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Electrical Characterization of HV (10 kV) Power 4H-SiC Bipolar Junction Transistor

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Abstract: In this paper, the static and dynamic characterization of a High Voltage (10kV) 4H-SiC Bipolar Junction Transistor (BJT) is presented. Using a high-voltage source in vacuum conditions, a breakdown voltage of 11 kV was measured. Results showed that both large and small BJTs exhibit similar on-state resistance per unit area and collector current density of 55 A.cm^{-2}. The current gain increases with a decrease in temperature, indicating reduced charge carrier recombination at lower thermal energies. Also, BJT have been characterized in switching mode at 1 kV. The study concludes that 4H-SiC BJT demonstrates promising electrical performance for high-efficiency applications in harsh environments.

Introduction

4H-SiC Bipolar Junction Transistors (BJTs) offer significant advantages for high-voltage and high-temperature applications due to their superior characteristics, including low on-state resistance and elevated breakdown voltage [1]-[2]. These devices are highly efficient in various sectors. However, their performance can be affected by temperature change. Therefore, it is very interesting to study its behavior in extreme conditions, especially in high-power applications [3]-[4]. After a short description of the BJT structure, electrical characterization in static mode for a temperature range from -50°C up to 150°C will be demonstrated. This work reports the switching characteristics of the BJT using a double source test bench which involves providing controlled input pulses to the base while monitoring the response at the collector.

BJT's Structure

The BJTs were designed and fabricated on a 4H-SiC wafer with an epilayer of 120 µm thick and doping concentration of $8\times10^{+14}$ cm^{-3}(Fig.1). Mesa with JTE (Junction Termination Extension) and JTE rings has been implemented for the edge termination. Thermal oxidation followed by the deposition of several Si_3N_4 LPCVD (Low-Pressure Chemical Vapor Deposition) and PECVD (Plasma Enhanced Chemical Vapor Deposition) layers (yellow layer in Fig. 1) and also a thick polymide layer (brown layer in Fig. 1) is used for the device passivation. Three unique configurations of BJTs, each with varying finger length and active area, designed to enhance their electrical performance. The configurations include two distinct finger lengths of 420 µm and 640 µm, these lengths were paired with active area, specifically 15.6mm^2 for large devices and 2.12 mm^2 for small

BJTs, as detailed in Table 1. A maximum breakdown voltage of 11 kV was obtained in vacuum conditions with a high-voltage source [5].

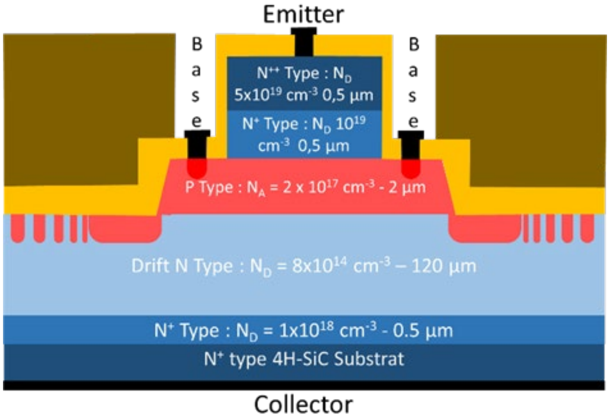

Fig.1. Cross-section of the studied 4H-SiC 10 kV BJT

Table 1. Summary of the different BJT configurations, square dies

Finger Length (µm)	Die area (mm^2)
420	2.12
420	15.6
640	15.6

Experimental Setup for Static Characteristics

The setup involves the static characterization of 4H-SiC BJTs using a B1505A, capable of handling up to 20 A in pulsed mode for the collector, 1 A for the base, and 3 kV in blocking mode, alongside a Thermal Conditioner Thermonics T2500/300E for temperature control from -50 °C up to 225 °C. Three samples were characterized with their respective finger length and active area. Measurements include applying a voltage sweep V_{CE} and measuring IC for different fixed values of IB from 0.1 A to 1 A to obtain the output characteristic curves. By analyzing these curves, we can assess the transistor behavior in different operating regions and extract key parameters like, current gain, b.

Results and Analysis of the static characteristics

The small and large BJTs exhibit similar on-state resistance per unit area as shown in Fig.2 Both devices achieved approximately 55 $A.cm^{-2}$ for collector current density with comparable base-current densities, 3.3 $A.cm^{-2}$ to 3.2 $A.cm^{-2}$, respectively corresponding to different base currents (70 mA and 0.5 A respectively). This observation suggests that the active area does not significantly impact the electrical characteristics concerning current density. Therefore, regardless of the physical size of the BJTs, their performance in terms of current density remains the same.

From Fig.3, we can observe that the current gain, b, is very similar between large and small BJTs (420 µm finger length, 15.6 mm^2 and 420 µm finger length, 2.12 mm^2). A similar trend is noticed between large BJTs with different finger length (640 µm and 420 µm), both having a 15.6 mm^2 area but there are measured on two different wafers.

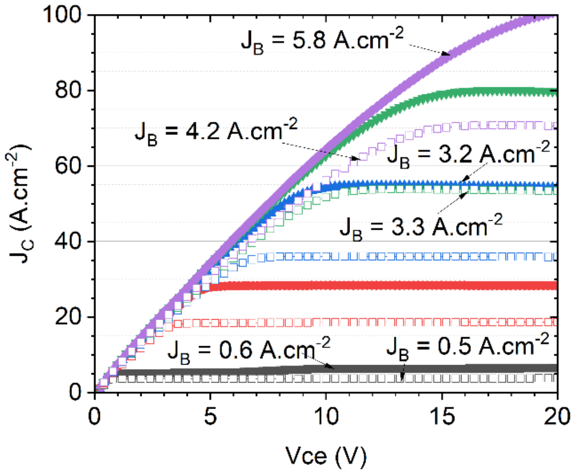

Fig. 2. J_C (V_{CE}) for different J_B at 25°C for a small (open symbol) and large (closed symbol) BJT, finger length of 420 µm

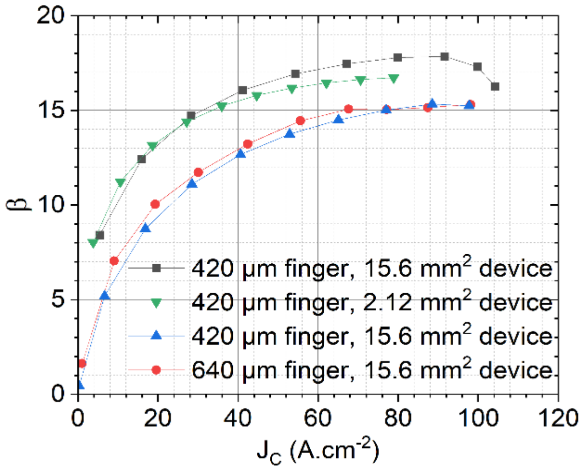

Fig. 3. Extracted β for 4 different BJTs (finger length and area) at 25°C

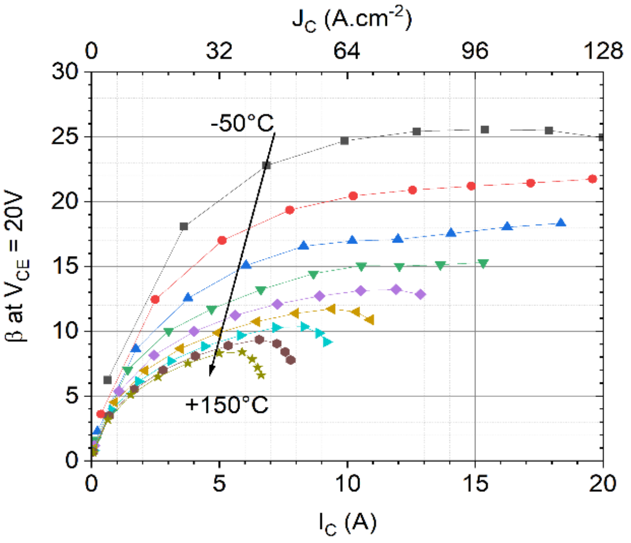

Fig. 4. Extracted β obtained with a B1505A (quasi static measurements) for the large BJT (finger length 420 µm, from triangular symbol on Fig. 2) for a temperature range of -50 °C to 150 °C

Additionally, the current gain of the large BJTs tends to increase with decreased temperature as seen in Fig. 4. This increase is as a result of the reduced recombination rate of charge carriers due to lower thermal energy, which means fewer charge carriers recombine, more contribute to the current. It could be also due to higher ionization of p-type doping base. Consequently, a smaller base current is required to control a given collector current, effectively enhancing the transistor's amplification capacity. This implies that at lower temperatures, the BJTs become more efficient in amplifying the base current.

Experimental Setup for Switching Characteristics

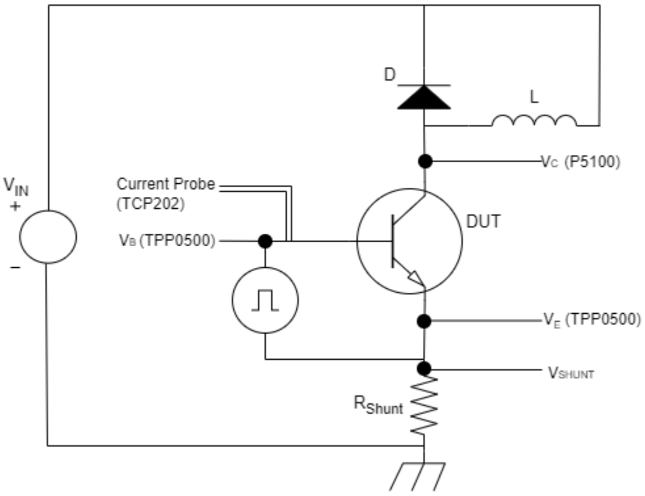

Fig. 5. Double pulse test schematic diagram for switching characteristics on the 4H-SiC BJTs

To investigate the switching characteristic of the 4H-SiC BJTs, a double pulse test circuit was configured as per the provided schematic in Fig. 5. The setup includes a voltage supply (V_{IN} from 100 V to 1000 V) a base driver is connected to the base of the SiC BJTs. A fast recovery diode and an inductor are used to manage the switching transitions and energy storage respectively. The different voltages (Base, Collector and Emitter), the Base current using a current probe and the collector current using a shunt resistance are measured at each V_{IN} step to analyze the BJT switching performance.

Results and Analysis of the Switching Characteristics

Fig. 6 shows the behavior of I_C and I_B respect to time for the switching characteristics of the BJT samples. I_C exhibits a sharp rise as the BJT turns on due to the inductance charging, reaching higher peaks with increased V_{IN}. However, the current starts dropping from its peak indicating that the base current is insufficient to maintain the BJT in saturation mode, leading to a transition towards the linear mode. This is evident in the V_{CE} graph in Fig. 7 where V_{CE} drops rapidly during the initial turn-on and then stabilizes at a higher voltage as the device exhibit saturation.

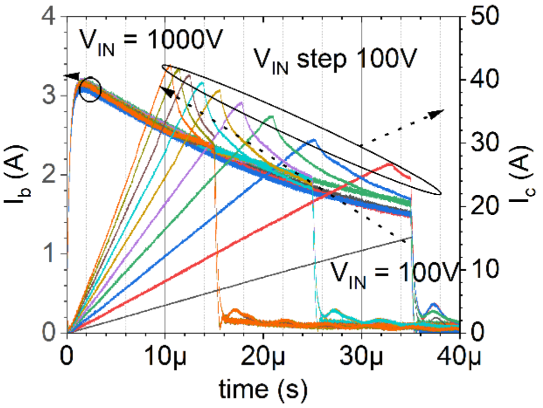

Fig. 6. I_C and I_B versus time for various V_{IN} steps

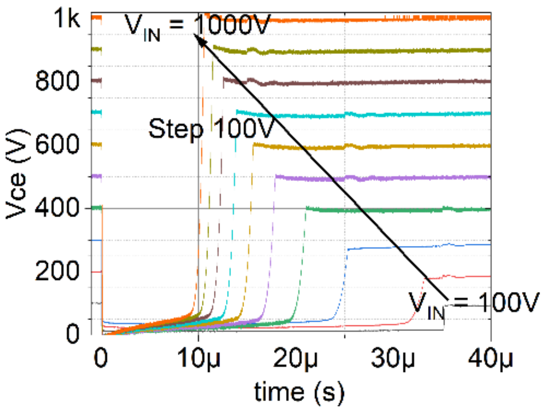

Fig. 7. V_{CE} versus time for various V_{IN} steps

Fig. 8 shows how the current gain (β) initially spikes, indicating strong carrier injection but then decreases as a reflection of I_C due to the linear mode.

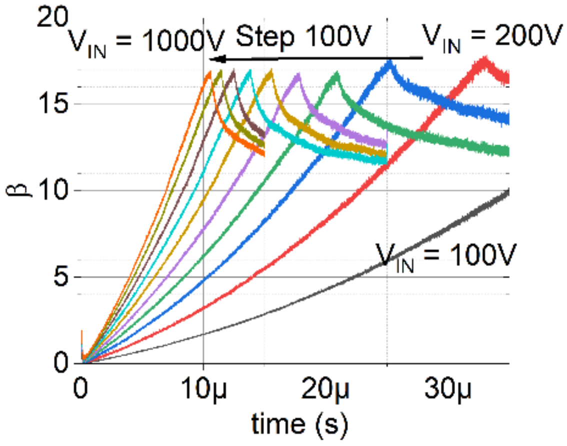

Fig. 8. Extracted β versus time for various V_{IN} steps

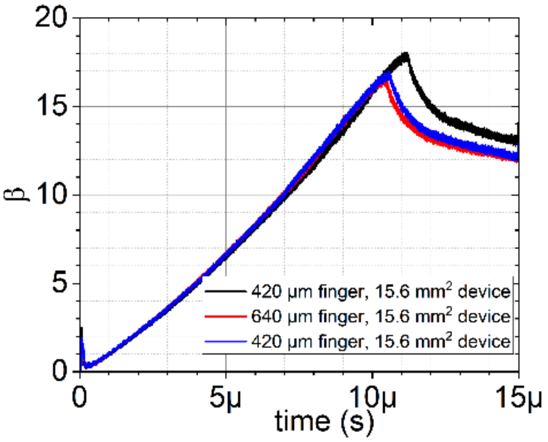

Fig. 9. Extracted β for 3 different BJTs (finger lengths)

Fig. 9 shows the variation of extracted b versus time for the 3 different large BJTs. A similar b is obtained between these 3 different BJTs. The values (17 and 18) are very similar to those obtained in the static mode (Fig. 3, 15 and 18). We can therefore conclude that the finger length and size have no impact on the current gain of the device even if it extracted in static or dynamic mode.

Summary

This paper presents the static and dynamic characteristics of 10 kV 4H-SiC BJTs, which demonstrates promising electrical performance, making it suitable for high-efficiency applications in harsh environments and their performance improves at lower temperatures due to enhanced carrier dynamics. Similar extracted b have been obtained for both static and dynamic mode even with different finger lengths and areas of the BJTs.

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