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$^5$ $\Omega$-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 $\mu$m emitter stripe width and 150 $\mu$m 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 Si$_C$ [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 $f_{MAX}$ 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.

* Previously PowerSicel, Inc.
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].

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 $\mu$m collector drift region.

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]:

$$ |h_{21}| = \frac{2 \cdot s_{31}}{s_{12} \cdot s_{21} + (1 - s_{11}) \cdot (1 + s_{22})} $$  \hspace{1cm} (1)

$$ U = \frac{|s_{21} / s_{12} - 1|^2}{2 \cdot k[s_{21} / s_{12} - 2 \cdot \text{Re}(s_{21} / s_{12})]} $$  \hspace{1cm} (2)

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

$$ k = 1 - \frac{|s_{11}|^2 - |s_{22}|^2 + |s_{11} \cdot s_{22} - s_{12} \cdot s_{21}|^2}{2s_{12} \cdot s_{21}} $$  \hspace{1cm} (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 fitted 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.

#### TABLE I

**Nominal Doping Density and Thickness of Epi-Layers**

<table>
<thead>
<tr>
<th>Wafer (S.I.)</th>
<th>Thickness</th>
<th>Doping</th>
<th>Dopant</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-contact</td>
<td>40 nm</td>
<td>9×10$^{19}$ cm$^{-3}$</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>n-emitter</td>
<td>100 nm</td>
<td>3×10$^{19}$ cm$^{-3}$</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>p-base</td>
<td>140 nm</td>
<td>8×10$^{19}$ cm$^{-3}$</td>
<td>Aluminum</td>
</tr>
<tr>
<td>n-collector</td>
<td>1000 nm</td>
<td>8×10$^{19}$ cm$^{-3}$</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>n-buffer layer</td>
<td>700 nm</td>
<td>1×10$^{19}$ cm$^{-3}$</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>Substrate</td>
<td>300 μm</td>
<td>-10$^{18}$ cm$^{-3}$</td>
<td>Vanadium</td>
</tr>
</tbody>
</table>

![Fig. 3. I-V characteristics of a 4-finger RF transistor. $I_B = 2, 4, \ldots, 18$ and 20 mA.](image)
The extracted $f_T$ and $f_{\text{MAX}}$ 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]:

$$\frac{1}{2\pi f_T} = \tau_{C} = \tau_{E} + \tau_{B} + \tau_{C} + \tau_{S}$$

$$f_T = \frac{V_T (C_{j,BC} + C_{j,BE})}{J_E} + \frac{w_2}{2\mu_{n,B} V_T} + \frac{x_{dep,BC}}{2v_{sat} R_{C} C_{j,BC}} \quad (5)$$

$$f_{\text{MAX}} = \sqrt{\frac{f_T}{8\pi R_s C_{j,BC}}} \quad (6)$$

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 $2 \times 10^7$ cm/s [17].

Fig. 5. $f_T$ and $f_{\text{MAX}}$ 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 $f_{\text{MAX}}$ 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 $f_{\text{MAX}}$. With the improvement of $f_T$ and $f_{\text{MAX}}$, the maximum available power gain $G_{\text{MAX}}$ 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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REFERENCES


