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SiGe Quantum Dots on Si Pillars for Visible Photodetection

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1. Introduction

In light of the high absorption coefficient together with the wide-range bandgap engineering, Ge has being progressively deployed to integrate active photonic devices on a Si complementary metal-oxide-semiconductor (CMOS) platform. This not only gives rise to significant enhancement on the communication and information technologies [1] but also addresses promising implications to the biological and medical sensing applications [2]. On the other hand, the intriguing tunable electronic structure and optical properties of Ge nanowires (NWs) and quantum dots (QDs) provide another gain media for active photonic devices because of the increased exciton binding energy, enhanced oscillator strength, and improved electo-optical conversions with a decrease in the nanostructure size thanks to the inherent quantum confinement effects. These Ge nanoheterostructures are of practical interest for further advancing the development of photodetectors.

Many efforts have been devoted to the growth of high-quality Ge nanostructures in sufficient quantities (or thicknesses) for the performance improvement of Ge/Si photodetectors, in view of the large lattice mismatch of 4.2% between Ge and Si inevitably resulting in plenty of interfacial and threading dislocations. The recent innovative nanoheteroepitaxy (NHE) technique has demonstrated successful selective growth of Ge on 50 nm-wide Si (100) nanopillars using reduced pressure chemical vapor deposition [3], providing more efficient three-dimensional strain relief of the Ge QD through the partitioning of strain energy between epi-Ge and the Si pillar based on the compliant substrate effect [4]. Due to small QD volume, the epitaxial structure quality is significantly improved in the reduction of misfit interfacial dislocations and threading dislocations by gliding them through the substrate material and annihilation at the surface. In this paper, we advanced this NHE on the selective growth of $Si_{0.3}Ge_{0.7}$ QDs on 5–30 nm Si nanopillars array and demonstrated a significant performance improvement of indium tin oxide (ITO)/$Si_{0.3}Ge_{0.7}$ QDs/Si pillar metal/semiconductor (M/S) photodiodes in the reduction of dark current and enhancement of photoresponsivity for visible to near infrared photodetection.

2. Experimental

The device fabrication starts from the generation of Si nanopillars using a combination of electron-beam lithography and SF_6/C_4F_8 plasma etching on ⟨111⟩ p^+ silicon substrate followed by a self-terminating thermal oxidation [5]. Figure 1(a) shows the scanning electron microscopy (SEM) image of a pad (50 μm × 50 μm) of 80 nm initial diameter pillars after oxidation at 900 °C. Inset illustrates the corresponding pillar with a silicon core of 12.5 nm wide and the surrounding oxide of 75 nm thick imaged by reflection mode transmission electron microscopy (TEM). After breaking the Si pillars (Fig. 1(b)), $Si_{0.3}Ge_{0.7}$ was grown onto the top of Si pillars with high selectivity over on oxide (Fig. 1(c) and (d)) using low-pressure chemical vapor deposition at 400 °C for 5–15 min. The nominal deposition rate of $Si_{0.3}Ge_{0.7}$ on a planar Si substrate is 1.0–1.3 nm/min. Lastly, a 30 nm-thick transparent ITO metal was deposited on top of the $Si_{0.3}Ge_{0.7}$ QDs/Si pillar array and patterned as the top-gate electrode, and a 500 nm-thick alumina (Al) was deposited on the backside of the Si substrate as the back-gate electrode for M/S photodiodes. M/S diodes with Si pillars only (without Ge QDs) were fabricated for reference.

3. Results and Discussion

The cross-sectional TEM (CTEM) image in Fig. 2 illustrates the successful selective growth of an oblong, 26-nm-height, 50-nm-wide $Si_{0.3}Ge_{0.7}$ QD on the Si pillar over SiO_2. The SiGe QD is in a mixing state of poly- and amorphous-phase. No visible defects are observed either within the QD or at the interface between the QD and Si pillar, which is beneficial for the reduction in the dark current and enhancement of the photocurrent because of less scattering and recombination centers for photodetecting device applications. Figure 3(a) illustrates typical current-voltage (*I-V*) characteristics of M/S diodes with Si pillars only, and the symmetrical current behaviors under different bias polarities are a result of the mid-gap work function ITO relative to Si. There appears no difference in the *I-V* characteristics for Si pillars diodes between in the dark and under illumination from 300 to 1500 nm. Whereas the $Si_{0.3}Ge_{0.7}$ QD/Si pillar diode manifests asymmetrical bias-dependent *I-V* characteristics, and the dark current in the positive-biased regime has an offset voltage of +0.3 V and is significantly lower than the case for the negative-biased condition. Interestingly light illumination plays indiscernible effect on the negatively-biased current,

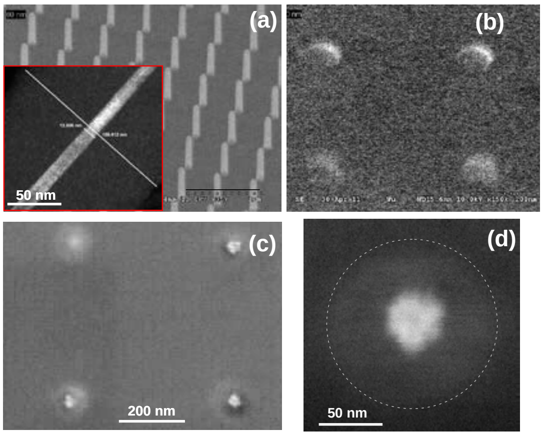

Fig. 1 SEM images of (a) Si pillars formed by lithographic patterning followed by self-terminating thermal oxidation. Inset is the corresponding Si pillar with a core diameter of 12.5 nm. (b) The plane-view of the Si pillar array after breaking the top pillars, (c)/(d) selective growth SiGe QDs on Si pillars over SiO_2.

whereas the photocurrent is significantly enhanced in the positive-biased regime together with an offset voltage shift from +0.3 V to -0.3–0.15 V when the wavelength of the incident light increases from 300 to 1500 nm. Both the photocurrent and the offset voltage reveal the same spectral response and a noticeable change as the wavelength is higher than 780 nm or the photon energy is lower than 1.6 eV. Opposed to the Si pillar diodes, the lower dark current for the $Si_{0.3}Ge_{0.7}$ QD/Si pillar diodes manifests the good epitaxial quality of the SiGe QD on Si pillars making a significant reduction in the dark current, and the asymmetrical *I-V* characteristics indicates an effective hole confinement within the QD because of the valence band offset between $Si_{0.3}Ge_{0.7}$ and Si under the positive gate bias condition. Illuminating light of wavelength less than 780 nm generates a tremendous amount of excess electron-hole pairs within the QD and proliferates considerable hole population wherein by the valence band offset, making the flatband voltage a negative shift to -0.3 V.

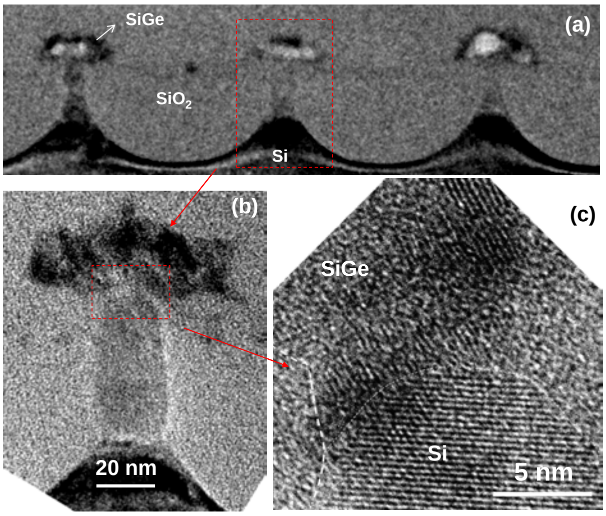

Fig. 2 CTEM images of selective deposition of SiGe QDs on Si pillars.

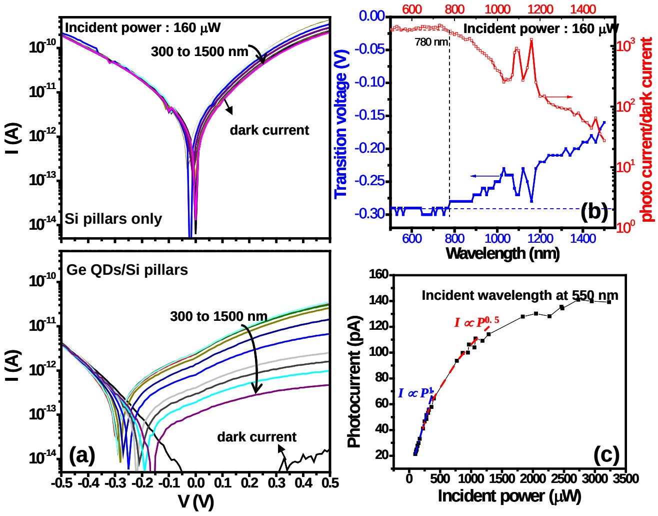

Fig. 3 Power-dependent I-V characteristics of (a) Si-pillar and (b) SiGe QDs/Si pillar M/S photodiodes, (c) Transition voltage and photo/dark current ratio as a function of incident light wavelength, and (c) photocurrent as a function of incident power at wavelength at 550nm.

Under 550nm illumination, the photocurrent increases linearly with incident light power (*P*) at *P* less than 0.3 mW, then follows a power law of $I \propto P^{0.5}$, and get saturated as *P* reaches to 2 mW with the maximum current enhancement (i.e., photo current to dark current ratio) up to 10,000. Notably there appears observable enhancement in photocurrent of more than 30 as the incident light wavelength reaches up to 1500 nm with a weak incident power of 0.15 mW. The much enhanced photoresponse for incident photon energy larger than 1.6 eV probably originates from the interband optical transitions of charge carriers from the excited energy states of SiGe QDs to the volumetric energy band states of Si pillars.

4. Conclusions

We have selective deposited $Si_{0.3}Ge_{0.7}$ QD on Si nanopillars using chemical vapor deposition and demonstrated evident performance improvement in dark current reduction and photorsensitivy enhancement for visible to near infrared photodetection.

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