



Power Systems Design: Empowering Global Innovation

Assessing next-generation discretes

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Measuring SiC Schottky Diode Ruggedness with A High Voltage Pulse Generator

When the first generation of silicon carbide (SiC) Schottky diodes was introduced more than 10 years ago, their widespread adoption was somewhat challenged by unforeseen dV/dt limitations within certain manufacturers' devices. In particular, devices with lower dV/dt capability were susceptible to failure from large in-rush currents.

An initial reliability study of some of these early 600V SiC Schottky diodes reported an upper dV/dt limit of 55–60V/ns (volts per nanosecond), which unfairly tarnished the reputation of SiC diodes in general [1]. Observing that their SiC Schottky diodes were not included in the initial study, researchers at Cree (now Wolfspeed, A Cree Company) performed a subsequent reliability study on their first-generation 600V SiC Schottky diode, and demonstrated that their SiC diodes could withstand a turn-on rate of 75V/ns and a turn-off rate of 100V/ns for more than 100,000 cycles without failure [2].

Industry adoption

Since that time, the power conversion industry has seen large-scale adoption of these SiC diodes into efficiency-critical applications, such as power factor correction (PFC) circuits and motor drives, due to significant performance improvements achieved through the elimination of minority carrier reverse recovery charge and the resulting switching loss associated with traditional PiN diodes.

This, in turn, has resulted in the development of several new generations of commercial SiC Schottky diodes, with each generation bringing better performance and quality [3]. However, although SiC Schottky diode technology has progressed markedly over the past decade, all but eliminating industry-wide performance concerns, it is important to note that some end-users are still concerned that the dV/dt capability of these diodes is a potential vulnerability. Thus, in order to remain competitive, SiC diode manufacturers need to devise a universally acceptable test method that enables them to report dV/dt ruggedness as a measure of SiC Schottky diode reliability.

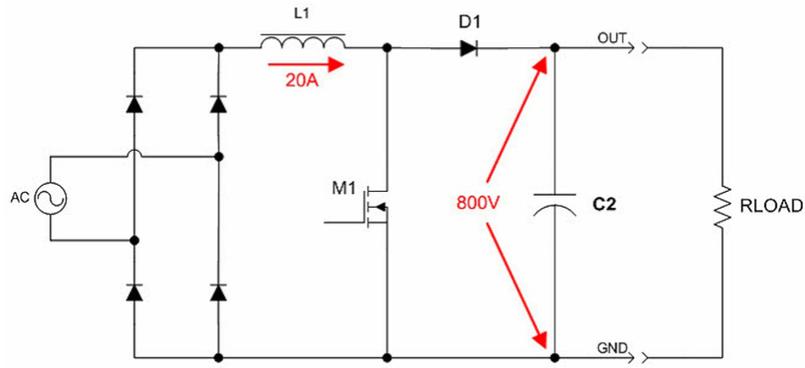
Let's examine the design of a high-speed, high voltage pulse generator (pulser) and how it was used to demonstrate the dV/dt ruggedness of current-generation SiC Schottky diodes. One of the first tasks was to increase the capabilities of the pulser to enable it to drive the diodes to their limits, stressing the devices at a dV/dt significantly faster than what would be experienced in most normal power conversion applications.

While the original experiments were performed using a pulser with switching times of approximately 5ns, it was necessary to develop a pulser with switching times approaching 1ns. This was achieved by employing currently available avalanche transistors in addition to state-of-the-art SiC MOSFETs. The design, construction, and test of this high-speed pulser is described herein, along with the measured dV/dt ruggedness of 600V and 1200V SiC Schottky diodes.

Application considerations

dV/dt ruggedness is one of the more significant design factors that set the limits on achievable switching speed in hard-switched applications. This can be illustrated by considering a popular application of SiC devices: the power factor correction circuit (PFC) as shown in Figure 1. The maximum switching speed of

MOSFET [M1] is limited by the maximum dV/dt of the boost diode [D1]. In this example, the turn-on loss experienced by M1 is considered for the case of two diodes, each with different dV/dt limits: 50V/ns and 100V/ns.

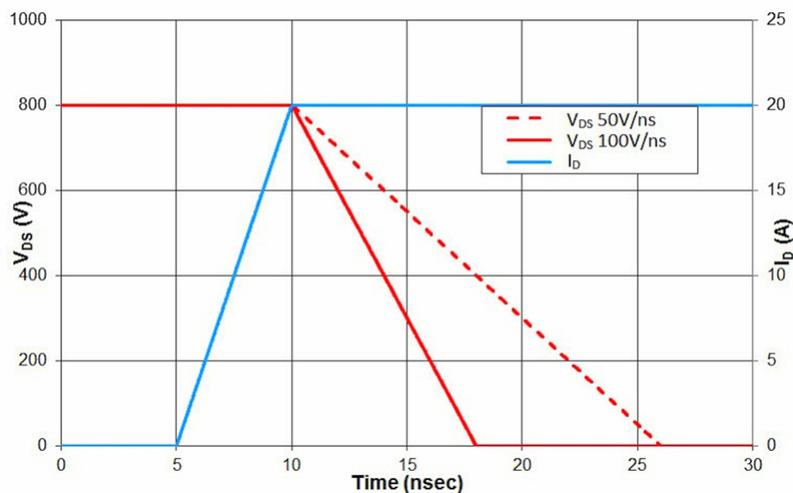


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Figure 1: Basic PFC application

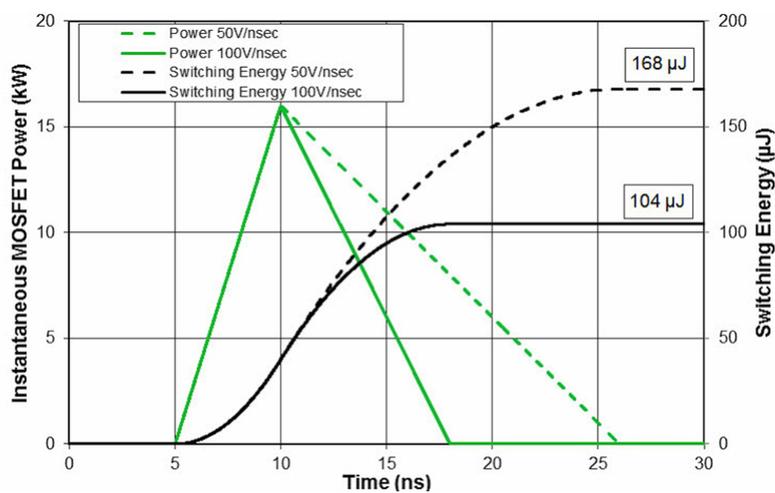
This first order analysis assumes ideal components (no parasitics) and perfectly linear switching. Initial conditions are that MOSFET M1 is off, a 20A current is flowing through L1 causing D1 to conduct, and the current flows out to the load. The voltage across C2 is 800V. When M1 turns on, D1 is rapidly reverse-biased, and the dV/dt limit on D1 (50V/ns or 100V/ns) sets the maximum turn on drain-to-source (V_{DS}) dV/dt of the MOSFET.

The turn-on V_{DS} and drain current (I_D) of the MOSFET for the case of each diode is illustrated in Figure 2, in which dV/dt is shown as a negative value because the voltage is falling. The current rise-time is assumed to be the same for both cases. The MOSFET's instantaneous power ($P = I \cdot V$) and switching energy ($E = \int P dt$) were calculated based on these waveforms, and the results are shown in Figure 3.



Click image to enlarge

Figure 2: Ideal MOSFET turn-on waveforms for dV/dt limits of 50V/ns and 100V/ns



Click image to enlarge

Figure 3: Instantaneous power dissipation and turn-on energy loss for 50V/ns and 100V/ns

The peak instantaneous power remains the same for the two cases. Additionally, the instantaneous power is the same during the current rise of the switching event ($t = 5\text{ ns}$ to 10 ns). However, the time it takes the power to drop to zero is twice as long for the 50V/ns case. Switching energy during the current rise time (5 to 10ns) is the same for both cases.

The major difference in switching energy occurs during the voltage fall time (time $> 10\text{ ns}$). The switching energy for the 50V/ns case during this time period is twice as high as the 100V/ns case, which has a strong influence on the total switching energy. The total switching energy for the 50V/ns case is $168\mu\text{J}$ compared to $104\mu\text{J}$ for the 100V/ns — a 61.5% increase. Note that system switching-losses are equal to the switching frequency multiplied by the switching energy. Therefore, the significant difference in switching energy for the two cases illustrates the need for higher dV/dt ruggedness to minimize switching losses, maximize system efficiency, and enable higher switching frequencies.

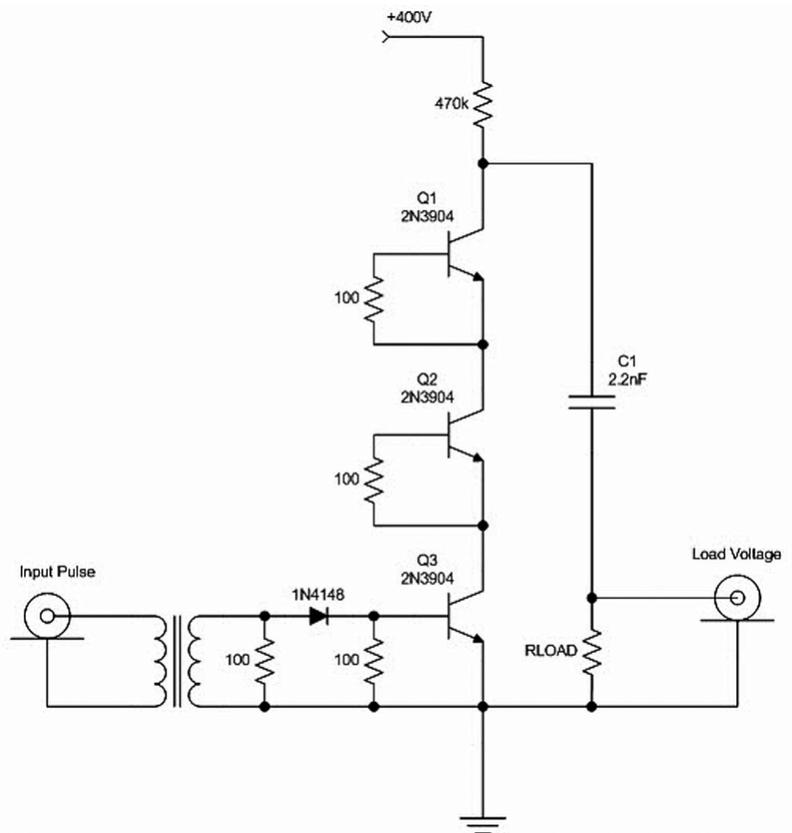
Series-connected avalanche transistor pulser

The evaluation of dV/dt ruggedness requires a means of generating an extremely fast high voltage pulse. Some existing techniques include a mercury-wetted relay pulse generator [4] and avalanche transistors [5-13].

The mercury-wetted relay approach has been historically used to generate extremely fast pulses; however, a custom relay design would be required to handle the higher voltage levels necessary for this study. A second widely used approach involves operating bipolar junction transistors (BJTs) in avalanche breakdown region. This condition occurs when the BJT's collector-to-emitter voltage (V_{CEO}) is exceeded and the transistor enters secondary breakdown.

By limiting the time the BJT is subjected to secondary breakdown, the device can be used as an extremely fast low-jitter high-voltage switch that could be applied to characterize the dV/dt ruggedness of SiC power devices. However, the performance and reliability of commonly available BJTs is not guaranteed for repeated operation in this mode; as such, the test circuit requires an avalanche transistor type (e.g., BJTs designed specifically for avalanche mode operation). This type of avalanche transistor pulser is widely used to drive Pockels cells, streak cameras, lasers, etc., and is an excellent choice for this study. One popular configuration for a high voltage avalanche transistor pulser is the series connection generator.

In evaluating the series-connected avalanche transistor pulser for this work, a 200Ω resistive load was used in the circuit schematic shown in Figure 4. Voltage measurements were taken with a high voltage probe connected directly to the BNC connector, with an adapter to eliminate the ground wire inductance. Waveforms were observed with a 350MHz (1ns rise time) digital sampling oscilloscope with 400MHz 100:1 probe (900psec rise time). The frequency response limitations of the oscilloscope and probe resulted in a system rise time of 1.35ns.

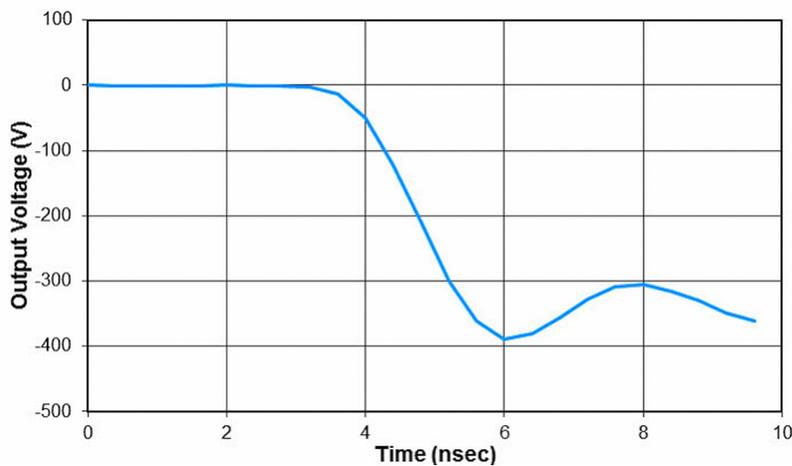


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Figure 4: Pulse generator using series connected avalanche transistors

The circuit places three transistors with a maximum VCEO of 40V in series. At steady state, the 400VDC input voltage is divided equally among the transistors resulting in a collector-to-emitter voltage (VCE) of 133V across each transistor, placing them close to avalanche mode. Operation of the circuit is as follows: a pulse is applied to the input and causes transistor Q3 to avalanche.

Similar to a domino effect, this action essentially causes the two remaining transistors to avalanche. This causes the top terminal of capacitor C1 to discharge to ground in less than 2ns, resulting in a high dV/dt negative-going pulse produced across the load resistor (RLOAD). The output voltage pulse is presented in Figure 5, in which the 1.35ns rise time is observed.



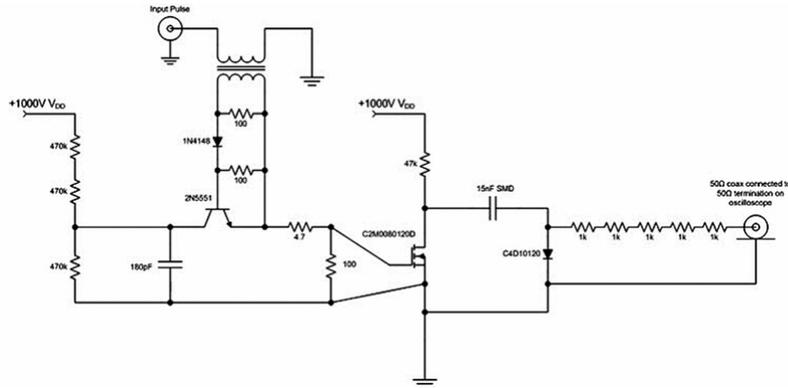
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Figure 5: Series connected pulse generator output terminated into 200Ω RLOAD

SiC Schottky diode dV/dt ruggedness testing

With a verified high-speed pulser in place, Cree conducted a series of dV/dt ruggedness tests on a 600V 3A Schottky diode*. The intent of the tests was to use the new setup to exercise the diode with an extremely fast

of the dV/dt ruggedness at the higher rated voltages. The DUT for these tests was a 1200V 10A SiC diode**. The schematic of the test setup is shown in Figure 8, with the applied voltage (V_{DD}) set to 1000V. Note that the pulse generator circuit required modification to account for V_{DD} and the rated VRRM of 1200V of the higher voltage Schottky diode being tested.

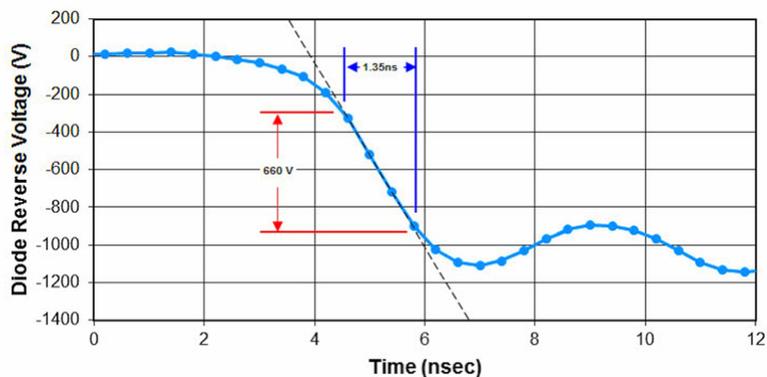


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Figure 8: Schematic for the 1200V 10A SiC Schottky diode** dV/dt ruggedness test setup

Two of the 2N5551 silicon transistors have been replaced by a single 1200V SiC MOSFET***. The SiC MOSFET is turned on quickly via a pulse applied to the remaining 2N5551 avalanche transistor. The activation of the SiC MOSFET causes the top terminal of the SMD capacitor to discharge to ground, resulting in a reverse bias pulse of 1000V to be applied to the DUT. The voltage was measured with the low impedance resistive divider to minimize ringing.

As shown in Figure 9, the measured reverse dV/dt was 490 V/ns, or approximately six times faster than the typically reported diode dV/dt ruggedness value of 80V/ns of 1.2kV SiC JBS diodes [16]. No device failures were encountered during the course of these tests, which clearly demonstrates the dV/dt ruggedness of this higher voltage SiC diode and provides a clear indication of the ruggedness of the entire device family.



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Figure 9: 1200V 10A SiC Schottky diode** reverse $dV/dt = 490$ V/ns

Conclusions

The dV/dt ruggedness of SiC Schottky diodes can be still a concern for many designers. The goal of this work was to design a pulser capable of subjecting the test devices to a dV/dt significantly faster than what would be experienced in practice, in order to further characterize the 600V and 1200V SiC Schottky diodes that are increasingly employed in modern high-voltage power-conversion systems.

Furthermore, the Wolfspeed diodes tested demonstrated six times higher dV/dt ruggedness than what is typically reported in the industry, with values of 295V/ns and 490V/ns, respectively. Most importantly, no failures were observed with any of the devices tested, which means the actual limits of these diodes exceeds these values. As of this writing, the ultimate dV/dt ruggedness of these devices remains unknown.

Footnotes

*Cree C3D03060A

** Cree C4D10120A

*** Cree C2M0080120D

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