Fabrication and Optical Analysis of Titanium-doped Indium-Tin-Oxide Thin-Films

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***Abstract*—This paper presents a comprehensive investigation on the fabrication and characterization of titanium-doped indium-tin-oxide (ITO) thin films. The fabrication process involved the use of a sputtering system, followed by annealing at elevated temperatures in a furnace, resulting in the production of eight distinct samples. In order to comprehend the optical properties of each sample, UV-Vis absorption measurements were conducted. Moreover, Tauc and Urbach plots were generated to determine the band gap and Urbach energies, respectively.**

***Index Terms*—Thin-Films, Annealing, UV-Vis, Tauc plot, Band gap, Urbach energy**

I. INTRODUCTION

Light-emitting displays are crucial components in contemporary electronics, spanning from smartphones to large advertising screens. The performance and efficiency of these displays heavily depend on the quality of the thin film layers employed in their production. For instance, in solid oxide fuel cells (SOFC), dip-coating enables exceptional contact between the thin film layer and the anode support layer (ASL), minimizing delamination issues after sintering the cell [1]. Similarly, the cost-effective production of thin film solar cells is hindered by lower photonic conversion efficiency and complex fabrication processes [1-3]. However, traditional methods for fabricating these thin film layers are often intricate, time-consuming, and expensive, involving ultrahigh vacuum systems, complex instrumentation, and the use of toxic or corrosive chemical precursors [4-6]. This proposal aims to address these challenges by exploring low-cost and user-friendly techniques to develop intelligent thin films suitable for light-emitting display applications. The objective is to establish a more accessible and efficient approach to thin film fabrication, revolutionizing the display industry.

Johansson et al. (2019) investigated transparent ZnO and TiO2 thin films for UV protection in photovoltaic modules, demonstrating significant reduction in destructive UV transmittance [7]. Jeon et al. (2022) reviewed multifunctional encapsulation technologies for reliable organic light-emitting diodes (OLEDs), discussing solutions such as atomic layer deposition and customized encapsulation techniques [8]. Sasani Ghamsari et al. (2016) explored nanostructured ZnO thin films for UV protection, emphasizing their excellent UV-protection ability and potential in various applications [9]. These studies highlight the importance of optimizing thin film fabrication and performance for improved efficiency and reliability, offering promising avenues for future research in the field.

Doping ITO thin films with Titanium can enhance their conductivity and improve their performance. The addition of Titanium can passivate defects in the bulk of the sensing material and fix dangling bonds at the oxide interface [10]. Optimal optoelectronic properties were observed in Titanium-doped ITO thin films grown at a sputtering power of 100W, yielding reduced resistivity and high transmittance [11]. The best-performing Titanium-doped ITO thin films were achieved with a 4% Titanium concentration, annealed at $500°C$, exhibiting low resistivity, high transmittance, and a high optical band gap [12].

Here in this work, we have fabricated Titanium-doped ITO thin films on glass substrates with different percentages of Titanium within ITO matrix. Subsequently, the samples were annealed at elevated temperatures 200, 400 and $600°C$ for 2 Hrs each. A comparative analysis in terms of optical characteristics have been carried out for the samples with and without thermal treatment.

II. EXPERIMENTAL METHODOLOGY

A. Sample Preparation

a) Thin film deposition: To fabricate the thin films, we employed a sputtering coater. Initially, we deposited Indium Tin Oxide (ITO) films on glass substrates using different powers of Titanium (15W, 45W, and 75W at the DC gun) in argon flow rate of 30 SCCM.

b) Annealing: Following the deposition process, the samples were annealed at three different temperatures: $200°C$, $400°C$, and $600°C$. Annealing was performed to enhance the structural and optical properties of the thin films.

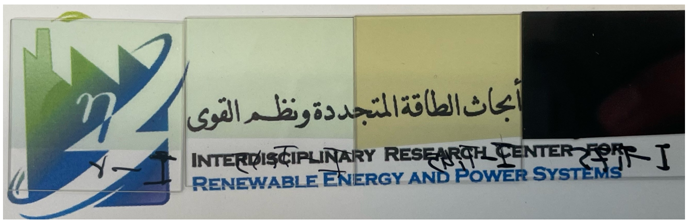


Fig. 1. Picture of prepared samples of ITO doped with Titanium at 75W

B. Characterization Techniques

The thin film samples were characterized using a series of techniques to evaluate their structural, optical, and electrical properties. As for the optical characterizations, UV-Vis spectroscopy was carried out for each sample. The characterization techniques employed in this research included:

- DektakXT profilometer: Used to determine the thickness of the thin films.
- UV-Vis spectroscopy: Employed to investigate the optical properties of the samples, including transmission and absorption.

- X-ray diffraction (XRD): Utilized to analyze the crystal structure of the thin films.
- Hall effect measurements: Performed to evaluate the electrical conductivity and carrier concentration of the thin films.
- Ellipsometry: Employed to determine the refractive index and thickness of the thin films.
- I-V diagram: Used to assess the electrical behavior of the thin film samples.
- 4-point probe: Employed to measure the sheet resistance of the thin films.

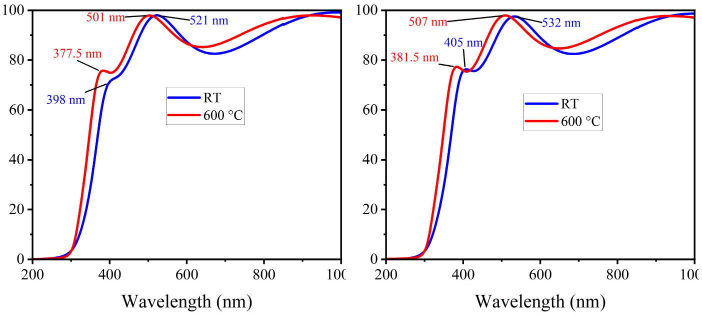
All of these characterization utilities have been used, but only the UV-Vis has been analyzed.

By employing these characterization techniques, we aimed to gain insights into the structural, optical, and electrical properties of the thin films and assess their suitability for light emitting display applications. The detailed steps are mentioned in Appendix A.

III. RESULTS AND FINDINGS

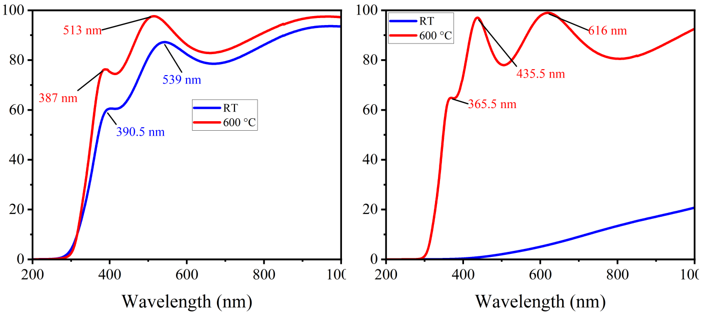
A. UV-Vis Transmission Analysis

a) Transmission peaks shift: We can notice a shift in the peaks in Figure 2 when the Titanium power increases, the shift is towards the visible range. Moreover, when we anneal it, the transmission in the visible range gets improve. This can be shown more pronounced in Figure 2(d), where the transmission improved from 20% to around 90%.



(a) Reference Sample

(b) ITO with 15W Titanium



(c) ITO with 45W Titanium

(d) ITO with 75W Titanium

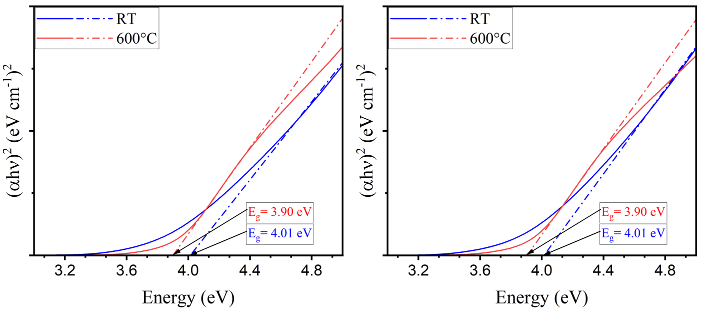
Fig. 2. Transmission plots for ITO doped with Titanium with different powers.

The shift of UV-Vis transmission peaks towards the visible range through annealing and increasing Titanium power offers valuable benefits. It enhances light absorption in the visible spectrum, improving performance in optoelectronic devices like solar cells and photodetectors. This tunability enables customized materials for specific wavelength requirements, facilitating advancements in energy conversion, sensing, and optical communications.

B. UV-Vis Absorption Analysis

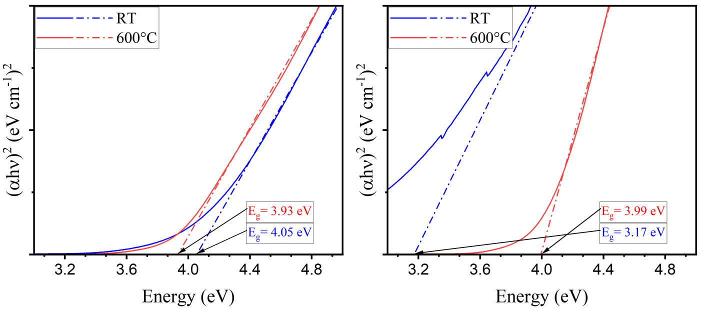
a) Tauc plot: A Tauc plot is used to determine the optical bandgap of either disordered or amorphous semiconductors. Typically, a Tauc plot shows the quantity $h\nu$ (the photon energy) on the x-axis and the quantity $(\alpha h\nu)^2$ on the y-axis, where α is the absorption coefficient of the material, which was set to $2.302\ A/cm$. Extrapolating this linear region to the x-axis yields the energy of the optical bandgap of the amorphous material [13]. In the following figures, we will show the Tauc plots for different doping power of Titanium, annealed to $600°C$.

$$(\alpha h\nu)^2 = A(h\nu - E_g) \tag{1}$$



(a) Reference Sample

(b) ITO with 15W Titanium



(c) ITO with 45W Titanium

(d) ITO with 75W Titanium

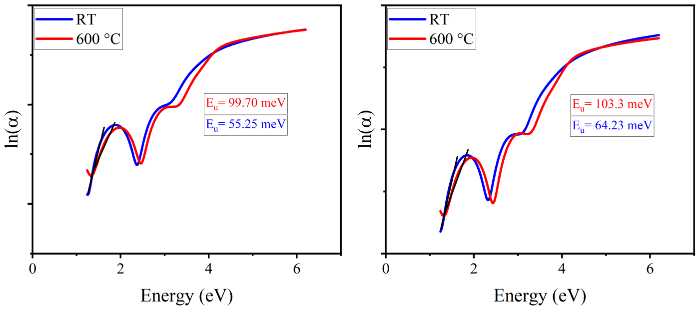
Fig. 3. Tauc plots for ITO doped with Titanium with different powers.

The Tauc plot reveals a noticeable trend in the bandgap dependence on Titanium power. At a temperature of $600°C$, the bandgap starts at $3.90\ eV$ and increases to $3.99\ eV$ with increasing Titanium power, as shown in Figure 3(d). This observation highlights the ability to manipulate and control the bandgap by annealing at $600°C$ resulting in an enhanced bandgap energy of $3.99\ eV$.

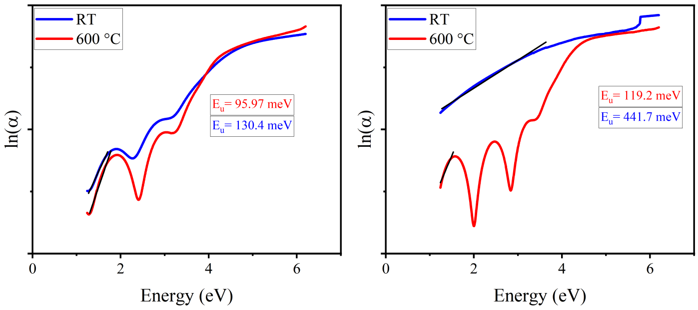
b) Urbach plot: The Urbach plot characterizes disorder and localized states in semiconductors by plotting the natural logarithm of the absorption coefficient α against photon energy $h\nu$. An increase in the Urbach energy, observed as an upward trend in the plot, indicates a higher degree of disorder and an increased presence of localized states within the material [14].

$$\ln\alpha = \frac{1}{E_u}h\nu - \ln\alpha_0 \tag{2}$$

The Urbach energy E_u, which can be found by inverting the slope at the linear region, represents the width of the exponential absorption tail resulting from defects or impurities. In the following figures, we will show the Urbach plots for different doping power of Titanium, annealed to $600°C$.



(a) Reference Sample (b) ITO with 15W Titanium

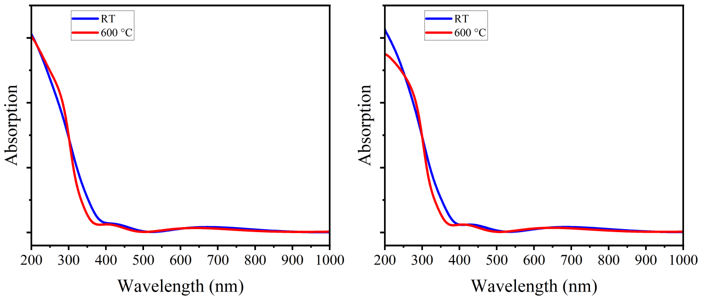


(c) ITO with 45W Titanium (d) ITO with 75W Titanium

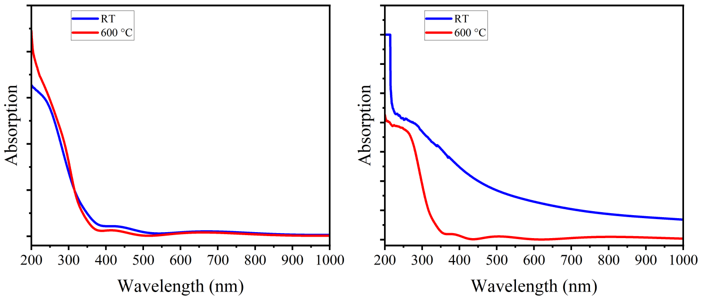
Fig. 4. Urbach plots for ITO doped with Titanium with different powers.

First, when we increase the Titanium power, the Urbach energy E_u, increases, which indicate the sample getting more disordered. Moreover, we notice that by annealing, E_u got tuned to an almost constant value around 100 meV. For example, in Figure 4(d), E_u decreases from 441.7 meV to 119.2 meV.

c) Absorption analysis: The samples show good absorption in the UV range with low absorption in the visible range. This was one of the goals of this research. Moreover, Figure 5(d) shows that by annealing, the absorption drastically improved, to low absorption in the visible range, and 50% absorption for UV range.



(a) Reference Sample (b) ITO with 15W Titanium



(c) ITO with 45W Titanium (d) ITO with 75W Titanium

Fig. 5. Absorption plots for ITO doped with Titanium with different powers.

IV. APPLICATION POTENTIAL

The findings of this study hold great potential for addressing one of the main challenges in the solar industry, which is the degradation of solar cells due to prolonged exposure to UV radiation. By utilizing the optimized composition and annealing temperature determined in this research, it is possible to develop a UV-protection film that is transparent, flexible, and shields against harmful UV rays. This UV-protection film can be applied as a protective layer on solar panels, extending their lifetime and improving their efficiency by minimizing the degradation caused by UV radiation.

Furthermore, the transparent and flexible nature of thin films opens up possibilities for their application in various industries beyond solar energy. For instance, they can be utilized in the production of UV-protective coatings for windows, wearable devices, and displays. The ability to create UV-protection films with high transparency and flexibility provides a significant advantage in these applications, as it enables the development of lightweight, durable, and visually appealing products that effectively safeguard against UV radiation.

V. CONCLUSION

We have successfully fabricated Titanium-doped ITO with different percentage of Titanium doping using sputtering technique. The films were found transparent in low percentage of Titanium doping. However, the transparency increased with thermal treatment at high temperatures. Bang gap of the treated sample was found higher with reference to that obtained without annealing. On the other hand, the Urbach energy was found higher with reference to that obtained without annealing. The research conducted in this study has successfully demonstrated the potential of thin films for UV protection and transparency applications. The optimized composition and annealing temperature determined through our experimental investigations show promise for the development of UV-protection films that can be applied in various industries, including solar energy, consumer electronics, and architectural applications.

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APPENDIX

In this Appendix, we outline the materials, equipment, and step-by-step procedures used in the fabrication and characterization of the thin films. The goal of the experimental methodology was to determine the optimized composition and annealing temperature for achieving the best UV protection and transparency.

A. Materials

- Glass substrate
- Indium Tin Oxide (ITO) target
- Titanium (Ti) target
- Nitrogen gas (N_2)

B. Equipment

- Sputtering coater
- DektakXT profilometer
- UV-Vis spectroscopy
- X-ray diffraction (XRD) machine
- Hall effect measurement system
- Ellipsometer
- Four-point probe

C. Fabrication and Characterization Procedures

Preparation of Glass Substrate:

1) Clean the glass substrate using a suitable cleaning agent to remove any contaminants or residues.
2) Rinse the substrate thoroughly with deionized water and dry it using a clean and lint-free cloth.

Deposition of ITO Films:

1) Load the cleaned glass substrate into the sputtering coater chamber.
2) Place the ITO target in the coater chamber.
3) Set the desired power for sputtering (15W, 45W, and 75W) of Titanium.
4) Start the sputtering process to deposit the ITO films on the glass substrate.
5) Repeat the deposition process for different powers of Titanium.

Nitrogen Doping:

1) After depositing the ITO films, introduce nitrogen gas N_2 into the sputtering chamber.
2) Set the desired deposition conditions for nitrogen doping.
3) Conduct the sputtering process to introduce nitrogen into the ITO films.

Annealing of Samples:

1) Transfer the fabricated samples to an annealing furnace.
2) Set the desired annealing temperatures (200°C, 400°C, and 600°C).
3) Anneal the samples at the specified temperatures for a defined duration.
4) Allow the samples to cool down to room temperature.

Thickness Measurement:

1) Use the DektakXT profilometer to measure the thickness of the fabricated thin films.
2) Find a suitable spot for the thickness measurement, that crosses both the thin film and the glass substrate.
3) Record the thickness measurements for further analysis.

Optical Property Measurement:

1) Employ UV-Vis spectroscopy to determine the absorbance and transmittance of the fabricated samples.
2) Measure the UV-Vis spectra of the thin films in the desired wavelength range (200nm to 1000nm).
3) Analyze the data to obtain information about the optical properties and bandgap of the samples, using Tauc and Urbach plots techniques.

X-ray Diffraction (XRD) Analysis:

1) Send the fabricated samples to an XRD machine.
2) Record the XRD patterns to identify the crystal structure of the thin films.

Hall Effect Measurement:

1) Utilize the Hall effect measurement system to determine the electrical properties of the fabricated samples.
2) Measure the electrical conductivity, carrier concentration, and mobility of the thin films.

Ellipsometry:

1) Use an ellipsometer to measure the refractive index and thickness of the thin films.
2) Follow the ellipsometer's operating instructions for accurate measurements.
3) Record the ellipsometry raw data for further analysis.

I-V Characterization:

1) Perform current-voltage (I-V) measurements on the thin film samples.
2) Record the I-V characteristics to assess the electrical behavior of the samples.

By following these steps, we were able to fabricate the thin films with different compositions and annealing conditions, and subsequently characterize their optical, structural, electrical, and thickness properties. The obtained data served as a basis for analyzing the relationship between the film's composition, annealing temperature, and its UV protection and transparency properties.

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