SiGe/Si Power HBTs for X- to K-Band Applications

Saeed Mohammadi, Zhenqiang Ma, Jaehoon Park, Pallab Bhattacharya, Linda P. B. Katehi,
George E. Ponchak[+], Samuel A. Alterovitz[+], Karl M. Strohm[++], Johann-Friedrich Luy[++]

EECS Department, The University of Michigan, Ann Arbor, MI 48109-2122, [+]NASA Glenn Research
Center, Cleveland, OH 44135, [++]Daimler-Chrysler Research Center, Ulm, Germany

ABSTRACT — **High performance power SiGe/Si HBTs at X-band (8.4 GHz), Ku-band (12.6GHz) and K-band (18GHz) have been demonstrated. Under continuous wave operation, a single 20-finger $Si/Si_{0.75}Ge_{0.25}/Si$ (emitter area of 1200 μm^2) HBT, biased in class AB, delivers 28.5dBm (700 mW) of RF output power at X-band, 25.5dBm (350mW) at Ku-band and 22.5dBm (180mW) at K-band. These represent the state-of-the-art power performance of SiGe-based HBTs at frequencies above X-band. An in-depth analysis of the power performance of HBTs with different geometry and configuration is also presented, which will eventually serve as a design guide for SiGe/Si power HBTs at different frequency of operation.**

I. INTRODUCTION

Power GaAs based HBTs have become the device of choice for power amplifiers up to K-Band frequencies due to their good linearity and high power density characteristics [1]. However, the GaAs based power amplifier modules cannot be integrated on the same chip with the rest of the transmit/receive system since in most applications, signal processing and even small-signal RF circuitry are implemented on a Si-based CMOS or BiCMOS chip. In this work, we have developed a novel power SiGe/Si HBT technology suitable for up to K-Band frequencies that allows the integration of the power amplifier on the same chip with CMOS circuitry and is expected to significantly reduce the cost of the future wireless systems. The performance characteristics of the HBTs in our technology are comparable with those of GaAs HBTs.

II. SIGE/SI HBT TECHNOLOGY

In order to achieve such a good power performance characteristics from a Si-Based device, the HBT layer structure, physical layout and fabrication technology are optimized to reduce parasitic impedances and achieve high power handling capability and thermal stability. The HBT layer structure is grown by MBE as shown in Fig. 1. In this design, a $Si_{0.7}Ge_{0.3}$ base layer with a thickness

of 250 Å has been employed to optimize the f_{max} of the device, while a relatively thick Si collector layer (5000 Å $2\times10^{16}cm^{-3}$) has been designed to achieve high breakdown and high power operation. As a result, a unique Si-based technology with Johnson's figure of merit ($f_T\times BV_{CEO}$) in excess of 400GHzV has been realized. Effort has been made to design the layout of the device with minimal parasitics. Multi-finger HBT devices have been designed in both common-emitter (CE) and common-base (CB) configurations. The processing technique developed at the University of Michigan consists of a combination of dry and wet-etching steps, thin film metalizations and SiO_2 passivation. This technology has been optimized to produce 1 μm emitter fingers with a high yield.

Emitter cap	Si	n+	2×10^{20}	250 nm
Emitter	Si	n	2×10^{18}	50 nm
Spacer	$Si_{0.7}Ge_{0.3}$	i		3 nm
Base	$Si_{0.7}Ge_{0.3}$	p+	1×10^{20}	25 nm
Spacer	$Si_{0.7}Ge_{0.3}$	i		7 nm
Collector	Si	n-	2×10^{16}	500 nm
Sub-collector	Si	n+	2×10^{19}	1000 nm
Substrate	Si(100)	10000 ohm-cm		540 μm

Fig. 1. Heterostructure design for power SiGe/Si HBT.

II. DC AND RF CHARACTERISTICS

Power HBTs with different device geometry were characterized for their DC, and small-signal RF performance. Fig. 2 depicts the DC characteristics of a 15 finger $1.4\times32\mu m^2$ HBT device in common-base configurations. High breakdown voltages $BV_{CEO}=13V$ and $BV_{CBO}=20V$ are achieved for this HBT. Fig. 3 shows the results of small-signal S-parameter measurements for 9 finger 1.4×32 μm^2 HBT device. The highest reported maximum

oscillation frequency f_{max} of 100GHz for a large area SiGe/Si HBT (area>400μm^2) is achieved by a 6dB/octave extrapolation from MAG as shown in the figure. More importantly, a maximum available gain of ≈15dB at Ku-Band frequencies was achieved for this HBT, which is an indication of good power performance for this technology up to 20GHz.

III. POWER CHARACTERIZATIONS

The developed HBTs were measured for their power performance at X- Ku- and K-Bands (8.4GHz, 12.6GHz and 18GHz, respectively) using a Focus Microwave automatic load-pull system. The system has two computer-controlled tuners that
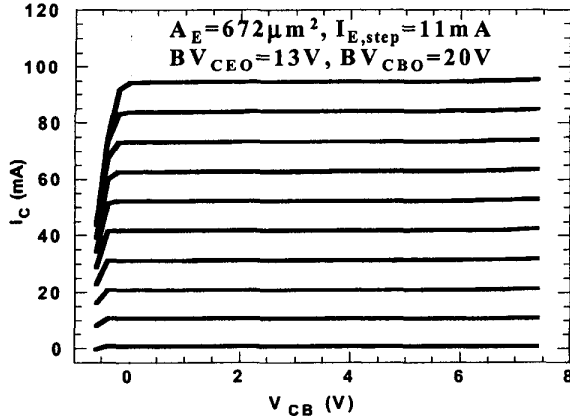
provide different matching conditions at the input and output of the device under test.

Fig. 4 shows the results of load-pull characterization for a 6-finger 2×30 μm^2 HBT in common-emitter (CE) configuration. The optimum load for maximum output power and the optimum load for maximum power added efficiency (PAE) are also shown in the figure. Fig. 5 shows the results of power characterizations for a common-base (CB) HBT with an emitter finger area of 1200 μm^2 at Ku-band (12.6GHz). In this case, load and source tuners are fixed at their optimum condition for maximum output power and input power is varied. A maximum output power of 25.5dBm (350mW) at

Fig. 2. DC Characteristics of a 15 finger 1.4×32 μm^2 CB Power SiGe/Si HBT. This device has a BV_{CEO}=13V and a BV_{CBO}=20V.

POUT Max=19.38 dBm at 25.8+j46.8
P.A.EFF Max=22.01 % at 21.7+j50.1

Fig. 4. Load-pull characterization of a 6 finger 2×30 μm^2 CE power SiGe/Si HBT. This device has an emitter area of 470μm^2.

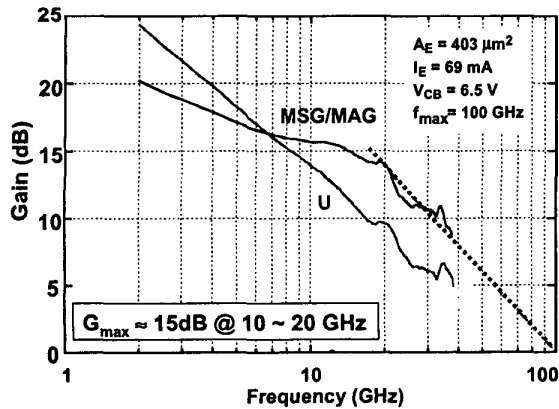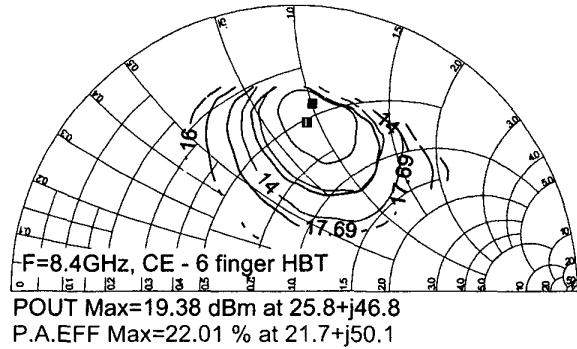Fig. 3. RF Characteristics of a 9 finger 1.4×32 μm^2 CB Power SiGe/Si HBT. This device has about 15dB power gain at frequencies between 10 and 20GHz.
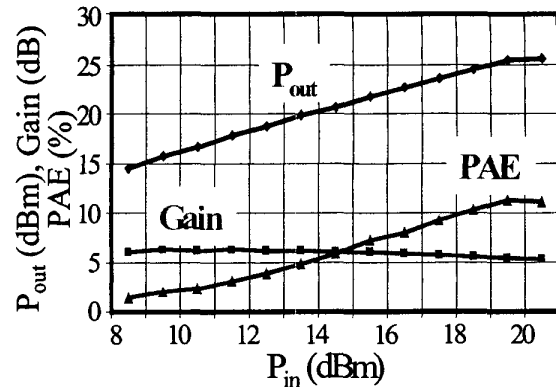

Fig. 5. Power characterization of a 20 finger 2×30 μm^2 CB power SiGe/Si HBT. This device has an emitter area of 1200μm^2

12.6GHz with a power gain of 5dB has been achieved in Class AB amplification.

Table 1 summarizes the results of power characterizations for a 20-finger 2×30 μm^2 HBT in common-base (CB) configuration at different frequency bands. The device generates an output power of 700mW at X-band, 350mW at Ku-band and 180mW at K-band, when tuned for maximum output power.

IV. DESIGN OF POWER HBT

The geometry, layout sketch and configuration of the power HBTs were found to be very important aspects of the device design. Fig. 6 shows a photomicrograph of the fabricated 10-finger 2×30 μm^2 HBT in common-base configuration. A pair of emitter fingers is grouped in a sub-cell surrounded by a base region. In order to find the optimum device geometry for best power applications we varied the following design parameters: *1.* Device emitter area (45μm^2 < area <1200μm^2); *2.* Length of the emitter fingers (15 and 30μm); *3.* Width of the emitter fingers (1, 1.4 and 2μm); *4.* Number of emitter fingers per sub-cell (2 and 3); *5.* Device configuration (CB and CE); *6.* The area of the emitter finger via (6μm^2 and 20μm^2). All devices were tuned to their optimum load and source matching for maximum output power. They were all measured only at X-band in class AB amplification under similar collector current density and collector voltage. The comparison at Ku- and K-band is not yet performed, and will be presented later. The following preliminary conclusions were drawn. Power characterization at higher frequency bands, extraction of thermal resistance and accurate large signal modeling of each measured device would be necessary to further clarify some of the observed trends:

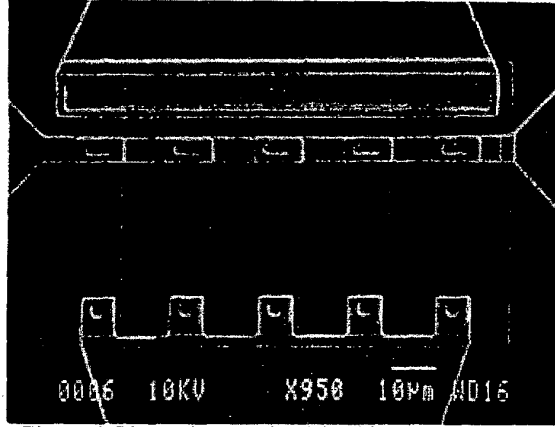1. At X-band, it was found that as the device

Figure 6: Photomicrograph of the fabricated 10-finger C-B SiGe/Si power HBT.

emitter area increases (emitter area < 1200μm^2), the maximum output power of the device increases, while the power gain of the device slightly decreases and the maximum PAE slightly increases. This conclusion may sound trivial since larger devices are biased at higher collector current whereas they present smaller maximum oscillation frequency f_{max} compared to smaller devices. Therefore, larger devices present higher output power (P_{out}~I_c) and smaller power gain (Power Gain~f_{max}). However, the same conclusion may not be valid at higher frequencies (Ku and K-band) as the operating frequency becomes closer to the f_{max} of large area devices.

2. At X-band, it was found that devices with longer emitter finger (<30μm) provide better power performance. However, due to photolithographic limitations in our lab, we did not increase the emitter length beyond 30μm.

3. Devices with similar area, but with different emitter width, were measured at X-band. No significant differences in power performance among these devices were observed, indicating that emitter finger width (<2μm) is not a critical

	X-band (8.4GHz)	Ku-band (12.6GHz)	K-band (18GHz)
Max Pout	28.5dBm (700mW) [2]	25.5dBm (350mW)	22.5dBm (180mW) [3]
Max PAE	32%	12%	10%
Pout @1db compression	25dBm	24.8dBm	22.5dBm
Gain @1dB compression	9.8dB	5.5dB	4.5dB
PAE @1dB compression	25%	10%	10%

Table 1. Summary of power performance of a 20 finger 2×30μm^2 (total emitter area 1200μm^2) SiGe/Si HBT at X-, Ku- and K-band

design parameter for X-band devices. This may not be true as the operating frequency increases to Ku- and K-band regions.

4. Devices with similar area, but with different number of emitter fingers per sub-cell, were measured at X-band. Again, no significant differences in power performance among these devices were observed, indicating that number of emitter fingers per sub-cell width (2 or 3) is not a critical design parameter for X-band devices. This may not be true as the operating frequency increases to Ku- and K-band regions.

5. Common-base (CB) and common-emitter (CE) devices with similar geometry were measured at X-band. It was found that for $2\mu m$ emitter width, CB devices present about the same output power, but much higher Gain and PAE than CE devices. However, for devices with emitter width of $1.4\mu m$ and $1\mu m$, CE devices showed higher output power than CB devices, but Gain and PAE were about the same. As the emitter area was increased, the difference in the power characteristics of CE and CB devices became clearer. It needs to be seen whether or not similar observation can be made at Ku- and K-band frequencies.

6. The effect of emitter via size on the power performance of multi-finger $2\times30\mu m^2$ CE HBTs was studied. It was found that for any number

of fingers (>4), the devices with smaller emitter via area ($6\mu m^2$) outperform the devices with larger emitter via area ($20\mu m^2$). Fig. 7 shows such a comparison made for 6-finger $2\times30\mu m^2$ CE HBTs. To further clarify the underneath mechanism, large-signal Gummel-Poon models of the two HBTs were extracted. The extracted models were identical with the exception of emitter AC resistance which was 23Ω/finger for the device with smaller emitter via area and 17Ω/finger for the device with larger emitter via area. It was concluded that, the HBT with smaller emitter via area presents an optimum value of ballast resistance in the emitter, which in turn, distributes the current among the fingers more evenly, hence improving the power performance of the multi-finger design.

V. SUMMARY

This paper presents the power performance of the state-of-the-art SiGe/Si HBTs at X-, Ku- and K-band frequencies. Multi-finger HBTs with different device designs were characterized for their power performance at X-band. It was found that larger emitter area ($<1200\mu m^2$), longer emitter length (characterized up to $30\mu m$) and small emitter via area ($6\mu m^2$), would result in better power performance at X-band. The effect of emitter width ($<2\mu m$) and the number of emitter fingers in sub-cells (2 or 3) on the power performance of the devices were insignificant at X-band. These trends at higher frequencies will be characterized and presented.

Fig. 7. Effect of emitter via size on the power performance of 6-finger $2\times30\mu m^2$ CE HBTs. *Pouts, Gains* and *PAEs* refer to the power performance of the device with smaller emitter via size ($6\mu m^2$). *PoutL, GainL* and *PAEL* refer to the power performance of the device with larger emitter via size ($20\mu m^2$).

REFERENCES

[1] H.-F. Chau, et al., "1 Watt, 65% PAE K-band AlGaAs/GaAs heterojunction bipolar transistors using emitter air-bridge technology," *IEEE Radio Frequency Integrated Circuits (RFIC) Symposium*, pp. 219-223, June 1997.
[2] Z. Ma et al., "Si/SiGe Power Heterojunction Bipolar Transistors for Ku-Band Applications," Late news paper in *59th Device Research Conference*, Notre Dame, IN, June 2001.
[3] Z. Ma et al., "A 180mW 18GHz Si/SiGe power heterojunction bipolar transistor," *IEEE Topical Workshop on Power Amplifier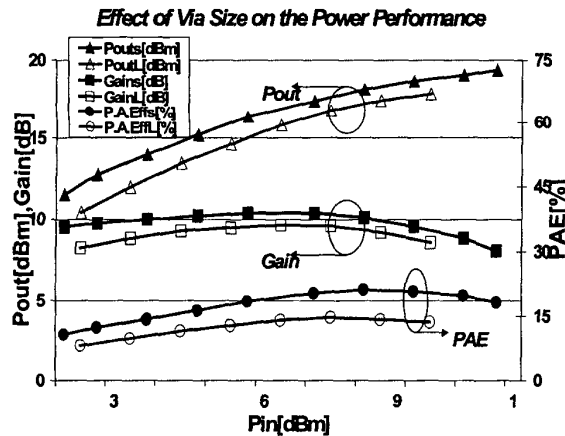s for Wireless Communications*, San Diego, CA, Sep 2001.