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High-quality thin-film-like multifold Ge/Si/Ge composite quantum-dot hetero-structures for visible to near-infrared photodetection

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Abstract

We demonstrated an effective approach to grow high-quality thin film (>1μm) of 40-stacked, multifold Ge/Si heterostructured composite quantum dots (CQDs) as an effective building block for photoelectric materials. An otherwise random, self-assembly of variable-fold Ge/Si CQDs on Si has been controlled through the insertion of spacer layers of Si, modifying the growth mechanism through surface-mediated diffusion and SiGe alloying, to produce micron-scale-thick Ge CQD layers with desired QD morphology, interface density, and composition distribution. The high crystalline quality of the multifold Ge CQD heterostructures is evidenced by an extremely low dark current density of 3.68 pA/μm^2, superior photoresponsivity of 267 and 220 mA/W under 850 and 980 nm illumination, respectively, and very fast temporal response time of 0.24 ns of the Ge/Si CQD photodetectors.

1. Introduction

The growth of high-quality Ge thin films over the Si substrate is a venerable subject for active photonic devices such as photodetector, modulator, and light sources for optical interconnect and communication technologies[1]. In particular, the great promise of high absorption coefficient and wide-range bandgap engineering from the Ge/Si system enables a cost-effective Si platform for visible to near-infrared detection which is useful as common detectors for both data and transport applications. However, the epitaxial growth of high-quality, micrometer-scale Ge films over Si is very challenging because of large lattice mismatch of 4.2 % between these two materials.

Many approaches have been proposed for the reduction of threading dislocations and surface roughness. We have demonstrated variable-fold Ge/Si/Ge composite QD (CQD) heterostructure being able to break through this growth bottleneck and effectively suppressing the generation of dislocations in the thin-film-like Ge/Si materials, through a considerate spacer layer design[2]. In this study, we further advanced the heterostructures of the multifold Ge/Si CQD heterostructures for the fabrication of visible to infrared photodetectors with high figure of merit of low dark current, high photoresponsivity, and fast temporal response time.

2. Experimental

The experimental epitaxial growth and fabrication procedures are summarized in Fig. 1. In this study, all Ge-QD samples were grown at 600 ^oC in an ultra-high vacuum chemical vapor deposition system. Pure SiH_4 and GeH_4 were used as precursors for Si and Ge deposition, respectively. Prior to deposition, the p-Si wafers were dipped in a 10 % HF solution for producing a hydrogen-passivated surface, followed by deposition of a 50-nm-thick buffer layer of Si. 40-period multifold Ge/Si heterostructured stacks with (a thickness up to ~ 1.2 μm) were then deposited for the formation of self-assembly of CQDs with the respective growth rates for Si and Ge are 0.03 nm/s and 0.8 monolayer (ML)/s. The Ge (12.6 MLs)/Si (2 nm)/Ge (12.6 MLs) structure and the Ge (12.6 MLs)/Si (2 nm)/Ge (12.6 MLs)/Si (2 nm)/Ge (12.6 MLs) structure were referred as 2-fold and 3-fold CQDs, respectively. A set of conventional Ge QDs by deposition of 12.6 MLs of Ge (denoted by single Ge QD) was also prepared for comparison. For each case of stacked QD structure, a 20 nm-thick spacer layer of Si was inserted between each CQD layer. Lastly, a 150 nm-thick transparent ITO metal layer was deposited over

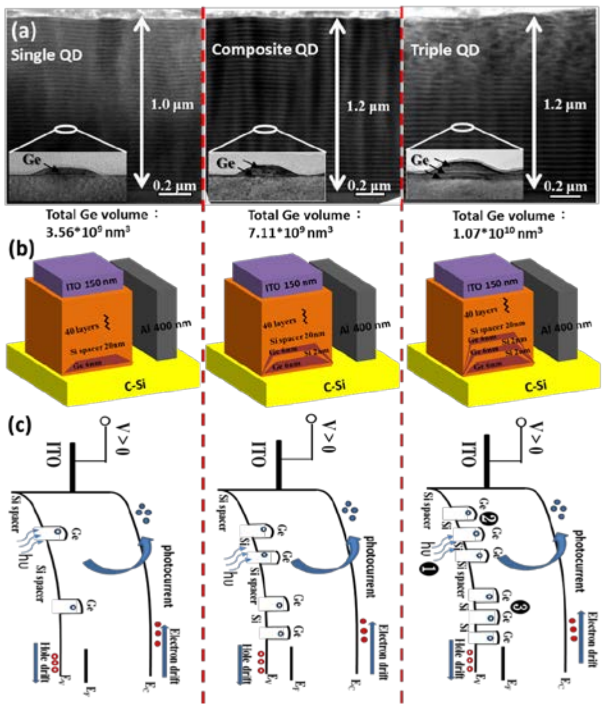

Fig. 1 (a) CTEM images of CQDs, (b) schematic diagrams of a CQD photodetector and (c) energy band diagrams.

the stacked CQD layers and patterned as the top-gate electrode, followed by the deposition of a 400 nm-thick alumina on the backside of the Si substrate as the back-gate electrode forming the ultimate ITO/Ge CQDs/Si photodiodes. The DC responsivity was measured with a monochromatic light source in the wavelength range of 500–1500 nm on studied diodes with gate area of 10,000 μm^2.

3. Results and Discussion

Cross-sectional TEM (XTEM) micrographs in Figure 1(a) illustrate stacked microstructures of 40-period single Ge QD/Si, 2-fold and 3-fold CQDs/Si, respectively. Insets show the corresponding high-resolution TEM micrographs for a given CQD near the top stacks, and the estimated Ge contents for the single, 2-fold, and 3-fold CQDs per stack are 3.56×10^9 nm^3, 7.11×10^9 nm^3, and 1.07×10^{10} nm^3, respectively. No threading defect, such as dislocation or stacking fault, was observed from these CQD/Si stacks in the experimental regions, suggesting these Ge CQDs layers an effective building block for producing thin-film-like CQD materials of high quality and sufficient quantity, which are ready for photodetectors fabrication.

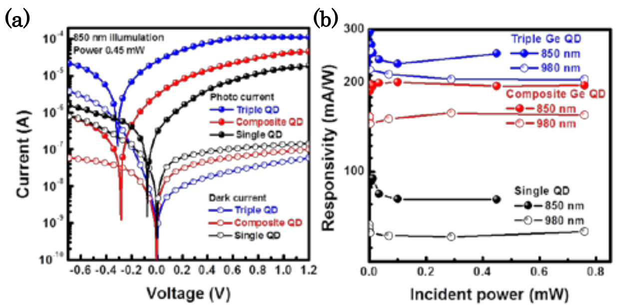

Fig. 2 (a) I-V characteristics of CQD photodiodes under 850 nm light illumination of 0.45 mW. (b) Responsivity versus light intensity at 850, and 980 nm, respectively.

We have demonstrated metal-semiconductor (M/S) photodetectors based on our designer variable-fold CQD structures with an ITO transparent gate electrode. The corresponding schematic device and energy band diagrams are sketched in Figure 1(b) and (c), respectively. Figure 2(a) illustrates typical current-voltage (*I-V*) characteristics of ITO/Ge-Si CQD photodiodes under dark environment, and it is clearly to see that not only the current rectification but also the dark current improve with the fold number of the Ge QD within the CQD structures[3]. Illumination of 0.45 mW at 850 nm indeed induces tremendous current enhancement of 126, 452, and 2000 for the single, 2-fold, and 3-fold CQD diodes in the forward bias regime coupled with a negative open-circuit voltage (V_{OC}) of -0.08, -0.28, and -0.31 V, respectively, at which the minimum current occurs. The current enhancement increases with the fold number of the Ge QD not only because of the increased Ge content within the CQD structure but also enhanced hole confinement within the Ge/Si CQD, thanks to the valence band offset between the Ge QD and Si (Figure 1(c)).The high DC photocurrent at zero bias indicates that a large built-in *E*-field is already established within the CQDs without applying a bias, suggesting good intrinsic Ge/Si CQD material quality. Also the built-in *E*-field increases with the fold number of the Ge QD within the CQDs, because of enhanced photohole confinement within the CQD structures. The 3-fold, 2-fold, and single Ge CQD/Si photodiodes have constant photoresponsivities (*R*) of 267 (220), 200 (157), 84 (64) mA/W at wavelengths of 850 (980) nm, respectively, in the power range of 0.25－760 μW (Figure 2(b)). High external quantum efficiency (EQE = $R \times E$, where $R = (I_P - I_D)/P_{opt}$ with I_P denoting photo current, I_D being the dark current, P_{opt} being the optical power incident on the photodiode and E being the photon energy) of 40 % were measured on our 3-fold CQD photodiodes under incident power of 7 μW at 850 nm illumination.

It is clearly to see from Figure 3(a) that for the CQD photodiodes, a decrease in temperature from 300 to 77 K significantly reduces the dark current by a factor of more than 3 order in magnitude due to suppressed thermal activation and hopping, whereas the fact of photocurrent keeping nearly constant with temperature suggests these non-thermal photocurrent in the CQD photodiodes primary resulting from the light absorption by the high-quality Ge/Si CQDs instead of traps. The high-quality Ge/Si CQDs materials is further evidenced by very fast response time of 0.24, 0.69, and 0.95 ns for single, 2-fold, and 3-fold CQD/Si photodiodes, respectively (Figure 3(b)).

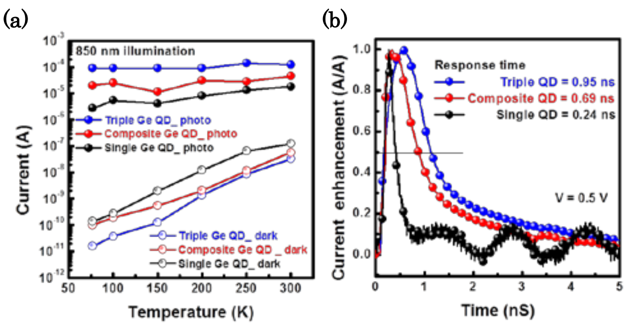

Fig. 3 (a) Temperature dependence of current measured in the dark and under illumination at 850nm. (b) Temporal response of CQD photodiodes under 850 nm illumination.

3. Conclusions

High-performance heterostructured Ge/Si photodetectors have been realized based on variable-fold CQD structures. An increase in the fold-number of the Ge QDs within the CQD structures significantly improves the photocurrent, photoresponsivity, and EQE. A fast temporal response of <1 ns of the Ge-CQD diodes offers a great promise for future Si-based optical interconnection applications.

Acknowledgements

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