Effects of Drying Temperature and Molar Concentration on Structural, Optical, and Electrical Properties of $\beta$-Ga$_2$O$_3$ Thin Films Fabricated by Sol–Gel Method

Taejun Park, Kyunghwan Kim and Jeongsoo Hong *

Abstract: In this study, $\beta$-Ga$_2$O$_3$ films were fabricated on a quartz substrate by the sol–gel method using different drying temperatures and solutions of different molar concentrations, and their structural, optical, and electrical properties were evaluated. The as-fabricated films exhibited a monoclinic $\beta$-Ga$_2$O$_3$ crystal structure, whose crystallinity and crystallite size increased with increasing molar concentration of the solutions used and increasing drying temperature. Scanning electron microscopy of the as-prepared samples revealed dense surface morphologies and that the thickness of the films also depended on the deposition conditions. The average transmittance of all the samples was above 8% in visible light, and the calculated optical bandgap energy was 4.9 eV. The resistivity measured using a 4-point probe system was $3.7 \times 10^3 \ \Omega \ \text{cm}$.

Keywords: $\beta$-Ga$_2$O$_3$; sol–gel; film; solution process; semiconductor

1. Introduction

Wide-bandgap semiconductors exhibit excellent properties such as high breakdown field, high temperature stability, and high thermal conductivity. Due to these properties, such semiconductors have been investigated for application in various devices that require these properties (e.g., power semiconductors such as Schottky barrier diodes, thin-film transistors, ultraviolet (UV) photodetectors, and gas sensing devices) [1–5].

Silicon carbide (SiC), gallium nitride (GaN), and gallium oxide (Ga$_2$O$_3$) are well-known wide-bandgap semiconductor materials [6]. Among them, Ga$_2$O$_3$ is a promising candidate material for application in next-generation power devices operated at high voltages and temperatures. Ga$_2$O$_3$ has five crystal structures: rhombohedral ($\alpha$), monoclinic ($\beta$), defective spinel ($\gamma$), cubic ($\delta$), and orthorhombic ($\epsilon$). Notably, $\beta$-Ga$_2$O$_3$ ($a = 1.2 \ \text{nm}$, $b = 0.9 \ \text{nm}$, $c = 0.6 \ \text{nm}$, $\beta = 104^\circ$) has a wide bandgap ($E_g = 4.8–4.9 \ \text{eV}$) and a high breakdown field ($E_{br} = 6–8 \ \text{MV/cm}$) [7,8], along with the most stable properties at high temperatures compared to the other crystal structures. The Johnson’s figure of merit (JFOM), which is a performance index for maximizing frequency, of $\beta$-Ga$_2$O$_3$ is 40 times higher than that of Si [9]. In addition, the Baliga’s FOM (BFOM), which is a performance index for minimizing conduction loss, of $\beta$-Ga$_2$O$_3$ is 3444 times higher than that of Si [10]. Therefore, $\beta$-Ga$_2$O$_3$ films have been investigated for applications in power semiconductors.

Various deposition methods have previously been proposed for the deposition of high-quality $\beta$-Ga$_2$O$_3$ films including pulsed laser deposition, chemical vapor deposition, metal organic chemical vapor deposition, and radio-frequency sputtering [11–14]; however, they are energy-intensive and require expensive equipment [15]. On the other hand, the solution process for film fabrication has many advantages including low environmental load and cost [15–17]. However, the structural properties of $\beta$-Ga$_2$O$_3$ are not stable, and the solution process requires an annealing process at temperatures higher than 900 °C; therefore, a solution process for fabricating $\beta$-Ga$_2$O$_3$ films is required [18].
In this study, $\beta$-Ga$_2$O$_3$ films were prepared using a sol–gel method, which has advantages of low-temperature processing, uniform coating thickness, and low manufacturing cost [19]. In this process, solutions containing Ga ions at different molar concentrations were spin-coated on a quartz substrate, followed by treatment at different drying temperatures. The molar concentration of the solution and the drying temperature are important factors governing film formation and crystal structure. The thickness, structural, optical, and electrical properties of the film were compared according to each change in the drying temperature and molar concentration of the solution.

2. Experimental Procedure

The quartz substrate (1 cm $\times$ 1 cm, thickness: 0.5 mm, iNexus, Inc., Seongnam, Republic of Korea) was ultrasonically cleaned for 10 min with ethyl alcohol (C$_2$H$_5$OH, 94%, extra pure, DUKSAN pure chemicals, Ansan, Republic of Korea) and acetone (CH$_3$COCH$_3$, 99.5%, extra pure, SAMCHUN pure chemicals, Pyeongtaek, Republic of Korea), followed by rinsing with deionized water. The solution process has poor adhesion between the substrate and film compared to vapor deposition, which may cause peeling off [20]. UV irradiation has been suggested to have more hydroxyl groups attached to the surface, indicating a hydrophilic surface [21]. To improve the adhesion between the film and substrate, the substrate was subjected to UV-C irradiation (G15T8, wavelength: 253.7 nm, 1.4 mW/cm$^2$, SANKYO DENKI, Hiratsuka, Japan) for different durations to modify the hydrophilic surface before deposition [22]. Among the substrates irradiated for different irradiation times, those irradiated with UV-C for 24 h exhibited the lowest contact angle of 24.7$^\circ$. The details of the contact angle data are presented in Figure 1.

![Figure 1. Contact angles of the quartz substrate irradiated with UV-C for different irradiation times. (a) Without UV irradiation, (b) 3 h, (c) 6 h, (d) 12 h, (e) 24 h.](image)

The reagents used in this study for the fabrication of $\beta$-Ga$_2$O$_3$ films were gallium nitrate hydrate (Ga(NO$_3$)$_3$·xH$_2$O, 99.9% pure, supplied by Alfa Aesar, Seoul, Republic of Korea) and polyoxyethylene lauryl ether (non-ionic, Brij-4, Sigma-Aldrich, Seoul, Republic of Korea). Different amounts of water-soluble gallium nitrate hydrate were dissolved in deionized water to form solutions with molar concentrations ranging from 0.5 to 1.0 M. These solutions were added to 0.1 vol.% Brij-4 (used as a surfactant) for the fabrication of $\beta$-Ga$_2$O$_3$ films [23]. Then, the solution was stirred at 60 °C for 90 min. The gallium solutions with different molar concentrations were drop-casted onto the UV-C-treated quartz substrates, and then the coated films were dried at different temperatures ranging from 60 to 100 °C. This procedure was repeated 10 times. Then, the dried films were annealed in a muffle furnace (DMF-3T, Lab House, Pocheon, Republic of Korea) at 700 °C for 30 min in ambient air. Detailed conditions for film deposition and sample names are listed in Table 1.
Table 1. Conditions for film deposition.

| Sample | A  | B  | C  | D  | E  | F  | G  | H  | I  |
|--------|----|----|----|----|----|----|----|----|----|
| Drying temperature (°C) | 60 | 80 | 100 | 60 | 80 | 100 | 60 | 80 | 100 |

The hydrophilic surface was evaluated by using a contact angle meter (DSA100, Kruss, Seoul, Republic of Korea) and the intensity of UV-C irradiation was measured using a UV-C light meter (UVC-254SD, Lutron, Seongnam, Republic of Korea). The crystallographic properties of the fabricated films were evaluated using X-ray diffraction analysis (XRD, SmartLab, Rigaku, Tokyo, Japan). Scanning electron microscopy (SEM, S-4700, Hitachi, Seoul, Republic of Korea) and the intensity of UV-C irradiation was measured using a UV-C light meter (UVC-254SD, Lutron, Seongnam, Republic of Korea). Atomic force microscopy (AFM, Park NX10, Park Systems, Suwon, Republic of Korea) was used to evaluate the surface morphologies and roughness of the films. The optical and electrical properties of the fabricated films were evaluated using a UV–Vis spectrometer (Lambda 750 UV–Vis-NIR, Perkin Elmer, Seoul, Republic of Korea) and a 4-point probe system (CMT-SR1000, Changmin Tech, Seongnam, Republic of Korea), respectively.

3. Result and Discussion

3.1. Structural Properties

Figure 2 shows the XRD patterns of β-Ga2O3 films fabricated using different drying temperatures and gallium solutions of different molar concentrations. These patterns confirmed that β-Ga2O3 films were successfully formed without any impurities by the sol–gel process. In addition, with increasing molar concentration of the gallium solution, the peak intensity increased, implying improved crystallinity of the β-Ga2O3 films.

![Figure 2. The XRD patterns of the β-Ga2O3 films prepared at different drying temperatures: (a) 60 °C, (b) 80 °C, and (c) 100 °C. (d) Crystallite size of the β-Ga2O3 thin films fabricated at drying temperatures of 80 and 100 °C.](image-url)
Figure 2a shows weak peaks at 2θ = 30.1°, 31.7°, and 64.7°, which corresponded to the (400), (202), and (712) planes, respectively, of monoclinic β-Ga2O3, according to the reference data of ICDD card (41-1103). Figure 2a also shows that for a drying temperature of 60 °C, broad peaks were obtained and crystallite size could not be calculated [24]. However, sharper peaks of greater intensity were obtained at higher drying temperatures (Figure 2b,c). Additional peaks appeared at 2θ ≈ 35.2° and 38.5°, corresponding to the (111) and (311) planes of β-Ga2O3, respectively, indicating that crystallization of β-Ga2O3 was facilitated by increasing both the molar concentration and the drying temperature. The Scherrer formula was used to calculate the crystallite sizes at the (202) plane, which is the preferential growth plane, as follows:

\[
D = \frac{k \lambda}{\beta \cos \theta}
\]  

(1)

Here, \(k\) is the Scherrer constant (=0.9); \(D\) is the crystallite size; \(\lambda\) is the X-ray wavelength (=0.15406 nm); \(\theta\) is the Bragg angle; and \(\beta\) is the full width at half maximum (FWHM) [25]. The crystallite sizes obtained using the above equation increased with increasing molar concentration of the gallium solution (Figure 2d). The increase in molar concentration leads to an increase in Ga concentration on the substrate, which results in faster nucleation and greater condensation of Ga atoms, leading to the growth of larger crystallites [26]. The crystallite size of the samples also increased with increasing drying temperature. This phenomenon may be related to the film thickness [27]. In addition, the micro-strain (ε) induced in the thin films due to lattice misfit was calculated using Equation (2).

\[
\varepsilon = \frac{\beta}{4 \tan \theta}
\]  

(2)

The variations in \(\varepsilon\) are shown in Figure 3. The \(\varepsilon\) value decreased with increasing molar concentration and drying temperature. Compared with Figure 2d, we can conclude that the crystallite size of the thin film decreased with increasing microstrain, which supports the fact that reduction in the quantity of imperfections promotes the formation of larger crystals. Reportedly, a decrease in the microstrain of the film indicates improved crystallinity of the film, along with a reduction in lattice imperfections [28]. Therefore, increasing both the molar concentration and the drying temperature is favorable for the crystallization of monoclinic β-Ga2O3.

![Figure 3](image_url)

Figure 3. Strain of the β-Ga2O3 films fabricated using solutions of different molar concentrations at drying temperatures of 80 and 100 °C.
The surface morphologies of the β-Ga2O3 films fabricated using different drying temperatures and solutions of different molar concentrations are shown in Figure 4. The top-view SEM images show that all the samples exhibited a dense surface morphology regardless of the experimental conditions. In addition, it was confirmed through the SEM images that the surface density increased and became more compact when the molar concentration of the solution was increased at the same drying temperature and also when the drying temperature was increased at the same molar concentration. It has been reported in previous studies [29,30], and it can be seen that a compact thin film can be obtained by increasing the molar concentration and drying temperature. However, the thickness of the samples changed upon varying the experimental conditions, and Table 2 summarizes the thicknesses of all samples fabricated under different conditions. As shown in Table 2, for samples prepared at the same drying temperature, thickness of the β-Ga2O3 films increased with increasing molar concentration. Furthermore, for samples prepared at the same molar concentration, the thickness of the β-Ga2O3 films increased with increasing drying temperature. These results have been reported in previous papers [31,32], and are closely related to the crystallite size calculated using the Scherrer formula.

Figure 4. SEM images of the as-deposited β-Ga2O3 thin films at different molar concentrations and drying temperatures.

Table 2. Thickness values of the samples prepared under different conditions.

| Sample | A  | B  | C  | D  | E  | F  | G  | H  | I  |
|--------|----|----|----|----|----|----|----|----|----|
| Thickness (nm) | 52 | 65 | 70 | 120 | 130 | 176 | 238 | 254 | 412 |
The root-mean-square (RMS) roughness and surface morphologies of the samples were further investigated using AFM. The three-dimensional (3D) AFM images of the β-Ga$_2$O$_3$ thin films fabricated under different experimental conditions (Figure 5) showed that all samples possessed flat surface morphologies, and sample A had a low RMS roughness value of 0.2 nm. For samples A, B, and C (drying temperature = 60 °C), the RMS roughness increased with increasing molar concentration. Furthermore, for samples A, D, and G (molar concentration = 0.5 M), the RMS roughness of the thin film increased with increasing drying temperature. These results suggest that using a high molar concentration and a high drying temperature increased the thickness of the β-Ga$_2$O$_3$ films, leading to large crystallite sizes and large surface roughness values [33].

![AFM Images](image)

**Figure 5.** 3D AFM images of the as-deposited β-Ga2O3 thin films at different molar concentrations and drying temperatures. (a) 0.5 M, 60 °C, (b) 0.7 M, 60 °C, (c) 1.0 M, 60 °C, (d) 0.5 M, 80 °C, and (e) 0.5 M, 100 °C.

### 3.2. Optical Properties

The UV–Vis spectra shown in Figure 6 revealed that in the wavelength range from 190 to 850 nm, the optical transmittance of the samples in the visible region decreased with increasing molar concentration from 0.5 to 1.0 M, regardless of the drying temperature. Furthermore, in the spectra of samples A, D, and G prepared at a molar concentration of 0.5 M, the transmittance in the visible region decreased with increasing drying temperature, which is attributed to an increase in the thickness of the β-Ga$_2$O$_3$ films with increasing drying temperature [34]. Optical transmittance is very sensitive to changes in the surface scattering caused by surface roughness and film thickness [35]. It was found that the absorption edge shifted slightly to longer wavelengths with increasing film thickness, which was due to the change in thickness with increasing crystallite size. Hence, optical scattering may increase due to the increase in surface roughness and film thickness, which may reduce the optical transmittance.

Figure 6d shows the change in the optical bandgap energy of β-Ga$_2$O$_3$ film calculated by the Tauc plot (Equation (3)).

\[
ahv = \beta (h
u - E_g)^{1/2}
\]

Here, $h\nu$ is the photon energy; $\alpha$ is the absorption coefficient; and $\beta$ is a fixed constant. The Tauc plot shows that the optical bandgap energy is estimated by extrapolating the linear section to the axis energy. It was found that the optical bandgap energy decreased from 4.9 to 4.1 eV with increasing molar concentration and drying temperature. Among the as-prepared β-Ga$_2$O$_3$ films, sample A deposited at 0.5 M and 60 °C showed the highest
optical bandgap energy (4.9 eV), which is consistent with previously reported values for \( \beta \)-Ga\(_2\)O\(_3\) [36–38]. However, the optical bandgap energies of the samples decreased with increasing molar concentration as well as drying temperature. Reportedly, the optical bandgap energy depends on the thickness of the films [39]. This is in good agreement with the reports on films prepared by direct current magnetron sputtering [40], radio frequency sputtering [41], spin pyrolysis [42], and ion beam sputtering [43].

Figure 6. Optical properties of the as-deposited samples prepared at different molar concentrations and drying temperatures. Transmittance (%) values of different samples at drying temperatures of (a) 60 °C, (b) 80 °C, and (c) 100 °C. (d) Optical bandgap energies of samples prepared at different drying temperatures using different molar concentrations.

As above-mentioned, it was confirmed that the crystallite size and thickness of the \( \beta \)-Ga\(_2\)O\(_3\) films increased as the molar concentration and drying temperature increased, which might be one of the reasons for the decreased optical bandgap energy [44].

3.3. Electrical Properties

Figure 7 shows that the electrical resistivity of the as-deposited samples, measured by a 4-point probe system, increased with increasing molar concentration and drying temperature. The fabricated films had high resistivities in the range from \( 3.7 \times 10^3 \) to \( 5.1 \times 10^4 \) \( \Omega \) cm, regardless of molar concentration and drying temperature, and film thickness. However, a high resistivity implies a low electrical conductivity, according to the equation \( \rho = 1/\sigma \), which is due to the large optical bandgap energy. Therefore, this high resistivity hinders practical applications that require conduction response [45].
Based on these results, we plan to improve the electrical properties (i.e., lower the electrical resistivity) by raising the annealing temperature or by doping with Sn, Ti, etc.

4. Conclusions

The β-Ga$_2$O$_3$ films were successfully fabricated on a quartz substrate by spin-coating, and the effects of drying temperature and molar concentration of the starting solution on the film properties were investigated. With increasing molar concentration and drying temperature, crystallinity of the β-Ga$_2$O$_3$ thin film increased gradually, with a crystallite size of ~21.1 nm. All the films showed a dense surface morphology, and their roughness and thickness both increased with increasing molar concentration and drying temperature. Sample A showed a high transmittance of over 80% to visible light, and the corresponding optical bandgap energy calculated from the Tauc plot was 4.9 eV. The transmittance and optical bandgap energy decreased due to the increase in thickness according to the experimental conditions. The electrical resistivity measurement results showed that the films exhibited a high resistivity ranging from $3.7 \times 10^3$ to $5.1 \times 10^4$ Ω cm. It is difficult to use it as an n-type semiconductor at present due to its high resistivity. However, due to its wide band-gap energy and other features, it is used as a depletion layer in semiconductor devices, and is suitable for power electronics applications such as pin diodes, Schottky barrier diodes and thin-film transistors. In future studies, we plan to improve the electrical properties of these films (i.e., lower their resistivities by using doping or annealing methods.

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References

1. Oh, S.; Yang, G.; Kim, J. Electrical characteristics of vertical Ni/β-Ga2O3 schottky barrier diodes at high temperatures. *ECS J. Solid State Sci. Technol.* 2016, 6, Q3022. [CrossRef]

2. Thomas, S.R.; Adamopoulos, G.; Lin, Y.-H.; Faber, H.; Sygellou, L.; Stratakis, E.; Pliatsikas, N.; Patsalas, P.A.; Anthopoulos, T.D. High electron mobility thin-film transistors based on Ga2O3 grown by atmospheric ultrasonic spray pyrolysis at low temperatures. *Appl. Phys. Lett.* 2014, 105, 092105. [CrossRef]

3. Pratiyush, A.S.; Krishnamoorthy, S.; Muralidharan, R.; Rajan, S.; Nath, D.N. Advances in Ga2O3 solar-blind UV photodetectors. In *Gallium Oxide*; Elsevier: The Netherlands, 2019; pp. 369–399.

4. Yu, M.; Lv, C.; Yu, J.; Shen, Y.; Yuan, L.; Hu, J.; Zhang, S.; Cheng, H.; Zhang, Y.; Jia, R. High-performance photodetector based on sol–gel epitaxially grown α/β Ga2O3 thin films. *Mater. Today Commun.* 2020, 25, 101532. [CrossRef]

5. Jang, Y.-G.; Kim, W.-S.; Kim, D.-H.; Hong, S.-H. Fabrication of Ga2O3/SnO2 core–shell nanowires and their ethanol gas sensing properties. *J. Mater. Res.* 2011, 26, 2322–2327.

6. Wellmann, P.J. Power Electronic Semiconductor Materials for automotive and energy saving applications-SiC, GaN, Ga2O3, and diamond. *Z. Anorg. Allg. Chem.* 2017, 643, 1312–1322. [CrossRef] [PubMed]

7. Yoshioka, S.; Hayashi, H.; Kuwabara, A.; Oba, F.; Matsunaga, K.; Tanaka, I. Structures and energetics of Ga2O3 polymorphs. *J. Phys. Condens. Matter* 2007, 19, 346211. [CrossRef]

8. Ueda, N.; Hosono, H.; Waseda, R.; Kawazoe, H. Synthesis and control of conductivity of ultraviolet transmitting β-Ga2O3 single crystals. *Appl. Phys. Lett.* 1997, 70, 3561–3563. [CrossRef]

9. Baliga, B.J. Power semiconductor device figure of merit for high-frequency applications. *IEEE Device Lett.* 1989, 10, 455–457. [CrossRef]

10. Johnson, E.O. Physical limitations on frequency and power parameters of transistors. In *Semiconductor Devices: Pioneering Papers*; World Scientific: Singapore, 1991; pp. 295–302.

11. Xu, C.X.; Shen, L.Y.; Liu, H.; Pan, X.H.; Ye, Z.Z. High-Quality beta-Ga2O3 films with influence of growth temperature by pulsed laser deposition for solar-blind photodetectors. *J. Electron. Mater.* 2021, 50, 2043–2048. [CrossRef]

12. Rafique, S.; Han, L.; Tadjer, M.J.; Freitas, J.A.; Mahadik, N.A.; Zhao, H.P. Homoepitaxial growth of beta-Ga2O3 thin films by low pressure chemical vapor deposition. *Appl. Phys. Lett.* 2016, 108, 182105. [CrossRef]

13. Tadjer, M.J.; Alema, F.; Osinsky, A.; Mastro, M.A.; Nepal, N.; Woodward, J.M.; Myers-Ward, R.L.; Glaser, E.R.; Freitas, J.A.; Jacobs, A.G.; et al. Characterization of beta-Ga2O3 homoeptaxial films and MOSFETs grown by MOCVD at high growth rates. *J. Phys. D Appl. Phys.* 2021, 54, 034005. [CrossRef]

14. Schurig, P.; Michel, F.; Beyer, A.; Volz, K.; Becker, M.; Polity, A.; Klar, P.J. Progress in sputter growth of beta-Ga2O3 by applying pulsed-mode operation. *Phys. Status Solidi A* 2020, 217, 1901009. [CrossRef]

15. Hong, J.; Wagata, H.; Katsumata, K.; Okada, K.; Matsushita, N. Effects of thermal treatment on crystallographic and electrical properties of transparent conductive ZnO films deposited by spin-spray method. *Jpn. J. Appl. Phys.* 2013, 52, 110108. [CrossRef]

16. Hong, J.S.; Wagata, H.; Ohashi, N.; Katsumata, K.; Okada, K.; Matsushita, N. Transparent ZnO films deposited by aqueous solution process under various pH conditions. *J. Electron Mater.* 2015, 44, 2657–2662. [CrossRef]

17. Chen, D.Z.; Xu, Y.; An, Z.Y.; Li, Z.; Zhang, C.F. Thin-film transistors based on wide bandgap Ga2O3 films grown by aqueous-solution spin-coating method. *Micro. Lett.* 2019, 7, 1052–1055. [CrossRef]

18. Pandeeswari, R.; Jeyaprakash, B. High sensing response of β-Ga2O3 thin film towards ammonia vapours: Influencing factors at room temperature. *Sens. Actuators B Chem.* 2014, 195, 206–214. [CrossRef]

19. Park, S.-S.; Mackenzie, J. Sol-gel-derived tin oxide thin films. *Thin Solid Films* 1995, 258, 268–273. [CrossRef]

20. Hong, J.; Lin, H.E.; Katsumata, K.; Matsushita, N. The study of correlation between electrical conductivity of solution-processed ZnO film and UV irradiation. *Mat. Sci. Semicon. Proc.* 2020, 120, 105266. [CrossRef]

21. Rico, V.; López, C.; Borrás, A.; Espinos, J.; Gonzalez-Elipe, A. Effect of visible light on the water contact angles on illuminated oxide semiconductors other than TiO2. *Sol. Energy Mater. Sol. Cells* 2006, 90, 2944–2949. [CrossRef]

22. Krhanovský, V.; Ekblad, T.; Yakimova, R.; Hultman, L. Surface morphology effects on the light-controlled wettability of ZnO nanostructures. *Appl. Surf. Sci.* 2012, 258, 8146–8152.

23. Ohya, Y.; Okano, J.; Kasuya, Y.; Ban, T. Fabrication of Ga2O3 thin films by aqueous solution deposition. *J. Ceram. Soc. Jpn.* 2009, 117, 973–977. [CrossRef]

24. Patil, P.; Park, J.; Lee, S.Y.; Park, J.-K.; Cho, S.-H. White light generation from single gallium oxide nanoparticles co-doped with rare-earth metals. *Appl. Sci. Converg. Technol.* 2014, 23, 296–300. [CrossRef]

25. Cullity, B.D. *Elements of X-ray Diffraction*; Addison-Wesley Publishing: Boston, MA, USA, 1956.

26. Dhaouadi, M.; Jlassi, M.; Sta, J.; Miled, I.B.; Moussid, G.; Komptas, M.; Dimassi, W. Physical properties of copper oxide thin films prepared by sol–gel spin–coating method. *Am. J. Phys. Appl. Phys.* 2018, 6, 43–50. [CrossRef]

27. Necib, K.; Touam, T.; Chelouche, A.; Ouanes, L.; Djouadi, D.; Boudine, B. Investigation of the effects of thickness on physical properties of AZO sol-gel films for photonic device applications. *J. Alloys Compd.* 2018, 735, 2236–2246. [CrossRef]

28. Korotcenkov, G.; Brinzari, V.; Cerneaevschi, A.; Ivanov, M.; Golovanov, V.; Cornet, A.; Morante, J.; Cabot, A.; Arbiol, J. The influence of film structure on In3O5 gas response. *Thin Solid Films* 2004, 460, 315–323. [CrossRef]

29. Kong, K.; Deka, B.K.; Kim, M.; Oh, A.; Kim, H.; Park, Y.-B.; Park, H.W. Interlaminar resistive heating behavior of woven carbon fiber composite laminates modified with ZnO nanorods. *Compos. Sci. Technol.* 2014, 100, 83–91. [CrossRef]
30. Zhang, H.; Wang, Y.; Wang, H.; Ma, M.; Dong, S.; Xu, Q. Influence of drying temperature on morphology of MAPbI$_3$ thin films and the performance of solar cells. *J. Alloys Compd.* **2019**, *773*, 511–518. [CrossRef]

31. Dekeijser, M.; Dormans, G.J.M.; Vanveldhoven, P.J.; Deleeuw, D.M. Effects of crystallite size in PbTiO$_3$ thin-films. *Appl. Phys. Lett.* **1991**, *59*, 3556–3558. [CrossRef]

32. Boudenbala, M.; Hamzaoui, S.; Amrani, B.; Reshad, A.H.; Adnane, M.; Zerda, M. Thickness dependence of structural, electrical and optical behaviour of undoped ZnO thin films. *Phys. B* **2008**, *403*, 3326–3330. [CrossRef]

33. Guo, P.; Xiong, J.; Zhao, X.; Sheng, T.; Yue, C.; Tao, B.; Liu, X. Growth Characteristics and Device Properties of MOD Derived β-Ga$_2$O$_3$ Films. *J. Mater. Sci.: Mater. Electron.* **2014**, *25*, 3629–3632. [CrossRef]

34. Chen, H.; Battenov, A.; Li, Y.Y.; Vasileva, E.; Popov, S.; Sychugov, I.; Yan, M.; Berglund, L. Thickness dependence of optical transmittance of transparent wood: Chemical modification effects. *ACS Appl. Mater. Interf.* **2019**, *11*, 35451–35457. [CrossRef] [PubMed]

35. Liu, Y.; Tung, S.; Hsieh, J. Influence of annealing on optical properties and surface structure of ZnO thin films. *J. Cryst. Growth* **2006**, *287*, 105–111. [CrossRef]

36. Mastro, M.A.; Kuramata, A.; Calkins, J.; Kim, J.; Ren, F.; Peartong, S.J. Opportunities and future directions for Ga$_2$O$_3$. *Ecs J. Solid State Sci. Technol.* **2017**, *6*, P356–P359. [CrossRef]

37. Pearton, S.J.; Yang, J.C.; Cary, P.H.; Ren, F.; Kim, J.; Tadjer, M.J.; Mastro, M.A. A review of Ga$_2$O$_3$ materials, processing, and devices. *Appl. Phys. Rev.* **2018**, *5*, 011301. [CrossRef]

38. Higashiwaki, M.; Jessen, G.H. Guest Editorial: The dawn of gallium oxide microelectronics. *Appl. Phys. Lett.* **2018**, *112*, 6. [CrossRef]

39. Kayani, Z.N.; Iqbal, M.; Riaz, S.; Zia, R.; Naseem, S. Fabrication and properties of zinc oxide thin film prepared by sol-gel dip coating method. *Mater. Sci.-Pol.* **2015**, *33*, 515–520. [CrossRef]

40. Shin, J.; Kim, K.; Hong, J. Zn-Al Layered double hydroxide thin film fabricated by the sputtering method and aqueous solution treatment. *Coatings* **2020**, *10*, 669. [CrossRef]

41. Martinez, M.; Herrero, J.; Gutierrez, M. Properties of RF sputtered zinc oxide based thin films made from different targets. *Sol. Energy Mater. Sol. Cells* **1994**, *31*, 489–498. [CrossRef]

42. Lokhande, B.; Uplane, M. Structural, optical and electrical studies on spray deposited highly oriented ZnO films. *Appl. Surf. Sci.* **2000**, *167*, 243–246. [CrossRef]

43. Qu, Y.; Gessert, T.; Coutts, T.; Noufi, R. Study of ion-beam-sputtered ZnO films as a function of deposition temperature. *J. Vac. Sci. Technol. A Vac. Surf. Films* **1994**, *12*, 1507–1512. [CrossRef]

44. Ashour, A.; Kaid, M.A.; El-Sayed, N.Z.; Ibrahim, A.A. Physical properties of ZnO thin films deposited by spray pyrolysis technique. *Appl. Surf. Sci.* **2006**, *252*, 7844–7848. [CrossRef]

45. Mi, W.; Du, X.; Luan, C.; Xiao, H.; Ma, J. Electrical and optical characterizations of β-Ga$_2$O$_3$: Sn films deposited on MgO (110) substrate by MOCVD. *RSC Adv.* **2014**, *4*, 30579–30583. [CrossRef]