

# A Fully-Manufacturable 0.5mm SiGe BiCMOS Technology for Wireless Power Amplifier Applications

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*We present for the first time a fully-manufacturable 0.5 mm/3.3V SiGe BiCMOS technology that supports multiple mode (GSM/ PCS/ WCDMA) power amplifier applications, highlighting HBT device design, safe-operating area, and module performance. This technology features a high-breakdown transistor ( $BV_{CBO} > 20V$ ), with  $f_T$  exceeding 25GHz, along with a suite of device elements that is fully compatible with the IBM's mature 0.5mm SiGe BiCMOS technology. PA design is discussed and hardware measurements presented demonstrating that this SiGe BiCMOS technology meets the demanding ruggedness, linearity and efficiency requirements for wireless PA applications.*

## INTRODUCTION

Power amplifiers (PAs) are a core component in the high-growth wireless communications industry, rapidly evolving in both architecture and communication protocols [Jos (1)] to satisfy ever-increasing bandwidth requirements. Bipolar transistors are the critical PA building block due to their power handling capabilities at high frequencies. GaAs HBTs have dominated such applications, however bandgap-engineered SiGe heterostructure bipolar transistors (HBTs) are an emerging alternative due to their ability to provide high integration and to reduce cost [Hame et al. (2)]. Further, SiGe has several advantages over GaAs for PA applications: (i) A heat-conductive substrate that drives down the chip area and contributes to chip robustness, and (ii) temperature-insensitive current-gain behavior providing immunity to thermal runaway.

The challenge faced by SiGe-based PA technologies is providing sufficient high-voltage immunity without compromising PA performance. PA devices must withstand high voltage excursions and large current densities to survive in wireless environments. Circuit design solutions to this problem add cost and degrade performance. Thus, for SiGe to be a compelling alternative for wireless PAs, SiGe HBT ruggedness needs to be enhanced without degrading RF performance. In this paper, we demonstrate for the first time a fully manufacturable 0.5  $\mu\text{m}$  SiGe BiCMOS technology where a very non-uniform collector design has provided a significant improvement in HBT ruggedness while maintaining a performance suitable for PA development across several different wireless standards.

## 0.5mm SIGE BICMOS PA TECHNOLOGY

The 0.5 $\mu\text{m}$  3.3V BiCMOS technology contains two SiGe HBTs, a high-performance (HP) HBT with  $f_T/f_{\text{max}}$  of 50/90GHz and a high-breakdown (HB) HBT with  $f_T/f_{\text{max}}$  of 25/80GHz. Several kinds of resistors complement a high-Q varactor, a Schottky barrier diode, and silicon and metal-to-metal capacitors.

For circuit applications requiring both ruggedness and performance, the HB SiGe HBT has been designed to achieve a  $BV_{CBO}$  greater than 20V and minimum  $BV_{CEO}$  of 6.5V. This technology follows a "base-equals-gate" integration scheme [Hame et al. (3)], with a buried subcollector and deep and shallow trench isolation. AC performance degradation resulting from the device modifications to increase breakdown voltage was avoided by the addition of a precisely placed collector implant. This implant acts to suppress the Kirk effect without contributing significantly to the carrier heating that leads to device breakdown. Figure 1 shows the experimentally observed performance/ruggedness trade-off provided by this collector implant approach. Under optimal implant conditions,  $f_T$  for the HB device peaks at a collector current density of 0.4mA/ $\mu\text{m}^2$ , enabling significant device scaling. As an open base situation will rarely be witnessed in wireless PA applications [Jos (1)], the  $BV_{CER}$  measurements shown in Figure 3 are expected to reflect the critical ruggedness characteristics of the HB HBT.

Figure 2 compares the characteristics of this technology's HB HBT to those of other published devices [Jos (1), Deixler et al. (4), Schuegraf et al. (5)]. The ruggedness/speed characteristics of this

device are seen to depart favorably from industry trends for both SiGe and Si transistors and approach those of GaAs. Figure 4 plots the  $f_T/f_{\max}$  vs  $I_c$  characteristics for the HB transistor, indicating the large RF-performance range spanned by this technology.

### HBT SAFE OPERATING AREA

Apart from straightforward junction breakdown, other phenomena play a role in limiting the safe operating area (SOA) of a HBT as a PA, such as second breakdown, HBT self-heating and electro-migration. We have explored comprehensively the SOA of the HB NPN device by recording the emitter current as a function of base-emitter forward bias for different values of  $V_{CB}$  and looking for avalanche conditions. We define SOA limits for the device by the  $V_{CB}$  and  $J_E$  at which avalanche commences. The condition at which  $J_E$  becomes independent of  $V_{be}$ , denoted in Figure 5 as ' $J_E$  at breakover', is the operating limit of the device due to HBT runaway. Device operation up to these limits is non-destructive and completely reversible. As shown in Figure 5, the preferred operating point at peak  $f_T$  for the HBT falls well within the device SOA limits, and so PA applications will not be limited by SOA constraints.

### CIRCUIT DESIGN AND PERFORMANCE

The current PA design approaches are targeting the GSM and GPRS standards both using the Gaussian Minimum Shift Key (GMSK) modulation scheme and the WCDMA standard using Hybrid Phase Shift Keying (HPSK) modulation. For GMSK standards the signal envelope is constant and as a consequence linearity of the PA is not an issue.

The GMSK PA is serving the two GSM bands at 900MHz and at 1800MHz together with the American 1900GHz PCS GSM band. The main figures of merits are output power, efficiency and robustness. The output power requirements for GSM and GPRS are 33dBm from the antenna. In order to provide sufficient margin for losses in antenna near components the output from the PA should exceed 34.5dBm. Such high output power imposes severe demands on both the voltage immunity of the output device and the thermal stability of the entire design. For the GPRS standard, multiple time slot operation further increases the requirement on the thermal performance and robustness of the power amplifier. The current PA design has been demonstrated to operate at a 4-time slot time division scheme without performance degradation.

The circuit topology chosen is a single ended two - or three-stage solution with built in biasing circuitry and power control. Inter-stage matching is performed both

on- and off-chip. The off-chip components are either designed directly into a Low Temperature Cured Ceramic (LTCC) substrate or mounted on top of the substrate surface. The die is mounted by means of C4 flip-chip technology onto the substrate surface, thereby providing extremely low parasitic inductance, good thermal conductivity together with a small footprint. No external components outside of the module are needed for matching or decoupling. The output power and efficiency characteristics of the PA for 900MHz are shown in Figure 6. Note the high power added efficiency (PAE) at higher output levels. The slope of the power curve as a function of control voltage, as can be seen in Figure 6, determines the controllability of the PA. The slope is close to constant thus providing a transfer function making the power control easier to implement. The constant current gain as a function of temperature together with the high current density of the PA SiGe HBT technology makes it possible to make use of smaller output devices thereby minimizing parasitic effects. The low parasitics increase the inherent gain of the devices, which together with an efficient biasing scheme can be utilized for achieving high efficiency.

Concerns have been raised on using Si technologies in PA applications for wireless standards requiring high outputs at high efficiency and the changing load characteristic of the GSM/GPRS standards. The high breakdown voltage of the SiGe PA technology,  $BV_{CBO} > 20V$ , constant current gain as a function of temperature and a Si substrate thermal conductivity significantly exceeding that of GaAs, makes this technology extremely well suited for applications requiring both ruggedness and high output power, such as the multiple-slot-operation GPRS standard. A fully functional test was performed into a load presenting a VSWR ratio of 50:1 at the SiGe PA output through all phase angles at a 5V supply voltage. The DC current was kept at a level that would give 35dBm output power in a 50Ω load at 5V supply voltage.

The HPSK modulation scheme together with the filtering used in WCDMA standard puts specific requirements on the PA performance. The varying signal envelope makes the linearity of the transceiver chain and the PA essential. The linearity requirement is formulated as Adjacent Channel Leakage Ratio (ACLR1) describing how much power is leaking into the next channel as a result of non-linearities in the transmitter chain. The power leaking into the next nearer channel is termed ACLR2. The 3GPP standard (25.100.v5.3.0 June 2002) requires the linearity to be  $ACLR1 < -33dBc$  and  $ACLR2 < -43dBc$ .

The circuit topology is a two-stage solution with built in biasing circuitry and linearization. Inter-stage matching is performed on chip. The off-chip components are either designed directly into a Low Temperature Cured Ceramic (LTCC) substrate or

mounted on top of the substrate surface. The die is mounted by means of C4 flip-chip technology onto the substrate surface, providing extremely low parasitic inductance and good thermal conductivity together with a small footprint. No external components outside of the module are needed for matching or decoupling. Simulated output power and PAE characteristics of the PA at 1.95GHz are shown in Figure 7. Measured WCDMA output power and linearity data from an early prototype module are shown in Figure 8. Note that the ACPR characteristics are exceeding the WCDMA requirement all the way up to the 1 dB compression point.

The SiGe PA technology demonstrates high Early voltages even at lower collector-emitter voltages and pushes the onset of avalanche breakdown towards the higher voltage regime, thus increasing the linear region of operation for the output transistor. Increasing the linear range of operation can be explored for the WCDMA PA application.

## CONCLUSIONS

A PA design has been demonstrated for GSM, GPRS and WCDMA wireless standards using a SiGe HBT technology specifically tailored to meet the divergent requirements of high VSWR robustness at high output power and high linearity. The GMSK PA shown here exceeds the 10:1 VSWR requirement at 35dBm with a maximum efficiency=57%. For the WCDMA PA, an ACLR1 < -33dBc and ACLR2 < -43dBc is achieved up to and even beyond the 1 dB compression point. The SiGe HBT was optimized to simultaneously provide ruggedness and speed and is compatible with the base 0.5µm CMOS. The favorable thermal properties, lower cost of wafer processing and the higher integration capabilities demonstrated by these SiGe PAs make them a compelling choice for wireless applications.

## REFERENCES

- (1) R. Jos, *Technology Developments Driving an Evolution of Cellular Phone Power Amplifiers to Integrated RF Front-End Modules*, IEEE J. Solid-State Cir., Vol. 36 pp. 1382-1389, September 2001.
- (2) D.L. Harame, D.C. Ahlgren, D.D. Coolbaugh, J.S. Dunn, G.G. Freeman, J.D. Gillis, R.A. Groves, G.N. Henderson, R.A. Johnson, A.J. Joseph, S. Subbanna, A.M. Victor, K.M. Watson, C.S. Webster and P.J. Zampardi, *Current Status and Future Trends of SiGe BiCMOS Technology*, IEEE Trans. Elec. Dev., Vol. 48 pp. 2575-2594, November 2001.
- (3) D.L. Harame, J.H. Comfort, J.D. Cressler, E.F. Crabbe, J.Y.-C. Sun, B.S. Meyerson and T. Tice, *Si/SiGe Epitaxial Base Transistors II: Process Integration and Analog Applications*, IEEE Trans. Elec. Dev., Vol. 42 pp. 469-482, March 1995.

- (4) P. Deixler, H. G.A. Huizing, J.J.T.M. Donkers, J.H. Klootwijk, D. Hartskeerl, W.B. De Boer, R.J. Havens, R. Van der Toorn, J.C.J. Paasschens, W.J. Kloosterman, J.G.M. Van Berkum, D. Terpstra and J.W. Slotboom, *Explorations for High Performance SiGe Heterojunction Bipolar Transistor Integration*, Proceedings IEEE Bipolar/BiCMOS Circuits and Technology Meeting 2001, pp. 30-33, 2001.
- (5) K. Schuegraf, M. Racanelli, A. Kalburge, B. Shen, C. Hu, D. Chapek, D. Howard, D. Quon, D. Feiler, D. Dornisch, G. U' Ren, H. Abdul-Ridha, J. Zheng, J. Zhang, and K. Bell, *0.18 µm SiGe BiCMOS Technology for Wireless and 40 Gb/s Communication Products*, Proceedings IEEE Bipolar/BiCMOS Circuits and Technology Meeting 2001, pp. 147-150, 2001.

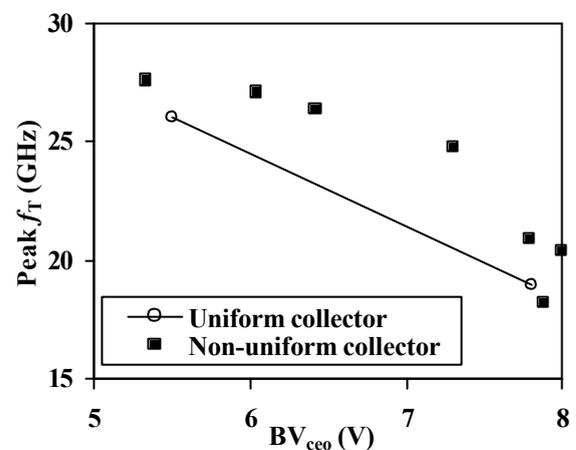


Figure 1. Leverage of non-uniform collector profiles for SiGe HBT  $BV_{ceo}$ - $f_T$  tradeoff, as observed from single transistors.

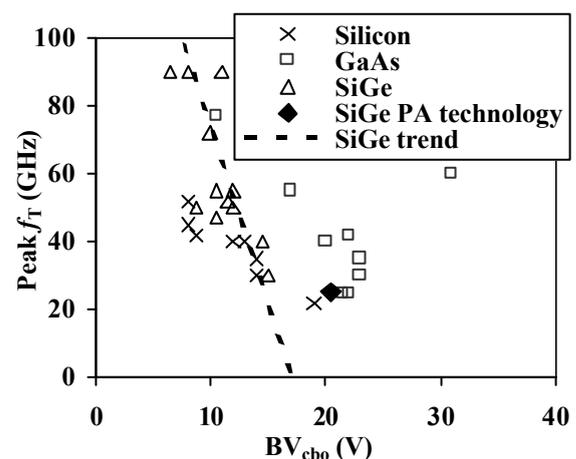


Figure 2. Comparison of published technology  $f_T$ - $BV_{cbo}$  trade-off. Characteristics of SiGe technology discussed in this paper appear to be significantly more favourable than expected from industry trends. Based on data from Jos (1), Deixler et al. (4) and Schuegraf et al. (5), omitting GaAs mesa devices.

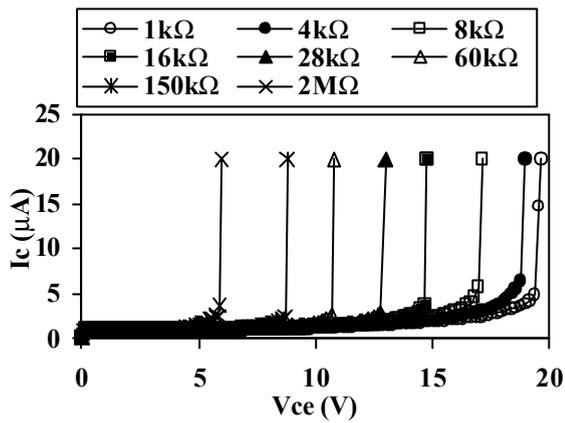


Figure 3. Effect of external base resistance on HB HBT breakdown. These characteristics indicate that actual device ruggedness is significantly greater than suggested by  $Bv_{ceo}$ . Device size is  $2 \times 0.5 \text{mm} \times 20 \text{mm}$ .

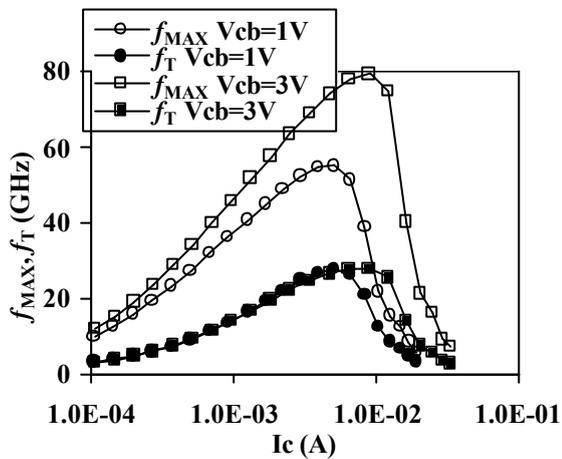


Figure 4.  $f_T$  and  $f_{MAX}$  characteristics of high-breakdown (HB) SiGe HBT. Device size is  $2 \times 0.5 \text{mm} \times 20 \text{mm}$ .  $f_{MAX}$  defined by U extrapolation with  $-20 \text{ dB/dec}$  slope.

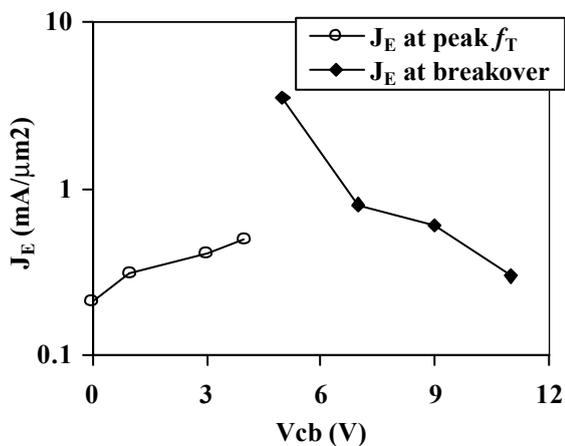


Figure 5. Safe operating area (SOA) measurements for the  $0.5 \text{mm} \times 20 \text{mm}$  HB HBT. ' $J_E$  at breakover' is the device operating-limit due to HBT runaway. The preferred operating point for the device, at or below peak  $f_T$ , is observed to be well within the SOA limit.

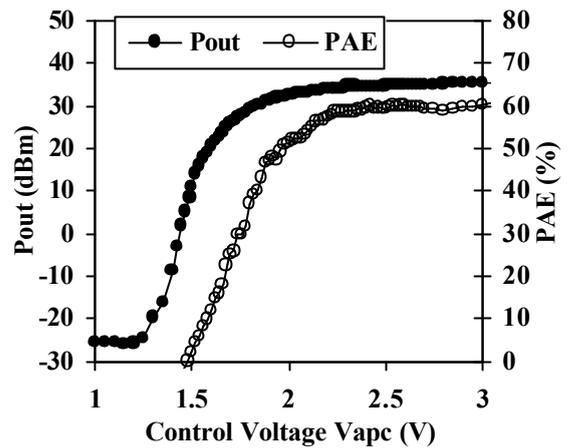


Figure 6. GMSK PA characteristics showing output power and power added efficiency (PAE) at 900MHz and  $P_{in} = 8.5 \text{dBm}$ .

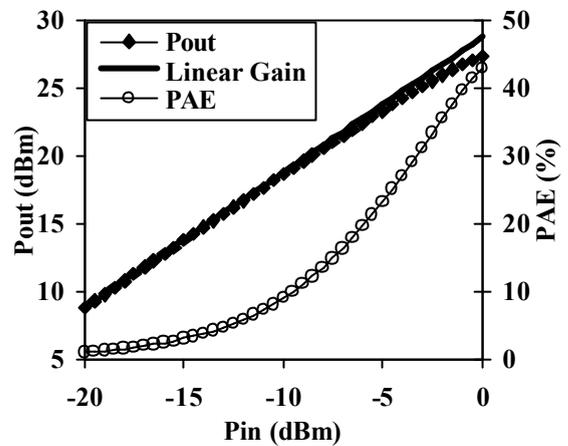


Figure 7. Simulated WCDMA PA characteristic showing output power and power added efficiency (PAE) at 1.95 GHz.

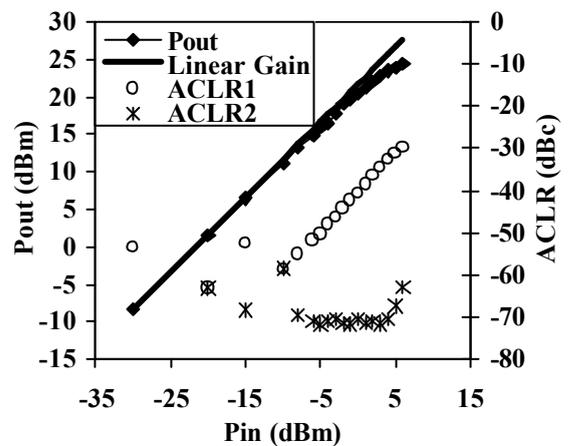


Figure 8. Measured output power and linearity data from WCDMA prototype hardware.  $ACL R1 < -32 \text{dBc}$  and  $ACL R2 < -48 \text{dBc}$  at 1dB compression point.