Silicon Photodetectors Based on Internal Photoemission Effect: the Challenge of Detecting Near Infrared Light

Maurizio Casalino[1]*, G. Coppola[1], M. Iodice[1], I. Rendina[1], U. Sassi[2], A. Lombardo[2], S. Milana[2], R.S. Sundaram[2], A.C. Ferrari[2], and L. Sirleto[1]

[1] *Institute for Microelectronics and Microsystems–Research National Council, P. Castellino 111, Naples, Italy*
Tel: (0039) 081 6132345, Fax: (0039) 081 6132598, e-mail: maurizio.casalino@na.imm.cnr.it
[2] *Cambridge Graphene Centre, University of Cambridge, CB3 0FA, UK*

ABSTRACT

In this paper an advance overview of our activity in the field of near-infrared silicon photodetectors, is presented. Proposed photodetectors are based on the internal photoemission effect through a Schottky junction and their fabrication results completely compatible with the silicon technology. Taking advantages by both new structures and new two-dimensional emerging materials a progressive increase in device performance has been demonstrated along the last years. Our insights show that silicon devices based on the internal photoemission effect are already suitable for power monitoring application and they could play a key role in the telecommunications opening new frontiers in the field of low-cost silicon photonic.

Keywords: internal photoemission effect, photodetector, Fabry-Perot, near-infrared, silicon.

1. INTRODUCTION

In order to develop all-Si PD 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) [1], incorporation of optical dopants/defects with midbandgap energy levels into the Si lattice [1] and internal photoemission effect (IPE) [1]. The main advantages of these devices reside in their extremely large bandwidth and simple fabrication process, but, unfortunately, their efficiency is very low.

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 [2]. 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 [3]. Finally, a further enhancement in IPE can be obtained due to the increase of the reverse voltage which lower the Schottky barrier increasing the amount of emitted carriers [1]. Concerning photodetectors, due to the very low signal-to-noise ratio, for a long time IPE-based Si PDs, at 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) [4], micro- and nano-metric optical waveguide [5], optical microcavity [6].

2. NIR IPE-BASED SILICON PHOTODETECTORS

In this paragraph we have summarized our results of the last few years devoted to increase the performance of IPE-based Si PDs

2.1 IPE enhancement by an optical microcavity

In 2008, we experimentally demonstrated the influence of the optical microcavity on IPE for a Schottky Si junction [6]. 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. 1a). The dielectric bottom mirror is a distributed Bragg reflector (DBR) formed by alternating layers of amorphous hydrogenated silicon (a−Si:H) and silicon nitride (Si_3N_4) having $\lambda/4$ 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 into the range of 1545 – 1558 nm (step of 0.05 nm). Figure 1b shows the room temperature responsivity versus the wavelength for two devices: the first one with a bottom mirror reflectivity (R_{BM}) of 0.3, (realized by a simple Si/air interface), and the second one, with a bottom mirror reflectivity (R_{BM}) of 0.99 (realised by a DBR with five pairs of Si_3N_4/a-Si:H), respectively. In both cases we observe four peaks. The measured free spectral range of 3.3 nm is in a perfect agreement with the cavity thickness (100 μm). By looking at device having $R_{BM} = 0.3$, the measured cavity finesse F and responsivity are 2.9 and 1.6 μA/W, respectively. Moving our attention on device having $R_{BM} = 0.99$, we get a measured cavity finesse F and responsivity of 4.7 and 4.3 μA/W, respectively. Ultimately, a peak responsivity enhancement, due to the increased finesse, of about three times, was demonstrated.

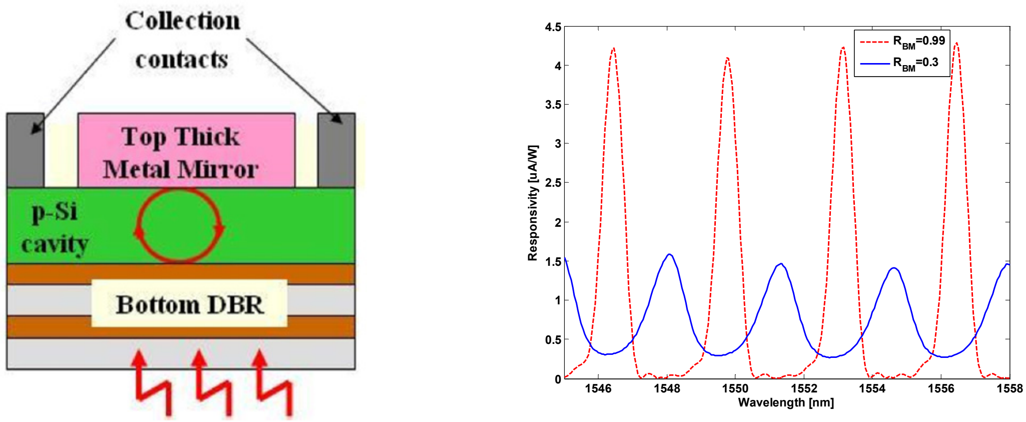

Figure 1. PD reported in ref. [8]: (a) Schematic cross section and (b) responsivity vs. wavelength.

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) can be obtained [7]. Finally, in 2012 we proved, both theoretically and experimentally, that a significant increase in responsivity of 0.063 mA/W could be obtained by fulfilling the critical coupling conditions (Fig. 2a and 2b) [8].

(a) (b)

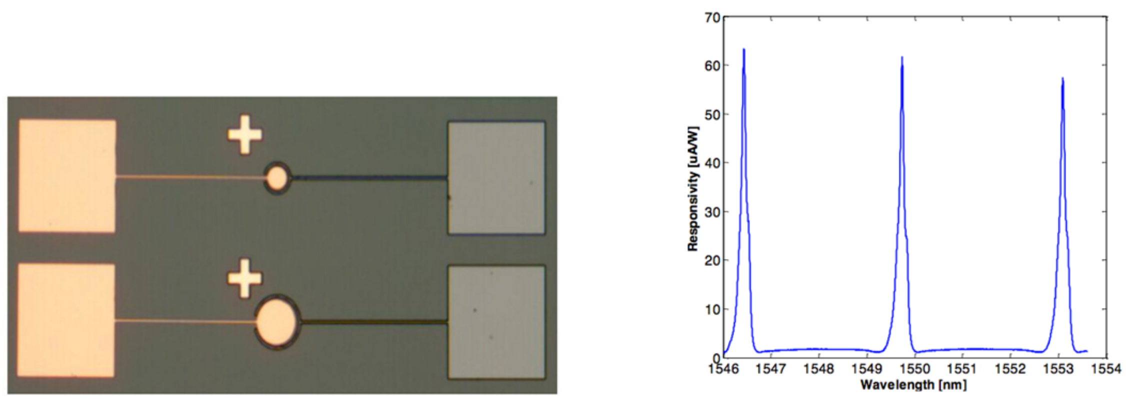

Figure 2. PD proposed in ref. 10: (a) sketch and (d) responsivity vs. wavelength.

2.2 IPE enhancement by a waveguide structure

From the IPE theory is well known that emission of photogenerated carriers into silicon can be increased by lowering the potential barrier. It can be obtained by applying a reverse bias to the Schottky junction [2], but, unfortunately, the high the revere voltage, the high the dark current. Increase in dark current could be limited by reducing the Cu active area in contact with Si but, in this case, the light coupling on a small size of absorbing layer is not a trivial task to reach. A guiding structure can be used in order to overcome this drawback. Very recently we proposed a silicon-on-insulator (SOI) waveguide asymmetric metal-semiconductor-metal (MSM) PD based on IPE and working at 1550 nm [9]. The main novelty of the structure was that the absorbing metal (Cu) is in contact with silicon only on the vertical wall of the optical waveguide. The main advantage was that the device is able to tackle typical responsivity/dark current trade-off, afflicting IPE-based devices performances. Taking advantage of a small contact area of about 3 µm^2 it was possible to increase the reverse applied voltage up to 21 V with a very low dark current of 2.2 nA. In addition an increased responsivity of 4.5 mA/W, and a bandwidth of 1 GHz were demonstrated. Finally, the device exhibits the capability to extend its wavelength cut-off under an applied reverse bias and could be useful for applications in the mid-infrared regime [9].

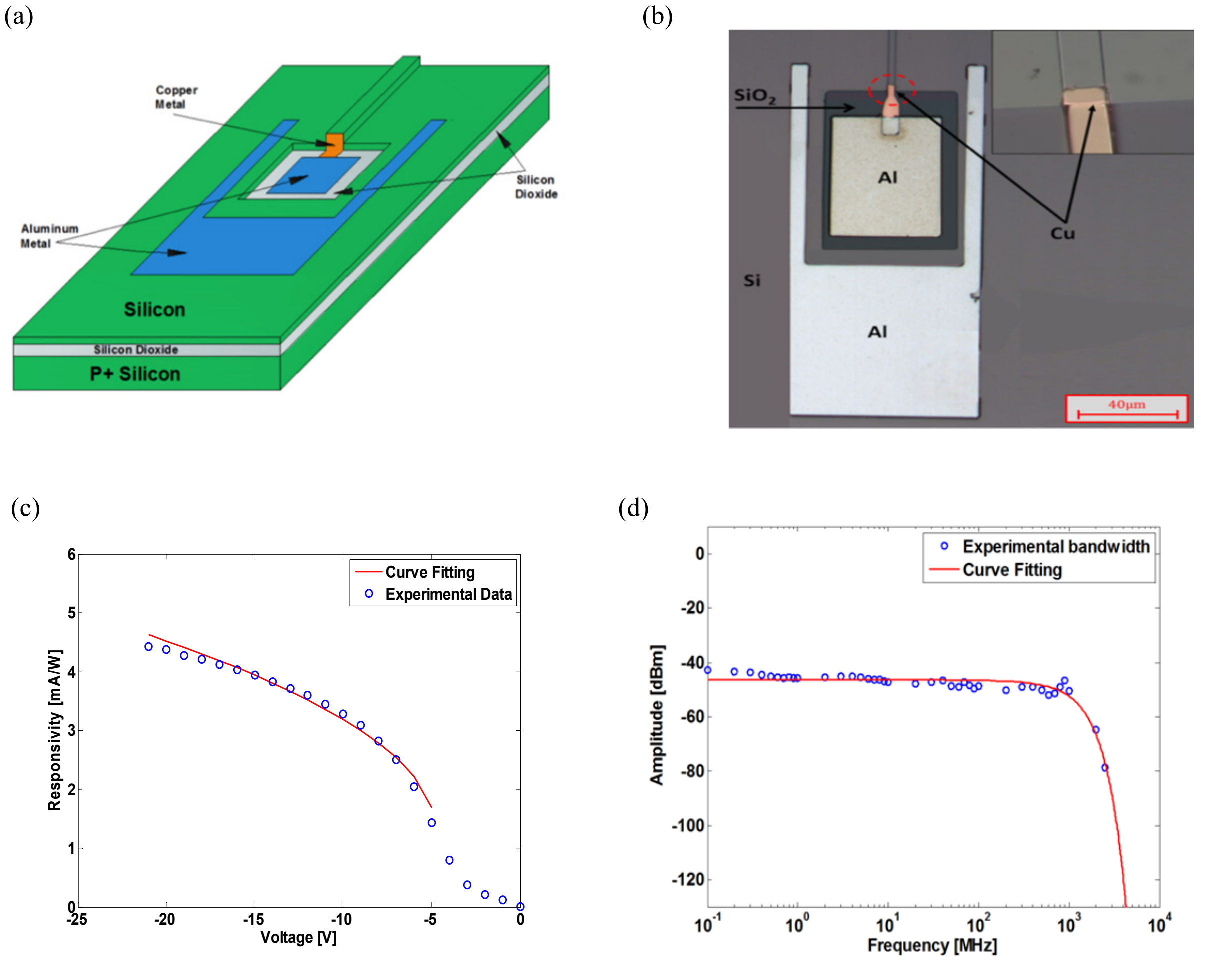

Figure 3. PD proposed in ref. 11: (a) sketch, (b) top view, (c) responsivity vs. reverse voltage and (d) bandwidth.

2.3 IPE enhancement by two-dimensional materials (graphene)

In a recent paper Amirmazlaghani *et al.* [10] show that canonical Fowler's theory is not suitable to describe Schottky junction in which a two-dimensional layer plays the role of the metal. The main reason is that, due to the two dimensionality of the material, the photoexited carriers have more chance to gain the right momentum to overcome the Schottky barrier providing a significantly increase in responsivity. Graphene is a two-dimensional emerging material that is able to form Schottky junction on Si [11] and due to its excellent electrical properties it is the best option to realize IPE-based devices. Unfortunately due to the low graphene absorption (only 2.3%) [12] only a limited responsivity can be expected, however, by introducing the Schottky junction inside e Fabry-Perot microcavity a significant increase in responsivity can be obtained. We have fabricated a Fabry-Perot vertical-to-the-surface structure formed by a bottom and a top metal mirror surrounding a λ/2 silicon layer. The air-silicon and graphene/silicon interfaces act as bottom and top mirror, respectively. The samples were fabricated starting from a quasi-intrinsic bi-polished 100-μm-thick silicon wafer. Substrate was chosen quasi-intrinsic in order to avoid free carrier absorption (Fig. 4a). Graphene was grown on copper foil by the typical chemical vapour deposition (CVD) method and then transferred on Si (Fig. 4b). Responsivity measurements into the range of 1543 – 1558 nm (step of 0.05 nm) at -1V of reverse voltages have been carried out and reported in Fig. 4c. It is possible to observe four distinct peaks due to the interference inside the Fabry-Perot micorcavity. It is worth noting that the higher the wavelength the lower the peak responsivity, this behaviour is typical of IPE whose absorption reduces by increasing the wavelength due to the decrease in photon energy. The same analysis has been repeated to various reverse voltages of -2, -3, -5 V (Fig. 4d). A maximum responsivity of about 0.08 mA/W at -5 V around 1550 nm, has been experimentally demonstrated. This value is more than one order of magnitude higher than that reported in Fig. 1b (blue solid line) for a similar device but realized with Cu.

3. CONCLUSIONS

In this work we have reported the advances of our activity in the field of Si PDs based on IPE working at 1550 nm and at room temperature. The best performance of our device in term of responsivity, bandwidth and dark current are 4.5 mA/W, 1 GHz and 2.2 nA, respectively. Our results prove that these devices are already suitable for power monitoring applications, in addition, new perspectives seem to be opened by the rise of new two dimensional material like graphene. It is our opinion that this material combined to the fabrication of new structures will push IPE-based Si PDs to play a key role in the telecommunications, opening new frontiers in the field of low-cost silicon photonic.

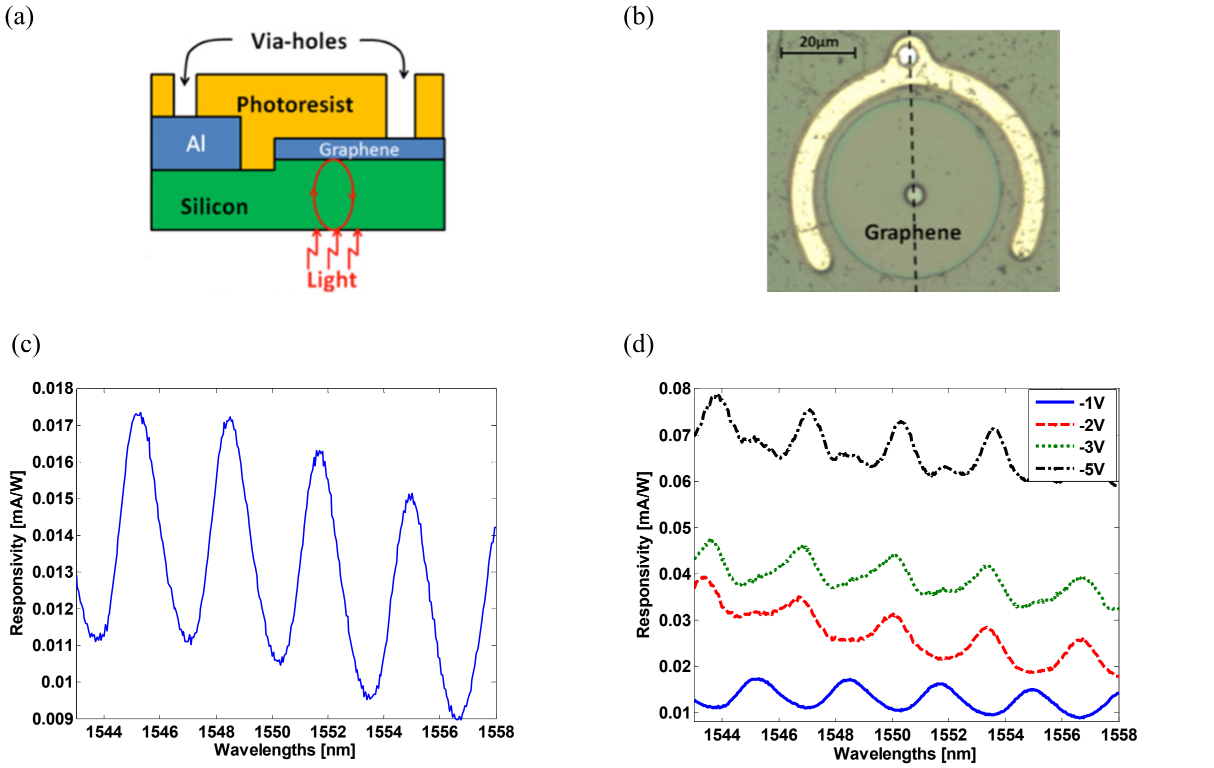

Figure 4. New resonant cavity enhanced vertically-illuminated graphene/Si PD: (a) schematic cross section, (b) top view, (c) responsivity vs. wavelength at -1V and (d) responsivity vs. wavelength at -1V, -2V, -3V and -5V.

REFERENCES

[1] M. Casalino *et al.*: Near-infrared sub-bandgap all-silicon photodetectors: State of the art and perspectives, *Sensors*, vol. 10, pp. 10571-10600, 2010.

[2] R.H. Fowler: The analysis of photoelectric sensitivity curves for clean metals at various temperatures, *Phys. Rev.*, vol. 38, pp. 45-56, 1931.

[3] V.E. Vickers: Model of Schottky barrier hot-electron-mode photodetection, *Appl. Opt.,* vol. 10, pp. 2190-2192, 1971.

[4] P. Berini *et al.*: Thin Au surface plasmon waveguide Schottky detectors on p-Si, *Nanotechnology*, vol. 23, pp. 444011, 2012.

[5] I. Goykhman *et al.*: Waveguide based compact silicon Schottky photodetector with enhanced responsivity in the telecom spectral band, *Opt. Express*, vol. 20, pp. 28594-28602, 2012.

[6] M. Casalino *et al.*: Silicon resonant cavity enhanced photodetector based on the internal photoemission effect at 1.55 micron: Fabrication and characterization, *Appl. Phys. Lett.*, vol. 92, pp. 251104, 2008.

[7] M. Casalino *et al.*: Cavity enhanced internal photoemission effect in silicon photodiode for sub-bandgap detection, *Lightwave Technol.*, vol. 28, pp. 3266-3272, 2010.

[8] M. Casalino *et al.*: Critically coupled silicon Fabry-Perot photodetectors based on the internal photoemission effect at 1550 nm, *Opt. Express*, vol. 20, pp. 12599-12609, 2012.

[9] M. Casalino *et al.*: Asymmetric MSM sub-bandgap all-silicon photodetector with low dark current, *Optics Express*, vol. 21, pp. 28072-28082, 2013.

[10] M. Amirmazlaghani *et al.*: Graphene-Si Schottky IR detector, *IEEE J. of Quant. Elect.*, vol. 49, pp. 589-594, 2013.

[11] C. Chen *et al.*: Graphene-silicon Schottky diodes, *Nano Lett.*, vol. 11, pp. 1863-1867, 2011.

[12] K.S. Novoselov *et al.*: A roadmap for graphene, *Nature*, vol. 490, pp. 192-200, 2012.