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Tin Chalcogenide-Based Thin Films for Photovoltaic Applications: Progress, Challenges and Future Prospects

Dr. Shammi Kumar
Associate Professor, Department of Physics, Government Degree College, Akhnoor

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ABSTRACT

The growing demand for sustainable and affordable energy has intensified research into earth-abundant and environmentally benign materials for next-generation photovoltaic technologies. Tin chalcogenides have emerged as an important family of semiconductors because of their favourable optical and electronic properties, low material toxicity, elemental abundance, and compatibility with a wide range of thin-film fabrication techniques. Binary tin chalcogenides such as tin monosulfide (SnS), tin disulfide (SnS_2), tin selenide (SnSe), and tin diselenide ($SnSe_2$), together with related ternary and multinary tin-containing chalcogenides, have demonstrated considerable potential for solar-energy conversion. Among these materials, SnS has received particular attention as a photovoltaic absorber because of its strong optical absorption, suitable direct band gap, and predominantly p-type electrical conductivity.

Despite these attractive properties, the photovoltaic performance of tin chalcogenide-based devices remains below their theoretical potential. The main limitations originate from complex defect chemistry, chalcogen vacancies, secondary-phase formation, unfavourable band alignment, interface recombination, and poor charge extraction. Recent investigations have increasingly focused on understanding photovoltage losses and improving the absorber-buffer interface. A 2026 study on electrochemically grown SnS thin-film devices, for example, identified surface recombination, detrimental interfaces, and shunting as important contributors to low conversion efficiency [1].

This review presents a comprehensive discussion of tin chalcogenide-based thin films for photovoltaic applications. The fundamental properties of major tin chalcogenides are examined, followed by a critical review of deposition methods including thermal evaporation, sputtering, chemical bath deposition, electrodeposition, spray pyrolysis, and vapour-phase growth. The influence of deposition parameters on crystal structure, morphology, stoichiometry, defects, and optoelectronic properties is discussed. Particular attention is given to heterojunction formation, interface engineering, charge-carrier transport, and photovoltaic performance. Finally, the major challenges and future research directions are critically analysed. The review concludes that the future development of tin chalcogenide photovoltaics will depend primarily on precise stoichiometric control, defect passivation, optimized interfaces, and reproducible large-area thin-film processing.

Keywords: Tin chalcogenides; SnS; SnSe; SnS_2; $SnSe_2$; thin films; photovoltaics; solar cells; defect engineering; heterojunction.

1. INTRODUCTION

The increasing global demand for clean and sustainable energy has accelerated the development of new photovoltaic materials. Silicon continues to dominate the commercial solar-cell industry because of its excellent stability and well-established manufacturing infrastructure. However, the production of crystalline silicon solar cells requires relatively energy-intensive processing, which has encouraged the development of alternative thin-film photovoltaic technologies. Thin-film solar cells offer several advantages, including reduced material consumption, compatibility with lightweight substrates, and the possibility of large-area fabrication [2,3].

Commercial thin-film technologies based on cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) have achieved remarkable photovoltaic performance. Nevertheless, the scarcity of some constituent elements and environmental concerns associated with cadmium have motivated researchers to investigate alternative absorber materials based on abundant and less hazardous elements. Tin-based chalcogenides have emerged as an attractive material family in this context [2,4].

Tin can form several binary, ternary, and quaternary compounds with sulfur and selenium. These compounds exhibit a broad range of band gaps and can show either p-type or n-type electrical behaviour depending on their composition and crystal structure. The major binary tin chalcogenides include SnS, SnS_2, SnSe, and $SnSe_2$. More complex materials containing tin, such as Cu_2SnS_3 and $Cu_2ZnSn(S,Se)_4$, have also attracted considerable attention for photovoltaic applications [4-6].

Among the binary compounds, tin monosulfide (SnS) is one of the most extensively studied materials. SnS is considered attractive because it is composed of relatively abundant elements and possesses strong optical absorption. It also exhibits a band gap suitable for photovoltaic energy conversion [3,7]. However, practical device efficiencies have remained significantly lower than theoretical expectations. This difference between intrinsic material potential and experimental device performance has become one of the central scientific challenges in SnS research.

Tin selenide (SnSe) is another important member of the tin chalcogenide family. SnSe has a layered crystal structure and attractive optical and electronic properties. Its potential applications extend beyond photovoltaics to thermoelectric devices, photodetectors, batteries, and other optoelectronic technologies [8]. Recent reviews have specifically discussed the application of SnSe in solar cells and other energy devices [8].

Recent research also shows that the performance limitations of tin chalcogenide solar cells cannot be solved by improving the absorber material alone. Interface recombination, charge-selective contacts, secondary phases, and device architecture play equally important roles. Therefore, a modern review of tin chalcogenide photovoltaics must consider the complete relationship between material synthesis, defect formation, interface properties, and solar-cell operation.

2. TIN CHALCOGENIDES FOR PHOTOVOLTAIC APPLICATIONS

Tin chalcogenides constitute a chemically diverse family of semiconductor materials. Their properties can be tuned through changes in composition, crystal structure, thickness, stoichiometry, and processing conditions. This flexibility makes them attractive for photovoltaic and optoelectronic applications, but it also creates challenges in controlling phase purity.

SnS is generally considered the leading binary tin chalcogenide absorber. It typically exhibits an orthorhombic layered structure and predominantly p-type electrical conductivity. Its strong optical absorption makes it possible to absorb a substantial portion of incident solar radiation using a relatively thin semiconductor layer [3,7].

SnS_2 possesses a different crystal structure and wider band gap compared with SnS. It is generally associated with n-type semiconducting behaviour and can therefore be useful in heterostructure and charge-transport applications. The coexistence of multiple tin-sulfur phases, however, creates a major challenge because slight deviations in composition can result in the formation of SnS_2 or mixed-valence phases such as Sn_2S_3.

SnSe is structurally related to SnS but contains selenium instead of sulfur. It has attracted attention because of its high optical absorption, anisotropic electronic properties, and relatively good carrier mobility [8]. Its layered structure also provides opportunities for heterostructure engineering and low-dimensional device applications.

$SnSe_2$ is another layered semiconductor that can be useful for electronic and heterojunction applications. Although its direct role as a conventional photovoltaic absorber is less established than that of SnS or SnSe, it remains important in the broader development of tin chalcogenide-based devices.

Table 1. Important properties of tin chalcogenides for photovoltaic applications

Material	Crystal characteristics	Approximate band-gap range	Typical conductivity	Potential role
SnS	Orthorhombic, layered	~1.1–1.5 eV	Mainly p-type	Main absorber
SnS_2	Layered hexagonal	~2.0–2.5 eV	Mainly n-type	Buffer/transport layer
SnSe	Orthorhombic, layered	~0.9–1.3 eV	Mainly p-type	Absorber
$SnSe_2$	Layered	~1.0–1.5 eV	Generally n-type	Heterostructure/transport layer
Cu_2SnS_3	Polymorphic	~1.0–1.5 eV	Mainly p-type	Absorber

The exact values reported in the literature vary with phase, film thickness, stoichiometry, and measurement conditions [4-6].

3. THIN-FILM DEPOSITION TECHNIQUES

The properties of tin chalcogenide thin films depend strongly on the deposition technique. The selected fabrication method influences film thickness, crystallinity, grain size, surface morphology, chemical composition, and defect concentration. Therefore, deposition is not merely a fabrication step but a major parameter controlling photovoltaic performance.

3.1 Thermal Evaporation

Thermal evaporation is widely used for preparing SnS and SnSe thin films. The method offers good thickness control and can produce relatively pure films under suitable vacuum conditions. However, maintaining the correct stoichiometric ratio is difficult because sulfur and selenium are volatile.

During high-temperature processing, chalcogen loss may result in vacancies and secondary phases. For this reason, post-deposition annealing under sulfur-rich or selenium-rich conditions is often used to improve stoichiometry and crystallinity [3,7].

3.2 Sputtering

Sputtering is particularly attractive for large-area deposition because it provides good film uniformity and is compatible with industrial manufacturing. Both compound and elemental targets can be used.

The major advantage of sputtering is its reproducibility. However, phase purity and stoichiometric control remain important challenges. Post-deposition annealing is commonly required to improve crystallinity and obtain the desired phase.

3.3 Chemical Bath Deposition

Chemical bath deposition is a low-cost technique suitable for preparing semiconductor films at relatively low temperatures. The method is particularly useful for large-area substrates and potentially flexible photovoltaic devices.

Film formation depends strongly on precursor concentration, solution pH, bath temperature, deposition time, and complexing agents. Although the technique is simple, controlling thickness and composition uniformly across large areas remains challenging.

3.4 Electrodeposition

Electrodeposition provides a promising route for low-cost and scalable fabrication. The method can be performed at relatively low temperatures and offers direct control over film thickness through deposition time and electrical parameters.

Recent work on electrochemically grown SnS films has demonstrated both the potential and limitations of this approach. A 2026 investigation found that crystalline SnS films could be produced at low temperature, but surface trapping, interface recombination, shunting, and contact limitations significantly reduced the final device efficiency [1].

3.5 Spray Pyrolysis and Solution Processing

Spray pyrolysis is another attractive method for low-cost thin-film preparation. A precursor solution is converted into a solid semiconductor film on a heated substrate. The technique is simple and suitable for large-area applications.

Solution processing is particularly interesting for future flexible and printed photovoltaics. However, achieving dense, uniform films with low defect density remains a significant challenge.

Table 2. Comparison of deposition techniques for tin chalcogenide thin films

Technique	Main advantages	Main limitations	Photovoltaic relevance
Thermal evaporation	Good purity and thickness control	Chalcogen loss	High-quality absorbers
Sputtering	Uniform and scalable	Complex process optimization	Large-area thin films
Chemical bath deposition	Low cost and low temperature	Composition control	Buffer and semiconductor layers
Electrodeposition	Simple and scalable	Secondary phases and morphology	SnS absorber films
Spray pyrolysis	Low-cost large-area deposition	Non-uniform morphology	Solution-processed films
Vapour transport/CVD	High material quality	Higher equipment complexity	Advanced photovoltaic absorbers

4. CRYSTAL STRUCTURE AND OPTOELECTRONIC PROPERTIES

The photovoltaic performance of a semiconductor is strongly dependent on its crystal structure and electronic properties. Tin chalcogenides are particularly interesting because several of them have layered structures. This anisotropic structure means that carrier transport and optical absorption may vary with crystallographic direction. In SnS, the layered orthorhombic structure influences grain growth and charge transport. The orientation of the crystallites can therefore affect the behaviour of a thin film. A highly textured film may exhibit different carrier-collection characteristics compared with a randomly oriented film.

The strong optical absorption of SnS is one of its most important advantages. A relatively thin film can absorb a significant fraction of incident visible light. However, efficient light absorption alone is not sufficient to produce an efficient solar cell. The photogenerated carriers must also survive recombination and reach the respective electrical contacts.

SnSe also possesses attractive optoelectronic properties. Its layered structure and comparatively favourable charge-carrier transport have encouraged investigation of SnSe for solar cells and other energy applications [8]. Recent studies continue to investigate methods for reducing interface-related losses in SnSe solar-cell structures [9].

5. DEFECT CHEMISTRY AND SECONDARY PHASES

Defect formation is one of the most important challenges in tin chalcogenide photovoltaics. Native defects can strongly influence carrier concentration, carrier lifetime, and recombination.

In SnS, sulfur vacancies are particularly important. Sulfur deficiency can alter the electronic properties of the material and may contribute to the formation of unwanted phases. Similarly, selenium vacancies can influence the electronic behaviour of SnSe.

Secondary-phase formation represents another major problem. The tin-sulfur system can contain SnS, SnS_2, and Sn_2S_3 phases. Therefore, even small deviations in the sulfur-to-tin ratio may change the phase composition.

These secondary phases may introduce regions with different band structures and electrical conductivity. Consequently, they can act as recombination centres or create barriers to charge transport.

Modern characterization therefore requires the combined use of X-ray diffraction, Raman spectroscopy, electron microscopy, X-ray photoelectron spectroscopy, and optical measurements. No single characterization technique is sufficient to establish the complete defect and phase chemistry of a tin chalcogenide thin film.

6. DEVICE ARCHITECTURE AND INTERFACE ENGINEERING

Tin chalcogenide thin films are generally incorporated into heterojunction photovoltaic devices. A typical device contains a transparent conducting electrode, a window or buffer layer, a tin chalcogenide absorber, and a metallic back contact.

A simplified device configuration is:

Glass / Transparent Conducting Oxide / Buffer Layer / Tin Chalcogenide Absorber / Back Contact

The absorber-buffer interface is particularly important. Photogenerated carriers must be efficiently separated at this interface. If a large density of defects is present, electrons and holes may recombine before reaching the contacts.

The band alignment between the absorber and buffer layer must also be carefully controlled. An unsuitable conduction-band or valence-band offset can create an energy barrier that reduces carrier extraction.

Recent SnS studies have shown the importance of this interface. The formation of a p-SnS/n-CdS junction can substantially reduce surface recombination compared with bare SnS surfaces [1].

However, future research should also focus on environmentally safer alternatives to CdS. The development of cadmium-free buffer layers would strengthen the environmental advantage of tin chalcogenide photovoltaics.

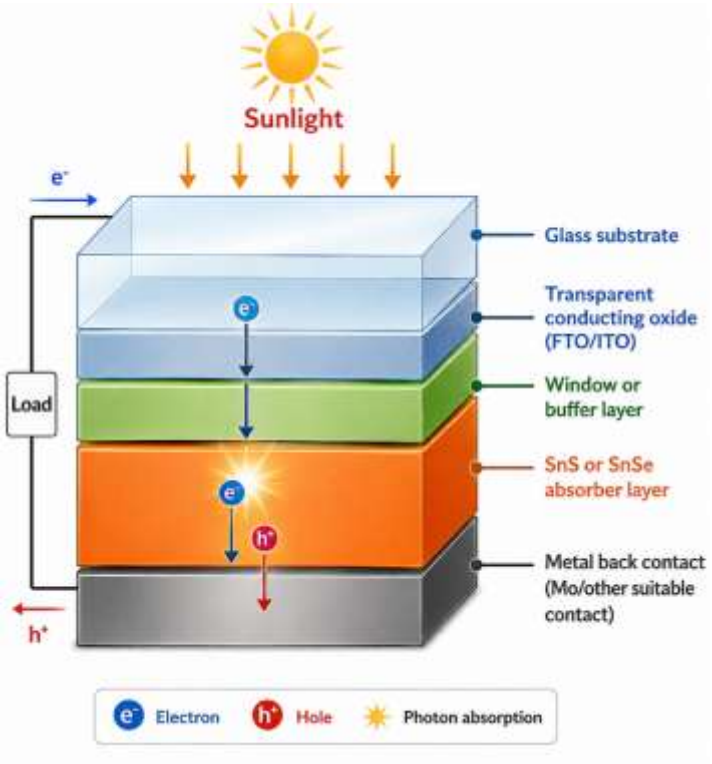

Figure 1. Schematic representation of a tin chalcogenide thin-film solar cell

Figure 1. Schematic illustration of a typical tin chalcogenide-based heterojunction thin-film photovoltaic device. Photogenerated electrons and holes are separated at the semiconductor junction and transported toward opposite electrodes.

7. SNS-BASED PHOTOVOLTAIC DEVICES

SnS is the most extensively investigated binary tin chalcogenide for photovoltaic applications. Its attractive properties include earth abundance, relatively low toxicity, strong optical absorption, and a suitable band gap [3,4].

Nevertheless, practical SnS solar cells have historically suffered from low open-circuit voltage and poor fill factor. These limitations indicate substantial non-radiative recombination and contact-related losses.

Recent research has focused on identifying the origin of photovoltage deficits. The 2026 study by Najaf and co-workers demonstrated that electrochemically grown SnS films can suffer from surface charge trapping, recombination, shunting through open microcrystalline structures, and detrimental interfaces [1]. The reported work highlights an important principle: improving the absorber crystallinity alone does not guarantee high solar-cell efficiency. The complete device architecture must be optimized.

Future improvements in SnS solar cells will therefore require simultaneous optimization of the absorber, buffer layer, back contact, and interface chemistry.

8. SNSE-BASED PHOTOVOLTAIC DEVICES

SnSe has attracted significant interest because of its favourable optical properties and layered electronic structure. It has been investigated as an absorber material in several solar-cell configurations [8].

Recent research has increasingly focused on reducing interface defects and improving electron-transport layers. Modelling and device studies suggest that careful selection of charge-selective layers can significantly improve carrier extraction and reduce recombination [9].

This indicates that SnSe photovoltaics may benefit strongly from heterojunction engineering. Rather than treating the absorber as an isolated material, future research should optimize the complete energy-band structure of the device.

Table 3. Major challenges and possible solutions in tin chalcogenide photovoltaics

Challenge	Main effect	Possible strategy
Chalcogen vacancies	Increased recombination	Chalcogen-rich processing
Secondary phases	Electrical inhomogeneity	Precise stoichiometry control
Small carrier lifetime	Reduced carrier collection	Defect passivation
Interface defects	Low open-circuit voltage	Interface engineering
Poor band alignment	Reduced carrier extraction	Optimized buffer layers
High contact resistance	Low fill factor	Back-contact engineering
Film non-uniformity	Poor reproducibility	Controlled deposition conditions

9. RECENT DEVELOPMENTS AND RESEARCH TRENDS

Recent research indicates that tin chalcogenide photovoltaics are entering a stage where the focus is shifting from simple material synthesis toward detailed device engineering. The important questions are increasingly related to the origin of voltage losses, carrier recombination, and interface behaviour.

The 2026 study on electrochemically grown SnS thin films is particularly relevant because it systematically investigated photovoltage deficits using surface photovoltage measurements and device characterization [1]. The work showed that surface recombination and unfavourable interfaces can dominate device losses even when crystalline SnS is successfully produced.

Research on related tin chalcogenide materials is also expanding. Recent reviews have examined tin-containing ternary chalcogenides such as Cu_2SnS_3 for photovoltaic applications [5].

Similarly, research on SnSe and mixed tin chalcogenide systems continues to explore band-gap engineering and interface modification [8,9]. These developments suggest that future tin chalcogenide photovoltaics may increasingly involve alloying, heterostructures, and multifunctional device architectures.

10. FUTURE PROSPECTS

The future of tin chalcogenide photovoltaics depends on overcoming the difference between promising intrinsic material properties and relatively modest experimental device performance.

The first major requirement is reproducible stoichiometric control. The composition of the absorber must remain stable during deposition and post-deposition processing. Chalcogen-rich treatment may reduce vacancy-related defects, but excessive processing can also create secondary phases.

The second requirement is improved defect passivation. Deep electronic defects reduce carrier lifetime and create non-radiative recombination pathways. Future research should identify the most harmful defects and develop targeted passivation strategies.

The third requirement is interface engineering. The absorber-buffer and absorber-contact interfaces should be designed to minimize recombination and resistance. Advanced characterization techniques such as surface

photovoltage spectroscopy, time-resolved photoluminescence, Kelvin probe measurements, and transient electrical measurements will be important for identifying loss mechanisms.
Finally, future photovoltaic technology must be scalable. Laboratory-scale high-quality films are scientifically valuable, but industrial application requires reproducible large-area deposition using economically viable processes.

11. CONCLUSIONS

Tin chalcogenide-based thin films represent a promising family of sustainable semiconductor materials for photovoltaic applications. Materials such as SnS and SnSe possess strong optical absorption and favourable electronic properties, while SnS_2 and $SnSe_2$ provide additional opportunities for heterostructure and charge-transport engineering.
SnS remains the most important binary tin chalcogenide absorber, but its photovoltaic performance is strongly limited by sulfur-related defects, secondary-phase formation, interface recombination, and photovoltage deficits. Recent studies confirm that the improvement of solar-cell efficiency requires a detailed understanding of complete device operation rather than only absorber optimization.
SnSe is also a promising photovoltaic material, particularly when combined with optimized electron- and hole-transport layers. Continued development of heterojunction architectures and interface engineering may improve its practical performance.
Overall, the most important future directions are precise stoichiometric control, defect passivation, optimized band alignment, improved contacts, and scalable thin-film fabrication. With continued progress in these areas, tin chalcogenides may become important candidates for environmentally sustainable and low-cost photovoltaic technologies.

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