Technology development of 4H-SiC RF BJTs with 5GHz f_{MAX}

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Abstract

4H-SiC RF BJTs were developed on a semi-insulating (>10^5 Ω-cm) substrate using an triple mesa-etch and interdigitated emitter-base finger design. The sheet conductance of the emitter layer was measured during the etch to accurately determine the location of the base-emitter interface. On-wafer small signal s-parameter measurements were performed on a 4-finger device with 3 μm emitter stripe width and 150 μm finger length. Both, the current gain and unilateral power gain, were extracted from the measured s-parameters, yielding an f_T of 7 GHz and an f_{MAX} of 5.2 GHz biased in common-emitter configuration at J_E = 10.6 kA/cm^2 and V_{CE} = 20 V. The maximum available power gain (G_{MAX}) is 18.6-dB at 500 MHz and 12.4-dB at 1 GHz, demonstrating the potential of 4H-SiC BJTs for both UHF and L-band applications. Small-periphery (4x150μm) devices were tested using on-wafer load pull measurements up to 1.5GHz. Under pulsed conditions, the devices exhibited 10dB of power gain at 1GHz and a peak power density of 2.3W/mm (1.4W) with less than 0.1dB pulse droop for a 100μs pulse width and a 1% duty cycle. The power gain decreased to 8dB at 1GHz under CW conditions at a power density of 1.6W/mm (1W).

INTRODUCTION

Silicon carbide is a wide bandgap semiconductor that has been identified as a prime candidate for use in high power RF frequency (~ 1GHz) devices due to its higher breakdown field and higher thermal conductivity, resulting in a higher RF power density as well as a higher power dissipation capability compared to both Si and GaAs-based devices [1,2,3,4]. Together these material properties provide the basis for the potential of superior SiC-based power RF devices at UHF and L -band frequencies, with high power and high gain.

In this paper, we present the evolution of the 4H-SiC BJT device technology from university-based research and process development within a small start-up company to product development within a component manufacturer. Emphasis of the technology development has been on reducing parasitic elements resulting in improved RF performance while demonstrating initial reliability and yield. This includes the development of a uniform SiC etch processes, compatible low resistance ohmic contact metals and the use of thick insulators and a semi-insulating substrate.

The SiC BJT development resulted in record current and power dissipation densities of 180kA/cm^2 and 6 MW/cm^2 [5], operation up to 500^{o}C and radiation hardness up to 1.6 Mrad [6]. The current gain is typically between 30 and 60 and was measured to reduce to 60% of its room temperature value at 200^{o}C and to 40% at 500^{o}C [6].

Improved RF performance was obtained by decreasing the base sheet resistance and the base contact resistivity. Further improvement was obtained by fabricating devices on a semi-insulating SiC substrate and increasing the thickness of the dielectrics. Over a three year period the small signal RF performance improved from f_T/f_{MAX} of 0.6GHz/0.2GHz [7] to 7GHz/5GHz [8] – the highest values for any SiC BJT to date - , resulting in up to 17dB, 12 dB and 6dB gain at 500 MHz, 1GHz and 1.5 GHz [9]. Maximum power exceeding 200W was demonstrated at 500 MHz [3] as well as a power density of 2.3W/mm at 1 GHz [9].

Single device yield exceeds 65% and was in part obtained by identifying the location of the base-emitter junction during the emitter etch process.

DEVICE STRUCTURE AND FABRICATION

Bipolar transistors were fabricated using reactive ion etching to create a triple mesa structure as shown in Figure 1. The device layer doping densities and thicknesses are listed in Table 1. The emitter mesa area of a single device is 3×150 μm^2 with a corresponding base mesa area of 11×150 μm^2. The surface was passivated with a thermally grown oxide followed by a layer of deposited oxide. Ni/Cr was used for the emitter and collector contacts, Ti/Al for the base contacts, and Ti/Au for the wiring and pads The device reported here consists of four 150μm long emitter fingers with a pitch of 80μm to improve thermal spreading. Each emitter was isolated on individual mesas to minimize parasitic capacitance. The emitter fingers were wired together in parallel using a pad layout compatible with GSG probes for on-wafer measurements.

FIGURE 1
CROSS SECTION OF AN RF BJT ON A SI 4H-SIC SUBSTRATE

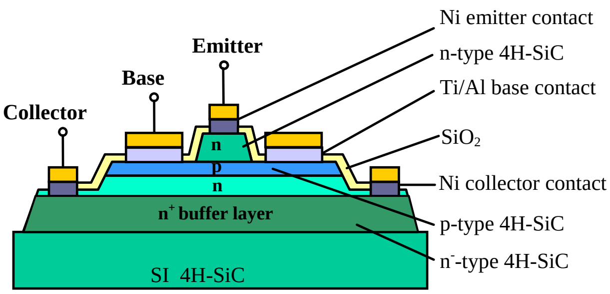


TABLE I
NOMINAL DOPING DENSITY AND THICKNESS OF EPI-LAYERS

	Thickness (nm)	Doping (cm^{-3})
n-contact	40	9×10^{19}
n-emitter	100	3×10^{19}
p-base	140	8×10^{18}
n-collector	1000	8×10^{15}
n-buffer layer	700	1×10^{19}

PROCESS DEVELOPMENT

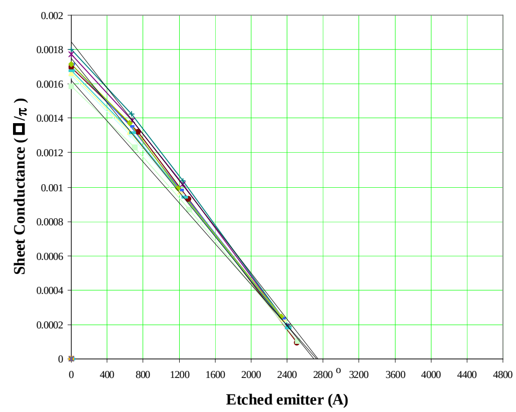
A critical step of the SiC BJT fabrication is the etching of the emitter down to the base layer. Under-etching will result in a parasitic leakage path between the emitter and base contact as well as a poor p-type contact, while over-etching results in a high base sheet resistance between the base contact and the emitter, which reduces the RF gain of the device. This challenge is further compounded by any non-uniformity of the epitaxial layers and the non-uniformity of the RIE etch.

Our approach is to measure the remaining sheet conductance of the emitter layer and graph it as a function of the etch depth and/or time. As an example we present in Figure 2 the sheet conductance versus etch depth as measured across a two inch wafer. Nine different sites were measured at different times during the etch and the measured data was extrapolated to identify both the optimum etch depth and time. The etch time was then adjusted so that the emitter layer was accurately removed, while minimizing the etching of the base layer.

The data presented in Figure 2 is typical in that the initial measurement reveals a distinct variation in the total conductance, which can be due to both a doping density variation and thickness variation of the emitter layer. However, as the emitter layer is etched the curves converge toward a single intercept with the x-axis, indicating that the variation is primarily due to a doping density variation and much less due to a thickness variation. From Figure 2 one finds that this particular emitter has an average thickness of 287nm and standard deviation of 4nm. The maximum deviation from the average is 4.7% or better depending on the etch uniformity.

We have used this analysis and feedback technique to consistently etch the SiC BJT layers to accurately expose the base layer as we reduced the base thickness.

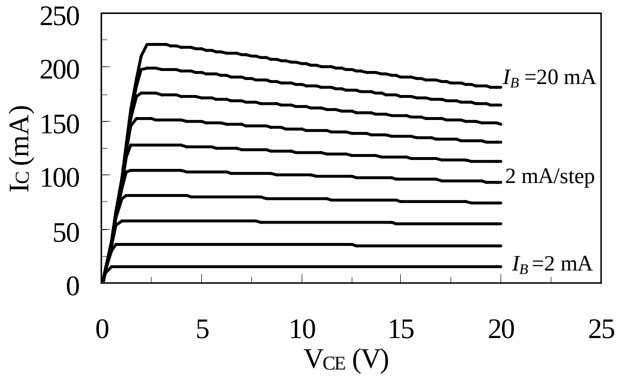
FIGURE 2
SHEET CONDUCTANCE VERSUS ETCH DEPTH AS OBTAINED ON NINE DIFFERENT SITES ACROSS A TWO INCH WAFER



DC RESULTS

A DC characterization for the common-emitter configuration was performed to qualify the RF transistors as well as to identify the proper DC bias points for the small signal measurements. A typical *I-V* is illustrated in Fig. 3. The maximum DC current gain β_{max} is 11 and decreases at higher bias due to the self-heating. The maximum emitter current density J_E is 10.1 kA/cm^2 at V_{CE} = 20 V with a corresponding DC power dissipation of 200 kW/cm^2 normalized to the emitter mesa area. The breakdown voltage is greater than 100 V in spite of the 1 μm collector drift region.

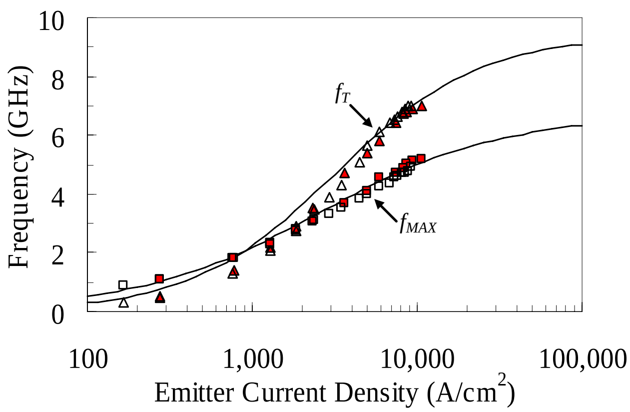
FIGURE 3
I-V CHARACTERISTICS OF A 4-FINGER RF TRANSISTOR.
I_B = 2, 4, …, 18 AND 20 mA



RF RESULTS

Small signal s-parameters were measured with an Agilent 5071B network analyzer. Both the transit frequency, f_T, and the maximum oscillation frequency, f_{MAX}, were extracted from these measurement and are presented in Figure 4 as a function of the emitter current density and compared to calculated values based on a transit time model [8,10]. An f_T/f_{MAX} of 7/5.2 GHz was extracted at 10.6kA/cm^2 at a collector bias of 20V. These record figures of merit are attributed to the use of a SI substrate which completely removes the effect of the parasitic capacitance of the base-collector pad. The effect of this capacitance is further amplified by the large base resistance typical of npn SiC BJTs.

FIGURE 4
f_T AND f_{MAX} VERSUS EMITTER CURRENT DENSITY FOR TWO 4-FINGER RF TRANSISTORS (OPEN AND FILLED SYMBOLS) COMPARED TO THE CALCULATED VALUES BASED ON A TRANSIT-TIME MODEL.



Large signal measurements were then performed in class-A operation using a load-pull setup. As expected, the power gain under pulsed operation at low power levels was consistent with the maximum available gain, G_{MAX}, extracted from the s-parameters. As the output power is increased, the gain compressed as shown in Figure 5a. Under CW operation, self heating began to occur, which leads to a reduction in both the power gain and output power. However, as can be seen in Figure 5b, the device is still capable of delivering 6dB gain at 1.5GHz at a power density of 2W/mm (1.2W).

FIGURE 5a
CLASS-A OPERATION OF A 600µm LONG EMITTER BJT UNDER PULSED OPERATION AT 1 GHZ

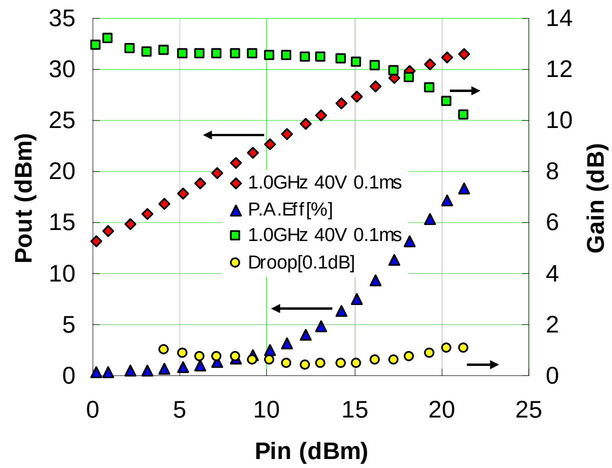
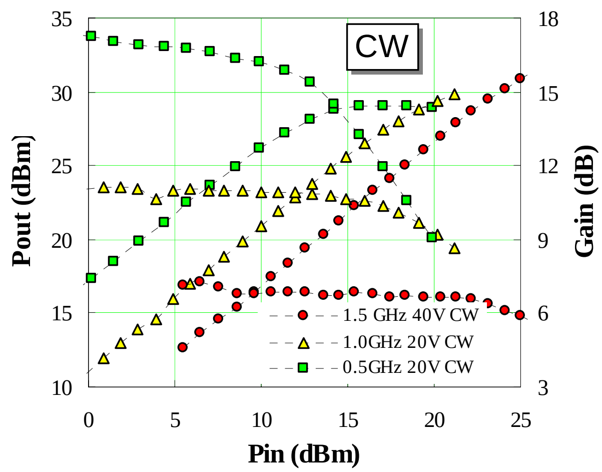


FIGURE 5b
OUTPUT POWER AND POWER GAIN OF A 600 µm LONG EMITTER BJT UNDER CW OPERATION AT 0.5, 1 AND 1.5 GHZ IN CLASS-A OPERATION



The power gain measured at 1GHz in 2-dB compression was 10dB with a 0.1dB pulse droop when operated using a 1% duty cycle and 100µs pulse width. The corresponding peak power density was 2.3W/mm (1.4W). The device exhibited a PAE of 18% in Class A. The chosen DC bias point was a collector voltage of 40V. The corresponding DC collector current was set to 170mA. According to SPICE simulations, for a full AC voltage swing to appear at the collector, and therefore achieve the ideal maximum efficiency of 50%, the input power should be in excess of 800mW (>29dBm). At this point, the power gain would be compressed to about 6dB.

CONCLUSION

4H-SiC RF BJTs on a semi-insulating substrate were designed, fabricated and tested for the first time. On-wafer small signal s-parameter measurements show a 7 GHz f_T and a 5.2 GHz f_{MAX}. With the improvement of f_T and f_{MAX}, the maximum available power gain G_{MAX} is 12.4-dB at 1 GHz and 18.6-dB at 500 MHz, showing the potential of these devices for UHF and L-band applications. We have demonstrated pulsed and CW operation of 4H-SiC BJTs up to 1.5GHz. The improved RF performance over previous reports is attributed to the use of a SI wafer. Under pulsed conditions, the devices exhibited 10dB of power gain at 1GHz and peak power density of 2.3W/mm (1.4W). Under CW operation the device is capable of delivering 6dB gain at 1.5GHz at a power density of 2W/mm (1.2W). We conclude, based on the results presented here, that SiC BJTs are attractive candidates for use in high power UHF and L-band applications.

ACKNOWLEDGEMENTS

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ACRONYMS

BJT: Bipolar Junction Transistor
CW: Continuous Wave
RF: Radio Frequency
SI: Semi Insulation
SiC: Silicon Carbide
UHF: Ultra High Frequency