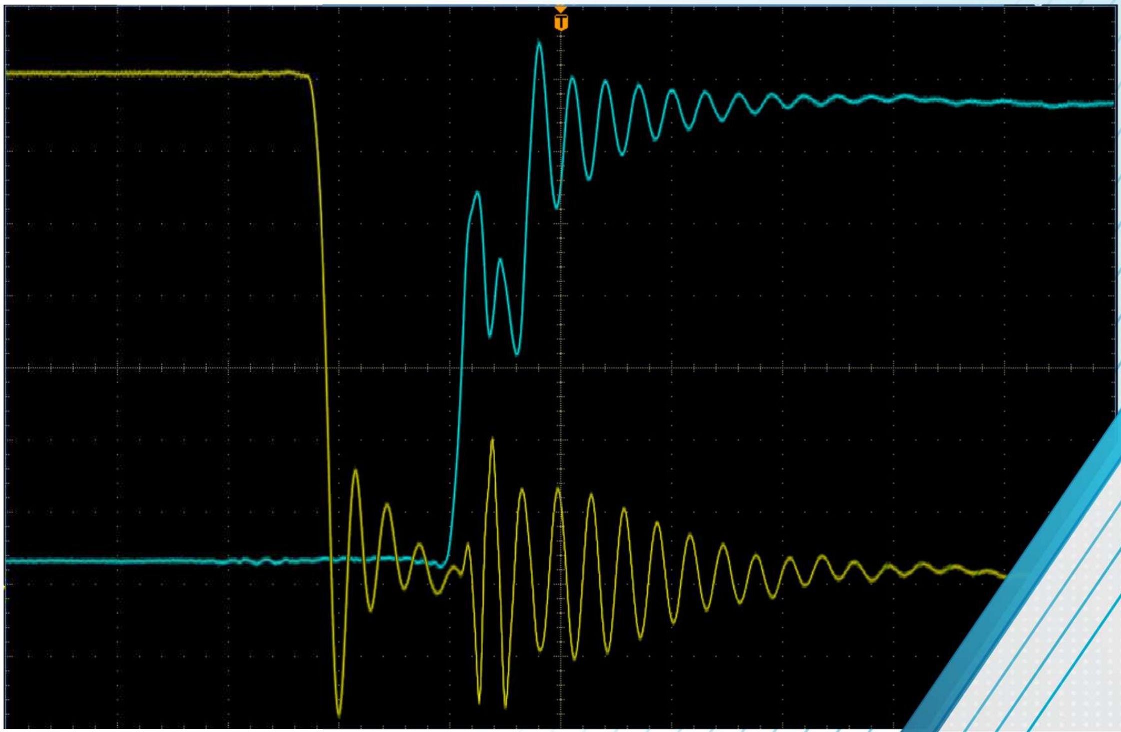
# Effective Measurement of Signals in Silicon Carbide (SiC) Power Electronics Systems

APPLICATION NOTE



## Introduction

After years of research and design, Silicon Carbide (SiC) power devices are rapidly being designed into a variety of power electronics applications. The shift from silicon to SiC is driving new energy-efficient designs from the ground up.

SiC has higher efficiency, faster switching, and improved thermal performance compared to silicon IGBTs and MOSFETs, resulting in increased power density and lower system costs.

SiC is finding applications in higher power, higher voltage designs such as motor drives in Electric Vehicles (EVs), EV fast-charging stations, on-board and off-board chargers, wind and solar inverters, and industrial power supplies.

As a sign of technology maturity, implementation of SiC technology in power conversion design has been documented in JEDEC standard JC-70.2; which defines SiC Power Electronic Conversion Semiconductor Standards and testing approaches.

Another sign of technology maturity is advanced evaluation boards from SiC FET suppliers like the Wolfspeed WolfPACK™ KIT-CRD-CIL12N-FMC. These boards enable engineers to characterize the dynamic performance and measure timing, speed, switching losses, and tune gate driver behavior for different applications.

Figure 1. Example of a Wolfspeed WolfPACK FM3 Power Module with pin grid design which allows for scalability and flexibility. *Photo © Wolfspeed. Reprinted with permission.*

What follows are some questions that a power system designer needs to consider when they shift to SiC;

- Is my test equipment capable of accurately measuring the fast switching dynamics in a SiC system?
- How can I accurately optimize gate drive performance and deadtime?
- Will common-mode transients affect the accuracy of measurements?
- Is the ringing that I see real, or the result of probe response?

Solving these challenges is tough for engineers. Also important is accurate visibility into all these signals 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. Using the right measurement equipment can make all the difference.

Designers can address validation of SiC circuit level performance with Tektronix IsoVu™ probes paired with a 4, 5 or 6 Series MSO Oscilloscope and the automated measurements which are available on the instrument.

To provide the needed visibility, the test equipment must electrically isolate the measurement channel before it goes to the oscilloscope. Power devices based on SiC can switch on and off in a few nanoseconds, driving the need for oscilloscope and probe bandwidths of 200 MHz or greater in order to capture the fast rising and falling edges of the transient. For example, using a 30 MHz Rogowski current sensor results in a 30% lower switching loss measurement compared to a 400 MHz current viewing resistor due to the fact that the 30 MHz probe does not capture the complete behavior of the switching waveform (Reference 3). A high-bandwidth, low noise signal provides the accuracy required for these important measurements.

This document focuses on the CAB011MI2FM3 high-performance, half-bridge module. The module features Wolfspeed® C3M® silicon carbide (SiC) MOSFETs and is part of the flexible Wolfspeed WolfPACK Power Modules family, one of which is shown in Figure 1. These modules eliminate the traditional baseplate for improved thermal performance. Additionally, the pin grid design allows for scalability and flexibility, with many module options in the same standard housing. This allows for the development of alternate converter configurations and topologies with minimal changes to thermal management systems and electrical design.

# Hardware Overview

## ENSURING MEASUREMENT ACCURACY IN SIC VALIDATION

The accuracy of time domain measurements and switching loss calculations is influenced by the accuracy, bandwidth, and delay of the probes used to collect the measurements. Several comparisons are shown between common instrument probes. While this discussion emphasizes the difference between oscilloscope probes, the specific implementation (such as layout, parasitics, and coupling) also plays a critical role in measurement accuracy. There are three important parameters to measure that enable proper validation of the power module utilizing SiC technology:

- Gate voltage
- Drain voltage
- Current

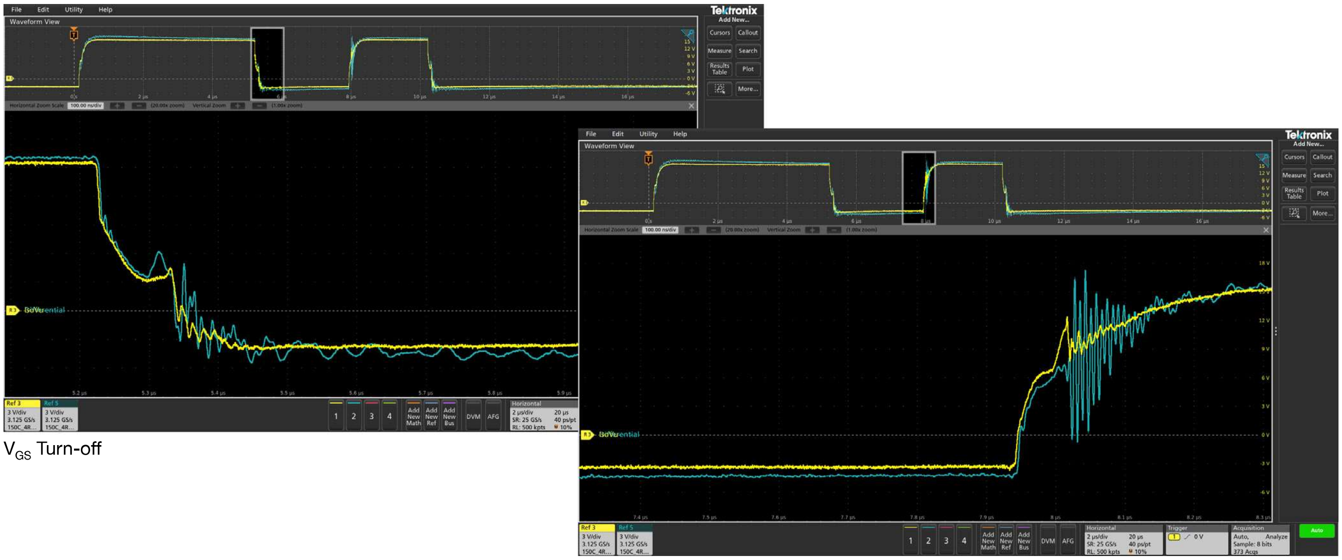
## GATE VOLTAGE MEASUREMENTS

Measuring the gate voltage of a SiC power device is challenging due to the fact that it is a low voltage signal (~20 Vpp) that is referenced to a node that may have a high DC offset and high dv/dt relative to the scope ground. Moreover, the greatest dv/dt occurs during the switching event, which is the time of most interest when measuring the gate signal. Even in topologies where the source of the device is connected to ground, the parasitic impedances between circuit ground and scope ground can still introduce erroneous readings due to the rapid transients. This requires a measurement device which is both decoupled from ground and which features a very large common mode rejection ratio. The traditional metrology for this gate voltage measurement is a standard differential probe (Figure 2), but newer, optically isolated probes such as the IsoVu Probing System (Figure 3) can make this measurement much more accurately.

Figure 4 shows a comparison of the high-side gate voltage for the standard differential probe versus the optically isolated probe. Both at turn-off and turn-on, high-frequency ringing can be seen on the gate after the device's gate passes through the threshold region. Due to coupling between the gate and power loop, some ringing is expected. However, in the case of the differential probe, the ringing has a significantly higher amplitude than is measured by the optically isolated probe. This is likely due to the changing reference voltage inducing common mode currents within the probe and an artifact of the standard differential probe. While the waveform measured by the differential probe in Figure 4 appears to pass the maximum gate voltage of the device, the more accurate measurement of the optically isolated probe makes it clear that the device is within specification. Application designers using standard differential probes for gate voltage measurements should use caution as it may not be possible to differentiate between the probing and measurement system artifact shown here and an actual violation of the device ratings. This measurement artifact may cause the designer to increase the gate resistance to slow down the switching transient and reduce the ringing. However, this would unnecessarily increase losses in the SiC device. For this reason, it is essential to have a measurement system that accurately reflects the actual dynamics of the device in order to appropriately design the system and optimize performance.

Figure 2. Example of a differential voltage probe, Tektronix Differential Probe THDP0200 with accessories.

Figure 3. Tektronix IsoVu TIVP1 optically isolated probe (TIVPMX10X, ±50 V Sensor Tip).



$V_{GS}$ Turn-off

$V_{GS}$ Turn-on

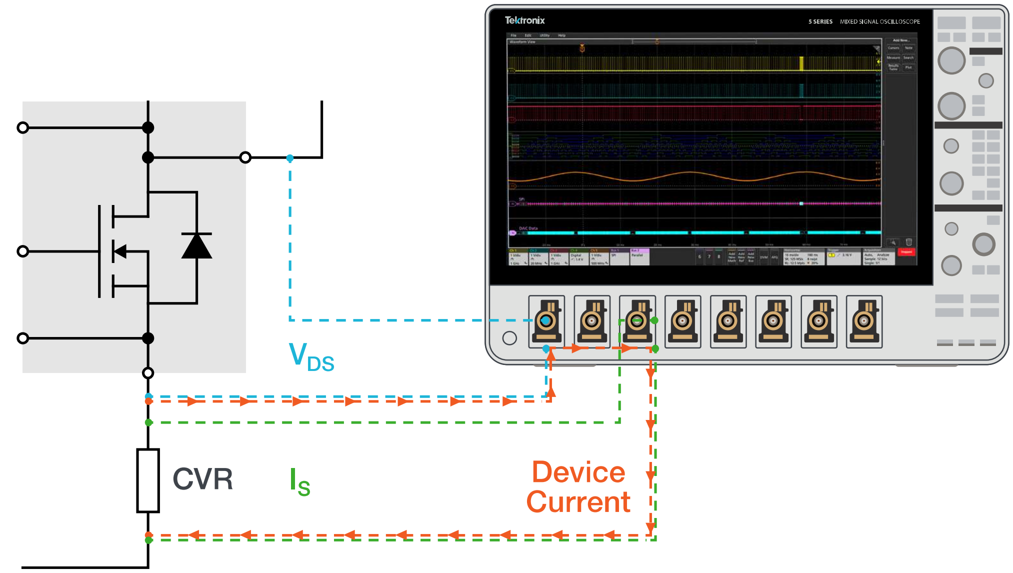
Figure 4. Differential Probe (blue trace) vs. IsoVu Optically Isolated Probe (yellow trace).

## DRAIN VOLTAGE MEASUREMENT

Two common methods for voltage measurement in power electronics systems are the differential probe and the ground-referenced probe. The differential probe, such as the one shown in Figure 2, is a popular choice since it can be added across arbitrary nodes of the circuit without issue. In contrast, the ground-referenced probes like the one in Figure 5 require caution in implementation as their shield pins are attached to the earth ground of the oscilloscope. Incorrect implementation of a ground-referenced measurement will generally lead to small ground currents on the probe reference which substantially reduce the accuracy of the measurement. This effect is more significant in SiC designs due to the high dv/dt which can introduce parasitic currents to flow in the scope probe ground reference, leading to measurement error. In more serious cases (where the ground reference shield is connected to a power signal), large currents can flow through the earth ground destroying the probe or oscilloscope. In the worst case, a failed connection from the instrument to earth ground can cause the outer metal casing of the oscilloscope to float to the bus voltage and pose a serious threat to operator safety.

Figure 5. Tektronix TPP0850 Voltage Probe. Single-ended, ground-referenced probe with 50× attenuation (up to 100$V_{RMS}$) and 800 MHz bandwidth.

The grounding issue becomes more critical when also using a ground-referenced current viewing resistor (CVR). As shown by Figure 6, when using a ground-referenced probe in combination with a CVR, it is possible to bypass the CVR via the scope shielding path. This can lead to the entire device current flowing through the oscilloscope, which is likely to destroy the voltage probe or oscilloscope. It also presents a substantial safety hazard. In general, differential probes are recommended for measurements of drain to source voltage.



Incorrect Probe Grounding

Figure 6. When two ground-referenced probes are attached to references at different voltage levels, the device current will bypass the CVR and flow through the ground leads and oscilloscope. This will cause erroneous measurements and possibly equipment damage.

## CURRENT MEASUREMENT

Figure 7. Probe examples, (a) Current Viewing Resistor (T & M Research SSDN-005, 400 MHz). *Photo © Wolfspeed. Reprinted with permission.* (b) Rogowski Current Probe (TRCP0600 Current Waveform Transducer, 30 MHz).

Two common methods for current measurement in power electronics systems are the current viewing resistor (CVR) and the Rogowski coil (Figures 7a and b). The Rogowski coil is a popular choice since it can easily be added to a circuit and is a non-invasive measurement; however, such probes often have significant bandwidth limitations that make them unsuitable for use with SiC. CVRs, on the other hand, have extremely high bandwidth and can be used to make accurate current measurements. Unfortunately, the need to add an additional component in series with the transistor requires careful planning during PCB layout, and the addition of a CVR will generally increase parasitic inductance in the circuit.

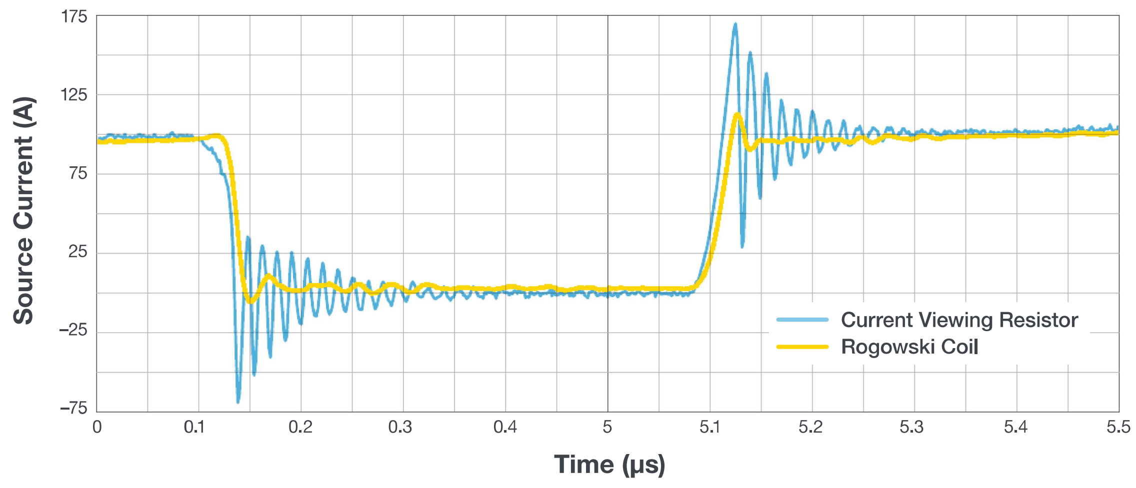


Figure 8. CVR vs Rogowski Current Probe, CAB016M12FM3 (TJ = 25°C, RG = 6.8, Vos= 600 V, Is = 100 A).

Figure 8 shows a comparison of the Rogowski coil and CVR for a typical SiC hard switching event. The substantially lower bandwidth of the Rogowski coil leads to an artificial suppression of the ringing present in the experimental waveform. More importantly, it artificially suppresses the initial overshoot and alters the di/dt of the measurement.

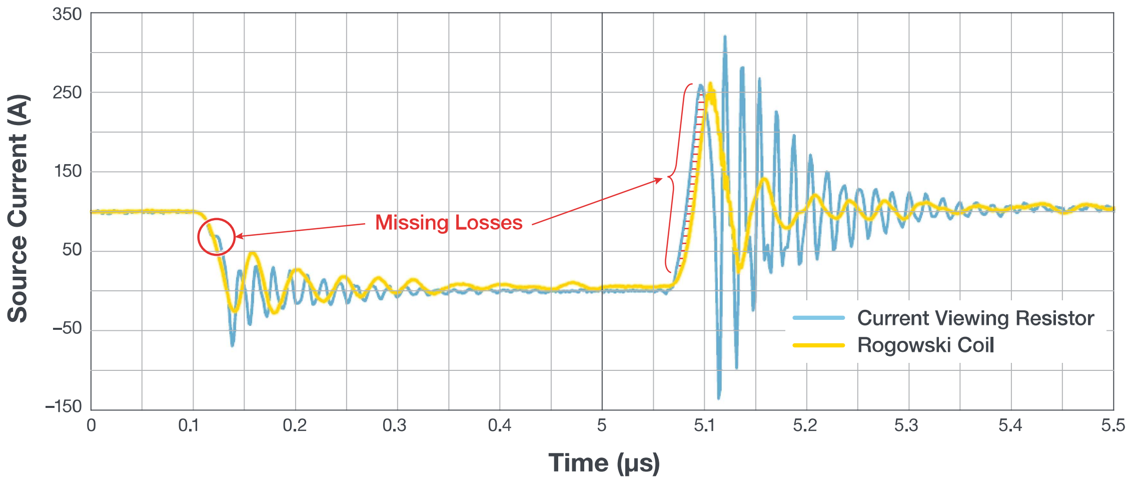


Figure 9. CVR vs Rogowski Current Probe, CAB011M12FM3 (TJ = 150°C, RG = 1 Ω), VDS = 600 V, IS = 100 A).

Figure 9 shows a comparison of the probes under a more aggressive switching condition. In the comparison, two points of interest are highlighted. First, at turn-off, the Rogowski coil cannot adequately capture the shape of the current waveform, missing the slight knee which will decrease the apparent switching losses. Additionally, the reduced di/dt shown at turn-on will also contribute to a lower predicted switching loss. The cumulative effect of the Rogowski coil's reduced bandwidth is a decreased estimate of switching losses.

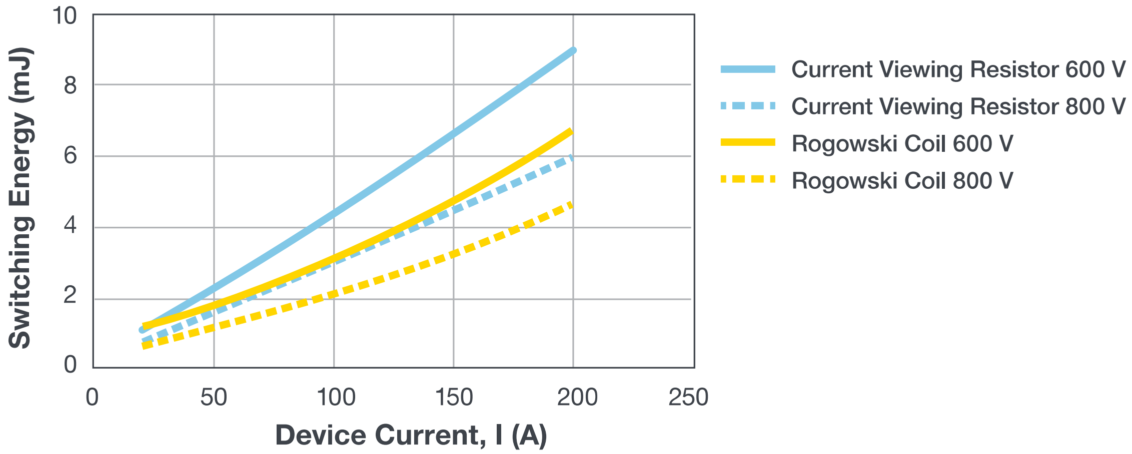


Figure 10. Switching loss (Eoff + Eon) estimation using different probes (CAB011M12FM3, TJ = 150 °C, RG = 1 Ω).

Figure 10 shows a direct comparison of the estimated switching losses for the Wolfspeed WolfPACK™ CAB011MI2FM3 across drain current. As mentioned above, the Rogowski coil consistently underpredicts the switching losses of the circuit giving an overly optimistic impression of the circuit losses. Because the discrepancy is related to the probe bandwidth limitations, it is dependent on edge rates of the transistor and will increase with more aggressive gate resistances. For slow switching technologies (such a IGBTs) the difference in metrology may be negligible.

## PROBE DESKEWING

In addition to using probes with sufficient bandwidth and noise rejection, the probes must be deskewed in time to ensure that the voltage and current signals have matched delays. A mismatch in delay between the voltage and current probes of just 1–2 ns can cause Eon and Eoff measurement error of 30% or more. Deskewing properly is critical for fast switching transients inherent in a SiC system.

Prior to deskewing, make sure to auto-zero and calibrate the probes as necessary to eliminate any offset or scaling errors.

Voltage probes for $V_{DS}$ and $V_{GS}$ can be deskewed by connecting both probes to a function generator with symmetrical connections. Use a square wave output from the function generator, and check that both the rising and falling edges of the signals are aligned.

There are several methods for deskewing $V_{DS}$ and $I_D$ probes to ensure proper switching loss measurements. The principle behind all the methods is to have a test circuit, such as the fixture shown in Figure 11, that is as close to purely resistive as possible so that the voltage and current waveforms are aligned. This test circuit can then be used to deskew the current probe to match the voltage probe response.

Figure 11. Power Measurement Deskew & Calibration Fixture (067-1686-00). These connections provide you with a convenient way to compensate for timing differences between voltage and current probes.

## Probe Connectivity Techniques for SiC Circuit-Level Validation

Performing the gate measurement involves careful consideration of connectivity options to ensure a clean signal capture from the power conversion module. Given that this is an ungrounded measurement made at higher voltages, connectivity is critical.

There are two primary connectivity approaches; MMCX, which provides a modular, pre-fabbed approach to device connectivity, and square pin, which has a connector that is adaptable to different PC board implementations. Here is a deeper review of both.

### MMCX STYLE SENSOR TIP CABLES (HIGH PERFORMANCE UP TO 250 V APPLICATIONS)

The best performance from the IsoVu Gen 2 measurement system is achieved when an MMCX connector is inserted close to the test points. Figures 12 and 13 show two different applications. MMCX connectors are an industry standard and are available from many electronic component distributors. These connectors offer high signal fidelity. The solid metal body and gold contacts provide a well-shielded signal path. The mating MMCX interface offers a snap-on connection with a positive retention force for a stable, hands free connection. The disengage force provides a safe, stable connection for high voltage applications. MMCX connectors are available in many configurations as shown below and can be adapted to many designs, even if the connector was not designed into the board. Information for soldering these connectors into your design can be found at [www.tek.com/isolated-measurement-systems](www.tek.com/isolated-measurement-systems).

Figure 12. MMCX connectors - Example 1. *Photo © Wolfspeed. Reprinted with permission.*

Figure 13. MMCX connectors - Example 2. *Photo © Wolfspeed. Reprinted with permission.*

### SQUARE PIN TO MMCX ADAPTERS

When an MMCX connector cannot be used, the tip cable can be adapted to fit onto industry standard square pins. Tektronix provides probe tip adapters to connect the sensor tip cables to square pins on the circuit board. Two adapters with different pitches are available, MMCX-to-0.1-inch (2.54 mm) and MMCX-to-0.062-inch (1.57 mm).

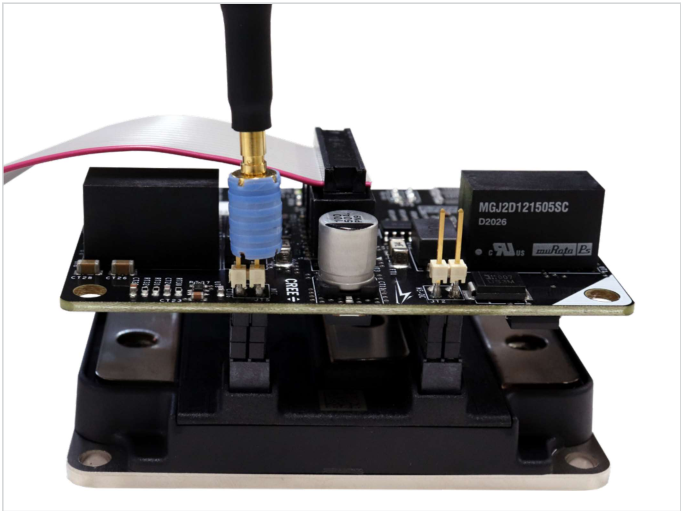


Figure 14. MMCX to Square Pin Adapter. *Photo © Wolfspeed. Reprinted with permission.*

The adapters (Figure 14) have an MMCX socket for connection to an IsoVu tip cable. The other end of the adapter has a center pin socket and four common (shield) sockets around the outside of the adapter. Notches on the adapters can be used to locate the shield sockets. The best electrical performance is achieved when the probe tip adapter is close to the circuit board.

### SQUARE PIN STYLE SENSOR TIP CABLES

The TIVP Series (IsoVu Gen 2) probes also include square pin style sensor tip cables to achieve higher input differential voltage capability, as shown in Figure 15. These tip interfaces offer both ease of connectivity and a secure connection for safe, hands free operation in high voltage environments. The square pin style sensor tip cables are available in both 0.100˝ (2.54 mm) pitch which can be used in applications up to 600 V and 0.200˝ (5.08 mm) pitch which can be used in applications up to 2500 V.

Figure 15. Square pin style sensor tip cables. *Photo © Wolfspeed. Reprinted with permission.*

### UNPLANNED TEST POINTS

Ideally, test points are planned ahead of time and integrated into the layout of your gate driver or evaluation boards such as in the Wolfspeed KIT-CRD-CIL12N-FMC Wolfpack Evaluation Kit. In this scenario, MMCX connectors will provide the best performance and are recommended if the signal of interest fits within their 300 Vpk voltage rating.

Of course, one cannot always anticipate every possible test point. When the situation calls for adding an unplanned test point, like the one in Figure 16, follow these guidelines to ensure the most accurate measurement possible:

1. Use an MMCX connector when voltage ratings allow.
2. Position the connector as close to the IC or component as safely possible.
3. Likewise, keep any required flying leads short or non-existent.
4. Mechanically reinforce the connector using non-conductive hot glue, kapton tape, or similar.

In the following example, a square pin header was added to a $V_{GS}$ test point after the boards were assembled. The test point is reinforced with non-conductive hot glue to add strength.

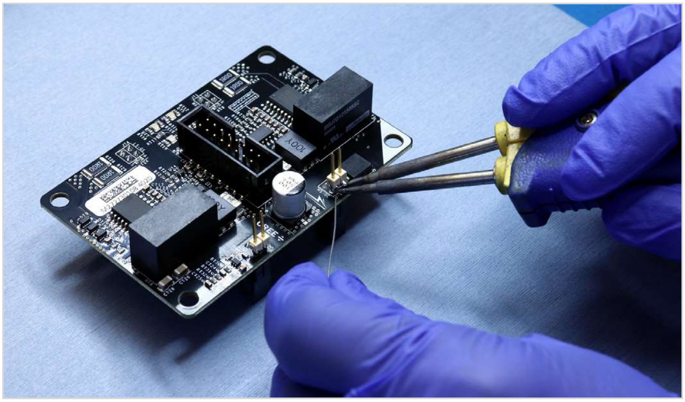


Figure 16. Soldering a square pin header across $V_{GS}$ nodes to measure high-side gate drive signal. *Photo © Wolfspeed. Reprinted with permission.*

## Summary

In summary, wideband gap semiconductor technology will play a big role in the future of power conversion and energy-efficiency. SiC switches are smaller, faster, and more efficient than their silicon equivalents. They are being used in a wide variety of applications from electric vehicles to photovoltaics. So, it becomes important to test using proper tools so that designers can design, develop and integrate into final applications correctly. Tektronix portfolio solutions play a key role.

IsoVu™ Isolated Probing Systems provide a floating, non-grounded differential probing experience well-suited for gate measurement needs. Bandwidth models range from 200 MHz to 1 GHz with a variety of probing tips attenuated for higher voltage signals, if needed.

5 Series MSO Oscilloscope is a high resolution (12-bit) oscilloscope ideal for testing small voltages in presence of much higher voltages. For example, testing $V_{GS}$, RDS_ON, and conduction losses in presence of $V_{DS}$ voltage requires high vertical resolution. Additionally, it has 8 available channels for you to see more timing signals at the same time to optimize your performance and investigate correlation between a high number of signals.

5-PWR software is designed to run automated, accurate, and repeatable power measurements on the 5 Series MSO Oscilloscope including switching losses, conduction losses, RDS_ON, magnetic losses, SOA, and more under real operating conditions.

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