Investigation of the Photodetector Performance Based on the Ga$_2$O$_3$/Sb$_2$Se$_3$ Heterojunction

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Abstract. This work demonstrates the fabrication of the p-n heterojunction photodetector between the n-type gallium oxide (Ga$_2$O$_3$) and the p-type antimony selenide (Sb$_2$Se$_3$). The p-n junction exhibits a turn voltage of 0.44 V and a rectification ratio of 28.25. The responsivity and detectivity of the photodetector device are as high as 9.28 mA/W and $4.23 \times 10^{11}$ Jones at 0 V bias voltage, along with the excellent photoresponse speed (the rise/decay time of 834 $\mu$s/822 $\mu$s). Such results are mainly due to the good charge separation as a result of the formation of the built-in field. Our work provides value information on the Ga$_2$O$_3$/Sb$_2$Se$_3$ heterojunction based photodetector and enriches the opportunities on the photonic and electronic applications.

1. Introduction
Antimony selenide (Sb$_2$Se$_3$) has recently attracted great attentions as one of the next-generation optoelectronic applications [1, 2]. Particularly, the Sb$_2$Se$_3$ based near-infrared photodetectors (PDs) are emerging as a research hotspot based on its excellent optical property (the absorption coefficient is more than $10^5$ cm$^{-1}$ and the band gap is 1.12 eV) [3]. As far as we know, great potentials need to be explored for these PDs on the civilian and military applications, such as military reconnaissance, biological sensing, target location et al. Moreover, the types of the device structure are various including the photoconductor PDs [4, 5], Schottky barrier PDs [6, 7], mental–semiconductor–mental PDs [8, 9] and the p-n heterojunction PDs [10, 11]. Among these types, the p-n heterojunction structure has drawn great interests due to its specific advantage of low dark-current (I$_{dark}$), fast photoresponse speed and simple fabrication process. To our best knowledge, Sb$_2$Se$_3$ is a stable p-type semiconductor, however, the gallium oxide (Ga$_2$O$_3$) is a kind of material that always exhibits the n-type conductivity. Moreover, the Ga$_2$O$_3$ has a large band gap ($E_g = 4.9$ eV), which could extend the spectral absorption range to the deep ultraviolet [12]. So, the Ga$_2$O$_3$/Sb$_2$Se$_3$ heterojunction (GSH) is predicted to present superior p-n junction behaviour and excellent device performance.

In this study, the GSH PDs are fabricated through the molecular beam epitaxy (MBE) and the ingredients of the films are characterized. We further investigate the rectifying characteristic and the photoresponse property of the GSH device. Finally, the responsivity (R) and the detectivity (D$^*$) of the GSH PDs are calculated.
2. Experimental
Before the growth, the Si (100) substrate was cleaned by detergent, ethanol and acetone for 60 min each along with the ultrasonic agitation, after that, the substrate was transferred to 0.1 mM HF aqueous solution for 3 min to remove the surface oxides and finally rinse with the deionized water. The n-type Ga2O3 layer was firstly grown on the cleaned Si (100) substrate through MBE process. Then, the p-type Sb2Se3 layer was deposited on the top of the Ga2O3 to fabricate the p-n junction with a mask as a front contact. To complete the PD device, the Ti/Au electrodes were deposited each on the Sb2Se3 and Ga2O3 film.

3. Result and discussion
The X-ray photoelectron spectroscopy (XPS) spectra are employed to confirm the information of the elementary composition of the films. Fig. 1(a-b) shows the Sb 3d and Se 3d close-up images of the Sb2Se3 film. The two typical strong peaks of 539.48 eV for Sb 3d and 54.07 eV for Se 3d are observed, indicating the existence of the Sb2Se3. Moreover, the XPS spectra of the Ga2O3 film are given in Fig. 1(c-d). The peak energies of 105.3 eV and 539.92 eV are clearly observed, corresponding to the band energies of Ga 3p and O 1s. Noteworthily, no other obvious peaks could be observed from the spectra, indicating both of the Sb2Se3 and the Ga2O3 are of a great purity.

![Figure 1. XPS spectra of Sb2Se3 film and the Ga2O3 film: (a, b) close up survey of Sb 3d and Se 3d; (c,d) close up survey of Ga 3p and O 1s.](image)

With the aim to investigate the optoelectronic property of the as-prepared PDs, a series of characterizations are carried out. The device schematic diagram of the GBH PD is shown in Fig. 2a. The typical current-voltage (I-V) curves of the GBH devices are shown in Fig. 2b, which are under dark condition and room temperature. As shown, an obvious rectifying characteristic could be clearly detected. Such phenomenon demonstrates that the GBH device could behave as a diode. The turn on voltage of the heterojunction is 0.44 V by extrapolating the linear portion of Current versus Voltage plots. The rectification ratio (IF/IR) of the GBH is 28.25 (where the IF is the forward current and IR is the reverse current) under no irradiation.
The time-dependent response properties of the GBH PD are illustrated in Fig. 3. Fig. 3a shows the I-V curve of the device with an 870 nm light periodically turn on and off at a bias voltage of 0 V. When the light is off, the I_{dark} of the device is 0.17 nA, while the light turns on, the photocurrent (I_{photo}) is instantaneously increased to 326 nA. A more than $1.9 \times 10^3$ of the $I_{photo}/I_{dark}$ rate is achieved, which is a quite competitive result among the Sb$_2$Se$_3$ based PD devices. Moreover, it is also found that the device present a great repeatability and stability after several cycles. The amplification photoresponse curve of a single cycle for the GBH PD is shown in Fig. 3b. It could be observed that the characteristic values of the rise time and the decay time are 834 $\mu$s and 822 $\mu$s, respectively. Such excellent results would be attributed to the good charge separation with the assist of the built-in field formed by the Ga$_2$O$_3$ and Sb$_2$Se$_3$ heterojunction. Fig. 3c shows the time-dependent photoresponse I-V curve with different bias voltages (-5 V, -10 V, -15 V). As shown, the values of the current are improved as the bias increasing and all the curves present a great stability with the light turns on and off. To further investigate the relationship of the device performance with the different light intensities, the 870 nm monochromatic source with the intensity ranging from 4.41 to 14.05 $\mu$W/cm$^2$ is applied on the GBH PD with a bias voltage of -10V. It could be clearly observed the current enhances as the intensity increasing and also shows great stability. To evaluate the device performance of the GBH PD in terms of the quantity, two important parameters of the R and D' are calculated through the following formula:

$$R = \frac{I_{ph}}{P_{ill} \times S}$$  \hspace{1cm} (1)

$$D' = R \times \left(\frac{S}{2eI_{dark}}\right)^{1/2}$$  \hspace{1cm} (2)

Where the $I_{ph} = I_{light} - I_{dark}$ ($I_{light}$ is the value of current with the light illumination, $I_{dark}$ presents the current under dark condition), $P_{ill}$ stands for incident light power intensity, $S$ is the active area of the device, the $e$ is the charge of one electron. The value of $R$ is achieved to be 9.28 mA/W at 0 V bias voltage under the light of 870 nm and the value of $D'$ is calculated to be $4.23 \times 10^{11}$ Jones. Such excellent results are attributed to the ultra-low $I_{dark}$ of 0.17 nA and the high-quality heterojunction formed by Ga$_2$O$_3$ and Sb$_2$Se$_3$. 

Figure 2. (a) Schematic illustration of the GSH based PD device; (b) the I-V curves of the GSH PD measured at dark condition.
Figure 3. (a)Time-dependent photoresponse of the GSH at 0 V voltage and (b) the enlarged view of the rise/decay edge for GSH device; (c) the photoresponse of GSH PD at the bias of -5 V, -10 V, -15 V; (d) the photoresponse of the GSH PD with various incident light intensity.

4. Conclusion
In summary, the GSH PD is firstly fabricated and the components of the films are well confirmed. The device exhibits as a well-defined diode with a low $I_{\text{dark}}$ of 0.17 nA. Moreover, the GSH PD also achieves excellent photoresponse properties: a fast rise/decay time of 834 $\mu s$/822 $\mu s$, a desired $R = 9.28$ mA/W and $D^* = 4.23 \times 10^{11}$ Jones with the bias voltage of 0 V. Such excellent results indicate that the GSH PD possesses great potential for photodetection applications.

Acknowledgments
This work was financially supported by the National Nature Science Foundation of China under contract 51572043 and 61875029.

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