An 18-GHz 300-mW SiGe Power HBT

Zhenqiang Ma, Ningyue Jiang, Guogong Wang, and Samuel A. Alterovitz

***Abstract*—An 18-GHz, 300-mW SiGe power heterojunction bipolar transistor (HBT) is demonstrated. The optimization of SiGe HBT vertical profile has enabled this type of devices to operate with high gain and high power at this high frequency. In the common–base configuration, a continuous wave output power of 24.73 dBm with a power gain of 4.5 dB was measured from a single 20-emitter stripe SiGe ($2 \times 30\ \mu m^2$ of each emitter finger) double HBT. The overall performance characteristics represent the state-of-the-art SiGe power HBTs operating in the K-band frequency range.**

***Index Terms*—Common-base, heterojunction bipolar transistors (HBTs), SiGe.**

I. INTRODUCTION

IN COMPARISON to III-V device technologies, a SiGe BiCMOS technology platform offers a low-cost solution for integrating RF/microwave circuits and CMOS on a single chip for future communication units. While the high-frequency performance of low-power SiGe HBTs has increased dramatically in the past few years [1], [2], high power SiGe HBTs operating at high frequencies (K-band and higher), however, have not been successfully developed. As the 20–30-GHz frequency range is of growing interest for wireless communications, the development of SiGe power HBTs for these applications has thus reached the high-level urgency. In this letter, we report the design and performance characteristics of SiGe HBTs developed for K-band power amplifications. Under continuous wave (CW) operation at 18 GHz, a device RF output power of 300 mW with 4.5-dB power gain has been achieved.

II. DEVICE DESIGN AND FABRICATION

In order to achieve a high $f_{\max}$ (>60–90 GHz) value for large-area SiGe power HBTs such that sufficient power gain is available in the 20–30-GHz frequency range, while maintaining high breakdown voltages and relaxing the lithography restriction to lower the fabrication cost of these devices, the most efficient measure is to reduce the base resistance (R_B) by increasing the base doping concentration. However, in most high-speed SiGe HBTs a low base doping concentration in conjunction with a low Ge content of a trapezoid shape is employed in order to maintain a high current gain β (the doping profile is analogous to that of traditional Si BJTs). Alternatively, the decoupling of base Gummel number from intrinsic base resistance due to SiGe induced bandgap narrowing permits a high base doping concentration (higher than emitter region) with more Ge content to be employed in the base region [3]. In this way, the reduction of current gain due to high base doping concentration can be effectively restored with a large valence band offset between emitter and base that can be obtained by incorporating a high Ge content in the base.

In addition, the high-speed characteristics (e.g., f_T) of high-performance SiGe HBTs are generally obtained with the sacrifice of breakdown voltages [1], [2]. In contrast to these low-breakdown voltage devices for which emitter transit time τ_E is the dominant component in τ_{EC}, [4], [5], the collector space charge layer delay τ_{CSCL} is instead the dominant time delay component in τ_{EC} for high breakdown voltage ($\mathrm{BV}_{\mathrm{CBO}}$) SiGe HBTs [3]. As a result, for such high breakdown voltage SiGe HBTs, although such parameters as Ge content and Ge profile in the base region will affect τ_E (as well as τ_B), the variation of these two parameters will not have a major influence on the $f_T (f_T = 1/2\pi\tau_{\mathrm{EC}})$ values. Since τ_B is also not a dominant component in τ_{EC} for high breakdown voltage devices, the increase of τ_B due to the increase of base doping concentration in the base region will have minimal impact on τ_{EC} and thus on f_T. However, the reduction of R_B resulting from a heavy base doping concentration can significantly enhance the $f_{\max}$ values without involving substantial scaling of the emitter widths. As a result, a high power gain can be achieved at higher frequencies by employing a heavily doped base region.

In the heterostructure design of the SiGe power HBTs, the collector epilayer is made thick (nominal thickness: 0.45 μm) and lightly doped (3×10^{16} cm^{-3}) in order to realize a high breakdown voltage. A high Ge content (24%) with a box-shape profile is used to maintain a large valence band offset between the emitter and the base. Such a high Ge content thus permits a high doping concentration (2×10^{20} cm^{-3}) to be employed in a thin (30 nm) base region while still maintaining reasonable current gain values. In order to reduce boron outdiffusion during the chemical vapor deposition (CVD) growth and processing, 0.2 atom% carbon was added during the epi-growth of the SiGe base. The SIMS analysis results of the heterostructure are shown in Fig. 1(a). The SiGe base sheet resistance measured from TLM patterns is only 705 $\Omega/\square$, much lower than any reported values, which is directly resulted from using heavy base doping concentration. With a mesa-type structure used for device fabrication for which both the intrinsic and the extrinsic base regions are made on the same SiGe layer [6], such a small sheet resistance hence directly results in a small total base resistance. A uniformly distributed subcell structure (with two $2 \times 30\ \mu m^2$ emitter stripes in each subcell) is used in this power

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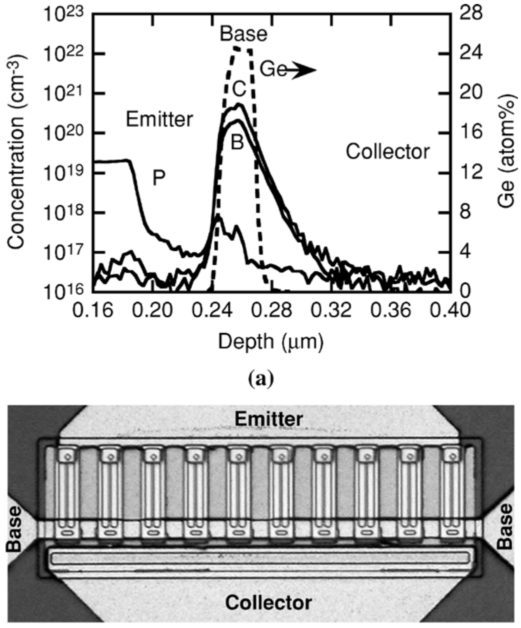

(a)

(b)

Fig. 1. (a) Measured SIMS profile for a CVD-grown Si–SiGe–Si double heterostructure. (b) Photomicrograph of a fabricated 20-emitter stripes (each of size 2 × 30 μm^2) SiGe power HBT. The total emitter area is 1200 μm^2.

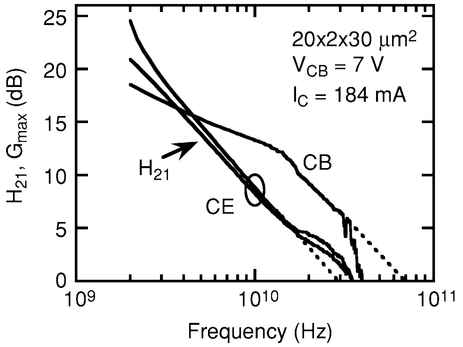

Fig. 2. $G_{\max}$ versus frequency measured for power SiGe HBTs in two different configurations. MAGs are 4.7 dB for the common–emitter configuration and 10 dB for the common–base configuration at 18 GHz with the respective extrapolated $f_{\max}$'s of 31 and 70 GHz, if assuming a -20 dB/decade degradation trend.

device layout and detailed structure can be found in elsewhere [6]. The total emitter area of a 20-finger device is 1200 μm^2. The mesa-type power devices were fabricated from heterostructures grown on 0.5-mm-thick Si substrates using CVD using an in-house research double-mesa process [6]. The photomicrograph of a fabricated power SiGe HBT is shown in Fig. 1(b).

III. DEVICE PERFORMANCE

High breakdown voltages are measured from the SiGe power HBTs with $\mathrm{BV}_{\mathrm{CBO}} = 26$ V and $\mathrm{BV}_{\mathrm{CEO}} = 14$ V. The measured small-signal RF characteristics for both the CE and the CB configurations are shown in Fig. 2. The CE configuration demonstrates an f_T of 28 GHz, resulting in an $f_T \cdot \mathrm{BV}_{\mathrm{CBO}} = 728$ GHz·V, comparable to the reported SiGe HBTs [7] having a similar $\mathrm{BV}_{\mathrm{CBO}}$. The $G_{\max}$ values at 18 GHz are 4.7 dB for the CE and 10 dB for the CB configuration, which can be extrapolated to an $f_{\max}$ value of 31 and 70 GHz, respectively, if assuming a -20/dB/decade degradation trend. The relationship of $G_{\max}$ between the two configurations shown in Fig. 2 agrees well with the behavior predicted by our recent theoretical studies [8].

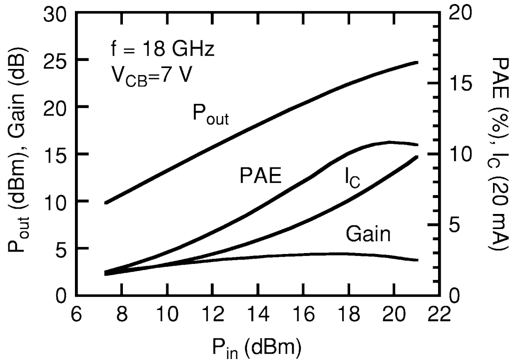

Fig. 3. Power performance of the common–base SiGe HBT biased under class AB operation ($V_{\mathrm{EB}} = -0.69$ V and $V_{\mathrm{CB}} = 7$ V). The matching for source and load is optimized for maximum P_{out}. 24.73-dBm P_{out} and 4.5-dB power gain with a peak PAE of 11% were obtained.

Since a higher $G_{\max}$ (MAG) value is available from the CB than from the CE configuration at 18 GHz, the CB configuration was then used for source/load pull power characterization. The large-signal performance of the device was tested on wafer at 18 GHz using a Focus CCMT1816 source/load pull system. Under CW operation and biased at class AB mode ($V_{\mathrm{EB}} = -0.69$ V, $V_{\mathrm{CB}} = 7$ V), the device was matched for maximum output power, P_{out}. No oscillation was observed at any matching points during the test. Fig. 3 shows the measured output power (P_{out}), power gain (*G*), power added efficiency (PAE) and collector current as a function of input power (P_{in}). The measured maximum P_{out} is 24.73 dBm with a peak PAE value of 11% and an associated power gain of 4.5 dB. The corresponding dc power (P_{DC}) density of the device is 1.26 mW/μm^2 and the RF power density is 0.25 mW/μm^2. The power performance of the same device was also measured at lower frequencies. At 8 GHz, the measured highest RF power density is 0.56 mW/μm^2 with a PAE of 34% ($P_{\mathrm{DC}} = 1476$ mW). The lowered RF power density at 18 GHz is ascribed to the power gain degradation with the increase of operation frequency. The degradation of power gain results in a degraded PAE $(=P_{\mathrm{in}} \cdot (G-1)/P_{\mathrm{DC}})$, which causes a smaller portion of the DC power being converted into RF power at the high frequency. At the two different operation frequencies, the heating power $(P_{\mathrm{heat}} = P_{\mathrm{DC}} \cdot (1-\mathrm{PAE}))$ increased from 974 mW at 8 GHz to 1351 mW at 18 GHz. The increased heating power thus raises the device junction temperature and further degrades the power performance of the devices. It is thus speculated that, by reducing the emitter finger width, the power gain and thus PAE values can be substantially improved. The improvement of PAE will in turn enhance the RF power levels. In spite of the large emitter width (2 μm) used in the device, the overall power performance values achieved in this study are, to our knowledge, still the best among those reported SiGe power HBTs [9] and power amplifiers [7], [10] operated nearby this frequency point. For comparison, a summary of the reported RF power levels versus frequency for SiGe power

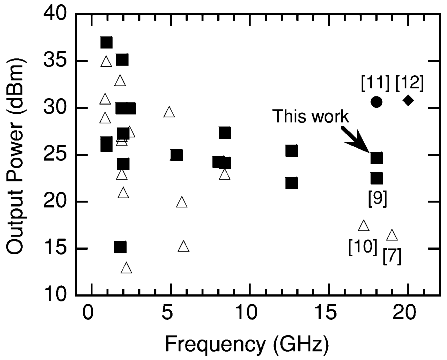

Fig. 4. Total output power versus frequency from single-chip discrete devices (square) or power amplifiers (open triangle) for SiGe HBTs. The performance results of state-of-the-art AlInAs–InGaAs–InP [11] and AlGaAs–GaAs HBTs [12] are also shown for reference.

HBTs and power amplifier modules is shown in Fig. 4 with reference to the performance of state-of-the-art InP-based [11] and GaAs-based HBTs [12]. The high performance of SiGe HBTs demonstrated here results from a low base (sheet) resistance and high device breakdown voltages. These characteristic values are realized by optimizing the device heterostructure with the goal of achieving a high $f_{\max}$ value. These optimizations also permit the CB configuration to be favorably employed at the operation frequency [8].

IV. CONCLUSION

In conclusion, an 18-GHz, 300-mW SiGe power HBT employing a box-type Ge (24%) profile and a heavily doped (2×10^{20} cm^{-3}) base region has been developed with the highest performance. The high $f_{\max}$ value (70 GHz), achieved by using the optimized heterostructure, enables a higher power gain value at 18 GHz and the lightly doped collector region enables high breakdown voltages ($\mathrm{BV}_{\mathrm{CBO}} = 26$ V), permitting high power operations. The heavy doping concentration in the base region, resulting in a low base resistance, favors the common–base configuration for power amplifications.

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