10 kV SiC BJTs – static, switching and reliability characteristics

Siddarth Sundaresan, Stoyan, Jeliazkov, Brian Grummel, Ranbir Singh
GeneSiC Semiconductor, Inc.
43670 Trade Center Pl, Suite 155,
Dulles, VA 20166, USA.
siddarth.sundaresan@genesicsemi.com

***Abstract*— Open-base breakdown voltages as high as 10.5 kV (91% of theoretical avalanche limit and 125 V/µm), on-resistance of 110 mΩ-cm^2 close to the unipolar limit of 94 mΩ-cm^2, and current gain as high as 75 are measured on 10 kV-class SiC BJTs. Monolithic Darlington-connected BJTs fabricated on the same wafer yield current gains as high as 3400, and show Si BJT-like output characteristics with a differential on-resistance as low as 44 mΩ-cm^2 in the saturation region and a distinct quasi-saturation region. Switching measurements performed at a DC link voltage of 5 kV and collector current of 8 A feature a collector current rise time as low as 30 ns during turn-on and collector voltage recovery time as low as 100 ns during turn-off. Very low turn-on and turn-off switching energies of 4.2 mJ and 1.6 mJ, respectively, are extracted from the switching transients, which are 19 and 25 times smaller than the corresponding switching energies reported on 6.5 kV Si IGBTs. When turned-on to a short-circuited load at a collector bias of 4500 V, the 10 kV BJT shows a temperature-invariant, withstand time in excess of 20 µs. Leakage currents < 1µA (system limit) are measured, even after 234 hours of operation under a DC collector bias of 5000 V at elevated temperatures.**

I. Introduction

10 kV-class SiC BJTs are extremely attractive for significantly reducing the size, weight, cooling requirements and increasing the efficiency of power conversion electronics for the medium-voltage range of applications. Previous reports on ≥ 10 kV SiC BJTs describe either un-optimized device designs with very low (< 30) current gain [1] or small-area (100 µm diameter) test BJTs with mA current capability [2]. None of these reported devices are suitable for insertion into actual power electronics systems. This article presents a comprehensive analysis of the experimental characteristics of single-stage and monolithic Darlington SiC *npn* BJTs recently fabricated at GeneSiC Semiconductor with large chip sizes of 3.65 mm x 3.65 mm (active area = 2.7 mm^2) and 7.3 mm x 7.3 mm (active area = 28 mm^2).

II. Experimental

The SiC BJTs presented in this article were fabricated on 84 µm thick, 7x10^{14} cm^{-3} doped n- collector layers. The emitter and base epilayers were appropriately designed for maximizing the current gain of the BJTs. In addition to discrete BJTs, two-stage Darlington BJTs were also fabricated on the same wafer with an output to driver transistor ratio of 3:1. After device fabrication, static electrical characterization of the 10 kV BJTs were performed with a Tek 371 curve tracer and a custom-built high-voltage measurement system with a 20 kV limit. The switching characteristics were measured with an inductive load and a standard double-pulse scheme. An off-the-shelf IGBT gate driver (IXDD614) was used for driving the BJTs with a 18 nF dynamic capacitor connected in parallel with the gate resistor for fast charging and discharging of the BJT's internal capacitances. GeneSiC's 8 kV/10 A SiC JBS rectifier was used as the free-wheeling diode for the switching measurements. A schematic of the gate driver circuit used for testing the BJTs is provided in Fig. 1.

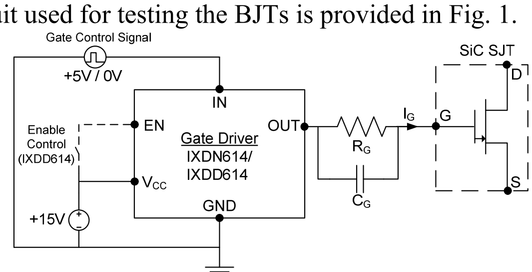

Figure 1. Simplified schematic of the gate drive configuration used in this work for driving the high-gain SiC BJTs. A typical C_G of 18 nF and a RG of 11 Ω were used for the switching measurements.

III. Static Electrical Characteristics

A. Blocking Characteristics

The on-wafer blocking I-V characteristics measured on one 100 mm SiC wafer populated with 10 kV BJTs is shown in Fig. 2(a). The on-wafer testing was performed up to to 6 kV, which is the limit of the on-wafer probing system for three terminal devices. Extremely low leakage currents are observed for these devices up to the testing limit. The high background leakage observed at voltages < 1000 V is due to the capacitive contribution of the testing apparatus.

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To test the 10 kV BJTs up to avalanche breakdown, selected die were packaged in special test coupons, which have a 13 kV isolation rating. As shown in Fig. 2(b), the SiC BJTs display a breakdown voltage in the range 10000-10500 V, which corresponds to 91% of the avalanche breakdown limit, calculated by direct integration of the 4H-SiC impact ionization co-efficients [3] for the 84 µm thick/7×10^{14} cm^{-3} doped n-collector layer.

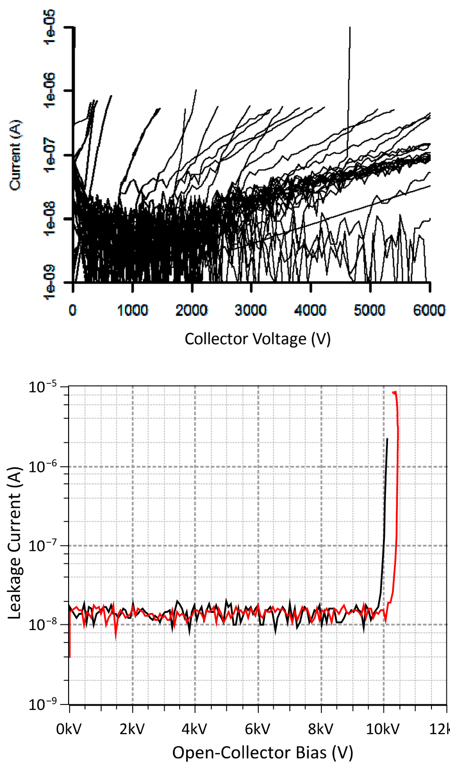

Figure 2. (Top,a): Collector-Emitter (BV_{CEO}) blocking characteristics measured on-wafer to the 6 kV limit and (Bottom,b): BV_{CEO} characteristics measured on packaged SiC BJTs up to avalanche breakdown at 10-10.5 kV.

B. *Output Characteristics*

Fig. 3(a) shows the output characteristics measured on a 2.7 mm^2 SiC BJT, while Fig. 3(b) shows the output characteristics measured on 28 mm^2 discrete and two-stage, monolithic Darlington BJTs at 25°C. The 2.7 mm^2 BJT in Fig. 3(a) has an on-resistance ($r_{on,sp}$) as low as 110 mΩ-cm^2 in the saturation region, which is only slightly larger than the drift resistance of the collector region, calculated as 94 mΩ-cm^2, using an electron mobility of 800 cm^2/V.s and assuming 100% ionization of the nitrogen donors in the n-collector region. The discrete BJTs also show distinctly majority carrier-like output characteristics with the different base current curves overlapped in the saturation region, and the absence of a quasi-saturation region. The high ionization energy (≈190 meV) of the Al acceptors in the p-base layer, combined with the short minority carrier lifetimes (≈1-2 µs) in 4H-SiC makes it difficult to achieve conductivity modulation of the collector region in SiC BJTs [4]. A high current gain (β) of 75 is also measured for both the 2.7 mm^2 and 28 mm^2 discrete BJTs. On the other hand, the output characteristics of the Darlington BJTs shown in Fig. 3 shows distinct saturation (up to I_C = 8 A) and quasi-saturation regions, reminiscent of a Si BJT, combined with a very high current gain of 3400. The differential $r_{on,sp}$ for the Darlington BJT in the saturation region is calculated as 44.8 mΩ-cm^2, which is 69% lower than the $r_{on,sp}$ observed on the discrete BJT, and also significantly lower than the unipolar limit for the n- collector region.

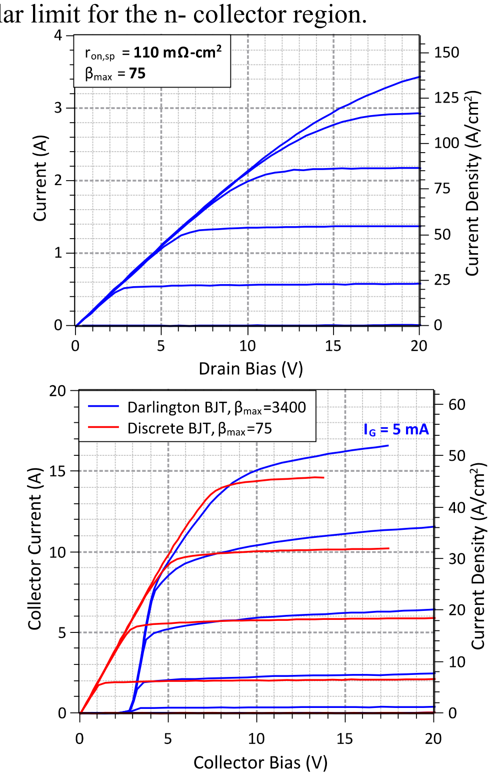

Figure 3. Output characteristics measured on (Top,a): 10 kV/2.7 mm^2 SiC BJTs and (Bottom,b): 10 kV/28 mm^2 Discrete and Monolithic Darlington BJTs.

It is noteworthy that 1200 V-rated SiC Darlington BJTs reported earlier by our group [5] on 1×10^{16} cm^{-3} doped n-collector layers with similarly high values of β did not show quasi-bipolar characteristics (see Fig. 4).

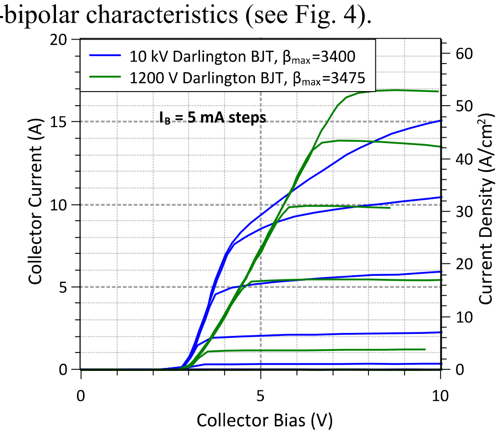

Figure 4. Comparison of output characteristics measured on 4 mm^2, 1200 V and 53 mm^2, 10 kV SiC Darlington BJTs. The 10 kV Darlington BJT shows distinct saturation and quasi-saturation regions resulting from minority carrier storage in the collection region, which are absent in the 1200 V transistor.

Since the base layer doping concentrations were the same in both the 1200 V and 10 kV BJTs, the conductivity modulation observed in the 10 kV transistor is attributed to the lower collector doping (7×10^{14} cm^{-3}) in the 10 kV devices, which results in minority carrier storage in the collector region.

IV. Switching Characteristics

Turn-on and turn-off waveforms from clamped inductive load switching of 10 kV/28 mm^2 SiC BJTs, under a double-pulse scheme are shown in Fig. 5 for a DC link voltage of 5 kV, and collector current of 8 A. The measurements were performed at a base-plate temperature of 150°C. The BJT was driven with a constant base current of ≈ 1 A by connecting a 11 Ω gate resistor at the output of the gate driver. Peak turn-on and turn-off currents of 2.5 A and -3 A, respectively, were supplied by connecting a 18 nF capacitor in parallel with the gate resistor, as shown in Fig. 1. The voltage output of the gate driver was switched from -8 V to 15 V. The high dynamic peak base currents enable rapid charging and discharging of the BJT's base-emitter and base-collector capacitances, resulting in fast switching transitions.

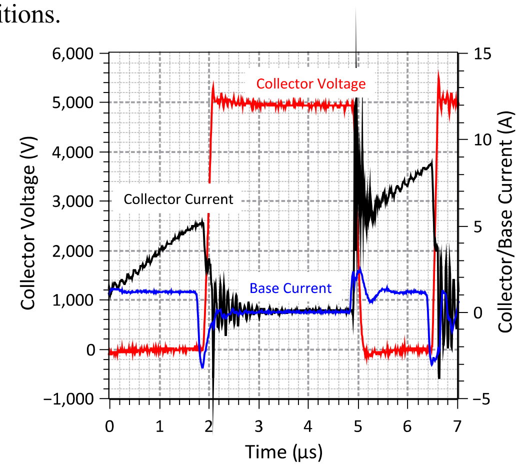

Figure 5. Clamped inductive load switching of 10 kV/28 mm^2 SiC BJTs at a DC link voltage of 5000 V, collector current up to 8 A, and base-plate temperature of 150°C.

High-resolution switching waveforms from the BJT turn-on portion are shown in Fig. 6. The BJT shows ultra-fast turn-on capability with collector current rise times < 30 ns, and collector voltage fall times of < 200 ns. The collector current overshoot up to 15 A in Fig. 6 is due to the capacitive charge stored in the free-wheeling SiC JBS rectifier, which adds to the turn-on current of the BJT. The oscillations observed in the collector current are caused by resonances between the reactive elements of the test circuit and the wire bonds of the power devices. The turn-on energy loss is calculated as 4.2 mJ by integrating the product of the collector current and collector voltage waveforms.

High-resolution switching waveforms from the BJT turn-off portion are shown in Fig. 7. Rapid extraction of the minority carriers stored in the base region of the BJT is enabled by the peak negative base current of – 3 A, which results in fast recovery of the collector voltage in 100 ns. The collector current fall time is about 150 ns. There is no tail in the collector current waveform, which indicates purely majority carrier operation with no minority carrier storage in the collector region. There was no difference in switching waveforms measured at 25°C (not shown) and 150°C, which is further proof of the majority carrier operation of the 10 kV discrete SiC BJTs. The ledge observed in the collector current waveform at ≈ 3.5 A is caused by the parasitic capacitance of the test setup, while the periodic oscillations are caused by resonance between the parasitic circuit reactances. The turn-off energy loss is calculated as 1.6 mJ by integrating the product of the collector current and voltage waveforms.

The turn-on and turn-off losses obtained from the 10 kV/8A SiC BJT switching measurements are compared with a 6.5 kV Si IGBT from ABB [6] in Table I. It can be seen that the SiC BJT achieves 19 times lower turn-on energy loss and 25 times lower turn-off energy loss as compared to the Si IGBT, in-spite of operating at a higher temperature (150°C) as compared to the Si IGBT (125°C).

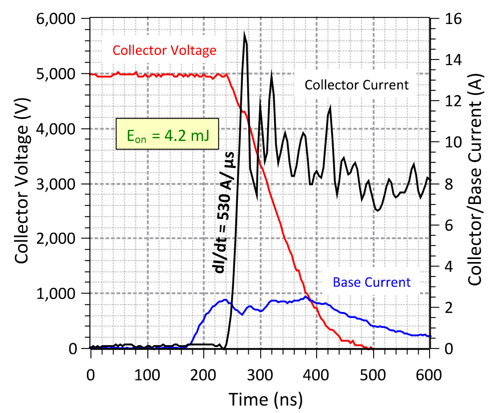

Figure 6. High-resolution switching waveforms measured on a 10 kV/28 mm^2 BJT turning on from a DC link voltage of 5 kV to a collector current of 8 A, at a base-plate temperature of 150°C. A turn-on dI/dt as high as 530 A/µs is extracted from the collector current waveform.

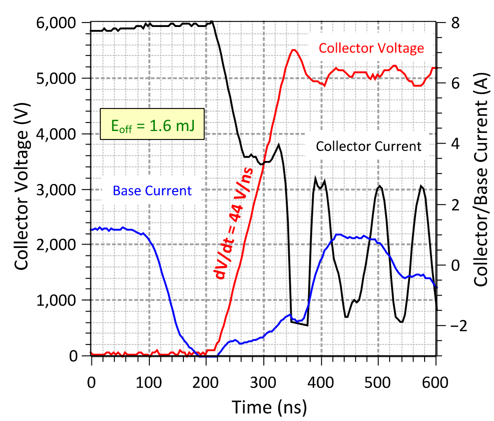

Figure 7. High-resolution switching waveforms measured on a 10 kV/28 mm^2 BJT turning off to a DC link voltage of 5 kV from a collector current of 8 A, at a base-plate temperature of 150°C. A turn-off dV/dt as high as 44 V/ns is extracted from the collector voltage waveform.

TABLE I. LOSS COMPARISON BETWEEN 10 KV SIC BJT AND 6.5 KV SI IGBT TECHNOLOGIES

Device	BV	I_C	Temp.(°C)	Eon (mJ)	Eoff (mJ)
SiC BJT	10 kV	8 A	150°C	4.2	1.6
Si IGBT	6.5 kV	10 A	125°C	80	40

V. RELIABILITY CHARACTERISTICS

A. *Short Circuit Safe Operating Area*

The time-to-failure under short circuit conditions is an important reliability parameter, which needs to be experimentally determined for any power device technology. When a 10 kV/2.7 mm^2 BJT was turned-on to a short-circuited load at a collector bias of 4500 V, with a gate current of 20 mA, a short-circuit current (I_{SC}) of 1 A, and a withstand time (t_{SC}) in excess of 20 µs were measured, which is invariant of base-plate temperatures in the range of 25 °C – 125 °C (see Fig. 8). A t_{SC} of 20 µs is well in excess of the response time of typical $V_{CE,SAT}$ based short-circuit protection circuitry [7].

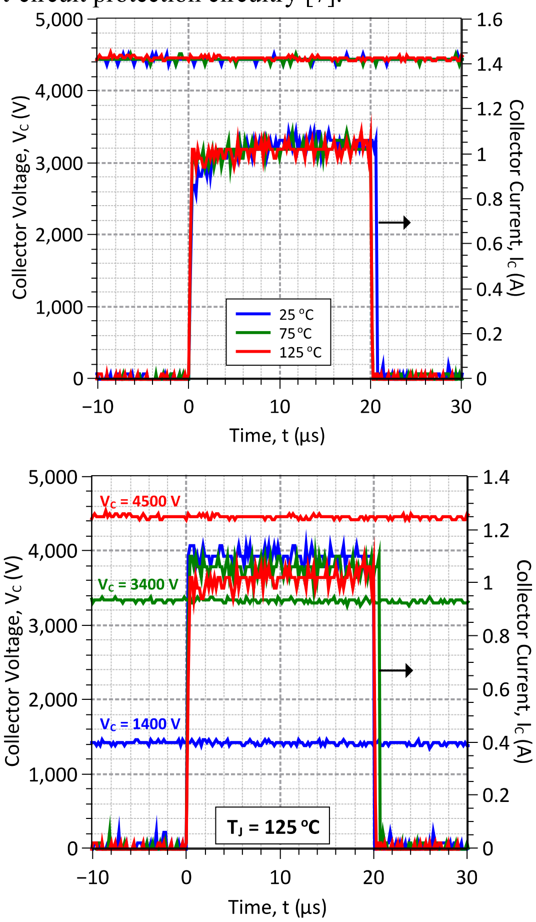

Figure 8. Short circuit switching measurements peformed on 10 kV/2.7 mm^2 SiC BJTs. (Top,a): Temperature-invariant short circuit switching with t_{SC} = 20 µs, and (Bottom,b): Near collector bias-invariance of short circuit currents resulting from perfectly flat output characteristics in the active region of 10 kV SiC BJTs

A near-∞ Early voltage can be inferred in Fig. 8(b) by the invariance of I_{SC}, when the collector bias is increased from 1400 V to 4500 V, at a base plate temperature of 125 °C. This observation confirms lack of any short channel effects in the BJT output characteristics, unlike SiC MOSFETs.

B. *Stability of leakage currents under long-term high-voltage operation*

Another important reliability parameter is the long-term stability of the leakage current, when the BJT is biased at high-voltages at elevated base plate temperatures. To simulate these conditions, a 10 kV/2.7 mm^2 SiC BJT was subjected to a DC collector bias (BV_{CES}) of 5 kV, at a base-plate temperature of 125°C for 162 hours, followed by 72 hours at 175°C.The leakage current flowing through the BJTs was monitored for this test (system limit = 1 µA), as a function of time and is shown in Fig. 9.

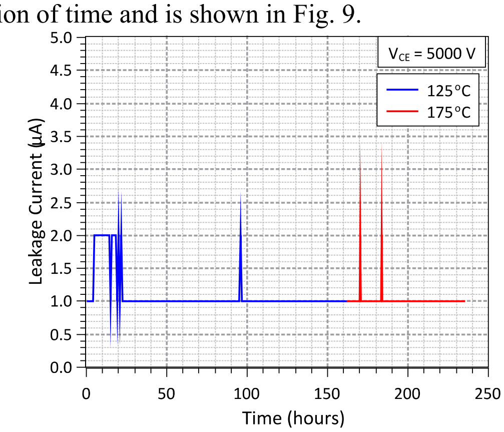

Figure 9. Time evolution of leakage currents under a DC collector bias (BV_{CEO}) of 5 kV impressed upon 10 kV/2.7 mm^2 SiC BJT for 162 hours at a base-plate temperature of 125°C followed by 72 hours at 175°C.

It can be seen from Fig. 9 that the leakage current is extremely stable for the duration of this long-term HTRB-like test. Leakage currents < 1µA (system limit) are measured at 175°C on even after 234 hours of DC operation under a collector bias of 5000 V.

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