β-Ga$_2$O$_3$ nanorod arrays with high light-to-electron conversion for solar-blind deep ultraviolet photodetection

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Vertically aligned nanorod arrays (NRAs), with effective optical coupling with the incident light and rapid electron transport for photogenerated carriers, have attracted much interest for photoelectric devices. Herein, the monoclinic β-Ga$_2$O$_3$ NRAs with an average diameter/length of 500 nm/1.287 μm were prepared by the hydrothermal and post-annealing method. Then a circular Ti/Au electrode was patterned on β-Ga$_2$O$_3$ NRAs to fabricate solar-blind deep ultraviolet photodetectors. At zero bias, the device shows a photocurrent responsivity ($R_p$) of 10.80 mA W$^{-1}$ and a photo response time of 0.38 s under 254 nm light irradiation with a light intensity of 1.2 mW cm$^{-2}$, exhibiting a self-powered characteristic. This study presents a promising candidate for use in solar-blind deep ultraviolet photodetection with zero power consumption.

1. Introduction

Solar-blind ultraviolet (UV) photodetectors (PDs) are useful as an answer to the technical challenge of operating at wavelengths less than 290 nm, while exposed to a large background radiation of sunlight. With the continuous improvement of device integration, environment complexity, and interference technology, solar-blind ultraviolet region photodetectors can effectively reduce false alarm rates in early-warning, searching, and tracking systems, to improve the accuracy and versatility of detection systems in various situations. Up to now, a number of wide bandgap semiconductors have been investigated to design solar-blind photodetectors, such as AlGaN, ZnMgO, β-Ga$_2$O$_3$, etc. AlGaN-based photodetectors present more excellent performance than the other wide bandgap semiconductors devices. However, with increasing Al composition for solar-blind photodetectors, the performance of AlGaN photodetectors rapidly becomes poor due to the obvious degradation of the crystal quality. ZnMgO alloys with a band gap in solar-blind region also suffer from the poor crystal quality due to the phase separation.

It is noticed that Ga$_2$O$_3$ has a direct wide bandgap of ~4.9 eV, directly corresponding to the wavelength less than 280 nm, which is an ideal solar-blind detection material without any doping and alloying process. Among all five phases of Ga$_2$O$_3$ (α, β, γ, δ and ε), the β-Ga$_2$O$_3$ with monoclinic crystal structure is the thermally and chemically most stable phase, has been widely studied in solar-blind photodetectors. So far, β-Ga$_2$O$_3$-based photodetectors mainly fall into three categories: film type, single crystals and nanorod arrays (NRAs) type. Compared to thin films, vertical nanowire array structures display more superior optical absorption ability and higher carrier generation, resulting from high surface-to-volume ratio and effective optical coupling, which can further improve the performance of photodetectors. He et al. first reported the ultraviolet photodetector based on vertical β-Ga$_2$O$_3$ nanowire arrays by thermally oxidizing GaN nanowires grown by molecular beam epitaxy (MBE) on Si substrate. Nevertheless, this complexity and high cost in fabrication will limit the practical application of β-Ga$_2$O$_3$ NRAs photodetector.

In this work, the vertically aligned β-Ga$_2$O$_3$ NRAs are successfully synthesized by economical hydrothermal and simple post-annealed method on fluorine doped tin oxide (FTO) substrate. And then a circular Ti/Au electrode was patterned on β-Ga$_2$O$_3$ NRAs to fabricate solar-blind deep ultraviolet photodetectors. The fabricated devices exhibited a great broadband spectral response with the high responsivity.
exceeding 550 A W⁻¹ at −5 V bias voltage. At zero bias, the device shows a photoresponsivity \( R_\text{p} \) of 10.80 mA W⁻¹ and a photo response time of 0.38 s under 254 nm light irradiation with a light intensity of 1.2 mW cm⁻², exhibiting a self-powered characteristic. Our findings indicated that this simple synthesize method can be used to fabricate \( \beta \)-Ga₂O₃ NRAs based self-powered solar-blind photodetectors with fast response speed for the potential applications in secure communication and space detection.

2. Experimental details

2.1 Materials
Ethanolamine \( (\text{C}_2\text{H}_7\text{NO}, 99\%) \), gallium isopropoxide \( (\text{C}_9\text{H}_{21}\text{GaO}_3, 99\%) \), gallium nitrate aqueous solution \( [\text{Ga(NO}_3)_3\cdot9\text{H}_2\text{O, 10\%}] \) were purchased from Shanghai Saen Chemical Technology Co., Ltd. Triethanolamine \( (\text{C}_6\text{H}_{15}\text{NO}_3, 78\%) \) was obtained from Hangzhou Gaojing Fine Chemical Industry Co., Ltd. A fluorine doped tin oxide (FTO) with 350 nm conductive layer is used as a substrate. FTO conductive glass \( (14 \Omega \text{ cm}^{-2}, \text{ size: } 10 \times 20 \times 2.2 \text{ mm}^3) \) was bought from Japan Nippon Sheet Glass Co., Ltd. All chemicals are analytical grade.

2.2 Synthesis and characterization of the \( \beta \)-Ga₂O₃ NRAs

The GaOOH NRAs were fabricated as described in our previous reports.²⁴ The substrate coated with Ga₂O₃ seed layer was placed in the growth solution of \( \text{Ga(NO}_3)_3\cdot9\text{H}_2\text{O} \) and heated at 150 °C for 12 h in an oven. After the growth, the product was washed by DI water, dried in air at 80 °C. The as-prepared GaOOH NRAs calcined at 700 °C for 4 h were converted into the \( \beta \)-Ga₂O₃ NRAs.

![Schematic illustration of preparation of the \( \beta \)-Ga₂O₃ NRAs](image)

![The top views of SEM images at low (a) and high (b) magnification of \( \beta \)-Ga₂O₃ NRAs grown on the FTO substrate. (c) The edge view of \( \beta \)-Ga₂O₃ NRAs. (d) The cross-section of \( \beta \)-Ga₂O₃ NRAs on the FTO substrate.](image)
The morphologies of β-Ga₂O₃ NRAs were observed by a Hitachi S-4800 field-emission scanning electron microscope (SEM). The crystal structure of samples was analyzed by a Bruker D8 Advance X-ray diffractometer (XRD) using Cu Kα radiation (λ = 0.154 nm). The ultraviolet-visible (UV-vis) absorption spectrum was taken using a Hitachi U-3900 UV-vis spectrophotometer.

2.3 Fabrication and characterization of the photodetector

The photodetector was fabricated by depositing circular Ti/Au electrodes on the vertically aligned β-Ga₂O₃ NRAs with direct current magnetron sputtering. The photoelectric characteristics of the fabricated device were characterized by a Keithley 4200 at room temperature. And a 7 W lamp of 254 nm was used as the UV light source.

3. Results and discussion

The vertically aligned β-Ga₂O₃ NRAs have been grown on the FTO glass substrate and the fabrication process is schematically illustrated in Fig. 1. The β-Ga₂O₃ NRAs are fabricated by three steps procedure: (1) the seed layer was acquired by spin coating ethylene glycol monomethyl ether solution of ethanolamine and gallium isopropoxide onto the FTO substrate; (2) the substrate coated with Ga₂O₃ seed layer was placed in the growth solution of Ga(NO₃)₃·9H₂O and heated at 150 °C for 12 h in an oven; (3) the as-prepared GaOOH NRAs calcined at 700 °C for 4 h were converted into the β-Ga₂O₃ NRAs.

The SEM result shows that a large-area, highly dense, and vertically aligned β-Ga₂O₃ NRAs have been successfully grown on the FTO glass substrate [Fig. 2(a–d)]. Fig. 2(a) displays a representative top-view SEM micrograph of as-synthesized β-Ga₂O₃ nanorods. Fig. 2(b) is a magnified image of Fig. 2(a). Fig. 2(c) is a top view SEM image in the boundaries of NRAs. Obviously, there has a high density and flat surface of β-Ga₂O₃ NRAs aligned vertically grown on FTO substrate. It also can be observed that the tips of the nanorods are the diamond shape, whose diameter has changed in the range of 100 to 500 nm. Fig. 2(d) shows the cross-section image of β-Ga₂O₃ NRAs on FTO substrate, we can estimate that the average length of nanorods is ~1.287 μm. Fig. 3(a) shows the XRD patterns of the FTO, FTO/GaOOH and β-Ga₂O₃ NRAs, respectively. In addition to the diffraction peak of the FTO substrate, four peaks located at 35.3°, 37.4°, 62.3° and 66.7° were observed in FTO/GaOOH, which can be indexed to (021), (111), (002) and (102) planes.

![Fig. 3](image)

**Fig. 3** (a) XRD patterns of the FTO, FTO/GaOOH NRAs and FTO/β-Ga₂O₃ NRAs. (b) The absorption spectrum of β-Ga₂O₃ nanorod, the inset is (αhv)² versus hv.

![Fig. 4](image)

**Fig. 4** (a) The schematic diagram of the β-Ga₂O₃ NRAs solar-blind photodetector. (b) I–V curves of the device in dark and under 254 nm illumination with various light power densities.
(070) crystal planes of orthorhombic GaOOH (JCPDS file no. 06-0180). The NRAs show a preferred growth orientation of [111] direction. After the annealing of as-prepared GaOOH NRAs, three additional peaks located at 31.7°, 35.3° and 37.9° were observed, which can be ascribed to the (002), (111) and (401) planes of monoclinic β phase of Ga2O3 (JCPDS file no. 41-1103). The UV-vis absorbance spectra of the β-Ga2O3 NRAs is shown in Fig. 3(b). It shows that the absorption onset of β-Ga2O3 is at ~270 nm. The optical bandgaps of β-Ga2O3 NRAs can be determined based on the equation: $(a h v)^2 = A (h v - E_g)$. The energy bandgap ($E_g$) is measured by linear extrapolation to the $h v$-axis. The $(a h v)^2$ versus $h v$ curve of the β-Ga2O3 NRAs is shown in the inset of Fig. 3(b), the band-gap of β-Ga2O3 NRAs was estimated to be ~4.63 eV, which is almost identical with previous reports. A circular Ti/Au electrode was patterned on β-Ga2O3 NRAs to fabricate a solar-blind deep ultraviolet photodetector. The schematic diagram of the device is presented in Fig. 4(a). Fig. 4(b) depicts the current voltage ($I$–$V$) curves of the device in dark and under 254 nm illumination with various light intensities. The rise time ($\tau_r$) and decay time ($\tau_d$) were measured at 0 V bias under 254 nm illumination with various light intensities. The relationship between the light intensity and photocurrent is depicted in Fig. 5(a). The relationship between the light intensity and photoresponse time is shown in Fig. 5(c). The rise time and decay time of the device at 0 V bias under 254 nm light irradiation with a light intensity of 1.2 mW cm$^{-2}$ are shown in Fig. 5(c). The relationship between the light intensity and photoresponse time is shown in Fig. 5(d). The photoresponse switching behaviors of the device were measured at different applied bias voltages. The relationship between the light intensity and applied bias voltage is shown in Fig. 5(e).
distributions. Obviously, under the 254 nm ultraviolet illumination, the current in the reverse bias is larger than that in the forward bias. The inset of Fig. 4(b) is the enlarged curves around zero bias. It can be seen at 0 V bias that the current of the device increases in negative direction with the increase of the light densities, exhibiting a self-powered characteristic.

Fig. 5(a) shows the time-dependent photoresponse ($I-t$) of the device measured at 0 V bias under 254 nm illumination with various light intensities. It exhibits stable and reproducible characteristics under an on/off interval of 20 s. The dark current is approximately 0.18 pA. Under 254 nm light illumination, along with the light densities increased from 0.2 to 1.2 mW cm$^{-2}$, the negative photocurrent value of device increase from 0.421 to 1.644 pA. The corresponding light/dark ratios ($I_{	ext{light}}/I_{	ext{dark}}$) are gradually increased from 2.34 to 9.14. Notably, the photocurrent of the device linearly increases with the increase of the light intensities, as shown in Fig. 5(b), revealing that the stronger ultraviolet light can excite more photogenerated carriers. $I-t$ curve of self-powered β-Ga$_2$O$_3$ NRAs solar-blind photodetector at 0 V bias under 1.2 mW cm$^{-2}$ 254 nm light irradiation is enlarged in Fig. 5(c). The rising and decaying edges were fitted by an exponential relaxation equation of the following type:

$$I = I_0 + A e^{-t/\tau_1} + B e^{-t/\tau_2}$$

(1)

where $I_0$ is the steady state photocurrent, $t$ is the time, $A$ and $B$ are constant, $\tau_1$ and $\tau_2$ are two relaxation time constants. $\tau_1$ and $\tau_2$ are the time constants for the rising edge and falling edge, respectively. The rise time ($\tau_1$) and the decay time ($\tau_2$) of are approximately 0.64 s and 0.38 s respectively. It is noticed in Fig. 5(d) that $\tau_1$ and $\tau_2$ show downward trend with the increase of light intensity. The photoresponse switching behaviors of the device at different applied bias voltages were measured under 254 nm illumination as shown in Fig. 5(e). Apparently, both the dark current and photocurrent increases along with the increase of the bias voltages ranging from 0 V to −1.5 V. Meanwhile, the photocurrent of 17.60 pA at −1.5 V is about 11 times than that at 0 V under the same conditions. Notably, the photocurrent increases linearly with the increase of the electric field, because a more separation and transportation of electron–hole pairs would excite more pairs of the photo-generated electron–hole, resulting in a higher photocurrent. Photoreponsivity ($R_s$) and external quantum efficiency (EQE) are two important parameters to evaluate the sensitivity of PDs. $R_s$ is defined as the photocurrent generated by per unit power of incident light on the effective area of a PD and EQE is bound up with the number of electron–hole pairs excited by a PD per adsorbed photon and per unit time. $R_s$ and EQE can be expressed in the following equations:

$$R_s = \Delta I / P_s$$

(2)

$$\text{EQE} = \frac{\Delta I}{P_s} \frac{1}{S}$$

(3)

where $\Delta I = I_\text{r} - I_\text{dark}$ is the difference between photocurrent and dark current, $P_s$ is the incident light intensity, $S$ is the effective illuminated area, $h$ is the Planck’s constant, $c$ is the velocity of light, $e$ is the electron charge, and $\lambda$ is the incident light wavelength. It can calculate that the device exhibits a photoreponsivity ($R_s$) of 10.80 mA W$^{-1}$ and an external quantum efficiency (EQE) of 5.27 × 10$^{-3}$% at 0 V bias under 1.2 mW cm$^{-2}$ 254 nm illumination. Simultaneously, the $R_s$ and EQE are estimated to 85.52 mA W$^{-1}$ and 4.18 × 10$^{-2}$% for −1.5 V bias, respectively. It can be seen from the Fig. 5(f) that $R_s$ increases near linearly with the bias voltage. Accordingly, applying bias voltage is a good way to rationally optimize the photoelectric performance of photodetector. For comparison, we list the photoresponse parameters of β-Ga$_2$O$_3$ NRAs PD and other types of devices reported in the literature in Table 1. It can be seen that compared with the other type device our device can work at zero bias. The β-Ga$_2$O$_3$ NRAs PD with a simple structure renders relatively high performance, wide absorption region and low fabrication cost, promising building high performance optoelectronic devices with a self-powered worked characteristic in the future.

4. Conclusions

In conclusion, a self-powered solar-blind photodetector was successfully fabricated by simple and low cost β-Ga$_2$O$_3$ NRAs growth process. The fabricated β-Ga$_2$O$_3$ NRAs based PD showed an obvious photoresponse in solar-blind ultraviolet region with good repeatability and stability. Under 0 V bias and 1.2 mW cm$^{-2}$ 254 nm illumination, the photodetector exhibits a $I_{\text{light}}/I_{\text{dark}}$ ratio of 9.14, a $R_s$ of 10.80 mA W$^{-1}$, $\tau_1$ of 0.64 s and $\tau_2$ of 0.38 s. The self-powered photodetector based on β-Ga$_2$O$_3$ NRAs with high light-to-electron conversion and low power consumption abilities is a promising candidate for solar-blind photodetection application.
Conflicts of interest

There are no conflicts to declare.

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References

1 L. W. Sang, M. Y. Liao, M. Sumiya, et al., A comprehensive review of semiconductor ultraviolet photodetectors: from thin film to one-dimensional nanostructures, Sensors, 2013, 13(8), 10482–10518.
2 D. S. Tsai, W. C. Lien, D. H. Lien, et al., Solar-blind photodetectors for harsh electronics, Sci. Rep., 2013, 4(9), 2628.
3 B. Zhao, F. Wang, H. Y. Chen, et al., Solar-blind avalanche photodetector based on single ZnO–Ga2O3 core–shell microwire, Nano Lett., 2015, 15(6), 3988.
4 Q. Zhang, J. S. Jie, S. L. Diao, et al., Solution-processed graphene quantum dot deep-UV photodetectors, ACS Nano, 2015, 9(2), 1561–1570.
5 N. Shouleh, H. Michael, D. J. April, et al., Single photon counting UV solar-blind detectors using silicon and III-nitride materials, Sensors, 2016, 16(6), 927.
6 C. Y. Cho, Y. Zhang, E. Cicek, et al., Surface plasmon enhanced light emission from AlGaN-based ultraviolet light-emitting diodes grown on Si (111), Appl. Phys. Lett., 2013, 102, 211110.
7 F. H. Teherani, D. C. Look, D. J. Rogers, et al., Optical properties of ZnMgO films grown by spray pyrolysis and their application to UV photodetection, Semicond. Sci. Technol., 2015, 30(10), 105026.
8 X. C. Guo, N. H. Hao, D. Y. Guo, et al., β-Ga2O3/p-Si heterojunction solar-blind ultraviolet photodetector with enhanced photoelectric responsivity, J. Alloys Compd., 2016, 660, 136–140.
9 K. W. Liu, M. Sakurai and M. Aono, ZnO-based ultraviolet photodetectors, Sensors, 2010, 10, 8604–8634.
10 L. K. Wang, Z. G. Ju, J. Y. Zhang, et al., Single-crystalline cubic MgZnO films and their application in deep-ultraviolet optoelectronic devices, Appl. Phys. Lett., 2009, 95, 131113.
11 X. L. Du, Z. X. Mei, Z. L. Liu, et al., Controlled growth of high-quality ZnO-based films and fabrication of visible-blind and solar-blind ultra-violet detectors, Adv. Mater., 2009, 21, 4625–4630.
12 Y. P. Qian, D. Y. Guo, X. L. Chu, et al., Mg-doped p-type β-Ga2O3 thin film for solar-blind ultraviolet photodetector, Mater. Lett., 2017, 209, 558–561.
13 D. Y. Guo, X. L. Zhao, Y. S. Zhi, et al., Epitaxial growth and solar-blind photoelectric properties of corundum-structured α-Ga2O3 thin films, Mater. Lett., 2016, 164, 364–367.
14 D. Y. Guo, Y. L. Su, H. Z. Shi, et al., Self-powered ultraviolet photodetector with super high photoresponsivity (3.05 A/W) based on the GaN/Sn:Ga2O3 pn junction, ACS Nano, 2018, 12, 12827–12835.
15 D. Y. Guo, H. Liu, P. G. Li, et al., Zero-power-consumption solar-blind photodetector based on β-Ga2O3/NSTO heterojunction, ACS Appl. Mater. Interfaces, 2017, 9(2), 1619–1628.
16 D. Y. Guo, H. Z. Shi, Y. P. Qian, et al., Fabrication of β-Ga2O3/ZnO heterojunction for solar-blind deep ultraviolet photodetection, Semicond. Sci. Technol., 2017, 32(3), 03LT01.
17 D. Y. Guo, Z. P. Wu, P. G. Li, et al., Fabrication of β-Ga2O3 thin films and solar-blind photodetectors by laser MBE technology, Opt. Mater. Express, 2014, 4(5), 1067.
18 L. P. Dong, R. X. Jia, C. Li, et al., Ab initio study of N-doped β-Ga2O3 with intrinsic defects: the structural, electronic and optical properties, J. Alloys Compd., 2017, 712, 379–385.
19 H. P. Zhang, R. X. Jia, L. Yuan, et al., Leakage current conduction mechanisms and electrical properties of atomic-layer-deposited HfO2/Ga2O3 MOS capacitors, J. Phys. D: Appl. Phys., 2018, 51(7), 1.
20 T. He, Y. K. Zhao and X. D. Zhang, Solar-blind ultraviolet photodetector based on graphene/vertical Ga2O3 nanowire heterojunction, Nanophotonics, 2018, 7, 1557.
21 H. O. Li, Y. Li, G. L. Xiao, et al., Simple fabrication ZnO/β-Ga2O3 core/shell nanorod arrays and their photoresponse properties, Opt. Mater. Express, 2018, 8, 794.
22 W. W. Zhong, S. J. Shen, S. S. Feng, et al., Facile fabrication of alveolate Cu2-xSe microsheets as a new visible-light photocatalyst for discoloration of Rhodamine B, CrystEngComm, 2018, 20, 7851.
23 W. W. Zhong, W. G. Tu, S. F. Feng, et al., Photocatalytic H2 evolution on CdS nanoparticles by loading FeSe nanorods as co-catalyst under visible light irradiation, J. Alloys Compd., 2019, 772, 669–674.
24 Y. L. Wu, S. J. Chang, W. Y. Weng, et al., Ga2O3 nanowire photodetector prepared on SiO2/Si template, IEEE Sens. J., 2013, 13, 2368–2373.
25 H. J. Lin, J. P. Baltrus, H. Y. Gao, et al., Perovskite nanoparticle-sensitized Ga2O3 nanorod arrays for CO detection at high temperature, ACS Appl. Mater. Interfaces, 2016, 8, 8880.
26 K. Chen, C. R. He, D. Y. Guo, et al., Low-voltage-worked photodetector based on Cu2O/GaOOH shell-core heterojunction nanorod arrays, J. Alloys Compd., 2018, 755, 199–205.