Letter

Investigation of Ga₂O₃-Based Deep Ultraviolet Photodetectors Using Plasma-Enhanced Atomic Layer Deposition System

Shao-Yu Chu ¹, Meng-Xian Shen ¹, Tsung-Han Yeh ², Chia-Hsun Chen ³, Ching-Ting Lee ^{1,4} and Hsin-Ying Lee ^{1,*}

¹ Department of Photonics, National Cheng Kung University, Tainan 701, Taiwan; l78081517@ncku.edu.tw (S.-Y.C.); s230813355@gmail.com (M.-X.S.); ctlee@ee.ncku.edu.tw (C.-T.L.)

² Department of Electrical and Electronic Engineering, Chung Cheng Institute of Technology, National Defense University, Taoyuan 335, Taiwan; cciti09001@ndu.edu.tw

³ Department of Optometry, Chung Hwa University of Medical Technology, Tainan 701, Taiwan; chen1985ch@mail.hwai.edu.tw

⁴ Department of Electrical Engineering, Yuan Ze University, Taoyuan 320, Taiwan

* Correspondence: hylee@ee.ncku.edu.tw; Tel.: +886-6-2082368

Received: 30 September 2020; Accepted: 28 October 2020; Published: 29 October 2020

Abstract: In this work, Ga₂O₃ films were deposited on sapphire substrates using a plasma-enhanced atomic layer deposition system with trimethylgallium precursor and oxygen (O₂) plasma. To improve the quality of Ga₂O₃ films, they were annealed in an O₂ ambient furnace system for 15 min at 700, 800, and 900 °C, respectively. The performance improvement was verified from the measurement results of X-ray diffraction, X-ray photoelectron spectroscopy, and photoluminescence spectroscopy. The optical bandgap energy of the Ga₂O₃ films decreased with an increase of annealing temperatures. Metal-semiconductor-metal ultraviolet C photodetectors (MSM UVC-PDs) with various Ga₂O₃ active layers were fabricated and studied in this work. The cut-off wavelength of the MSM UVC-PDs with the Ga₂O₃ active layers annealed at 800 °C was 250 nm. Compared with the performance of the MSM UVC-PDs with the as-grown Ga₂O₃ active layers, the MSM UVC-PDs with the 800 °C-annealed Ga₂O₃ active layers under a bias voltage of 5 V exhibited better performances including photoresponsivity of 22.19 A/W, UV/visible rejection ratio of 5.98×10^4 , and detectivity of 8.74×10^{12} cmHz^{1/2}W⁻¹.

Keywords: detectivity; gallium oxide films; plasma-enhanced atomic layer deposition system; metal-semiconductor-metal ultraviolet C photodetectors; photoresponsivity; X-ray photoelectron spectroscopy spectra

1. Introduction

Due to the ozone hole and thinner ozone layer, a large amount of ultraviolet (UV) light passes through the space to the earth. The UV light seriously damages human skin—UVA (315–400 nm) causes melanin in human skin, UVB (280–315 nm) reduces the skin's immune system, and UVC (200–280 nm) damages skin cells and causes skin cancer [1,2]. Among them, the deep UV light seriously harms human health. Consequently, UVC photodetectors (UVC-PDs) have received widespread attention. Recently, wide bandgap semiconductors, such as aluminum gallium nitride (AlGaN) [3], magnesium zinc oxide (MgZnO) [4,5], and gallium oxide (Ga₂O₃) [6,7], were widely developed and applied to solar-blind UVC-PDs. However, it is difficult to grow high-quality AlGaN epitaxial layers with high Al content due to the quality degradation caused by the more structural defects [8]. Moreover, it is difficult to obtain a high-quality MgZnO film with a bandgap energy larger than 5.0 eV. Since more Zn²⁺ ions are replaced by Mg²⁺ ions in the ZnO lattice as the Mg content increases more than 0.36, the c-axis

orientation degrades [9,10]. Because the binary Ga_2O_3 has inherent advantages of stable thermal and chemical properties [11], it becomes a promising material for fabricating solar-blind UVC-PDs [12]. Several growth techniques, such as metalorganic chemical vapor deposition (MOCVD) [13,14], pulsed laser deposition (PLD) [15,16], molecular beam epitaxy (MBE) [17,18], magnetron sputtering [19–21], and vapor cooling condensation system [22,23], were used to deposit Ga_2O_3 films. In this work, a plasma-enhanced atomic layer deposition (PE-ALD) system was used to grow Ga_2O_3 films on sapphire substrates. The advantages of the PE-ALD system include low temperature growth, excellent conformality, precise film thickness control, self-limiting growth effect, and large area uniformity [24,25]. Moreover, due to the high reactivity of plasma source on the deposited surface, it provides greater freedom of processing conditions during the deposition process [24]. The material characteristics of the as-grown Ga_2O_3 films were measured and analyzed. To further improve the performances of the Ga_2O_3 films, the annealing treatment with various temperatures was utilized. The resulting Ga_2O_3 films were applied as active layers in metal-semiconductor-metal ultraviolet C photodetectors (MSM UVC-PDs). The performances of the resulting devices with various Ga_2O_3 active layers were measured and studied in this work.

2. Experimental

The PE-ALD system was used to deposit 80-nm-thick Ga_2O_3 films on sapphire substrates. The precursors of trimethylgallium ($\text{Ga}(\text{CH}_3)_3$, TMGa) and oxygen (O_2) plasma were used as the Ga and O sources, respectively. One depositing cycle of the Ga_2O_3 layer includes four steps. Firstly, to provide Ga source and carry off the residual gas and reactant, TMGa precursor and argon (Ar) gas were sequentially pulsed into the PE-ALD chamber for 0.5 s and 3 s, respectively. After metallization, to provide the O source and carry off the residual gas and reactant, O_2 plasma and Ar gas were sequentially pulsed into the PE-ALD chamber for 5 s and 3 s, respectively. The chamber pressure and the growth temperature were kept at 0.6 torr and 50 °C, respectively. The growth rate of the Ga_2O_3 films was approximately 0.33 Å/cycle. Subsequently, to improve the quality of the Ga_2O_3 films, they were annealed in an O_2 ambient furnace system at various temperatures of 700, 800, and 900 °C for 15 min. The material characteristics of the as-grown and annealing-treated Ga_2O_3 films were characterized by X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), photoluminescence (PL) spectroscopy, and ultraviolet-visible (UV-Vis) spectroscopy.

Figure 1 illustrates the schematic configuration of Ga_2O_3 -based MSM UVC-PDs. To define the active window with a size of $100 \times 100 \mu\text{m}^2$ on the Ga_2O_3 active layer, the traditional photolithography technique was used. The redundant Ga_2O_3 material was etched away using a dilute hydrofluoric acid ($\text{HF}:\text{H}_2\text{O} = 1:25$) solution. Interdigitated electrode of Ni/Au (20/100 nm) metals with a spacing of 2 μm and a width of 2 μm was deposited on the patterned Ga_2O_3 active layer using an electron-beam evaporator. The current-voltage characteristics of the resulting Ga_2O_3 -based MSM UVC-PDs were measured using an Agilent 4156C semiconductor parameter analyzer. The photoresponsivity spectra of the prepared MSM UVC-PDs were measured using a monochromator and a deuterium lamp source. The low frequency noise performance was measured using an Agilent 4156C semiconductor parameter analyzer, an HP 35670A dynamic signal analyzer, and a BTA 9812 noise analyzer.

Figure 1. Schematic configuration of metal-semiconductor-metal ultraviolet C photodetectors.

3. Results and Discussion

Figure 2 presents the crystallinity of the as-grown Ga_2O_3 films and the annealing-treated Ga_2O_3 films carried out by XRD with $\text{CuK}\alpha$ radiation. Since no diffraction peak was observed in the XRD spectrum of the as-grown Ga_2O_3 film, it could be deduced that it was an amorphous structure. There were two diffraction patterns in the XRD spectra of the all annealing-treated Ga_2O_3 films. The diffraction peaks at 18.9° and 38.4° corresponded to the $(\bar{2}01)$ and $(\bar{4}02)$ planes of the $\beta\text{-Ga}_2\text{O}_3$, respectively [26]. The intensity of $(\bar{2}01)$ and $(\bar{4}02)$ peaks increased with the annealing temperature until 800°C . The phenomenon was attributed to that the suitable temperature annealing treatment could improve the crystallinity of the Ga_2O_3 films. However, the intensity of the above-mentioned two peaks decreased with an increase of the annealing temperature to 900°C . It was deduced that more oxygen vacancies and defects would be induced in the Ga_2O_3 films annealed at 900°C . Consequently, their crystallinity was degraded.

Figure 2. X-ray diffraction (XRD) spectra of Ga_2O_3 films annealed at various temperatures.

To verify the existence of more oxygen vacancies and defects residing in the Ga_2O_3 films annealed at 900°C , they were measured using an X-ray photoelectron spectroscopy (XPS) and photoluminescence (PL) system. The chemical binding energy of the as-grown Ga_2O_3 films and the annealing-treated Ga_2O_3 films were analyzed using XPS. Figure 3 shows the $\text{O}1s$ core level spectra of the prepared Ga_2O_3 films. The $\text{O}1s$ peak was composed of two bands located at the binding energy of 530.8 eV

and 532.1 eV, which were assigned to the Ga-O bonds and the oxygen vacancy, respectively [27]. The peak ratio of the Ga-O bonds in Ga₂O₃ to the oxygen vacancy for the as-grown Ga₂O₃ films and the annealing-treated Ga₂O₃ films could be derived from the area under the XPS spectra. The peak ratios were 5.92, 7.85, 12.71, and 10.07 for the as-grown Ga₂O₃ films and the Ga₂O₃ films annealed at 700, 800, and 900 °C, respectively. The peak ratio of the annealing-treated Ga₂O₃ films was larger than that of the as-grown Ga₂O₃ films, which verified that the oxygen vacancy in the Ga₂O₃ films could be improved by annealing treatment in an O₂ ambience. Besides, since the largest peak ratio was obtained in the Ga₂O₃ films annealed at 800 °C, it could be deduced that the lowest oxygen vacancy could be obtained in the Ga₂O₃ films annealed at 800 °C.

Figure 3. X-ray photoelectron spectroscopy (XPS) spectra of O1s core level spectra of (a) as-grown Ga₂O₃ films and Ga₂O₃ films annealed at (b) 700 °C, (c) 800 °C, and (d) 900 °C.

Figure 4 shows the room-temperature PL spectra of the as-grown Ga₂O₃ films and the annealing-treated Ga₂O₃ films excited by a He-Cd laser with a wavelength of 325 nm. For all the Ga₂O₃ films, the broad band caused by the oxygen vacancies and defects in the visible wavelength region was observed [22,28]. As shown in Figure 4, the PL intensity of the broad band for the Ga₂O₃ films decreased with an increase of the annealing temperature until to 800 °C and then increased at a higher annealing temperature of 900 °C. Consequently, it could be deduced that the Ga₂O₃ films annealed at 800 °C had the least amount of oxygen vacancies and defects.

Figure 4. Room-temperature photoluminescence (PL) spectra of as-grown Ga_2O_3 films and Ga_2O_3 films annealed at various temperatures.

The transmission and reflection spectra of the as-grown Ga_2O_3 films and the annealing-treated Ga_2O_3 films were measured using an UV-Vis spectroscopy. Consequently, from the corresponding transmittance (T) and reflectivity (R), the absorption coefficient (α) was obtained by using the formula of $\alpha = \ln[(1 - R)^2/T]/d$, where d is the thickness of the films. The optical bandgap energy (E_g) of the direct bandgap films could be determined using Tauc plot, $(\alpha h\nu)^2 = A(h\nu - E_g)$, where A is a constant and $h\nu$ is a photon energy. The curve of $(\alpha h\nu)^2$ versus $h\nu$, as shown in Figure 5, was fitted, and the linear line extended to the photon energy axis to obtain the optical bandgap energy. The optical bandgap energy of 5.07, 5.01, 4.96, and 4.98 eV was obtained for the as-grown Ga_2O_3 films and the Ga_2O_3 films annealed at 700, 800, and 900 °C, respectively. It was found that the optical bandgap energy of the Ga_2O_3 films decreased with an increase of the annealing temperature until to 800 °C and then increased at an annealing temperature of 900 °C. In general, the Ga_2O_3 films with the better crystallinity have a lower bandgap energy in comparison with the amorphous Ga_2O_3 films [22]. Consequently, the crystallinity of the Ga_2O_3 films could be improved by annealing treatment.

Figure 5. The $(\alpha h\nu)^2$ versus $h\nu$ characteristics of as-grown Ga_2O_3 films and Ga_2O_3 films annealed at various temperatures.

Since the wide bandgap Ga_2O_3 films deposited using the PE-ALD system were obtained, they were applied to MSM UVC-PDs as active layers. Figure 6 shows the dark current-voltage characteristics of the various Ga_2O_3 -based MSM UVC-PDs. By illuminating the light with a wavelength of 250 nm and a power intensity of $10.6 \mu\text{W}/\text{cm}^2$, the photocurrent of the devices was measured and was shown in Figure 6. Compared with the as-grown Ga_2O_3 -based MSM UVC-PDs, the dark current and photocurrent of the MSM DUV-PDs with the Ga_2O_3 active layer annealed at 800°C decreased from 43.87 pA to 2.03 pA and increased from 2.77 nA to 27.45 nA , respectively, at bias voltage = 5 V . The improvement in dark current and the photocurrent was attributed to the reduction of oxygen vacancies and defects in the Ga_2O_3 film annealed at 800°C . Furthermore, compared with the MSM UVC-PDs with 800°C -annealed Ga_2O_3 active layer, the larger dark current of 6.01 pA of the devices with the 900°C -annealed Ga_2O_3 active layer at bias voltage = 5 V was attributed to more resided oxygen vacancies and defects. Furthermore, its lower photocurrent of 13.20 nA was attributed to the degraded crystallinity of the 900°C annealed Ga_2O_3 active layer compared with that of the 800°C annealed Ga_2O_3 active layer.

Figure 6. Dark current and photocurrent of various Ga_2O_3 -based metal-semiconductor-metal ultraviolet C photodetectors (MSM UVC-PDs) as a function of bias voltage.

Figure 7 illustrates the photoresponsivity spectra of the various Ga_2O_3 -based MSM UVC-PDs under a bias voltage of 5 V . The cut-off wavelength and the maximum photoresponsivity of the MSM UVC-PDs with the as-grown Ga_2O_3 active layer were about 245 nm and 3.51 A/W , respectively. The cut-off wavelength of the MSM UVC-PDs with the annealing-treated Ga_2O_3 active layers was about 250 nm . The corresponded cut-off wavelength of the various Ga_2O_3 -based MSM UVC-PDs coincided with the associated optical bandgap energy of the used Ga_2O_3 active layers. The maximum photoresponsivity of the MSM UVC-PDs with the Ga_2O_3 active layers annealed at 700 , 800 , and 900°C was 6.17 , 22.19 , and 12.53 A/W , respectively. Since the Ga_2O_3 active layers annealed at 800°C exhibited the best crystallinity and the lowest oxygen vacancy and defect, its resulting MSM UVC-PD had the best photoresponsivity. The UV (245 nm)/visible (450 nm) rejection ratio of the photoresponsivity (R_{rj}) of the MSM UVC-PDs with the as-grown Ga_2O_3 active layers was 6.22×10^3 . The UV (250 nm)/visible (450 nm) rejection ratio of the photoresponsivity was 1.37×10^4 , 5.98×10^4 , and 3.09×10^4 for the MSM UVC-PDs with the Ga_2O_3 active layers annealed at 700 , 800 , and 900°C , respectively. The largest rejection ratio of the MSM UVC-PDs with the 800°C -annealed Ga_2O_3 active layers was attributed to the associated lowest dark current and the largest photoresponsivity resulted from the possession of the best crystallinity and the lowest oxygen vacancy and defect.

Figure 7. Photoresponsivity spectra of various Ga_2O_3 -based MSM UVC-PDs.

Figure 8 shows the frequency-dependent noise power density spectra of the various Ga_2O_3 -based MSM UVC-PDs under a bias voltage of 5 V. It could be found that the fitting curve of noise power density spectra was consistent with $1/f$, where f is frequency. This result demonstrated that the main low-frequency noise was flicker noise. The flicker noise is mainly affected by lattices and surface traps resided in the material. The total noise current (i_n) could be determined by integrating the noise power density ($S_n(f)$):

$$i_n^2 = \int_0^{\Delta f} S_n(f) df \quad (1)$$

where $\Delta f = 1$ kHz is bandwidth. To characterize photodetectors, the important parameters of noise equivalent power (NEP) and detectivity (D^*) were respectively calculated as follows:

$$\text{NEP} = \frac{\sqrt{i_n^2}}{R} \quad (2)$$

$$D^* = \frac{\sqrt{A} \sqrt{\Delta f}}{\text{NEP}} \quad (3)$$

where R is the photoresponsivity and A is the area of active window. The NEP of 5.24×10^{-13} , 2.24×10^{-13} , 3.62×10^{-14} , and 8.79×10^{-14} W was obtained for the MSM UVC-PDs with the as-grown Ga_2O_3 active layer and the Ga_2O_3 active layers annealed at 700, 800, and 900 °C, respectively. The corresponding D^* was 6.04×10^{11} , 1.41×10^{12} , 8.74×10^{12} , and 3.60×10^{12} $\text{cmHz}^{1/2}\text{W}^{-1}$, respectively. The detectivity of the MSM UVC-PDs with the annealed Ga_2O_3 active layers was larger than that of the as-grown Ga_2O_3 -based MSM UVC-PDs. Furthermore, the detectivity increased with an increase of annealing temperature until 800 °C and then decreased by further increasing annealing temperature to 900 °C. The improvement in detectivity was attributed to that the annealing treatment up to 800 °C could improve the Ga_2O_3 crystallinity and could decrease the oxygen vacancies and defects resided in the Ga_2O_3 active layer. However, the properties of the 900 °C-annealed Ga_2O_3 active layers were degraded. Consequently, due to the obtained best crystallinity and the lowest oxygen vacancies and defects in the 800 °C annealed Ga_2O_3 active layers, the resulting MSM UVC-PDs had the largest detectivity.

Figure 8. Noise power density of various Ga₂O₃-based MSM UVC-PDs as a function of frequency under a bias voltage of 5 V.

To further highlight our work, the performance of metal oxide-based MSM PDs with many other similar devices reported previously, as depicted in Table 1. The performance of the MSM UVC-PDs with the 800 °C annealed Ga₂O₃ active layers was good.

Table 1. Comparison of the performance of metal oxide-based MSM PDs.

Materials and Structure	Photoresponsivity (A/W)	UV/Visible Rejection Ratio	Detectivity (cmHz ^{1/2} W ⁻¹)	Ref
Ga ₂ O ₃ thin films	22.19 (at 250 nm)	5.97×10^4	8.74×10^{12}	This work
Ga ₂ O ₃ nanostructures	38.161 (at 365 nm)	—	8.39×10^9	[29]
Ga ₂ O ₃ thin films	17 (at 255 nm)	8.5×10^6	7.00×10^{12}	[30]
Ga ₂ O ₃ thin films	0.893 (at 250 nm)	9.75×10^2	—	[31]
Ga ₂ O ₃ thin films	29.8 (at 254 nm)	9.4×10^3	1.00×10^{12}	[32]
α/β -Ga ₂ O ₃ nanorods	0.00026 (at 254 nm)	2.7×10^3	2.8×10^9	[33]
TiO ₂ thin films	13.29 (at 365 nm)	—	4.91×10^{13}	[34]
MgZnO thin films	0.14 (at 325 nm)	3.83×10^3	4.42×10^{12}	[35]
ZnO thin films	27 (at 365 nm)	—	8.5×10^{13}	[36]

4. Conclusions

In this work, Ga₂O₃ films were successfully deposited on sapphire substrate using a PE-ALD system and were applied as active layers in MSM UVC-PDs. The annealing treatment with various temperatures was used to improve the properties of Ga₂O₃ films. The XRD experimental results verified that the crystallinity of the Ga₂O₃ films could be improved by annealing treatment. Besides, the dependence of oxygen vacancies and defects of the Ga₂O₃ films on annealing temperature was verified by XPS and PL experimental results. The best crystallinity and the lowest oxygen vacancy and defect were obtained, when the Ga₂O₃ films were annealed in an O₂ ambience at 800 °C for 15 min. The lowest dark current of 2.03 pA and the largest photoresponsivity of 22.19 A/W were obtained for the MSM UVC-PDs with the 800 °C annealed Ga₂O₃ active layers. Compared with the as-grown Ga₂O₃-based MSM UVC-PDs, the detectivity of the 800 °C annealed Ga₂O₃-based MSM UVC-PDs increased from 6.04×10^{11} to 8.74×10^{12} cmHz^{1/2}W⁻¹. Consequently, it is expected that the PE-ALD is a promising system for depositing high-quality Ga₂O₃ films, which has high potential in the fabrication of solar-blind deep ultraviolet C photodetectors.

Author Contributions: Conceptualization, H.-Y.L. and C.-T.L.; data curation, S.-Y.C., M.-X.S., T.-H.Y. and C.-H.C.; funding acquisition, H.-Y.L., C.-T.L.; investigation, S.-Y.C., M.-X.S., H.-Y.L. and C.-T.L.; Writing—Original draft, S.-Y.C. and M.-X.S.; Writing—Review and editing, H.-Y.L. and C.-T.L. All authors have read and agree to the published version of the manuscript.

Funding: This work was supported by the Ministry of Science and Technology (MOST), Republic of China under No. MOST-108-2221-E-006-196-MY3 and MOST-108-2221-E-006-215-MY3.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jheng, J.S.; Wang, C.K.; Chiou, Y.Z.; Chang, S.P.; Chang, S.J. MgZnO/SiO₂/ZnO metal-semiconductor-metal dual-band UVA and UVB photodetector with different MgZnO thicknesses by RF magnetron sputter. *Jpn. J. Appl. Phys.* **2020**, *59*, SDDF04. [\[CrossRef\]](#)
2. Wang, H.L.; Liu, J.; Pang, D.R.; Li, T.; Liu, R.H. Mechanisms underlying the protective effects of blueberry extract against ultraviolet radiation in a skin cell co-culture system. *J. Funct. Foods* **2020**, *52*, 603–610. [\[CrossRef\]](#)
3. Kuryatkov, V.; Chandolu, A.; Borisov, B.; Kipshidze, G.; Zhu, K.; Nikishin, S.; Temkin, H.; Holtz, M. Solar-blind ultraviolet photodetectors based on superlattices of AlN/AlGa(In)N. *Appl. Phys. Lett.* **2003**, *82*, 1323–1325. [\[CrossRef\]](#)
4. Ju, Z.G.; Shan, C.X.; Jiang, D.Y.; Zhang, J.Y.; Yao, B.; Zhao, D.X.; Shen, D.Z.; Fan, X.W. Mg_xZn_{1-x}O-based photodetectors covering the whole solar-blind spectrum range. *Appl. Phys. Lett.* **2008**, *93*, 173505. [\[CrossRef\]](#)
5. Liu, K.W.; Sakurai, M.; Aono, M. ZnO-Based Ultraviolet Photodetectors. *Sensors* **2010**, *10*, 8604–8634. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Wang, J.; Ye, L.J.; Wang, X.; Zhang, H.; Li, L.; Kong, C.Y.; Li, W.J. High transmittance beta-Ga₂O₃ thin films deposited by magnetron sputtering and post-annealing for solar-blind ultraviolet photodetector. *J. Alloys Compd.* **2019**, *803*, 9–15. [\[CrossRef\]](#)
7. Lee, H.Y.; Liu, J.T.; Lee, C.T. Modulated Al₂O₃-alloyed Ga₂O₃ materials and deep ultraviolet photodetectors. *IEEE Photon. Technol. Lett.* **2018**, *30*, 549–552. [\[CrossRef\]](#)
8. Li, X.H.; Detchprohm, T.; Kao, T.T.; Satter, M.M.; Shen, S.C.; Yoder, P.D.; Dupuis, R.D.; Wang, S.; Wei, Y.O.; Xie, H.E.; et al. Low-threshold stimulated emission at 249 nm and 256 nm from AlGaIn-based multiple-quantum-well lasers grown on sapphire substrates. *Appl. Phys. Lett.* **2014**, *105*, 141106. [\[CrossRef\]](#)
9. Lee, H.Y.; Wang, M.Y.; Chang, K.J.; Lin, W.J. Ultraviolet photodetector based on Mg_xZn_{1-x}O thin films deposited by radio frequency magnetron sputtering. *IEEE Photon. Technol. Lett.* **2008**, *20*, 2108–2110.
10. Zhao, D.X.; Liu, Y.C.; Shen, D.Z.; Lu, Y.M.; Zhang, J.Y.; Fan, X.W. Photoluminescence properties of Mg_xZn_{1-x}O alloy thin films fabricated by the sol-gel deposition method. *J. Appl. Phys.* **2001**, *90*, 5561–5563. [\[CrossRef\]](#)
11. Mastro, M.A.; Kuramata, A.; Calkins, J.; Kim, J.; Ren, F.; Pearton, S.J. Perspective—Opportunities and future directions for Ga₂O₃. *ECS J. Solid State Sci. Technol.* **2017**, *6*, 356–359. [\[CrossRef\]](#)
12. Pearton, S.J.; Yang, J.; Cary, P.H.; Ren, F.; Kim, J.; Tadjer, M.J.; Mastro, M.A. A review of Ga₂O₃ materials, processing, and devices. *Appl. Phys. Rev.* **2018**, *5*, 011301. [\[CrossRef\]](#)
13. Zhang, D.; Zheng, W.; Lin, R.C.; Li, T.T.; Zhang, Z.J.; Huang, F. High quality beta-Ga₂O₃ film grown with N₂O for high sensitivity solar-blind-ultraviolet photodetector with fast response speed. *J. Alloys Compd.* **2018**, *735*, 150–154. [\[CrossRef\]](#)
14. Alema, F.; Hertog, B.; Mukhopadhyay, P.; Zhang, Y.; Mauze, A.; Osinsky, A.; Schoenfeld, W.V.; Speck, J.S.; Vogt, T. Solar blind Schottky photodiode based on an MOCVD-grown homoepitaxial β-Ga₂O₃ thin film. *APL Mater.* **2019**, *7*, 022527. [\[CrossRef\]](#)
15. Zhang, F.; Arita, M.; Wang, X.; Chen, Z.; Saito, K.; Tanaka, T.; Nishio, M.; Motooka, T.; Guo, Q. Toward controlling the carrier density of Si doped Ga₂O₃ films by pulsed laser deposition. *Appl. Phys. Lett.* **2016**, *109*, 100–104. [\[CrossRef\]](#)
16. Guo, Q.; Nishihagi, K.; Chen, Z.; Saito, K.; Tanaka, T. Characteristics of thulium doped gallium oxide films grown by pulsed laser deposition. *Thin Solid Films* **2017**, *639*, 123–126. [\[CrossRef\]](#)
17. Huang, Y.Q.; An, Y.H.; Wu, Z.P.; Guo, D.Y.; Zhi, Y.S.; Cui, W.; Zhao, X.L.; Tang, W.H. Structural and photoelectrical properties of Ga₂O₃/SiC/Al₂O₃ multilayers. *J. Alloys Compd.* **2017**, *717*, 8–13. [\[CrossRef\]](#)

18. Pratiyush, A.S.; Krishnamoorthy, S.; Kumar, S.; Xia, Z.; Muralidharan, R.; Rajan, S.; Nath, D.N. Demonstration of zero bias responsivity in MBE grown β -Ga₂O₃ lateral deep-UV photodetector. *Jpn. J. Appl. Phys.* **2018**, *57*, 060313. [\[CrossRef\]](#)
19. Kim, J.H.; Holloway, P.H. Microstructural characterization of radio frequency magnetron sputter-deposited Ga₂O₃: Mn phosphor thin films. *J. Vac. Sci. Technol. A* **2002**, *20*, 928–933. [\[CrossRef\]](#)
20. Li, Z.; An, Z.Y.; Xu, Y.; Cheng, Y.L.; Cheng, Y.N.; Chen, D.Z.; Feng, Q.; Xu, S.R.; Zhang, J.C.; Zhang, C.F.; et al. Improving the production of high-performance solar-blind β -Ga₂O₃ photodetectors by controlling the growth pressure. *J. Mater. Sci.* **2019**, *54*, 10335–10345. [\[CrossRef\]](#)
21. Dyndal, K.; Zarzycki, A.; Andrysiewicz, W.; Grochala, D.; Marszalek, K.; Rydosz, A. CuO-Ga₂O₃ Thin Films as a Gas-Sensitive Material for Acetone Detection. *Sensors* **2020**, *20*, 3142. [\[CrossRef\]](#)
22. Lin, C.H.; Lee, C.T. Ga₂O₃-based solar-blind deep ultraviolet light-emitting diodes. *J. Lumin.* **2020**, *224*, 117326. [\[CrossRef\]](#)
23. Lee, H.Y.; Lin, C.H.; Lee, C.T. Whole metal oxide p-i-n deep ultraviolet light-emitting diodes using i-Ga₂O₃ active emissive film. *IEEE Photon. Technol. Lett.* **2020**, *32*, 941–943. [\[CrossRef\]](#)
24. Profijt, H.B.; Potts, S.E.; Van De Sanden, M.C.M.; Kessels, W.M.M. Plasma-assisted atomic layer deposition basics opportunities and challenges. *J. Vac. Sci. Technol. A* **2011**, *29*, 050801. [\[CrossRef\]](#)
25. O'Donoghue, R.; Rechmann, J.; Aghaee, M.; Rogalla, D.; Becker, H.W.; Creatore, M.; Wieck, A.D.; Devi, A. Low temperature growth of gallium oxide thin films via plasma enhanced atomic layer deposition. *Dalton Trans.* **2017**, *46*, 16551–16561. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Wei, W.; Qin, Z.X.; Fan, S.F.; Li, Z.W.; Shi, K.; Zhu, Q.S.; Zhang, G.Y. Valence band offset of beta-Ga₂O₃/wurtzite GaN heterostructure measured by X-ray photoelectron spectroscopy. *Nanoscale Res. Lett.* **2012**, *7*, 562. [\[CrossRef\]](#)
27. Guo, D.; Qin, X.; Lv, M.; Shi, H.; Su, Y.; Yao, G.; Wang, S.; Li, C.; Li, P.; Tang, W. Decrease of oxygen vacancy by Zn-doped for improving solar-blind photoelectric performance in β -Ga₂O₃ thin films. *Electron. Mater. Lett.* **2017**, *13*, 483–488. [\[CrossRef\]](#)
28. Terasako, T.; Kawasaki, Y.; Yagi, M. Growth and morphology control of beta-Ga₂O₃ nanostructures by atmospheric-pressure CVD. *Thin Solid Films* **2016**, *620*, 23–29. [\[CrossRef\]](#)
29. Jubu, P.R.; Yam, F.K. Development and characterization of MSM UV photodetector based on gallium oxide nanostructures. *Sens. Actuator A-Phys.* **2020**, *312*, 112141. [\[CrossRef\]](#)
30. Hu, G.C.; Shan, C.X.; Zhang, N.; Jiang, M.M.; Wang, S.P.; Shen, D.Z. High gain Ga₂O₃ solar-blind photodetectors realized via a carrier multiplication process. *Opt. Express* **2015**, *23*, 13554–13561. [\[CrossRef\]](#)
31. Peng, Y.K.; Zhang, Y.; Chen, Z.W.; Guo, D.Y.; Zhang, X.; Li, P.G.; Wu, Z.P.; Tang, W.H. Arrays of solar-blind ultraviolet photodetector based on beta-Ga₂O₃ epitaxial thin films. *IEEE Photon. Technol. Lett.* **2018**, *30*, 993–996. [\[CrossRef\]](#)
32. Oh, S.; Kim, C.K.; Kim, J. High responsivity beta-Ga₂O₃ metal-semiconductor-metal solar-blind photodetectors with ultraviolet transparent graphene electrodes. *ACS Photon.* **2018**, *5*, 1123–1128. [\[CrossRef\]](#)
33. Wu, C.; He, C.; Guo, D.; Zhang, F.; Li, P.; Wang, S.; Liu, A.; Wu, F.; Tang, W. Vertical α/β -Ga₂O₃ phase junction nanorods array with graphene silver nanowire hybrid conductive electrode for high-performance self-powered solar-blind photodetectors. *Mater. Today Phys.* **2020**, *12*, 100193. [\[CrossRef\]](#)
34. Kumbhar, S.M.; Shaikh, S.K.; Rajpure, K.Y. Hydrothermally-grown TiO₂ thin film-based metal-semiconductor-metal UV photodetector. *J. Electron. Mater.* **2020**, *49*, 449–509. [\[CrossRef\]](#)
35. Wang, H.B.; Liu, Q.S.; Wang, X.C.; Yan, J.B.; Tang, H. Ultraviolet photodetector fabricated using laser sintering method grown Mg_{0.2}Zn_{0.8}O film. *J. Mater. Sci.-Mater. Electron.* **2020**, *31*, 15659–15668. [\[CrossRef\]](#)
36. Zheng, M.J.; Gui, P.B.; Wang, X.; Zhang, G.Z.; Wan, J.X.; Zhang, H.; Fang, G.J.; Wu, H.; Lin, Q.Q.; Liu, C. ZnO ultraviolet photodetectors with an extremely high detectivity and short response time. *Appl. Surf. Sci.* **2019**, *481*, 422–437. [\[CrossRef\]](#)

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).