

Article

The Impact of the Amorphous-to-Crystalline Transition on the Upconversion Luminescence in Er³⁺-Doped Ga₂O₃ Thin Films

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Abstract: Gallium oxide (Ga₂O₃) is an emerging wide bandgap semiconductor promising a wide range of important applications. However, mass production of high-quality crystalline Ga₂O₃ still suffers from limitations associated with poor reproducibility and low efficiency. Low-temperature-grown amorphous Ga₂O₃ demonstrates comparable performance with its crystalline counterparts. Lanthanide Er³⁺-doped Ga₂O₃ (Ga₂O₃: Er) possesses great potential for developing light-emitting devices, photodetectors, solid-state lasers, and optical waveguides. The host circumstance can exert a crystal field around the lanthanide dopants and strongly influence their photoluminescence properties. Here, we present a systematical study of the impact of amorphous-to-crystalline transition on the upconversion photoluminescence in Ga₂O₃: Er thin films. Through controlling the growth temperature of Ga₂O₃: Er films, the upconversion luminescence of crystalline Ga₂O₃: Er thin film is strongly enhanced over 100 times that of the amorphous Ga₂O₃: Er thin film. Moreover, the variation of photoluminescence reflects the amorphous-to-crystalline transformation of the Ga₂O₃: Er thin films. These results will aid further designs of favorable optoelectronic devices integrated with lanthanide-doped Ga₂O₃ thin films.

Keywords: amorphous-to-crystalline transition; upconversion luminescence; wide bandgap semiconductor; thin films; lanthanide doped phosphors



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1. Introduction

Silicon has been a primary material in the semiconductor industry since the 1950s. Silicon-based technologies have been a main driving force behind the rapid advancement of human society. With the development of electronic and optoelectronic technologies, it also faces limits in a growing number of emerging applications. Conventional semiconductors like silicon exhibit a bandgap within the range of 0.6–1.5 eV, which is not fit for applications requiring high voltage capabilities. Wide bandgap semiconductors are an intriguing class of semiconductor materials that are distinguished by larger bandgaps. Wide bandgap semiconductors can sustain much higher voltages, frequencies, and working temperatures than conventional semiconductors. Thus, wide bandgap semiconductors are gaining significant attention for power electronics endowed with greater energy efficiency [1,2]. Gallium oxide (Ga₂O₃), as an emerging wide bandgap semiconductor, has sparked intense interest over recent years for its superior chemical and thermal stability, radiation hardness, and notably high breakdown electric field (~8 MV/cm) [3,4]. Owing to its unique electric and optical characteristics, Ga₂O₃ has been explored as a workhorse for applications such

as solar-blind ultraviolet photodetectors, power electronic devices, etc. [5,6]. Given the ultrawide bandgap, Ga_2O_3 is regarded as an ideal host material for incorporating lanthanide elements [7]. Lanthanide ions, referred to as magic dopants, are highly effective in promoting the electrical properties of the host materials [8–10]; moreover, lanthanide dopants can introduce an additional luminescent functionality to the semiconductor [11]. The most stable oxidation state of lanthanide elements is the trivalent state (Ln^{3+}), which exhibits efficient upconversion and downconversion luminescence. Upconversion means the nonlinear optical processes by successive absorption of two or more photons via the intermediate energy levels. Upconversion luminescence can convert near-infrared photons to ultraviolet (UV) and visible photons. Ln^{3+} ions demonstrate unique luminescent characteristics, including abundant energy levels, sharp emission bandwidths, large Stokes shift, and high photoresistance, making them an important class of phosphor materials [12,13]. Ga_2O_3 has a bandgap up to 4.4–4.8 eV corresponding to the wavelength of 258–281 nm, which matches the solar-blind UVC zone induced by the ozonosphere's absorption of solar radiation below 280 nm. Moreover, Ga_2O_3 is optically transparent to visible and near-infrared light, allowing it to be utilized as a host for various lanthanide dopant ions in various optical devices.

Among lanthanide elements, Er^{3+} -doped phosphors exhibit strong visible and near-infrared emissions from the intra-4f shell transition of Er^{3+} ions, enabling diverse applications, including full-color displays, solid lasers, biological imaging, optical storage, and optical communications [14–16]. Erbium-doped glass and crystals are especially used for solid-state lasers, fiber lasers, and amplifiers. For example, the light emission from the $^4\text{I}_{13/2}$ manifold to the ground-state manifold $^4\text{I}_{15/2}$ is extensively used for laser transitions. A solid-state laser based on erbium ions was first realized using Er^{3+} -doped YAG crystals. In recent years, Ln^{3+} -doped gallium garnets have been used as solid-state lasers. As just mentioned above, Ga_2O_3 can be a host material for incorporating lanthanide elements and is optically transparent for most dopant ions. Ln^{3+} -doped Ga_2O_3 could be promising materials for lasers and amplifiers. So far, Er^{3+} -doped Ga_2O_3 has been developed for electroluminescence (EL) devices, light-emitting devices (LEDs), solid lasers, optical waveguides, and photodetectors [17–21]. In terms of fundamental research and real applications, luminescent thin films are of great importance from both scientific and technological aspects [22]. To date, Er^{3+} -doped Ga_2O_3 thin films have been fabricated using pulsed laser deposition (PLD) and radio frequency magnetron sputtering methods on various substrates. Ga_2O_3 has five different polymorphs, including corundum (α), monoclinic (β), defective spinel (γ), cubic (δ), and orthorhombic (ϵ) structures. Among these different phases of crystalline Ga_2O_3 , β - Ga_2O_3 of the orthorhombic β -gallia structure represents the most stable form under ambient conditions and has been extensively investigated for various applications [23,24]. However, the fabrication of single-crystalline β - Ga_2O_3 with perfect stoichiometry remains a daunting challenge. High-quality crystalline β - Ga_2O_3 with perfect stoichiometry is a prerequisite to survive superior breakdown fields, but it faces difficulties in achieving heteroepitaxy and alleviating the defects and dislocations during high-temperature growth. Recently, low-temperature deposited amorphous Ga_2O_3 (a- Ga_2O_3) has demonstrated comparable optoelectronic properties with its crystalline counterparts [25]. Moreover, low-temperature fabricated a- Ga_2O_3 is compatible with mature CMOS technologies and favorable for flexible devices. It has been proven that a- Ga_2O_3 is qualified for high-performance X-ray and solar-blind photon detectors [26,27]. Previous studies have shown that the electronic properties of different polymorphs and amorphous Ga_2O_3 are very different. To date, there is no investigation on the luminescent properties of lanthanide-doped a- Ga_2O_3 . The host circumstance can exert a crystal field around the lanthanide dopants and strongly influence their photoluminescence properties. According to the Judd-Ofelt theory, local symmetry around the doped lanthanide ions can render their radiative transition probabilities [28]. Previous studies have shown that growth temperature has a huge impact on the crystallinity of Ga_2O_3 [29].

Herein, we present an experimental investigation on the crystallinity of the Ga₂O₃ host impact on the upconversion photoluminescence (PL) from Ga₂O₃: Er thin films. Ga₂O₃: Er thin films were grown using PLD methods under different temperatures. PLD technology has the advantage of stoichiometric deposition, which is notable for depositing complex oxides. The amorphous-to-crystalline transformation of the Ga₂O₃: Er thin films can be rendered by controlling the growth temperature. Along with the X-ray diffraction (XRD) characterization, the variation of PL clearly reflects the amorphous-to-crystalline transformation of the Ga₂O₃: Er thin films. We demonstrate that a strong enhancement of the upconversion emissions is associated with the improved crystallinity of Ga₂O₃ by increasing the growth temperature. These results identify the interplay between the crystallinity and the dopant lanthanide luminescence, which paves the way for developing lanthanide-doped Ga₂O₃-based optoelectronic devices.

2. Experimental Section

Target Synthesis: Er³⁺-doped Ga₂O₃ targets were synthesized via a high-temperature solid-state reaction method, which is famous for its scalability and simplicity, using reagent grade Ga₂O₃ (Aladdin) and Er₂O₃ (Aladdin) powders as the raw materials. Er³⁺-doped Ga₂O₃ powders with different doping concentrations of 0.5 at%, 0.75 at%, 1 at%, 1.25 at%, and 1.5 at% were weighted with the designed stoichiometric quantities. The weighted Ga₂O₃ and Er₂O₃ powders were thoroughly ball-milled in an agate mortar with alcohol for 3 h. And then, the obtained slurry was dried at 80 °C in an alumina crucible for 12 h in a muffle furnace under air. After that, the dried compounds were put into an alumina crucible and calcinated at 1300 °C in air for 8 h. The resulting powders were granulated with 10 wt% polyvinyl alcohol binder, pressed into disk-shaped pellets of 1-inch diameter and 3 mm thickness, and sintered at 1450 °C in air for 4 h. High temperature induces defects in Ga₂O₃, and some Er³⁺ ions are substituted at Ga³⁺ site in the Ga₂O₃ host. The as-prepared pellets were used as the PLD targets.

Thin Film Fabrication: Ga₂O₃: Er thin films were deposited on (0001) sapphire substrates by PLD using a 248 nm KrF excimer laser (COMPex205, Coherent, Santa Clara, CA, USA). Before deposition, sapphire substrates were ultrasonically cleaned in acetone solvents for 30 s, rinsed in deionized water for 30 s, and then blown dry with nitrogen gas. Then, the substrates were inserted into the growth chamber. A KrF excimer laser was used with a fluence of 1.5 J cm⁻² and a repetition frequency of 5 Hz. The distance between target and substrate was set at 50 mm, and the basic vacuum was below 1 × 10⁻⁴ Pa, controlled by a turbo molecular pump. During the growth, the oxygen pressure was controlled to be 1 Pa. These films were achieved by setting different substrate temperatures, including room temperature (RT), 300 °C, 400 °C, and 500 °C. The temperature increasing rate was set to 20 °C/min. After the deposition of an hour, except for RT-grown sample, other samples were slowly cooled down to room temperature.

Characterization and Luminescence Measurement: The X-ray diffraction (XRD) measurement was carried out with the D8 Advanced X-ray Diffractometer (Bruker, Bremen, Germany) under CuKα1 (λ = 1.5406 Å) radiation. Scanning electron microscopy (SEM) was measured using a field emission scanning electron microscope (Sigma 500, Zeiss, München, Germany). The UV/Vis absorption spectra were recorded with the U-3900 UV/Vis Spectrophotometer (Hitachi, Tokyo, Japan). The photoluminescence spectrum was measured by an Acton SpectraPro 300i Spectrophotometer (Princeton Instruments, Trenton, NJ, USA). All upconversion spectra were excited by a 980 nm diode laser. The spectrum ranges from 480 to 700 nm. Transient decay curves were measured with a Tektronix DPO3034 oscilloscope combined with photomultiplier tube (H11902-04, Hamamatsu, Shizuoka, Japan). All measurements were carried out at room temperature.

3. Results and Discussion

The primary advantage of the PLD technology is the stoichiometric transfer of the target material to the grown film on the substrate. In order to filter out the most efficient

luminescent composition, we prepared Er^{3+} -doped Ga_2O_3 powders with different doping concentrations from 0.5% to 1.5%. Figure 1a shows the XRD θ - 2θ patterns of Er^{3+} -doped Ga_2O_3 powders with different doping concentrations. The characteristic diffraction peaks correspond to the monoclinic (β) phase of Ga_2O_3 . The results imply that Er^{3+} ions are efficiently doped into the Ga_2O_3 host. Besides the diffraction peaks of Ga_2O_3 , a small amount of secondary-phase $\text{Er}_3\text{Ga}_5\text{O}_{12}$ (ErGG) appears along with the Ga_2O_3 phase. Note that the (420) peak at 32.6° of the secondary ErGG phase increases along with the concentration of Er^{3+} dopant. Compared with pure Ga_2O_3 shown in Figure 1a, there are minor left shifts of the diffraction peak (111) for the Er^{3+} -doped Ga_2O_3 samples, as seen in the inset of Figure 1a. Considering that the ionic radius ($0.881 \text{ \AA}$) of the Er^{3+} ion is larger than that of the Ga^{3+} ion ($0.62 \text{ \AA}$), it means that the lattice constant of Er^{3+} -doped Ga_2O_3 expands, contributing to the diffraction peaks shift to lower angles. Figure 1b shows the upconversion PL spectra of Ga_2O_3 powders doped with different Er^{3+} ion concentrations. The typical upconversion spectra of Er^{3+} consist of strong green and red emission bands. Green emissions located at 524 nm and 552 nm correspond to $^2\text{H}_{11/2}/^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ transitions, respectively. The red emission band between 645 nm and 678 nm is ascribed to the $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$ transition of the Er^{3+} ion. We also did a control experiment in non-doped Ga_2O_3 powders. No light emission can be observed in non-doped Ga_2O_3 powders under 980 nm laser excitation. Previous studies have shown that ErGG can emit green luminescence. But the amount of ErGG phase in our case is quite small, which has little influence on the measured luminescence properties. It can be found that the emission intensity increases monotonically from 0.5% to 1.25% Er^{3+} doping concentration, reaching its maximum value at 1.25%. And then, the PL intensity decreases when the doping concentration arrives at 1.5%. Such concentration quenching is associated with the competition between the radiative and non-radiative transitions of the luminescent centers.

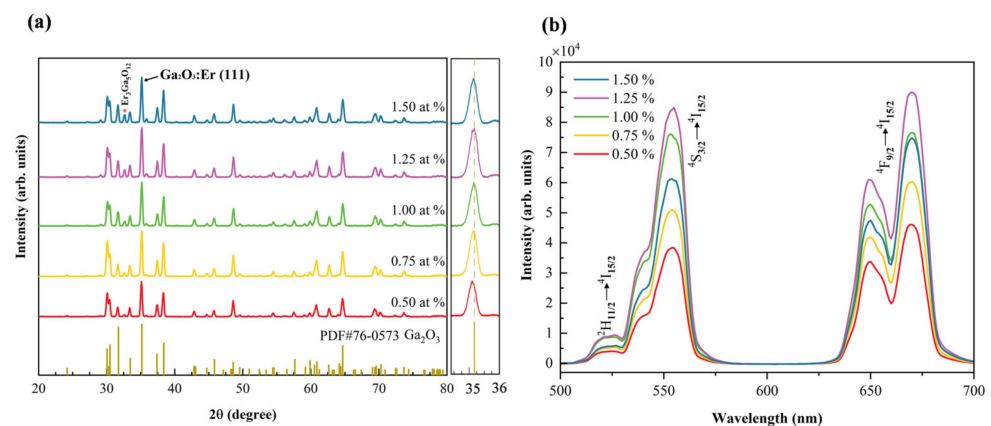


Figure 1. (a) XRD θ - 2θ scan of Er^{3+} -doped Ga_2O_3 targets with different concentrations. Dashed lines represent the positions of the characteristic bulk Ga_2O_3 : Er (111) reflections. (b) PL spectra of the Ga_2O_3 : Er targets with different Er doping concentrations at room temperature.

The upconversion emission of Ga_2O_3 : Er arrives at the peak at 1.25% Er^{3+} doping concentration. But the XRD results show that the ErGG secondary phase increases along with the doping concentration increases. Taking both structural and luminescent factors into account, the Ga_2O_3 :1%Er target was chosen for growing Ga_2O_3 : Er thin films as well as for investigating the effect of amorphous-to-crystalline transition on the luminescent properties. It is well known that the growth temperature has a great influence on the crystallinity of Ga_2O_3 during the PLD growth. Figure 2a shows the XRD patterns of the PLD-grown Ga_2O_3 : Er thin films on (0001) sapphire substrate at RT, 300°C , 400°C , and 500°C . The diffraction peaks at 20.4° , 41.7° , and 64.5° correspond to the (0003), (0006), and (0009) planes of sapphire, respectively, while the peak at 38° corresponds to the $k\beta$ diffraction of the (0006) planes of sapphire. Besides the diffraction peaks of the sapphire substrate, no diffraction peaks corresponding to β - Ga_2O_3 can be found in the

XRD patterns of Ga_2O_3 : Er thin films grown at substrate temperatures of RT, 300 °C, and 400 °C. Thus, the low-temperature-grown Ga_2O_3 : Er films tend to be an amorphous phase. As the temperature increases, three diffraction peaks located at 30.1°, 38.2°, and 58.9° corresponding to β - Ga_2O_3 (400), (402), and ($\bar{6}$ 03) are observed at a substrate temperature of 500 °C, indicating the formation of a crystalline β - Ga_2O_3 phase. Figure 2b illustrates the cross-sectional SEM image of the Ga_2O_3 : Er thin film grown at 500 °C. The Ga_2O_3 : Er thin film grown at high temperatures exhibits a smooth and flat surface with a uniform thickness of 480 nm. Figure 2c, d show the surface morphology images of the Ga_2O_3 : Er thin films grown at RT and 500 °C. The RT-grown Ga_2O_3 : Er thin film exhibits an amorphous phase. And the Ga_2O_3 : Er thin film grown at 500 °C turns into a crystalline phase.

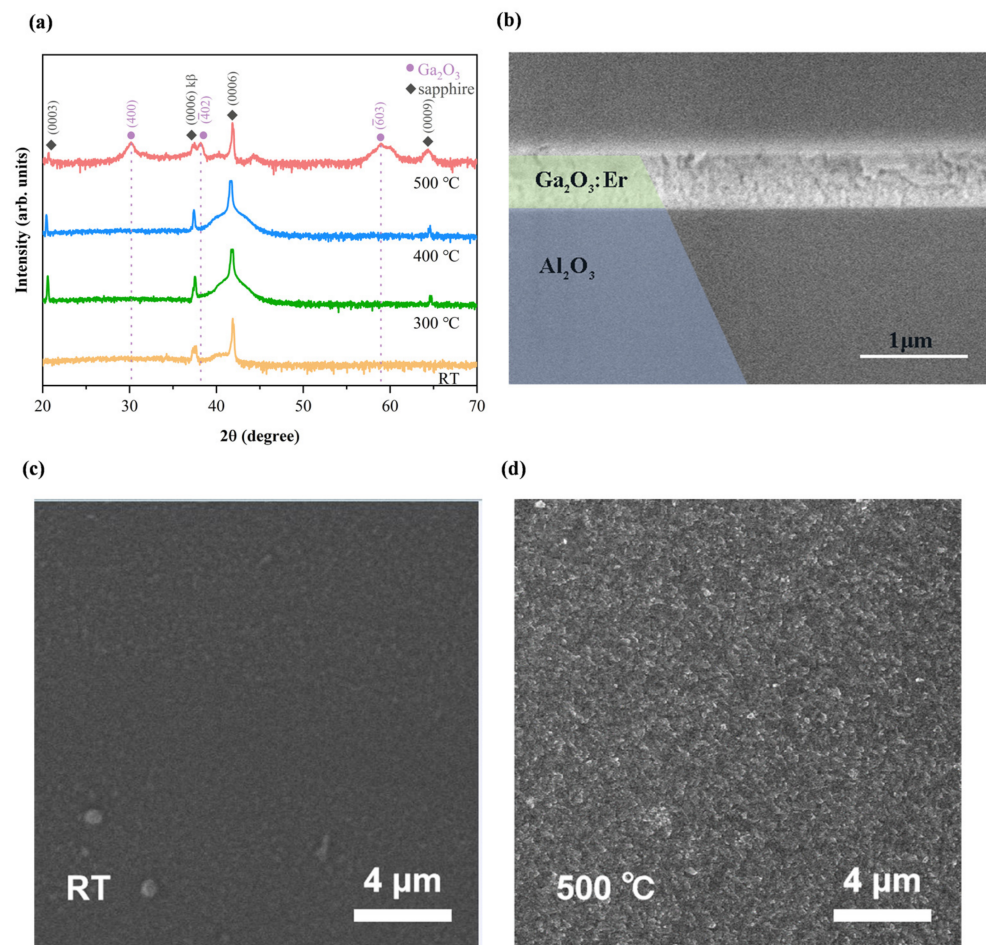


Figure 2. (a) XRD θ - 2θ scan of Ga_2O_3 : Er thin films grown at different temperatures. (b) The cross-sectional SEM image of the Ga_2O_3 : Er thin film grown at 500 °C. (c) The surface SEM image of the Ga_2O_3 : Er thin film grown at RT. (d) The surface SEM image of the Ga_2O_3 : Er thin film grown at 500 °C.

Figure 3a shows the normalized ultraviolet–visible (UV–Vis) transmittance spectra of Ga_2O_3 : Er thin films. All Ga_2O_3 : Er thin films exhibit a sharp intrinsic transmittance edge at the wavelength of around 280 nm. The broad absorption band before 300 nm corresponds to the valence-to-conduction band transition of Ga_2O_3 . There are also some absorption bands centered at about 460 nm, 532 nm, and 660 nm derived from Figure 3a, which can be ascribed to the 4f-4f transition of Er^{3+} ions as well as the defects absorption. The bandgap E_g can be calculated by extrapolating the linear region of the plot $(\alpha h\nu)^2$ versus $h\nu$, as shown in Figure 3b, where h is Planck's constant, α is the linear absorption coefficient, and ν is the transition frequency of the incident photon. It can be found that E_g increases from 4.10 eV to 4.22 eV for Ga_2O_3 : Er thin films grown from RT to 500 °C, respectively. As the growth temperature increases, the E_g gradually increases, though it remains smaller than

that of pristine Ga_2O_3 . Several factors modulate E_g , including defect formation, lattice strain, structural disorder, oxygen ratio, and bandgap renormalization. Previous studies have shown that both increased structural disorder and the excess oxygen of the films raise E_g in undoped Ga_2O_3 thin films. Higher temperatures also cause more lattice strain due to the thermal mismatch between the film and the substrate, resulting in a bandgap expansion due to the deformation potential. Moreover, the bandgap renormalization effect, arising from the electrostatic interaction between the added electrons and the conduction band edge, also enhances the bandgap with the carrier concentration [30]. Thus, the observed bandgap enhancement with temperature reflects a complex interplay of these factors, which merits further investigation.

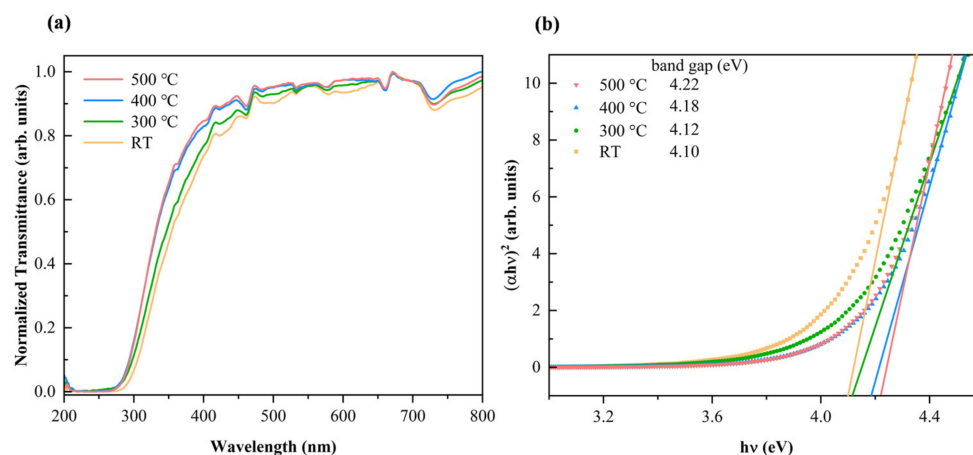


Figure 3. (a) Transmittance spectra of Ga_2O_3 : Er thin films grown at different substrate temperatures. (b) The square of optical coefficient versus photon energy of Ga_2O_3 : Er thin films, revealing the bandgap of different samples.

Figure 4a shows the upconversion PL spectra from Ga_2O_3 : Er thin films grown under different temperatures (RT, 300 °C, 400 °C, and 500 °C). The PL spectra of the Ga_2O_3 : Er films were investigated under 980 nm laser diode excitation. It was found that the RT-grown Ga_2O_3 : Er thin film showed almost no PL emission, suggesting that an amorphous environment hinders dopant Er^{3+} ions from emitting light within an amorphous host. In other upconversion spectra, similar to the spectra of Ga_2O_3 : Er targets, green emissions located at 525 nm and 549 nm arise from $^2\text{H}_{11/2}/^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ transitions of Er^{3+} ions, while the red emission around 659 nm corresponds to $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$ transition of Er^{3+} ions. As seen from Figure 4a, the emission intensities increase sharply with growing temperature. Notably, the emission intensity of the Ga_2O_3 : Er film grown at 500 °C was significantly enhanced compared to that of the Ga_2O_3 : Er film grown at 300 °C, at a ratio of 127 times. This means that growth at higher temperatures improves the crystallinity, which in turn enhances the upconversion emission. Several factors contribute to the enhanced crystallinity at higher temperatures, including the increased adatoms/nuclei mobility on the substrate surface, which enables the formation of larger and more ordered crystallites. The transferred material from the target forms complex plasmas, which may be droplets rather than atomic/molecular particles/clusters. Nevertheless, the droplets can still undergo partial evaporation and diffusion on the substrate, especially at higher temperatures. This process can increase the nucleation density and reduce the surface roughness, leading to better crystalline quality. Since the 4f-4f transitions of free lanthanide ions are Laporte forbidden, the incorporation of uneven components of the crystal field when doping into a crystalline lattice allows for intra-configurational transitions to occur [31]. Thus, compared with an amorphous Ga_2O_3 host, the high-temperature-grown crystalline Ga_2O_3 : Er film exerts a larger crystal field around the doped Er^{3+} ions, contributing to the observed enhanced upconversion emissions [32]. The observed enhanced upconversion emission in the high-temperature-grown crystalline Ga_2O_3 : Er film is similar to the previously reported

enhanced photodetection characteristics of annealed Ga_2O_3 nanorods and thin films [33,34]. The improved crystal structure has been reported in the annealed sample. The average crystallite size of the annealed samples was found to be larger than that of the as-deposited samples. In our case, the high-temperature-grown crystalline Ga_2O_3 : Er films exhibit stable host lattices around dopant Er^{3+} ions. A larger crystal field gives rise to enhanced upconversion emissions [35].

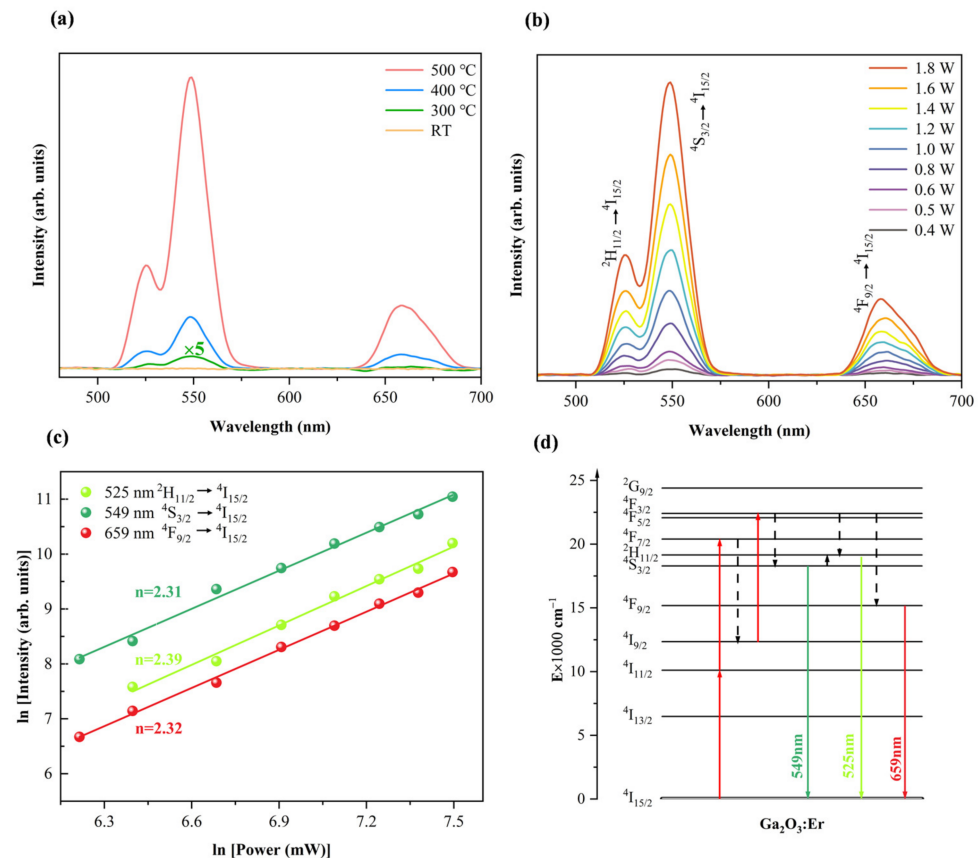


Figure 4. (a) The upconversion PL spectra of Ga_2O_3 : Er thin films grown at different temperatures. (b) The upconversion emission spectra of the Ga_2O_3 : Er thin film grown at 500 °C under 980 nm laser excitation with different power densities. (c) Double-logarithmic plot of upconversion emission intensity at 525 nm, 549 nm, and 659 nm, respectively. (d) The energy scheme of Er^{3+} ions and the mechanism to produce the upconversion spectra.

To further explore the upconversion processes in Ga_2O_3 : Er thin films, the pump power dependence of the upconversion emissions was investigated, as shown in Figure 4b. Under 980 nm laser excitation, the upconversion emission intensity for each emission band (I) depends nonlinearly on the excitation laser power (P). It can be typically written that the upconversion emission intensity (I) depended on the incident pump power (P) according to the formula $I \propto P^n$, where n is the number of near-infrared photons. Thus, the number of photons can be calculated from the relationship between upconversion emission intensity and incident pump power. We give double-logarithmic plots of emission intensity variation for three peaks (525 nm, 549 nm, and 659 nm) with excitation power from 0.4 to 1.8 W, which are recorded based on Ga_2O_3 : Er film grown at 500 °C. The double-logarithmic plots with slopes indicate the number of photons that are required to populate the emitting states. Within the power range, the slope values of green and red bands can be obtained as 2.39 (525 nm), 2.31 (549 nm), and 2.32 (659 nm) by a linear fit, respectively (Figure 4c). This indicates that all these upconversion emissions belong to two-photon processes in Er^{3+} ions under 980 nm excitation. Figure 4d illustrates the possible up-conversion processes through the energy level diagram of Er^{3+} ions. Upon 980 nm laser excitation, Er^{3+} ions

can populate into the $^4F_{7/2}$ energy level via the excited state absorption or energy transfer processes. These processes involve two 980 nm photons. Subsequently, the Er^{3+} ions relax nonradiatively to the $^2H_{11/2}$ and $^4S_{3/2}$ energy levels by the multiphoton relaxation, contributing to the green emissions at 525 nm and 549 nm, respectively. Some electrons of excited Er^{3+} ions can further relax to the $^4F_{9/2}$ level, which gives rise to the red emissions at 659 nm.

In the end, we investigated the fluorescence lifetime of $\text{Ga}_2\text{O}_3:\text{Er}$ thin film grown at 500 °C. Figure 5a shows that the lifetime at 549 nm of $\text{Ga}_2\text{O}_3:\text{Er}$ target is about 173 μs , which is in the same order as reported Er^{3+} -doped oxide bulks, while as shown in Figure 5b, the lifetime of $\text{Ga}_2\text{O}_3:\text{Er}$ thin film grown at 500 °C has greatly reduced to $\sim 4.3 \mu\text{s}$. The strongly reduced fluorescence lifetime observed in $\text{Ga}_2\text{O}_3:\text{Er}$ thin film may arise from the appearance of abundant defects in the as-grown thin film. These defects introduce non-radiative relax channels, resulting in the reduced lifetime of the $\text{Ga}_2\text{O}_3:\text{Er}$ thin film.

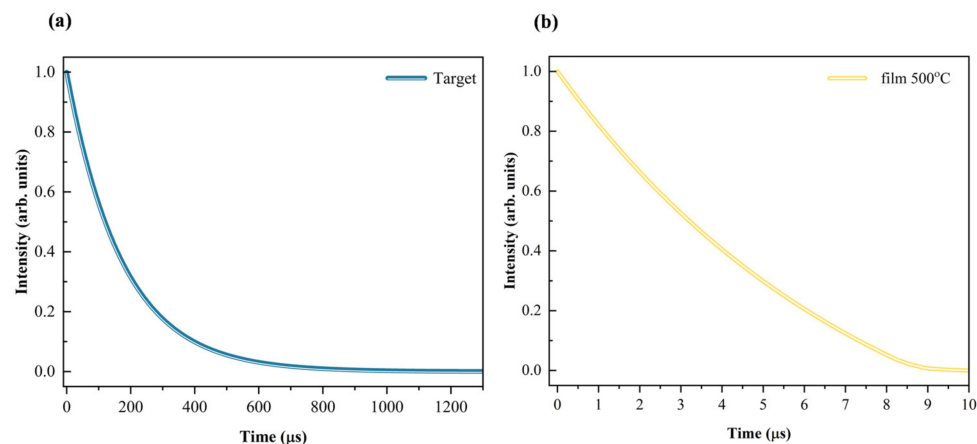


Figure 5. (a) PL decay curve of the $\text{Ga}_2\text{O}_3:\text{Er}$ target with 1% concentration. (b) PL decay curve of the $\text{Ga}_2\text{O}_3:\text{Er}$ thin film grown on sapphire substrate at 500 °C.

4. Conclusions

In summary, we have investigated the amorphous-to-crystalline transition's impact on the upconversion properties of lanthanide Er^{3+} -doped Ga_2O_3 thin films. XRD results show that Er^{3+} ions can be effectively incorporated into the Ga_2O_3 host lattice. A small amount of secondary-phase ErGG can coexist with $\text{Ga}_2\text{O}_3:\text{Er}$. The upconversion emission of $\text{Ga}_2\text{O}_3:\text{Er}$ samples arrives at a maximum value at 1.25% doping concentration; further increasing the doping concentration could induce PL concentration quenching, which is associated with the competition between the radiative and non-radiative transitions of the luminescent centers. $\text{Ga}_2\text{O}_3:\text{Er}$ thin films were grown on (0001) sapphire substrate at different temperatures by PLD methods. With increasing growth temperature, $\text{Ga}_2\text{O}_3:\text{Er}$ thin films undergo the amorphous-to-crystalline transformation, and the $\beta\text{-Ga}_2\text{O}_3$ phase gradually dominates in the $\text{Ga}_2\text{O}_3:\text{Er}$ films. There is almost no upconversion emission observed in amorphous $\text{Ga}_2\text{O}_3:\text{Er}$ thin film. The PL intensity of the $\beta\text{-Ga}_2\text{O}_3$ phase at 500 °C is strongly enhanced. The observed remarkable PL enhancement with increasing growth temperature is associated with the improved crystallinity of the as-grown Ga_2O_3 thin films. The appearance of abundant defects gives rise to the strongly reduced lifetime in the $\text{Ga}_2\text{O}_3:\text{Er}$ thin film. The interplay between the upconversion emission and the crystallization condition provides a feasible method to explore the intrinsic crystallinity state of Ga_2O_3 . Our finding offers more insight into developing lanthanide-doped wide bandgap semiconductor Ga_2O_3 materials, which hold promise for multi-functional optoelectronic applications.

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