Frequency Response Enhancement of a Single Strained Layer SiGe Phototransistor Based on Physical Simulations

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***Abstract*— An original approach based on a physical model is used to evaluate opto-microwave performances of a vertically illuminated single strained layer SiGe HPT. Analysis of opto-microwave performance is presented at $940nm$. The contribution of each region on the dynamic performances is studied. Frequency response enhancement is shown for base optical detection first and also by wavelength analysis while maintaining whole component detection. Increases up to a 9.8 factor for the -3dB-bandwidth (f_{-3dB}) in photodiode mode and of a 2.2 factor for the transition optical frequency (f_{Topt}) in phototransistor mode are presented, reaching respectively $19.7GHz$ and $15.3GHz$.**

I. Introduction

In the context of short distance communications, the wavelength is not a priority and values in the range of 0.8 to 1 micrometers offer new potential for low costs applications, in which silicon-based structures might play an important role. This paper deals with the optimization of the frequency behaviour of a SiGe microwave phototransistor. First proposition of such a device was made according to theoretical results in [1]. Experimental results were presented in [2], [3] and more completely in [4] within a single strained layer SiGe/Si HPT developed in a commercially compatible SiGe/Si process. Another group has investigated since then an approach using Multiple Quantum Well heterojunction phototransistors structures [5] and [6]. However the given MQW structure blocks into wells some holes, which has to be removed as it provides a slow current contribution and limits the bandwidth [7]. More recently a team from IBM [8] entered the field of SiGe HPT with similar structures than in [1], [4].

This paper investigates the frequency limits of the phototransistor, through numerical simulations using a complete physical model developed with Silvaco/Atlas modules. 940nm-wavelength opto-microwave characteristics analysis are presented and the contribution of main regions of the phototransistor is investigated. The increase of opto-microwave frequency performances due to the base-region absorption contribution is discussed.

II. The Single Strained SiGe Layer HPT

The HPT structure proposed in Fig. 1 is based on a single strained SiGe layer bipolar technology presented in [9]. The $30nm$ SiGe-Base is highly doped and presents a 20% abrupt Germanium profile. This permits lateral size enlargement of the HPT in order to improve optical coupling without dramatically lowering the dynamic performances.

For a $1\mu m$-width pure electrical HBT, a f_T of $30GHz$ and a f_{MAX} of $50GHz$ are obtained. For our $12\mu m$-width HPT, a f_T of $20GHz$ and a f_{MAX} of $25GHz$ are experimentally demonstrated and presented in [3] and [4].

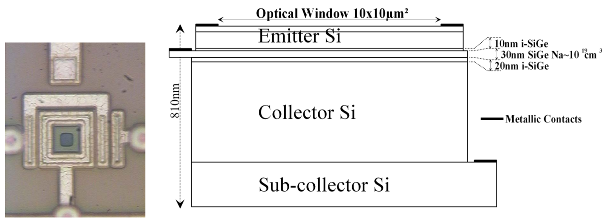


Fig. 1. SiGe HPT picture and structure

The HPT is vertically illuminated through a 10 by 10 μm^2 optical window opened above the emitter contact. This allows optical absorption in the three different regions: emitter, base and collector.

The SiGe layer is used to increase optical absorption and spectral range over $1\mu m$-wavelength by reducing the base bandgap.

For opto-microwave characterization of the HPT ([3] and [4]), a responsivity with 50Ω loads of $1.49A/W$ was measured and a $-3dB$-bandwidth of $0.4GHz$ is exhibited at $940nm$ in phototransistor mode: $Vbe = 0.82V$ and $Vce = 1.5V$.

III. The Physical Model

A complete physical model, presented precisely in [4] and [1], was built on a 2D drift-diffusion simulator: modules Atlas from Silvaco. A strained SiGe layer model was developed based on empirical laws extracted from literature. This model takes into account:

- The bandgap reduction.
- The effective bandgap reduction due to the doping for $N_A \geq 10^{18}cm^{-3}$.
- The effective densities of state reduction at 300K in relation to the Silicon case.

Then, an optical absorption coefficient model is used, based on a one-phonon model applied on measurement published by Lang et al. in [10].

This physical model gives also the possibility to activate region by region the optical absorption model and then to demonstrate the influence of each region on the optical-microwave performances.

Physical simulation was compared to experimental datas in [4] obtained by a two laser beating technique presented in [11].

IV. Opto-Microwave Simulation

The HPT can be considered as a 3 ports devices with the base access, the collector access and the optical access. We can write relation between each port through S-parameters.

Physical simulations outputs in electrical analysis are current, voltage and power small signal results, and in optical analysis only current outputs under short circuit. To obtain Responsivity with 50Ω loads results, we need numerical computations to convert H parameters to S-Parameters, [1] and [4].

To characterize phototransistors, we use different parameters recalled in Fig. 2 as:

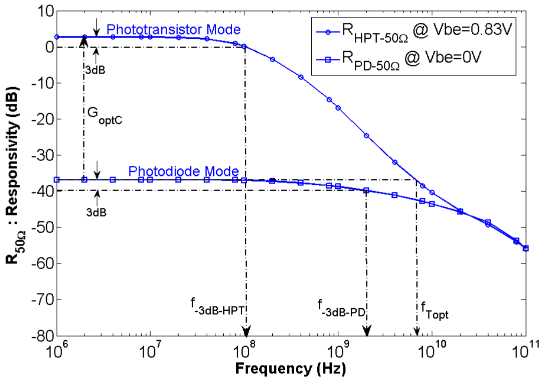


Fig. 2. Opto-microwave Parameters for a HPT

- $R_{pd-50\Omega}$: Responsivity with 50Ω loads in photodiode mode ($Vbe = 0$)
- $R_{hpt-50\Omega}$: Responsivity with 50Ω loads in phototransistor mode
- $GoptC$: Optical current gain which informs on the photo-generated current amplification
- $f_{-3dB-pd}$: $-3dB$-bandwidth in photodiode mode ($Vbe = 0$)
- f_{Topt}: optical transition frequency where the amplified collector current is equalled to the dc photogenerated current I_{ph}

V. Frequency Response Enhancement

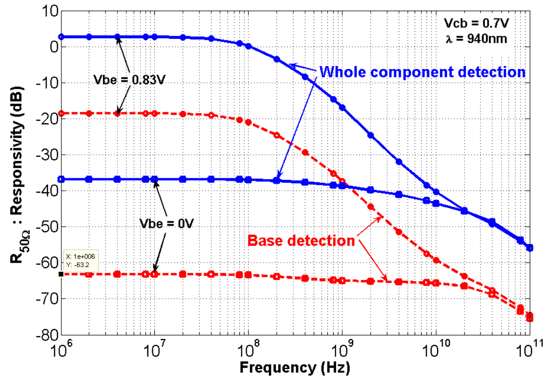
The following results that will be presented in this part are obtained from physical simulations. First we will focus on the opto-microwave characteristics of two different absorption regions: the whole component detection with optical absorption in all regions and absorption in the base only at $940nm$ and constant collector-base voltage $Vcb = 0.7V$.

A. Opto-microwave Analysis at $940nm$

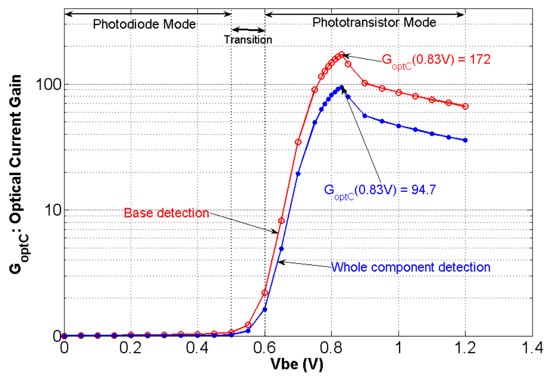
Fig. 3(a) shows the responsivity in photodiode and phototransistor mode for both absorption cases.

For the whole component detection, a low-frequency responsivity of $0.014A/W$ in photodiode mode and $1.36A/W$ in phototransistor mode are exhibited. This last value can be compared to the experimental result of $1.5A/W$. A G_{optC} of 94, $-3dB$-bandwidth of $2GHz$ and a f_{Topt} of $7GHz$ are also obtained.

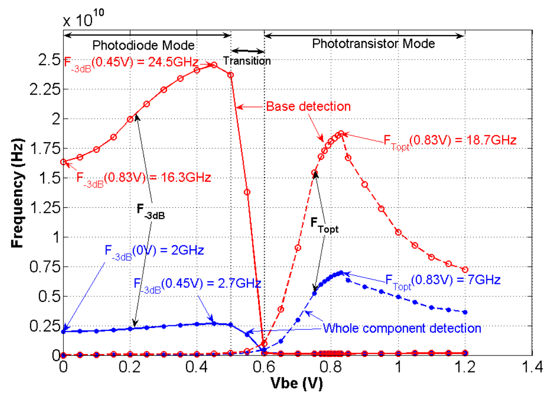
For the base detection compared to the whole component detection, a 20.7 and a 11.5 factors responsivity diminution, respectively in photodiode and phototransistor mode, result from the diminution of the absorption layer. Moreover, a significant improvement of the other opto-microwave characteristics is obtained: the optical current gain grows up to a 1.8 factor at $Vbe = 0.83V$ (Fig. 3(b)), frequency response (Fig. 3(c)) increase, for the f_{-3dB} up to a 9.2 factor at $Vbe = 0.45V$ and for the f_{Topt} up to a 2.7 factor at $Vbe = 0.83V$ to reach respectively $G_{optC} = 172$, $f_{-3dB} = 24.5GHz$ and $f_{Topt} = 18.7GHz$.



(a) Responsivity $R_{50\Omega}(f)|_{dB}$



(b) Optical Current Gain $G_{optC}(V_{be})|_{dB}$



(c) 3dB Frequency $F_{-3dB}(V_{be})$ and Optical Transition Frequency $F_{Topt}(V_{be})$

Fig. 3. Comparison of optical-microwave results for whole component and base absorption only at $\lambda = 0.94\mu m$

A similar behaviour is found in UTC-photodiode and lateral illumination devices: the absorption layer, here the SiGe-base is p-doped and the photogenerated holes are majority, then only photogenerated electrons diffuse to the collection layer and then contribute to the transit time calculation. Only the fastest carriers are used and we obtain a component faster than with the whole component detection where both holes and electrons move in.

B. Lateral Illumination Responses at 940nm

In this part, we focus on the frequency responses of the different HPT region by illuminating the HPT laterally. The aim of this analyze is to study precisely the fast regions for the photo-generated carriers and their transit time in function of their photo-generated place. Then a theoretical 10nm lateral optical beam was moved vertically between the base and the sub-collector by 10nm-step.

Fig. 4 presents the evolution of the optical frequency (f_{Topt}) in HTP-mode and the 3dB-frequency ($f_{-3dB-Pd}$) in PD-mode versus the beam position. The figure is divided in four regions: the base (0.11 to 0.14 μm), the space charge region (0.14 to 0.37 μm), the quasi-neutral collector region (0.37 to 0.61 μm) and the sub-collector (0.61 to 0.81 μm).

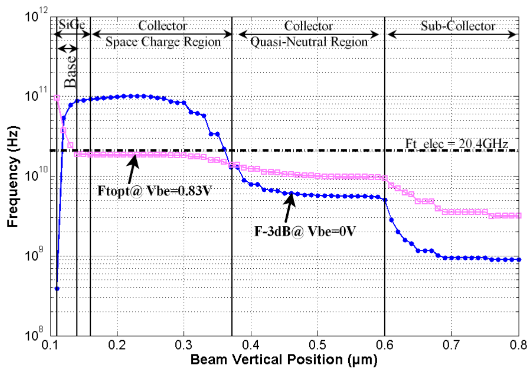


Fig. 4. $f_{-3dB-Pd}$ in photodiode mode and f_{Topt} in phototransistor mode vs 10nm lateral illuminated beam vertical position with $Vcb = 0.7V$

In the sub-collector region, we obtain approximatively a $1GHz f_{-3dB-Pd}$ and a $4GHz f_{Topt}$. This region is highly n-doped ($Nd = 2e20cm^{-3}$). Only holes limit the transit time . The response is then slow as they move through the structure with a mobility inferior to $52.9cm^{-2}/V \cdot s$.

In the quasi-neutral collector region, which is n-doped ($Nd = 4e16cm^{-3}$), the holes mobility goes up to $400cm^{-2}/V \cdot s$ and the $f_{-3dB-Pd}$ and f_{Topt} reach respectively $6GHz$ and $10GHz$.

In the space charge region, holes and electrons move together. Their mobility are respectively around $400cm^{-2}/V \cdot s$ and $850cm^{-2}/V \cdot s$ for $4e16cm^{-3}$ n-doped region. The $f_{-3dB-Pd}$ is maximized with a value of $101GHZ$ and the f_{Topt} reaches almost the f_{T-elec} value with $18.4GHz$.

Finally, the base region presents a maximized f_{Topt} of $96.2GHz$ due to the transistor effect on the electron. Holes and electrons are photo-generated in a highly p-doped region. The holes in the base in excess call directly electrons from the emitter, this is the phototransistor effect. The amplified carriers transit time is then reduced to the electron transit time through the base and the space charge region. This is coherent with the UTC-effect. On the contrary, the $f_{-3dB-Pd}$ decrease down to $390MHz$ due to the absence of electrical field in the base region in photodiode mode.

To conclude this part, if we need to optimize the $f_{-3dB-Pd}$ value, we must privilege the photo-generation in the space charge region while to optimize the f_{Topt} value in HPT-mode the base is the best region.

C. Wavelength Analysis

This part deals with a technical solution to favour the absorption in the base. Solutions as a direct lateral illumination or lateral coupling [8] are possible. Another solution is to increase the wavelength over $1\mu m$ and then to favour SiGe layer absorption while maintaining a vertical illumination system. In order to evaluate the opto-microwave performances of the last solution, a wavelength study was done and the results are presented here below.

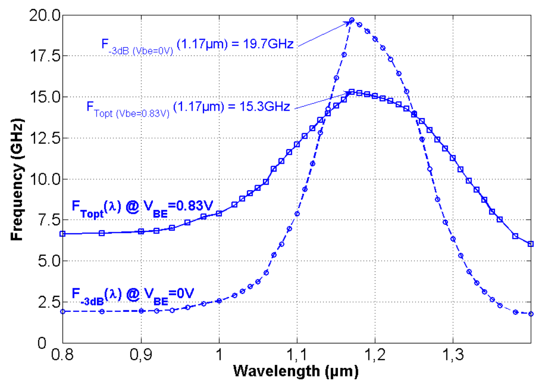


Fig. 5. $f_{-3dB}(\lambda)$ in photodiode mode and $f_{Topt}(\lambda)$ in phototransistor mode

Fig. 5 shows the f_{-3dB} at $Vbe = 0V$ and the f_{Topt} at $Vbe = 0.83V$ evolutions as a function of wavelength. A 19.7GHz f_{-3dB} and a 15.3GHz f_{Topt} peak values are obtained for $\lambda = 1.17\mu m$.

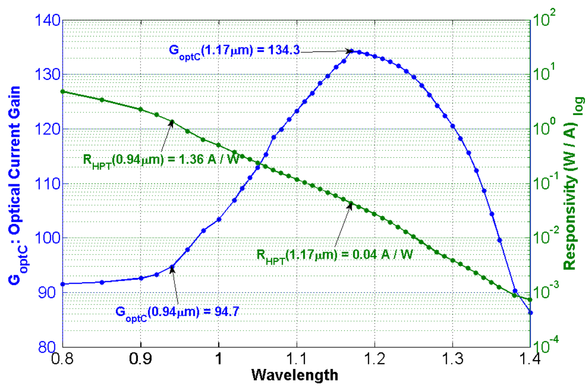


Fig. 6. $G_{optC}(\lambda)$ and $R_{hpt-50\Omega}(\lambda)$

At the same wavelength, the optical current gain reaches his maximum with $G_{optC} = 134$, in Fig. 6. Only the responsivity at $Vbe = 0.83V$ fall down to $0.04A/W$ (Fig. 6).

Frequency responses are improved compared to the $940nm$-wavelength values of a 9.8 factor for f_{-3dB} and of a 2.2 factor for f_{Topt}. G_{optC} increase of a factor of 1.4 and the responsivity in phototransistor mode decrease of a factor of 34.

VI. Conclusion

Based on physical simulations, opto-microwave characteristics of a single strained SiGe layer HPT were presented at $940nm$ first. The contribution of each region on dynamic performances was analyzed and a significant improvement on frequency response was obtained for base optical detection. A $24.5GHz$-f_{-3dB} and a $18.7GHz$-f_{Topt} are exhibited compared to the whole component detection values with respectively $2GHz$-f_{-3dB} and a $7GHz$-f_{Topt}. These results demonstrate an Uni-Travelling-Carrier (UTC) behaviour of the SiGe HPT.

This was confirmed by a fine analysis of transit time in the structure with respect to the depth position of the photo-generated carriers.

This behaviour is also obtained while increasing wavelength with detection in the whole device. This comes from the difference in absorption behaviour between silicon and SiGe layers according to the wavelength. At $1.17\mu m$ the absorption is then predominant and maximum frequency performances are exhibited with $19.7GHz$ for f_{-3dB} and $15.3GHz$ for f_{Topt}, which almost reach the former theoretical values.

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