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Photoresponse enhancement of metal-oxide-semiconductor near ultraviolet photodetector with multi-stack germanium quantum dots embedded in oxide

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1. Introduction

So far most effort concentrates on photonics made of III-V compound semiconductors. Less interest has been paid on the most common semiconductor Si or Ge bulk materials since their photon emission or absorption efficiency is far from satisfactory for photonic applications, due to their inherent indirect band gap. Notably, recent research shows that reducing the size of a Si or Ge crystal to nanometer regime effectively induces Si or Ge quantum dots (QDs) exhibiting quasi-direct band-gap optical properties. It has been demonstrated that the incorporation of Ge QDs into a Si matrix greatly improve its near infrared absorption (using interband transitions) and far infrared absorption (using intersubband transitions), due to the relaxation of the *k*-conservation rules, leading to extensive studies on infrared light emitters and detectors based on this material system. In addition, it has also been reported that Ge QDs embedded in a SiO_2 matrix would emit blue to ultraviolet photoluminescence due to strong quantum confinement effects [1]. This strongly motivates us to explore the Ge-QD metal-oxide-semiconductor (MOS) near ultraviolet (UV) photodiodes (PDs).

The major challenge to implement Ge-QD photodetectors is that QD size should be smaller enough (<< 10 nm) with good uniformity and high spatial density. In the past, people have employed cosputtering or ion implantation techniques to form Ge QDs embedded in a SiO_2 matrix. However, they all face the issues of controllability/reproducibility and inevitable defect states. The solution we propose to alleviate this problem is the control of selective oxidation of polycrystalline SiGe-on-insulator (poly-SGOI) structure [2]. The process is simple and compatible with the prevailing MOS technology, which implies that this novel Ge-QD MOS UV PDs has great potential to be incorporated with integrated circuits.

2. Experimental and Results

The fabrication of Ge-QD MOS photodiodes began with a <100> n-Si substrate with a resistivity of 0.09-0.7 Ω-cm. After a 5 nm SiO_2 grown by dry oxidation at 900 ^oC, zero, one or three periods of amorphous Si (a-Si)/poly-$Si_{0.88}Ge_{0.12}$/a-Si/ tetraethyl orthosilicate (TEOS) oxide (3.5 nm/6 nm/3.5 nm/7 nm) multilayers were deposited (Fig. 1.) The poly- $Si_{0.88}Ge_{0.12}$ film was deposited at 550 ^oC using SiH_4 and GeH_4 as precursors with flow rates of 256 sccm and 16 sccm, respectively. It is noted that there is an initial time delay in the deposition of poly-SiGe directly onto oxide before a constant deposition rate is established, originating from GeH_4 retarding the formation of stable nuclei by the evolution of GeO or hydrogen effects. To circumvent such incubation time, a nucleation step of depositing a thin pure a-Si layer is included before poly-SiGe deposition. The TEOS oxide was deposited as cap layer to prevent Ge atoms get vaporized during the subsequent thermal oxidation process. Next, thermal oxidation is performed at 900 ^oC in H_2/O_2 ambient to completely oxidize the a-Si/poly-$Si_{0.88}Ge_{0.12}$/a-Si layers to form elliptical Ge QDs embedded in a SiO_2 matrix due to Ge atoms segregation and agglomeration (Fig. 2). Finally, ITO and Al films were sputtered and patterned as gate and bottom electrodes, respectively, to complete the device fabrication.

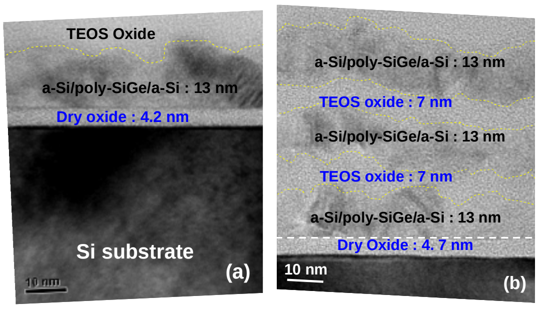

Fig. 1 TEM image of as-deposited (a) one and (b) three periods of a-Si/poly-SiGe/a-Si/TEOS oxide on top of a p-Si substrate.

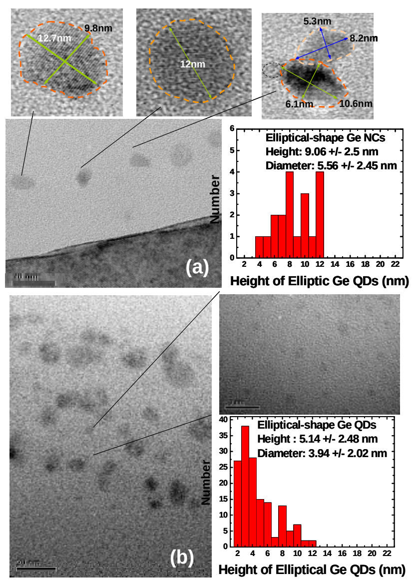

Fig. 2 TEM image of oxidized (a) one and (b) three periods of a-Si/poly-SiGe/a-Si/TEOS oxide on top of a p-Si substrate.

Figure 3 shows current-voltage (*I-V*) characteristics of a 200 μm × 200 μm MOS photodiodes with various Ge QD layers in the dark and illuminated with 405 nm light of 48 μW. The photocurrent to dark current ratio is greatly enhanced with the incorporation of Ge QDs in the MOS photodiodes. The photocurrent of MOS photodiodes with Ge QDs slightly increases with applied voltage and displays a kink at V_g ~ -2 V, corresponding to the onset of deep depletion from the capacitance-voltage (C-V) curves.

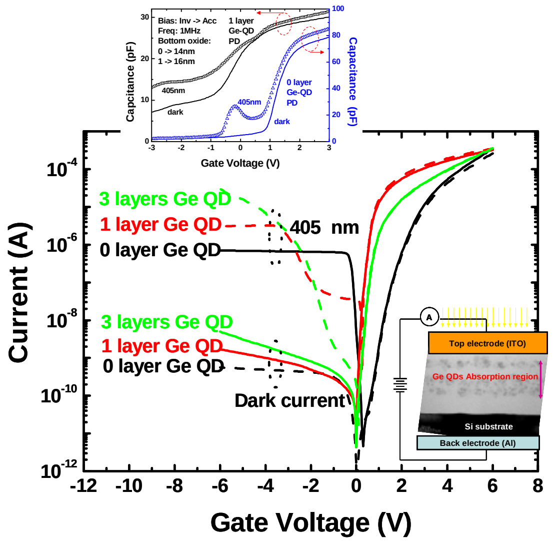

Fig. 3 I-V characteristics of MOS photodiodes with various Ge QD layers in the dark and illuminated by 405 nm light. The corresponding C-V curves are inserted.

Figure 4 summarizes the measured photoreeponse over a wide range of incident light wavelengths for Ge-QD MOS photodiodes at bias voltage of -5 V. The photoresponse of a MOS diodes without Ge QD increases essentially linearly with wavelength from 300 to 700 nm by three times (0.01 → 0.03 A/W). On the other hand, the spectral response of a MOS photodiode shows one major peak at 475 nm for the case of 1-layer Ge QDs (with an average diameter of 5.56 ± 2.45 nm and an average height of 9.56 ± 2.05 nm) and two pronounced peak at 400 nm and 525 nm for that of 3-layer Ge QDs (with an average diameter of 3.9 ± 2.0 nm and an average height of 5.1 ± 2.5 nm). The blue-shift of absorption peaks with Ge QD size originates from the strong quantum confinement effect and makes good agreement with the corresponding cathodoluminescence observation [2]. Significantly, enhanced photoresponse was measured from MOS diodes with three-layer Ge QDs (a factor of 10). The conversion quantum efficiency is more than 100% for the spectral range of 375-700 nm and even as high as nearly 200 % for the wavelengths of 375-425 nm and 475-525 nm. This indicates that there must be an amplification mechanism to enhance the measured photoresponse from Ge QDs.

The dark current as a function of bias voltage from 300 to 120 K are shown in Fig. 5. The current increases along a straight line in the log-log plot (Fig. 5(a)), corresponding to an $I \propto V^m$ dependence, where m (0.8~1.1) is slightly proportional to $1/T$. This excludes out the space-charge-limited conduction to be the main conduction mechanism for dark current. On the contrary, the conductance drops as the temperature decreases and can be shown to follow a $T^{1/2}$ law for the bias range of -1 ~ -6 V (Fig. 5(b)), corresponding to variable range hopping with a Coulomb interactions due to QDs [3].

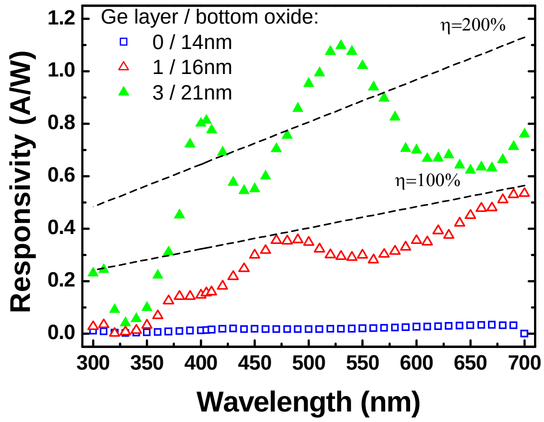

Fig. 4 Responsivity spectra of MOS photodiodes with various Ge QD layers at bias voltage of -5 V.

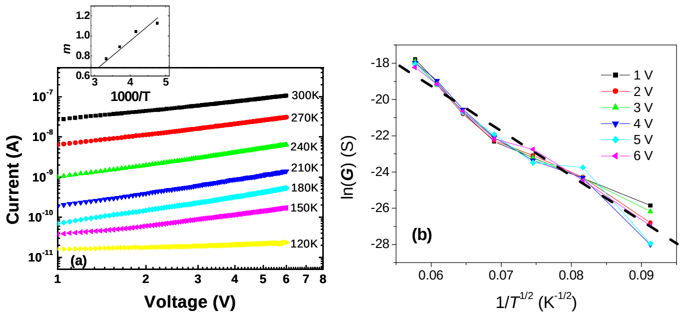

Fig. 5 Dark current versus voltage of MOS diodes from 120 to 300 K.

3. Conclusions

We have demonstrated efficient multi-stack Ge-QD MOS photodetectors with enhanced photoresponse for near UV light. The temperature and bias dependent dark current has been investigated, which implies that possible dark current mechanism would be ascribed to variable hopping with a Coulomb gap.

Acknowledgements

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