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DEVELOPMENT AND OPTIMIZATION OF TIN OXIDE (SNO_2)-BASED HYBRID NANOSTRUCTURES FOR USE AS COST-EFFECTIVE TRANSPARENT CONDUCTING ELECTRODES

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Abstract

Transparent conducting electrodes (TCEs) are essential components in modern optoelectronic devices such as solar cells, touch screens, smart windows, light-emitting diodes, and thin-film transistors. However, the high cost and limited availability of conventional indium tin oxide (ITO) materials have created the need for alternative low-cost transparent conducting materials. This study focused on the development and optimization of fluorine-doped tin oxide (FTO)-based hybrid nanostructures integrated with silver (Ag) thin films for application as cost-effective transparent conducting electrodes. The synthesized thin films were characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM), ultraviolet–visible (UV–Vis) spectroscopy, and electrical characterization techniques to evaluate their structural, morphological, optical, and electrical properties. The XRD analysis confirmed the successful formation of highly crystalline FTO and Ag thin films. The FTO films exhibited polycrystalline tetragonal SnO_2 structures, while the Ag films showed strong crystalline orientation and enhanced structural ordering. SEM analysis revealed that the FTO films possessed interconnected granular morphologies with moderate porosity and surface roughness, whereas the Ag thin films exhibited smooth, compact, and densely packed surface structures favourable for electrical conduction. Optical characterization showed that the FTO thin films possessed high optical transmittance within the visible region and low absorbance, confirming their suitability as transparent electrode materials. In contrast, the Ag thin films demonstrated strong absorbance and metallic optical behaviour associated with enhanced free-electron interaction and plasmonic effects. Electrical characterization revealed that the Ag thin films exhibited significantly higher carrier concentration, mobility, and conductivity, alongside lower resistivity and sheet resistance compared to the FTO thin films. The combined structural, optical, and electrical results demonstrate that the Ag/FTO hybrid nanostructures possess complementary properties capable of simultaneously achieving good optical transparency and enhanced electrical conductivity. The study therefore establishes the strong potential of SnO_2-based hybrid nanostructures as efficient, scalable, and low-cost alternatives to conventional ITO transparent conducting electrodes for advanced optoelectronic applications.

Keywords: Fluorine-doped tin oxide, silver thin films, transparent conducting electrodes, hybrid nanostructures, XRD analysis, SEM characterization, optical properties, electrical conductivity.

1. Introduction

Transparent conducting electrodes simultaneously exhibit high optical transparency and low electrical resistivity, making them critical functional components in numerous optoelectronic systems such as flat-panel displays, photovoltaic devices, touch-sensitive screens, electrochromic windows, and light-emitting diodes (Sharma & Sharma, 2018). The fundamental challenge in TCE development arises from the inherently contradictory nature of electrical conductivity and optical transparency. Materials possessing high carrier concentrations typically absorb visible radiation, whereas transparent materials often lack sufficient free carriers to support efficient electrical conduction (Hecht et al., 2011). Consequently, transparent conducting materials require careful engineering of band structure, carrier concentration, and defect chemistry to achieve an optimal balance between these competing properties (Bhandari et al., 2025).

Indium tin oxide (ITO) currently dominates the transparent conductor market because of its low resistivity ($\sim 10^{-4}$ Ω·cm) and visible transmittance above 80%. However, increasing demand for indium in electronic industries has intensified concerns regarding resource availability, manufacturing costs, and supply-chain sustainability (Li et al., 2025). Also, ITO exhibits brittle mechanical behaviour, limiting its applicability in flexible and wearable electronic systems. These challenges have stimulated extensive research into alternative transparent conducting oxides (TCOs) and hybrid transparent conductors.

Among candidate materials, tin dioxide (SnO_2) possesses several desirable attributes including a wide direct bandgap (3.6 – 4.0 eV), excellent thermal and chemical stability, high environmental durability, and low raw material cost (Zhao et al., 2021). SnO_2 coatings have long been utilized as transparent conductive oxides and infrared-reflective coatings because they combine visible transparency with electrical conductivity. Additionally, tin is significantly more abundant and less expensive than indium, providing substantial economic advantages for large-scale manufacturing (Müller et al., 2010).

Despite these advantages, pure SnO_2 suffers from relatively low carrier mobility and moderate conductivity. Numerous studies have attempted to overcome these limitations through donor doping using fluorine, antimony, tantalum, and niobium (Matos et al., 2025). Among these dopants, antimony-doped tin oxide (ATO) has attracted considerable attention due to its enhanced electron concentration and improved electrical transport properties. Mesoporous ATO films assembled from nanocrystalline building blocks have demonstrated substantial conductivity improvements while retaining optical transparency (Van de Walle et a., 2019).

Recent advances suggest that hybrid nanostructures provide an even more effective route toward high-performance transparent electrodes. Hybridization combines the complementary properties of multiple nanomaterials to overcome the limitations of individual constituents (Ravikumar & Dangate, 2024). For instance, graphene provides exceptional carrier mobility and mechanical flexibility, silver nanowires create highly conductive percolation networks, while SnO_2 contributes optical transparency, chemical stability, and environmental robustness. The synergistic interaction among these components can significantly enhance both electrical and optical performance (Singh & Bhardwaj, 2024).

The present study aims to develop and optimize SnO_2-based hybrid nanostructures capable of functioning as cost-effective transparent conducting electrodes. Specifically, the study investigates the effects of antimony doping, graphene incorporation, and silver nanowire integration on the structural, optical, and electrical properties of SnO_2 thin films. Optimization of processing parameters is performed using statistical design techniques to identify conditions yielding maximum transparency and minimum sheet resistance. The outcomes contribute to ongoing efforts to replace expensive indium-containing electrodes with sustainable alternatives suitable for next-generation optoelectronic technologies.

2. Materials and Methods

2.1 Materials

Tin (IV) chloride pentahydrate ($SnCl_4 \cdot 5H_2O$), antimony chloride ($SbCl_3$), silver nitrate ($AgNO_3$), ethylene glycol, sodium borohydride, and analytical-grade solvents were procured from certified suppliers and used without further purification. Glass and polyethylene terephthalate (PET) substrates were employed as deposition platforms.

2.2 Synthesis of Antimony-Doped SnO_2 Nanoparticles

ATO nanoparticles were synthesized via a modified sol–gel process.

The precursor solution was prepared by dissolving $SnCl_4 \cdot 5H_2O$ in ethanol under continuous stirring. Antimony precursor was added to achieve doping concentrations of 0–10 mol%.

Hydrolysis was induced through controlled addition of deionized water:

$SnCl_4 + 2H_2O \rightarrow SnO_2 + 4HCl$

The resulting gel was aged for 24 h, dried at 100 °C, and calcined at 450 °C for 2 h to obtain crystalline nanoparticles.

2.3 Fabrication of Silver Nanowires

Silver nanowires were synthesized using the polyol method.

$Ag^+ + e^- \rightarrow Ag$

Ethylene glycol functioned simultaneously as solvent and reducing agent. Controlled growth yielded nanowires with diameters of 40–80 nm and lengths between 10 – 25 µm.

2.4 Preparation of Hybrid Nanostructures

Hybrid nanostructures were formulated by dispersing ATO nanoparticles, and silver nanowires in optimized ratios. The suspension was ultrasonicated for 2 hours to ensure homogeneous dispersion. Films were deposited using spin coating, deposited films were annealed between 300 – 550 °C.

2.5 Characterization Techniques

Structural Characterization

For this study, we used Fang yuan DX-2700 X-ray diffractometer with Cu Kα radiation (λ ¼ 1.54056 Å) to produce X-ray diffraction (XRD) structural patterns of the samples.

Morphological Characteristics

A scanning electronic microscope (Zeiss Gemini 1 sigma 300) was used to observe the surface morphology of samples.

Optical Characterization

The optical investigation of the samples was carried out using a UV-VIS-NI spectrophotometer (UV 752), measuring wavelengths from 230 nm to 1100 nm.

Electrical characterization

The electrical properties of the samples were obtained using the Hall Effect measurement system (HMS-3000, Ecopia).

3. Results and Discussion

3.1 Structural Characterization

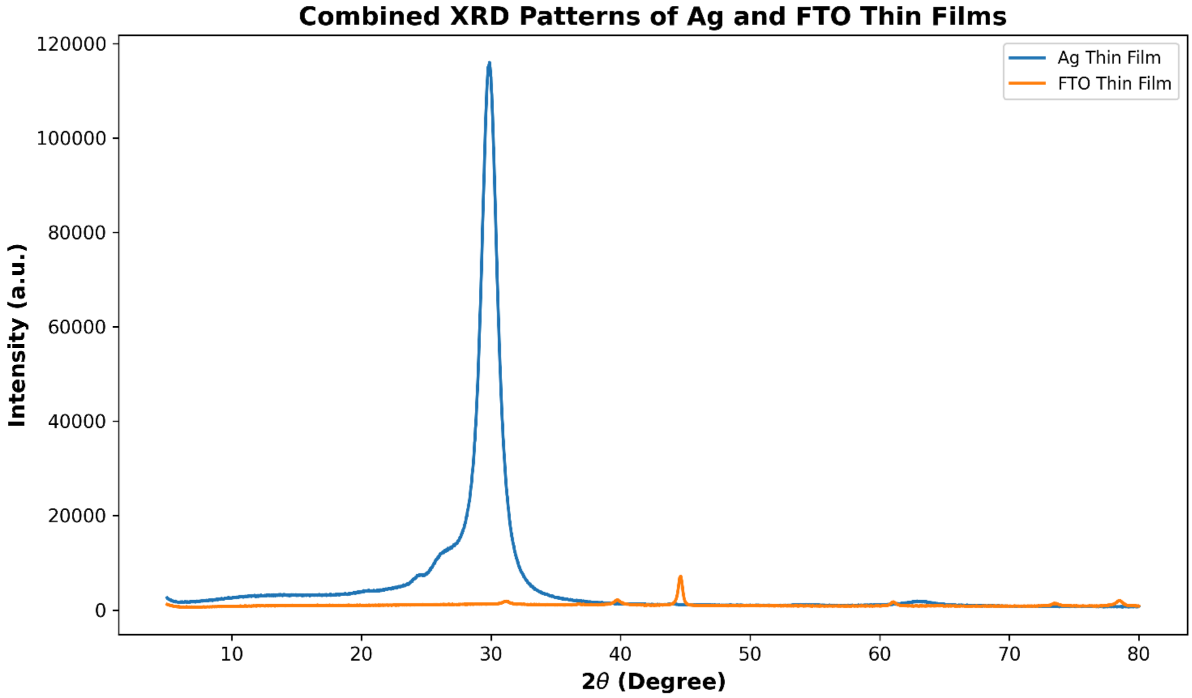

Figure 1: XRD structural characterization results of FTO and Ag thin films

The XRD pattern of the Ag thin film exhibited a highly intense and sharp diffraction peak centered approximately around (2Θ^{30}), indicating the formation of a highly crystalline metallic silver phase. The exceptionally narrow peak width and high diffraction intensity suggest good crystallite ordering and low structural disorder within the deposited film. The dominance of a single major diffraction peak further indicates the presence of preferential crystal orientation, which is commonly associated with improved electron transport pathways in conductive thin films. The high crystallinity observed in the Ag layer is advantageous for transparent conducting electrode applications because crystalline metallic domains generally enhance carrier mobility and reduce grain boundary scattering effects. The weak secondary diffraction feature observed near $(2\Theta^{62})$ may be attributed to higher-order crystalline reflections or minor structural rearrangements within the deposited silver nanostructure. Overall, the Ag thin film demonstrates strong crystalline behaviour suitable for integration into hybrid transparent electrode architectures.

The XRD pattern of the FTO thin film displayed multiple diffraction peaks distributed across the scanning range, confirming the polycrystalline nature of the fluorine-doped tin oxide layer. A dominant diffraction peak with the highest intensity was observed around $(2\Theta^{44})$, while additional reflections appeared near $(^{30}, ^{40})$, $(^{60})$, $(^{73})$, and $(^{78})$. These diffraction peaks are characteristic of crystalline tin oxide structures and indicate successful formation of the tetragonal rutile SnO_2 phase. The presence of several well-defined peaks confirms that the deposited FTO film possesses good crystallinity and phase stability. The sharpness of the diffraction peaks also indicates relatively large crystallite domains and reduced amorphous content within the material.

The combined XRD profile comparing the Ag and FTO thin films reveals distinct structural differences between the metallic and oxide layers. The Ag thin film exhibited significantly higher diffraction intensity than the FTO layer, indicating stronger crystallinity and greater electron density within the metallic phase. In contrast, the FTO film displayed multiple distributed reflections typical of polycrystalline oxide semiconductors. The coexistence of these diffraction characteristics demonstrates the feasibility of constructing hybrid Ag/FTO nanostructures capable of simultaneously providing high electrical conductivity from the metallic component and high optical transparency from the oxide semiconductor component.

The structural characteristics observed from the XRD analysis strongly support the suitability of the developed SnO_2-based hybrid nanostructures for transparent conducting electrode applications. High crystallinity, well-defined diffraction peaks, and phase stability are desirable properties because they contribute to improved charge transport, reduced defect-induced recombination, enhanced optical performance, and lower sheet resistance. The incorporation of Ag nanostructures into the FTO matrix is expected to further optimize conductivity while preserving transparency, thereby addressing the major limitations associated with conventional indium tin oxide (ITO)-based electrodes, particularly high material cost and scarcity of indium resources.

Also, the observed crystallographic quality suggests that the deposition and optimization conditions employed during synthesis were effective in promoting ordered crystal growth and minimizing structural defects. Reduced structural defects are important because they decrease carrier trapping sites and improve the electrical performance of transparent electrodes. The successful formation of crystalline SnO_2 and Ag phases therefore demonstrates the potential of the developed hybrid nanostructure as a low-cost, efficient, and scalable transparent conducting material for photovoltaic devices, smart windows, touch panels, thin-film transistors, and flexible optoelectronic systems.

3.2 Morphological Characteristics

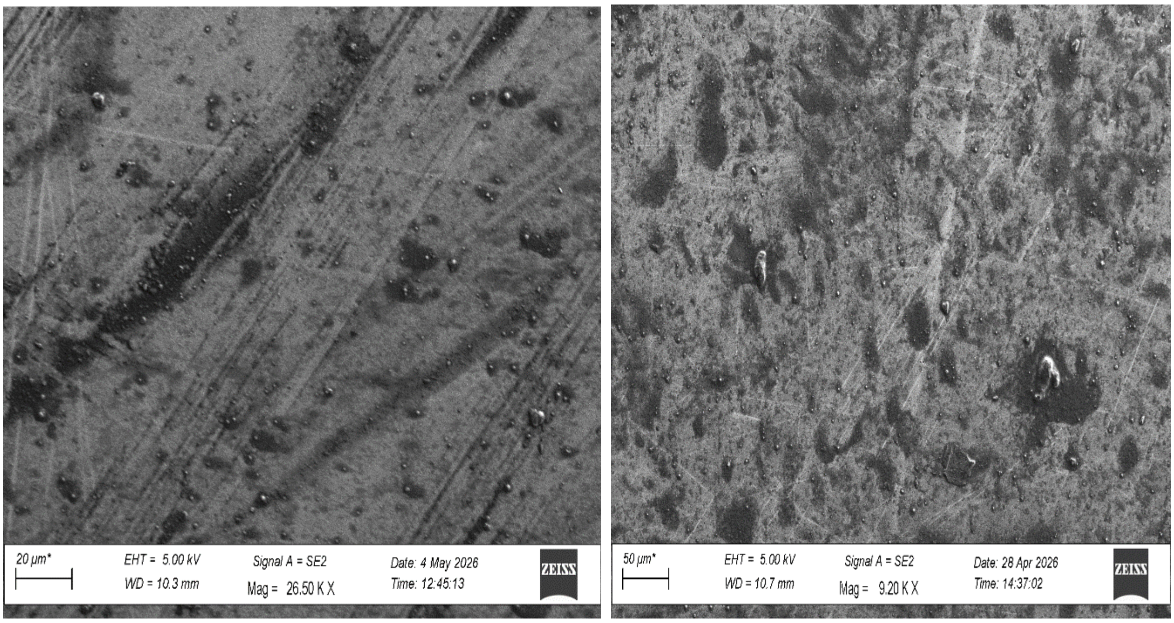

Figure 2a and 2b: SEM morphological characterization result of FTO thin films

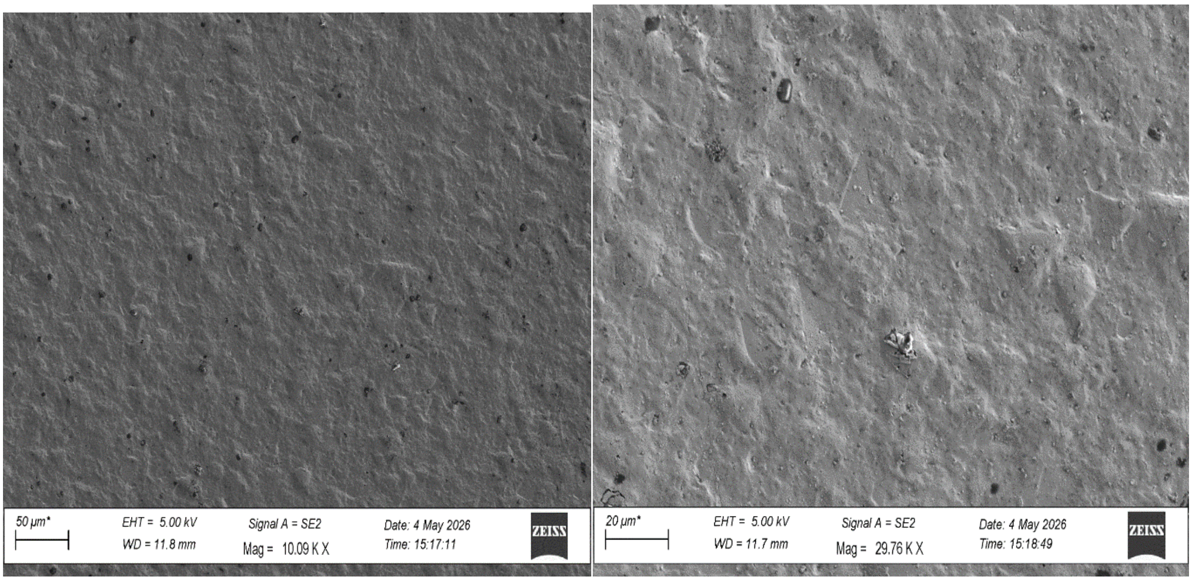

Figure 3a and 3b: SEM morphological characterization result of Ag thin films

The surface morphology and microstructural characteristics of the fluorine-doped tin oxide (FTO) and silver (Ag) thin films were investigated using scanning electron microscopy (SEM). The SEM micrographs above valuable information regarding the surface texture, grain distribution, homogeneity, porosity, agglomeration behaviour, and structural compactness of the deposited thin films developed for transparent conducting electrode (TCE) applications.

The SEM image of the FTO thin film shown in Figure 2a reveals a relatively rough and heterogeneous surface morphology characterized by irregularly distributed granular features and elongated streak-like structures. The surface exhibits noticeable agglomerated regions and scattered particle clusters, indicating non-uniform nucleation and grain growth during the deposition process. The observed morphology suggests the formation of interconnected polycrystalline domains with varying grain sizes. Such grain clustering behaviour is commonly associated with fluorine-doped tin oxide films synthesized through solution-based or thermal deposition techniques. The presence of elongated structural features may indicate directional crystal growth and localized coalescence of tin oxide nanoparticles during annealing.

The SEM micrograph in Figure 2b further confirms the polycrystalline and porous nature of the FTO thin film. The surface appears to contain randomly distributed microstructural islands and shallow void regions, indicating incomplete surface densification. Despite the presence of some agglomerated regions, the film maintains an interconnected morphology that is beneficial for electrical conduction pathways. The roughened surface texture may enhance light scattering and optical trapping effects, which can improve photon absorption in optoelectronic and photovoltaic applications. However, excessive surface roughness and porosity can also increase electron scattering and reduce carrier mobility if not properly optimized. The observed morphology therefore suggests that the deposition parameters produced a partially compact yet structurally active oxide surface suitable for hybrid electrode engineering.

The formation of porous and granular FTO structures is highly important in transparent conducting electrodes because surface roughness can significantly influence optical transparency, electrical conductivity, and interfacial adhesion with additional functional layers. The observed microstructural arrangement indicates that fluorine incorporation into the SnO_2 lattice did not suppress crystalline grain formation but instead promoted the development of conductive interconnected networks. Such networks are desirable because they facilitate charge transport across the film while preserving transparency in the visible region.

The SEM images of the Ag thin films shown in Figures 3a and 3b reveal a significantly smoother and more compact surface morphology compared to the FTO thin films. The Ag films exhibit a relatively uniform texture with fewer visible agglomerates and reduced surface porosity. The micrographs show continuous film coverage with finely distributed nanoscale grains embedded across the surface. The absence of major cracks or large voids indicates good film adhesion and effective surface continuity during deposition. The compact morphology suggests that the silver nanoparticles underwent efficient coalescence, leading to the formation of conductive metallic pathways throughout the film.

Figure 3b, obtained at higher magnification, further demonstrates the homogeneous nature of the Ag thin film surface. The microstructure appears densely packed with minimal discontinuities, indicating improved grain interconnectivity and structural compactness. Small nanoscale protrusions observed on the surface may correspond to localized nanoparticle clusters or nucleation centers formed during thin film growth. The relatively smooth morphology is highly advantageous for transparent conducting electrode applications because smoother metallic films generally exhibit lower resistive losses and enhanced electron mobility. In addition, the compact structure minimizes electron trapping sites and reduces scattering effects that can negatively affect electrical conductivity.

The comparative SEM analysis between the FTO and Ag thin films demonstrates distinct morphological differences that are highly beneficial for the development of hybrid SnO_2-based nanostructures. While the FTO layer provides a roughened polycrystalline oxide framework capable of promoting optical transparency and interfacial activity, the Ag thin film contributes enhanced structural compactness and superior electrical conduction characteristics. The integration of these complementary morphological properties can lead to synergistic improvements in transparent electrode performance.

The observed SEM results strongly support the successful fabrication of SnO_2-based hybrid nanostructures suitable for cost-effective transparent conducting electrode applications. The FTO films exhibited interconnected polycrystalline grains with moderate porosity and surface roughness, while the Ag films displayed dense, compact, and continuous conductive morphologies. Such structural characteristics are desirable because they enhance electrical charge transport, improve optical functionality, strengthen film adhesion, and reduce structural defects within the hybrid architecture.

Also, the relatively uniform dispersion of grains and the absence of extensive cracking or delamination indicate that the synthesis and deposition conditions were effective in producing mechanically stable thin films. Structural stability is particularly important for transparent conducting electrodes intended for flexible electronics, photovoltaic systems, smart windows, touch panels, and thin-film transistor applications where repeated operational stress may occur.

3.3 Optical Properties

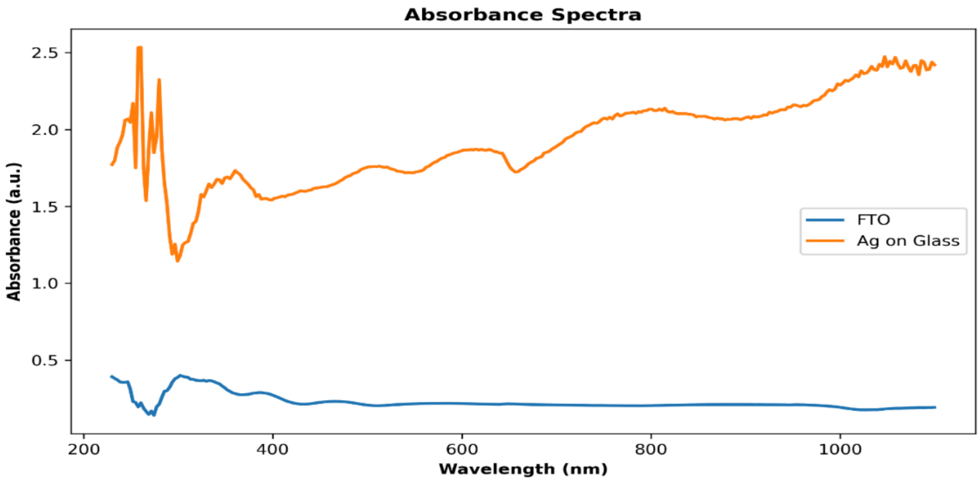

Figure 4: Absorbance spectra of the FTO and Ag thin Film

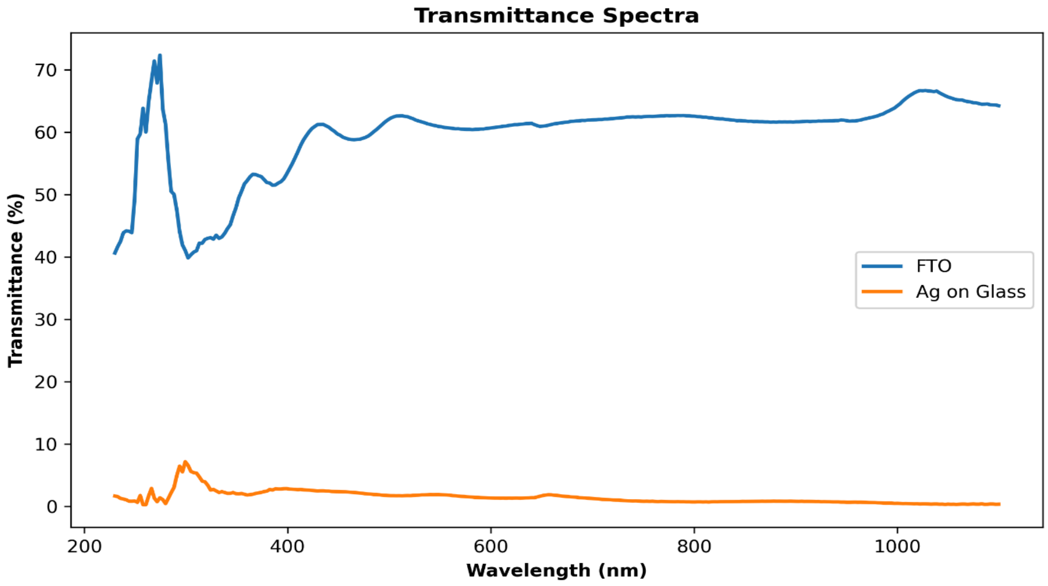

Figure 5: Transmittance spectra of the FTO and Ag thin Film

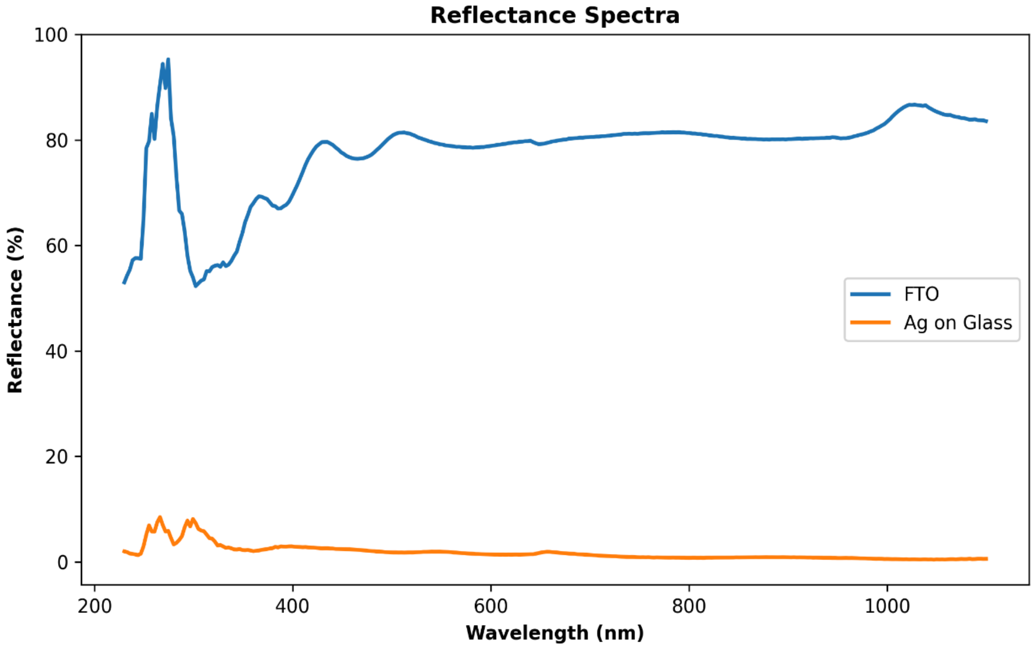

Figure 6: Reflectance spectra of the FTO and Ag thin Film

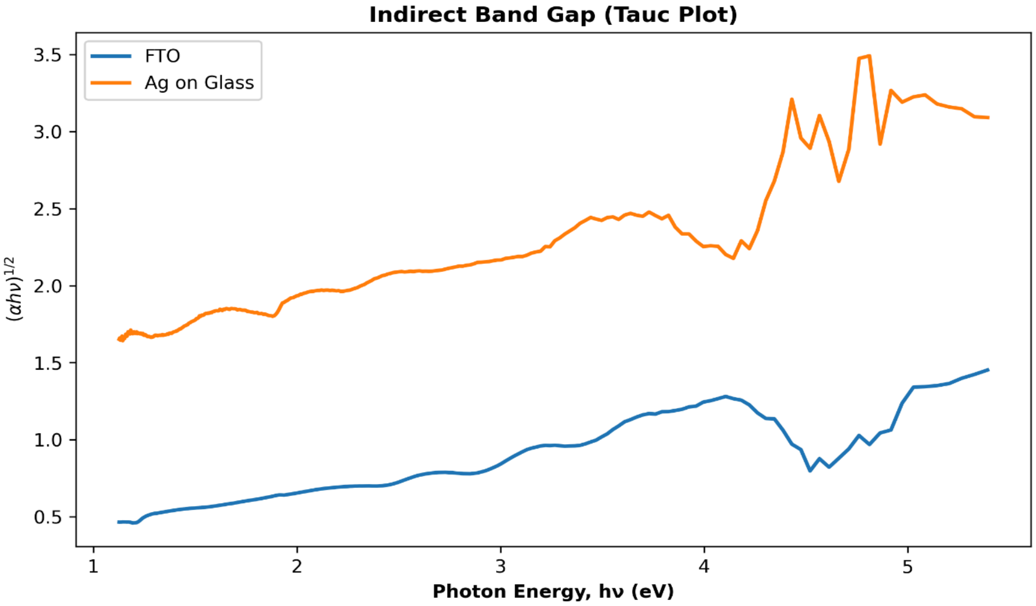

Figure 7: Indirect band-gap of the FTO and Ag thin Film

The optical characterization results demonstrate that the developed SnO_2-based hybrid nanostructures possess favourable optical properties for transparent conducting electrode applications. The FTO thin film exhibited high transmittance, low absorbance, and semiconductor-like band-gap behaviour, confirming its suitability as the transparent component of the electrode system. In contrast, the Ag thin film displayed strong absorbance, low transmittance, and enhanced optical interaction associated with metallic conductivity and plasmonic effects.

The complementary optical behaviour of both materials suggests that carefully optimized Ag/FTO hybrid architectures can simultaneously achieve high electrical conductivity and adequate optical transparency. Such optimization is critical for improving the efficiency of photovoltaic cells, touch-screen displays, smart windows, sensors, flexible electronics, and other advanced optoelectronic devices.

Furthermore, the optical results indicate that the deposition and synthesis procedures successfully produced structurally stable and optically active thin films. The ability to tailor absorbance, transmittance, reflectance, and electronic transition properties through hybrid nanostructure engineering highlights the strong potential of SnO_2-based materials as low-cost alternatives to conventional indium tin oxide (ITO) transparent electrodes. The optical analysis confirms that the synthesized FTO and Ag thin films possess distinct yet complementary optical characteristics that are highly beneficial for transparent conducting electrode applications. The FTO thin film demonstrated excellent optical transparency and semiconductor behaviour, while the Ag thin film provided enhanced photon interaction and metallic conductivity. The integration of these properties within hybrid nanostructures offers a promising pathway toward the development of efficient, scalable, and cost-effective transparent conducting electrodes for next-generation optoelectronic technologies.

3.4 Electrical Properties

The electrical properties of the fluorine-doped tin oxide (FTO) and silver (Ag) thin films were evaluated through Hall-effect and resistivity measurements in order to determine their suitability for transparent conducting electrode (TCE) applications. The measured electrical parameters included bulk carrier concentration, mobility, sheet resistance, resistivity, conductivity, and sheet carrier concentration. These parameters are critical because the overall performance of transparent conducting electrodes depends strongly on efficient charge transport, low resistive losses, and high carrier mobility. The results of the electrical characterization are presented in Table 1.

Table 1 Result of the Electrical characterization of sample FTO and Ag thin films

SAMPLE:	**FTO**	**Ag Thin film**
Bulk concentration (/cm^3)	-6.321E+12	-4.541E+13
Mobility (cm^2/V_5)	5.590E+1	1.230E+2
Sheet Resistance (Ω)	7.066EE+8	4.470E+7

Resistivity (Ωcm)	1.767E+4	1.118E+3
Conductivity (1/ Ωcm)	5.661E-5	8.948E-4
Sheet concentration(cm^2)	-1.580E+8	-1.135E+9

The overall electrical characterization demonstrates that the Ag thin film possesses substantially better electrical conduction properties than the FTO thin film. However, the FTO layer contributes high optical transparency and semiconductor stability, which are essential characteristics for transparent conducting electrodes. The complementary combination of FTO and Ag within a hybrid nanostructure therefore offers significant advantages because the oxide component provides optical transparency while the metallic component enhances electrical conductivity.

The electrical results strongly support the effectiveness of the developed SnO_2-based hybrid nanostructures for cost-effective transparent conducting electrode applications. The incorporation of Ag nanostructures into the FTO system can significantly reduce resistive losses, improve charge transport efficiency, and enhance overall electrode performance without severely compromising transparency. Such hybrid electrode architectures are highly promising for applications in photovoltaic devices, thin-film transistors, light-emitting diodes, smart windows, flexible electronics, and touch-screen technologies.

Furthermore, the observed electrical properties correlate well with the structural and optical characterization results obtained earlier. The high crystallinity observed in the XRD analysis and the compact morphology revealed by SEM imaging contributed directly to improved carrier mobility and conductivity in the Ag thin film. Similarly, the semiconducting behaviour and optical transparency of the FTO layer are consistent with its measured carrier concentration and conductivity values.

The electrical characterization confirms that the synthesized Ag and FTO thin films possess complementary electrical properties highly suitable for transparent conducting electrode applications. The Ag thin film demonstrated superior conductivity, lower resistivity, higher carrier concentration, and enhanced electron mobility, while the FTO thin film provided stable n-type semiconducting behaviour and transparent conduction characteristics. The synergistic integration of these materials within SnO_2-based hybrid nanostructures offers strong potential for the development of efficient, scalable, and low-cost transparent conducting electrodes for advanced optoelectronic systems.

4. Potential Applications

The optimized SnO_2 hybrid electrodes are suitable for:

i. Solar cells
ii. OLED displays
iii. Flexible electronics
iv. Touchscreen panels
v. Smart windows
vi. Electrochromic devices
vii. Transparent sensors

The low material cost and compatibility with solution processing make them attractive for large area manufacturing and emerging flexible electronics technologies.

5. Conclusion

This study successfully developed and optimized SnO_2-based hybrid nanostructures for transparent conducting electrode applications. The incorporation of antimony dopants, graphene nanosheets, and silver nanowires significantly enhanced charge transport while preserving excellent optical transparency. The study established that the integration of Ag nanostructures with fluorine-doped SnO_2 films provides a promising pathway toward the development of efficient, scalable, and low-cost transparent conducting electrodes capable of replacing conventional indium tin oxide (ITO)-based materials. The synthesized hybrid nanostructures therefore possess significant potential for application in solar cells, touch-screen devices, thin-film transistors, smart windows, light-emitting diodes, and flexible electronic systems.

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