SILICON CARBIDE “SUPER” JUNCTION TRANSISTORS OPERATING AT 500 °C

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Abstract

1200 V/ 3 mm^2 active-area SiC “Super” Junction Transistors (SJTs) display current gains as high as 88 and majority carrier operation up to 250 °C. The SJT operation shifts from purely unipolar to bipolar-mode at temperatures $\geq$ 300 °C. The leakage currents at a blocking voltage of 1200 V remain below 100 µA, even at 325 °C. Temperature-independent turn-on and turn-off times < 15 ns are measured up to 250 °C. A short-circuit withstand time of 22 µs at V_{DS}=800 V, and a single-pulse avalanche energy of 20.4 mJ are measured. No degradation of the blocking I-V characteristics was observed after a 934 hour repetitive avalanche stress test.

Keywords: Super Junction Transistor, Silicon Carbide Power Devices, 500 °C Operation, Avalanche Ruggedness, Short-Circuit Operation

Introduction

Power electronics components for Venus-type NASA exploration missions are required to function at ambient temperatures in excess of 485 °C, at over 92 atmospheres of pressure and under a high concentration of sulfuric acid vapor in the Venusian atmosphere. At the moment, there is no existing power device technology on the market, which can reliably operate under these stringent requirements. While SiC is the semiconductor material of choice for high-temperature power electronics, existing high-temperature SiC device technologies are based on discretely connected MOSFETs or JFETs in combination with free-wheeling Schottky barrier diodes to form motor control power modules. However, discretely connected MOSFET or JFET based SiC device technologies are prone to vastly degraded electrical characteristics at ultra-high-temperatures (> 485 °C), due to significant Gate oxide reliability concerns in case of MOSFETs[i,ii,iii] and an unacceptably high temperature co-efficient of on-state voltage drop and drastic reduction in Gate threshold voltages at > 300 °C temperatures making it difficult to fabricate normally-OFF JFETs[iv].

SiC “Super” Junction Transistors (SJTs) are high current gain, majority carrier transport SiC NPN BJTs developed by GeneSiC in 1200 V -10 kV ratings. 1200 V-class, 3 mm^2 active area SiC SJTs with current gains as high as 88, low on-resistance of 5.8 mΩ-cm^2 and switching times of < 15 ns were recently reported[v]. This paper is focused on the high-temperature operation of the SiC SJTs up to 500 °C, after packaging the devices in special test coupons.

Experimental

Device fabrication of the 1200 V/3 mm^2 SiC SJTs (please refer to [v] for details) was performed with Al topside and Au backside metallization. After fabrication, selected die were attached to DBC alumina substrates with off-eutectic AuSn die-attach, which is capable of operation up to 600 °C for short durations. The die were then wire bonded using thick 8 mil Al wire bonds. Output characteristics of the packaged die were measured up to 500 °C. The blocking and switching characterization of the packaged SJTs after high-voltage encapsulation were performed up to 325 °C. The assembly was then placed on a high temperature stage for testing.

High-Temperature Output Characteristics

Output characteristics of the packaged die were measured in 100 °C increments up to 500 °C and the I-V characteristics are shown in Figure 1. A 250 W/cm^2 package dissipation curve is included in the plots to indicate a possible current rating for these devices. At 25 °C, a current gain (β) of 62 and a specific on-resistance of 5.5 mΩ -cm^2 is obtained from the I-V characteristics. The positive temperature co-efficient of on-resistance observed in Figure is desirable for paralleling multiple devices for high-current configurations. Up to a temperature of 300 °C, the I-V curves show a distinct lack of a quasi-saturation region and the merging of the different Gate current I-V curves in the saturation region, which indicate unipolar operation mode of the SiC SJT. These features clearly distinguish the SiC SJT from a "bipolar" Si BJT and enables temperature independent, fast switching transients. However, in the temperature range of 400 – 500 °C, clearly demarcated saturation and quasi-saturation regions appear in the I-V characteristics, implying a shift in operation from unipolar mode to bipolar mode. This is due to an increase in resistivity of the lightly doped n- drift region at such high temperatures and 100% ionization of Aluminum acceptors in the p-type base region, which results in significant forward biasing of the base-drift layer p-n junction[vi].

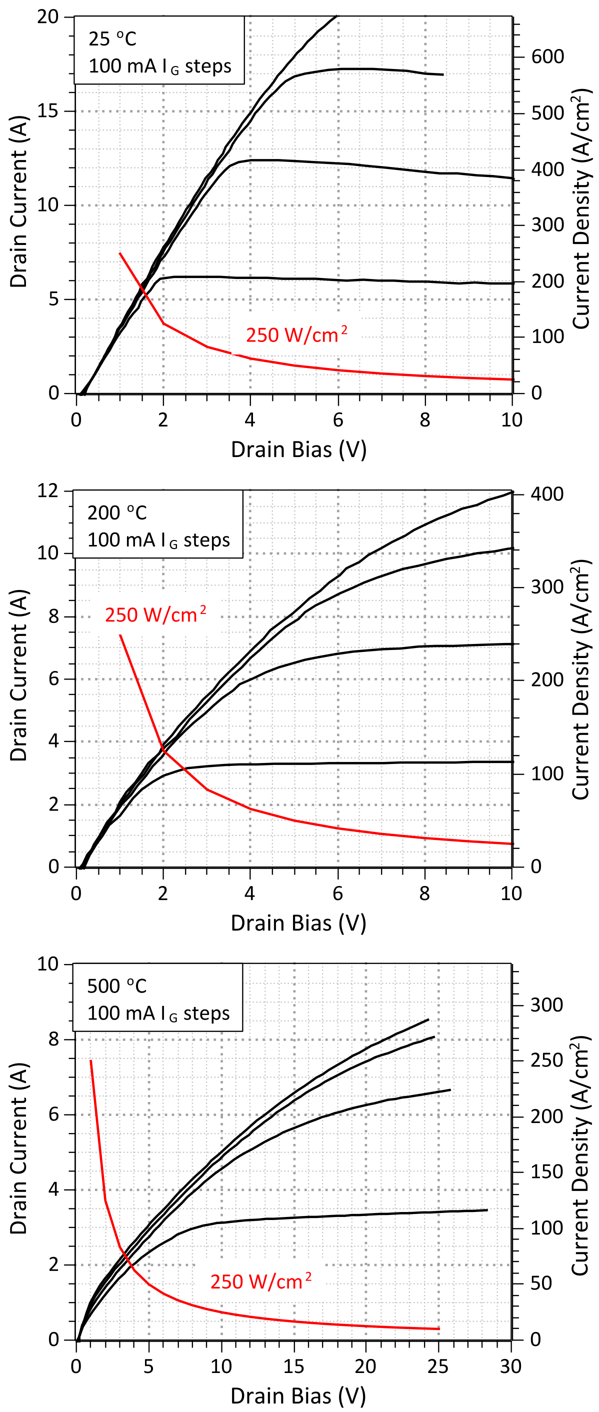

Figure 1: Output Characteristics of packaged 1200 V/3 mm^2 SiC SJTs measured from 25 °C to 500 °C.

The variation of β with operating temperature is shown in Figure 2(a). Due to an increase in ionization of the p-type acceptors in the base region, the current gain shows a negative temperature co-efficient up to 300 °C. However at > 300 °C temperatures, the current gain increases with temperature, due to an increase in carrier lifetime with temperature. The on-state characteristics measured at a constant Gate current of 500 mA at different temperatures is shown in Figure 2(b). A clear transition from unipolar mode of operation to a bipolar mode of operation of the SJT can be observed at temperatures ≥ 300 °C. Clear saturation and quasi-saturation regions can be observed in the output characteristics above 300 °C.

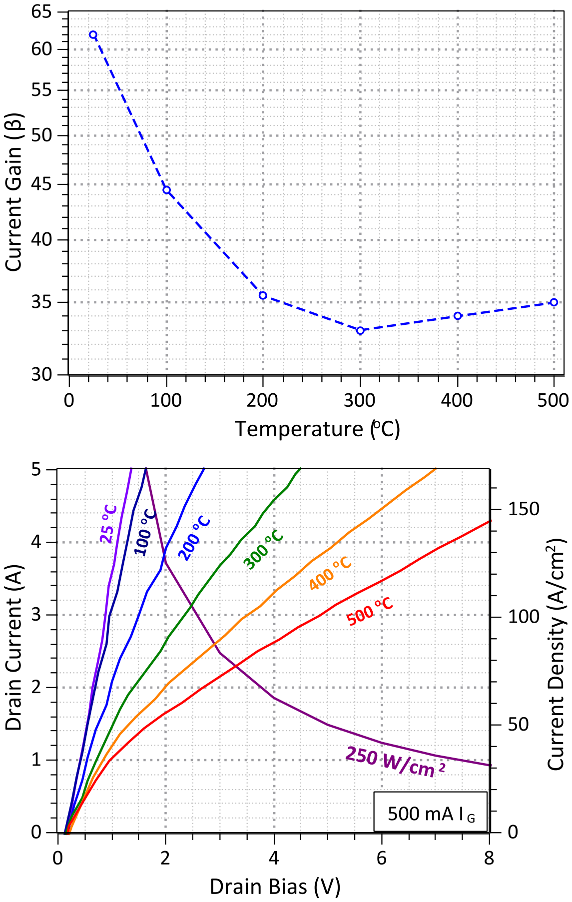

Figure 2: (Top,a): Variation of maximum SJT current gain (β) as a function of operating temperature and (Bottom,b) Output I-V characteristics measured at a constant Gate current of 500 mA at different temperatures.

High-Temperature Blocking Characteristics

After performing the on-state characterization, selected devices were provided with high-voltage encapsulation for high-voltage blocking measurements. Open-Gate blocking I-V characteristics of a 1200 V/3 mm^2 SiC SJT from 25 °C to 325 °C is shown in Figure 3. Optimized SJT process design and fabrication resulted in near-theoretical breakdown voltages and temperature independent, low reverse leakage currents up to 325 °C. Even at 325 °C, the leakage currents at 1200 V are below 100 µA or 58 mA/cm^2.

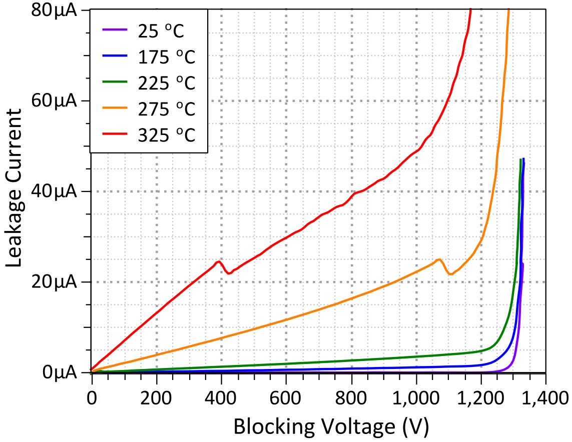

Figure 3: Open-Gate Blocking I-V characteristics measured on a 1200 V/3 mm2 SiC SJT up to 325 °C.

Switching Characterization

Switching measurements on the 1200 V/3 mm^2 SiC SJTs were performed with an inductive load and free-wheeling 1200 V/ 7 A GeneSiC SiC Schottky rectifiers. A commercially available IGBT gate driver with an output voltage swing from -8 V to 15 V was used for driving the SJTs. 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. Ultra-low Drain current rise and fall times of 12 ns and 13 ns, respectively, were recorded (Figure 4) for switching 8 A and 800 V by the 3 mm^2 SJT. Interestingly, there is no difference in switching times, when the measurement temperature is increased from 25 °C to 250 °C, which is further proof of the majority carrier operation of the SiC SJT, i.e. there is no minority carrier storage in the n- layer.

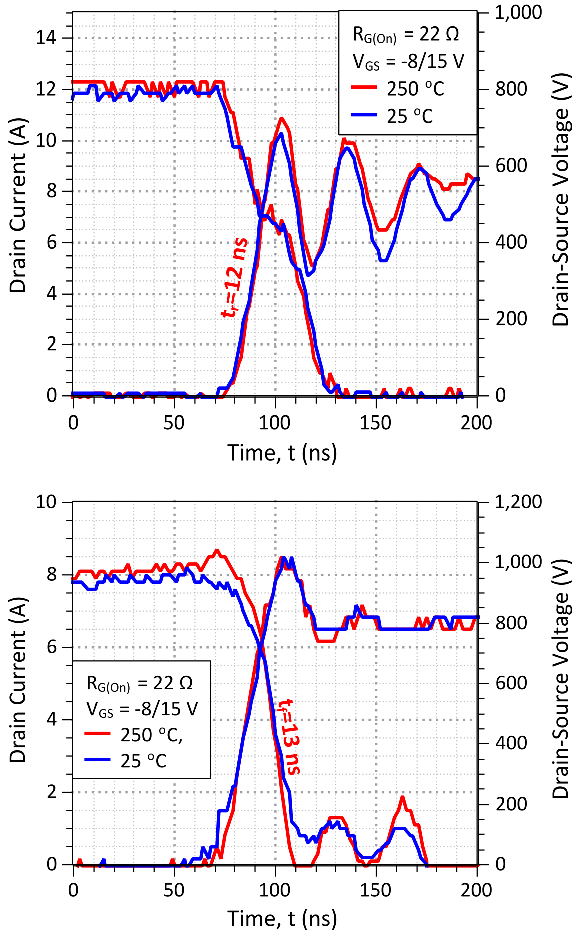

Figure 4: (Top, a) Turn-On and (Bottom, b) Turn-Off Drain Current and Voltage transients recorded for switching 800 V and 8 A through a 3 mm^2 SiC SJT. There is no difference in switching speed between 25 °C and 250 °C, due to the unipolar nature of the SJT device design.

Device Robustness Measurements

Preliminary results from the short-circuit capability and avalanche ruggedness of the 3 mm^2 SJTs fabricated in this work are shown in Figure 5(a) and (b). 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 withstand time of 22 µs are observed in Figure , which is considerably higher than the 10 µs 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 from Unclamped Inductive Switching (UIS) performed on the 4 mm^2 SJT at the rated current of 7 A with a 1 mH inductor.

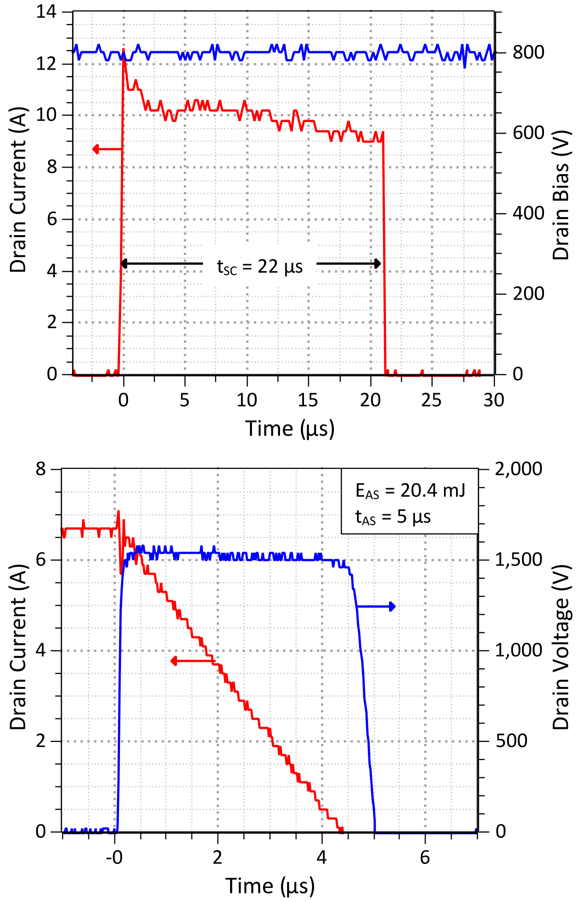

Figure 5: A short circuit withstand time of 22 µs is obtained, when a 3 mm^2 SJT is switched on to a short-circuited load at a

Drain bias of 800 V and a Gate current of 0.2 A. (Right) A single-pulse avalanche energy of 20.4 mJ is obtained for unclamped Inductive switching (UIS) of a 3 mm^2 SJT at the rated Drain current of 7 A.

In a separate experiment, another device was subjected to repetitive 2.3 mJ avalanche mode pulses with a frequency of 14.3 kHz and a duty cycle of 30%. This test was run for 934 hours. The blocking I-V characteristics measured before and after this long-duration test (Figure 6) indicated a slight improvement of the breakdown voltage from 1400 V to 1450 V, after 934 hours of operation under avalanche mode. These results indicate that the SiC SJTs reported in this study offer stable operation, even after long-term avalanche-mode operation, which clearly distinguishes them from Si BJTs, which undergo destructive failure, when exposed to avalanche-mode conditions.

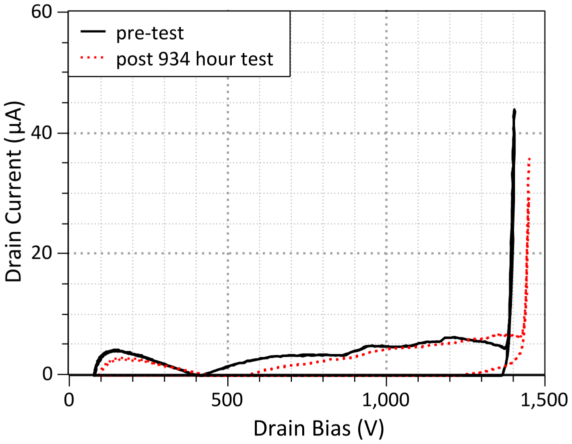

Figure 6: Examination of the Drain-Source blocking characteristics of the SJT before and after a repetitive avalanche-stress was applied to the device for 934 hours.

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