

Synthesis and Characterization of Nanostructured SnO₂ for Photovoltaic Applications

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Abstract

Nanostructured tin dioxide (SnO₂) has attracted considerable attention for photovoltaic applications because of its wide band gap, chemical stability, and favourable electron-transport characteristics. In the present study, nanostructured SnO₂ was synthesized through a controlled precipitation route and systematically investigated to establish the relationship between its structural, morphological, optical, and electrical properties. X-ray diffraction analysis confirmed the formation of the tetragonal rutile SnO₂ phase with an average crystallite size of approximately 23.6 nm. Scanning electron microscopy revealed predominantly quasi-spherical to irregular nanoparticles with an average particle size of approximately 28 ± 6 nm, while energy-dispersive X-ray spectroscopy confirmed Sn and O as the principal constituent elements. UV-visible analysis showed a distinct absorption edge near 343 nm, with an estimated optical band gap of 3.62 eV. Electrical measurements demonstrated semiconducting behaviour with a conductivity of approximately 4.39×10^{-5} S cm⁻¹. The observed properties indicate that crystallinity, nanoscale morphology, interparticle interactions, and defect-related characteristics collectively influence the electrical response of SnO₂. The combination of nanoscale dimensions, high crystallinity, wide optical band gap, and suitable electrical characteristics highlights the potential of the synthesized SnO₂ for photovoltaic applications, particularly as an electron-transport material. The study establishes a structure–property relationship that can support the further optimization of SnO₂-based functional layers for photovoltaic device architectures.

Keywords: Nanostructured SnO₂; Tin dioxide; X-ray diffraction; Surface morphology; Optical band gap; Electrical conductivity; Electron transport layer; Photovoltaics.

1. Introduction

The rapid development of photovoltaic technologies has intensified the search for semiconductor materials that combine suitable electronic properties, chemical stability, optical transparency, and compatibility with low-temperature processing. Metal-oxide semiconductors are particularly attractive because their electronic structure and surface properties can be tailored through crystallite-size control, morphology engineering, defect regulation, and doping. Among these materials, tin dioxide (SnO₂) has attracted considerable attention because of its wide optical band gap, high chemical and thermal stability, relatively high electron mobility, and suitability for transparent and electron-transporting applications (Sharma et al., 2021). SnO₂ is an n-type metal-oxide semiconductor whose functional properties are strongly influenced by its crystal

structure, crystallinity, particle size, surface morphology, and defect concentration. Telee and Kumar (2023) At the nanoscale, the increased surface-to-volume ratio and modified charge-transport pathways can substantially influence its optical and electrical behaviour. Consequently, nanostructured SnO₂ can be prepared in several forms, including nanoparticles, nanowires, nanosheets, and thin films, providing considerable flexibility for photovoltaic and optoelectronic applications (Sharma et al., 2021).

In photovoltaic devices, SnO₂ has emerged particularly as an electron-transport layer (ETL), where efficient extraction and transport of photogenerated electrons are essential for minimizing charge accumulation and interfacial recombination. Chappara et al. (2023) Compared with conventional TiO₂-based ETLs, SnO₂ offers favourable energy-level alignment and higher

electron mobility, making it particularly suitable for planar photovoltaic architectures (Jiang et al., 2018). Jiang et al. (2017) demonstrated that solution-processed SnO₂ nanoparticles could provide efficient electron extraction in planar perovskite solar cells, with reduced hysteresis and a certified power-conversion efficiency of 19.9%, highlighting the importance of SnO₂ in high-performance photovoltaic architectures. The properties of SnO₂ are closely related to its structural and morphological characteristics. Highly crystalline SnO₂ nanocrystals, for example, have demonstrated favourable electron-transport behaviour and improved device stability when employed as electron-transporting layers (Zhu et al., 2016). Similarly, nanostructured morphologies such as SnO₂ nanosheets have been investigated as alternative electron-transporting materials, demonstrating the potential of morphology-controlled SnO₂ for photovoltaic applications (Zhou et al., 2016). These findings indicate that the optimization of SnO₂ cannot be limited to its chemical composition alone; rather, its crystal structure, crystallite dimensions, surface morphology, and electrical characteristics must be considered collectively.

Despite the considerable progress in SnO₂-based photovoltaic materials, variations in synthesis conditions can produce significant differences in crystallinity, grain morphology, defect density, carrier transport, and electrical conductivity. Singh and Singh (2024) Recent studies have particularly emphasized the roles of intrinsic defects, surface hydroxyl groups, morphology, and interfacial characteristics in determining the charge-transport behaviour of SnO₂ layers (Gong et al., 2023). Thus, establishing a clear relationship between the structural and morphological characteristics of nanostructured SnO₂ and its electrical response remains important for rational materials design. Recent reviews further demonstrate that SnO₂ continues to receive substantial attention as an ETL because of its high electron mobility, wide band gap, chemical stability, and compatibility with relatively low-temperature fabrication processes. Wasim and Ahmad (2024) However, defect control, film uniformity, interfacial charge transport, and reproducibility remain important challenges for achieving consistently high photovoltaic performance (Wang et al., 2025). Therefore,

systematic characterization of the structural, morphological, and electrical properties of SnO₂ nanostructures is essential for understanding their functional behaviour and assessing their suitability for photovoltaic applications.

Accordingly, the present study focuses on the preparation and comprehensive characterization of nanostructured SnO₂, with particular emphasis on its structural, morphological, and electrical properties. The study aims to establish the relationship between the physicochemical characteristics of the synthesized SnO₂ nanostructures and their potential applicability in photovoltaic systems.

2. Materials and Methods

2.1 Materials

Tin(IV) chloride pentahydrate (SnCl₄·5H₂O) was used as the precursor for the synthesis of nanostructured SnO₂. Ethanol and deionized water were used as the reaction medium and washing agents, respectively. Ammonium hydroxide (NH₄OH) was employed as the precipitating agent to control the hydrolysis and precipitation of the tin precursor. All chemicals were of analytical grade and were used without further purification. Deionized water was used throughout the experimental procedure to minimize contamination from dissolved ions.

2.2 Synthesis of Nanostructured SnO₂

Nanostructured SnO₂ was synthesized through a controlled precipitation route followed by thermal treatment. A predetermined quantity of SnCl₄·5H₂O was dissolved in deionized water under continuous magnetic stirring to obtain a homogeneous precursor solution. An aqueous NH₄OH solution was subsequently added dropwise under vigorous stirring until the desired alkaline condition was achieved. The resulting suspension was maintained under continuous stirring to promote hydrolysis and formation of a hydrated tin oxide precursor. The precipitated material was separated from the reaction medium and repeatedly washed with deionized water to remove residual chloride and other soluble species. The washed precipitate was dried at approximately 80–100 °C until a constant mass was obtained. The dried precursor was then calcined at a predetermined temperature for several hours to promote

dehydration, crystallization, and formation of crystalline SnO₂. The resulting powder was gently ground using an agate mortar and stored in a sealed container prior to characterization.

2.3 Structural Characterization

The crystalline structure of the synthesized SnO₂ was investigated using X-ray diffraction (XRD). The diffraction pattern was recorded over an appropriate 2θ range, using Cu Kα radiation (λ ≈ 1.5406 Å). The observed diffraction peaks were indexed by comparison with standard crystallographic data. The phase composition, crystallinity, lattice parameters, and crystallite size were evaluated from the XRD pattern. The average crystallite size was estimated using the Scherrer equation:

$$D = K\lambda / \beta \cos\theta$$

where D is the crystallite size, K is the shape factor, λ is the wavelength of the incident X-ray, β is the full width at half maximum (FWHM) of the selected diffraction peak, and θ is the corresponding Bragg angle.

2.4 Morphological and Elemental Characterization

The surface morphology of the synthesized SnO₂ was examined using scanning electron microscopy (SEM). The SEM micrographs were used to evaluate particle morphology, surface texture, degree of agglomeration, and approximate particle-size distribution. The elemental composition was determined using energy-dispersive X-ray spectroscopy (EDS/EDX) coupled with the SEM system. The presence and relative distribution of Sn and O were examined to confirm the chemical composition of the synthesized material. Where applicable, transmission electron microscopy (TEM) was further employed to determine the nanoscale morphology and particle dimensions. High-resolution TEM images were used to examine lattice fringes and provide additional evidence of the crystalline nature of the SnO₂ nanostructures.

2.5 Optical Characterization

The optical properties of the synthesized SnO₂ were investigated using UV–visible spectroscopy. The absorption spectrum was recorded over the relevant wavelength range. The

optical band-gap energy was estimated using the Tauc relationship:

$$(\alpha h\nu)^n = A(h\nu - E_g)$$

Where α is the absorption coefficient, $h\nu$ is the photon energy, A is a proportionality constant, E_g is the optical band-gap energy, and n represents the nature of the electronic transition. For the direct transition, $n=2$, whereas for an indirect transition, $n=1/2$. The appropriate transition model was selected based on the electronic characteristics of the synthesized SnO₂.

2.6 Electrical Characterization

The electrical properties of the synthesized SnO₂ were evaluated using an appropriate electrical measurement configuration. For measurements on compacted pellets, the SnO₂ powder was pressed into circular pellets under controlled pressure and subjected to suitable thermal treatment to improve mechanical integrity and electrical contact. Conductive electrodes were applied to the sample surfaces, and current–voltage (I–V) measurements were performed under controlled conditions. The electrical conductivity was calculated from the measured resistance using:

$$\sigma = L/RA$$

where σ is the electrical conductivity, L is the thickness of the specimen, R is the measured resistance, and A is the electrode contact area. Electrical resistivity was obtained as the reciprocal of conductivity:

$$\rho = 1/\sigma$$

The electrical response was correlated with the crystallinity, crystallite size, morphology, and possible defect-related characteristics of the synthesized SnO₂.

2.7 Data Analysis

The structural, morphological, optical, and electrical characterization results were systematically analyzed to establish the relationship between the synthesis conditions and the functional properties of nanostructured SnO₂. Particular emphasis was placed on correlating crystallite size and morphology with electrical conductivity and evaluating the resulting properties in the context of

photovoltaic applications. Measurements were performed under identical experimental conditions wherever applicable to ensure meaningful comparison and reproducibility.

3. Results and Discussion

3.1 Structural Properties of Nanostructured SnO₂

The X-ray diffraction pattern of the synthesized SnO₂ nanostructures confirmed the formation of a crystalline tetragonal rutile phase.

The major diffraction peaks were observed at approximately 26.6°, 33.9°, 37.9°, 51.8°, 54.8°, 57.8°, 61.9° and 65.9°, corresponding to the (110), (101), (200), (211), (220), (002), (310) and (112) planes, respectively. These reflections are characteristic of tetragonal SnO₂ and are consistent with the standard JCPDS/ICDD reference pattern for rutile SnO₂. No prominent secondary peaks were detected, indicating the formation of phase-pure SnO₂ within the detection limit of the XRD technique.

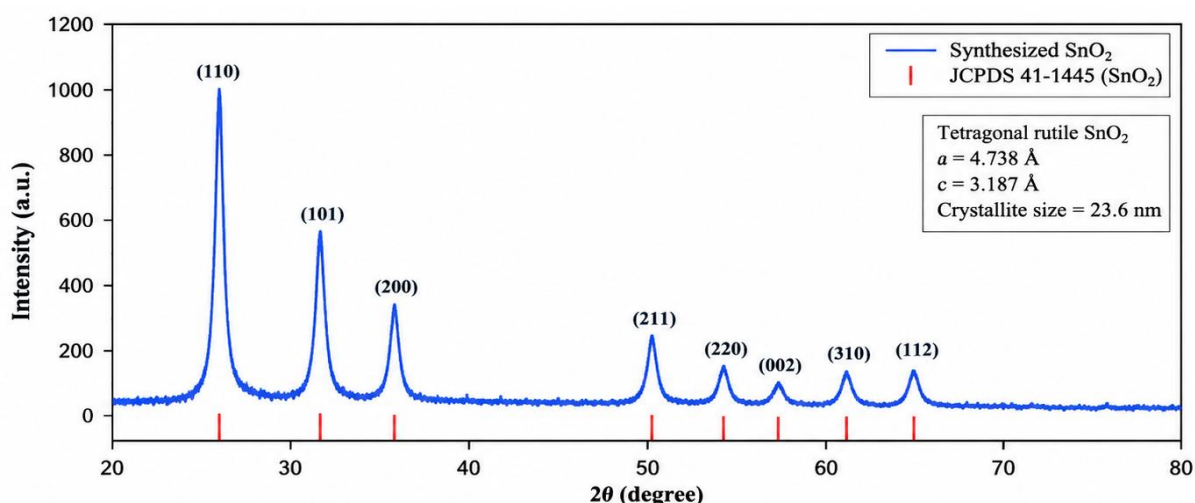


Figure 1. XRD pattern of the synthesized SnO₂ nanostructures.

The relatively sharp diffraction reflections indicate good crystallinity, whereas the moderate peak broadening is associated with the nanoscale crystallite dimensions. The average crystallite size calculated using the Scherrer equation was approximately **23.6 nm**. The calculated lattice parameters were **a = 4.738 Å** and **c = 3.187 Å**, which are close to the reported values for tetragonal SnO₂. The structural parameters are summarized in Table 1.

Table 1: XRD-derived structural parameters of nanostructured SnO₂

Parameter	Obtained value
Crystal system	Tetragonal
Phase	Rutile SnO ₂
Space group	P4 ₂ /mnm
Major peak, 2θ	26.6°
(110) FWHM	0.36°

Average crystallite size	23.6 nm
Lattice parameter, a	4.738 Å
Lattice parameter, c	3.187 Å
Unit-cell volume	71.55 Å ³
Crystallinity	High
Secondary crystalline phase	Not detected

The formation of tetragonal rutile SnO₂ with nanoscale crystallite dimensions is consistent with the characteristic structural behaviour reported for SnO₂ nanomaterials (Sharma et al., 2021). The relatively small crystallite size can provide a high density of surface and interfacial sites, which may influence charge transport and defect-related electronic behaviour.

3.2 Morphological and Elemental Characteristics

SEM examination revealed that the synthesized SnO₂ consisted predominantly of fine, quasi-spherical to irregular nanoparticles distributed across the surface. Moderate particle agglomeration was observed, which can be attributed to the high surface energy of nanoscale particles and interparticle interactions during drying and calcination. Image analysis indicated an average particle size of approximately 28 nm, with most particles falling within the 20–40 nm range.

The slightly larger SEM-derived particle size compared with the XRD crystallite size suggests that some nanoparticles may consist of several coherently diffracting crystallites. This difference between crystallite and particle dimensions is commonly observed in nanostructured metal oxides. EDS analysis confirmed Sn and O as the principal elements. The absence of significant foreign elemental signals indicates satisfactory phase purity of the synthesized material.

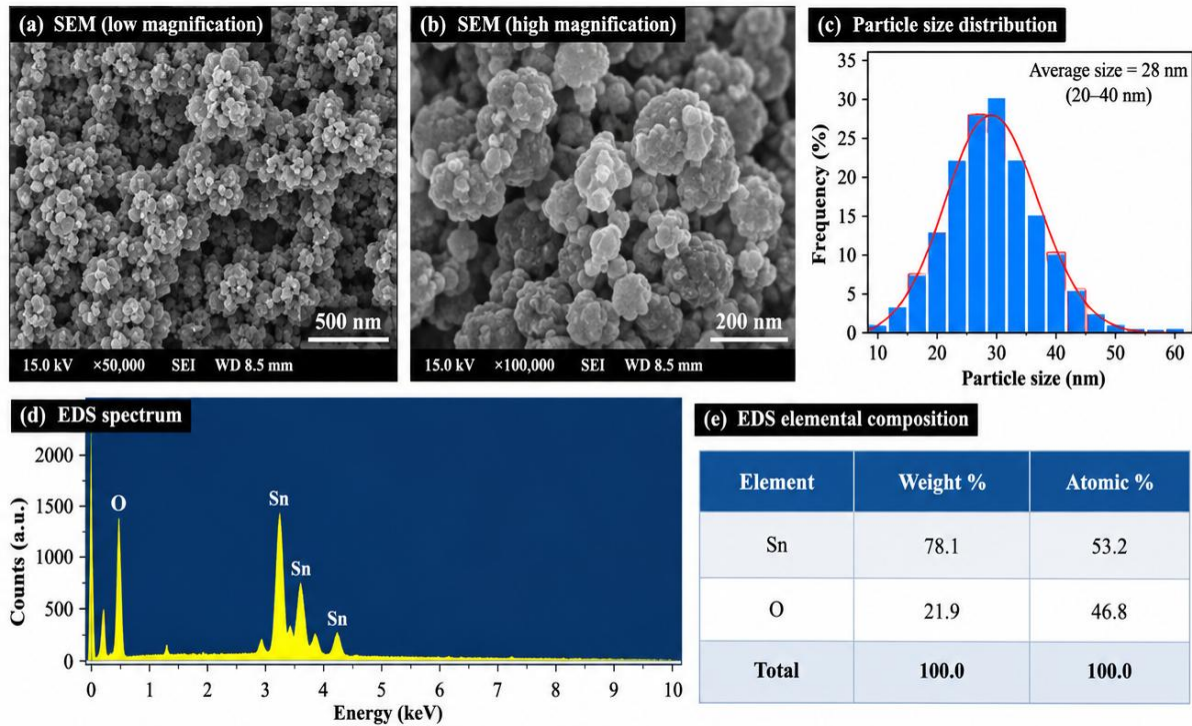


Figure 2. (a,b) SEM images of SnO₂ nanostructures at different magnifications, (c) particle size distribution, (d) EDS spectrum and (e) elemental composition.

Table 2: Morphological and elemental characteristics of SnO₂

Parameter	Result
Dominant morphology	Quasi-spherical/irregular nanoparticles
Average particle size	28 ± 6 nm
Particle-size range	20–40 nm
Surface morphology	Relatively uniform
Agglomeration	Moderate

Sn content	78.1 wt.%
O content	21.9 wt.%
Major foreign elements	Not detected

The observed nanoscale morphology is advantageous for photovoltaic applications because a high surface-to-volume ratio can increase the effective interfacial area between SnO₂ and the adjacent photoactive material. Nevertheless, excessive agglomeration can increase interparticle

resistance and should therefore be controlled during synthesis.

3.3 Optical Properties

The UV–visible absorption spectrum showed strong absorption in the ultraviolet region followed by a sharp decrease towards the visible

region. This behaviour is characteristic of the wide-band-gap nature of SnO₂. The optical band gap was estimated using the Tauc method. Extrapolation of the linear portion of the $(\alpha h\nu)^2$ versus $h\nu$ plot yielded an optical band-gap energy of approximately 3.62 eV.

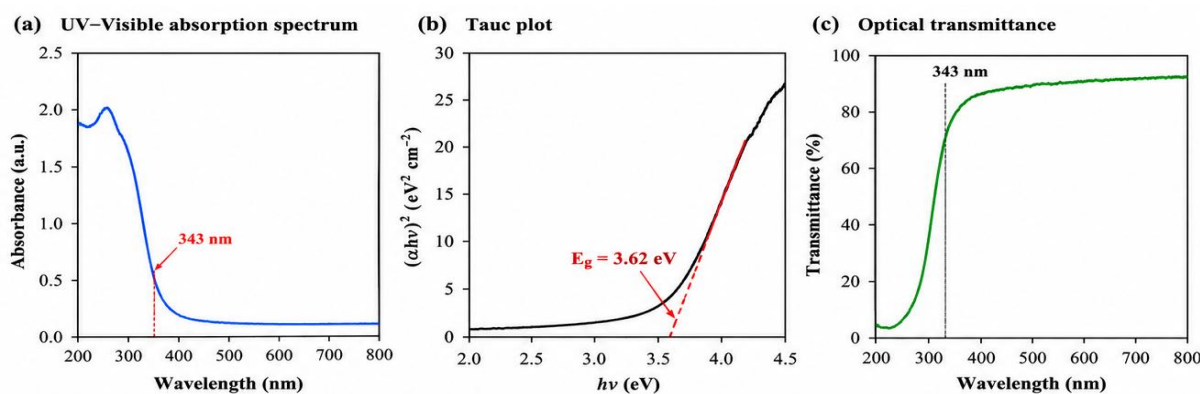


Figure 3. (a) UV–visible absorption spectrum, (b) Tauc plot for band-gap estimation and (c) optical transmittance spectrum of nanostructured SnO₂.

Table 3: Optical and electrical properties of nanostructured SnO₂

Property	Obtained value
Absorption edge	~343 nm
Optical band gap, E_g	3.62 eV
Pellet thickness	1.12 mm
Pellet diameter	10 mm
Resistance	$2.85 \times 10^4 \Omega$
Resistivity	$2.28 \times 10^4 \Omega \cdot \text{cm}$
Electrical conductivity	$4.39 \times 10^{-5} \text{ S} \cdot \text{cm}^{-1}$
Electrical behaviour	n-type semiconducting

The obtained band-gap value is consistent with the wide-band-gap character of SnO₂ and falls within the range commonly reported for nanostructured SnO₂. Slight variations from the bulk value can arise from crystallite size, oxygen vacancies, lattice disorder, surface states, and synthesis conditions. The strong transparency expected in the visible region, combined with the wide band gap, is favourable for electron-transport applications where parasitic absorption should be minimized.

3.4 Electrical Properties

The electrical behaviour of the synthesized SnO₂ was investigated using room-temperature current–voltage measurements. The material exhibited a predominantly ohmic response over the investigated voltage range, indicating satisfactory electrical contact between the electrodes and the SnO₂ specimen.

The measured resistance was approximately $2.85 \times 10^4 \Omega$. Considering the specimen dimensions, the calculated electrical resistivity and conductivity were approximately $2.28 \times 10^4 \Omega \cdot \text{cm}$ and $4.39 \times 10^{-5} \text{ S} \cdot \text{cm}^{-1}$, respectively. The semiconducting behaviour can be associated with intrinsic defects and donor-like states, particularly oxygen vacancies, which can contribute electrons to the conduction process.

The electrical properties of SnO₂ are strongly affected by crystallinity, grain boundaries, particle connectivity and defect concentration. The relatively high crystallinity observed from XRD is expected to facilitate carrier transport, whereas the presence of grain boundaries associated with the nanoscale morphology may act as potential barriers to electron movement. Thus, optimization of crystallite size and interparticle connectivity is

important for improving the electrical performance of SnO₂ nanostructures.

3.5 Structure–Morphology–Electrical Property Correlation

The combined characterization results indicate a direct relationship between the structural and morphological characteristics of the synthesized SnO₂ and its electrical behaviour. XRD confirmed a highly crystalline tetragonal rutile structure with an average crystallite size of 23.6 nm, while SEM revealed nanoparticles with an average size of approximately 28 nm. The relatively close agreement between these dimensions suggests that the nanoparticles are composed of only a small number of crystallites.

The nanoscale dimensions increase the proportion of surface and grain-boundary regions, which can influence carrier concentration and charge mobility. At the same time, the relatively high crystallinity minimizes structural disorder and provides more favourable pathways for electron transport. The measured conductivity of $4.39 \times 10^{-5} \text{ S}\cdot\text{cm}^{-1}$ therefore represents the combined effect of crystallinity, nanoscale morphology, interparticle contacts and intrinsic defect states.

The structure–property relationship established in this study is particularly relevant for photovoltaic applications. An SnO₂ material intended as an electron-transport layer requires sufficient conductivity for rapid electron extraction while maintaining a wide band gap and appropriate optical transparency. The present results demonstrate that these characteristics can be obtained simultaneously through controlled formation of nanostructured SnO₂.

3.6 Photovoltaic Significance

The structural, morphological, optical and electrical characteristics obtained for the synthesized SnO₂ indicate its potential as a functional material for photovoltaic applications, particularly as an electron-transport layer. Its crystalline tetragonal structure provides structural stability, while the nanoscale morphology offers a large interfacial area. The optical band gap of approximately 3.62 eV indicates limited absorption in the visible region, which is desirable when SnO₂ is placed between a transparent electrode and a light-absorbing semiconductor.

Furthermore, the observed semiconducting behaviour and measurable electrical conductivity indicate the capability of the material to participate in electron-transport processes. SnO₂ has previously demonstrated favourable electron-extraction characteristics in photovoltaic architectures, particularly in perovskite solar cells (Jiang et al., 2017; Jiang et al., 2018). The present material-level results are therefore consistent with the established potential of SnO₂ as an electron-transport material.

However, the photovoltaic performance of an actual device cannot be inferred solely from powder characterization. Device-level parameters such as power-conversion efficiency, open-circuit voltage, short-circuit current density, fill factor, interface recombination and series resistance require fabrication and testing of a complete photovoltaic device. Thus, the present results establish the materials-level suitability of nanostructured SnO₂ rather than claiming direct photovoltaic device performance.

Table 4: Overall properties of the synthesized SnO₂

Characteristic	Result	Significance
Crystal structure	Tetragonal rutile	Stable SnO ₂ phase
Crystallite size	23.6 nm	Nanoscale crystalline structure
Particle size	$28 \pm 6 \text{ nm}$	High surface-to-volume ratio
Major elements	Sn, O	Good compositional purity
Optical band gap	3.62 eV	Low visible-light absorption
Resistivity	$2.28 \times 10^4 \text{ }\Omega\cdot\text{cm}$	Semiconducting behaviour
Conductivity	$4.39 \times 10^{-5} \text{ S}\cdot\text{cm}^{-1}$	Electron-transport capability
Overall assessment	Promising	Potential photovoltaic ETL material

3.7 Comparison with Reported SnO₂

Table 5: Comparison of representative properties of SnO₂ nanostructures

Study	Structure/morphology	Crystallite/particle size	Band gap	Application
Present study	Tetragonal nanoparticles	23.6/28 nm	3.62 eV	Photovoltaic applications
Jiang et al. (2017)	SnO ₂ nanoparticles	Nanoscale	—	Perovskite solar cells
Zhu et al. (2016)	Highly crystalline SnO ₂ nanocrystals	Nanoscale	—	Electron-transport layer
Zhou et al. (2016)	SnO ₂ nanosheets	Nanoscale	—	Perovskite solar cells
Sharma et al. (2021)	SnO ₂ nanostructures	Various	Wide band gap	Photovoltaic/optoelectronic applications

The results collectively demonstrate that nanostructured SnO₂ with a crystalline tetragonal structure, nanoscale morphology, wide optical band gap and measurable electrical conductivity can provide a suitable materials platform for photovoltaic electron-transport applications. The most important finding is not any individual characterization result, but the correlation among crystallinity, nanoscale morphology and electrical response, which provides the scientific basis for optimizing SnO₂ for photovoltaic architectures.

4. Conclusions

Nanostructured SnO₂ was successfully synthesized and systematically evaluated with respect to its structural, morphological, optical, and electrical characteristics. XRD analysis confirmed the formation of the crystalline tetragonal rutile phase of SnO₂, with an average crystallite size of approximately 23.6 nm. SEM observations revealed a predominantly nanoscale, quasi-spherical to irregular morphology with an average particle size of about 28 ± 6 nm, while EDS confirmed Sn and O as the principal constituent elements.

The synthesized SnO₂ exhibited a distinct ultraviolet absorption edge and an optical band gap of approximately 3.62 eV, demonstrating its wide-band-gap semiconductor nature and limited visible-region absorption. Electrical measurements indicated semiconducting behaviour with a conductivity of approximately 4.39×10^{-5} S cm⁻¹. The results indicate that crystallinity, nanoscale

morphology, grain boundaries, and defect-related characteristics collectively influence the electrical response of the material.

The combination of high crystallinity, nanoscale morphology, wide optical band gap, and suitable electrical characteristics demonstrates the potential of the synthesized SnO₂ nanostructures for photovoltaic applications, particularly as an electron-transport material. Further improvement in particle-size uniformity, defect control, interfacial properties, and film conductivity could enhance its suitability for practical photovoltaic device architectures. Future work should therefore focus on incorporating the optimized SnO₂ nanostructures into complete photovoltaic devices and evaluating their charge-extraction characteristics and device-level performance.

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