Low Frequency Noise in SiGe Bipolar Transistor: Effect of Extrinsic base Implantation Traps

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ABSTRACT
This paper reports a numerical modeling of a NPN SiGe heterojunction bipolar transistor (HBT) taking into account the impact of electrically active defects in the HBT device. The purpose was to investigate the DC and low frequency noise performances of SiGe HBT taking into account effect of base implantation defects. These defects physically located at emitter-base junction, are responsible for parasitic current fluctuations at the origin of low frequency noise in devices.

The first part of the paper deals with degradation of DC characteristics of the device due to the influence of extrinsic base implantation defects. The aim was to identify the parasitic effects of implantation defects on the HBT static characteristics. Generally, the presence of these defects in the structure, results in a no ideal behavior of the base currents.

The second part of the paper deals with the analysis of low frequency noise (LFN) in the SiGe HBT. Usually, LFN of these devices was related to the existence of defects and imperfections in the semiconductor. The purpose was to examine the impact of implantation defects on the noise in SiGe HBTs. In this fact, the LFN of SiGe HBT was characterized, and a discussion of the possible physical origins of low-frequency noise is presented.

Keywords
SiGe HBT, defect, low frequency noise (LFN).

1. INTRODUCTION
Silicon-germanium (SiGe) BiCMOS technology continues to receive significant interest as a candidate for RF (Radio Frequency) applications. Today, SiGe technology allows improving the performances of bipolar transistors without leaving the silicon environment. The contribution of the SiGe material in the base region of the transistor allows to revise the Silicon energy bands, conferring to bipolar transistor an improvement of its static properties and its dynamic parameters [1,2].

However, these performances reached by the SiGe heterojunction bipolar transistor can be seriously penalized by defects creating during technological process. Presence of these defects in semiconductor layers can induce parasitic fluctuations in the charge carriers usually referred as noise origin in electronic devices. Under 100 KHz this random microscopic behaviors of the charge carriers within electronic devices refer to Low-frequency noise (LFN).

Noise as one of the fundamental properties associated with semiconductor devices, acts an important role, not only for an individual device, but also for the whole circuit. Transistor low-frequency noise is one of the major factors limiting the spectral purity of RF communication system due to its conversion to phase noise.

The main goal of this research is to investigate the physics and characteristics of LFN noise in SiGe HBT. As first we analyze DC characteristics of SiGe HBT, we briefly discuss the effect of implantation defects on static characteristics of the device. Next, we report on the low frequency noise characterization, the study pointe to demonstrate sensitivity of the SiGe HBT noise parameter to these defects. In this fact, we investigate basic characteristics of LFN such as noise variation, the dominant noise source and base current dependence. The physical mechanism of this noise will be systematically discussed in terms of number carrier fluctuation. We will show that trapping detrapping processes give an essential contribution to the 1/f and Generation-Recombination noise formation in these devices.

2. DEVICE STRUCTURE AND TECHNOLOGY
The investigated device is a self-aligned Si/SiGe Heterojunction Bipolar Transistor (HBT), integrated in CMOS technology. This structure has polysilicon emitter with a maximum doping concentration of $1.5\ 10^{20} cm^{-3}$ at the poly/mono Silicon interface. The collector epi-layer thickness is chosen to be 600 nm with doping level peaks around $3 \times 10^{16}\ cm^{-3}$. The active base of the transistor is formed by low energy implantation of bore leading to maximum doping concentration of $2.5 \times 10^{18}\ cm^{-3}$.

The SiGe base layer with 100nm thickness is integrated using selective epitaxial growth. The Germanium concentration is typically graded with a maximum of 20% localized at the middle of the base.

Germanium incorporation in the base of transistor results in a material with a smaller bandgap than pure Silicon. The bandgap of the SiGe alloy is dependent on the fractional concentration of Germanium. In this case, for every 10% of Germanium introduced, the bandgap present a reduction of about 75 (meV) [3]. In addition, a Germanium gradient results in a progressive reduction of the band gap along the base region corresponding to an electric quasi-field in this one. This electric quasi-field accelerate electrons injected into the base, and reduce their transit time [4].

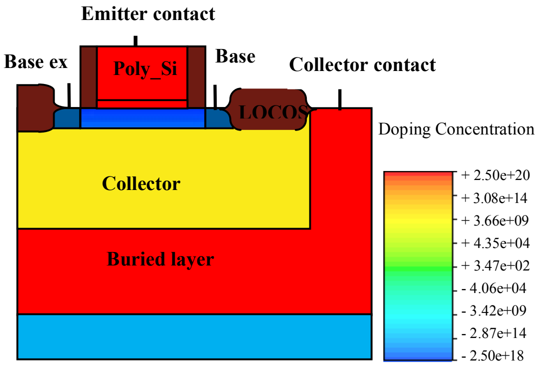

Fig 1: Schematic cross section of the investigated Si/SiGe Heterojunction Bipolar Transistor (HBT) with a polysilicon emitter.

Defects electrically active in the structure are suspected to be created during extrinsic base implantation process. Ion-implantation is currently a very destructive step in the process flow of electronic devices. It causes damage to the lattice, usually repaired by thermal treatment. In bipolar transistor, the extrinsic base of the transistor is defined by an implantation through the emitter window. If alignment base-emitter reduces the spacing weakly doped between intrinsic and extrinsic base, ion implantation processing step generate electrically active defects that accelerate diffusion of common dopants. In this fact, extrinsic base implantation damage was sources of excess interstitials, which enhance the boron diffusivity in the SiGe base layer, and degrade transistor static and high-frequency characteristics [5,6]. Recently, the suppression of boron transient enhanced diffusion (TED) has been demonstrated through the incorporation of substitutional carbon in the SiGe layer [7, 8].

Presence of these defect in structure introduce electronic states in the band gap energy, which present a deep level in the band gap diagram of the device. Deep levels act as carrier traps or recombination centers, they present an effective transition levels for capture and emission of carriers. In addition, deep levels control the lifetime of charge carriers in the device which easily modify electrical characteristics of this one.

The physical characteristics of the implantation defects are deduced by DLTS analysis (Deep Level Transient Spectrometry). It established the presence of two types of implantation defect. The first defect (D1) is a hole trap with a cross capture section $\sigma=10^{21}$ cm^{-2}, an effective density $N_T=10^{16}$ cm^{-3} and an activation energy $E_T=0.12eV$. The second defect (D2) is also a hole trap with a cross capture section $\sigma=10^{18}$ cm^{-2} an effective density $N_T=2.10^{16}cm^{-3}$ and an activation energy $E_T= 0.25eV$ [9].

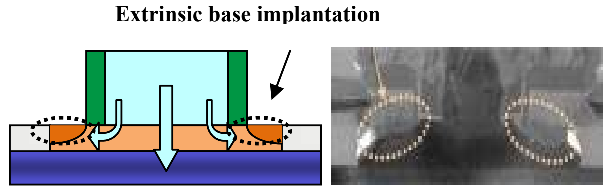

Fig 2: Localisation of extrinsic base implantation defect in the study structure [10].

3. SIMULATION PROCEDURE

3.1 Static Model Simulation

First, we will provide a development of fundamental method to analyze the effect of implantation defect on static electric characteristics of HBT device. The physical simulation of Si/SiGe HBT was performed with a commercial device simulator (SILVACO_TCAD) [11]. The so-called DDM (Drift Diffusion model) implemented in the atlas simulator is used for the transistor analysis in common emitter configuration. This model is based on the resolution of the Poisson and current density equations of a two-dimensional (2D) structure.

All important physical effects, such as bandgap narrowing due to heavy doping, generation-recombination, and mobility dependent for electric-field and doping, are properly modelled and accounted in the simulation. The recombination assisted by deep traps is considered by the simulator through the Shockley-Read-Hall (SRH) model.

The generation recombination ratio is affected as: GR= G_{SHR}.

$$G_{SHR}=\frac{np-n_i^2}{\tau_{pdef}\left(n+n_i\exp\left(\frac{E_T-E_F}{kT}\right)\right)+\tau_{ndef}\left(p+n_i\exp\left(\frac{E_F-E_T}{kT}\right)\right)}$$

(1)

Where ni is the intrinsic carrier concentration, n and p are respectively electron and hole concentrations, E_T is the trap energy level in the semiconductor gap, and E_F is the intrinsic Fermi level.

τ_{ndef}, τ_{pdef} are the carrier life times of electrons and holes, they depend on the electric properties of the defect.

$$\tau_{ndef}=\frac{1}{c_n},\quad \tau_{pdef}=\frac{1}{c_p}$$

(2)

The rates of capture for the two types of carrier's holes (p) and electrons (n) are:

$$c_n=\sigma_n n\langle V_{thn}\rangle,\ c_p=\sigma_p p\langle V_{thp}\rangle$$

(3)

$\sigma_{n,p}$ are the capture cross sections of the deep defect. They translate the surface in which the free carrier must approach the deep to be captured.

3.2 Noise model simulation

Defects in the device can randomly capture and emit carriers, causing a fluctuation in the number of carriers available for current transport. This fluctuation in carrier number present one of the major physical origins of the device noise.

In SiGe HBT, the implantation defects localized at the base emitter interface present one of the main sources of the noise in these devices. The presence of these defects in the device introduces intermediate energy levels in the bandgap, which result in generation–recombination noise through the capture and emission of carriers.

Conventionally, the major low-frequency noise in typical SiGe HBT is denoted by base current spectral density SIb since the base current is amplified by the transistors and constitutes the dominate noise source.

The current-noise spectral density of the spontaneous fluctuations in the base current SIb can consist of several contributions. There is always diffusion noise, l/f noise and occasionally, there is generation-recombination (GR) noise and burst noise, or so-called random telegraph signal (RTS) noise. All these noise sources contribute to the SiGe HBTs LFN spectrum independently.

ATLAS software includes models for three types of microscopic noise source: diffusion noise, generation-recombination noise, and l/f noise, therefore we can express the LFN as:

LFN = Diffusion noise + GR noise + 1/f noise

In the simulations, the noisy transistor is modeled as a noisy four-pole. The noise generated by the device is modeled by taking an ideal (noiseless) device and adding a random current source to each port Figure 3. The noise properties are concentrated in two external partially correlated noise current generators. This method has several advantages; it enables analysis of transistor low frequency noise without making any assumption about possible internal noise sources.

The noise generated by the device was achieved using a small-signal simulation, where AC analysis is automatically performed on the device before the noise simulation. The noise power spectrum was simulated from 1 to 10^5 Hz for each device.

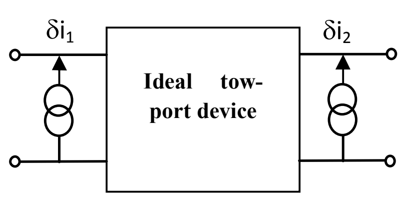

Fig 3: device noise modeled as an ideal device with random current sources attached to the ports.

4. RESULTS AND DISCUSSION

4.1 Statics characteristics

In a first approach, we investigate extrinsic base implantation defects, in order to determine their effect on the DC electrical characteristics of an HBT with an SiGe base. In this fact, we investigate the effect of the implantation defects on the base, and collector current of the considered device. Figure 4 shows Gummel characteristics for tow identically SiGe HBT, one without defects, and the other with base implantation defects positioned at the base/emitter interface. The obtained results reveal that the non-ideal part of the base current due to Generation Recombination was more significant for transistors with base implantation defects. This can be interpreted as an increase in the density of traps induced by implantation defects. The presence of this defects in the device introduces the deep Generation Recombination centers near the interface base/emitter, at which recombination can occur. On the other hand, we note that the collector current does not present any variation with defect presence. The presence of these defects act directly on the current gain of transistor, and induced a notable degradation on this last figure 5.

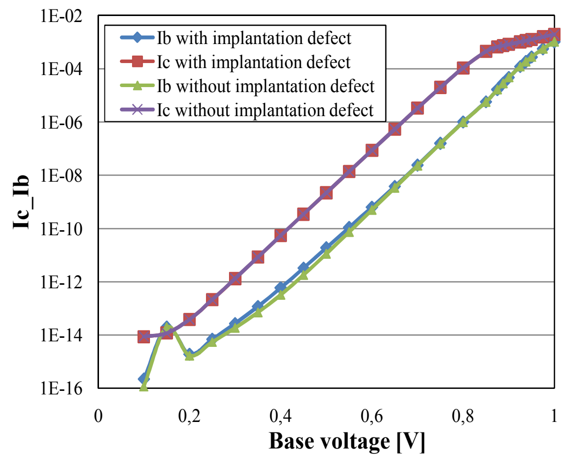

Fig 4: Gummel curves of both SiGe HBT without defect and HBT with extrinsic base implantation defects

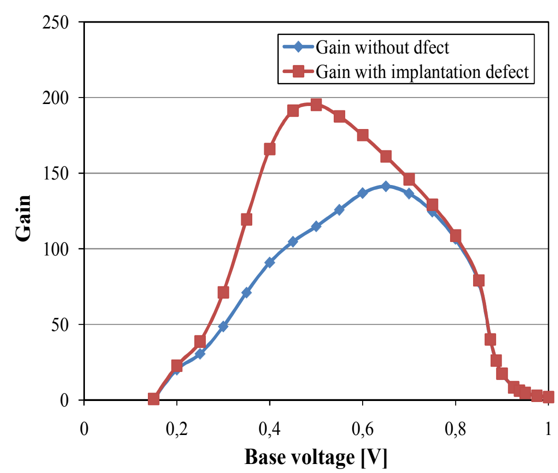

Fig 5: Evolution of the current gain of both SiGe HBT without defect and HBT with extrinsic base implantation defects

4.2 Low frequency noise characteristics

In this part, we investigate the impact of extrinsic base implantation on SiGe HBTs low frequency noise. In this fact, a series of current noise power spectral density (PSD) simulation have been done. The aim was to find how these noise source acts on the LFN performances of the SiGe HBTs in various aspects, such as finding the dominant noise source, and current dependence.

Figure 6 compares the low frequency noise base current spectra for tow identically SiGe HBT: one with base implantation defects positioned at the base emitter junction and the other without defects. The base current spectrum (SIb) was obtained for fixed collector emitter voltage Vce to 1V and current base I_B to10µA.

As expected, the base low frequency noise SIb for study HBT is closely related to traps localized at base emitter junction. As shown the noise level for SiGe HBT with implantation defects augment with a cumulative noise generated by electrically active defects. In this fact we can observe that, these additional noise sources are added to generation recombination and 1\f noises. Indeed, not only the generation recombination noise is sensitive to implantation defects, but also the 1/f noise is sensitive to these defects. This indicate that G–R centers induced by implantation defects responsible of trapping detrapping processes at base emitter interface play an important role in 1/f noise formation.

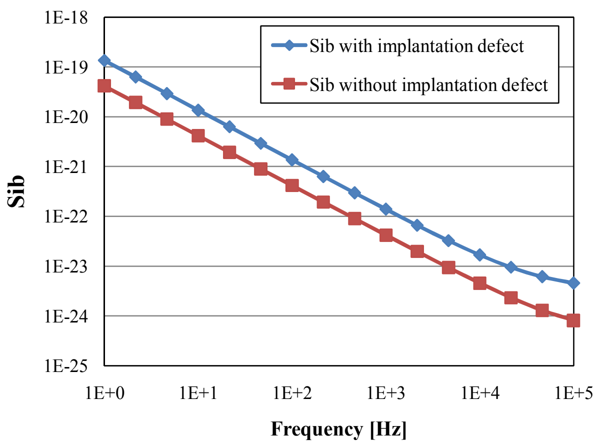

Fig 6: Comparison of the low-frequency noise characteristics of an SiGe HBT without defects and with extrinsic base implantation defects

Figure 7 reports a typical simulated low-frequency base current noise spectrum of an SiGe/Si HBT versus the frequency. The collector–emitter voltage Vce is fixed to 1V and the base current is variable. In this fact, five Ib values have been considered for this simulation: 0.1 µA, 0.5 µA, 1 µA, 5 µA and 10µA.

From figure 7, it has been established that at low frequency, the major noise source is the 1/f base current noise. For more important frequency the device noise is contributed by GR noise sources.

In this fact, we can see that for base current higher than $1e^{-7}$A, the noise spectral density showed a dominant 1/f noise spectrum with a slope of 1 for all over the considered frequency range between 1Hz and 1 kHz.

As the base current decreases, while the collector-emitter voltage is still constant, the contribution of this 1\f noise decrease in comparison to increased generation noise as illustrated in figure 7. The noise starts to change its nature and becomes G–R noise rather than 1/f noise. At high frequencies, we can observe that G–R noise has a flat spectrum, which is the reciprocal of the maximum time scale where the variation of the carrier's fluctuation may occur.

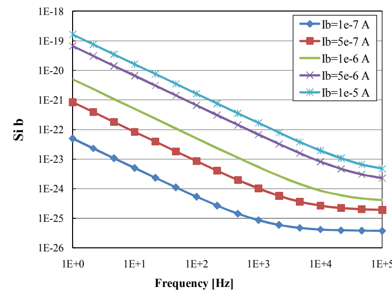

Fig 7: Typical low-frequency noise spectrum of SiGe HBT versus the frequency, for current base varied from Ib=1e-7 to 1e-5A

Usually, in SiGe HBT the base current noise spectral density SIb is proportional to the base current Ib. The low frequency noise dependence on base current Ib is generally an indication of physical processes which govern this phenomena. For this reason, the dependence of the noise on the base current is classically used in order to identify noise sources in the considered devices.

The main noise source in a bipolar transistor is the 1/f noise. Carrier fluctuations originating from the emitter base heterojunction are the dominant source for 1/f noise in SiGe HBTs [12].

The base current noise spectral density (SIb) depends on the base current Ib. This dependence on the base current provides information on the physical origins of the 1/f noise. In some papers, it is assumed that the amplitude of 1/f noise is proportional to the square of the base current (I_b^2) [13], but in a few papers it has been reported that this relation is more complex [14]. In this fact, the origin of 1/f noise is still a controversial dispute; some researchers believe that the fluctuation in the carrier's mobility causes noise [15], while others consider that the presence of defects in the device is the predominant source of this type of noise [16].

In this part, we investigate the SiGe HBT base low-frequency noise versus the base current. The aim was to identify the origin of physical processes which govern the noise in these devices.

Since 1/f noise is dominant at 100 Hz, we study the dependence of the base noise spectra SIb at 100 Hz on the base current. The variation was obtained for SiGe HBT with implantation defect localized at the base emitter junction and polarised at fixed collector emitter voltage Vce to 1V.

From figure 8 we can observe that the 1\f noise spectral density, present two distinct evolutions versus the base current. For low base current, the 1\f base noise has a quadratic dependence with base current Ib (Ib ~2.14). However for higher base current, the noise spectral density

SIb present a linear evolution, where SIb varies with a slope of 1.12 versus the base current Ib.

This variation of the 1/f noise slope confirms that the physical mechanisms responsible of 1/f base noise in SiGe HBT are the result of two sources of different nature. One more associated with fluctuations in carriers mobility at high base current. While, the second is associated with fluctuations in the number of carriers participating in conduction, due to trapping and detrapping phenomena at low polarization.

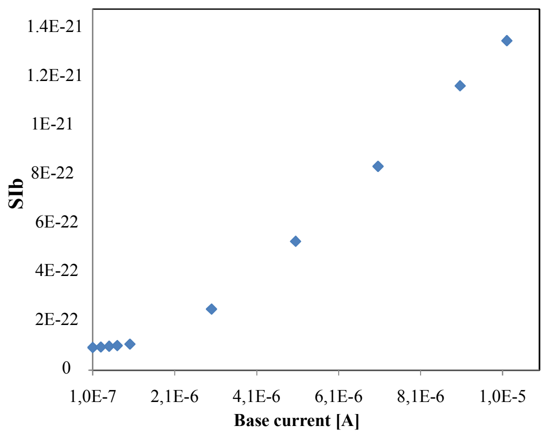

Fig 8: The dependence of LFN SIb on base current Ib for SiGe HBTs at 100Hz frequency

Figure 9 shows base current noise spectrum SIb at 100 KHz as a function of current base Ib obtained for collector emitter voltage Vce equal to 1V.

We can notice that the base current spectral density SIb at 100 KHz frequency has only one linear evolution as a function of the base current. For this range of frequency, where low frequency noise in device is dominated by generation recombination noise, the noise spectrum SIb exhibit approximates a quadratic dependence with base current.

The generation recombination noise in SiGe HBT obeys to a classical quadratic dependence on Ib over the simulated base current range. This dependence corresponds to a noise originating from carrier number fluctuations due to generation-recombination phenomena on traps located at base emitter interface.

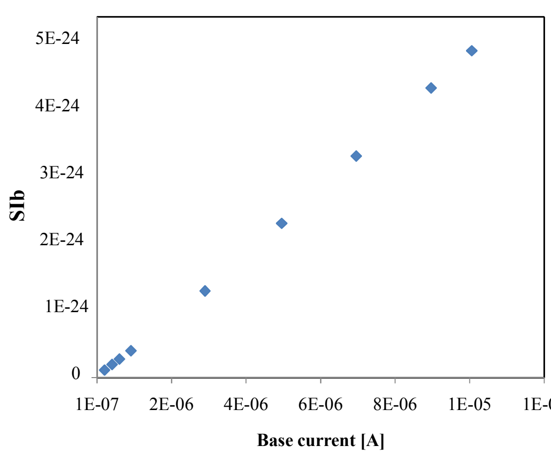

Fig 9: The dependence of LFN SIb on base current Ib for SiGe HBTs at 100KHz Frequency

5. CONCLUSION

In this paper we have investigate the impact of extrinsic base implantation defects on SiGe HBT. It has been observed that the electric performances of the HBT are penalized by the presence of these deep level traps. The simulation predicts a notable increase in the parasitic non-ideal base current, which induce degradation of the current gain of transistor.

The second part of this study pointe demonstrates sensitivity of the device low frequency noise parameter to extrinsic base implantation defects. Implantation defects physically located at the emitter-base junction are found to produce generation recombination noise, but also had a significant contribution on 1/f noise.

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