Role of RF Magnetron Sputtering Power on Optical and Electrical Properties of ITO Films on Soda-Lime Glass Substrates

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Abstract. The optical and electrical properties of indium tin oxide (ITO) thin films grown on soda-lime glass substrates using a radio frequency (RF) magnetron sputtering technique were studied as a function of the sputtering RF power. Fixed 100 nm thickness of ITO films were deposited on the soda-lime glass substrates at 300 °C, using RF powers ranging between 50 to 150 W. The optical and electrical properties of the sputtered ITO films were characterized by Ultraviolet–Visible Spectroscopy (UV-Vis), Hall Effect Measurement and Atomic Force Microscope (AFM). Varying the substrate temperature and RF sputtering power affected surface roughness to decrease from 5.80, 4.59 and 3.46 nm while the resistivity also decreased from 18.73 x 10^{-4}, 6.484 x 10^{-4} and 2.421 x 10^{-4} Ω.cm. Deposition of ITO thin films on soda-lime glass substrates by RF magnetron sputtering at 300 °C substrate temperature contributed to 74 to 79 % of optical transmittance in the 450 nm region. Results of this study suggested that a better performance of both optical transparency and electrical conductivity of ITO films can be achieved by operating at high temperature substrate and high level of sputtering power.

1. Introduction

Indium tin oxide (ITO) thin films are ohmic transparent and conductive films that are extensively used for solar cells, photodetectors, photovoltaic devices, organic light-emitting devices and electroluminescent devices [1, 2]. It has extraordinary excellent electrical conductivity and optical transparency in the visible spectrum range. The optical and electrical properties of the transparent conductive film are significant part on the final device performance for light-emitting devices to increase the light collection, [1, 3].

The ITO thin films are often deposited by employing various practices such as pulsed laser deposition, sol–gel process [4], reactive thermal evaporation [5], chemical vapor deposition[6], spray pyrolysis [7] and magnetron sputtering [8, 9]. All of these deposition techniques have advantages and disadvantages, but RF magnetron sputtering has inherent and perceptible advantages such as good reproducibility, high quality film, and better uniformity over large area and greater adherence. However, various deposition parameters of RF magnetron sputtering play important role towards the properties of ITO films, such as RF power, substrate temperature, film thickness, target to substrate distance, target specification working gas pressure, chamber environment and post deposition treatment [9].

In this work, ITO thin films have been successfully deposited using RF magnetron sputtering at 300 °C onto soda-lime glass substrates. The effect and influence of RF magnetron sputtering power on the
surface morphology, optical transmittance, and electrical resistivity of ITO thin films were studied. Atomic force microscopy (AFM) was used for surface roughness and morphology of ITO films evaluation. Transmittance value was measured by a Cary Series UV-Vis-NIR spectrophotometer. Electrical properties were investigated using the Hall measurement. The final objective of this work is to get a better and a proper understanding of the ITO thin films with regard to surface morphology, electrical and optical properties to be applied as upper p-contact for blue nitride-based light-emitting diodes (LEDs).

2. Experimental
In the present study, the ITO films successfully grown on soda-lime glass substrates using RF magnetron sputtering by applying different sputtering powers. The ITO target (10 wt.% SnO2 and 90 % In2O3) with diameter 3 inch and thickness 3 mm was used in this work. The substrate and target were kept at a constant distance of 3.5 cm. Prior to deposition, the substrate was cleaned in acetone by ultrasonic cleaner before rinsed with deionized water for 10 min. After that the substrate was blown dry in nitrogen gas. Turbo-molecular pump was used to pump down the chamber pressure. The main purpose is to avoid residual atmosphere consequence on the composition of the deposited films. The deposition process was conducted at 300 °C substrate temperature. Base chamber pressure was applied approximately 2.02 x 10^{-5} mbar and working pressure was applied 6.46 x 10^{-3} mbar. Then, pure argon (99.99 %) was introduced in 10 sccm as sputtering gas with free oxygen content. The surface was undergone plasma cleaning at 80 W for 10 min prior the sputtering deposition process. In order to improve the uniformity of the film, the substrate holder continuously rotated during the deposition process. Samples were grown at constant temperature using RF powers of 50, 100 and 150 W until achieved 100 nm thickness. No post annealing was conducted after the sputtering deposition.

Atomic force microscope (AFM) Model Bruker Dimension Edge was used for surface roughness measurement. The sheet resistance was verified by hall-effect measurements while the optical transmittance measurement was performed using a UV–visible spectrophotometer (Cary Series UV-Vis-NIR). Wavelength for the optical transmittance measurement is in 300 - 800 nm range.

3. Result and Discussion
Intended for the application of ITO thin films as p-contact in blue nitride-based LED applications, the most important aspects are the value for electrical resistivity must be low while the optical transmittance must be high. In this current work, it is presented the finding of the effect of RF magnetron sputtering power at 300 °C substrate temperature on the surface morphology, electrical, and optical behaviors of ITO thin films.

3.1. Surface Morphology
The surface morphology of deposited ITO films obtained by AFM. Figure 1 shows the surface topography of ITO films grown with RF sputtering powers ranging 50 to 150 W at 300 °C of substrate temperature, respectively. The root means square roughness (RMS), Rq of ITO films was determined from 10.0 µm x 10.0 µm scan area. From Figure 2, the RMS surface roughness values of 5.80, 4.59 and 3.46 nm were obtained for RF sputtering power 50, 100 and 150 W, correspondingly. Clearly seen there is variation in the surface morphology of the samples when conducted at various RF sputtering powers. The results point to that increasing the sputtering power causes a decrease in the surface roughness of ITO films. Generally, surface roughness value is controlled by the process parameters for instance sputtering power, substrate temperature, working pressure and oxygen partial pressure. In this study, variation of sputtering powers and elevated substrate temperature cause the changes of surface roughness of the ITO films.

As shown in Figure 1, the morphology of ITO films exhibited uniformly distributed collar grains with fine crystallinity as the RF sputtering powers increased. Additional of kinetic energy is introduced into the deposited atoms by way of the increment of RF sputtering power. It leads to an increase in the migration mobility, which results in a decrease of surface roughness [10]. Previous reports by [11, 12]
also reported that, transparent films grown at elevated substrate temperature ensuing in more compact film. This is due to the sputtered particles have more energy to diffuse causing in the densification of the film during the deposition process.

Figure 1. Surface topography of deposited ITO films at various RF sputtering power (a) 50 W, (b) 100 W and (c) 150 W.

Figure 2. RMS roughness Rq of the deposited ITO films at various RF sputtering power ;50 W, 100 W and 150 W.
3.2. Electrical Properties

The difference and variation of electrical resistivity, carrier concentration, and hall mobility of the ITO films deposited at substrate temperature 300 °C as a function of RF sputtering power were demonstrated in Table 1. From Table 1, it is observed that resistivity reduces with the increment in the RF sputtering power from 50 W to 150 W. These values of resistivity are very encouraging for ITO application by way of transparent conductive thin films [12,13]. Also, there is increment in carrier concentration when RF sputtering power increases and reaching a maximum of $3.41 \times 10^{16} \text{cm}^{-3}$. Hall mobility also shown the increment, follows the trend of carrier concentration. With decreasing the surface roughness, the resistivity of ITO film decreases. In a reduced roughen surface, the mean free path length of electron’s scattering increasing, therefore decreasing the resistivity. Based on this result, it indicates that the surface roughness also acts as a significant part in electrical properties of the ITO films.

Figure 3 shows the sheet resistance at various of RF sputtering power. It shows that the sheet resistance drops promptly by way of the increment of RF sputtering power from 50 to 100 W. Further increment of RF sputtering power above 100 W, the sheet resistance slowly decreases. The lowest sheet resistance achieved is around $24.1 \Omega \text{sq}^{-1}$ for RF sputtering power 150 W. Decrement in sheet resistance as increment in RF power is credited as a result of lower collision of negative ions [13]. Reduction of the resistivity of ITO film is also owing to the increase in the crystallinity. The crystallinity of ITO films can be improved with substrate bias [14]. Ion bombardment on the substrates due to the sputtering power has effects similar to that of substrate bias [15].

In addition, the sheet resistance for deposited ITO film samples using RF sputtering power 50 and 100 W conducted at room temperature is also measured to compare with the samples deposited ITO film samples conducted at 300 °C. Figure 4 show the value of sheet resistance of deposited ITO film samples conducted at room temperature. From Figure 4 (a), the value of sheet resistance for 50 W is 9514 $\Omega \text{sq}^{-1}$ while for 100 W is 1048 $\Omega \text{sq}^{-1}$. The sheet resistance decreased rapidly when conducted at 300 °C compared conducted at room temperature. It can be stated clearly that by conducting ITO film deposition at elevated temperature caused the value of sheet resistance decreased. A few reports previously also stated by that increment of the substrate temperature during sputtering deposition process provide a better result in resistivity values [16, 17]. In overall through this finding, it indicates that a higher RF sputtering power is favored in order to reduce the resistivity of ITO film, which is important for the current spreading of LEDs.

**Table 1.** Electrical properties of ITO thin films grown at various RF sputtering power.

| Sputtering Power (W) | Electrical Resistivity ($10^4 \Omega \text{cm}$) | Carrier Concentration ($10^{16} \text{cm}^{-3}$) | Hall Mobility (V.s) | Mobility (cm$^2$/V.s) |
|---------------------|---------------------------------------------|---------------------------------------------|---------------------|----------------------|
| 50                  | 18.73                                       | 2.37                                        | 1.41                | 2.37                 |
| 100                 | 6.484                                       | 2.59                                        | 3.72                | 3.72                 |
| 150                 | 2.421                                       | 3.41                                        | 7.57                | 7.57                 |

3.3. Optical Properties

Figure 5(a) shows the optical transmittance spectrum over the wavelength range of 300 to 800 nm for ITO films prepared at different RF sputtering powers; 50 to 150 W while the close-up view transmittance spectrum in the range of 300 to 450 nm is plotted in Figure 5(b). Figure 5(a) shows the optical transmittance spectrum over the wavelength range of 300 to 800 nm for ITO films prepared at various RF sputtering powers; 50 to 150 W while the close-up view transmittance spectrum in the range of 300 to 450 nm is plotted in Figure 5(b). As observed in the Figure 5(a), presence of fluctuations in optical the transmittance spectra for all samples started 400 nm wavelength were due to the fluctuations refraction between ITO thin film and the soda-lime glass substrate [18, 19].
Figure 3. Sheet resistance of the deposited ITO films at various RF power; 50 W, 100 W and 150 W conducted at 300 °C.

Figure 4. Sheet resistance of the deposited ITO films at various RF power; 50 W and 100 W conducted at room temperature.

The transmittance value was focused in the 450 nm as shown in Figure 5(b) since the main objective is to apply on the blue LED. For all the samples, all the transmittances were measured to be in the range 74 to 79 % as showed in inserted Figure 5(a). As the sputtering power was increased from 50 to 150 W, it can be seen that in the visible wavelength region of 400 - 450 nm, the transmittance increases from 74 to 79 %. The 150 W sample displayed the highest average transmittance of 79 %. By increasing the RF sputtering power from 50 to 150 W, it manages towards the improvement of the transmittance properties.
of the ITO films. It is due to the enhancement in the crystalline structure and decrement of surface roughness. Several similar reports from previous studies were found by to support the idea [13, 20, 21].

![Figure 5](image)

**Figure 5.** (a) Transmittance spectra in the wavelength range of 300 - 800 nm at various sputtering powers, (insert Figure. 5a) transmittance values for three different RF sputtering powers and (b) close up view of transmittance spectra in the wavelength range of 300 - 450 nm at various sputtering powers.

4. Conclusion
This work has investigated the deposition of ITO thin films on soda-lime glass substrates. The ITO thin films were successfully deposited using RF magnetron sputtering at substrate temperature 300 °C with variation of RF magnetron sputtering powers ranging from 50 to 150 W. The main purpose is to get a better and proper understanding of the ITO behaviors based on surface morphology, electrical and optical properties to be applied as upper p-contact for blue nitride-based LEDs. The surface roughness, electrical resistivity and sheet resistance decreased as the magnetron sputtering power was increased. It was found that the transmittance of ITO thin films showed increment as the sputtering power was increased. Deposition of ITO thin films on soda-lime glass substrates conducted using RF magnetron sputtering at elevated substrate temperature contributed to 74 to 79 % of optical transmittance in the 450 nm region.

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