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Near-infrared photodetectors based on embedded graphene

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Abstract. In last years, the introduction of 2-dimensional materials such as graphene has revolutionized the world of silicon photonics. In this work, we demonstrate a new approach for integrating graphene into silicon-based photodetectors. We leverage a thin film of hydrogenated amorphous silicon to embed the graphene within two different photonic structures, an optical Fabry-Pérot microcavity, and a waveguide, achieving a stronger light-matter interaction. The investigated devices have shown promising performance resulting in responsivities as high as 27 mA/W and 0.15 A/W around 1550 nm, respectively.

1 Introduction

In the last few decades, photonic integrated circuits (PIC) and Silicon Photonics have emerged to face the increasing data centers demand for high data rates and low power dissipation [1-3]. The main drawback of the use of silicon (Si) in photonics originates from its indirect bandgap of 1.12 eV that causes transparency in the Near Infrared range required for telecommunication operations. Recently, new materials such as graphene (Gr) have been employed to overcome these limitations [3-5]. Here, we present a new approach for sub-bandgap photodetection in silicon based on Gr embedded between crystalline (c-Si) and hydrogenated amorphous silicon (a-Si:H). Such a method allows a stronger light-matter interaction and the confinement of the optical field where the Gr is placed. More in detail, we have studied photodetectors (PDs) integrated into two different photonic structures, an optical Fabry-Pérot microcavity and a waveguide (WG), both fabricated starting from a Silicon-On-Insulator (SOI) substrate. In our study, we observed a new photoconversion mechanism able to enhance the current generated by the PDs. This effect is induced by the traps at the Gr/a-Si:H interface that release charge carriers into the Gr when a NIR light illuminates the device.

2 PDs based on Fabry-Pérot microcavities

2.1 Device concept

A sketch of the photodetector based on the a-Si:H/Gr/c-Si hybrid optical cavity is shown in Figure 1a. The a-Si:H/Gr/c-Si three-layer system represents the Fabry-Pérot microcavity whose mirrors are constituted by the air/a-Si:H and c-Si/SiO_2 interfaces. Numerical simulations, performed by implementing the Transfer Matrix Method in Matlab codes, show an increase in Gr optical absorption as a consequence of the interference phenomena inside the Fabry-Pérot microcavity from 2.3 % (suspended Gr) to 12 % (Gr embedded in the cavity). The band diagram of the Metal-Semiconductor-Metal (MSM) Gr/c-Si/Al junction is shown in Fig. 2 when a positive voltage higher than flat-band voltage is applied to Al with respect to Gr.

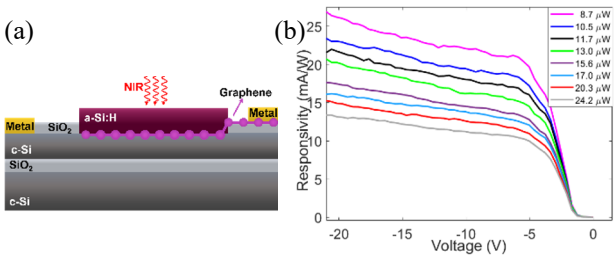

Figure 1 : (a) Device sketch of the Fabry-Pèrot PD. (b) Measured responsivity at 1543 nm vs. negative voltage applied to the PD at various incident optical powers.

2.2 Experimental results

Responsivity (ratio between the photogenerated current and the incident optical power) measurements are shown in Fig. 1b. The measured responsivity (ratio between the photogenerated current and the incident optical power) under NIR illumination, raises the question of which photoconversion mechanism is involved. Indeed, the measurements carried out on the Gr/c-Si Schottky junction before the a-Si:H deposition (not reported in this abstract) showed a responsivity of only 0.06 mA/W at 1550 nm and −20 V not dependent on the incident optical power in line with the IPE theory [4].

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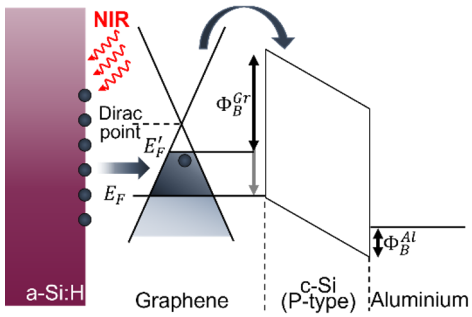

Figure 2 : Photodetection mechanism described through the band diagram of the Gr/c-Si/Al MSM junction.

After the deposition of the a-Si:H, the PD exhibits a responsivity After the increased by more than one order of magnitude and not more constant at different values of the optical power as shown in Fig. 1b. We have ascribed this behavior to the traps at the a-Si:H/Gr interface. Trapped charges are released under the effect of the light causing a change in the Gr Fermi energy and consequently a lowering of the Schottky barrier. As a result, the thermionic current of the Gr/c-Si junction increases (Fig. 2). By following this line of reasoning, we have developed a theoretical model able to match the experimental observations [6]. The responsivity of our devices has a maximum value of 27 mA/W at 1543 nm under an optical power of 8.7 µW, which could be further improved at lower optical power.

3 PDs based on optical waveguides

3.1 Device concept

In the PD integrated into the a-Si:H/c-Si WG (Fig. 3a), the graphene is placed where the propagating field intensity is highest to minimize the length necessary for full absorption of the whole propagating radiation at 1.55 µm. The dimensions of the WG were optimized through numerical simulations performed with the finite-element mode solver COMSOL Multiphysics. The device was fabricated starting from a 220 nm SOI substrate.

3.2 Experimental results

A preliminary optical characterization was accomplished by using a modulated light source at 1.55µm and a tapered optical fiber to launch the laser beam into the WG. The photogenerated current shown in Fig. 3b was measured by using a lock-in technique. Starting from these results, a preliminary responsivity evaluation shows a value of 0.15 A/W at a wavelength of 1540 nm when a reverse bias of -4V is applied to the PD. The higher responsivity of these devices compared to the counterpart based on optical microcavities, has been ascribed to the increased Gr optical absorption.

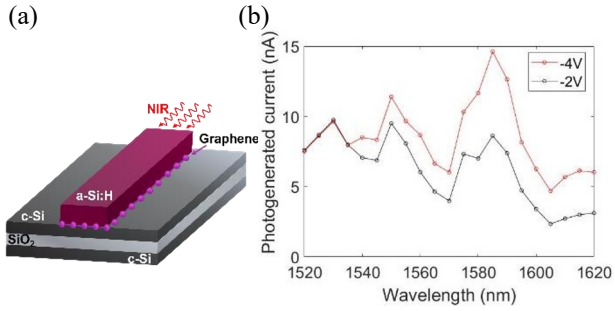

Figure 3 : (a) Device sketch of the waveguide PD. (b) Photogenerated current at different wavelengths and values of polarization.

3 Conclusion

In this work, we have presented the design, fabrication, and electro-optical characterization of a novel kind of Schottky photodetector operating at 1.55µm based on graphene embedded between hydrogenated amorphous and crystalline silicon realized starting from an SOI substrate. We have investigated two configurations based on a Fabry-Pérot optical microcavity and a guiding structure to develop free-space and WG photodetectors, respectively. Under near-infrared illumination, our devices show a not-predicted increase in the thermionic current whose physics has been developed, leading to a good agreement with the experimental observations [6]. A maximum responsivity of 27 mA/W has been measured in the PD based on optical microcavity where the optical absorption of the Gr is estimated to be around the 12%, and a maximum value of 0.15 A/W in the PD integrated into the WG which allows the full absorption of the incident radiation. The investigated devices have shown promising performance opening intriguing perspectives in the field of silicon photonics.

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