

Article

Structural and Electrical Properties of Si-Doped β -Ga₂O₃ Thin Films Deposited by RF Sputtering: Effects of Oxygen Flow Ratio and Post-Annealing Temperature

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Abstract

Beta-gallium oxide (β -Ga₂O₃) is a semiconductor with an ultra-wide bandgap, high optical transparency, and excellent electrical properties, which can be finely tuned for a wide range of electronic devices. This study optimized the process conditions for fabricating β -Ga₂O₃ thin films with desired electrical characteristics. β -Ga₂O₃ films were deposited on (100) Si substrates via RF magnetron sputtering with varying O₂ flow rates and post-annealed at temperatures ranging from 600 °C to 800 °C. The structural and electrical properties of the films were analyzed using X-ray diffraction (XRD) spectroscopy, scanning electron microscopy (SEM), and Hall effect measurements. The XRD results confirmed the formation of nanocrystalline β -Ga₂O₃, with variations in peak intensities and shifts observed based on O₂ flow rates. The films exhibited carrier concentrations exceeding $5 \times 10^{22} \text{ cm}^{-3}$, mobilities ranging from 50 to 115 cm²/Vs, and resistivity around $1 \times 10^{-6} \Omega\text{-cm}$. This study demonstrates that the electrical properties of β -Ga₂O₃ thin films can be modulated during the deposition and post-annealing processes. The ability to control these properties underscores the potential of β -Ga₂O₃ for advanced applications in high-performance high-power devices and optoelectronic devices such as deep ultraviolet photodetectors.

Keywords: β -Ga₂O₃; sputtering; post-annealing; oxygen vacancy; oxide; thin film



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1. Introduction

Silicon-based devices have long dominated the semiconductor market because of their established manufacturing facilities and advanced processing technologies. However, Si has a narrow bandgap (1.12 eV), and alternative materials need to be explored for high-power devices [1] and short-wavelength photodetectors [2]. For such applications, gallium oxide (Ga₂O₃) can replace Si. Ga₂O₃ offers unique advantages over other Si alternatives such as SiC and GaN because it exists in multiple phases (α , β , γ , δ , ϵ), with the monoclinic β -phase preferred for device applications due to its thermodynamic stability and ease of thin epitaxial layer growth. β -Ga₂O₃ is particularly suited for high-power and optoelectronic devices due to its ultra-wide bandgap (4.5–4.9 eV), which results in a high breakdown field and excellent thermal stability [3–6]. Moreover, despite its lower electron mobility and thermal conductivity, the ability to grow single crystals of Ga₂O₃ using melt-growth

techniques adds to its practical advantages [7,8]. Consequently, β -Ga₂O₃-based devices are highly advantageous for high-voltage power applications [9–11] (such as Schottky barrier diodes, heterojunction diodes, and field-effect transistors) and deep ultraviolet (DUV) optoelectronic devices [12–16]. Compared to narrow bandgap semiconductors, β -Ga₂O₃ can achieve higher breakdown voltages with thinner drift layers [17]. In DUV photodetectors, the wide bandgap of β -Ga₂O₃ provides superior noise characteristics and high sensitivity without the need for additional filters [18]. Its high thermal and chemical stabilities further enhance device reliability in harsh environments. β -Ga₂O₃ hosts various native point defects, including vacancies and interstitials; among them, oxygen vacancies (V_O) are the most widely discussed. First-principles and experimental studies indicate that V_O can adopt multiple charge states (V_O^0 , V_O^{1+} , V_O^{2+}). In β -Ga₂O₃, the formation of V_O generates local stress and associated restoring forces that drive the lattice toward a new local equilibrium, producing local strain whose behaviors are charge-state dependent [19,20]. This strain modifies thin-film properties [21–23] and thereby alters device performance [24,25]. To improve the conductivity of β -Ga₂O₃, impurity doping is essential. In this study, Si-doped β -Ga₂O₃ films were deposited on (100) Si substrates via RF magnetron sputtering, followed by post-annealing. To fabricate β -Ga₂O₃ films with different electrical properties, the process conditions were varied. Highly conductive β -Ga₂O₃ films were achieved, and the effects of different Ar:O₂ ratios and post-annealing temperatures. While many sputtering studies are device-centric or report only structural/optical metrics, studies that address structural and electrical properties as a function of process conditions for sputtered Si-doped β -Ga₂O₃ remain scarce. We provide a comparative linking structural properties with electrical properties at various fabrication conditions.

2. Materials and Methods

Si-doped Ga₂O₃ was deposited via sputtering on a (100) Si substrate under different conditions. Before the deposition, the substrates were cleaned with acetone, IPA, and deionized water. A Si-doped Ga₂O₃ target was used because doping improves the conductivity of the Ga₂O₃ film. For oxygen vacancy density (V_O) control, sputtering was conducted at various Ar:O₂ flow rates. The sputtering process parameters are listed in Table 1. Because the sputter employs a non-parallel target–substrate geometry, we rotated the substrate during deposition to improve film uniformity. The notation of SiO₂ in Table 1 reflects the fact that SiO₂ powder was used during the target fabrication process. Metallic Si cannot be used in the fabrication process of Si-doped Ga₂O₃ targets due to technical limitations. Therefore, the target was prepared by mixing SiO₂ powder (1 wt%) with Ga₂O₃ powder through mechanical agitation.

Table 1. RF magnetron sputtering process parameters.

Parameters	Set Values					
Target	Si-doped Ga ₂ O ₃ (4N, 99.99%) (wt% Ga ₂ O ₃ :SiO ₂ 99:1)					
Substrate						
Base pressure	1.5 × 10 ^{−6} Torr					
Working pressure	4 mTorr					
Ar:O ₂ ratio [sccm:sccm]	20:0	19:1	18:2	17:3	16:4	
Deposition rate [nm/min]	14.7	12.3	9.6	9.2	6.5	
Substrate temperature	Room temperature					
Input power	200 W					
Film thickness	180 nm					
Substrate rotation speed	3 rpm					

The film sputtered at room temperature (RT) exhibited an amorphous structure. After deposition, post-annealing was conducted by electrical furnace to achieve the β phase gallium oxide film. Table 2 lists the post-annealing conditions.

Table 2. Post-annealing process parameters.

Parameters		Set Values	
Process time		1 h	
Ambient		Air	
Working pressure		Atmospheric pressure	
Annealing temperature	600 °C	700 °C	800 °C

To calculate the deposition rate, the film thickness was measured using a surface stylus profiler (Alpha Step D-500 Stylus Profiler, KLA-Tencor, Milpitas, CA, USA). The structural properties were evaluated using scanning electron microscopy (SEM; Hitachi S-4700, Hitachi, Marunouchi, Chiyoda-ku, Tokyo, Japan), high-resolution X-ray diffraction (XRD; Rigaku X-ray diffractometer MPA-2000, Rigaku, Tokyo, Japan) with a diffracted beam monochromator curved and flat Cu crystal and X-ray photoelectron spectroscopy (XPS; AXIS SUPRA, Kratos, Manchester, United Kingdom) with a monochromatic Al $K\alpha$ source (1486.6 eV). XRD was conducted by grazing-incidence XRD (GIXRD) to suppress Si wafer peaks. The incident angle (ω) was fixed at 0.5° , and scans were taken from $15\text{--}75^\circ$ (2θ) at $4^\circ/\text{min}$ with 0.05° step. The film thickness of the samples was measured using cross-sectional SEM images. The electrical properties were characterized using an Hall-effect measurement system (Ecopia HMS-3000, Ecopia, Anyang, Republic of Korea) at room temperature ($\sim 25^\circ\text{C}$) with a measurement current of 20 mA magnetic field of 0.53 T. Magnetic field was formed perpendicular to the substrate by a permanent magnet. Hall measurements were performed in a four-probe van der Pauw configuration using contacts labeled A, B, C, D. To reduce errors and improve reliability, instrument first recorded twelve voltages without magnetic field in forward and reverse for each pair (AB/BA, BC/CB, AC/CA, CD/DC, AD/DA, BD/DB). Instrument then measured the Hall voltage under magnetic field provided by permanent magnet using the pairs AC/CA and BD/DB. For each pair, data were acquired for both field polarities (+B and −B), yielding a total of eight Hall-voltage measurements. Measurement reliability was evaluated by checking that the absolute values of the forward and reverse voltages (without magnetic field) closely agreed. Because of the poor ohmic contact with the probe, Hall effect measurements were performed with a Ti/Au electrode deposited by a DC magnetron sputtering system.

3. Results

3.1. Structural Properties

3.1.1. XRD Results

Figure 1 shows the XRD spectra of the samples prepared at different post-annealing temperatures. GIXRD measurements were performed to determine the minimum temperature required for crystallization. The samples remained amorphous at temperatures below 500°C . Crystallization occurred at 600°C and above, with the samples forming nanocrystalline structures. The XRD peaks were identified by comparison with PDF#43-1012, confirming that the observed peaks correspond to the (403), (−201), (002), and (400) peaks of $\beta\text{-Ga}_2\text{O}_3$.

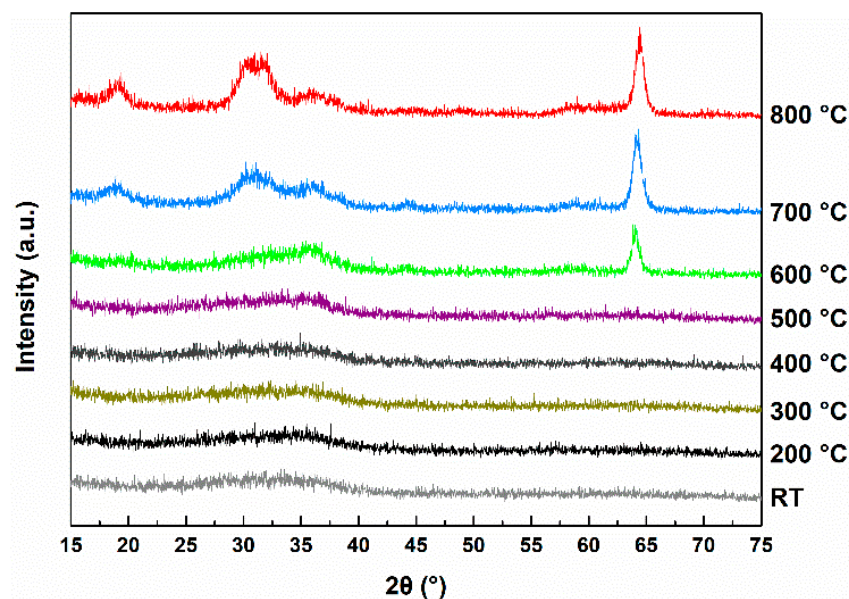


Figure 1. XRD results at different post-annealing temperatures in the 100–800 °C range and without annealing (RT).

Figure 2 shows the XRD spectra as a function of the O₂ flow ratio and post-annealing temperature. All samples annealed at temperatures above 600 °C exhibit β phase (403) peaks, with additional (-201), (002), and (400) peaks depending on the fabrication conditions. Figure 2a shows the XRD results of 600 °C annealed samples with varying Ar:O₂ ratios. At 600 °C, other than the (403) peak, no distinct peaks can be observed. After the introduction of O₂, there is a slight increase in the (400) and (002) peak positions; however, they are not clearly separated. In addition, increasing the O₂ flow rate did not significantly change the diffraction peaks. Figure 2b shows XRD results of 700 °C annealed samples with varying Ar:O₂ ratios. At 700 °C, the (403) peak is more intense than at 600 °C. Without O₂ introduction (Ar only), as in the 600 °C condition, the (403) peak is the only prominent feature, but its intensity is noticeably stronger than at 600 °C. After the introduction of O₂, distinct (-201), (400), and (002) peaks appear in addition to the (403) reflection. As the O₂ flow rate increases, the intensity of the (403) peak gradually decreases. At 800 °C, the overall behavior is similar to that at 700 °C, but with two notable differences. First, after the O₂ introduction, the (-201), (400), and (002) peaks exhibit lower intensities compared to the 700 °C case. Second, even without O₂ flow, the (-201), (400), and (002) peaks are present, whereas at 700 °C these reflections appear distinct only after O₂ introduction. In summary, the results indicate that both the O₂ flow rate and the post-annealing temperature influence the structural characteristics of the Si-doped Ga₂O₃ thin films. Increasing the O₂ flow rate reduces the intensity of the (403) reflection while enhancing the intensity of the other peaks. During deposition, the increasing O₂ flow rate results in a decrease in the kinetic energy of the sputtered atoms, which leads to the low mobility of adatoms on the substrate. Low adatom mobility inhibits the migration of the adatom to its preferred position, leading to a change in the dominant peak [26]. In addition, an increase in the O₂ flow rate results in a decrease in V_O , providing sites for ion migration [27]. Increasing the post-annealing temperature leads to an overall increase in the peak intensities of the (-201), (400), (002), and (403) planes. This is likely because the higher temperature provides sufficient energy for the atoms in the film to migrate to the more stable lattice sites.

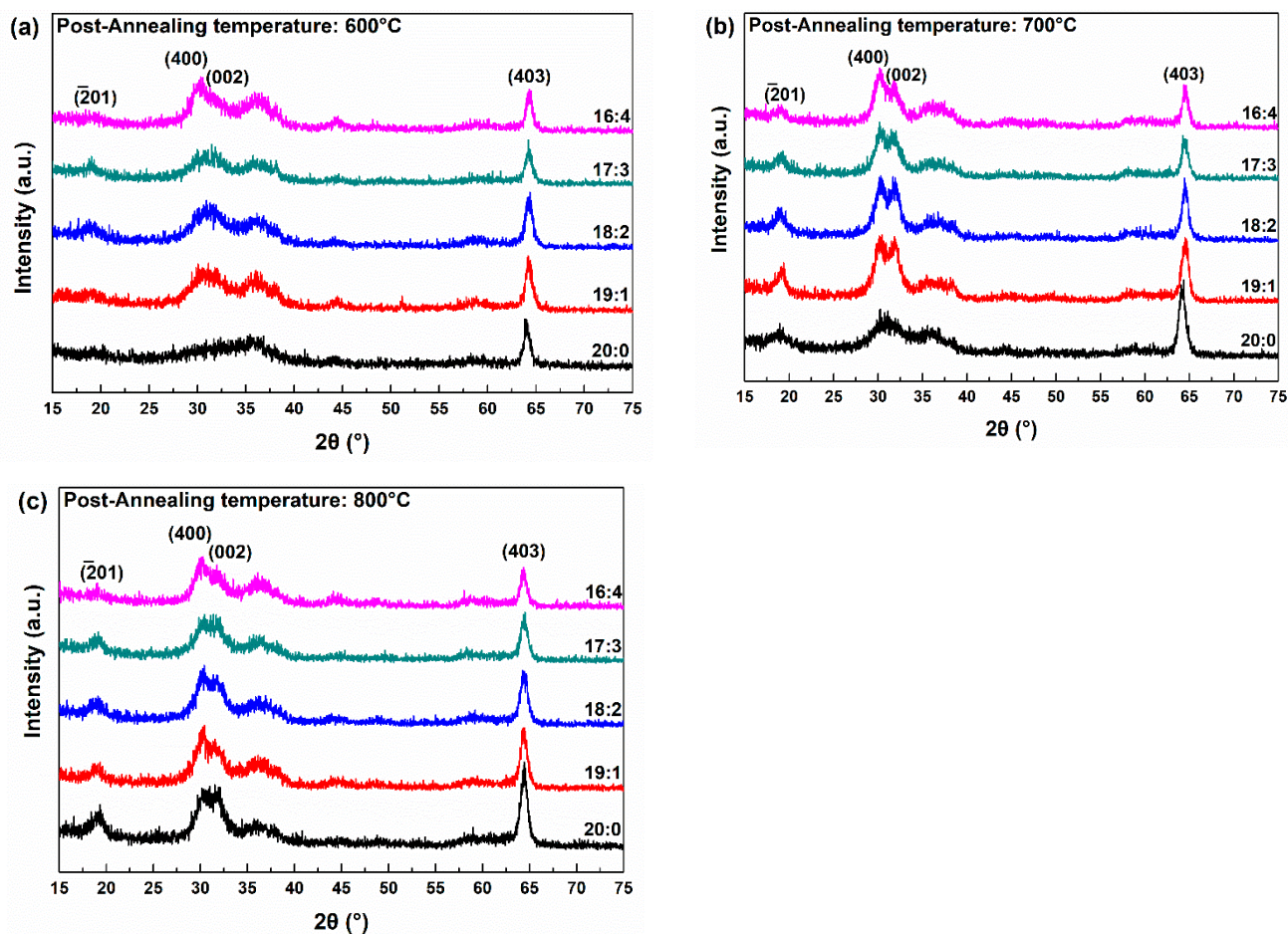


Figure 2. XRD spectra at different Ar:O₂ ratios and post-annealing temperatures: (a) 600 °C, (b) 700 °C, and (c) 800 °C.

Table 3 shows (403) peak information derived from XRD.

Table 3. (403) peak information derived from XRD.

Post-Annealing Temperature	2 Theta [°]	Peak Height [cps]	FWHM [°]	Crystallite Size [nm]	Strain ϵ
600 °C	64.06	201.2	0.84345	7.98	0.07439
700 °C	64.21	332.7	0.99654	6.75	0.04853
800 °C	64.42	343.0	0.96399	6.97	−0.00517

Because the (403) peak was distinctly present in all crystallized samples, Gaussian fitting was performed for the (403) peak. Based on this fitting, the full width at half maximum (FWHM) and the crystallite size were calculated. The crystallite size (D) was calculated using the Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (1)$$

where K is the shape factor (0.9), λ is the X-ray wavelength (0.154 nm), β is the FWHM, and θ is the Bragg angle. Figure 3a–c shows that the FWHM and crystallite size vary with the post-annealing temperature and O₂ flow rate. All samples have nanocrystalline structures with crystallite sizes ranging from 6.6 to 8.3 nm. The crystallite sizes exhibit different trends depending on the post-annealing temperature. For samples annealed at 600 °C and

800 °C, the crystallite size decreases as the O₂ flow ratio increases from 0 to 2 sccm, then increases from 2 to 4 sccm. In contrast, for samples annealed at 700 °C, the crystallite size increases with the O₂ flow ratio, except at 3 sccm. Figure 3d shows the strain induced by crystal imperfections and distortions in the samples as a function of the post-annealing temperature and O₂ flow rate. Strain (ϵ) was calculated by following equation [28].

$$\epsilon = \frac{\beta}{4\tan\theta} \quad (2)$$

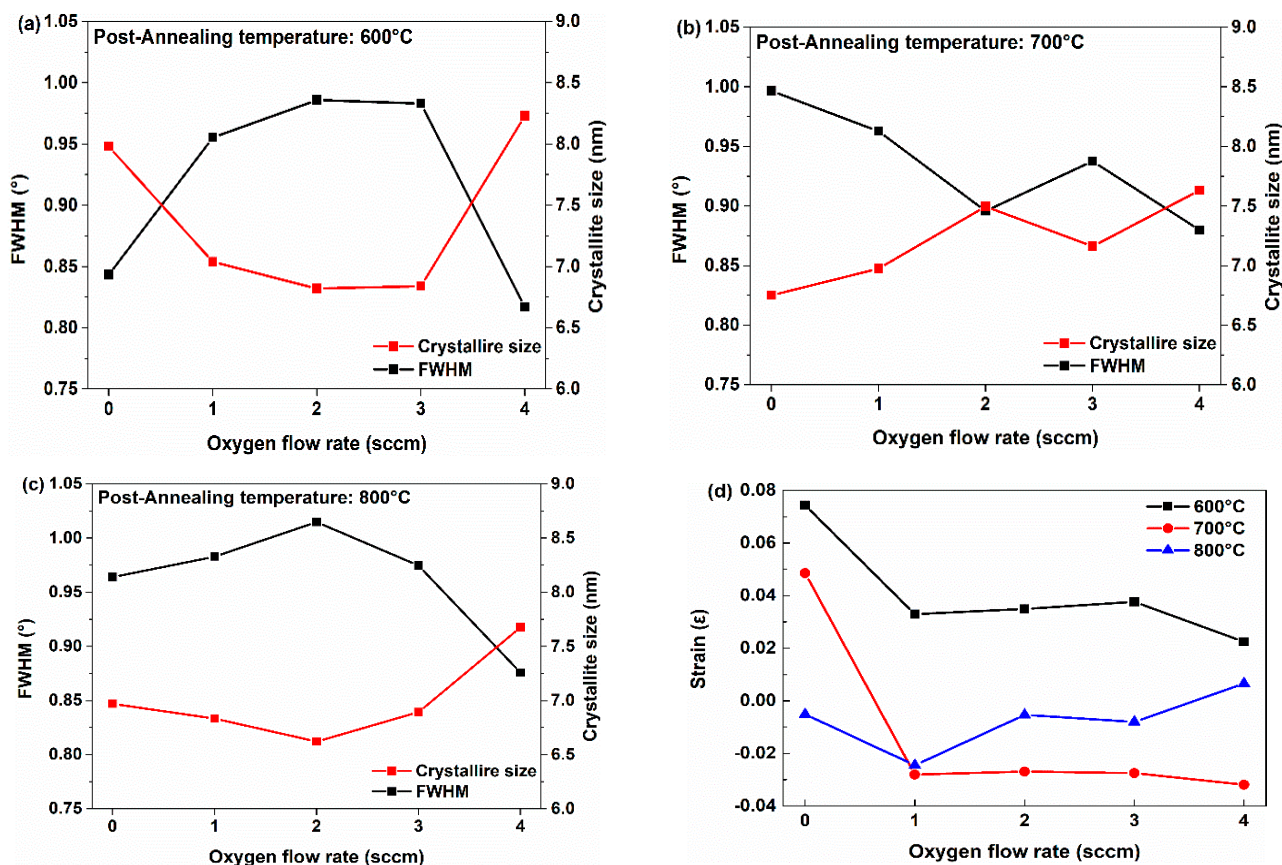


Figure 3. FWHM and crystallite size calculated using XRD results at various temperatures: (a) 600 °C, (b) 700 °C, and (c) 800 °C. (d) Calculated strain.

Strain in thin films arises from a combination of multiple factors, including the film composition, crystal orientation, and lattice mismatch with the substrate [29,30]. Therefore, it is challenging to pinpoint the exact cause of strain based solely on XRD results. In Figure 3d, under the Ar-only condition (i.e., before O₂ is introduced), the strain decreases as the annealing temperature increases, and the sample annealed at 800 °C shows a relatively small strain. This result aligns with the earlier explanation that a higher annealing temperature provides sufficient energy for atoms in the film to migrate to more stable sites, thereby reducing the overall strain. After post-annealing at 600 °C, the film appears to be in a tensile-strained state due to the presence of oxygen vacancies. Once O₂ was introduced (from 0 to 1 sccm), the strain value decreased significantly. This implies that the reduction in V_O at higher O₂ flow rates helped relieve the tensile strain. This trend is attributed to the decreased V_O formation energy with higher oxygen flow rates, leading to reduced V_O in the samples [20,31]. At 700 °C, a similar trend is observed; however, the strain is negative, indicating compressive strain in the film. With the introduction of O₂, the tensile strain transitioned to compressive strain. In other words, although annealing at 700 °C enables higher atomic mobility than that at 600 °C, it does not fully stabilize the crystal

structure, making it an intermediate temperature at which compressive strain emerges in the film [32,33].

3.1.2. SEM Results

Figures 4 and 5 shows the SEM results of Ar:O₂ = 20:0 samples post-annealed at temperatures ranging from RT to 800 °C. Samples annealed at temperatures of 600 °C and above, where crystallization occurs, exhibit cracks. These cracks appear to be due to the lattice mismatch between β -Ga₂O₃ and Si. β -Ga₂O₃ has a monoclinic C2/m structure with lattice constants $a = 12.23 \text{ \AA}$, $b = 3.04 \text{ \AA}$, $c = 5.8 \text{ \AA}$, $\alpha = \gamma = 90^\circ$, and $\beta = 103.7^\circ$ [34], while Si has a cubic Fd $\bar{3}$ m structure with a lattice constant of $5.43 \text{ \AA}$ [35,36], leading to a significant lattice mismatch with β -Ga₂O₃. Therefore, at the crystallization temperature, lattice mismatch induces stress, leading to the formation of cracks. However, as the post-annealing temperature is increased, crack formation and propagation are inhibited, and this behavior is consistent with the results shown in Figure 3d. This is likely due to the sufficient mobility of atoms within the thin film during post-annealing, which induces crystallization and minimizes cracks.

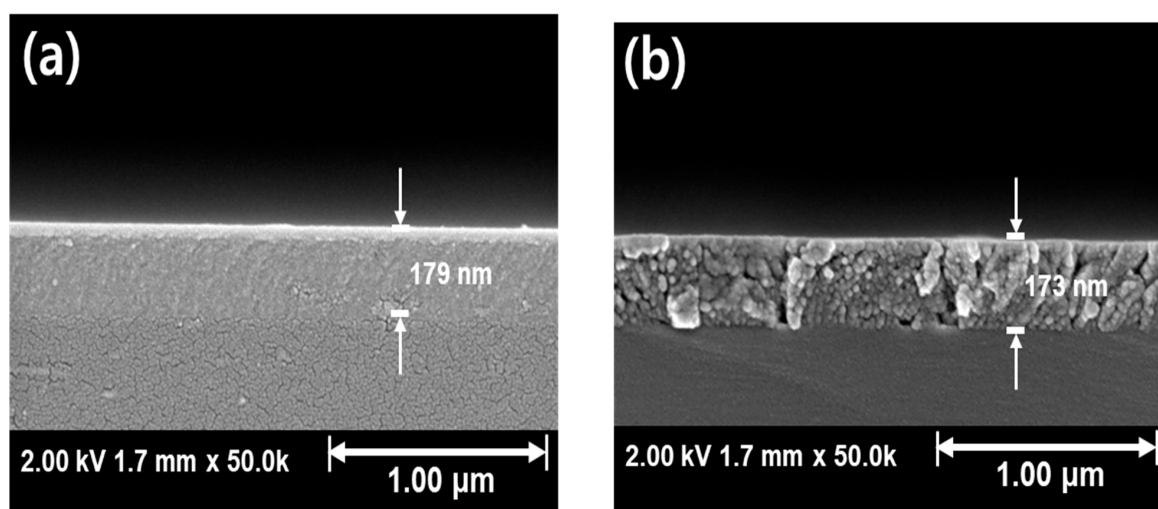


Figure 4. SEM cross-sectional image of Ar:O₂ = 20:0 samples: (a) without annealing, post-annealed at (b) 800 °C.

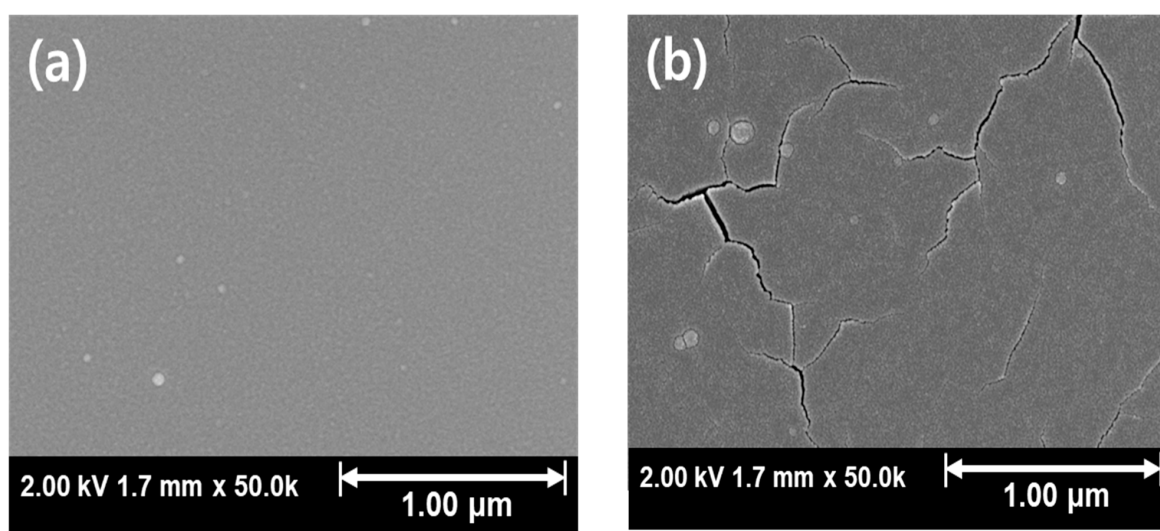


Figure 5. Cont.

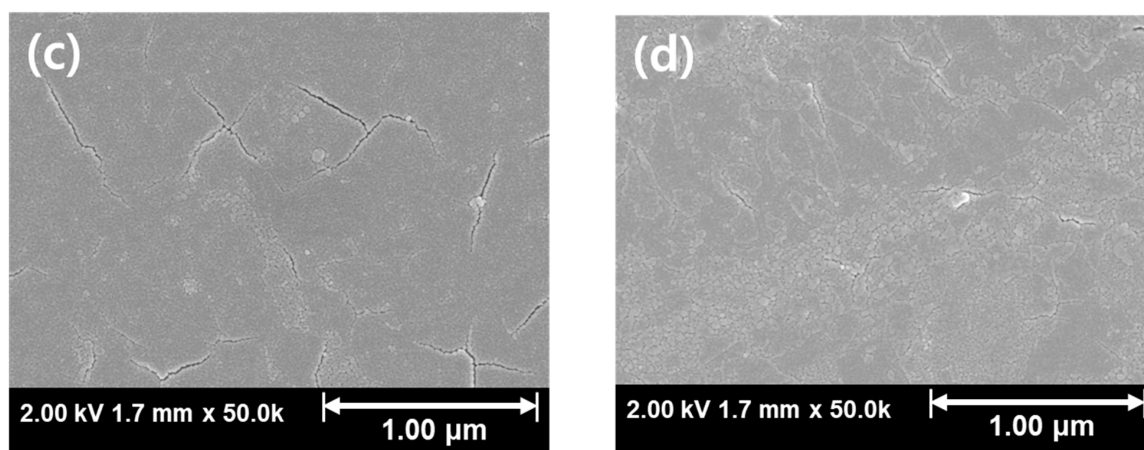


Figure 5. SEM results for Ar:O₂ = 20:0 samples with different post-annealing temperatures: (a) without annealing, annealed at (b) 600 °C, (c) 700 °C, and (d) 800 °C.

3.1.3. XPS Results

To elucidate the evolution of chemical states and defect structures in the Ga₂O₃ thin films, high-resolution XPS measurements were performed on samples subjected to different post-annealing temperatures. Because no depth profiling or sputter cleaning was applied, the reported XPS values correspond to the near-surface of the Ga₂O₃ films. XPS spectra were fitted in Origin using Gaussian peak functions

Figure 6 displays the O 1s and Ga 2p core-level spectra of the undoped Ga₂O₃, as-fabricated, and annealed samples (600, 700, 800 °C). After thermal annealing, the O/Ga atomic ratio exhibited a decreasing trend, which can be primarily attributed to the reduction of chemisorbed oxygen species on the film surface. These surface-adsorbed components (represented by the O_{III} peak at 531.96 eV) are known to desorb upon annealing, especially at elevated temperatures, thereby reducing the total oxygen signal detected by XPS. The O 1s peak was deconvoluted into three components to calculate oxygen vacancy concentration. Each peak was centered at 530.50 eV (O_I), 531.03 eV (O_{II}), and 531.96 eV (O_{III}), as shown in Figure 6 each component corresponds to a distinct chemical state of oxygen:

- O_I is attributed to lattice oxygen (O^{2−}) bound in Ga–O–Ga networks.
- O_{II} is attributed to oxygen vacancies (V_O), indicative of non-stoichiometric regions or local disorder.
- O_{III} is attributed to chemisorbed species such as hydroxyl groups or adsorbed oxygen molecules on the film surface.

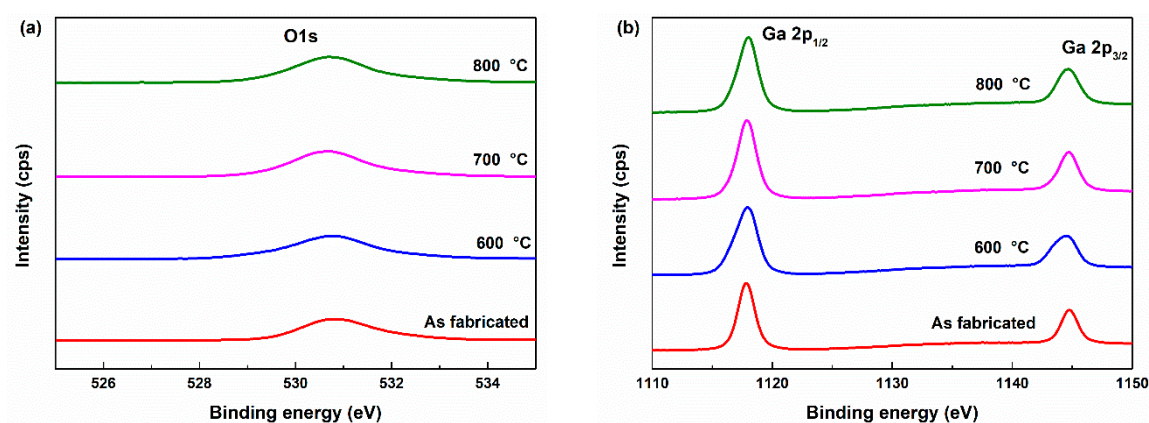


Figure 6. Cont.

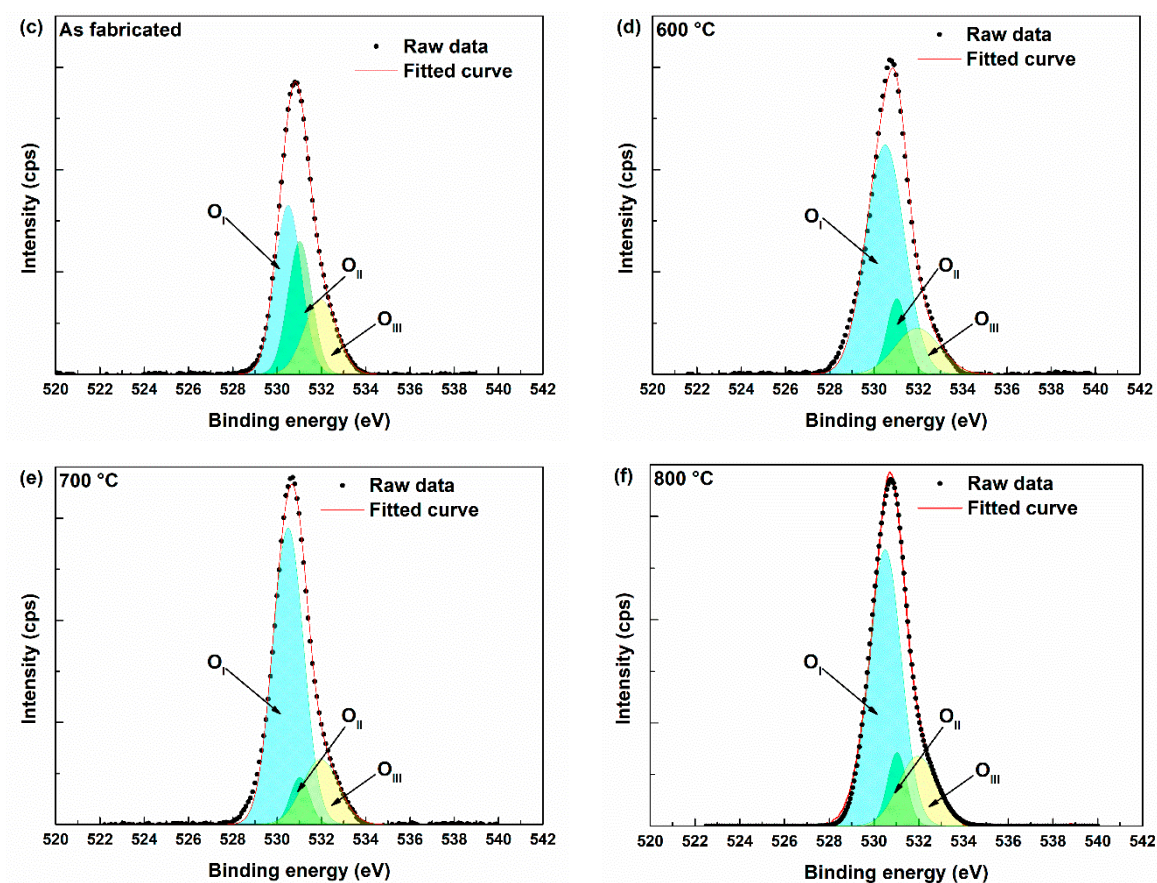


Figure 6. XPS results (a) O 1s peak, (b) Ga 2p peak, peak deconvolution of (c) As fabricated sample, (d) 600 °C annealed sample, (e) 700 °C annealed sample, (f) 800 °C annealed sample.

The oxygen vacancy concentration at surface was evaluated using the area ratio $O_I/(O_I + O_{II})$ obtained from the O 1s fitting results, as summarized in Table 4. This ratio serves as an indicator of the degree of lattice oxygen preservation versus vacancy-related oxygen species. With increasing annealing temperature V_O concentration, drop from 41.54% in the as-fabricated sample to 9.05% after 700 °C annealing (Table 4). Notably, the 800 °C sample shows a slight increase in V_O content (13.60%), possibly due to re-evaporation or the onset of defect formation from high temperature.

Table 4. Summary of O/Ga Stoichiometry and V_O Fraction from XPS.

Condition	O/Ga Ratio	$O_I/(f_I + O_{II})$ [%]
Undoped Ga_2O_3	2.04	51.47
As fabricated	1.90	41.54
600 °C	1.78	14.37
700 °C	1.78	9.05
800 °C	1.85	13.60

3.2. Electrical Properties

Ga_2O_3 exhibits properties suitable for its use as an n-type material due to two main reasons. First, the 4s orbital of Ga has a wide spatial distribution, and its wave functions overlap with each other, providing a facile pathway for electron conduction. Second, because of the contraction of the Ga 3d orbitals, the Ga 4s orbitals have lower energies than those of other pre-transition metals. This results in a relatively high electron affinity, which

facilitates n-type doping [37]. When Si is used as a dopant, Ga^{3+} ions are replaced by Si^{4+} ions, contributing to n-type conductivity [38].

Figure 7 shows the electrical properties of the Ga_2O_3 thin films determined from Hall effect measurements. All samples exhibited carrier concentrations above 10^{22} cm^{-3} , mobilities exceeding $50 \text{ cm}^2/\text{V}\cdot\text{s}$, and resistivities on the order of $10^{-6} \Omega\cdot\text{cm}$, demonstrating their high conductivity. Comparable values have also been reported in previous studies on sputtered Sn-doped Ga_2O_3 thin films at similar doping concentrations [39]. Figure 7a shows the carrier concentration as a function of the $\text{Ar}:\text{O}_2$ ratio and post-annealing temperature. Several n-type oxide semiconductors obtain free electrons through oxygen vacancies [40,41]. However, in the case of gallium oxide, a comparison between the measured carrier concentration and the oxygen vacancy ratio calculated from XPS revealed that an increase in oxygen vacancy concentration does not correspond to an increase in carrier concentration. This different behavior of Ga_2O_3 toward oxygen vacancies is attributed to the fact that, in Ga_2O_3 , oxygen vacancies act as deep donors rather than shallow donors. Numerous previous studies have reported that oxygen vacancies in Ga_2O_3 indeed exist as deep donors [25,42–44]. The carrier concentration exhibits a trend similar to that of the strain shown in Figure 3d. For samples post-annealed at 600°C and 700°C , the carrier concentration decreases with increasing O_2 flow rate, with the most significant decrease occurring from 0 sccm to 1 sccm. Samples post-annealed at 800°C maintain relatively low carrier concentrations, mirroring the trend seen in Figure 3d. It is considered that the strain relaxation or modification caused by thermal annealing may have affected the carrier concentration, possibly by altering the band structure, defect formation energy, or trap state distribution within the film. Figure 7b shows the variation in mobility as a function of the O_2 flow ratio and post-annealing temperature. The characteristics of oxide semiconductors can be inferred from the mobility data. In the case of non-oxide semiconductors such as Si, the sp^3 orbital characteristics result in increased disorder and significantly reduced mobility when the material is amorphous. However, for Ga_2O_3 , the Ga 4s orbital, with its wide distribution and overlapping wave functions, provides a facile pathway for electrons that are not significantly affected by direction [45]. Therefore, Ga_2O_3 does not exhibit a substantial decrease in mobility. All fabricated samples exhibit high mobility above $50 \text{ cm}^2/\text{Vs}$. Among the samples annealed in Ar, the one treated at 800°C exhibited the highest mobility, which is likely due to the most significant crack mitigation. Figure 7c,d shows the variation in resistivity and sheet resistance as a function of the O_2 flow ratio and post-annealing temperature. All the samples exhibited resistivities ranging from 9×10^{-7} to $1.3 \times 10^{-6} \Omega\cdot\text{cm}$ and sheet resistance ranging from 0.05247 to $0.05412 \Omega/\text{sq}$. Although some changes in the resistivity and sheet resistance were observed depending on the conditions, the differences were not statistically significant.

Table 5 shows electrical properties with different post-annealing temperatures.

Table 5. Electrical properties with different post-annealing temperatures.

Post-Annealing Temperature	Carrier Concentration [cm^{-3}]	Mobility [$\text{cm}^2/\text{V}\cdot\text{s}$]	Resistivity [$\Omega\cdot\text{cm}$]	Sheet Resistance [Ω/sq]
As fabricated	9.46×10^{22}	68.0	9.73×10^{-7}	0.05407
600°C	1.02×10^{23}	69.9	9.45×10^{-7}	0.05247
700°C	1.03×10^{23}	55.0	1.10×10^{-6}	0.05372
800°C	6.04×10^{22}	115.4	1.08×10^{-6}	0.05412

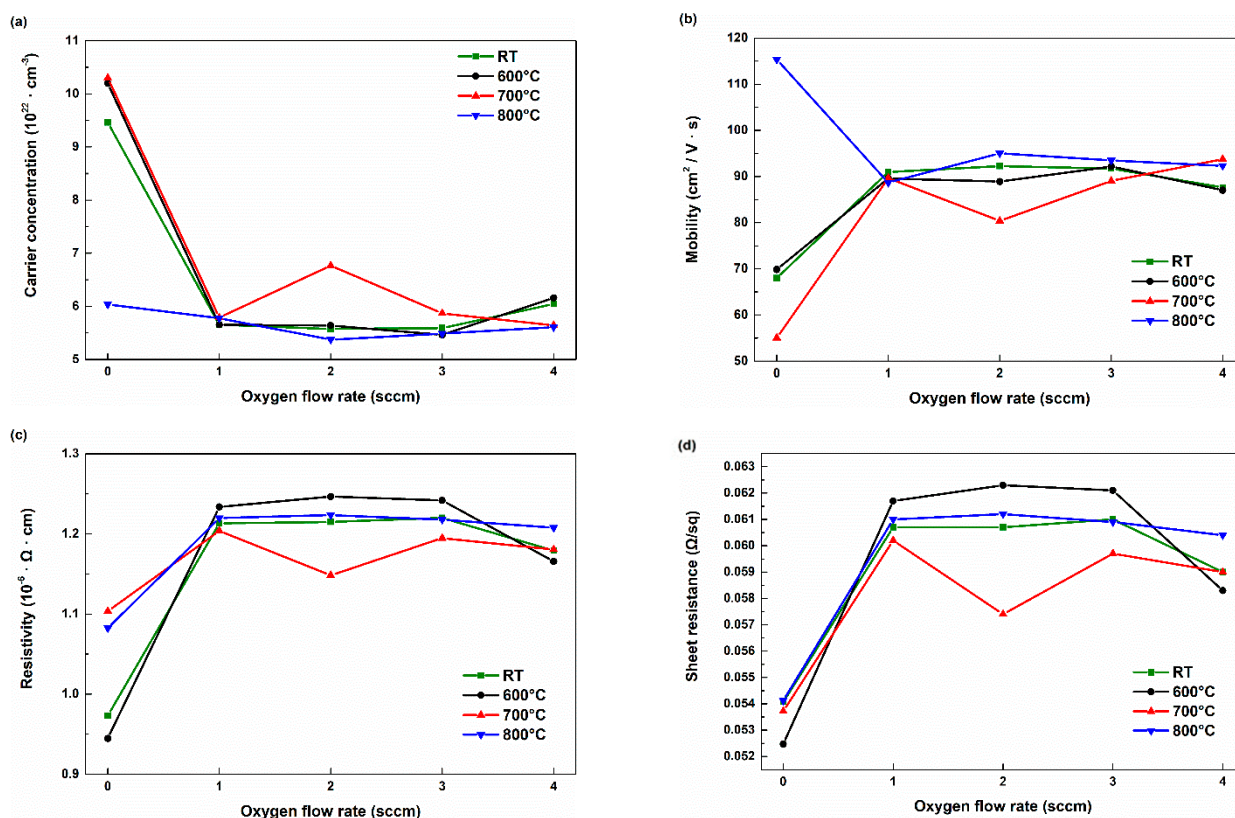


Figure 7. Hall effect measurement results. (a) Carrier concentration, (b) mobility, (c) resistivity, (d) sheet resistance.

4. Conclusions

In this study, we investigated the effects of deposition conditions on the structural and electrical properties of β -Ga₂O₃ thin films. Our experimental results demonstrated that both the post-annealing temperature and the O₂ flow rate during deposition significantly influence the properties of β -Ga₂O₃ thin films. The X-ray diffraction (XRD) analysis revealed that β -Ga₂O₃ films have distinct β -phase peaks at post-annealing temperatures of 600 °C and above, confirming the formation of the β -Ga₂O₃ phase. Structural characterization showed that increasing the O₂ flow rate shifts the XRD peaks and changes in the strain, indicating variations in the crystallinity of the film and the density of oxygen vacancies. The oxygen vacancy ratio at the surface of the film was determined by XPS, while changes in crack formation with post-annealing temperature were examined using SEM. At 700 and 800 °C, the films exhibited relatively higher crystallinity. Under Ar-only annealing, increasing the post-anneal temperature reduced the (apparent) strain and alleviated crack formation. The results confirm that excellent electrical properties can be achieved by optimizing the deposition parameters. The β -Ga₂O₃ thin films exhibited carrier concentrations exceeding $5 \times 10^{22} \text{ cm}^{-3}$, mobilities in the range of 50 to 115 cm^2 / Vs , and resistivities around $1 \times 10^{-6} \Omega \cdot \text{cm}$. The observed electrical characteristics are closely linked to the structural characteristics of the films. The study underscores the interplay between the structural features and electrical performance of β -Ga₂O₃ thin films. Overall, our findings highlight that the properties of β -Ga₂O₃ thin films can be engineered through careful control of sputtering and post-treatment conditions. The ability to fine-tune these properties is crucial for the development of the next generation of high-performance electronic and optoelectronic devices. In future work, we plan to investigate the effect of varying Si doping concentrations on the electrical and structural properties of β -Ga₂O₃ thin films. While this study focused on the general trends in electrical properties as influenced by

annealing and doping conditions, the underlying physical mechanisms—such as carrier scattering and trap-related effects—remain to be fully understood. Future work will involve temperature-dependent measurements and advanced spectroscopic analysis to provide a deeper understanding of these mechanisms. Comparison table of Ga₂O₃ films (Table 6).

Table 6. Comparison table of Ga₂O₃.

Ref.	Deposition	Substrate	Doping Con. of Target	n (cm ^{−3})	μ (cm ² /V·s)	ρ (Ω·cm)
[46]	PLD	Fe-doped β-Ga ₂ O ₃ , Al ₂ O ₃	Si, 1 wt%	1.74 × 10 ²⁰	26.5	1.37 × 10 ^{−3}
[47]	PLD	Al ₂ O ₃	Si, 0.01 to 0.3 wt%	1 × 10 ¹⁵ –2.4 × 10 ²⁰	0.02–0.04	0.76 to 2.13 × 10 ⁴
[48]	Sputtering	Glass	Cu, below 3 at%	1 × 10 ²¹ –5 × 10 ²²	0.38–9.7	3.52 × 10 ^{−3} –6 × 10 ^{−6}
[49]	Sputtering	Quartz	Undoped	3.077 × 10 ¹³	19.01	1.07 × 10 ⁴
This work	Sputtering	Si	Si, 1 wt%	6.04 × 10 ²² –1.03 × 10 ²³	55–115.4	9.45 × 10 ^{−7} –1.1 × 10 ^{−6}

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