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Research Paper

Properties of ZnO:Ga thin films deposited by RF magnetron sputtering under various RF power

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Abstract ZnO:Ga thin films were deposited by RF magnetron sputtering technique from ZnO (3 wt.% Ga_2O_3) target onto glass substrates under various RF power. The influence of RF power on the structural, electrical, and optical properties of ZnO:Ga thin films was investigated by X-ray diffraction, atomic force microscopy, Hall method and optical transmission spectroscopy. As the RF power increases from 50 to 110 W, the crystallinity is deteriorated, the root main square surface roughness is decreased and the sheet resistance is increased. The increase of sheet resistance is caused by decreasing carrier concentration due to interstitial Ga ion. All films are transparent up to 80% in the visible wavelength range and the adsorption edge is a red-shift with increasing RF power.

Keywords: ZnO:Ga, RF magnetron sputtering, RF power, interstitial Ga ion

I. Introduction

Zinc oxide (ZnO) transparent conducting films have excellent electrical and optical properties and find uses in liquid crystal displays, solar cells, various optoelectronic devices [1-3]. ZnO has drawn attention due to the abundance of raw materials, nontoxicity, and chemical stability [4]. The addition of Group III metal dopants, such as Al, In and Ga, increases the electrical conductivity and transparency of ZnO films [5]. Of these dopants, Ga has several advantages, in that it is less reactive and more resistant to oxidation than Al [6]. In addition, ZnO:Ga (GZO) have some merits due to their lower material cost, high transparency, and small lattice mismatch upon doping compared with that of ZnO:Al films [7]. Many techniques have been used to prepare ZnO:Ga thin films, such as magnetron sputtering, pulsed laser deposition (PLD), atomic layer deposition (ALD) [8-10]. Among these deposition methods, RF magnetron sputtering is used most often due to high deposition rates, process stability and reliability, and preparation of high-quality thin films on large-scale substrates [11]. In this paper, we investigated the structural, electrical, and optical properties of GZO films deposited under different RF power and discussed the RF power dependence of the resistivity of GZO thin films.

II. Experimental Procedure

ZnO:Ga thin films were deposited on glass by conventional RF magnetron sputtering with a 3-inch-diameter target consisting of Ga_2O_3 and ZnO with a weight ratio of 0.3:0.97. The base pressure of the chamber was maintained at a pressure below $2.0\times10^{-}$ Torr. Ar gas of 40 sccm was used as a reaction gas for thin film deposition and the process pressure was maintained at 7 mTorr. The RF power was set at 50, 80, and 110 W, and the experiment was conducted at RT. The detailed deposition conditions are shown in Table 1.

The crystallinity of the deposited GZO films was examined by X-ray diffraction (XRD, D/MAXIIIA) using CuKα radiation. Atomic force microscopy (AFM, PUCOTECH) was performed to measure the surface morphology. The electrical resistivity of the films was obtained using a Hall method (HMS-3000). The optical transmittance was analyzed using a UV/Vis-NIR spectrophotometer (V-670).

Table 1. Deposition conditions of GZO thin films deposited at various RF power.

Deposition	Target	ZnO:Ga (3wt%)
	Substrate	Glass(Corning #1737)
	RF Power [W]	50, 80, 110
	Ar flow rate [sccm]	40
	Base pressure [Torr]	2.0×10^{-6}
	Working pressure [Torr]	7.0×10^{-3}
	Deposition Temperature [°C]	RT
	Film thickness [nm]	200

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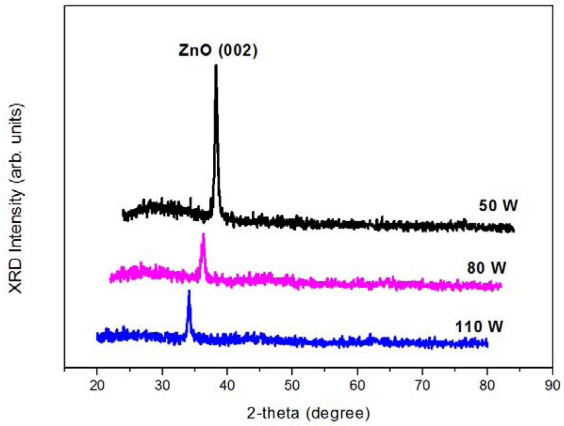

Figure 1. XRD patterns of GZO thin films deposited at different RF power.

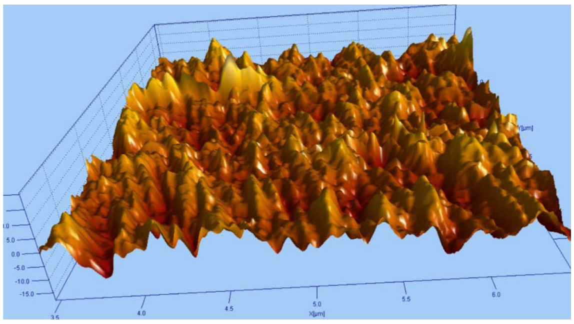

Figure 2. AFM image of GZO thin films deposited at 50 W.

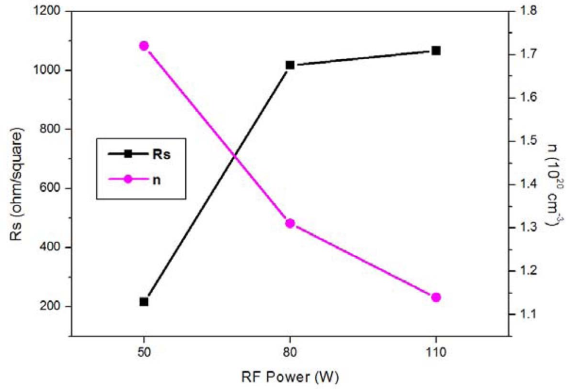

Figure 3. Electrical properties of GZO thin films deposited at different RF power.

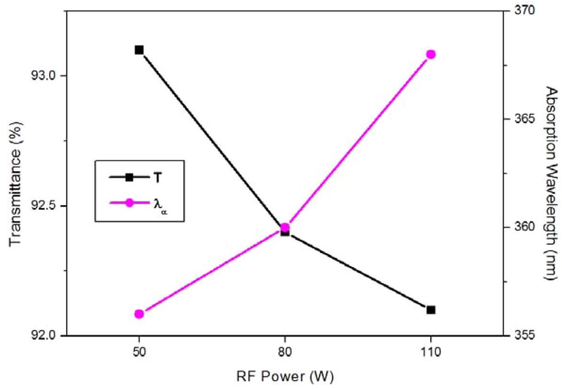

Figure 4. Transmittance spectra of GZO thin films deposited at various RF power.

III. Results and Discussions

Fig. 1 shows XRD patterns of the GZO films grown on glass substrates, measured with conventional theta - 2theta mode. Regardless of the RF power, the same peaks of the (002) plane were observed around 2theta=34.3°. Compared with the (002) peak position of bulk ZnO (34.42°), the diffraction angle of GZO thin films decreases, which results in the increase of interplanar spacing. This result indicated that all samples are under compressive stress. The strong peak of the (002) plane indicated that the crystalline of GZO film was the polycrystalline with a hexagonal structure and the c-axis of the GZO thin film grew vertically from the substrate. The intensity of (002) peak was decreased and the full width at half maximum (FWHM) value of (002) peaks was increased and as the RF power was increased from 50 to 110 W. These results indicate that the crystal quality of GZOl film is deteriorated with increasing the RF power.

Fig. 2 shows 2D surface images of the GZO thin films deposited at 50 W with a scan area of 4×4 μm^2 obtained by AFM measurements. It can also be seen that the roughness of the GZO thin films decreases from 3.9 nm to 3.6 nm as the RF power was raised from 50 to 110 W. The size of the grains became smaller and the number of grains increased with increasing RF power. It is found that the RMS surface roughness is dependent on RF power. The GZO thin film with a surface roughness of 10 nm is sufficient to meet the requirement for optical device applications.

Fig. 3 shows the variations in sheet resistance and carrier concentration as functions of RF power for the GZO films. As the RF power increased from 50 to 110 min, the sheet resistance increased from 217 ohm/sq to 1066 ohm/sq, whereas carrier concentration decreased from 1.7×10^{20} cm^{-3} to 1.1×10^{20} cm^{-3}. The increase in sheet resistance at higher RF power is due to the decrease in carrier concentration with increasing substrate temperature. Generally, the carrier concentration in GZO thin film is generated from the contribution of Ga ions on substitutional sites of Zn ions, as well as from oxygen vacancies [12]. The formations of Ga interstitial atoms and oxygen vacancies lead to deterioration of crystal quality in GZO thin film. In our case, the crystal quality in GZO thin film is degraded with increasing the RF power. Therefore, the main effect in reduction of carrier concentration is the contribution of Ga interstitial atom instead Ga ions on substitutional sites of Zn ions. We can conclude that the increase of sheet resistance of GZO film with increasing the RF power can be ascribed to the decrease in the carrier concentration caused by interstitial Ga ion.

Fig. 4 represents the optical transmittance results of GZO films deposited at various RF power. The average transmittance of samples in the visible range (400- 800 nm)

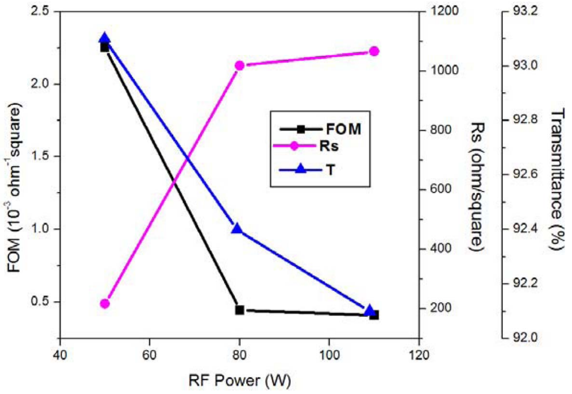

Figure 5. FOM of GZO thin films deposited at different RF power.

was higher than 80%, which is a sufficient value for transparent electrode application. The optical transmittance decreased as the RF power was increased. Also, it can be seen that the absorption edge for the GZO film is observed at 388 nm, and a red shift of the absorption edge occurs with increasing substrate temperature, indicating that the optical energy gap is decreased. This band gap narrowing can be explained using the Burstein-Moss (BM) effect. According to BM effect, the conduction band becomes significantly filled at high doping concentration and the lowest energy states are blocked which is responsible for the increase in the band gap of the films [13, 14]. Therefore, the red-shift of the absorption edge with RF power is mainly attributed to the BM effect, since the absorption edge of a degenerate semiconductor is shifted to longer wavelengths with decreasing carrier concentration [15]. The variation of electron concentration was discussed in above in the text.

Fig. 5 shows the figure of merits (FOM) suggested by Haacke [16] a function of the RF power. It is defined as

$$\Phi = \frac{T_a^{10}}{Rs}$$

where T_a is the average transmittance in the visible range and Rs the sheet resistance of the film. Expressions are derived to predict the transparent electrode properties of material from its fundamental electrical and optical constants. In our case, the FOM was strongly dependent on sheet resistance because the change of FOM shows the same trend with that of sheet resistance. It is possible to observe a decrease in the figure of merit with increasing the RF power. The maximum value of FOM was found when the RF power was 50 W.

IV. Conclusions

GZO thin films have been deposited by RF magnetron sputtering at RF power ranging between 50 and 110 W. The effect of RF power on the morphology, electrical and optical properties of the films was studied. The films are oriented along the c-axis of the hexagonal structure whatever the RF power. FWHM was found to increase as the RF power increases. Sheet resistance increases with RF power. The increment of sheet resistance was ascribed to the decrement of carrier concentration. GZO thin films were transparent up to 80% in the visible range. The RF power is a major factor to determine the structural, electrical and optical of GZO films.

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