An SiGe/Si Heterojunction Phototransistor for Opto-Microwave Applications: Modeling and first Experimental Results

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***Abstract* — A first SiGe bipolar heterojunction phototransistor developed in a commercial available SiGe/Si technology is presented. Emphasis on the development of a complete numerical model for the simulation of strained-SiGe based devices is given. The SiGe HPT exhibits a dc opto-microwave power gain of 3.46dB, i.e. a responsivity with 50Ohms loads of 1.49A/W, and a –3dB bandwidth of 0.4GHz at 940nm. Power budgets are drawn with the use of the opto-microwave power gain's monogram chart.**

I. Introduction

Optical communications give the opportunity to carry high data rates on long distances, but efforts still have to be put on the last miles to distribute data to the home (FTTH) or also simply between two neighbor systems. In these short distances applications, like in 10Gbits/s optical back-planes in spatial and avionics applications, optical wavelength of 1.55µm is no longer an imperative, because low costs benefits can be found in working at lower wavelengths in the range of 0.8-1µm.

This paper deals with a new bipolar heterojunction phototransistor developed in a commercially compatible SiGe/Si process, within which a single strained SiGe layer is used instead of MQW structures as in *[1]*, *[2]*. A special insight in the numerical simulations of the device will be given. The use of high base doping enables to enlarge the structure for convenient vertical optical coupling. Germanium is shown besides to warranty a sufficient detection in the all 0.8-1µm optical wavelength range, as well as improving the dynamic behavior up to operating frequencies of around 20GHz.

The potential of such a structure is first theoretically demonstrated before prototypes were produced. A strained-SiGe layer model is presented. The absorption coefficient of strained-SiGe is worthily developed, taking into account its dependence on the Germanium content, the incident optical wavelength and on temperature. Main ways of applications of such layers are then depicted from the absorption curve.

Then the structure of the SiGe HPT is proposed and prototypes are characterized at a wavelength of 940nm. Results are presented and compared to numerical simulations. Discussion is provided.

II. Physical Modeling of Strained SiGe Layers

Bulk SiGe is studied from the beginning of the 60's, but it was in the middle of the 80's that thin film deposition techniques have allowed the realization of strained SiGe alloy layers deposited on Silicon. Since then, the constraint effect on the electrical properties of the material has been well investigated. Strain is responsible for the enhancement of the material bandgap reduction, but also for energy shifts in the k-space that lead to modification in carrier's mobility, effective densities of states and intrinsic concentration. However, most of the proposed numerical models often only consider the bandgap reduction and neglect the others parameters changes, which nevertheless strongly affect the electrical behavior, especially at high Germanium rates. Also, not any absorption model was presented on single strained SiGe/Si layers before. In order to fulfill this need, physical laws are gathered from the literature and compared in *[3]*. A synthesis is proposed here that is divided in three parts: the bandgap reduction, the valence and conduction bands effective density of states, and last the optical absorption coefficient.

Bandgap reduction

The bandgap of the strained-SiGe material is altered both by the Germanium content, the temperature and the doping. Each effect is shown to be independent on each other. The bandgap dependence on the Germanium content comes from both the strain and the alloy composition effects. In a full strained layer, the bandgap reduction follows the well-known linear law given by People *[4]*:

$$\Delta E_{g,Ge}(meV) = 0.74 \cdot x \qquad (1)$$

The effective bandgap reduction due to doping is also different from the Silicon case. Different models are presented in the literature, but results of *[5]* are shown to be in the best agreement with most of the experimental reports up to date. This model is given in eq. (2) for $N_A \geq 10^{18} cm^{-3}$:

$$\Delta E_{bgn,app}\left(meV\right) = 27.4 \cdot \log_{10}\left(\frac{N_A}{10^{18} cm^{-3}}\right) \qquad (2)$$

Last, temperature also affects the bandgap of the alloy. However, it is shown that this can be neglected on an electrical point of view. The temperature dependence is then only computed for the optical absorption computation purposes.

Effective densities of states

Both alloy-composition and strain strongly affect the energy bands in SiGe layer in either the valence or the conduction band. While the bandgap values change, the states distribution is also affected, giving altered effective

densities of states. A new model dedicated to numerical simulations is developed to take into account the reduction in the effective density of states with Germanium content and temperature. Matutinovic-Krstelj *[5]* proposes a theoretical model that considers how bands are changed from the Silicon case, with $\Delta E_{so,SiGe}$ the split-off energy between the highest and lowest valence band energies of the SiGe case, $\Delta E_{so,Si}$, the split-off of the Si case, ΔE_{hl}, the degeneracy energy distance responsible of heavy and light holes in the top valence band, and last ΔE_{cb}, the conduction band splitting.

Such a full theoretical model can be developed but is shown to be not quite convenient for simple integration into a numerical simulator. A simplified model is then build on the basis of numerical approximation of this first model. An approximation form using a sum of two exponential terms is developed for the $N_c.N_v$ product reduction, while the N_c reduction is simply expressed by a single exponential term. Expression of the N_c reduction is temperature dependent and is given as follows:

$$\frac{N_c)_{SiGe}}{N_c)_{Si}} \approx \frac{2}{3} + \frac{1}{3}\cdot\exp\left(\frac{-0,69\cdot x}{k\cdot T}\right) \qquad (3)$$

On a counterpart, coefficients of the $N_c.N_v$ product reduction are fit parameters that change with temperature. At 300K, it comes.

$$\frac{N_c\cdot N_v)_{SiGe}}{N_c\cdot N_v)_{Si}} \approx 0,306 + 0,319\cdot\exp(-34,1\cdot x) + 0,375\cdot\exp(-8\cdot x) \qquad (4)$$

Results that take into account the temperature dependence of the $N_c.N_v$ product will be presented in a simple analytical form elsewhere.

Optical absorption coefficient

Then, a model of the optical absorption coefficient is used, *[6]*, which is developed on the basis of a one-phonon model applied on measurements published by Lang et al. *[7]*:

$$\alpha_{absorption} = A\cdot\left[\frac{\left(h\nu - E_g - E_{phonon}\right)^2}{1-\exp\left(-E_{phonon}/kT\right)} + \frac{\left(h\nu - E_g + E_{phonon}\right)^2}{\exp\left(E_{phonon}/kT\right)-1}\right] \qquad (5)$$

Fitting the model to data of Lang, it comes:

$$A(x) \approx 3200\cdot\left(1-1.161\cdot x+9.581\cdot x^2\right) \ (cm^{-1}.eV^{-2}) \qquad (6)$$

$$E_{phonon}(x) \approx 0.050\cdot\left(1+0.026\cdot x-1.066\cdot x^2\right) \ (eV) \qquad (7)$$

At the knowledge of the authors not any other measurements, dealing with the wavelength dependence at different Germanium content values, were performed on single strained SiGe layers. Partial results were only found in some case, giving either higher or lower values. Lang et al measurements are then taken as a starting point for furthers investigation and examination. However, until today, the validity of such a model appears to be convenient, as it will be discussed in the later part of the paper.

III. The Single SiGe Layer HPT Structure

The preceding absorption model is used to plot the SiGe absorption coefficient as a function of the Germanium content at different wavelengths, see Fig. 1.

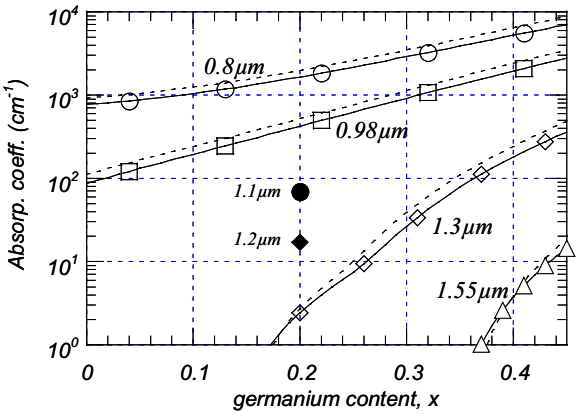

Fig. 1: Optical absorption coefficient at 300K of strained SiGe layers as a function of the Germanium content as derived from [7] measurements. 1.1µm and 1.2µm data are from [8].

A separation in two main applications regions can be derived from this figure: - short range optical communications where the optical wavelength lies between *0.8* and *1µm*; - long range optical communications where wavelength range from *1.3* to *1.55µm*. In the last case, the Germanium content has to be higher than *40%*, which makes the need in multiplying the SiGe/Si stacks due to the quite low SiGe layer's maximum thickness available for stability reasons. This leads to the use of multiple quantum wells structures, MQW, which are not industrially producible for now. In the first case, the Germanium content could be low or medium and afford the possibility to be compatible to industrial requirements. In each of this category, Germanium does not play the same role.

The HPT structure proposed here is based on a purely bipolar technology presented elsewhere *[9]*. The base profile is an abrupt one with Germanium content in the order of 20%. The base doping is significantly increased as compared to a pure Si HBT. This is advantageously taken into account for the enlargement of the lateral size of the HPT. That way the optical coupling to the fibre is eased without lowering the dynamic performance of the phototransistor. The HPT is vertically illuminated through a 10 by 10 micrometer optical window drawn above the emitter. A 5x5µm² HPT is also proposed.

A photograph of the 10x10µm² HPT is shown on Fig. 2 with a sketch of the vertical stack. This structure is opposed to MQW-SiGe HPTs where a multiple quantum well was put in the base-collector region to get detection at 1.3µm, [1], [2]. The SiGe HPT device is however only designed for short-range applications as the detected radiations are in the 0.81µm wavelength range.

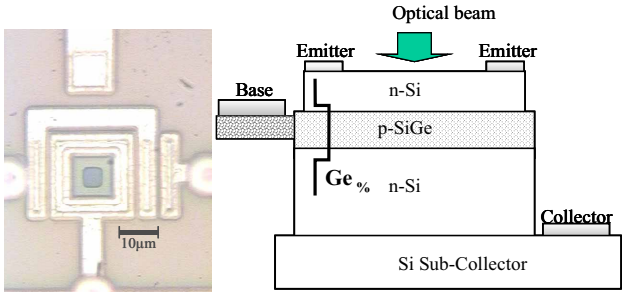

Fig. 2: Left: Photograph of the top view of a SiGe HPT with a 10x10µm² optical window in the emitter; Right: Sketch of the vertical stack.

The technological process is based on an industrial planar process, in which the SiGe layer need to be inserted between two top and bottom Si layers. The optical illumination is then realized through an optical window opening into the emitter contact. Both base-emitter and base-collector region are illuminated, giving then two opposed generated photocurrent. However both photo-generated current are additive in the way they both contribute to increase the photo-generated holes injection into the base, and then gives higher equivalent photo-generated base current. Numerical simulations are used to evaluate the effective contribution of each region.

IV. Measurements and Results

The prototypes are first electrically characterised with the help of the IEF, France. Measured maximum electrical f_T values, without structure optimisation, is *18.9GHz* at *Vce=1.5V* and *20.4GHz* at *Vce=2.5V*. The higher f_T value of the pure HBT is given for comparison at *30GHz* for a 1µm emitter size. Electrical measurements and numerical simulations are compared in Fig. 3, which gives really good agreement for the modelling. Shifts in the electrical f_T with respect to the collector current however exist. These are explained by collector doping differences between the simulated and the real structure.

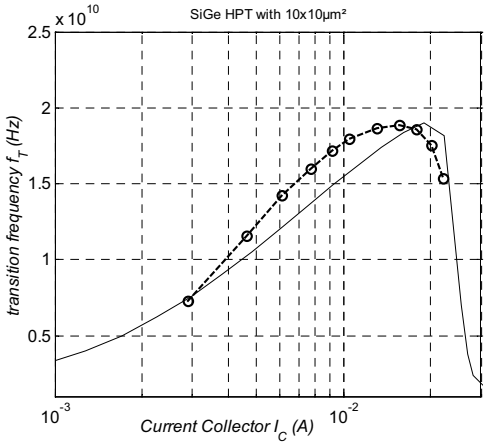

Fig. 3 : Transition frequency of the 10x10µm² SiGe HPT versus the collector current at Vce=1.5V.

The Opto-microwave characterisation are made with the setting up of a new measurement apparatus operating with a two lasers beating technique at 940nm. Extended cavity lasers were used. Measurements on InP/InGaAs HPTs were also driven on this experimental set-up and compared to measurements on others test systems for comparison and validation *[10]*.

The HPT terminals are connected to *50Ohms* loads. Discussion on the importance of the loads on the opto-microwave power gain is provided in *[11]*. The injected optical power is estimated to be *1mW* with the HPT biased at *Vce=1.5V* and *Ib=60µA*.

A reference photodiode is used to control the beating of the lasers, which makes the microwave signal generated on the optical carrier. The difference in *dBm* between the HPT output power and the reference

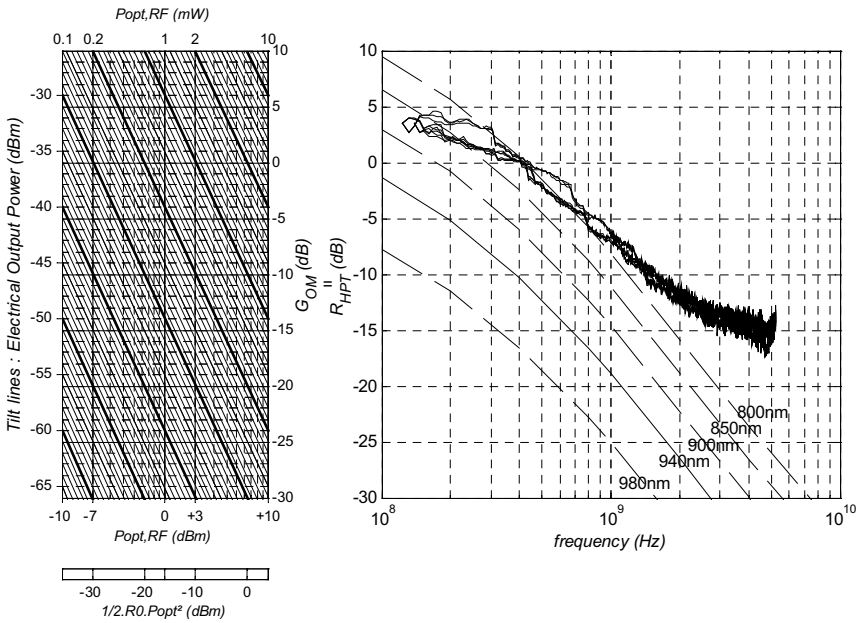

Fig. 4: Measured and simulated opto-microwave power gain with 50Ohms load (i.e. phototransistor mode responsivity) of the HPT at 940nm. The left part of the graphics exhibits an abacus designed for opto-microwave power gain toward Electrical Output Power conversion with the value of the injected $P_{opt,RF}$ power. Simulated curves at others wavelength are also presented.

photodiode output power, gives the opto-microwave power gain, except the calibration terms. The result is shown on Fig. 4 that exhibits the measured opto-microwave power gain of the HPT at 940nm. The opto-microwave power gain is useful for a power analyse of the HPT with respect to its terminal load values. It is also simply related to the HPT responsivity, as their *dB* values are equalled if *50Ohms*-loading conditions are respected.

A *0.4GHz –3dB* opto-electrical bandwidth is then exhibited. A power budget could however be drawn at higher frequencies through the use of the opto-microwave power's monogram chart, described in *[11]* and plotted on the left part of the figure. At 2GHz, if an input optical peak power of *200µW* is considered, an output microwave power of *-45dBm* can be figured out. It decreases to –60dBm at 10GHz.

Also, theory and experiment show discrepancies in the order of 11dB, with theory lower than experiment. This implies a factor of 3 on the photo-generated collector current. This discrepancy is however explained by the difference in the vertical stack of the simulated and the real structure, as it is also observed in the electrical dc current gain value. If the dc discrepancy is yet explained, still are opto-microwave dynamic discrepancies, while electrical ones are corresponding. Ongoing studies make in evidence the importance of the position of the optical spot, which is 5µm in diameter, while the HPT optical window is larger as it is 10x10µm² in size. It is then shown that illuminating the device far from the base contact, both enhance the responsitivity and the optical f_T, and so, the overall opto-microwave power dynamic behaviour.

V. Conclusion

A first bipolar heterojunction phototransistor developed in a commercial available SiGe/Si technology was presented with a special insight in its numerical simulation. A complete numerical model for the stained-SiGe layer was developed and presented. This model was successfully used to correctly predict the behaviour of the HPT.

A dc opto-microwave power gain at *940nm* of *3.46dB*, i.e. responsivity with *50Ohms* loads of *1.49A/W*, was measured at *940nm*. A –3dB bandwidth of 0.4GHz is exhibited and power budgets are drawn with the use of the opto-microwave power gain's monogram chart with example at *10GHz*.

Those results open the road to the integration of low cost design photodetectors which would be able to fulfil requirements for large-scale applications as high data rate delivery to the home through fibre, as well as optical interconnections, RF microwave signal distribution or optical back-plane, all that belongs to the growing field of short-range opto-microwave communication applications.

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