A Solar-Blind Ultraviolet Photodetector With Graphene/MgZnO/GaN Vertical Structure

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Graphene (Gr) has high transmittance to ultraviolet (UV) light and high mobility, which can effectively collect and transfer carriers. In this work, MgZnO (MZO) films were grown on the surface of the p-GaN by magnetron sputtering. A heterojunction solar-blind UV detector with Gr/MZO/GaN structure was constructed by introducing Gr as the window layer film. The test results show that the device has excellent detection ability for solar-blind UV light. The light response cut-off edge of the device is 263 nm, under the illumination of 255 nm and the bias voltage of −5 V, the responsivity is 14.6 mA/W, the rise time is 0.79 s, the decay time is 0.2 s, and the external quantum efficiency is 71.1%. The importance of this work lies in providing a reference for the application of Gr-based photodetectors.

Keywords: MgZnO, solar-blind ultraviolet photodetector, graphene, vertical structure, heterojunction

INTRODUCTION

Semiconductor solar-blind UV detectors have attracted widespread attention from researchers and can be applied in many fields such as spatial data transmission, discharge detection in substations, etc (Xie et al., 2013; Xu et al., 2019; Klas et al., 2021). Among them, MZO, as one of the most common solar-blind UV wide band gap semiconductor materials (Zheng et al., 2015), has a continuously adjustable band gap width of 3.3–7.8 eV, and has the advantages of low defect density, high radiation resistance (Hou et al., 2011; Jyun-Yi et al., 2015; Tian et al., 2016; Hu and Kai, 2017).

Many works have shown that the quality of the photo-responsive layer film will also affect the performance of the detector. Too low quality of the film may result in slow response speed, poor frequency response and low responsivity of the detector (Zhang D. et al., 2018; Li et al., 2019). In addition, the vertical structure of the heterojunction detector has better performance than the planar structure of the MSM detector (Liang et al., 2016; Goswami et al., 2020; Wang et al., 2021). This is because the vertical structure of the device has a shorter transmission distance, and the heterojunction detector has a built-in electric field that promotes the transmission of carriers (Wu et al., 2010; Xie et al., 2018).

Therefore, in order to improve the device performance of the MZO heterojunction detector, it is necessary to start with the quality of the film and the structure of the device. At first, the quality of MZO film is related to its growth method, at present, a great deal of work has focused on improving the quality of MZO film (Li et al., 2011; Xie et al., 2012; Shiau et al., 2016; Rana et al., 2018). Yanmin Zhao et al. (Zhao et al., 2009) used magnetron sputtering to obtain high-quality MZO film. In this work, MZO films are also grown by RF magnetron sputtering (Kelly...
its responsivity is 14.6 mA/W. This MZO-based photodetector of the device under cut-off edge is 263 nm. Under solar-blind UV light, the rise time of the device has a selective response to solar-blind UV light, and its upper conductive layer. As a natural p-type material, it not only hardly absorbs solar-blind UV light, but also has a very high mobility (Allen et al., 2010; Zheng et al., 2018a; Zhang et al., 2019b; Hu et al., 2019), which can effectively collect the carriers generated in the light absorption layer.

To sum up, in this work, an MZO film was grown on the p-GaN substrate, and Gr was introduced to construct a heterojunction solar-blind UV detector with a vertical structure of p-Gr/MZO/p-GaN. Due to the absorption characteristics of the photoresponse layer (MZO film), the device has a selective response to solar-blind UV light, and its cut-off edge is 263 nm. Under solar-blind UV light, the rise time of the device under ~5 V bias is 0.79 s, the decay time is 0.20 s, and its responsivity is 14.6 mA/W. This MZO-based photodetector also provides a reference for the application of Gr-based heterojunction detectors.

RESULTS

Film Characterization Results

Figure 2A demonstrates the XRD result of MZO grown on GaN substrate. Due to the film thickness, there are very strong substrate diffraction peaks in the image, which leads to the weak signal peak of MZO film. However, three diffraction peaks (002), (111), (200) of the MZO film can still be observed, indicating that the MZO film is dominated by hexagonal phase and has good crystallinity (Senthil Kumar and Kumar, 2003; Wang et al., 2010; Young and Liu, 2018). The absorption spectrum of MZO film on sapphire substrate shown in Figure 2B, the preparation method and the conditions of MZO/sapphire structure and MZO/GaN structure are the same. The figure shows the absorption cut-off edge is 263 nm, on the basis of the connection between the band gap and the absorption value (Wu et al., 2010), we have made the corresponding band gap diagram by plotting the curve of $(a h v)^2$ vs $h v$, where $a$ means absorption coefficient, $h$ means Planck constant, $v$ means optical frequency. As shown in Figure 2B and the insertion diagram, we can see that the film has a sharp cut-off edge at 263 nm, the band gap width is 4.71 eV. The material with this band gap width can be used as the light photoresponse layer of solar-blind UV photodetectors. Figure 2C shows the surface morphology of MZO measured byFocused Ion Beam etching system and AFM, which shows that the surface of MZO film is smooth. Figure 2C also shows the element distribution of MZO film, the element of Mg and Zn is evenly distributed and the proportion of Mg component is 72.5% of the...
total of Mg and Zn. In addition, it can be seen from the cross-sectional SEM image in the figure that the thickness of the MZO film is 220 nm.

**Device Performance Measurements Results**

The device is a heterojunction solar-blind photodetector with Gr/MZO/GaN structure. **Figure 3A** demonstrates the structure of the detector. MZO film is on the GaN substrate, and single-layer Gr is above MZO film. Ti/Au electrode and In electrode was fabricated on GaN and Gr side respectively. In this work, many tests have been carried out on the electrical characteristics of the device. **Figure 3B** shows the dark current curve under dark conditions and the photocurrent curve under 255 nm illumination. By comparison, it can be seen that the device has an obvious response to 255 nm light. When the device is in positive bias voltage, the photocurrent under 255 nm light is very close to the dark current, while in the negative bias voltage, the photocurrent of the device is nearly an order of magnitude greater than the dark current, which indicates that the device will have a very large signal-to-noise ratio under negative bias voltage, which is suitable for working under negative bias voltage. The dark current of the device has three different stages, which are analyzed by drawing the schematic diagram of the rectification principle as shown in **Figure 3B**-inset. The reverse-breakdown voltage of Gr/MZO junction is relatively high, while that of MZO/GaN junction is low. When the whole device is reverse biased, the Gr/MZO junction is in the reverse bias voltage, and the MZO/GaN junction is in the forward direction bias voltage, the whole device shows the current cut-off state. When the whole device is in forward bias, the Gr/MZO junction is in forward bias, but for the MZO/GaN junction in reverse bias, there are two cases: when the bias is small, the device is still in the current cut-off state; when the bias is large, the MZO/GaN junction is in the breakdown state, and the device is in the current on state (Zheng et al., 2018a). Moreover, this structure can effectively inhibit the thermal diffusion of positive and negative carriers in theory, which makes the noise current density of the device very low (Chi On et al., 2003), which is an additional significant advantage of the device.

In addition, the current curve of the device under 255 nm light with periodic switching was also tested. As the device is under 0 bias voltage, the device has obvious capacitance effect, as shown in **Figure 3C**, its rise time and decay time are 0.56 and 0.21 s respectively. **Figure 3D** and **Figure 3E** are the time-dependent curves of the current measured under $-2$ V and $-5$ V bias respectively, the photocurrent is 300 nA under $-2$ V bias and 670 nA under $-5$ V, which are two orders of magnitude greater.
than the photocurrent 2 nA at zero bias, and there exists no obvious capacitance effect. The time required for the device current to change from 10% of the maximum value to 90% of the maximum value is regarded as the rise time of the device (Kan et al., 2020), the rise time under −2 V bias is 0.16 s, and the rise time under −5 V bias is 0.79 s; by the same token, the time required for the current to change from 90% of the maximum value to 10% of the maximum value is also determined as the device decay time (Li et al., 2020), the decay time under −2 V bias is 0.70 s, and the decay time under −5 V bias is 0.20 s. In addition, the results of these three pictures also prove that the device has stable performance and can be used repeatedly.

In order to test the response of the device under different illumination densities, the devices were irradiated with 255 nm light sources with different illumination densities, and the corresponding current and voltage values were measured, and the I-V characteristic curve as shown in Figure 4A was made. It is apparent that under the same bias voltage, as the light density increases, the photoresponse current of the device also increases. In order to see the connection between the photoresponse current and the light density more intuitively, we have drawn the relationship between the current and the light density under different negative bias voltages. As Figure 4B proves, it follows that under five different negative bias voltages, the photo generated current increases with the growth of light density, forming a linear relationship. The responsivity R is a significant reference to study the optical response ability of the device, the responsivity R is defined as $R = \frac{I_{\text{light}}-I_{\text{dark}}}{P_S}$, where $I_{\text{light}}$ is the photocurrent, $I_{\text{dark}}$ is the dark current, $P$ is the light power density, and $S$ is the effective irradiation area of the incident light (Boruah et al., 2016; Lin et al., 2018; Zhang et al., 2019a). As Figure 4C demonstrates, the responsivity of the device decreases in the wake of the growth of light intensity, which is caused by the gradual saturation of the carrier generation rate. However, it is worth noting that when the light power density is small, the responsivity of the device is very large. At −1 V bias, the device’s responsivity to 255 nm light with an illumination density of 50.92 μm/W is 4.3 mA/W. At −5 V bias, the device’s responsivity to light with the same illumination density reaches 14.6 mA/W, which shows that the sensitivity of the device is very high, and it has a high response to weak light. This is related to the $p$-Gr/MZO/$p$-GaN structure of the device can effectively inhibit the thermal diffusion of positive and negative carriers. In addition, the external quantum efficiency (EQE) calculation formula is $EQE = \frac{P_{e\text{ff}}}{P_S}$, where $R$ is the responsivity, $h$ is the Planck constant, $c$ is the speed of light, $e$ is the electron charge, and $\lambda$ is the wavelength of light (Zheng et al., 2018b; Jia et al., 2020). When the device is illuminated at 255 nm light and biased at -1V, its external quantum efficiency is 20.9%, and when biased at −5 V, its external quantum efficiency can reach 71.1%, which explains that the device has great optical gain in operation.

In addition, in order to determine whether the photogenerated carriers are mainly produced in MZO film, the spectral response characteristics of the devices was tested. Under multiple negative bias voltages, the photoresponse current of the device is measured with different wavelengths of light. After calculation, the selective optical response map of the device is drawn, as Figure 4D shows, it looks beyond dispute that under 255 nm illumination, the device has relatively obvious responsivity, while under 371 and
442 nm illumination, the responsivity is lower by more than an order of magnitude that under 255 nm illumination, which is in accordance with the optical absorption diagram measured as Figure 2A, indicating that the photogenerated carriers are the same as the original idea and mainly generated in the MZO layer. It is worth mentioning that the responsivity at 280 nm in this figure is lower than that at 311 nm, which is related to the fact that we did not use light with the same light power density.

The detector was compared with other detectors, and the relevant data is shown in Table 1. By comparison with the reference (Zhao et al., 2014), it can be seen that the responsivity of the detector in this paper is far greater than that of the MSM structure detector mentioned in the reference under the same bias voltage, the MSM detectors in some other articles (Wang et al., 2009; Zhao et al., 2015; Zhang W. et al., 2018), even if they work under a relatively high bias voltage, their responsivity is only comparable to the detectors in this article. It should be noted that the responsivity in the above-mentioned articles is the maximum value of its responsivity. In our test of responsivity, the shortest wavelength of the light source used is only 255 nm, which is far away from the wavelength at the absorption peak of MZO film. In other words, the responsivity of the detector in this paper will be far higher than 14.6 A/W in practical application, which indicates the detector in this article has excellent response performance. For this, we analyze that there are at least the following three reasons: First, the device uses Gr with high mobility and high light transmittance as the window layer to establish a vertical structure, which is beneficial to the transfer of photogenerated carriers; second, high quality MZO film is
fabricated as optical absorption layer, which means that the recombination of photo-generated carriers due to trapping will be significantly reduced and, naturally, the photo-generated current generated by the device will increase; The p-Gr/MZO/p-GaN structure of the device can not only suppress noise electricity, but also contribute to the separation and transfer of photo-generated electron-hole pairs.

**DISCUSSION**

All in all, this work first uses magnetron sputtering to grow a high-quality MZO film on a p-type GaN substrate. Then the p-type single-layer Gr is introduced to form a heterojunction solar-blind UV detector with a Gr/MZO/GaN vertical structure, which has good response characteristics. The light response cut-off edge of the device is 263 nm, when expose to 255 nm light, the rise time of the device under ~5 V bias is 0.79 s, the decay time is 0.2 s, its responsivity is 14.6 mA/W. In this article, we verified the feasibility and advantages of Gr as a window layer, and analyzed the reasons for the good performance of the device from multiple aspects in this article. More importantly, the MZO-based photodetector provides a reference for the application of Gr heterojunction detectors, and the construction method can also be used in the construction of other detectors, thereby improving the performance of other photodetectors.

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**DATA AVAILABILITY STATEMENT**

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

**AUTHOR CONTRIBUTIONS**

ZW: Experiment, Data curation, Discussion, Writing. JL: Experiment, Data curation, Discussion. XW: Discussion. WZ: Conceptualization, Discussion. QH: Conceptualization, Discussion, Writing.

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