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Photodetectors based on 3D self-assembled Ge and Si micro-crystals

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1. Introduction

The direct epitaxial growth of silicon and germanium on silicon (Ge-on-Si) has fostered the development of visible - near-infrared detectors for telecom and imaging applications [1]. A viable route to enhance the responsivity of such photodetectors 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 detectors, obtained from Si and Ge micro-crystals epitaxially grown on a patterned Si substrate [2,3]. The faceted morphology and relatively high aspect ratio of the micro-crystals is seen to enhance the fraction of absorbed light and the detector responsivity as compared to conventional planar devices. This enhancement is present in the indirect regime of absorption of Ge, for the Ge micro-crystals, and in the NIR for the Si micro-crystals.

2. Epitaxial growth, modelling and characterization

2.1. Epitaxial growth

The 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 [3]. Due to crystal faceting and pattern periodicity, enhanced light absorption as compared to conventional epitaxial layers, is expected.

2.2. FDTD simulation

Modeling of the visible - near-IR absorption properties of Si and Ge-on-Si micro-crystals has been performed by finite difference time domain (FDTD) simulations [4,5]. 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 represented in Fig.1. The simulations confirmed that crystal faceting and pattern periodicity lead to enhanced light absorption as compared to conventional epitaxial layers and

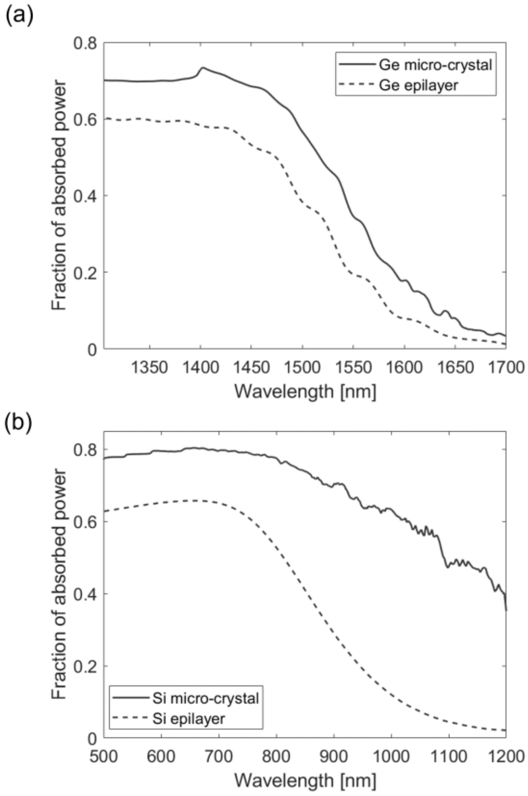

Fig. 1. Fraction of absorbed power for: (a) Ge micro-crystal and Ge equivalent planar epilayer; (b) Si micro-crystal and Si equivalent planar epilayer.

makes Si-Ge micro-crystals promising building blocks for optoelectronic devices operating in the VIS- NIR spectral region.

2.3. 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 was 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 to 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. This gain reaches a maximum value of 10^4, comparable to state-of-the-art literature reports [6].

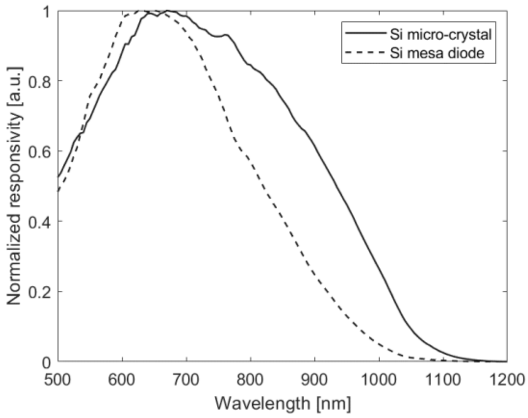

Fig. 2. Comparison between the responsivity of a Si micro-crystal and a Si mesa diode. An enhancement of the responsivity is observed in NIR region.

After the characterization of the single as-grown micro-crystal we proceeded with the fabrication of a photodetector based on such 3D micro-crystals. The main challenge in realizing vertically illuminated photodiodes based on micro-crystals is the formation of a top transparent contact that can adapt to the 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 fabricated 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 the epitaxial layer in the 1550-1800 nm wavelength range (Fig.4) [5].

3. 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.

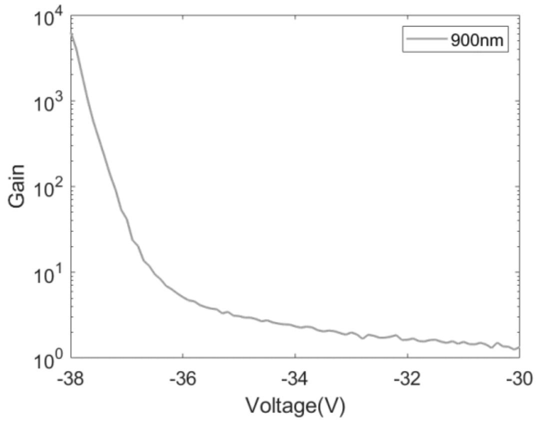

Fig. 3. Gain of Si micro-crystal operating as APD for a wavelength of 900 nm.

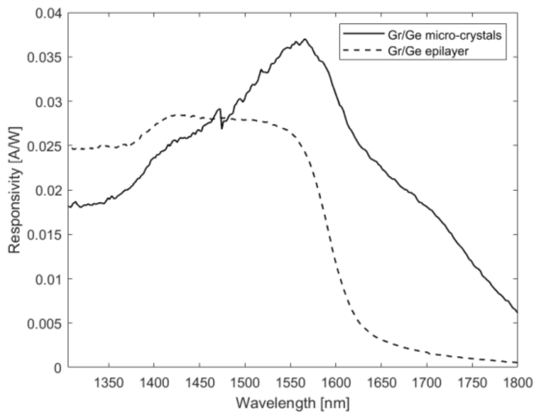

Fig. 4. Responsivity of graphene/Ge micro-crystals device and of graphene/Ge equivalent epilayer.

Acknowledgements

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