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# Opto-microwave experimental mapping of SiGe/Si phototransistors at 850 nm

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*This paper presents measurement results providing the mapping of the opto-microwave transfer function performed on an SiGe microwave heterojunction phototransistor (HPT). This measurements will be used to extract a guideline for designing phototransistors. A mapping of the HPT's gain in low frequency helps to estimate the shape of the optical beam used for the measurement. The study also focuses on the cutoff frequency mapping of the device in phototransistor mode. Finally, these results are used to determine the general optimization rules in the SiGe HPTs design.*

**Keywords:** Si-based detectors, SiGe, Heterojunction bipolar phototransistors, HPT, Opto-microwave gain mapping

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## I. INTRODUCTION

The SiGe/Si heterojunction phototransistors (HPTs) were initially developed in 2003 by two teams simultaneously: ESYCOM, France [1] and ERSO, Taiwan [2]. These microwave SiGe phototransistors provide an innovative solution for the integration of opto-electronic functions in commercial SiGe bipolar or BiCMOS process technologies, as opposed to SiGe multi-quantum-wells structures. These devices have since been fabricated using several industrial process technologies: Atmel [1], [3], TSMC [2], IBM [4], and AMS [5].

Two key aspects for the optimization of this component are: identification of fast and slow areas within the structure [6, 7], investigation on their impact through more efficient opto-electrical compact circuit models [6, 8, 10]. It has been shown theoretically that the proximity of the base contact to the optical window promotes rapid degradation in the gain of the phototransistor. The proximity of the collector contact in turn degrades the cutoff frequency of the phototransistor with any significant impact on the gain [6]. It is essential to verify these simulated results experimentally in order to provide information on the proper device sizing.

## II. THE SIGE/SI PHOTOTRANSISTOR

### A) Device under test

The SiGe/Si phototransistor was fabricated using the available SiGe1 ATMEL Bipolar Process. The structure is a heterojunction bipolar transistor in which a $10 \times 10\ \mu m^2$ optical window is designed at the center of the emitter. The base is highly doped to reach base sheet resistance below 1 kΩ/□, with an abrupt strained-SiGe profile. A top view of the phototransistor highlighting the emitter window is shown in Fig. 1. A cross-section representation of the phototransistor is given in Fig. 2. The HPT structure is discussed in [1], and its physical modeling is developed in [3, 11].

### B) Measurement setup

A test bench was setup in order to perform opto-microwave measurements in which the optical probe is scanned all over the HPT surface. A vector network analyzer directly modulates an 850 nm multimode VCSEL laser via Port 1.

The laser diode output is injected into the phototransistor through a focusing lensed fiber vertically placed above the HPT optical window. The optical power is 1.14 mW at the end of the fiber. Such a probe is mounted on a nanopositioner. This allows the fiber extremity to have precise movements in the three axes. The nanopositioner is used to achieve a very close fiber-to-chip distance, with the goal of minimizing the spot size on the component. The control of the optical probe height above the HPT surface is made by its observation through a 45° angled mirror as shown in Fig. 3. The spot size is however expected to be greater than the optical window of the HPT, inducing optical coupling losses.

The HPT is a grounded emitter topology, its base and collector are connected to separate Ground-Signal-Ground (GSG) pads in order to perform on-wafer microwaves measurements. Device bias voltages are added through high-frequency bias tees. The collector is connected to Port 2 of the VNA, whereas the base is connected to a 50 Ω load through the bias tee.

For each position of the optical fiber, the opto-microwave gain of the optical link is measured with the use of the VNA over a [50 MHz–10 GHz] frequency range. The dynamic laser diode response is removed through a calibration technique. Finally, a 1 μm step is used for the movement of the optical probe to map a complete 50 μm × 60 μm surface, above the HPT. A diagram of the measurement setup is given in Fig. 4.

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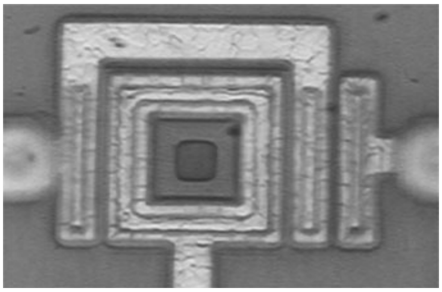

**Fig. 1.** Top view of the phototransistor: collector contact is taken on the right side, emitter contact is the center square, and the base contact is taken on the left side. The 10 μm × 10 μm optical window is visible in the device center.

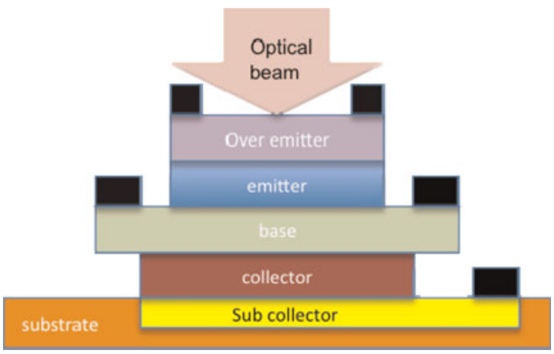


**Fig. 2.** Cross section of the phototransistor.

## III. EXPERIMENTAL RESULTS

The *S*-parameters measurement allowed us to extract the opto-microwave properties of the phototransistor. The $S_{21}$ parameter provides the opto-microwave power gain of the phototransistor, known to be the responsivity of the HPT as both base and collector terminals are connected to a 50 Ω load [2, 9].

The bias collector–emitter voltage is set to 1.5 V and the base–emitter junction is biased at a constant voltage of 0.81 V. Induced base current is 74 μA in dark condition. At the peak illumination, accumulation of holes into the base reduces the current value down to 61.3 μA.

From these measurements, a topographical map of the 50 MHz opto-microwave gain of the phototransistor, versus the position of the optical beam, is determined in Fig. 5.

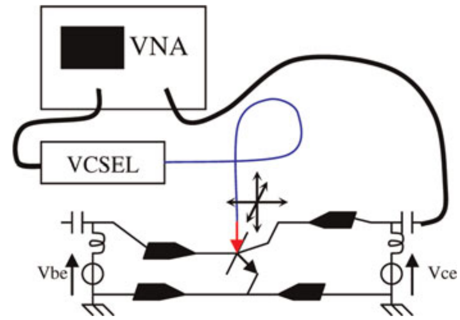


**Fig. 4.** Schematic view of the measurement setup.

To isolate the phototransistor effect from the illumination conditions, we evaluated the shape of the optical beam by a mathematical model with a Gaussian profile. As the base and emitter metalized contacts of the device reflect the injected light, the detection region is limited to the inner part of the phototransistor optical window.

Therefore, the mapping of the opto-microwave response of the phototransistor is the correlation between the square opening window and the Gaussian profile of the optical beam. Thus, the *Erf* function is used to model such a correlation and to fit to the measurements. We then estimated the full-width at half-maximum (FWHM) power of the incident optical beam according to the axes to be 23.5 μm × 28.3 μm, which is higher than the HPT window.

The mapping of the gain is not symmetrical along the *X* axis as shown on the cross-section of the mapping given in Fig. 7. An unexpected secondary peak (centered at $X = 760$ μm) arises to the right side of the maximum gain. However, this region has a very low cutoff frequency as can be seen in Figs 6 and 7, which is the map of the HPT cutoff frequency in phototransistor mode (−3 dB).

This is probably caused by the illumination of the gap area, located between collector and base contacts, which stimulates the collector–substrate junction. The electrical output signal, at the collector, can then be considered as a correlation function of the central optical square window with the sum of two Gaussians, one related to the optical beam injected into the HPT, and the other related to the decentralized detection of the substrate. The second Gaussian has enabled us to significantly reduce the error between simulations and

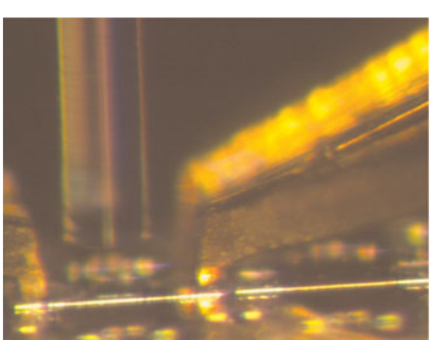

**Fig. 3.** Edge view of the fiber probe illuminating the phototransistor, with base and collector terminals connected with GSG probes.

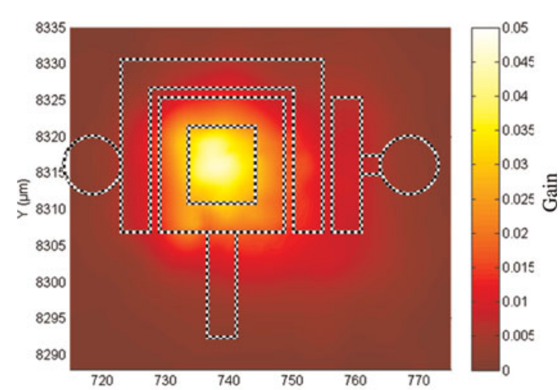


**Fig. 5.** Topographical map of opto-microwave gain at 50 MHz with the estimated position of electrodes.

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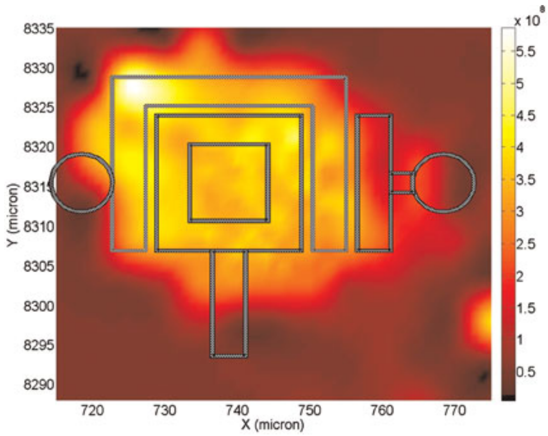


**Fig. 6.** Topographical map of the cutoff frequency in phototransistor mode with the estimated position of electrodes.

measurements. We then obtain very good fit between model and measurement as shown in Fig. 7.

The total error on the integrated energy is less than 20% (less than 1 dB) throughout the measurement area, which allows us to validate our approach. Thus, the real FWHM of the central beam profile is estimated to be 22.0 μm × 27.8 μm.

An optical coupling rate of 77% between the lensed fiber and the HPT window is then deduced.

## IV. DISCUSSION

The proposed correlation model between a Gaussian beam and a square optical window fits to the low-frequency mapping of the HPT response. This indicates that there is no spatial dependence on the HPT responsivity, i.e. opto-microwave gain, when moving the fiber across the optical window. Only the optical coupling ratio is affected and the effective responsivity of the phototransistor keeps then flat whatever is the position of the optical probe along $X$ and $Y$ axes.

On a design concern, this means that the position and distance of electrodes with respect to the optical window seems not to affect significantly the low-frequency responsivity of the HPT. It has to be noticed that modeling results from [6] may indicate that in case of a very thin and collimated 1 μm optical beam some changes may nevertheless infer.

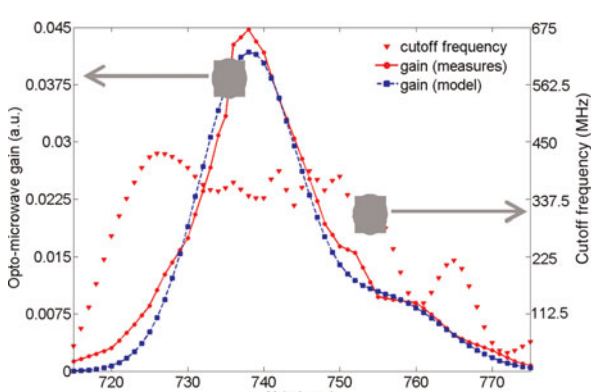


**Fig. 7.** Slice of the phototransistor topographical map at $Y = 8317$ μm.

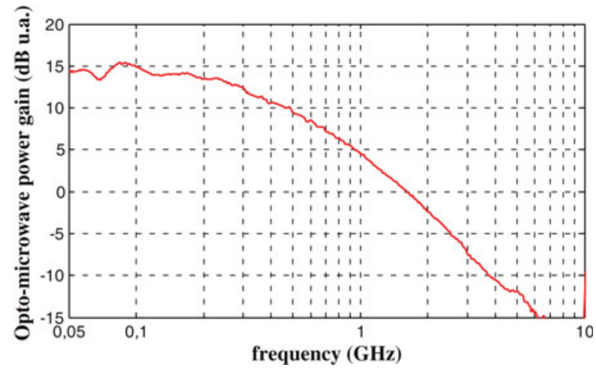


**Fig. 8.** Opto-microwave power gain in relative dB versus frequency at the peak detection point ($X = 738$ μm and $Y = 8317$ μm).

Dynamic behavior however is modified by the position of the fiber, as shown in Figs 6 and 7. The analysis is conducted through the measurement of the 3 dB cutoff frequency of the HPT. The opto-microwave response at the peak detection is plotted in Fig. 8. The cutoff frequency is usually small in the phototransistor mode as the HPT has a −20 dB/dec slope response. This value, while not fully representing the HPT's ability to handle high-frequency signals, is representative of the optical transition frequency mapping as well.

In this case, when the optical beam fully illuminates the optical window, a 340 MHz value is obtained. An increase is then obtained when the fiber moves toward the border of the optical window. The increase is exacerbated when the fiber is illuminating the left side of the HPT. A maximum cutoff frequency of 430 MHz at $Y = 8317$ μm (Fig. 7) and a global maximum of 590 MHz across the whole area (Fig. 6) is obtained.

The main explanation considers that the distance with respect to the collector contact helps to create a lateral gradient for the potential into the structure, as shown in [3], that benefits to the acceleration of holes generated in the base–collector region.

Therefore, it is worth to design an HPT with either interdigitated base and emitter electrodes to minimize the gap between each electrode across the optical window, at the expense of lower optical coupling ratio, or asymmetric collector to exacerbate lateral field within the collector region.

## V. CONCLUSION

A topographical map of a SiGe/Si HPT was presented for the first time. It has been experimentally identified that the removal of contacts to maximize the gain is not crucial, as long as the injected optical beam into the phototransistor is comparable to the size of the optical window. However, the effect of the proximity of base, emitter, and collector contacts to the optical window provides influence on the dynamic characteristics. Design rules may be deduced from such experiments. The effect of lateral electric field due to asymmetry of the structure has been proposed. This information will also possibly help in defining the topology of compact-circuit models to be used for opto-electrical modeling of HPTs.

## ACKNOWLEDGEMENT

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