This is an author's version published in: https://oatao.univ-toulouse.fr/24088

Official URL : https://doi.org/10.1109/MWP.2015.7356678

To cite this version :

Tegegne, Zerihun Gedeb and Viana, Carlos and Rosales, Marc D. and Polleux, Jean-Luc and Algani, Catherine and Grzeskowiak, Marjorie and Richalot, Elodie Substrate diode effect on the performance of Silicon Germanium phototransistors. (2015) In: 2015 International Topical Meeting on Microwave Photonics (MWP), 26 October 2015 - 29 October 2015 (Paphos, Cyprus).

Substrate diode effect on the performance of Silicon Germanium phototransistors

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Abstract— **This paper provides a study on the substrate effect on the opto-microwave behavior of Silicon-Germanium Heterojunction bipolar Photo-Transistors (HPT). An Opto-Microwave Scanning Near Field Optical Microscopy (OM-SNOM) is performed to observe the distribution of photocurrent and dynamic behavior over the structure of the phototransistor. The photocurrent generated in the photodiode created by a n++ sub-collector and p+ substrate is extracted and analyzed. A maximum substrate diode current of 700µA is observed at 850nm with a related cutoff frequency of 0.42GHz. We have extracted low frequency responsivity (at 50MHz) bandwidth product of 109.2 MHzA/W. Finally, this study will provide a design guide line for Si base phototransistors.**

Keywords— SiGe HPT, microwave-photonics, Silicon-based photodetectors, Radio-over-Fiber, phototransistor, opto-microwave performances, substrate effet

I. INTRODUCTION

Nowaday's wireless technologies have been developed to replace wire lines installed in the Home Area Network (HAN). The increase of new services and wireless devices leads us towards high data rate reaching Giga bits per second. For this purpose, new wireless network standards arise such as the IEEE802.11.ad [1] which is the extension of the Wi-Fi toward the millimeter wave ranges (60GHz). However, the propagation is limiting to a single room, due to both the high propagation attenuation at 60GHz and to the wall absorption and reflections [2]. Therefore, an infrastructure is needed to cover the whole home area so as to distribute the signal from one room to another one. As a result an interest has been recently put to Radio-over-Fiber (RoF) home area network application [3], for which low cost silicon based optoelectronics are highly desirable. SiGe hetrojunction bipolar phototransistor (SiGe HPT) are potential candidates for light detection that were proposed first in 2003 [4][5] to be integrated in standard SiGe HBT technology. Since then, several laboratories are working on SiGe HPTs using different industrial process technologies like TSMC [6], AMS SiGe BiCMOS[7] and IBM SiGe BiCMOS[8]. Hybrid photo-receiver based on SiGe HPT for 60 GHz intermediate-frequency RoF applications was implemented in [9].

There is a continuous need to verify the ability of integrating phototransistors in newer commercial SiGe process technologies offering faster operating frequencies but also to improve the performances of the HPT without modification of the technology vertical stacks of layers. To optimize the speed of the phototransistor, [10] identified the fastest and slowest region of the structure based on physical simulations. References [11] and [12] are investigating the perfomances of phototransitor through opto electric compact circuit modeling. M. D. Rosales et al [13] verifies that the proximity of the base, emitter and collector contacts to the optical window has an influence on the dynamic response characteristic of the phototransistor.

This paper investigates the effect of the substrate photodiode created by the p type substrate and n++ sub collector on the dynamic response the HPT. It also provides relavat information interms of bandwidth responsivity product to be used this HPT into microwave photonics applications. Finally a conclusion will be made on the design aspects of SiGe/Si HPT structure.

II. SIGE/SI HPT STRUCTURE UNDER TEST

The SiGe phototransistor (HPT) was fabricated using the existing SiGe2RF Telefunken GmbH SiGe Bipolar process technology. Indeed, the phototransistor fabrication does not modify the vertical stacks of layers that are used to define a standard SiGe2RF HBT technology. This ensures the compatibility with the process technology and potential integration of complete OE-RF circuits.

The basic HPT structure is designed by extending the emitter, base and collector layers of the reference HBT [1]. The optical opening is made through the emitter. To improve the optical illumination, the superficial Silicon oxide and nitride layers on top of the defined optical window are removed by using Reactive-Ion Etching (RIE) process. A cross-section representation of the phototransistor structure is given in Figure 1. The light paths goes through the polysilicon of the emitter before entering the Si emitter, SiGe base and Si collector region. This HPT is essentially one large HBT whose emitter metallization was removed on the side.

The optical opening of the phototransistor is of 10x10 μm^2.

The total emitter size is 11.3x9.2 μm^2 and the total collector dimension is 16.5x10.6 μm^2. The base profile is thin 40-80nm abrupt SiGe layer with Ge content in the range of 20-25% and high p doping in the range of 10^{19}cm^{-3}. The collector is typically 300-400nm thick with low doping.

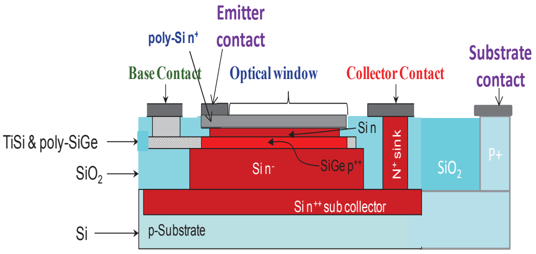

Figure 1: Simplified schematic cross section of an extended Emitter Base Collector HPT

III. EXPERIMENTAL RESULTS AND DISCUSSION

By using the bench setup described in [13], we perform the experimental mapping of the HPT at two different bias conditions (photodiode (PD) and phototransistor mode) and, also, at different optical probe position. For this study, we use a multimode optical source at 850nm and optical probe in order to make sure that our study is more realistic for HAN application where multimode source and fiber is used. The phototransistor mode is studied at a fixed collector-emitter voltage of 3V and fixed base emitter voltage of 0.857V. The photodiode mode is studied by setting collector emitter voltage of 3V and base emitter voltage of 0V. These biasing conditions are the optimum biasing conditions in terms of opto-microwave responsivity.

Figure 2-a) shows the microscopic picture of the phototransistor where the ground (left and right) and signal (up and down) lines are clearly visible. The base contact is taken from the top side, collector contact is taken from the down side and the emitter contact is connected at its left and right side to the ground. The layout is accordingly sketched in Figure 2-b) which defines the optical probe coordinate with its origin given at the center of the optical window.

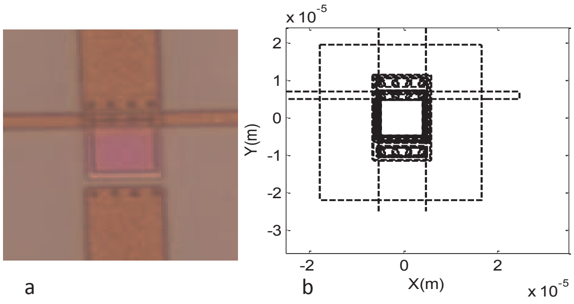

Figure 2: a) Top view of the phototransistor microscopic picture b) The layout of the HPT as a function of the optical probe position.

Figure 3 shows the experimental topological map of the base current in phototransistor mode (a) and photodiode mode (b) respectively. The plot shows the current as a function of the optical probe position. The design of the phototransistor is superimposed to better observe the correspondence between the measurement and the different regions of phototransistor. The shape of the optical beam that is scanned over the HPT is Gaussian profile in the *x* and *y* axes. The resulting photocurrent is the correlation between the optical window and the Gaussian profile of the optical beam.

The base current mapping is symmetric along both *x* and *y* axis as shown in Figure 3 in both HPT (a) and PD (b) mode. In HPT mode, the sign of the base current is changed when the optical probe is moving in to the center of the phototransistor. The negative sign, when the active area is illuminated, indicates that parts of holes generated in the active area are flowing out through the base contact. However, parts of the holes are moving to the emitter for transistor amplification. In the PD mode, *Ib* has negative sign at all position of the optical probe as there is no any transistor action, all the holes generated are flowing out through the base contact. The base current (*Ib*) measured in PD mode operation is the sum of the dark current and the photogenerated current. Thus, the photocurrent generated in the structure, called the primary photocurrent, can be computed from the difference between the base current measured with and without light illumination.

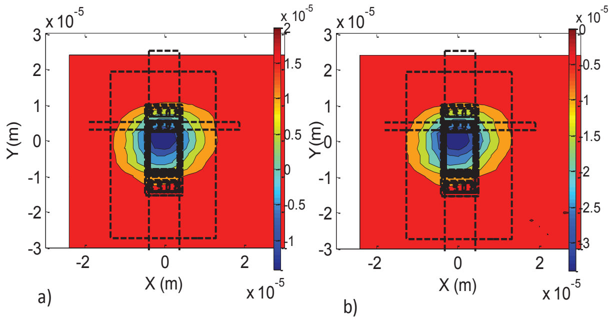

Figure 3: Base current mapping over the structure of the SiGe HPT. a) Phototransistor mode, b) Photodiode mode

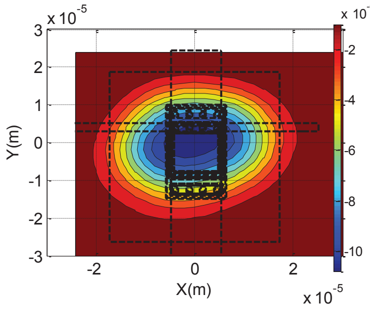

Figure 4: Primary photocurrent distribution over the HPT structure.

The primary photocurrent topological map as a function of optical probe position is shown in Figure 4. It reveals to be symmetrical to the *x* and *y* axes; and its peak appears at the center of the optical window.

The collector current topological mapping is presented in Figure 5 in HPT (a) and PD (b) mode. The collector current mapping is not symmetrical along both *x* and *y* axes. In HPT mode the *Ic* peak is located at *x*=0µm and *y*=0µm. In the PD mode, the peaks appear outside the active region near to the base and collector contact. Those peaks on the side of the contacts are meanly due to the parasitic photocurrent in the substrate.

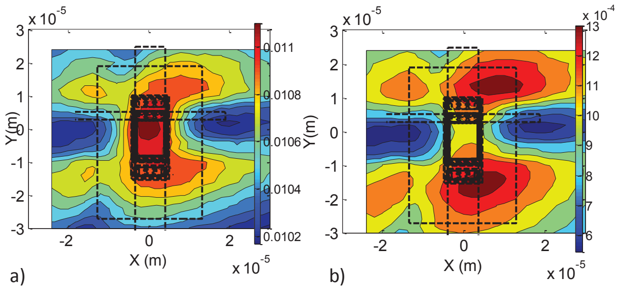

Figure 5: *Collector current as a function of optical probe position a) HPT mode, b) PD mode*

In phototransistors such as InGaAs/InP; when operating in photodiode mode(base emitter junction is off), the number of electrons collected at the collector contact is equal to the number of holes collected at the base contact at every position of the optical probe as InP substrate is not light sensitive[15]. However, in Si based phototransistors in PD mode operation, the current measured at the base contact is much less than measured at collector contact at *x*=0µm and *y*=0µm (*Ib=30µm* and *Ic=1mA*). This difference can be explained from the structure of the phototransistor. As shown in Figure 1, we intentionally design a substrate contact to collect the holes which are generated in the substrate diode. Thus, the current measured at the base contact (*Ib*) does not include the substrate photocurrent. The electrons which are generated in the substrate are still collected at the collector contact.

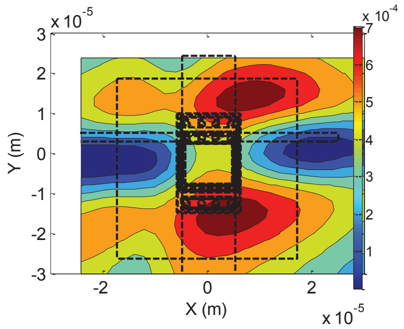

Figure 6: Topological map of substrate photocurrent for dc bias Vbe=0.857V and Vce=2V

The difference in the value between collector current and base current at Vbe=0V in is the photocurrent from the substrate diode called substrate photocurrent. The topological mapping of the substrate photocurrent as a function of the probe position is given in Figure 6. There are two main peaks outside the active area, one near to the base contact (top) and the other near to the collector contact (down).

The peaks of the substrate photocurrent can be explained from the vertical and lateral structure of the HPT shown in Figure 1. When the optical probe moves over the structure, the optical beam passes through different stacks depending on the position of the probe. The two peaks of the substrate photocurrent, one near the collector contact and the other near the base contact, are due to the illumination of the photodiode created by n++ sub-collector and p type Si substrate.

Figure 7 shows the frequency behavior of HPT at the center of the optical window. We recognize a slope close to -20dB / decade in phototransistor mode, characteristic of the behavior of HPT, while the photodiode mode has a slope of about -10 dB/decade. The latter characterizes the behavior of the substrate, due to the difference in transit time of the photo-carriers based on the detection depth into the substrate.

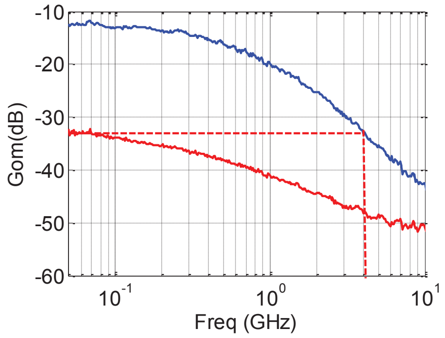

Figure 7: *Optical-microwave gain versus frequency for the photodiode mode (red) and the phototransistor manual (blue) at the center of HPT (x = y = 0µm) for Vbe = 0V (resp. 0.857V) and Vce = 3V*

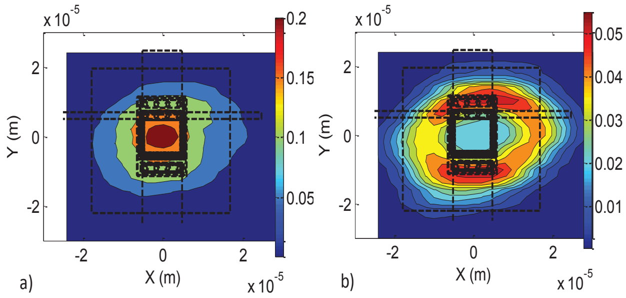

Figure 8: *Low frequency opto-microwave responsivity in a) HPT mode, b) PD mode*

Figure 8-a) and b) shows the Optomicrowave Scanning Near Field Optical Microscopy (OM-SNOM) view of the low frequency opto-microwave responsivity under 50Ω condition in HPT and PD mode, respectively. In HPT mode, the peak of the responsivity appears inside the optical window. Whereas, in PD mode, the peak appears when the optical probe position starts to move outside the optical window and eventually creates a ring shape as shown in Figure 8-b).

The ring is due to the illumination of the substrate diode created by n++ subcollector and p substrate. Indeed, it is much stronger than the photodiode created by the base and collector in the active area region. As shown in Figure 8-a) the ring shape does not appear in the phototransistor mode topological map as the substrate diode effects are hidden by the transistor amplification. A peak responsivity of 0.26A/W is measured at 50MHz and under Vce=3V and Vbe=0.857V (HPT mode).

The dynamic behavior of the phototransistor over the surface of the structure is analyzed through the measurement of the cutoff frequency of the HPT on both PD and HPT mode. Figure 9 presents the slice plot of the -3dB cutoff frequency at x=0µm. The cutoff frequency is usually small in phototransistor mode due to the large capacitance found in the forward biased base-emitter junction. Thus, it is assumed that the cutoff frequency is higher in the photodiode mode. However, the experimental result shown in Figure 9 indicates that the HPT mode cutoff frequency is much higher than PD mode cutoff frequency. This is due to the substrate diode that dominates over the diode created by the base and collector in PD mode operation. In HPT mode, the substrate diode is dominated by the transistor effect. Thus the substrate diode effect is stronger in PD mode operation than HPT mode.

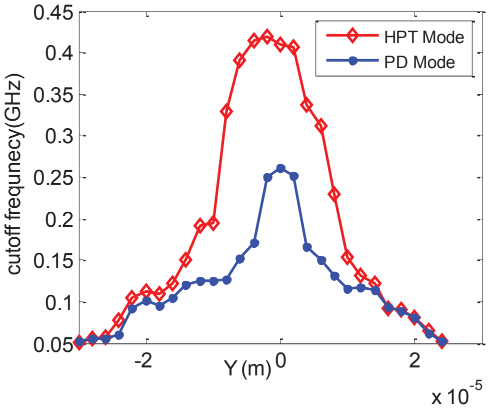

Figure 9: Opto-microwave -3dB frequency of the photodiode and phototransitor mode at X=0m for dc bias Vbe=0.857V and Vce=2V

The cutoff frequency for y>-6µm and y<+6µm is meanly the dynamic response of the active area region. We reach up to 420MHz in HPT mode and 260MHz in PD mode operation. For y<-6µm and y>+6µm the cutoff frequency getting smaller and becomes equal in both modes. It indicates that in this region the cutoff frequency is extracted from the substrate.

IV. CONCLUSION

This paper considered a phototransistor developed by using the existing SiGe HBT technology without modifying the vertical stacks and layers. The OM SNOM analysis revealed to be crucial to understand the behavior of SiGe HPTs. This allowed the extraction of the DC and dynamic behavior over the surface of the device. Slow carriers from the substrate highly affect the dynamic response of the structure in PD mode operation and it affects less in HPT mode of operation. We extract a maximum -3dB cutoff frequency of 0.42GHz in HPT mode and 0.26GHz in PD mode. We also extract a bandwidth responsivity product of 109.2MHzA/W. An alternative to get rid of the substrate contribution could be through a proper design of the optical window with proper metal diaphragms around it. Indeed, the substrate photodiode is hidden either by metal contacts or by upper layers of the intrinsic HPT, or through the use of a lateral illumination of the HPT.

References

[1] IEEE 802.11 standards Tutorial http://www.radio-electronics.com/info/wireless/wi-fi/ieee-802-11ad-microwave.php

[2] NAVAIR Electronic Warfare/Combat Systems "Electronic warfare and radar systems engineering handbook" NAWCWD TP 8347, April 1997

[3] J. Guillory et al., "60GHz Intermediate Frequency over Fiber using a passive Multipoint-to-Multipoint architecture", 16th European conference on Networks and Optical Communications, July 2011.

[4] J.L. Polleux, F. Moutier, A.L. Billabert, C. Rumelhard, E. Snmez, H. Schumacher, "A Strained SiGe layer Heterojunction BipolarPhototransistor for Short-Range Opto-Microwave Applications," in IEEE International Topical Meeting on Microwave Photonics, MWP2003, Hungary, September 2003.

[5] J.L. Polleux, F. Moutier, A.L. Billabert, C. Rumelhard, E. Snmez, H. Schumacher, "An SiGe/Si Heterojunction Phototransistor for Opto-Microwave Applications: Modeling and first Experimental Results, ", awarded in the GAAS Conference of the European Microwave Week, Munich, Germany, october 2003.

[6] Z. Pei et al., "Bandwidth Enhancement in an Integratable SiGe Phototransistor by Removal of Excess Carriers", IEEE Electron Device Letters, Vol. 25, N5, pp286-288, May 2004.

[7] Egels, M. et al.: "Design of an optically frequency or phase-controlled oscillator for hybrid fiber-radio LAN at 5.2 GHz". Microwave Opt. Technol. Lett., 45 (2) (2005), 104–107.

[8] Yin, T. et al.: "Low-cost, high efficiency and high-speed SiGe phototransistors in commercial BiCMOS". IEEE Photonics Technol. Lett., 18 (1) (2006).

[9] C. Viana, Z.G. Tegegne, M. Rosales, J.L. Polleux, C. Algani, V. Lecocq, C. Lyszyk and S. Denet "Hybrid photo-receiver based on SiGe heterojunction photo-transistor for low-cost 60 GHz intermediate-frequency radio-over-fibre applications" IEEE electronic letters, 2015.

[10] F. Moutier, J.L. Polleux, C. Rumelhard, H. Schumacher, "Frequency response enhancement of a single strained layer SiGe phototransistor based on physical simulations". GAAS Conf. of the European Microwave Week 2005, Paris, France, 2005.

[11] Helme.J.P, Houstron.P.A, "Analytical modeling of speed response of heterojunction bipolar phototransistors". Lightwave Technology. 25(5)(20007), 1247-1255.

[12] Yuan.F.et al. "MEXTRAM modeling of Si-SiGe HPTs". IEEE Trans. Electron Devices, 51(6), 2004, 870-876.

[13] M. D. Rosales, F. Duport, J. Schiellein, J.-L. Polleux, C. Algani, C. Rumelhard, "Opto-microwave experimental mapping of SiGe/Si phototransistors at 850nm", International Journal of Microwave and Wireless Technologies, Volume 1, Issue 06, pp 469-473, 2009

[14] M. D. Rosales, Jean-luc Polleux, Catherine Algani "Improving Optical Detection in SiGe Heterojunction Phototransistors" ISMOT 2011, June 20 - 23, Prague, Czech Republic, EU

[15] J. Schiellein, M. Rosales, J.L. Polleux, C. Algani, T. Merlet, M. Riet, J. Godin, and A. Scavennec, "Analysis of opto-microwave paths into a InP/InGaAs UTC-HPT," in *Microwave Conference (EuMC), 2011 41st European*, pp. 949 –952, oct. 2011.