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Self-powered solar-blind photodiodes based on EFG-grown (100)-dominant β-Ga_2O_3 substrate*

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We report the edge-defined-film-fed (EFG)-grown β-Ga_2O_3-based Schottky photodiodes. The device has a reverse leakage current of ~nA and a rectified ratio of $\sim 10^4$ at ±5 V. In addition, the photodiode detector shows a dark current of 0.3 pA, a photo-responsivity (R) of 2.875 mA/W, a special detectivity (D^*) of 10^{10} Jones, and an external quantum efficiency (EQE) of 1.4% at zero bias, illustrating a self-powered operation. This work may advance the development of the Ga_2O_3-based Schottky diode solar-blind photodetectors.

Keywords: β-Ga_2O_3 substrate, Schottky photodiode, solar-blind detection

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1. Introduction

The β-phase gallium oxide (β-Ga_2O_3) is most chemical and thermal stable among its five phases of α, β, ε, δ, and γ.[1–3] Owing to its high breakdown electric field ($E_{br} \sim$ 8 MV/cm) and wide direct band gap ($E_g \sim 4.9$ eV) responding in the ultraviolet (UV) solar-blind region, β-Ga_2O_3 is extensively employed to construct the solar-blind photodetectors with various device structures,[3–6] including the typical metal–semiconductor–metal (MSM), p–n junctions, heterojunctions, and Schottky junctions structures, exhibiting many decent optoelectrical characteristics.

Thereinto, the junction-based devices may provide many promising device characteristics caused by the dispersive energy-band edges. In comparison, the heterojunctions with large enough band offsets are always good candidates for fabricating devices, while the two (or more) layers in heterojunctions need to be deposited at high temperatures and ultrahigh-vacuum conditions, translating to complex technologies and high costs, so the metals with high work functions contacting onto the semiconductor seem to be easier and cheaper. The Schottky-type photodetectors may well be more captivating due to the low dark current, fast response speed, and low noise performances, contributed by the constraint of carriers across the interfaces of the Schottky junctions.[7–11] As referenced by the reported papers, owing to the separation of electron–hole pairs in the Au/β-Ga_2O_3 Schottky junction, an energy-saving self-powered device was achieved, showing a very low dark current of $\sim 10^{-11}$ A and a short response time of 64 μs.[10] A graphene/β-Ga_2O_3 Schottky photodetector was fabricated and showed a high photo-responsivity of 29.8 A/W, a photo-to-dark current ratio of $\sim 10^6$, and a detectivity of $\sim 10^{12}$ Jones.[12] Thanks to the construction of built-in electrical filed at the interface between Ni and β-Ga_2O_3, a self-powered β-Ga_2O_3 photodiode was developed by sputtering equipment and showed stable operation,[13] in which the high photo-responsivity of 144 A/W (10 V) was displayed. Moreover, a metal–oxide–semiconductor (MOS)-

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structured photodiode presented more desired performances for solar-blind photodetection, including self-powered operation and high external quantum efficiency.[14]

In consideration of the advantages of Schottky photodiode in performing solar-blind detection, we constructed Schottky diode photodetectors based on the edge-defined-film-fed (EFG)-grown (100)-dominated β-Ga_2O_3 substrate, by using conventional UV photolithography, electron beam evaporation, and lift-off techniques. The breakdown and the solar-blind photodetection were tested. The self-powered operation without any external energy apply (at zero bias) was further discussed.

2. Experimental details

Firstly, the 10 mm × 10 mm β-Ga_2O_3 substrate was grown by the EFG method.[15] The x-ray diffraction (XRD) was performed to verify the quality of the β-Ga_2O_3 substrate. To fabricate the Schottky photodiodes, the conventional standard photolithography and lift-off technique were performed. The Ti/Au (30 nm/60 nm) and Ni/Au (30 nm/60 nm) were patterned by electron beam evaporation, serving as Ohmic and Schottky electrodes, respectively. The electron pattern is 400 μm wide and 600 μm long with 4 μm spacing distance, so the effective UV illuminated area of the fabricated device is calculated to be 4×600 μm^2.

For characterizing the performances of the Schottky solar-blind photodiodes, the voltage–current (I–V) and time-dependent current (I–t) measurements were carried out by using a Keithley 4200 semiconductor analyzer in air at room temperature (22.4 ℃) in our lab. For the illuminated opto-electrical behaviors, a UV lamp that could emit 254 nm wavelength light was used, the distance between the measuring samples and the UV light source could be tuned to change the incident light intensity upon the surface of the samples.

3. Results and discussion

Using a single crystal XRD measuring equipment, the β-Ga_2O_3 substrate sample was measured, the results show that the lattice parameters are $a = 12.22$ Å, $b = 3.04$ Å, $c = 5.80$ Å, $\alpha = 90°$, $\beta = 103.88°$, and $\gamma = 90°$. In Fig. 1, the XRD shows the (400), (600), (800), and (002) peaks for the β-Ga_2O_3, suggesting a polycrystalline β-Ga_2O_3 substrate used in this work. The 10 mm × 10 mm β-Ga_2O_3 substrate is shown in the inset of Fig. 1.

We constructed 16 Schottky diodes on the 10 mm × 10 mm β-Ga_2O_3 substrate in this study. As presented in Fig. 2(a), all the Schottky diodes exhibit good rectified behaviors due to the asymmetric Ti and Ni metal electrodes. In Fig. 2(b), the I–V performances of the β-Ga_2O_3 Schottky diodes in the dark and under illumination with light intensity of 100 μW·cm^{-2} are displayed. Clearly, the rectified ratio of the device is 7.58×10^4 at ±5 V. In addition, the reverse leakage current of the device is as low as 8.47 nA in the dark at a reverse bias of −5 V. The photo-to-dark current ratio (PDCR) is ∼ 68.8 at −5 V responding to the 254 nm UV light with intensity of 100 μW·cm^{-2}. For the diode device in this work, the Ohmic contact at the Ti/β-Ga_2O_3 side could be referenced by electron tunnelling,[16,17] while the Schottky contact at the Ni/β-Ga_2O_3 side is usually described according to the thermal electron (TE) model[17]

$$I = I_0 \left[\exp\left(\frac{qV}{nkT} \right) - 1 \right], \tag{1}$$

$$I_0 = AA^* T^2 \exp\left(-\frac{\varphi_B}{kT} \right), \tag{2}$$

$$\varphi_B = \frac{kT}{q} \ln\left(\frac{AA^* T^2}{I_0} \right), \tag{3}$$

where I_0 is the reverse saturation current, A is the effective metal–semiconductor (M–S) contacted area, A^* is the effective Richardson constant, n is the ideal factor, k is the Boltzmann constant, and φ_B is the Schottky barrier height (SBH). Here, A^* is 41.1 A/cm^2·K^2, and is always expressed as[17]

$$A^* = \frac{4\pi q m^* k^2}{h^3}. \tag{4}$$

For Ga_2O_3, m^* is taken as $0.342m_0$, where m_0 is the mass of free electron.[18] For the two devices, the spacing distance (L) between Ti/Au and Ni/Au is 4 μm, the area of the electron pattern is 3.6×10^4 μm^2. Therefore, the SBH can be calculated to be 0.67 eV for the device, based on Eqs. (1)–(4). In addition, the ideality factor n is estimated to be 1.72 for the device, in the range from 1 to 2, indicating a desired behavior of Schottky diode.

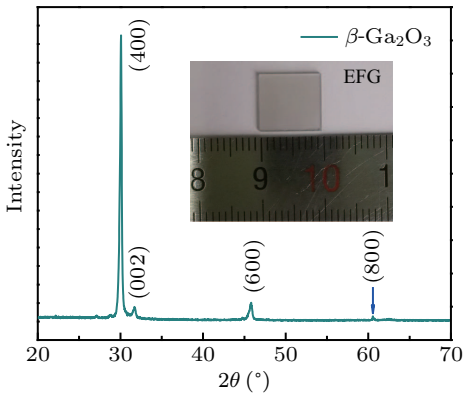


Fig. 1. The XRD pattern of the EFG-grown β-Ga_2O_3 crystal substrate (shown in the inset).

Three selected Schottky diode samples from the fabricated devices were tested breakdown in air at room temperature (22.4 ℃), suggesting that the breakdown voltages are 46.8 V, 49.6 V and 50 V, as presented in Fig. 2(c). Except for the different device scales, the low breakdown voltages in this report may be due to the inferior quality of the crystal. The improvement of the crystal quality could promote the higher breakdown voltages.[19–22] The work functions of Ti (Φ(Ti)) and Ni (Φ(Ni)) are 4.33 eV and 5.15 eV, respectively.[23] And the electron affinity of β-Ga_2O_3 ($\chi(\beta\text{-}Ga_2O_3)$) is 4.00 eV

as reported in Ref. [24]. According to the Schottky–Mott rule,[25] the theoretical M–S interfacial barriers are 0.33 eV and 1.15 eV, for the Ti/β-Ga_2O_3 and Ni/β-Ga_2O_3 interfaces, respectively, as displayed in Fig. 2(d). Such asymmetric barriers contribute to the rectified effects of the Schottky diodes in this work, indicating the on-state at forward biases and off-state at reverse biases. The quite different results (great varies in reverse leakage currents) in Fig. 2(a) may be due to the not very uniform surface of the β-Ga_2O_3 substrate and/or the inconformity in micromachining processes. Under illumination, the electron–hole pairs are photo-generated, the absorbance of the incident photons ($hv > E_g$) could happen via the excitation of the electrons from the valence band edge to the conduction band edge of the β-Ga_2O_3 substrate.

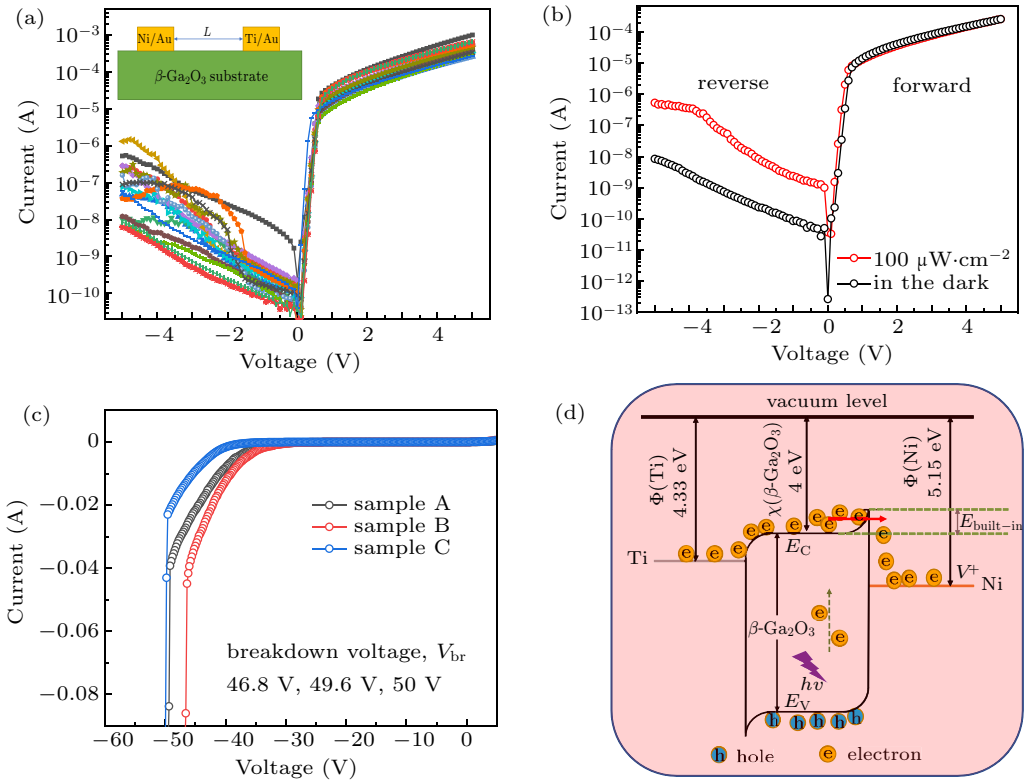


Fig. 2. (a) The semi-log scale current–voltage characterizations of the 16 β-Ga_2O_3-based Schottky photodiodes on the 10 mm × 10 mm substrate, (b) the semi-log scale current–voltage curves of the β-Ga_2O_3-based Schottky photodiode in the dark and under illumination with intensity of 100 μW·cm^{-2}, (c) the breakdown of three selected device samples, (d) the energy-band diagram of the β-Ga_2O_3-based Schottky photodiode.

For the Schottky photodiodes in this study, the built-in electrical field ($E_{built-in}$) is developed when the Ni and β-Ga_2O_3 contact, owing to the interfacial barrier caused by the energy band bending at the edge of the conduction band (E_C) (as shown in Fig. 2(d)), leading to the rectified effects, as given in Fig. 2(a). The electron–hole pairs are effectively separated by $E_{built-in}$ in the space charge region. Benefiting from this phenomenon, as shown in Fig. 3(a), the devices could operate at zero bias, i.e., self-powered operation.[26–28] The photo-generated electrons could move to the conduction band and contribute to the photocurrent, as shown in Fig. 2(d). The dark current (I_{dark}) and the PDCR are ∼ 0.3 pA and 138 for the Schottky photodiode at zero bias under illumination with intensity of 600 μW·cm^{-2}. The photo-responsivity (R), specific detectivity (D^*), and external quantum efficiency (EQE) are key parameters to evaluate the performances of a photodetector, and could be given as[29,30]

$$R = \frac{I_{photo} - I_{dark}}{P \cdot S}, \tag{5}$$

$$D^* = \frac{R}{\sqrt{2qI_{dark}/S}}, \tag{6}$$

$$\mathrm{EQE}(\eta) = \frac{hcR}{q\lambda}, \tag{7}$$

where I_{dark} is the dark current, I_{photo} is the photocurrent when the UV solar-blind light illuminates on the surface of the devices, P is the light intensity, S is the effective illuminated area (4×600 μm^2), q is the electron charge of 1.6×10^{-19} C, λ is the light wavelength of 254 nm, c is the light velocity of 2.998×10^8 m/s, and h is Planck's constant. The photo-response of a detector, to a large degree, relies on the transport time of the photo-generated electron–hole pairs in the illuminated active area. Always, due to the absorption of the oxygen vacancy (maybe also other defects) at the surface and the grain boundaries of the employed semiconducting materials, the slow response is the common phenomenon. As seen in Fig. 3(b), the Schottky diode photodetector displays a rise time of ∼ 0.61 s and a decay time of 2.26 s by fitting the response curves on the basis of relationship $I = I_0 + Ae^{-t/\tau}$,[13] where I_0 is the photocurrent at stable state, A is a constant, t is the time, and τ is the relaxation time constant.

Based on Eqs. (5)–(7), the R, D^*, and EQE of the Schottky diode photodetector can be determined to be 2.875 mA/W,

4.5×10^{10} cm·Hz$^{1/2}$·W^{-1} (Jones), and 1.4%, respectively. Therefore, at zero bias, the photo-generated electron–hole pairs effectively generate I_{photo}.[13,31] The decent self-powered performances suggest that the Schottky diode photodetector is well coupled to the UV light source for the detection of solar-blind UV incident light, as well as the ability to characterize the signal-to-noise performances.[30] The R of 2.875 mA/W at zero bias indicates a fact that the photo-generated carriers may also be driven by the E_{built} at the space charge region, although no external energy is supplied to the operating Schottky diode photodetector. This kind of energy-saving device is more desired for practical applications.[32–36]

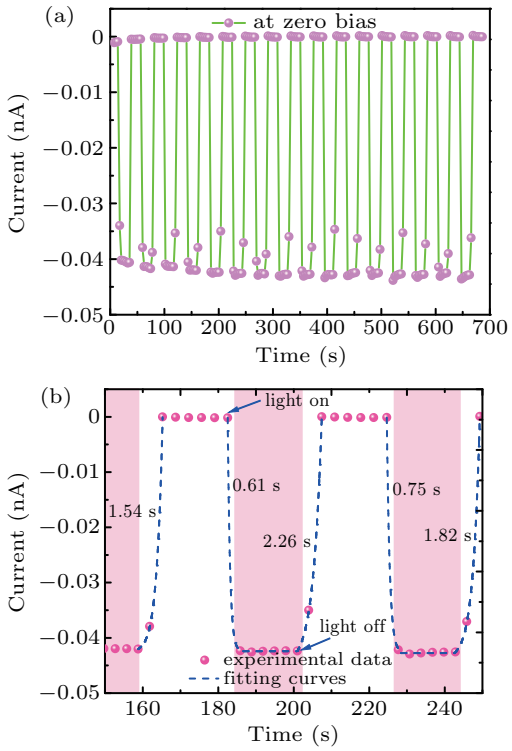


Fig. 3. (a) The time-dependent currents and (b) the response (rise and decay) time of the β-Ga_2O_3-based Schottky photodiode at zero bias.

4. Conclusion

In summary, we investigate the electrical characteristics of the β-Ga_2O_3 Schottky solar-blind photodiode. The results indicate that the devices could achieve high rectified ratio, low reverse leakage current, and decent breakdown voltages. Working as a UV solar-blind photodetector, a self-powered operation is realized. At zero bias, the photodetector shows a R of 2.875 mA/W, a D^* of 10^{10} Jones and an EQE of 1.4%, suggesting decent performances of the detector. In all, this work indicates the feasibility of self-powered EFG-grown β-Ga_2O_3 Schottky diode detector and may well guide the advance and development of the building blocks of the Ga_2O_3-based solar-blind UV photodetector.

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