In this paper, we present 71 W SiC bipolar junction transistors (BJTs) using state of the art technology. The devices were fabricated on a commercial n-type 4H–SiC substrate using a double-mesa etch and interdigitated emitter-base finger design. When operating under common-emitter configuration and long pulse RF conditions of 15 ms pulse width and 25% duty cycle, the packaged devices without internal matching exhibited 8.5 dB power gain and 71 W output power with a 50.7% power added efficiency (PAE) at 500 MHz. The power density is 19.7 W/mm normalized to total emitter finger length. The normally-off characteristic and superior long pulse RF performance makes these SiC transistors promising for use in compact power amplifiers in long-pulse UHF radar systems.
215 cm²/V s based on the author's prior study [12]. Transistors were fabricated using a double-mesa etch and an interdigitated emitter–base finger structure. Both isolation mesa and emitter mesa were patterned by reactive ion etch (RIE) in a SF₆ gas and the etch depth was accurately controlled by an innovative technique [13]. Both emitter and base finger width is 2 µm, and the base to emitter alignment is 1 µm. The emitter finger length is 75 µm, and there are 24 emitter fingers in each single transistor. The device surface was passivated with a thin layer of dry thermal oxide, followed by a layer of deposited oxide by plasma enhanced chemical vapor deposition (PECVD). Ni/Cr was used for the emitter and collector (back of the wafer) contacts, and Ti/Al for the base contacts. Both n- and p-type ohmic contacts were prepared by rapid thermal annealing (RTA) at 950 °C in the high-purity Ar ambient. Ti/Au was deposited for the wiring and pads. The entire device surface was covered by another layer of PECVD oxide, followed by a forming gas anneal process. The windows for bonding pads were opened by RIE etching. More detailed fabrication procedures can be found elsewhere [14]. A cross-sectional drawing of a single finger structure and an optical image of a 2-in. SiC wafer after fabrication is shown in Fig. 1.

After fabrication, the wafer was diced and each SiC BJT die was attached to a package, which incorporates a 40-mil thick BeO layer over a 65-mil thick CuW flange. Fig. 2 shows a RF BJT die in a flanged package. There are six identical transistors on each die. For large-signal RF measurements, two transistors were bonded in the package through emitter and base pads by Au bond wires which are straight and directly go to leads of the package. There was no internal matching used in the package during this study. The impedance matching was performed with a pre-matching circuit on the test fixture and two triple-stub tuners at both input and output.

3. Results and discussion

3.1. DC characterization

An on-wafer DC current–voltage (I–V) characterization for the common-emitter configuration was performed on a single transistor under low and high voltage conditions with an Agilent 4155e semiconductor parameter analyzer to qualify the RF transistors as well as to identify the proper DC bias points for RF measurements. A typical I–V is illustrated in Fig. 3. The maximum DC gain is 20 and the theoretical breakdown voltage $BV_{CEO}$ based on collector thickness and doping is over 400 V. However, devices were only tested up to 200 V due to the voltage limitation of the test equipment (4155e).

3.2. Small-signal RF characterization

Small-signal RF measurements were performed at room temperature using an Agilent E5071B network analyzer. The network analyzer was calibrated using a Thru-Reflect-Line (TRL) technique. The s-parameters were measured from 50 MHz to 4 GHz at a bias of $V_{CE} = 50$ V and $J_C = 3.7$ kA/cm². The package itself is "purely" capacitive and was de-embedded from the devices using g-parameters [15,16] converted from the measured s-parameters. The emitter inductance due to the bond wires was also de-embedded by subtracting it from the resulting g-parameters. The transit frequency $f_T$ was extrapolated from the 20 dB/decade fitted line of current gain $|h_{21}|$, while the maximum oscillation frequency $f_{MAX}$ was obtained from the unilateral power gain $U$ and maximal available gain $G_{MAX}$ at the frequency where the gain has decreased to 0-dB. The results are shown in Fig. 4 with $f_T = 2.1$ GHz and $f_{MAX} = 3.9$ GHz. The maximal available power gain $G_{MAX}$ is 12.7 dB at 500 MHz.

3.3. Large-signal RF characterization

The RF performance of the transistors was also characterized by large-signal measurements. Two identical transistors on a RF BJT die were bonded in common-emitter configuration. DC voltage was fed to the collector lead of the transistor; base was biased with a positive voltage and synchronized with a RF pulsing. The pulse width of the base pulsing was 0.2 ms wider than the RF pulse to compensate for the RF delay. This bias configuration makes sure that the RF signal is not chopped off. The pre-matching circuit was designed on the test fixture with a three-section transformation of
Two triple-stub tuners at the input and output match both input and output impedances to 50 \( \Omega \) to obtain maximum gain at the required input power. The input and output peak power was measured by Agilent E4417A series power meter. A 30 dB coupler was employed at the input side to monitor input power. A water-cooling heat sink was used to cool down the test fixture and the device. The thermal-couple clapped on the package flange showed that the flange temperature was maintained to be at room temperature during the RF test.

Fig. 5 shows the RF performance at 500 MHz under pulsed Class AB operation mode with 15 ms pulse width and 25% duty cycle. The transistors were biased at \( V_{CE} = 100 \text{ V} \) and \( J_C = 5.5 \text{ kA/cm}^2 \). At a power gain of 10 dB, the devices can deliver 52 W output power and a PAE of 43%. The pulse droop is less than 0.5 dB as shown in Fig. 6. When the output power is increased to 71 W corresponding to a power density of 19.7 W/mm, the transistors can still deliver 8.5 dB power gain and the PAE increases to 50.7%. The author believes that the improved RF performance compared to the results from [11] is due to the optimized design, both in epi (doping and thickness) and lateral layout, as well as fabrication process development. The narrower emitter finger width (2 \( \mu \text{m} \)) and tighter alignment (1 \( \mu \text{m} \)) between base contact to emitter mesa lead to a smaller total isolation-mesa area which reduces the base–collector junction capacitance and base resistance. Base ohmic contacts with lower contact resistivity (an average of 8 \( \times 10^{-4} \text{ ohm cm}^2 \) across the wafer) were obtained which are lower than those in [11]. Previously in [11], the author also reported 4H–SiC BJTs characterized with IR scan measurements on a test stage of 70 \( \times 10^{-4} \text{ ohm cm}^2 \). The devices can deliver 50 W output power with more than 7.5 dB gain when operated with a 150 \( \mu \text{s} \) pulse and 5% duty cycle, even though the

8 \( \Omega \) – 25 \( \Omega \) – 50 \( \Omega \). Two triple-stub tuners at the input and output match both input and output impedances to 50 \( \Omega \) to obtain maximum gain at the required input power. The input and output peak power was measured by Agilent E4417A series power meter. A 30 dB coupler was employed at the input side to monitor input power. A water-cooling heat sink was used to cool down the test fixture and the device. The thermal-couple clapped on the package flange showed that the flange temperature was maintained to be at room temperature during the RF test.

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temperature of the devices increases to more than 250 °C. This much better thermal performance as opposed to Si devices, when combined with the RF performance reported in this paper, shows that 4H–SiC BJT is a promising candidate for long-pulse UHF radar applications. Compared to the state-of-the-art 1 kW Si RF BJTs [17], the output power from 4H–SiC BJTs is still much lower. Further development work especially in power scaling is required to achieve a comparable output power.

4. Conclusion

4H–SiC RF BJTs on a n-type substrate demonstrated an output power of 71 W, a power gain of 8.5 dB and an efficiency of 50.7% under long pulse RF conditions of 15 ms pulse width and 25% duty cycle at 500 MHz. The power density is 19.7 W/mm and the pulse droop is less than 0.5 dB. These results are testimonies to the potential of SiC BJTs for compact RF power amplifiers and to replace Si BJTs in long-pulse UHF radar applications.

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References