

# Progress in the Preparation and Application of SnSe Thin Films

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## Abstract

**Tin selenide (SnSe) is a typical layered two-dimensional P-type semiconductor material. Because of its excellent photoelectric and thermoelectric properties and the advantages of its abundant elements in the earth and environment-friendly, it is widely used in solar cells, photoelectric detection, thermoelectric devices and other fields, and has great application prospects in rechargeable batteries. Therefore, the research and application of SnSe thin film has gradually become the current hot spot. This paper first describes the characteristics of SnSe materials, then introduces the research status of SnSe thin films at home and abroad, and studies the preparation methods of three typical SnSe thin films. Finally, it summarizes and prospects the application of SnSe thin films in solar cells, lithium ion batteries, flexible thermoelectric devices and other fields. The appearance of SnSe thin film has once again promoted the remarkable development of photovoltaic industry.**

## Keywords

**SnSe Thin Films, Thermoelectric Properties, Solar Cells.**

## 1. INTRODUCTION

With the advancement of social science and technology, issues such as energy depletion and environmental pollution have emerged. The concept of sustainable development permeates various research fields, with the exploration and development of clean energy emerging as a focal research topic among researchers. Currently, various clean energy sources, including solar, wind, bioenergy, hydro, geothermal, and hydrogen energy, have been developed and adopted. However, among the numerous new energy systems, thermoelectric materials, which can replace traditional fossil fuels, stand out with their remarkable advantages.

Thermoelectric materials are functional materials capable of converting thermal and electrical energy into each other, offering the advantage of being environmentally friendly. The thermoelectric power generation technology, utilizing these materials, directly converts waste heat into usable electrical energy, thereby enhancing energy utilization efficiency. Thermoelectric materials play a pivotal role in numerous fields. Given the escalating energy crisis, researching novel thermoelectric materials holds significant practical importance. For instance, thermoelectric thin films can regulate their thermoelectric properties through low-dimensional structures and are compatible with current semiconductor device manufacturing processes, presenting broad application prospects. A thermoelectric generator, based on the thermoelectric effect (including Seebeck, Peltier, and Thomson effects), has a conversion efficiency directly proportional to the thermoelectric figure of merit (ZT) of the materials. The definition formula of ZT is:

$$ZT = S^2 \sigma T / \kappa \quad (1)$$

Where,  $S$ ,  $\sigma$ ,  $\kappa$  and  $T$  are Seebeck coefficient, conductivity, thermal conductivity and absolute temperature, respectively.  $S^2\sigma$  is the power factor (PF). By measuring the Seebeck coefficient, conductivity, thermal conductivity and absolute temperature of the material, the thermoelectric merit of the material can be calculated. From the formula, we can also conclude that thermoelectric materials with excellent performance often have high power factor and low thermal conductivity.

In two-dimensional layered metal chalcogenides, IV-VI main group compounds have the advantages of moderate band gap (1.0-2.0eV), high visible light absorption, high chemical stability, and rich element content. SnSe is an important IV-VI main group compound semiconductor material, which belongs to orthogonal crystal system, and its single crystal film usually shows p-type conductivity. Therefore, it can absorb most of the sunlight in the visible spectrum and has good photoelectric performance. In 2014, Zhao et al. [1] used the Bridgman method to prepare better single crystal SnSe, and found that single crystal SnSe has good photoelectric and thermoelectric properties. According to the experiment, the ZT of SnSe can reach 2.6 at 923K. The major discovery of this property has led researchers to turn their attention to SnSe materials. These excellent properties enable SnSe to be widely used in optoelectronic devices.

## 2. RESEARCH PROGRESS OF SNSE THIN FILMS

As a p-type narrow band gap semiconductor material, SnSe bulk material has a direct band gap of 1.3 eV, which has a high optical absorption coefficient and can absorb sunlight in most wavebands. As a member of the IV-VI family of compounds, it has other special properties besides the common excellent properties of the family of compounds: layered structure, anisotropy, excellent photoelectric and thermoelectric properties, etc. Since 2014, Zhao has prepared better single crystal SnSe, so SnSe thermoelectric material is considered to be the most promising thermoelectric material, which has attracted researchers from various countries to research and develop it. It can be found from previous experiments that although single crystal SnSe has excellent thermoelectric properties, it also has great limitations in practical applications, such as strict crystal growth conditions and high production costs, which are not suitable for commercial production. However, it is difficult for polycrystalline SnSe to reach the ZT value as high as that of single crystal SnSe. Therefore, researchers have turned their attention to SnSe thin films. This section introduces the preparation and research of SnSe thin films by researchers at home and abroad in recent years and summarizes them into a table.

### 2.1. Research progress of SnSe thin films in China

In 2017, Suen et al. [2] used pulsed laser deposition (PLD) to deposit polycrystalline SnSe films with a grazing incidence angle of  $80^\circ$  on a 300 nm thick silicon substrate. This method greatly reduces the grain size of the film, resulting in a significant increase in PF, which can reach more than 100%. The maximum Seebeck coefficient and PF are  $498.5 \mu\text{V/K}$  and  $18.5 \mu\text{Wm}^{-1}\text{K}^{-2}$  respectively. Through experiments, it is further proved that the ZT value of SnSe films prepared by this method is significantly higher than that of corresponding single crystal films.

In 2018, Wenting Wang et al. [3] prepared n-type SnSe thin films by thermal evaporation using SnSe powder directly prepared by mechanical alloying. Then the samples were annealed, and the thermoelectric properties of the films were improved. When the annealing temperature was 673K, the Seebeck coefficient of the n-type conductive films prepared reached  $209 \mu\text{V/K}$ , the conductivity exceeded  $5\text{S/cm}$ , and the maximum PF reached  $21 \mu\text{Wm}^{-1}\text{K}^{-2}$ . When the annealing time is increased to 4h, a higher PF value of  $120 \mu\text{Wm}^{-1}\text{K}^{-2}$  is obtained. This experiment shows that annealing is an effective way to improve the thermoelectric properties of SnSe films.

In 2019, Lirong Song et al.<sup>[4]</sup> used a single SnSe compound target to prepare SnSe films on fused quartz substrates by magnetron sputtering technology. The effects of annealing process on PF, Seebeck coefficient and internal structure were studied. The results show that the films annealed at 700K have better thermoelectric properties than bulk polycrystalline SnSe and films annealed at other temperatures (600, 800 and 1000K).

In 2020, Cui Shusong et al.<sup>[5]</sup> prepared SnSe films on glass substrates by electron beam evaporation and re selenidation of prefabricated layers. The phase, micro morphology and optical properties of SnSe thin films were studied by means of X-ray diffraction (XRD), Raman spectroscopy and scanning electron microscopy (SME). The pure phase polycrystalline SnSe thin films with a band gap of 0.93eV can be prepared by seleniding annealing at 450 °C for 60min. Under the irradiation of 980nm laser, the response time and recovery time are 62 and 80 ms respectively, which have good infrared response performance.

In the same year, Lanzhong Hao et al.<sup>[6]</sup> prepared 5nm thick SnSe films on 300nm thick silicon substrate by magnetron sputtering. In order to obtain high-quality films, the team optimized the target substrate distance, deposition temperature (450 °C), air pressure (1.0Pa) and sputtering power (10W). The prepared SnSe thin films show high crystallinity and uniform continuity in wafer size. It is worth mentioning that the SnSe photodetector prepared by the team shows ultraviolet visible near infrared light response, has a high responsivity of 277.3 AW<sup>-1</sup>, and the detection rate is  $7.6 \times 10^{11}$  Jones. These excellent properties make SnSe thin films have broad application prospects in developing high-performance optoelectronic devices.

In 2021, Cui Yan et al.<sup>[7]</sup> prepared SnSe films with a thickness of about 500 nm on Si/SiO<sub>2</sub> substrates by magnetron sputtering technology, and analyzed the influence of deposition temperature on the structure and thermoelectric properties of SnSe films. At 573K deposition temperature, the film has a PF of about  $1.25 \mu\text{Wm}^{-1}\text{K}^{-2}$ . When the deposition temperature rises to 773K, the maximum PF of the film at 573K is  $0.5 \mu\text{Wm}^{-1}\text{K}^{-2}$ . The experimental results prove the importance of high deposition temperature on the microstructure and thermoelectric properties of SnSe films.

## 2.2. Research progress of SnSe thin films abroad

In 2016, Urmila et al.<sup>[8]</sup> successfully deposited p-type SnSe polycrystalline films on glass substrates by reactive evaporation. The film exhibits a direct permissive transition with an optical band gap of 1.2 eV. The Seebeck coefficient of SnSe films is 7863  $\mu\text{V}/\text{K}$ , and the PF is  $7.2 \times 10^{-4} \mu\text{Wm}^{-1}\text{K}^{-2}$ . At 42K, the ZT of the films is 1.2. The experiment proves that the SnSe thin film is an ideal material for low-temperature thermoelectric applications.

In 2017, Giuk et al.<sup>[9]</sup> prepared 1~2  $\mu\text{m}$  SnSe films on borosilicate glass by thermal co evaporation. The results show that SnSe thin films can be widely used due to the wide adjustability of carrier concentration. For example, SnSe films with a carrier density of  $10^{15} \text{cm}^{-3}$  are suitable for photovoltaic devices, while SnSe films with higher carrier density are suitable for thermoelectric devices.

In 2018, Matthew et al.<sup>[10]</sup> prepared SnSe nanosheets with a thickness of about  $1\mu\text{m}$  on a glass substrate by thermal evaporation, showing a low thermal conductivity of  $0.08\text{Wm}^{-1}\text{K}^{-1}$  between 375-450K.

In 2020, Van Quang Nguyen team<sup>[11]</sup> used thermal evaporation to prepare SnSe films, and explored the influence of Se/Sn flux ratio on the growth and thermoelectric properties of SnSe films on MgO substrates. It is found that the Seebeck coefficient is positive at room temperature and decreases with the increase of temperature. When the film Se/Sn=1, the Seebeck coefficient becomes negative. When Se/Sn=0.8 and SnSe film is at 550K, the maximum PF obtained is  $3.74 \mu\text{Wm}^{-1}\text{K}^{-2}$ .

In 2021, Tomoya Horide et al.<sup>[12]</sup> successfully prepared Bi doped n-type SnSe films by pulsed laser deposition. When Bi content is 5.7%, it shows n-type Hall resistivity and n-type Seebeck coefficient. The Seebeck coefficient and conductivity of the film at 300 °C are – 608 and – 385  $\mu\text{V/K}$ , 0.44 and 1.5S/cm, respectively.

In the same year, P. S. Satheesh Kumar et al.<sup>[13]</sup> successfully prepared p-type semiconductor SnSe films by spray pyrolysis at a substrate temperature of 250 °C~375 °C, and studied the photoelectric properties of SnSe films by XRD and SEM. The optical band gap of the films prepared is 1.14~1.24eV, and the optimal substrate temperature for SnSe films deposited by this technology is determined to be 300 °C. It further confirmed the feasibility of SnSe film as a window layer of solar cells.

In 2022, Pinaki Mandal et al.<sup>[14]</sup> prepared SnSe films by electrodeposition and solvothermal methods. The optical band gaps of SnSe films prepared by the two methods are 1.33eV and 1.19eV respectively. And the optical properties of them are studied. The photoluminescence (PL) spectrum shows that there is a strong blue emission band near 435 nm, which once again proves the potential application of SnSe thin films in optoelectronic devices.

**Table 1.** In the past seven years, researchers at home and abroad have studied SnSe thin films.

Year	Preparation technology	substrate	temperature	Seebeck coefficient	Power factor
2016 <sup>[8]</sup>	Reaction evaporation method	glass	42K	7863 $\mu\text{V/K}$	7.2 $\times 10^{-4}\mu\text{Wm}^{-1}\text{K}^{-2}$
2017 <sup>[2]</sup>	Pulsed laser deposition technology	Si	478K	498.5 $\mu\text{V/K}$	18.5 $\mu\text{Wm}^{-1}\text{K}^{-2}$
2017 <sup>[9]</sup>	Co evaporation method	Borosilicate glass	773K	/	/
2018 <sup>[3]</sup>	Thermal evaporation method	BK7glass	673K	209 $\mu\text{V/K}$	21 $\mu\text{Wm}^{-1}\text{K}^{-2}$
2018 <sup>[10]</sup>	Thermal evaporation method	glass	375-450K	/	0.08 $\text{Wm}^{-1}\text{K}^{-1}$
2019 <sup>[4]</sup>	Applied Film	fused silica	700K	100 $\mu\text{V/K}$	1.3 $\mu\text{Wm}^{-1}\text{K}^{-2}$
2020 <sup>[11]</sup>	Thermal evaporation method	MgO	550K	400 $\mu\text{V/K}$	3.74 $\mu\text{Wm}^{-1}\text{K}^{-2}$
2020 <sup>[5]</sup>	Electron beam thermal evaporation	glass	723K	/	/
2020 <sup>[6]</sup>	Applied Film	Si	723k	/	/
2021 <sup>[7]</sup>	Applied Film	Si/SiO <sub>2</sub>	573K	450 $\mu\text{V/K}$	1.25 $\mu\text{Wm}^{-1}\text{K}^{-2}$
2021 <sup>[12]</sup>	pulsed laser deposition	STO	573K	-250 $\mu\text{V/K}$	0.3 $\mu\text{Wm}^{-1}\text{K}^{-2}$
2021 <sup>[13]</sup>	spray pyrolysis	glass	523K-648K	/	/
2022 <sup>[14]</sup>	Electrodeposition and solvothermal	FTO	/	/	/

It can be seen from Table 1 that different preparation technologies, substrate temperature, annealing temperature and time length have a great impact on the thermoelectric properties of SnSe films. With the in-depth understanding of SnSe materials by researchers and the growing maturity of relevant preparation technologies, SnSe thin films with high power factor can be prepared and widely used in the field of thermoelectric conversion. However, as far as the current development level is concerned, there is still a big gap between the thermoelectric

properties of SnSe thin films and bulk materials. How to further improve the thermoelectric properties of SnSe thin films has become an urgent problem for researchers of thin film thermoelectric materials.

### 3. PREPARATION METHOD OF SNSE FILM

SnSe has excellent photoelectric and thermoelectric properties. Its optical absorption band and absorption ability can be controlled by the number of layers and band gap of SnSe. The thin film material has fewer SnSe layers, which can scatter longer wavelength phonons, reduce thermal conductivity, and facilitate practical applications. In addition to the important influence of substrate selection on the film characteristics, the properties of SnSe films prepared by different methods are also different. At present, the preparation of SnSe films by researchers is mainly through chemical vapor deposition (CVD) and physical vapor deposition (PVD). Common CVD methods include atmospheric CVD, atomic layer deposition (ALD), etc. Common PVD methods include pulsed laser deposition (PLD), thermal evaporation, flash evaporation, molecular beam epitaxy (MBE) and magnetron sputtering. The thermoelectric properties of the films prepared by different methods are different. This paper mainly introduces the pulsed laser deposition, vacuum evaporation and magnetron sputtering in physical vapor deposition.

#### 3.1. vacuum evaporation

The principle of vacuum evaporation is shown in Figure 1. In the vacuum chamber, the raw material is turned into steam by heating, and the mixture of steam is transported to the surface of the substrate. The molecules adsorbed on the surface of the substrate condense into nuclei and crystallize into films. Vacuum evaporation is the mainstream process in vacuum plating, mainly including thermal evaporation, electron beam evaporation and plasma enhanced evaporation technology<sup>[15]</sup>. SnSe thin films are prepared by thermal evaporation method by depositing bulk SnSe materials on the substrate through thermal evaporation to form SnSe thin films. This technology is widely used on glass, mica and sapphire substrates. Vacuum evaporation technology can prepare micron or even nanometer coatings, and the resulting coatings have excellent adhesion, density, hardness and corrosion resistance<sup>[16]</sup>.

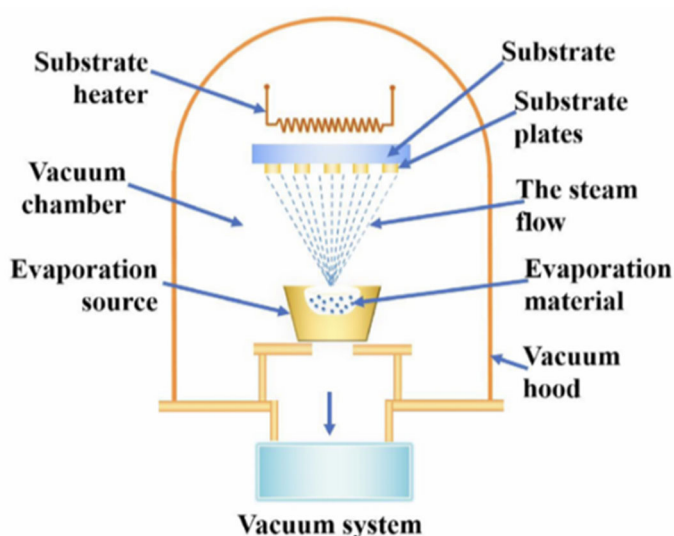


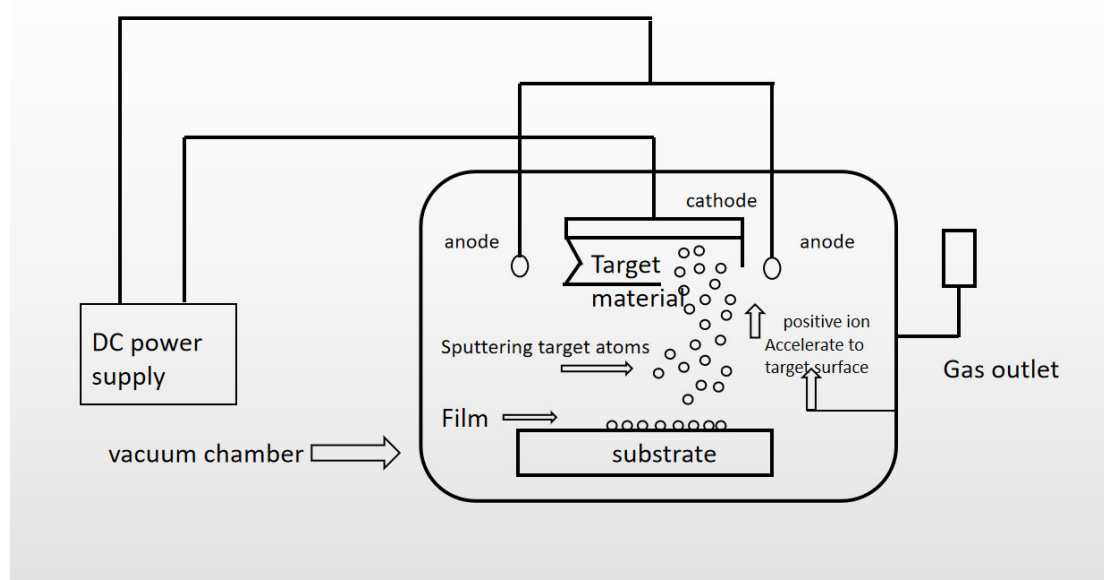
Figure 1. Principle of vacuum evaporation

#### 3.2. Magnetron sputtering

The principle of film preparation by magnetron sputtering is shown in Figure 2. Fill the vacuum chamber with an appropriate amount of inert gas argon as the discharge carrier, place

the target (deposition material) on the cathode, use the wall of the coating chamber as the anode, add a cross magnetic field and electric field between the cathode and anode, and apply a voltage of several hundred volts between the cathode and anode. High voltage will cause plasma glow discharge in the coating chamber, and the Ar atom will be ionized into  $\text{Ar}^+$  and electrons. During the process of accelerating to the substrate, electrons will constantly collide with Ar atoms, ionizing a large amount of  $\text{Ar}^+$ . Under the effect of high voltage electric field,  $\text{Ar}^+$  will be accelerated by the cathode and hit the cathode target surface, causing the atoms in the target to obtain the energy of  $\text{Ar}^+$ . In the cascade collision, the neutral target atoms escape from the original lattice and deposit on the substrate, finally forming the film.

Compared with other preparation methods of thermoelectric thin films, the method of magnetron sputtering to prepare SnSe thin films has a wide range of dynamic adjustment of working parameters; The deposition speed and thickness of the coating are easy to control; These advantages are beneficial to the preparation, doping and carrier concentration adjustment of SnSe films with multi-layer and low dimensional structures. In conclusion, SnSe thin films with large area and high uniformity can be prepared by magnetron sputtering technology.



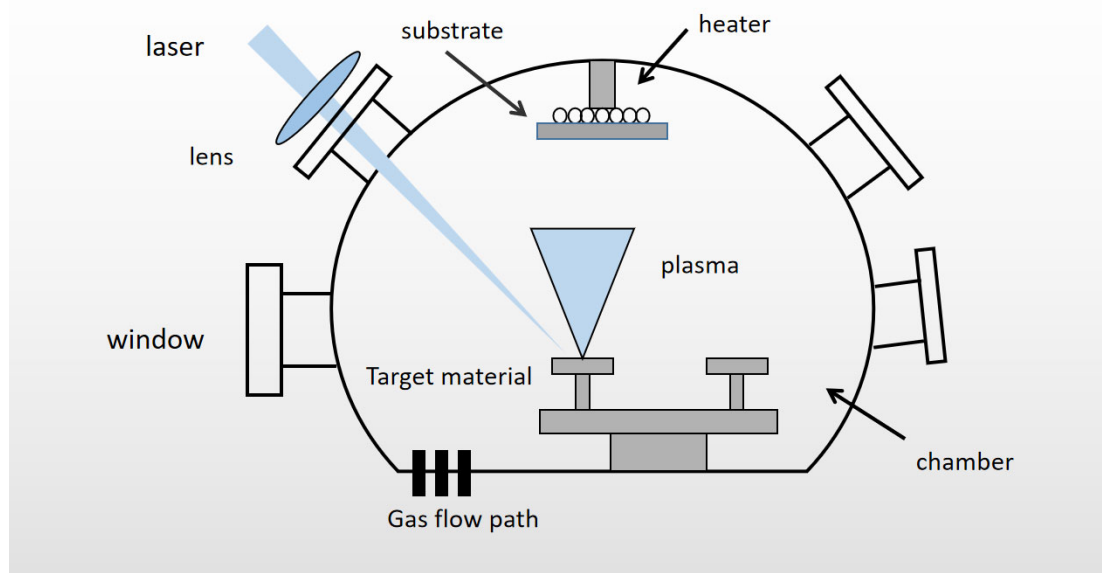
**Figure 2.** Magnetron sputtering principle diagram

### 3.3. Pulse laser deposition (PLD)

The basic principle of pulsed laser deposition (PLD) technology is shown in Figure 3. A high-energy pulsed laser is focused to the target surface through the entrance window of the vacuum chamber under the focus of the lens. At the focus, the laser interacts with the target to generate vaporization, ionization, phase explosion and other effects. The ablation of the target surface produces particles such as ions, electrons, atoms and atomic clusters. These particles continue to interact with the laser and expand directionally in the chamber to form a localized ellipsoidal plasma plume of high temperature and pressure ( $T > 10^4 \text{K}$ ). During the expansion of the plasma, with the interaction of particles and gas molecules in the cavity, these particles reach the surface of the substrate after a series of actions, and a large number of particles nucleate and grow on the substrate, finally forming a deposit product with specific composition and structure<sup>[17]</sup>.

The preparation of thin films by PLD is generally divided into three processes<sup>[18]</sup>: (1) the process of laser interacting with solid surface to generate plasma; (2) Directional local

isothermal adiabatic expansion emission of the plasma towards the substrate; (3) The plasma plume interacts with the substrate surface and forms a film on the substrate surface. Compared with the above two film preparation technologies, PLD can be deposited at room temperature<sup>[19]</sup>. Therefore, PLD technology has great advantages in thin film preparation. Using PLD technology, SnSe thin films can be prepared on a variety of substrates<sup>[20]</sup>.



**Figure 3.** Principle diagram of pulsed laser technology

## 4. APPLICATION PROGRESS OF SNSE THIN FILMS

Generally, the thermoelectric merit of traditional industrialized semiconductor thermoelectric materials is 1-2 at most, while SnSe has such a high ZT value and very low thermal conductivity, so researchers unanimously believe that SnSe will be a kind of lead-free chalcogenide with great research prospects, and will be deeply developed and widely used in new thermoelectric materials, internal memory switches, holographic recording, sensors, laser materials, infrared optoelectronic devices, anode materials, solar cell devices and other fields.

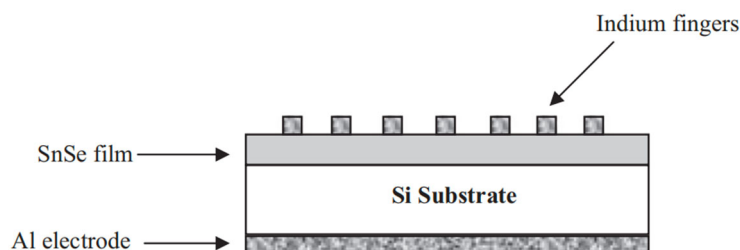
### 4.1. Application progress of solar cells

Solar energy has been placed with great hope in solving the global energy crisis. Solar cells are based on the photovoltaic effect of semiconductors. When sunlight shines on the cells, the cells use the photoelectric conversion effect to convert light energy into electric energy for use. SnSe thin films show good absorption in the visible light to near infrared region, which enables them to become the absorption layer materials of solar cells.

In 2010, Matthew A. Franzman et al.<sup>[21]</sup> used a simple liquid phase method to synthesize SnSe nanocrystals with quantum confinement effect. Its direct optical band gap  $E_g=1.71\text{eV}$  matches the solar spectrum, and the SnSe thin film solar cell is manufactured under 1.5G light, achieving 0.06% photoelectric conversion efficiency.

In 2014, Rahman et al.<sup>[22]</sup> deposited SnSe thin films on n-Si single crystals to prepare p-SnSe/n-Si heterojunction photovoltaic cells, as shown in Figure 4. Electrical and photoelectric tests were carried out at different temperatures. At low voltage ( $V<0.55\text{V}$ ), dark field current density is controlled by multi-step tunneling effect mechanism. However, at relatively high voltage ( $V>0.55\text{V}$ ), the current limiting conductance mechanism is dominant, and the trap concentration is  $2.3 \times 10^{-3}/\text{cm}^3$ . The capacitance voltage measurement shows that the

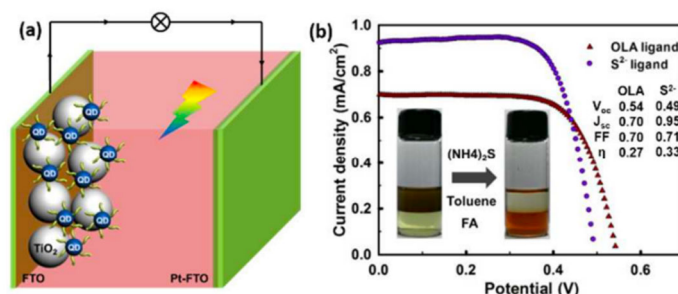
connection is abrupt, and the built in electric field is 0.62V, and the speed of the built in electric field decreasing with temperature is  $2.83 \times 10^{-3} \text{V/K}$ . Under 425mV open circuit voltage, the battery shows a strong photovoltaic property, with a turn on current of  $17.23 \text{mA} \cdot \text{cm}^{-2}$  and an energy conversion efficiency of 6.44%.



**Figure 4.** In/SnSe/Si/Al heterojunction schematic

In 2018, Farid, Jamali Sheini et al.<sup>[23]</sup> used electrodeposition method to deposit nanostructured SnSe films, studied the influence of lead (Pb) and zinc (Zn) on electrical and photovoltaic performance, and achieved 0.23%, 0.42% and 0.06% efficiency respectively in three cases of lead doped, zinc doped and undoped. The results show that the solar cell devices made of Zn doped SnSe films have higher efficiency due to higher carrier concentration.

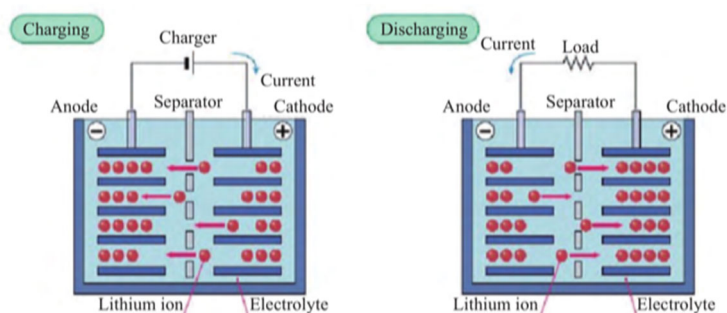
In 2020, Behnaz et al.<sup>[24]</sup> By studying the influence of In doping on its physical properties and the application of solar cells, the carrier concentration and efficiency of SnSe thin film solar cells were increased by adjusting the concentration of In ions, and the highest photoelectric conversion efficiency of 0.36% was obtained.



**Figure 5 (a).** The schematic of quantum dot sensitized solar cell. (b) JV characteristics of solar cell devices before and after ligand exchange under AM1.5 irradiation are simulated<sup>[25]</sup>.

#### 4.2. Application progress of lithium-ion battery

With the rising demand for energy in various countries in the world, finding new energy storage devices has become a hot topic in new energy related fields. Lithium ion batteries have the advantages of high specific energy, low self discharge, good cycling performance, no memory effect and green environmental protection. They are currently the most promising high-efficiency secondary batteries and the fastest developing chemical energy storage power supply. In recent years, the application of lithium-ion batteries in the aerospace field has been gradually strengthened. There are lithium-ion batteries in UAVs, earth orbiters, civil airliners and other aerospace vehicles <sup>[26]</sup>. The working principle of the lithium-ion battery is shown in Figure 6. It is composed of positive pole, negative pole, diaphragm and electrolyte. The positive and negative pole materials can embed and remove lithium ions. It uses a working principle similar to a rocking chair. During the charging and discharging process, lithium ions shuttle back and forth between the positive and negative poles, "rocking" from one side to the other, and cycling back and forth to realize the charging and discharging process of the battery<sup>[27]</sup>.



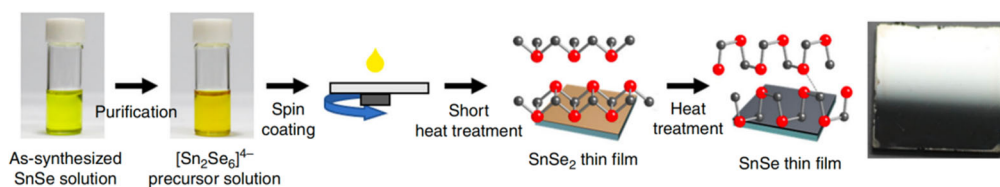
**Figure 6.** Lithium ion battery charge and discharge principle diagram

Mingzhe Xue et al.<sup>[28]</sup> prepared SnSe films by reactive pulsed laser deposition (PLD). The cyclic voltammetric CV and charge discharge behavior of Li/SnSe battery were studied. The reversible discharge capacity of 400~681mAh/g was achieved in the first 40 cycles. The reversible capacity of SnSe film electrode is greater than 5.9Li/Sn atom. A pair of reduction and oxidation peaks of Li/SnSe battery at 1.2 and 1.9 V were observed from the CV curve. The research shows that SnSe can improve its electrochemical performance, has high reversible capacity and good cycle stability, and is an ideal anode material for rechargeable lithium batteries.

#### 4.3. Application Progress of Flexible Devices

Solid state thermoelectric devices have unique advantages such as quiet operation, zero harmful emissions, and long service life. They have broad application prospects in refrigeration, power generation, waste heat recovery and other technical fields<sup>[29]</sup>. With the rapid development of flexible electronic devices and micro sensors, low-cost flexible thermoelectric energy collectors, as a potential power supply, have attracted extensive attention. SnSe can be used to manufacture two-dimensional flexible thermoelectric generators. The preparation process can be divided into two types: one is to assemble the SnSe based films prepared by die casting technology with flexible substrates; The other is to prepare organic/inorganic composite films with SnSe nanocrystals as film fillers<sup>[30]</sup>.

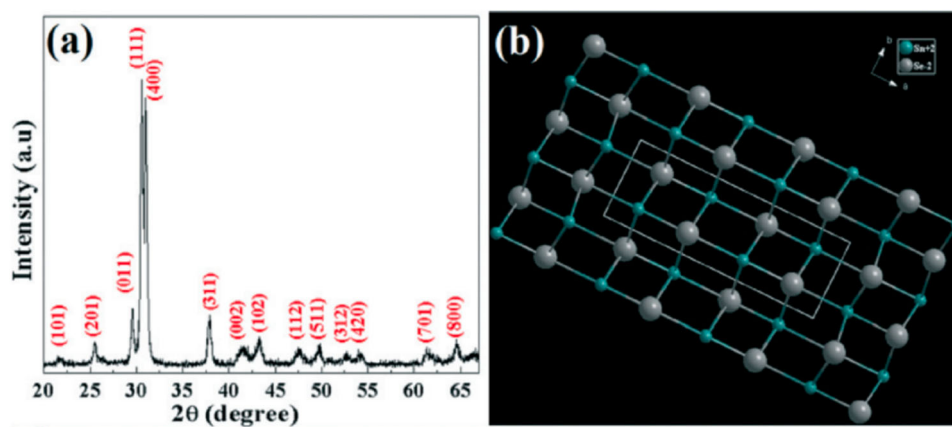
Seung Hwae Heo et al.<sup>[31]</sup> prepared a highly textured and hole doped SnSe film with single crystal horizontal thermoelectric PF by solution method, with a thickness of about 1  $\mu$  m. The optimized SnSe film shows a thermoelectric PF of 4.27  $\mu$  Wm<sup>-1</sup>K<sup>-2</sup>, as shown in Figure 7.



**Figure 7.** Preparation of highly textured SnSe films by solution method

In 2014, Faheem K. Butt<sup>[32]</sup> et al. prepared high-quality single crystal SnSe nanowires by chemical vapor deposition (CVD). As shown in Figure 8, the length of nanowires is about tens of microns, and their average diameter is 30-40 nm. During the growth process, the position of the substrate is taken as a variable, and other conditions remain unchanged. Different morphologies of SnSe can be obtained at different substrate temperatures, including columnar and flaky. At 500  $^{\circ}$ C, high-quality nanowires can be obtained. The photocurrent of the nanowire

is 4 times higher than that of the nanowire without light. Further demonstrate the potential of SnSe nanowires in photovoltaic and optical devices.



**Figure 8(a).** XRD patterns of SnSe nanowires. (b) Crystal structure of SnSe

## 5. CONCLUSION

In this paper, the thermoelectric properties of SnSe thin films and the research progress of researchers at home and abroad in recent years are reviewed. The typical preparation technologies of SnSe thin films and the applications of SnSe thin films in photovoltaic, rechargeable batteries, flexible devices and other fields are introduced. Due to the complex manufacturing process of thin films, structural defects such as cavities and dislocations will inevitably be introduced in the preparation process, so it is difficult to achieve excellent thermoelectric properties in thin film thermoelectric materials and devices. Although SnSe thin films have the development prospect of high performance and practicability, the comprehensive properties of thin film materials are required to meet the increasingly demanding and complex working environment. At present, researchers are looking for various preparation methods to improve the quality and performance of SnSe films. However, the selection of the substrate and the substrate temperature also have a great impact on the thermoelectric properties of SnSe films. Researchers of thermoelectric materials can improve the quality of SnSe films from this aspect. Thus, SnSe thin films are applied in diversified directions.

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