258.0e-3	15.82e-3	91.45	164.6e-3
StdDev	1.0392535e+3	8.660e-3	14.19e-3	30.65e-3	3.321	5.978e-3
CV	52.69 %	210e-3 %	5.50 %	193.67 %	3.63 %	3.63 %

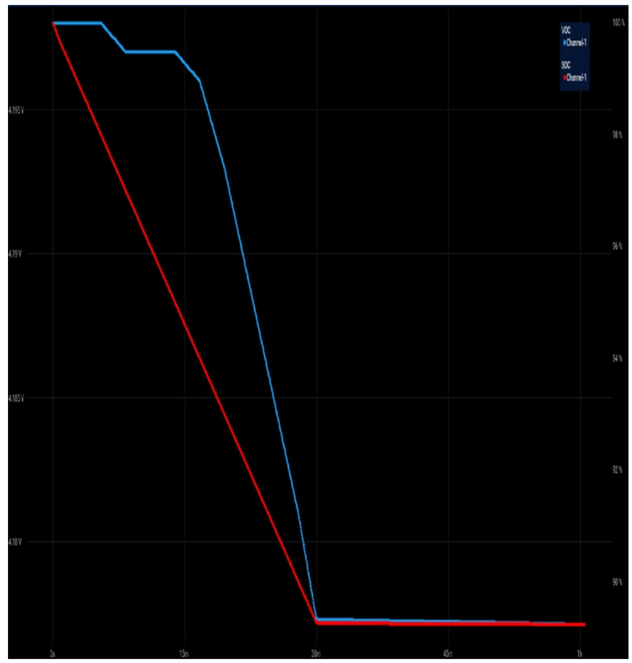


Figure 11: Room Temperature Exercise Mode Table/Graph

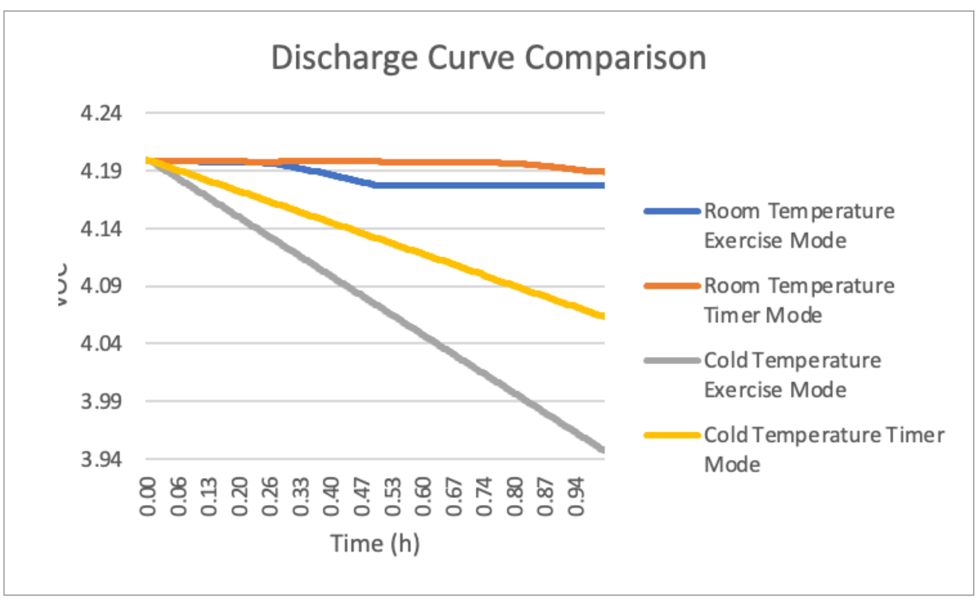


Figure 12: Discharge Comparisons

Figure 11 shows the changes in SOC and VOC as the battery discharges, as well as the table containing all the measurements taken over the simulation. **Figure 12** combines each discharge curve from every test into a single graph to compare battery life over the subsequent runs. From this, it can be seen that the battery discharges much faster at colder temperatures. Both the cold temperature exercise mode and cold temperature timer mode dropped to a lower voltage compared to the room temperature models in the same amount of time. After these simulations were performed and the data was collected, a test engineer could instantly "recharge" their model back to 100% or switch to a different model for further testing. For the purposes of this example, the power consumptions of two device operating modes were compared with two separate battery models. However, a test engineer may be interested in making improvements to a certain device behavior, rather than comparing between different modes. Battery simulation is perfect for this because they can restart the model after changes to the device design or software and know that the simulated battery behavior is the same for each test.

It should also be noted that although the KickStart Software, and the Battery Simulator App, does not directly output power consumed, it can easily be calculated using the formula:

$$\frac{\Delta Capacity \times Vnominal}{time}$$

To do so, just the starting capacity, capacity at the end of simulation, time of simulation, and nominal voltage are needed. Using the Room Temperature Exercise model as an example, the difference between the beginning and ending capacities of 180 mAh and 160 mAh, 20 mAh, is converted into mWh by multiplying by the nominal voltage of 3.7 V. This leads to a Wh capacitity of 74 mWh. With a simulation time of one hour this leads to 74 mW of power consumed:

$$\frac{(180 - 160) \times 3.7}{1} = 74\ mW$$

Conclusion

In conclusion, KickStart software's battery simulator app paired with the 2281S enables easy repetition of tests under various conditions and allows for a simple method to generate battery models for simulation. The simplicity afforded by a total software solution means that it is possible for anyone to set up and run tests quickly and efficiently – from students to technicians to design engineers.

Kickstart software provides a no code solution to generate battery models with a few simple mouse clicks and straight forward battery simulation tools. Simulation makes it easy to optimize battery life and overall performance without needing to test tens of dozens of batteries individually. Through battery simulation, tests are repeatable with consistent comparable performance, and with the power of software, data gathered during these tests can be saved, visualized, and analyzed all in one place on the PC.

For more information about the new KickStart Software Battery app visit: https://www.tek.com/en/products/keithley/keithley-control-software-bench-instruments/kickstart#

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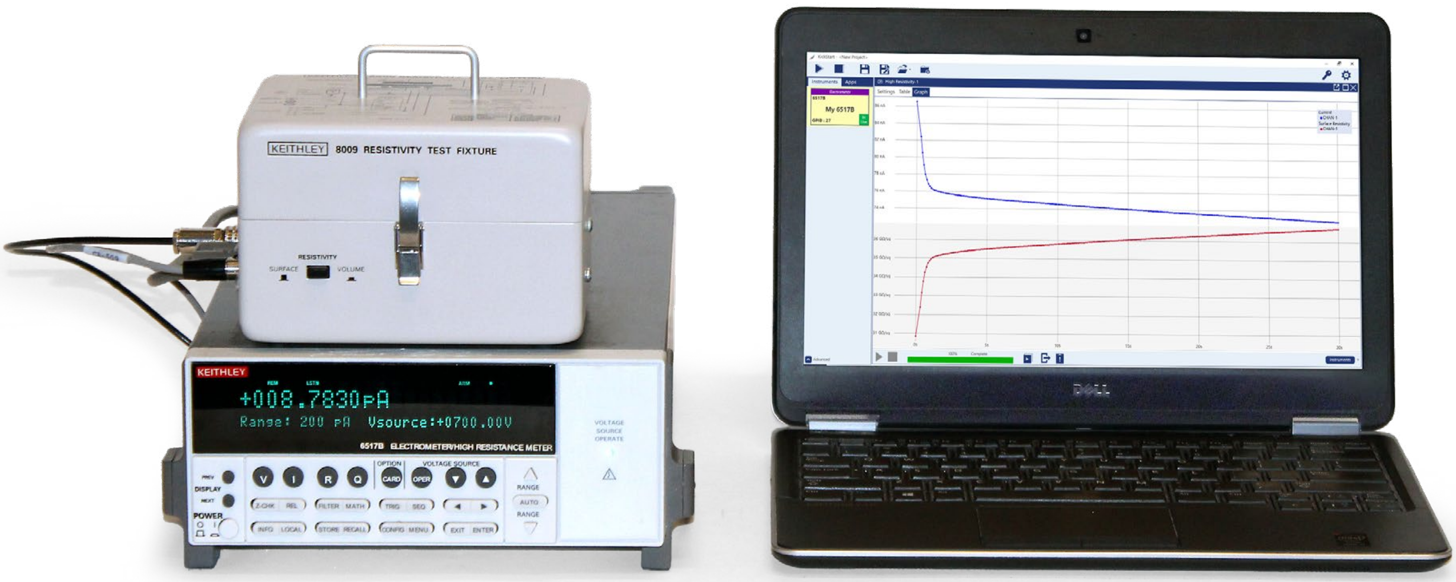
Measuring the Electrical Resistivity of Insulating Materials

APPLICATION NOTE



Introduction

Electrical resistivity is a basic material property and defines how well the material will conduct an electric current. Insulators are poor conductors of electrical current and typically have a high resistivity in the range of 10^9 to 10^{20} ohm-cm. The electrical resistivity of an insulator is determined by measuring resistance, then converting it to resistivity by taking geometric considerations into account.

The resistance of an insulating material is measured by applying a known potential to the sample and measuring the resulting current. Because the measured current is very low, usually in the nanoamp or picoamp range, an electrometer is often used. The Keithley 6517B Electrometer/High Resistance Meter is commonly used to make these measurements because of its ability to force voltage up to ±1000 V DC and measure very small current (<3 fA input bias current) and high resistances (up to 10^{18} Ω).

To account for the sample's geometry, electrodes with convenient dimensions should be used to make contact to the sample. The electrode configuration depends upon whether the volume or surface resistivity is measured. The Keithley 8009 Resistivity Test Fixture can be used for either volume or surface resistivity measurements on insulating materials.

This app note explains how to make volume and surface resistivity measurements of insulators using the 6517B Electrometer/High Resistance Meter, 8009 Resistivity Test Fixture, and the Kickstart High Resistivity Application that can be used to automate the measurements.

Standard Test Methods

The resistivity of a solid insulating material is usually measured by sourcing a known voltage for a specified time period and then measuring the resulting current. The resistivity is calculated using Ohm's law, the sample thickness, and the physical dimensions of the electrodes. The specific details of a test procedure including electrode configuration, sample preparation, electrification time, and other details are often described in standard test methods.

Two common standard resistivity test methods for insulating materials include ASTM D-257 "DC Resistance or Conductance of Insulating Materials" and the IEC 62631-1 "Dielectric and Resistive Properties of Solid Insulating Materials". These standards provide detailed information on calculations, sample preparation, correction factors and other measurement considerations.

The test configurations will vary depending on whether measuring the surface or volume resistivity of the sample.

Surface Resistivity

Surface Resistivity is defined as the electrical resistance of the surface of a material and is expressed in ohms or ohms/square. It is measured by placing two electrodes on the surface of the test sample, applying a potential difference between them, and measuring the resulting current.

A configuration for measuring surface resistivity using circular electrodes and the 6517B Electrometer is shown in **Figure 1**. In this example, the Hi terminal of the 6517B V-Source is connected to the Ring Electrode and the Hi terminal of the 6517B Electrometer is connected to the Guarded Electrode. The LO of the Electrometer is the Guard

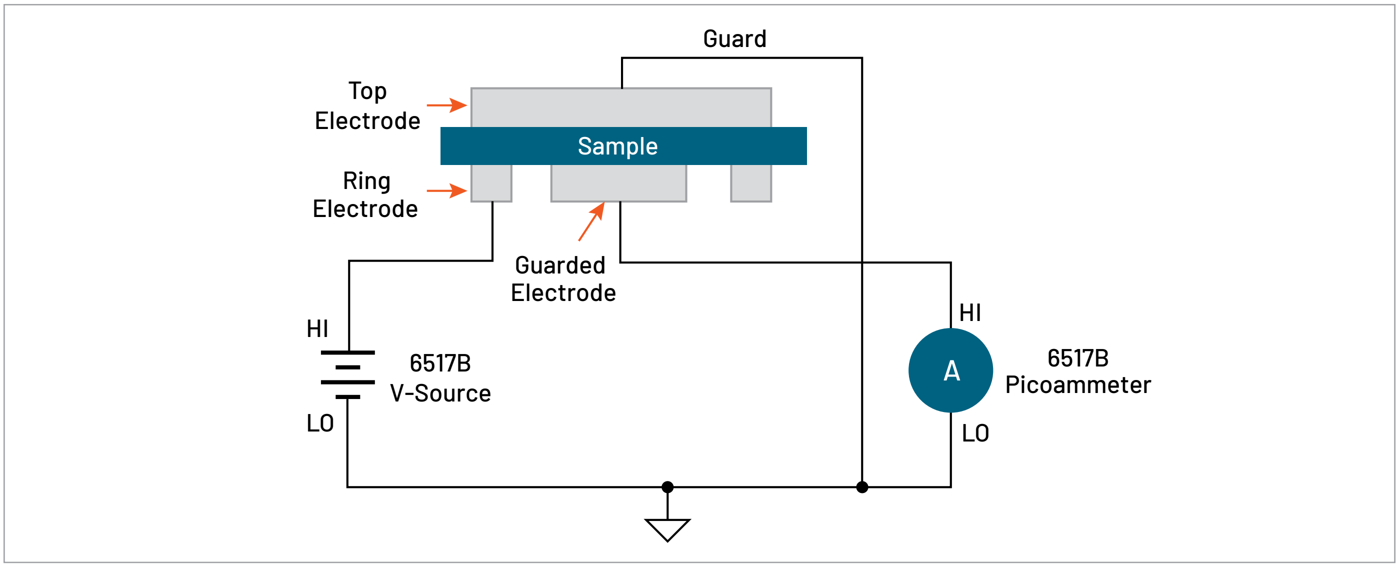


Figure 1. Surface resistivity test configuration using circular electrodes and the 6517B Electrometer

and is connected to the Top Electrode to prevent leakage current from flowing through the material. The 8009 Resistivity Test Fixture uses circular electrodes like the ones shown.

Using this test configuration and referring to the circular electrodes shown in **Figure 2**, the surface resistivity can be calculated as follows:

$$\sigma = K_s \frac{V}{I}$$

where:

σ = surface resistivity in Ω (or Ω/square)

K_s = geometric constant equivalent to P/g

P = the effective perimeter of the guarded electrode (cm) = πD_0

$D_0 = D_1 + g$

g = distance between the guarded electrode and the ring electrode (cm)

V = applied voltage (volts)

I = measured current (amps)

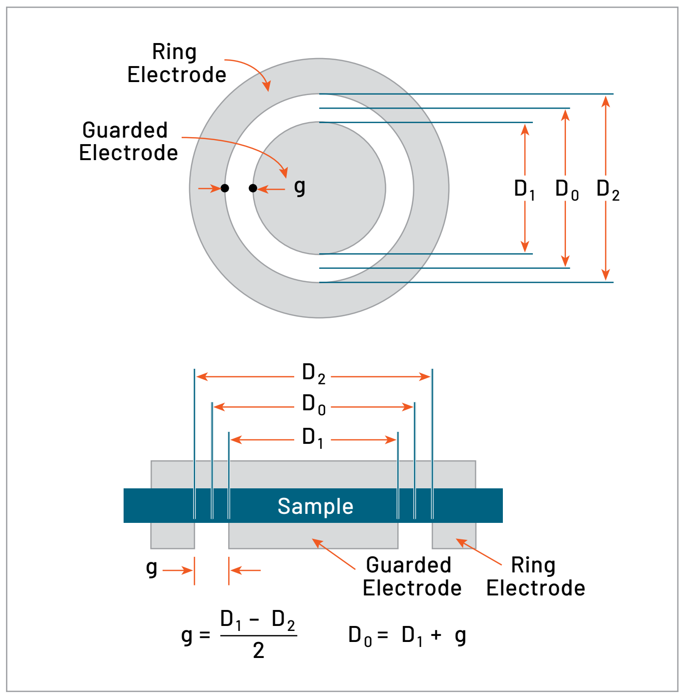


Figure 2. Circular electrode dimensions

If using the Keithley 8009 Resistivity Test Fixture, the diameter of the circular electrodes and gap are shown in inches as follows:

D1	2.000 in
D2	2.125 in
D3	2.250 in
g	0.125 in

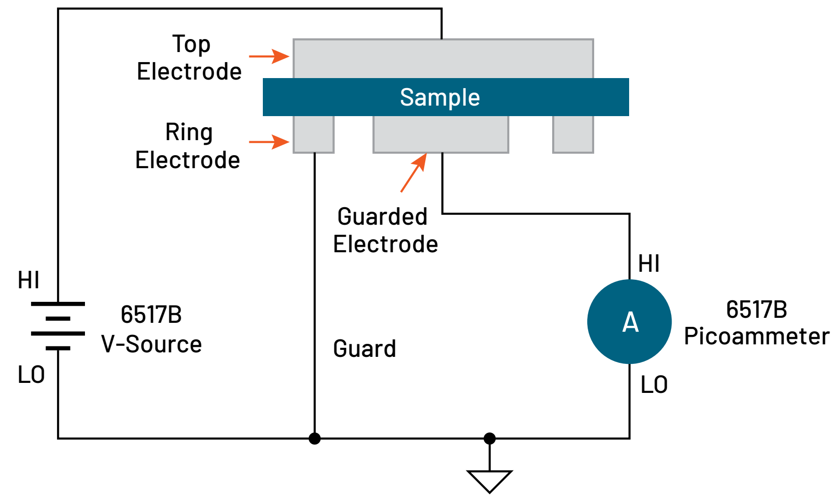


Figure 3. Volume resistivity test configuration using circular electrodes and the 6517B Electrometer

Volume Resistivity

The volume resistivity is a measurement of the leakage current directly through a material. It is defined as the electrical resistance of an insulating material and is expressed in ohm-cm. The volume resistivity is measured by placing the test sample between two electrodes, applying a potential difference between them, and measuring the resulting current using an electrometer, such as the 6517B Electrometer.

A configuration for measuring the volume resistivity of a sample using circular electrodes and the 6517B Electrometer is shown in **Figure 3**. In this example, the HI terminal of the 6517B V-Source is connected to the Top Electrode and the Hi terminal of the 6517B Electrometer is connected to the Guarded Electrode. The LO of the Electrometer is the Guard and is connected to the Ring Electrode to prevent leakage current from flowing between the Ring and Guarded Electrodes.

From this example the volume resistivity can be calculated as follows:

$$\rho = \frac{K_V}{t} \frac{V}{I}$$

Where:

ρ = volume resistivity (Ω-cm)

K_V = the effective area of the Guarded Electrode for a particular electrode arrangement

For circular electrodes, $K_V = \pi\left(\frac{D_1}{2} + \frac{g}{2}\right)^2$

D_1 = outside diameter of guarded electrode

g = distance between the guarded electrode and the ring electrode

t = average thickness of the sample (cm)

V = applied voltage (volts)

I = measured current (amps)

Test Parameters and Dependencies

Several factors can affect resistivity measurements of insulators including the applied voltage, electrification time, and environmental factors.

Resistivity measurements of insulators are a function of the applied voltage. Sometimes, the voltage is varied intentionally to determine an insulator's voltage dependency. Typically, the resistivity decreases as the voltage increases.

The resistivity of insulators also varies as a function of the electrification time. The longer the voltage is applied, the lower the measured current (and the higher the resistivity) becomes because the material continues to charge exponentially. Using an electrification time of 60 seconds is common. When comparing samples, it is always important to use the same electrification time.

Humidity greatly affects the results of surface resistivity measurements and, to a lesser degree, volume resistivity measurements. Moisture will cause the surface resistivity to be lower than normal.

To make accurate comparisons between specific tests, the applied voltage, electrification time, and environmental conditions should be kept constant from one test to the next.

Using the 6517B Electrometer and the 8009 Resistivity Test Fixture

Because of its ability to measure very low current, high resistance, and force up to ±1000 V DC, the 6517B Electrometer/High Resistance Meter is an ideal choice for measuring resistivity of insulating materials. The 6517B has built-in test sequences that enable the user to automatically set-up resistivity measurements and save the results in its internal buffer.

The 8009 Resistivity Test Fixture allows volume resistivity measurements up to 10^{18} Ω-cm or surface resistivity measurements up to 10^{17} Ω. The Keithley 8009 Resistivity Test Fixture contains an electrode configuration like the one shown previously in **Figure 2**. In this test fixture the circular electrodes are in a shielded box to minimize stray electrostatic pick-up, which can cause measurement errors. The electrodes are made of stainless steel and are built to ASTM standards and are compatible with the IEC standard.

The 8009 has conductive rubber electrodes that allow it to make better contact with rigid samples, such as epoxy or ceramics. Refer to the instruction manual for the 8009 for installing the insulator sample in the test fixture. If the 8009 is not suitable for a particular application, then the ASTM procedure also describes several other electrode configurations, depending on the size and shape of the specimen.

Connections between the 6517B and the 8009 are shown in **Figure 4**. To optimize low current measurements, the ammeter is connected to the test fixture using low noise triax cabling. All of the cables and adapters needed to make the measurements are included with the test fixture.

Built-In Test Sequences for Resistivity

The 6517B Electrometer includes several built-in test sequences including the Normal Resistivity Tests (based on standard test methods) and the Alternating Polarity Resistance/Resistivity Test. These test sequences can be used to simplify the front panel configuration of these

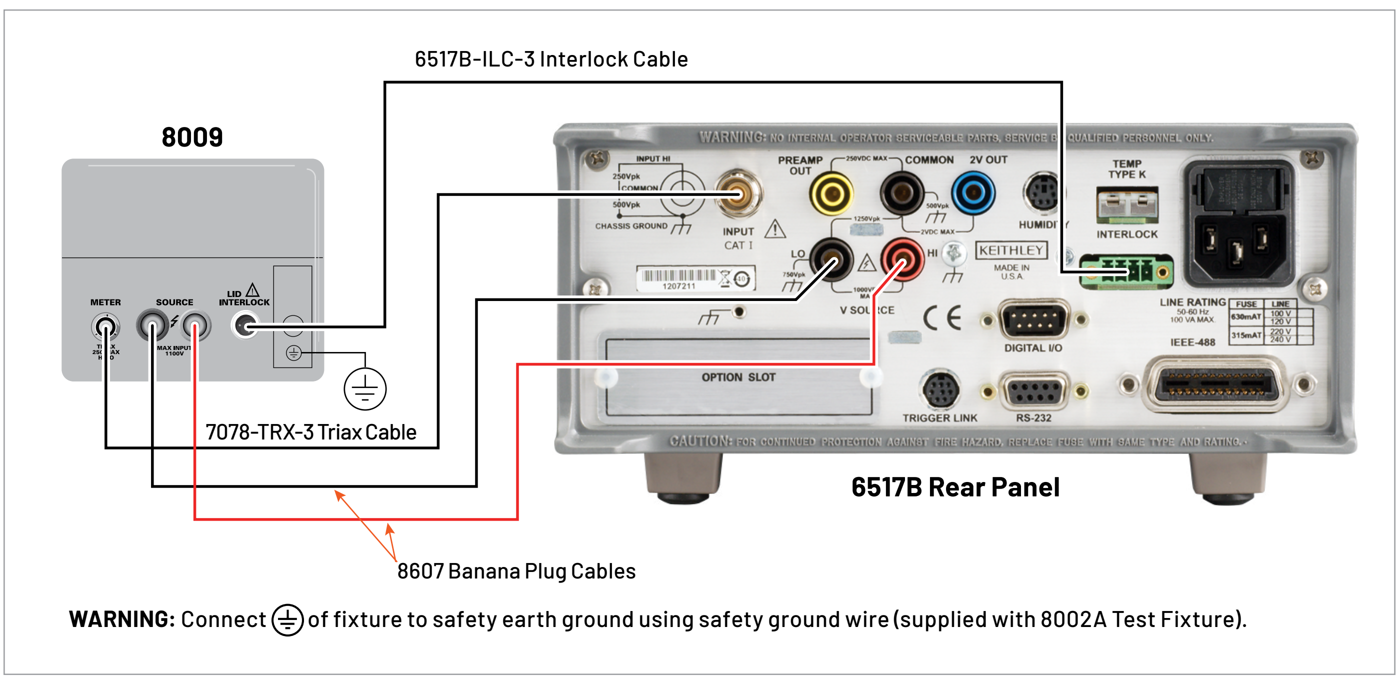


Figure 4. Connections from the 6517B Electrometer to the 8009 Resistivity Test Fixture

resistivity measurements. Below is an overview of these test methods. Please refer to the 6517B Reference Manual for instruction on using these test sequences.

Normal Resistivity Tests (Surface and Volume)

The normal resistivity tests for both volume and surface resistivity involve applying a voltage bias for a specified period of time (electrification time). At the end of the electrification time, the current is measured and resistivity is calculated using the formulas for surface and volume resistivity that are noted earlier in this document. The user can also choose to discharge the sample for a specified time period. When used with the 8009 Resistivity Test Fixture, the test conforms to the ASTM D-257 and IEC 62631-3-1 standards.

Alternating Polarity Resistance/Resistivity Test

The Alternating Polarity Resistance/Resistivity test sequence is designed to improve high resistance/resistivity measurements by eliminating the effects of background currents on the sample. Background currents may be due to charge stored in the material, static or triboelectric charge, or piezoelectric effects. If the background current is the same polarity as the measured current, the resultant measured current value will be much higher than the true value. If the background current is the opposite polarity, these unwanted currents could cause a reverse polarity current reading. That is, the current polarity is opposite the polarity of the applied voltage, so the calculated resistance will be negative. To counter these problems, the Alternating Polarity method can virtually eliminate the effects of the background currents on the sample.

The Alternating Polarity method applies a bias voltage of positive polarity, then the current is measured after a specified delay. Next, the polarity is reversed and the current is measured again, using the same delay. The resistance is calculated based on a weighted average of the most recent current measurements. The resistance value is then converted to a resistivity value if the meter has been configured for resistivity measurements. With this method, the user enters the test voltage, measurement time, and the number of iterations. **Figure 5** shows an example of the Alternating Polarity test showing the applied voltage and resulting sample current measured as a function of time from a typical high resistance sample.

KickStart High Resistivity Application

Keithley offers software to automate resistivity measurements using both the standard test methods and the alternating polarity method. The KickStart High Resistivity Application performs measurements of volume and surface resistivity of insulators according to ASTM D257 and IEC 62631-3-1 standards. This application is designed for use with Keithley's 6517B Electrometer/High Resistance Meter and the 8009 Resistivity Test Fixture. However, if the user does not have the 8009, they can enter in their own geometric constants based on their electrodes.

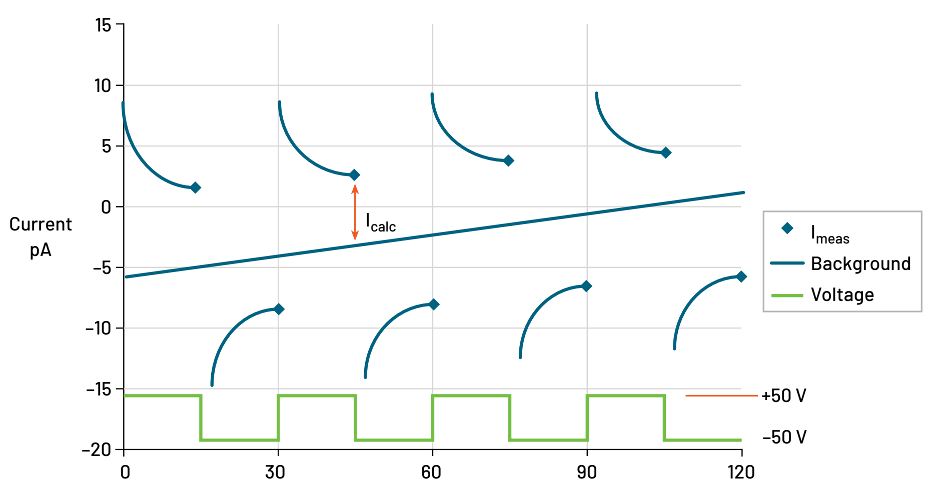


Figure 5. Alternating Polarity test sequence

Figure 6 is a screen capture of the Surface Resistivity simplified settings page. The user selects between the surface, volume or resistance measurement types. The measurement mode can be set to step response, normal, or alternating polarity. Other settable parameters include the test voltage, test time, number of readings, current range, and NPLC. Further information on the settings will be described in the following paragraphs.

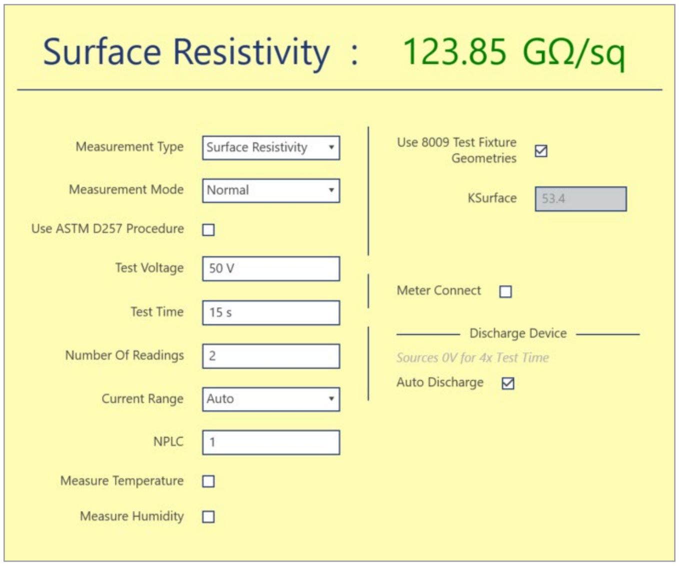


Figure 6. KickStart High Resistivity Application settings page

The KickStart High Resistivity application can be used to:

- Perform a voltage step response to determine an electrification time appropriate to the material's time constant. **Figure 7** is a screen capture from the KickStart software showing both the current and resistivity as a function of time due to a voltage step applied to an insulating material.
- Observe resistivity dependency on temperature and relative humidity using optional 6517-TP and 6517-RH probes.
- Use the alternating polarity technique to eliminate inherent background currents. **Figure 8** shows graphs of the alternating polarity technique from KickStart software. The top graph shows the current as a function of time and the bottom graph shows the surface resistivity.
- Perform normal resistivity measurements as a function of time (without alternating polarity) as shown in **Figure 9**. This normal method complies with ASTM D257 standard as well as IEC-62631-3-1 standards.

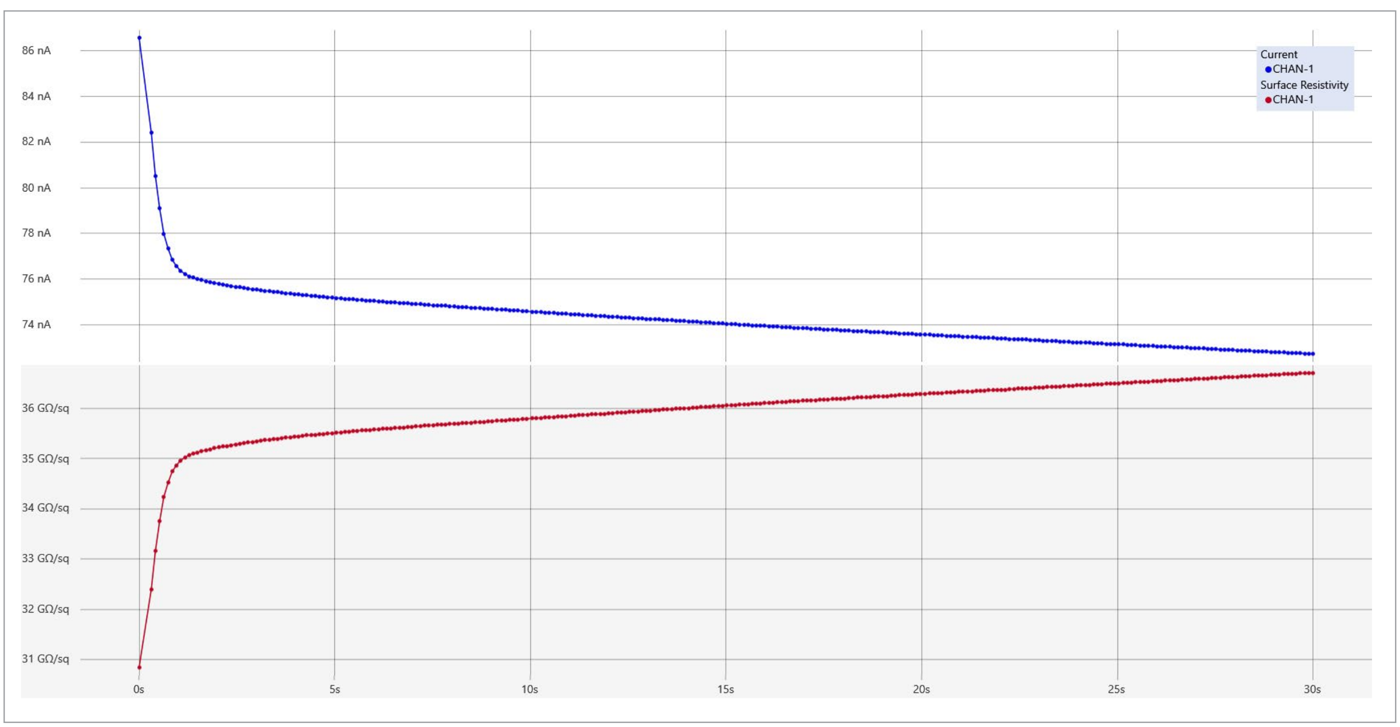


Figure 7. The step response test enables the user to determine the electrification time that will allow current measurements to settle for repeatable resistivity results..

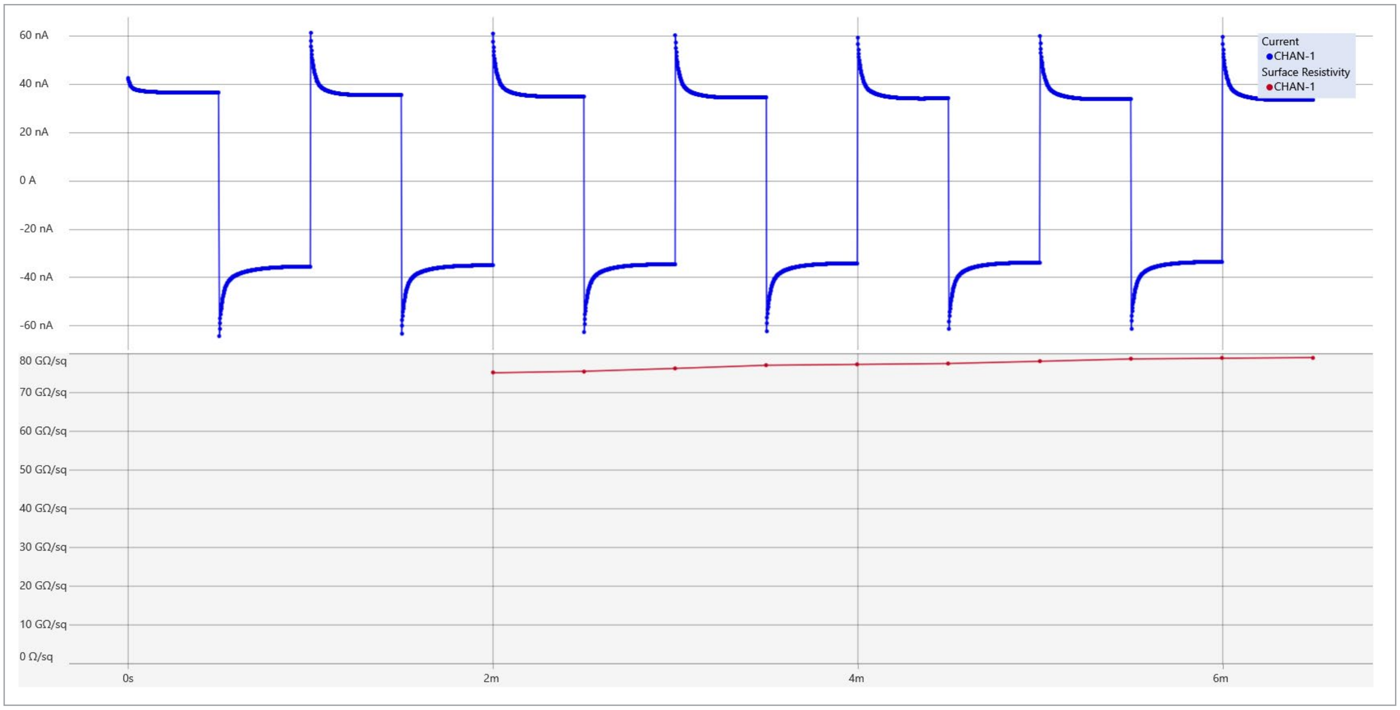


Figure 8. Alternating Polarity method test results displaying current and resistivity as a function of time

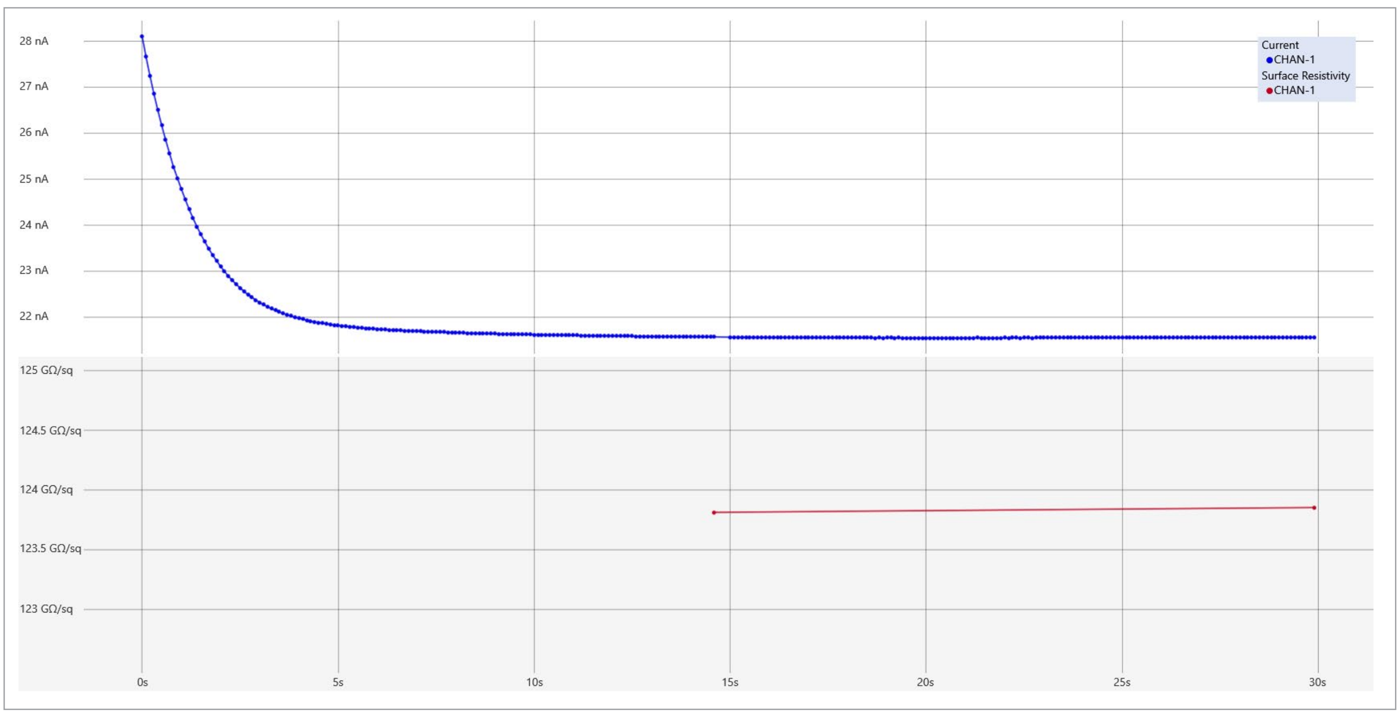


Figure 9. Current and surface resistivity measurements using the Normal (standard) test method

Additional Features of the KickStart High Resistivity Application:

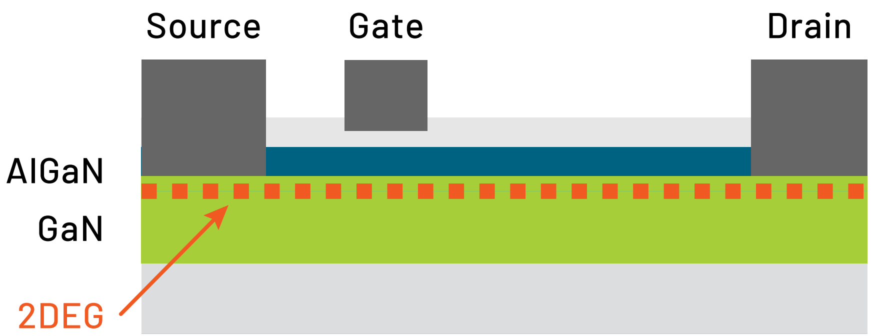
- Has an option to apply voltage and time settings from the ASTM D257 standard (note that voltage specified by IEC-62631-3-1 standard is different, but that user can configure that voltage setting within KickStart).
- Includes the ability to discharge samples after testing. Uses timing values recommended by ASTM D257 standard.
- Exposes 6517B's meter-connect function in the software to reduce number of external connections user needs to make.
- Returns real-time measurements while step response is executing.
- Consolidates graph data onto one screen for simplified viewing.
- Simplified tabular data display so that users can focus on final resistivity measurement value.
- Take advantage of many built-in KickStart 2.x features including:
  - Automatically saves all data to file and allows users to access in Run History
  - Allows users to easily compare measurements using Run History compare
  - Includes option to automatically export data to file

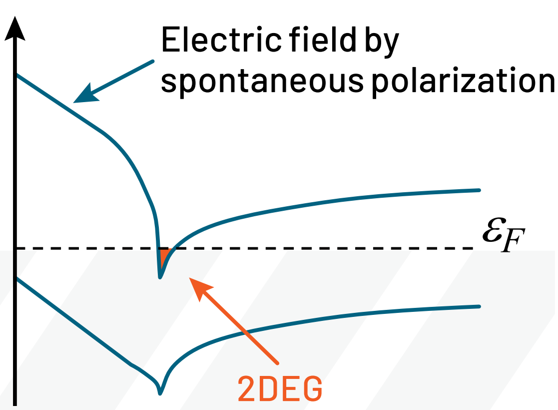
Download your free trial of the KickStart High Resistivity Application today at www.tek.com/keithley-kickstart.

Ordering information can be found at https://www.tek.com/keithley-kickstart.

Battery External Short Transport Safety Testing with the DMM6500, DAQ6510, and 2260B

APPLICATION NOTE





Introduction

The electric vehicle market is one of the largest drivers of the increase in demand for rechargeable batteries. These batteries must meet not only tight performance specifications with regard to capacity and lifespan, but also strict safety standards. Electric vehicles necessitate batteries with high energy density, meaning a failure can be catastrophic. These failures can occur at any point in a battery's useful lifespan, including during operation, storage and transport. Since battery demand is increasing globally, transport of batteries is unavoidable.

Transporting batteries can expose them to hazardous conditions that can trigger a failure. Battery manufacturers must take steps to ensure that a battery will not cause harm if damage occurs. These steps include rigorous testing like thermal explosion testing to ensure that a battery will fail safely. Using high quality test equipment like Keithley's DMM6500 digital multimeter, DAQ6510 data acquisition unit and 2260B Series power supply to perform such testing gives manufacturers confidence that their batteries meet all requirements.

Thermal Runaway

Rechargeable lithium-ion batteries are sensitive to changes in temperature. During normal charging and discharging, heat is generated due to internal resistances and the chemical reaction inside the battery. If the temperature of the battery increases enough, the chemical reaction occurs faster. The battery is internally shorted and the increase in current leads to additional heat generation, which creates the cycle of thermal runaway. This continues until the battery is at risk of rupturing, fire or explosion.

Batteries with defects such as higher internal resistance or flaws in their materials and aged batteries are more susceptible to failures. In addition to this, failures such as a fire in one battery can quickly affect nearby batteries. It is critical to prevent a failure such as a rupture or fire from occurring in the first place, so damage is not compounded.

Uncontrolled discharge, or shorting the battery, is one-way thermal runaway can occur. The discharge current can rapidly increase without restriction, generating heat and putting the battery at risk of failure. Transporting batteries puts them at increased risk of unintentional shorting. The short could occur from physical movement or from outside components like shipping containers and contaminants coming in contact with battery terminals. In addition, transportation can expose batteries to heightened temperatures, increasing the risk of thermal runaway.

While it's important to prevent these events from occurring, they do happen, and a battery should be capable of being shorted for a short period of time without catastrophic failure. Standards like "The UN Manual of Tests and Criteria" extensively lay out regulations and criteria for transporting materials that may be hazardous, such as batteries. One test, UN38.3.4.5 tests batteries for behavior regarding an accidental short circuit.

Testing for External Short Transport Safety

The UN38.3.4.5 test for external short circuits requires that batteries are heated to approximately 57 ± 4 °C before beginning the test. The battery is then shorted with less than 100mΩ and the battery is allowed to heat and cool. The short is removed after battery has returned the starting temperature and remained there for at least one hour. For larger battery packs, the temperature can remain below half of the maximum temperature increase observed. A battery passes the test if the overall temperature stays below 170 °C and the battery does not rupture, catch fire or explode during or within six hours of the battery being disconnected after shorting.

Depending on the size and construction of the battery, this test may call for several temperature measurement points. The temperature is to be measured on the external shell of the battery. For a prismatic or pouch cell, transducers such as thermocouples can be placed on each side of the battery to detect any hot spots that may be early indicators of failure. The temperature also must be monitored for over seven hours during the test, so an automated solution that doesn't collect too much data is desirable.

A multichannel solution like a datalogger is ideal for this type of testing. Multiple temperature measurements can be made with a single instrument using a multiplexing scan card. The datalogger can then be programmed to scan and measure each channel in a defined scan interval. An adjustable scan interval allows enough data to be recorded to observe behavior, but not more than is necessary, as measuring over days and weeks can present challenges in data management.

It may also be useful to monitor the battery's voltage during the test. Depending on the requirements for that, this measurement could be a dedicated channel of the datalogger. A separate digital multimeter (DMM) could also be used for continuous monitoring during testing.

The final component needed is a means to heat the battery prior to testing. This could be done using an environmental chamber, though in the event of a failure, damage can occur to the chamber. The shorting test is also intended to be conducted in ambient room temperature, with the battery at the set temperature. Therefore, an external heater can be used to heat the battery, with a DC power supply to power the heater.

The full test setup is shown in **Figure 1**.

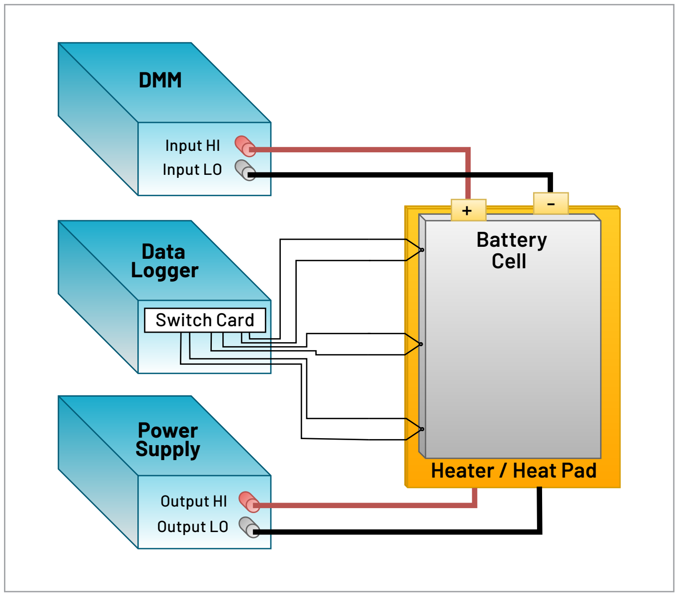


Figure 1: External Short Testing.

The Keithley Solution

Keithley's portfolio covers the entire external short transport safety test. The DAQ6510 Datalogger is an ideal solution for multiple temperature point testing. The DAQ6510 is capable of monitoring both the temperature and the battery voltage, but for true parallel voltage and temperature monitoring, a separate DMM is required to monitor voltage. The DMM6500 has the same performance as the DAQ6510 for voltage measurements. Finally, the 2260B Series DC power supplies provide a simple solution with a variety of power levels to control the heat source for the battery. Information about each of these products is shown in **Figure 2**.

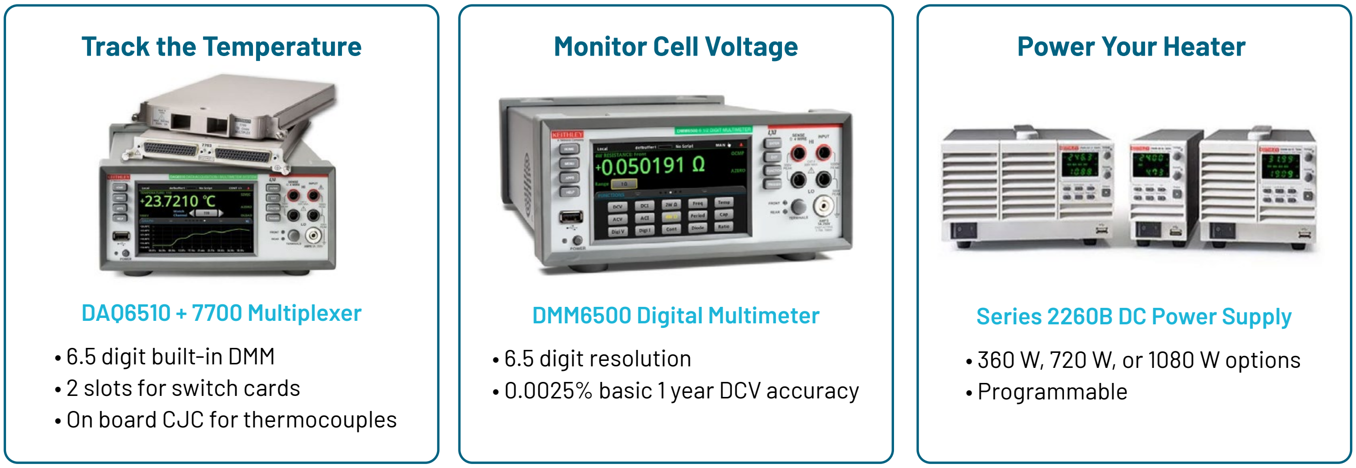


Figure 2: Keithley Solution for UN 38.3.4.5 External Short Circuit Testing.

Test automation saves time to configure, run and get results from the test. Both the DAQ6510 and DMM6500 are equipped with Test Script Processing (TSP). TSP is a Lua based language that can be executed directly on the instruments, as well as sent from the PC. TSP enables the user to add features such as limits testing. For example, the DAQ6510 can monitor the temperature of the battery while it heats and then switch off the power supply to the heater when the desired temperature is reached, through a communication method called TSP-Net. The DAQ6510 also has pass-fail limits built in, so the instrument can mark data and alert the user when the temperature has exceeded 170 °C.

For GUI-based PC automation, Keithley offers Kickstart software. Kickstart makes it simple to configure scans with the Datalogger App, monitor the voltage with the DMM App and control the power supply with the Power Supply App, without the need to write code. Kickstart also has built in table and graph tools to view data collected in real time. The Kickstart configuration view is shown in **Figure 3**.

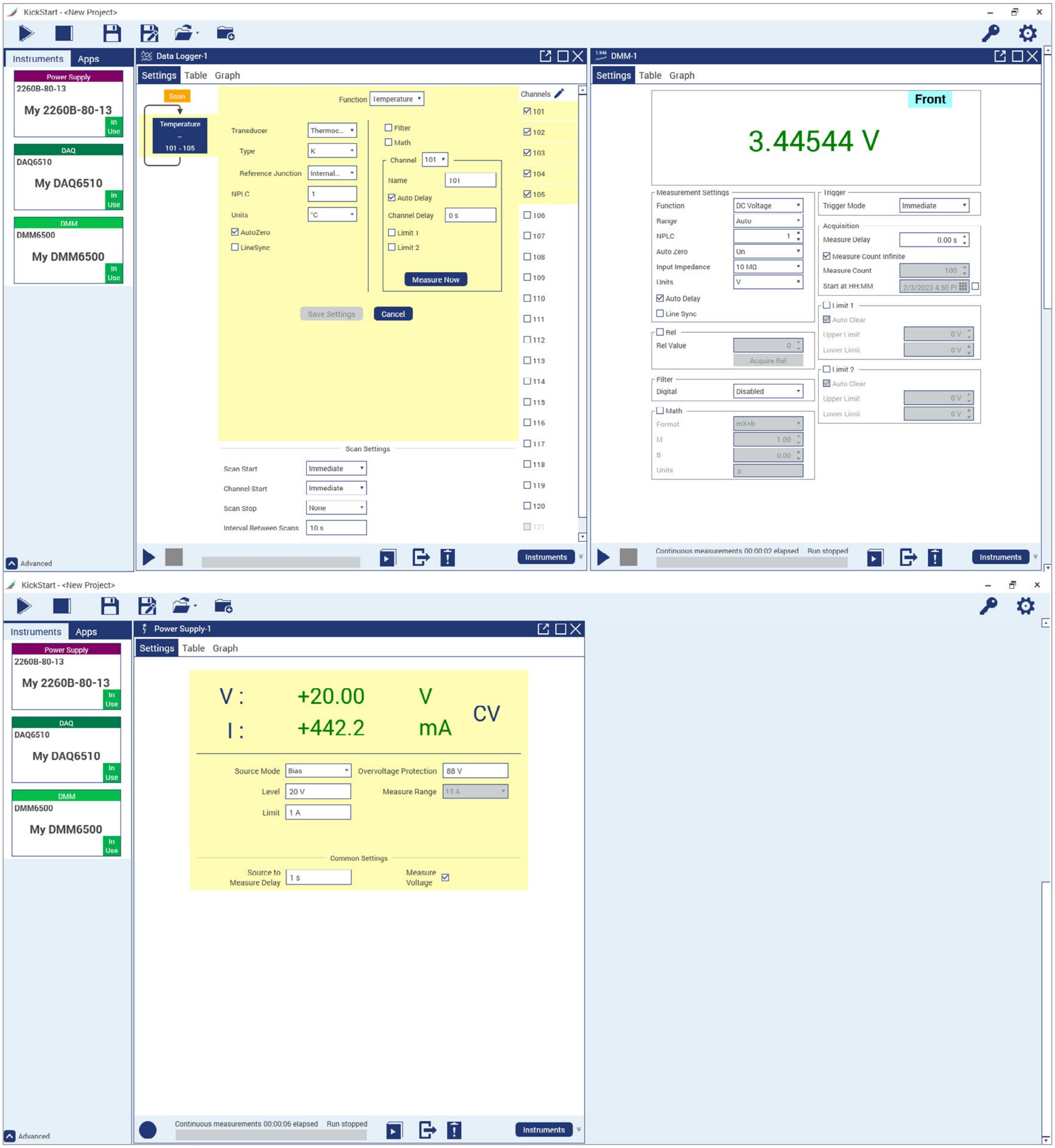


Figure 3: Configuring the External Short Test in Kickstart.

Conclusion

Global push to sustainable transportation means we will be shipping increasing numbers of rechargeable batteries. Manufacturers must be able to guarantee that their batteries are compliant with transport regulations like the "The UN Manual of Tests and Criteria" because batteries contain hazardous material and have the potential for extreme failure. Keithley Instruments provides high quality test solutions like the DAQ6510 data logger, DMM6500 digital multimeter and 2260B Series power supply to ensure batteries meet all requirements.

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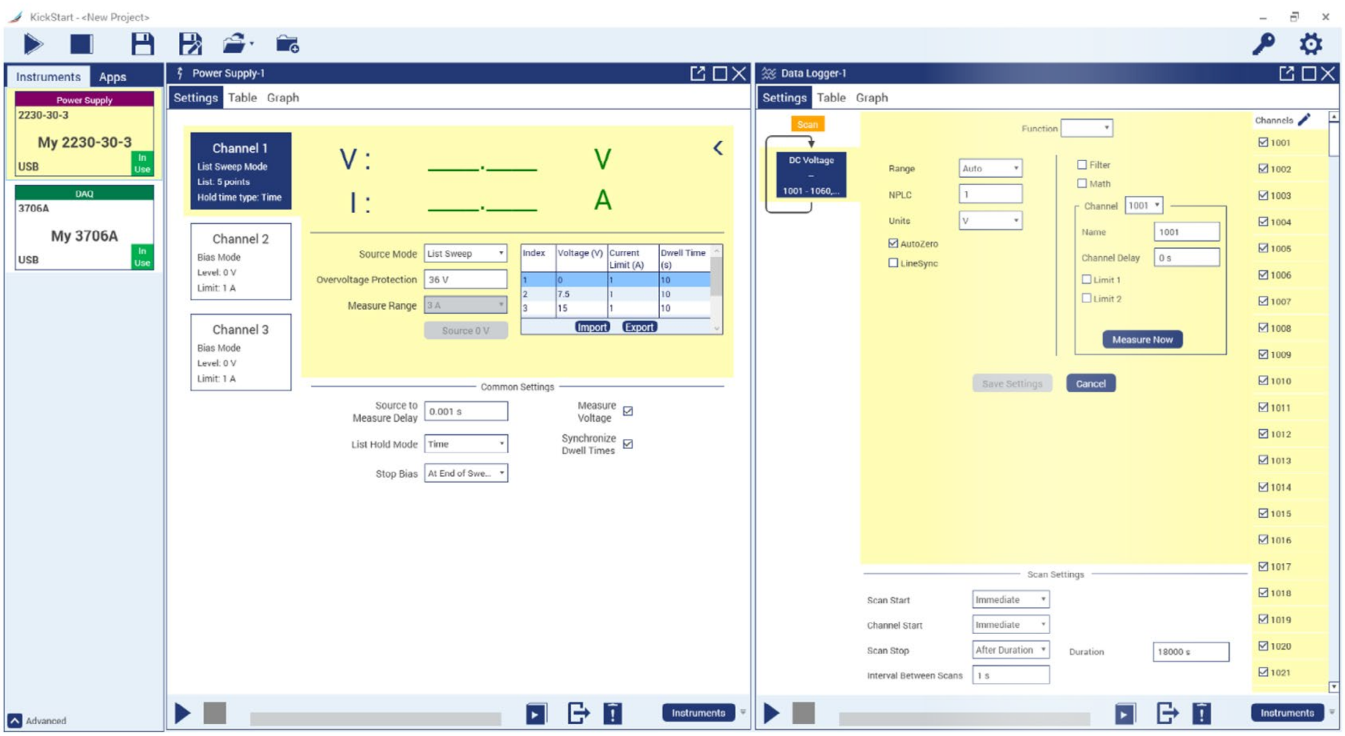
Wide Bandgap Device Reliability Testing with Keithley's KickStart Software

APPLICATION NOTE



Introduction

Wide bandgap (WBG) semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) are overtaking standard silicon devices thanks to their high-power efficiency, operation at higher switching frequencies, and promise of far lower leakage. Their increased performance makes them ideal for high energy applications where efficiency is crucial, such as drive systems for electric vehicles (EVs) or charging stations used to rejuvenate EV batteries. As wide bandgap semiconductors penetrate more applications, ensuring their long-term reliability is an important step in the device design process. Testing early in the device design is critical to identifying problem spots before the devices are packaged or make their way into a production environment. Along with high quality test equipment such as DC power supplies, data acquisition units, source measure units (SMUs), and digital multimeters (DMMs), engineers can expedite their device analysis using powerful software tools that save time in test automation and data collection. One such software package is Keithley's KickStart Software that controls a wide assortment of the aforementioned equipment and helps ensure that you can get the best results faster.

Wide Bandgap Reliability Testing

One of the main goals for these new devices is to have a longer lifespan than their predecessors while being subjected to as much as ten times the operating voltage as their predecessors, likely in high temperature environments. Reliability testing is a must to ensure that the devices are robust and dependable in their end applications.

Typical reliability tests involve stressing a batch of sample devices for hundreds or thousands of hours with bias voltages that are greater than or equal to their normal operating voltages while subjecting them to temperatures that are well beyond normal operating conditions. During this stress, a variety of key operating parameters are measured at specific time intervals. Changes in device performance may indicate a defect in the part, allowing it to be pulled for failure analysis before it gets to the end user. For more information on reliability testing see our application note Optimizing Reliability Testing of Power Semiconductor Devices and Modules with Keithley SMU Instruments and Switch Systems.

Testing Solutions

When considering a test and measurement solution for reliability testing, a few factors are important. There are two parts to a reliability testing solution: the instrument powering the device and the instrument measuring the device. A multi-channel, programmable power supply can be used to power and stress the device. The channels of the power supply can be routed together in series or parallel to increase the voltage or current output of the supply. Programmable power supplies that have sweeping functionality allow you to customize the stressing routine to fit your testing needs. Batches of devices can be connected in parallel to a single supply to increase test density as shown in **Figure 1**.

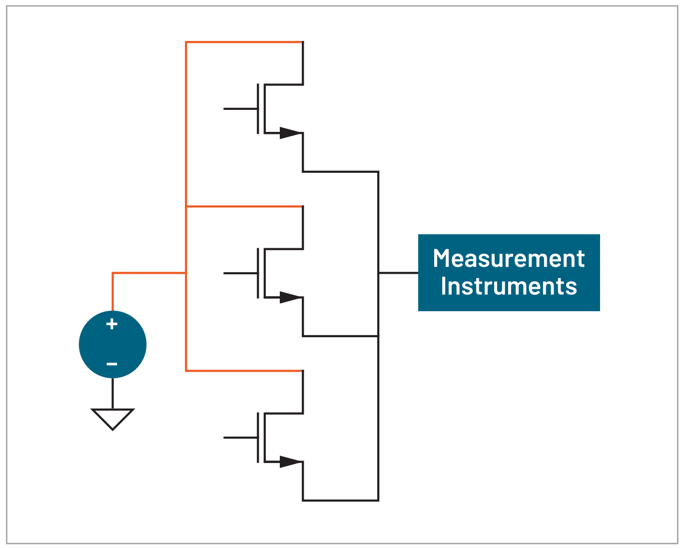


Figure 1: Parallel devices connected to a power supply.

On the measurement side, a DMM provides options to choose the level of accuracy and resolution that you need with either a 6½-digit or 7½-digit meter. DMMs can also have switching capabilities, increasing the number of devices that can be tested at a given time and decreasing overall test time. Some switch cards may be limited to voltage measurements, but current can still be measured by connecting a known value resistor in series with the device and measuring the voltage across the resistor. This configuration is shown in **Figure 2**. Multi-channel DMMs are great tools to monitor temperature, as well, during temperature-controlled tests.

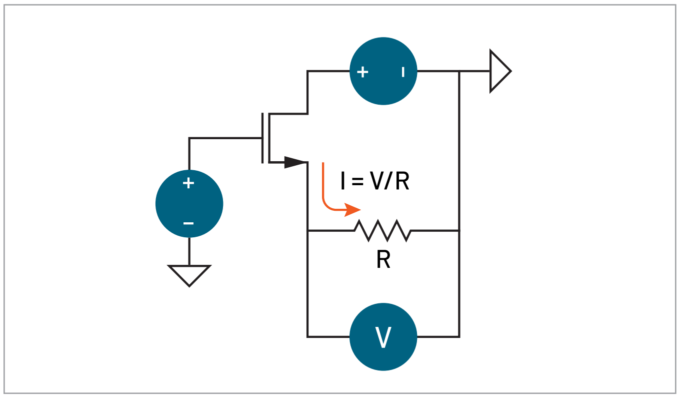


Figure 2: Current measurement using series resistance.

For applications where the device needs to be fully characterized within the stressing routine, an SMU may be the best option, as it provides the ability to accurately source voltage or current and measure voltage and current simultaneously. Like power supplies, SMUs may offer multiple channels, helping to provide a full device characterization solution for two- and three-terminal devices.

Software that controls the whole solution can ease integration and setup by automating the process. The software should be able to collect data for extended periods of time, ensuring you can view trends in the devices.

The Keithley Solution

Keithley Instruments provides high quality testing solutions that are optimal for wide bandgap reliability testing. **Figure 3** shows a selection of models to power, monitor, and characterize your device. The 2230 Series DC Power Supply has several models including the 2230-60-3 for higher voltage and the 2230-30-6 for higher current. Keithley also offers the DAQ6510, a 2-slot system with a 6½-digit DMM for monitoring and the 2657A SMU for characterization testing requiring more than 1100 V.

Power The Device

2230 DC Power Supply

- 2230-30-6: 2 channels of 30 V, 6 A and 1 channel of 5 V, 3 A
- 2230-60-3: 2 channels of 60 V, 3 A and 1 channel of 5 V, 3 A
- Programmable
- Combine channels in parallel or series
- mV resolution

Monitor The Device

3706A System Switch/Multimeter

- 7.5 digit digital multimeter
- 6 slots for switch cards
- 14 switch card options
- Up to 576 2 wire channels per mainframe

Characterize The Device

2470 Graphical High Voltage SMU

- 1100 V / 1 ADC 20 Wmax
- Source and sink operation
- 10 fA measure resolution
- 5 inch touch screen GUI

Figure 3: Keithley solutions for wide bandgap semiconductor testing.

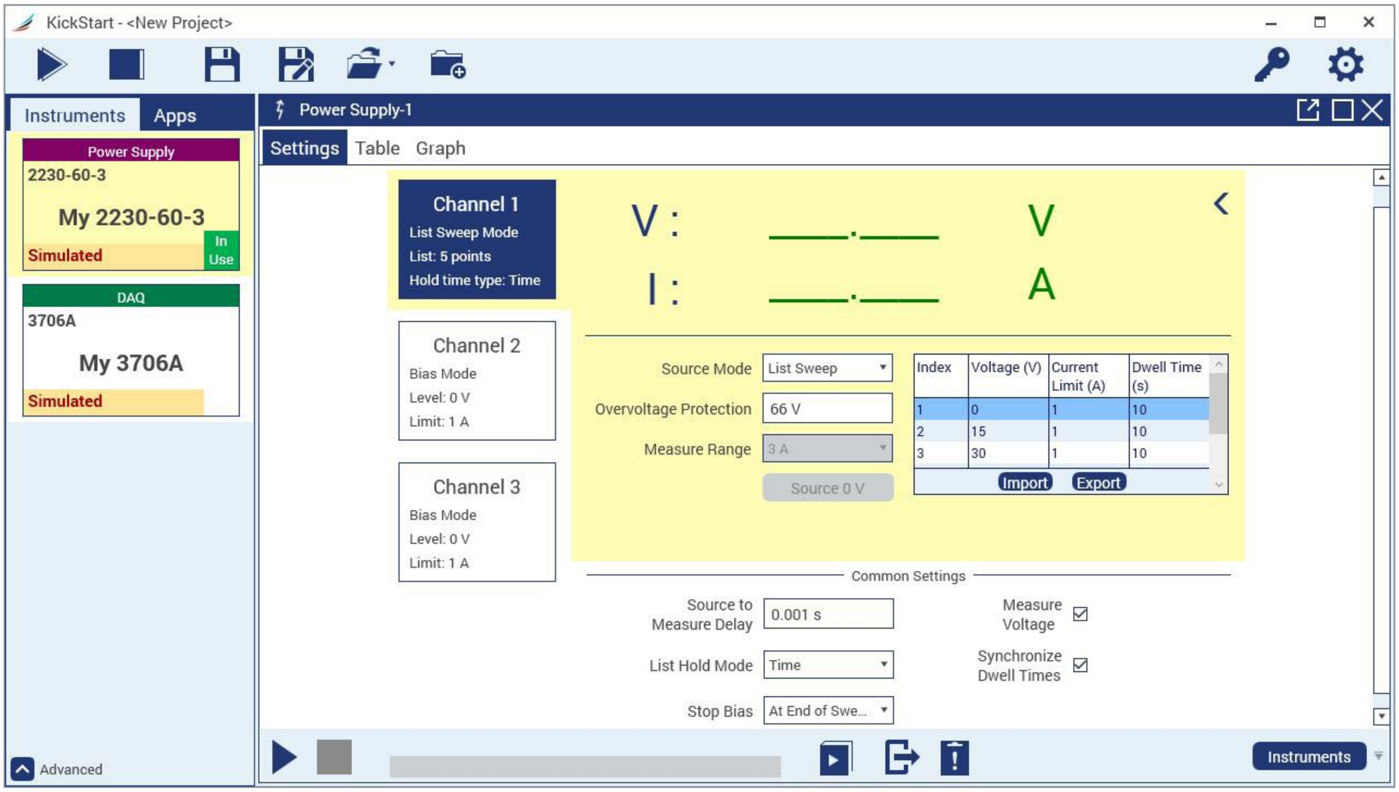


Figure 4: Configuring the 2230-60-3 DC Power Supply using the Power Supply App in KickStart Software.

Keithley's KickStart Software ties the whole solution together, with intuitive controls and long-term data collection. KickStart Software can control up to eight instruments at a time, allowing you to do more with one PC. The Power Supply App, shown in **Figure 4**, can configure each of the power supply channels individually. You can output a constant bias voltage for stressing or customize the output sequence using the list sweep function. The sweep points can be defined directly in KickStart Software or by importing a ready-made CSV file. The time for each point in the sweep is controlled by the list hold time setting. Setting this to Points sets up a number of measurements to take per step in the sweep. Changing this setting to Time allows you to set a custom dwell time in seconds for each step, truly customizing the stress sequence applied to the device.

At the same time, the 3706A System Switch/Multimeter can be configured to monitor the device behavior during stressing. KickStart Software's Data Logger App allows you to configure a scan to make voltage measurements on the desired channels as shown in **Figure 5**.

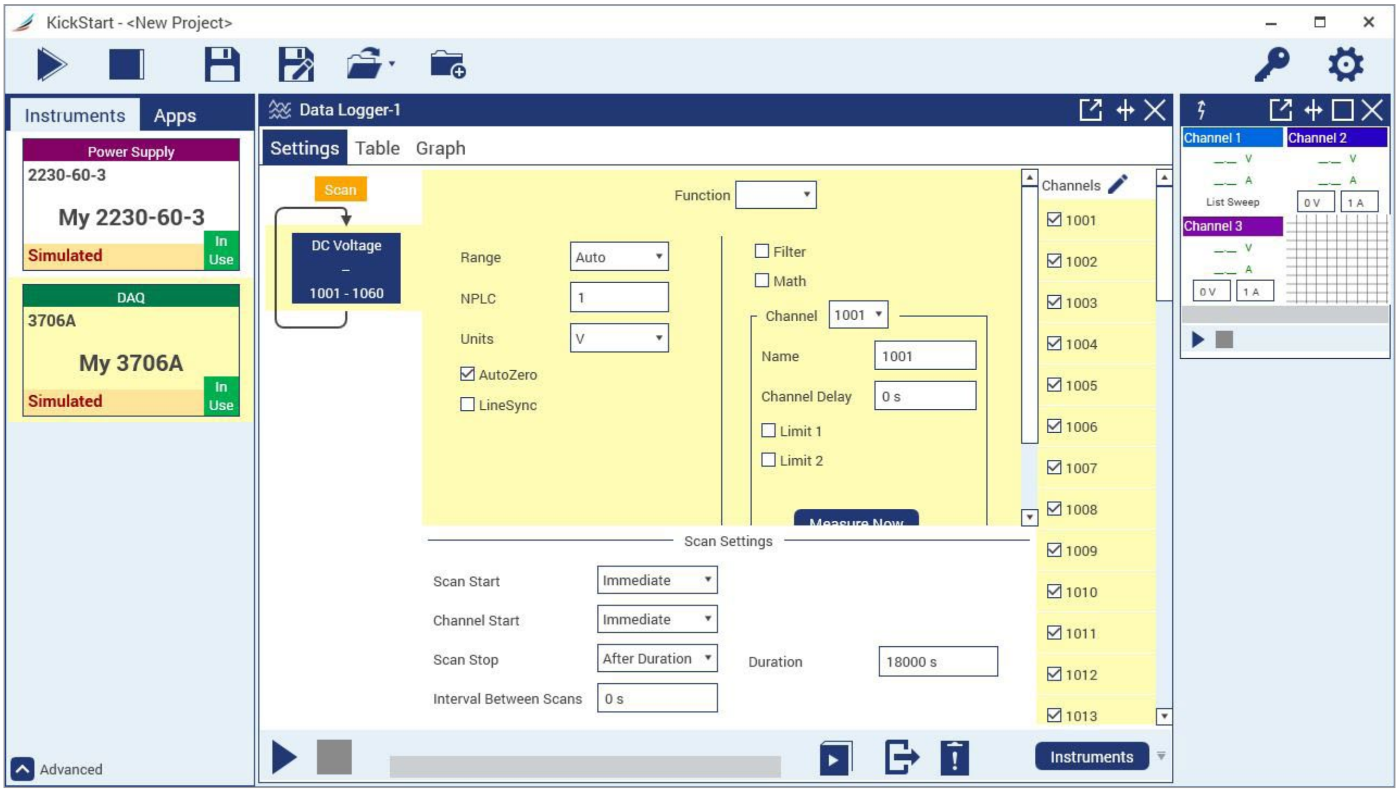


Figure 5: Configuring the 3706A System Switch / Multimeter using the Data Logger App in KickStart Software.

Reliability testing is conducted over a long period of time, and KickStart Software makes it easy to select whether to end the test after a certain number of scans have been completed or after a time duration, by using the Scan Stop setting. The interval between scans can be set to ensure the right amount of data is captured.

The I-V Characterizer App is perfect for configuring the SMU for characterization. For more information on using KickStart Software to characterize these devices, see our application note, Breakdown and Leakage Current Measurements on High Voltage Semiconductor Devices Using the Keithley 2470 SourceMeter® Source Measure Unit (SMU) Instrument and KickStart Software.

Once the stressing configuration is set up, all apps can be started at the same time by using the Run All button at the top of the KickStart Software screen. Alternatively, each app can be run individually by using the run button at the bottom of the app screen. While the tests are running, the data is returned to the built-in graph and table in real time, so you can observe trends in the data as they occur.

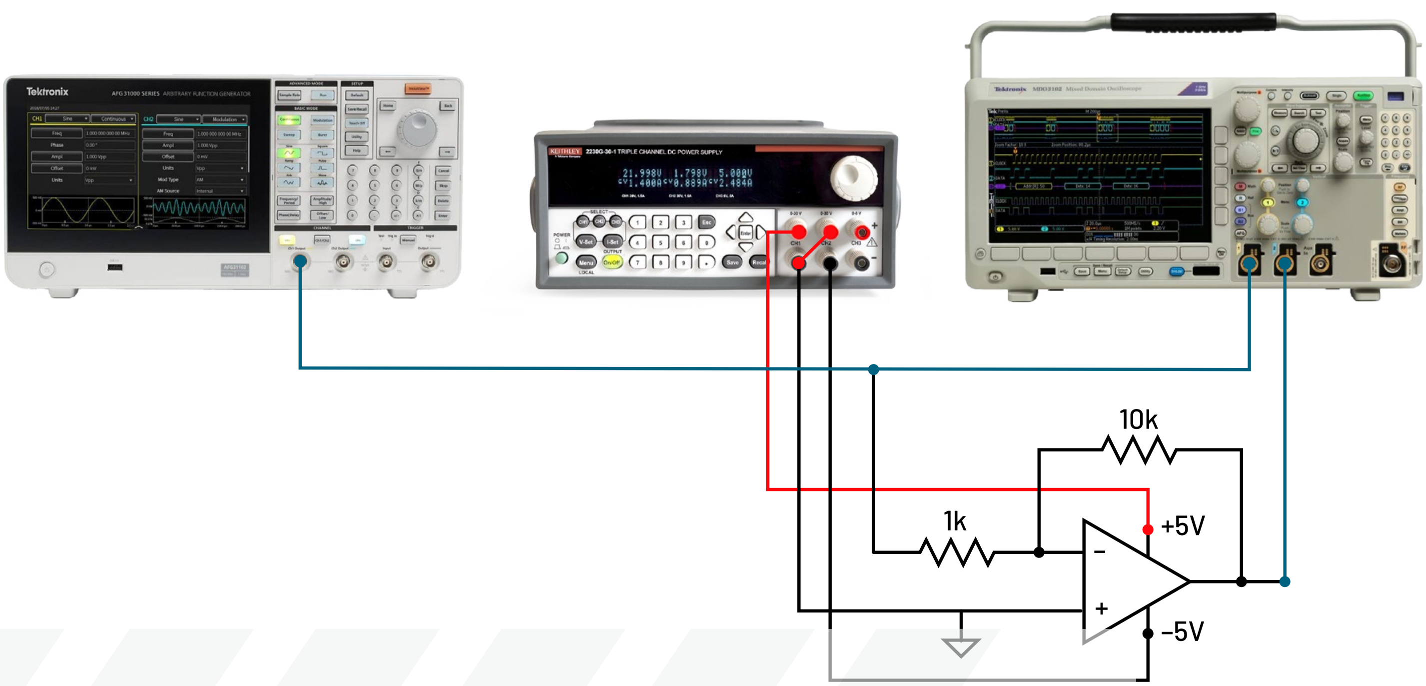
Conclusion

Reliability testing is an important part of the design process for wide bandgap semiconductors. Using Keithley's Kickstart Software to control your power supply, multi-channel DMM, or SMU means you can spend less time writing code and configuring your setup, and more time getting results.

Tektronix®

Analyzing Frequency Response Using the AFG31000, MDO3000, and Kickstart Software

APPLICATION NOTE



Introduction

Filter and amplifier circuits can be found in every corner of modern-day life. The speakers in our cars, the AC/DC converters on our device chargers, and the headphones we use to work remotely all utilize filters and amplifier circuits. These types of circuits are so common that studying standard configurations is required in electronics education labs. Analyzing the frequency response of these circuits is one of the most useful tools for characterizing their performance. Keithley's Kickstart Software makes using the AFG31000 Arbitrary Function Generator and MSO5 Oscilloscope to measure frequency response simple.

Measuring Frequency Response

The goal of an amplifier or a filter is to be effective at a known range of frequencies. We may want an amplifier to only amplify low frequency signals, or a filter to remove only high frequency signals. To understand the behavior of the circuit, we can measure the frequency response. The frequency response of a circuit is a characterization of how the output of the circuit behaves when varying input signals are applied. The easiest way to accomplish this is to use an arbitrary function generator (AFG) to generate the input signals and an oscilloscope to measure and compare the input and output. It is necessary to apply a wide range of input signals, so an AFG that has a built-in sweeping mode is useful. Sweep mode automatically changes the frequency of the output signal, so hundreds or thousands of measurements can be taken without manually changing the frequency.

The results of the frequency analysis usually compare the amplitude change and the phase change of the signal from input to output with respect to the frequency. A common way of displaying the results is in a Bode plot. The frequency is plotted in log scale on the x-axis to account for the wide range of frequencies and the amplitude or magnitude is plotted on the y-axis in decibels using the following formula:

$$A_{dB} = 20 \log \frac{V_{out}}{V_{in}}$$

The phase can be represented in degrees on the y-axis for the phase plot.

Frequency Response of an Amplifier in Kickstart

The frequency response of an inverting amplifier such as the one shown in **Figure 1**, can be measured using Kickstart.

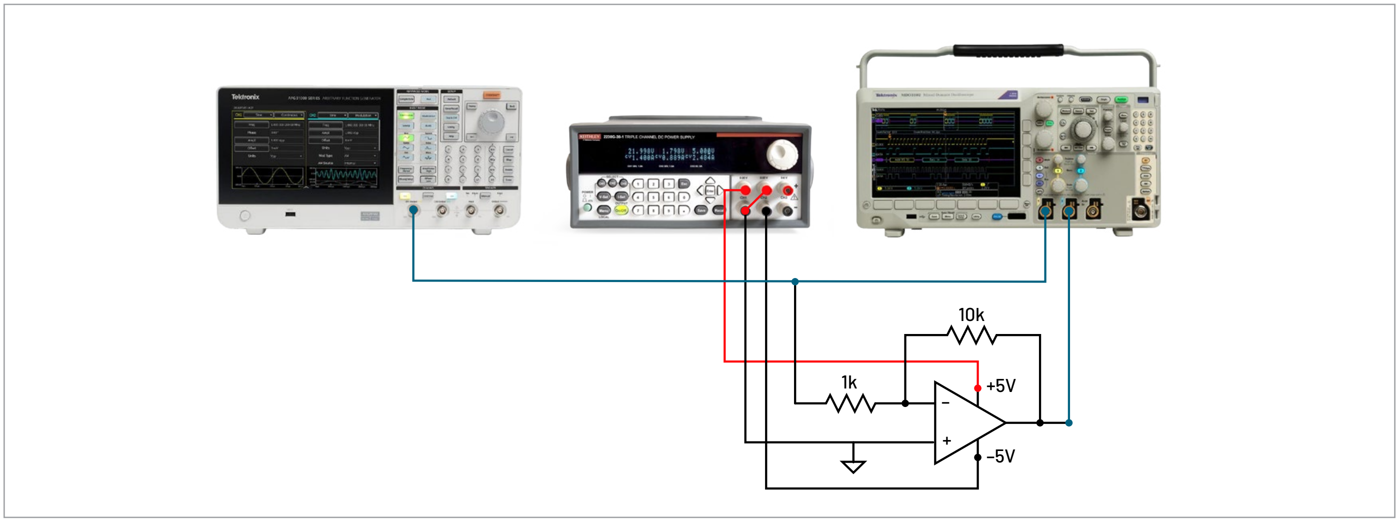


Figure 1: Inverting amplifier circuit.

Starting with Version 2.8.0, Kickstart allows you to configure the power supply and the AFG and collect measurements from the scope. For this example, a Keithley 2230G-30-1 Power Supply was used to provide ±5 V to the op amp and a Tektronix AFG31251 was used to provide the input signal. A Tektronix MDO3104 was used to measure both the input and output signals for comparison. All three instruments were connected to the controlling PC using USB cables.

Begin by opening the Power Supply App to configure the power supply to output 5 V on channels 1 and 2 as shown in **Figure 2**. Channel 3 can be disabled.

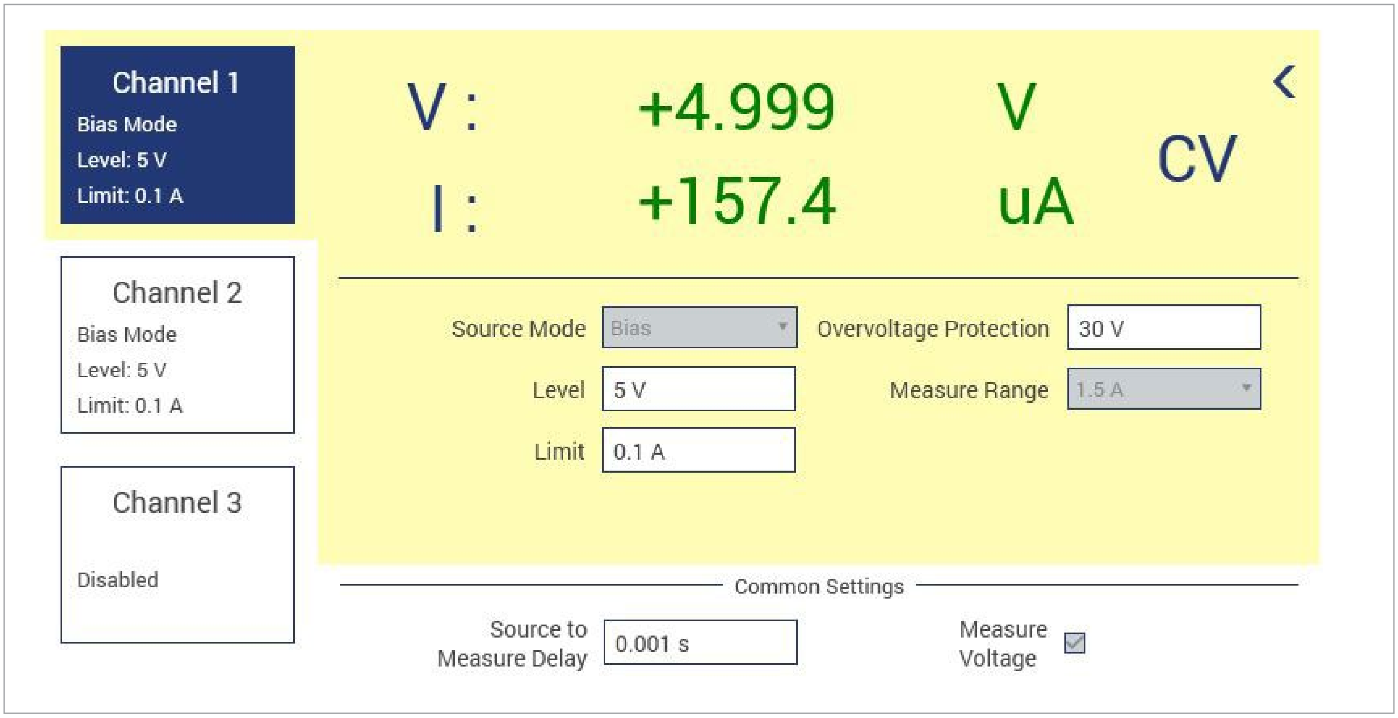


Figure 2: Power supply configuration.

Next, select the AFG App and configure channel 1 of the AFG. Since frequency response analysis requires observation over a range of frequencies, the sweep mode of the AFG will be used. For the purposes of this example, the AFG is set to sweep a 100 mV sine wave from 1 kHz to 100 kHz in a logarithmic sweep. The sweep time is extended to 200s to give the scope time to trigger the measurements. The settings in Kickstart for the AFG are shown in **Figure 3**.

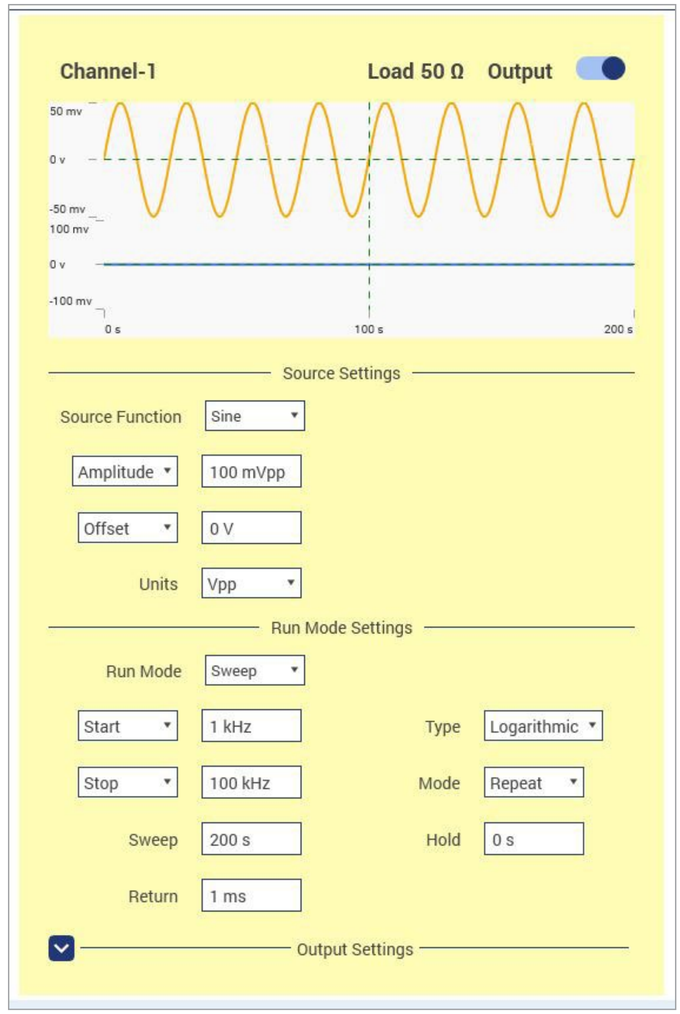


Figure 3: AFG configuration in Kickstart.

Finally, the scope can be set up to capture the waveforms from the front panel. When the Scope App is opened, the settings on the front panel are reflected in the Kickstart screen. Key measurements like the frequency and amplitude of channels 1 and 2 can be set up in the Measurements tab as shown in **Figure 4**. We will configure the scope to take 100 measurements while the AFG sweeps the frequencies.

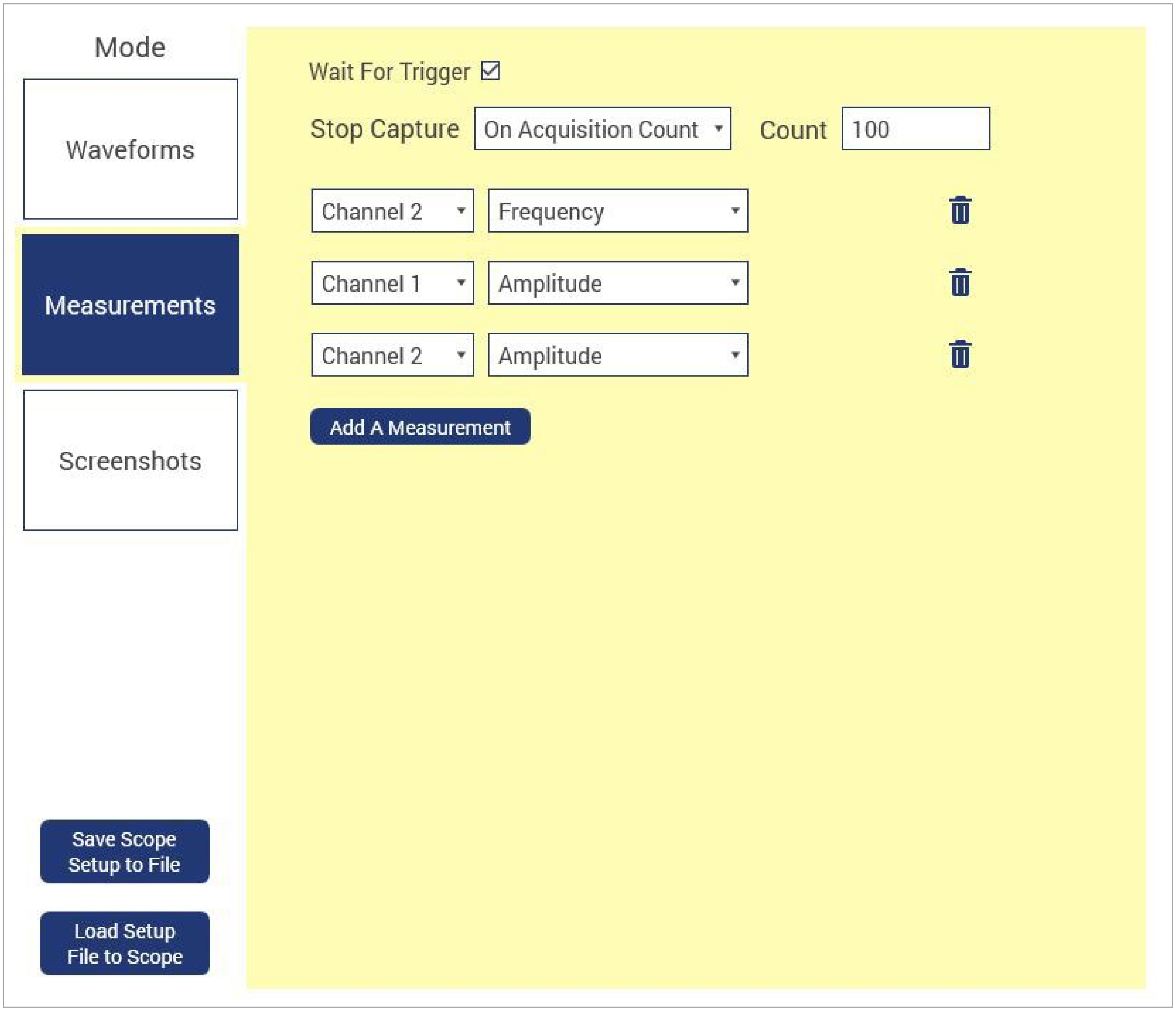


Figure 4: Configure measurements on the oscilloscope.

The AFG channel can be turned on by switching the toggle button in the AFG App. Note that this control is available even while the app is minimized, allowing you to turn the output on and off while keeping the scope app maximized for data collection. Measurements from the scope can be collected to the table by pressing the run button in the measurements tab of the Scope App. The data is populated in the table as shown in **Figure 5**.

Scope-1

Settings | Table | Graph

	Channel 2			Channel 1
	Time (s)	Frequency (Hz)	Amplitude (V)	Amplitude (V)
1	0.000000	1.471000e+3	1.860000	172.0000e-3
2	2.599803	1.552000e+3	1.860000	172.0000e-3
3	5.176722	1.657800e+3	1.860000	172.0000e-3
4	7.796496	1.758100e+3	1.860000	172.0000e-3
5	10.434952	1.865100e+3	1.860000	172.0000e-3
6	13.034024	1.983300e+3	1.840000	172.0000e-3
7	15.651684	2.105300e+3	1.840000	172.0000e-3
8	18.271700	2.238600e+3	1.840000	172.0000e-3
9	20.874643	2.374200e+3	1.840000	172.0000e-3
10	23.497854	2.526500e+3	1.840000	172.0000e-3
11	26.115130	2.679500e+3	1.820000	172.0000e-3
12	28.736185	2.850600e+3	1.820000	172.0000e-3
13	31.352715	3.039500e+3	1.800000	172.0000e-3
14	33.951297	3.211300e+3	1.800000	172.0000e-3
15	36.581931	3.403700e+3	1.800000	172.0000e-3
16	39.200625	3.606200e+3	1.800000	172.0000e-3
17	41.797082	3.852100e+3	1.800000	172.0000e-3
18	44.477658	4.088300e+3	1.800000	172.0000e-3
19	47.095868	4.344000e+3	1.760000	172.0000e-3
20	49.713745	4.629600e+3	1.760000	172.0000e-3
21	52.372146	4.899600e+3	1.760000	172.0000e-3

Figure 5: Collecting measurements from the oscilloscope to the Kickstart table.

The data can be exported automatically after each run, or manually using the built in export tool. The exported data can then be analyzed and presented in a Bode plot such as the one shown in **Figure 6**.

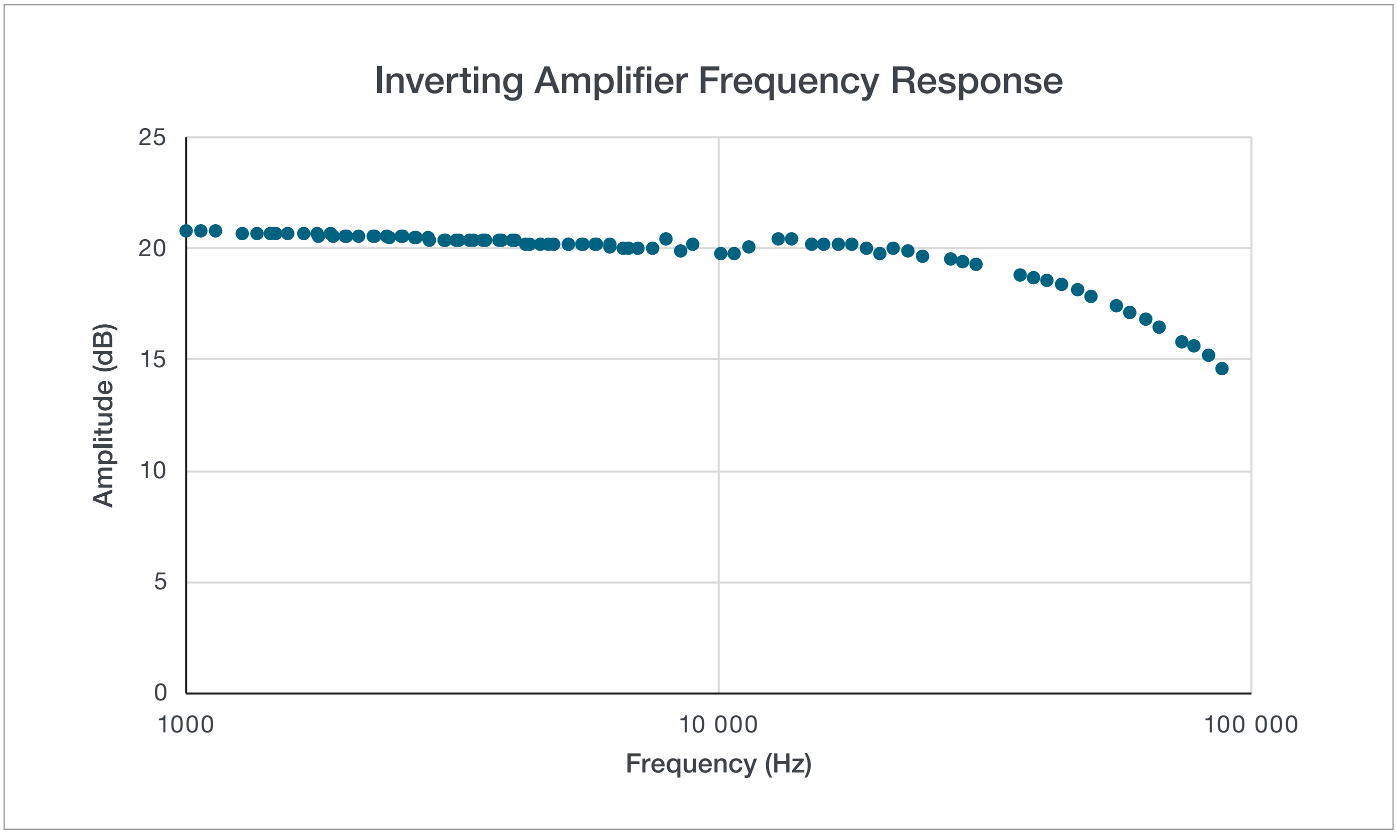


Figure 6: Bode plot of inverting amplifier circuit.

Conclusion

Frequency response of a circuit is a common method of analyzing a circuit's behavior. Keithley's Kickstart Software makes testing frequency response in a circuit simple, with apps for each instrument and the ability to control multiple instruments at once. For more information on Kickstart, visit tek.com/keithley-kickstart.

Contact Information:

Australia 1 800 709 465
Austria* 00800 2255 4835
Balkans, Israel, South Africa and other ISE Countries +41 52 675 3777
Belgium* 00800 2255 4835
Brazil +55 (11) 3530-8901
Canada 1 800 833 9200
Central East Europe / Baltics +41 52 675 3777
Central Europe / Greece +41 52 675 3777
Denmark +45 80 88 1401
Finland +41 52 675 3777
France* 00800 2255 4835
Germany* 00800 2255 4835
Hong Kong 400 820 5835
India 000 800 650 1835
Indonesia 007 803 601 5249
Italy 00800 2255 4835
Japan 81 (3) 6714 3086
Luxembourg +41 52 675 3777
Malaysia 1 800 22 55835
Mexico, Central/South America and Caribbean 52 (55) 88 69 35 25
Middle East, Asia, and North Africa +41 52 675 3777
The Netherlands* 00800 2255 4835
New Zealand 0800 800 238
Norway 800 16098
People's Republic of China 400 820 5835
Philippines 1 800 1601 0077
Poland +41 52 675 3777
Portugal 80 08 12370
Republic of Korea +82 2 565 1455
Russia / CIS +7 (495) 6647564
Singapore 800 6011 473
South Africa +41 52 675 3777
Spain* 00800 2255 4835
Sweden* 00800 2255 4835
Switzerland* 00800 2255 4835
Taiwan 886 (2) 2656 6688
Thailand 1 800 011 931
United Kingdom / Ireland* 00800 2255 4835
USA 1 800 833 9200
Vietnam 12060128
* European toll-free number. If not accessible, call: +41 52 675 3777

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