SiGe Power Heterojunction Bipolar Transistors (HBT's) Fabricated by Fully Self-Aligned Double Mesa Technology

Liang-Hung Lu, Saeed Mohammadi, Zhenqiang Ma, George E. Ponchak[+], Samuel A. Alterovitz[+], Karl M. Strohm[++], Johann-Friedrich Luy[++], Pallab Bhattacharya and Linda P. B. Katehi
The University of Michigan, Ann Arbor, MI 48109-2122
[+]NASA Glenn Research Center, Cleveland, OH 44135
[++]Dailmer-Chrysler Research Center, Ulm, Germany

Abstract- **Multi-finger SiGe HBT's have been fabricated using a novel fully self-aligned double-mesa technology. With the advanced process technology, a maximum oscillating frequency (f_{max}) of 78 GHz and a cut-off frequency (f_T) of 37 GHz were demonstrated for a common-emitter device with emitter area of 2×2×30 μm². For class-A operations, 10-finger devices (A_E=2×2×30 μm²) exhibit an output power of 24.13 dBm with a maximum power added efficiency (PAE) of 26.9% at 8.5 GHz.**

I. INTRODUCTION

Recent advances in the growth of epitaxial SiGe layers have led to high quality SiGe heterojunctions and consequently high performance SiGe heterojunction bipolar transistors (HBT's)[1]-[3]. With the mature Si process technology, the Si-based microwave monolithic integrated circuits (MMIC's) have received great attention as a potential candidate for the wireless communication market. Microwave circuits such as low-power broadband amplifiers[4], Gilbert mixers[5] and voltage controlled oscillators[6] have been demonstrated using SiGe HBT's. However, it is still a challenge to implement power amplifiers at frequencies above X-band. The availability of high-performance SiGe power devices will be the key to the success of realizing a microwave system on a chip using Si substrate.

Double-mesa technology has been widely used to investigate the HBT performance. In this work, a novel fabrication technology has been developed to achieve a fully self-aligned double-mesa structure for power SiGe HBT's, resulting in a significant reduction of device parasitics. Common-emitter multi-finger devices have been fabricated and characterized for both small-signal and large-signal operations.

II. DESIGN AND FABRICATION

The epitaxial growth of the SiGe power HBT structure starts with a high-resistivity Si substrate (ρ=3000 Ω-cm), followed by a CVD buried layer for subcollector. Then complete heterostructure is grown in one step by molecular beam epitaxy (MBE) as shown in Table 1. In this design, a $Si_{0.7}Ge_{0.3}$ base layer with a thickness of 200 Å has been employed to optimize the f_{max} of the device, while a relatively thick Si collector layer has been designed to achieve high power operation.

Table 1 Power SiGe HBT structure.

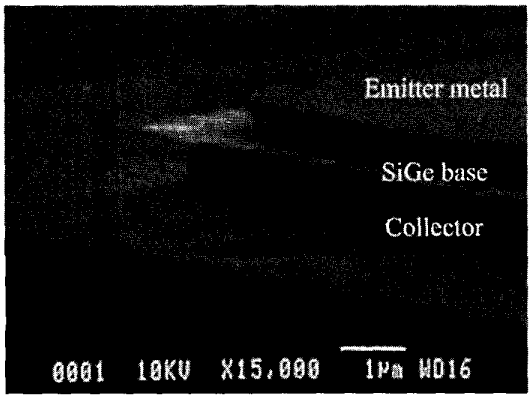
Emitter cap	Si	n^+	1×10^{20}	150 nm
Emitter	Si	n	1×10^{18}	50 nm
Spacer	$Si_{0.7}Ge_{0.3}$	i		5 nm
Base	$Si_{0.7}Ge_{0.3}$	p^+	1×10^{20}	20 nm
Spacer	$Si_{0.7}Ge_{0.3}$	i		5 nm
Collector	Si	n^-	1×10^{16}	500 nm
Subcollector	Si	n^+	1×10^{19}	1 μm
Substrate	Si	p^-	1×10^{12}	540 μm

Multi-finger HBT devices have been designed and fabricated in common-emitter configuration. Effort has been made to design the layout of the unit cell with minimal parasitics. For device layout, emitter fingers with a dimension of 2×30 μm² are surrounded by two base electrodes with a width of 1.5 μm, and contact are made through emitter pads, which are isolated from the intrinsic part of the device. In order to alleviate the thermal stability problems, the spacing between two emitter fingers is chosen to be 12 μm. In addition, collector electrodes are

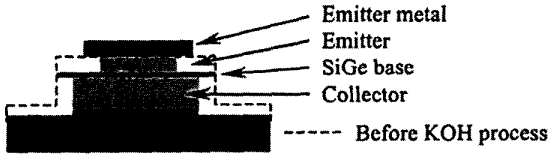
0-7803-6538-0/01/$10.00 © 2001 IEEE

inserted in between the emitter fingers, minimizing the collector resistance of the HBT devices.

A novel fully self-aligned process technology has been developed to fabricate the double-mesa SiGe HBT's. The fabrication starts with emitter metal (Cr/Au) deposition, followed by two consecutive reactive ion etch (RIE) steps for base mesa formation and device isolation, respectively. Up to this point, either p^+ base nor n^+ subcollector has been exposed for contact. Then a KOH etch step is performed to expose base and collector contact simultaneously without lithography patterning. Due to the etch selectivity of KOH between Si and SiGe alloy, only Si layers are etched away, creating undercuts underneath the emitter metal and the SiGe base as shown in Fig. 1. After the KOH process, Ti/Au is deposited for base and collector metalization simultaneously, resulting in a fully self-aligned double-mesa structure. An 1 μm-thick PECVD SiO_2 deposition is employed for device passivation, followed by via formation using RIE. Finally, a deposition of 1.5 μm-thick interconnection (Ti/Al/Ti/Au) completes the device fabrication.



(a)



(b)

Fig.1 Base/subcollector exposure using KOH etch. (a) Photomicrograph. (b) Cross section.

This unique process technology provides several advantages; First of all, self-aligned base and collector metal are available, resulting in a reduction in both base and collector access resistance. Secondly, the laterally etched undercut created underneath the SiGe base layer reduces the area accountable for extrinsic base-collector capacitance C_{BC}. As a result, the f_{max} of the device can be improved significantly. In addition, the KOH process, which has been performed after the device isolation, also removed the Si layers underneath the emitter metal outside the intrinsic region. As a result, isolated pads for emitter contact are available for this technology, resulting in smaller parasitic capacitance between base and emitter. Figure 2 shows the photomicrograph of the fabricated SiGe HBT with 10 emitter fingers.

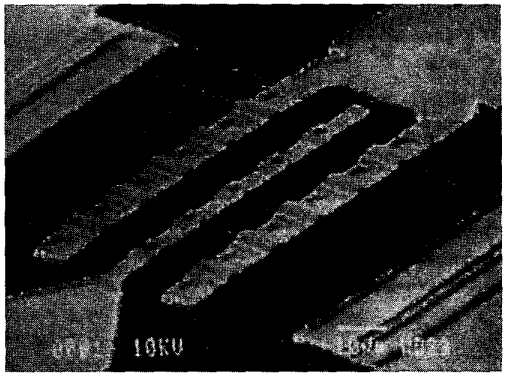


Fig. 2 Photomicrograph of the fabricated 10-finger common-emitter power HBT.

III. DEVICE CHARACTERISTICS

The DC characteristics of the devices have been measured with HP4155 semiconductor parameter analyzer. With a collector thickness of 5000 Å and a collector doping concentration of 1×10^{16} cm^{-3}, the open-base breakdown voltage BV_{CBO} and the open-emitter breakdown voltage BV_{CEO} are 25 V and 10 V, respectively. The I-V characteristics of a 2-finger device is shown in Fig. 3, and it exhibits a maximum DC current gain β of 26 and a maximum differential current gain Δβ of 33.

For small-signal RF characteristics, on-wafer probing S-parameter measurement has been performed using HP8510C network analyzer from 2 to 40 GHz. Figure 4 shows the current gain $|h_{21}|$ and the unilateral power gain U of the two-finger device at a DC bias of I_C = 28 mA and V_{CE} = 6V. The values of f_T and f_{max}, extrapolated with the assumption of –20 dB/decade roll-off, are 37 and 78 GHz, respectively. In order to investigate the improvement on device parasitics by employing the process technology, parameters of the small-signal equivalent circuits have been extracted from the measured S-parameters. The small-signal equivalent circuit and the extracted parameters are shown in Fig. 5. Compared with the standard double-mesa technology, a significant reduction of C_{BC}, up to 40%, has been observed.

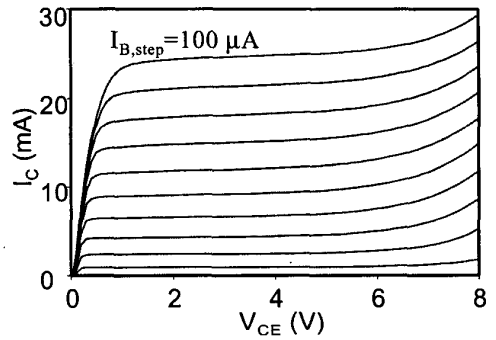


Fig. 3 The I-V characteristics of the 2-finger common-emitter device.

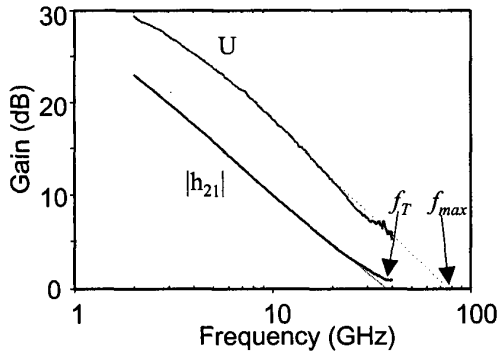


Fig. 4 Measured small-signal frequency response of the 2-finger device. (I_C=28 mA, V_{CE}=6 V)

In addition to the small-signal operation, load-pull measurement has been performed on fabricated devices to characterize power performance of the multi-finger HBT's. Both source and load tuners are optimized for maximum output power during the measurement. Then the power gain G, output power P_{out} and power added efficiency PAE are measured as a function of input power P_{in} at 8.5 GHz in CW mode.

For class-A operations, a 10-finger common-emitter device (A_E = 10×2×30 μm^2) is biased at V_{BE} = 0.82 V and V_{CE} = 6 V. The source and load tuners are optimized for maximum output power. With a source reflection coefficient (Γ_S) of 0.702∠173.6° and a load reflection coefficient (Γ_L) of 0.42∠99.2°, the power saturation curve is obtained by sweeping the input power from –20 to 20 dBm as shown in Fig. 6. As input power increases, the power gain decreases from an initial value of 10.7 dB, which is the small-signal gain of the device. At an input power of 18 dBm, the PAE reaches a maximum value of 26.9% while the power gain and output are 6.13 dB and 24.13 dB, respectively.

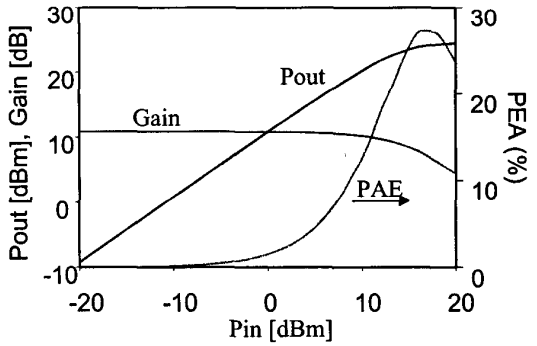


Fig. 6 Power measurement of the fabricated common-emitter SiGe HBT's with emitter area of 10×2×30 μm^2. (V_{BC} = 0.82 V, V_{CE} = 8 V, Γ_S=0.702∠173.6°, Γ_L=0.42∠99.2°)

IV. CONCLUSION

Using KOH process to expose the p^+ base and n^+ subcollector layers after double-mesa formation, a SiGe HBT with self-aligned base

and collector contacts has been demonstrated. By adopting this technology, the lateral undercut in the collector layer underneath the base contact also reduces the base-collector capacitance, C_{BC}, resulting in a significant improvement on f_{max}. In addition, DC, small-signal and large-signal characterization have been performed on the multi-finger devices for circuit applications. Load-pull measurement of the MBE grown power devices will be presented and discussed.

ACKNOWLEDGEMENT

This work is being supported by NASA-JPL under contract 961358.

REFERENCES

[1] A. Gruhle, H. Kibbel, U. Erben and E. Kasper, "91 GHz SiGe HBTs grown by MBE," *Electronics Lett.*, 1993, Vol. 29, pp. 415-417.

[2] A. Schüppen, U. Erben, A. Gruhle, H. Kibbel, H. Schumacher and U. Kogin, "Ehbanced SiGe heterojunction bipolar transistors with 160 GHz-f_{max}," *IEDM 95*, pp. 743-746.

[3] U. Kogin and H. Dämbkes, "SiGe HBTs and HFETs," *Solid-State Electronics*, Vol. 38, No. 9, pp. 1595-1602, 1995.

[4] H. Schumacher, A. Gruhle, U. Erben, H. Kibbel, and U. Kogin, "A 3V supply voltage, DC-18 GHz SiGe HBT wideband amplifier," *BCTM '95*, 1995, pp. 190-193.

[5] J. Glenn, M. Case, D. Harame, B. Meyerson, and R. Poisson, "12-GHz Gilbert mixer using a manufacturable Si/SiGe epitaxial-base bipolar technology," *BCTM '95*, 1995, pp. 186-189.

[6] A. Gruhle, A. Schüppen, U. Kogin, U. Erben, and H. Schumacher, "Monolithic 26 GHz and 40 GHz VCO's with SiGe heterojunction bipolar transistors, " *IEDM Tech. Dig.*, 1995, pp. 725-728.