IL NUOVO CIMENTO **45 C** (2022) 203
DOI 10.1393/ncc/i2022-22203-8

Communications: SIF Congress 2021

Optoelectronic characterization of NIR photodetectors based on Ge-on-Si microcrystals and microcrystal arrays

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received 11 February 2022

Summary. — We report on the electro-optical characterization of Ge-on-Si microcrystals grown on Si patterned substrates, that can be used as absorbing elements for photodetection in the near-infrared (NIR). In such microstructures, light confinement effects, due to crystal faceting and pattern periodicity, enhance light absorption as compared to conventional epitaxial layers. By means of current-voltage and photoresponse measurements, performed on single microcrystals, we have investigated the optoelectronic properties of individual microcrystals and compared them with those of microcrystal arrays connected by a suspended graphene layer and those of a planar reference device. Microcrystal-based devices show enhanced photoresponse in the 1550–1700 nm spectral range, as compared with planar devices, in agreement with finite difference time domain (FDTD) simulations of light-trapping effects in such microstructures.

1. – Introduction

The direct epitaxial growth of germanium on silicon (Ge-on-Si) has pushed towards the development of detectors in the near-infrared (NIR) wavelength range, suitable for telecom and imaging applications [1]. However, the responsivity of these devices at long wavelengths is limited to ≈1550 nm, corresponding to the direct gap of Ge ($E_{g\Gamma} = 0.8\,\text{eV}$). Indeed, at longer wavelengths the absorption coefficient strongly decreases, and at indirect gap $E_{gL} = 0.66\,\text{eV}$ ($\lambda \approx 1800\,\text{nm}$) it is about two orders of magnitudes lower as compared to the one at $\lambda = 1550\,\text{nm}$ [2]. A larger photoresponse in the 1550–1800 nm region would be beneficial for imaging applications, yet thick epilayers would be required, which may lead to wafer bowing and crack formation. To overcome these issues, microstructuring can be exploited for increasing the effective volume of interaction between the incoming light and the absorbing layer.

In this work we investigate the electrical and optical properties of Ge-on-Si microcrystals for photodetection applications. Due to crystal faceting and pattern periodicity, enhanced light absorption is expected in such microstructures, when compared with conventional epitaxial layer. This is demonstrated both by numerical modelling and photocurrent experiments performed on individual microcrystals and microcrystals array.

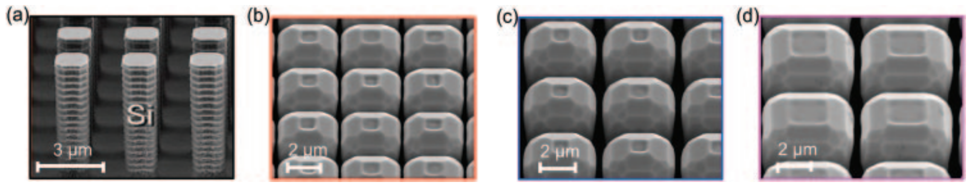

Fig. 1. – Bird's eye view SEM images of (a) a patterned Si substrate and Ge-on-Si microcrystals deposited on Si pillars with lateral dimension W and inter-pillar gap G equal to: (b) $W = 2\,\mu$m $G = 2\,\mu$m; (c) $W = 2\,\mu$m $G = 3\,\mu$m; and (d) $W = 3\,\mu$m $G = 3\,\mu$m.

2. – Sample growth and numerical modelling

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, characterized by a limited lateral expansion and well defined top facets, are obtained by using low-energy plasma-enhanced CVD (LEPECVD) [3]. A p-i-n heterojunction is obtained by depositing 5 μm of intrinsic Ge followed by 200 nm of p-type Ge on an n-type patterned Si substrate. Figure 1 shows the top-view scanning electron microscopy (SEM) images of Ge-on-Si microcrystals deposited on $\approx$8 μm tall patterned Si pillars with lateral dimension W and interpillar gap G ranging from 2 to 3 μm. Modelling of the near-IR absorption properties of the Ge-on-Si microcrystals has been performed by finite difference time domain (FDTD) simulations [4, 5]. In the simulations, the fraction of absorbed power A has been calculated for both the microcrystals and a reference Ge-on-Si epilayer in the 1300–1700 nm range.

3. – Opto-electronic characterization

To experimentally investigate the simulated optical properties, electrical and optical characterization of the microcrystals have been performed. By combining a confocal

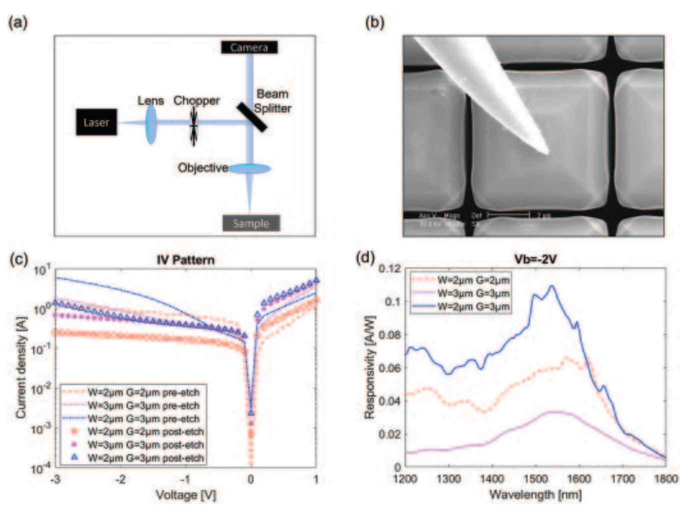

Fig. 2. – (a) Sketch of the confocal set-up. (b) SEM image of the nanomanipulator tip contacting a single microcrystal; (c) IV curve of three different microcrystal morphologies pre- and post-etch; (d) responsivity of single microcrystals.

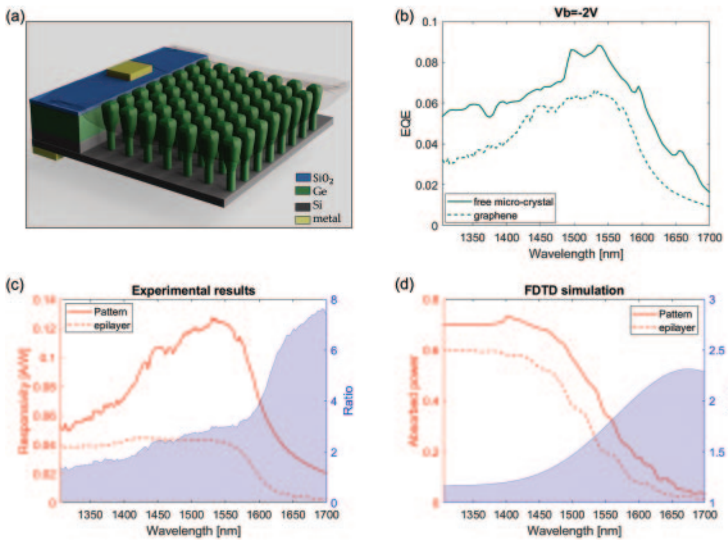

Fig. 3. – (a) Sketch of the fabricated device (b) external quantum efficiency (EQE) of a single microcrystal and of a microcrystal array with graphene top contact. (d) Responsivity of the microcrystal array and of the epilayer photodiodes (left axis), and their ratio (shadowed area, right axes). (e) Absorbed power for the microcrystal and epilayer obtained by FDTD simulations (left axis), and their ratio (shadowed area, right axis).

microscope with a nanomanipulator (fig. 2(a), (b)), it has been possible to measure the IV curve and photocurrent of a single microcrystal. The IV curves of as-grown microcrystals feature poor rectifying behaviour, an improvement of the post-growth IV curve is achieved after a 2 min H_2O_2 wet etch (see fig. 2(c)).

The optical characterization of a single microcrystal was performed in the wavelength range between 1300 and 1800 nm using a supercontinuum laser focused by an objective yielding a spot with almost the same size of a single microcrystal. A mechanical chopper, working at 831Hz, was used to modulate light. The photocurrent generated by the single microcrystals was then collected and amplified by a transimpedance amplifier (TIA) and demodulated by a lock-in amplifier. The resulting responsivity of the microcrystal is shown in fig. 2(d), for the three different morphologies shown in fig. 1 at the same reverse bias of -2 V.

Notably, the responsivities of the three microcrystals show a similar spectral dependence. The microcrystal showing the highest ratio between indirect and direct regime is the one with predominant (001) facet ($W = 3\,\mu$m $G = 3\,\mu$m). In this case, the responsivity at 1700 nm is 40% of the responsivity at 1550 nm. To analyse the optical properties of the microcrystal array, a further fabrication process is required to obtain a top transparent contact connecting in parallel all the microcrystals as shown in fig. 3(a). To this purpose, graphene has been chosen, since its absorption does not exceed 2.4% of the incoming light [5] and its mechanical properties could, in principle, fit all the requirements posed by the microcrystal morphology. The fabricated devices, schematically shown in fig. 3(a), have been characterized by electrical and optical measurements (analogous to those already described) that confirm the near-IR photoresponse [5]. A comparison between the photoresponse of a single microcrystal and of the microcrystal array is shown in fig. 3(b). The shape and the ratio between the indirect and direct absorption regimes are nicely similar in the two cases.

Finally, the photoresponse of graphene Ge-on-Si microcrystal device can be compared with that of a planar photodiode fabricated in the unpatterned region, as done in fig. 3(c), (d). We notice enhanced responsivity in the NIR of the microcrystal device when compared to a planar device (fig. 3(c), continuous and dashed lines). The ratio between the responsivity of the device and of flat Ge (fig. 3(c), shaded area) clearly shows this enhancement in the long wavelength range (>1550 nm). Notably, the same trend is also predicted with the simulations. Indeed, fig. 3(d) shows the fraction of absorbed power for the microcrystals pattern and for the planar epilayer, as obtained by the FDTD simulations. The ratio between the two is represented by the shaded area, which nicely agrees with the photocurrent data. Indeed, enhancement in the fraction of the absorbed power for the microcrystal pattern will also imply enhancing its responsivity in the wavelength range 1550–1700 nm.

4. – Conclusions

The optoelectronic properties of single microcrystals and of microcrystal arrays have been analysed by means of FDTD simulations and dark current/photocurrent measurements demonstrating an increased responsivity in the 1550–1700 nm spectral range, as compared with conventional photodiodes. The single microcrystal responsivity has been compared with that of a device based on an array comprising ≈300 microcrystals, demonstrating that NIR absorption enhancement can be obtained also in large area devices.

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This work has been funded by the EU Horizon-2020 projects microSPIRE Grant No. 766955 and Graphene Flagship Core 3 Grant No. 881603. The author would like to acknowledge A. Ballabio, A. Barzaghi, C. Zucchetti, L. Anzi, F. Bottegoni, J. Frigerio, R. Sordan, P. Biagioni and G. Isella for collaborating to this work.

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