Improving the opto-microwave performance of SiGe/Si Phototransistor through edge illuminated structure

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ABSTRACT

This paper demonstrates the experimental study of edge and top illuminated SiGe phototransistors (HPT) implemented using the existing industrial SiGe2RF Telefunken GmbH BiCMOS technology for opto-microwave (OM) applications using 850nm Multi-Mode Fibers (MMF). Its technology and structure are described. Two different optical window size HPTs with top illumination ($5x5\mu m^2$, $10x10\mu m^2$) and an edge illuminated HPTs having 5µm x5µm size are presented and compared. A two-step post fabrication process was used to create an optical access on the edge of the HPT for lateral illumination with a lensed MMF through simple polishing and dicing techniques. We perform Opto-microwave Scanning Near-field Optical Microscopy (OM-SNOM) analysis on edge and top illuminated HPTs in order to observe the fastest and the highest sensitive regions of the HPTs. This analysis also allows understanding the parasitic effect from the substrate, and thus draws a conclusion on the design aspect of SiGe/Si HPT. A low frequency OM responsivity of 0.45A/W and a cutoff frequency, f_{-3dB}, of 890MHz were measured for edge illuminated HPT. Compared to the top illuminated HPT of the same size, the edge illuminated HPT improves the f_{-3dB} by a factor of more than two and also improves the low frequency responsivity by a factor of more than four. These results demonstrate that a simple etched HPT is still enough to achieve performance improvements compared to the top illuminated HPT without requiring a complex coupling structure. Indeed, it also proves the potential of edge coupled SiGe HPT in the ultra-low-cost silicon based optoelectronics circuits with a new approach of the optical packaging and system integration to 850nm MMF.

Keywords: Edge SiGe-HPT, Phototransistor, Microwave Photonics, Radio-over-Fiber, Si photonics, RoF

1. INTRODUCTION

With the recent explosive growth of connected objects, for example in Home Area Networks, the wireless and optical communication technologies see more opportunity to merge with low cost Micro-Wave–Photonics (MWP) technologies [1]. Millimeter frequency band from 57GHz to 67GHz is used to accommodate the very high speed wireless data communication requirements [2]. However, the coverage distance of these wireless systems is limited to few meters (10m). The propagation is then limiting to a single room mostly, due to both the high propagation attenuation of signals in this frequency range and to the wall absorption and reflections. Therefore, an infrastructure is needed to lead the signal to the distributed antennas configuration through MWP technology. Moreover, MWP technology has recently extended to address a considerable number of applications [1] including 5G mobile communication, biomedical analysis, Datacom, optical signal processing and for interconnections in vehicles and airplanes. Many of these novel application areas also demand high speed, bandwidth and dynamic range at the same time they require devices that are small, light and low power consuming. Furthermore, implementation cost is a key consideration for the deployment of such MWP systems in home environment and various integrated MWP applications. Thus, BiCMOS compatible SiGe heterojunction bipolar phototransistors (SiGe HPT) are potential candidates for high speed photoreception [3] 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 SiGe BiCMOS industrial process technologies like TSMC [6], AMS [7] and IBM [8]. All these approaches have led to top illuminated structures. Moreover, microwave HPTs have the advantage to combine a PIN photodiode with HBT, thus avoiding the need in Trans-Impedance-Amplifier (TIA) due to their high internal gain [9].

Vertically illuminated photodetectors are known for their ease of light coupling but suffer from a tradeoff between conversion efficiency and frequency performance, the latter being limited by the transit time and capacitances [9] [10]. Edge-coupled devices overcome this problem as the optical signal enters through the side of the device and propagates orthogonally to the bias field. This gives the freedom to design longer devices to ensure a high proportion of the optical signal to be absorbed while maintaining a narrow absorption region to keep transit times low [9] [11]. Edge coupled HPTs based on InP-InGaAs technology have been intensively studied since 1993 [10] [11].

This paper presents and compares the performance of edge and top illuminated SiGe phototransistors based on the available commercial SiGe/Si BiCMOS technology.

2. SIGE/SI HPT STRUCTURE UNDER STUDY

The SiGe phototransistor (HPT) was fabricated using the existing SiGe2RF Telefunken GmbH SiGe Bipolar process technology as shown in Figure 1. This BiCMOS technology has a base profile thickness of 40-80nm with 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.
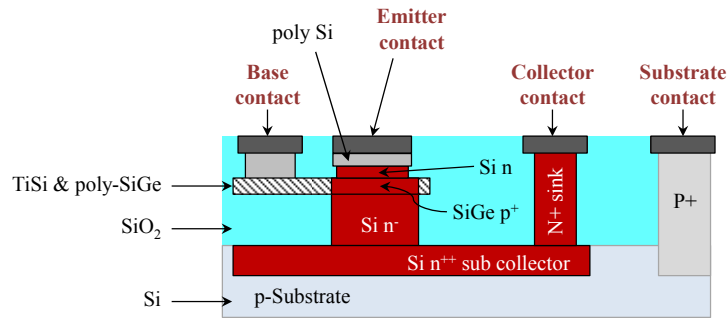

Figure 1: Schematic cross-section of SiGe2RF technology from Telefunken

The phototransistor fabrication does not modify the vertical stacks of layers that are used to define a standard technology SiGe2RF HBT. This ensures the compatibility with the process technology and the potential integration of complete opto-electronic radio-frequency (OE-RF) circuits. The basic HPT structure is designed by extending the emitter, base and collector layers of the reference HBT [12] to provide an optical access as presented in Figure 2. This HPT is essentially one large HBT whose emitter metallization was put only on the side.
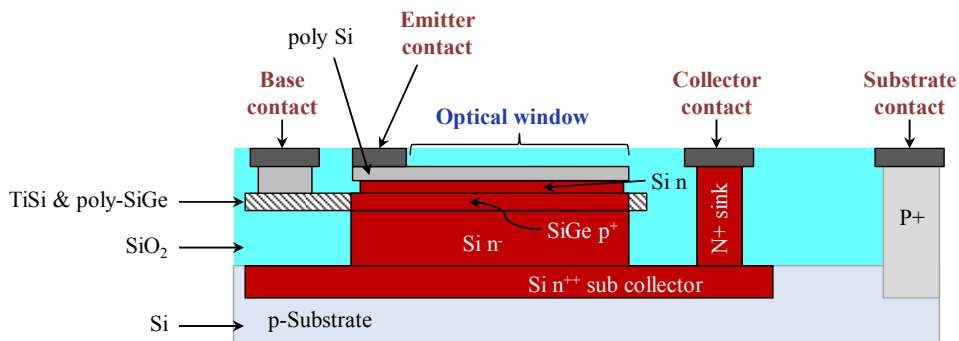

Figure 2: Simplified schematic cross section of an extended Emitter Base Collector HPT

For top illuminated HPTs structures [3][16][17], the optical opening is made through the emitter. Thus, the injected light path goes through the oxide and polysilicon layers of the emitter before entering the Si emitter,

SiGe base and Si collector regions. The designed optical openings of the top illuminated phototransistor are $5x5\mu m^2$ and $10x10 \mu m^2$.

For edge illuminated HPT structure [18], the optical access at the edge is obtained after the standard fabrication process through polishing and dicing close to the active area of the devices as shown in Figure 3 a). We polish 80µm down to the substrate to have smooth surface at the optical beam input and we then dice it to separate the processed chip from the wafer. We have designed a 4.5µm thick (where light is coupled through) and 5µm long (maximum absorption length) phototransistor as shown in Figure 3 b). The $Si_{1-x}Ge$ base layer sandwiched between the collector and emitter, both made of Silicon, is used as an evanescent optical waveguide that detects light.

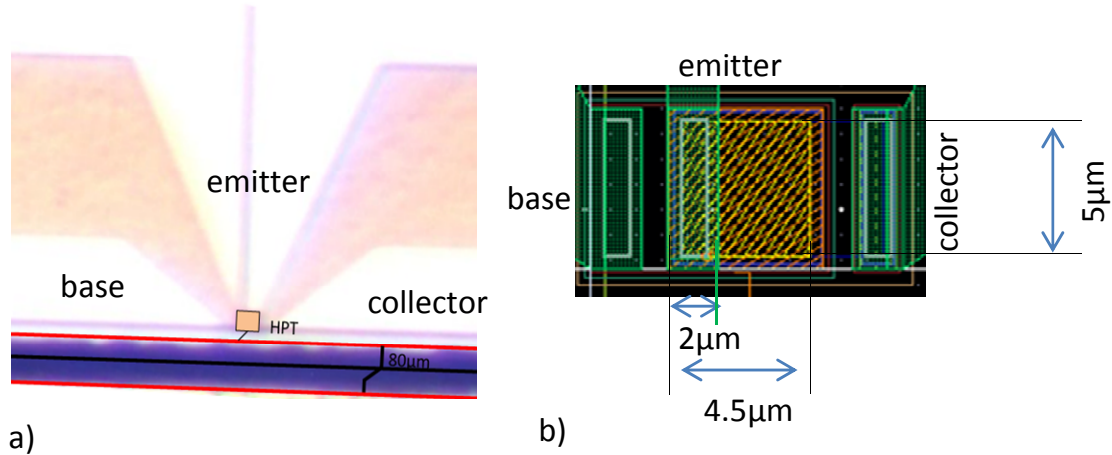a)   b)

Figure 3: a) The microscopic picture of the edge illuminated HPT where the metal contacts, HPT and the edge of the HPT are shown clearly. b) The layout of the edge illuminated HPT along with its dimensions.

In both top and edge illuminated structures, the substrate is grounded through a p+ guard ring.

3. ON-WAFER OPTO-MICROWAVE CHARACTERIZATION

On-wafer bench setup described in [12] is used to measure the opto-microwave performances of top and edge side illuminated HPTs. An 850nm light source, which is directly modulated, illuminates the HPT through a lensed multimode fiber (MMF). This light source has a -3dB cutoff frequency of 12 GHz [13]. A tilted mirror is used to monitor the alignment of the optical probe to the optical window of the HPT on the top and edge through the microscope as shown in Figure 4 and Figure 6 respectively. The distance is set at 50µm from the surface to align the optical window with the beam waist. We use a multimode light source and multimode optical probe to characterize our device as it is targeted to implement in Home Area Network (HAN) applications at 850nm where multimode sources and MMF are largely deployed [2].

The HPTs are mounted in a common emitter configuration topology with 100µm-pitch GSG pads in order to perform on wafer opto-microwave measurements as shown in Figure 4 a). The base is biased through an external bias tee loaded to 50Ω which is the standard normalization load in microwave applications and which is required for the HPT characterization [19][20]. The collector is connected to the port 2 of the VNA and biased through the internal bias tee of the VNA. An Agilent B1500 semiconductor parametric analyzer is used to monitor and generate the biasing levels required for the HPT.
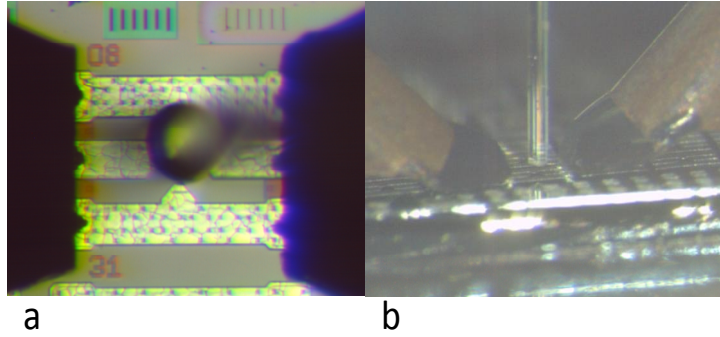
Figure 4: a) Top view of the fiber probe spot illuminating the phototransistor, with RF probes and GSG access lines; b) Side view through the tilted mirror of the fiber probe illuminating the phototransistor from the top side.

Figure 5 a) shows the microscope picture of the $10x10\mu m^2$ phototransistor where the ground (top and bottom) and signal (left and right) lines are clearly visible. The base contact is taken from the left side, collector contact is taken from the right side and the emitter contact is connected at its top and bottom sides to the ground. The layout is accordingly sketched in Figure 5 b) which defines the optical probe coordinates with its origin given at the center of the optical window. The $5x5\mu m^2$ HPT has similar structure as in Figure 5 except the optical window size difference. We perform the experimental mapping on $5x5\mu m^2$ and $10x10\mu m^2$ HPTs at appropriate dc biasing conditions with top illumination. The phototransistor is studied at a fixed collector-emitter voltage of 3V and fixed base-emitter voltage of 0.857V. These biasing conditions are the optimum biasing conditions in terms of opto-microwave responsivity.
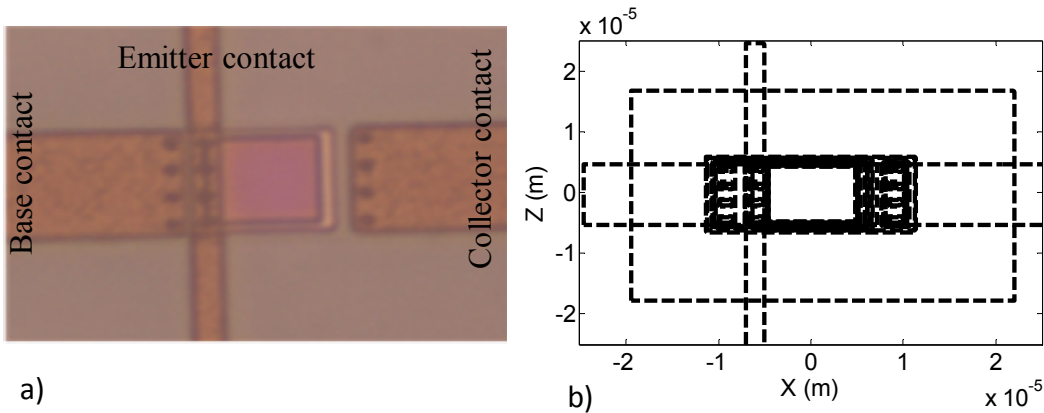

Figure 5: a) Top view of the $10x10\mu m^2$ phototransistor. b) The layout of the HPT with optical window at the center as a function of the optical probe position.

Figure 6 shows the alignment of the optical probe for edge illuminated structure. The GSG probes are put on the GSG pads and the optical probe is positioned on the side of the HPT. One of the ground panels of the HPT is removed during dicing so that one of the GSG ground line is suspended on air. The center location of the HPT's optical window is determined by scanning the optical probe along x and y axes in the vicinity of the optical window.
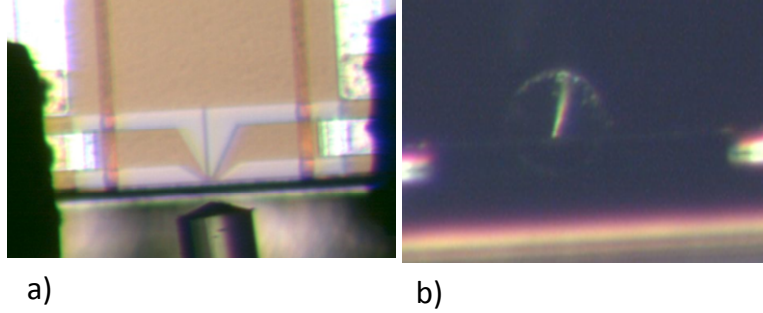
Figure 6: a) Top view of the fiber probe illuminating the phototransistor on the edge, with RF probes on the side and GSG access lines; b) Front view through the tilted mirror of the fiber probe spot illuminating the phototransistor.

The optical probe is scanned all over the HPT optical window surface on the top and edge side. For each position, S-parameters of the optical link are measured in the [50MHz-20GHz] frequency range using the VNA. A 2µm step (+/-20nm) is used to cover a 60µmx60µm surface over the top and edge of the HPT. It then provides a complete Opto-Microwave Scanning Near-field Optical Microscopy (OM-SNOM) view of the HPT frequency response.

A proper de-embedding technique is required to extract the behavior of the HPT from the pads, interconnections, optical links and probes. We use T-matrix approach [14] to remove all the parasitic from the measurement bench setup.

4. EXPERIMENTAL RESULTS

4.1 Top illumined HPTs

The responsivity at 50MHz of top illuminated HPT having an optical window size of $10x10µm^2$ and $5x5µm^2$ as a function of optical probe position is presented in Figure 7 a) and b) respectively. The optimum biasing conditions are Vce=3V and Vbe=0.857V that maximizes both the low frequency responsivity and cutoff frequency. In both HPT the peak of the responsivity appears inside the optical window. For smaller HPT, the peak of the responsivity is still visible outside the optical window. This is related to the effect of the substrate diode which is stronger for smaller size HPT [15]. The maximum responsivity is higher for $10x10µm^2$ optical window size HPT than $5x5µm^2$ optical window size HPT. This is due to better coupling efficiency and higher internal current gain in larger size HPT.
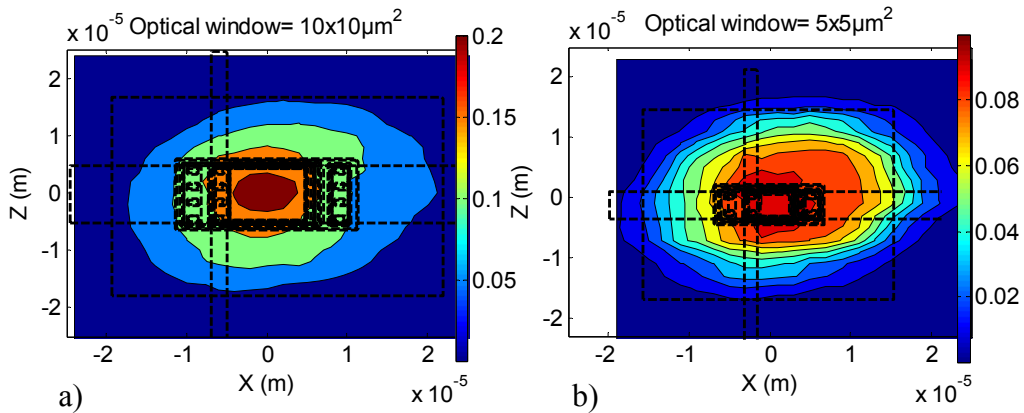

Figure 7: Low frequency responsivity (A/W) topological maps at Vce=3V and Vbe=0.857V a) $10x10µm^2$ optical window HPT, b) $5x5µm^2$ optical window HPT.

Figure 8 a) and b) presents the topological map of the -3dB cutoff frequency of $10x10µm^2$ and $5x5µm^2$ optical window HPTs respectively. It is well centered and the peak appears at the center of the optical window in both

HPTs. The cutoff frequency is usually small in phototransistor mode as the HPT has a -20dB/dec slope response (related to its internal amplification processes).
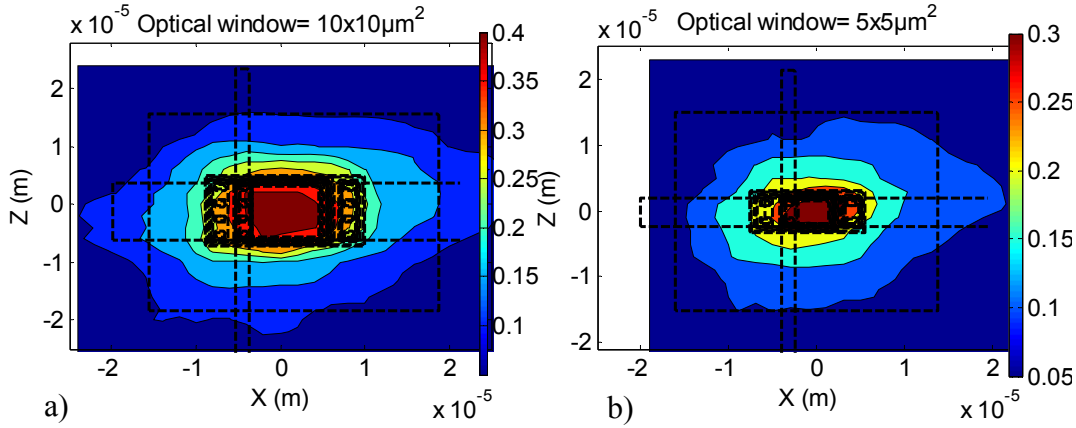

Figure 8: -3dB cutoff frequency (in GHz) topological maps at Vce=3V and Vbe=0.857V a) 10x10μm^2 optical window HPT, b) 5x5μm^2 optical window HPT.

Figure 9 shows the slice curves of low frequency responsivity (a) and cutoff frequency (b) for 10x10μm^2 and 5x5μm^2 optical window size HPT at x=0. These curves can be decomposed into two different regions (A and B) as shown in Figure 9. Region A represents responsivity and cutoff frequency extracted mainly from the substrate diode. In region B the extracted responsivities and cutoff frequencies correspond to the frequency response of the phototransistor and hence the peak appears in this region. The peak responsivity of about 0.25A/W and 0.1A/W were measured for 10x10μm^2 and 5x5μm^2 optical window size HPTs respectively. We were also able to extract a cutoff frequency up to 420MHz for 10x10μm^2 and 350MHz for 5x5μm^2 HPT at x=z=0μm.
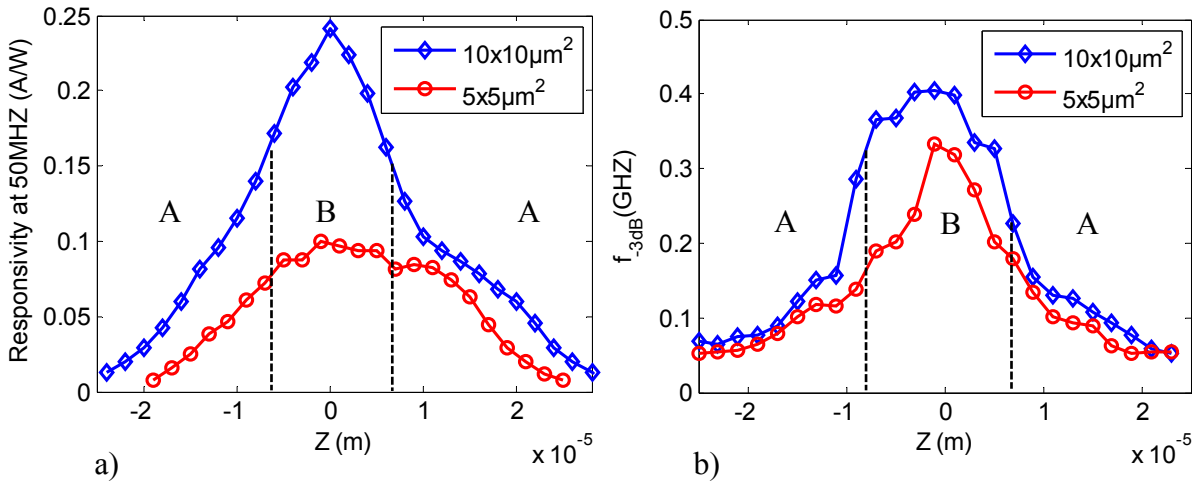
Figure 9: The slice curve at x=0 of 10x10μm2 and 5x5μm2 optical window size HPTs at Vce=3V and Vbe=0.857V a) Responsivity, b) cutoff frequency.

Theoretically, the cutoff frequency of smaller surface area transistors has to be higher than larger surface area due to the RC limit. However, from our experimental result, the -3dB cutoff frequency of 5x5μm^2 optical window size HPT is smaller than the cutoff frequency of 10x10μm^2 optical window size HPT. This is due to the presence of excess substrate photocurrent in smallest size HPT. This excess substrate current is related to the weak coupling efficiency of 5x5μm^2 HPT [15]. Thus 10x10μm^2 optical window size HPT is the optimal structure to improve both the cutoff frequency and responsivity compared to 5x5μm^2 optical window size HPT.

As a result in discussion section we will focus on the experimental results of $10 \times 10 \mu m^2$ optical window size HPT to compare with the edge illuminated one.

4.2 Edge illumined HPT

Figure 10 shows the SNOM view of the low frequency responsivity and cutoff frequency of an edge illuminated HPT under 50Ω condition at 50MHz in HPT obtained by setting Vbe=0.85V and Vce= 1.5V. At this biasing condition the low frequency responsivity reaches 0.26A/W and the cutoff frequency 798MHz as it is also shown in the cross section curve in Figure 11.

The maximum of the responsivity appears at $x=y=0\mu m$. However, the maximum of the cutoff frequency is shifted to the positive x axis as it is shown in Figure 10 b). The cutoff frequency increases when the optical probe moves towards the positive x axis (when it moves towards the base contact) and it drops to small value when the fiber moves towards the center of active region eventually towards negative x axis (when moving towards the collector contact). The main explanation considers the lateral distance that electrons and holes need to go across to reach the collector and base contacts respectively. Under illumination of the HPT structure, the holes and electrons generated in the base collector junction move towards the base and collector contacts respectively. However, the distance covered by electrons and holes to reach their respective contact depends on the position of the light illumination. When it is illuminated near the base contact the lateral distance to travel by electrons is larger, whereas the distance travelled by holes is shorter. When it is illuminated near the collector the lateral distance traveled by electrons is shorter and the distance travelled by holes is longer. However, the speed of electrons is much higher than the speed of holes. As a result, when the optical beam illuminates near to the collector contact, the photogenerated holes take a longer time to reach the base contact than electrons does to reach the collector contact when the optical beam illuminates close to the base. As a result the speed of the HPT becomes slower when light is injected farther than the base contact.
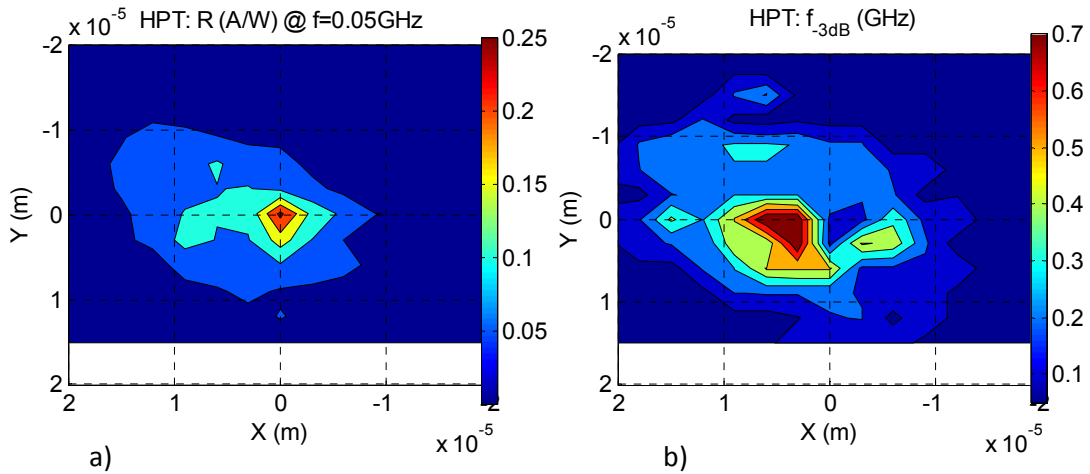

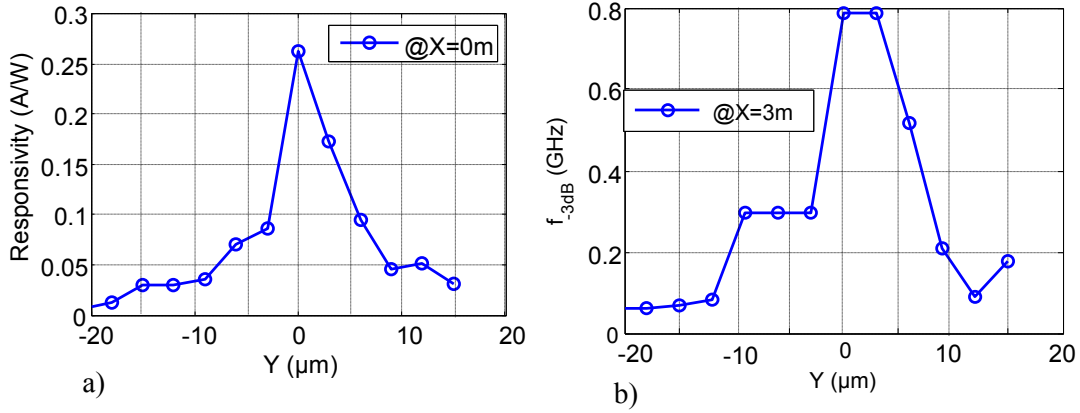Figure 10: The edge map of lateral illuminated HPT at Vce=1.5V and Vbe=0.85V a) Responsivity, b) -3dB cutoff frequency (in GHz).

Figure 11: The cross section curve along y axis (for top into the substrate) of lateral illuminated HPTs at Vce=1.5V and Vbe=0.85V a) Low frequency responsivity, b) Cutoff frequency

We measure the opto-microwave response of the edge illuminated HPT with a very good and well optimized optical coupling under Vbe =0.85V and Vce =1.5V at the both peaks ((x=0μm, y=0μm) and (x=4μm, y=0μm)). The low frequency responsivity and cutoff frequency are largely improved. Figure 12 a) presents the opto-microwave gain (Gom) versus frequency for an edge illuminated HPT at x=y=0μm (where the peak of responsivity appears) and x=4μm, y=0μm (where the peak of f_{-3dB} appears). As shown in Figure 12 a), we observe a low frequency (50MHz) opto-microwave gain of -7dB (opto-microwave responsivity of 0.45A/W) at x=y=0μm.

Figure 12 b) shows the normalized Gom versus frequency of edge illuminated HPT at (x=4μm, y=0μm) and at (x=0μm, y=0μm). We observe the cutoff frequency can reach up to 890MHz. The cutoff frequency when the low frequency Gom is maximum (x=0μm, y=0μm) is only 150MHz. This clearly indicates the influence of the substrate diode on the cutoff frequency and responsivity [15] (responsivity increases in the presence of substrate diode effect whereas cutoff frequency decreases).

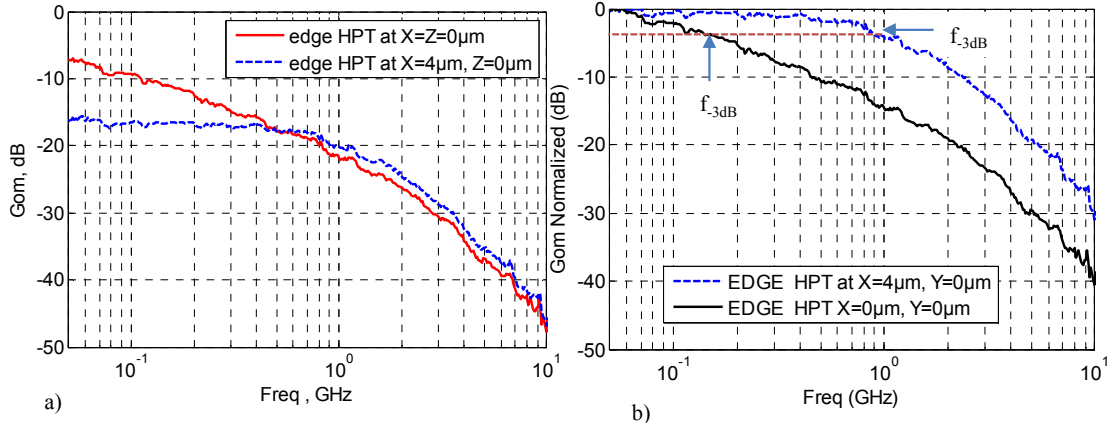
Figure 12: The opto-microwave responsivity of edge HPT versus frequency at x=-4μm and y=0μm and x=y=0μm a) directly extracted. b) Normalized.

5. DISCUSSION

Figure 13 compares the opto-microwave gain versus frequency for an edge illuminated HPT at x=y=0μm (where the peak of responsivity appears) and x=-4μm, y=0μm (where the peak of f_{-3dB} appears) with a top illuminated

HPT having a $10\times10\mu m^2$ optical window. For a top illuminated SiGe HPT, a $10\times10\mu m^2$ optical window size leads to the best performances in terms of opto-microwave responsivity and cutoff frequency compared to $5\times5\mu m^2$ optical window sizes HPT. As shown in Figure 13 a), we observe a low frequency (50MHz) opto-microwave gain of -7dB (opto-microwave responsivity of 0.45A/W) and -10dB (opto-microwave responsivity of 0.32A/W) for edge and top side illuminated HPTs respectively.

The improvement in the responsivity for edge side illumination is related to the increase of the absorption length. It can be up to 5µm long whereas for top illuminated HPT the absorption length is less than 1µm (which is the total thickness of the active area including emitter, base and collector).

Figure 13 b) shows the normalized Gom versus frequency for $10\times10\mu m^2$ HPT with top illumination and for edge illuminated HPT. We observe edge illuminated HPT can reach up to 890MHz cutoff frequency whereas the top illuminated one is limited to 420MHz. We measure higher cutoff frequency for lateral illuminated HPT as its surface area is smaller compared with $10\times10\mu m^2$ optical window size HPT. Compared with the top illuminated structure of about the same size ($5\times5\mu m^2$), the speed of lateral illuminated HPT is much higher.
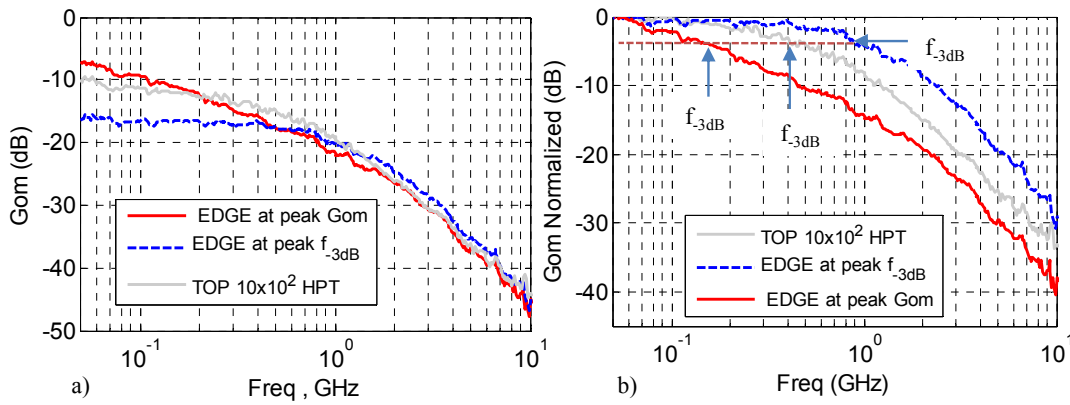

Figure 13: a) The opto-microwave responsivity versus frequency of edge and top ($10\times10\mu m^2$) illuminated HPT. b) The normalized opto-microwave responsivity versus frequency for edge illuminated HPT at x=-4µm and z=0µm and x=y=0µm, and top illuminated HPTs at its peak detection.

6. CONCLUSION

The lateral and edge illuminated SiGe/Si HPTs were designed and fabricated by using the existing SiGe BiCMOS technology. The optical opening is designed by extending the base, emitter and collector of the HBT technology. A two-step post fabrication process was used to create an optical access on the edge through polishing and dicing techniques. A low frequency opto-microwave responsivity of 0.45A/W and opto-microwave cutoff frequency of 890MHz was measured for edge illuminated structure. Compared to top illuminated HPT, edge illuminated HPT improves the cutoff frequency by more than a factor two and also improves the responsivity from 0.32A/W to 0.45A/W while using a simple lensed MMF fiber for the coupling. This phototransistor could be used in further opto-microwave applications whose operating frequency could lie in the 1-10GHz range where integration to Si Integrated Circuits (ICs) and costs are the main issues. Further optical coupling structures could improve the performances. However, these results demonstrate that a simple etched HPT is still enough to achieve improvements compared to the top illuminated HPT without the need of complex coupling structure, even when using MMF

Further improvements of the edge SiGe-HPT performances could be achieved by extending the emitter metallization through the entire emitter contact region. Another way could be to use either smaller optical beam optical source with SMF at 850nm or use MMF with a proper optical coupling structure to characterize the HPTs. One could also take the advantage of the substrate diode to enhance the low frequency responsivity at low frequency.

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