1-W SiGe Power HBT's for Mobile Communication

A. Schüppen, *Member, IEEE*, S. Gerlach, H. Dietrich, D. Wandrei, U. Seiler, and U. König

Abstract— **Silicon Germanium (SiGe) power heterobipolar transistors (HBT's) with 10 and $60 \times 2.25 \times 15\,\mu m^2$ emitter fingers, respectively, were fabricated in a completely passivated manner by a production-like process. Each emitter stripe of the big transistors includes a ballast resistance of 6 Ω. Class A load pull measurements at 1.9 GHz revealed a power-added efficiency (PAE) of 44% at 1-W rf output power for the 60-stripes transistor. In addition, a ten-finger driver HBT reached a PAE of 72% at 0.9 GHz for class A/B operation.**

I. Introduction

SILICON GERMANIUM (SiGe) power heterobipolar transistors (HBT's) are ideal candidates for volume market applications at frequencies of 1–10 GHz concerning their outstanding high frequency behavior and their compatibility to standard silicon bipolar technology. Recently the superior performance of SiGe-HBT's was demonstrated by a current mode logic (CML) gate delay time of 11 ps [1], by extremely high $f_{\max}$ and f_T values of 160 and 116 GHz [2], [3], respectively, by good high-frequency noise figures of 0.9 dB at 10 GHz [4] and by low $1/f$-corner frequencies down to 370 Hz [5]. In addition, a lot of circuit demonstrators were built showing the potential of SiGe-HBT's for rf-components above 10 GHz, e.g., a 12-GHz Gilbert Mixer [6], a low-power broadband amplifier up to 18 GHz [7] and voltage-controlled oscillators (VCO's) at 26 and 40 GHz [8]. The first products with SiGe-HBT's, however, will be expected in the 1–5 GHz range. For that reason, power amplifiers are required with low-voltage operation and additionally high power-added efficiencies (PAE's). First results on PAE measurements on SiGe-HBT's were shown by Erben *et al.* [3] for C-band frequencies with a PAE of 33% at 5.7 GHz. Also, for 1–2 GHz power applications, SiGe-HBT's have a real advantage over Si-BJT's due to their low base sheet resistances down to 500 Ω/□. Hence, it will be possible to build HBT's with high $f_{\max}$ values in spite of wide emitter stripes above 2 μm.

This paper deals with investigations on SiGe-HBT's for 0.9–1.9 GHz power modules, which were fabricated by a production-like process.

Manuscript received April 4, 1996. This work was supported by the LOTUS project.

A. Schüppen, U. Seiler, and U. König are with Daimler-Benz AG, Research Ctr. Ulm, 89081 Ulm, Germany.

S. Gerlach and H. Dietrich are with TEMIC Telefunken Microelectronic GmbH, 74025 Heilbronn, Germany.

D. Wandrei is with ATN Microwave, Inc., Billerica, MA 01821 USA.

Publisher Item Identifier S 1051-8207(96)06518-X.

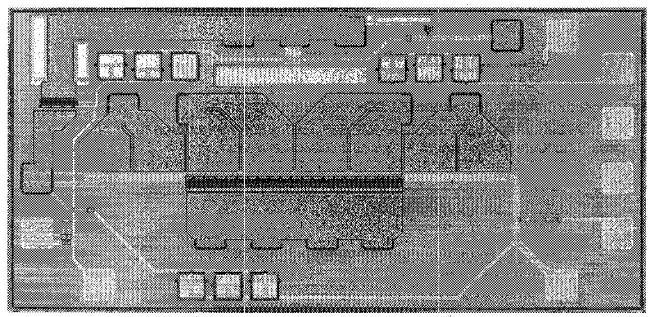

Fig. 1. Photograph of a 60-emitter stripe and a ten-emitter stripe power SiGe HBT for a power module.

II. Technology

The power SiGe-HBT's were fabricated at TEMIC's bipolar line. The process is described elsewhere [10] and starts with a buried layer formation and a channel stop implantation on a 20-Ω cm substrate. The collector layers were formed by a 700-nm chemical vapor deposition (CVD) silicon deposition and were separated by a recessed LOCOS process. The collector contact regions were implanted with phosphorus. Subsequently the molecular beam epitaxy (MBE) growth of the SiGe-base and the n-emitter followed. The 26% Ge in the base and the 4×10^{19} cm^{-3} boron were kept constant. This process mainly differs from a conventional double poly self-aligned silicon bipolar technology in using the MBE-poly as base lead contact by BF_2 implantation. In order to reduce the lead and contact resistances of the emitter and the base, titanium silicide were formed by a silicide process with oxide spacers. The fabrication process finishes by passivation and a two-level Al metallization. A photograph of a 60-stripe and a ten-emitter finger transistor are depicted in Fig. 1. The emitter stripes are arranged in one row, but for higher frequencies the lateral transistor design have to be improved to reduce collector resistances and to suppress phase shift due to propagation delay.

III. Electrical Results

DC measurements on SiGe power HBT's with $60 \times 2.2 \times 15\,\mu m^2$ revealed good output-characteristics with high current gains of up to 200 and collector–emitter breakdown voltages of 4–5 V correlated with the effective collector thickness of 430 nm and the high current gain. No current crush effects as often described in III–V HBT's were observed. As shown in Fig. 2, the negative slope and the current loops in the I–V

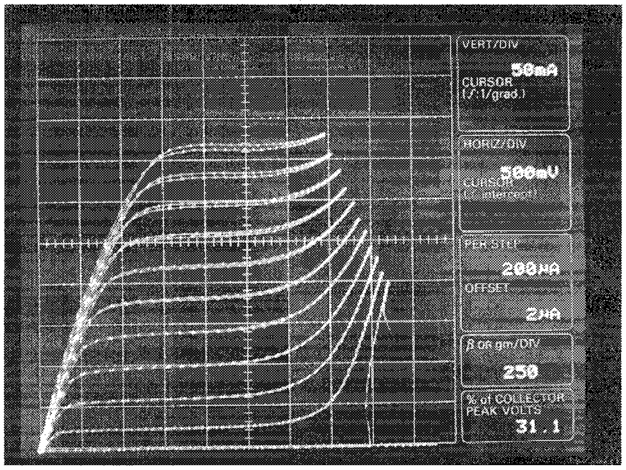

Fig. 2. DC output characteristics of a 60-emitter-finger HBT.

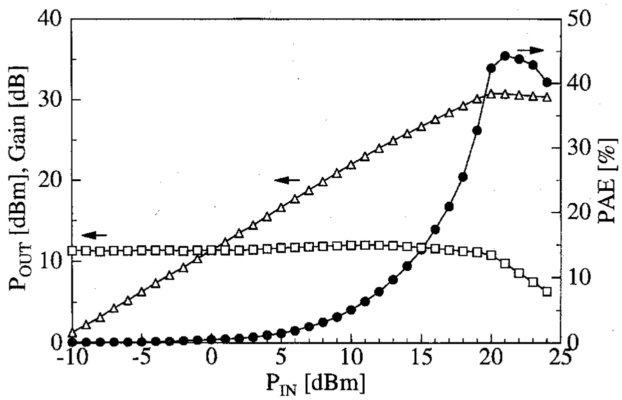

Fig. 3. Input power versus power gain □, output power △, and PAE • for a power HBT with 60 emitter stripes (2.2 × 15 μm^2).

curves at higher currents remain relatively small owing to the good thermal conductivity of silicon. From high-frequency S-parameter measurements transit frequencies f_T of 16 GHz and maximum oscillation frequencies $f_{\max}$ of 11 GHz at 400 mA collector current and $V_{CE} = 3$ V were extracted. These are acceptable values regarding the 6-Ω balance series resistances of each emitter stripe. Theoretical investigations on SiGe-HBT's concerning thermal effects hint to the possibility of reducing or removing these emitter resistances in future designs. Load pull measurements in class A operation of the 60-stripes HBT's were performed at 1.9 GHz from −10 dBm up to 24-dBm input power. The measurements had been done on an automatic load pull measurement setup of ATN. The dc operation point was: $V_{BE} = 0.78$ V, $V_{CE} = 4.7$ V, $I_B = 10$ mA, and $I_C = 585$ mA. The highest PAE was measured for a source impedance of 0.7 Ω and a phase of −175.9°, and a load impedance of 0.77 Ω and −172.1° phase showing that both matching points lay near short circuit. A maximum PAE of 44% was attained with a rf output power of 1 W as depicted in Fig. 3. The power increases linearly with rf-input and the gain is constant at 12 dB up to the 1-dB compression point at 19 dBm. At 3-dB compression, the 60 finger SiGe-power-HBT reaches its maximum PAE value.

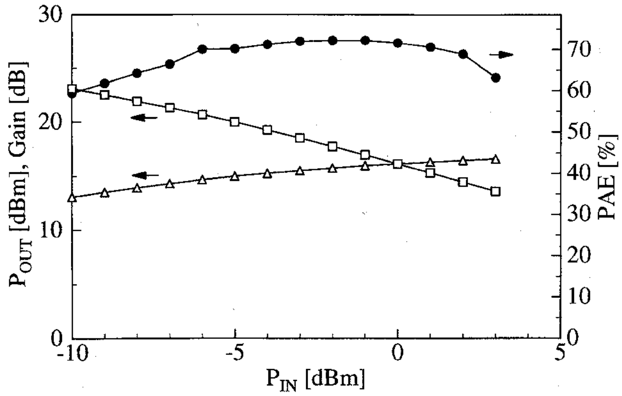

Fig. 4. Input power versus power gain □, output power △, and PAE • for a driver SiGe-HBT with ten emitter stripes (2.2 × 15 μm^2).

Additional measurements on HBT's at 2.7 V collector voltage revealed reduced maximum rf power of 25 dBm and a PAE fell off to 38%. By an optimization of the HBT layer structure, however, e.g., by a higher doped and shorter collector, it will be possible to rise the power-added efficiency up to 45% also for 2.7 V in class A operation.

For power modules in mobile communication systems besides an output stage also a suitable driver transistor is required. Hence, we investigated a 10 × 2.2 × 15 μm^2 emitter SiGe-HBT without emitter balance resistances at 0.9 GHz. The results are shown in Fig. 4. For these load pull measurements the emitter-base voltage V_{BE} and the collector emitter voltage V_{CE} was fixed to 0.7 V and 2.7 V, respectively, so the transistors run to A/B operation for higher rf input power. At small input powers up to −8 dBm, the base current was in the 100-μA range and was increased up to 1.6 mA for 3-dBm rf input. For the same input sweep the collector current rose from 14–25 mA. The highest PAE values were detected between −6 dBm and 1 dBm with a broad maximum at 72%. As expected, by changing from class A over to class B operation, the power gain decreased by 6 dB from 22 dB at −8 dBm to 16.1 dB at 0 dBm. The maximum output power was 16 dBm.

IV. Conclusion

SiGe-power-HBT's were investigated with regard to applications for mobile communication systems in the 0.9–2.4 GHz range. Load–pull measurements at transistors with an emitter geometry of 60 × 2.2 × 15 μm^2 exhibited at 1-W rf-output power a PAE of 44% at 1.9 GHz. A driver transistor with ten equally sized emitter fingers reached a PAE of 72% for class A/B operation at 0.9 GHz. These results demonstrate the potential of SiGe-HBT's for power applications. By layer and design optimizations it will be possible to build complete power modules operating in 1–10 GHz range.

Acknowledgment

For load–pull measurement, the authors would like to thank the co-workers at ATN Inc. For rf measurements, they would like to thank U. Erben from the University of Ulm.

REFERENCES

[1] T. F. Meister, H. Schäfer, M. Franosch, W. Molzer, K. Aufinger, U. Scheler, C. Walz, M. Stolz, S. Boguth, and J. Böck, "SiGe base bipolar technology with 74 GHz $f_{\max}$ and 11 ps gate delay" in *IEDM Tech. Dig.,* 1995, pp. 739–742.

[2] A. Schüppen, U. Erben, A. Gruhle, H. Kibbel, H. Schumacher, and U. König, "Enhanced SiGe heterojunction bipolar transistors with 160 GHz-$f_{\max}$," in *IEDM Tech. Dig.,* 1995, pp. 743–746.

[3] A. Schüppen, A. Gruhle, H. Kibbel, U. Erben, and U. König, "SiGe-HBT's with high f_T at moderate current densities," *Electron. Lett.,* vol. 30, no. 14, pp. 1187–1188, 1994.

[4] H. Schumacher, U. Erben, and A. Gruhle, "Low-noise performance of SiGe heterojunction bipolar transistors," in *MTT-Symp.,* San Diego, CA, 1994, pp. 1167–1171.

[5] J. D. Cressler, L. Vempati, J. A. Babcock, R. C. Jaeger, and D. L. Harame, "Low-frequency noise characteristics of UHV/CVD epitaxial Si- and SiGe-base bipolar transistors," *IEEE Electron Device Lett.,* vol. 17, no. 1, pp. 13–15, 1996.

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

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

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

[9] U. Erben, M. Wahl, A. Schüppen, and H. Schumacher, "Class-A SiGe HBT power amplifiers at C-band frequencies," *Microwave Guided Wave Lett.,* vol. 5, no. 12, pp. 435–436, 1995.

[10] H. Dietrich and A. Schüppen, "High speed hetrobipolar transistors," *J. Crystal Growth,* vol. 157, pp. 207–214, 1995.