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Development of Solution-Processed p-Type Polycrystalline SnSe Thermoelectric Nanomaterials

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Abstract: SnSe has emerged as a promising mid-temperature thermoelectric (TE) material, noted for its intrinsically low lattice thermal conductivity and favorable electronic properties. Solution-processing provides a scalable and adaptable approach to synthesizing polycrystalline SnSe, allowing for precise control over nanostructure, defect density, and dopant distribution, which are essential factors in optimizing TE performance. Advances in doping/alloying, defect engineering and surface functionalization have been shown to enhance carrier concentrations, Seebeck coefficients, and reduced lattice thermal conductivity in p-type SnSe, resulting in notable TE efficiency. However, achieving comparable efficiency in solution-processed n-type SnSe remains challenging due to limited electron carrier concentration. In addition,~~Additionally,~~ low carrier mobility further limits the TE performance of polycrystalline SnSe at low temperatures. This perspective briefly explores the development of solution-processed SnSe nanostructures, with a focus on ongoing advancements in processing techniques and optimization strategies essential for promoting~~advancing~~ solution-processed SnSe toward practical TE applications.

Key words: Thermoelectric; Solution processing; Tin selenide

Thermoelectric (TE) materials enable the direct and reversible conversion of heat into electricity, making them highly valuable for applications in clean energy, aerospace technology, and solid-state cooling. TE devices consist of multiple p-type and n-type inorganic semiconductors, which are~~are composed of multiple p-type and n-type inorganic semiconductors~~ arranged electrically in series and thermally in parallel to form an all-solid-state module[1]. The efficiency of TE devices is determined by the figure of merit (zT), which integrates the Seebeck coefficient (S), electrical conductivity (σ), and thermal conductivity (κ). Achieving high zT values requires a precise balance of these properties, thereby enhancing~~High zT values are achieved by carefully balancing these properties, resulting in improved~~ energy conversion efficiency[2,3].

SnSe has become as a promising candidate for medium-temperature TE applications, owing~~attributed~~ to its unique layered structure and excellent TE properties[4,5]. In 2014, Zhao *et al.* first reported the ultralow thermal conductivity and high figure of merit zT in single-crystalline SnSe, this material has consistently demonstrated remarkable zT values along specific crystallographic directions[6]. These outstanding properties are primarily attributed to its intrinsically low lattice thermal conductivity (κ_L) and favorable electronic characteristics~~.~~[7]. The application of single-crystal SnSe has been constrained by high production costs and challenges in mechanical stability[4]. Thus, polycrystalline SnSe provides a mechanically robust alternative with the potential for scalable production. However, polycrystalline SnSe synthesized via both solution-based[8–30] and solid-state[31–43] methods often exhibits carrier mobility that is~~often~~ reduced by an order of magnitude compared to single crystals (Figure 1a)[6]. This reduction is primarily caused by strong carrier scattering at closely arranged grain

boundaries and surface oxidation at grain interfaces, which together lead to lower σ, particularly at low temperatures, and higher κ compared to SnSe crystals[4,44]. To enhance the TE performance of polycrystalline SnSe and address existing challenges, strategies including stoichiometry control[8,9,11,12,16], doping/alloying[10,13,15,17,18,20,22–26,31–38,40–43], nanocomposites (NCPs) formation[14,19,21,28,29], and surface oxide removal have been applied[39,45], leading to significant improvements in zT values for materials produced by both solid-state and solution-processed methods.

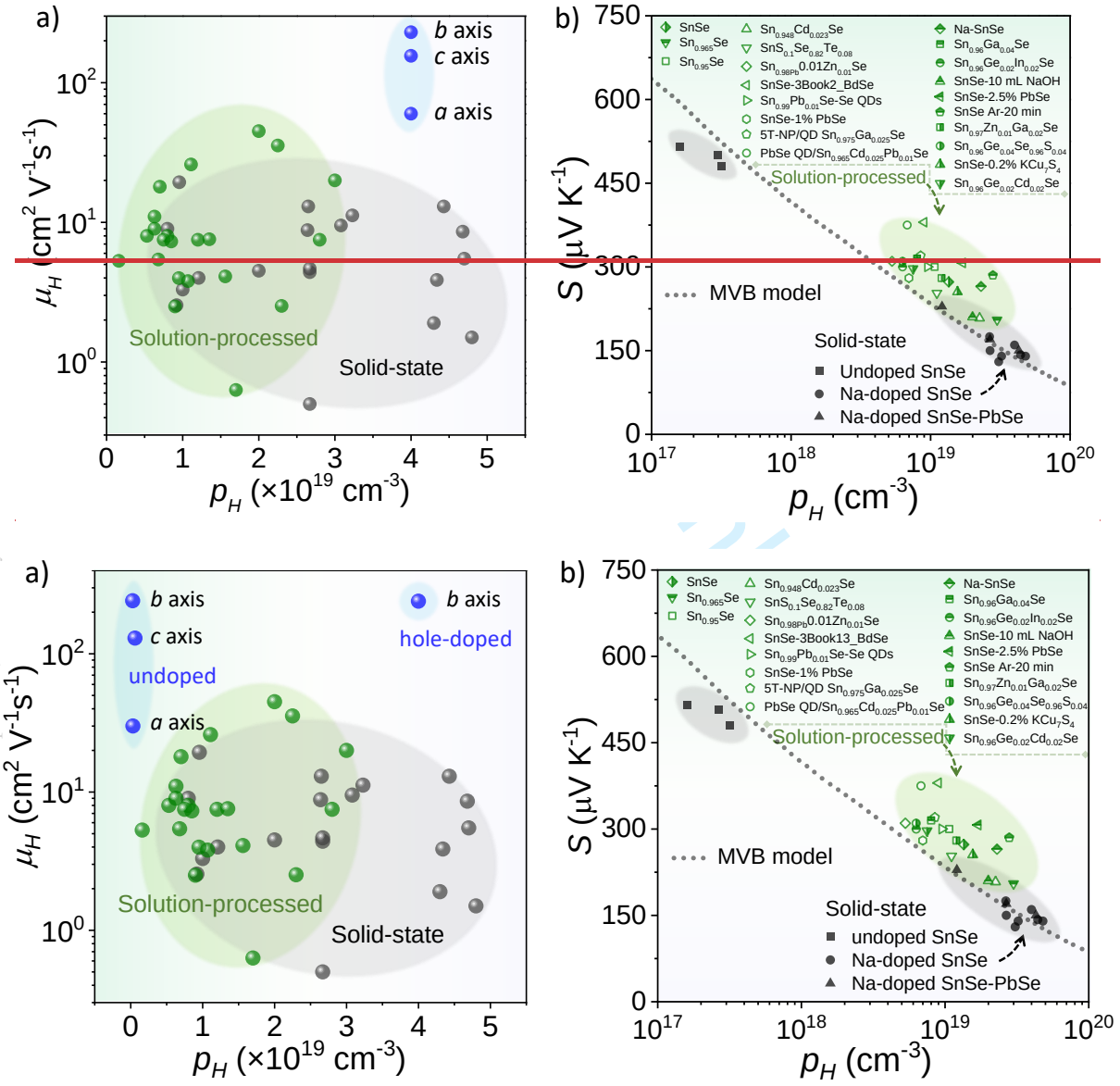

Figure 1. (a) Hall mobility (μ_H) of p-type polycrystalline SnSe as a function of hole concentration (p_H) for solution-processed (green dots)[8–30], solid-state (gray dots)[31–43], and single-crystal SnSe (blue dots)[6,46]. (b) Pisarenko plot at 300 K, with green symbols representing solution-processed materials[8–22,24–30] and black symbols denoting solid-state synthetic methods[31,35–40], including single crystals[6,46]. The dashed line was calculated using a multiple band model[47].

In comparison to solid-phase methods, solution-processing provides a cost-effective and scalable approach that allows precise control over material morphology, grain size, composition, and crystalline structure, while traditional solid-state synthesis requires high temperatures and substantial energy[1]. The control available~~This control~~ in solution-processed SnSe enables the formation of specific nanostructural features, *i.e.*, defect engineering, grain boundary construction, and optimized dopant distribution, which are essential for improving phonon scattering and thus enhancing TE properties, ultimately providing~~offering~~ distinct advantages in tailoring overall performance. Additionally, this technique allows for the incorporation of various dopants and secondary phases, providing a versatile approach for optimizing both carrier concentration and mobility[48]. Therefore, while polycrystalline SnSe-based TE materials prepared by solution-processing methods exhibit slightly lower carrier concentrations than those produced by solid-state techniques (Figure 1a), the comparable carrier mobility and reduced κ_L contribute to enhanced TE performance.

Initially, SnSe attract~~s~~ed attention as a key p-type IV-VI semiconductor due to its nearly optimal bandgap for photovoltaic applications, before being recognized as a promising TE

material, with synthetic approaches primarily using colloidal methods that, despite their ability to produce high-quality SnSe nanocrystals (NCs) in various morphologies including nanostars, nanowires, nanoflowers, and nanosheets, face significant limitations in scalability and practical application resulting from their reliance on TOP-Se, a highly toxic and expensive trioctylphosphine-based precursor[49–51]. This limitation has directed researchers toward hydrothermal/solvothermal[8,9,21,23,24,26,27,29,30,10–12,15–18,20], and aqueous solution-based synthesis methods[13,14,19,22,25,28,52], which provide safer, more economically feasible alternatives for large-scale production by reducing the dependence on toxic reagents, thereby facilitating~~supporting~~ the scalable development of TE materials. The production of surfactant-free SnSe nanomaterials typically involves polar solvents, such as water or ethylene glycol, in hydrothermal/solvothermal methods, or is carried out~~conducted~~ in aqueous solution-based methods at atmospheric pressure in boiling water. These reactions commonly employ sodium-containing compounds, including $NaBH_4$, NaOH, and Na_2SeO_3, *etc*, as redox agents and acid/base additives[8–30]. Compared to conventional hydrothermal and solvothermal methods, aqueous solution-based approaches present notable advantages by minimizing the reliance on specialized reaction vessels and conditions, enhancing economic efficiency, and providing significant potential for large-scale production.

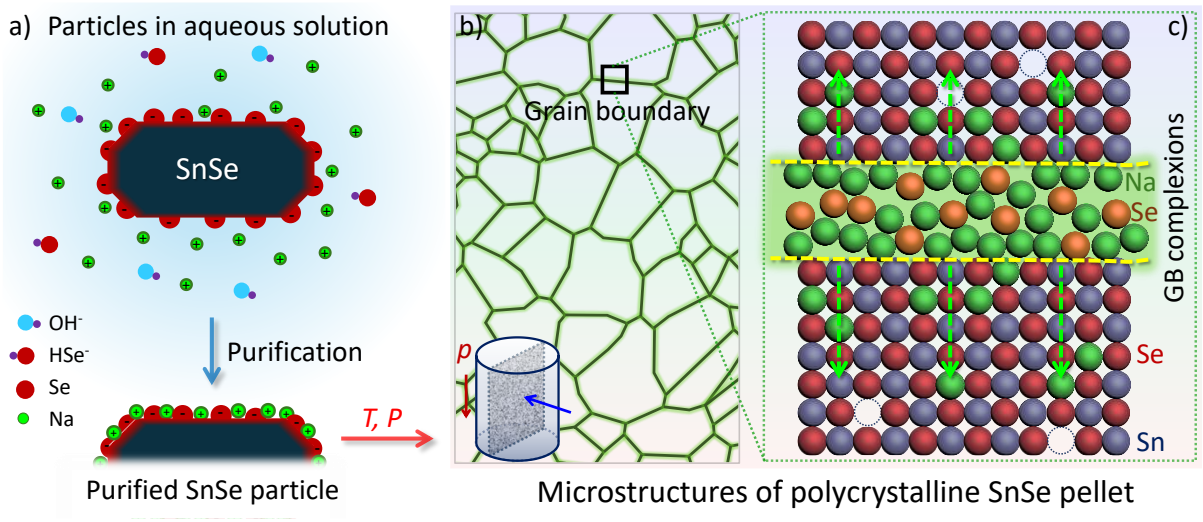

Figure 2. (a) Schematic representation of a SnSe particle in aqueous solution, with Na^+ ions adsorbed to maintain charge neutrality after purification[13]. (b) Diagram of the grain boundary interface in aqueous-synthesized SnSe after thermal annealing and sintering. (c) Enlarged view of the grain boundary (GB), showing the complexions and atomic diffusion mechanisms within the matrix of the system.

Surfactant-free SnSe particles synthesized ~~by~~ via aqueous solution methods exhibit high σ and S after consolidation, while maintaining relatively low κ_L, a combination that enables superior TE performance without requiring intentional doping. Compared to SnSe produced via conventional solid-state methods, this method yields samples with significantly high carrier concentrations ($>2 \times 10^{19}$ cm^{-3}), a characteristic attributed in previous studies not solely to intrinsic Sn vacancies[13,53]. The aqueous solution synthesis process involves alternating purification steps with solvents of different polarities, such as water and ethanol, which are essential for controlling composition and optimizing performance. Our recent studies have thoroughly examined the critical chemical processing steps involved in the solution-based

synthesis of SnSe, including particle synthesis, purification, annealing, and consolidation[53]. During these steps, residual Na^+ ions, electrostatically adsorbed onto the negatively charged surfaces of SnSe particles, remain partially unremovable through purification and subsequently combine with excess Se on the particle surface to form Na_2Se_x phases[13]. Upon annealing in forming gas (95% N_2+ 5% H_2) and subsequent consolidation, these low-melting Na_2Se_x phases facilitate microstructural optimization[54,55], significantly enhancing TE transport properties by increasing carrier concentration and enhancing the *S* through the energy-filtering effect at grain boundary barriers. Furthermore, the Pisarenko plot reveals that most solution-processed SnSe samples (green symbols) exhibit *S* values exceeding the expected values, a trend not observed in Na-doped solid-state synthesized SnSe samples (black symbols, including single crystals), as shown in Figure 1b. Na^+ ions ultimately stabilize within bulk SnSe in two distinct forms: i) as partial substitutes for Sn^{2+} within the lattice, acting as p-type dopants; and ii) at grain boundaries and defects, accumulating during sintering to form Na-enriched interfacial complexions or precipitates at grain boundaries (Figure 2). Therefore, the influence of surface adsorbates requires careful consideration, especially when alkali metal salts or hydroxides (such as Li^+ or K^+, in addition to Na^+) are employed as reactants in solution-based synthesis. Precise control over the purification, thermal annealing treatment, and sintering processes of SnSe particles is crucial, accompanied by detailed documentation of these steps in the experimental section to ensure reproducibility[53].

While the~~is~~ solution-processed p-type SnSe bulk materials have achieved ideal carrier concentration levels (10^{19} cm^{-3}) and exhibit superior TE performance, it is notable that n-type SnSe synthesized via aqueous or other solution-based methods shows considerably lower TE

efficiency in comparison to its p-type SnSe. Despite increasing the content of n-type dopants, achieving a substantial enhancement in electron carrier concentration remains challenging[22,56]. We believe this is correlated to the fact that all synthetic methods use of alkali metal Na salts in the preparation of SnSe particles, where the presence of Na induces a pinning effect when n-type dopants are introduced and is further supported by the fact that all reported high-performance n-type polycrystalline SnSe materials (zT>2) have been synthesized through solid-state methods[57–60]. Therefore, to develop high-performance n-type polycrystalline SnSe through solution-processed methods, avoiding the use of alkali metal salts or alkali hydroxides is recommended, with alternative reagents, *e.g.*, tetramethylammonium salts and ascorbic acid, serving as potential substitutes.

Moreover, we suggest that for p-type SnSe particles synthesized via aqueous solution methods with alkali metal compounds as reactants, efforts to improve electrical transport properties through doping/alloying are often ineffective, with these strategies potentially further reducing the already low carrier mobility of the polycrystalline SnSe, leading to an additional decrease in σ, especially at low temperatures. For example, during the alloying process where surfactant-free SnSe particles are combined with colloidal PbSe NCs to form SnSe-PbSe NCPs some Na^+ ions electrostatically adsorbed on the surfaces of the SnSe particles interact with the oleate capping ligands on PbSe NCs, forming Na-oleate, which is subsequently removed through particle purification[14].

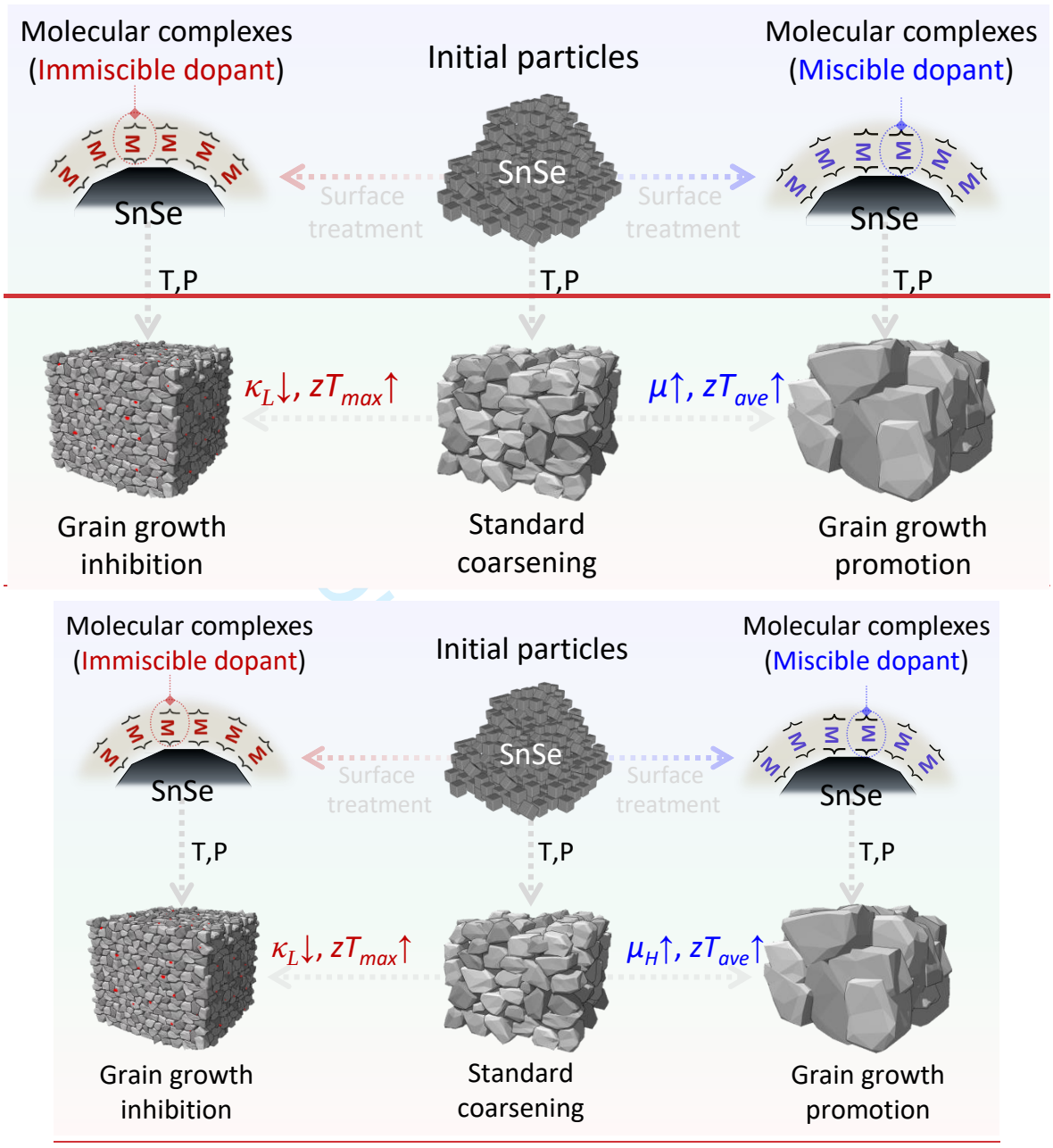

Figure 3. Schematic of crystal domain growth during the annealing and consolidation of SnSe particles under conditions without and with different types of molecular complexes.

The surface functionalization of SnSe particles with CdSe molecular complexes, prepared in an "amine-thiol" solution, results in SnSe-CdSe NCPs in which CdSe remains insoluble within the SnSe matrix across the entire operating temperature range. CdSe nanoprecipitates

are uniformly distributed within the SnSe matrix, creating a high density of grain boundaries through a Zener pinning effect that inhibits significant grain growth in SnSe-CdSe samples during thermal processing, thereby preserving the dimensional advantages characteristic of low-dimensional nanostructured TE materials[28,61]. With coordinated control of dislocations and multiscale defects, this structure effectively reduces the κ_L of the NCPs. Simultaneously, the consistent level of unavoidable Na impurities during the surface treatment of polycrystalline SnSe maintains electrical properties, significantly enhancing its high-temperature TE performance, yielding a zT of 2.2 at 786 K. This approach is particularly effective for systems with high carrier concentrations, such as SnTe, $Cu_{2-x}Te$ and Ag_2Se-based materials[62,63], that seek to maximize TE performance (zT_{max}) in the mid-to-high temperature range by reducing κ_L. For materials requiring a high average thermoelectric figure of merit (zT_{ave}) across low-temperature ranges, enhancing carrier mobility through grain boundary engineering and optimized doping mechanisms is essential, as is identifying molecular complexes compatible with the SnSe matrix that effectively function as "solders" mutually soluble with the matrix. ~~However, for materials requiring a high average TE figure of merit (zT_{ave}) across low temperature range, it is essential to identify molecular complexes compatible with the SnSe matrix, effectively functioning as "solder" that are mutually soluble with the matrix~~[64]. These "solder" complexes, when applied to the SnSe particle surface, facilitate atomic diffusion into the grains during high-temperature treatment, thereby promoting solid solution formation, accelerating grain boundary migration, and inducing grain growth. This process reduces grain boundary barriers and enhances carrier mobility in polycrystalline SnSe at low-temperature range (Figure 3)[2,65–68]. However, identifying compatible systems and optimizing post-

treatment conditions based on the phase diagrams of SnSe and related compounds remains challenging.

In this perspective, the strategies discussed above~~these above strategies~~ provide valuable insights into the transport mechanisms of TE materials and open new avenues for the controlled synthesis of advanced polycrystalline SnSe-based TE nanostructures. Solution-processed SnSe demonstrates significant~~considerable~~ potential for high TE performance through defect and surface engineering; however, further optimization remains crucial for advancing solution-processed SnSe toward practical applications, with key improvements including refining solution-processing conditions to achieve greater reproducibility, enhancing material stability against oxidation, and optimizing carrier mobility~~however, further investigation into process optimization is essential to advance solution-processed SnSe toward practical applications~~.

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Conflict of interest

The authors declare no conflict of interest.

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Development of Solution-Processed p-Type Polycrystalline SnSe Thermoelectric Nanomaterials

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Abstract: SnSe has emerged as a promising mid-temperature thermoelectric (TE) material, noted for its intrinsically low lattice thermal conductivity and favorable electronic properties. Solution-processing provides a scalable and adaptable approach to synthesizing polycrystalline SnSe, allowing for precise control over nanostructure, defect density, and dopant distribution, which are essential factors in optimizing TE performance. Advances in doping/alloying, defect engineering and surface functionalization have been shown to enhance carrier concentrations, Seebeck coefficients, and reduced lattice thermal conductivity in p-type SnSe, resulting in notable TE efficiency. However, achieving comparable efficiency in solution-processed n-type SnSe remains challenging due to limited electron carrier concentration. In addition, low carrier mobility further limits the TE performance of polycrystalline SnSe at low temperatures. This perspective briefly explores the development of solution-processed SnSe nanostructures, with a focus on ongoing advancements in processing techniques and optimization strategies essential for promoting solution-processed SnSe toward practical TE applications.

Key words: Thermoelectric; Solution processing; Tin selenide

Thermoelectric (TE) materials enable the direct and reversible conversion of heat into electricity, making them highly valuable for applications in clean energy, aerospace technology, and solid-state cooling. TE devices consist of multiple p-type and n-type inorganic semiconductors, which are arranged electrically in series and thermally in parallel to form an all-solid-state module[1]. The efficiency of TE devices is determined by the figure of merit (zT), which integrates the Seebeck coefficient (S), electrical conductivity (σ), and thermal conductivity (κ). Achieving high zT values requires a precise balance of these properties, thereby enhancing energy conversion efficiency[2,3].

SnSe has become as a promising candidate for medium-temperature TE applications, owing to its unique layered structure and excellent TE properties[4,5]. In 2014, Zhao *et al.* first reported the ultralow thermal conductivity and high figure of merit zT in single-crystalline SnSe, this material has consistently demonstrated remarkable zT values along specific crystallographic directions[6]. These outstanding properties are primarily attributed to its intrinsically low lattice thermal conductivity (κ_L) and favorable electronic characteristics[7]. The application of single-crystal SnSe has been constrained by high production costs and challenges in mechanical stability[4]. Thus, polycrystalline SnSe provides a mechanically robust alternative with the potential for scalable production. However, polycrystalline SnSe synthesized via both solution-based[8–30] and solid-state[31–43] methods often exhibits carrier mobility that is reduced by an order of magnitude compared to single crystals (Figure 1a)[6]. This reduction is primarily caused by strong carrier scattering at closely arranged grain boundaries and surface oxidation at grain interfaces, which together lead to lower σ, particularly at low temperatures, and higher

κ compared to SnSe crystals[4,44]. To enhance the TE performance of polycrystalline SnSe and address existing challenges, strategies including stoichiometry control[8,9,11,12,16], doping/alloying[10,13,15,17,18,20,22–26,31–38,40–43], nanocomposites (NCPs) formation[14,19,21,28,29], and surface oxide removal have been applied[39,45], leading to significant improvements in zT values for materials produced by both solid-state and solution-processed methods.

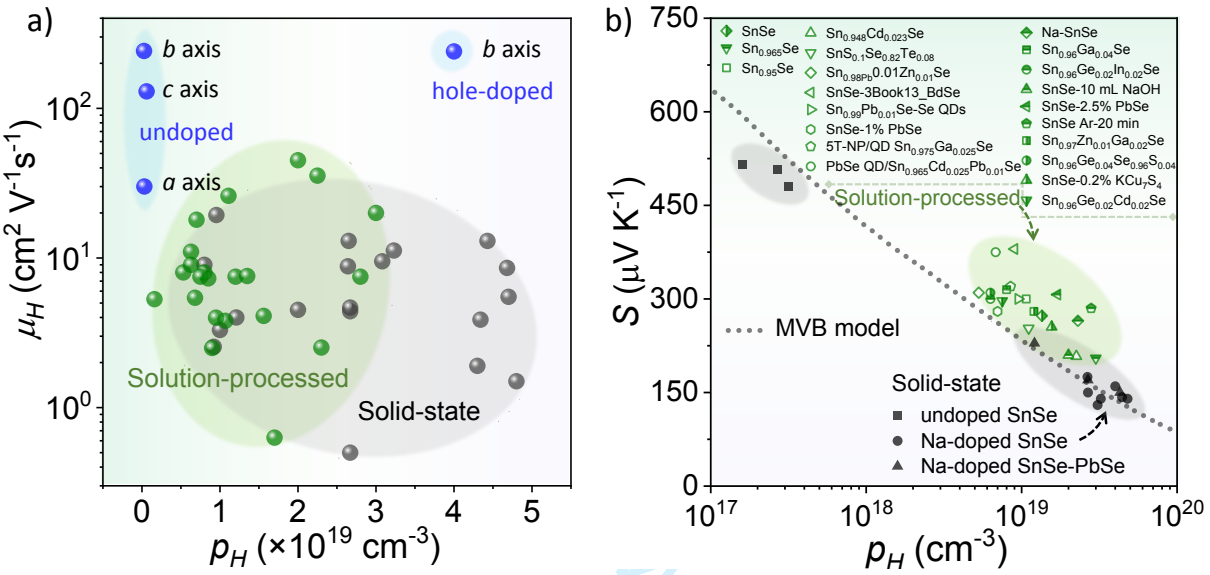

Figure 1. (a) Hall mobility (μ_H) of p-type polycrystalline SnSe as a function of hole concentration (p_H) for solution-processed (green dots)[8–30], solid-state (gray dots)[31–43], and single-crystal SnSe (blue dots)[6,46]. (b) Pisarenko plot at 300 K, with green symbols representing solution-processed materials[8–22,24–30] and black symbols denoting solid-state synthetic methods[31,35–40], including single crystals[6,46]. The dashed line was calculated using a multiple band model[47].

In comparison to solid-phase methods, solution-processing provides a cost-effective and scalable approach that allows precise control over material morphology, grain size, composition,

and crystalline structure, while traditional solid-state synthesis requires high temperatures and substantial energy[1]. The control available in solution-processed SnSe enables the formation of specific nanostructural features, *i.e.*, defect engineering, grain boundary construction, and optimized dopant distribution, which are essential for improving phonon scattering and thus enhancing TE properties, ultimately providing distinct advantages in tailoring overall performance. Additionally, this technique allows for the incorporation of various dopants and secondary phases, providing a versatile approach for optimizing both carrier concentration and mobility[48]. Therefore, while polycrystalline SnSe-based TE materials prepared by solution-processing methods exhibit slightly lower carrier concentrations than those produced by solid-state techniques (Figure 1a), the comparable carrier mobility and reduced κ_L contribute to enhanced TE performance.

Initially, SnSe attracted attention as a key p-type IV-VI semiconductor due to its nearly optimal bandgap for photovoltaic applications, before being recognized as a promising TE material, with synthetic approaches primarily using colloidal methods that, despite their ability to produce high-quality SnSe nanocrystals (NCs) in various morphologies including nanostars, nanowires, nanoflowers, and nanosheets, face significant limitations in scalability and practical application resulting from their reliance on TOP-Se, a highly toxic and expensive trioctylphosphine-based precursor[49–51]. This limitation has directed researchers toward hydrothermal/solvothermal[8,9,21,23,24,26,27,29,30,10–12,15–18,20], and aqueous solution-based synthesis methods[13,14,19,22,25,28,52], which provide safer, more economically feasible alternatives for large-scale production by reducing the dependence on toxic reagents, thereby facilitating the scalable

development of TE materials. The production of surfactant-free SnSe nanomaterials typically involves polar solvents, such as water or ethylene glycol, in hydrothermal/solvothermal methods, or is carried out in aqueous solution-based methods at atmospheric pressure in boiling water. These reactions commonly employ sodium-containing compounds, including $NaBH_4$, NaOH, and Na_2SeO_3, *etc*, as redox agents and acid/base additives[8–30]. Compared to conventional hydrothermal and solvothermal methods, aqueous solution-based approaches present notable advantages by minimizing the reliance on specialized reaction vessels and conditions, enhancing economic efficiency, and providing significant potential for large-scale production.

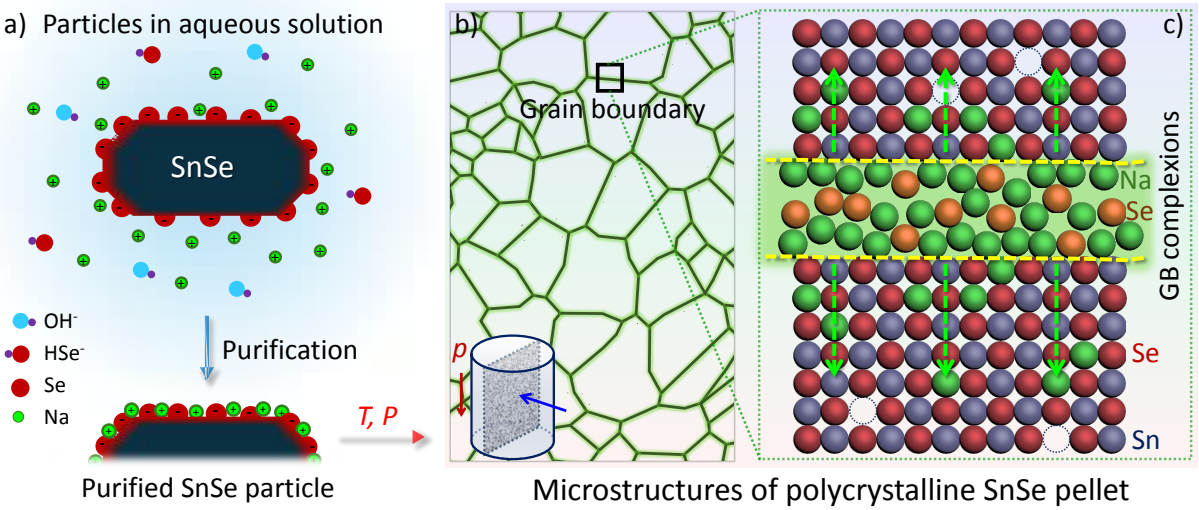

Figure 2. (a) Schematic representation of a SnSe particle in aqueous solution, with Na^+ ions adsorbed to maintain charge neutrality after purification[13]. (b) Diagram of the grain boundary interface in aqueous-synthesized SnSe after thermal annealing and sintering. (c) Enlarged view of the grain boundary (GB), showing the complexions and atomic diffusion mechanisms within the matrix of the system.

Surfactant-free SnSe particles synthesized via aqueous solution methods exhibit high σ and S after consolidation, while maintaining relatively low κ_L, a combination that enables superior TE performance without requiring intentional doping. Compared to SnSe produced via conventional solid-state methods, this method yields samples with significantly high carrier concentrations (>2 × 10^{19} cm^{-3}), a characteristic attributed in previous studies not solely to intrinsic Sn vacancies[13,53]. The aqueous solution synthesis process involves alternating purification steps with solvents of different polarities, such as water and ethanol, which are essential for controlling composition and optimizing performance. Our recent studies have thoroughly examined the critical chemical processing steps involved in the solution-based synthesis of SnSe, including particle synthesis, purification, annealing, and consolidation[53]. During these steps, residual Na^+ ions, electrostatically adsorbed onto the negatively charged surfaces of SnSe particles, remain partially unremovable through purification and subsequently combine with excess Se on the particle surface to form Na_2Se_x phases[13]. Upon annealing in forming gas (95% N_2+ 5% H_2) and subsequent consolidation, these low-melting Na_2Se_x phases facilitate microstructural optimization[54,55], significantly enhancing TE transport properties by increasing carrier concentration and enhancing the S through the energy-filtering effect at grain boundary barriers. Furthermore, the Pisarenko plot reveals that most solution-processed SnSe samples (green symbols) exhibit S values exceeding the expected values, a trend not observed in Na-doped solid-state synthesized SnSe samples (black symbols, including single crystals), as shown in Figure 1b. Na^+ ions ultimately stabilize within bulk SnSe in two distinct forms: i) as partial substitutes for Sn^{2+} within the lattice, acting as p-type dopants; and ii) at grain

boundaries and defects, accumulating during sintering to form Na-enriched interfacial complexions or precipitates at grain boundaries (Figure 2). Therefore, the influence of surface adsorbates requires careful consideration, especially when alkali metal salts or hydroxides (such as Li^+ or K^+, in addition to Na^+) are employed as reactants in solution-based synthesis. Precise control over the purification, thermal annealing treatment, and sintering processes of SnSe particles is crucial, accompanied by detailed documentation of these steps in the experimental section to ensure reproducibility[53].

While the solution-processed p-type SnSe bulk materials have achieved ideal carrier concentration levels (10^{19} cm^{-3}) and exhibit superior TE performance, it is notable that n-type SnSe synthesized via aqueous or other solution-based methods shows considerably lower TE efficiency in comparison to its p-type SnSe. Despite increasing the content of n-type dopants, achieving a substantial enhancement in electron carrier concentration remains challenging[22,56]. We believe this is correlated to the fact that all synthetic methods use of alkali metal Na salts in the preparation of SnSe particles, where the presence of Na induces a pinning effect when n-type dopants are introduced and is further supported by the fact that all reported high-performance n-type polycrystalline SnSe materials (zT>2) have been synthesized through solid-state methods[57–60]. Therefore, to develop high-performance n-type polycrystalline SnSe through solution-processed methods, avoiding the use of alkali metal salts or alkali hydroxides is recommended, with alternative reagents, *e.g.*, tetramethylammonium salts and ascorbic acid, serving as potential substitutes.

Moreover, we suggest that for p-type SnSe particles synthesized via aqueous solution

methods with alkali metal compounds as reactants, efforts to improve electrical transport properties through doping/alloying are often ineffective, with these strategies potentially further reducing the already low carrier mobility of the polycrystalline SnSe, leading to an additional decrease in σ, especially at low temperatures. For example, during the alloying process where surfactant-free SnSe particles are combined with colloidal PbSe NCs to form SnSe-PbSe NCPs some Na^+ ions electrostatically adsorbed on the surfaces of the SnSe particles interact with the oleate capping ligands on PbSe NCs, forming Na-oleate, which is subsequently removed through particle purification[14].

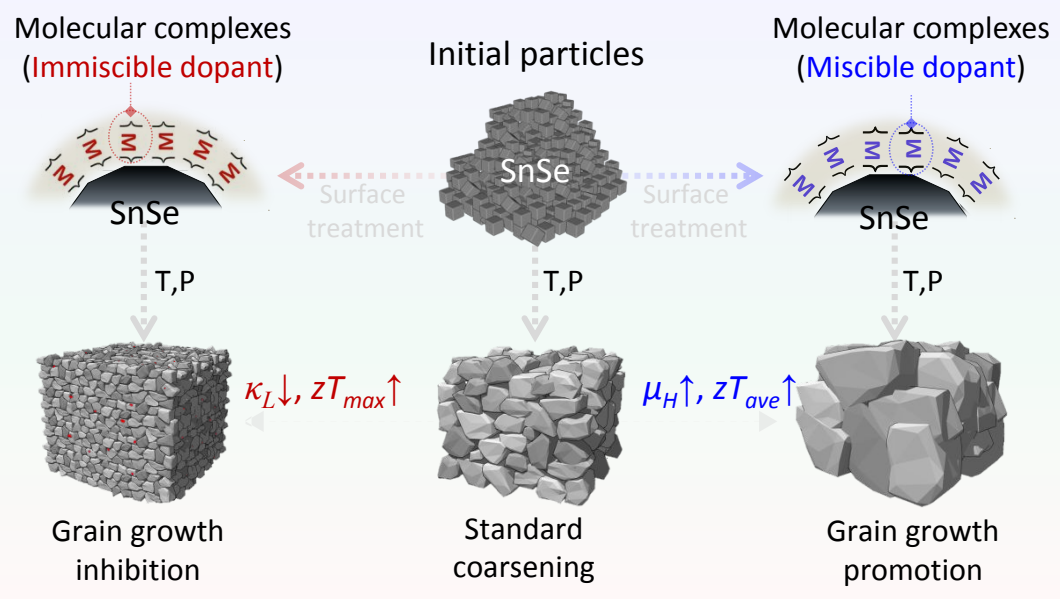

Figure 3. Schematic of crystal domain growth during the annealing and consolidation of SnSe particles under conditions without and with different types of molecular complexes.

The surface functionalization of SnSe particles with CdSe molecular complexes, prepared in an "amine-thiol" solution, results in SnSe-CdSe NCPs in which CdSe remains insoluble within the SnSe matrix across the entire operating temperature range. CdSe nanoprecipitates

are uniformly distributed within the SnSe matrix, creating a high density of grain boundaries through a Zener pinning effect that inhibits significant grain growth in SnSe-CdSe samples during thermal processing, thereby preserving the dimensional advantages characteristic of low-dimensional nanostructured TE materials[28,61]. With coordinated control of dislocations and multiscale defects, this structure effectively reduces the κ_L of the NCPs. Simultaneously, the consistent level of unavoidable Na impurities during the surface treatment of polycrystalline SnSe maintains electrical properties, significantly enhancing its high-temperature TE performance, yielding a zT of 2.2 at 786 K. This approach is particularly effective for systems with high carrier concentrations, such as SnTe, $Cu_{2-x}Te$ and Ag_2Se-based materials[62,63], that seek to maximize TE performance (zT_{max}) in the mid-to-high temperature range by reducing κ_L. For materials requiring a high average thermoelectric figure of merit (zT_{ave}) across low-temperature ranges, enhancing carrier mobility through grain boundary engineering and optimized doping mechanisms is essential, as is identifying molecular complexes compatible with the SnSe matrix that effectively function as "solders" mutually soluble with the matrix.[64]. These "solder" complexes, when applied to the SnSe particle surface, facilitate atomic diffusion into the grains during high-temperature treatment, thereby promoting solid solution formation, accelerating grain boundary migration, and inducing grain growth. This process reduces grain boundary barriers and enhances carrier mobility in polycrystalline SnSe at low-temperature range (Figure 3)[2,65–68]. However, identifying compatible systems and optimizing post-treatment conditions based on the phase diagrams of SnSe and related compounds remains challenging.

In this perspective, the strategies discussed above provide valuable insights into the transport mechanisms of TE materials and open new avenues for the controlled synthesis of advanced polycrystalline SnSe-based TE nanostructures. Solution-processed SnSe demonstrates significant potential for high TE performance through defect and surface engineering; however, further optimization remains crucial for advancing solution-processed SnSe toward practical applications, with key improvements including refining solution-processing conditions to achieve greater reproducibility, enhancing material stability against oxidation, and optimizing carrier mobility.

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Conflict of interest

The authors declare no conflict of interest.

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