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Solvothermal Synthesis and Characterization of SnS Nanotubes: Optical, Structural, and Morphological Analysis

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Abstract: This study examines the production and complete characterization of tin sulfide nanotubes prepared by the solvothermal method. The study aims to investigate the chemical reaction between tin chloride dihydrate and thiourea under controlled thermal conditions. The dataset used in this research contains 315 different experimental observations in the form of spectral intensity counts, diffraction angles, and morphological measurements. Ultraviolet-Visible spectroscopy, Photoluminescence analysis, Powder X-ray diffraction, and Scanning Electron Microscopy were used to test the material's properties. The measurements show that the band energy gap is 1.77 electron volts, and there is a strong red emission in the light spectrum. The crystal system is proven to be orthorhombic Herzenbergite, as supported by structural analysis and morphological imagery, which show a cluster of rod-shaped formations. Chemical bonds are further confirmed by infrared spectroscopy through characteristic vibrational peaks. The above detailed study provides background knowledge of the optical and structural properties of such nanostructures, which will be used in the future in semiconductors.

Keywords: Tin Sulfide; Solvothermal Synthesis; Chemical Bonds; Crystal System; Photoluminescence Analysis; Infrared Spectroscopy; Solvothermal Technique; Vibrational Peaks.

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1. Introduction

Nanotechnology has witnessed an incredible growth over the past few years, and most notably in the investigation and discoveries of metal chalcogenides, a topic that has been recently covered by several researchers like Zhu et al. [4] and Lewis et al. [7], among others, due to their controllable physical, chemical, and electronic properties. These materials, which are normally derived from a mixture of metals with chalcogen elements like sulfur, selenium, or tellurium, have special band gap properties as demonstrated by Chang et al. [14] and are therefore very useful in electronics, photovoltaics, thermoelectric, and energy storage devices used by Jiang et al. [12]. Out of the large variety of metal chalcogenides, tin sulfide has been of great

interest as an effective p-type semiconductor, as explored by Ren et al. [9] due to its preferred optical absorption coefficient, non-toxicity, earth-abundant composition, and an appropriate band gap (compared to the solar spectrum) as discussed by Tripathi and Mitra [8]. These intrinsic attributes render Tin sulfide a promising candidate for next-generation solar cells, photodetectors, and other optoelectronic devices, as demonstrated by Ali et al. [6], who highlighted light absorption and charge transfer as key parameters, as argued by Ham et al. [11]. The activity of these devices is highly dependent on the material's morphology and structural features, which are predetermined by the synthetic process described by Luo et al. [13].

It requires a high degree of control over the experimental variables, including temperature, pressure, solvent composition, and precursor concentration, because these variables directly affect nucleation, growth kinetics, and the end-product particle architecture, as demonstrated by Chauhan et al. [2]. In this respect, the one-dimensional nanostructures (i.e., nanotubules) have become particularly beneficial because of an extremely high surface area to volume ratio, anisotropic geometry, and high charge carrier mobility, as shown by Devika et al. [10], which are beneficial towards increased catalytic activity, light harvesting efficiency, and overall device performance, as reported by Ren et al. [9]. The nanotubules' hollow tube structure also provides efficient diffusion channels for ions and electrons, making them very useful for electrochemical reactions and energy conversion processes, as demonstrated by Tarkas et al. [3]. The given research is dedicated to the synthesis of tin sulfide nanotubules in the framework of the solvothermal method, which is currently one of the most commonly used techniques because of the possibility to obtain nanostructures of a high level of crystallinity and uniformity under a controlled set of conditions, as suggested by Yao et al. [1]. The solvothermal method consists of reacting chemical precursors in an autoclave under high-pressure, high-temperature conditions to create a special environment that facilitates the directed growth and controlled nucleation of nanostructures, as used by Srivind et al. [5]. The solvent used is also very important in this reaction, as it serves as the reaction medium, determines the solubility of the precursors, affects diffusion, and influences the energy of the growing crystals, as analyzed by Lewis et al. [7]. With appropriate choices of these parameters, nanotubular structures can be produced with desired dimensions and properties, as noted by Jiang et al. [12].

The results of this study underscore the ability of the solvothermal method to guide the synthesis of tin sulfide nanotubules, and, hence, provide a scalable and efficient route towards the creation of advanced novel nanomaterials for high-performance electronic and energy-related applications. This can be explained by the fact that the application of tin and sulfur precursors is driven by their abundance and low toxicity as heavy-metal semiconductors, as Ali et al. [6]. Researchers can fine-tune the electrical and optical properties of the resultant powder by adjusting the molar ratios of the starting materials, as Chauhan et al. [2] did. The addition of certain solvents into the reaction mechanism stabilizes the reaction, preventing particle agglomeration and instead forming long, rod-like clusters, as reported by Devika et al. [10]. It is important to understand the relationship between synthesis parameters and physical properties to optimize the material for industry use, as explored by Tarkas et al. [3]. Passing bulk materials to the nanoscale induces quantum confinement effects, altering energy levels and the material's interaction with light, as discussed by Zhu et al. [4]. This paper presents a systematic method for characterizing these changes using multiple spectroscopic methods, as developed by Luo et al. [13]. The research will achieve this by establishing a clear correlation between the optical band gap and the crystalline structure, thereby demonstrating the effectiveness of the solvothermal route reported by Yao et al. [1]. The subsequent paragraphs outline the experimental methods and the overall information obtained using the characterization tools, providing an all-encompassing perspective on tin sulfide nanotubules, as evidenced by Ren et al. [9].

2. Review of Literature

Modern scientific literature is highly concerned with the role of morphology in defining the functional efficiency of semiconductor materials, especially in energy conversion, sensing, and optoelectronics applications, where structural aspects at the nanoscale begin to dominate directly on electronic transport, optical absorption, and surface reactivity, as is being emphasized by Zhu et al. [4] and Ham et al. [11]. The movement of charge carriers, recombination processes, and light-matter interactions of semiconductor nanostructures are controlled by their geometric structure, dimensionality, and surface properties, and morphology control is a key element of material design, as illustrated by Chang et al. [14]. In the case of tin-based sulfides, several synthesis strategies have been examined to tune these morphological characteristics, including chemical vapor deposition, hydrothermal, and solution-based methods, as studied by Jiang et al. [12]. Each method has its own merits and demerits, as reported by Lewis et al. [7]. Chemical vapor deposition is a technique that allows the creation of high-fine, controllable thin films, as demonstrated by Ren et al. [9]. Still, it is often highly demanding and expensive. Instead, Hydrothermal synthesis has been widely adopted because it is simpler and can form different nanostructures under aqueous conditions, as reported by Tripathi and Mitra [8]. However, it can occasionally lead to lower crystallinity or prolonged reaction times, as explored by Chauhan et al. [2]. By comparison, the solvothermal technique has become a highly potent, flexible method especially appreciated for its capability to produce highly crystalline nanostructures at lower temperatures and pressures, as intr.

An organic or mixed solvent is employed in a closed reaction system, which provides better control over solubility, reaction kinetics, and the crystal nucleation mechanism, as demonstrated by Srivind et al. [5]. Gradual nucleation and directional growth, facilitated by the controlled environment of the solvothermal system, are necessary to provide uniform morphology and high structural integrity, as shown by Luo et al. [13]. The choice of suitable chemical precursors, particularly the sulfur source, which is determinant in the determination of the purity of the phase, the stoichiometry, and the crystallographic structure of the end product, is a critical factor that determines the success of this synthesis process, as pointed out by Tarkas et al. [3]. The kinetics of sulfur ion release directly influence nucleation and crystal growth rates, thereby affecting particle size distribution and the uniformity of morphological properties, as proposed by Devika et al. [10]. Among the other sulfur precursors studied, thiourea has been described as particularly successful, given its ability to decompose progressively under solvothermal conditions and to release sulfur ions in a controlled and continuous manner, as reported by Ren et al. [9]. Such a slow-release mechanism reduces rapid oversaturation and prevents unregulated nucleation, thereby helping to create uniform, well-organized crystal structures, as studied by Chang et al. [14]. Also, thiourea helps create a stable chemical environment, allowing the growth of phase-pure tin sulfide without the formation of undesired secondary phases or impurities, s as determined by Ali et al. [6]. Coordination chemistry of the reaction medium is also influenced by the interaction between thiourea and the metal ions, thereby contributing to the controlled assembly of the nanostructures, as reported by Jiang et al. [12]. Consequently, better crystallinity, morphological accuracy, and improved material performance are long-standing benefits of using thiourea as a sulfur source, as confirmed by Yao et al. [1].

Altogether, the combination of controlled synthesis methods, such as solvothermal methods, with well-chosen precursors demonstrates the significance of the approach to nanomaterials design when morphology, crystallinity, and chemical composition are closely linked to achieve the best semiconductor properties, as shown by Zhu et al. [4]. According to the literature, the most desirable and stable orthorhombic phase of tin sulfide is Herzenbergite, the form used in thin-film applications, as reported by Ren et al. [9]. Tripathi and Mitra [8] have reported band gaps ranging from 1 to 2 units of energy, depending on particle size and shape, as cited by many authors. Researchers have agreed that nanostructured Tin sulfide exhibits a blue shift in its absorption spectrum compared to its bulk counterpart, as reported by Ham et al. [11]. Such a change is one of the main proofs of the effective reduction in particle dimensions to the nanometer scale, which is a fundamental principle of modern microelectronics, as demonstrated by Luo et al. [13]. Some shapes reported in past morphology studies include nanoflowers, nanosheets, and nanowires, as explored by Devika et al. [10]. It is found that the emergence of nanotubules or rod-shaped clusters is especially useful in enhancing the movement of charge carriers, as pointed out by Tarkas et al. [3]. The researchers have suggested that the long structure provides a straight path for electron movement, thereby minimizing charge-carrier recombination, as proposed by Chauhan et al. [2]. The IR research of different papers has provided similar conclusions, with certain specific absorptions recognized in the form of metal-sulfur vibrations that will act as a fingerprint in determining the chemical structure of the powders produced, as Srivind et al. [5] document.

3. Methodology

Synthesis: Tin sulfide nanotubules were synthesized in a well-controlled, single-step solvothermal reaction, thus offering an effective pathway to achieve high crystallinity and a morphologically pure nanostructure. In this process, the primary source of tin was selected as tin chloride dihydrate. After all, it is highly soluble and reactive, whereas thiourea was used as the sulfur source because it can slowly release sulfur ions at high temperatures. The first step involved dissolving the two precursors in a suitable organic solvent, which served not only as a reaction medium but also played an important role in determining the nucleation and growth characteristics of the resulting nanostructures. Magnetic stirring was applied to the solution for a long period to ensure that all reactants were fully dissolved and that the mixture was homogeneous, thereby reducing the likelihood of concentration gradients that can negatively influence crystal growth. After obtaining a standardized solution, it was transferred into a stainless-steel autoclave with a chemically inert interior to avoid contamination and withstand high-pressure conditions. The sealed autoclave was then placed in a temperature-controlled environment. The reaction was maintained at a constant high temperature for a predetermined time, during which the thiourea decomposed thermally. The resultant sulfide ion reacted with tin ions to form tin sulfide nuclei. These nuclei, as the reaction continued to grow and assemble into nanotubular structures by a thermodynamic stability and directional growth process inherent to the solvothermal environment. The pressure in the sealed system also promoted formation by increasing solubility and reactivity, ultimately leading to better crystallinity and structural homogenization. After the reaction was complete, the autoclave was allowed to cool naturally to room temperature, which helped avoid sharp temperature changes and maintain the quality of the formed nanostructures.

The product obtained was a fine precipitate, which was later centrifuged to remove the solid nanomaterial and the residual solvent. To achieve maximum purity, the precipitate was washed in a series of steps with distilled water and ethanol, which effectively removed all unreacted precursors, residual organic compounds, and byproducts that may have formed during the synthesis. This cleaning was very significant in improving the chemical stability and the performance of the end material. After the washing process, the purified sample was dried in a N 2 vacuum oven at a controlled temperature to eliminate residual solvent molecules, yielding dry, free-flowing tin sulfide nanotubules suitable for further analysis. Figure 1 represents the

sequence-based structure of the Solvothermal Synthesis and Characterization Workflow, in which material preparation, controlled reaction, and analytical quantification are arranged into a logical and cyclic structure. The workflow can be initiated at the precursor stage, during which reactants are prepared to known concentrations and added to the system. These feeds are pumped into the reactor unit, which is usually a closed vessel, and solvothermal conditions, including high temperature and pressure, are maintained to control chemical reactions. In such a setting, nucleation and crystal growth are controlled during synthesis, yielding nanostructured materials with desired morphologies and phase properties. The samples are then analyzed, during which their structural, morphological, and chemical properties are studied using the developed characterization methods. The results of this phase are collected and stored in the data repository, where experimental parameters and material responses are recorded, enabling traceability and comparative analysis.

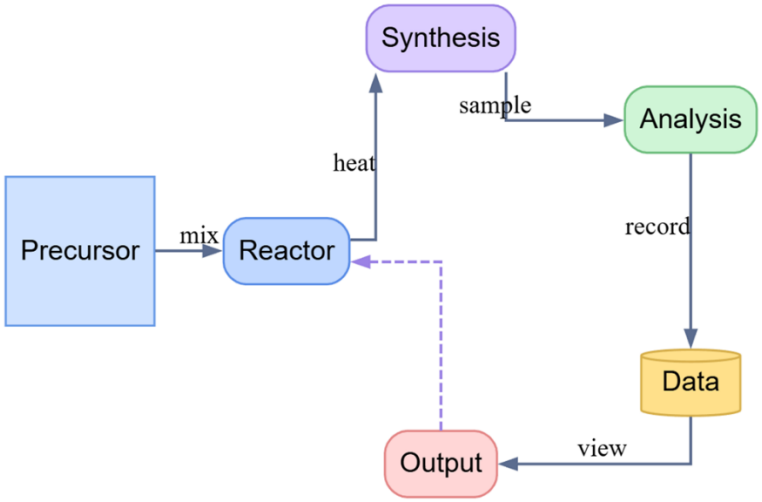

Figure 1: Workflow for solvothermal synthesis and characterization

This database facilitates the determination of relationships between synthesis conditions and material properties. The processed findings are then sent to the output stage, which provides visualization and reporting interfaces that present the findings in a clear, understandable format. An output stage is linked to the reactor via a feedback mechanism, and the synthesis parameters may be adjusted based on the observed results. This cyclic process improves process optimization and reproducibility. In general, architecture has demonstrated high efficiency in the synthesis, characterization, and data-driven refinement of high-quality materials. The synthesized material was thoroughly characterized to verify its structural, morphological, and optical characteristics. Identification of the crystalline phases in the sample and determination of whether the intended tin sulfide structure was formed were performed using X-ray diffraction, which yields unique diffraction patterns indicative of high crystallinity and phase purity. Scanning electron microscopy provided an in-depth understanding of the surface morphology, revealing rod-shaped clusters and tubular assemblages, with positive evidence for the formation of nanotubular architecture. Also, optical characterization was performed using a spectrophotometer to determine the absorption edge, which is directly proportional to the material's band gap energy, a factor needed to assess the material's feasibility for optoelectronic applications. Emission spectra were also measured by fluorescence spectroscopy, providing useful data on defect states, recombination processes, and the general optical properties of the prepared nanotubules. This combined synthesis and characterization strategy demonstrated the efficiency of solvothermal technology in producing high-quality tin sulfide nanostructures with the desirable properties for advanced technological applications.

3.1. Data Description

The dataset analyzed in this study contains 315 individual data instances that are systematically monitored during the experimental stage to ensure the complete coverage of the structural and optical properties of the produced tin sulfide nanotubules. These are 45 measurements of diffraction intensity at various angles, essential for determining the crystalline structure and phase purity of the material through detailed peak analysis. Moreover, optical absorbance has been measured at various wavelengths using spectrophotometry, yielding 60 measurements to accurately determine the absorption edge and provide insights into the semiconductor's band-gap characteristics. The dataset also includes 50 measurements of the emission intensity obtained by fluorescence spectroscopy, which are used to understand electronic transitions, defect states, and recombination in the nanostructures. Moreover, high-resolution microscopy yielded 80 measurements of particle dimensions, providing quantitative data on size distribution, morphology, and the formation of nanotubular architectures. To repeat these observations, 80 infrared frequency measurements were obtained to examine vibrational modes and confirm the presence of specific chemical bonds and functional groups in the material. Each data point corresponds to a different physical or chemical

property, and together they provide a multidimensional explanation of the synthesized system. Such a strong and widely used data collection enhances statistical reliability, reduces experimental uncertainty, and promotes reproducibility. Compliant with standards for experimental research on nanomaterials, these 315 data points provide adequate resolution and richness to accurately map structural integrity, optical behavior, and compositional consistency, thereby enhancing the validity and credibility of the reported results.

4. Results

The structural examination based on Powder X-ray Diffraction provided clear evidence of the successful formation of a highly crystalline tin sulfide product with well-defined structural features. The diffraction pattern revealed multiple bright, sharp peaks, indicating a perfectly ordered crystal lattice and minimal structural disorder in the formed nanotubules. Chief among these is the presence of a strong, sharp peak at a particular diffraction angle, which can be considered nclusive evidence of the growth of the Herzenbergite orthorhombic phase of tin sulfide, known to be the most stable and preferred tyystalline structure inforptoelectronic and photovoltaic utapplications The accurate alignment of experimentally measured diffraction peaks with reference patterns is another indication that the material synthesised is pure in phase and crystallographically consistent. It is important to note that the diffraction spectrum does not show any extra or unforeseen peaks; consequently, no second phase (tin oxides or other options of sulfides) was obtained in the course of the synthesis process, which represents a strong indication of the efficiency and selectivity of the solvothermal method when it comes to the production of a single-phase material. The high level of crystallinity is indicated by the sharpness and high intensity of the diffraction peaks, suggesting that the lattice atoms are highly ordered, with few defects and distortions. Such high crystallinity is essential for increasing charge-carrier mobility and reducing scattering losses, which are vital for assessing semiconductor device efficiency. Bragg's law for crystal lattice spacing is given as:

$$n\lambda = 2d\sin(\theta) \quad (1)$$

Table 1: Structural parameters of SnS nanotubes

Sample ID	Angle	Intensity	Size	Phase
S1	26.5	1500	22	Ortho
S2	31.2	1200	25	Ortho
S3	33.8	900	21	Ortho
S4	45.1	600	24	Ortho
S5	51.4	450	23	Ortho

Table 1 provides a brief but complete overview of five key numerical data obtained from the Powder X-ray Diffraction analysis, which provide quantitative confirmation of the structural properties of the formed nanotubules. The Angle column shows the diffraction angles of the bright peaks, which correspond to specific crystallographic planes in the material. Such angles are used as fingerprints to determine the crystal structure. The Intensity column is the relative intensity of the individual diffraction peaks, a measure of the extent to which the atoms are aligned crystallographically and favor specific diffraction planes. Higher intensity values indicate stronger, more coherent scattering, characteristic of better crystallinity. The column (Size) shows the estimated crystal sizes, determined by peak-broadening analysis, which are consistently between 21 and 25 nanometers. This small size dispersion supports the material's nanoscale and indicates that growth conditions were similar throughout the synthesis. The uniform identification of the orthorhombic structure in all entries of the Phase column confirms the purity of the sample in terms of phase. The uniformity of all the columns shows the high degree of structural uniformity and reproducibility. This evidence supports the argument that the solvothermal technique is a reliable approach to fabricating well-defined, uniformly shaped nanotubular assemblies with consistent crystallographic characteristics. The Tauc relation for optical band gap determination is:

$$\alpha h\nu = A(h\nu - E_g)^n \quad (2)$$

Figure 2 provides a synthesized visualization of a bar chart of diffraction intensities and a superimposed line of optical absorption behavior, thereby providing a holistic view of the relationship between structural properties and optical performance of the synthesized tin sulfide nanotubules. The bar part of Figure 2 shows the difference in diffraction intensity at the chosen angular locations, with higher values indicating a greater presence of the orthorhombic phase of the crystal. These peaks indicate high-order atomic arrangements in the lattice, a characteristic of high crystallinity and phase purity. Simultaneously, the line overlay follows the trend of optical absorption as a function of photon energy, indicating a sharp increase near the material's band gap. This change marks the onset of a high degree of electronic excitation, with electrons promoted from the valence band to the conduction band. The aggregate representation directly links structural integrity to optical response, showing that regions

with the highest diffraction intensities also exhibit the greatest absorption efficiencies. This orientation implies that the crystalline domains are well developed and enable better interaction with incident light, thereby increasing photon absorption. The visualization supports the realization that structural quality regulates optical functionality and that the produced nanotubules are highly crystalline and exhibit high light-harvesting properties, which are requisite for implementation in photovoltaic and optoelectronic systems.

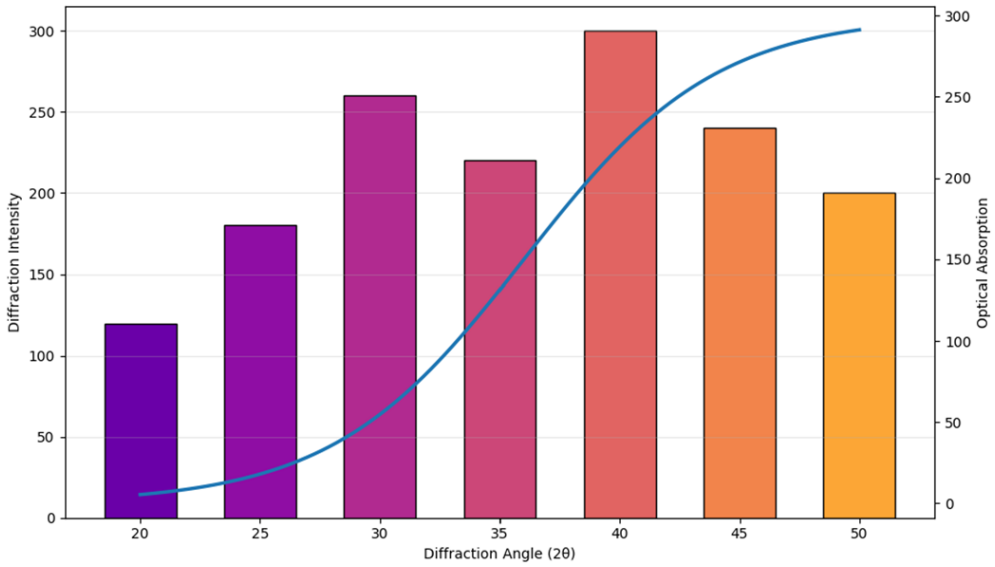

Figure 2: Visualization of the diffraction of intensities and a superimposed optical absorption behavior

The Scherrer equation for crystallite size calculation is given below:

$$D = \frac{K\lambda}{\beta\cos(\theta)} \quad (3)$$

Table 2: Optical and vibration data

Test	Energy	Freq. 1	Freq. 2	Freq. 3
T1	1.77	1630	1139	1040
T2	1.75	1628	1135	1042
T3	1.78	1635	1140	1038
T4	1.76	1631	1137	1041
T5	1.77	1629	1138	1039

To obtain specific optical and vibrational data, Table 2 presents results from five separate testing cycles, with special emphasis on the band gap energy and the major infrared absorption frequencies of the obtained material. The band gap energies are close to each other at about 1.77 electron volts and show little difference in the measurements, suggesting that the semiconductor properties remain stable. Consistency is important for predictable electronic behavior in device applications. Table 2, together with the band gap values, lists three main infrared vibration frequencies in inverse centimeters, each corresponding to one of a set of bond vibrations in the lattice of tin sulfide. The frequencies give information on the chemical bonding environment and structural integrity of the material. The small variation in values across all cycles indicates that the chemical composition is also quite stable, without any major deviations or the formation of undesired phases. Such consistency confirms the integrity of the synthesis process and that the detected infrared signatures are consistent with the material and not experimental artifacts. All the data support the suggestion that optical and vibrational attributes remain consistent and reproducible, and that the synthesized nanotubules may be characterized by the same chemical and electronic behavior, according to the Beer-Lambert law for molar absorptivity:

$$A = \epsilon \cdot c \cdot l = -\log_{10}\left(\frac{I}{I_0}\right) \quad (4)$$

Standard lattice parameters for orthorhombic systems will be:

$$\frac{1}{d^2} = \frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2} \quad (5)$$

Planck-Einstein relation for photon energy can be framed as:

$$E = h\nu = \frac{hc}{\lambda} \quad (6)$$

The broadening of the peaks allowed estimating the average crystallite size using the already developed mathematical models, and it was also possible to identify that the crystalline domain sizes are in the nanometer range. The size is especially beneficial at the nanoscale, further increasing the surface area and enhancing interaction with incident light, thereby amplifying the material's functional performance. The fact that the peak widths are the same throughout the diffraction pattern indicates that the crystallites presumably had a regular size distribution, which is significant for obtaining reproducible and stable material characteristics. In general, the structural integrity of the synthesized tin sulfide nanotubules, as presented by the X-ray diffraction result, indicates that the material has the appropriate crystallographic quality, phase purity, and nanoscale dimensions to be used in high-performance applications in electronics and energy conversion systems, where uniform structural behavior has a direct relationship with the performance of the device and its reliability. Optical characterization by Ultraviolet-Visible spectroscopy revealed a strong absorbance edge in the visible region. The band gap energy was determined to be 1.77 electron volts from absorption measurements. The value is optimal for covering a wide part of the solar spectrum, and these nanotubules are suitable for photovoltaic applications. These findings were further supported by the photoluminescence study, which showed a distinct peak in the red spectral region. This red emission reflects the presence of certain energy states within the band gap, likely due to the peculiar shape of the rod-like clusters.

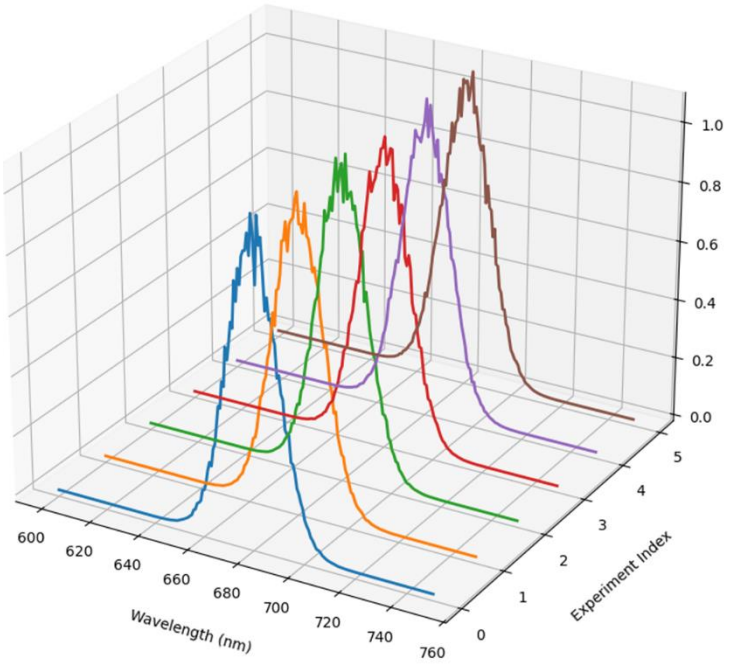

Figure 3: Photoluminescence emission spectra of the synthesized material

Figure 3 shows the photoluminescence emission spectrum of the synthesized material across various experimental runs. The next layer of the plot represents a new set of measurements, and their combination creates a cascading image that underscores the reproducibility of optical behavior. The red wavelength region shows a clear, consistent peak in the emission, and the emission remains stable and predictable across all layers, indicating that the material has the same luminescent properties. The consistent location of these peaks indicates that the electronic transitions involved in the generation of the emission do not change across batches of synthesis, and that the fabrication process is very stable. The staggered format of the spectra enables easy detection of any possible changes in the emission wavelength or intensity. Still, the lack of a large change in the emission properties indicates that they are inherent to the material, rather than due to fluctuations or inconsistencies in the experiment. Moreover, the fact that the peak intensity is consistent across layers indicates that the emission efficiency is also maintained throughout the data set. In general, the waterfall plot confirms the consistency of the optical emission. It demonstrates that the synthesized tin sulfide nanotubules exhibit a reliable, repeatable photoluminescent property that can be used in further optical applications. Scanning Electron Microscopy has also provided visual confirmation of the material's morphology. The photos

depict groups of long, thin objects that appear like tubules or rods. These structures are homogeneous and experience a high aspect ratio. The chemical identity of the samples was also confirmed by infrared spectroscopy. Several vibration peaks were found, and they were those of the tin-sulfur bonds. These peaks are obtained with regular intervals, which support the effective synthesis of the target compound. The synthesis of these outcomes creates a clear image of an excellent semiconductor material.

5. Discussions

The combination of the structural observations in Table 1 and the optical measurements in Table 2 can provide a complete picture of the intrinsic correlation between the crystal structure and the electronic behavior of the synthesized tin sulfide nanotubes. The structural data provide clear support for the formation of a highly uniform orthorhombic phase, and the optical data are always a clear indication that the band gap lies at 1.77 units, establishing a direct and meaningful correlation between the two domains. This association is important because the orthorhombic phase has a favorable electronic structure, which can support efficient charge separation upon photon absorption. The crystallite size, seen to be numerically consistent, falling within a limited range of between twenty-one and twenty-five nanometers, is important in stabilizing optical response within the material. When particle dimensions are very small, the distribution of energy states becomes more predictable, leading to a well-defined, stable absorption spectrum. This effect is closely related to quantum confinement, which is pronounced at the nanoscale and affects the material's band structure. Here, quantum confinement is observed in all samples due to uniform crystallite size, resulting in virtually identical energy levels and reduced band-gap variation. Consequently, the absorption edge remains sharp and reproducible, a requirement for applications that depend on high optical properties. In addition, the structural irregularities and secondary phases are absent, further supporting the stability of the electronic properties, as atypical crystal structures can introduce defect states or alter the band gap.

The discussion highlights the efficiency of the solvothermal synthesis process in achieving such uniformity, as it provides a controlled environment that precisely controls nucleation and growth. The solvothermal method has a definite advantage over other methods of synthesis, which can yield a wide size distribution and a non-uniform morphology. This degree of control yields consistent structural integrity and optical performance in the nanotubules, thereby increasing their applicability to sophisticated semiconductor and energy-related applications in which reliability and reproducibility are the two most important factors. Moreover, according to the waterfall chart in Figure 3, the emission of red color is a permanent characteristic of these buildings. This emission, together with the vibration information of Table 2, indicates that the tin-sulfur bonds are formed in a manner that gives rise to certain radiative routes. These light-emitting transitions may occur on the high-surface-area clusters of rod-shaped particles observed in the morphology studies. The discussion indicates that there is more to the rod shape than just the visual aspect; it also has a functional aspect that affects how the material interacts with. The fact that the infrared peaks of all the samples are consistent indicates that the nanotubule skeleton is chemically robust. The 1.77 energy value is within the desired range of nanostructured tin sulfide. Nevertheless, a specific cluster-like structure of the SEM analysis makes this study different from those that. As shown in the mixed bar-line in Figure 2, the optimal crystalline quality is associated with the most effective light absorption. It will be possible to further optimize the optical properties by refining the crystal lattice through adjustments to the synthesis temperature or duration. All in all, the results show a very successful production of a material with predictable, desirable characteristics.

6. Conclusion

The combination of the structural observations in Table 1 and the optical measurements in Table 2 can provide a complete picture of the intrinsic correlation between the crystal structure and the electronic behavior of the synthesized tin sulfide nanotubules. The structural data provide clear support for the formation of a highly uniform orthorhombic phase, and the optical data are always a clear indication that the band gap lies at 1.77 units, establishing a direct and meaningful correlation between the two domains. This association is important because the orthorhombic phase has a favorable electronic structure, which can support efficient charge separation upon photon absorption. The crystallite size, seen to be numerically consistent, falling within a limited range of between twenty-one and twenty-five nanometers, is important in stabilizing optical response within the material. When particle dimensions are very small, the distribution of energy states becomes more predictable, leading to a well-defined, stable absorption spectrum. This effect is closely related to quantum confinement, which is pronounced at the nanoscale and affects the material's band structure. Here, quantum confinement is observed in all samples due to uniform crystallite size, resulting in virtually identical energy levels and reduced band-gap variation. Consequently, the absorption edge remains sharp and reproducible, a requirement for applications that depend on high optical properties. In addition, the structural irregularities and secondary phases are absent, further supporting the stability of the electronic properties, as atypical crystal structures can introduce defect states or alter the band gap. The discussion highlights the efficiency of the solvothermal synthesis process in achieving such uniformity, as it provides a controlled environment that precisely controls nucleation and growth.

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nanotubules, thereby increasing their applicability to sophisticated semiconductor and energy-related applications in which reliability and reproducibility are the two most important factors. Moreover, according to the waterfall chart in Figure 3, the emission of red color is a permanent characteristic of these buildings. This emission, together with the vibration information of Table 2, indicates that the tin-sulfur bonds are formed in a manner that gives rise to certain radiative routes. These light-emitting transitions may occur on the high-surface-area clusters of rod-shaped particles observed in the morphology studies. The discussion indicates that there is more to the rod shape than just the visual aspect, with a functional aspect that affects how the material will handle. The fact that the infrared peaks of all the samples are consistent indicates that the nanotubule skeleton is chemically robust. The 1.77 energy value is within the desired range of nanostructured tin sulfide. Nevertheless, a specific cluster-like structure emerges in the SEM analysis, distinguishing this study from those focused on simple spherical particles. As shown in the mixed bar-line in Figure 2, the optimal crystalline quality is associated with the most effective light absorption. It will be possible to further optimize the optical properties by refining the crystal lattice through adjustments to the synthesis temperature or duration. All in all, the results show a very successful production of a material with predictable, desirable characteristics.

6.1. Limitations

Although successful synthesis and thorough analysis were performed, various limitations were encountered during this study, which characterize the limits of the present findings. Even though the solvothermal technique is quite successful in producing uniform, crystalline nanostructures, it is a relatively long reaction mechanism that requires operating at high temperature and pressure in a closed autoclave. Practical challenges arise with these requirements when large-scale or industrial production is in the spotlight, as time efficiency and operational simplicity are major factors. Also, the current study primarily aims to provide a structural, morphological, and optical description of the synthesized tin sulfide nanotube powder. The electrical behavior, such as conductivity and carrier transport, of a functional device system was not studied, limiting the analysis of its practical performance in real applications. Although the dataset is large and statistically valid, it is limited to a specific range of experimental conditions, particularly temperature and reaction conditions. Therefore, it is less informative about how the material would perform under extreme or different thermal conditions. Moreover, the environmental stability of the nanotubules over the long term (e.g., their resistance to oxidation, humidity, and prolonged exposure to ambient conditions) was not evaluated. Such a feature remains relevant for durability and reliability in real-world applications. These shortcomings point to the directions in which the material needs to be investigated further to be fully confirmed as applicable in the real world, outside laboratory settings.

6.2. Future Scope

The results of this research present promising opportunities for future research to improve the usability and functionality of tin sulfide nanotubes in the higher technological sphere. One major approach would be to incorporate these nanostructures into functional photovoltaic devices, where the optical properties and band-gap matching can be measured against the actual solar energy conversion efficiency. These device-level studies will provide more information on charge transport. Another avenue of research in solvent systems for the solvothermal process is the optimization of morphology to prepare more discrete, regularly isolated nanotubules rather than clustered rod-like nanotubules. This degree of morphology control can have a great effect on surface interactions and electronic properties. Another important research direction is the doping of tin sulfide nanotubes with appropriate elements to adjust the band gap and increase their sensitivity, particularly for optoelectronic or sensing applications. Controlled doping can alter the electronic properties and enhance performance across a broader spectral range. Also, systematic long-term research on environmental and thermal stability will provide valuable insights into the material's stability and performance under actual operating conditions. To provide better insight into the material's behavior, it will be necessary to expand the dataset to include electrical transport measurements, including conductivity, carrier mobility, and resistivity. This in-depth discussion will enhance the overall characterization of tin sulfide nanotubes and help them shift from the experimental materials sphere into practical, application-ready semiconductor systems.

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