1200 V SiC "Super" Junction Transistors operating at 250 °C with extremely low energy losses for power conversion applications

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***Abstract*— The electrical performance of GeneSiC's 1200 V/7 A SiC Super Junction Transistor (SJT) is compared with three best-in-class commercial Si IGBTs in this paper. Low leakage currents of <100 µA at 325 °C, turn-on and turn-off switching transients of <15 ns at 250 °C, current gain as high as 72, on-resistance as low as 235 mΩ, second-breakdown-free square RBSOA, and short- circuit withstand time of 22 µs were measured on the SiC SJTs. For switching 7 A and 800 V at 100 kHz, the SiC SJT + GeneSiC SiC Schottky rectifier as Free Wheeling Diode (FWD) achieved a total power loss reduction of about 64% when compared to the best all-Si IGBT+FWD configuration and a power loss reduction of about 47 %, when compared to the best Si IGBT + SiC Schottky FWD.**

I. INTRODUCTION

GeneSiC is aggressively developing Silicon Carbide (SiC) "Super" Junction Transistors (SJTs) in voltages ranging from 1.2 kV to 10 kV for high efficiency power conversion in aerospace, defense, down-hole oil drilling, geothermal, Hybrid Electric Vehicle (HEV) and inverter applications. The SiC SJT is a normally-off "Super-High" current gain SiC BJT that exhibits a square reverse biased safe operating area (RBSOA), high temperature (> 300 °C) operation capability, low $V_{DS(on)}$ as well as faster switching capability (10's of MHz) as compared to any other competitor SiC switch. Unlike SiC MOSFETs, the SiC SJT is free from metal oxide semiconductor (MOS) interface reliability concerns [1] and high channel resistance, which have limited the SiC MOSFET to less than 150 °C operation temperatures and necessitated >15 V Gate biases. The SiC SJTs display a lower positive temperature coefficient of $R_{DS(on)}$ and higher temperature capability when compared with normally-OFF SiC JFETs. GeneSiC's SJTs are packaged in industry standard TO-220 plastic packages and custom high-temperature metal-can packages. When incorporated in power electronic circuits, the SJTs can improve the circuit efficiencies significantly while reducing the overall system size, component count, cooling requirements and cost. This paper investigates the high temperature (>250 °C) blocking, on-state, switching and reliability characteristics of 1200 V/ 7 A SiC SJTs by comparing their static, dynamic characteristics and the associated losses with the following best-in-class 1200V Si IGBTs:

- NPT1: 125 °C/1200 V/14 A rated Si Non Punch-Through IGBT
- NPT2: 150 °C/1200 V/10 A rated Si Non Punch-Through IGBT
- TFS: 175 °C/1200 V/15 A rated Si TrenchStop™ IGBT

All the above co-packs have Si FREDs associated in anti parallel direction with the Si IGBTs.

II. STATIC CHARACTERISTICS

The temperature independent blocking characteristics of a 1200 V/7 A SiC SJT is shown in Fig. 1. The SJT blocks the rated 1200 V even at 325 °C with a low leakage current < 100 µA. Fig. 2 shows the leakage currents measured on a SJT and

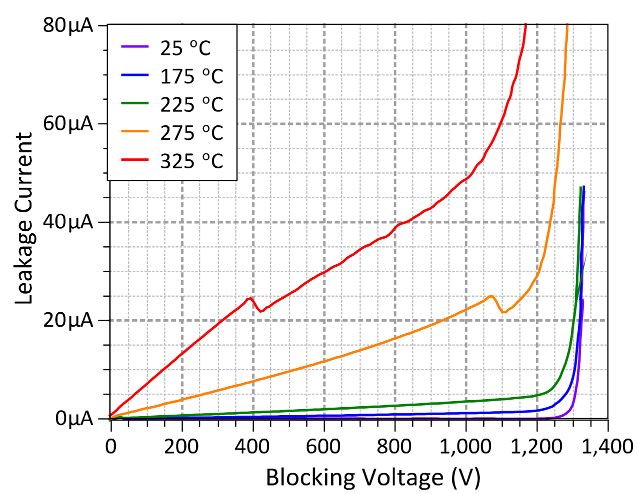

Figure 1. Open-Gate Blocking characteristics of a representative 1200 V/ 7A SiC SJT.

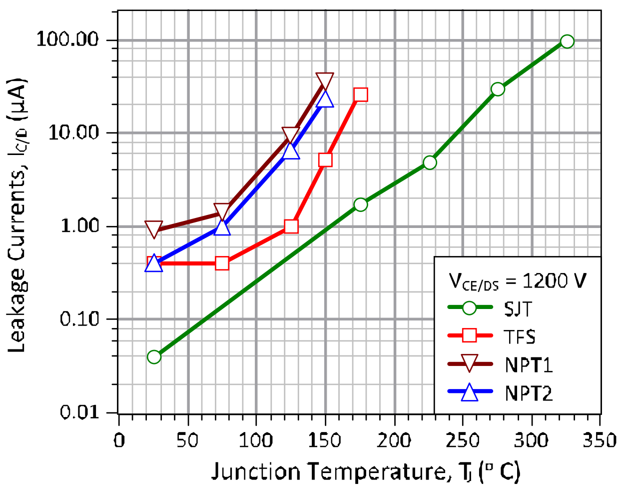

Figure 2. Comparison of leakage currents of SiC SJT and Si IGBTs as a function of temperature.

the three Si IGBTs at a blocking voltage of 1200 V at various temperatures. Extremely high leakage currents preclude the operation of even high-temperature-rated Si IGBTs beyond 175 °C. On the other hand, the maximum operational temperature of the SiC SJTs is limited to 325 °C in this present study only by the capability of the power packaging. As compared to the Si IGBTs, the SiC SJT also displays a lower positive temperature co-efficient of leakage current in the blocking voltage mode. The output I-V characteristics of the SiC SJTs (shown in Fig. 3) feature a near-zero Drain-Source offset voltage, distinct lack of a quasi-saturation region and the merging of the different Gate current I-V curves in the saturation region. The last two features imply lack of charge storage in the drift region of the SiC SJT and clearly distinguish it from a "bipolar" Si BJT. This inherent property of the SiC SJT enables temperature independent fast switching transients, as will be shown in the next section. At a given temperature, the on-state voltage drops of SJT are smaller than the Si IGBTs with $V_{DS(on)}$ values of 1.5 V at 25 °C and 2.5 V at 125 °C and 7 A of drain current. Like a typical majority carrier device, the SJT displays a positive temperature coefficient of $V_{DS(on)}$ which is a desirable feature for reliable paralleling of multiple SJTs for high current configurations. An on-resistance of 235 mΩ (calculated at a Gate current of 400 mA) was measured at 25 °C operating temperature on a 7 A SJT. As the junction temperature is increased from 25 °C to 250 °C, the maximum current gain decreased from 72 to 39 (see Fig. 4).

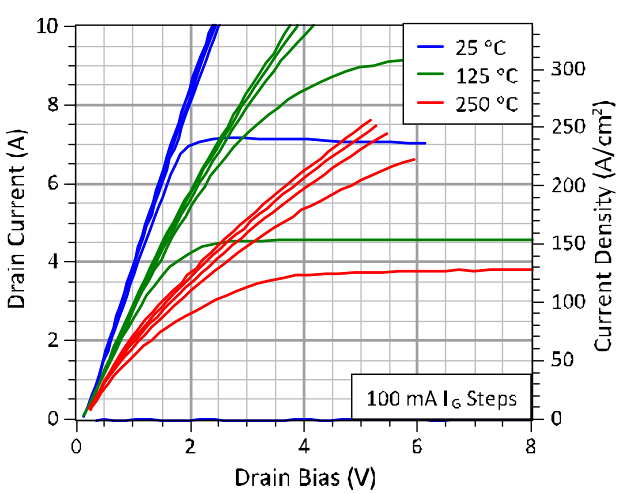

Figure 4. Output characteristics of a representative 1200 V/ 7A SiC SJT as a function of temperature.

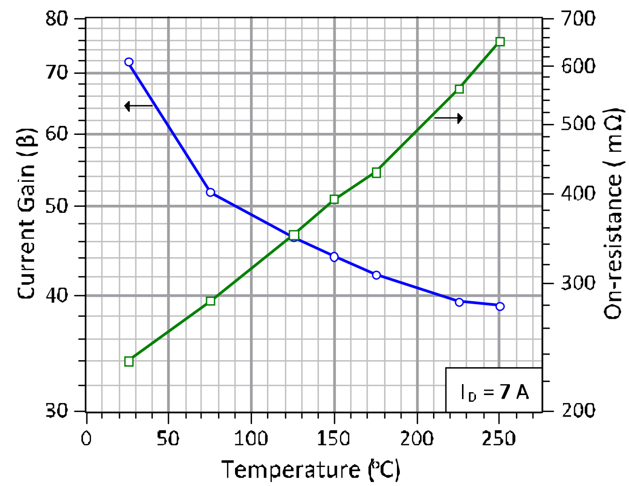

Figure 3. Temperature variant On-resistance and Common Source Current Gain of a representative 1200 V/7 A SiC SJT.

III. Gate Voltage Control Mode Operation

In addition to the SJT operation under Gate current control shown in Fig. 3, it is also possible to operate the SiC SJT under Gate voltage control. The output characteristics of a 1200 V/7 A SJT measured under Gate voltage control is shown in Fig. 5. Fig. 5 shows that the rated current of 7 A can be obtained by supplying a Gate voltage (V_{GS}) of 4 V, which is significantly lower than V_{GS} as high as 20 V required to satisfactorily drive 1200 V SiC MOSFETs. The transfer characteristics of a 7 A SiC SJT at different temperatures are

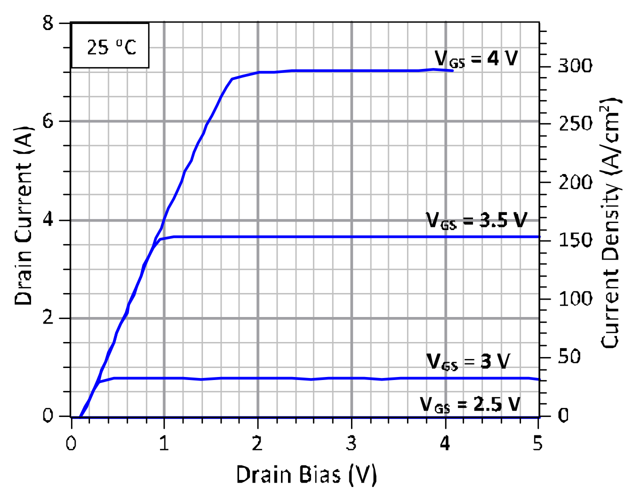

Figure 5. Output characteristics of a 1200 V/7 A SiC SJT in Gate voltage control mode at 25 °C.

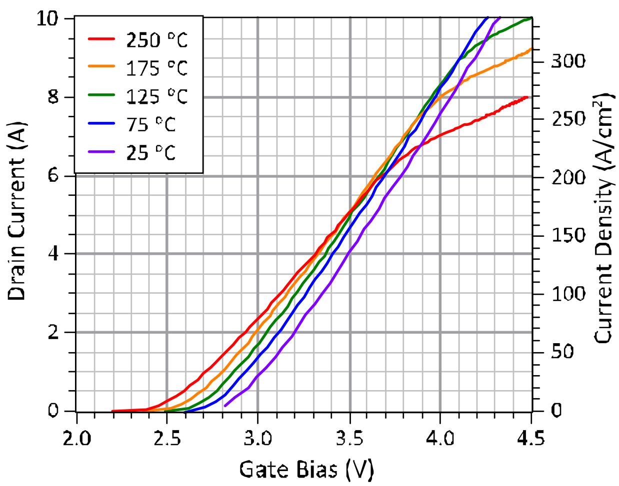

Figure 6. Transfer characteristics of a 1200 V/7 A SiC SJT at different temperatures.

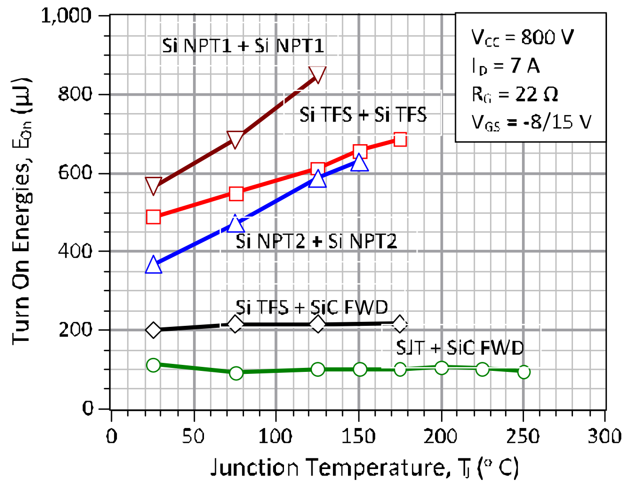

Figure 7. Turn On Switching Energy comparison of the SiC SJT and Si IGBTs at various operating temperatures.

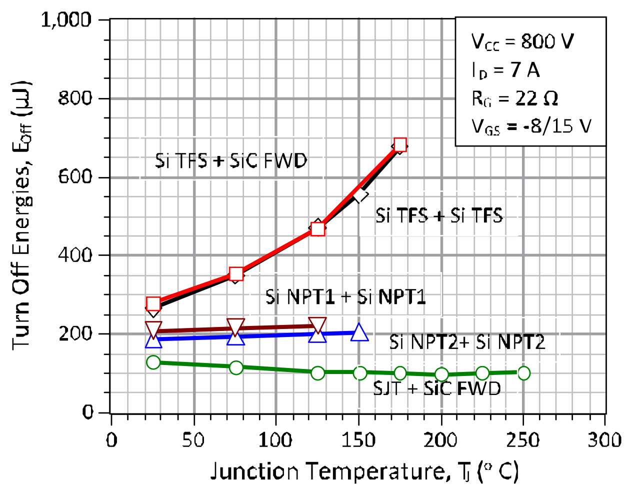

Figure 8. Turn Off Switching Energy comparison of the SiC SJT and Si IGBTs at various operating temperatures.

shown in Fig. 6. A small-signal transconductance (g_m) of 7.4 S at 7 A is extracted from the room-temperature transfer curve in Fig. 6, which decreases to 7.1 S at 125 °C. A Gate threshold voltage of 2.8 V is obtained from Fig. 6 at 25 °C, which decreases to 2.4 V at 250 °C. The apparent saturation of the transfer curves at higher current levels is due to the power limitations of the Gate drive circuit of the curve tracer used for these measurements.

IV. DYNAMIC CHARACTERISTICS

An inductively clamped double pulse switching setup [2] was used to investigate the switching performance of the SJT and Si IGBTs. A GeneSiC 1200 V/ 7A SiC Schottky diode [3] and Si IGBT co-packs were used as Free Wheeling Diodes (FWDs) in the switching test circuit. The Gate and Source terminals of the Si IGBT co-pack (FWD) were tied together (VGS = 0 V) to avoid the IGBT conduction during the dynamic testing. A 1 µF charging capacitor, a 150 µH inductor, 22 Ω Gate resistor and a supply voltage of 800 V were used in the testing process. A commercially available IGBT gate driver with an output voltage swing from -8 V to 15 V is used for driving all the devices. While driving the SiC SJT, a 100 nF dynamic capacitor connected in parallel with the Gate resistor generated high initial dynamic Gate currents of 4.5 A and -1 A during turn-on and turn-off switching respectively, while maintaining a constant Gate current of 0.52 A during its turn-on pulse. These large initial dynamic Gate currents charge/discharge the device input capacitance rapidly, yielding a faster switching performance.

A comparison of the turn-on (Fig. 7) and turn-off (Fig. 8) energy losses of the various Si and SiC power device configurations was performed at temperatures ranging from 25 °C to their respective maximum operating temperatures. Si TFS + SiC FWD represents Si TFS IGBT as the DUT and SiC Schottky diode as FWD respectively where as Si TFS + Si TFS represents Si TFS IGBT as DUT and Si TFS IGBT co-pack as FWD respectively. The SiC SJTs displayed a temperature independent (up to 250 °C) Drain current rise time as low as 12 ns and a fall time as low as 14 ns for switching at 800 V and 7 A, resulting in significantly lower switching losses as compared to any of the all-Si or Si IGBT+SiC FWD configurations.

Fig. 9 shows an overall power loss comparison of all the devices, extracted from the measured dynamic and static characteristics for a 100 kHz switching frequency and a 0.7 Duty Cycle (D). The measured gate drive, conduction and switching losses of the SJT are 5.25 W, 26.65 W and 20 W respectively at 250 °C. Though the gate driver losses of SJT are higher than Si IGBTs, their contribution to the overall losses is insignificant. Replacing a Si FRED with a SiC Schottky diode for FWD applications alone reduces the overall switching losses by more than 30%. An All-SiC SJT/Schottky rectifier solution as opposed to an all-Si IGBT/PIN rectifier solution resulted in more than 50% power loss reduction.

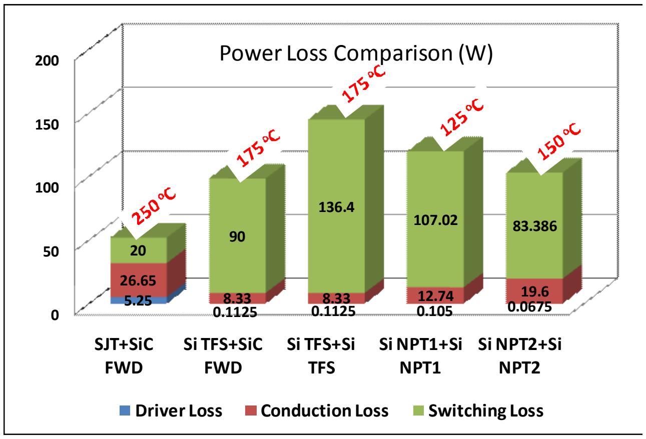

Figure 9. Overall loss comparison of SJT and Si IGBTs at their respective maximum operating temperatures.

V. RBSOA LIMITS

The SiC SJT has a perfectly square RBSOA and is not affected by the second breakdown mechanism, which limits the maximum current that can be safely turned-off by Si BJTs at high operating voltages [4]. In this work, the switching capability of the 1200 V/7 A SiC SJT was investigated under two extreme turn-off SOA conditions: (i) 22 A (3x the rated Drain current) turn-off at a nominal Drain Bias of 800 V shown in Fig. 10, and (ii) Rated 7 A turn-off under a high Drain bias of 1250 V shown in Fig. 11. From these graphs, it is evident that the SiC SJT is able to safely turn-off under both ultra-high Drain current and Drain bias conditions and with very clean waveforms. A perfectly square RBSOA for the SiC SJT can be inferred from the high SOA switching waveforms shown in Figs. 10 and 11.

VI. SHORT-CIRCUIT SOA (SCSOA) AND AVALANCHE RUGGEDNESS

Preliminary results from the short-circuit capability and avalanche ruggedness of the 1200 V/7 A SJTs are shown in Fig. 12 and Fig. 13, respectively. When the SJT is turned on to a short circuit at a Drain voltage of 800 V with 0.2 A of Gate current, a short circuit current of 13 A and a short circuit

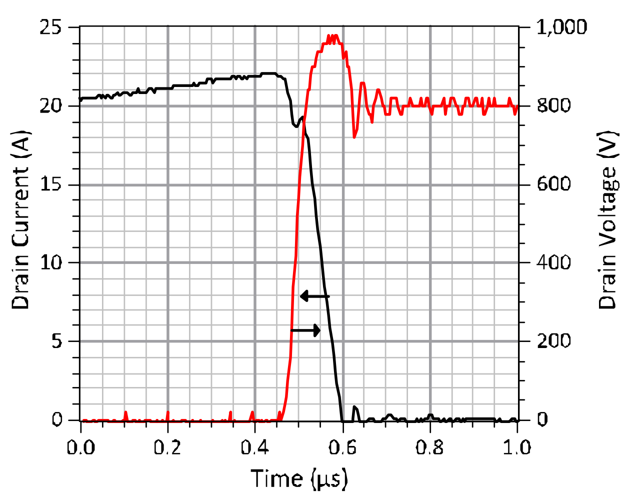

Figure 10. Switching waveforms demonstrating the capability of a 1200 V/7 A rated SiC SJT to turn-off under a high current (22 A) SOA condition.

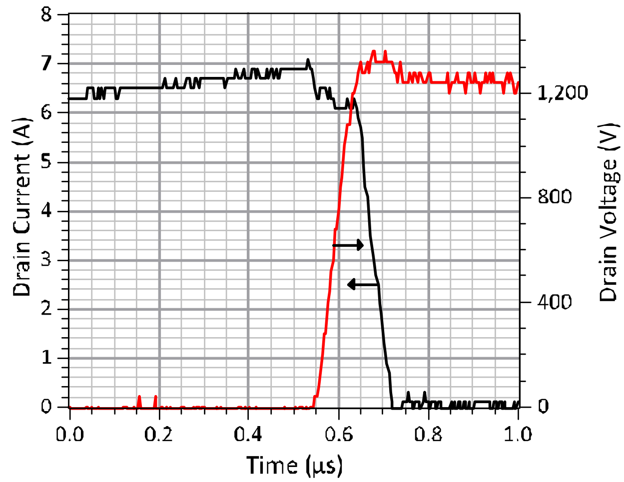

Figure 11. Switching waveforms demonstrating the capability of the 1200 V/7 A rated SiC SJT to turn-off under a high voltage (1250 V) SOA condition.

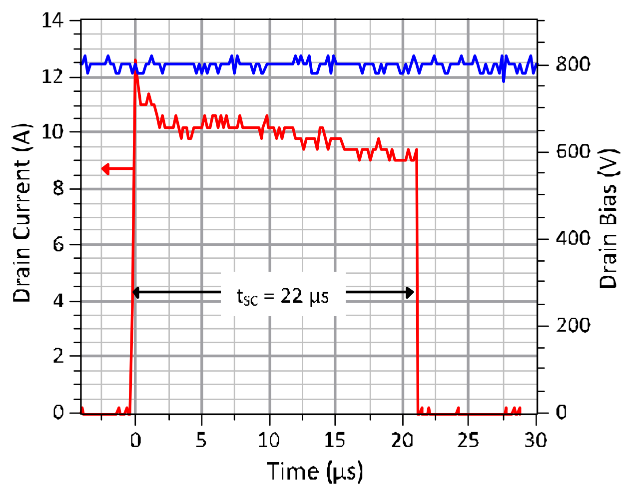

Figure 12. A short circuit withstand time of 22 µs is obtained, when a 1200 V/7 A SJT is switched on to a short-circuited load at a Drain bias of 800 V and a Gate current of 0.2 A.

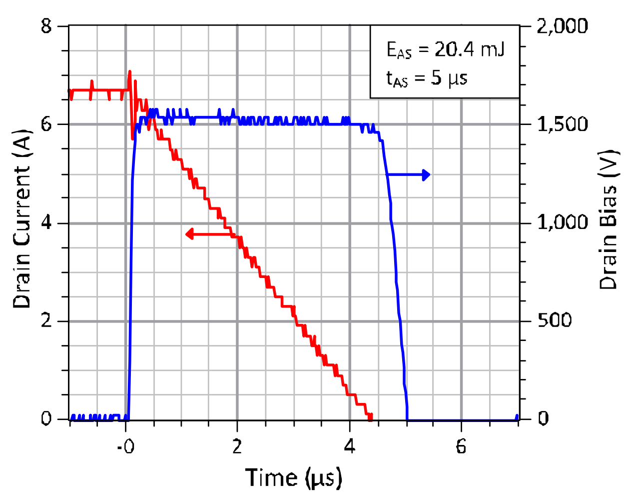

Figure 13. A single-pulse avalanche energy of 20.4 mJ is obtained for unclamped Inductive switching (UIS) of a 1200 V SJT at the rated Drain current of 7 A.

withstand time of 22 µs are observed in Fig. 12, which is considerably higher than the 10 µs short-circuit withstand time reported on SiC MOSFETs. Under these short circuit conditions, device destruction occurred at 25 µs.

A single-pulse avalanche energy (E_{AS}) of 20.4mJ was extracted (see Fig. 13) from Unclamped Inductive Switching (UIS) performed on the 7 A rated SJT at the rated current of 7 A with a 1 mH inductor. Measurements of repetitive avalanche energies at different operating pulse width/duty cycles and under different base-plate temperatures will be the focus of a different study.

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