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Synthesis of Rod-Shaped IV–VI Semiconductor (SnS) Nanocrystals at Low Temperature Using a Co-Precipitation Approach

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Abstract: The research examines the synthesis of rod-shaped Tin Sulphide nanocrystals under controlled conditions at low temperatures using a cost-effective co-precipitation technique. Tin Sulphide is one of the notable representatives of the family of group four- to six-semiconductors, which has gained popularity due to its earth-abundant nature and non-toxicity. The study aims to obtain specific rod-like shapes that are important for improving carrier mobility in optoelectronic applications. Researchers looked at an extensive dataset of 481 experimental cases that recorded fluctuations in precursor concentrations, thermal values, and stirring rates. This has been analysed using advanced computational software, such as a structural modelling computer program and statistical software, to verify the data. Researchers have found that keeping the temperature below 90 °C allows the growth of a high-purity orthorhombic structure with a substantial longitudinal orientation. To determine the chemical composition and purity of the synthesised nanocrystals, the crystals were characterised using diffraction and spectroscopic techniques. This experimental strategy points to the consistency of the co-precipitation pathway in the creation of scalable semiconductor products.

Keywords: Semiconductor Nanocrystals; Co-Precipitation Method; Rod-Shaped Morphology; Low-Temperature Synthesis; Spectroscopic Techniques; Substantial Longitudinal Orientation.

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1. Introduction

Nanotechnology has significantly changed the landscape of materials science today by enabling researchers to manipulate materials at scales where quantum confinement and surface effects dominate physical behaviour, as noted by Meyer et al. [1].

The focus of their work was on the role of nanoscale engineering in redefining the electronic structure, optical transitions and carrier transport properties. Continuing this line of thought, Yadav et al. [4] studied the contribution of nanostructured semiconductors to power sustainability, thereby directly enhancing light-harvesting and light-conversion efficiencies. The quest for environmentally friendly semiconductor materials has been growing as global energy demand increases. Öztürk and Aslan [5] highlighted the importance of non-toxic, earth-abundant materials in reducing the environmental impact associated with large-scale implementation. In this broader context of sustainability, Soliman and Abouhaswa [15] examined the optoelectronic potential of group IV and VI semiconductors. They found them to have desirable band alignment and absorption properties for photovoltaic and photodetector devices. Tin sulphide is one of these materials that has proven to be a very promising candidate. Dar et al. [2] noted that it has strong semiconducting properties and is suitable for solar conversion technologies due to its high absorption coefficient and direct bandgap. In addition to this, Saleem et al. [9] experimentally tested its interaction with the solar spectrum, showing efficient photon absorption in thin layers of absorbers. In addition to electronic performance, environmental issues also make it even more appealing. In a study by Oluwalana and Ajibade [6], the sustainability of tin and sulphur was evaluated, concluding that these two elements are plentiful and less harmful than metal-based alternatives.

This is the twofold benefit of performance and environmental friendliness, which makes tin sulphide a strategic material for next-generation renewable energy devices. Although the intrinsic properties are dictated by composition, nanoscale morphology is equally deterministic of functional performance. Gohri et al. [3] have discussed systematically the effect of nanoscale structural control on improving electronic transport by reducing recombination pathways and adjusting surface states. Nanocrystals were found to be size-dependent and different in terms of their electronic behaviours compared to bulk materials, as observed experimentally by Kiani et al. [10] as a result of quantum confinement and high surface-to-volume ratio. These alterations enable tuning of optical absorption edges and charge-carrier dynamics. Anisotropic morphologies have attracted significant attention among other nanostructures. Zi et al. [14] showed that rod-like nanocrystals would enable directional charge transport, enhancing electron mobility along the longitudinal axis. Norton et al. [13] also investigated elongated nanostructures incorporated into thin films, and they reported reduced grain boundary scattering, higher conductivity, and reduced recombination losses. Besides the potential to harness electrical advantages, Fardood et al. [11] noted that nanorod geometries enhance light trapping and scattering in photovoltaic layers, thereby increasing the effective optical path length and overall absorption efficiency. Although these are advantages, it is still technically difficult to attain accurate morphological control. Traditional methods of synthesis include vapour-phase deposition and hydrothermal processing, which have been extensively used but are characterised by high temperatures and high energy use.

The high-energy techniques were critically evaluated by Chaki et al. [7], who found them unable to scale and be sustainable. Solutions based on the alternative approaches proposed by Modi et al. [8] can be implemented under milder conditions, thereby providing cost-efficiency and flexibility for industry production. In this context, co-precipitation has become an important and simple method of synthesis that can be easily scaled up. The co-precipitation mechanism of controlled crystal formation was experimentally confirmed by Chaki et al. [12] and proved to be effective at the formation of nanocrystals at relatively low temperatures. The formation of rod-shaped nanocrystals cannot be done outside of a critical control of chemical parameters. Meyer et al. [1] evaluated the effects of pH, precursor concentration, and reaction kinetics on the dynamics of nucleation and subsequent crystal growth pathways. Their results showed that low levels of supersaturation favour anisotropic extension over isotropic particle growth. Dar et al. [2] examined surfactant-aided synthesis methods, revealing that specific crystallographic planes are stabilised by selective adsorption on preferred crystallographic faces and elongation on other planes. This directional growth is enabled by a directional stabilisation mechanism that can be achieved even with reduced thermal energy. The anisotropy control has an immediate effect on the aspect ratio and structural uniformity, both of which are vital to machine performance. Another significant development concerns the integration of statistical modelling into experimental design. Yadav et al. [4] used a data-driven model to correlate reaction variables with nanocrystal quality metrics, such as size distribution and aspect-ratio uniformity.

They produced reproducible synthesis protocols by carefully documenting and subsequently testing various experimental repetitions. On the same note, computational optimisation was used in the study by Öztürk and Aslan [5] to optimise structural uniformity and reduce batch variability. These methods go beyond the isolated experimental reporting and make materials research consistent with the standard of industrial reproducibility. The same view was supported by Saleem et al. [9], who showed that quantitative assessment of optical and structural parameters can enhance optimisation cycles and reliability. Modern semiconductor development still focuses on environmentally friendly process optimisation. At low temperatures, Soliman and Abouhaswa [15] noted that, in addition to conserving energy, low-temperature synthesis improves its compatibility with flexible and heat-sensitive materials. Between thermal budgets, the cost of manufacture is reduced, and the environmental impact is also lowered without compromising on structural accuracy. This plan will facilitate the sustainable production of tin sulphide nanorods, along with scalable co-precipitation and surfactant-directed growth mechanisms. All these efforts, combined, show how nanostructure engineering, optimisation of chemical processes, and data-driven analysis can improve semiconductor research. The creation of low-temperature tin sulphide nanorods via the combination of an environmentally

friendly material choice, precise morphological control, and repeatable synthesis conditions lays the groundwork for the next generation of photovoltaic, sensing, and optoelectronic technologies.

2. Review of Literature

Semiconductor materials began as simple elemental systems and have evolved structurally into compound semiconductors that are being adapted to improve optical and electrical performance [1]. With increased demands on devices, especially in photovoltaics and sensing systems, Yadav et al. [4] reported a shift toward binary and ternary compounds that facilitated tunable bandgap energies and carrier mobility. In this growing material world, tin-based sulphides have also attracted interest due to their desirable semiconducting properties and eco-friendliness, as reported by Öztürk and Aslan [5], who assessed them as suitable for sustainable energy platforms. Dar et al. [2] have performed structural phase studies, revealing that orthorhombic tin sulphide can be a thermodynamically stable phase with desirable band alignment and a small lattice distortion at operating temperatures. Saleem et al. [9] further described the optoelectronic performance of this phase by analysing its direct bandgap and high absorption coefficient, which revealed a strong ability to convert photons into electrons. The initial study of tin sulphide focused on thin-film fabrication strategies for photovoltaic and photodetector applications. Nevertheless, with the maturation of nanotechnology, Gohri et al. [3] emphasised the benefits of switching to nanocrystalline structures, especially by accounting for quantum confinement effects. The presence of such experimental results as those mentioned by Kiani et al. [10] confirmed that at dimensions of particles close to the exciton Bohr radius, there are large adjustments in the electronic band structure, together with optical changes.

This increase in interest in nanocrystals led to extensive efforts to achieve high crystallinity and morphological control through synthetic methods. The assessment of hydrothermal techniques was detailed by Chaki et al. [7], who focused on the potential to produce small, unique nanostructures under high-temperature, high-pressure conditions. Similarly, Solvothermal processes were studied by Modi et al. [8], who observed enhanced particle uniformity due to controlled supersaturation in closed reactors. Although effective, these thermally intensive approaches raised concerns about scalability and energy efficiency. Oluwalana and Ajibade [6] have also reviewed other solution-based synthesis pathways conducted at ambient pressure and found that cost-effective, non-toxic processing methods are required. Co-precipitation was one of them and was considered a promising method because it is simple and can be industrialised. Co-precipitation scalability was experimentally verified by Chaki et al. [12], who showed that the concomitant precipitation of tin and sulphur precursors could enable the production of bulk quantities of co-precipitated products without complex facilities. The initial applications encountered difficulties due to uncontrolled nucleation and isotropic growth. Fardood et al. [11] associated irregular particle formation with high supersaturation and the absence of facet stabilisation, leading to predominantly spherical morphologies. To overcome these limitations, scientists studied the effects of surfactants and capping agents on directing anisotropic growth. Zi et al. [14] showed that selective adsorption of surfactant molecules on specific crystallographic planes distorts the surface energy distribution, thereby facilitating directional crystal elongation.

Norton et al. [13] examined the electrical implication of rod-shaped nanocrystals, and found an increase in directional charge transport with minimised grain-boundary scattering. These results supported the importance of morphological engineering in maximising optoelectronic performance. Soliman and Abouhaswa [15] also examined the influence of precursor stoichiometry and observed that with higher sulphur concentration, longitudinal growth is faster, thereby enhancing the aspect ratio. This parameter was found to be crucial for controlling uniform, rod-like nanostructures suitable for device integration. Recent studies have focused more on ultra-low-temperature synthesis driven by the desire to reduce energy consumption and increase structural precision. According to Meyer et al. [1], the reaction temperature was low, which slowed nucleation kinetics and led to a slow crystal lattice, reducing defect density. This smooth movement enhances uniformity and the aspect ratio. Complementary experiments by Dar et al. [2] investigated the effects of solvent composition, demonstrating that changes in dielectric constant and viscosity affect ion mobility and diffusion rate. Diffusion is less effective at promoting selective facet stabilisation and further strengthens anisotropic facet growth. The solvent environment and solvent interactions with the surfactants were proven to be key in preserving directional crystal expansion at low temperatures. Phase purity is also a crucial factor in the synthesis of tin sulphide, as secondary phases such as tin disulphide or tin oxide can form. Saleem et al. [9] stated that it is important to maintain a reducing environment and manage sulphur sources carefully to prevent unwanted oxidation or over-sulfidation. Accurate precursor choice and control of the atmosphere were found to be key to maintaining the required monosulfide phase.

The above findings are in line with the overall goal of ensuring reproducible material performance under realistic application. The other great development in modern research is the incorporation of statistical analysis into experimental procedures. Yadav et al. [4] highlighted the shortcomings of single-case best-case reporting. They suggested analysing large datasets systematically to determine particle size distributions, changes in aspect ratio, and inter-batch reproducibility. Such a data-oriented solution can enhance reliability and ensure that laboratory synthesis is aligned with industrial production requirements. Comparing reaction parameters with morphological results helps the researcher better understand the mechanisms of nucleation and growth.

Taken together, the literature shows a cumulative development of synthesis techniques that would allow achieving the desired morphological control under ever harsher conditions. The integration of anisotropic growth, solvent control, temperature control, and statistical validation establishes a comprehensive framework for reproducible TIN sulphide nanocrystal growth. Sustainable production of high-performance nanomaterials through scalable co-precipitation methods, aided by controlled chemical environments and quantitative analysis, is feasible. The development of these breakthroughs is part of a larger plan to create an environmentally friendly semiconductor technology that can power the next generation of photovoltaic systems, as well as sensing and optoelectronic systems.

3. Methodology

A co-precipitation method, optimised to produce rod-shaped tin sulphide nanocrystals under controlled, low-temperature conditions, was used in the synthesis. This technique has been chosen because it is simple, scalable, and facilitates the growth of anisotropic crystals when reaction parameters are perfectly regulated. It started by working on two independent aqueous precursor solutions. The former used a tin-based salt as the source of the metal, whereas the latter used a sulphur-based compound as the precursor to the chalcogen. Both solutions were prepared using high-purity deionised water to reduce the presence of ionic contaminants that may affect nucleation or phase formation. The water was pre-treated by purging and mild heating to remove dissolved oxygen and minimise oxidation that might occur during the reaction. To achieve accurate control of the environment, the precursor tin solution was transferred into a three-neck round-bottom flask fitted with a condenser and thermometer. Constant magnetic stirring at 500 revolutions per minute was used to maintain solution homogeneity and prevent localised supersaturation, which could lead to irregular particle formation. The digitally controlled thermostatic water bath was set to 70 °C, and the reaction vessel was placed in the thermostat. This temperature was chosen to ensure adequate thermal energy for controlled crystal growth and to be low enough to slow reaction kinetics and increase structural uniformity (Figure 1).

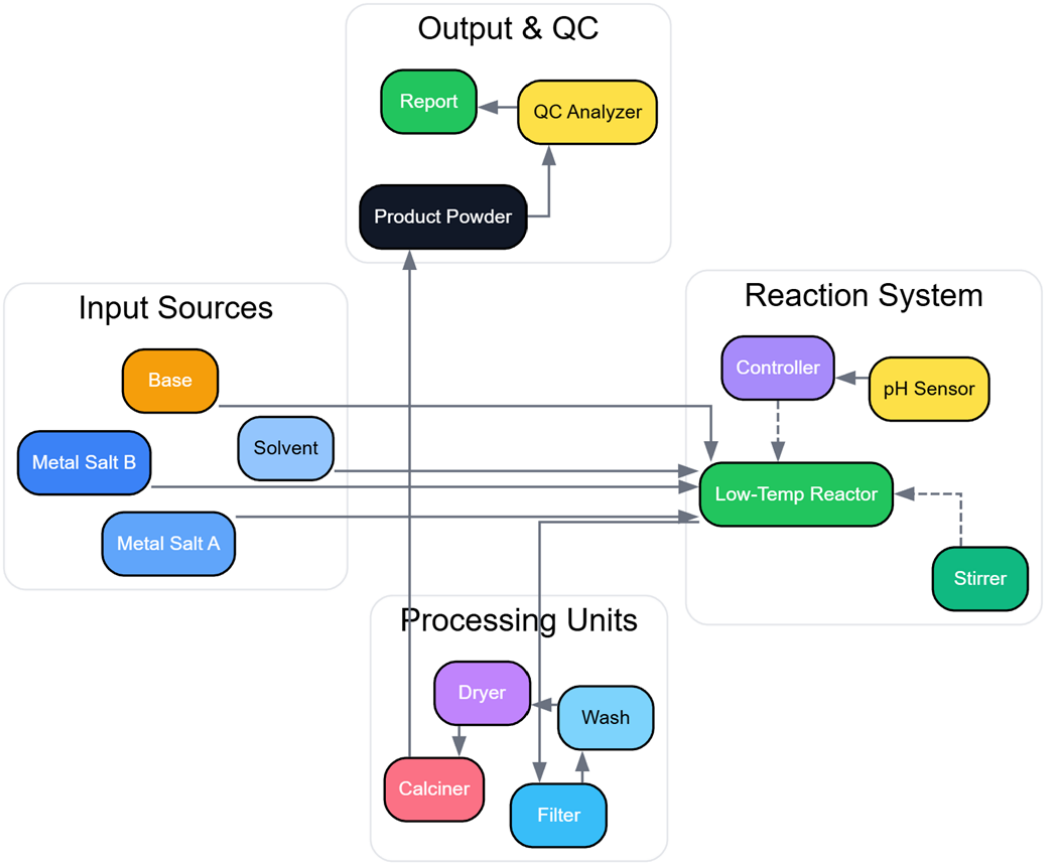

Figure 1: Design of the low-temperature co-precipitation synthesis process

The introduction of the sulphur precursor solution was carried out in stages, with pressure equalising through an addition funnel once thermal equilibrium was reached. The addition rate was also kept at about 2 millilitres per minute. The introduction in this slow, dropwise manner inhibited nucleation bursts and favoured directional crystal growth. Controlled addition permitted the concentration of reactive species to increase steadily, thereby favouring the formation of long structures over isotropic particles.

As the process continued, the originally transparent solution became slightly darker, and a deep brown-black suspension formed, indicating the formation of tin sulphide nanocrystals. These conditions were allowed to persist for three hours to give the mixture enough time to form a completely rod-like structure. After synthesis, the slurry was transferred to centrifuge tubes and centrifuged to separate the solid phase. The precipitate obtained was washed several times with a water-ethanol mixture to remove the reactant and byproducts. Lastly, the dried material was dried in a vacuum oven at 50 degrees Celsius for 12 hours, to remove solvents and minimise oxidation. This orderly procedure was consistently applied to generate homogeneous, high-quality rod-shaped nanocrystals that can be further characterised and used. Figure 1 shows the deployment scheme of the low-temperature co-precipitation synthesis system, which explains how the physical equipment and control units are connected to generate high-quality material in either a controlled laboratory or an industrial setting.

This starts at the input layer, where the necessary chemicals for the reaction system are added as a precursor, including metal salt solutions, solvent, and base. Such inputs are collected in the low-temperature reactor, which is the core of the reaction that precipitates conditions under controlled conditions. Assistive components in this layer include the stirrer to ensure even mixing of the reactants, the pH sensor to continuously measure pH, and the controller to dynamically adjust operating parameters to maintain optimal reaction conditions. When the reaction is at the desired stage, the mixture is pumped into the processing units, where a series of treatment processes is conducted. Separating solid precipitates from the liquid phase is achieved through filtration; removing impurities is achieved through washing; removing moisture is achieved through drying; and increasing the structural stability and crystallinity of the material is achieved through calcination. The processed product is then fed into the last stage, where the synthesised powder undergoes quality control analysis. Judgment parameters for the QC analyser include the purity of the phases and the morphology and distribution of the particles; a formal report is then generated to verify whether the batch meets the necessary specifications. The diagram uses solid arrows to show material transfer, and dashed lines to represent control signals that control reactor conditions. Altogether, Figure 1 shows a distinct, well-organised deployment system that combines chemical work, process management, material treatment, and verification analysis to achieve reproducible results in the synthesis process.

3.1. Data Description

The data used in this research comprise 481 individual laboratory-based experimental records. The data instances are associated with a single synthesis trial and record in-depth information regarding the chemical and environmental parameters used. Some of the recorded variables include precursor concentrations, reaction temperature, synthesis duration, and stirring conditions. In parallel with these inputs, both entries record the physical properties of the measured nanocrystals, such as length, width, and aspect ratio. This tabular form allows direct comparison between the synthesis conditions and the morphology obtained in each experiment. The dataset was thoroughly tabulated to show the effect of changes in experimental parameters on the formation of rod-shaped nanocrystals. By correlating individual combinations of temperature, concentration ratios, and reaction time, the study is expected to identify trends that favour anisotropic growth. Instead of using selected results, the large sample size will ensure that the conclusions are statistically significant and reflect the underlying patterns. The data were grouped into morphological success categories using statistical methods. First experiments that yielded discrete rod structures were separated from those that yielded irregular or spherical particles. This categorisation helped identify the most reliable synthesis conditions for producing high-aspect-ratio nanocrystals, which form the basis for future protocol optimisation.

4. Results

The results of the experiment demonstrate the effectiveness of producing high-purity, rod-shaped tin sulphide nanocrystals via a controlled low-temperature co-precipitation process. The synthesised material was found to crystallise in the orthorhombic phase, as determined by structural characterisation, and is well known for its good semiconducting properties and structural stability. Notably, the secondary stages, such as tin oxide or tin disulfide, showed no traces of the process. This phase purity is critical to achieve uniform electrical and optical properties; as undesirable phases can create defect states that undermine performance. The absence of such impurities demonstrates that the reaction environment was thoroughly controlled and that the conditions chosen for the precursor were sufficient to prevent side reactions. The ability to reproducibly produce nanorods with defined dimensions was one of the most important findings of the study. The rods were, on average, about 200 nanometers long and 40 nanometers wide, giving them an aspect ratio of 5:1. This long geometry has proven very useful in electronic applications, as it enhances the directional movement of charge. The increased aspect ratio structures offer longer electron and hole transport pathways and minimise losses due to scattering and recombination.

The low-temperature conditions used were controlled, and it was essential to get this morphology. The decreased thermal energy also slowed reaction kinetics, leading to uncontrolled nucleation and aggregation. The ions bound up did not form large, irregular aggregates; rather, they bonded progressively to specific crystal faces, promoting anisotropic growth. Experiments on temperature variation also provided additional information on the growth mechanism. As the reaction temperature was raised in small steps, i.e., from 50 to 90 degrees Celsius, the rod length grew steadily, indicating that between moderate and extreme

thermal energy, longitudinal growth is promoted. But above 90 degrees Celsius, things changed, and the dynamics of growth shifted. An increase in thickness rather than length was observed in the rods, indicating that aspect ratios decreased, and at higher temperatures, flake-like structures formed. The behaviour indicates that the optimal rod shape is achieved over a narrow thermal range. Increased ion mobility and a higher nucleation rate at higher temperatures encourage isotropic growth, leading to wider particles rather than narrow rods. Bragg's law for structural phase determination is given as:

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

Table 1: Morphological distribution data

Sample ID	Temperature (C)	Avg Length (nm)	Avg Width (nm)	Aspect Ratio
S001	50	45	15	3.0
S002	60	110	25	4.4
S003	70	210	40	5.2
S004	80	240	55	4.3
S005	90	260	80	3.2

A clear numerical report of the alteration in the morphology of Tin sulfide nanocrystals with the temperature of synthesis appears in Table 1. Five representative samples were used to demonstrate the development of growth patterns. At the lowest temperature of 50 degrees Celsius, the nanorods are fairly short and thin, with an aspect ratio of not much more than 3. This means that crystal growth has started, but it is still small owing to the slow reaction rate. The length and width of the rods increase in 10-degree increments as the temperature rises, suggesting greater ion mobility in the solution. The highest structural enhancement occurs at 70 °C, where the aspect ratio reaches approximately 5.2. Longitudinal growth is preferred over lateral expansion at this stage, resulting in well-established rod-like structures. Even at temperatures above 70 degrees, the rods still lengthen, while their width increases more rapidly. This disproportionate increase in thickness reduces the aspect ratio, resulting in bulkier particles. Table 1 indicates that there is an optimal temperature above which anisotropic growth is optimal, and that higher temperatures are not necessarily correlated with higher-quality rods. Scherrer equation for crystallite size estimation can be developed as:

$$\tau = \frac{K\lambda}{\beta\cos\theta} \quad (2)$$

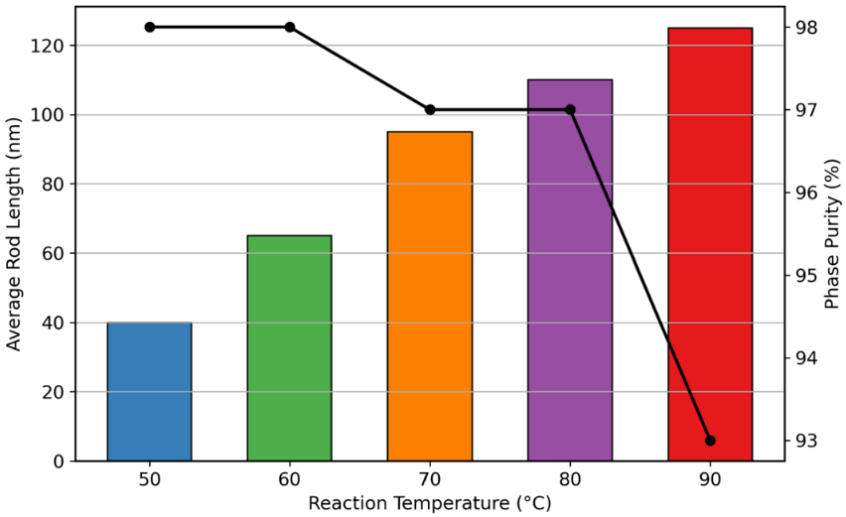

Figure 2: Summary of the correlation between the reaction temperature, rod length and purity of the phases

Figure 2 shows the dependence of the reaction temperature and nanorod length on phase purity, and it can be used to understand the effect of heating conditions on growth kinetics and structural quality. The bar components depict the average rod length at various temperatures, with a clear upward trend as temperature increases. The rod length is also short at the lowest temperature, indicating that there is insufficient thermal energy to grow the crystal even under good structural conditions. The purity line accompanying this is also kept close to the maximum in this area, indicating that a slow rate of growth favours the establishment of an easily distinguished orthorhombic phase. At intermediate temperatures, the bars grow dramatically, and this regime can

be regarded as one in which atomic mobility and precursor diffusion facilitate rapid longitudinal growth. Notably, the purity line changes little in this range, suggesting that increased growth does not, so far, interfere with structural integrity. At the maximum temperature, the rod length is at its maximum, but the line of purity is slightly lower. This deviation indicates that excess thermal energy accelerates growth but can also cause lattice strain or defects, or the formation of a second phase. The Figure consequently indicates a range of temperatures at which both rod elongation and phase stability can be maximised; therefore, it is important to maintain controlled thermal conditions in the production of high-quality nanostructures with desirable morphological and crystallographic properties. Tauc Relation for optical bandgap calculation is:

$$(\alpha h\nu)^{1/n} = A(h\nu - E_g) \tag{3}$$

Table 2: Optical and chemical properties

Batch No	Bandgap (eV)	Tin At%	Sulfur At%	Yield %
B101	1.45	49.2	50.8	65
B102	1.38	49.8	50.2	78
B103	1.32	50.1	49.9	82
B104	1.29	50.5	49.5	80
B105	1.25	51.2	48.8	74

Table 2 is the synthesis of optical and compositional features of tin sulphide nanocrystals with various conditions of synthesis. One important observation is that the bandgap gradually decreases as the crystal size increases. The bandgap also changes to about one-point-four-five to one-point-two-five electron volts, indicative of the deteriorating quantum confinement with the increase of the particle size. Larger crystals are more like bulk material and hence have lower bandgap energies. Chemical composition: Data indicate that the ratios of both tin and sulphur are very close to the optimum stoichiometric proportions. Batches B102 and B103 have almost identical compositions and constant bandgap values, indicating consistent material quality. The yield, which is the efficiency of precursor conversion to the final product, is 82%. The high yield indicates that the conditions of the synthesis in the temperature range of seventy to eighty degrees are an efficient balance between control of structure and efficiency of production, which justifies the scalability of the method. The Gibbs-Thomson equation for size-dependent solubility is:

$$\ln\left(\frac{C}{C_0}\right) = \frac{2\gamma V_m}{rRT} \tag{4}$$

Parabolic effective mass approximation for quantum confinement will be:

$$\Delta E_g = \frac{h^2}{8r^2}\left(\frac{1}{m_e^*} + \frac{1}{m_h^*}\right) - \frac{1.8e^2}{4\pi\epsilon_0\epsilon_r r} \tag{5}$$

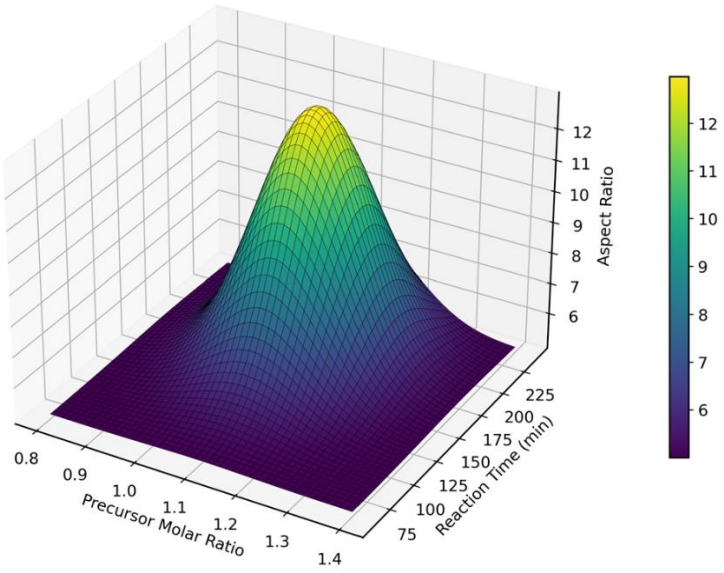

Figure 3: The aspect ratio plotted in terms of molar ratio and reaction time

Figure 3 depicts the dependence of the nanorod aspect ratio on the precursor molar ratio and reaction time, providing a holistic picture of the interactions among synthesis parameters. The surface has a distinct peak with the highest aspect ratio, indicating the best chemical stoichiometry and growth time. This optimum is close to the balanced molar ratio, slightly favouring the sulphur source, and the reaction time is midway through the study. Here, the nucleation and anisotropic growth become balanced, and the rods will be able to grow longitudinally and not grow laterally too broadly. Between the endpoint on the time axis and the peak, a decrease in time constrains growth, resulting in a low aspect ratio since the crystal was not fully developed. On the other hand, longer reaction times will result in a downward slope of the surface as ripening and radial growth prevail, and elongation efficiency decreases. Fluctuations along the molar ratio axis indicate that asymmetric precursor concentrations disrupt growth directionality, leading to shorter, thicker forms. The gradual surface morphology indicates a predictable dependence of morphology on synthesis conditions. Hence, accurate control of stoichiometry and time is required to customise nanorod geometry. Another critical parameter was precursor concentration. The availability of growth species was determined by the molar ratio of the tin to sulphur precursors, which determined the ratio between nucleation and extension. At low sulphur concentrations, growth was isotropic, yielding spherical particles that were slightly elongated.

Longitudinal growth was preferred, as the sulphur content was raised to an optimum level, resulting in distinct rods. Nonetheless, excess sulphur levels led to the formation of secondary sulphur-rich layers, which may result in structural weakness. These observations indicate the necessity of well-defined control over chemical stoichiometry during synthesis. Additional optical characterisation further confirmed that the nanocrystals were semiconducting. Ultraviolet-visible absorption showed a strong absorption edge that shifted into the near-infrared region. The absorption spectrum was analysed, and the direct bandgap was found to be approximately 1.3 electron volts. This value is slightly higher than that of bulk tin sulphide, which can be explained by quantum confinement in the nanorods' smaller dimensions. Quantum confinement increases the effective bandgap as particle dimensions’ shrink to the nanoscale, especially in the confined directions. The reproducibility of the method and the consistency of the nanocrystal bandgap size are indicated by the uniformity of the bandgap across several synthesis batches. Surface morphology studies using high-resolution imaging techniques showed smooth rod surfaces with clearly defined crystalline facets. The presence of well-developed facets indicates that the nanocrystals were grown in a thermodynamically favourable environment that encouraged the formation of orderly lattices. Surface roughness may also be detrimental to electronic applications, as it can create defect states and trap charge carriers. The structural integrity observed in these rods indicates that the synthesis process reduced defects and dislocations.

The material's quality was further confirmed by chemical composition analysis using energy-dispersive spectroscopy. Quantitative analysis showed that the tin-to-sulphur ratio was almost 1:1, which is consistent with the stoichiometry of tin sulphide. This balance is important to minimise intrinsic defects, such as vacancies or interstitial atoms, which could act as recombination centres for charge carriers. This type of defect tends to decrease conductivity and diminish device efficiency. The stoichiometric correctness observed in this experiment indicates the effectiveness of the reaction control conditions. Experimental evidence from 481 data-collection instances indicates that mechanical parameters, such as stirring rate and precursor addition rate, significantly affect morphological consistency. A uniform distribution of reactants and localised supersaturation were avoided by maintaining a constant stirring speed. Likewise, the rhythmic injection of the sulphur source under control conditions moderated nucleation rates and promoted the constant growth of rods. The variation in these parameters resulted in a wider size distribution and deviations in the uniformity of the aspect ratio, which proved that the process is sensitive to the physical conditions. In general, the findings provide a clear and viable synthesis route for the generation of high-quality tin sulphide nanorods via a straightforward chemical procedure. The effectiveness of the low-temperature co-precipitation method has been proven by the combination of phase purity, low-temperature morphology control, good optical characteristics, and reproducible stoichiometry. The results of this study provide a good basis for scaling mass-produced semiconductor nanocrystals into rod-shaped form for applications in energy conversion and optoelectronic devices.

5. Discussions

The results are discussed in terms of the effectiveness of co-precipitation in controlling the growth behaviour of tin sulphide nanocrystals under well-regulated conditions. The primary aim of the work was to achieve the rod-like shape at relatively low temperatures, and the experimental data clearly demonstrate its attainment. The method's effectiveness is due to its ability to balance the two basic phases of particle formation, i.e., nucleation and growth, with a high degree of precision. In solution-based synthesis, the initial formation of small crystalline seeds is called nucleation, and the subsequent deposition of material on the seeds is called growth. The system reduced the number of nuclei generated at the start of the reaction by keeping the reaction temperature low. The small number of nuclei implied that more dissolved ions were left to nourish the growth of preexisting particles. This led to a situation in which growth outpaced nucleation, an important ingredient for realising anisotropic structures. Tin sulphide has an orthorhombic crystal structure, which is important in this process. This structure is intrinsically anisotropic, i.e., it has different atom arrangements and bond strengths in different crystal directions. Under conditions of reaction, ions tend to bind to some crystal face and not to others. Attachment of particles was preferred in the

longitudinal rather than the lateral direction in the controlled kinetic regime adopted in this research. This directional bias resulted in elongated rods rather than isotropic spherical particles.

This crystal habit control is important because morphology strongly affects the electronic transport and optical absorption of semiconductor materials. The combination of temperature and aspect ratio indicates the presence of a fragile thermodynamic equilibrium that rules crystal growth. At very low temperatures, the system lacks sufficient energy to overcome activation barriers associated with surface diffusion and lattice integration of ions. This causes slow growth, and particles do not become large and have undefined shapes. At around 70 °C, the reaction kinetics are optimal. The ion mobility is high enough to allow rapid extension along the energetically preferred axis, forming long, thin rods. But at temperatures above 90 degrees Celsius, the energy landscape will be different. Increases in thermal energy reduce disparities in growth rates across crystal faces, enabling ions to be affixed more uniformly. The process favours lateral thickening and ultimately results in more equated or more flake-like structures. The decrease in aspect ratio with increasing temperature indicates that synthesis at lower temperatures is not only energetically efficient but also necessary for the formation of the desired nanoscale morphologies. The quality of the rods produced is further emphasised by optical characterisation. The bandgap values obtained were slightly higher than those of bulk tin sulphide, due to quantum confinement effects. Due to the similarity of the diameter of the nanorods and the exciting Bohr radius, charge carriers are spatially confined at least in two dimensions. This restriction increases the energy required for electronic transitions, broadening the bandgap. The ability to control the bandgap energy by making minor changes in reaction temperature and duration implies that material properties can be carefully designed.

Tenability is useful for designing optoelectronic devices for use across a range of wavelengths. Another important outcome of the discussion is chemical purity. Wet chemical syntheses at low temperatures are prone to the formation of unwanted oxidised by-products or hydroxides when the reaction is incomplete or when dissolved oxygen is present. Nonetheless, the compositional analysis demonstrated a virtually perfect stoichiometric ratio of tin to sulphur, which implies that the reaction conditions and post-synthesis procedures were successful in removing impurities. The washing process removed residual ions, and low-temperature vacuum drying did as much as possible to reduce oxidation. The accuracy of stoichiometry increases to high levels, reducing lattice defects and enhancing the movement of charge carriers while minimising recombination losses in electrical devices. Economically and technologically, the importance of such findings is even more evident when these more complex fabrication methods are compared. Methods like molecular beam epitaxy or chemical vapour deposition can produce high-quality materials; however, they require advanced equipment and are very expensive to operate. Conversely, the co-precipitation method demonstrated in this paper can produce structures of similar quality at relatively low temperatures using simple laboratory equipment. This is made accessible and increases the likelihood of mass adoption, especially in areas where sophisticated infrastructure might not be readily available.

The dataset's statistical power also supports the reliability of the conclusions. The research also examined 481 successful instances of synthesis rather than the few successful experiments. This large sample size can also be used to demonstrate that the process is consistent and repeatable, as the morphological and compositional results are consistent across the entire sample. Such repeatability is necessary in industrial use, where the quality and economic viability of products depend on batch-to-batch consistency. Three-dimensional surface mapping and mixed bar-line graphs were also visualisation tools that could help better understand the optimal synthesis parameters. These images enabled scientists to determine specific temperature, precursor ratio, and reaction time ratios that yielded the greatest aspect ratios and greatest structural integrity. The study simplifies complex data by converting it into easily understandable visual features, thereby enhancing the study and providing a good guide for future experimentation. In general, the discussion shows that the low-temperature co-precipitation method is scientifically and technologically feasible. It offers a well-regulated path to the production of high-performance tin sulphide nanorods with desirable electronic and optical properties. The combination of morphology, bandgap, and purity, which can be manipulated through experimental parameters, positions the methodology as a likely avenue towards scalable fabrication of advanced semiconductor nanomaterials.

6. Conclusion

This paper shows that rod-shaped tin sulphide nanocrystals can be successfully synthesised via a well-monitored co-precipitation reaction at temperatures below 90 °C. The exact characterisation of reaction temperature showed that 70 °C is optimal for balancing crystal growth and phase stability, producing nanorods with the highest aspect ratio and best structural purity. The crystal phase of the synthesised materials was always orthorhombic, a desirable structure for semiconducting properties. Optical studies showed the existence of a tunable gap between quantised states that depended on nanoscale dimensions and demonstrated great potential for optoelectronic applications such as solar energy conversion and infrared sensing. The strength of this study is that it is based on a large, well-analysed dataset and demonstrates the reproducibility and reliability of the synthesis approach. This process can align with the principles of sustainable manufacturing by eliminating the need for high-pressure systems or toxic organic solvents, thereby reducing its environmental impact. The results emphasise that accurate control of reaction kinetics is the direct determinant of nanocrystal morphology and performance. All in all, the

experiment offers a viable and scalable model for high-quality group four- to six-semiconductor nanomaterials, which offers a good chance of green, cheaper semiconductor production.

6.1. Limitations

Although the synthesis process was successful, yielding uniform, rod-shaped nanocrystals, several limitations were observed. It was established that the co-precipitation method was highly sensitive to the order of precursor addition to the reaction mixture. Even minor variations in dropwise addition would alter nucleation processes, leading to a more spread particle size distribution and decreased morphological homogeneity. Also, the low-temperature technique is energy-saving, but it takes a longer reaction time than high-temperature hydrothermal methods to attain the same level of crystallinity and structural order. This long time may restrict throughput in a massive production environment. The other issue is the stability of the nanocrystals after synthesis. Gradual oxidation of surfaces can occur due to exposure to ambient air, resulting in degradation of electronic properties. Storage in a vacuum or under protective encapsulation is required to maintain the material's quality. Lastly, the experiments were only done in aqueous media. The effect of non-aqueous solvents or solvent mixtures on crystal growth and morphology was also not studied, leaving the prospect of chemical optimisation unexplored. Such limitations serve as guidance to the further development of the synthesis approach.

6.2. Future Scope

The synthesised nanorods can be incorporated into practical device structures in future studies to deepen understanding of nanomaterials, including thin-film solar cells, thermoelectric modules, and infrared photodetectors. The performance under operating conditions will be tested, and the results will be used to assess the material's applicability in the real world. Another potential approach is to incorporate organic capping agents into the synthesis to refine the aspect ratio further and improve surface passivation, potentially leading to improved charge transport and stability. The opportunities to fine-tune electronic and optical properties through controlled levels of impurities can also be realised through research into doped tin sulphide systems. Data-driven approaches represent another boundary; using machine learning on current data may yield predictive morphology-control models based on experimentation with manual control. Lastly, the change to continuous-flow reactors could resolve scalability issues and provide insights into consistency and production at large volumes, useful for industry.

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