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Article

Optimizing the Indium Tin Oxide Layer Characteristics toward a Low-Cost Dust-Cleaning Process for Solar Panels

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Abstract: The deposition of dust particles on solar panel modules constitutes a significant challenge, leading to a potential reduction in solar cell performance. This work tackles this issue by investigating the surface modification of a layer of transparent indium tin oxide (ITO), with a detailed analysis of the influence of its characteristics via different annealing conditions/processing. The ITO layer has been studied to enhance its characteristics for dust removal applications. Of particular note is that the developed ITO layer can be applied to dust removal using electrostatic or magnetic-based approaches. Thus, the correlation between annealing gas (using Argon, Oxygen, and Nitrogen), annealing temperature, and annealing ramping rate is explored with the obtained surface topography, as well as electrical and optical properties. The developed ITO layers annealed in the Argon medium at 600°C with an annealing ramping rate of 50°C/s showed smooth surface roughness, the highest electrical conductivity, and a relatively low refractive index. Such findings can play a crucial role in the future implementation of using the enhanced ITO layer for dust mitigation in solar panels, thus improving their long-term performance.

Keywords: ITO annealing; Dust mitigation; Surface modification; ITO resistivity; ITO refractive index

1. Introduction

Renewable energy is a concept that is gaining increasing importance in modern society, it is seen as a necessary solution to address the negative impacts of fossil fuel usage, which contribute significantly to climate change 1. Among the main renewable energy sources such as tidal, wind, geothermal, and solar radiation, the solar energy source stands out 2. Solar energy holds great promise worldwide, especially in the Middle East, in areas such as desalination, heating and cooling systems, and meeting residential energy needs 3. With its geographic suitability for solar energy production and location in the sun belt, the Middle East has emerged among the largest solar energy producers 4. However, solar panels face challenges, which can affect their efficiency and productivity. Factors such as temperature, humidity, and a cloudy atmosphere can have a negative impact on energy production 5. Moreover, external factors like dust accumulation, stains, and surface contamination can further decrease the efficiency of solar panels 6. The accumulation of dust on solar panels can reduce their efficiency by up to 30%, while high temperatures can further decrease efficiency by up to 10% 7. It can also modify the irradiance angle, which varies between clean and dirty cells, and this effect is measured as irradiation daily losses 8. Dust accumulation, especially in desert environments where dust storms are frequent, poses a serious issue, while the typical methods for mitigating the dust, such as wet and dry cleaning, have their advantages and limitations 9.

Wet cleaning involves using water or chemical solutions to remove dirt and dust from the panels 13. While it is the most common method used for cleaning solar panels, it requires a sufficient water supply, which may not be readily accessible or cost-effective in some areas, especially deserts 14. Dry

cleaning methods, such as mechanical brushing or the use of compressed air, eliminate water consumption [10, 11]. However, they may not be as effective in removing tiny particles and can potentially scratch the panels, leading to distortion and surface changes [12]. Nevertheless, novel cleaning methods such as electrostatic cleaning utilize an electrostatic field created by applying a high voltage across electrodes to attract and repel charged dust particles on the panel surface [15]. This method offers significant advantages, including eliminating large water usage, making it a more sustainable option, and reducing labor and maintenance costs [16, 17, 18]. Studies have shown that electrostatic cleaning can remove over 90% of deposited dust within a short time [19]. Other innovative approaches, such as magnetic cleaning, have emerged as promising solutions. The method is based on the magnetic concept, which states that when two objects with a magnetic force between them are separated, a magnetic field forms between them, influencing nearby particles and dust [20]. When magnets or magnetic objects are brought close, their magnetic fields interact, leading to either attraction or repulsion, affecting the surrounding particles [21]. The disturbances caused by the magnetic field on particles and dust depend on factors like size, composition, and magnetic susceptibility [22]. This method offers the advantage of non-contact cleaning, which minimizes the risk of mechanical damage and scratches on the panels [23, 24].

A supporting layer is necessary for solar panels to implement the two above mentioned noncontact cleaning methods (electrostatic and magnetic) effectively, combining transparency to allow sunlight passage and electrical conductivity. The optimal and promising choice for this purpose can be indium tin oxide (ITO). The ITO is a transparent conducting oxide commonly used as a layer coating in various electronic devices. It fulfills the dual requirements of transparency and conductivity. It is highly transparent to visible light, with transparency levels ranging from 80% to 90% or even higher, depending on the layer thickness and deposition conditions [25]. Additionally, it exhibits excellent electrical conductivity as a highly doped n-type semiconductor, with a conductivity range of several hundred to several thousand Siemens per centimeter (S/cm) and a low resistivity of around $10^{-4} \Omega \cdot \text{cm}$ [25]. As an added advantage, ITO has a high melting point of $1500 - 1900^\circ\text{C}$, ensuring stability under high-temperature conditions [26]. With this in mind, the ITO roughness can be thermally optimized to reduce the challenges of dust staking within the surface structure of the layer.

In this work, a deep exploration of ITO thin film characteristics is conducted with a keen interest in the effects of the annealing gas, annealing temperature, and annealing ramping rate on the surface topography, electrical properties, and optical properties. Thermal processes are utilized with different annealing gas mediums, as well as different annealing temperatures and ramping rates, with the ultimate goal of minimizing surface roughness, increasing conductivity, and reducing the refractive index. The findings and conclusions of this work can support the development of the future implementation of ITO thin films, which need to be adjusted judiciously to enhance the solar panel's performance through dust-removing approaches and other related applications.

2. Materials and Methods

Indium tin oxide is an oxide layer, with interesting properties like highly transparent and highly conductive, which make it an excellent choice as a layer over silicon, in applications that require good optical transparency. ITO layer over silicon, enhances the absorption of light, allows light to pass through it while conducting. The technique used in our work, to deposit ITO over silicon is electron-beam physical vapor deposition (EBPVD), in which ITO is heated using high energy electron beam, until it is vaporized and later condenses into silicon surface forming a thin uniform layer of ITO over Silicon.

In our work, ITO thin film was deposited onto a 4-inch, $500\text{-}\mu\text{m}$ thick, single-side polished, and p-type boron-doped silicon substrate with a resistivity range of $0.001 - 100 \Omega \cdot \text{cm}$ by EBPVD. The ITO thin film was composed of a mixture of indium oxide (In_2O_3) and tin oxide (SnO_2) in a ratio of 90:10, respectively, as shown in Figure 1. The process involved adjusting parameters such as a temperature of 250°C , a chamber pressure of $5.0 \times 10^{-5} \text{ Torr}$, a rotation speed of 65%, a targeted ITO thin film thickness of 100 nm, and the use of argon gas. The selection of a 100-nm ITO thickness

was based on its desirable attributes, such as a high carrier concentration and impressive transmittance of 91% in the visible region 27, low refractive percentage, typically less than 20%, and relatively low absorption percentage, less than 2%, in the visible spectrum, enabling the transmission of light through the thin film without significant loss 25.

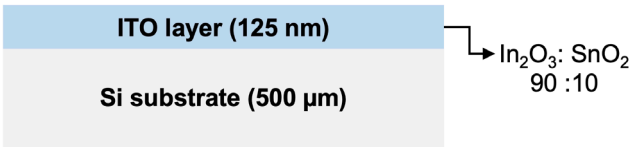


Figure 1. Cross-sectional view of the deposited ITO thin film. The ITO thin films were deposited onto a 4-inch, 500- μm thick, single-side polished, and p-type boron-doped silicon substrate with a resistivity range of 0.001-100 $\Omega\text{-cm}$ by EBPVD. The figure illustrates the resulting thin film of a 125-nm thick ITO. The ITO thin film was composed of a mixture of indium oxide (In_2O_3) and tin oxide (SnO_2) in a ratio of 90:10, respectively, providing a transparent and conductive coating for the substrate.

To ensure optimal thin film adhesion, the substrate surface underwent a cleaning process to remove residual contaminants. The cleaning process involved two steps: initial cleaning with acetone and subsequent air cleaning to remove any organic residues or contaminants from the wafer surface to eliminate impurities and enhance the adhesion between the ITO thin film and the silicon substrate, which ensuring a uniform and defect free thin film. The ITO target was then evaporated using an electron beam and condensed onto the heated and rotating silicon substrate, resulting in a uniform ITO thin film. Then, the coated wafers were manually diced into smaller samples. These samples were subsequently subjected to an annealing process using a rapid thermal processing (RTP) machine. This study examined three key factors during the annealing stage: the type of annealing gas, the annealing temperature, and the annealing ramping rate. To study the effect of annealing gas, separate samples were prepared and annealed in Argon (Ar), Nitrogen (N_2), and Oxygen (O_2) medium at 500 $^\circ\text{C}$ for 600 seconds with an annealing ramping rate of 25 $^\circ\text{C/s}$. Moreover, the impact of annealing temperature was investigated by annealing five samples in an Ar medium at temperatures spanning 300 $^\circ\text{C}$ to 500 $^\circ\text{C}$, all with a 600-second duration and 25 $^\circ\text{C/s}$ annealing ramping rate. Also, the influence of the annealing ramping rate was examined by preparing five samples annealed in an Ar medium at 600 $^\circ\text{C}$ for 600 seconds, with annealing ramping rates spanning 25 $^\circ\text{C/s}$ to 125 $^\circ\text{C/s}$.

The thickness of the ITO thin films was measured using an ellipsometer, which was found to be 125 $\pm$ 5 nm. Ultimately, the surface roughness, the electrical resistivity, and the optical properties have been studied in detail. Table 1 shows the list of studied samples at different annealing conditions.

Table 1. The table provides the annealing conditions for each tested sample. Samples in group (A) were used to select the annealing gas, while in group (B), the samples were used to identify the optimal annealing temperature. Finally, in group (C), samples were used to find the optimal annealing ramping rate.

Sample Group	Sample Number	Gas	Temperature ($^\circ\text{C}$)	Annealing Ramping Rate ($^\circ\text{C/s}$)
Reference	As deposited (0)	-	-	-
Group A	A_1	Ar	500	25
	A_2	N_2	500	25
	A_3	O_2	500	25
Group B	B_1	Ar	300	25
	B_2	Ar	400	25
	B_3	Ar	500	25
	B_4	Ar	600	25

	B_5	Ar	700	25
Group C	C_1	Ar	600	25
	C_2	Ar	600	50
	C_3	Ar	600	75
	C_4	Ar	600	100
	C_5	Ar	600	125

For the surface roughness measurements of the annealed ITO thin films, atomic force microscopy (AFM) was used. The roughness data was further processed and analyzed using NanoScop analysis software. This software allowed for advanced visualization and quantitative analysis of the surface topography, providing detailed information on features such as roughness parameters, surface texture, and topography. Two common parameters used to quantify surface roughness from AFM data, which are average roughness (R_a) and root mean square (RMS) roughness (R_q). Average roughness represents the average deviation of the surface from a reference plane over a given sampling length, calculated by averaging the absolute values of the height deviations of the surface profile 28. The equation for R_a is:

$$R_a = \frac{1}{L} \int |z(x)| \, dx, \tag{1}$$

where L is the sampling length, and $z(x)$ is the surface height deviation from the reference plane 28. Root means square roughness measures the overall magnitude of height variations across the surface, representing the root mean square value of the height deviations within a sampling length. The equation for R_q is 28:

$$R_q = \sqrt{\frac{1}{L} \int z(x)^2 \, dx}, \tag{2}$$

where L is the sampling length, and $z(x)$ is the surface height deviation from the reference plane 28. In addition to R_a and R_q , other parameters, such as skewness (S_{sk}), play a vital role in understanding surface characteristics. Skewness measures the asymmetry of the surface profile to its mean plane. A positive skewness value in roughness indicates an abundance of high or positive deviations from the mean, suggesting the presence of more peaks or higher elevations on the surface. Conversely, negative skewness signifies an excess of low or negative deviations, implying the existence of more valleys or lower elevations on the surface 29. The calculation of skewness from AFM data is given by the equation 29:

$$S_{sk} = \frac{1}{n \times R_q^3} \sum_{i=1}^n (z_i - \bar{z})^3, \tag{3}$$

where n is the number of data points, R_q is the root mean square roughness, and $\bar{z}$ is the mean vertical value of the image 29.

For the electrical resistivity measurements of the ITO thin films, two methods have been utilized. A standard digital multimeter was used to directly measure electrical resistance, while a specialized four-point probe resistivity measurement system was utilized to precisely determine sheet resistance (R_s) and resistivity (ρ). Sheet resistance is a measure of the resistance and is typically expressed in ohms per square ($\Omega/square$). It is an important parameter for assessing the conductivity of ITO thin films, as it reflects both the material's intrinsic resistivity and the thickness of the thin film 30. Lower sheet resistance indicates higher electrical conductivity. The sheet resistance of an ITO thin film can be calculated using the formula 30:

$$R_s = \frac{\rho}{h}, \tag{4}$$

where ρ is the material's resistivity ($\Omega - cm$), and h is the thickness of the thin film (cm) 30. The information about the overall thin film quality can be inferred by measuring the sheet resistance. Resistivity, on the other hand, is an intrinsic material property that describes how strongly a material opposes the flow of electric current, independent of the material's shape or size. It is typically measured in ohm-centimeters ($\Omega - cm$) and is a fundamental parameter that characterizes the material's ability to conduct electricity 30.

For the optical properties measurements of the annealed ITO thin films, an ellipsometer has been used to measure the refractive index and extinction coefficient of ITO at 632 nm. The refractive index (n) determines how much light bends as it travels through the ITO thin film, which is crucial for designing optical devices like solar cells, while the extinction coefficient (k) represents the absorption of light by the ITO thin film, and it is essential for understanding the film's optical losses.

Combining these advanced characterization techniques, including ellipsometer for thickness measurement (and optical measurements), AFM for surface roughness analysis, and multimeter and four-point probe for resistivity evaluation, allows for a comprehensive assessment of the surface, electrical, and optical properties of the annealed ITO thin films under various processing conditions examined in this study.

3. Results and Discussion

A detailed study is carried out on ITO thin films to underline the correlation of annealing gas, temperature, and annealing ramping rate on the surface topography, electrical properties by means of thin film resistivity, and optical properties by means of refractive index and extinction coefficient. The goal was to find the finest conditions for a uniform, conductive, low light reflective, and transparent ITO surface. The experiment was conducted systematically, first examining the finest annealing gas medium, then fixing it to test the annealing temperature influences, and finally fixing the chosen gas medium and temperature to find the optimal annealing ramping rate.

3.1. Surface Topography

The average roughness (R_a), RMS roughness (R_q), and skewness (S_{sk}) have been studied to provide insights into the surface topography of the processed samples. The low surface roughness is preferable as it helps increase transparency by reducing dust accumulation on the surface. Additionally, low surface roughness decreases resistivity due to its direct influence on electron scattering. By decreasing the roughness, electron scattering decreases, which in turn increases the mean free path lengths of electrons and subsequently reduces resistivity [31]. The R_a values across all the samples are relatively low, spanning 0.6 nm to 1.2 nm. This indicates the overall surface roughness of these samples is somewhat minor. Similarly, the R_q values also fall within a tight range, from around 0.7 nm to 1.5 nm. The R_q values are consistently higher than the corresponding R_a values, as expected, but the proximity of these measurements further confirms the surfaces exhibit low roughness characteristics. Furthermore, the S_{sk} values for all the annealed samples are positive, falling between 0.1 and 1.4. This positive skewness suggests the surface height distributions are slightly asymmetric, with more pronounced peaks than valleys. This indicates that less dust will accumulate due to the reduced number of valleys. Compared to the as-deposited (reference) sample, where the R_a was 0.968 nm, the R_q was 1.215 nm, and the S_{sk} was 0.269, the annealed samples show further improvement in surface roughness (see Figure 2).

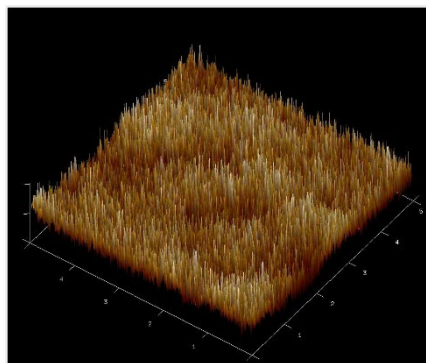


Figure 2. The AFM image was captured over a scan area of $5\ \mu\text{m} \times 5\ \mu\text{m}$ using the NanoScope software of ITO thin film prior to undergoing RTP. The roughness parameters, R_a and R_q , are quantified as 0.968 nm and 1.215 nm, respectively. The image reveals the initial surface characteristics of the ITO thin film, showing a relatively smooth surface with low roughness. These measurements

provide valuable insights into the surface topography and pave the way for further analysis of the effects of RTP on the surface properties of the ITO thin film.

For the annealing medium investigation, as in sample group A, the R_a values range from 0.567 nm to 0.627 nm, the R_q values range from 0.714 nm to 0.789 nm, and the S_{sk} values range from 0.19 to 0.302. These results indicate that the surfaces in this group exhibit relatively low roughness characteristics, with more peaks on the surface. Specifically, the use of N_2 gas resulted in the lowest roughness, suggesting a smoother surface, while Ar showed moderate roughness values. These findings align with the work of Boussoum *et al.* 32. Instead, the use of oxygen gas led to the highest roughness, likely due to an increase in grain size 33.

For the annealing temperatures investigation, as in sample group B, the R_a values range from 1.01 nm to 1.22 nm, the R_q values range from 1.34 nm to 1.52 nm, and the S_{sk} values range from 0.236 to 1.43. This suggests the surfaces in this group have higher roughness, with the 500°C sample showing the lowest roughness and the 600°C sample having the highest, as shown in Figure 3. It is worth noting that the roughness values did not show any clear trend as they almost remained constant with increasing temperature, which agrees with the results in the literature 34

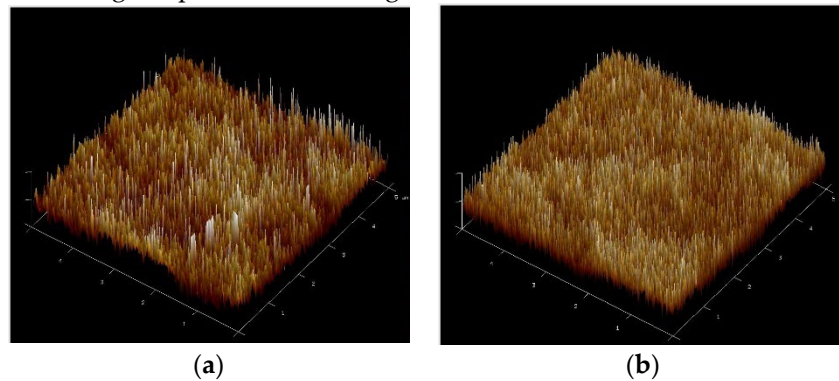
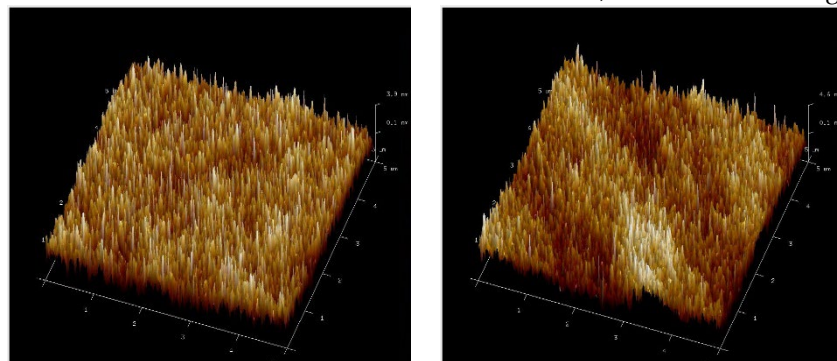


Figure 3. The AFM images were captured over a scan area of $5\ \mu\text{m} \times 5\ \mu\text{m}$ using the NanoScope software of the ITO thin film after RTP at different annealing temperatures. In (a) AFM image of Sample B_3 annealed at 500°C, showing a R_a value of 1.01 nm and an R_q value of 1.34 nm. In (b), the AFM image of Sample B_2 annealed at 600°C, exhibiting a R_a value of 1.22 nm and an R_q value of 1.52 nm. The measured roughness parameters provide quantitative information about the surface characteristics, with both samples showing slightly increased roughness compared to the pre-annealing state. These observations demonstrate the impact of annealing temperature on the surface properties of the ITO thin film.

For the annealing ramping rate investigation, as in sample group C, the R_a values range from 0.888 nm to 1.04 nm, the R_q values range from 1.11 nm to 1.30 nm, and the S_{sk} values range from 0.142 to 0.859. These values suggest that the surfaces in this group exhibit a moderate level of roughness. Among all samples, the one subjected to an annealing ramping rate of 50°C/s shows the lowest roughness, while the sample with an annealing ramping rate of 100°C/s demonstrates the highest roughness. This can be attributed to the high annealing ramping rate, which induces greater stress and leads to the formation of further defects on the surface, as illustrated in Figure 4.



(a) (b)

Figure 4. The AFM images were captured over a scan area of $5\ \mu\text{m} \times 5\ \mu\text{m}$ using the NanoScope software of the ITO thin film after RTP at different annealing ramping rates. (a) AFM image of Sample C_2 annealed with a 50°C/s annealing ramping rate, showing a R_a value of $0.888\ \text{nm}$ and an R_q value of $1.11\ \text{nm}$. (b) AFM image of Sample C_4 annealed with a 100°C/s annealing ramping rate, displaying a R_a value of $1.04\ \text{nm}$ and an R_q value of $1.30\ \text{nm}$. The images depict the surface topography of the ITO thin film after undergoing RTP with varying annealing ramping rates. These results highlight the influence of the annealing ramping rate on the surface properties of the ITO thin film, indicating changes in surface topography as a result of the thermal treatment.

Overall, the results suggest that the annealing processes slightly affect the change in surface topography. While the overall roughness values remain relatively low, there are detectable differences in the R_a , R_q , and S_{sk} parameters depending on the specific annealing conditions used. This indicates the annealing techniques can yield surfaces with slightly modified roughness characteristics, and such a process can be tuned to increase the performance of the ITO layer for the dust-cleaning process of solar panels.

3.2. Electrical Properties

The sheet resistance and resistivity measurements are averages taken at three different points to enhance accuracy. These measurements offer crucial insights into the electrical performance of the ITO thin films under different annealing conditions. To use the material as a conductive layer, it is necessary to achieve a lower resistivity that enables the material to transport electrical charges and signals efficiently. Across the different sample groups, the sheet resistance and resistivity values generally decreased after annealing by 84%, where the highest sheet resistance among all samples was $201.99\ \Omega/\text{square}$ and the lowest was $27.42\ \Omega/\text{square}$.

For the annealing medium investigation, as in sample group A, the ITO thin films were annealed in different gas medium, being Ar, N_2 , and O_2 , at 500°C for 600 seconds. As shown in Figure 5, the sheet resistance dropped from $173.03\ \Omega/\text{square}$ for the as-deposited (reference) sample to around $31 - 34\ \Omega/\text{square}$ after annealing, corresponding to a resistivity decrease from $8.43\ \Omega - \text{cm}$ to $1.65\ \Omega - \text{cm}$, as shown in Figure 6. Annealing in Ar as showed the lowest sheet resistance of $31.49\ \Omega/\text{square}$ and resistivity of $1.65\ \Omega - \text{cm}$ due to the oxygen-deficient medium that increases carrier concentration through O_2 vacancy creation 35. The highest values were observed for O_2 gas, with a measurement of $201.99\ \Omega/\text{square}$ and $10.58\ \Omega - \text{cm}$, which can be attributed to the oxidation process and reduction of the O_2 vacancies that occur during annealing, leading to high resistance values 33-36.

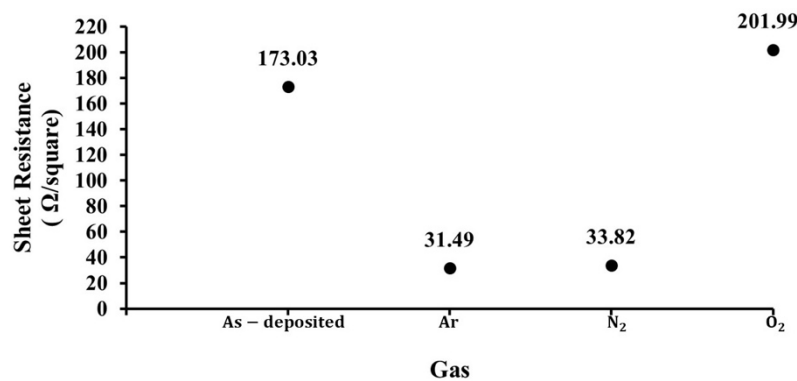


Figure 5. The sheet resistance measurements of ITO thin film annealed in different gas medium (Ar, N_2 , and O_2) at 500°C for 600 seconds. The x-axis represents the annealing gas medium (Ar, N_2 , and O_2) and the y-axis represents the sheet resistance in ohms per square. The chart shows that the sheet resistance decreased from $173.03\ \Omega/\text{square}$ in the as-deposited (reference) sample to approximately

31.49 Ω/square after annealing. It is worth noting that annealing in Ar gas resulted in the lowest sheet resistance.

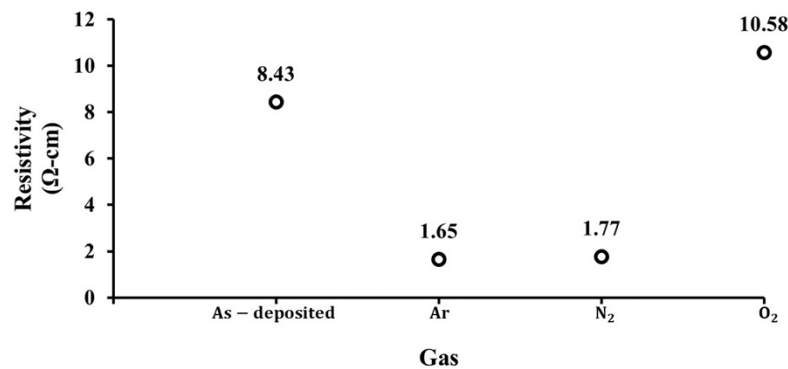


Figure 6. The resistivity of ITO thin film annealed in different gas medium (Ar, N₂, and O₂) at 500°C for 600 seconds. The x-axis represents the annealing gas medium (Ar, N₂, and O₂), and the y-axis represents the resistivity in the ohm-centimeter. The chart illustrates the decrease in resistivity from 8.43 $\Omega\text{-cm}$ in the as-deposited (reference) sample to around 1.65 $\Omega\text{-cm}$ after annealing. It is worth noting that annealing in Ar gas exhibited the lowest resistivity.

For the annealing temperatures investigation, as in sample group B, the ITO thin films annealed in Ar gas at temperatures spanning 400°C to 700°C. As shown in Figure 7, as the annealing temperature increased, the sheet resistance decreased from 147.41 Ω/square at 300°C to 27.43 Ω/square at 600°C, and the resistivity decreased from 7.72 $\Omega\text{-cm}$ to 1.44 $\Omega\text{-cm}$. This decrease can be attributed to the increase in carrier concentration and Hall mobility, which agrees with findings in 34-36-37. While there is a slight difference between the values at 600°C and 700°C, annealing at 600°C might be the preferred choice as it is a more economical option.

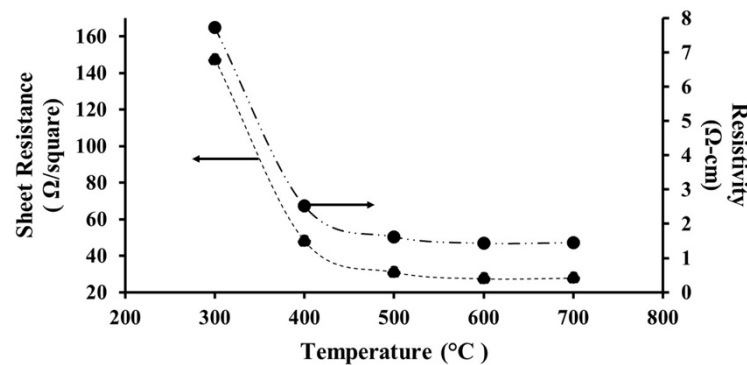


Figure 7. Sheet resistance and resistivity of ITO thin film annealed in Ar gas at temperatures spanning 400°C to 700°C. The x-axis represents the annealing temperatures in degrees Celsius, and the y-axis represents the sheet resistance in ohms per square on the right side and resistivity in ohm-centimeters on the left side. The chart demonstrates that as the temperature increased, the sheet resistance decreased from 147.41 Ω/square at 300°C to 27.43 Ω/square at 600°C. The resistivity also decreased from 7.72 $\Omega\text{-cm}$ to 1.44 $\Omega\text{-cm}$ over the same temperature range.

For the annealing ramping rate investigation, as in sample group C, the ITO thin films were annealed in Ar gas at 600°C, with the annealing ramping rate increased from 25°C/s to 125°C/s. Here, the sheet resistance increased from 27.42 Ω/square at annealing ramping rate of 50°C/s to 31.13 Ω/square at an annealing ramping rate of 125°C/s. Similarly, the resistivity increased from 1.43 $\Omega\text{-cm}$ to 1.63 $\Omega\text{-cm}$, as illustrated in Figure 8. It is observed that when the annealing ramping

rate exceeded 50°C/s , the resistivity began to increase. This increase can be attributed to the higher annealing ramping rate, which causes increased stress. When the ITO thin films are subjected to mechanical stress, such as bending or stretching, microcracks or delamination can develop, disrupting the continuous conductive pathway. These defects impede the flow of electric current and ultimately lead to an increase in resistivity 38.

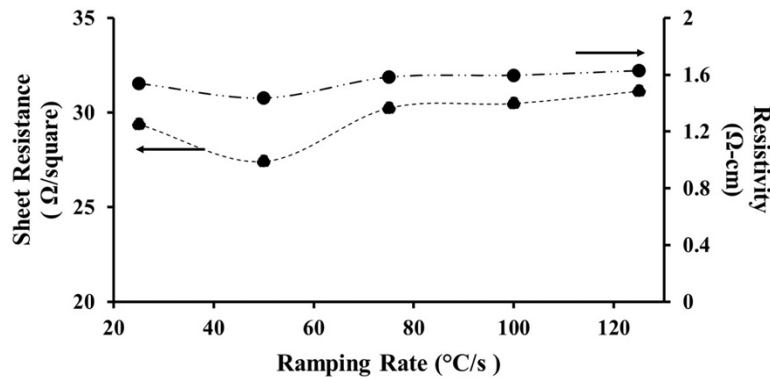


Figure 8. Sheet resistance and resistivity of ITO thin film annealed in Ar gas at 600°C with different annealing ramping rates. The x-axis represents the annealing ramping rates in degrees Celsius per second ($^{\circ}\text{C/s}$), and the y-axis represents the sheet resistance in ohms per square on the right side and resistivity in ohm-centimeters on the left. The chart indicates that the sheet resistance decreased from $31.13 \Omega/\text{square}$ at an annealing ramping rate of 125°C/s to $27.42 \Omega/\text{square}$ at an annealing ramping rate of 50°C/s . Similarly, the resistivity decreased from $1.63 \Omega\text{-cm}$ to $1.43 \Omega\text{-cm}$.

Comprehensively, to enhance the electrical conductivity of the ITO layer, it is recommended to expose the ITO thin films to a thermal annealing process by using Ar gas at 600°C , and using a 50°C/s annealing ramping rate. These parameters can ensure high conductivity, which is essential for the intended application. The fundamentals of the measurements have been taken at multiple locations on each sample to further validate the findings. However, the optical property of the layer is crucial for the intended applications, which will be discussed in the following subsection.

3.3. Optical Properties

The refractive index (n) and extinction coefficient (k) have been studied with respect to the annealing medium, annealing temperature, and annealing ramping rate. The refractive index for the as-deposited (reference) sample is relatively the highest among most the samples. However, after the annealing process, most of the samples display a reduction in refractive index, the reduction in refractive index is crucial to minimize the light beam reflection when the light transfer from the air medium ($n = 1$) to the ITO layer medium. On the other hand, the extinction coefficient remains consistently low for all the samples. This indicates that the material exhibits low light absorption properties, implying a high level of transparency or low light-scattering behavior, which is appropriate for the dust-cleaning process of solar panels.

For the annealing medium investigation, the lowest refractive index value was 1.85, which is relatively close to the refractive index value obtained by annealing in N_2 medium—and was observed when Ar gas was used. This suggests that the use of Ar gas may enhance the crystallinity of the ITO thin film, resulting in a lower refractive index compared to the other samples. On the other hand, the sample annealed with O_2 gas exhibits the highest refractive index value of 2.03, which is even higher than the as-deposited (reference) sample, as shown in Figure 9. Additionally, as discussed before, the extinction coefficient remains small for all samples in group A, while O_2 has the highest value of 0.023, as shown in Figure 10.

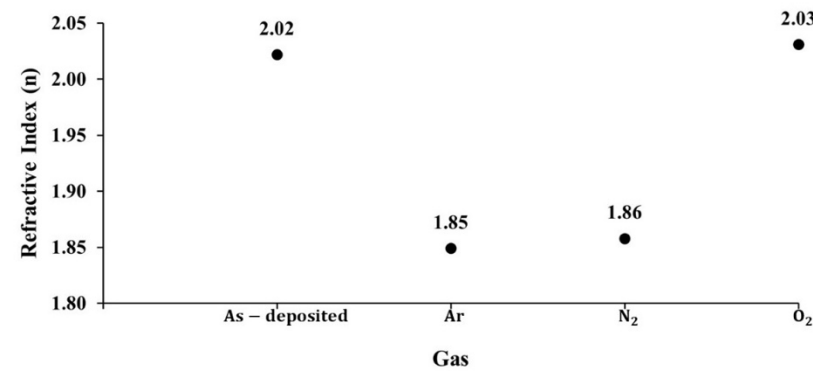


Figure 9. The refractive index of ITO thin film annealed in different gas medium (Ar, N₂, and O₂) at 500°C for 600 seconds. The x-axis represents the annealing gas medium (Ar, N₂, and O₂) and the y-axis represents the refractive index. The chart shows that the refractive index decreased from 2.02 in the as-deposited (reference) sample to approximately 1.85 after annealing. Annealing in Ar gas resulted in the lowest refractive index, while annealing in O₂ gas resulted in the highest refractive index.

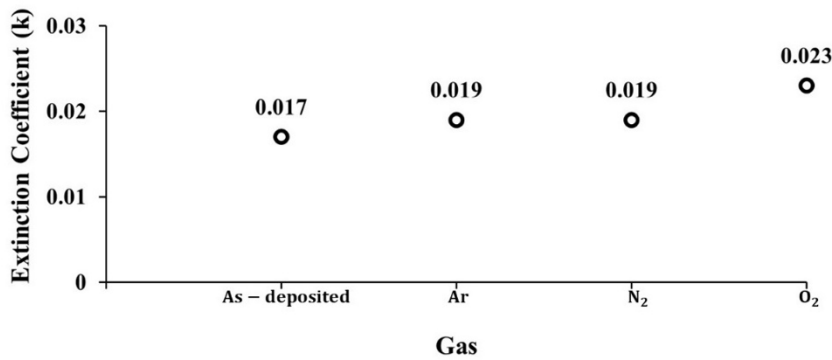


Figure 10. The extinction coefficient of ITO thin film annealed in different gas medium (Ar, N₂, and O₂) at 500°C for 600 seconds. The x-axis represents the annealing gas medium (Ar, N₂, and O₂) and the y-axis represents the extinction coefficient. The chart shows that the extinction coefficient remains small for all samples, while O₂ has the highest value of 0.023.

For the annealing temperatures investigation, as in sample group B, the values indicate that the refractive index decreases rapidly as the temperature increases, which agreed with the prior findings in 28. As depicted in Figure 11, the highest refractive index value is 1.94 at 300°C, while the lowest value is 1.81 at 700°C. This improvement may be attributed to the rearrangement of atoms caused by the elevated temperatures. Additionally, the highest extinction coefficient value is 0.038 at 300°C, whereas the lowest value is 0.018 at 400°C.

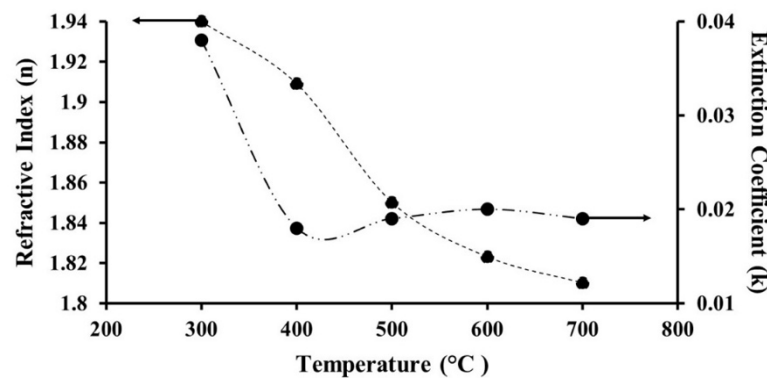


Figure 11. The refractive index and extinction coefficient of ITO thin film annealed in Ar gas at temperatures spanning 300°C to 700°C. The x-axis represents the annealing temperatures in degrees Celsius, and the y-axis represents the refractive index on the left side and the extinction coefficient on the right side. The chart demonstrates that as the temperature increased, the refractive index decreased from 1.94 at 300°C to 1.81 at 700°C. The extinction coefficient also decreased from 0.038 to 0.018 over 300°C and 400°C, respectively.

For the annealing ramping rate investigation, as in sample group C, the observed trend in the refractive index values is that they start to increase after a heating rate of 50°C/s. This indicates that as the temperature rises more rapidly, the material's refractive index also increases. The lowest refractive index value of 1.817 for 50°C/s suggests a lower density or arrangement of atoms, while the highest value of 1.848 corresponds to a higher density or arrangement of atoms caused by the faster heating rate. When it comes to the extinction coefficient values, they remain relatively small across the heating rates considered. The highest value of 0.025 at a heating rate of 25°C/s indicates a higher absorption or scattering of light. On the other hand, the lowest values of 0.011 for heating rates of 100°C/s and 125°C/s, as shown in Figure 12.

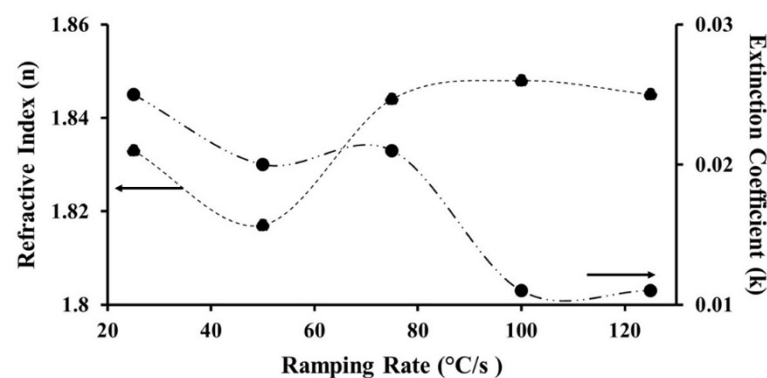


Figure 12. The refractive index and extinction coefficient of ITO thin film annealed in Ar gas at 600°C with different annealing ramping rates. The x-axis represents the annealing ramping rates in degrees Celsius per second (°C/s), and the y-axis represents the refractive index on the left side and extinction coefficient on the right. The chart indicates that the refractive index starts to increase after 50°C/s, which has the lowest refractive index value of 1.817, which was found to be the optimal annealing ramping rate. The extinction coefficient also decreased from 0.025 to 0.011 over 25°C/s and 100°C/s respectively.

4. Conclusions

This work presented a detailed investigation of the thermal processing correlation of the ITO layer with its surface characteristics, as well as electrical and optical properties, with the ultimate goal of creating an efficient system for reducing dust buildup on solar panels. The study conducted a series

of annealing experiments to analyze the impact of annealing gas, annealing temperature, and annealing ramping rate on the properties of ITO thin films. The results showed that the recommended conditions for annealing within Ar gas medium, at 600°C, and with an annealing ramping rate of 50°C/s. With relatively low R_a and R_q , the sheet resistance decreased from 31.13 $\Omega/square$ at an annealing ramping rate of 125°C/s to 27.42 $\Omega/square$ at an annealing ramping rate of 50°C/s, while the resistivity is also decreased from 7.72 $\Omega - cm$ to 1.44 $\Omega - cm$ over the same temperature range. Despite the fact that the annealing in the O₂ medium increased the refractive index from 1.85 (without annealing) to 2.03, the annealing in Ar at the recommended conditions can slightly reduce the refractive index to 1.817. These findings provide valuable insights into enhancing the ITO layer characteristics, which can be utilized in the development of an electrostatic or magnetic cleaning system that overcomes the challenges associated with dust buildup on solar panels. By applying the judiciously chosen processing conditions, electrostatic (or magnetic) cleaning using ITO-coated solar panels can bring about improved performance and durability, leading to better dust mitigation and overall solar energy production efficiency.

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