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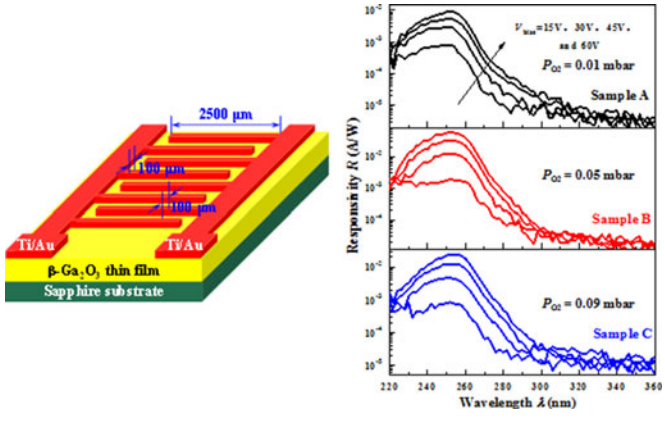

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Comparison Study of β-Ga_2O_3 Photodetectors Grown on Sapphire at Different Oxygen Pressures

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Abstract: In this paper, β-Ga_2O_3 ultraviolet photodetectors were grown on sapphire utilizing the laser molecular beam epitaxy tool. The impact of oxygen pressure P_{O2} in growth chamber on the crystal quality, the surface morphology, the chemical component of Ga_2O_3 films, and the electrical performance of photodetectors are characterized. As the P_{O2} is increased during growth, the concentration of oxygen vacancy (V_O) is effectively reduced. The photodetector grown at the P_{O2} of 0.05 mbar exhibits the significantly improved photocurrent I_{photo} and responsivity R characteristics in comparison with the device grown with the P_{O2} of 0.01 mbar, which is attributed to a reduction in the number of V_O. However, as the P_{O2} continuously increased to 0.09 mbar, I_{photo} and R of the detector are degraded, which might be due to the fact that the gallium vacancies (V_{Ga}), as the dominant trapping centers, lead to the recombination of photo-generated carriers.

Index Terms: β-Ga_2O_3, photodetectors, oxygen pressure.

1. Introduction

Ultraviolet photodetectors are important devices that can be used in various civil and military applications, including solar UV monitoring, missile tracking, UV astronomy, flame sensors, and chemical/biological analysis [1], [2]. The materials with wide bandgap E_G are considered to be ideal for solar-blind photodetectors to minimize the chance of false detection. Gallium oxide (Ga_2O_3) is one of the promising candidates for the deep ultraviolet detection because of its 4.8–4.9 eV E_G producing high transparency at the wavelength λ longer than 300 nm [3] and the excellent chemical and thermal stability. Up to now, the great research efforts have been devoted to exploring the epitaxial growth of Ga_2O_3 films by pulsed laser deposition (PLD) or laser molecular beam epitaxy (MBE) [3]–[6], metalorganic chemical vapor deposition (MOCVD) [7], solid source MBE [8], and magnetron sputtering [9] on different substrates [10]–[13]. Compared to the other epitaxial growth techniques, laser MBE has the advantages of higher purity of source materials and lower impurity levels. The Ga_2O_3 based solar blind photodetectors have been demonstrated based on Ga_2O_3

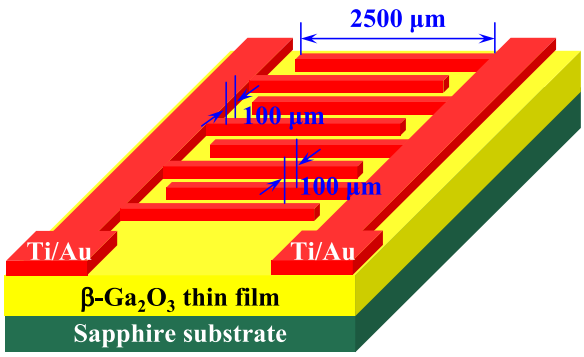


Fig. 1. The schematic of the Ga_2O_3 photodetector.

films [14], Ga_2O_3 nanowires [15], Ga_2O_3 single crystals [15], and $(AlGa)_2O_3$ films [16]. However, the experimental results indicated that the point defects, including oxygen vacancy V_O, interstitial oxygen atom, gallium vacancy V_{Ga}, and interstitial atom, could serve as trapping and recombination centers, which reduced the collection efficiency of the photogenerated carriers by the electrodes, therefore leading to the degradation of photocurrent I_{photo} and responsivity R [17], [18]. The process parameters during material growth directly affected the formation of point defects in Ga_2O_3 [19], which determined the photodetector performance. The influence of growth temperature, annealing, and Sn doping on the Ga_2O_3 photodetectors performance has been studied [3], [5], [6]. There is still a lack of the experimental study on the dependence of Ga_2O_3 photodetector performance on the oxygen pressure P_{O2} in the laser MBE chamber.

In this paper, we report the demonstration of Ga_2O_3 photodetectors with β-Ga_2O_3 epitaxially grown on sapphire at different oxygen pressure P_{O2} utilizing laser MBE. The impacts of P_{O2} in growth chamber on the stoichiometries of Ga_2O_3 and the device performance are investigated.

2. Materials Characterization and Device Fabrication

The β-Ga_2O_3 films were epitaxially grown on sapphire (0001) substrate using laser MBE at 600 °C with three different P_{O2}, 0.01, 0.05, and 0.09 mbar, denoted as sample A, B, and C, respectively. The cylindrical Ga_2O_3 ceramic target (99.99% purity) was irradiated by the KrF excimer laser beam with the laser energy density of 2 J/cm^2 at the repetition rate of 5 Hz and the distance between the sapphire substrate and Ga_2O_3 target was fixed at 5 cm. The base pressure of the growth chamber was 1.5×10^{-8} Torr. Photodetectors with interdigital Ti/Au (20 nm/100 nm) contacts were fabricated on the β-Ga_2O_3 films. The electrode fingers were 100 μm wide and 2500 μm long with a 100 μm spacing gap. Fig. 1 shows the schematic diagram of the fabricated device.

The crystal structure and orientation of Ga_2O_3 samples were studied by the high-resolution X-ray diffraction (HRXRD). The surface morphology was investigated with atomic force microscope (AFM) with Agilent 5500 in tapping mode. The stoichiometries of Ga_2O_3 samples were analyzed with X-ray photoelectron spectroscopy (XPS). Characterization of I_{photo}, R, time-dependent photoresponse, and the dark current I_{dark} of the Ga_2O_3 photodetectors were carried out utilizing a low-pressure mercury lamp U3900 with the illumination λ from 254 to 365 nm and the various power densities P_{light}. The illumination λ on the devices was measured using the optical grating.

3. Results and Discussion

3.1 Material Characterization

Fig. 2 presents the HRXRD curves of the Ga_2O_3 films grown with different P_{O2} on sapphire. Three diffraction peaks corresponding to β-Ga_2O_3 $(\bar{2}01)$, $(\bar{4}02)$, and $(\bar{6}03)$ planes are observed, which indicates the single crystallinity of the β-Ga_2O_3 phase. Fig. 3 shows the surface morphologies of

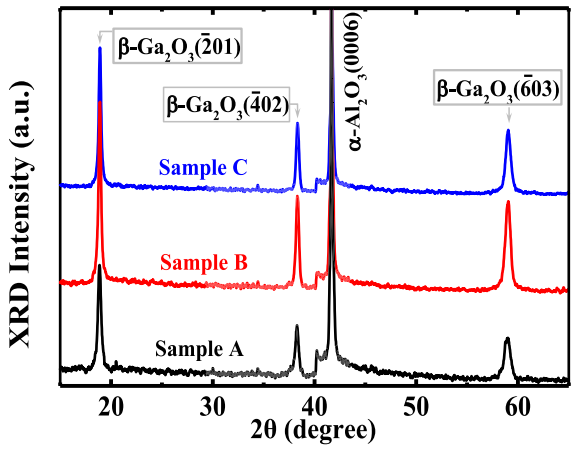


Fig. 2. HRXRD diffraction curves of the Ga_2O_3 samples on sapphire.

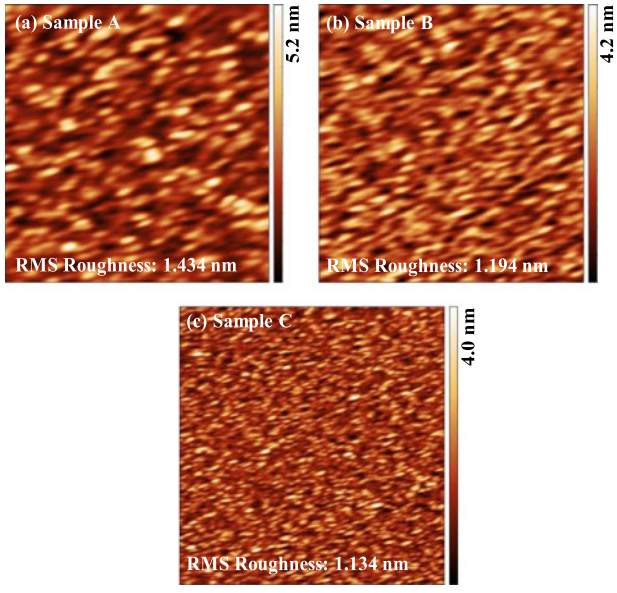


Fig. 3. AFM images of Ga_2O_3. (a) Sample A, (b) Sample B, and (c) Sample C.

the β-Ga_2O_3 samples measured by AFM with a scanning area of 5 μm $\times$ 5 μm. The values of the root-mean-square (RMS) roughness of Sample A, B, and C are 1.434, 1.194, and 1.134 nm, respectively. With the increasing P_{O2} during the growth, the mobility of adatoms on the surface of substrate decreases, which might reduce the surface roughness of the Ga_2O_3 film [20].

The O1s and Ga2p3/2 core level XPS spectra are shown in Fig. 4. Before measurement, the *in-situ* Ar plasma etching was performed to remove the surface layer of a few nanometers and the peaks were calibrated by the adventitious C1s of 284.6 eV. The O1s peaks can be deconvoluted into three distinct peaks associated with Ga_2O_3, oxygen vacancy, and the assorted gallium suboxides of Ga_2O and GaO. Taken into account both the sensitivity factor and the area of peaks, the ratio of O/Ga in three Ga_2O_3 samples is 1.03, 1.08, and 1.09, respectively. The O1s binding energy has a shift toward the higher binding energy with the increasing of P_{O2}, which is indicative of the increasing in the number of oxygen atoms, i.e., the reduction in the concentration of V_O [21]. The Ga2p3/2 peaks can also be deconvoluted into two distinct peaks associated with Ga_2O_3 and the gallium suboxides. What's more, the Ga2p3/2 peaks also shift to the higher binding energy, which is due to the increasing of Ga-O binding structure [21].

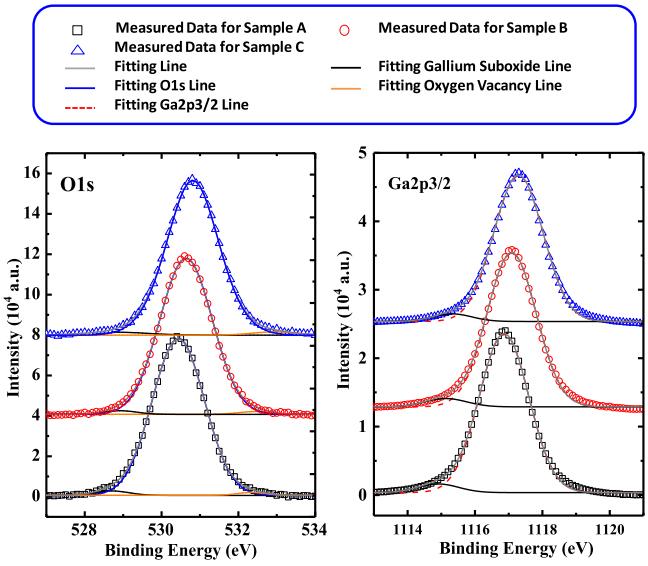
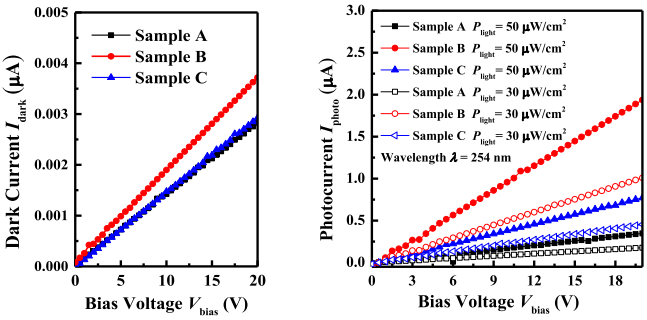


Fig. 4. XPS spectra of O1s and Ga2p3/2 core level of the Ga_2O_3 samples.



(a) (b)

Fig. 5. (a) I_{dark} and (b) I_{photo} versus V_{bias} characteristics for the Ga_2O_3 photodetectors.

3.2 Electrical Characteristics of the Devices

The $I_{dark} - V_{bias}$ and $I_{photo} - V_{bias}$ curves for the photodetectors under various P_{light} are depicted in Fig. 5. I_{photo} and I_{dark} of devices have the obvious relation to the P_{light}. Compared with the other two samples, the Sample B obtains a higher I_{dark} and I_{photo}. It is speculated that the Sample B has fewer V_O than the Sample A, owing to the higher P_{O2} during growth. For the growth of Sample C, the even higher P_{O2} might produce a large number of V_{Ga} and $V_O - V_{Ga}$ complexes [22]. The point defects, whether V_O, V_{Ga} and $V_O - V_{Ga}$, can act as trapping centers to capture the photo-generated carriers, leading to the degradation of I_{photo} of the devices.

As illustrated in Fig. 6, the Sample B demonstrates a photo to dark current ratio (PDCR) of 510, which is much higher than those of the other two samples, less than 300. Thus, it is considered that, compared to Samples A and C, Sample B has a much smaller number of such points defects acting as trapping centers to capture the photo-generated carriers. Fig. 7 shows the superlinear I_{photo} as a function of P_{light} at different bias voltage V_{bias} for the devices, indicating the optical gain of the three photodetectors. This is due to the channel resistance reduction resulted from the increasing of photo-generated carriers and the decreasing of the effective barrier height for electrons at the ground contact caused by the accumulation of holes at the Ga_2O_3/metal junction [23].

Fig. 8 shows the R as a function of λ of the illumination light for the Ga_2O_3 detectors. Solar-blind operation was obtained for all the three samples with the excellent solar rejection ratio for λ larger than 300 nm and the strong photoconductive gain for λ smaller than 280 nm. The Sample

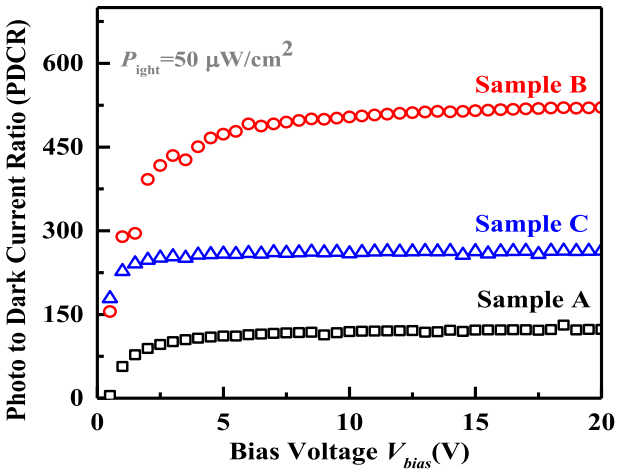


Fig. 6. PDCR of the β-Ga_2O_3 photodetectors.

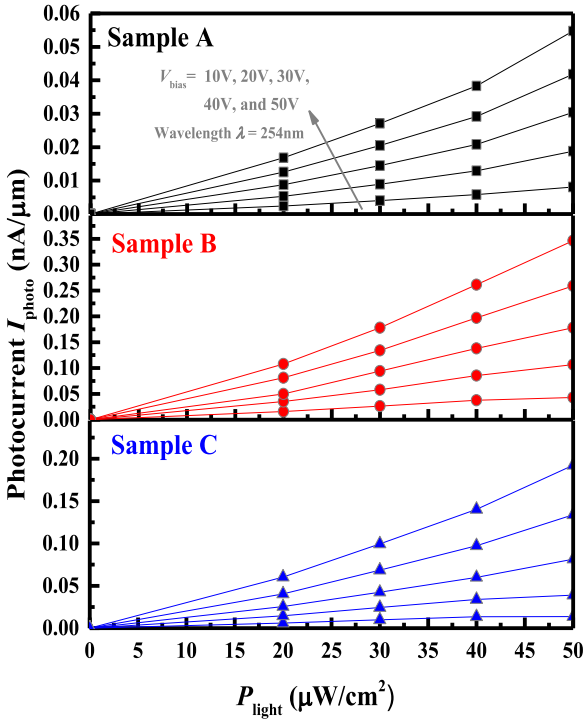


Fig. 7. Superlinear I_{photo} as a function of P_{light} of the devices.

B achieves the improved R compared to the others. At a V_{bias} of 60 V, the maximum R, R_{max}, of 0.009, 0.058, and 0.025 A/W are obtained in the Sample A, B, and C, respectively. The values of external quantum efficiency (EQE), calculated by EQE $= hcR_{max}/(e\lambda)$, are 4.39%, 28.3%, and 12.2% for the Sample A, B, and C, respectively. Here, h is Planck's constant, c is the velocity of light, e is the electronic charge, and λ is the incident light λ. The value of cutoff λ of Ga_2O_3 devices, defined as the λ at $\sqrt{1/2}R_{max}$ is about 259 nm, indicating the E_G of 4.79 eV. We compare the I_{dark}, I_{photo}, PDCR, R_{max}, and EQE characteristics of the devices in Table 1, showing that sample B has the improved performance compared to the other two. The sample B also demonstrates the higher PDCR compared to devices in Refs. [3] and [6]. In Ref. [5], heterostructure was used to further enhance the device performance.

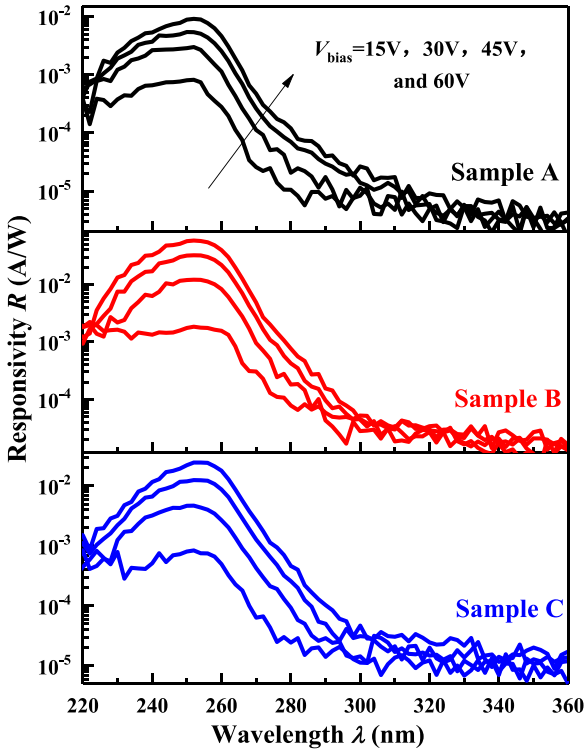


Fig. 8. Responsivity versus illumination optical λ for the Ga_2O_3 photodetectors at various V_{bias}.

TABLE 1
Comparison of the Electrical Performance of the Photodetectors

	I_{dark} @ 10 V (nA)	I_{photo} @ 10 V (μA)	PDCR @ 10 V	R_{max} (A/W)	EQE
Sample A	1.4	0.17	119	0.01	4.39%
Sample B	1.9	1.00	504	0.06	28.3%
Sample C	1.5	0.38	259	0.03	12.2%

Fig. 9 presents the transient response curves of the Ga_2O_3 photodetectors on sapphire. Measurements of the time-dependent photoresponse characteristics were carried out utilizing a 254 nm square-wave light with a period of 6 s under a P_{light} of 20 μW/cm^2 and a V_{bias} of 10 V. In all devices, we can find two different relaxation durations in the rise and decay processes: the fast-response and the slow-response. Table 2 lists the values of the rise time constants (τ_{r1} and τ_{r2}) and those of the decay time (τ_{d1} and τ_{d2}). The fast responses, τ_{r1} and τ_{d1}, are related to the direct band to band transition, and the slow response during the rise process might be associated with the transition between band edge and defects bands. The slow response in the decay process could be ascribed to the recombination of the carriers trapped by the trapping center through the defects bands, thus resulting in the obvious persistent photoconductivity (PPC) phenomenon.

It was reported that V_O, having the lower formation energy under O-poor (or Ga-Rich) condition, acts as the deep donor [24], [25]. Some studies showed that V_O interacted with V_{Ga} to form $V_O - V_{Ga}$ compounds, acting as the acceptors [26]–[30]. For Ga_2O_3 grown under a P_{O2} of

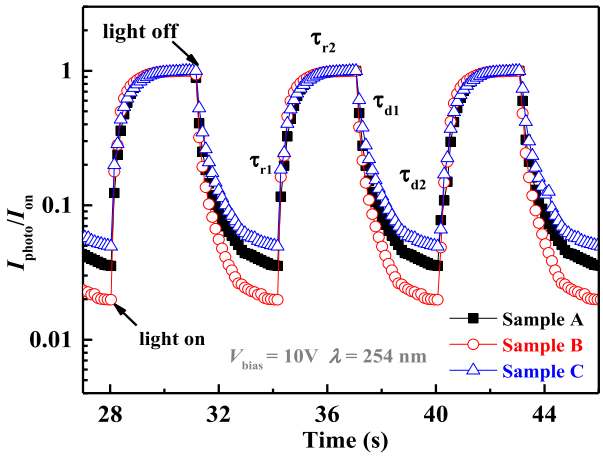


Fig. 9. Time-dependent photoresponse characteristics of the Ga_2O_3 photodetectors on sapphire.

TABLE 2
The Rise Time Comstans (τ_{r1} and τ_{r2}) and Values of Decay Time (τ_{d1} and τ_{d2})

	τ_{r1}	τ_{r2}	τ_{d1}	τ_{d2}
Sample A	0.46 s	2.55 s	0.23 s	2.78 s
Sample B	0.47 s	2.45 s	0.28 s	2.69 s
Sample C	0.45 s	2.55 s	0.23 s	2.78 s

0.01 mbar, the generated V_O could trap photo-generated carriers, leading to the slower response in the decay process. As P_{O2} rising, the oxygen concentration in the epitaxial Ga_2O_3 increases and the concentration of V_O decreases, and thus the value of τ_{d2} in Sample B is reduced compared to Sample A. For the sample grown under a P_{O2} of 0.09 mbar, although the generation of V_O is further suppressed, other point defects, such as V_{Ga} and $V_O - V_{Ga}$ might be the dominant trapping centers to trap carriers during illumination [28], [30], so the τ_{d2} becomes larger again in Sample C.

4. Conclusion

The β-Ga_2O_3 photodetectors were grown on sapphire (0001) substrate at the different P_{O2} by laser MBE. Compared to Sample A and C, Sample B achieves the improved I_{photo}, R, and time-dependent photoresponse characteristics. It is speculated the P_{O2} has a great impact on the formation of V_O and V_{Ga} defects. Sample A might contain more V_O than Sample B due to the lower P_{O2} during growth, resulting in the reduced I_{photo}, and for the Sample C, the P_{O2} is much higher in comparison Sample B, which could lead to the formation of a large number of V_{Ga}, lowering the I_{photo}.

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