Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp419-420

Fabrication of Multi-Stack Ge Quantum-Dots for Blue to Near-Ultraviolet MOS Photodetectors

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1. Introduction

Photodetectors are necessary in an optical communication system. In the past, III－V compound semiconductors were widely adopted as photodetector material due to their high speed and good quantum efficiency. However, their disadvantages were higher cost and inability to be integrated with the conventional Si ICs. Hence, the realization of high performance Si-based optoelectronic integrated circuits in a complementary metal-oxide-semiconductor (CMOS) compatible process has been pursued in the fields of high speed telecommunication and advanced optoelectronics. However, this pursuit has been inhibited by the low conversion efficiency of Si-based photonic devices which associated with the inherent indirect bnadgap of bulk Si materials. Such an indirect band structure-related limitation is overcome by the spatial confinement of electrons or holes in a nanometer-scaled quantum dot (QD) structure. Recently, many researches have been reported that Ge-QDs embedded in SiO_2 matrix can be produced by several ways, such as co-sputtering of Ge and SiO_2 [1] and ion implantation [2] with subsequent annealing. However, the above methods were not easily compatible with conventional Si process and costly. Incorporating Ge-QDs into a dielectric matrix reveal significant blue to near-ultraviolet light emission [3], therefore, provided strongly motivation to investigate MOS diodes for blue to near-ultraviolet photodetection. In this paper, we fabricated MOS-structure photodiodes (PDs) with 3-stack Ge-QDs/a-SiON:H structures as the active region for detecting blue to near-ultraviolet light. Ge-QDs in the SiGeO layer are formed by thermally annealing stacks of 3 periods of a-SiGO:H/a-SiON:H layers prepared by a conventional plasma-enhanced chemical vapor deposition (PECVD) system.

2. Experimental

First, the p-type (100) Si substrates (2–5 Ω-cm) were cleaned with the standard RCA process. Then, the 3 periods of a-SiGeO:H (10 nm)/a-SiON:H (5, 7, and/or 16, 23 nm) thin-films deposited with a PECVD (ULVAC CPD 1108D) system for samples 1 and 2. During the deposition, the substrate temperature was kept constant at 270 °C and chamber pressure were 100 and 130 mtorr for a-SiGeO:H and a-SiON:H films, respectively. Subsequently, a thermal -annealing process with a high-temperature furnace at 900 °C in N_2 ambient for 90 and 120 min. were executed to agglomerate Ge-QDs in a-SiGeO:H/a-SiON:H dielectrics for samples 1 and 2, respectively. The cross-section TEM micro-graph of samples 1 and 2 are shown in Figs. 1 (a) and (b), respectively. It could be observed that the formed multi-stack Ge-QDs piled up along the interface between the SiO_2 and SiON were clearly observed. The sizes of upper layer Ge-QDs were ranging from 5~6 nm and 5~8 nm for samples 1 and 2, respectively. The sizes of middle and bottom layer QDs were smaller and ranging from 2~4 nm for sample 1 and 3~4 nm for sample 2, respectively. Then, ITO film was sputtered with ULVAC RFS-200 sputtering system for upper electrodes through a metal mask and the device area was 1.13×10^{-2} cm^2. Finally, Al metal was deposited with a thermal coating system (ULVAC-VTC-410) onto the substrate for bottom electrode. After metal deposition, sintering was executed with a rapid thermal-annealing (RTA) system at 350 °C in N_2 ambient for 15 min. The schematic structures of samples 1 and 2 were shown in Fig. 2.

3. Results and Discussion

Figure 3 illustrates the current-electric-field (I-E) characteristics of samples 1 and 2 measured in darkness and under 0.7 mW 400 nm light illumination, respectively. The total oxide thickness of samples 1 and 2 were 57.5 and 63.8 nm, individually. Upon illumination with the 400 nm light, the PDs in the inversion mode exhibited significantly higher photo responses and the obtained photocurrents tended to saturate in the high voltage range. The ratios of photocurrent to dark current at 0.871 MV/cm electric-field were 4.46×10^3 and 9.39×10^3 for samples 1 and 2, respectively. The increased oxide thickness for sample 2 could be effective to reduce the dark current caused by ground state tunneling at low voltage. Because of unobvious barrier band-bending at low voltage, the thermally assisted tunneling current was insignificant, and this would result in a lower dark current. At the higher voltage, thermally assisted tunneling current was increased due to the more significant band-bending resulted from the higher electric-field, and dark current would increase. Notably, in sample 2, not only dark current but also photo-current was decreased by thicker oxide thickness. But the influence of thicker oxide layer on photo-current was slighter than on dark current, so the higher ratio of photocurrent to dark current was obtained for sample 2. Figure 4 illustrates the measured responsivities of samples 1 and 2. The incident light wavelength was ranging from 350 to 760 nm and the PDs were biased at 10 V voltage. As the average size of Ge-QDs lessened from 12.78 nm in sample 2 having the density of 2.79×10^{11} cm^{-2} to 12.2 nm in sample 1 having the density of 2.95×10^{11} cm^{-2}, the two outstanding responsivity peaks at 410 and 475 nm for sample 2 blue-shifted to 400 and 465 nm for sample 1. According to the calculated exciton energy as a function of dot diameter, we had the peak at 465 nm or 475 nm would be arisen from the photo response of the upper Ge-QDs layer because of the larger average Ge-QD size in the upper layer, and the middle and bottom Ge-QDs layers would contribute to the photo response at 400 nm or 410 nm [4]. The blue-shifted of peak wavelength with decreasing Ge-QD size indicated that the absorption of Ge-QD PDs originated mainly from the quantum confinement effect of Ge-QDs [5], rather than from the interface traps between Ge-QDs and SiO_2 [3]. With the higher dot density and the thinner total oxide thickness in sample 1, an enhanced photocurrent was obtained, and this brought about the increased responsivity and quantum efficiency. The thicker a-SiON layer in sample 2 resulted in a lower E-field at the same 10 V bias and would also cause the lower responsivity and quantum efficiency as compared with those of sample 1. The responsivities dropped off for the wavelength less than 400 and 410 nm for samples 1 and 2, respectively. As could be due to the photo transmittance of ITO was lower than 40% at 400 nm and even than 34% at 350 nm, so the fall of responsivity below 400 nm would be arisen from the lower ITO transmittance at shorter wavelength. As to the quantum efficiency, the PDs exhibited amplified responsivities (i.e. with a quantum efficiency, η, >100%). This responsivity amplification phenomenon might have the relation with excess hole injection induced by trapped electrons in Ge-QDs. Because of the Ge/SiO_2 valence-band discontinuity is larger than that of Si/SiO_2, such a hole-trapping phenomenon would occur in the Ge-QDs/SiO_2 system with n-type Si substrate. On the other hand, a electron-trapping phenomenon would appear in the Ge-QDs/SiO_2 system with p-type Si substrate due to the Ge/SiO_2 conduction-band discontinuity is larger than that of Si/SiO_2. When the PD was operated in the inversion regime, the high E-field separated the photo-generated e-h pairs, nevertheless, the high oxide potential barriers might trap electrons in QDs during carrier transportation. In order to maintain charge neutrality, more holes injected from the upper electrode, and hence would contribute to the photocurrent.

4. Conclusion

In this paper, MOS PDs with multi-stack and discrete Ge-QDs embedded in a-SiON/SiO_2 matrix have been fabricated with thermal anneal of as-deposited amorphous alloy layers. It was found that the increasing of the oxide barrier thickness was effective to decrease the PD dark current and obtained a higher ratio of photocurrent to dark current of PD. However, decreasing the oxide barrier thickness would obtained a higher density of Ge-QDs and resulted in a higher photo-current, a better photo responsivity, and blue-shifted of peak response wavelength.

Acknowledgements

This work is supported by the National Science Council of Republic of China under contract no. NSC 99-2218-E-468-001.

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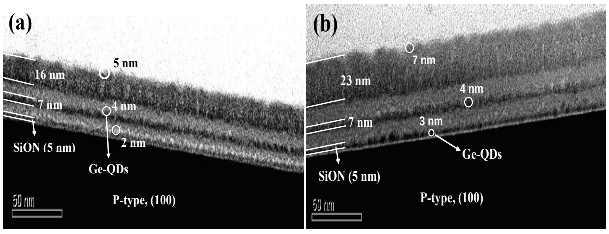

Fig. 1 The cross-section TEM micro-graph of (a) sample 1 and (b) sample 2.

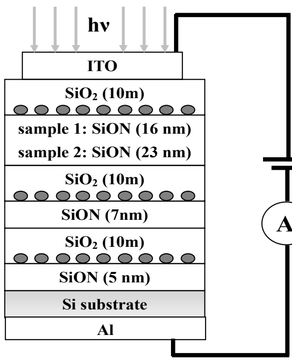

Fig. 2 Schematic structures of samples 1 and 2.

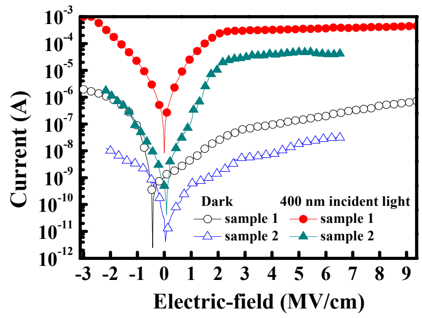

Fig. 3 I-E characteristics of Ge-QDs PD with different SiON thicknesses in dark and under 400 nm light illumination.

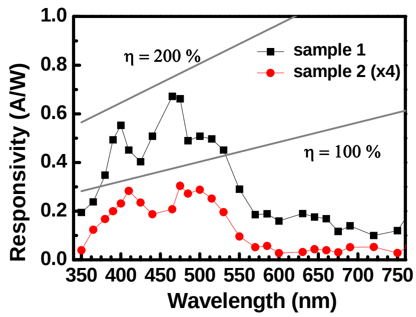

Fig. 4 The responsivities as a function of incident light wavelength for samples 1 and 2 biased at 10 V.