Materials Research Express

PAPER

Enhancement of infrared shielding property of SnO$_2$ using Sb as a dopant

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Keywords: transparent conducting oxides, Sb doping, transmittance, IR Reflection, band gap

Abstract

Transparent conducting oxides (TCO) are essential to the operation of advanced energy harvesting and storage devices, as well as display technology. Doped tin oxide (SnO$_2$) exhibits enhanced optical and thermal characteristics in comparison to undoped SnO$_2$. In this article, the cost-effective sol-gel methodology was employed in the synthesis of tin oxide (SnO$_2$) and antimony (Sb) doped tin oxide nanoparticles. According to the XRD analysis, the tetragonal structure was maintained despite the apparent reduction in crystal size as the amount of Sb increased. In the study, the effect that Sb doping has on absorption and reflection in the visible and near-infrared regions was analyzed. The band gap of the nanoparticles was observed to broaden as the concentration of Sb doping was increased from 3.44 eV (ATO-0) to 4.62 eV (ATO-6). The results from UV–vis-NIR spectra demonstrated that the ATO films efficiently reduced the amount of infrared light that passed through them. The results of the heat-insulation test showed that ATO-coated glass outperformed uncoated glass in terms of heat insulation. Because of these characteristics, ATO could be a good replacement material, especially for solar cells and smart windows.

1. Introduction

Around past few decades, researchers from all over the world have been more interested in studying metal oxides, namely transparent conducting oxides (TCO). A metal oxide has an ionic makeup of positive ions and negative oxygen ions. The metal oxides have filled s-shell, due to which they exhibit high thermal and chemical stability [1–3]. However, their distinctive features are attributed to their partially filled d-shells, making them potentially useful in a wide range of electronic devices. The distinctive, unique features include a broader band gap, a high dielectric constant, high sensing properties, and good optoelectronic characteristics. The peculiar properties of metal oxides make them so versatile that they are rigorously employed in many fields [4, 5]. Transparent conducting oxides (TCOs) include binary TCOs including SnO$_2$, ZnO, CdO, In$_2$O$_3$, and some tertiary TCOs such as GaSbO$_3$, Sn$_2$SbO$_4$, Cd$_2$SnO$_4$ and CdIn$_2$O$_4$ [6].

The synthesis and characterization of SnO$_2$ enable novel approaches to the existing issues. Tin oxide resembles an n-type semiconductor with a band gap of about 3.6 eV and a high binding energy of the order of 130 eV for excitons [7]. To satisfy market demands for SnO$_2$, a variety of metals or ions may be doped into SnO$_2$ material to improve its optical and electrical properties. Undoped SnO$_2$ possesses a high resistivity due to its limited oxygen vacancies [8], poor carrier density and low mobility [9]. The mostly used TCO is ITO (indium doped tin oxide) which exhibits small resistivity of the order of $10^{-5}$ Ω cm and high visible-range transmission (more than 85 percent) [10]. However, well-known challenges like indium scarcity and expenses, as well as slow and expensive vacuum-based deposition method, account for a significant portion of total costs for optoelectronic device manufacturing, thus making it unrealistic in modern-day research [11]. Although remarkable results have been achieved recently via the solution method, there are still considerable issues with the depletion of indium [12]. Indeed, with an ever-increasing need for cost-effective, simple formation, the market for transparent electrodes must find new materials for the fabrication process. Keeping in view the said

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issues with ITO, Sb-doped SnO₂ is regarded as a substitute for it, as it has dynamic and versatile features in electrical and optical properties [5]. Additionally, ATO has a broad band gap (> 3.60 eV) and high electron mobility [13]. Antimony (Sb) appears to be a good dopant for SnO₂ since substitution of Sn²⁺ for Sb⁵⁺ in the SnO₂ lattice greatly enhances the n-type semiconductor properties in it. The ionic radii of Sb²⁺ (0.62 Å) is comparable to that of an Sn ion (0.69 Å) [14] due to distortion caused by incorporation of Sb in SnO₂ lattice. Therefore, the fabrication of ATO nanoparticles is essential for a range of applications.

The different methods used for the preparation of ATO nanoparticles are sonochemical method [15], hydrothermal method [16], co-precipitation method [17], sol-gel method [18], nanoparticle deposition method [19] and solvothermal method [20]. The sol-gel method is suitable for the fabrication of metal oxide nanoparticles with large dispersion and fine distribution, and they are widely employed for the manufacture of tin oxide nanoparticles [7].

The research on synthesis and characterization of ATO thin films and nanoparticles has been carried out by an enormous number of experimentalists. Subramaniam et al [21] synthesized tin oxide using the sol-gel technique to observe the influence of pH on the structural, electrical and optical properties of tin oxide. Kim et al [11] deposited ATO thin films employing the spray pyrolysis technique to examine the structural, electrical and optical properties of these films. Anil et al [7] synthesized SnO₂ nanoparticles using a sol-gel and precipitation tool to investigate the influence of dopants on the structural and morphological properties of tin oxide. Balasubramanian et al [22] compared the effects of different synthesis methods on different properties of ATO nanoparticles.

In this work, we have fabricated and characterized cost-effective Sb-doped SnO₂, an alternate to ITO, by employing a simple and customizable sol-gel technique. Structural and optical properties have been carried out to an expert level and discussed thoroughly. In addition to structural and optical characteristics (transmittance, IR reflection, band gap), the effect of Sb concentration has been explored in detail.

2. Experimental and thermal performance

2.1. Synthesis of ATO nanoparticles

Antimony doped tin oxide nanoparticles were prepared from stannous chloride dihydrate (SnCl₂·2H₂O), antimony trichloride (SbCl₃), ethanol (C₂H₅OH) and ammonia solution (NH₃). From these, SnCl₂·2H₂O acted as a precursor, ethanol acted as a solvent and antimony trichloride (SbCl₃) served as the dopant with an Sb doping amount of 0–6 mol%. The addition of ammonia solution was done to maintain the pH value of the solution at around 7–8. The synthesis process may be easily understood by looking at figure 1. A white precipitate was formed, which was washed several times with ethanol and distilled water and then dried at a temperature of 70 °C. The dried precipitate was then calcinated at a temperature of 500 °C to 1000 °C in a furnace after naturally setting down to room temperature. The ATO material has been prepared using different concentrations of Sb doping, and has been named accordingly as ATO-0, ATO-2, ATO-4 and ATO-6. ATO nanoparticles were obtained, which were confirmed by different characterization techniques discussed ahead.

2.2. Film preparation

A thin film was created by spin coater using the ‘Milman’ spin coating technique (Model No. SPN 1000A). ATO nanoparticles of 0.5 gm that had been prepared were added to 50 ml of DI water and stirred for 15 min to create a stable ATO nanoparticle dispersion. To ensure appropriate ATO nanoparticle dispersion, the prepared solution was transferred to ultrasonication. As a dispersant, polyvinyl alcohol (PVA) was utilized, and its concentration was around 3% of the ATO dispersion. The solution was constantly agitated at 85 °C for 20 min. Finally, ATO coatings were applied to the glass substrate using the spin coating process, which involved five times the coating of film at 3000 RPM for 30 s. Every time after the coating of ATO on glass substrate, we have dried the film for approximately for 10 min on hot plate at 80 °C and finally for two hours at 100 °C.

2.3. Thermal performance test

The thermal performance of ATO material was evaluated in order to determine its thermal insulation performance. The thermometer used in the experiment to test the thermal insulation performance was a Digital Thermometer (YUV-200), with a temperature range of −50 °C to 100 °C and a temperature display resolution of 0.1 °C. The infrared source was an E27 230V Red 1CT/12 lamp with a model number (company) PAR38 IR murphy Wattage of 150 W. The range of wavelength was from 780 nm to 1 mm.
3. Characterisation

The crystal structure of synthesised ATO nanoparticles has been confirmed using an x-ray diffractometer (XRD, Rigaku with CuKα (1.54 Å)) with a scan range of 2θ between 20° to 80° degree and Raman analysis has been done using (Invia Raman microscopes, Renishaw) with a range of 500–1000 cm⁻¹. The crystallite size of the ATO has been obtained by using Scherer’s formula and W-H plot from x-ray diffraction data. The texture coefficient has been calculated using the Harris method. The optical properties were observed using a UV–vis-NIR spectrophotometer (Shimadzu UV-3600) and the Kubelka-Munk function was employed for estimation of the band gap of synthesised ATO nanoparticles. The FTIR measurements of the ATO nanoparticles were conducted using (Perkin Elmer) in the range of 400 to 3000 cm⁻¹. A thin film was created by spin coater using the ‘Milman’ spin coating technique (Model No. SPN 1000A).

4. Results and discussion

4.1. Structural analysis

X-ray diffraction (XRD) was done in order to observe the crystalline character of tin oxide with a variable concentration of antimony doping, and the results are shown in figure 2(a). The XRD patterns of ATO’s doped with different Sb concentrations confirm that SnO₂ and Sb-doped SnO₂ (ATO) nanoparticles have a polycrystalline structure with a tetragonal rutile structure of single phase SnO₂, and the data matches with standard joint committee on powder diffraction standards (JCPDS) card No: 41–1445. No new diffraction peaks were observed from the XRD pattern, indicating ATO nanoparticles in the SnO₂ phase, and no phases corresponding to Sb₂O₃ and Sb₂O₅ were observed.

Therefore, it is confirmed that Sb is successfully incorporated into the lattice structure as no other crystal phases were observed [8]. The intensity of peaks becomes weaker with an increase in Sb doping concentration, which indicates that doping weakens crystallinity. These results reveal the presence of Sb ions in the SnO₂ tetragonal matrix by substituting Sn⁴⁺ or a separation of Sb ions in the noncrystalline region between grain boundaries [18].

The crystallite size (D) of ATO nanoparticles has been calculated from ‘XRD data’ using the Debye-Scherer equation [23].
Here, \( k \) denotes constant with value 0.9, \( \lambda \) is wavelength of the incident x-ray (\( \lambda = 1.54 \text{ Å} \)), \( \beta \) is 'FWHM' (full width at half maximum) and were \( \theta \) represent Bragg's diffraction angle.

The crystallite size was calculated from the high intensity peaks of the XRD pattern of the ATO samples. The estimated crystallite size is shown in table 1. It has been found that Sb insertion reduces the crystallite size from 8 nm (for ATO-0) to 3 nm (for ATO-4) of SnO\(_2\) samples. This is because the stress in the matrix inhibits crystal formation that generated due to the ionic radii difference of Sb\(^{5+}\) (0.062 nm) and Sn\(^{4+}\) (0.069 nm) [24]. Also, we can see from the zoomed picture of the XRD of the (110) peak (figure 2(a)) that the shifting of peaks towards the lower 2\( \theta \) value for ATO-0, ATO-2 and ATO-4 is due to the incorporation of Sb in the SnO\(_2\) lattice. However, little shift was observed in ATO-6 towards the higher 2\( \theta \) due to more stress. Moreover, at higher doping levels, it

![Figure 2. (a) X-ray diffraction pattern of ATO nanoparticles along with Zoomed view of (110) peak of XRD (b) Effect of Sb doping concentration on lattice parameters, crystallite size and strain calculate using William Hall method (c) Texture coefficient of various diffraction planes of ATO nanoparticles and found preferred growth along (211) plane.](image)

| Sb doping Concentration (mol.%) | Crystallite size \( D \) (nm) | Dislocation density \( \delta \) (nm\(^{-2}\)) | Lattice parameters \( a = b \) | Unit cell Volume \( V \) (\( \text{Å}^3 \)) | Mean lattice strain \( \varepsilon \times 10^{-3} \) |
|---------------------------------|-----------------|---------------------|-----------------|-----------------|---------------------|
| ATO-0                           | 8               | 8.5                 | 0.013           | 4.737           | 3.180               | 71.36               | 3.2                |
| ATO-2                           | 4               | 5.6                 | 0.018           | 4.744           | 3.173               | 71.40               | 7.4                |
| ATO-4                           | 3               | 3.8                 | 0.049           | 4.744           | 3.170               | 71.30               | 4.5                |
| ATO-6                           | 5               | 5.4                 | 0.012           | 4.744           | 3.173               | 71.40               | 8.9                |

\[
D = \frac{k \lambda}{\beta \cos \theta}
\]  

Here, \( k \) denotes constant with value 0.9, \( \lambda \) is wavelength of the incident x-ray (\( \lambda = 1.54 \text{ Å} \)), \( \beta \) is 'FWHM' (full width at half maximum) and were \( \theta \) represent Bragg's diffraction angle.
can be seen that Sb$^{3+}$ changes to Sb$^{5+}$, and the ionic radii of Sb$^{3+}$ (0.74 nm) are higher than those of Sb$^{5+}$ which results in an increase in crystallite size and stress in the system [25].

Figure 2(c) is made in accordance with the values of table 1 where we can see intuitively the variation of lattice parameters, crystallite size, strain calculated using the Scherrer formula and Williamson-Hall measurement with the increase of Sb doping [26]. It has been observed that proper incorporation of Sb in the ATO-4 lowers the crystallite size and strain as compared to ATO-0, ATO-2 and ATO-6. It has also been seen from table 1 that with an increase in Sb concentration, the cell volume and lattice strain decrease for TO-4 as compared to ATO-2 and ATO-6.

The lattice constants of unit cells $a$ and $c$ as well as their cell volume were calculated using tetragonal phase relations

$$\left(\frac{1}{d}\right)^2 = \left(\frac{h^2 + k^2}{a^2}\right) + \left(\frac{l^2}{k^2}\right)$$

$$V = a^2c$$

Where, $d$ represents interplanner spacing and $hkl$ denotes miller indices of the lattice planes. Table 1 summarizes the outcomes, as we can clearly see that the lattice constants and unit cell volume are very similar to JCPDS (card No: 41-1445) values $a = b = 4.738$ Å, $c = 3.188$ Å and volume $V = 71.57$ Å$^3$ of the typical tetragonal rutile structure [27].

The dislocation density ($\delta$) determines the length of dislocation lines per unit volume and represents the quality and defects in nanoparticles [28, 29]. We estimated the crystallite size and lattice strain of the nanoparticles using the Williamson-Hall method [30].

$$\delta = \frac{1}{D^2}$$

$$\beta \cos \theta = \frac{0.9\lambda}{D} + 4\varepsilon \sin \theta$$

Where, $\beta$ represents the full width at half maxima of the XRD peak, $\theta$ is the Bragg’s angle, $\lambda$ (1.54 Å) is the wavelength of the x-ray, $D$ is the average crystallite size and $\varepsilon$ represents the strain. For line broadening analysis, the five most intense peaks were examined. For all four ATO-0, ATO-2, ATO-4 and ATO-6, the ratio of $\beta \cos \theta$ was plotted against $4\sin \theta$, where $\beta \cos \theta$ represents the full width at half maximum of the XRD peak. These curves allow for estimation of both the internal strain (slope) and the crystallite size (intercept at $\sin \theta = 0$). The figures illustrate that Sb incorporation creates strain in the system by increasing Sb doping in the system. It rises from 0.0032 for ATO-0 to 0.0089 for ATO-6, with a slightly lower value for the ATO-4 with a magnitude of 0.00425. This results from proper incorporation of the Sb dopant in the SnO$_2$ lattice. The crystallite size of ATO-0, ATO-2, ATO-4 and ATO-6 were calculated using W-H plot and obtained as 8.5 nm, 5.6 nm, 3.8 nm, 5.4 nm respectively. A higher concentration of Sb results in a rise in the strain, which is attributed to the particle size effect. Based on these results, it seems that the amount of Sb dopant in SnO$_2$ controls the size-dependent strain in the nanoparticles.

The estimated values of dislocation density and strain were clearly increases with an increment in the Sb concentration, as mentioned in the table 1. These increments are attributed to the increased grain boundaries that arise due to smaller crystallite sizes for large values of Sb doping concentration.

The texture coefficient (Tc (hkI)) is used to examine the structural characteristics of ATO, which is a significant factor that determines the physical properties of the nanoparticles and indicates the preferred orientation of each peak to a particular crystallographic plane (hkI) direction [31]. The Tc (hkI) of ATO nanoparticles is calculated using the Harris approach [32].

$$T_{c}(hkI) = \frac{I_{hkI}}{I_{0}^0 (hkI)} \left[ \frac{1}{n} \sum_{n} I(hkI) \right]^{-1}$$

Where ‘I’ is the observed intensity of the plane (hkI) from the sample, ‘I$^0$’ is the matching standard intensity of samples, and ‘n’ is the number of diffraction peaks.

The texture coefficient has been calculated for ATO nanoparticles and observed as an effect of annealing temperature. From figure 2(b) it can be seen that ATO has the preferred growth along the (211) plane. Calcination temperature plays a vital role in the preferred growth of the plane. In our present paper synthesis process, we calcined the ATO samples at a temperature of 500 °C and found out that the preferred orientation to the plane is (211). Paloly et al [33] have reported dependency of preferred orientation on the solvent used. It has been calculated and found that of all the ATO samples (211) plane has the higher texture coefficient. An increase in texture coefficient from unity indicates a high degree of preferred orientation, which is associated with growth in atomic density along the specific crystal plane [34].
4.2. FTIR analysis
The FTIR spectra of Sb-doped SnO$_2$ (ATO) nanoparticles are shown in figure 3(a). The IR feature of the SnO$_2$ nanoparticles appears at 458 cm$^{-1}$ and 631 cm$^{-1}$, which are allocated to 'O-Sn-O' and 'Sn-O' stretching vibrations, respectively. Peaks at 765 cm$^{-1}$ and 975 cm$^{-1}$ correspond to $\nu$(Sn-OH) vibrations while the peak at 1650 cm$^{-1}$ is due to the OH group. Spectral differences due to the presence of Sb in SnO$_2$ are most pronounced in the most intense bands. There is a gradual red shift observed with an increase in Sb doping concentration. Sb ions are substitutes for Sn ions in SnO$_2$:Sb (ATO) nanoparticles due to their identical ionic size\[18, 35\]. Because of the bond length (O-Sn-O: 2.597; Sn-O: 2.053), it can be seen in FTIR that substitution is simply happening on the group of O-Sn-O. Unrestricted electrons may be released or retained when Sb is substituted for Sn. The oxidation state of Sb exists in 2 states (Sb$^{+3}$, Sb$^{+5}$) which coexist in SnO$_2$:Sb. As the concentration of Sb increases, the system becomes more disordered, as evidenced by the gradual shift in vibration peaks\[36\].

4.3. Raman spectra analysis
The Raman spectra of SnO$_2$ samples with varied Sb doped concentrations are shown in figure 3(b). The pronounced Raman peaks at 632 cm$^{-1}$ and 773 cm$^{-1}$ correspond to A$_{1g}$ and B$_{2g}$ modes and are related to the expansion and contraction of 'Sn-O' bonds\[37\]. The zoomed picture of the A$_{1g}$ peak shown in figure 3(d), which shows the shift of the peaks due to Sb doping that are induced by distortion of the Sn-O plane due to an increase in disordered structure\[38\]. This shifting of peaks further confirms the successful incorporation of Sb ion in place of Sn ion. This replacement makes sense as the shifting is in accordance with XRD shifting\[21\]. Moreover, a decrease in intensity can be observed for ATO-6 with an increase in Sb concentration that can be attributed to the disorder in the system brought by Sb doping. The peak at 570 cm$^{-1}$ mode resulted from higher oxygen vacancy concentration\[35\]. It is well known that some inactive vibrations in bulk become active in very small nanostructures with reduced dimensions. The strength of the bands changes as the concentration of antimony (Sb) ions in the SnO$_2$ lattice increases, and this can be linked to the vibration modes of doped antimony (Sb) ions in the lattice\[38\].
4.4. Field emission scanning electron microscopy (FESEM) and energy dispersive x-ray analysis (EDX)

The surface morphology and particle dispersion of the different Sb-doped samples are analyzed by field emission scanning electron microscopy. Figure 4 displays the SEM images of different Sb-doped samples. There appears to be minimal aggregation of the particles, and no apparent form can be observed. It has been observed that there is no definite shape to the ATO sample, with little agglomeration of the particles observed. The EDX spectrum of various Sb doping levels is shown in figure 5. EDX was run multiple times over different ATO samples and it was confirmed that tin and oxygen are present in SnO₂ and tin, antimony, and oxygen in Sb-doped SnO₂. The consistent chemical makeup of the nanocrystals is also confirmed by EDX.

4.5. UV–Vis-NIR spectra analysis

The optical absorption spectra, as shown in figure 3(c), of ATO nanoparticles were examined over a wavelength range of 200 nm to 1800 nm. All of the peaks in the 200–400 nm wavelength range had intense absorption curves, absorption edge occurring in the range 300–400 nm due to high exciton binding energy. The quantum confinement effect for nanoparticles is generally responsible for the observed blue shift in excitation absorption. As the particle size reduces, the band gap increases in the quantum confinement range (less than 10 nm), causing the absorption edge to move to a lower wavelength region. All the ATO samples show enhanced UV absorption and high transparency in the visible range [39]. They also show absorption in the NIR region, which is typically a feature of doped semiconductors and a strong indication of n-type doping, which can be related to ‘surface plasmon absorption’. According to the Drude model, the $\alpha$ (absorption coefficient) is proportionate to N (the charge carrier density) in n-type semiconductors.

$$\alpha = \frac{Ne^2}{m_e e_0 n \pi \tau \omega^2}$$  \hfill (7)

where $e$, $m_e$ is charge and effective mass of an electron, $n$ is the refractive index of an undoped semiconductor, $\tau$ relaxation time for free electrons, $e_0$ vacuum permittivity, $c$ and $\omega$ are the speed and frequency of light, respectively [40].

Figure 6 (a) depicts the transmittance curves of ATO samples throughout the spectral region of 380–1800 nm. The transmittance of ATO-0 (SnO₂) in the visible and near-infrared regions of the electromagnetic range is depicted in the figure. The ATO nanoparticles’ transmittance falls marginally in the visible range and
dramatically in the infrared area as the amount of Sb doping increases. Table 2 shows the findings of integrating the transmittance of visible light (380–780 nm) and infrared light (780–2500 nm), respectively.

Table 2 and figure 5(b) show that as Sb doping increases, the transmission of ATO nanoparticles in the visible region changes, but the range of variation is slight, and the transmittance of these nanoparticles in the NIR range continues to fall, from 67% of (ATO-0) to 6.2% of (ATO-4) nanoparticles. The transmittance of the infrared portion decreases by nearly 60% with an increasing Sb doping amount. It can be observed that variation in the optical characteristics of ATO nanoparticles in the IR range is consistent with the trend for electrical properties to vary. The higher the carrier concentration, the higher the conductivity and the lower will be the transmittance.
The phenomenon of a reduction in transmittance for the visible region due to an increment in Sb concentration was reported by Ponja et al. [41]. At the same time, reflectance in infrared increases with the rise in Sb doping amount, and the plasma edge shifts gradually towards the high frequency region.

The ATO nanoparticles’ transmittance can be described as: ATO has superior electrical characteristics due to its high concentration of free electrons. According to free electron theory, the relation of plasmon frequency with its corresponding plasmon wavelength \( \lambda_p \) and free electron concentration is as follows [42, 43]:

\[
\omega_p = \left( \frac{4\pi ne^2}{\varepsilon_0 \varepsilon_{\infty} m^*} \right)^{\frac{1}{2}}
\]

Here, \( n \) denotes the concentration of free electrons, \( \varepsilon_0, \varepsilon_{\infty} \) signifies the vacuum dielectric constant and high frequency dielectric constants, respectively, \( m^* \) symbolizes an electron’s effective mass in the conduction band, \( e \) indicates the charge of an electron.

Plasmon frequency has a cut-off effect on light frequency and is found in the visible region NIR (near infrared light), which decides the transparent conductive nanoparticles’ upper transmittance frequency limit. With increase of Sb doping, carrier concentration in ATO nanoparticles increases and the Plasmon wavelength \( \lambda_p \) increasingly advances towards shorter wavelength, as shown by the expression number (8). The ATO nanoparticles have strong infrared reflectivity for wavelengths greater than \( \lambda_p \) and high visual transparency for wavelengths less than the plasmon cutoff frequency [14].

The band gap of ATO nanoparticles can be estimated using the Tauc formula and the nanoparticles’ transmittance spectrum, which is given below [44].

\[
\alpha \chi = A (\hbar \nu - E_g)^n
\]

where \( \alpha \) denotes absorption coefficient, \( \hbar \nu \) represents photon energy, \( E_g \) signifies optical band gap, \( A \) is a constant, and \( m \) is a constant with dependency on the electron’s band structure. As SnO\(_2\) is a direct band semiconductor, \( n = 1 \).

In a Tauc plot, \( E_g \) is derived mostly from the junction of a straight line fit to the area associated with the optical absorption edge (TS) and the \( \nu \) axis in the related (\( \alpha \chi \))\( ^{1/2} \) vs \( \hbar \nu \) plot. It is obsolete that it gives accurate values, when approximately executed [45]. As \( \alpha \) is used to create tauc plots, minor light scattering is essential to apply the method effectively.

As the scattering factor cannot be overlooked in powder materials, optical absorption spectroscopy is not an effective approach to determine the energy band gap (\( E_g \)). As established by Escobedo et al, diffusive reflectance is a preferable alternative [46]. The reader is directed to outstanding reviews of the Kubelka-Munk theory of diffusive reflectance (DR) phenomena and DRS for more information [47, 48].

The Kubelka-Munk or reemission function, \( F(R) \), can be calculated using DRS (diffusive reflectance spectroscopy)

\[
R = \frac{R_{\text{Sample}}}{R_{\text{Standard}}}
\]

\[
F(R) = \frac{K}{S} = \frac{(1 - R)^2}{2R}
\]

\[
F(R) = C (\hbar \nu - E_g)^n
\]

Where \( R \) is sample reflectance, \( K \) and \( S \) represent absorption and scattering K-M coefficients, respectively, and \( C \) is the constant of proportionality. In practice, a thickness of more than 2 mm is sufficient to elude impact from the supporting material (the sample holder), and \( R \) is equal to the ratio of the sample reflectance \( (R_{\text{sample}}) \) to the diffusive reflectance of standard material \( (R_{\text{standard}}) \). The value of the energy gap \( E_g \) is determined in an identical Tauc plot, \( (F(R)\hbar \nu)^{1/n} \) vs \( \hbar \nu \) at the intersection of TS and the \( \hbar \nu \) axis, which corresponds to optical absorption spectroscopy [47, 49].

The optical band gap values of ATO nanoparticles are listed in table 3 with Sb doping of 0 mol%, 2 mol%, 4 mol%, and 6 mol%. The band gap of ATO-0 is the lowest, with a value of 3.44 eV as displayed in figure 7 and table 3. The band gap gradually widens as the quantity of Sb doping increases, reaching a value 3.62 eV for ATO-6 when the amount of Sb doping reaches 6 mol%. From the data in table 3, it is understood that the optical band gap of these ATO nanoparticles varies with the amount of Sb.

The optical band gap becomes broader than that of undoped SnO\(_2\) and increases as the Sb doping level increases, phenomenon is described by the Moss-Burstein effect [50]. Following Pauli’s Exclusion Principle, which states that when the amount of Sb doping rises, the band gap of the nanoparticles alters, separating the vacant energy levels in the valance band top and conduction band. Fermi level changes appear in the conduction band of an n-type doped semiconductor [51]. Because some electrons are occupied in the conduction band as a
result of higher carrier concentration, electrons require extra energy to transit from the valance band to the conduction band, hence the band gap of these ATO nanoparticles widens as doping concentration rises [52].

4.6. Thermal performance

As it has been seen from its optical characteristics, ATO-4 shows good results as compared to other ATO samples, retains good visible and small IR transmittance. This transmittance property is useful in transparent and heat-insulating coatings where the majority of infrared radiation must be blocked. To examine the thermal insulating capabilities of ATO nanoparticles in a real-world setting, ATO-4 film was prepared on glass using the spin coating technique. The prepared thin film was analyzed using a self-made thermal insulating box, whose schematic diagram is shown in figure 9. In this simulated experiment in which we irradiated sealed boxes with a 10 mW cm$^{-2}$ intensity light covered by glass/coated glass to confirm the thermal insulation performance. Temperature was taken using a thermometer and data was gathered up to 40 min, when equilibrium is attained. The thermometer is kept away from glass in order to minimize the error. The first box is irradiated using pure glass (1 cm$^2$) without coating and the temperature has been noted to reach its maximum equilibrium value of 22.90 °C. Next coated glass (1 cm$^2$), Now it has been is irradiated and temperature has been noted down to about 22 °C.

Table 3. Effect of Sb doping on optical band gap on SnO$_2$ nanoparticles.

| S.No. | Sb doping concentration (mol%) | Band gap $E_g$ (eV) |
|-------|-------------------------------|---------------------|
| 1     | 0                             | 3.44                |
| 2     | 2                             | 3.52                |
| 3     | 4                             | 3.57                |
| 4     | 6                             | 3.62                |

Figure 7. Estimation of optical band gap and its dependency on Sb doping for samples ATO-0, ATO-2, ATO-4, ATO-6.
The temperature variation observed is depicted in figure 8(a). The temperature difference between the pure glass and ATO-coated glass has been calculated, its graph is plotted with respect to irradiated time. From the graph, it can be seen that there is a linear relationship between temperature and irradiation time. So, we can conclude that with an increase in temperature, the difference in temperature between coated and uncoated glass increases. There is a decrease in the temperature of glass coated with ATO. Thus, ATO can be used in a vast array of applications as an energy-conserving material.

The percentage temperature change has been calculated using a formula,

\[
\Delta T\% = \left( \frac{\text{Pure glass Temperature} - \text{ATO coated glass Temperature}}{\text{Pure glass Temperature}} \right) \times 100 \tag{10}
\]

The data points obtained using relation (10) has been plotted shown in figure 8(b) with help of linear fitting. It can be seen that figure 8(b) that it is showing as the linear relation of irradiation time versus percentage temperature change. This can now be concluded as an increase in the temperature difference between the plane glass and the glass coated with the ATO material. Thus, a decrease in temperature has been observed by using ATO material coatings.

5. Conclusion

To provide a brief summary, the synthesis of SnO₂ and SnO₂ doped with Sb was accomplished by the use of a cost-effective sol-gel process. The SnO₂ retains its tetragonal structure after doping with Sb, and crystallite size reduction was observed at its lowest for ATO-4. The (110) peak of XRD and the A₁₅ mode of vibration indicate the left shift with the increment in Sb doping concentration in ATO nanoparticles. The ATO nanoparticles...
showed a preferred orientation along the (211) plane. The transmittance and absorbance of ATO nanoparticles have been observed. It has been seen that the NIR reflection of the samples increases with an increase in Sb doping. The ATO nanoparticles retain excellent visible transmittance and good IR reflection. The visible transmittance and IR reflection were seen at their maximum in the ATO-4 sample. Furthermore, from their thermal performance characteristics, it is confirmed that ATO samples have enhanced features with respect to their insulating nature. Our findings show that ATO nanoparticle-coated films are potential candidates for heat insulation in the fields of energy conservation and optoelectronics. They serve as transparent electrodes, exhibiting exceptional optical characteristics.

Acknowledgments

Towseef Ahmad is thankful to National Institute of Technology Srinagar for providing us platform to perform my research work and highly great full to MHRD (ministry of human resource development) for providing financial support.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The manuscript has not been previously published and also is not currently submitted for review to any other journal and will not be submitted elsewhere before a decision is made by this journal. The authors declare that there is no conflict of interest.

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