# First Demonstration of 4H-SiC RF Bipolar Junction Transistors on a Semi-insulating Substrate with $f_T/f_{MAX}$ of 7/5.2 GHz

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***Abstract*** — **4H-SiC RF BJTs on a semi-insulating (>$10^5$ Ω-cm) substrate were designed and fabricated for the first time using an n-p-n triple mesa-etch and interdigitated emitter-base finger design. 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 calculated 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. These are the highest RF figures of merit reported to date for any SiC bipolar transistor. The calculated 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.**

***Index Terms*** — **4H-SiC, RF BJTs, semi-insulating substrate, $f_T$, $f_{MAX}$, $G_{MAX}$, UHF, L-band.**

## I. INTRODUCTION

4H-SiC bipolar junction transistors (BJTs) are promising RF power devices for operation up to 1 GHz with the ability to handle large power [1, 2] and to operate at a large collector voltage [3]. More specifically, compared to its silicon counterparts, SiC devices can be operated at 10 times the voltage, for a given drift region thickness, due to the 10 times larger breakdown field of SiC [4]. The attainable power density is also higher due to the excellent thermal conductivity of SiC and its wide energy band-gap. Previously, a 4H-SiC BJTs was reported with up to 4 GHz $f_T$ and up to 1.8 GHz $f_{MAX}$ [5, 6, 7]. In this work we have improved $f_{MAX}$ almost threefold.

Recently, high purity semi-insulating 4H-SiC wafers were developed [8, 9] and are now commercially available. Devices on semi-insulating substrates have been demonstrated [10, 11] with improved RF performance due to the reduction of parasitic components. In this paper, we report the first 4H-SiC RF BJTs fabricated on a semi-insulating substrate with an $f_T/f_{MAX}$ of 7/5.2 GHz, and $G_{MAX}$ of 12.4-dB at 1 GHz and 18.6-dB at 500 MHz. These are, to the best of our knowledge, the highest values published to date for any SiC bipolar transistor.

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## II. DEVICE DESIGN AND FABRICATION

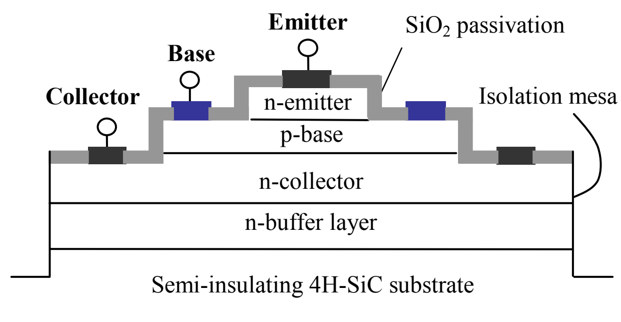


Fig. 1. The schematic cross-sectional structure of a 4H-SiC BJT on a semi-insulating substrate.

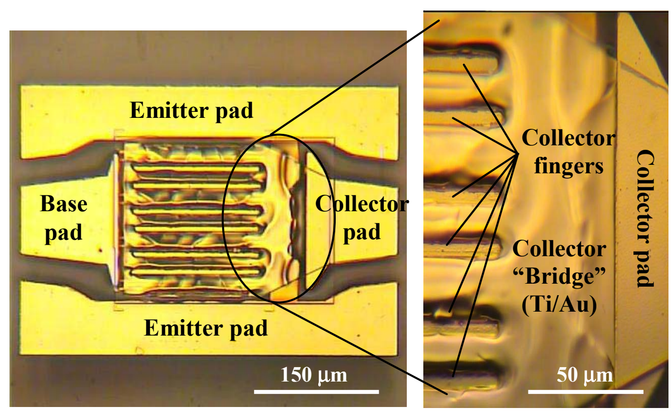


Fig. 2. Micrographs of a 4-finger RF BJT with front-collector-"bridge" contacts and on-wafer RF pad layout.

The epitaxial structures (n-p-n) were grown by Acreo AB (Sweden) on a 2-inch 4H-SiC semi-insulating substrate (>$10^5$ Ω-cm). The nominal thickness and doping density of each epi-layer are listed in Table I. Bipolar transistors were fabricated using a triple mesa-etch and an interdigitated emitter-base finger structure. Each device was completely isolated by etching the isolation mesa into the semi-insulating substrate. A cross-sectional drawing of a single finger structure is shown in Fig. 1. The emitter mesa area is 3×150 µm$^2$ and the base mesa area is 11×150 µm$^2$. The surface was passivated with a thin layer of thermal oxide followed by a layer of deposited oxide. Ni/Cr was used for the emitter and collector contacts, Ti/Al

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for the base contacts, and Ti/Au for the wiring and pads as well as the front-collector-“bridge” contacts as shown in Fig. 2. The fabrication process has been discussed in detail elsewhere in the literature [12].

TABLE I
NOMINAL DOPING DENSITY AND THICKNESS OF EPI-LAYERS

| Wafer (S.I.) | Thickness | Doping | Dopant |
|---|---|---|---|
| n-contact | 40 nm | $9\times10^{19}$ cm$^{-3}$ | Nitrogen |
| n-emitter | 100 nm | $3\times10^{19}$ cm$^{-3}$ | Nitrogen |
| p-base | 140 nm | $8\times10^{18}$ cm$^{-3}$ | Aluminum |
| n-collector | 1000 nm | $8\times10^{15}$ cm$^{-3}$ | Nitrogen |
| n-buffer layer | 700 nm | $1\times10^{19}$ cm$^{-3}$ | Nitrogen |
| Substrate | 300 μm | ~$10^{18}$ cm$^{-3}$ | Vanadium |

The DC current-voltage (*I-V*) properties of the transistors shown in Fig. 2 were measured with an HP 4155C. The on-wafer small signal RF measurements were performed using an Agilent E5071B network analyzer with GSG probes. All measurements were done at room temperature. The network analyzer was calibrated using Short-Open-Load-Thru (SOLT) standards. The s-parameters were measured from 8 MHz to 8 GHz at a collector-emitter voltage ($V_{CE}$) of 20 V and at multiple emitter bias current densities ($J_E$).

## III. RESULTS AND DISCUSSION

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 $\beta_{max}$ 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.

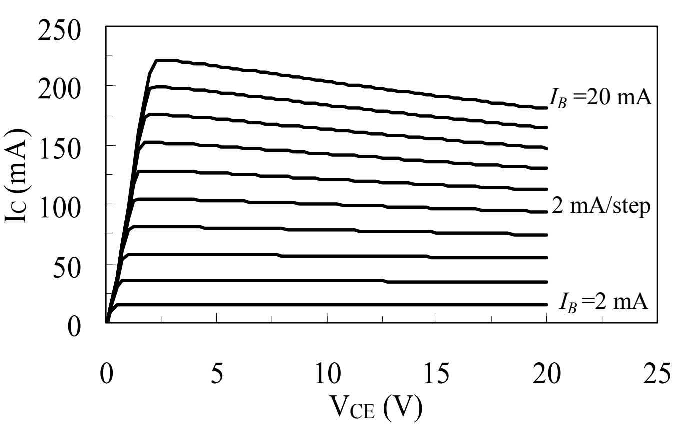



Fig. 3. *I-V* characteristics of a 4-finger RF transistor. $I_B$ = 2, 4, …, 18 and 20 mA.

The high frequency performance is characterized by on-wafer small signal s-parameter measurements with the remaining parasitic components de-embedded based on a widely used correction procedure [13]. The AC common emitter current gain $|h_{21}|$, the unilateral power gain $U$, and the maximum available power gain $G_{MAX}$ were calculated from measured s-parameters using the following formulae [14, 15]:

$$|h_{21}| = \left|\frac{2\cdot s_{21}}{s_{12}\cdot s_{21} + (1-s_{11})\cdot(1+s_{22})}\right| \tag{1}$$

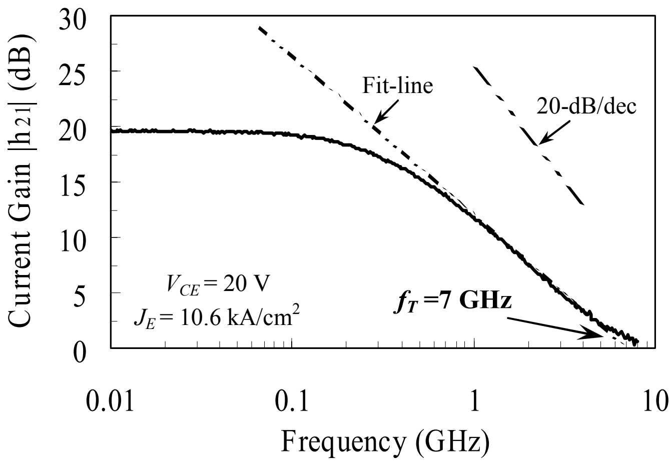
$$U = \frac{|s_{21}/s_{12}-1|^2}{2\cdot k|s_{21}/s_{12}| - 2\cdot \mathrm{Re}(s_{21}/s_{12})} \tag{2}$$

$$G_{MAX} = |s_{21}/s_{12}|\cdot(k-\sqrt{k^2-1}) \tag{3}$$

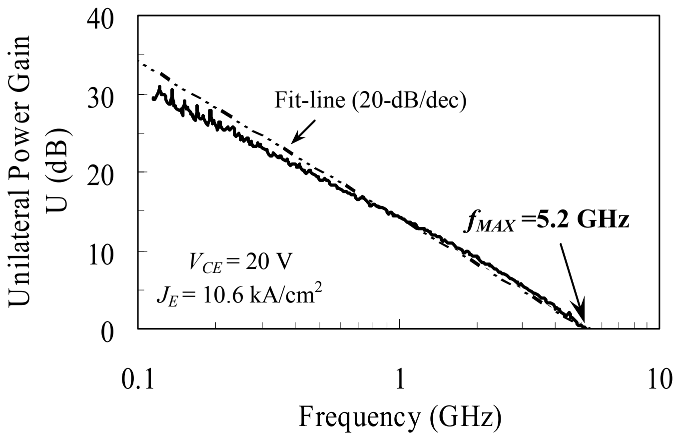
$$k = \frac{1-|s_{11}|^2 - |s_{22}|^2 + |s_{11}\cdot s_{22} - s_{12}\cdot s_{21}|^2}{2|s_{12}\cdot s_{21}|} \tag{4}$$

Where k is the Rollett stability factor. The de-embedded frequency dependence of $|h_{21}|$, $U$ and $G_{MAX}$ from a 4-finger 4H-SiC transistor biased at $V_{CE}$ = 20 V and $J_E$ = 10.6 kA/cm$^2$ are presented in Fig. 4. $f_T$ was extrapolated from the fitted line of $|h_{21}|$. $f_{MAX}$ was obtained from $U$ and $G_{MAX}$ at the frequency where the gain has decreased to 0-dB. The values of $f_T$ and $f_{MAX}$ are 7 GHz and 5.2 GHz respectively, the highest numbers reported to date for any SiC bipolar transistor. The improvement of $f_T$ and $f_{MAX}$ is due to the reduction of parasitic components achieved by the use of the semi-insulating substrate. A more detailed discussion of this can be found elsewhere [12]. The maximum available power gain $G_{MAX}$ was calculated to be 12.4-dB at 1 GHz and 18.6-dB at 500 MHz, showing the potential of SiC RF bipolar devices for UHF and L-band applications such as radar, broadcast and wireless communication.

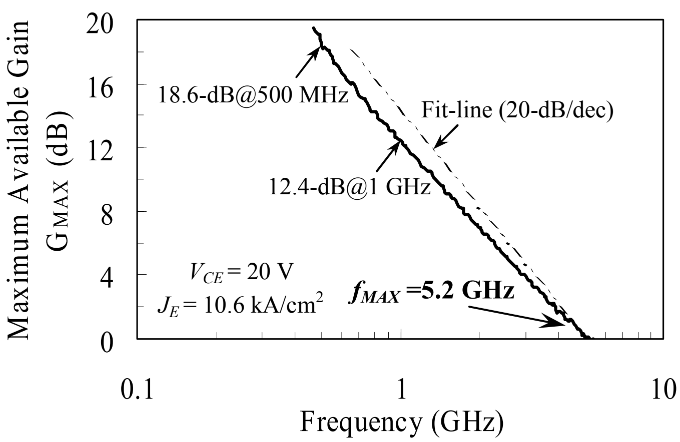
It is worth noticing that the calculated $U$ and $G_{MAX}$ follow the expected 20-dB/decade slope, however, the slope of the fit-line to $|h_{21}|$ is not 20-dB/decade, but 14-dB/decade. The latter is explained by the back-injection current flowing from base to emitter in homojunction bipolar transistors, resulting in the small signal emitter injection efficiency significantly lower than one [14]. With the increase of back-injection effects, the slope of $|h_{21}|$ versus frequency decreases from 20-dB/decade to 10-dB/decade.




(a)




(b)




(c)

Fig. 4. (a) Current gain $|h_{21}|$; (b) unilateral power gain $U$; and (c) maximum available power gain $G_{MAX}$ calculated from the measured s-parameters versus frequency of a 4-finger 4H-SiC BJT.

The extracted $f_T$ and $f_{MAX}$ from the measured s-parameters of two 4-finger RF transistors biased at various emitter current densities are summarized in Fig. 5, with the calculated results based on an ideal small signal transit-time model [16]:

$$\frac{1}{2\pi f_T} = \tau_{EC} = \tau_E + \tau_B + \tau_{SC} + \tau_C$$

$$= \frac{V_T (C_{j,BE} + C_{j,BC})}{J_E} + \frac{w_B'^2}{2\mu_{n,B} V_T} + \frac{x_{dep,BC}}{2v_{sat}} + R_C C_{j,BC} \qquad (5)$$

$$f_{MAX} = \sqrt{\frac{f_T}{8\pi R_B C_{j,BC}}} \qquad (6)$$

Where $C_{j,BE}$ and $C_{j,BC}$ are the base-emitter and base-collector junction capacitance. The electron mobility in the base region, $\mu_{n,B}$, is 185 cm$^2$/V-s [12] and the saturation velocity $v_{sat}$ is $2\times10^7$ cm/s [17].

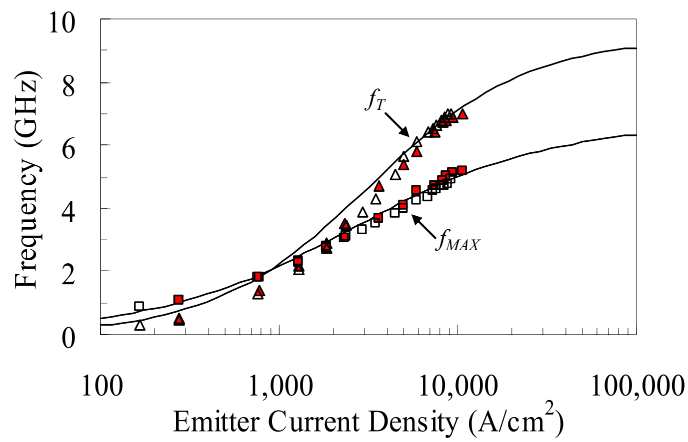



Fig. 5. $f_T$ and $f_{MAX}$ extrapolated from s-parameter measurements at different $J_E$ for two 4-finger RF transistors (open and filled symbols) at two different locations on the wafer. Solid lines represent the calculated values of $f_T$ and $f_{MAX}$ using the transit-time model.

## IV. 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.

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