High-Performance Deep Ultraviolet Photodetector Based on NiO/β-Ga2O3 Heterojunction

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Abstract

Ultraviolet (UV) photodetector has attracted extensive interests due to its wide-ranging applications from defense technology to optical communications. The use of wide bandgap metal oxide semiconductor materials is of great interest in the development of UV photodetector due to their unique electronic and optical properties. In this work, deep UV photodetector based on NiO/β-Ga2O3 heterojunction was developed and investigated. The β-Ga2O3 layer was prepared by magnetron sputtering and exhibited selective orientation along the family of (0 2 1) crystal plane after annealing. The photodetector demonstrated good performance with a high responsivity (R) of 27.43 AW−1 under a 245-nm illumination (2.7 μW cm−2) and the maximum detectivity (D*) of 3.14 × 1012 cmHz1/2 W−1, which was attributed to the p-NiO/n-β-Ga2O3 heterojunction.

Keywords: β-Ga2O3, NiO, Heterojunction, UV photodetector

Background

There have been much research interests in the development of ultraviolet (UV) photodetectors due to their wide-ranging applications, such as missile warning, biochemical analysis, flame and ozone detections, and optical communications. As compared to SiC and GaN semiconductors, UV photodetectors based on wide bandgap metal oxide semiconductors offer many advantages. For example, the metal oxide-based photodetectors do not oxidize easily and exhibit sensitive response. Furthermore, they are easy to operate and can be made small in size [1, 2]. Hence, wide bandgap metal oxides and their devices have attracted much research attention in recent years. To date, metal oxides such as ZnO [3–5], TiO2 [6, 7], SnO2 [8], NiO [9], and Ga2O3 [10, 11] have been studied for use as high-performance UV photodetectors. Among them, the stable phase of Ga2O3 (β-Ga2O3) is becoming a preferred material for UV photodetector as it is a direct bandgap semiconductor with ultra-wide bandgap of ~ 4.9 eV that responds to the UV band effectively. The facile growth process of the material is an added advantage.

Several groups have attempted to enhance the performance of UV photodetectors by developing heterojunction devices consisting of two different metal oxide semiconductors. For example, Zhao et al. reported the studies of ZnO-Ga2O3 core-shell heterostructure UV photodetectors, which demonstrated ultra-high responsivity and detectivity due to an avalanche multiplier effect [12, 13]. In this work, a different metal oxide heterojunction, such as NiO/β-Ga2O3, was investigated to provide a high-performance UV photodetector. Firstly, the lattice mismatch of β-Ga2O3 and NiO is relatively small. Also, the bandgap of NiO is larger than that of ZnO used in previous study. The p-type behavior of NiO and n-type β-Ga2O3 has led to several reports on the studies of the electrical properties of NiO/β-Ga2O3 heterojunction for power electronics applications [14]; however, there is limited report on the use of the heterojunction in photodetector. In this study, the NiO/β-Ga2O3-based UV photodetector was produced by magnetron sputtering on indium tin oxide (ITO) transparent substrate. The results showed that the NiO/β-Ga2O3 photodetector exhibited excellent sensitivity to UV light (245 nm) with good stability.
Methods

Ga$_2$O$_3$ and NiO ceramic targets (99.99%) were purchased from Zhongnuo Advanced Material (Beijing) Technology Co. Ltd. Sapphire substrate with (0001) plane was purchased from Beijing Physike Technology Co. Ltd. ITO-coated quartz substrate was purchased from Beijing Jinji Aomeng Technology Co. Ltd. All chemical reagents used in the experiments were used without further purification.

β-Ga$_2$O$_3$ film was prepared by RF magnetron sputtering at room temperature. For characterization, the film was deposited on to sapphire substrate with (0001) plane. Prior to deposition, the substrate was wet-cleaned in a mixed solution of ammonia water, hydrogen peroxide, and deionized water (1:1:3) at 80 °C for 30 min. It was rinsed repeatedly with deionized water and dried using nitrogen to remove surface fouling, which would enhance uniformity and adhesion of the film on the substrate. Sputtering was performed at a pressure of 0.7 Pa with oxygen and argon flowing at a rate of 5 and 95 sccm, respectively. A sputtering power of 200 W was used for a duration of 60 min in the deposition of the film. Finally, the deposited film was annealed in air at 800 °C (60 min) at a heating rate of 10 °C/min. For characterization, the film deposited and annealed films can be determined from thicknesses measured by AFM, the small root-mean-square (RMS) surface roughness of 1.36 nm. After annealing, the RMS roughness of the film increased to 1.68 nm. Such increase in the RMS roughness after annealing was also reported by Hao et al [19]. It is possible that the annealing treatment could result in surface structural defects. Further studies are required to understand the cause of change in surface morphology after annealing. AFM topography images of the step edge between the film and substrate before and after annealing are shown in Fig. 1g and h, which the line profiles (in the inset) indicated a film thickness of 114 ± 6.4 nm and 123 ± 2.0 nm (about 8% increase), respectively. The increase in film thickness and RMS after annealing could be that the phase transition from amorphous to crystallinity leads to the nanocrystal grain growth.

UV-Vis absorption spectra of the β-Ga$_2$O$_3$ films before and after annealing are shown in Fig. 1b. Both films exhibited strong UV absorption in the range of 190–300 nm and almost no absorption in the visible light band. This showed that the annealing treatment did not have a significant effect on the absorption edge. It only resulted in a small red shift of about 10 nm with slight enhancement on the absorption peak. Eq. (1) can be used to estimate the optical bandgap energy ($E_g$) of the film.

$$a(hv) = A(hv - E_g)^{1/2}$$

where $a$ is absorption coefficient, $hv$ is photon energy, and $A$ is a constant. Taking into account of the film thicknesses measured by AFM, the $E_g$ of the as-deposited and annealed films can be determined from the plots in Fig. 1c, which indicated a value of 5.137 eV and 5.135 eV, respectively. These values are close to the theoretical $E_g$ of 4.9 eV for β-Ga$_2$O$_3$.

Results and Discussion

Figure 1a show the XRD patterns of the Ga$_2$O$_3$ film grown on (0001) plane of sapphire substrate before and after annealing. Before annealing, the as-deposited film exhibited an amorphous state as only two peaks (marked as “•”) that associated with the substrate were observed in the pattern. After annealing the film at 800 °C, the XRD pattern showed six characteristic peaks corresponding to crystal planes of β phase of Ga$_2$O$_3$, which belongs to the monoclinic crystal system. The observed pattern is consistent with previously reported work [15, 16]. These characteristic peaks of the annealed β-Ga$_2$O$_3$ film revealed good crystallinity with preferential orientation along the family of (2 01) crystal planes.
fitted with two components associated with oxygen vacancies (OV) and lattice oxygen (OL). The area ratios of OV and OL (e.g., S_{OV}:S_{OL}) before and after annealing were 0.47 and 0.12, respectively. This suggests an increase in the lattice oxygen atoms due to the annealing treatment leading to crystallization as oxygen atoms move to their appropriate lattice sites.

An UV photodetector consisting of the β-Ga2O3 film was fabricated. A simple vertical structure was designed for the photodetector, which comprised of ITO/NiO/Ga2O3/Al. A schematic diagram of the device structure is shown in Fig. 3a. A NiO layer was first sputtered on an ITO-coated quartz substrate after applying the same wet cleaning procedures as the sapphire substrate, and the detailed preparation and characterizations of NiO film were shown in Additional file 1: Figure S1 and Figure S2. Ga2O3 layer was then sputtered using the above mentioned deposition parameters. The prepared heterojunction was annealed in air at 600 °C for 30 min to avoid heating damage to ITO (with the knowledge that β-Ga2O3 can be formed at annealing temperature above 550 °C), followed by vapor deposition of Al electrodes (2 × 2 mm²) on the surface of Ga2O3 film. Finally, the Al electrodes and ITO substrate were used as top and bottom electrodes, respectively.

Figure 3b shows the energy band diagram of the photodetector. We calculated the \( E_g \) of NiO film according to Eq. (1) as shown in Additional file 1: Figure S3. The \( E_g \) of NiO film is about 3.4 eV after annealing. The wide bandgap energy of the β-Ga2O3 (5.1 eV) and NiO (3.4 eV) layers is responsive to UV light. Under UV illumination (\( h \nu \)), electrons gain enough energy to transit into the conduction band generating electron-hole pairs. These photogenerated electron-hole pairs were separated by the built-in electric field and collected by the respective electrodes. Here, the heterostructure with appropriate band alignment can facilitate the charge separation and collection.

The performance of the heterojunction photodetector was studied from the measured \( J-V \) and log \( J-V \) plots,
which were acquired from the backlighting incident device. Figure 3 c and d illustrate the $J$-$V$ and log $J$-$V$ curves of the photodetector illuminated with different wavelength lights and under dark condition, respectively. When the photodetector was illuminated by a 245-nm UV light at 27 $\mu$Wcm$^{-2}$, a drastic increase of a current density, up to 1.38 mAcm$^{-2}$, was observed at an applied voltage of 10 V. The current density also increases when illuminated with 285 and 365 nm UV lights. However, more electron-hole pairs can be effectively excited by 245 nm UV light compared with other two UV lights, showing the deep UV detection of the device.

$J$-$V$ and log $J$-$V$ curves of the photodetector were measured under an UV illumination of 245 nm with varying power density, as shown in Fig. 3 e and f, respectively. Measurements were performed under dark and UV light conditions. The current density increases with the light intensity under a 245-nm UV illumination which suggests that the photodetector has the ability to generate photocurrent in response to 245 nm UV light.

The effect of bias voltage on the responsivity ($R$) of the device is shown in Fig. 3g. $R$ is related to the photocurrent density ($J_{ph}$) according to Eq. (2) [5]:

$$R = J_{ph}/P_{opt}$$  \hspace{1cm} (2)

where $P_{opt}$ is photon power density having a value of 1.5 mWcm$^{-2}$. An increase in $R$ was evident from Fig. 3g as the bias voltage of the device increases under fixed photon power density. The maximum $R$ was 27.43 AW$^{-1}$ measured under a 245-nm illumination (27 $\mu$Wcm$^{-2}$) at the bias voltage of 10 V.

Detectivity ($D^*$) is another important parameter for evaluating the performance of photodetectors. $D^*$ of the photodetector can be calculated using Eq. (3) as follows [20, 21]:

$$D^* = R/(2q|J_d|)^{1/2}$$  \hspace{1cm} (3)

where $q$ is absolute electron charge ($1.602 \times 10^{-19}$ C) and $J_d$ is dark current density. The relationship between $D^*$ and the bias voltage is shown in Fig. 3h, which shows an increase in $D^*$ as the bias voltage increases. The maximum $D^*$ was 3.14 $\times$ 10$^{12}$ cmHz$^{1/2}$W$^{-1}$ measured under a 245-nm illumination (27 $\mu$Wcm$^{-2}$) at the bias voltage of ~10 V. Based on the values of $R$ and $D^*$, the NiO/β-Ga$_2$O$_3$ photodetector demonstrated high performance in UV detection, compared with other NiO-based and Ga$_2$O$_3$-based UV detectors shown in Table 1.

**Conclusions**

In conclusion, β-Ga$_2$O$_3$ film was prepared by RF magnetron sputtering and exhibited good crystallinity after annealing at 800 °C. The wide bandgap material revealed strong UV absorption in the range of 190–300 nm. The deep UV photodetector based on NiO/β-Ga$_2$O$_3$...
Fig. 3  a Schematic diagram showing the device structure consisting of ITO/NiO/β-Ga2O3/Al.  
b Energy band diagram of the photodetector.  
c–d Measured J-V and log J-V curves, respectively, of the photodetector illuminated with a light of different wavelengths, and under dark conditions.  
e–f Measured J-V and log J-V curves, respectively, of the photodetector under an UV illumination of 245 nm with different power density.  
g–h Responsivity (R) and detectivity (D*), respectively, of the photodetector at different bias voltages under 245 nm light illumination.

Table 1 Comparison of characteristic parameters of other NiO-based and Ga2O3-based UV detectors

| Device              | Preparation method | Wavelength | Bias voltage | R (AW⁻¹) | Year | Ref. |
|---------------------|--------------------|------------|--------------|----------|------|------|
| ITO/NiO/β-Ga2O3/Al | RF magnetron sputtering | 245 nm     | 10 V         | 27.43    |      | This work |
| Ni/NiO/ZnO/FTO     | RF/DC sputtering    | 400 nm     | – 5 V        | 3.85     | 2015 | [22] |
| Al/ZnO/Ni/ITO      | Sol-gel/spin-coating | 350 nm     | – 1 V        | 10.2     | 2014 | [23] |
| ZnO/Ga2O3 microwires| CVD                | 251 nm     | –            | 9.7 × 10⁻³| 2017 | [12] |
| Graphene/β-Ga2O3   | CVD                | 245 nm     | 20 V         | 39.3     | 2016 | [11] |
| GaN/Sn:Ga2O3       | PLD                | 254 nm     | –            | 3.05     | 2018 | [24] |
| Graphene/β-Ga2O3   | Mechanical exfoliation | 254 nm   | –            | 29.8     | 2018 | [25] |
| β-Ga2O3/Nb:SrTiO3  | RF magnetron sputtering | 254 nm  | – 10 V       | 43.31    | 2017 | [26] |
heterostructure was highly sensitive to 245 nm UV light with high responsivity (R) and detectivity (D*) of up to 27.43 \text{ A W}^{-1} and 3.14 \times 10^{12} \text{ cm Hz}^{1/2} \text{ W}^{-1}, respectively. It is believed that the performances of the UV photodetector can be further improved by means of doping or optimizing the device structure.

**Supplementary information**

Supplementary information accompanies this paper at https://doi.org/10.1186/s11671-020-3271-9.

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**Authors’ Contributions**

MJ carried out the experiments and drafted the manuscript. LT and JX supervised the experiments. FW, KST, and SPL designed the experiments and drafted the manuscript. LT and JX helped to draft and revise the manuscript. All authors read and approved the final manuscript.

**Availability of Data and Materials**

The conclusions made in this manuscript are based on the data (main text and figures) presented and shown in this paper.

**Competing Interests**

The authors declare that they have no competing interests.

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