Low-Frequency Noise and Phase Noise Behavior of Advanced SiGe HBTs

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Abstract **This paper addresses low frequency noise and residual phase noise in advanced SiGe HBTs featuring different Ge profile shape. Under certain bias conditions, increasing the Ge content decreases the base current fluctuations and hence improves the residual phase noise performance. Additional low frequency noise and phase noise measurements have provided a better insight into the physical location of the 1/f noise sources in these devices.**

I. INTRODUCTION

SiGe HBT technology is receiving much attention because it can deliver a low-cost solution with sufficient performance to support 1-3 GHz mobile phone applications as well as wireless local area networks with frequencies up to 6 GHz. Recent effort has been directed towards extending SiGe technology for emerging higher frequency needs, such as multimedia satellites, radio links, wireless local loop and LMDS. In these applications one critical constraint centers on the short term frequency stability of the microwave source, and is related to the transistor phase noise. A detailed understanding of phase noise is thus critical for the successful deployment of next generation SiGe technology, and will prove critical for the successful design of low phase noise microwave oscillators.

It has been already demonstrated that increasing the Ge content in the base region of the yields an improvement of the frequency characteristics, as well as enabling a shrinking of the device size. The aim of this paper is to assess, using a detailed noise characterization, how the device behaves when the Ge content is increased, both in terms of its low frequency noise sources and the impact of these noise sources on the phase noise performance. The paper is organized as follows: Section II presents a brief overview of the SiGe technology for the devices under discussion. Section III addresses the low frequency noise characterization that has been carried out, and the subsequent noise modeling which was used to better locate the excess noise sources. Section IV focuses on the low phase noise capabilities of the devices, which is investigated through transistor-level residual phase noise measurements. We will demonstrate that appropriate measurements can be very helpful in physically locating the up-converted low frequency noise sources in the device. Finally, the conclusions are outlined in Section V.

II. SiGe TECHNOLOGY DESCRIPTION

The SiGe HBTs investigated are contained in a full SiGe HBT BiCMOS technology currently in commercial production (IBM’s 5HP SiGe technology) [1]. It consists in a graded-base SiGe HBT featuring a non-constant Ge profile shape from the emitter to the collector. More technological details can be found in [2].

The devices feature an emitter width of 0.5 µm and a variable emitter length of 10 µm and 20 µm, with one or two emitter fingers for the 20 µm emitter length. In this work, we measured devices featuring different Ge contents of: 0% (e.g. Si BJT), 10%, 14% and 18%, and which were fabricated in the same wafer lot to facilitate unambiguous comparisons (refer to [3] for details on the Ge profile shape.

The device structure has been optimized with respect to the minimization of the device parasitics, and are self-aligned, with deep and shallow-trench isolation. A schematic cross-section is shown in Figure 1. The SiGe base layers were deposited using a UHV/CVD epitaxial growth system. This SiGe technology is 100% Si-processing compatible.

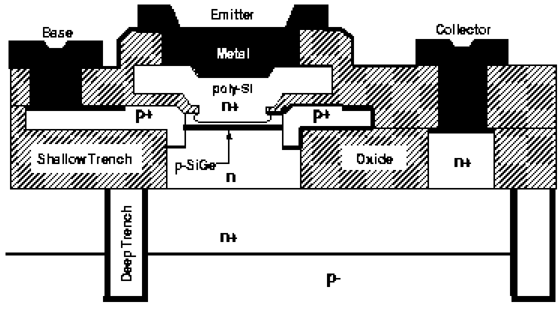

Figure 1: Schematic SiGe HBT cross-section.

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An exhaustive electrical characterization has been performed on these devices and the results are summarized in Table 1. With respect to the current gain, we found that increasing the Ge content leads to an increase of the current gain, as expected [4]. A decrease in the collector-to-emitter breakdown voltage results from this current gain increase with increasing Ge content was also observed, again, as expected. The dynamic device characterization, represented by the peak cutoff frequency, the maximum oscillation frequency, and the minimum noise figure at 2 GHz, shows that increasing the Ge content leads to an improvement of these quantities, as previously reported [3].

peak Ge in the base	None	10%	14%	18%
β (current gain) at V_{BE}=0.7V	67	114	350	261
BV_{CEO} (V)	3.5	3.2	2.7	2.7
peak f_T (GHz)	38	52	52	57
peak f_{max} (GHz)	57	64	62	67
NF_{min} (dB) @ J_C=0.1 mA/μm^2 and f=2 GHz	0.66	0.43	0.21	0.20

Table 1: Summary of electrical characteristics of the devices.

III. LOW FREQUENCY NOISE BEHAVIOR

It is understood that the noise behavior of a bipolar transistor is fully described by two noise generators, together with their correlation. Different characterization techniques can be used to measure the noise. The first one consists of measuring the noise generators (voltage and current) and their correlation referred to the input. This method gives results that can then easily be used to predict the phase noise [5,6]. Nevertheless, it is an indirect method involving a long characterization time and a numerical procedure. In stead, here we use a direct method, including direct measurements of the noise current generators referred to the input, and to the output, together with their correlation [7]. In this approach we therefore directly obtain the base current and collector current fluctuations. In addition, this procedure is very time efficient in gathering the numerous data such as those needed for non-linear low frequency noise characterization. Further, it is possible from these measurements to derive the input noise voltage and current generators, including the correlation [8].

The input noise current generator (referred to as S_{IB}), the output noise current generator (referred to as S_{IC}) and their cross-correlation (referred to as S_{IBIC*}) have been measured on devices featuring different Ge content, different emitter areas, and different bias conditions.

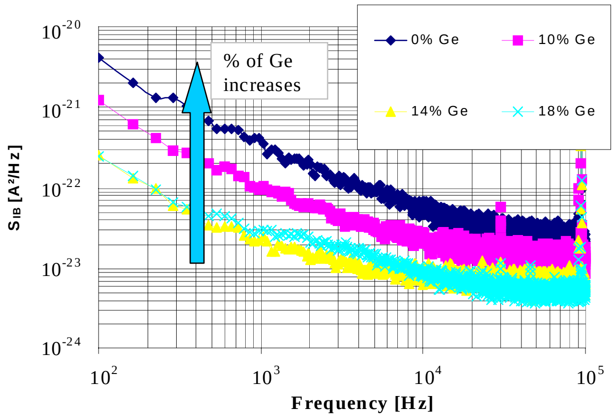

Figure 2: Evolution of S_{IB} versus different Ge content (J_C=2kA/cm^2, V_{CE}=1V, emitter area=20μm²)

Figure 2 shows the frequency evolution of S_{IB} versus different Ge content measured at a constant collector current. The results indicate, for both spectra, a transition from the 1/f region to a white noise region occurring in the 10 kHz range. We further observe that increasing the Ge content leads to a decrease in the S_{IB} generator. This behavior can simply be explained by considering that the current gain of the devices increase with the increasing Ge content (Table 1), meaning that devices featuring higher Ge exhibit a lower DC base current and thus a lower current noise magnitude (the gain difference between 14 and 18% is expected from the details of the profile shape [3]). From measurements of different device area and bias, we confirmed that the input current generator can be expressed as follows:

$$S_{Ib} = 2qI_B + K\frac{I_B^2}{Af} \qquad (1)$$

where A represents the emitter area in μm² and I_B is the DC base bias current. This expression assumes that the recombination rate in the device is very low and not influenced by the Ge content. From equation (1), we obtain a 1/f coefficient K in the 2x10^{-9}μm² range, independent of the Ge content. First, this low value of the K coefficient demonstrates the low 1/f noise magnitude exhibited by these SiGe devices and secondly, we can state that the 1/f noise is not influenced by the Ge content. This is a very important result, since it suggests that we can use SiGe to increase device performance without degrading the 1/f noise magnitude.

Concerning the output noise current generator, the results depicted in Figure 3 indicate that the noise spectra shape are all similar. The 1/f noise corner frequency is in the 1kHz range. Note that at very low frequency the 1/f spectra are disturbed by spurious signals originating from the test set environment, not the device. Once again, S_{IC} is not influenced by the Ge content. The measurements of the noise generator correlation show no differences for the various Ge profiles.

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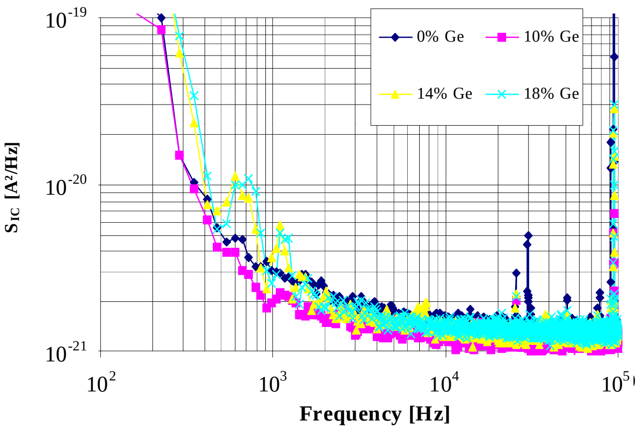

Figure 3: Evolution of S_{IC} versus different Ge content (J_C=1kA/cm^2, V_{CE}=1V, emitter area=10µm²)

From DC and noise measurements, we have developed a low frequency noise model for these devices. Our aim was to try to locate the noise sources with a physical point of view. We used the concept of correlation resistance, which is a very efficient tool to discriminate the noise sources. We found that for these devices, where the recombination rate is very low, only two 1/f noise sources are present at the emitter base and collector-emitter terminals. Moreover, we found for the four different Germanium profiles, the same intrinsic low frequency noise model, with three noise sources as shown in fig. 4:

- one voltage noise source for the access resistances $S_{Rbb'}$ and $S_{Ree'}$,
- one current noise source for the base-emitter junction, S_{Ibe},
- another current noise source across the collector-to-emitter of the device, S_{Ice}.

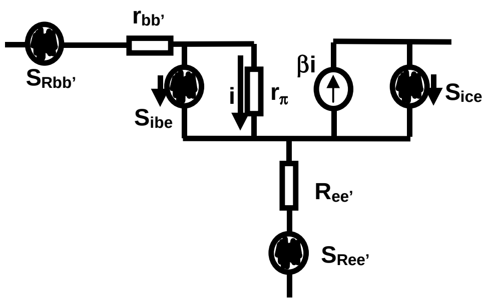

Figure 4: Low frequency noise model used with 0%, 10%, 14% and 18% Ge profiles (J_C=2kA/cm^{-2}, V_{CE}=1V, emitter area=20µm²)

From the evolution of the correlation resistance, we have confirmed that no additional noise source associated to surface recombination has been observed.

IV. RF PHASE NOISE BEHAVIOR

Three different but correlated kinds of noise can be assessed to evaluate the phase noise capability of a device used in a microwave oscillator: the low frequency noise, the residual phase noise near the carrier frequency in an open loop configuration, and the oscillator phase noise near the carrier. When the transistor is used as an amplifier, its low frequency noise sources create fluctuations of the capacitive and resistive nonlinear elements through the device, which in turn leads to residual phase noise. If this amplifier is used in an oscillator loop, the phase fluctuations are directly converted into frequency fluctuations through the loop effect [9].

Low frequency noise does not provide any information on the up-conversion process. The oscillator phase noise measurements give insight into the final circuit, but an oscillator is a complex circuit in which all the parameters are not easy to control. For this reason, the transistor's residual phase noise is the best parameter to characterize the device's performance for these types of applications.

The residual phase noise measurements have been carried out with a 3.5 GHz RF signal featuring 0 dBm magnitude. Note that the device is in an open loop configuration terminated on 50 Ω loads both at the input and at the output. More details on the measurement technique can be found in [10].

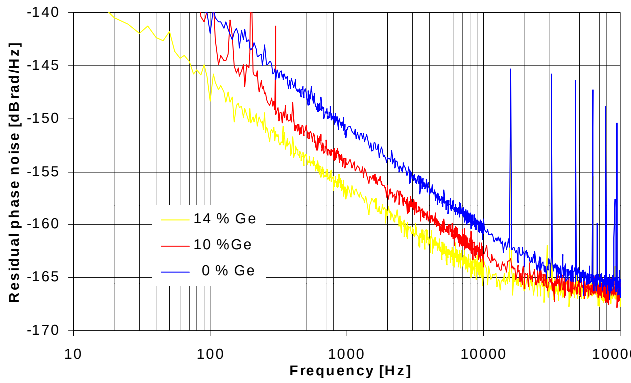

Figure 5: Residual phase noise with three different Ge profiles, 0%, 10% and 14% (J_C=4kA/cm^2, V_{CE}=1V, emitter area=10µm²)

Figure 5 shows the residual phase noise measurements versus the offset frequency for three devices featuring 0%, 10% and 14% Ge content. In the test configuration, high value capacitors are used on the base and collector bias in order to reduce the possible low frequency noise fluctuations of the device's control voltages V_{BE} and V_{CE}, independent of whether these fluctuations came from the device itself or from outside. The measured phase noise is very low, approximately –165 dBrad/Hz at 10 kHz, which is in good agreement with previous published results on high quality SiGe devices [10]. The results indicate that between 0% Ge and 10% Ge and between 10% Ge and 14% Ge, devices exhibits a residual phase noise magnitude approximately 4 dB lower than the lower Ge rate, which confirms the results we presented in the low frequency noise section.

We have also observed that increasing the emitter area produces a residual phase noise reduction which also is consistent with the low frequency noise behavior. Additional measurements are in progress and will be presented in the extended version of the paper.

Finally, the residual phase noise measurement technique has been used to also obtain physical insight into the transistor 1/f noise sources. Residual phase noise measurements have been performed on different low frequency pp terminations through the addition of a decoupling capacitor. Figure 6 shows residual phase noise measurements on a device with a decoupling capacitor both at the input and at the output. Residual phase noise measurements exhibit a 10 dB/decade slope which is consistent with the 1/f noise source behavior.

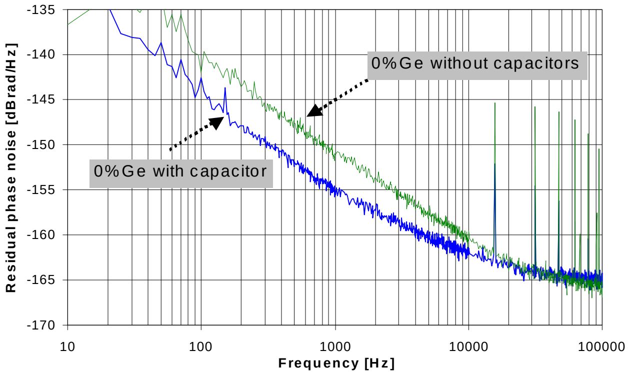

Figure 6: Residual phase noise with and without capacitors at the input and the output of the transistor (0% Ge, J_C=4kA/cm^2, V_{CE}=1V, emitter area=20µm²)

Table 2 shows a comparison of the residual phase noise measured with and without capacitors for three different Ge profiles. The results indicate that adding the capacitor leads to a dramatic improvement of the phase fluctuations, confirming the physical existence of 1/f noise sources at the emitter-base junction and on the collector of the device.

	Residual phase noise @ 1 kHz (dBc/Hz)	Residual phase noise @ 10 kHz (dBc/Hz)
Without capacitors		
0 % Ge	-151	-160.5
10% Ge	-154	-162.7
14% Ge	-157	-164
With capacitors		
0% Ge	-155	-162.3
10% Ge	-157.8	-163.5
14% Ge	-159.5	-165.4

Table 2: Comparison of the residual phase noise measured with and without capacitors at the input and the output of the devices.

V. CONCLUSIONS

The low frequency noise and the residual phase noise of the SiGe HBTs featuring different Ge content have been presented. We demonstrate that the intrinsic noise behavior of these devices is not influenced by the Ge profile and that under appropriate bias conditions both low frequency noise and phase noise can be improved using SiGe. From exhaustive low frequency noise characterization, we have also developed an intrinsic low frequency noise model that can be introduced into a commercial microwave software to predict the phase noise performance of SiGe HBT microwave oscillators. The model topology has been validated through specific residual phase noise measurements.

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