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Dynamic Characterization of SiC Diodes

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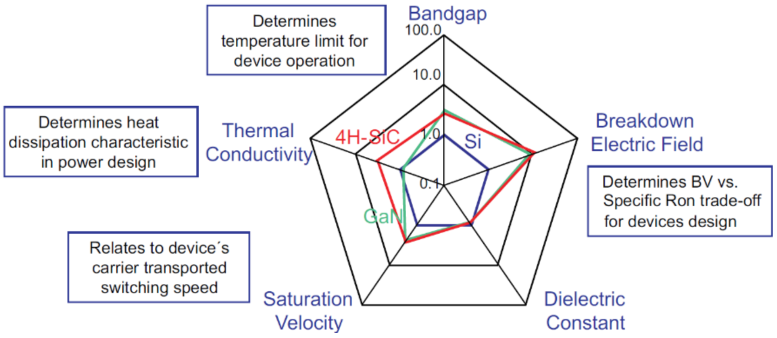
1. Introduction

This application note describes the switching behaviour of silicon carbide (SiC) Schottky barrier diodes (SBD) and how they differ from MOSFET pn body diodes.

1.1 Silicon vs silicon carbide

Silicon and silicon carbide products are made from different base materials. Silicon products are made from pure Si wafers, whereas SiC wafers contain both silicon and carbon. The differences in material give SiC a wide range of benefits over pure silicon, such as a higher switching speeds and heat dissipation (Figure 1).

Figure 1: Impact of different physical parameters of semiconductor materials [2]

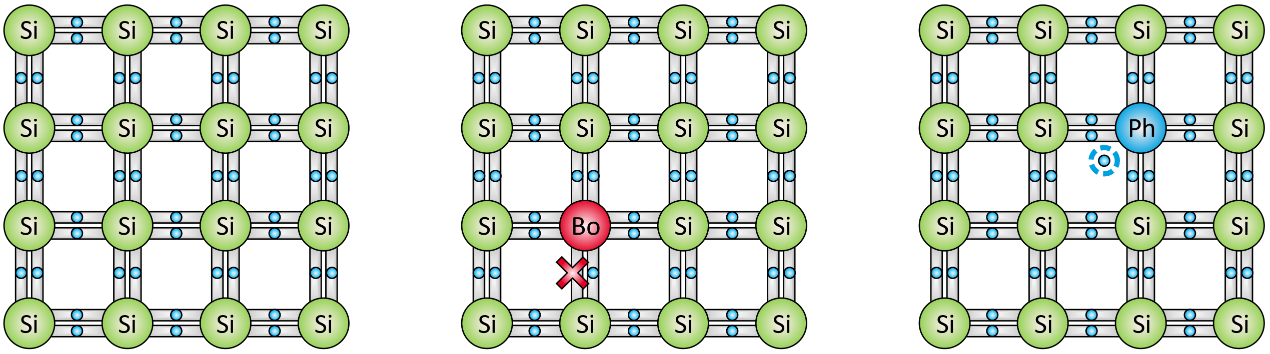


1.2 Semiconductor doping

Silicon can be positively or negatively doped by implanting various elements into the crystal structure. For example, boron has one fewer electron than silicon. When it takes the place of a silicon atom (Figure 2, left/middle), the missing electron from the boron creates a "hole" (the absence of an electron) which is considered a positive charge carrier. The boron-doped silicon is then said to be positively doped (p) and the relative amount of doping is often indicated by the signs + (strongly) or – (weakly).

Conversely, phosphorous has one more electron than silicon. When silicon is doped with phosphorus (Figure 2, right), the extra electron becomes a negative charge carrier. The phosphorous-doped silicon is then said to be negatively doped (n). Other positive and negative dopants are used.

Figure 2: Pure silicon (L), boron doping (M), phosphorous doping (R)

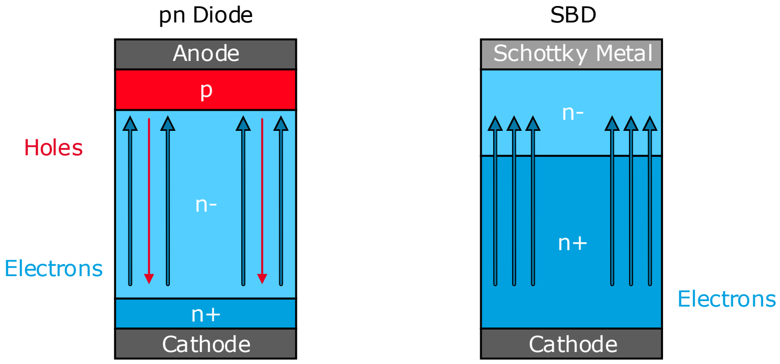


1.3 pn junctions vs. Schottky barrier junctions

A pn junction is formed where positively (p) and negatively (n) doped silicon meet. A pn diode is composed of a single pn junction (Figure 3, left). When forward biased, free electrons in the n-doped region and holes in the p-doped region move through the crystal, creating electron-hole plasma. Since both electrons and holes carry the current when conducting, pn diodes are called bipolar devices.

A Schottky barrier junction is formed when a layer of metal is in direct contact with an n-doped semiconductor. This junction behaves as a diode, and the resulting device is called a Schottky barrier diode (SBD). These devices have no p-dopant, and therefore no holes are generated during conduction. This lack of holes means only electrons are used to carry the current in a SBD (Figure 3, right), therefore they are called unipolar devices.

Figure 3: Generic structure of two diode types



Silicon pn diodes typically become forward biased around 0.7V. Without a pn junction to bias, the initial forward voltage drop of Schottky barrier diodes is lower, in the range of 0.3V for Si.

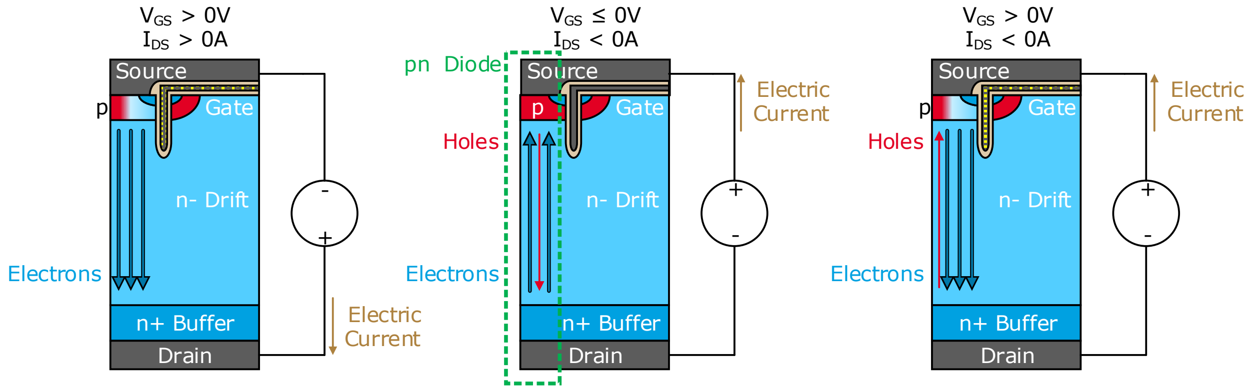
Silicon carbide devices have a wider bandgap (Figure 1). This is the energy required to move an electron from the valence band to the conduction band where it can be used to carry current. Because of this wider bandgap, more energy is needed to forward bias the junction and as a result silicon carbide pn diodes have a much higher voltage drop than Si. For this reason, diodes constructed from silicon carbide (and other "wide bandgap" materials) are typically Schottky barrier type rather than pn.

Another reason for that SBDs are often used in silicon carbide is related to blocking voltage capability. Without a pn junction to reverse bias, Schottky barrier diodes have a much lower breakdown voltage. This has historically limited the application of silicon SBDs in high voltage power electronics. However, the higher breakdown electric field strength of SiC has enabled commercially available 650V and higher SBDs.

1.4 MOSFET body diode

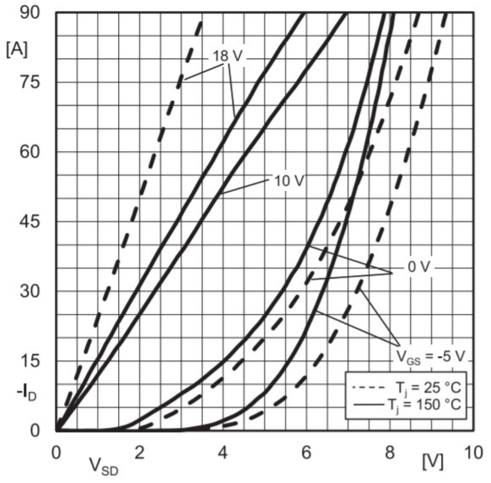
When a positive gate voltage is applied to a MOSFET, the p-doped body region is biased and a channel is opened. Positive (conventional) current can then flow through the device from drain to source (Figure 4, left). The p-doped body and n-doped drift regions of a MOSFET (whether Si or SiC) form a pn diode. This "body" diode becomes forward biased (active) when the MOSFET is reverse biased (Figure 4, middle).

Figure 4: Generic structure of trench MOSFET



The body diode is electrically in anti-parallel with the drain-source channel of the MOSFET, so the behaviour of the diode varies dramatically with the gate voltage. If the MOSFET channel is off (V_{GS} ≤ 0V), the body diode behaves like a typical pn diode with an exponentially increasing forward voltage vs current (Figure 4, middle). With a positive gate voltage, the MOSFET channel is partially opened allowing for a lower impedance path (Figure 4, right) and the vast majority of current carried by electrons. This gives a lower voltage drop than if the body diode alone was conducting (Figure 5).

Figure 5: Example MOSFET body diode forward characteristic [4]



2. Turn-off Behaviour for Different Diode Types

The behaviour of a diode during turn-off is a key parameter in power electronic circuits for evaluating stability and switching losses. The pn and Schottky barrier diodes described above exhibit different behaviours when switching off (e.g. when current is commutating from a diode to a MOSFET in a half-bridge circuit).

When making measurements on a physical device, only the total drain-source current (I_{DS} or I_f) can be measured. Depending on the semiconductor structure (e.g. pn, SBD) different charge carriers contribute to the total current.

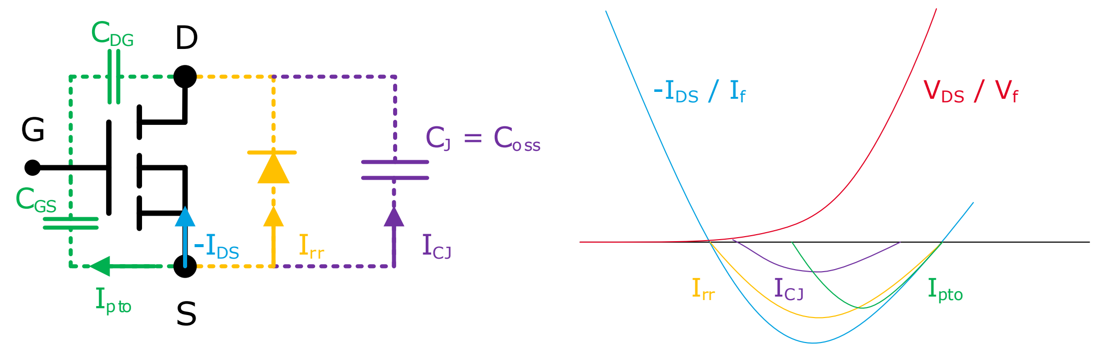
The total current is made up of multiple currents within the device, depending on its type. . When each part of the current is multiplied with V_{DS} (V_F) and integrated, a partial switching energy is calculated that contributes to the total measured switching energy.

2.1 MOSFET body diode

For any MOSFET, the measured current through the device during diode turn-off ($-I_{DS}$ / I_f) consists of up to three component currents:

- Reverse recovery current, I_{rr}
- Capacitive junction current, I_{CJ}
- And possibly parasitic turn-on current, I_{pto}

Figure 6: Components of reverse current in MOSFET body diode



The following description is a simplified model approach used for a better understanding of parallel dynamic processes.

I_{rr} in pn diodes (i.e. the MOSFET body diode) is the reverse recovery current generated by the recombination of electron-hole plasma which is proportional to the current flow before turn-off. As the plasma is removed from the device, the resulting reverse recovery charge (Q_{rr}) is dissipated in the chip. This is a loss mechanism and generates heat within the device, called E_{rr}.

I_{CJ}, another component of the current, flows into the junction capacitance as it is charged and voltage builds up across the device. The resulting energy that flows into the capacitance can be roughly estimated ($E_{CJ} \approx \frac{1}{2} \cdot C_J \cdot V^2$). However, because this is purely capacitive, no real power losses are generated by E_{CJ} aside from minor resistive losses in the circuit. The measured power is stored in the electric field across the junction.

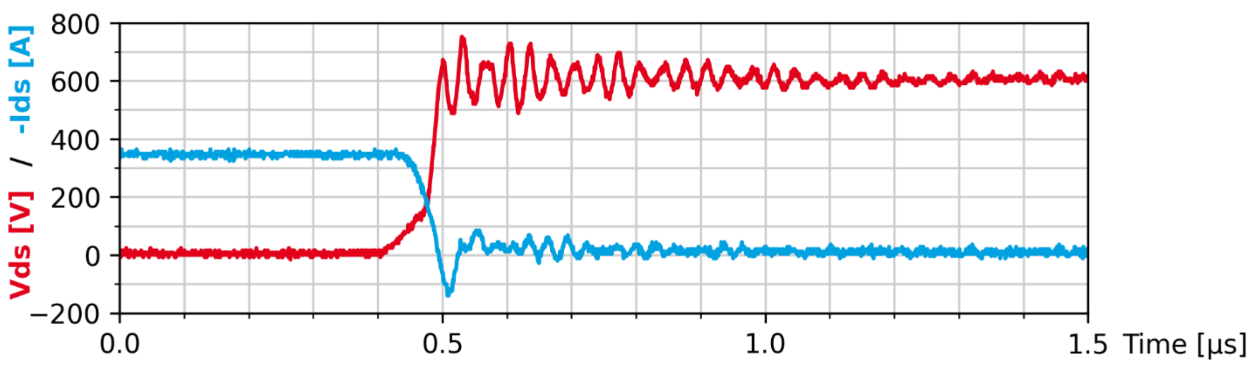
I_{pto} is the current that flows through the MOSFET if the gate voltage rises above the threshold voltage. Many SiC MOSFETs have a lower threshold voltage and a high V_{GSoff} (i.e. closer to zero, -4V rather than -15V for an IGBT). It is possible for a parasitic turn-on to occur due to the higher dv/dt caused by the higher switching speeds of SiC devices.

The drain-gate and gate-source capacitances are connected in series (Figure 6, green circuit). This creates a capacitive voltage divider. If a positive dv/dt is applied from drain to source, then C_{GS} can become charged and the channel can open slightly causing the MOSFET to unintentionally turn on. This is a loss mechanism and generates heat within the MOSFET, called E_{pto}.

While not necessarily damaging, this brief period of conduction causes additional losses within the device. Furthermore, these losses are not always evenly distributed across the chip. Local hotspots can occur if excessive I_{pto} is allowed to repeatedly flow through the device.

An example of the turn-off behaviour of a real SiC MOSFET body diode is shown in Figure 7. The module is an SKM350MB120SCH15 in the well-known 62mm SEMITRANS 3 package. The measurements have been taken at 600V and 350A. The peak reverse recovery current is -140A.

Figure 7: Sample SKM350MB120SCH15 diode turn-off

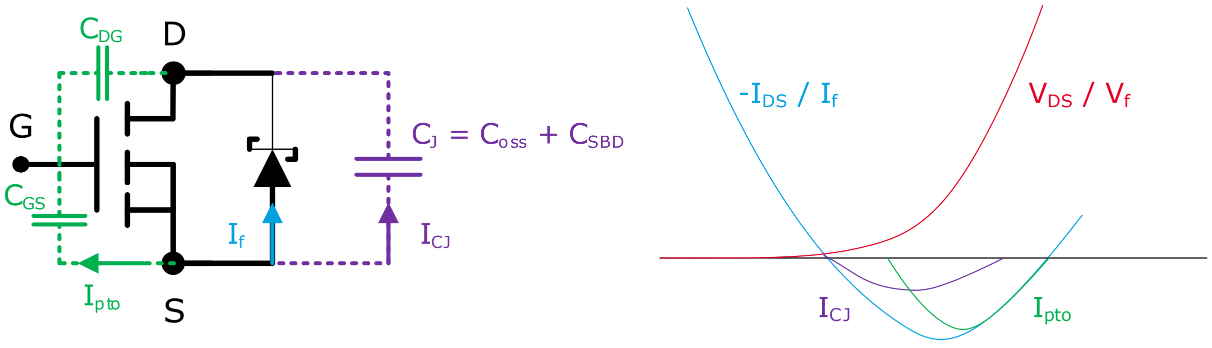


2.2 SiC MOSFET with anti-parallel Schottky barrier diode

For an SiC MOSFET with an anti-parallel Schottky barrier diode, the measured current through the device during diode turn-off ($-I_{DS}$ / I_f) consists of two component currents:

- Capacitive junction current, I_{CJ}
- Possibly a parasitic turn-on current, I_{pto}

Figure 8: Components of reverse current in SiC MOSFET and Schottky barrier diode



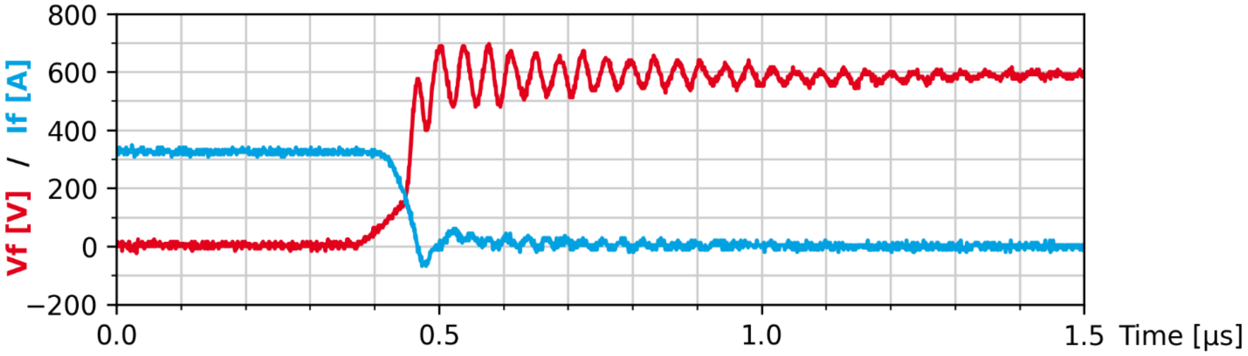
During normal operation, the SBD will carry the vast majority of the current and the body diode only a minimal amount. As a result, very few holes are generated within the body diode. Essentially no reverse recovery current will be generated by the pn body diode of the SiC MOSFET. As explained previously, this lossy recombination mechanism (E_{rr}) is not present in SBDs. This fundamental difference in the behaviour is why SiC Schottky barrier diodes generate far lower switching losses.

I_{pto} can appear very similar to I_{rr}, and can occur in cases where I_{rr} is not expected, for example if a SBD is connected in parallel with a MOSFET. If I_{pto} is present, it is important to avoid attributing the losses to the SBD because the heating occurs within the MOSFET and not the SBD.

A new term in Semikron Danfoss datasheets, $E_{rr(MOSFET)}$, describes the energy from only E_{CJ} and E_{pto}. Because E_{CJ} is purely capacitive and does not significantly contribute to device self-heating, it can be subtracted from $E_{rr(MOSFET)}$ to give a more accurate estimation of actual device losses. Semikron Danfoss does not pre-subtract E_{CJ} from $E_{rr(MOSFET)}$ so that device datasheets better reflect real-world measured values.

An example of the turn-off behaviour of a real Schottky barrier diode in parallel with an SiC MOSFET is shown in Figure 9. The module is an SKM350MB120SCH17 that is identical to the SKM350MB120SCH15 with the addition of a separate SBD. The remaining reverse current peak is much lower due to the lack of body diode I_{rr}. As a result, the reverse recovery current has been reduced to -70A, but not to 0A. What appears to be reverse recovery current is actually just the combination of I_{CJ} and I_{pto}. An exact determination of the ratio is not possible by direct measurement.

Figure 9: Sample SKM350MB120SCH17 diode turn-off

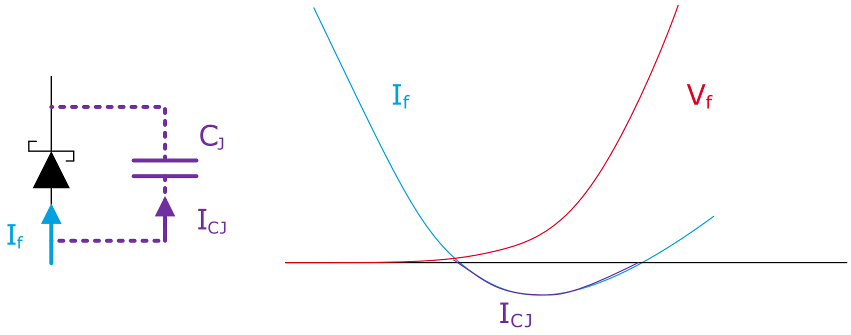


2.3 Schottky barrier diode only

If a Schottky barrier diode is used alone, the measured current during diode turn-off (I_f) consists of only one current:

- Capacitive junction current, I_{CJ}

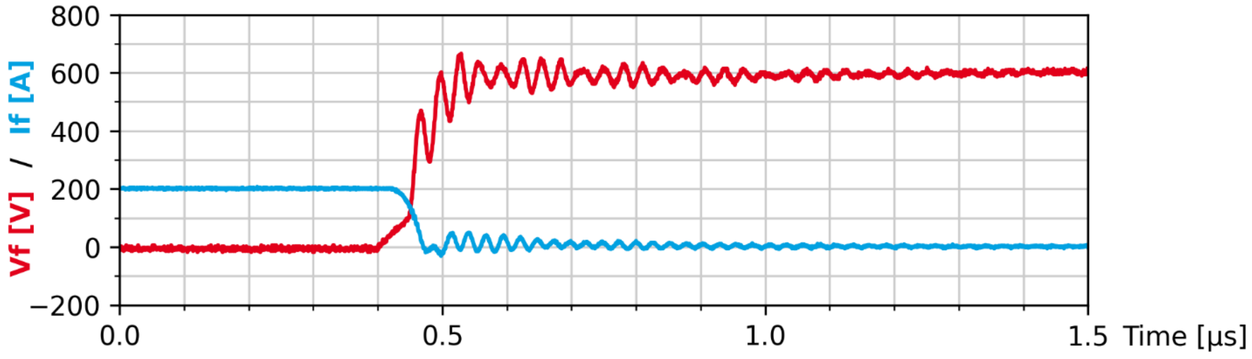
Figure 10: Components of reverse current in Schottky barrier diode alone



As described in 2.1, this capacitive current does not create losses within the chip; as a result, the switching losses of SiC SBDs alone are negligible.

An example of the turn-off behaviour of a real Schottky barrier diode by itself is shown in Figure 11. The module is an SKM200GB12T4SiC2 in the SEMITRANS3 package. It is a hybrid-SiC solution where a fast IGBT is paired with an anti-parallel SBD. The risk for parasitic turn-on of the IGBT is nearly zero because the V_{GEoff} is -15V and the resulting dv/dt is much lower in comparison to an SiC MOSFET. Only the Schottky diode is used during diode turn-off. The reverse recovery has been essentially eliminated. Some current caused by the recharging of the junction capacitances of the IGBT and SBD is still present and some ringing due to the system parasitics.

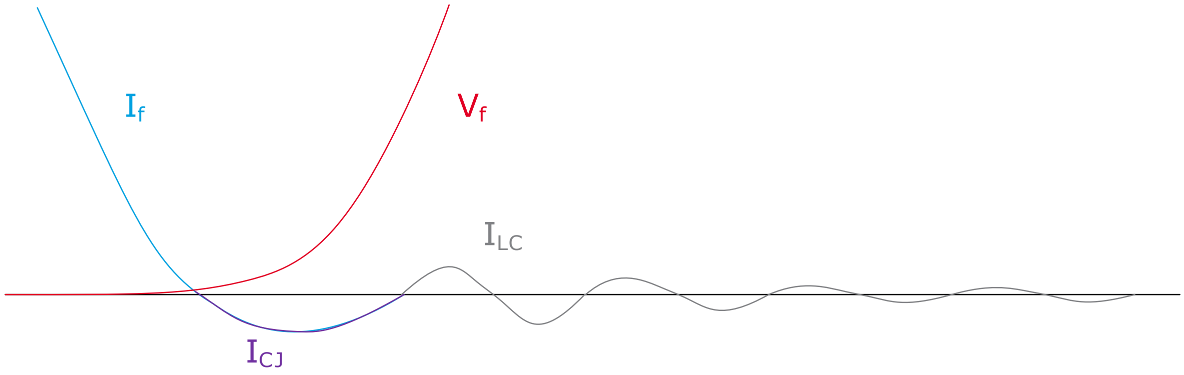
Figure 11: Sample SKM200GB12T4SiC2 diode turn-off



2.4 I_{LC}: parasitic oscillations

Any of the circuits previously discussed may have some current overshoot during or after turn-off depending on the system's commutation inductance and capacitances. In SiC SBDs, this ringing is simply a product of the parasitics and is not caused by recombination within the chip. These oscillations do not generate heat within the diode, aside from the resistive losses in the conductors of the circuit.

Figure 12: Ringing, not reverse recovery



3. Semikron Danfoss Module Datasheets

The following section explains how reverse recovery losses are stated in Semikron Danfoss modules for the various types of devices.

3.1 SiC MOSFET only

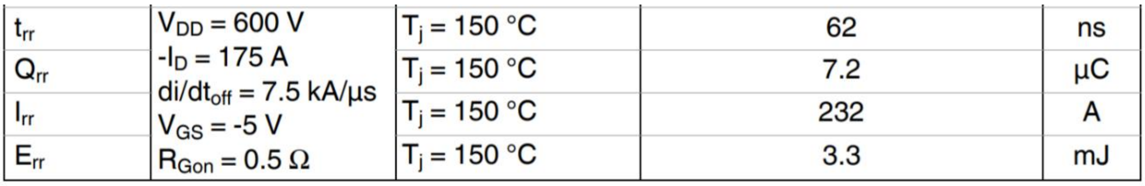
Because MOSFET-only modules rely on the body diode, reverse recovery will occur when turning off negative current. As a result, I_{rr}, Q_{rr}, and E_{rr} for the body diode are specified (Figure 13). These values also may include the effects of parasitic turn-on. But since both losses are generated in the same switch, it is not necessary to distinguish between them. Separation is not possible by direct measurement and not necessary because both happen at the same place and same time. These values also include the effects caused by charging of the junction capacitance C_{oss} which does not cause any power losses in the device.

For example, the amount for the SKM350MB120SCH15 can be estimated roughly using the formula below. Please be aware that junction capacitance values are dependent on the junction voltage.

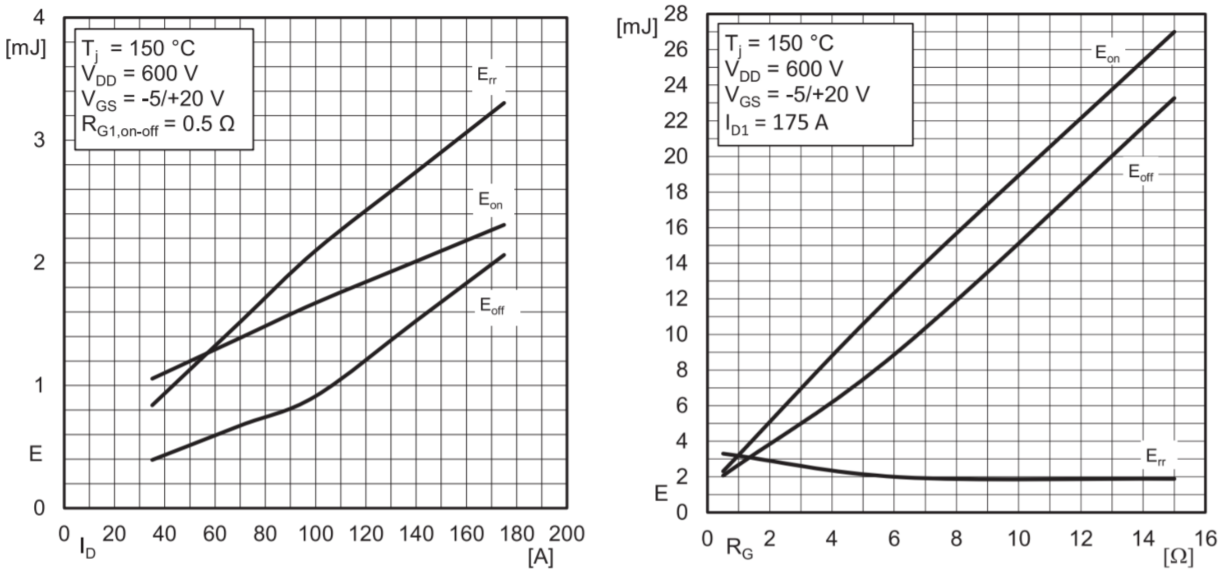
$E_{CJ} \approx ½\cdot C_{oss}\cdot V^2 = ½\cdot 1.1\text{nF}\cdot(600\text{V})^2 = 0.2\text{mJ}$

As with pn diodes, the current, di/dt, and junction temperature all affect the reverse recovery behaviour of the body diode of a MOSFET. Therefore, these values are included in the datasheet and must be considered when making comparisons to other datasheets.

Figure 13: Example values from SKM350MB120SCH15 datasheet [6]



t_{rr}	V_{DD} = 600 V $-I_D$ = 175 A di/dt_{off} = 7.5 kA/µs V_{GS} = -5 V R_{Gon} = 0.5 Ω	T_j = 150 °C	62	ns
Q_{rr}		T_j = 150 °C	7.2	µC
I_{rr}		T_j = 150 °C	232	A
E_{rr}		T_j = 150 °C	3.3	mJ



3.2 SiC MOSFET and Schottky barrier diode

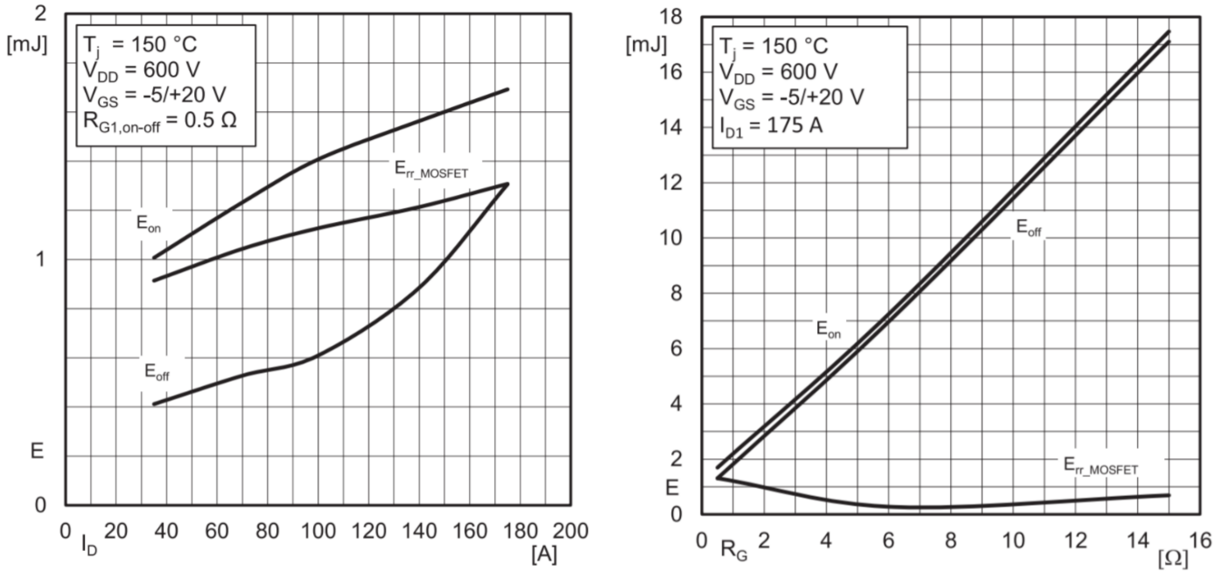
SBDs are often installed in anti-parallel with MOSFETs to additionally improve the reverse recovery behaviour of the body diode. $E_{rr(MOSFET)}$ is included in the dynamic curves to make the distinction between E_{pto} losses in the MOSFET and the lack of substantial switching losses in the SBD. In addition to charging the C_{oss} of the MOSFET, the junction capacitance of the diode must also be charged:

$E_{CJ} \approx ½\cdot(C_{oss} + C_J)\cdot V^2 = ½\cdot(1.1+0.42)nF\cdot(600V)^2 = 0.27mJ$

The SBD junction capacitance and the stored charge, specified in the module datasheet, describe the dynamic behaviour sufficiently (Figure 14).

Figure 14: Example values from SKM350MB120SCH17 datasheet [7]

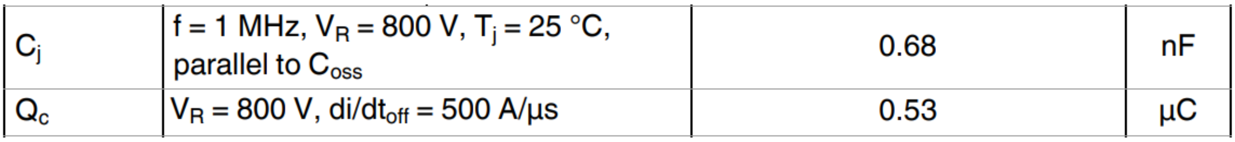
C_j	parallel to C_{oss}, f = 1 MHz, V_R = 800 V, T_j = 25 °C	0.42	nF
Q_c	V_R = 800 V, di/dt_{off} = 500 A/µs, T_j = 25 °C	0.33	µC



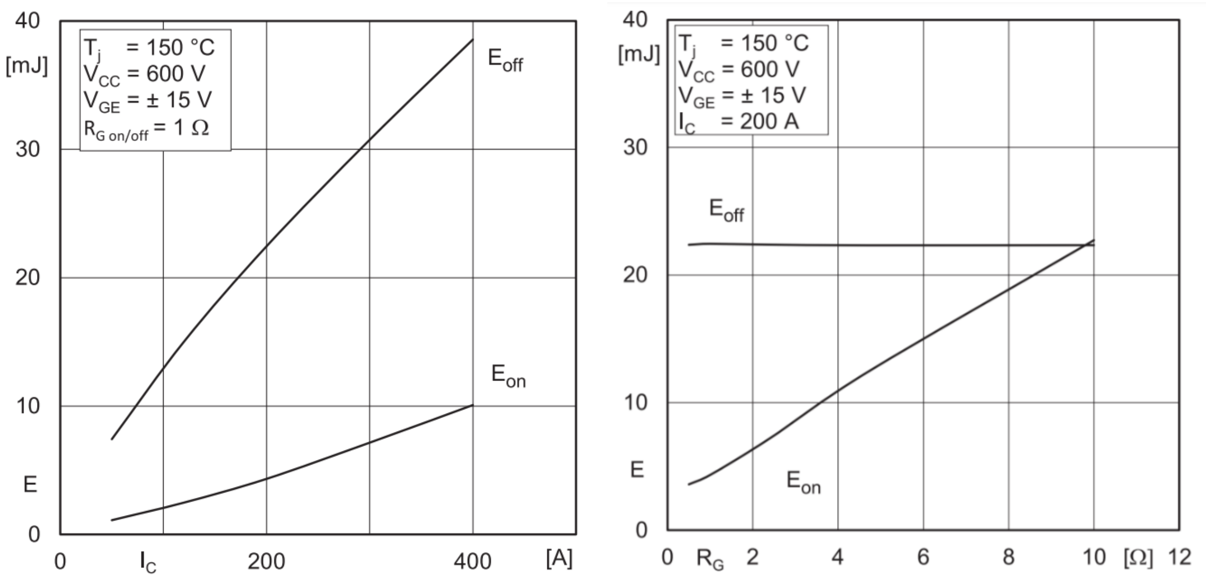
3.3 IGBT and Schottky barrier diode (hybrid module)

So-called hybrid modules with a Si IGBT and SiC SBD specify Q_c for diode mode, but not Q_{rr}, I_{rr}, E_{rr}, etc. The risk of parasitic turn-on (E_{pto}) of IGBTs is almost zero with a turn-off gate voltage of -15V. The dv/dt is also much lower when compared to an SiC MOSFET. Only the Schottky diode is used during diode turn-off. E_{rr} is not created by the SBD and as a result it is not specified. C_j and Q_c are included so that E_{CJ} can be calculated (Figure 15).

Figure 15: Example values from SKM200GB12T4SiC2 datasheet [5]



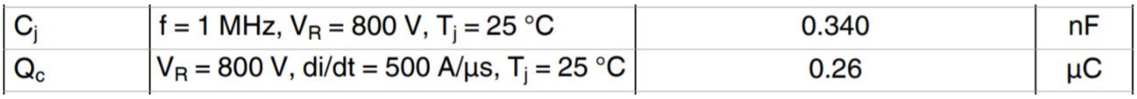
C_j	f = 1 MHz, V_R = 800 V, T_j = 25 °C, parallel to C_{oss}	0.68	nF
Q_c	V_R = 800 V, di/dt_{off} = 500 A/µs	0.53	µC



3.4 Schottky barrier diode only

When an SBD is used alone, only C_j and Q_c are specified in the datasheet to describe the dynamic behavior. Figure 16 shows these values for an SKKE60S12, which is a single SBD in the SEMIPACK2 package. As previously discussed, SBDs do not produce reverse recovery charge from recombination. Therefore, when used alone no other dynamic values or curves are needed for only an SiC SBD (e.g. rectifier or buck/boost converter).

Figure 16: Example values from SKKE60S12 datasheet [8]



C_j	f = 1 MHz, V_R = 800 V, T_j = 25 °C	0.340	nF
Q_c	V_R = 800 V, di/dt = 500 A/µs, T_j = 25 °C	0.26	µC

4. Conclusion

The introduction of silicon carbide has enabled the production of higher voltage Schottky barrier diodes. These diodes differ from traditional silicon pn diodes in some important ways. The lack of reverse recovery current may seem counterintuitive, but the benefits are substantial, especially in high switching frequency applications.

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Symbols and Terms

Letter Symbol	**Term**
SiC	Silicon Carbide
SBD	Schottky Barrier Diode
GaN	Gallium Nitride
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
I_{DS} / I_{SD}	Drain to Source / Source to Drain Current
E_{rr} / I_{rr} / Q_{rr}	Reverse Recovery Energy / Current / Charge
E_{CJ} / I_{CJ}	Junction Capacitance Energy / Current
E_{pto} / I_{pto}	Parasitic Turn-On Energy / Current
V_{GSoff} / V_{GEoff}	Gate Turn Off Voltage

A detailed explanation of the terms and symbols can be found in the "Application Manual Power Semiconductors" [2].

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