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# *Spurious Turn-On Investigation For SiC MOSFETs In Hard-Switched Half-Bridges*

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High-voltage 650-V and 750-V silicon carbide (SiC) MOSFETs are key enablers for hard-switching half-bridge topologies. However, in these designs, the SiC MOSFETs may encounter spurious or random turn-ons. These events are not well documented, but they can cause increased switching losses and, in worst case, device failures if not prevented or minimized. To understand these occurrences better, an in-depth study was conducted.

This article begins with a brief look at one of the half-bridge topologies where SiC MOSFETs are vulnerable to spurious turn-on—the totem-pole PFC. While bipolar drive can prevent this problem, it comes at a cost, so ideally it would be preferrable to apply unipolar drive with its various benefits. Next, the causes of spurious turn-on are explained and the conditions that ensure it will not occur are stated.

With that as background, a series of double-pulse test measurements are presented that compare the reverse-recovery charge of commercially available SiC MOSFETs under unipolar versus bipolar driving. This allows us to evaluate the impact of spurious turn-on on circuit performance under unipolar driving, and to quantify the performance differences between these two driving schemes under different circuit conditions. Based on that some guidance is offered on the use of unipolar driving of SiC MOSFETs.

## *Background*

Hard-switching half-bridge topologies that use high-voltage 650-V and 750-V SiC MOSFETs in a fast leg often have a slower leg that uses superjunction MOSFETs, IGBTs and diodes. For example, this occurs in a continuous conduction mode (CCM) totem-pole in power factor correction (PFC) operation. Using a relatively simple control strategy, this topology has enabled power supplies designers to push the efficiency of the PFC stage to 99% and above.

For SiC MOSFETs used in the fast leg of these topologies, many suppliers recommend a bipolar instead of unipolar gate drive. In addition to providing immunity against spurious turn-on in half-bridge hard-switched topologies, a bipolar drive minimizes turn-off losses as much as possible when $R_{g,off} = 0\ \Omega$ is not enough. However, this drive circuitry comes at the expense of an increased bill of materials (BOM) count and cost as well as greater design/layout complexity.

In contrast, a unipolar drive uses simpler gate-drive circuitry and bootstrapping is possible. In addition to a lower component count for Zener diodes, capacitors, transformer windings, and more, there is also a printed circuit board (PCB) area savings. From an electrical device parameter standpoint, the unipolar drive means a lower body diode $V_{SD}$ and lower bipolar charge during reverse recovery. With the advantages of unipolar drive, some suppliers (including Infineon) are recommending it for SiC MOSFETs.

## *Spurious Turn-On Explained*

To prove a device is fully immune to parasitic turn-on, it must have a gate-source voltage that is lower than the threshold voltage—even when the maximum switching speed is used, which is the absolute worst case.

Let’s consider a hard-switched half-bridge circuit and assume the inductor to be pre-energized (freewheeling current flows through the body diode of the low side (LS) MOSFET): when the $V_{GS}$ of the high-side (HS) MOSFET goes high, the MOSFET turns on. As a result, the $V_{DS}$ of the LS MOSFET rises from 0 V to 400 V (typical bus voltage for 650-V/750-V devices). The positive dV/dt results in a displacement current flowing through the $C_{gd}$ of the LS MOSFET. Part of this current flows through the $C_{gs}$ resulting in a $V_{GS}$ glitch.

If the $V_{GS}$ glitch > $V_{(GS)th}$ the LS MOSFET parasitically turns on (PTO), resulting in cross-conduction through the HS and LS switches. By applying a negative off-state voltage to the gate with a bipolar drive, it is possible to ensure that the device stays in the off-state.

The worst-case condition for Miller-capacitance-induced spurious turn-on occurs with an open gate, which implies an infinite impedance in the gate loop. The condition for the device to be off is $V_{GS} < V_{th}$, so the charge (Q) on the gate-drain ($Q_{GD}$) and gate-source ($Q_{GS}$) capacitance is:

$$\frac{Q_{GD} @\, 400\ V}{Q_{GS}\ @\ V_{th}} < 1$$

This is a sufficient but not necessary condition to verify the absence of a capacitive-induced parasitic turn-on condition under the assumption of negligible gate-drain PCB parasitic capacitance.

## *Verification Measurements*

Double pulse tests (DPT) provide the ability to test a power stack under worst-case corner operating conditions early in the design. For these tests, the circuit in Fig. 1 was used. According to theory, the SiC MOSFET used as device under test in this example is *not* fully immune to spurious turn-on.

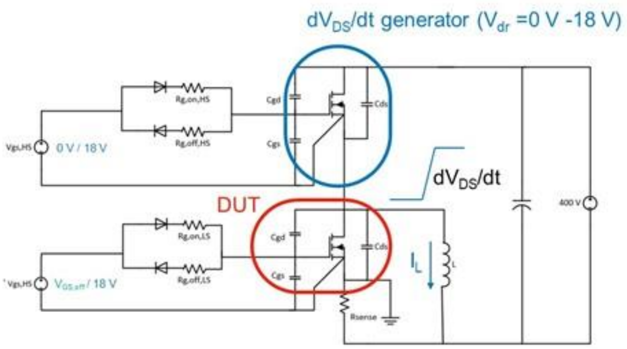

*Fig. 1. The test circuit for evaluating the theory and the possibility of using unipolar drive circuitry.*

Fixed parameters in the test circuit include

- $V_{bus}$ = 400 V
- $I_L$ = 35 A
- $R_{g,on} = R_{g,off}$ = 0 Ω for HS and LS MOSFETs to maximize switching speed (worst case)
- Power loop inductance ≈ 15 nH
- AIMDQ75R040M1H[1] SiC MOSFETs with:
    - 40 mΩ typ 750 V in PG-HDSOP-22
    - DUT charge ratio: $\frac{Q_{GD\ @\ 400\ V}}{Q_{GS} @\ V_{th @ 25\,°C}} = 1.8 > 1.$

For the verification testing, parameters to vary include

- Off-state gate-source voltage of LS MOSFET ($V_{GS,off}$)
- Device under test (DUT) case temperature ($T_c$)
- Body-diode conduction time ($T_{cond}$) ≈ dead-time.

In the double-pulse test, measurements and observations focused on

- DUT reverse recovery
- Impact of $V_{GS}$ off-state voltage
- Temperature impact
- Impact of body-diode conduction time.

The measurements provide a comparison of the reverse-recovery charge ($Q_{rr}$) of commercially available SiC MOSFETs driven with unipolar and bipolar driving to quantify the performance difference between these two driving schemes.

## *Findings*

As shown in Fig. 2, at ambient temperature ($T_c$ = 25°C) and $dV_{ds}/dt$ in excess of 100 V/ns, unipolar driving (with $V_{GS}$= 0, solid curves), compared to bipolar driving (with $V_{GS}$=-5 V, dotted-line curves) leads to mild spurious turn-on (higher $Q_{rr}$ and $E_{rr}$), softer body-diode-recovery behavior and lower $V_{ds}$ overshoot and $dV_{ds}/dt$.

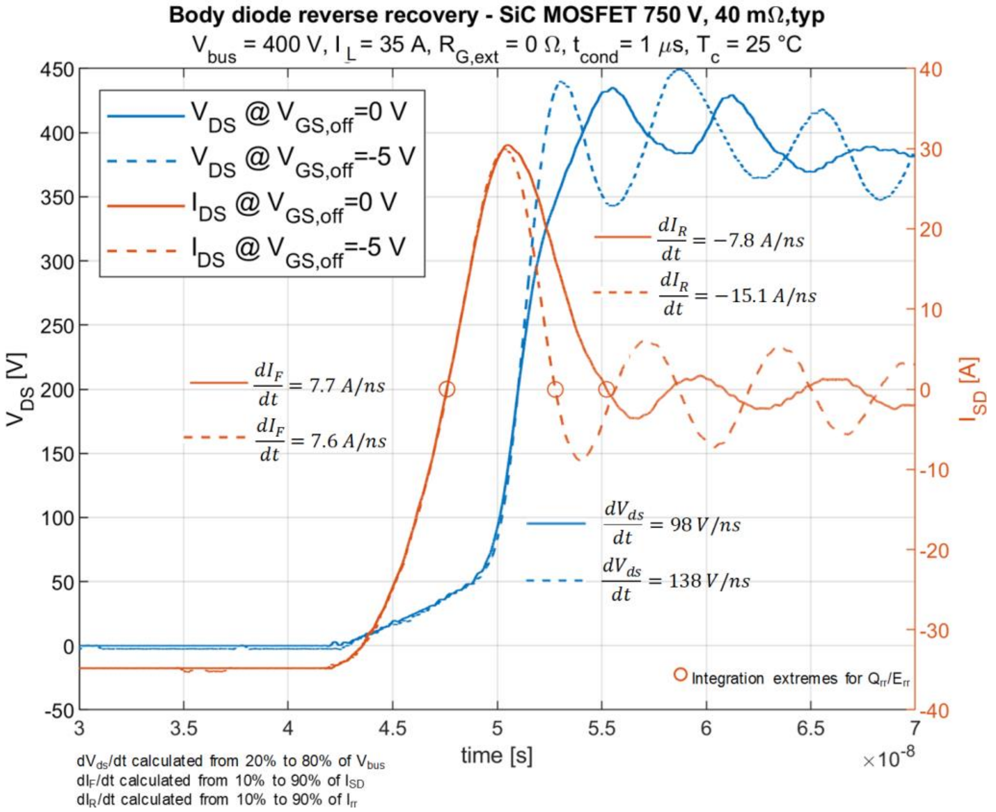

*Fig. 2. Unipolar to bipolar drive comparison at $T_c$ = 25°C.*

Looking at the reverse-recovery charge for 25°C for $V_{GS}$ off, 0 V, the charge is higher than when the MOSFET is kept off at -5 V. This suggests that at 25°C there is a fair amount of parasitic turn-on. However, at higher temperatures (125°C), the lines are essentially reversed. When driving the MOSFET with a negative voltage there is a slightly higher reverse-recovery charge as will be seen in subsequent measurements.

Varying the DUT case temperature for a given $V_{GS}$ off-state voltage of -5 V (the bipolar drive), showed that increasing $T_c$ from 25°C to 125°C resulted in more than a doubling of reverse-recovery charge, a substantial increase of $V_{ds}$ overshoot (> 60 V), an approximate halving of $dV_{ds}/dt$ and no significant change in body-diode softness (see Fig. 3).

As the results in Fig. 4 illustrate, at an operating temperature of 125°C unipolar driving results in no evident spurious turn-on similar to bipolar driving (-5 V). What's more, unipolar driving at this elevated temperature exhibits softer body-diode reverse recovery compared to bipolar driving (-5 V), lower $V_{ds}$ overshoot compared to bipolar driving (-5 V) and slightly lower $Q_{rr}$ compared to bipolar driving ($V_{GS,off}$ = -5 V).

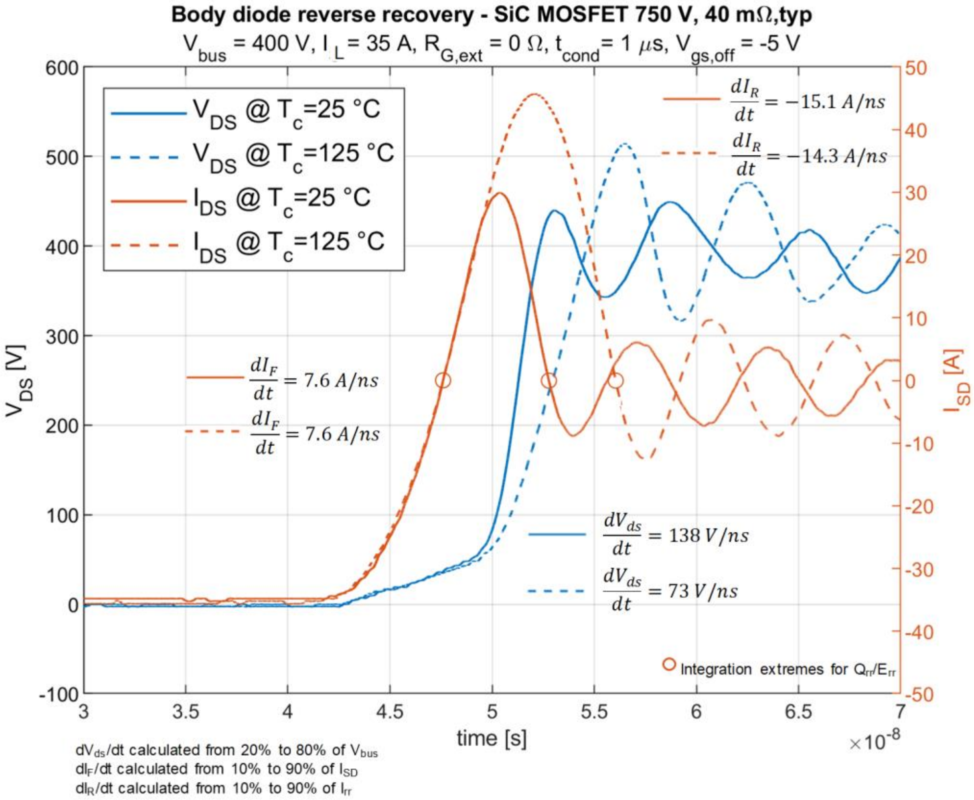

*Fig. 3. Impact of DUT case temperature for a given $V_{GS}$ off-state voltage (-5 V).*

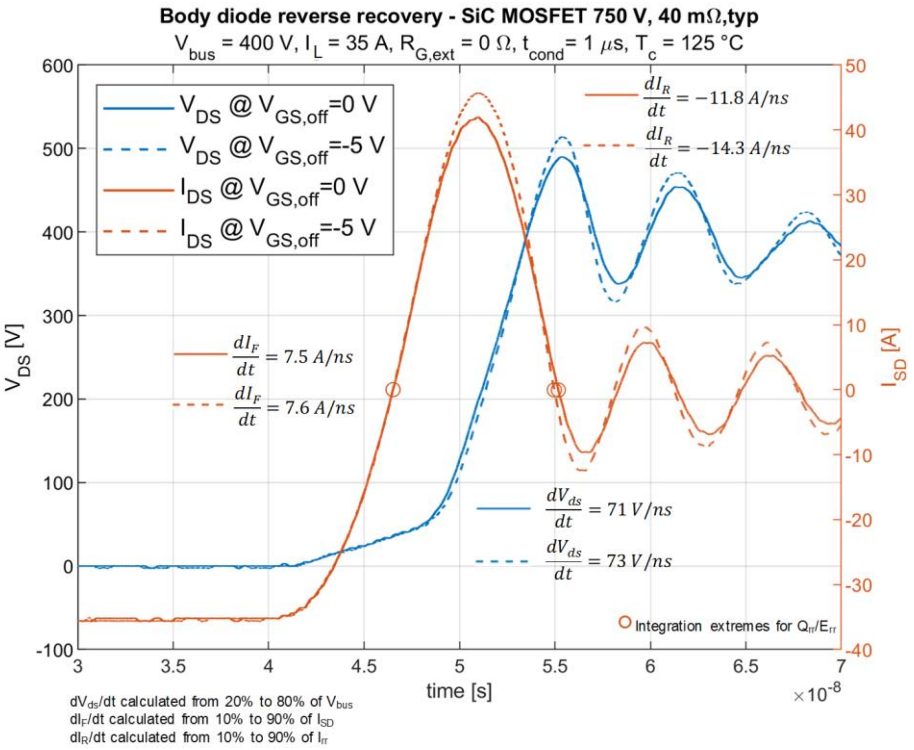

*Fig. 4. Impact of $V_{GS}$ off-state voltage at operating temperature ($T_c$ = 125°C).*

Evaluating the impact of body-diode conduction time at operating temperature ($T_c$ = 125°C) resulted in reducing the body-diode conduction time from 1 µs to 50 ns (see Fig. 5). This leads to a substantial reduction of $Q_{rr}$ reverse-recovery charge/energy as well as faster switching transition, but also lower $V_{ds}$ overshoot. Similar softness of the body-diode recovery behavior was observed, too.

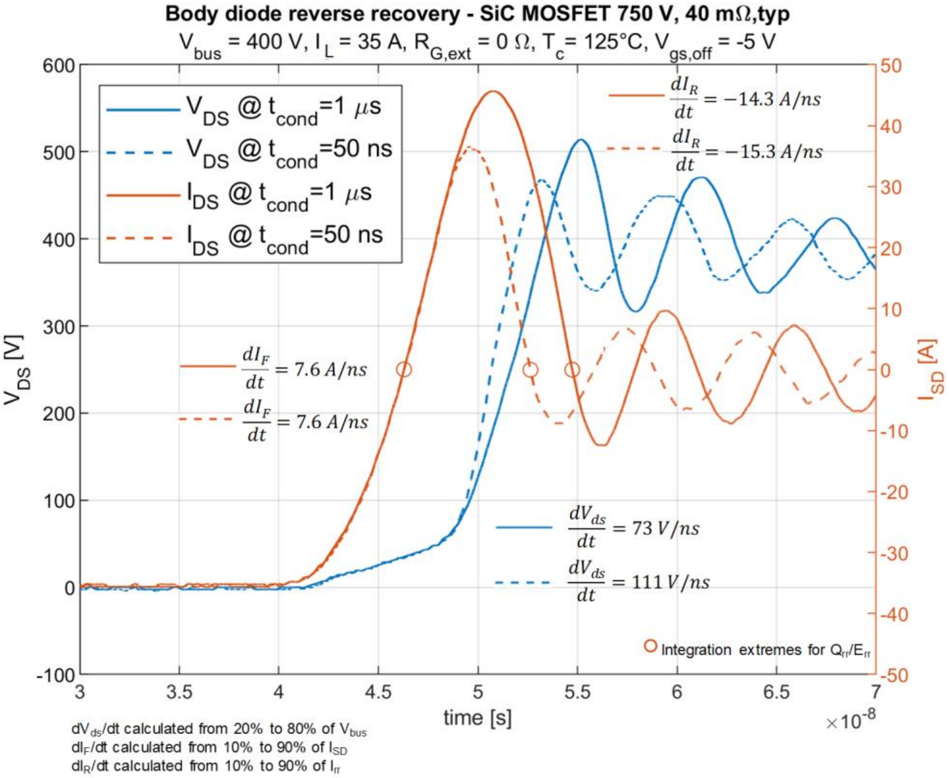

*Fig. 5. Impact of body-diode conduction time at operating temperature ($T_c$ = 125°C).*

Analyzing the impact of $V_{GS}$ off-state voltage at operating temperature ($T_c$ = 125°C) and short body-diode conduction time ($t_{cond}$ = 50 ns) (see Fig. 6), unipolar driving leads to a reduction of reverse-recovery charge vs $V_{gs,off}$ = -5 V, lower $V_{ds}$ overshoot, despite similar $dV_{ds}/dt$, and softer body-diode recovery behavior. So, there is no evident sign of spurious turn-on under these conditions.

Fig. 7 shows the summary of the double-pulse tests carried out at the highest possible switching speed. In these tests, the reverse-recovery behavior of the SiC MOSFET DUT body diode showed a strong dependency on both the DUT case temperature and body-diode conduction time. It can also be seen that to squeeze the best performance out of the device the body-diode conduction time, hence dead time, should be reduced as much as possible.

Finally, Fig. 7 shows that at operating temperature (125°C) and short body-diode conduction times the difference in the $Q_{rr}$ of the device between unipolar (0 V) and bipolar (-5 V) gate drive is negligible. However, when driven with unipolar gate drive the SiC MOSFET exhibits lower $V_{ds}$ overshoot and softer body-diode recovery behavior.

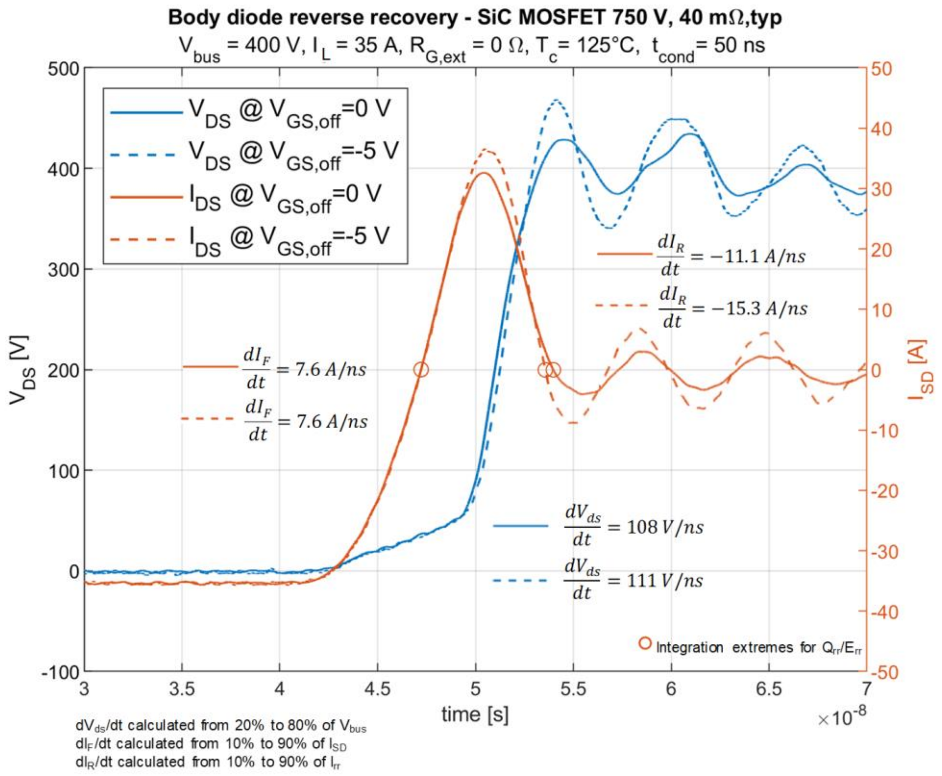

*Fig. 6. Impact of $V_{GS}$ off-state voltage at operating temperature ($T_c$ = 125°C) and short body-diode conduction time ($t_{cond}$ = 50 ns).*

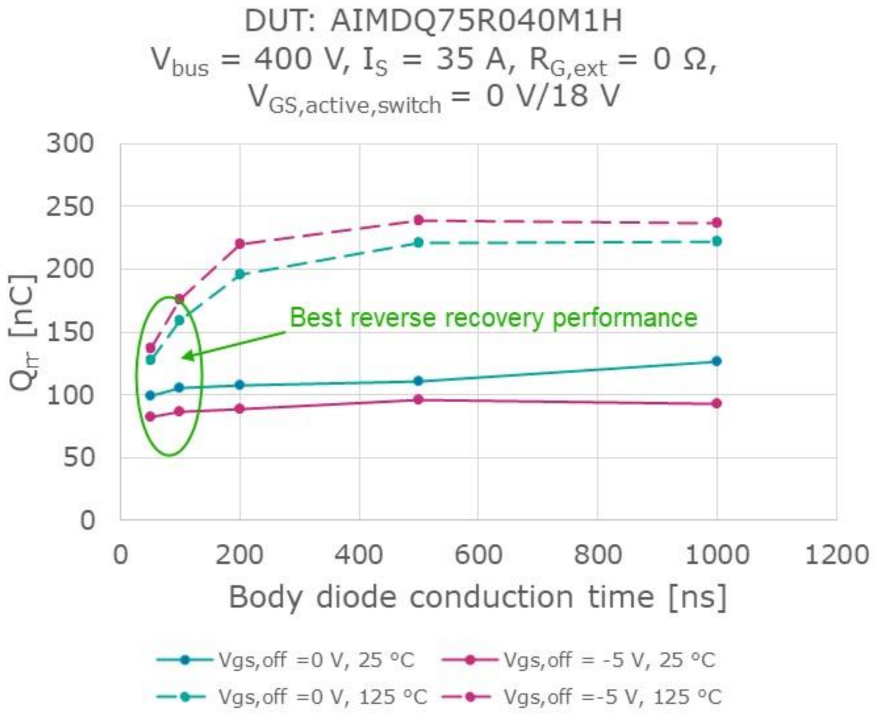

*Fig. 7. In the double-pulse test, the unipolar drive demonstrated excellent performance.*

## *Summary And Design Options*

A comparison of the switching energies of commercially available Infineon 750-V SiC MOSFETs[2] driven with unipolar and bipolar driving was conducted to quantify the performance difference between these two driving schemes. While unipolar drives have historically been dismissed for driving high-voltage SiC MOSFETs, this testing has verified/confirmed that high-voltage SiC MOSFETs can be safely driven with a unipolar drive.

However, since parasitic turn-on is strongly related to circuit parasitics, for complete confidence in a particular application, users need to perform their own testing to verify the entire circuit's viability. While Infineon devices have been shown to be capable of using a unipolar drive, they are also compatible with bipolar drives that have a negative voltage, so users have a choice and flexibility in their design.

### References

1. AIMDQ75R040M1H product page.
2. Silicon Carbide MOSFETs page.

## About The Author

*Nico Fontana joined Infineon Technologies Austria in 2016 where he works as principal product definition engineer for Automotive SiC MOSFETs. Nico has experience in the semiconductor industry with a focus on on-board-charger and traction inverter applications. He received his master's and bachelor's degrees in electronic engineering from the University of Udine, Italy.*

For more on designing with SiC power devices, see How2Power's Design Guide, locate the "Popular Topics" category and select "Silicon Carbide and Gallium Nitride".