Ge micro-crystals photedetectors with enhanced infrared responsivity

(Student paper) / (Invited paper)

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Ge-on-Si micro-crystals grown on Si patterned substrates can be used as absorbing elements for photodetection in the near-infrared. In such microstructures light confinement effects, due to crystal faceting and pattern periodicity, enhance light absorption in the near-infrared as compared to conventional epitaxial layers. The fabricated devices, with graphene as top contact, feature a responsivity exceeding that of planar devices with comparable thickness.

Keywords: *Microcrystal, photodetector, graphene, near-infrared enhancement*

INTRODUCTION

The direct epitaxial growth of germanium on silicon (Ge-on-Si) has fostered the development of near infrared detectors for telecom and imaging applications [1]. The long wavelength responsivity of these devices is limited to approximately 1550 nm corresponding to the direct energy gap of Ge $E_{g\Gamma}$= 0.8 eV. Indeed, the absorption coefficient at the indirect gap E_{gL}= 0.66 eV (λ≈1800 nm) is roughly two orders of magnitudes lower than that above the direct gap threshold. A sizable absorption within the 1550-1800 nm windows would, therefore, require exceedingly thick epilayers which would lead to wafer bowing and crack formation. An extended infrared absorption would be beneficial for imaging applications since long wavelength radiation is less affected by Rayleigh and Mie scattering limiting visibility in fog and dusty conditions.

A viable route to enhance the responsivity of Gen-on-Si photodetectors in the 1550-1800 nm region might be exploiting the micro-structuring of the absorbing layer to increase the effective volume of interaction between light and matter.

In this work we report on a new type of detector, obtained from Ge micro-crystals epitaxially grown on a patterned Si substrate [2]. The faceted morphology and relatively high aspect ratio of the microcrystals is seen to enhance the detector responsivity in the wavelength region comprised between the direct (λ≈1550 nm) and indirect (λ≈1800 nm) gap of Ge, as compared to conventional planar devices.

EPITAXIAL GROWTH, MODELLING AND DEVICE FABRICATION

The epitaxial growth has been performed by means of Low-Energy Plasma-Enhanced CVD (LEPECVD). Microcrystal formation is based on the self-assembly of Ge crystals on a Si substrate, deeply patterned by optical lithography and reactive ion etching. 3D microcrystals, several micrometer tall and characterized by a limited lateral expansion, are obtained by using optimized growth parameters [3]. Due to crystal faceting and pattern periodicity, enhanced light absorption as compared to conventional epitaxial layers, is expected. This makes Ge micro-crystals interesting building blocks for optoelectronic devices, able to operate in the near-infrared spectral region.

Modeling of the near-IR absorption properties of the Ge-on-Si micro-crystals has been performed by finite difference time domain (FDTD) simulations [4]. The ratio between the calculated fraction of absorbed power of an array of Ge-on-Si micro-crystals and a planar Ge-on-Si epilayer is represented in Figure 1. The absorbed power ratio is always higher than one, with a relevant increase in the indirect gap wavelength range.

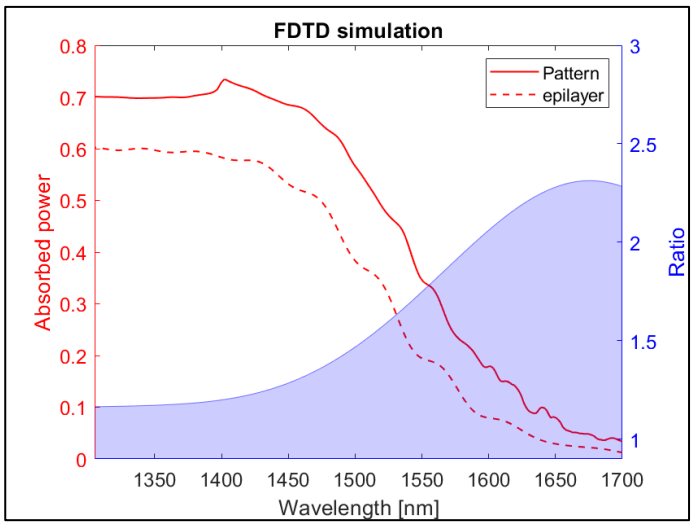

Fig.1 Fraction of absorbed power of Ge- on-Si microcrystals (continuous red line) and Ge epilayer (dashed red line). Ratio between the calculated fraction of absorbed power of Ge-on-Si micro-crystals and the fraction of absorbed power of an equivalent planar epilayer (blue curve).

The main challenge in realizing vertically illuminated photodiodes based on Ge-on-Si microcrystals is the formation of a top transparent contact that can adapt to the 3D-morphology of the surface and bridge the 100-200 nm gap between adjacent microcrystals. To this purpose, graphene can be used as a suspended continuous top contact, with an absorption that does not exceed 2.4%. The fabrication process consists in the depotision of a SiO_2 layer and a subsequent opening of a window on the patterned area by means of optical lithography and HF wet etch. In this way the graphene layer will establish an electrical contact with the Ge micro-crystals and be isolated from the unpatterned area. A second step of optical lithography and evaporation allow the generation of the metal contact, Au/Ti, on the unpatterned region. In the last fabrication step a wet-transfer process is used to form the graphene top contact, as schematically shown in Figure 2. After the wet transfer of a single graphene layer observation by SEM revealed the presence of cracks leading to a not continuum top contact over the patterned area, generating a "spider web" effect. The reason behind this could be capillary forces that play an important role for this type of patterned substrate in which the distance between the pillars is the order of a hundred nanometers.

Different strategies have been tried to solve this issue. Eventually, the number of suspended graphene layers was increased and a graphene bilayer was obtained by modifying the transfer process. The absorption due to such graphene bilayer, is estimated to be around 5% and therefore will not significantly affect the efficiency of the optoelectronic device.

PHOTOCURRENT MESUARUMENTS

The fabricated devices have been characterized by electrical and optical measurements that confirm the near- IR photoresponse [5].

A confocal microscope with a supercontinuum laser source (1300 - 1800 nm), has been used to obtain the photodetector responsivity. The spot size is smaller than the patterned area (100 µm x 100 µm) thus enabling the illumination of a few Ge-on-Si micro-crystals.

Responsivity measurements experimentally confirm the enhanced absorption close to the germanium indirect gap. Fixing the reverse bias at -2V the responsivity of the micro- crystals is substantially larger than that of the epitaxial layer in the 1550- 1800 nm wavelength range (Fig.3). This responsivity enhancement in the near-infrared region is linked to light-trapping effects taking place within the micro-crystals array. The responsivity ratio trend confirms the trend observed in the simulation (Fig.1). The detailed dependence of the photoresponse spectra shape on the pattern geometry and micro-crystals morphology, are still under investigation.

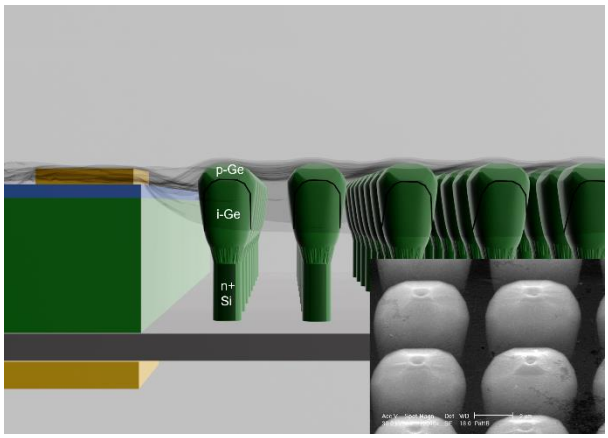

Fig.2 Schematic view and SEM image (inset) of the fabricated device. Graphene is used as a trasparent top contact to extract the photocurrent generated within the Ge-on-Si microcrystals.

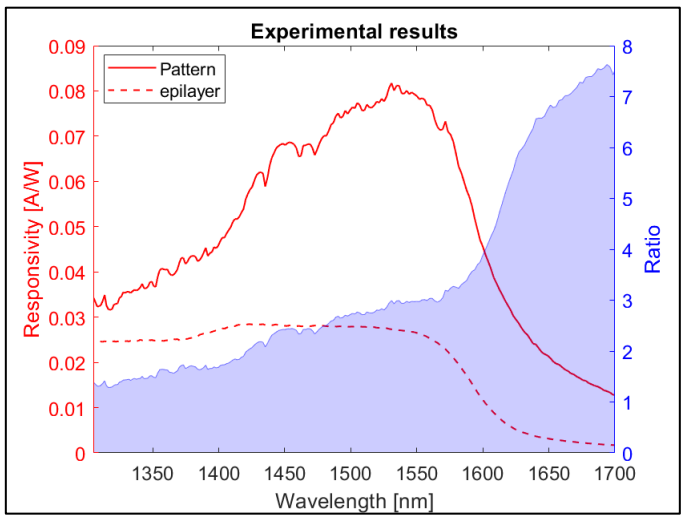

Fig.3 Responsivity at a reverse bias of -2V: of a Ge epitaxial layer (dashed red line) on Si substrate and Ge/Si micro-crystal (continuous red line); The blue curve is the ratio of these two quantities.

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