

Transistor Noise in SiGe HBT RF Technology

Guofu Niu, Zhenrong Jin, John D. Cressler, Rao Rapeta, Alvin J. Joseph, and David Hareme

Abstract—This brief presents experimental and modeling results of device noise in SiGe HBT RF technology. By careful bandgap engineering, a simultaneous reduction of RF noise, $1/f$ noise, and phase noise has been achieved. At a given I_B , transistors with different base bandgap profiles show similar $1/f$ noise. At a given I_C , however, transistors with a higher β (and hence lower RF noise) show lower $1/f$ noise. Circuit analysis and simulation shows that the phase noise is reduced as well.

Index Terms—Bipolar technology, flicker noise, modeling, phase noise, RF circuits, RF noise, SiGe HBT.

I. INTRODUCTION

MOBILE wireless communication links demand very sensitive and highly selective transceiver circuits. Key performance metrics for wireless RF links include: dynamic range, sensitivity, and selectivity. Dynamic range and sensitivity heavily depend on the RF noise and linearity of the transistors used in the low-noise amplifiers (LNAs). Small improvements of noise at the device level can have a large impact on overall system performance. For instance, a degradation of LNA noise figure by even 0.5 dB can be very detrimental to the RF link performance. On the other hand, selectivity depends on the local oscillator (LO) phase noise, which in turn depends on the phase noise capability of the transistors used, and to a large extent is determined by the low-frequency noise (also known as flicker noise or $1/f$ noise). Direct-conversion transceivers also demand transistors with extremely low $1/f$ noise [1].

It was shown earlier that the RF noise in SiGe HBTs can be reduced by careful optimization of SiGe profile [2], [3]. In this work, we examine the impact of such SiGe profile optimization on $1/f$ noise and phase noise capability of these SiGe HBTs. Details of the SiGe HBT technology can be found in [4].

II. RF NOISE

The primary RF noise sources in a bipolar transistor are the base current shot noise $2qI_B$, the collector current shot noise $2qI_C$, and the base resistance-induced thermal noise $4kTr_B$. A higher base doping and a smaller emitter width are thus desired to reduce r_B , which implies the need to move to a more aggressive technology with a lower thermal cycle. The net contribution

Manuscript received December 12, 2000; revised March 20, 2001. This work was supported by IBM under a University Partnership Research Award, the Alabama Microelectronics Science and Technology Center, and the Semiconductor Research Corporation under Contract SRC 2000-HJ-769.

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Publisher Item Identifier S 0018-9200(01)06109-1.

TABLE I
SUMMARY OF DEVICE ELECTRICAL CHARACTERISTICS

Performance	Si BJT	SiGe control	SiGe LN1	SiGe LN2
β at $V_{BE}=0.7V$	67	114	350	261
$V_A(V)$	19	60	58	113
$BV_{CEO}(V)$	3.5	3.2	2.7	2.7
R_{Bi} ($k\Omega/\square$)	12.8	9.8	10.3	10.7
peak f_T (GHz)	38	52	52	57
peak f_{max} (GHz)	57	64	62	67

of the base and collector current shot noise, however, can be reduced by increasing β (to reduce I_B) and increasing f_T (to increase h_{21}), both of which can be realized by SiGe profile optimization at a given technology generation [2], [3]. The resulting bandgap profiles in the base increase the current gain and speed. In particular, $2qI_B$ dominates the effective input noise current at relatively high I_C where RF gain is large. Noise improvement can only be achieved through the increase of β at those relatively high currents. The superior RF noise performance of HBTs lies in their ability to *simultaneously* achieve high β , high f_T , and low r_B .

We consider in the following four types of transistors: a control SiGe HBT, two low-noise SiGe HBTs (LN1 and LN2) with optimized SiGe profiles, and an Si BJT for comparison. Details of the SiGe profile optimization and related simulation issues can be found in [2]–[5]. All of the transistors were fabricated in the same wafer lot under identical processing conditions. Compared to the SiGe control HBT, LN1 and LN2 have a higher Ge content and a larger Ge gradient in the neutral base, but less Ge retrograding into the collector in order to keep the total amount of Ge within the SiGe film thermal stability limit. LN1 and LN2 thus have a much higher β , a slightly higher f_T , and hence lower NF_{min} at the expense of a stronger f_T roll-off at very high currents [2]. The peak Ge mole fraction is 10%, 14%, and 18% in the SiGe control, LN1, and LN2 HBTs, respectively. A summary of device electrical characteristics is given in Table I. The LN1 and LN2 HBTs achieve an impressive NF_{min} of 0.2 dB at 2 mA, 0.2 dB lower than the SiGe control profile [3].

III. LOW-FREQUENCY NOISE AND PHASE NOISE

SiGe HBTs have not only low RF noise, but also low phase noise [6]. It is logical to wonder how the SiGe profile optimization for RF noise improvement affects transistor phase noise capability. To answer this question, we need to examine

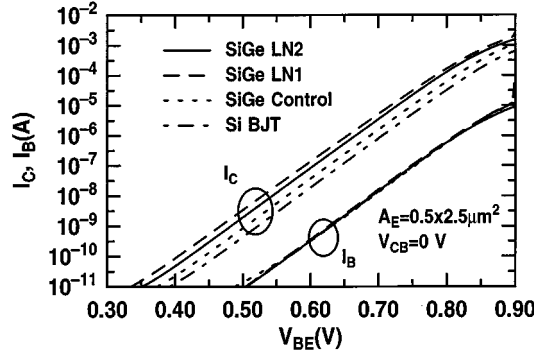


Fig. 1. Measured I_C and I_B versus V_{BE} for the Si BJT, SiGe control, and two low-noise SiGe HBTs.

the impact of bandgap engineering on low-frequency noise and device linearity (distortion), because physically phase noise is upconverted from low-frequency noise through device nonlinearities. In a transistor amplifier, the low-frequency noise is mixed with the RF signal through the physical nonlinearities (e.g., I_C - V_{BE} nonlinearity), which in turn leads to residual amplitude and phase noise at the output. The residual phase noise is translated into oscillator phase noise by the loop effect [7]. The amplitude noise is generally not important for oscillators because of the inherent stabilization. Load-pull measurements showed that the four types of transistors investigated in this work with various base bandgap profiles have nearly identical linearity [2], [3]. We will therefore focus on the impact of bandgap engineering on $1/f$ noise.

It has been established experimentally that only the base current has $1/f$ noise in bipolar transistors. The noise is typically proportional to I_B^α and inversely proportional to the emitter junction area A_e

$$S_{I_B} = \frac{K}{A_e} I_B^\alpha \frac{1}{f} \quad (1)$$

where K is a technology-dependent constant, and α has a typical value of 2 in modern transistors. The physical origin of $1/f$ noise is the mobility or number fluctuation (or both) of the carriers due to defects. Assuming that the $1/f$ noise process is solely determined by the number of minority carriers injected into the emitter, we intuitively expect the same $1/f$ noise at a given V_{BE} (and hence a given I_B) in transistors with different base bandgap profiles. At the same V_{BE} , a SiGe HBT has a higher I_C than its Si BJT counterpart because of a narrower base bandgap. However, a SiGe HBT has the same I_B as a Si BJT at a given V_{BE} , because of the identical emitter structure. I_B is dominated by hole injection into the emitter in modern bipolar transistors. The measured I_C and I_B as a function of V_{BE} of the four profiles are shown in Fig. 1. At a given V_{BE} , the two low-noise SiGe HBTs have higher I_C , and hence higher β , as expected.

To confirm the above speculation, extensive low-frequency noise measurements were made on the four kinds of transistors. From a pure device physics point of view, a comparison at constant V_{BE} (I_B) makes better sense, because it provides information on the rate of mobility or number fluctuation. However, from an RF circuit point of view, a comparison at constant I_C is

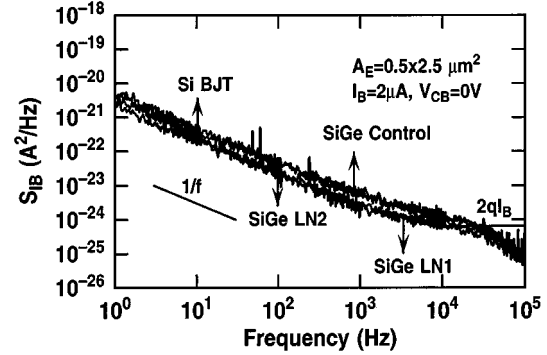


Fig. 2. S_{I_B} spectra for the Si BJT, SiGe control, and two low-noise HBTs measured at constant I_B .

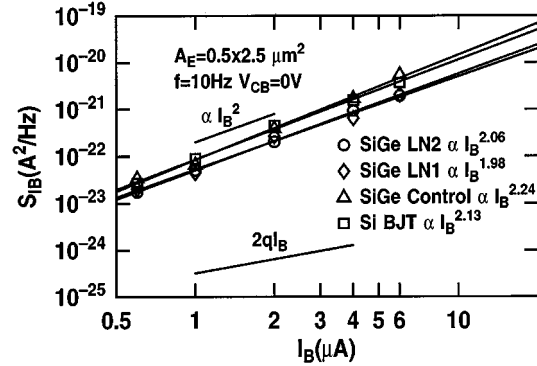


Fig. 3. Measured S_{I_B} at 10 Hz as a function of I_B for the Si BJT, SiGe control, and two low-noise HBTs.

more meaningful, because many RF figures-of-merit fundamentally depend on I_C instead of I_B (e.g., f_T and f_{max}). NF_{min} , though dependent on I_B , is often compared at the same I_C as well. Devices with an emitter area of $0.5 \times 2.5 \mu\text{m}^2$ are used here due to the power supply limitation of the experimental $1/f$ noise measurement setup.

A. Low-Frequency Noise at Constant I_B

Fig. 2 shows the measured base current low-frequency noise spectra (S_{I_B}) at a constant base current of $2 \mu\text{A}$. The noise spectra are all of $1/f$ type, and are nearly identical at this base current for the four kinds of transistors, despite the difference in base bandgap profile. The measured S_{I_B} at 10 Hz are shown as a function of I_B in Fig. 3. With increasing base current, these transistors start to show a larger difference in $1/f$ noise at constant I_B . The two low-noise SiGe HBTs show a slightly lower $1/f$ noise than the SiGe control and the Si BJT at higher I_B . A typical I_B^α dependence is observed, with α ranging from 1.98 in LN1 SiGe HBT to 2.24 in the SiGe control.

B. Low-Frequency Noise at Constant I_C

As discussed earlier, a constant I_C comparison is more meaningful for RF circuit applications. For example, the minimum noise figure is often compared at the same I_C for a Si BJT and a SiGe HBT. At the same I_C (DC power), the SiGe HBTs can be used for lower RF noise, because of the lower base shot noise $2qI_B$. A benefit of reduced $1/f$ noise comes naturally with this I_B reduction when comparison is made at the same collector

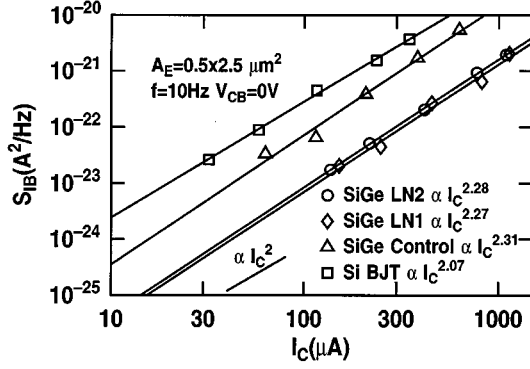


Fig. 4. Measured S_{IB} at 10 Hz as a function of I_C for the Si BJT, SiGe control, and two low-noise HBTs.

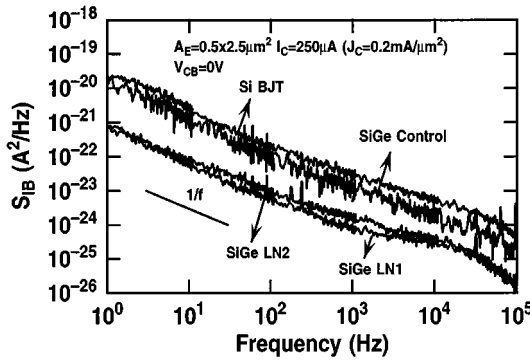


Fig. 5. S_{IB} spectra for the Si BJT, SiGe control, and two low-noise HBTs measured at the same I_C .

current (I_C). The higher β corresponds to a smaller I_B (or V_{BE}) because of fixed I_C , and thus a smaller S_{IB} , as can be seen from Fig. 4.

Fig. 5 shows the measured base current low-frequency noise spectra at a constant I_C of 0.25 mA, which corresponds to a current density where low-noise amplifiers are typically biased (0.2 mA/ μm^2) in this technology. As expected, the $1/f$ noise is much smaller in the two low-noise SiGe HBTs than in the SiGe control HBT and Si control BJT. Consequently, we expect a lower residual phase noise in those two low-noise SiGe HBT's, and hence simultaneous improvement in both RF noise and phase noise using bandgap engineering. This is an important result if verified.

C. Impact on Phase Noise

To verify the above result, the phase noise of a single-transistor amplifier is simulated using HP-ADS. A calibrated VBIC model was used. The model parameters were extracted from the measured dc data, s -parameters, and low-frequency noise data. Higher order effects including self-heating and avalanche multiplication were taken into account in the VBIC model. The source and load were both terminated at 50 Ω . Fig. 6 shows the comparison of the simulated phase noise for a 2-GHz carrier at $I_C = 10$ mA ($A_E = 0.5 \times 20 \times 2 \mu\text{m}^2$). The reduced $1/f$ noise in the LN1 and LN2 HBTs is translated into a reduction of phase noise at the output. The Si BJT has the highest phase noise because of the highest $1/f$ noise at a given I_C . The power gains

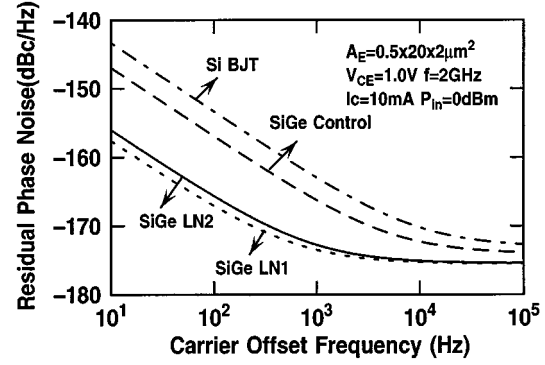


Fig. 6. Simulated phase noise spectra of a single-transistor amplifier for the Si BJT, SiGe control, and two low-noise HBTs at $I_C = 20$ mA. $A_E = 0.5 \times 20 \times 2 \mu\text{m}^2$. The source and load terminations are both 50 Ω . The input power is 0 dBm.

in the HBTs (LN1, LN2, and SiGe control) are nearly identical, and higher than for the Si BJT.

To gain intuitive understanding of the simulated results, let us examine the nonlinear equivalent circuit of a bipolar transistor in Fig. 7. To simplify analysis, we neglect the CB capacitance and avalanche multiplication. An examination of the equivalent circuit including those higher order effects will show that they do not change the conclusion, as confirmed by simulation. At a given I_C , the impact of I_B on the nonlinear circuit is twofold:

- 1) I_B determines the magnitude of $1/f$ noise S_{IB} , which is approximately proportional to I_B^2 . The incoming RF signal is modulated or mixed by the $1/f$ noise through nonlinear circuit elements. As a result, phase noise is generated at the output. The high β HBTs therefore have a natural advantage of smaller $1/f$ noise for upconversion into phase noise.
- 2) I_B determines the nonlinear base current i_1 , which can be approximated by a Taylor series [8]

$$i_1 = \frac{I_B}{V_t} v_{be} + \frac{I_B}{2V_t^2} v_{be}^2 + \frac{I_B}{6V_t^3} v_{be}^3 + \dots \quad (2)$$

where $V_t = kT/q$ is the thermal voltage. At RF frequencies, the conductance through the nonlinear EB capacitance C_{be} (i_2) dominates over i_1 . Thus, i_1 , and hence I_B , has no impact on the upconversion process.

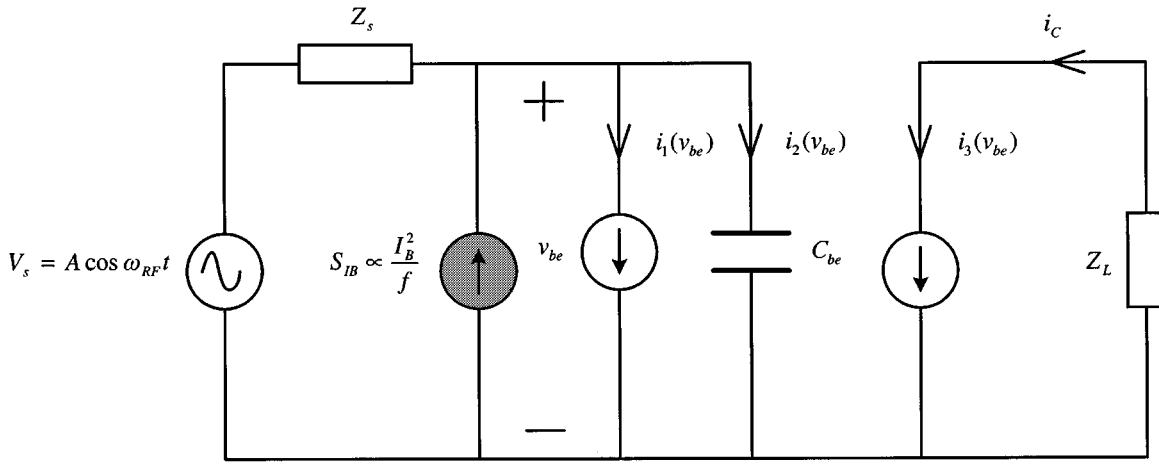
The nonlinear emitter-base capacitive current i_2 is related to v_{be} by

$$i_2 = \frac{d}{dt} \{ C_{be} v_{be} + K_{2C_{be}} v_{be}^2 + K_{3C_{be}} v_{be}^3 + \dots \} \quad (3)$$

where $K_{2C_{be}}$ and $K_{3C_{be}}$ are constants determined by the second- and third-order derivative of C_{be} with respect to v_{be} , respectively [8]. The nonlinear collector current i_3 is given by

$$i_3 = \frac{I_C}{V_t} v_{be} + \frac{I_C}{2V_t^2} v_{be}^2 + \frac{I_C}{6V_t^3} v_{be}^3 + \dots \quad (4)$$

At the same I_C , C_{be} , $K_{2C_{be}}$ and $K_{3C_{be}}$ are approximately the same for the three SiGe HBTs, because of similar transit time. For the same i_2 , v_{be} is the same because of negligible i_1 , resulting in the same upconversion gain (i_3). The β of LN1 and



$$i_1 = \frac{I_B}{V_t} v_{be} + \frac{I_B}{2V_t^2} v_{be}^2 + \frac{I_B}{6V_t^3} v_{be}^3 + \dots$$

$$i_2 = \frac{d}{dt} (C_{be} v_{be} + K_{2C_{be}} v_{be}^2 + K_{3C_{be}} v_{be}^3 + \dots)$$

$$i_3 = \frac{I_C}{V_t} v_{be} + \frac{I_C}{2V_t^2} v_{be}^2 + \frac{I_C}{6V_t^3} v_{be}^3 + \dots$$

Fig. 7. A simplified nonlinear equivalent circuit of a bipolar transistor.

LN2 HBTs, however, are much higher than that of the SiGe control. Consequently, at a given I_C , a higher β reduces the $1/f$ noise, the source for upconversion into phase noise (part of i_2). As a result, the phase noise generated at the output is smaller for LN1 and LN2 HB's because of the same upconversion gain.

The bandgap engineering for RF noise improvement is thus beneficial to the phase noise capability of these HBT's, as confirmed by both simulation and circuit analysis. A simultaneous improvement in RF noise and phase noise has been achieved using bandgap engineering. This, we believe, is an important result, and has significant implications on RF circuits demanding both low RF noise and low phase noise.

IV. CONCLUSION

We have presented experimental and modeling results of device noise in a SiGe HBT RF technology. Bandgap engineering through SiGe profile optimization not only improves the RF noise performance, but also improves the phase noise capability for circuit applications. At a given I_B , transistors with different base bandgap profiles show similar $1/f$ noise. At a given I_C , however, transistors with a higher β (and hence lower RF noise) show smaller $1/f$ noise. This natural reduction of $1/f$ noise reduces phase noise as well, as shown by simulation.

ACKNOWLEDGMENT

The wafers were fabricated at IBM Microelectronics, Essex Junction, VT. The authors would like to thank D. Ahlgren, S. Subbanna, B. Meyerson, and D. Herman for their support of this work.

REFERENCES

- [1] A. Abidi, "Low-power radio frequency IC's for portable communications," in *RF/Microwave Circuit Design for Wireless Communications*, L. Larson, Ed. Norwood, MA: Artech House, 1996, pp. 43–98.
- [2] G. F. Niu, S. Zhang, J. D. Cressler, A. J. Joseph, J. S. Fairbanks, L. E. Larson, C. S. Webster, W. E. Ansley, and D. L. Harnage, "SiGe profile design tradeoffs for RF circuit applications," in *Tech. Dig. IEDM*, 1999, pp. 573–576.
- [3] —, "Noise modeling and SiGe profile design tradeoffs for RF applications," *IEEE Trans. Electron Devices*, vol. 47, pp. 2037–2044, 2000.
- [4] S. Subbanna *et al.*, "Integration and design issues in combining very-high-speed silicon-germanium bipolar transistors and ULSI CMOS for system-on-a-chip applications," in *Tech. Dig. IEDM*, 1999, pp. 845–848.
- [5] G. F. Niu, W. E. Ansley, S. Zhang, J. D. Cressler, C. S. Webster, and R. A. Groves, "Noise parameter optimization of UHV/CVD SiGe HBT's for RF and microwave applications," *IEEE Trans. Electron Devices*, vol. 46, pp. 1347–1354, Aug. 1999.
- [6] G. Niu, J. D. Cressler, Z. Jin, S. Zhang, J. B. Juraver, M. Borgarino, R. Plana, and O. Llopis, "Transistor noise in SiGe HBT RF technology," in *Proc. IEEE BCTM*, 2000, pp. 207–210.
- [7] D. B. Leeson, "A simple model of feedback oscillator noise spectrum," *Proc. IEEE*, vol. 54, pp. 329–330, Feb. 1966.
- [8] P. Wambacq and W. Sansen, *Distortion Analysis of Analog Integrated Circuits*. Norwell, MA: Kluwer, 1998.