Creating Multi-SMU Systems with High Power System SourceMeter® Instruments

APPLICATION NOTE

KEITHLEY
A Tektronix Company

Creating Multi-SMU Systems with High Power System SourceMeter® Instruments

Introduction

The design and configuration of test systems for DC characterization of power semiconductor devices using high voltage and high current source measurement units (SMUs) involves several steps:

- Selecting equipment to meet test demands
- Selecting cabling and fixturing to connect the instruments to the device under test (DUT)
- Verifying system safety and instrument protection
- Optimizing the instrument setup to ensure measurement integrity
- Controlling the instrumentation hardware

Power semiconductor discrete devices are designed so that in the ON state, a device delivers a lot of power to the load and consumes minimal power from the power source (high efficiency); in its OFF state, the device delivers nearly zero power to the load and consumes minimal power from the power source (standby current is small). Therefore, characterization or DC parametric test of power semiconductors can be broken into two categories: ON-state and OFF-state characterization. This application note considers the application of test to these two categories. Specific examples of test systems built with a variety of Keithley SourceMeter® Source Measurement Unit (SMU) instruments will also be presented.

Select Equipment to Meet Test Demands

Power devices typically require high power instrumentation at only one or two terminals. For example, characterizing the OFF-state of a high voltage n-channel MOSFET requires a high voltage supply at the drain; all other terminals are driven with lower voltage supplies. Conversely, when characterizing the ON-state performance, high current flows from drain to source, thereby requiring that only those two terminals be rated for maximum power. Test researchers who are making the transition from testing lower power devices to higher power devices can reuse some of their existing test equipment at the gate and substrate terminals. Being able to use the same test equipment for multiple devices allows users to maximize their return on investment.

In order to select appropriate test equipment, it's essential to know the minimum and maximum current and voltages that will be necessary to source and measure. If at all possible, select equipment that has the capability to extend beyond these values in order to accommodate the development of new devices.

Keithley's Series 2650A and 2600B SMUs were designed with evolving test systems in mind. The TSP-Link® inter-unit communication bus supports creating mainframe-less systems while still allowing sub-microsecond synchronization of multiple SMU channels.

One of the most powerful features of the Series 2650A and 2600B is the ability it offers to build systems that address all of the application's test requirements while maintaining seamless system performance. The Series 2650A and 2600B families includes 11 models that offer a variety of functions and capabilities:

- Up to 50A pulse at 2000W (100A possible with two SMUs)
- Up to 3kV source at 60W, 1500V at 180W
- Sub-picoamp measurement capability
- Up to 1A or 3A DC on lower-power SMUs. This is ideal when testing high power BJTs with large base currents.

This level of capability is generally unavailable in an off-the-shelf commercial test mainframe and would have once required configuring a custom or semi-custom ATE. Moreover, using stand-alone instruments allows the test engineer to add new capabilities as new test needs evolve. Stand-alone high power SMUs can extend the current and voltage capabilities of semiconductor parametric analyzers and, therefore, the scope of devices that can be tested.

Selecting Cabling and Fixturing to Connect the Instruments to the Device

Determine the Interface to the Device

In the past, most power semiconductor manufacturers had to package a device in order to test it because there was no widely available technology that allowed delivering tens of amps or thousands of volts to a device on wafer.

The availability of commercial prober solutions is allowing many manufacturers to seize the opportunity to lower their cost of test by testing devices on wafer.

Deciding whether to test packaged devices or devices on wafer is a balance between the large capital costs of a prober versus the smaller (but repeated) costs of packaging devices prior to test. Keithley solutions apply to both packaged test and wafer-level testing.

For testing packaged devices, system developers should take advantage of commercial test fixtures, paying attention

to the supported device packages and any opportunity for customization. Keithley offers the Model 8010 High Power Test Fixture, which is equipped to measure devices in TO-220 and TO-247 packages using supplied and optional device test boards. Additionally, a device test board supplied with the Model 8010 allows customization for connecting to a variety of device packages. System developers can create a custom circuit or can use clips and an insulating block to connect to a device in an unsupported package.

The Model 8010 supports the following Keithley SMUs:

- Up to two Model 2651A High Current High Power SourceMeter Instruments (connected in parallel to allow up to a 100A pulse)
- One Keithley Model 2657A High Voltage High Power SourceMeter Instrument
- Up to two of the following SMUs: Models 2611/12B, Models 2635/6B, Model 4200-SMU, or Model 4210-SMU

Overvoltage protection circuitry for the lower voltage SMUs is installed in the Model 8010 so that instruments are protected in the event that a device failure results in an overvoltage from the Model 2657A. With the Model 8010, SMUs may be connected to up to three terminals on the device.

For some, a custom fixture may be necessary to handle packages or device types/terminals that commercial fixtures don't support. In such cases, consider the following guidelines:

- Plan for the variety of device package types to be tested.
- Find or design a socket that is rated for the maximum voltages and currents in the system.
- For high current testing, use a socket that has Kelvin connections. This ensures that four-wire connections are made all the way to the device pins and provides a true measure of the device characteristics without voltage errors induced by lead resistance in the socket.
- For high voltage testing, ensure that the socket is built with high quality insulators to ensure that measurements can be made to sufficiently low current levels.
- Use triaxial connections if possible for high voltage testing. For the Model 2657A High Power System SourceMeter Instrument, use the Keithley Model HV-CA-571-3 panel-mount HV triax to unterminated cable assembly to create a test fixture with high voltage triaxial connections. Ensure that cables are properly terminated for high voltage creepage and clearance specifications.
- Connect the enclosures of conductive fixtures to safety earth ground. Ensure that non-conductive fixture enclosures are rated to a voltage that's twice the maximum voltage of the test system. Follow all other safety precautions.

For testing devices on wafer, select a prober vendor with experience in testing with high voltage and high current on wafer. Power semiconductor devices are typically vertical devices with high voltage or current connections terminals on the backside of the wafer. This vertical orientation allows device designers to achieve higher breakdown voltages. The wafers are typically ultra-thin, which results in devices with lower ON resistance. Knowledgeable prober vendors have experience with a variety of chuck materials and chuck designs in order to achieve low contact resistance during ON-state characterization. In addition, they will have sufficient expertise in obtaining good low current measurements through the large chuck surface and will be able to provide guidance on selecting the appropriate cabling to meet specific needs.

Connecting the Instrumentation

Connections from the instrumentation to the device under test (DUT) are crucial to obtaining meaningful results. When using the Keithley Model 8010 High Power Test Fixture, connecting the instrument using Keithley supplied cables is straightforward. Review ***Figure 22*** in the "Example Systems" section of this document for a connection diagram. If connections are made to a prober or to a custom fixture instead, keep these guidelines in mind:

1. **Select the best cables for high current test.**

   Ensure that the cables used during test are rated for the maximum current in the test system. Use cables designed to achieve performance required for the high current, low voltage measurements commonly encountered during ON-state characterization.

   In high current testing, pay attention to lead resistance and lead inductance to avoid voltage source and measurement errors.

   Lead resistance

   Some power devices have ON resistances in the range of a few milliohms. Therefore, lead resistance can be on the same order as the parameter under test. When high current is applied, a small amount of lead resistance can result in voltage errors. Small amounts of offset or noise in the voltage measurement can lead to large errors in the ON-resistance result.

   Note the example of an RdsOn measurement of a MOSFET setup in ***Figure 1***, which depicts the instrument configuration. ***Figure 2*** illustrates how the lead resistance is large relative to the device resistance and how the lead resistance results in an 80% measurement error.

   To eliminate errors, use separate cables for the voltage measurement as depicted in ***Figure 3***; use additional cables to connect from the sense terminals of the instrument to the DUT. The test current travels in one set of cables and the voltage measurement is made through the sense lines in which nearly zero current is flowing.

   In high current testing, four-wire connections, also called Kelvin connections, are a must for accurate low voltage

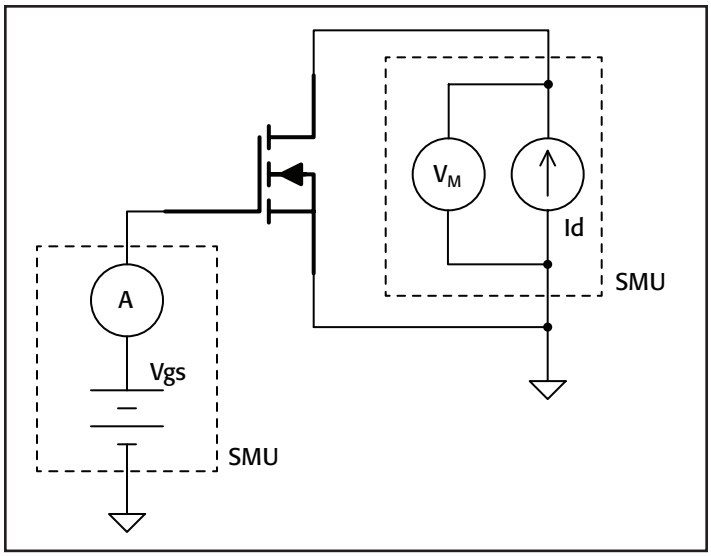

Figure 1. Typical instrument configuration for measuring RdsOn of a power MOSFET.

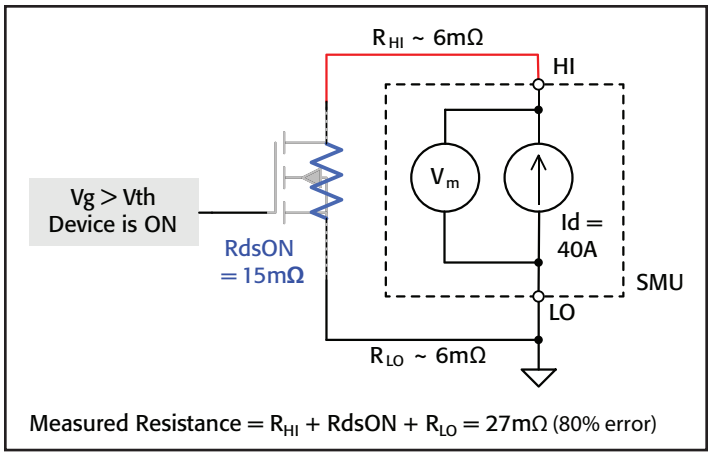

Figure 2. Resistance of test leads is large relative to the DUT resistance. Because the voltage measurement is made at the instrument's output terminals in a two-wire configuration, the measurement includes the sum of the test lead resistance and the DUT resistance.

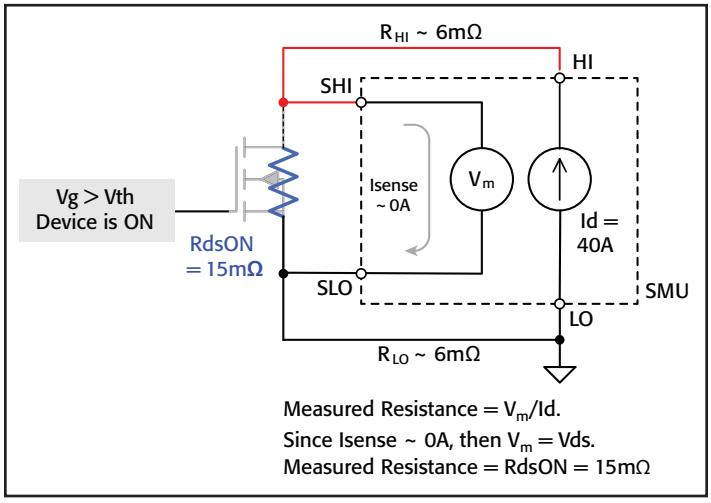

Figure 3. Use separate test leads to connect the device to the instrument's sense terminals. In this way, the voltage measured is only that across the device. The resulting resistance measurement will be a true measurement of the DUT resistance.

and low resistance measurements. To maintain good measurements, monitor force lead resistance to avoid exceeding the SMU's specification for the maximum voltage drop between the force and the sense leads.

Lead inductance

Excessive inductance results in voltage overshoots when there is a large change in current over a short period of time ($V = L[di/dt]$). This is especially important for pulse testing, when dt can be small. Excessive inductance requires the instrument to force more voltage in order to achieve the desired voltage at the DUT.

Keithley Model 2651A-KIT-1 cables are designed to have low resistance and inductance and are recommended whenever the Model 2651A High Power System SourceMeter Instrument is used.

2. Select the best cables for high voltage test.

Ensure that cables used during test are rated for the maximum voltage in the test system. Use cables designed to achieve the performance required for the high voltage, low current measurements common in OFF-state characterization.

In high voltage testing, ensure sufficient insulation and minimize the effect of leakage currents and system capacitance.

Proper insulation

Use a cable rated for at least the maximum voltage of the test system. Use high quality insulators in test fixtures to achieve low current measurements. The insulation resistance is in parallel with the resistance of the DUT and induces measurement errors. (See ***Figure 4***.) With the Model 2657A, up to 3kV may appear across the test circuit, so the amount of current generated through these insulators can be significant relative to the current to be measured through the DUT. For good results, ensure that the insulation resistance is several orders of magnitude higher than the resistance of the DUT.

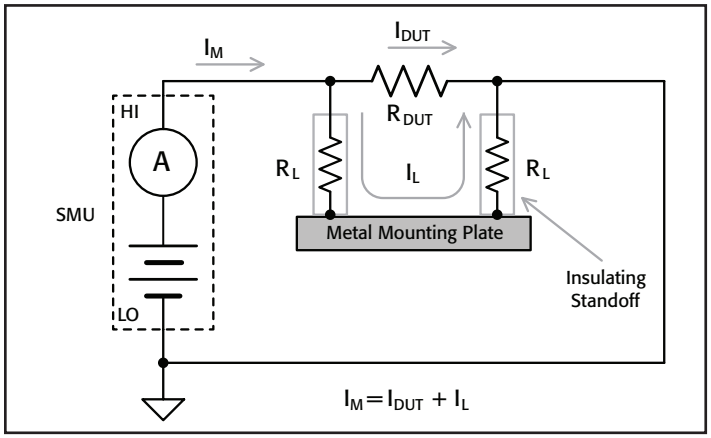

Figure 4. The current generated in the insulators affects the DUT current measurement. To minimize measurement error, ensure that the resistance of insulators (R_L) is much higher than the resistance of the device (R_{DUT}).

Leakage currents and system capacitances

Use guarding to minimize the effect of insulators in the test circuit. Guard is a low impedance terminal that is at the same potential as the high impedance terminal. In ***Figure 4***, the leakage from the insulators is still present, even with high quality insulators. This leakage may be problematic when measuring currents in the nanoamp range. Note how guarding improves the measurement in ***Figure 5***. The leakage currents are routed away from the high impedance measurement terminal (HI), which eliminates them from the measurement.

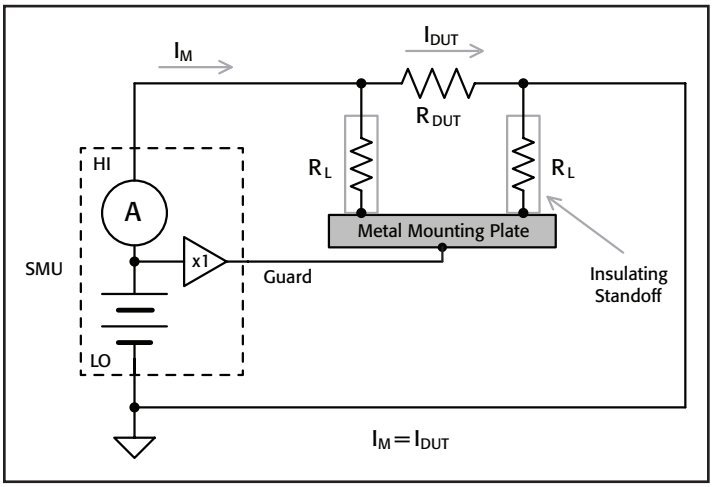

Figure 5. Guard is used to reduce leakage currents by reducing the voltage across the insulators in the circuit to nearly 0V. Any remaining leakage is routed away from the HI terminal where the measurement occurs.

Because the guard terminal is at the same potential as the high impedance terminal, the guard voltage is a hazardous voltage. Use triaxial cabling to carry guard and protect operators from risk of an electric shock. In a triaxial cable, the high impedance terminal is connected to the center conductor, guard is carried on the inner shield, and the outer shield is connected to ground. ***Figure 6*** shows the cross-section of a triaxial cable.

Guarding can also minimize the effect of system capacitances. System capacitances impact the settling of the voltage source and the current measurement. The test setup must allow for the charging of such capacitances and the settling of currents at or below the expected noise floor of the device measurement. The high impedance nature of these setups results in long settling times. ***Figure 6*** illustrates how guarding can reduce the impact of cable capacitance. A typical triaxial cable has a capacitance of about 40pF per foot. This can quickly result in several hundred picofarads of capacitance for a cable that is two or three meters long, and tens of milliseconds of voltage settling time, depending on the maximum current in the test setup. Placing guard on the inner shield of the cable means there is no voltage drop across the cable's insulator. Therefore, the capacitance of this insulator does not need to be charged. In steady-state conditions, the Model 2657A is specified so that the guard voltage is within 4mV of the high impedance terminal (HI). The Keithley Model HV-CA-554 is a high voltage triaxial cable that safely carries signal and guard voltages up to 3280V. Keithley Model HV-CA-554 cables are designed to meet the demands of a 3kV, low current measurement system. To minimize settling times and leakage current, carry the guard from the SMU all the way to the device pins. Doing so eliminates the need to charge other system capacitances. Because the guard voltage can be up to 3kV, make sure that the guard is terminated a safe distance away from other conductors.

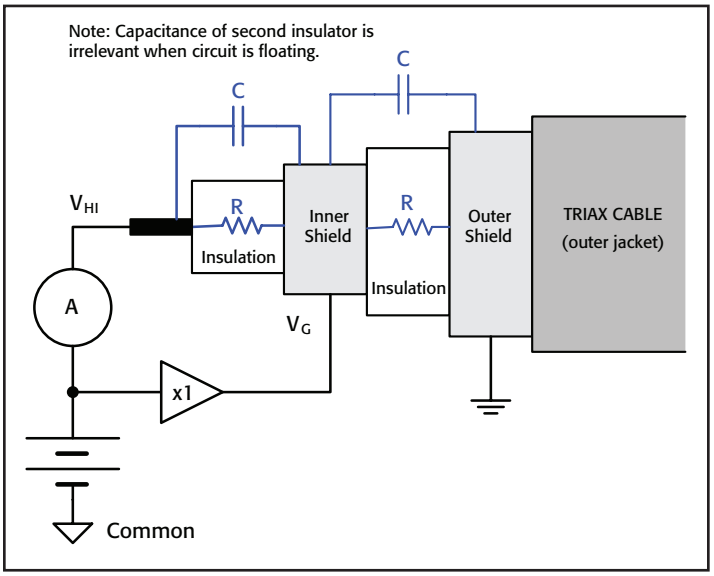

Figure 6. When $V_{HI} \approx V_G$, the voltage drop across the capacitor and resistor is 0V. Guarding virtually eliminates leakage current due to cable insulation and minimizes response time by eliminating the need to charge cable capacitance.

Converting to coaxial connection is a necessity in some systems. For high voltage testing, SHV is the industry standard coaxial connector. Keithley offers Model SHV-CA-553 cable assemblies that allow adapting from high voltage triaxial to SHV. These cable assemblies use a triaxial cable so that the guard is carried as far as possible before it must be terminated so that the connection can be made to SHV. Using coaxial connections results in degraded performance because the benefits of guarding are lost from the point at which the guard is terminated. This means that the remaining cable capacitance and the capacitance within the test system must be charged.

When designing a test fixture, a user can take steps to minimize the capacitances by shortening the length of the cabling and device connections after the conversion to coax from triax.

The effects of converting to coax become even more significant on a probe station, where cabling and connections

are a function of the size of the wafer and device orientation (vertical or lateral). When cable capacitances are taken into account, capacitances in a probe station can easily be on the order of nanofarads, resulting in significant capacitive charge time and measurement settling time.

3. Establish a common reference for the SMUs.

Few test system issues are as misunderstood as grounding. Here, a "ground" is defined as a connection to earth ground. However, many people often use the word "ground" to refer to the reference point for the SMUs in the test circuit. In this note, this reference point will be referred to as "circuit common."

Earth ground

For safety, most systems have a connection to earth ground to ensure that any faults within the instrument or test system do not expose the user to the risk of electric shock. For similar reasons, in high voltage systems, connect conductive test fixtures and their associated accessories to earth ground.

Circuit common

Identifying circuit common is important in order to obtain accurate source values and measurements. When connecting multiple supplies to a DUT, it is important that the supplies be referenced to the same point so that the desired voltages appear at each DUT terminal. Consider the example shown in ***Figure 7***.

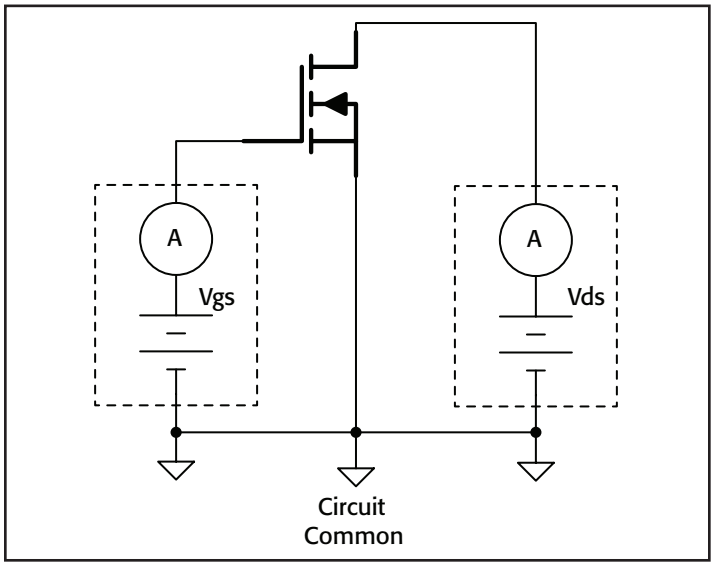

Figure 7. When using stand-alone instruments, the outputs must have the same reference so that the correct voltages and current appear at the device under test (DUT). In this example, the source terminal of the FET must be connected both to the LO of the gate supply and the LO of the voltage supply so that V_{GS} and V_{DS} are accurate. Because the LO terminals of both instruments are connected to the source terminal, this becomes circuit (or measurement) common.

Performance of the device is specified based on the relationship between V_{DS} and V_{GS}. We will consider connections to circuit common in the light of the two test configurations: ON-state characterization with a Model 2651A SMU on the drain and OFF-state characterization with a Model 2657A SMU on the drain.

Creating circuit common when performing ON-state characterization using the Model 2651A high current SMU

The section titled "Selecting Cabling and Fixturing to Connect the Instruments to the Device" addresses why four-wire connections are required for the high current instrument. Four-wire connections are also recommended for the SMU connected to the base of a BJT or gate of a MOSFET or an IGBT, even when there is little current flowing through the gate. Let's examine the reasons for this recommendation as it relates to the connections to circuit common.

Note the measurement configuration in ***Figure 8*** where ON-state characterization is performed on a power MOSFET. This configuration could apply for generating a family of curves for the MOSFET. Circuit common is created when the LO of the gate SMU (SMU 1) is tied to the LO of the drain SMU (SMU 2). Because little to no current is flowing in the gate-to-source loop, the gate SMU is measuring and correcting the output voltage based on the measurement at its force terminals, which is the difference between the voltage at the gate terminal and the voltage at circuit common, denoted as node S´ (prime) in ***Figure 8***. Circuit common is tied to the Source terminal of the FET (node S in ***Figure 8***) through a test lead that has a resistance R_{slead}. Because a high current (up to 50A pulse) is flowing in the drain-to-source loop, we cannot ignore R_{slead}. Even a 1mΩ resistance here may cause a difference between V_{GS} and V_{GS}´ (prime) of 50mV. Some devices are very sensitive to changes in the gate-to-source voltage. A 50mV difference in V_{GS} may cause hundreds of milliamps or even an amp or more difference in the drain current. To compensate for the voltage drop between the connection in circuit common and the actual device terminal, connect the sense terminals of the gate SMU separately to the DUT as shown in ***Figure 9*** [1]. Because nearly zero current is flowing in the sense leads, the gate SMU accurately measures the device voltage at the FET's Source terminal and can correct its output voltage to maintain the desired V_{GS} at the device.

In some cases, the response of the gate SMU must be slowed to compensate for ringing or oscillation in the gate circuit. This is done when high capacitance mode is enabled on the gate SMU. However, this slower response time can slow the feedback between the measurement of the sense voltage and the correction of the output voltage. In such cases, connect both the LO and Sense LO terminals of the gate SMU to the Sense LO of the drain SMU. Because little to no current is flowing in the gate-to-source loop, no voltage measurement

1 As nearly zero current flows in the sense circuit, the Sense LO of the gate SMU can be tied to the Sense LO terminal of the drain SMU without any impact on the voltage measurements.

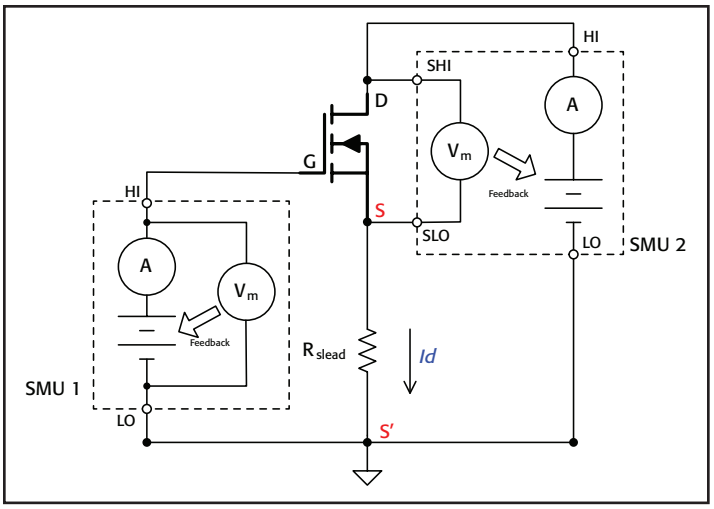

Figure 8. Because high current flows through circuit common, the resistance between circuit common and the FET's source terminal (R_{slead}) will result in voltage differences between measurements made at circuit common and measurements made at the source terminal of the FET. Therefore $V_{GS} \neq V_{GS}'$ (prime) when two-wire connections are used to connect the gate SMU (SMU 1) to the DUT.

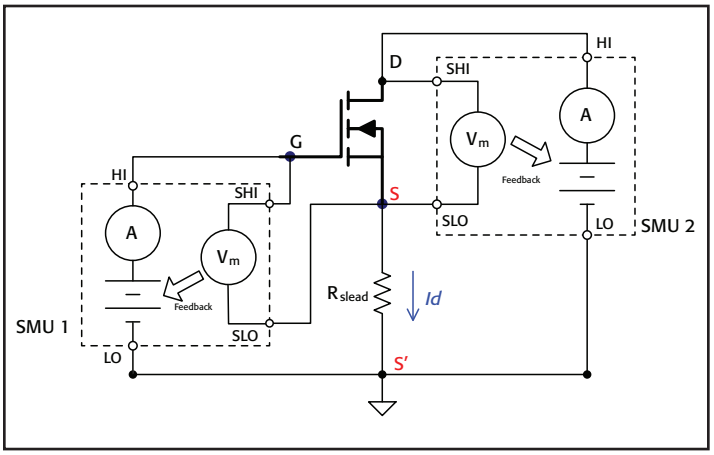

Figure 9. Using four-wire connections to the gate SMU negates the voltage errors that arise because of R_{slead}. In this way, the gate SMU can correct its output voltage to maintain the desired V_{GS}.

errors occur. However, this should not be done when testing BJTs because significant current can flow between base and emitter.

Creating circuit common when performing OFF-state characterization using the Model 2657A high voltage SMU

For OFF-state characterization, connections between the gate and drain SMUs and the DUT are made as shown in ***Figure 7***. If four-wire connections are desired, then simply connect the Sense LO terminals of the gate and drain SMUs.

Device faults can result in the presence of high voltages at lower voltage terminals. Therefore, the connection to the gate, source, and substrate must be made with high voltage connectors. To facilitate connections between the LO and Sense LO of the two instruments, Keithley offers the Model 2657A-LIM-3 LO Interconnect Module as an optional accessory. The LO and Sense LO of three SMUs can be easily routed through the Model 2657A-LIM-3. Additional SMUs can be routed with slight modifications in connections. (Consult Keithley's online FAQs or Keithley field applications engineers for more details.)

Creating circuit common for systems that will use both Models 2651A and 2657A High Power SMUs

Given that complete testing of a power semiconductor device involves both ON-state and OFF-state characterization, it is likely that a test setup will involve both the Model 2651A and the Model 2657A. To ensure the integrity of measurements in both configurations, route the Model 2651A's LO terminal separately from the device under test. Route the Model 2651A's Sense LO through the Model 2657A-LIM-3 so that it is common with the other SMUs in the test setup. Connect the Output LO terminal of the Model 2657A-LIM-3 to the LO terminal of the Model 2651A as close as possible to the DUT. These connections are illustrated in detail in ***Figure 21*** in the section of this note titled "Example Systems."

When performing ON-state characterization to devices on wafer, the connections recommended in the previous paragraph would result in three probe needles touching down on the pad that connects to the Source terminal of the FET. However, making three connections may be a problem because there may be insufficient space on the pad for three probe needles and because pad lifetime decreases as the number of probe touchdowns increases. This problem can be resolved by using the autosense resistor in the Model 2657A-LIM-3. The autosense resistor connects the output Sense LO of the Model 2657A-LIM-3 to the output LO of the Model 2657A-LIM-3 through a 100kΩ resistor. (See ***Figure 10***.) Although true four-wire connections are not maintained to the device under test, there is little impact on the voltage delivered to the FET or IGBT gate terminal because the gate current is small and the Model 2651A's LO is routed through a separate connection to circuit common[2]. ***Figure 21*** in the "Example Systems" section of this application note assumes that the autosense resistor of the Model 2657A-LIM-3 is used to connect to its Output LO and Sense LO terminals.

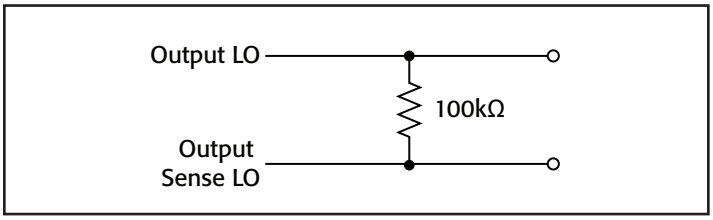

Figure 10. In the Model 2657A-LIM-3, a 100kΩ resistor is used to connect Output Sense LO to Output LO. This allows for quasi-Kelvin sense connections in cases where there is insufficient space to place four connections on the DUT. In cases where full Kelvin is desired, simply connect separate cables to Output Sense LO and Output LO, and the 100kΩ resistor is essentially ignored.

2 If true four-wire connections are not made to the DUT, voltage errors may appear when testing BJTs with high base currents.

Reviewing System Safety and Instrument Protection

When considering cabling and fixturing design, it is also important to consider system safety. Think through a variety of fault conditions, including those due to operator error and those due to a change in the device state, in order to determine what dangers are presented to the operator and to the instrumentation.

One of the potential dangers of high current testing is the risk of fire or burns. Enclose the device under test to protect users from the potential for fire or flying projectiles if the device fails during high current tests.

The risk of electric shock is one potential danger for high voltage testing. The risk of electric shock exists anytime an instrument (or device) has the ability to output more than 42VDC. Proper test system configurations must include mechanisms for protecting the operator and untrained users from electric shock.

While power is applied, such users should be unable to access systems in which high voltage is present. The safety interlock is one mechanism for limiting access. All modern Keithley SMUs include an interlock so that high power is only enabled when the interlock line is engaged. Interlock is intended to be used with a normally open switch at each system access point. When there are multiple instruments that present a risk of electric shock, wire the instruments so that the outputs of all instruments are disabled if the system access point is opened. When there are multiple access points, each point requires a separate switch and all such switches should be wired in series. This is illustrated in ***Figure 11***.

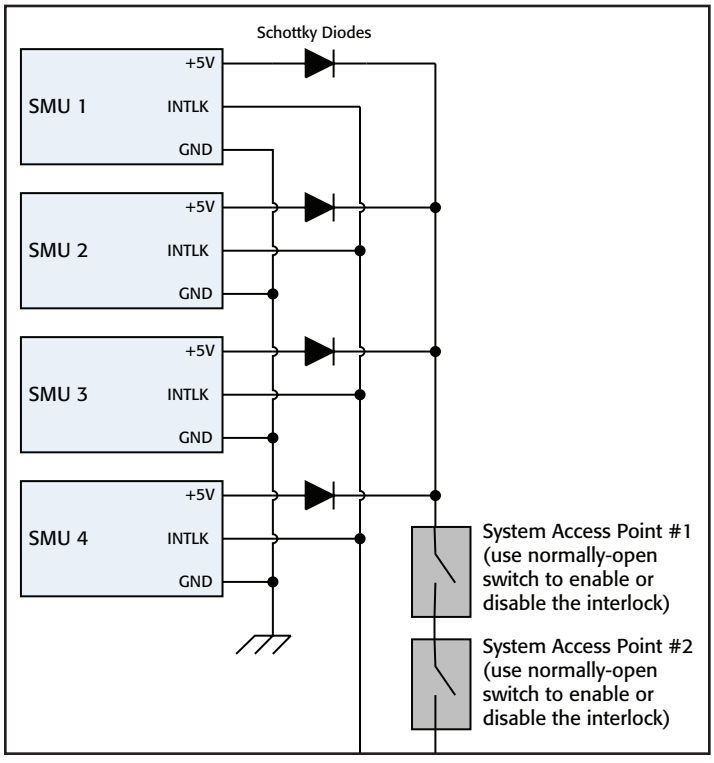

Figure 11. Configuration for connecting multiple SMUs to a system with multiple access points.

The 5V supplies from all instruments are combined, externally routed through the switch and used to enable the interlock. When the 5V supplies from multiple SMUs are used, use Schottky diodes to prevent the 5V supplies from each of the SMUs from back-driving each other. Schottky diodes are preferred because they have low forward voltage; therefore, they are less likely to affect the voltage needed to enable the interlock line.

Depending upon the number of SMUs in the test setup, the 5V supply from one SMU may be able to drive the interlock lines of the other SMUs in the system. Review the instrument specifications for the safety interlock pin to determine the amount of current required to drive the interlock pin of each SMU. Also review the specifications for the 5V power supply pin to determine its current capability. Alternatively, an external power supply may be used to drive the interlock lines of the SMUs.

In addition to operator safety, it is important to protect the investment in the system's test instrumentation. Carefully consider the effect of potential device failures. The test configuration shown in ***Figure 12*** is typical for measuring OFF-state leakage current of an n-channel FET near its specified drain-to-source breakdown voltage. The lower voltage SMU at the gate terminal ensures that the device is in the OFF state. The lower voltage SMU at the source terminal provides a direct measurement of the current at the source terminal. However, if there is a sudden breakdown from drain to source, then there is potential for a 200V SMU to be damaged by the 3kV SMU. The same potential for damage exists between the gate and drain terminals.

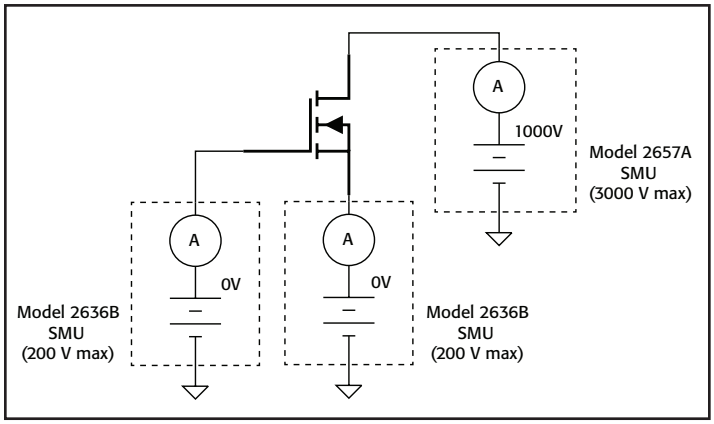

Figure 12. In the event of a device breakdown or failure, there is potential for the Model 2657A SMU to damage either Model 2636B SMU.

Use an overvoltage protection device to protect the lower voltage SMU in the event of device breakdown or device failure. The overvoltage protection device should have little effect on the

test circuit under normal conditions but will clamp the voltage during an overvoltage condition. The Keithley Model 2657A-PM-200 200V Protection Module is designed for use in test systems that contain both the Model 2657A SMU and lower voltage SMUs. In the event of an overvoltage, the protection module will clamp the external high voltage source to approximately 2V in microseconds. In an unclamped condition, picoamp-level current source and measure capability is maintained on the lower voltage SMU[3].

Instrument damage can also occur when device failures subject the instruments to high current. Ensure that the instruments at all terminals are capable of handling currents normally present at the specific device terminals. To limit instrument damage when device failure results in higher currents, use series resistors to limit the maximum current that can flow into any instrument. During characterization of breakdown voltage or leakage current, the user must be careful to limit the amount of current through the device so that the testing is not destructive. Although SMUs have programmable current limits, these active limits take some finite time to respond to changes in load (known as the "transient response time.") When the load impedance changes very quickly, then currents above the programmable limit may flow. Adding a series resistor enforces a maximum current at that terminal even under transient conditions.

Make sure to select a resistor rated for the maximum current, voltage, and power in the test system. Such resistors often serve a dual purpose. During ON-state characterization of transistors, resistors are often added in series with the gate to minimize the oscillation and ringing in the gate voltage commonly seen in high gain devices. In addition, during OFF-state characterization, resistors are often used to limit the maximum current that can flow during a breakdown, preventing premature device failure.

Optimizing the Instrument Setup to Obtain Good Measurements

Once the system setup is complete, it's time to test its functionality and optimize instrument setup to obtain the best measurements.

For ON-state Characterization

In most ON-state testing performed today, the device is pulsed on in order to minimize heating. In addition, the end application for many power semiconductor devices involves operating under pulsed conditions. Qualify the test system for pulsing by outputting a pulse of the SMU through the test system and capturing the response at the device terminals. The Model 2651A High Power System SourceMeter instrument includes high speed analog-to-digital converters (ADC) that allow the simultaneous digitization of current and voltage waveforms. These ADCs are useful in determining system pulse performance. If anomalies in the pulse shape occur, review cabling to make sure that lead inductance is minimized. Use the Keithley-supplied low impedance coaxial cabling wherever possible and minimize the inductive loop area of other leads.

For OFF-state Characterization

Understand the source and measure settling time of the system. High voltage sources are generally used to perform OFF-state measurements of the device, where currents are low and the device is in a high impedance state. However, there may be system capacitances that cannot be guarded out and the device itself will have some capacitance. Power semiconductor transistors typically have output capacitances on the order of 100pF or more. Device resistance in the OFF state can be 1GΩ or more, resulting in a single RC time constant of 100 milliseconds or longer. Note the plot of voltage vs. time for a charging capacitor in ***Figure 13***. In order to produce settled readings, it's important to wait at least four to six time constants (four time constants = 99%), which may mean nearly a second of settling time is required. Account for this settling time in estimating production throughput or the time required for long tests, such as device reliability testing.

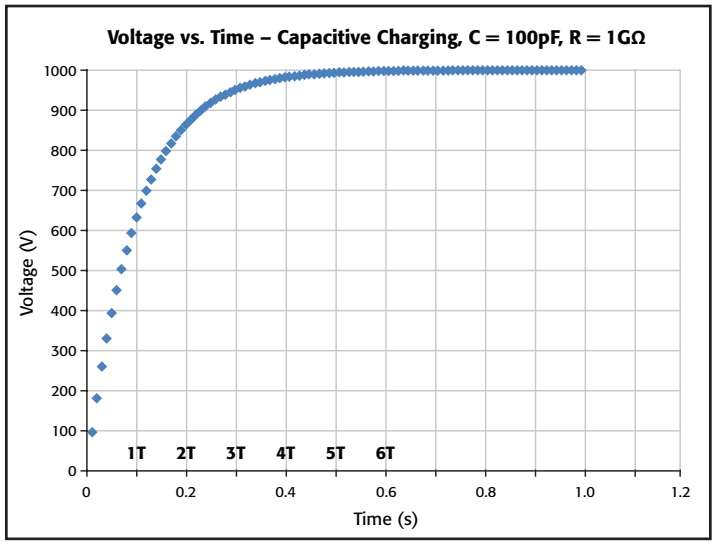

Figure 13. A simulated plot of voltage vs. time for a 100pF capacitor while it is being charged. Readings are settled at four to six time constants. T = RC time constant.

If coaxial connections are used instead of triaxial, be aware that additional settling time will be required to obtain accurate and repeatable low current measurements. In addition to the RC of the device, the settling time must now include the RC time constant of the cable and the probe station or fixture. Characterize the total settling time by applying a voltage step at the system input and measuring the current decay over time at the output. The fast analog-to-digital converter (ADC) of the

3 The overvoltage protection of the Model 2657A-PM-200 protection module is triggered at ~ 220V. Therefore, it is not recommended for use in SMUs with maximum output voltage capability of less than 200V. Additionally, the Model 2657A-PM-200 is not recommended for use in protecting the HI and LO terminals of the Model 2651A. The protection module is not rated for the maximum output current of the Model 2651A.

Model 2657A or Model 2651A affords the user a quick and easy way to capture settling time information. Select a measurement delay by observing the time at which the current falls below the expected noise floor for the device measurement.

Controlling the Instrumentation Hardware

Coordinating the source and measure sequence of the device under test is not trivial when multiple instruments are in use. Therefore, it is advantageous to use available software solutions to simplify and/or eliminate extensive programming.

Use the supplied free start-up software to validate the test system configuration and functionality. Series 2600B and Series 2650A SMUs are provided with TSP® Express software, free start-up software that is served from the web interface of the instrument. When the TSP-Link interface is used to create a network of instruments, TSP Express software can be used to control all of the instruments on the network. See ***Figure 14*** for an example diagram of the communication setup between three SMUs. Using TSP Express software, the user can easily set up DC and pulse sweeps on one or more SMUs and have other SMUs assigned to output static bias voltage or program a step change in bias voltages at each sweep. Built-in simplified graphing software allows the user to plot results quickly and assess whether all cabling, connections, and parameters have been correctly configured. ***Figure 15*** and ***Figure 16*** illustrate the capabilities TSP Express software.

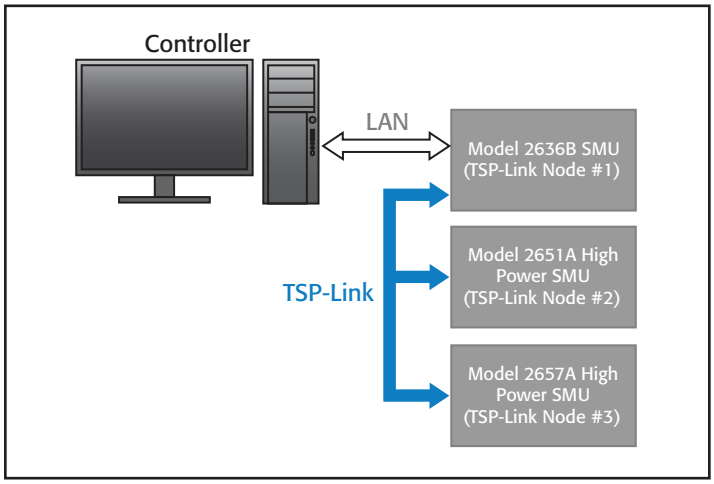

Figure 14. TSP-Link technology provides mainframe-less system expansion and enables communication between the instruments, precision timing, and tight channel synchronization.

TSP Express software can also access the fast ADC capability of the Model 2651A and Model 2657A high power SMUs. Use TSP Express software to output a single pulse from the Model 2651A through the test system and capture its response. These results can be used to set the required source and measure delays to ensure that data is taken during the settled portion of the pulse.

Simplify the testing of discrete semiconductor devices by using software designed for parametric test. Such software includes test libraries with pre-defined tests that simplify gathering data for various devices. Keithley's ACS Basic Edition software is recommended for semiconductor device testing with multiple-SMU systems in which the device is contacted using a manual prober or test fixture. Keithley's ACS Standard software is recommended when interfacing with devices using a semiautomatic or automatic prober.

Example Systems

This section provides detailed connections for several example configurations. For more information on how to apply any of these examples to a specific application, please contact your local Keithley field applications engineer. Worldwide contact information is available at the end of this application note or on www.keithley.com.

Packaged Device Testing Using a Test Fixture

The Keithley Model 8010 High Power Device Test Fixture completes the solution for testing power semiconductor devices with Model 2651A and Model 2657A High Power System SourceMeter instruments. ***Figure 22*** depicts the connections from the instrumentation to the Model 8010. Example device testing configurations are considered in detail in the Model 8010 Interconnect Reference Guide (IRG), which can be downloaded from www.keithley.com.

Custom test fixtures can be designed to incorporate any number of SMUs for testing. For high current testing, connections may be easily adapted from the Phoenix screw-terminal connectors provided on the Model 2651A. For highest integrity high voltage measurements using the Model 2657A, Keithley offers a bulkhead version of the custom HV triax connector, already assembled with a triax cable that is unterminated at one end. It is designed to be installed in a safe enclosure. Connections can easily be soldered to the device or adapted to another connector appropriate for the setup. This is illustrated in ***Figure 17***. The legend in ***Figure 18*** applies to this custom fixture connection example.

Wafer-Level Device Testing on a Probe Station

A few probe station vendors offer commercial solutions for high power semiconductor device testing and other vendors create custom solutions. Consult with a probe station vendor to determine the types of probing solutions available for the current voltage, and power required for a specific test application. Prober manufacturers can contact Keithley Instruments for information on how to use our custom high voltage triaxial cable and connector.

As part of a recent review of probe station solutions, we found that banana plugs and jacks are commonly used for high current testing and that SHV is an industry standard for high current connections. The high current Phoenix screw-terminal connectors can be easily adapted to banana connectors. To adapt

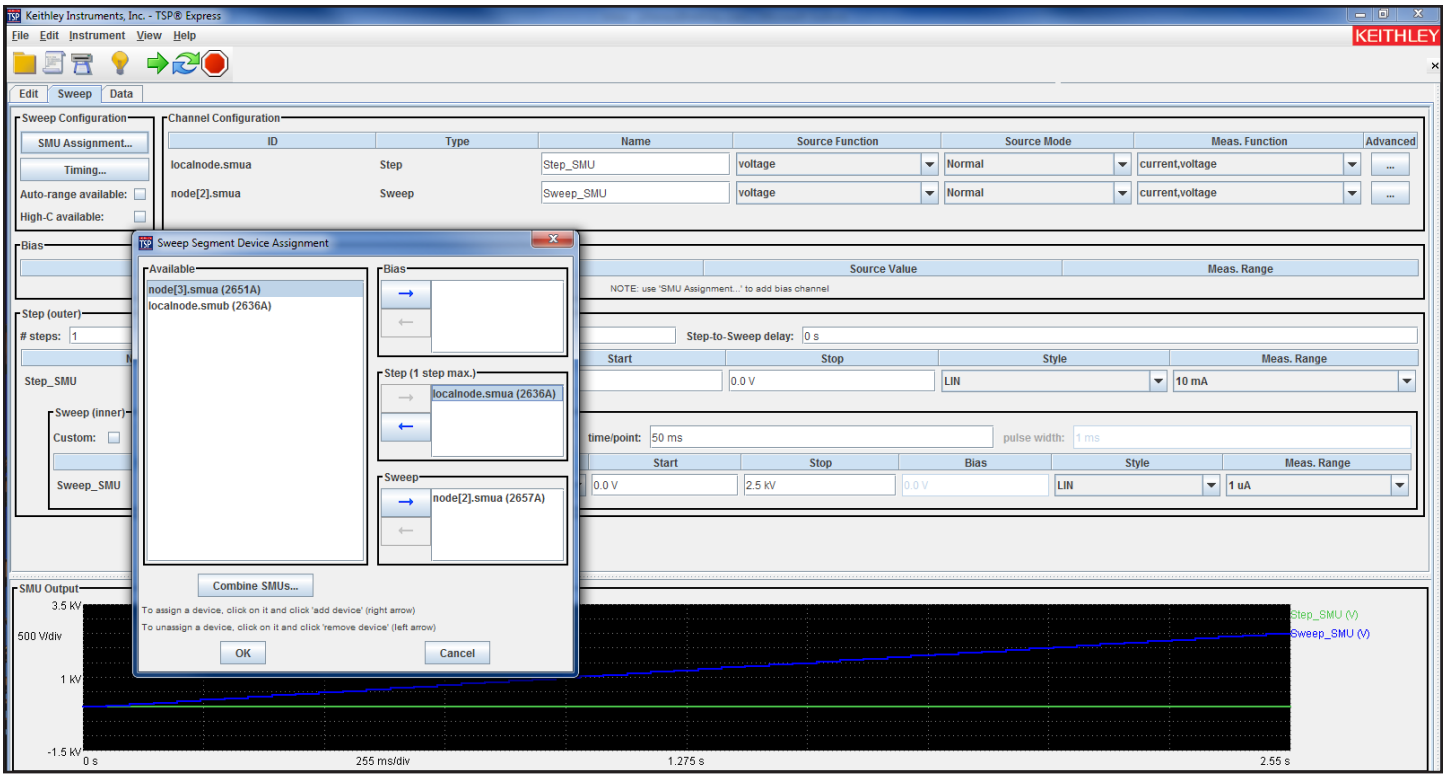

Figure 15. TSP Express software allows quick setup of source and measurement parameters of all instruments connected over the TSP-Link network.

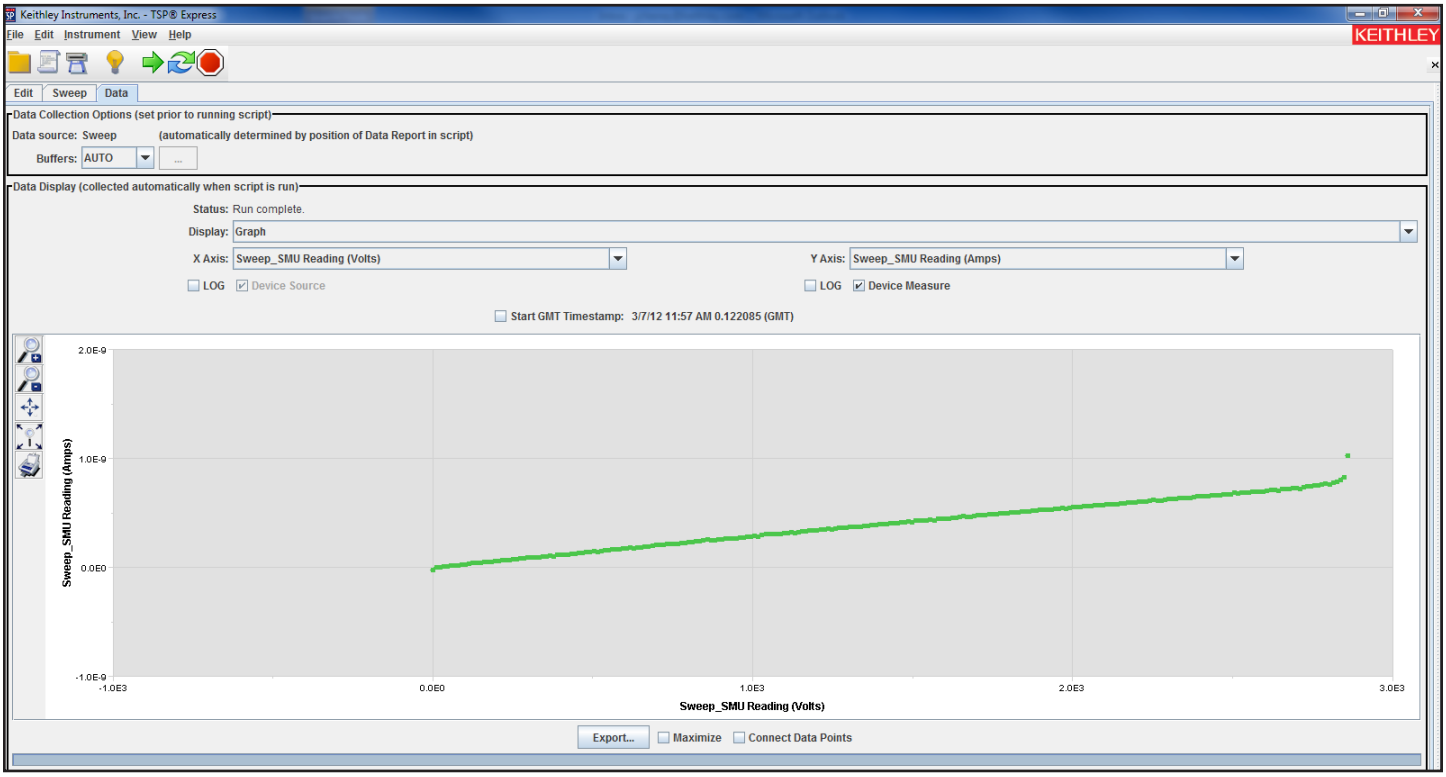

Figure 16. TSP Express software allows quick and easy plotting of measurements, such as the V_{ces} vs. I_c plot shown here for an IGBT with a rated BV_{ces} of 2500V.

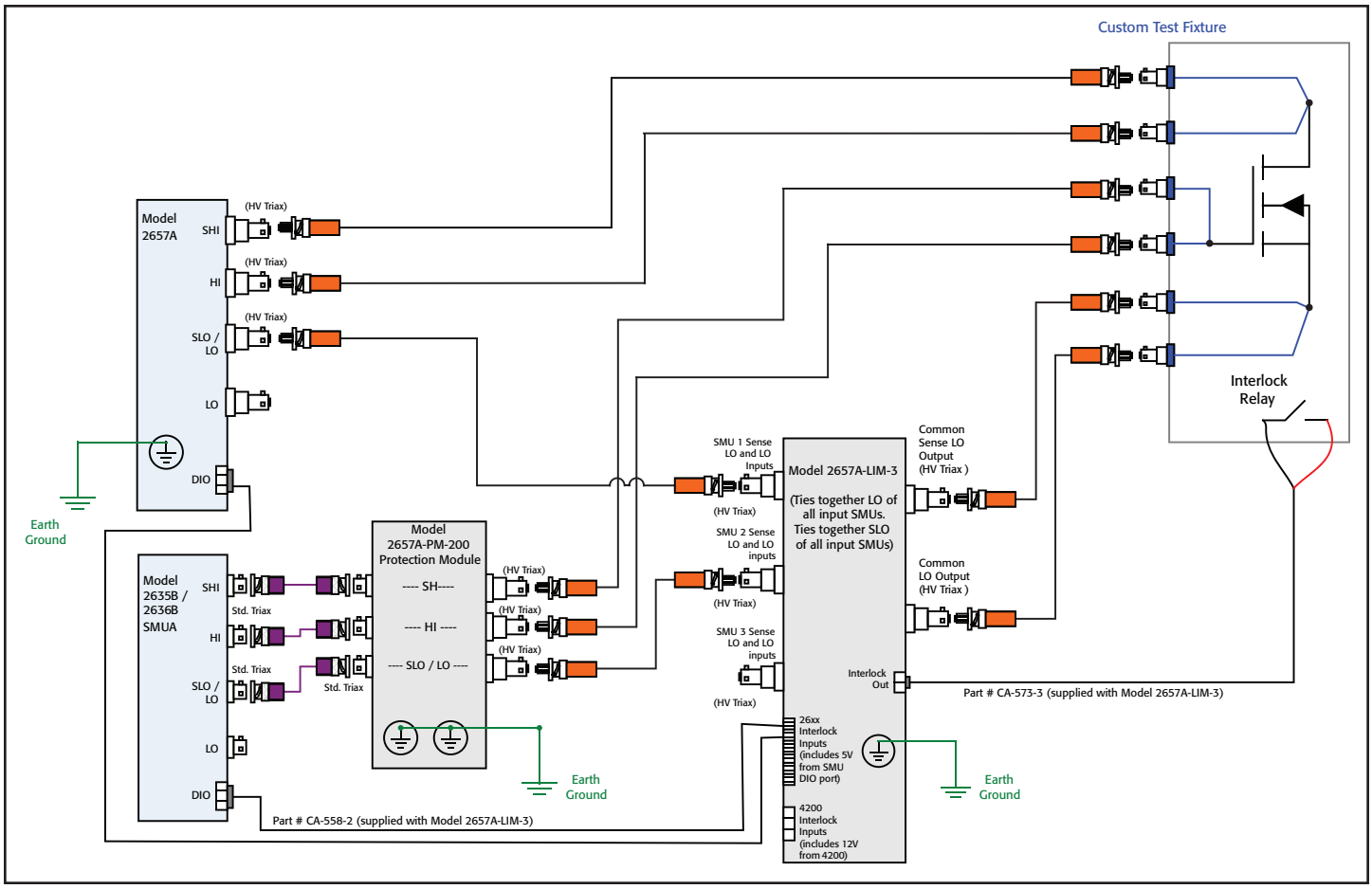

Figure 17. Custom fixture connection example for high voltage testing.

to SHV solutions, Keithley offers the Model SHV-CA-553, a cable assembly that has a high voltage triaxial connector on one end and an SHV (coaxial) connector on the other end. The diagrams that follow illustrate three example configuration connections to a wafer-level device using banana and SHV connections.

The legend in ***Figure 18*** applies to the wafer-level device connection examples.

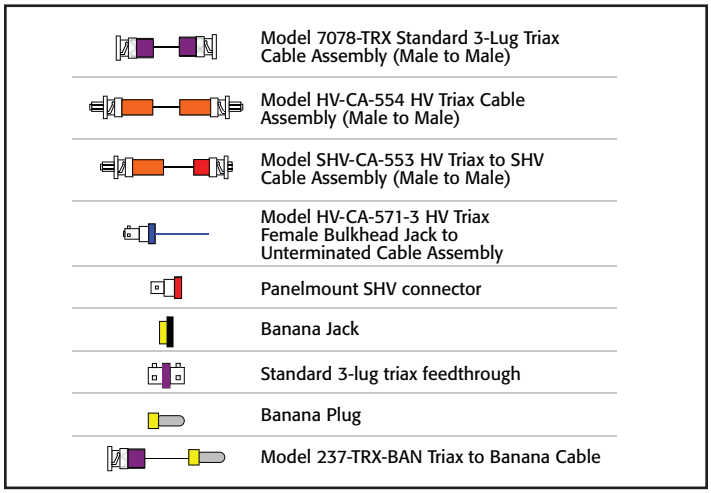

Figure 18. Legend for wafer-level device connection example diagrams.

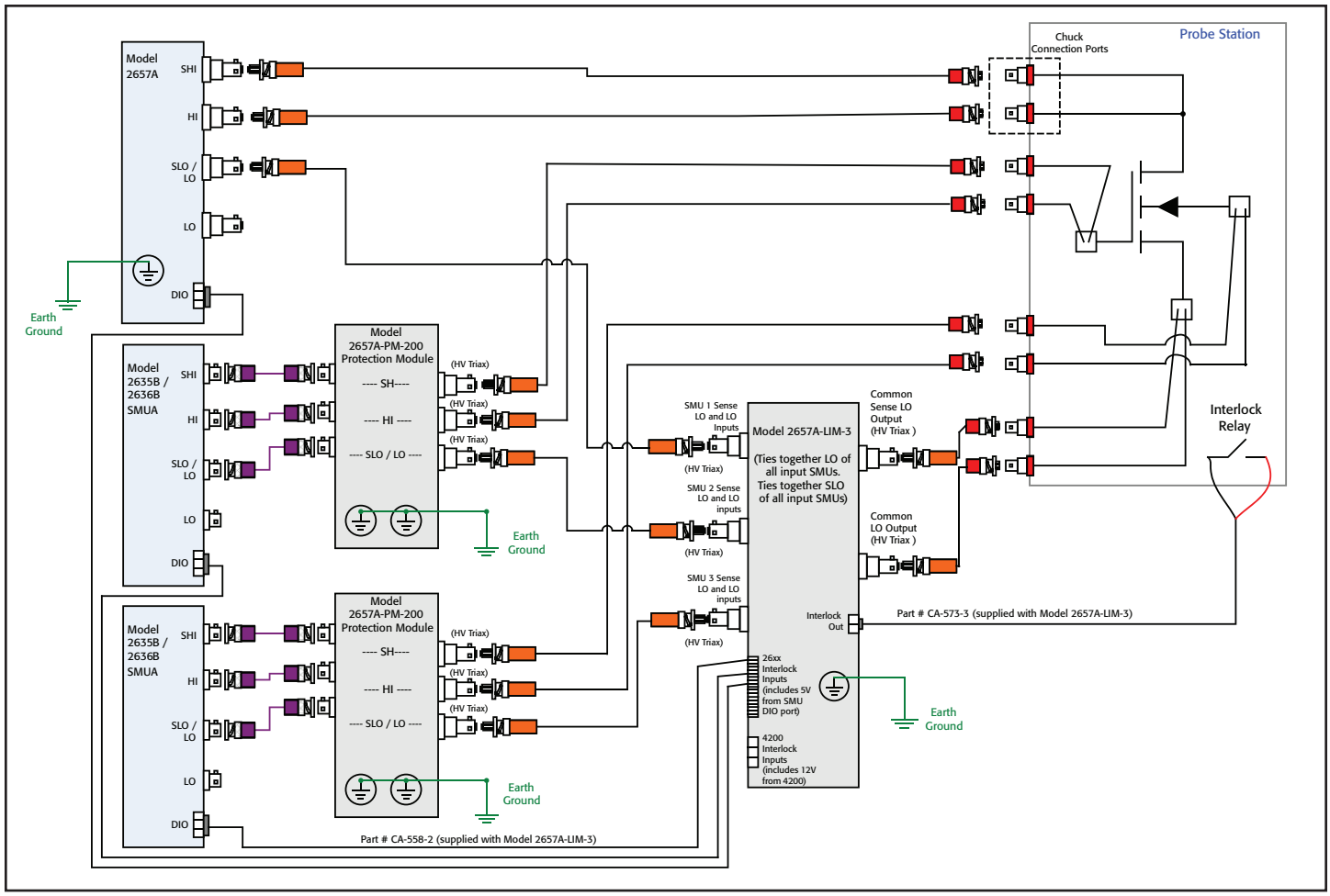

Figure 19. Connections to wafer-level device for high voltage only testing using SHV connections.

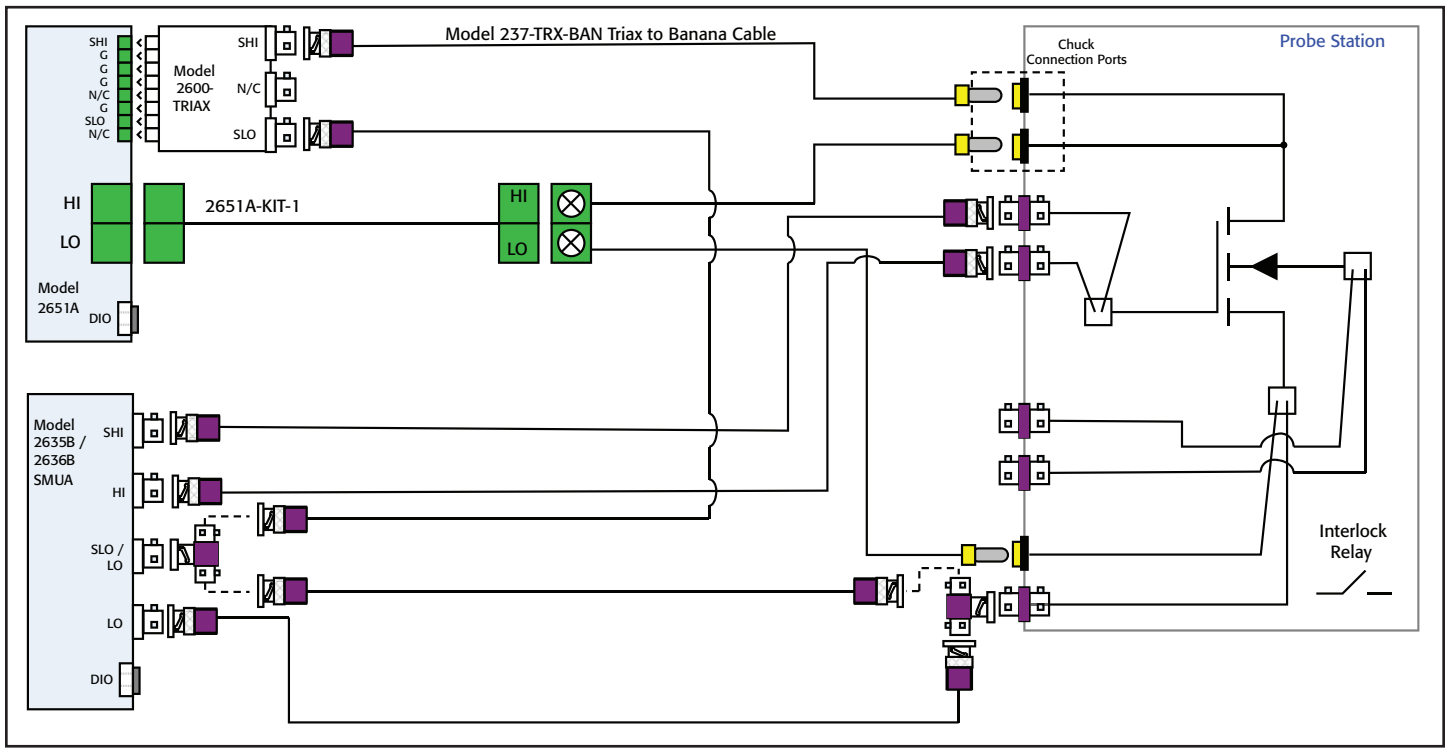

Figure 20. Connections to wafer-level device for high current only testing using banana connections.

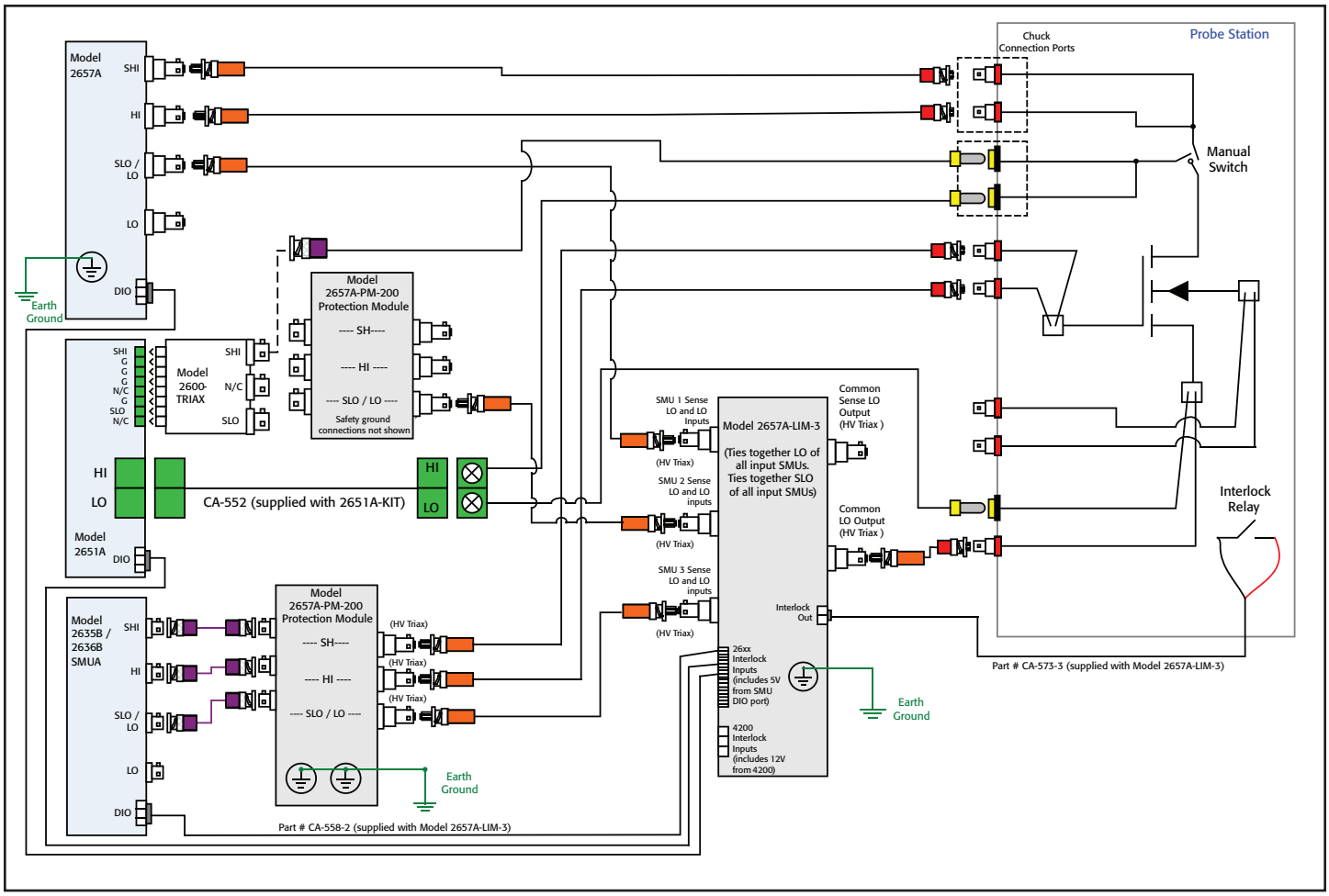

Figure 21. Connections to wafer-level device for high voltage and high current test.

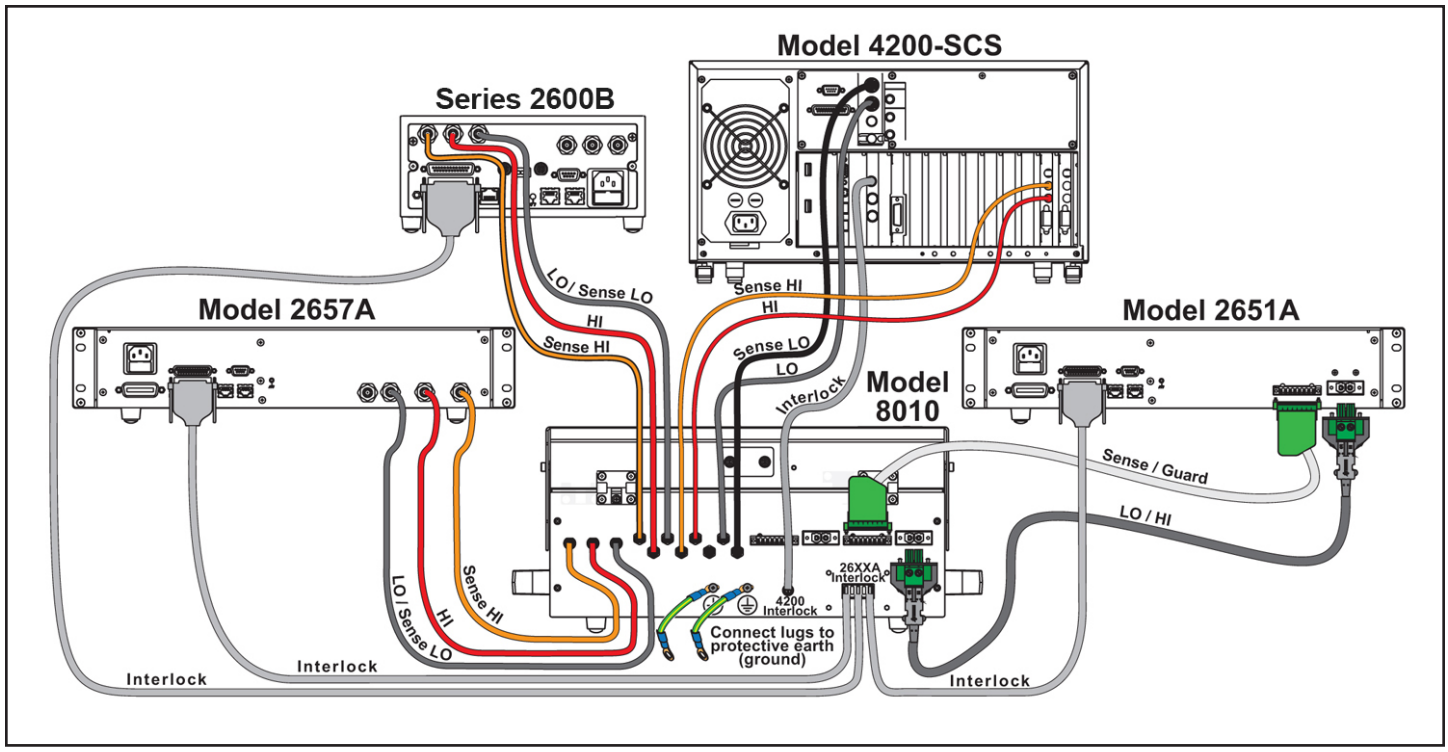

Figure 22. Connections from SMU instruments to Model 8010 High Power Device Test Fixture.

Contact Information:

ASEAN / Australia (65) 6356 3900

Austria 00800 2255 4835

Balkans, Israel, South Africa and other ISE Countries +41 52 675 3777

Belgium 00800 2255 4835

Brazil +55 (11) 3759 7627

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

Italy 00800 2255 4835

Japan 81 (3) 6714 3010

Luxembourg +41 52 675 3777

Mexico, Central/South America and Caribbean 52 (55) 56 04 50 90

Middle East, Asia, and North Africa +41 52 675 3777

The Netherlands 00800 2255 4835

Norway 800 16098

People's Republic of China 400 820 5835

Poland +41 52 675 3777

Portugal 80 08 12370

Republic of Korea 001 800 8255 2835

Russia / CIS +7 (495) 6647564

South Africa +41 52 675 3777

Spain 00800 2255 4835

Sweden 00800 2255 4835

Switzerland 00800 2255 4835

Taiwan 886 (2) 2656 6688

United Kingdom / Ireland 00800 2255 4835

USA 1 800 833 9200

Rev. 01/16

TEK.COM

For Further Information

Tektronix maintains a comprehensive, constantly expanding collection of application notes, technical briefs and other resources to help engineers working on the cutting edge of technology. Please visit tek.com

01/16 1KW-564660-1