Self-powered MSM deep-ultraviolet $\beta$-Ga$_2$O$_3$ photodetector realized by an asymmetrical pair of Schottky contacts

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Abstract: Self-powered photodetectors working in solar-blind region (below 280 nm) have attracted growing attention due to their wide applicability. Monoclinic Ga$_2$O$_3$ ($\beta$-Ga$_2$O$_3$) with excellent merits and a wide bandgap (4.9 eV) is regarded as a good candidate for solar-blind photodetector application. Self-powered photodetectors generally based on homo/heterojunction suffer from a complex fabrication process and slow photoresponse because of the interface defects and traps. Herein, we demonstrated a fabrication and characterization of a self-powered metal-semiconductor-metal (MSM) deep-ultraviolet (DUV) photodetector based on single crystal $\beta$-Ga$_2$O$_3$. The self-powered property was realized through a simple one-step deposition of an asymmetrical pair of Schottky interdigital contacts. The photocurrent and responsivity increase with the degenerating symmetrical contact. For the device with the most asymmetric interdigital contacts operated at 0 V bias, the maximum photocurrent reaches 2.7 nA. The responsivity $R_s$, external quantum efficiency $EQE$, detectivity $D^*$, and linear dynamic range $LDR$ are 1.28 mA/W, 0.63, $1.77 \times 10^{11}$ Jones, and 23.5 dB, respectively. The device exhibits excellent repeatability and stability at the same time. Besides, the device presents a fast response speed with a rise time of 0.03 s and a decay time of 0.08 s. All these results indicate a promising and simple method to fabricate a zero-powered DUV photodetector.

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1. Introduction

Solar-blind photodetectors (PDs) working in the region which wavelength is less than 280 nm, can effectively detect the signal without the intense sunlight interference due to its extremely low natural background caused by the intensive absorption of ozone layer [1]. Until now, solar-blind photodetectors based on wide bandgap semiconductors such as AlGaN, ZnMgO, and ZnGaO have been reported [2–5]. However, the alloying process for AlGaN, ZnMgO and ZnGaO are complex, and the crystal quality significantly deteriorates with the tuning of bandgap to meet the demand for the fabrication of solar-blind photodetectors. Metal oxides with unique optoelectronic and chemical properties, are always been exploited to various applications [6–8]. Recently, monoclinic Ga$_2$O$_3$ ($\beta$-Ga$_2$O$_3$) with a wide bandgap of 4.9 eV, possessing the merits of high carrier mobility, low-cost, easily synthesized, high physical and chemical stability, has been numerously applied for power and optoelectronic devices [9–13].

Up to now, various types of PDs based on $\beta$-Ga$_2$O$_3$ in different forms have been reported in the past years [14–17]. It is well known that conventional solar-blind photodetectors need to be driven by external power source. Afterwards, such power supplies are not ideal for a future smart sensor system in the practical application. Additionally, ultra-small and low
power-consumed properties are necessary for general-purpose integrated circuits (IC). Thus, self-powered PDs which can harvest energy from the environment have drawn great attention due to their sustainable and independent peculiarities. Chen et al. investigated the self-powered solar-blind photodetector based on Au/β-Ga2O3 nanowires array film Schottky junction [11]. Zhao et al. reported an ultrahigh responsivity (9.7 mA/W) self-powered solar-blind photodetector based on individual ZnO-Ga2O3 heterostructure [17]. Guo et al. fabricated zero-power-consumption solar-blind PD based on β-Ga2O3/NSTO heterojunction and a fast photoresponse time (decay time is 0.07 s) was achieved [18]. However, these fabrication processes are complex and thus costly.

In this work, a novel self-powered metal-semiconductor-metal (MSM) photodetector based on β-Ga2O3 single crystal was realized by an asymmetrical pair of Schottky interdigital contacts. The solar-blind PD was achieved by one step mask-deposition fabrication. The as-fabricated photodetector shows excellent performance operated without external power, with a high responsivity of 1.28 mA/W, a high detectivity of $1.77 \times 10^{11}$ Jones, and a fast response time (rise and decay time are 0.03 s and 0.08 s, respectively). The inner mechanism was interpreted by the energy band diagram. In this work, we demonstrate a simple and effective method to fabricate the zero-powered solar-blind photodetector.

2. Experimental section

The photodetector was prepared on (−201) oriented single crystal β-Ga2O3 substrate equipped with an asymmetrical pair of Schottky interdigital contacts, gold was chosen as the contact material. The electrodes were deposited through a physical metal-mask by direct current (DC) magnetron sputtering. Prior to the deposition, β-Ga2O3 substrates were ultrasonic washed sequentially in acetone and ethanol for 5 min, respectively. After that, the substrates were cleaned by deionized water and dried by pure nitrogen gas. To evaluate the homogeneity and validity of the contact, 5-nm thick Ti layer was inserted between the substrate and the Au layer (100 nm). The schematic diagram of the Au/β-Ga2O3/Au structure MSM photodetector is illustrated in Fig. 1(a). A pair of interdigital contacts named Au1 and Au2 with 1.5 mm length and 200 μm space was deposited on β-Ga2O3 substrate. The asymmetrical interdigital contact were realized by fixing electrode Au1 with 300 μm wide, while electrode Au2 varied from 300 to 100 μm with a step of −50 μm, and the space between the two contacts were also fixed. The corresponding fabricated devices were labeled as R1, R2, R3, R4, and R5, respectively. The optical images of the as-fabricated R1 and R5 are shown in Fig. 1(a), the effect caused by the degree of asymmetry on the photodetectors’ performance are investigated subsequently.

The current-voltage (I-V) performances of the photodetectors were analyzed with Keysight B1500A semiconductor parameter analyzer. The light source with a wavelength of 254 nm was applied by a DUV lamp with tunable power intensities. The power of the DUV lamp was measured by a NOVA II power meter. All measurements were performed in air condition at room temperature.

3. Results and discussions

The I-V curves of the as-fabricated DUV photodetector R1 under dark, 254 nm and 365 nm light illumination were plotted in Fig. 1(b). The device displays a typical metal-semiconductor-metal transport property with two back-to-back Schottky barriers. The dark current of the device is less than 5 nA at −6 V bias. The low dark current can attribute to the good formation of Schottky contacts between the interfaces of β-Ga2O3 substrate and Au. It is noted that the dark current exhibits a quasi-symmetrical characteristic, the slight deviation can be ascribed to the inhomogeneity of the two electrodes during the sputtering process. The I-V curve measured under 365 nm light does not show any obvious increase as compared to that in dark. The little variation can be attribute to the defects in the surface and bulk material, or the unpurified light source [19]. Once illuminated with 254 nm light source, a dramatical
increase in current is presented. Understandably, this sensitivity to DUV illumination can be ascribed to the excellent photoelectric and structural properties of the single crystal $\beta$-Ga$_2$O$_3$ substrate.

To investigate the self-powered property of the PDs with different asymmetrical electrodes, the I-V characteristics of R1, R2, R3, R4 and R5 were measured under dark and 254 nm illumination conditions. Figure 2(a) compares the I-V characteristics of the DUVPDs with different widths of electrode Au2 measured under dark condition. It shows that the dark current increases with the decreased electrode Au2. In addition, the I-V curves deviate from a quasi-symmetric to an asymmetric profile in the measured region with the decreasing width of Au2. For R5 with the most asymmetric interdigital contacts, the device exhibits the largest dark current and the asymmetry. Thus, R5 is expected to easily present self-powered character and the following study is mainly focus on R5. Figure 2(c) plots the quantitative relationship between the photocurrent versus the incident light intensity ranging from 1.78 to 0.66 mW/cm$^2$. The photocurrent of DUVPD R5 increases monotonously with the increasing light intensity. The relationship between the light intensity and photocurrent of the DUVPD R5 at 0 V bias is presented in Fig. 2 (d). The photocurrent increases almost linearly with the light intensity, which is identical to the previous study on self-powered solar-blind photodetector based on Au/$\beta$-Ga$_2$O$_3$ nanowires [11]. This result indicates a potential usage for the quantitative measurement of solar-blind ultraviolet light.
Fig. 2. (a) I-V curves of the DUVPDs measured under dark condition; (b) I-V curves of the DUVPDs measured under 254 nm light illumination; (c) I-V curve of the DUVPD R5 measured under 254 nm light illumination with various light intensities; (d) The relationship between the light intensity and photocurrent of the DUVPD R5 at 0 V bias.

Table 1. Comparison of the performance parameters of different MSM DUVPDs operated at 0 V under 254 nm light illumination (the light power density is 1.78 mW/cm²).

| Devices | Photocurrent (nA) | $R_\lambda$ (mA/W) | EQE (%) | Detectivity (10¹⁰ Jones) | LDR (dB) |
|---------|------------------|-------------------|---------|------------------------|----------|
| R2      | 0.16             | 0.03              | 0.01    | 0.66                   | 4.8      |
| R3      | 1.16             | 0.54              | 0.26    | 9.58                   | 20.6     |
| R4      | 1.68             | 0.78              | 0.38    | 11.6                   | 20.7     |
| R5      | 2.70             | 1.28              | 0.63    | 17.7                   | 23.5     |
To quantitatively evaluate the device performance of the DUVPD R5, the responsivity ($R_i$) and external quantum efficiency (EQE) were calculated. The $R_i$ defined as the photocurrent generated per unit power of the incident 254 nm light, which can be written as $R_i = (I_{ph} - I_d) / (P_s S)$. Here, $I_{ph}$ is the photocurrent, $I_d$ is the dark current, $P_s$ is the incident light power intensity, and $S$ is the effective illuminated area ($2.2 \times 10^{-2}$ cm$^2$ for the measured devices). The EQE defined as the number of electrons detected per incident photon, which can be calculated as $EQE = hcR_i / (e\lambda)$. Here, $h$ is the Planck's constant, $c$ is the velocity of light, $e$ is the electronic charge, and $\lambda$ is the wavelength of exciting light. In addition, the detectivity ($D^*$) and linear dynamic range (LDR) are calculated to evaluate the device ability to detect the weak signals from the noisy environment. The $D^*$ and LDR are calculated by the formula of $D^* = R_i / (2eI_d / S)^{1/2}$ and $LDR = 20\log(I_{ph} / I_d)$, respectively.

The comparison of the key performance parameters for different MSM DUVPDs operated at 0 V under 254 nm light illuminated are listed in Table 1. The parameters of R1 are absent here due to its weak performance without external power. Overall, the performance of the MSM DUVPDs improve with the decreasing width of Au2 electrode. For R5 with the narrowest Au2 electrode operated at 0 V bias, the maximum photocurrent reaches 2.7 nA. The obtained $R_i$, $EQE$, $D^*$, and LDR are 1.28 mA/W, 0.63, 1.77 $\times$ 10$^{11}$ Jones, and 23.5 dB, respectively.

Figures 3(a) and (b) plot the calculated $R_i$ and $EQE$ for DUVPD R5 of bias voltage, respectively. Both values of $R_i$ and $EQE$ increase with the increasing bias voltage in both forward and reverse directions. As the external bias applied for the device, the electric field at the reverse biased contact strengths with the increasing bias voltage, the depletion region at the metal-semiconductor interface widened. As a result, more photo-generated carriers are driven by the enhance electric field with faster drift velocity, improving the photocurrent and leading to higher $R_i$ and $EQE$. 
Response time and stability are two key figure-of-merits to evaluate the capability of photodetectors. Time-dependent photoresponse of the photodetector R5 was measured illuminated by 254 nm light with the intensity of 1.78 mW/cm² at a bias of 0 V, as presented in Fig. 4(a). The photodetector R5 switches between on and off state with the periodically turning on and off 254 nm light, indicating the high reversibility and stability of the MSM DUVPD. For a more detailed investigation of the response time, the transient response curves are fitted by an exponential relaxation equation, which is expressed as: \( I = I_0 + ce^{-t/\tau} \), where \( I_0 \) is the steady-state photocurrent, \( t \) is the time, \( c \) is a constant, and \( \tau \) is the relaxation-time constant. Figure 4(b) shows the enlarged view of the rise/decay edges and the corresponding fitting curves, \( \tau_r \) and \( \tau_d \) are the rise and decay time constants, respectively. \( \tau_r \) and \( \tau_d \) of R5 measured at a bias of 0 V are 0.03 and 0.08 s, respectively. Compared with available Ga₂O₃ PDs listed in Table 2, the asymmetric MSM DUVPD here possesses an excellent transient property with faster response and recovery. Actually, for most PDs based on Ga₂O₃ films, quantities of trapping states induced by the inherent existence of defects (such as oxygen vacancies, gallium-oxygen vacancies pairs, and structural disorders) are present in the film. These trapping states usually capture or release photon-generated carriers, which deteriorate the transient response performance of the devices. For our asymmetric MSM DUVPD based on single crystal, the defects and traps are dramatically decrease, thus an excellent transient property is expected. Besides, the back-to-back Schottky contacts reduce both dark and light current, making a compromise between the response time and photocurrent, which further improve the response and recovery time.

### Table 2. Comparison of the photodetector’s performance parameters based on Ga₂O₃ with different forms

| Photodetectors          | External bias | \( I_d \)  | \( I_{ph} \) | \( R_i \)       | Response time | Reference |
|-------------------------|---------------|------------|------------|----------------|---------------|-----------|
| single crystal          | None          | 0.18 nA    | 2.70 nA    | 1.28 mA/W      | 0.03/0.08 s   | This work |
| Single crystal          | –3 V          | 10 nA      | -          | \( 1 \times 10^4 \) A/W | -             | [20]      |
| multi-nanobelt amorphous| 5 V           | 0.1 pA     | 21 nA      | 851 A/W        | <0.3/0.3 s    | [21]      |
| Nanostructure film      | 10 V          | 338.6 pA   | -          | 70.26 A/W      | >2.04/0.35 s  | [22]      |
| \( \beta \)-Ga₂O₃/NSTO | None          | 10 pA (–30 V) | 120 pA     | 0.01 mA/W      | 1/60 μs       | [11]      |
Based on the above-calculated results, the energy band diagrams for R5 under both dark and DUV light illuminated conditions are analyzed and illustrated in Figs. 5(a) and (b), respectively. In the dark condition, built-in electric filed generated from Schottky barriers at both ends of the metal-semiconductor contacts, balances the spontaneously diffusion of the carriers. Thanks to the existence of the built-in electric filed, the dark current can be as low as $10^{-9}$ nA for MSM DUVPDs. Once illuminated with DUV light, electron-hole pairs are generated in the surface of $\beta$-Ga$_2$O$_3$, as exhibited in Fig. 5(b). Driven by the force of the built-in electric field, holes in the valence band (electrons in the conduction band) tend to flow close to (away from) the metal/semiconductor interfaces. The photo-generated electrons sequentially move until recombined or trapped with the intrinsic defects in the bulk $\beta$-Ga$_2$O$_3$, while the photo-generated holes are accumulated and trapped at the MS interfaces. However, since the large-are electrodes (Au1) are highly likely to include more surface states on the MS interface (compared with Au2), which can trap photo-generated holes and then reducing the Schottky barrier height, thus the Schottky barrier height is different for Au1/Ga$_2$O$_3$ and Au2/Ga$_2$O$_3$, as shows in Fig. 5(b) [23,24]. As a result, the local potential distribution is modified and lower Schottky barriers are expected. For MSM DUVPD R5, the number of holes in the region of two MS interfaces under illuminated are very different due to the asymmetric contacts Au1 and Au2. Hence, the variations of the modified local potential at two MS interfaces are different, which leads to the difference in the decrease of the Schottky height. As a result, a typical photovoltaic characteristic can be observed in the asymmetric MSM photodetectors at 0 V bias voltage. This zero-power characteristic induced by asymmetric contacts are also found in other metal oxides, such as InGaO, ZnO and BeZnO [25–27].

4. Conclusions

In this study, we demonstrate the fabrication and characterization of self-powered MSM DUV photodetector based on single crystal $\beta$-Ga$_2$O$_3$. The self-powered property was realized through a simple one-step deposition of an asymmetrical pair of Schottky interdigital contacts. The photocurrent and responsivity increase with the degenerating symmetrical contact. For R5 with the most asymmetric interdigital contacts operated at 0 V bias, the maximum photocurrent reaches 2.7 nA. The $R_s$, $EQE$, $D^*$, and $LDR$ are 1.28 mA/W, 0.63, $1.77 \times 10^{11}$ Jones, and 23.5 dB, respectively. The device exhibits excellent repeatability and stability. Besides, the device presents a fast response speed with a rise time of 0.03 s and a decay time of 0.08 s. At last, the electric potential distribution accompanied with an energy band plot were proposed to explain the self-powered characteristic of the device. All these results indicating a promising and simple method to fabricate a zero-powered DUV photodetector based on single crystal $\beta$-Ga$_2$O$_3$. 
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Disclosures
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