Numerical Modelling and optimization of SiGeC HBT for 0.13µm BiCMOS technology

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Abstract

SiGeC Heterojuncion Bipolar Transistor (HBT) BiCMOS technology represents a compelling low-cost, highly integrated, silicon-based solution for a wide variety of high-speed and low noise circuit and system applications, and is being aggressively developed around the world to support the global electronics infrastructure needed for the communications revolution. We report in this paper, the impact of carbon into SiGeC (HBT) devices realized in an industrial BiCMOS $Si_{1-x-y}Ge_xC_y$ 0.13 µm process with polysilicon emitter quasi self aligned structure, using our own software simulator (*SImulation BIdimensional by Finite Difference*) "SIBIDIF", taking into account an approach of non uniform heterostructure parameters. In order to the consideration of different geometry in the base layer for Si/SiGeC HBT is fundamental aspect to predict in precise way these electric characteristics.. The purpose of this work is the modelling and optimisation of high performance Si/SiGeC for different geometries of base layer varied between 100nm and30nm.

1. Introduction

In order to meet the demands of the explosive spread of high speed and mass data telecommunications, SiGe:C Herojunction Bipolar Transistors (HBTs) are being investigated. Devices containing SiGe alloys are demonstrating improved performance over their silicon counterparts. In fact, the SiGe heterojunction bipolar transistor based on SiGe epitaxial base is up to now the fastest device available on CMOS, with cut-off frequencies reaching (and more) 200GHz [1].

Although a large amount of Ge in the SiGe base improves the figures of merit of HBTs, the devices suffer from a lot of problems. First, in SiGe/Si devices the exodiffusion of Boron (B) across the junctions deteriorates devices performances. Next, the large lattice mismatch between Si and Ge in the SiGe base reduces the value of critical thickness affecting the stability of the base film.

We report in this paper, the impact of carbon into SiGeC (HBT) devices realized in an industrial BiCMOS $Si_{1-x-y}Ge_xC_y$ 0.13 µm process, using our own software simulator (*SImulation BIdimensional by Finite Difference*) "SIBIDIF", taking into account an approach of non uniform heterostructure parameters.

"SIBIDIF" [2] is a two dimensional Drift –Diffusion Model (DDM) simulator. It solves the continuity equations for electrons and holes, coupled with the Poisson's equation, based on the concept of the finite difference mesh using a revised Schafetter- Gummel type approach and solved numerically with the Gauss Seidel's method and matrix algebra. Simulation results obtained in this study are efficiently compared with electrical characteristics obtained by measurements via a compact model (HICUM) implemented in the commercial simulator ADS (*Advanced Design System, from AGILENT).*

2. Model for alloyed SiGeC HBT and device structure

We will provide a development of fundamental equations to analyze the electrical behaviour in semiconductors; we base our analysis on a macroscopic description of semiconductors with possible non uniform composition. Various semiconductors differ in their fundamental properties such as band gap, carrier mobility, effective electron and holes masses. In addition, interfaces between different materials must be properly described.

First, we briefly discuss the equations and physical model involved in the simulation of SiGeC HBT's devices as implemented in our program. To model alloyed SiGeC hetrostructure we revise the standard Drift Diffusion Equations. Poisson equation [3] must account for the fact that dielectric permittivity is a function of position. In the continuity equations the Shockley -Read- Hall generation and recombination terms must account for position-dependent intrinsic carrier concentration. Probably the most important revision to the standard semiconductor equations arises in current density equations.

a) Poisson equation:

$$\nabla^2\phi = \frac{-q}{\varepsilon_{S/C}}\ [\,p - n + N_D^+ - N_A^-\,] \qquad (1)$$

b) Continuity equations for electrons and holes:

$$\frac{\partial n}{\partial t} = GR_n + \frac{1}{q}\frac{dJ_n}{dx} \qquad (2)$$

$$\frac{\partial P}{\partial t} = GR_p - \frac{1}{q}\frac{dJ_p}{dx} \qquad (3)$$

c) Current equations for electrons and holes:

$$J_n = -qn\mu_n \frac{d\phi_n}{dx} \qquad (4)$$

$$J_p = -q\,p\mu_p \frac{d\phi_p}{dx} \quad (5)$$

In Poisson equation, N^+_D and N^-_A are the ionized impurity concentration; ε is the permittivity of the material and q is the magnitude of the charge associated with an electron or hole. The electron and hole current densities are functions of concentrations, carrier mobility μ_n and μ_p, and quasi Fermi potential for electron and holes, Φ_n and Φ_p respectively.

The equations and physical models involved in the simulation $Si_{1-x}Ge_x$ Cy HBTs are implemented in our program. "SIBIDIF"; a dimensional 2-D simulator dedicated to silicon germanium bipolar device optimization, in finite difference. First of all, the simulator SIBIDIF solves this Partial Differential Equations (PDE) for electrostatic potential Φ, and for electrons and holes concentration n and p, respectively.

For numerical implantation, (1) - (5) are discretized in 2D by finite difference mesh; the variables with are the potential Φ, the electron and hole concentration n and p; they can then be solved numerically using a Scharfetter – Gummel scheme and the Gauss Seidel method. E_{FN} and E_{FP} are the quasi –Fermi energies.

$$\phi_n = -\frac{1}{q}E_{FN},\ \phi_p = -\frac{1}{q}E_{FP} \quad (6)$$

$$E_{FN} = E_c + KT\,ln\left(\frac{n}{N_c}\right) + KT\,ln\,\gamma_n \quad (7)$$

$$E_{FP} = E_V - KT\,ln\left(\frac{p}{N_v}\right) + KT\,ln\,\gamma_p \quad (8)$$

E_C and E_V are the conduction and valence band energies , n and p are the electron and hole concentration, Nc and Nv are the effective density of states in conduction and valence bands; γ_n γ_p are parameters specified to the statistic of Fermi –Dirac.

$$E_C = -q\phi + \frac{E_g}{2} \quad (9)$$

$$E_V = -q\phi - \frac{E_g}{2} + \Delta E_v \quad (10)$$

ΔE_V is the valence band discontinuity; it is not well known how this band gap widening is allocated in SiGeC materials but it is known that bandgap narrowing distribution mainly occurs in valence band in SiGe materials and in conduction bandgap when talking about SiC. It is still discussed how bandgap narrowing is allocated in SiGeC [4] band, but some results suggest that the total bandgap reduction for SiGeC materials mainly occurs in valence band as in SiGe as well. So we keep this hypothesis. Our simulations were done assuming that band gap widening due carbon is completely allocated in valence band equal to the bandgap reduction (band gap narrowing)$\Delta Eg \cong \Delta Ev$.

So in order to simulate carbon introduction in SiGe base layer we have changed the default SiGe parameters related to bad gap (Eg) and carrier lifetime (τ_n and τ_p). Material parameters needed for SiGeC simulation were taken from periodical literature. In the $Si/Si_{1-x-y}Ge_xC_y/Si$ n-p-n HBT's the addition of carbon causes a shift in bandgap of +26meV. C% for germanium fractions x=0.2 and x=0.25 [5]. It has been reported that introduction of carbon in silicon alters minority carrier lifetime considerably; It is [6].

This study has been carried out on the process used for the development of very high speed SiGeC HBT. The investigated device has a polysilicon emitter quasi self aligned structure, similar to the SiGe HBT investigated in ST-BiCMOS9 0.13µm technology figure1 [7].

Advanced epitaxial growth techniques have permitted to introduce heavily doped Si or SiGeC bases suitable for future silicon bipolar technology. The investigated transistor structure is sketched in Fig. 1 it is characterized by having an emitter region bounded the field oxide (LOCOS) along one direction (walled emitter) and by sidewall oxide spacer along the other. The devices were fabricated by inserting a Si or $Si_{1-X}Ge_X$ epitaxial deposition module into an existing CMOS (Complementary metal oxide semiconductor) derived single – polysilicon bipolar process [8].

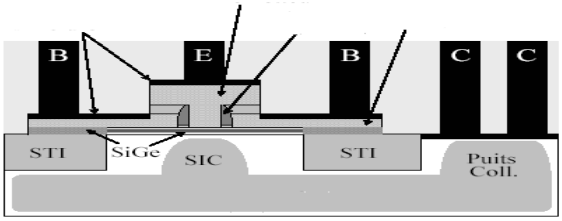

Fig.1. Schematic cross section of the investigated SiGeC Heterojunction Bipolar Transistor integrated in BiCMOS 0.13µm technology with a single polysilicon emitter quasi self-Aligned architecture [7].

3. Electrical Results

As we said, the numerical method used for the resolution of the equation system is the Gauss Seidel's one; criteria of the convergence have been fixed around 10^{-9}, 10^{-10}. In the first step, we have simulated the Gummel characteristics of the SiGeC base transistor, compared with the equivalent conventional SiGe (same geometry, same doping profiles). The aim is to analyze the impact of the carbon concentration on electrical characteristics of the device.

We have studied the effect of a small amount (0.5%, 0.75%, and 1%) of carbon in the HBT SiGe device. Fig.2 shows Gummel plot characteristics. The important DC consequence of adding the carbon into the base layer is a base current increasing and a collector current decreasing, consistently with the concentration of carbon. This increase in base current is due mainly to the reduction of the minority carrier lifetime in the base, due to this incorporation of the small amount of carbon in the SiGeC alloys and to the possible presence of deep traps at the base emitter junction. Decrease of (Ic) can be explained by the bandgap widening and above all increase of the boron dose in the neutral base region due to the reduction of the boron diffusion. An enhancement of I_B and reduction of I_C, induced a lowering in (β) current gain for different carbon concentration.

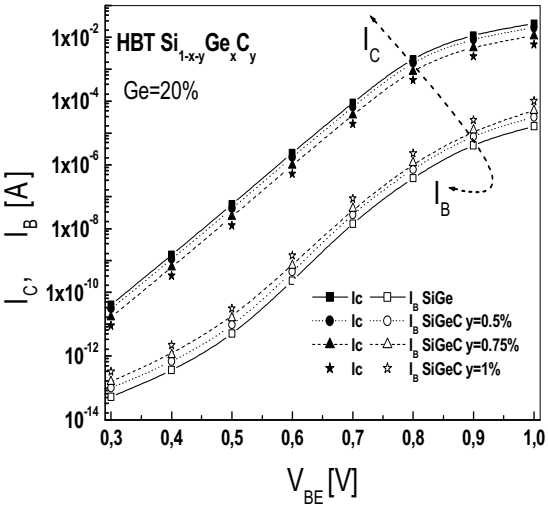

Fig. 2. Gummel plots current/voltage for HBT SiGeC (I_C and I_B) as a function of carbon concentration (0.5%, 0.75%, 1%) and without carbon simulated by Sibitif.

The figure 3 illustrates the evolution of the current gain versus the small concentration of carbon in the $Si_{1-x-y}Ge_xC_y$ (lower to 1%) and HBT SiGe without carbon. More, the carbon increase into the device, more the current gain decrease.

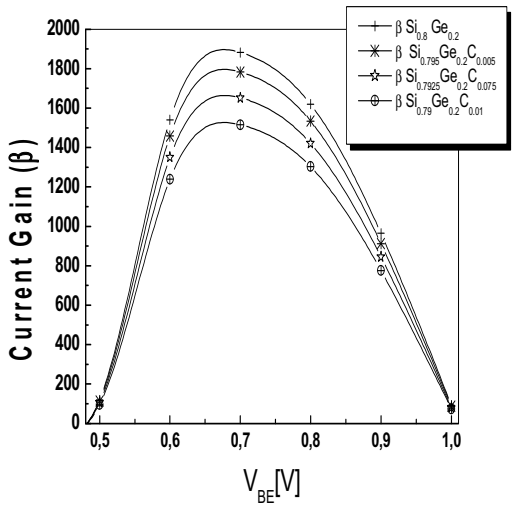

Fig. 3. Current gain (β) for HBT SiGeC as a function of carbon concentration (0.5%, 0.75%, 1%) and without Carbon simulated by Sibidif.

In the figure 4 we compare the results of simulation sibidif and those found in the literature [9] for the same component, with area of emitter 0.18x2.8 and the concentration of germanium 25% and 1% carbon.

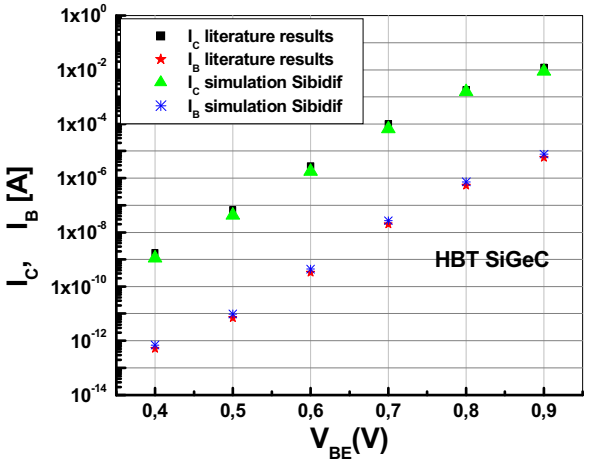

Fig. 4. Gummel characteristics for HBT SiGeC (I_C and I_B) simulated by sibidif and compared with the literatures results using commercial numerical simulator ATLAS [9].

The aptitude of our SIBIDIF simulator is verified. The results obtained in this study are efficiently compared with electrical characteristics obtained by measurements and SPICE-like parameter extractions from simulations via a compact model (HICUM) implemented in the so-called commercial simulator ADS (*Advanced Design System).* We report respectively on the figure 5 and figure 6 the Gummel plots and current gain (β).We represents DC characteristics for a SiGeC HBT simulated by SIBIDIF simulator and the commercial simulator ADS (0.17x6.2 μm^2) compared to the measurements on the transistors; from different emitter areas: (0.17x1.9 μm^2) and (0.17x19.9 μm^2) ; We distinguee a good agreement between simulations and measures. In addition, it should be noted that the maximum current β_{max} is constant for an emitter area varying form 0.3 μm^2 to 1600 μm^2 [10].

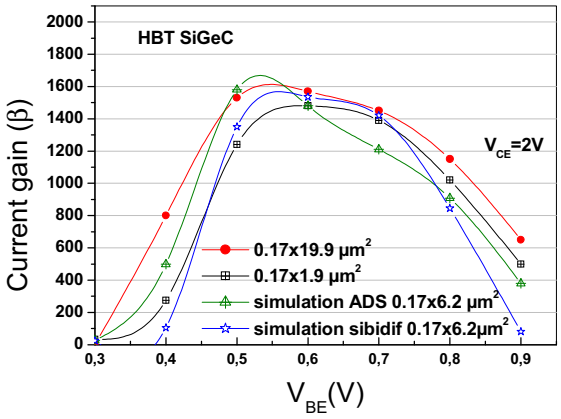

Fig.5. Current gain β- V_{BE} for HBT SiGeC simulate by SIBIDIF compared by commercial simulator ADS and measurements transistors with various emitter areas.

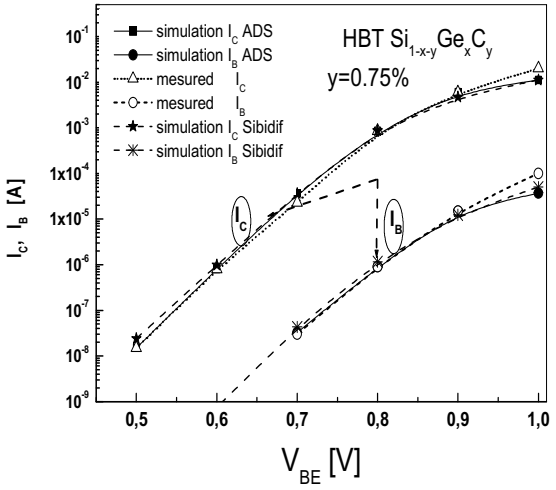

Fig.6. Current gain β- V_{BE} for HBT SiGeC simulate by SIBIDIF compared by commercial simulator ADS and measurements transistors with the emitter surface 0.17 x 6.2µm^2 simulations and 5.9x1.17 µm^2 for measurements.

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The discrepancy at high currents (where these transistors are normally operating, and where the transit frequency has already fallen off) between measures and ADS simulation could be, in part, due to emitter and base Re, Rb resistances. It is hard to extract both these resistances, although in this technology Re is of a few Ohm (Rb especially the intrinsic one is quite fundamental concerning the RF behavior, and is also current crowding dependent) (HICUM uses a current crowding factor

Moreover, the disagreements at high injection can be associated with the limitation of HICUM, despite that the selfheating effect has been taken into account; by using a Kelvin probe equipped with sense and probe tips, the reference plane can be moved from the DC analyzer to the contacted pad, closed to the DUT (device under test).

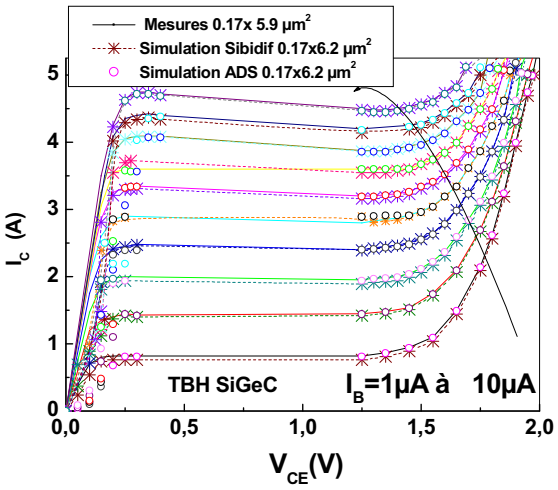

Fig.7. I_{C}-V_{CE} for HBT SiGeC, simulated by SIBIDIF compared to the commercial simulator ADS (0.17x6.2 µm^2) and measurements transistors (0.17x5.9 µm^2).

The figure 7 illustrate the I_C-V_{CE} characteristics for a SiGeC (the concentration of carbon is 0.75%) HBT simulated by SIBIDIF simulator and the simulator ADS (0.17x6.2 µm^2≈1.054 µm^2) compared to the transistor measurements from different emitter areas (eg .0.17x5.9 µm^2≈1.003 µm^2).In addition, we considered the area of the emitter sufficient in the order of 1µm^2.of both simulation and measurements.

We find a good agreement between simulation and measures. Consequently, the models and the physics parameters used in our simulation are reliable for the simulation of a heterojunction bipolar transistor HBT SiGe:C of 200GHz f_T and $f_{max.}$

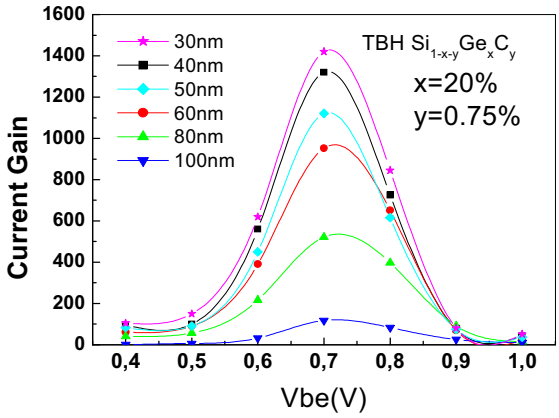

Fig.8. Current gain for HBT SiGeC, simulated by SIBIDIF for different geometries of base layer varied between 100nm and30nm.

The figure 8 show the optimisation of high performance Si/SiGeC HBT for different geometries of base layer varied between 100nm and 30nm. We can observe more, the larger of the base increase, more the current gain increase.

4. Conclusions

We have reported the performances electrical behaviour characteristics of high –speed SiGeC HBTs realized in an industrial 0.13µm BiCMOS. This paper models the SiGeC HBTs comparing DC electrical characteristics, with and without carbon, using our numerical device simulator SIBIDIF. The model focuses on band gap narrowing and carrier lifetime reduction in the base. We observe the increase of base current and decrease of the collector current with the incorporation of carbon small amount (0.5%, 0.75%,1%) in base layer. Current gain seems to decrease continuously with the increase of the carbon concentration. The results obtained in this study are efficiently compared with electrical characteristics obtained by measurements and ADS commercial simulator; we show a good agreement between simulation and measurement. In order to the consideration of different geometry in the base layer for Si/SiGeC HBT is fundamental aspect to predict in precise way these electric characteristics. The use of these components in microwaves applications requires complex structures shrinking. Exposed strong densities of current, accentuates enormously these effects. Consequently, a precise modelling of these phenomena is necessary. In-depth optimization of $Si_{1-x-y}Ge_xC_y$ at cryogenic temperature will be a subject for further study.

Cryogenic performances are indeed interesting for some specific applications.

At present, cryogenic electronics represents an important niche industry, with applications such as high-sensitivity cooled sensors and detectors, semiconductor–superconductor hybrid systems, space electronics, and eventually cryogenically cooled computer systems[11].

5. References

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