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Improving the Production of High-performance β-Ga_2O_3 Based Solar-Blind Schottky Barrier Photodiode

Zhe Li, Yanan Cheng, Yu Xu, Zhuangzhuang Hu, Weidong Zhu, Dazheng Chen, Qian Feng, Jincheng Zhang, Chunfu Zhang* and Yue Hao

Wide Bandgap Semiconductor Technology Disciplines State Key Laboratory, School of Microelectronics, Xidian University, Xi'an, China, 710071
*E-mail: cfzhang@xidian.edu.cn

Abstract

In this work, through the mechanical exfoliating method, we have achieved high-performance lateral β-Ga_2O_3 Schottky barrier photodiode (SBPD). The electrons in the SBPD are accelerated by the high electric field to gain huge energy and produce cascade collisions each other, which contributing to a large detectivity (D*) of 2×10^{16}, high photo-to-dark-current ratio (PDCR) of more than 10^5, responsivity (R) of 1.2×10^5 A/W and large external quantum efficiency (EQE) of 5.6×10^5 %. All results show that SBPD is an effective structure that can be applied to practical applications.

1. Introduction

When the sunlight pass through the stratospheric ozone, the wavelength less than 280nm is absorbed by stratospheric ozone. So the photodetector (PD) working in the wavelength less than 280nm is called the solar blind PD. In view of the above characteristics, the solar blind PD has a wide range of applications, such as flame detection, automobile exhaust detection and etc. β-Ga_2O_3 has a wide band gap of 4.9 eV, which falls precisely in the solar blind zone (100-280 nm) without being disturbed by visible light, UV-A and other wavelengths of light [1]–[3]. Therefore, it is considered to be an ideal ultraviolet detection material. And β-Ga_2O_3 also has high chemical and thermal stability, so that it also can work in harsh environments, which further enlarge the application range of the β-Ga_2O_3. Currently, various PD structures based on Ga_2O_3 thin films are widely studied, including metal-semiconductor-metal (MSM) PD, SBPD and etc. Various structures have their own advantages. MSM PD has a planar structure, which can be well compatible with field effect transistors; SBPD have faster response speed, high D* and etc [4]–[6].

In this work, first of all, based on the material growth method of magnetron sputtering, we have grown Ga_2O_3 thin film on rigid sapphire substrate and further prepared an MSM PD, and performed photoelectric detection performance characterization; Then, based on the method of exfoliating the bulk material, we prepared the SBPD. Because of large electric field at the edge of the anode electrode, the SBPD realized carrier multiplication process within gallium oxide film, enabling the SBPD a D* of 2×10^{16} Jones and shorter decay time of 90 ms. In comparison with MSM PD type, the SBPD is more efficient to engineer devices with high detection performance.

2. Mechanical exfoliating method

The tools used in the β-Ga_2O_3 mechanical exfoliating process are tweezers, ultra-thin surgical blades and tape. The ultra-thin blade can maintain the integrity of the material when exfoliated, and it is not easy to break the cleaved sheet material. Use the ultra-thin blade to slowly divide along the (100) cleavage surface to obtain the thinnest β-Ga_2O_3 thin films which are generally a few microns to a hundred microns. Then we put the exfoliated β-Ga_2O_3 wafer on the tape, and use the new tape repeatedly to tear it. After multiple tears, place the new tape on the substrate to be transferred, and apply appropriate pressure to maintain it for 1 hour. By removing the tape, a high-quality β-Ga_2O_3 film with a thickness of tens of nanometers to several microns, a length of tens of microns, and a width of several microns can be obtained on the target substrate. Using the step profiler to select the β-Ga_2O_3 thin film suitable for device preparation and position it with a microscope, so as to carry out the subsequent process flow.

3. Results and Discussion

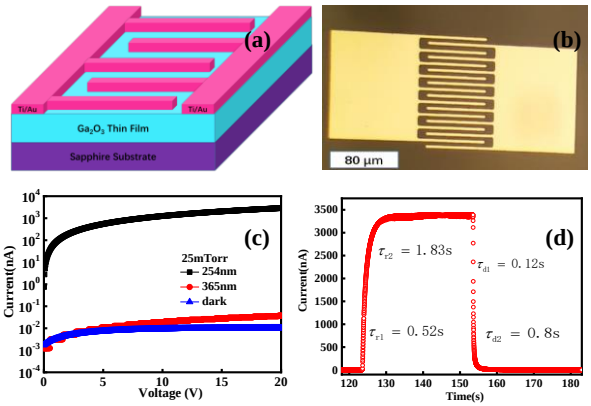

Fig. 1 (a) Schematic cross section (b) Top view (c) Current voltage (I-V) characteristics in dark, 254nm and 365nm and (d) Experimental curve and fitted curve of the current rise and decay process to 254 nm illuminations of the fabricated β-Ga_2O_3 thin film MSM structure PD based on magnetron sputtering method.

Firstly, we have fabricated β-Ga_2O_3 thin film MSM structure PD on rigid sapphire substrate under different deposition pressure based on magnetron sputtering method as shown in Fig. 1a and b. To evaluate the responsivity of the solar blind UV β-Ga_2O_3 PDs, we investigated the current voltage (I-V) characteristics under dark and UV irradiations,

respectively. The photodetector performs the best optical-electrical characteristic under 25 mTorr deposition pressure as shown in Figure 1c. The dark current is small (10.3 pA at 20 V), and the PDCR>10^5. The photocurrent is 37.4 pA under 365 nm irradiation and the device shows a very good UV/Visible rejection of about five orders. In contrast, the current increase significantly under 254 nm illumination, which can be assigned to that electron-hole pairs in the Ga_2O_3 film can be excited under 254 nm illumination. At the same time, the time-dependent photoresponses of the UV PDs were further investigated as shown in Figure 1d. It can be found that the decay time τ_d=0.12 s, which is still too longer to applicate. Furthermore, the detectivity (D*) of our MSM PD is only 10^{14} Jones.

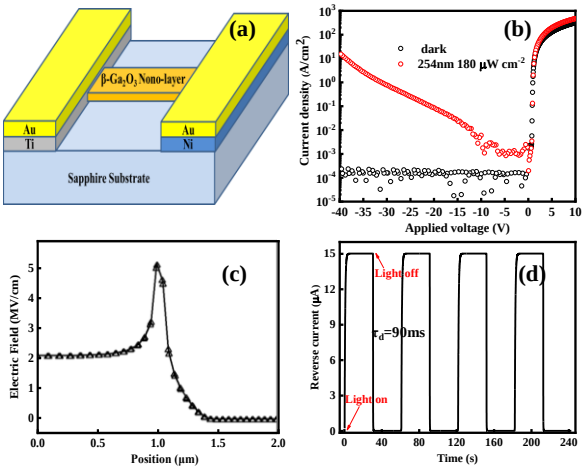

Fig. 2 (a) The schematic view (b) Semi-log I-V curves (c) Simulated electric field distribution under the reverse bias of −40 V and (d) Time-dependent photoresponse characteristics of the SBPD.

To solve above problems, we then fabricated β-Ga_2O_3 SBPD based on mechanical exfoliating method as shown in Figure 2a. The detailed device fabrication method and process have been illustrated in part 2. Figure 2b presents the semi-log curves of the β-Ga_2O_3 SBPD in the dark and under 254 nm light illumination. We can find that the device have good rectification characteristic. The current on/off ratio of the photodiode is approximately 10^6. The forward I-V curve can also be expressed as $I = I_s \times [\exp(q \times (V - I \times R_s)/\eta kT - 1)]$, where I_s, R_s, k and η is the reverse saturation current, the series resistance, the Boltzmann constant and the ideality factor, respectively [7]. The η and Is can be derived from the slope and intercept of the lnI-V plots, respectively. At the same time, the Schottky barrier height (ϕ_B) can be expressed by equation $\phi_B = (kT/q) \times \ln(AA^*T^2/I_s)$, where A is the diode area and A* is the Richard constant of 40.8 $Acm^{-2}K^{-2}$. The ϕ_B and η are determined to be 1.22 eV and 1.39.

When the SBPD is irradiated with 254 nm light, as shown in the red circle in Figure 1b, the forward current does not increase significantly, but the reverse current shows significant increase. When the bias voltage is -40 V, the photocurrent reaches 16 Acm^{-2}. The PDCR reaches five orders of magnitude and I_{254nm}/I_{365nm} (UV-C/UV-A) is also over 10^5. R is expressed as $(I_{photo}-I_{dark})/P$, where P is the optical power, which represents the ability of the SBPD to convert optical signals into electrical signals. R is calculated as 1.2×10^5 A/W. The D * is obtained from the equation $D^* = RS^{1/2}/(2qI_{dark})^{1/2}$ [8]. The D* of our SBPD is as high as 2×10^{16} Jones which is larger more than the MSM detector illustrated above. Among the reported PDs based on Ga_2O_3, this value is the largest. Such high D* can be attributed to high R and relatively low dark current. Another key indicator is EQE, which is equal to $hcR/q\lambda$, where h is the Plank's constant, c the velocity of light and λ the light wavelength. The EQE of SBPD even reaches 5.6×10^5%.

In order to explore the inherent reason why the detector exhibits such excellent characteristics, we used the Silvaco Atlas device simulation software to simulate the electric field of the device. As shown in Figure 2c, when the anode edge (Position = 1 μm), SBPD The electric field reaches 5.3 MV/cm, which is higher than the breakdown electric field of many gallium oxide power devices [9]–[11], that is to say, the electric field strength of 5.3 MV/cm is enough to achieve impact ionization and then realize the carrier multiplication effect. That is to say, under a large electric field, the electrons in the gallium oxide active layer are accelerated and collide with the lattice atoms to generate extra electrons. Further, the extra electrons generated are accelerated by the electric field again to form a cascade collision, thereby realizing carrier multiplication effect. This is why our detector has a large D*. At the same time, we also characterized the time response of the detector (as shown in Figure 2d). The decay time of the SBPD is only 90 ms, which is shorter than that of the MSM detector.

4. Conclusions

In summary, high-performance SBPD is prepared based on exfoliated β-Ga_2O_3 nano-layer. SBPD has large photocurrent combined with high PDCR of more than 10^5, R of 1.2×10^5 A/W and large EQE of 5.6×10^5 %. More importantly, the D* of SBPD reaches 10^{16} Jones through the carrier multiplication effect under high electric field. And its response time is only 90 ms. The resulting β-Ga_2O_3 SBPD have a great potential as future high performance PDs.

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