Near-infrared Silicon Schottky Photodiodes based on Non-metallic Materials

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Abstract: In this work we have investigated the performance of Schottky photodetectors based on materials non-conventionally used to detect near-infrared wavelengths. In the proposed devices the absorption mechanism is based on the internal photoemission effect. Both three-dimensional (sputtered erbium and evaporated germanium) and two-dimensional materials (graphene) have been considered and their performance compared. Our insights show that silicon Schottky photodetectors have the potentialities to play a key role in the telecommunications opening new frontiers in the field of low-cost silicon photonics.

1 INTRODUCTION

In order to develop all-Si photodetectors (PDs) and to take advantage of low-cost standard Si-CMOS processing technology without additional material or process steps, a number of options have been proposed: two-photons absorption (TPA) (Casalino, 2010), incorporation of optical dopants/defects with midbandgap energy levels into the Si lattice (Casalino, 2010) and internal photoemission effect (IPE) (Casalino, 2010). IPE is the optical excitation of electrons in the metal to energy above the Schottky barrier and then transport of these electrons to the conduction band of the semiconductor. The standard IPE theory is due to Fowler (Fowler, 1931). However, the Fowler's theory was obtained without taking into account the thickness of the Schottky metal layer. The enhancement of IPE in thin metal film was theoretically investigated by Vicker who introduce a multiplicative factor to the Fowler's formula (Vickers, 1971). In addition, a further enhancement in IPE can be obtained due to the increase of the reverse voltage that lowers the Schottky barrier increasing the amount of emitted carriers (Casalino, 2010). Concerning PDs, due to the very low signal-to-noise ratio, for a long time IPE-based Si PDs at infrared (IR) wavelengths were believed usable only at cryogenic temperature. However, in order to enhance the photoemitted current with respect to the noise (dark) current, many structures have been proposed based on: surface plasmon polaritons (SPP) (Berini, 2012), micro- and nano-metric optical waveguide (Goykhman 2012), optical microcavity (Casalino, 2006). Although optical microcavity (Casalino, 2009) has been adopted with success to increase device performance (Casalino, 2008), efficiency of Schottky PDs based on conventional metals or silicides remains two order of magnitude lower than commercial PDs based on III-V compounds (i.e., InGaAs).

In this work we investigate the performance of Schottky PDs based on materials not conventionally used to detect near-infrared wavelengths. Both three-dimensional (sputtered erbium and evaporated germanium) and two-dimensional materials (graphene) have been considered and their performance compared. Our insights show that silicon devices based on IPE are already suitable for power monitoring applications and they could play a key role in the telecommunications opening new frontiers in the field of low-cost silicon photonics.

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2 IPE ENHANCEMENT BY AN OPTICAL MICROCAVITY

In 2008, we experimentally demonstrated the influence of the optical microcavity on IPE for a Schottky Si junction (Casalino, 2008). In this work we proposed a device realized by a resonant cavity Fabry-Perot structure formed by a dielectric bottom mirror, a metallic top mirror and, in the middle, a silicon cavity (Fig. 1). The dielectric bottom mirror was a distributed Bragg reflector (DBR) formed by alternating layers of amorphous hydrogenated silicon (a–Si:H) and silicon nitride (Si_3N_4) having λ/4 thicknesses, while, the top mirror was realized by a copper (Cu) layer working both as absorbing material and as optical mirror.
Responsivity measurements were carried out in the range of 1545–1558 nm (step of 0.05 nm) showing a maximum value of 4.3 μA/W. In addition, a peak responsivity enhancement, due to the increased finesse, of about three times, was demonstrated. Then, in the 2010 we proved that by reducing the size of the device a further increase in responsivity of twice (its value was about 8 μA) could be obtained (Casalino, 2010). Finally, in 2012 we proved that a significant increase in responsivity could be obtained by fulfilling the critical coupling conditions (Casalino, 2012). Main results of (Casalino, 2012) are reported in Fig. 2 where responsivity versus the wavelength is characterized by four distinct peaks deriving from interference phenomenon. The measured free spectral range of 3.3 nm is in a perfect agreement with the cavity thickness (100 μm) while the maximum measured responsivity is 0.063 mA/W. It is worth noting that although responsivity has been increased due to the cavity effect, its value remains quite low due to the intrinsic poor characteristic of the active material used. In fact, metals are characterized by a high reflectivity reducing the amount of absorbed photons that can be converted into electrons. In addition, carriers excited in states far below the Fermi energy gets very low probability to overcome the Schottky barrier. Although efficiency has been increased in integrated device (Casalino, 2013) it remains quite poor in vertically-illuminated devices.

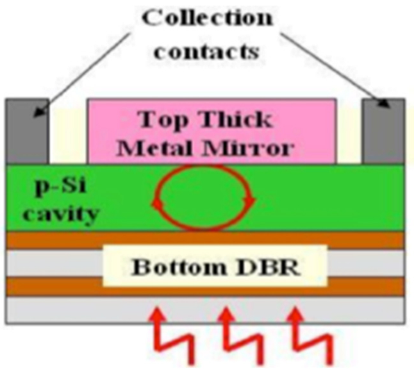

Figure 1: Schematic cross section of the PD reported in (Casalino, 2008).

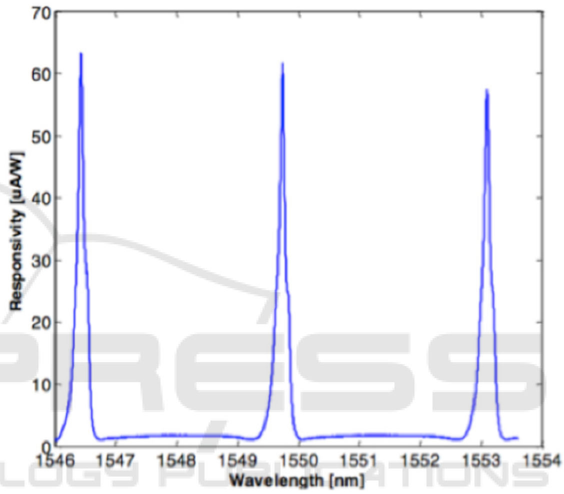

Figure 2: Responsivity vs wavelength of the device proposed in (Casalino, 2012).

In this context, the intrinsic limitations of metals and silicides could be overcome by investigating IPE through new not conventional metallic materials. Indeed, in this work, both three-dimensional (sputtered erbium and evaporated germanium) and two-dimensional materials (graphene), have been considered. The advantage in using non-metallic materials as absorbing active layer is linked to the fact that metals behaves like mirrors reflecting back the most part of the incoming radiation. In other words, only a little amount of the infrared radiation can be absorbed hindering device efficiency. For instance our ellipsometric characterizations show that at 1550 nm reflectivity at Si/Cu and Si/Er interface are 0.97 and 0.2, respectively, as reported in Fig. 3. This means that Cu and Er will be able to absorb 0.03 and 0.8, respectively. Er absorbs much more than Cu and we will expect that efficiency of PDs based on Er/Si Schottky junction will be at least one order of magnitude higher with respect to PDs based on Cu/Si.

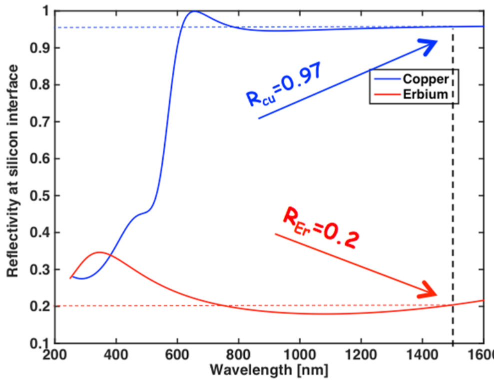

Figure 3: Reflectivity at Er/Si and Cu/Si interfaces.

3 DEVICE FABRICATION AND PRELIMINAR RESULTS

Devices reported in Fig. 1 have been fabricated starting from a bi-polished 200-µm-thick very lightly doped P silicon. Substrate was chosen slightly doped in order to avoid free carrier absorption. After a RCA Si cleaning, substrate has been thermally oxdidized in order to obtain a 100-nm-thick silicon dioxide (SiO_2).

The collecting Ohmic contact and the Schottky contact were both realized on the top of the sample. The collecting contact was made by a ring of 200-nm-thick aluminium film, thermally evaporated at $3 \cdot 10^{-6}$ mbar and 150 °C, patterned by a SiO_2 wet etching and lift-off process of a Shipley S1813 photoresist which, deposited by a spin-coater at 4000 rpm, had a thickness of 1.4 µm. Then, an annealing at 475 °C in nitrogen for 30 min, in order to get a not-rectifying behaviour, was carried out (Card, 1976).

On the wafer back side, a multilayer Bragg mirror was fabricated by Plasma Enhanced Chemical Vapor Deposition technique (PECVD). The mirror was composed by a quarter-wave stack of a–Si:H and Si_3N_4 layers, having nominal refractive index, at 1550 nm, of 3.52 and 1.82, respectively. The reflector was realized with five periods of a–Si:H/Si_3N_4 pairs, whose nominal thicknesses are 110 nm and 213 nm, respectively. Silicon nitride was deposited at pressure of 1.2 mbar, temperature of 250 °C, at 30 W of RF power. In the deposition chamber 10 sccm of NH_3, 88 sccm of SiH_4 (5% in He) and 632 sccm of N_2 are flowed. The deposition rate was about 23 nm/min and the suited Si_3N_4 thickness was obtained with a process time of about 9 min. Amorphous hydrogenated silicon, instead, was deposited at pressure of 0.8 mbar, temperature of 250°C, power of 2 W and a SiH_4 (5% in He) flow of 600 sccm. The a-Si:H deposition rate was about 3 nm/min and the desired thickness was obtained with a process time of about 35 min. A second photolithographic process has been carried out in order to realize two large PADs useful to connect the device to the macroscopic world. To this aim 5-nm-thick chromium (Cr) and 100-nm-thick- Gold (Au) have been thermally evaporated at $3 \cdot 10^{-6}$ mbar and 150 °C and patterned by a lift-off process.

Finally, the Schottky contact was fabricated. The top of the wafer was covered by Shipley S1813 photoresist, exposed and developed in order to obtain a disk surrounded by the Al ring Ohmic contact, as shown in Fig. 3.

Figure 4: Top view of the proposed device before depositing the active material.

Then the active materials was deposited and eventually patterned. On the device shown in Fig. 4 we have deposited three materials: erbium, germanium and graphene.

A Radio-Frequency (RF) Sputtering technique was used for depositing the Erbium (Er) thin film directly on the device, from a 99,9% pure metal Er target. The device was placed on the substrate holder and the deposition chamber was pumped down to a base pressure of $3 \cdot 10^{-6}$ mbar before introducing the process gas (Ar). Er film was then deposited at r.t., with 30 W RF power, at $2.5 \cdot 10^{-2}$ mbar pressure, with a constant 40 scan Ar flux and 11 min deposition time. To overcome the target surface oxidation a 30 min presputtering process at 150 W RF power was necessary before the deposition process.

Germanium (Ge) was thermally evaporated at a pressure of 3×10^{-6} mbar and at a temperature of 150 °C. Substrate was put in rotation in order to increase the uniformity of the deposited layer resulting 100-nm-thick film.

Graphene has been grown on a copper foil at 1000°C in a chemical vapour deposition (CVD) chamber under the flow of CH_4 and H_2. After growth, PMMA has been deposited on top of graphene followed by etching of the copper foil. Then, graphene has been transferred onto the silicon substrate and the PMMA layer has been removed. A characterization of the Raman spectrum of graphene transferred onto substrate has been performed in order to confirm the monolayer nature of the CVD-grown graphene.

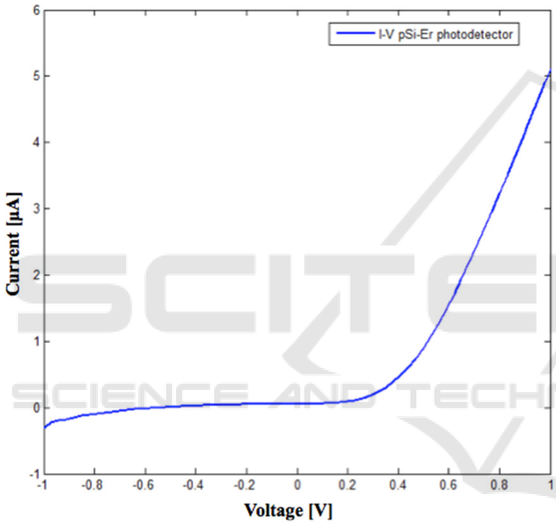

Figure 5: IV characteristic of the Er/pSi PD.

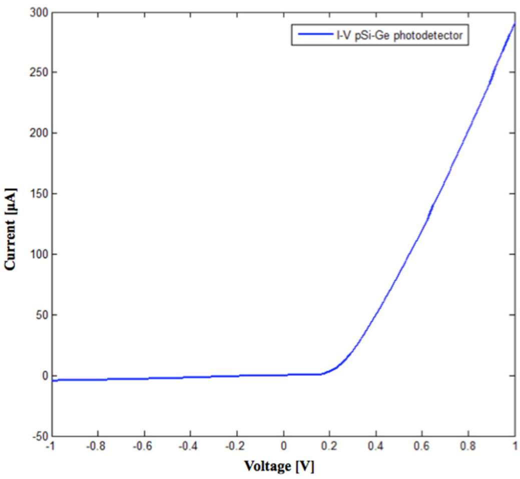

Figure 6: IV characteristic of the Ge/pSi PD.

We have characterized the I-V behaviour of the three junctions in order to extract the Schottky barrier height Φ_B (Aubry, 1994). In all three cases, the rectifying I-V characteristic confirms the Schottky nature of the junction. The IV characteristics of the Er/p-Si and Ge/p-Si Schottky junction have been reported in Fig. 5 and 6, respectively.

The potential barrier of Er/p-Si and Ge/p-Si are 0.49 eV, 0.50 eV, respectively. Moreover the graphene/p-Si Schottky barrier has been measured as 0.55 eV. It can be derived that the cut-off wavelengths for the aforementioned junction are 2.53 µm, 2.48 µm and 2.25 µm, respectively, and thus they are able to detect near-infrared wavelength.

In addition, preliminary responsivity measurements have been carried out with the experimental set-up shown in Fig. 7. The IR light beam emitted by a wavelength tunable laser, has been collimated, chopped and focused onto the device by a long working distance 50X microscope objective providing a beam diameter of about 5 µm. On the other hand, a 20X collecting objective microscope placed at the back of the device has been used to addresses light on an InGaAs Near-Ifrared CCD showing when the light impinges on the active material disk and thus simplifying the alignment procedure. A lock-in amplifier measures the photocurrent produced by our device. A trans-impedance amplifier is employed to provide a reverse bias voltage to the photodetector, and at the same time for reducing the dark current. The dark current cancellation circuit realized by using a trans-impedance amplifier has a limited bandwidth, however it is adequate for our scope, that is DC or quasi-static measurements. Incident optical power was measured with the same experimental set-up, replacing our PD with a calibrate commercial InGaAs PD whose responsivity is very close to the unity.

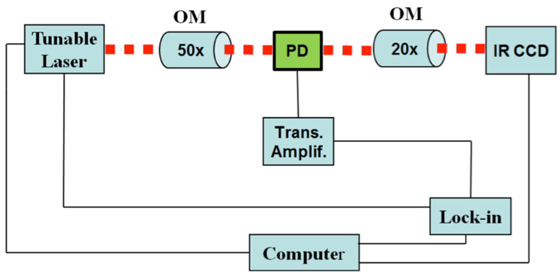

Figure 7: Experimental set-up for external responsivity measurements.

Some preliminary measurements show that the devices based on Ge are characterized by a very low responsivity of 0.02 mA/W. On the other hand, Er and graphene are characterized by a responsivity of about 0.2 mA/W and 0.08 mA/W, respectively. These values are two and one order of magnitude higher than the same devices realized with metals, respectively (Casalino, 2008). Proposed devices show the potentialities to play a key role in the field of silicon photonics.

4 CONCLUSIONS

In this paper we have investigated the responsivity of Schottky photodetectors based on materials non-conventionally used to detect near-infrared wavelengths. Both three-dimensional (sputtered erbium and evaporated germanium) and two-dimensional materials (graphene) have been considered and their performance compared. We have characterized the I-V behaviour of the three junctions in order to extract the Schottky barrier height Φ_B. The potential barrier of Er/p-Si and Ge/p-Si are 0.49 eV, 0.50 eV, respectively. Moreover the graphene/p-Si Schottky barrier has been measured as 0.55 eV. It can be derived that the cut-off wavelengths for the aforementioned junction are 2.53 µm, 2.48 µm and 2.25 µm, respectively, and thus they are able to detect near-infrared wavelength. Some preliminary measurements show that the devices based on Er and graphene are characterized by a responsivity of about 0.2 mA/W and 0.08 mA/W, respectively. These values are two and one order of magnitude higher than the same devices realized with metals, respectively. Our insights show that silicon Schottky photodetectors have the potentialities to play a key role in the telecommunications opening new frontiers in the field of low-cost silicon photonics.

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