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Utilization of SiC MOSFET body diode in hard switching applications.

A. Bolotnikov[1,a*], J. Glaser[1], J. Nasadoski[1], P. Losee[1], S. Klopman[1], A. Permuy[2], L. Stevanovic[1]

[1]General Electric Global Research Center, Niskayuna, NY, USA
[2]General Electric Energy Management Power Conversion, Massy, France
[a]bolotnik@ge.com

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Abstract. This work discusses the possibility of using SiC MOSFET body diode in switching power conversion applications, focusing on performance and reliability aspects.

Introduction. Tremendous progress has been made on SiC MOSFETs in the last few years. High voltage SiC devices offer the promise of efficient power conversion in areas that current silicon-based power semiconductors do not. System benefits such as improved efficiency, reduced part count, reduced size and weight will make this technology attractive for adoption in a variety of power conversion systems. The largest application space for SiC MOSFETs is between 1.2 and 3.3kV, where they have the potential to greatly reduce both switching and conduction loss in applications ranging from low power dc-dc converters to MW inverters. Nearly all of these applications make use of an anti-parallel diode. With IGBTs, the anti-parallel diode comprises a separate die, while with MOSFETs, the intrinsic body diode may be used, although it generally has poor switching performance. In either case, when the diode is implemented in silicon, the reverse recovery of such diodes results in high switching losses. In applications utilizing IGBTs this has led to the use of SiC Schottky diodes in cases where performance outweighs cost. On the other hand the use of the SiC MOSFET body diode could provide significant cost and size benefits. This work discusses the possibility of body diode use in switching power conversion applications, focusing on performance and reliability aspects.

Body diode switching performance evaluation. The dynamic performance of the GE 1200V/15A SiC MOSFET body diode [1] was evaluated using a double-pulse test circuit with inductive load (Fig. 1a, b). The lower device current was measured by utilizing a 50mOhm shunt having bandwidth of 1200MHz. The upper device current was monitored by a custom current transformer utilizing Epcos B64290P0037X038 core of T38 material and 10:1 wound ratio. Switching waveforms were obtained by Tektronix DPO7254 oscilloscope providing 500MHz bandwidth.

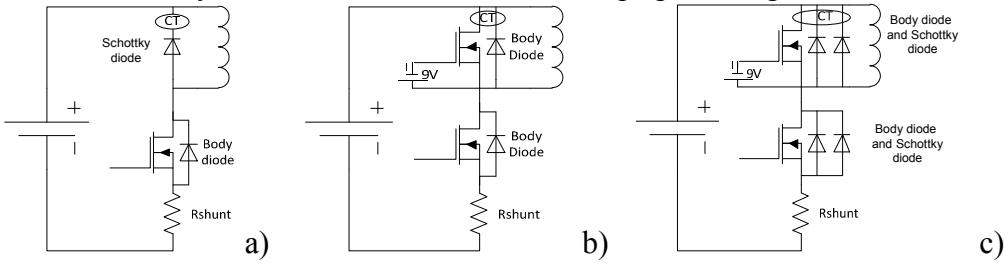

Fig. 1. Schematic of test circuits with lower GE 1200V SiC MOSFET and a) upper Schottky diode, b) upper SiC body diode and c) with two MOSFETs with a parallel Schottky diode.

Room temperature turn-on and turn-off characteristics of SiC MOSFET with 10A upper Schottky diode [2] and upper MOSFET (body diode) are shown in Fig. 2 and 3 respectively.

As it follows from waveforms, the turn on energy loss of lower MOSFET and diode's reverse recovery energy is higher for configuration utilizing body diode (269uJ and 23uJ) compared to configuration with Schottky diode (229uJ and 11.5uJ). On the other hand, lower turn off energy was measured in setup having the MOSFET with upper body diode (24.4uJ) compared to MOSFET with upper Schottky diode (28.2uJ).

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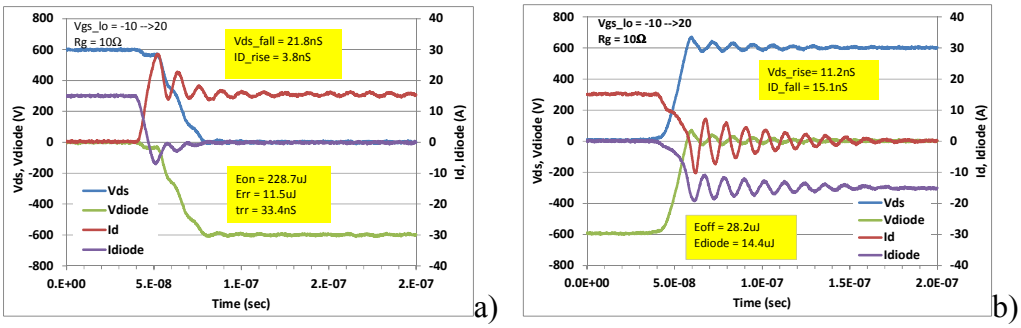


Fig. 2. Switching waveforms of lower GE SiC MOSFET with upper SiC Schottky diode: a) turn on waveforms; b) turn off waveforms (room temperature).

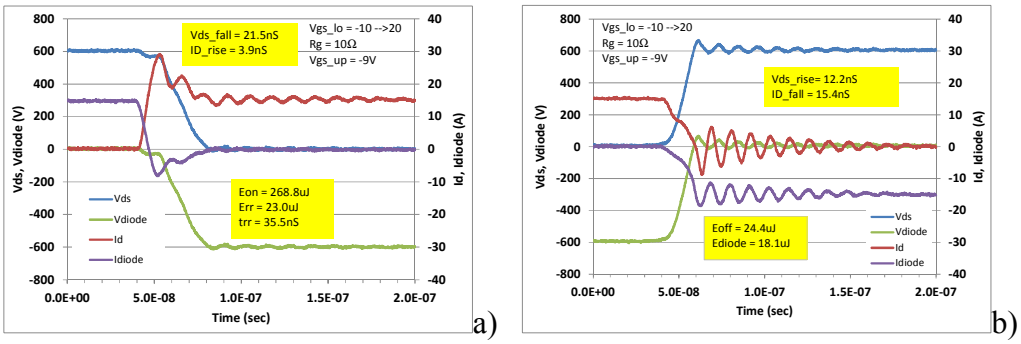


Fig. 3. Switching waveforms of lower GE SiC MOSFET with upper SiC body diode: a) turn on waveforms; b) turn off waveforms (room temperature).

Similar evaluation of switching characteristics of SiC MOSFET with 10A upper Schottky diode and upper MOSFET (body diode) was performed at elevated temperatures. Turn-on and turn-off characteristics of these devices at 125°C are shown in Fig. 4 and 5:

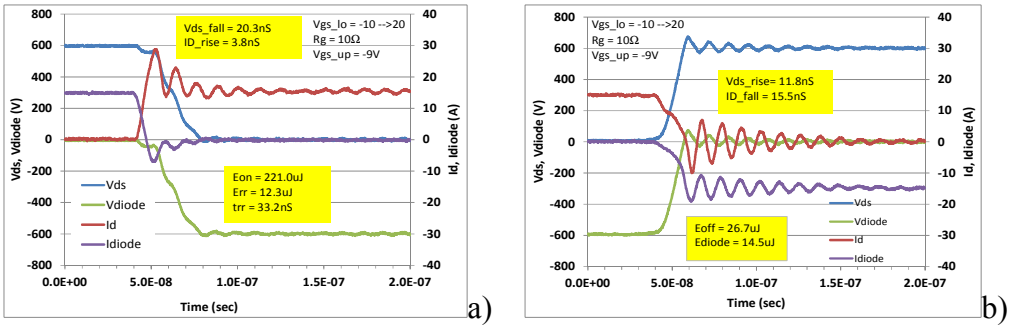


Fig. 4. Switching waveforms of lower GE SiC MOSFET with upper SiC Schottky diode (diode is at 125°C): a) turn on waveforms; b) turn off waveforms.

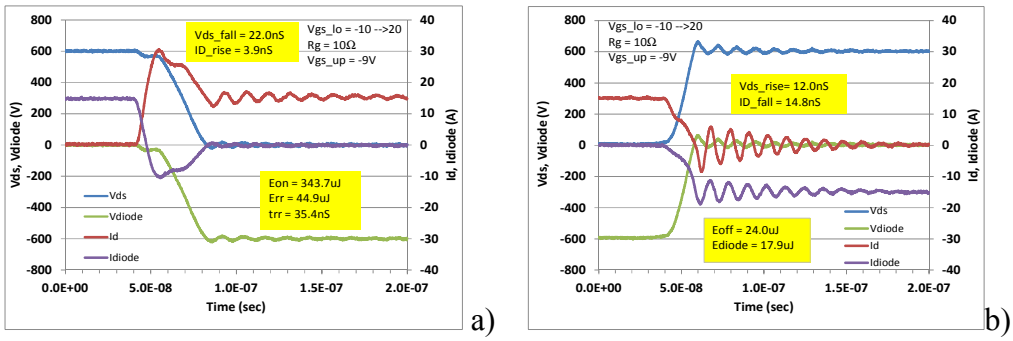
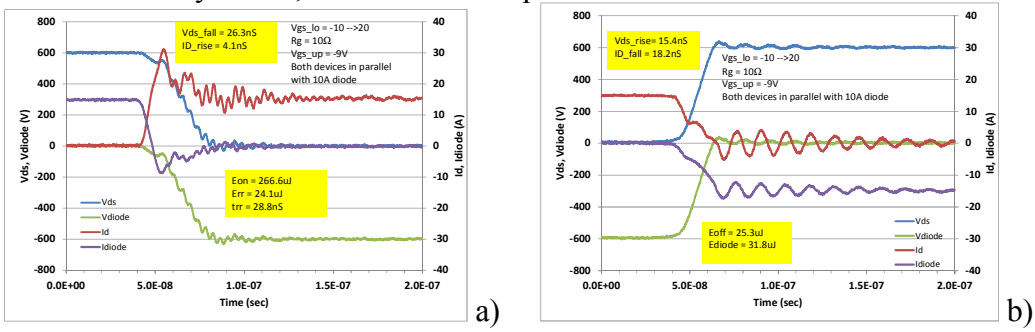


Fig. 5. Switching waveforms of lower GE SiC MOSFET with upper SiC body diode (upper MOSFET is at 125°C): a) turn on waveforms; b) turn off waveforms.

It is obvious that at 125°C the turn on energy loss of lower MOSFET and diode's reverse recovery energy is higher for configuration utilizing body diode compared to that at room temperature (343.7uJ and 44.9uJ). This increase results from carrier lifetime increase which on another hand results in larger stored charge in body diode drift layer during forward conduction. Please note that turn-off losses of such configuration are almost temperature invariant. The switching performance of configuration with Schottky diode exhibited no significant temperature dependence either.

Note, in a more typical application, two MOSFETs would be connected in a half-bridge. Room temperature testing of this configuration with anti-parallel SiC Schottky diodes on each MOSFET shows turn-on and recovery losses of 266.6uJ and 24.1uJ, with turn-off loss of 25.3uJ (Fig. 6). This is nearly identical to the case without the antiparallel Schottky diodes. While the Schottky diodes reduce the reverse recovery losses, the additional capacitance due to these diodes adds loss.



a) b)

Fig. 6. Switching waveforms of lower GE SiC MOSFET with antiparallel Schottky diode in half-bridge configuration: a) turn on waveforms; b) turn off waveforms (room temperature).

While increase in turn-on losses at elevated temperature is expected, utilization of internal body diode can still be beneficial provided it results in simpler module layout, better reliability and lower module/system cost due to smaller number of components and simpler assembly.

Body diode stability evaluation. In early applications of SiC MOSFETs, the use of intrinsic body diode was also avoided due to high voltage drop and the risk of bipolar degradation [3, 4]. Our interim results of long-term switching converter testing suggest these risks may be mitigated. The evaluation of body diode stability has been carried out utilizing twelve identical 6kW buck-boost converters operating at 200kHz frequency, 10A (~150A/cm^2), 600V bus voltage, 50% duty cycle. Each converter uses four SiC MOSFETs (2 switches and 2 synchronous rectifiers) running at T_j≈100°C. The schematic of buck-boost setup is shown in Fig. 7. The design is based on a pump-back system: buck converter followed by a boost converter. In this configuration power recirculates from one converter to another, thus voltage source (V_{BUS}) provides only power to compensate for the losses in the circuit. This allows direct measurement of the total loss with high accuracy. Additional converter hardware details can be found in [5].

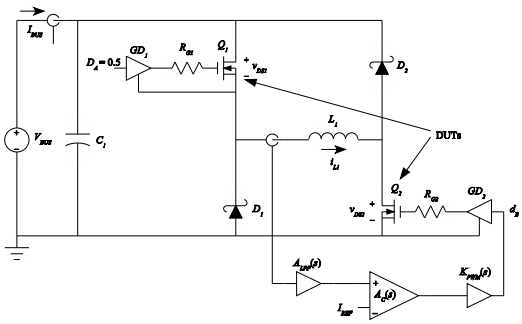


Fig. 7. Schematic of pump-back converter test scheme.

Results and discussion. As of August 2013, 24 devices have been running continuously for over 10,000 hours with no significant body diode performance deterioration. Based on periodic evaluation of body diode forward voltage drop at 15A (Fig. 8), less than +/-4% change was observed. With more than 260,000 cumulative device-hours of continuous operation, there have been no device failures. These results differ from our previous stress-testing of SiC MOSFETs with body diode operating under continuous DC current, where we observed the forward voltage degradation in a sub-population of parts.

The bipolar degradation was previously attributed to material defects, such as basal plane dislocations resulting in stacking fault generation [3, 6]. It is worth pointing out that the two groups of devices tested under DC bias and pulsed mode have the same design and have been produced on epi wafers with same specs. This raises an important question of why one population degrades and the other does not and, more importantly, what are safe boundaries for the body diode operating in pulsed mode. The authors believe that the observed stability of body diode can be attributed to:

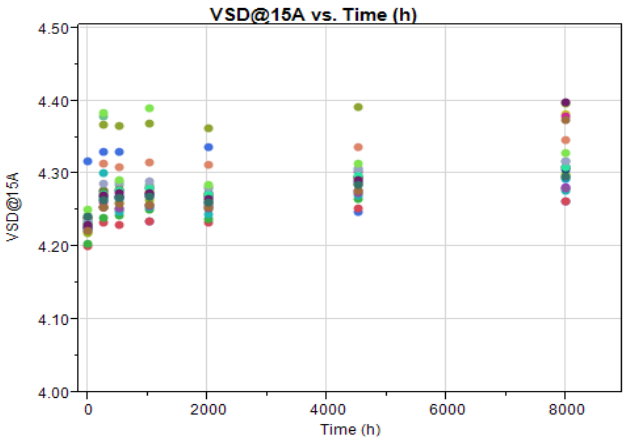


Fig. 8. Body diode forward voltage measured periodically (each device represented by a single dot)

1. Poor anode injection due to damage created by ion implantation used for p-well/p+ formation. In this case body diode operates at low injection levels, thus carrier recombination participation in conduction, which is believed to be a driving force of degradation [3], is negligible.

2. Relatively short duration of body diode bipolar conduction (250ns in the buck-boost testbed) also minimizing probability of minority carrier recombination.

3. Defect generation that recovers during unipolar conduction and off-state (4.75µs in the buck-boost testbed).

The observed results agree with previous work studying forward voltage drop degradation of 4H-SiC PIN diodes in pulse mode [7]. The authors of the referenced work indicated that there is a certain characteristic time required for stacking fault formation and that the pulses (bipolar conduction duration) shorter than milliseconds cause substantially smaller forward drift compared to DC stress with the same charge passed through the diodes. A self recovery of forward voltage drop was also observed.

While the obtained results look encouraging, further study is required to fully assess and explain the robustness of body diode in pulse applications (e.g., synchronous rectifier). The next steps will include evaluation of body diode stability at higher current densities, higher junction temperatures and longer bipolar conduction duration. Similar tests are planned for higher voltage devices (e.g. 3.3kV SiC MOSFET [8]).

Summary. The possibility of 1200V SiC MOSFET body diode use in switching applications was discussed. It was shown that utilization of body diode will provide similar room-temperature switching losses compared to configuration using antiparallel SiC Schottky diode. While increase of MOSFET turn-on losses at elevated temperatures (originated from upper body diode recovery) was observed, the use of the SiC MOSFET body diode could provide significant cost and size benefits. Finally, results of long-term switching converter testing suggest the possibility of reliable SiC MOSFET body diode operation in hard switching applications.

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