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Ge and Si Microcrystal Photodetectors with Enhanced Infrared Responsivity

Abstract— **Ge and 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 facet, enhance light absorption in the near-infrared as compared to conventional epitaxial layers. Devices based on single micro-crystals and on micro-crystals arrays have been fabricated and characterized.**

The photocurrent of Si photodetectors based on single micro-crystals have been measured in linear and avalanche regime, demonstrating a state-of-the-gain of ≈10^4.

Ge-on-Si photodetectors based on micro-crystal arrays, fabricated using graphene as top contact, have also been fabricated, showing a responsivity in the 1500-1800 nm exceeding that of conventional planar devices.

I. 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^{Γ}= 0.8 eV). Indeed, the absorption coefficient at the indirect gap (E_g^{L}= 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. On the other hand, 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 [2].

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 [3].

In this work we report on a new type of detector, obtained from Ge or Si micro-crystals epitaxially grown on a patterned Si substrate [4, 5]. 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.

II. Epitaxial Growth, Modeling and Characterization

A. Epitaxial growth

The micro-crystal epitaxial growth has been performed by means of Low-Energy Plasma-Enhanced CVD (LEPECVD). Micro-crystal formation is based on the self-assembly of Ge or Si crystals on a Si substrate, deeply patterned by optical lithography and reactive ion etching. 3D micro-crystals, several micrometer tall and characterized by a limited lateral expansion, are obtained by using optimized growth parameters [6]. Due to crystal faceting, enhanced light absorption, as compared to conventional epitaxial layers, is expected.

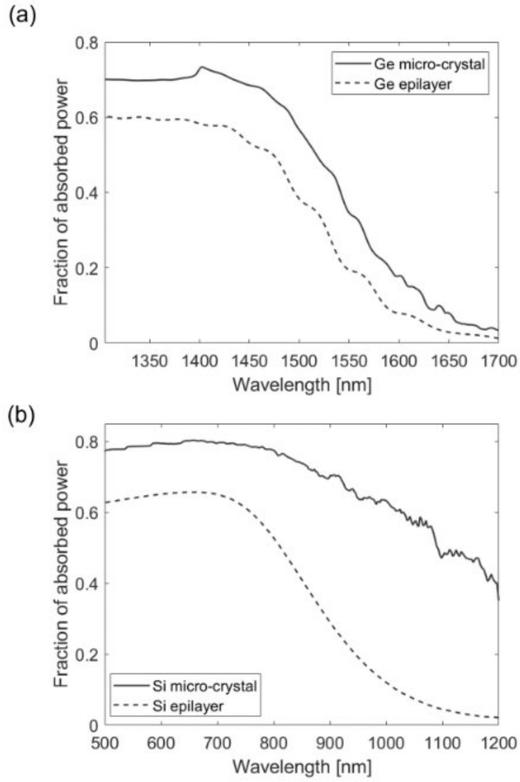

Figure 1. Figure 1. Fraction of absorbed power for: (a) Ge micro-crystal and Ge .equivalent planar epilayer; (b) Si micro-crystal and Si equivalent epilaye

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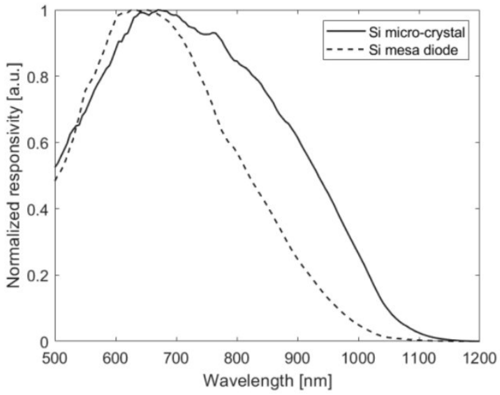

Figure 2. Comparison between the responsivity of a Si micro-crystal and a Si mesa diode.

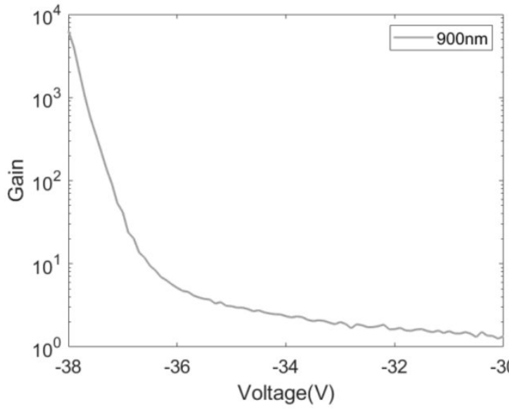

Figure 3. Gain of Si micro-crystal operating as an APD for a wavelength of 900 nm.

B. .FDTD simulations

Modeling of the visible and near-IR absorption properties of Si and Ge-on-Si micro-crystals has been performed by finite difference time domain (FDTD) simulations [3, 4]. The simulations have been implemented also for an equivalent planar epilayer, both for Si and Ge. The results of the simulations for patterns of Ge and Si micro-crystals and their equivalent planar epilayer are shown in Fig.1. The simulations confirmed that crystal faceting lead to enhanced light absorption as compared to conventional epitaxial layers and makes Si-Ge micro-crystals promising building blocks for optoelectronic devices operating in the VIS- NIR spectral region.

C. Responsivity measurements

To experimentally confirm the FDTD results we proceeded with the electro-optical characterization of a single micro-crystal. An experimental set-up based on a nanomanipulator with a tip of 100 nm and a confocal microscope has been used. The responsivity obtained for a single micro-crystal proved the VIS-NIR photoresponse and the enhancement with respect to an equivalent planar epilayer (Fig.2). The Si micro-crystals have been grown with a doping profile tuned for their operation as photodetector in the linear regime but also as avalanche photodiodes (APD). For this reason, with the same set-up described above, measurements in the avalanche regime, i.e. very close to the breakdown voltage, have been performed. Fig. 3 shows the measured gain as a function of the reverse bias for an incident wavelength of 900 nm. The measured watergain reaches a maximum value of 10^4, comparable to state-of-the-art literature reports [7].

After the characterization of a single micro-crystal we proceeded with the fabrication of a photodetector based on micro-crystal arrays. The main challenge in realizing vertically illuminated photodiodes based on micro-crystals is the formation of a top transparent contact that can adapt tothe 3D surface morphology and bridge the 100-200 nm gap between adjacent microcrystals. To this purpose, we decided to use graphene as a suspended continuous top contact, with an absorption that does not exceed 2.4%.

The Ge micro-crystals based devices have been characterized by electrical and optical measurements. Responsivity measurements confirm the enhanced absorption close to the germanium indirect gap. Fixing the reverse bias at -2V the responsivity of the micro-crystals is ten times that of treference epitaxial layer in the 1550-1800 nm wavelength range [5].

III.CONCLUSIONS

Simulations and measurements confirm the possibility of exploiting 3D self-assembled micro-crystals as a new class of photodetectors, exploiting light trapping phenomena in self assembled semiconductors microstructures.

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