How to Use an SiC Diode in a PFC Circuit

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An SiC diode is the optimal choice for power factor correction (PFC) in continuous conduction mode (CCM) because its particular reverse recovery characteristics reduce switching losses to almost zero.

The selection criteria for an SiC diode are different from the selection criteria for of an Si diode in the same circuit. Usually at high frequencies in CCM, Si diodes show switching losses that are not negligible. The current capability of each diode is defined as the DC current that in a certain thermal condition brings the T_J to its limit; normally 175 °C for an SiC diode and 150 °C to 175 °C for an Si diode.

The diode's current capability is related to the maximum power that the diode is able to manage, evaluated only with DC current. However, a PFC diode is switching, so the device should be able to manage all dissipated power, not only conduction losses.

Function of PFC output current

1.1 $P_{max.}$ of device > $P_{switching}$ + $P_{conduction}$

Negligible for SiC

INTRODUCTION

Active PFC has become quite common in AC/DC switch mode power supplies. For power supplies with output power ratings higher than 300 W, the harmonics, and consequently reactive power, loaded from the grid should be lower than the value specified in IEC61000-4-3. To meet this requirement, the input stage cannot be a simple rectifier bridge with a capacitor, but requires active PFC.

A typical active PFC circuit is made with a boost converter (Fig. 1).

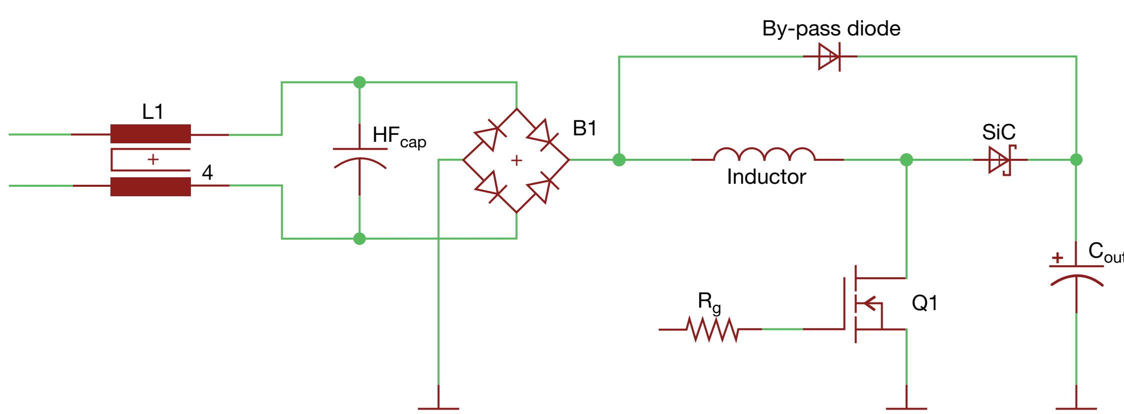

Fig. 1 - A Typical Active PFC Stage Implemented With a Boost Converter

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The boost circuit can work in three different ways: in discontinuous current mode (DCM), critical current mode (CrCM), and continuous current mode (CCM). These terms are related to the shape of the current through the inductor, which can completely change the stress on the diode.

If the current in the inductor reaches zero before the switch Q1 turns on, the turn-off of the diode is not stressful and the associated switching losses are very low. So for DCM, there is not a big difference between Si and SiC diodes, because their losses are more related to conduction behavior than the switching characteristic.

In theory, DCM and CrCM keep the diode at zero current or low current, as shown in Fig. 2. The switching losses in an Si diode are proportional at forward current, so a DCM and CrCM circuit can be built with an Si diode with good results.

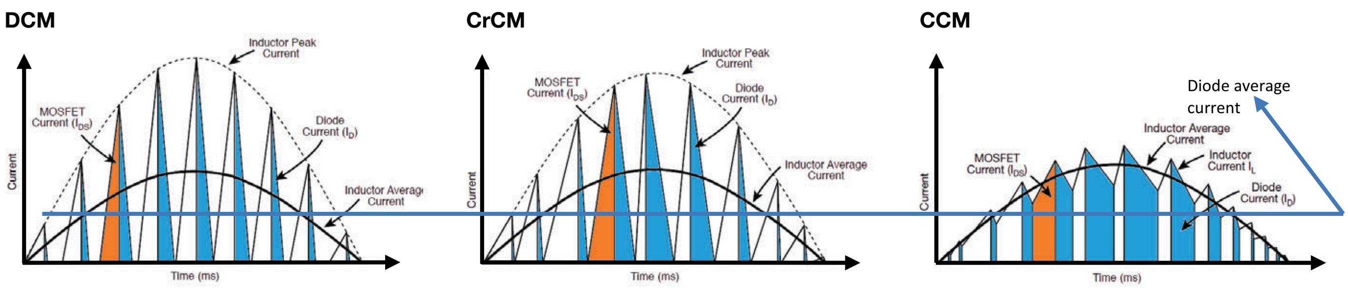

Fig. 2 - Instantaneous and Average Current in a PFC Boost Circuit

Fig. 2 shows how the choice of mode (DCM, CrCM, or CCM) affects the inductor currents are in the boost circuit. It is true that in DCM switching losses due to reverse recovery of the diode are negligible, but to have the same output average current and the same output power, the peak current is much higher. In DCM and CrCM an Si diode can be used because the forward voltage at high current is lower than the forward voltage of an equivalent SiC diode, as shown in Fig. 3.

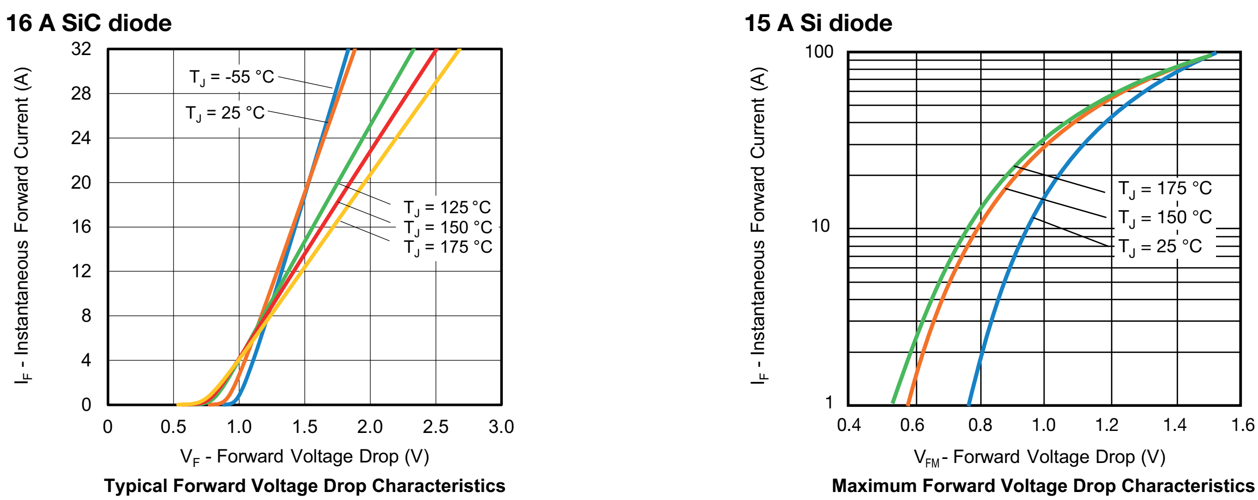

Fig. 3 - SiC and Si Diode Voltage Comparison

Ultrafast diodes show a lower forward voltage but the losses in the circuit are also proportional to the square value of the RMS current that grows with the value of peak current (ex. RMS value for triangular waveform is $I_{RMS} = \sqrt{\frac{I_P^2}{3}}$)
The losses in inductor series resistance or in a MOSFET switch ($R_{DS(on)}$) follow a law such as $P = R_{eq}\, I_{RMS}{}^2$.

This limits the application of DCM and CrCM in PFC circuits where the average currents are not too high. Otherwise, the current peak becomes very high and the associated losses, even if switching losses are near to zero, are too big for practical use.

In addition to the issue of conduction losses, working with a discontinuous current or with a high ripple current requires a better filter in the input to avoid injecting high frequency current into the grid. For example, in Fig. 1 the HF_{CAP} should be different for CCM and DCM / CrCM circuits.

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For high power circuits CCM is mandatory because it reduces the losses in all components. However, at diode turn-off there are large switching losses in the diode itself and in the active switch that is turning on. These losses are due to the reverse recovery current of the stored charge in the Si diode. For these reasons, the choice of Si diode in a CCM circuit generally requires in a device larger than the device required from an average current point of view. Another thing to take into account is that an active switch should be chosen to manage losses induced from the stored charge of the diode.

A SiC diode is the best solution for a CCM circuit because it has only capacitive reverse recovery current.

The switching losses in the diode will be near zero because there is not charge stored in the junction, and the reverse recovery current peak is so small that turn-on switching losses in the active switch are much lower than the losses of an equivalent Si diode. The benefit of reduced switching losses not only reduces the required die size for the diode, but also allows for a smaller switch.

THE SiC DIODE

The breakdown capability of a diode, its Schottky or PN junction, is proportional at the critical electric field that is proportional to the square of the semiconductor's energy gap, E_g (Fig. 4). The SiC diode has an E_g around 3.2 eV, while the pure Si diode has an energy gap around 1.1 eV.

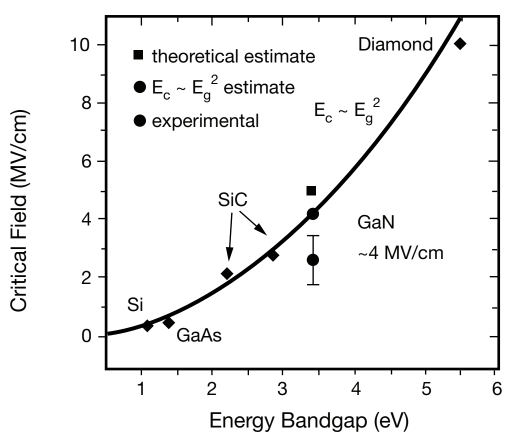

Fig. 4 - Energy Gap vs. Critical Electric Field

With this characteristic, the Si Schottky junction is very fast but is only able to work with a maximum reverse voltage of around 150 V. In a SiC diode with the same structure, this capability is more than 700 V.

For these reasons, with SiC, it is possible to build a Schottky diode with high voltage breakdown. For a Si diode, it is necessary to use more complex structures like PIN or MPS that involve other physical phenomena that induce much higher reverse recovery losses.

Building a diode with a pure Schottky junction has the advantage of the lowest possible forward voltage, but has some problems at high currents like the surge currents that are common in a PFC application.

For example, during voltage surges in the line at startup, short over currents that could damage the SiC pure Schottky diode are quite common. PFC is a direct converter and any overstress in the input can arrive to the output through the diode, creating dangerous overstress in the diode.

Vishay solves this problem by implementing a special MPS structure that keeps the forward voltage under control during high current events, providing a high surge current capability for a 10 ms sinusoidal pulse and increasing diode reliability when current through the diode has a high crest factor.

The MPS structure, compared with the pure Schottky structure, has a portion of the anode area with a PN junction that at high current could inject a minority carrier that increases the conductivity of the drift zone, helping to keep forward voltage at low value.

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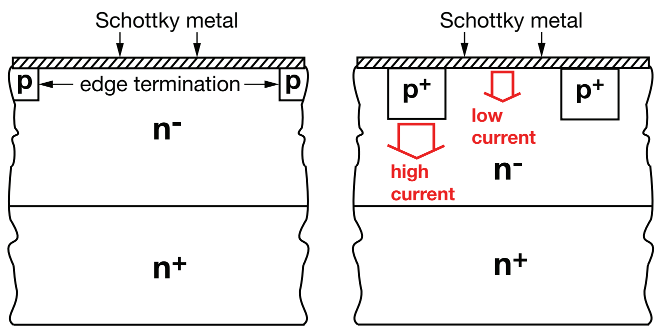

Fig. 5 - SiC Schottky Diode (left) and SiC MPS Diode (right) [1)]

The PN junction has a higher threshold voltage than the Schottky junction, so the forward voltage is not the same. The adding of PN area create some limitation because the Schottky area is reduced and diode became more bipolar. So at low current, the result is a Schottky diode with a smaller area compared to an equivalent pure Schottky diode with negative effect on forward voltage.

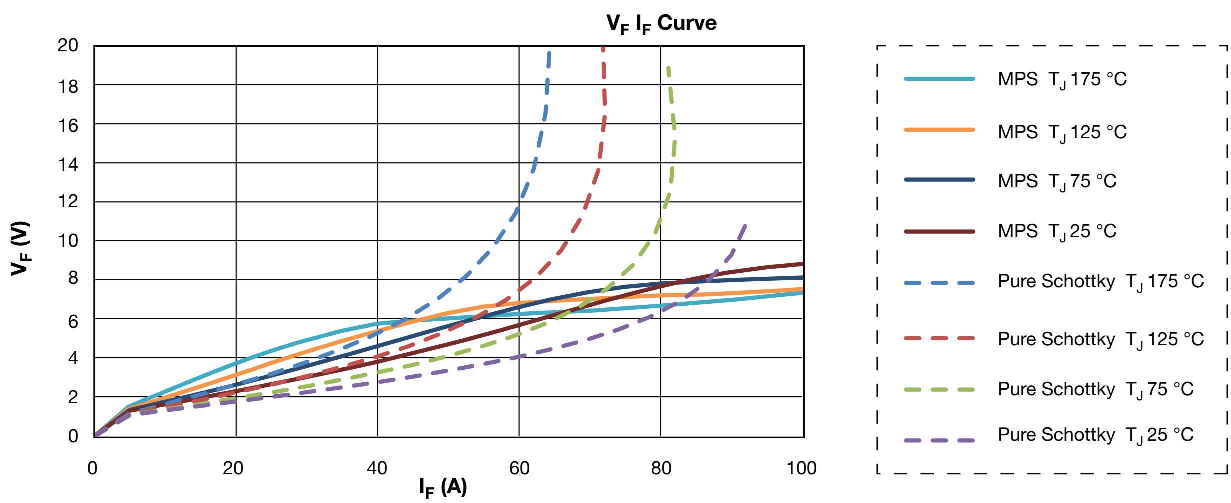

Fig. 6 - MPS and Pure Schottky

Fig. 6 shows the behavior of pure Schottky and MPS diodes with the same die dimensions in function of forward current and temperature. It can be seen that the MPS structure at high current has a forward voltage stable and that goes down with temperature. The pure Schottky diode at high temperature shows a forward voltage that grows with exponential behavior but at low current the pure Schottky has forward voltage lower than MPS.

Vishay utilizes an improved version of the MPS structure to minimize the forward voltage problem at high current without penalizing the forward voltage at low current. The forward voltage handicap due to PN area is compensated for with a Ti-Si junction that reduces voltage drop.

From this application point of view, the improved surge capability could suggest that a bypass diode between the input and DC capacitors (Fig. 1) is not necessary. However, it should be verified that at the start-up the overvoltage on the DC capacitor due to inrush current is not dangerous.

Compared with a standard Si diode, an SiC diode has a limit at the impulse current. For an Si diode, the peak current is substantially thermally limited. So very short pulse peak currents through the diode can be 30 x the average current. The SiC diode cannot work in this condition. For good reliability, it is recommended to not exceed 3 x the maximum current in the forward voltage graph of the datasheet.

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DIODE LOSSES MODEL

Losses in a diode are due to conduction, switching, and leakage losses. Vishay's devices have very low leakage below 10 μA at high temperatures to 175 °C. For example, the VS-C10ET07T-M3 has typical leakage of around 5 μA at 175 °C and 650 V. In a real application, the diode does not work at rated voltage so losses associated with reverse bias are generally negligible.

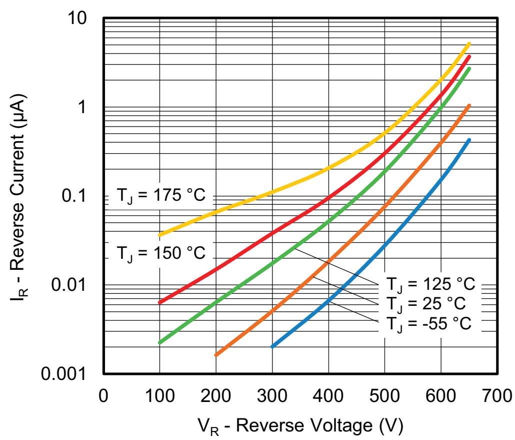

Fig. 7 - Typical Leakage of the VS-C10ET07T-M3 as a Function of Reverse Voltage and Temperature

For a PFC circuit with 500 V of output voltage and a junction temperature of 175 °C (Fig. 7), the typical leakage is 0.5 μA, so the instantaneous power is 250 μW. In a worst case scenario, for example at 650 V and 150 °C, the VS-C10ET07T-M3 has leakage lower than 125 μA. So with 650 V of reverse voltage, the instantaneous power is only 82 mW. The real reverse voltage will be lower than 650 V, confirming that losses associated with reverse polarity are negligible and the diode is stable.

Generally the largest source of losses in the SiC device is the conduction losses. The evaluation of conduction losses in theory is easy — forward voltage times forward current and duty cycle.

For a PFC circuit, the shape of current is continuously variable because the shapes of the input voltage and duty cycle change moment by moment. Using the forward voltage model and instantaneous current value with a worksheet, it's possible to evaluate the cycle by cycle instantaneous power and calculate the average value.

With the average power value and thermal characteristics of the system, it's possible to understand if a device is suitable or not for a certain application or what heatsink is required.

This task requires a certain number of iterations because the forward voltage is a function of junction temperature. That is the parameter that we need, so it is important to have a simple model for an interactive process.

In a PFC circuit, it's easy to evaluate the average current and RMS current in the diode. Average current through the diode is:

$$Id_{AVG} = P_{out}/V_{out}$$

For RMS current, there are many good models for diodes in CCM circuits, where an SiC device gives significant advantages, such as the following formula: [2)]

1.2

$$Id_{RMS} = \frac{P_{out}}{V_{out}}\sqrt{\frac{16\ V_{out}}{3\pi\ V_{in}\sqrt{2}}}$$

V_{out} = PFC output voltage V

P_{out} = PFC output power W

V_{in} = PFC AC input voltage RMS V

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The above model neglects the ripple current. More accurate models, such as the following formula, are available: [3)]

1.3

$$Id_{RMS} = \sqrt{\frac{16}{3\pi} \cdot \frac{P_{in}^2}{V_{pk} V_{out}} + \frac{1}{9\pi} \cdot \frac{T_s^2 V_{pk}^3}{L_{pfc}^2 V_{out}} - \frac{1}{16} \cdot \frac{T_s^2 V_{pk}^3}{L_{pfc}^2 V^2{}_{out}} + \frac{4}{45\pi} \cdot \frac{T_s^2 V_{pk}^5}{L_{pfc}^2 V^3{}_{out}}}$$

This model takes the effect of current ripple into account, but it is necessary to know the inductor and the switching frequency.It is recommended when PCF inductor is "smaller" and ripple is pretty high.

Usually when selecting a device, an evaluation done with model 1.2 is enough. As a second step, the junction temperature estimation could be little a bit more precise using model 1.3. With current stress, it's possible to evaluate dissipated power in the diode with model 1.4

1.4

$$P_d = V_{to} \cdot Id_{AVG} + R_d \cdot Id_{RMS}^2$$

The V_{to} and R_d values are the models of the diode for the dissipated power. These two coefficients are not the parameters for forward voltage of the diode used in model 1.5 to obtain the forward voltage.

Model 1.5 is often considered a simple model for the voltage drop of a diode, but V_t and R_d have different values compared to V_{to} and R_d. The number is similar but not equal. Using V_t instead of V_{to} could be negligible, but R_d in the V_f formula is related to differential resistance, while R_d in model 1.4 is a coefficient that fits power losses for RMS current in a sinusoidal shape.

1.5

$$V_f = V_t + R_d \cdot I_d$$

The forward voltage value obtained with model 1.5 could be similar to the forward voltage curve, but the parameters V_{to} and R_d, despite seeming to have a physical meaning, are only coefficients to evaluate the power in the diode. These coefficients are calculated to be the best fit for dissipated power in the diode when it is working with a sinusoidal current with an average equal to the rated current of the diode and dissipated power from the diode that is working with the same current but at 1/8 of the rated current.

As forward voltage also a coefficient, V_{to} and R_d are a function of temperature. V_{to} and R_d at a certain Tj temperature can be calculated with the following equation:

1.6

$$V_{to}(T_j) = k_V \cdot (T_j - 25) \cdot V_{to(25\ °C)}$$

$$R_d(T_j) = k_R \cdot (T_j - 25) \cdot R_{d(25\ °C)}$$

With these coefficients, a preliminary evaluation of the dissipated power could be performed starting from the initial junction temperature. After the first evaluation of power, it is possible to update the junction temperature.

For Vishay's SiC devices the coefficients are given in the following table:

1.7	**V_{to}**	**R_d**	**kV**	**kR**
	V	**Ω**	**°C^{-1}**	**°C^{-1}**
VS-C04ET07T-M3	0.9178	0.1327	-1.060E-03	7.957E-04
VS-C06ET07T-M3	0.9232	0.0768	-1.111E-03	5.184E-04
VS-C08ET07T-M3	0.9255	0.0673	-1.135E-03	3.433E-04
VS-C10ET07T-M3	0.9294	0.0570	-1.162E-03	3.038E-04
VS-C12ET07T-M3	0.9137	0.0419	-1.127E-03	2.241E-04
VS-C16CP07T-M3	0.9231	0.0656	-1.120E-03	3.569E-04
VS-C16ET07T-M3	0.9161	0.0306	-1.127E-03	1.687E-04
VS-C20CP07L-M3	0.9366	0.0541	-1.203E-03	2.721E-04
VS-C20ET07L-M3	0.9168	0.0243	-1.134E-03	1.142E-04
VS-C40CP07L-M3	0.9135	0.0235	-1.143E-03	1.077E-04

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In the table 1.7 the value are referred at single die also for 2 x dual anode device the value is referred at single die in the diode. As in formula 1.1, the losses in a diode are conduction losses plus switching losses. For an SiC diode, switching losses are near zero because the reverse recovery current is primarily due to capacitance and not the charge stored in the junction, as in a Si PIN diode. For this reason the charge measured during switching of SiC diode has an average value near to zero.

The charge in a SiC diode is essentially the charge of a non-linear capacitor and there is not energy dissipated in the diode.

In the Si diode there is a charge due to capacitance that is discharged when the diode is turned on and charged when the diode is turned off. In addition, at turn-off there is a stored charge that is proportional to the current flowing through the diode. This charge, removed with reapplied voltage, is the recovery energy E_{rec} that is present in the Si diode.

This is clear if we measure the charge during dv/dt at turn-on and turn-off. Fig. 8 shows the SiC diode's current during switching. The purple track 3 is the diode current. With the current during turn-on (Fig.8 left: 69.94 nC compressive of diode, layout and socket) it is possible to evaluate the charge necessary to perform a voltage transition from reverse voltage to the forward voltage of the circuit. This charge is, taking into account measurement errors, equal to the charge necessary at the turn-off to bring the voltage of the diode from forward to reverse voltage (Fig. 8 right: -70.83 nC). The value is negative because like a capacitor, while charging current flows in one direction and during discharge it flows in the opposite direction.

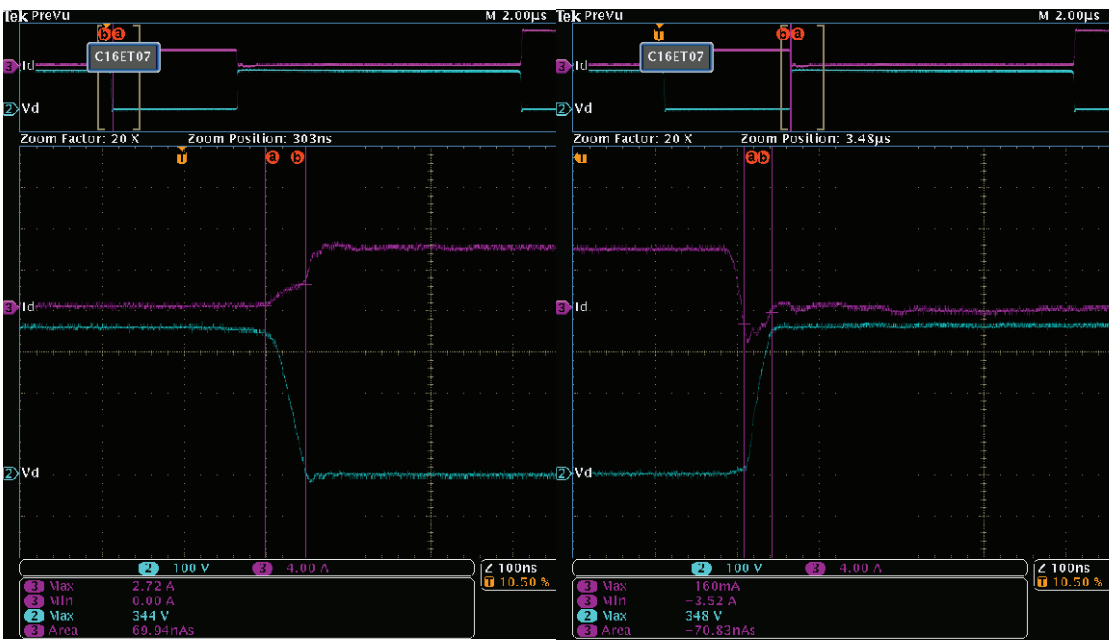

Fig. 8 - Charge to Change the Voltage Across an SiC Diode During Switching

The charges in this condition do not dissipate energy because the energy is only stored in the diode capacitance.

During switching a certain amount of charge is charged and the same amount is discharged (with equivalent voltage) for each cycle, so there are not losses in the diode.

During turn-off of the diode, there is a current that seems similar to the recovery current of the Si diode with I_{rr} peak. In reality this is only the effect of non-linear capacitance times dv/dt.

1.8

$$i_c = C(v)\,\frac{dv\,(t)}{dt}$$

The dv/dt is almost constant during switching, but the capacitance is quite variable with the voltage. So during the initial switching time, a current peak is visible that is similar to the reverse recovery of the Si diode.

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It is possible to perform the same measurement for the Si diode. In Fig. 9, the purple track 3 is the diode current. The current during turn-on is visible (Fig. 9: left, 34.63 nC) as the charge to perform the voltage transition from reverse recovery to zero.

At turn-off, the Si diode shows completely different behavior compared to the SiC diode (Fig. 9: right, 135.2 nC). For the Si diode, the turn-off charge is much higher than the turn-on charge, despite the turn-on charge being low.

In the Si diode, there is only a partial balance between turn-on charge and turn-off charge in this example: 35 nC at turn-on and 135 nC at turn-off. There is a charge in excess of 100 nC in the Si diode due to a charge stored in a drift area due to forward conduction. 35 nC is the charge that is returned in the circuit without losses because it is only a capacitor discharge. The remaining charge is drowned out by the reverse voltage, so this charge creates losses in the diode that become heat that should be dissipate. The stored charge increases with the recovery condition: voltage, current, di/dt, and temperature become much larger than the capacitive charge, increasing losses in the diode and the active device that should manage this amount of current.

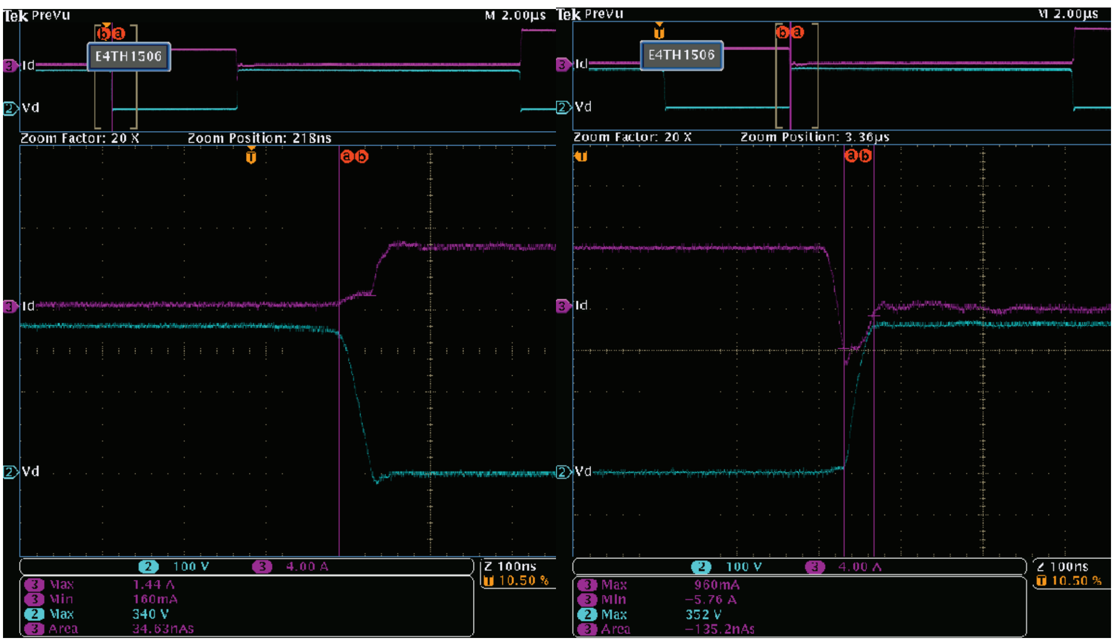

Fig. 9 - Charge to Change Voltage Across the Si Diode During Switching

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The two examples are refer to two similar diodes with average current capability around 15 A to 16 A. It can be seen that at turn-on, the charge required from the SiC diode is higher than charge required from the Si diode. This is because the junction capacitance of the SiC diode is higher than the junction capacitance of the Si diode.

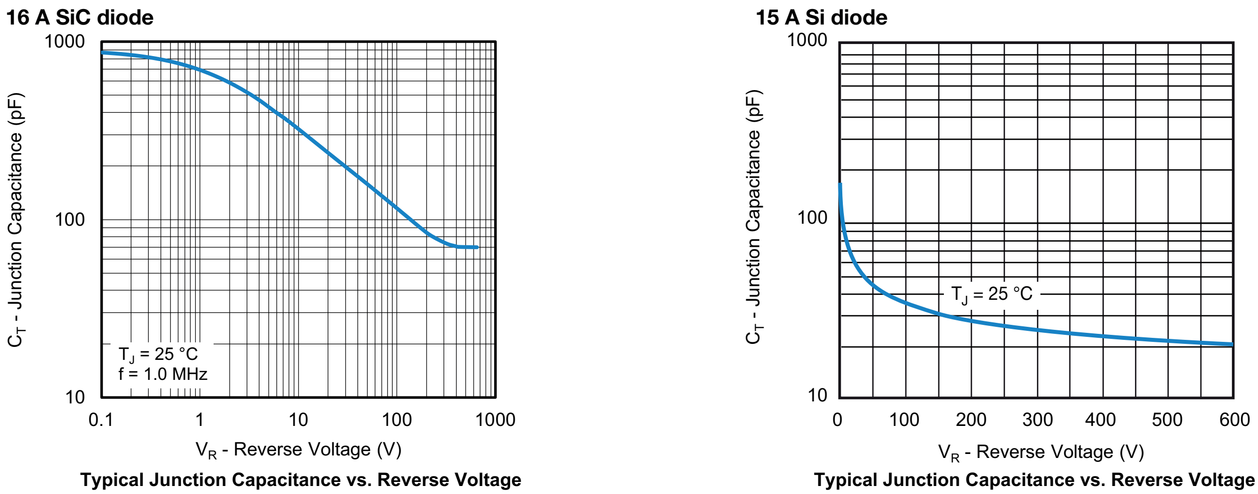

Fig. 10 - Typical Junction Capacitance of SiC and Si Diodes

The two diodes have comparable current capability but completely different capacitance. This is because while the SiC diode in general has a smaller die, its depletion layer is much thinner than that of the Si diode due to a higher electric field in the SiC diode.

The junction capacitance is not an issue for power losses in the diode because the only associated loss is the RMS current in the electrical resistance of the device, which is very low.

The charge of the junction capacitance can induce losses in the device that charge and discharge the diode. The reason for this is that like the energy dissipated in a resistor when it is charging and discharging, in a capacitor the active switch that changes the voltage across the diode dissipates (charge and discharge junction capacitance) the energy stored in the junction capacitance.

The Vishay diode has optimized junction capacitance vs. current ratio to minimize the losses in the active switch.

To simplify the evaluation of losses in the active switch in the datasheet, having already evaluated the integral, there are the charge and equivalent energy for the diode.

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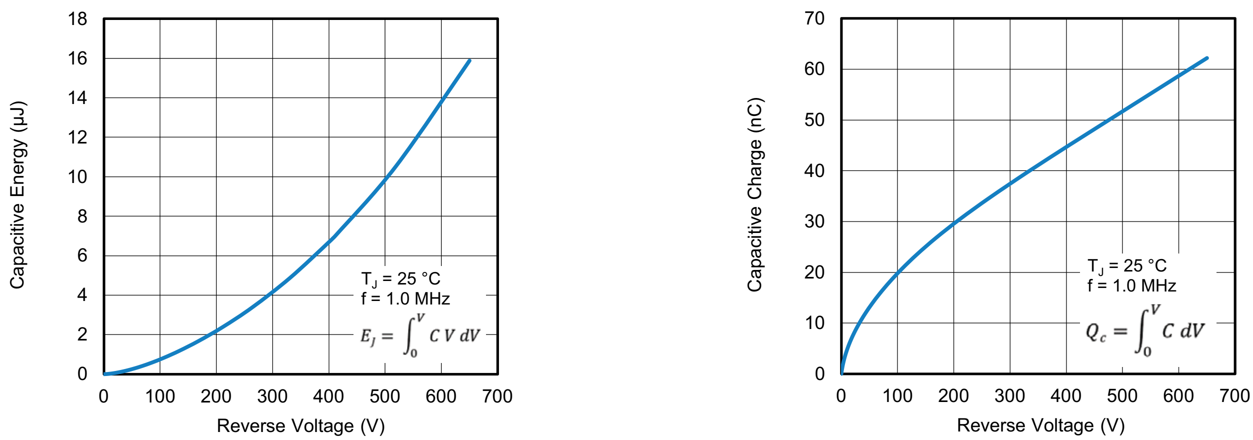

Typical Capacitive Energy vs. Reverse Voltage | **Typical Capacitive Charge vs. Reverse Voltage**

Fig. 11 - Typical Capacitive and Charge Curves From the 16 A Device's Datasheet

The value of energy and charge is not a function of temperature. The values are calculated from the measurement of C_j (V) at 25 °C, but in practice are the same at any temperature. So by changing the working temperature, the stress induced by the SiC diode on the active switch does not change.

For the reason described above, the capacitive energy and charge are the same for the turn-on and turn-off of the active switch.

EXAMPLE OF EVALUATION

To summarize a preliminary evaluation of an SiC diode in a certain application is easier than evaluating an Si diode, because verifying the junction temperature is enough to evaluate conduction losses — neglecting reverse losses and recovery losses.

For example:

- 3 kW PFC
- V_{in}: 230 V_{AC}
- V_{out}: 370 V_{DC}
- F_{sw}: 30 kHz

The first step in evaluating the current in the diode is using the following formula:

$$Id_{AVG} = P_{out}/I_{out} = 3000\ W/370\ V = 8.11\ A$$

$$Id_{RMS} = \frac{P_{out}}{V_{out}}\sqrt{\frac{16\ V_{out}}{3\pi\ V_{in}\sqrt{2}}} = \frac{3000\ W}{370\ V}\sqrt{\frac{16\ 370}{3\pi\ 230\sqrt{2}}} = 11.24\ A_{RMS}$$

With an average current around 8 A, the first tentative choice could be the VS-C10ET07T-M3, which is a 10 A device.
The second step in evaluating the losses in the diode with model 1.4 is using V_{to} and R_d around 25 °C:

$$P_d = V_{to} \cdot Id_{AVG} + R_d \cdot Id_{RMS}^2 = 0.9294\ V \cdot 8.11\ A + 0.0571\ \Omega \cdot 11.24\ A^2 = 14.75\ W$$

The VS-C10ET07T-M3 has a thermal resistance 1.8 °C/W with 14.75 W, which means a delta Tj of 26.6 °C.

Considering case at 80 °C junction temperature is around 107 °C

The third step is evaluating V_{to} and R_d for a Tj of 107 °C.

The new evaluation of power is 17.0 W, which means a delta Tj of 30.6 °C. The new Tj is 110 °C, and another iteration could be done with a new Tj of 110.8 °C. When difference between the two steps is less than 1 °C, the evaluation could be consider finished.

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Note that in a real evaluation the case temperature could change because of a change in the thermal load of the heatsink.

From this preliminary evaluation, a 3 kW PFC made with the VS-C10ET07T-M3 has 17 W of losses in the boost diode. To keep the junction at 110 °C, a very low value for the SiC, a heatsink is required with a thermal resistance case to ambient around 2.3 °C/W, considering an ambient of 40 °C.

CONCLUSION

The preliminary choice of an SiC diode for a PFC circuit is extremely easy.

The Vishay SiC diode does not require special precautions because all its parameters are optimized to be comparable with an Si diode, so the same good practice used for an Si diode can be used for an SiC without problem.

Switching losses are negligible and using the data in Table 1.7, the evaluation of conduction losses requires only a few steps. The PFC output current is enough to choose one or two devices, do a quick evaluation, and the most important data is available to decide the most promising device to put in the circuit prototype for the working test.

REFERENCES

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3) Analytic Expressions for Currents in the CCM PFC stage SLYY131 Colin Gillmor, Texas Instruments