# Influences of Sn doping on the properties of Ga<sub>2</sub>O<sub>3</sub> thin film and ultraviolet photodetector fabricated via sol-gel and spin-coating methods

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Gallium oxide (Ga<sub>2</sub>O<sub>3</sub>) has been considered as a promising ultrawide bandgap material, renowned for its exceptional breakdown electric field and stability. External doping serves as an effective method for modulating the characteristics of Ga<sub>2</sub>O<sub>3</sub> materials and devices. In this study, Sn-doped Ga<sub>2</sub>O<sub>3</sub> thin films and photodetectors were fabricated by sol-gel and spin-coating techniques. To minimize the usage of stabilizer and solvent, 1,2-propanediamine was incorporated into the precursor solution as a stabilizing agent. The impact of varying Sn doping concentrations on Ga<sub>2</sub>O<sub>3</sub> thin films and detectors was investigated. The experimental findings confirm the successful formation of Sn-doped Ga<sub>2</sub>O<sub>3</sub>, wherein the external doping of Sn enhances the crystallinity of Ga<sub>2</sub>O<sub>3</sub>. Furthermore, an optimal Sn doping concentration contributes to improved film compactness. Elements O, Ga, and Sn are uniformly distributed within the Sn-doped Ga<sub>2</sub>O<sub>3</sub>. Sn doping leads to a reduction in the direct band gap, an augmentation in photoluminescence intensity, and a suppression of dark current in the detectors. However, this improvement in certain aspects comes at the cost of a reduced response speed.

(Received January 8, 2025; Accepted May 5, 2025)

Keywords: Gallium oxide, Sn doping, Sol-gel, Photodetector

# 1. Introduction

In recent years, gallium oxide  $(Ga_2O_3)$  has attracted great attention as an emerging ultrawide bandgap material with potential applications in optoelectronics and power electronics.  $Ga_2O_3$  possesses an ultrawide bandgap of approximately 4.9 eV, a breakdown electric field of 8 MV/cm, a transmittance exceeding 95% in the visible light region, and notable thermal and chemical stability [1-4]. Various techniques have been employed for the fabrication of  $Ga_2O_3$  thin films, including magnetron sputtering [5], molecular beam epitaxy [6], chemical vapor deposition [7], pulsed laser deposition [8], atomic layer deposition [9], and solution-based methods [10,11]. Numerous studies have reported the design, fabrication, and characterization of  $Ga_2O_3$ -based devices, such as photodetector [12,13], Schottky barrier diode (SBD) [14], heterojunction [15], field effect transistor (FET) [16], and high electron mobility transistor (HEMT) [17]. Notably,

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https://doi.org/10.15251/DJNB.2025.202.465

Ga<sub>2</sub>O<sub>3</sub> ultraviolet detectors are of particular interest due to their sensitivity to solar-blind ultraviolet (UV) light within the 200~280 nm wavelength range that is absorbed by the ozone layer and is virtually absent at the Earth's surface [18-21]. Consequently, Ga<sub>2</sub>O<sub>3</sub> solar-blind UV detectors hold immense promise for diverse military and civilian applications.

Ga<sub>2</sub>O<sub>3</sub> solar-blind UV detector demands high light responsivity and rapid response speed. However, during the growth of Ga<sub>2</sub>O<sub>3</sub>, defects frequently form, which act as carrier recombination centers, leading to increased dark current and reduced responsivity in the detector [22,23]. Consequently, external doping is commonly employed, with various elements such as Si, Sn, Mg, Zn, Fe, In, Ti, Al, Bi, or N being used to modify the electrical properties of Ga<sub>2</sub>O<sub>3</sub> thin films [24-28]. Among these dopants, Sn<sup>4+</sup> doping acts as a donor impurity that replaces Ga sites, increasing electron concentration and reducing internal defects. While Sn doping has been shown to significantly improve the responsivity of solar-blind UV detectors, it can also slow down the response speed [29-32]. Vorobyeva et al. and Kim et al. have grown Sn-doped  $Ga_2O_3$  samples using aqueous co-precipitation and mist chemical vapor deposition methods, respectively [31,32]. In another study [33], Sn-doped  $Ga_2O_3$  thin films were deposited by the sol-gel method, with isopropyl alcohol tin and isopropyl alcohol gallium as the Sn and Ga sources, respectively. The solvents used were 2-methoxyethanol and ethanolamine as stabilizers. The results indicated that Sn doping led to a transformation in crystalline growth, resulting in an oriented texture and the formation of needle-like grains. The Sn-doped metal-semiconductor-metal (MSM) detectors demonstrated a high on/off ratio. However, the dark current of 0.76 nA was still considered high, and the use of isopropyl alcohol tin as a precursor can be costly. In previous study, we employed a novel precursor solution for Ga<sub>2</sub>O<sub>3</sub>, incorporating 1,2-propanediamine as a stabilizer to minimize the usage of both stabilizer and solvent [34]. We determined that nitrogen was the optimal atmosphere for annealing spin-coated Ga<sub>2</sub>O<sub>3</sub> precursor thin film. Nevertheless, the responsivity of the Ga<sub>2</sub>O<sub>3</sub> detector remained relatively modest.

In the present work, we introduced Sn dopants into the  $Ga_2O_3$  precursor solution to achieve Sn doping within the  $Ga_2O_3$  lattice. Anhydrous tin tetrachloride (SnCl<sub>4</sub>) was used as the Sn source, and 1,2-propanediamine served as the stabilizer. Sn-doped  $Ga_2O_3$  thin films were fabricated through spin-coating of the  $Ga_2O_3$  solution followed by post-annealing. We investigated the effects of Sn doping concentration on the structures, morphologies, and optical properties of  $Ga_2O_3$  thin films, as well as on the performance of  $Ga_2O_3$  solar-blind UV detectors.

## 2. Experimental

The precursor solution's gallium and tin sources were gallium nitrate hydrate  $(Ga(NO_3)_3 \cdot xH_2O)$  and anhydrous tin tetrachloride  $(SnCl_4)$ , respectively. These chemicals were dissolved in 9 mL of ethylene glycol monomethyl ether  $(C_3H_8O_2)$  solvent. The specific masses of gallium nitrate hydrate and volumes of anhydrous tin tetrachloride employed in the experiment are detailed in Table 1. The molar concentration of metal ions in the precursor solution was maintained at 2.0 mol/L. The Sn/(Sn+Ga) atomic ratios in the solutions were adjusted to 7.2%, 14.4%, 21.6%, and 28.8%. Additionally, a solution lacking anhydrous tin tetrachloride was prepared to investigate the impact of Sn-doping. These solutions were stirred at a uniform temperature of 50 °C for approximately 5 min to ensure complete dissolution, resulting in a transparent mixture.

Subsequently, 0.9 mL of 1,2-propanediamine ( $C_3H_{10}N_2$ ), serving as a stabilizer, was incorporated, and the mixture was continuously stirred at 50 °C for a duration of 2 h. Following filtration through a needle filter, both the undoped and Sn-doped gallium oxide precursor solutions were obtained, exhibiting a yellow and transparent appearance.

Sn/(Ga+Sn) (at. %)	Gallium nitrate hydrate (g)	Anhydrous tin tetrachloride (µl)		
0.0	5.1148	0		
7.2	4.7465	180		
14.4	4.3783	360		
21.6	4.0100	540		
28.8	3.6417	720		

 Table 1. Mass of gallium nitrate hydrate and volume of anhydrous tin tetrachloride
 for various Sn doping concentrations.

The substrates for the gallium oxide thin films were circular quartz glass with a thickness of 1 mm and a diameter of 15 mm. The precursor solutions were then utilized to deposit thin films onto the cleaned quartz glass substrates via the spin-coating technique. The spin-coating process was initially conducted at a lower speed of 1000 rpm for 10 s, followed by an increased speed of 3000 rpm for 20 s. Immediately after spin-coating, the samples were dried at 200 °C for 2 min. To ensure a uniform film, the spin-coating and drying processes were repeated five times, with the final drying period extended to 15 min.

The precursor thin film further underwent an annealing process in a tubular furnace under a nitrogen atmosphere. The annealing process began with a heating rate of 10 °C/min. As the temperature approached 1090 °C, the heating rate was significantly reduced to 1 °C/min for the subsequent increase to 1100 °C. Annealing was conducted at 1100 °C for 1 h. During the entire annealing process, any tail gas generated was absorbed by sodium hydroxide solution. Following the annealing process, the samples were allowed to cool naturally within the furnace.

The gallium oxide solar-blind detector adopts a MSM structure. To create the electrodes, a sputtering process was employed, specifically targeting the surface of gallium oxide with Au. A stainless steel mask was used during the sputtering process to ensure precise patterning of the electrodes. The sputtering time was controlled at 500 s to achieve an electrode thickness of approximately 100 nm. The Au finger electrodes were designed with six pairs of fingers, each pair consisting of two electrodes facing each other. Each finger electrode had a length of 5000  $\mu$ m, a width of 200  $\mu$ m, and a spacing between adjacent fingers of 300  $\mu$ m.

The structures of the thin films were investigated by X-ray diffractometry (D/MAX-Ultima IV, Rigaku) and Raman spectroscopy (LabRAM HR Evolution, HORIBA Jobin Yvon). Both the surface and cross-sectional morphologies of films were observed using field emission scanning electron microscopy (FE-SEM, SU8010, Hitachi). The atomic composition and distribution within the thin films were determined using energy dispersive spectroscopy (EDS, SDD3030, IXRF), which was integrated within the FE-SEM system. The transmittance and reflectance of the films were measured by UV-visible-near infrared spectrophotometer (UV-3600

Plus, Shimadzu). The photoluminescence (PL) properties of the films were characterized using a fluorescence photometer (Fluorolog-3, Horiba Instruments Incorporated) with the excitation wavelength, slit width and incident angle of 240 nm, 4 nm and 60°, respectively. 280 nm and 370 nm filters were employed to eliminate any diffraction from the excitation light. Finally, the detection performance of the Ga<sub>2</sub>O<sub>3</sub> detectors was assessed by measuring their current–voltage (I-V) and current–time (I-t) characteristic curves using a digital source meter (2635B, Keithley) and a probe station (SM4, Semishare). The detectors were illuminated with an ultraviolet light emitting diode ( $\lambda = 254$  nm) and a 405 nm laser to evaluate their response to different wavelengths of light.

## 3. Results and discussion

#### 3.1. The phase structures of Ga<sub>2</sub>O<sub>3</sub> thin films

X-ray diffraction (XRD) patterns of thin films with varying Sn concentrations are shown in Figure 1. The distinct peaks observed around 20° correspond to the quartz substrates, while the remaining peaks align with the standard XRD peaks of Ga<sub>2</sub>O<sub>3</sub>. Specifically, diffraction peaks originating from the (400), (-202), (111), (401), (-311), (-312), (-510), and (-712) planes of Ga<sub>2</sub>O<sub>3</sub> are evident in the XRD patterns, indicating the successful formation of polycrystalline Ga<sub>2</sub>O<sub>3</sub> structure within the thin films. Notably, the diffraction peaks attributed to the (400) and (-202) planes are prominent. When the Sn doping concentration is 14.4% or lower, the (-202) peak is intensified, accompanied by a suppression of the Ga<sub>2</sub>O<sub>3</sub> film growth along the (400) plane. This phenomenon is attributed to the impurity compensation caused by the presence of the coexistence of Sn<sup>2+</sup> and Sn<sup>4+</sup> ions in the solution.



Fig. 1. XRD patterns of Ga<sub>2</sub>O<sub>3</sub> with varying Sn doping concentrations.

The crystalline size (D) of Ga<sub>2</sub>O<sub>3</sub> is determined using the Debye-Scherrer formula:

$$D = \frac{k\lambda}{B\cos\theta} \tag{1}$$

where k = 0.89,  $\lambda$  represents the X-ray wavelength, B is the full width at half maximum of the

diffraction peak, and  $\theta$  represents the Bragg angle. Figure 2 illustrates the calculated crystalline size of Ga<sub>2</sub>O<sub>3</sub> with Sn doping concentration. The undoped Ga<sub>2</sub>O<sub>3</sub> has a crystallite size of 40.6 nm. All Sn-doped Ga<sub>2</sub>O<sub>3</sub> samples exhibit an enlargement in their crystallite sizes, indicating that Sn doping is conducive to the crystalline growth of Ga<sub>2</sub>O<sub>3</sub>. The film with a 14.4% doping concentration exhibits the highest crystallinity. However, when the doping concentration exceeds 14.4%, an excessive amount of Sn dopants may introduce additional crystal defects, adversely affecting the grain growth of Ga<sub>2</sub>O<sub>3</sub>.



Fig. 2. Average crystalline size of Ga<sub>2</sub>O<sub>3</sub> against Sn doping concentration.

Figure 3 depicts the Raman spectra of all prepared samples. The Raman spectrum of the quartz glass substrate, devoid of Ga<sub>2</sub>O<sub>3</sub>, was also characterized to differentiate the Raman peaks' origins.



Fig. 3. Raman spectra of  $Ga_2O_3$  with varying Sn doping concentrations.

As illustrated in Figure 3, compared to the quartz glass substrate spectrum, the Raman peaks at 167, 199, 346, and 415 cm<sup>-1</sup> are attributed to the prepared thin films. The Raman peaks at 167 and 199 cm<sup>-1</sup> are associated with the stretching and translational motion of the tetrahedral-octahedral chain, thereby eliciting molecular chain vibrations specific to  $Ga_2O_3$ . The

peaks at 346 and 415 cm<sup>-1</sup> stem from the bending of  $GaO_6$  structure within  $Ga_2O_3$  and the symmetric stretching of the  $GaO_2$  octahedral structure. All prepared samples display these four Raman peaks. The Raman peak intensity at 199 cm<sup>-1</sup> is more pronounced in the undoped thin film compared to all Sn-doped films. This discrepancy can be explained by the substitution of Ga atoms by Sn atoms within the  $GaO_4$  tetrahedra or  $GaO_2$  octahedral structures, which impedes the vibrational dynamic of the tetrahedral-octahedral chains. In contrast, the disparities observed in the intensities of other Raman peaks between undoped and Sn-doped  $Ga_2O_3$  are minimal.

## 3.2. The morphologies of Ga<sub>2</sub>O<sub>3</sub> thin films

Figure 4 presents the surface SEM images of  $Ga_2O_3$  thin films. The surfaces of both undoped  $Ga_2O_3$  thin films and those doped with 7.2% Sn exhibit a grainy appearance, characterized by inhomogeneous particle sizes and the presence of inter-particle voids. The average particle size is approximately 100 nm in these films. As the Sn doping concentration increases, there is a tendency for particle aggregation on the thin film surface, resulting in a less pronounced grainy texture. This trend is accompanied by an improvement in the compactness of the film's surface. In Figure 4(e), at a Sn doping concentration of 28.8%, the inter-particle voids are nearly absent, and the thin film surface achieves the highest compactness, although the particle size decreases.



Fig. 4. Surface SEM images of (a) undoped  $Ga_2O_3$  and Sn-doped  $Ga_2O_3$  with doping concentrations of (b) 7.2%, (c) 14.4%, (d) 21.6%, and (e) 28.8%.

# 3.3. The compositions of Ga<sub>2</sub>O<sub>3</sub> thin films

Table 2 presents the atomic ratios of Ga, O, and Sn, while Figure 5 illustrates the EDS mapping results for all samples. A monotonic increase in the Sn/(Sn+Ga) atomic ratio is observed in the Ga<sub>2</sub>O<sub>3</sub> thin films as the Sn doping concentration in the precursor solution is increased.

Table 2. Energy dispersive spectroscopy results for Ga<sub>2</sub>O<sub>3</sub> thin films doped with different Sn concentrations.

Doping concentration (at. %)	O (at. %)	Ga (at. %)	Sn (at. %)	Sn/(Ga+Sn) (at. %)
0.0	66.19	33.81	0	0
7.2	83.23	16.47	0.30	1.7
14.4	65.31	33.54	1.15	3.32
21.6	78.30	20.75	0.95	4.38
28.8	73.35	23.78	2.87	10.77



Fig. 5. EDS mapping results for Ga<sub>2</sub>O<sub>3</sub> with varying Sn doping concentrations.

However, the Sn/(Sn+Ga) ratio in the final thin films is significantly lower than in the precursor solution, attributed to the volatilization of anhydrous tin tetrachloride during precursor preparation process. Additionally, high-temperature annealing may contribute to a minor loss of Sn. Regarding the atomic ratio of O, it is observed to be higher than the stoichiometric ratio of 60%

expected for  $Ga_2O_3$  due to the contribution from the quartz glass substrate. The EDS mapping results in Figure 5 show a uniform distribution of O, Ga, and Sn elements in the doping samples.

## 3.4. The optical properties of Ga<sub>2</sub>O<sub>3</sub> thin films

Figure 6 displays the optical properties measured using a UV-visible-near infrared light spectrophotometer. Figure 6(a) shows the transmittance spectra of Ga<sub>2</sub>O<sub>3</sub>. Within the wavelength range of 200 to 500 nm, the thin film doped with 7.2% Sn exhibits the lowest transmittance, attributed to the presence of voids and pores as observed in the SEM images. For other Ga<sub>2</sub>O<sub>3</sub> thin films, transmittance in the visible light region exceeds 80%, while transmittance at 200 nm is below 5%. The reflectance spectra presented in Figure 6(b) indicate a decreasing reflectance of Ga<sub>2</sub>O<sub>3</sub> in the ultraviolet and blue light regions upon Sn-doping. The absorption coefficient ( $\alpha$ ) of the thin films is determined from the relation:

$$T = \left(1 - R\right)^2 e^{-\alpha d} \tag{2}$$

where T, R, and d are the transmittance, reflectance, and the thickness of thin film, respectively.



Fig. 6. Optical properties of  $Ga_2O_3$  with different Sn doping concentrations: (a) transmittance, (b) reflectance, and (c)  $(\alpha h v)^2$  versus hv plots.

Furthermore, in Figure 6(c), the optical band gap  $(E_g)$  of Ga<sub>2</sub>O<sub>3</sub> is estimated using the Tauc plot. The un-doped Ga<sub>2</sub>O<sub>3</sub> thin film exhibits an  $E_g$  value of 5.10 eV. Upon Sn-doping, the  $E_g$  values decrease to 4.76, 4.79, 4.81, and 4.71 eV for doping concentrations of 7.2%, 14.4%, 21.6%, and 28.8%, respectively. Sn acts as a donor impurity in Ga<sub>2</sub>O<sub>3</sub>, introducing additional electrons into the conduction band and occupying the energy levels at the conduction band bottom. This creates new electronic energy levels in the forbidden band, leading to a reduction in the band gap. The band gap is the narrowest for the sample with a 28.8% Sn doping concentration. Figure 7 presents the room-temperature PL spectra of  $Ga_2O_3$ . The PL peak positions remain largely consistent across the five fabricated thin films. The defect energy levels within the  $Ga_2O_3$  thin films can be derived from these PL peak positions, as previously outlined in [34]. Upon comparison with the undoped sample, the PL peak intensities are enhanced in the Sn-doped thin films. Among these, the sample with a 7.2% Sn doping concentration shows a relatively modest increase in PL intensity, which may be attributed to the increased pore defects in the thin film. The PL intensities of thin films with Sn doping concentrations of 14.4%, 21.6%, and 28.8% show substantial enhancement, attributed to the increased involvement of Sn-related radiative recombination within the  $Ga_2O_3$  thin films.



Fig. 7. Room-temperature PL spectra of Ga<sub>2</sub>O<sub>3</sub> with varying Sn doping concentrations.

### 3.5. The photoelectric properties of Ga<sub>2</sub>O<sub>3</sub> detectors

Figure 8 presents the I-V characteristic curves of Ga<sub>2</sub>O<sub>3</sub> photodetectors under both dark condition and illumination by UV light with a power density of 840  $\mu$ W/cm<sup>2</sup> and a wavelength of 254 nm. The analysis reveals that the slopes of the I-V curves under illumination are consistently higher than those measured under dark conditions, signifying the solar-blind response characteristic inherent in both un-doped and Sn-doped Ga<sub>2</sub>O<sub>3</sub> detectors. Notably, the detector with a Sn doping concentration of 21.6% exhibits the most significant difference between the slopes of the illuminated and dark I-V curves, indicating the most pronounced response to solar-blind ultraviolet light.



Fig. 8. Current–voltage characteristic curves of (a) undoped Ga<sub>2</sub>O<sub>3</sub> detectors and Sn-doped Ga<sub>2</sub>O<sub>3</sub> detectors with doping concentrations of (b) 7.2%, (c) 14.4%, (d) 21.6%, and (e) 28.8% measured under dark condition and upon irradiation with ultraviolet light ( $\lambda = 254$  nm).

Figure 9 shows the I-t curves of Ga<sub>2</sub>O<sub>3</sub> photodetector operating with a bias voltage of 5 V. Through sequential activation and deactivation of the UV light source, the light and dark currents of the Ga<sub>2</sub>O<sub>3</sub> detectors were measured over multiple cycles. The results indicate that Ga<sub>2</sub>O<sub>3</sub> detectors exhibit promising repeatability and stability in their response to UV light.



Fig. 9. Transient photoresponse (I–t curve) of (a) undoped  $Ga_2O_3$  detectors and Sn-doped  $Ga_2O_3$  detectors with doping concentrations of (b) 7.2%, (c) 14.4%, (d) 21.6%, and  $\notin$  28.8%, upon alternating on/off cycles of ultraviolet light ( $\lambda = 254$  nm).

To further investigate the effect of Sn doping, the performance parameters of  $Ga_2O_3$  photodetectors derived from Figures 8 and 9 were compiled and presented in Table 3. The responsivity  $(R_{\lambda})$  of the detector is calculated by:

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$$R_{\lambda} = \frac{I_{light} - I_{dark}}{P_{\lambda}S} \tag{3}$$

where  $I_{\text{light}}$ ,  $I_{\text{dark}}$ , S, and  $P_{\lambda}$  denote the light current, dark current, effective illuminated area of the device, power density of the incident light, respectively. The detectivity ( $D^*$ ) of detector is derived from the equation:

$$D^* = R_{\lambda} \sqrt{\frac{S}{2qI_{dark}}} \tag{4}$$

where q is the electron charge. Notably, both un-doped and Sn-doped Ga<sub>2</sub>O<sub>3</sub> detectors exhibit exceptionally low dark currents on the order of  $10^{-10}$  A or  $10^{-11}$  A, which is lower than the dark current reported in most literatures [22, 23, 32]. Furthermore, the Sn-doped Ga<sub>2</sub>O<sub>3</sub> detectors demonstrate an even lower dark current compared to their un-doped counterparts. When the Sn doping concentration reaches 7.2%, the Ga<sub>2</sub>O<sub>3</sub> detector shows the lowest  $I_{dark}$  value of  $2.74 \times 10^{-11}$  A. Under the irradiation of light with a wavelength of 254 nm and a power density of 840 µW/cm<sup>2</sup>, the detector with the Sn doping concentration of 21.6% shows the highest responsivity of  $1.52 \times 10^{-2}$  mA·W<sup>-1</sup> and detectivity of  $6.24 \times 10^6$  Jones, which are significant improvement to the un-doped Ga<sub>2</sub>O<sub>3</sub> detector. All Ga<sub>2</sub>O<sub>3</sub> detectors have fast response speeds. The un-doped Ga<sub>2</sub>O<sub>3</sub> detector are slower than those of un-doped detector due to the inhibition of defect states by Sn doping.

Doping concentration (at. %)	$I_{dark}\left(\mathrm{A} ight)$	$I_{light}/I_{dark}$	$R_{\lambda} (\mathrm{mA}\cdot\mathrm{W}^{-1})$	$D^*$ (Jone)	$t_r(\mathbf{s})$	$t_d(\mathbf{s})$
0.0	4.03×10 <sup>-11</sup>	2.54	4.06×10 <sup>-4</sup>	4.82×10 <sup>5</sup>	0.5409	0.3806
7.2	2.74×10 <sup>-11</sup>	1.79	1.41×10 <sup>-4</sup>	2.04×10 <sup>5</sup>	0.6211	0.4207
14.4	3.20×10 <sup>-11</sup>	1.94	1.97×10 <sup>-4</sup>	2.63×10 <sup>5</sup>	0.4808	1.5425
21.6	3.39×10 <sup>-10</sup>	7.87	1.52×10 <sup>-2</sup>	6.24×10 <sup>6</sup>	0.9468	1.3621
28.8	3.40×10 <sup>-11</sup>	2.06	2.35×10 <sup>-4</sup>	3.05×10 <sup>5</sup>	1.2620	0.6610

Table 3. Detection performance parameters of devices fabricated with different doping concentrations.

To investigate the photo response selectivity of the Ga<sub>2</sub>O<sub>3</sub> detectors, the *I*–*t* curves of all detectors were measured using violet light with a power density of 66770  $\mu$ W/cm<sup>2</sup> and a wavelength of 405 nm. The results, presented in Figure 10, were then compared to the *I*–*t* curves obtained under solar-blind UV light at 254 nm, as shown in Figure 9. All five Ga<sub>2</sub>O<sub>3</sub> detectors exhibit weak responses to the 405 nm violet light. Notably, the Ga<sub>2</sub>O<sub>3</sub> detector with a Sn doping concentration of 7.2% demonstrates an almost negligible response. The responsivities (*R*<sub>405 nm</sub>) of Ga<sub>2</sub>O<sub>3</sub> detectors with Sn doping concentrations of 0.0%, 14.4%, 21.6%, and 28.8% are found to be 9.86 × 10<sup>-8</sup>, 2.96 × 10<sup>-7</sup>, 7.23 × 10<sup>-6</sup>, and 1.15 × 10<sup>-7</sup> mA·W<sup>-1</sup>, respectively. Furthermore, the rejection ratios (*R*<sub>254 nm</sub>/*R*<sub>405 nm</sub>) for these detectors are calculated to be 4.12 × 10<sup>3</sup>, 6.66 × 10<sup>2</sup>, 2.10



 $\times$  10<sup>3</sup>, and 2.04  $\times$  10<sup>3</sup>, respectively. These findings indicate that the Ga<sub>2</sub>O<sub>3</sub> detectors exhibit strong selectivity towards UV light.

Fig. 10. Transient photoresponse (I–t curve) of (a) undoped Ga<sub>2</sub>O<sub>3</sub> detectors and Sn-doped Ga<sub>2</sub>O<sub>3</sub> detectors with doping concentrations of (b) 7.2%, (c) 14.4%, (d) 21.6%, and (e) 28.8%, upon alternating on/off cycles of ultraviolet light ( $\lambda = 405$  nm).

## 4. Conclusion

A novel precursor solution for the synthesis of Sn-doped  $Ga_2O_3$  was formulated, incorporating gallium nitrate hydrate as the gallium source, anhydrous tin tetrachloride as the tin source, ethylene glycol monomethyl ether as the solvent, and 1,2-propanediamine as the stabilizer. Sn-doped  $Ga_2O_3$  was subsequently deposited via spin-coating of the precursor solution followed by post-annealing. Metal-semiconductor-metal structure  $Ga_2O_3$  ultraviolet photodetectors were then constructed through sputtering gold finger electrodes onto the surface of  $Ga_2O_3$ . X-ray diffraction and Raman results confirmed the successful growth of Sn-doped  $Ga_2O_3$  thin films. The crystalline size of Sn-doped  $Ga_2O_3$  exceeded that of undoped  $Ga_2O_3$ . The Sn/(Sn+Ga) ratio in the  $Ga_2O_3$  thin film depended on the Sn ratio in the precursor solution.

The optical properties of Sn-doped  $Ga_2O_3$  exhibited low transmittances below 5% at 200 nm and high transmittances exceeding 80% in the visible light region. The optical band gaps were determined to be 5.10, 4.76, 4.79, 4.81, and 4.71 eV for Sn doping concentrations of 0.0%, 7.2%, 14.4%, 21.6%, and 28.8%, respectively. Photoluminescence intensities of the Sn-doped Ga<sub>2</sub>O<sub>3</sub> exhibited significant enhancement. Regarding device performance, the dark current of the Sn-doped Ga<sub>2</sub>O<sub>3</sub> detectors was on the order of  $10^{-11}$  A. The Ga<sub>2</sub>O<sub>3</sub> detector with a Sn doping concentration of 21.6% demonstrated the highest detectivity and responsivity, representing substantial improvements over undoped Ga<sub>2</sub>O<sub>3</sub> detectors.

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