Hybrid Si-IGBT/SiC Rectifier co-packs and SiC JBS Rectifiers offering superior surge current capability and reduced power losses

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Abstract: Novel device design and process innovations made at GeneSiC on SiC Junction Barrier Schottky (JBS) rectifiers result in a significant increase of surge current capability with a 33% decrease in power dissipation at 10x rated current. On the 1200 V-class rectifiers, a clear signature of avalanche-limited breakdown with low leakage currents is observed at temperatures as high as 240 °C. Almost temperature independent Schottky barrier heights of 1.2 eV and ideality factors < 1.05 are measured on GeneSiC's JBS rectifiers, which is evidence of a homogenous interface between the Schottky metal and the SiC surface. A near theoretical Richardson's constant of 138 A/cm^2K^2 (for 4H-SiC) is directly extracted from the forward I-V characteristics. When compared with an off-the-shelf all-Si IGBT power co-pack, GeneSiC's GA100XCP12-227 co-pack offers 88% and 47% reduction at 125 °C in the IGBT and free-wheeling diode switching energy losses, respectively. This results in an overall switching loss reduction of about 28% as compared to its silicon counterpart.

Introduction and Device Design

This paper reports on high-voltage SiC Junction Barrier Schottky (JBS) rectifiers and 1200 V/100 A Si IGBT with SiC anti-parallel diode co-packs designed and fabricated at GeneSiC. The SiC JBS rectifiers are designed for > 225 °C operation with high surge current capability, temperature independent ideality factors < 1.05, and low capacitive losses. These SiC rectifiers are ideal free-wheeling diodes for either Si IGBTs or SiC transistors in power converters required for aerospace, oil-drilling and space applications.

Enhanced Surge Current Capability

A comparison of 1200 V/20 A GeneSiC JBS rectifiers fabricated using a "Standard" process and a novel "High-Surge Current or HSC" process is shown in Figure 1(a). For comparison, a recently released 1200 V/20 A SiC JBS rectifier from another SiC device manufacturer is also shown in Figure 1(a). Above 150 A, a self-heating induced saturation of the I-V characteristics is visible in Figure 1(a) for the standard JBS rectifier. The HSC JBS rectifier circumvents this current saturation by injecting minority carriers into the drift region under surge-current conditions. A comparison of power dissipation through the Standard, HSC and other manufacturer JBS rectifiers are shown in Figure 1(b). Under normal conditions, the HSC rectifier dissipates the same amount of power as the Standard rectifier. Notably, both GeneSiC rectifiers dissipate lower power as compared to the device from the other manufacturer. However, once the surge function of the rectifier is activated at high current densities, a 33% decrease in power dissipation is observed in Figure 1(b) for the HSC JBS rectifier at 10x the rated current (200 A). This enhanced surge capability of GeneSiC JBS rectifiers makes them more resilient to fault-current events, and consequently increases their operating lifetime in the field.

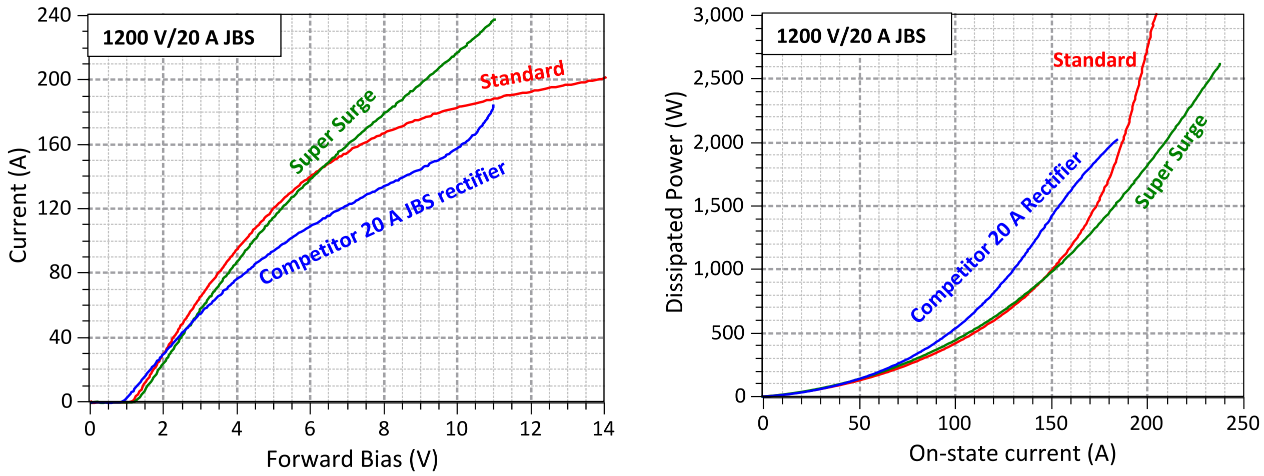

Figure 1: Comparison of (Left, a) Forward I-V characteristics and (Right, b) On-state Power Dissipation of 1200 V/20 A-class Standard, HSC and other manufacturer SiC JBS rectifiers.

Blocking characteristics and Schottky contact ideality

Optimized edge termination and surface passivation used for fabricating the JBS rectifiers resulted in a distinct positive temperature co-efficient of avalanche breakdown voltage (Figure 2(a)). Even at 240 °C, reverse leakage currents < 50 µA (2 mA/cm^2) are observed in Figure 2(a) for a 1200 V/10 A rectifier. A comparison of blocking voltage performance of a GeneSiC 1200 V/10 A JBS rectifier with other commercial SiC JBS rectifiers, shown in Figure 2(b) indicates a much smaller increase in leakage current for the GeneSiC rectifier, as the temperature is increased from 25 °C to 225 °C. None of the JBS rectifiers from other manufacturers display a clear positive temperature co-efficient of breakdown voltage, indicating that the device breakdown in those devices may be due to mechanisms other than avalanche breakdown.

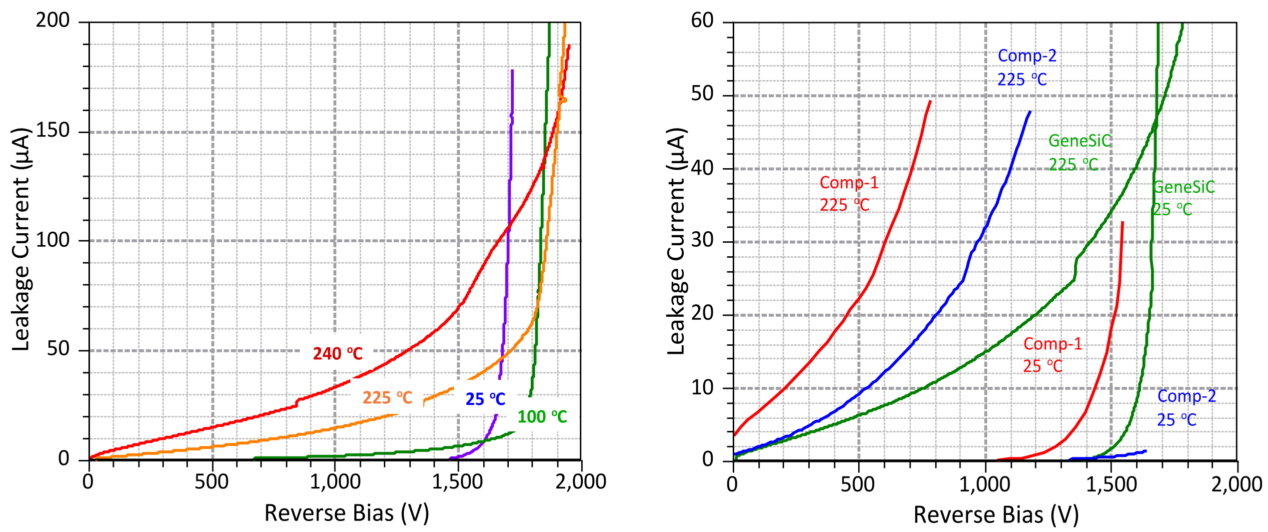

Figure 2: (Left, a) High-temperature blocking I-V characteristics measured on a 1200 V/10 A JBS rectifier and (Right, b) Blocking voltage performance of GeneSiC 1200 V/10 A SiC JBS rectifier is compared with offerings from other SiC device manufacturers.

Almost temperature independent Schottky barrier heights of 1.2 eV and ideality factors < 1.05 (Figure 3) were extracted from low-current (10^{-9} A to 10^{-5} A) forward I-V characteristics measured at different temperatures on GeneSiC's JBS rectifiers. As shown in Figure 3(b), a near theoretical Richardson's constant (A*) of 138 A/cm^{2}K^2 (for 4H-SiC) is directly extracted from the temperature dependent low-current forward I-V characteristics using the well-known procedure described in [1]. The extraction of a near-theoretical A* and ideality factors are evidence of a homogenous interface between the Schottky metal and the SiC surface in the JBS rectifier.

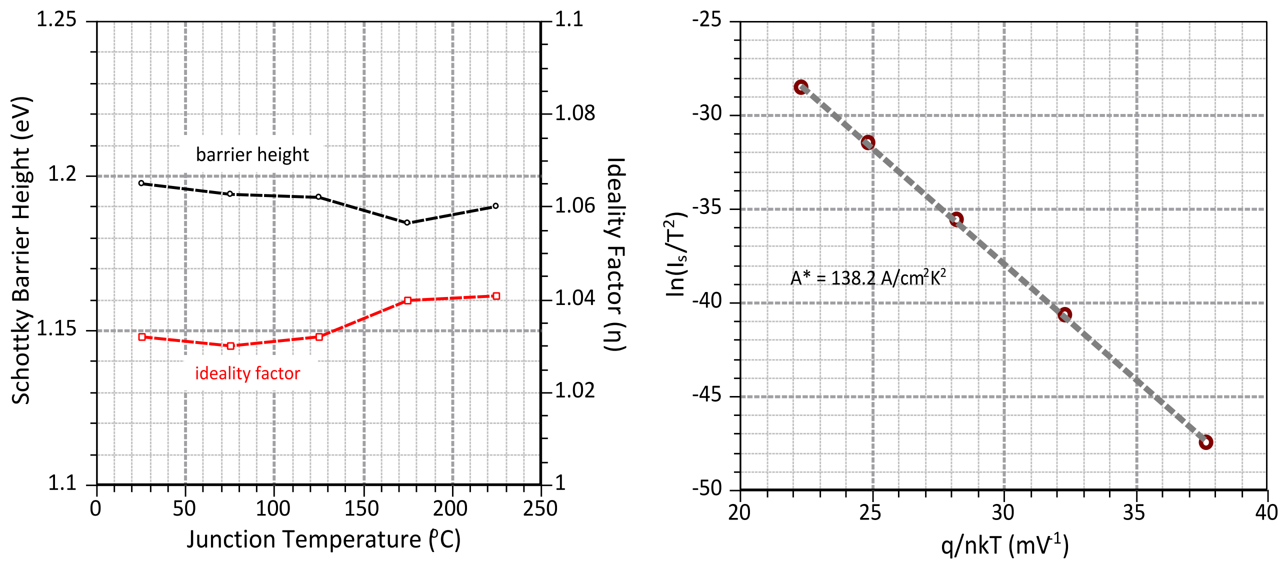

Figure 3: (Left, a) Schottky Barrier Height and Ideality factor and (Right, b) Near theoretical Richardson's constant extracted from low-current accurate I-V measurements performed on 1200 V/10 A SiC JBS rectifiers.

Hybrid Si IGBT + SiC JBS Rectifier Co-Pack Modules

The 1200 V SiC JBS rectifiers were co-packaged with Si IGBTs to create 1200 V/100 A Si IGBT with SiC anti-parallel diode co-packs (GA100XCP12). Detailed conduction and switching measurements were performed at 125 °C on GA100XCP12 and a commercial all Silicon IGBT co-pack for comparison. The switching measurements were performed by an inductively clamped double-pulse circuit described in [2]. A standard IGBT gate driver with a voltage output from – 8 V to 15 V and a Gate resistor of 9 Ω was used for driving the Si IGBTs. In the switching waveforms shown in Figure 4, the SiC JBS rectifier is clearly distinguished from the Si PiN rectifier by the absence of a pronounced reverse recovery (RR) current. The RR current generated during the Si PiN rectifier turn-off adds to the IGBT turn-on current, thereby increasing the IGBT turn-off power losses. Moreover, the RR current has a positive temperature co-efficient, which results in a systematic increase in power losses with temperature.

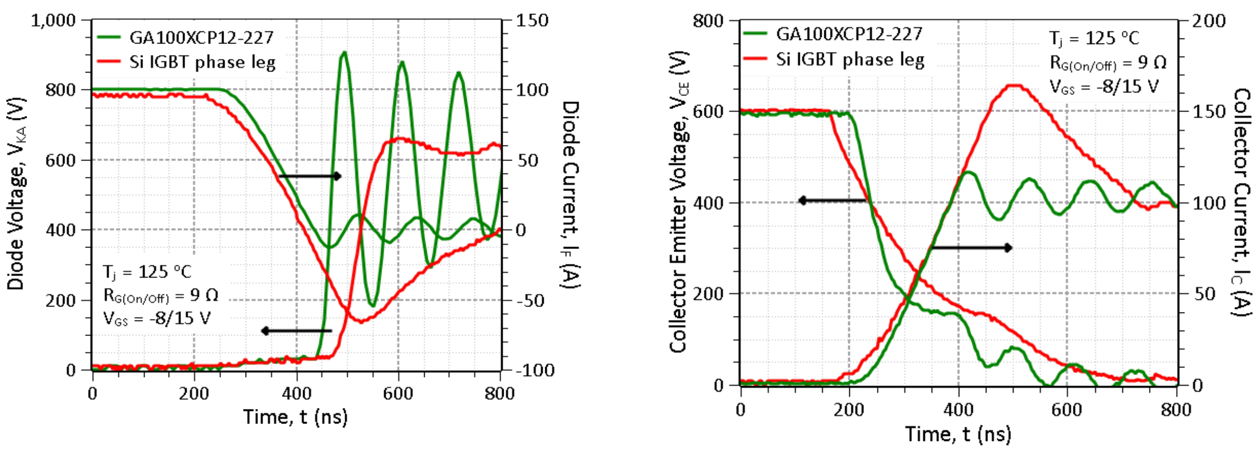

Figure 4: Comparison of an all-Si commercial 1200 V/100 A phase-leg module with a hybrid 1200 V/100 A Si IGBT + SiC JBS rectifier with respect to (Left, a) Free-wheeling diode turn-off I,V transients and (Right, b) IGBT turn-on I-V transients. The high-reverse recovery (RR) current generated during the Si PiN rectifier turn-off adds to the IGBT turn-on current, thereby increasing the IGBT turn-on power losses. This RR current is distinctly absent in the SiC JBS rectifier.

The high-level oscillations observed in the SiC FWD turn-off and IGBT turn-on waveforms shown in Figure 4 are possibly due to very small diode turn-off losses for the SiC JBS rectifiers and the low Gate resistor value used for the switching measurements. These undesirable phenomena can be attenuated by a more optimized package re-design with lower parasitic inductance and capacitance or by slowing down the switching process.

The switching energies of the all-Silicon IGBT module and GA100XCP12-227 were extracted from the measurements performed at 100 A, 600 V at 125 °C operating temperature and are shown in Figure 5. The turn-off characteristics of the integrated Si and SiC rectifiers in IGBT modules reflect on the IGBT turn-on characteristics. The temperature independent zero reverse recovery charge of the SiC JBS rectifier in the GA100XCP12-227 reduces the freewheeling SiC rectifier turn-off and Si IGBT turn-on energies by 88% and 47% respectively as compared to the all-Si IGBT module, while the Si IGBT turn-off and Si-SiC rectifier turn-on energies remain the same. As a result, the GA100XCP12-227 module reduces the overall switching energies by about 28% when compared to the all-Si solution.

Power losses were extracted from the measured static and switching characteristics for switching 100 kHz frequency at a Duty Cycle (D) of 0.5 at 125 °C. The various component contributions to the overall power losses of the two IGBT modules are shown in Figure 5(b). The IGBT turn-off losses constitute a very significant portion (> 50%) of the overall losses, which are not affected by the choice of the free-wheeling diode. For the hybrid Si-SiC module, the diode turn-off loss fraction is reduced from 18% to 3%, which reduces the IGBT turn-off loss fraction from 20% to 14%. The diode conduction losses (DCON) constitute a small, yet similar fraction (3%) of the total power loss for the two modules.

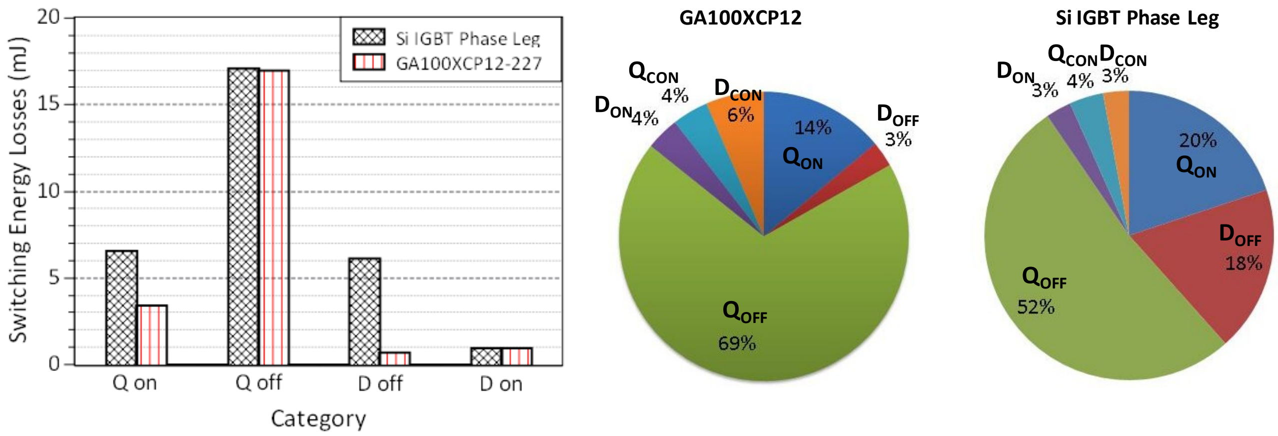

Figure 5: (Left, a) Switching energy comparison and (Right, b) Individual contribution of components to the overall loss for GeneSiC's hybrid 1200 V/100 A Si-SiC IGBT co-pack and an all-Si 1200 V/100 A IGBT power module tested at 125 °C. Q_{ON} and Q_{OFF} refer to the IGBT turn-on losses, D_{ON} and D_{OFF} refer to the free-wheeling diode turn-on and turn-off losses, Q_{CON} and D_{CON} refer to the IGBT and Diode conduction losses.

References

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[2] Z. Chen. MS Thesis. Virginia Tech. 2009.