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Buffer-Free GeSn Photodetector Based on Si with Extended Cutoff Wavelength

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Abstract

In this paper, We report the buffer-free $Ge_{0.93}Sn_{0.07}$ film based on Si(001) substrate, promising to achieve a detection wavelength λ over 2 μm. High resolution X-ray diffraction measurements manifest that $Ge_{0.93}Sn_{0.07}$ layer with a relaxation degree of 91.5% was directly formed on Si(001) after post thermal annealing at 600 °C. With the simulated spectral responsivity results, it definitely indicates that buffer-free $Ge_{0.93}Sn_{0.07}$ film could achieve a cut-off wavelength beyond 2 μm, which will contribute greatly to the development of mid-infrared detection.

1. Introduction

Germanium-tin (GeSn) alloys have attracted great interests as a photonic material because of the ability to improve the performance and extend the operation wavelength λ of germanium (Ge) photodetectors (PDs) [1-5]. Ge photodetectors on Si with an cutoff λ of 1.6 μm have been widely reported [6]. Extension of the spectral range of group IV photonics from 1.6 μm into the mid-infrared range (e.g. 2 - 5 μm) based on GeSn is highly desired for many applications, such as chemical-biological-physical sensing, medical diagnostics, active imaging, and free-space laser communications [7]. As GeSn is coherently grown on Ge buffer, the compressive strain will increase the bandgap and make a higher Sn composition required for indirect to direct bandgap transition [8]. It was reported that the relaxed GeSn can be grown on Si without buffer layer [9].

In this work, we demonstrate the buffer-free GeSn film on Si(001). The crystalline quality and relaxation degree of the buffer-free GeSn layer after post thermal annealing are systematically investigated and the photoelectric performance of the designed photodetector is simulated.

2. Material Growth and Device Design

GeSn film was epitaxially grown on Si(001) using the solid source molecular beam epitaxy (MBE) at a low temperature below 200 °C. And the post thermal annealing(PTA) with various temperatures was carried out. The sample underwent a PTA at 600 °C for the quality improvement and strain relaxation. Fig.1(a) shows the cross-sectional schematic of the designed PIN photodetector structure and the top view SEM images of the proposed device is presented in Fig.1(b).

3. Results and Discussion

Fig. 2(a) depicts high resolution transmission electron microscope (HR-TEM) images of the sample. Insets reveal HR-TEM images of the selected region, which demonstrates the defects at GeSn/Si interface, contributing to the strain relaxation of the GeSn film. No dislocation and Sn cluster observed

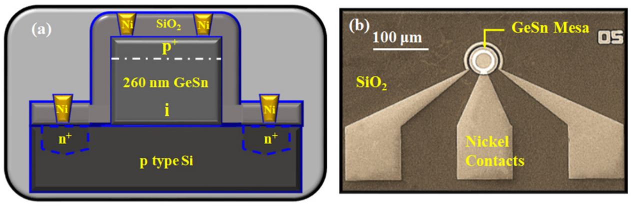

Fig.1. (a) Cross-sectional schematic of the designed buffer-free $Ge_{0.93}Sn_{0.07}$/Si PIN photodiode. (b) Top view SEM image of the proposed PIN photodetector having a diameter of 50 μm.

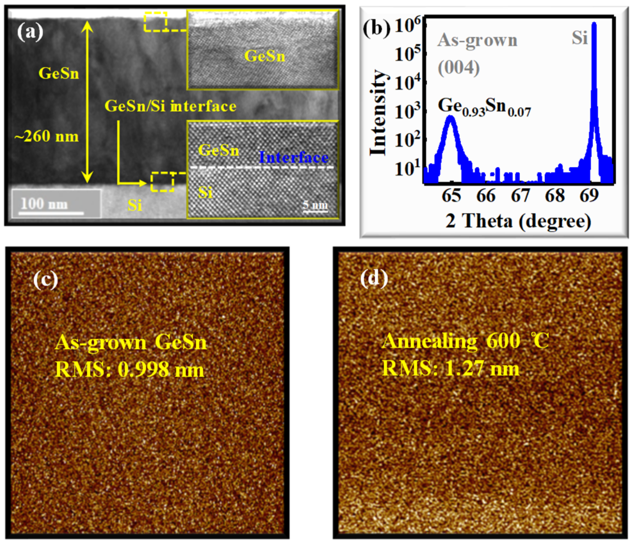

Fig.2. (a) TEM image of GeSn directly grown on Si(001). The thickness of GeSn film is about 260 nm. AFM images of the $Ge_{0.92}Sn_{0.07}$/Si(001) samples (c) before and (d) after the post annealing at 600 °C.

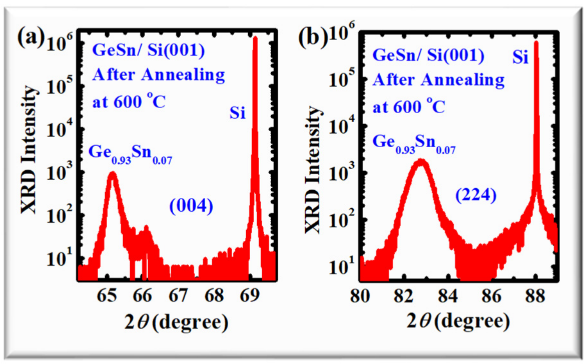

Fig.3. HR-XRD (a) (004) and (b) (224) 2θ - ω scans of the $Ge_{0.93}Sn_{0.7}$ on Si(001) sample after the 600 °C annealing.

reveal the defect-free and high crystallinity of GeSn film. High resolution X-ray diffraction (HR-XRD) curve of as-grown sample is shown in Fig. 2(b), the Sn composition calculated based on GeSn peak is 0.07. The surface morphology of the sample at room temperature is represented by Atomic Force Microscope(AFM) images in Fig. 2(c) and (d). Compared to as-grown, the similar Root-Mean-Square(RSM), 0.998 and 1.27 nm, illuminates that the sample maintains decent surface morphology and little Sn segregation after 600 °C PTA. Fig. 3 presents HR-XRD 2θ - ω scans curves of the sample annealed at 600 °C. According to the (004) and (224) shown in Fig. 3(a) and (b), respectively, the relaxation degree of $Ge_{0.93}Sn_{0.07}$ film is 91.5%. The small shoulders at the right side of the GeSn XRD peaks indicate that a thin SiGeSn layer formed at the GeSn/Si interface due to the interdiffusion between GeSn and Si. The excellent measurement results demonstrated that buffer-free $Ge_{0.93}Sn_{0.07}$ film could maintain initial properties and realize strain relaxation after rapid thermal annealing at a high temperature such as 600 °C, which has a prime importance in the GeSn detector fabrication process.

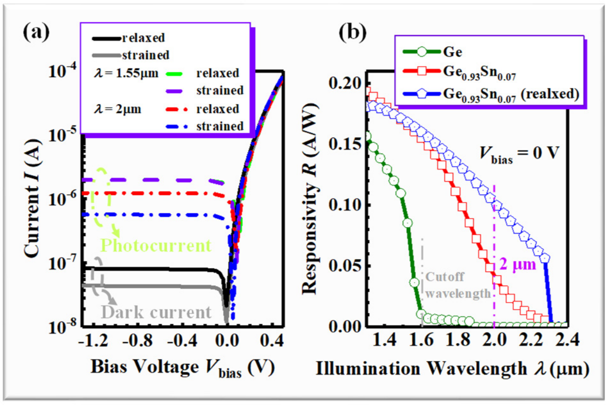

Fig.4. (a) I-V_{bias} characteristics of relaxed and strained $Ge_{0.92}Sn_{0.07}$ photodetector under darkness and normal incidence illumination with λ = 1.55 μm (dash curve) and λ = 2 μm (dash dot curve). (b) Simulated responsivity spectra of devices at a bias voltage of 0 V.

Based on the buffer-free $Ge_{0.93}Sn_{0.07}$ sample and the designed device structure, numerical simulation is utilized to theoretically investigate the device performance, which could provide guidances in the optimizing fabrication process. I - V_{bias} characteristics of relaxed and strained $Ge_{0.92}Sn_{0.07}$ photodetector under darkness and normal incidence illumination with λ= 1.55 μm (dash curve) and λ = 2 μm (dash dot curve) are shown in Fig. 4(a), and the responsivity spectra at a bias voltage of 0 V are presented in Fig. 4(b), respectively. It could be explicitly observed that the strain has a negligible influence on the photocurrent with the illumination λ = 1.55 μm in Fig. 4(a). And compressive strain due to the large lattice mismatch between GeSn and Si has less impact on the dark current of the PD. One can also observe in Fig. 4(b) that Ge has a cutoff wavelength at 1.6 μm and a remarkable optical response of the $Ge_{0.93}Sn_{0.07}$ PIN PD to the light signals at a wavelength of 2 μm even at zero bias with or without strain, which implies that the proposed structure based on buffer-free GeSn can extend the cut-off wavelength beyond 2 μm. Compared with a strained device, the relaxed one exhibits a superior photocurrent at the illumination λ = 2 μm and responsivity beyond 2 μm. The magnitude of photocurrent decreases in the strained GeSn PD compared with the relaxed device. That is because of the undesirable effect of compressive strain on GeSn bandgap. Therefore, the induced strain should be zealously eliminated in the fabrication process.

4. Conclusions

In this work, high quality buffer-free GeSn film was grown on Si(001) and PIN photodetector based on the sample was simulated. After PTA at 600 °C, the GeSn film achieves a relaxation degree of 91.5% with strain relaxation. GeSn PDs on Si demonstrate the operation wavelength above 2 μm. And in the fabrication process the induced strain needs to avoid for the device performance improvement.

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