

Research on Preparation Processes of Thin-Film Solar Cell Materials

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Abstract. Currently, the photovoltaic efficiency and cost control of crystalline silicon solar cells are constrained. Meanwhile, thin-film solar cells have drawn considerable attention due to cost-effectiveness and superior conversion efficiency. This paper presents a comparative analysis of the material properties and conventional fabrication techniques employed in three representative types of thin-film solar cells: cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and gallium arsenide (GaAs). Furthermore, future advances in three mainstream fabrication routes are primarily directed toward reducing costs, increasing conversion efficiency, and enhancing overall film quality: the close-spaced sublimation (CSS) process for CdTe deposition focuses on system modification to improve uniformity over large areas; the co-evaporation method for CIGS absorber layers emphasizes optimization of wide-bandgap top-cell fabrication and alkali metal doping techniques; and for GaAs, metalorganic chemical vapor deposition (MOCVD) for thin-film growth concentrates on the development of ultra-high growth rate technology and direct growth on flexible substrates. With these upgrades, thin-film cells can close the efficiency-cost gap with crystalline silicon counterparts.

Keywords: Cadmium telluride, copper indium gallium selenide, gallium arsenide, thin-film solar cells, fabrication processes

1. Introduction

Currently, although crystalline silicon solar cells dominate the global photovoltaic market, it is difficult to make significant breakthroughs in their photovoltaic efficiency and cost control. Thin-film solar cells, which have comparable or even higher conversion efficiency and lower cost, have attracted global attention and are expected to become the mainstream direction. In recent years, the main domestic thin-film solar cells include three types: cadmium telluride (CdTe) thin-film solar cells, copper indium gallium selenide (CIGS) thin-film solar cells, and gallium arsenide (GaAs) thin-film solar cells.

The ideal bandgap of CdTe gives it excellent absorption of sunlight, and it has a low temperature coefficient and excellent low-light performance. Its low production cost and process requirements also meet the needs of large-scale automated production. First Solar in the United States has achieved 19% efficiency for mass-produced CdTe modules [1]. CIGS has tunable composition, which can not only change the bandgap but also has excellent anti-interference capability. The U.S.

National Renewable Energy Laboratory used a co-evaporation process to increase CIGS efficiency to 19.9%, setting a world record for thin-film solar cells [2]. GaAs has a bandgap that perfectly matches the solar spectrum, and the resulting solar cells have the highest photoelectric conversion efficiency, and the thin films are highly flexible, but there are problems such as unstable power output and high production difficulty. MicroLink Devices in the U.S. has achieved a laboratory efficiency of up to 34.3% for four-junction thin-film GaAs solar cells, and China's San'an Optoelectronics has exceeded 34.5% for multi-junction GaAs cells [3].

The preparation of CdTe thin films is mainly divided into low-temperature methods (substrate heating temperature not exceeding 450 °C) and high-temperature methods (substrate heating temperature above 600 °C) [1]. The former includes vacuum evaporation, electrodeposition, and magnetron sputtering deposition techniques, and the latter includes close-spaced sublimation (CSS) and vapor transport deposition (VTD) processes, the essence of which is to condense CdTe vapor onto a low-temperature substrate surface. Currently, methods for preparing CIGS films include selenization of metal precursor layers, multi-step co-evaporation, hybrid methods, printing, and electrodeposition, among which the three-stage co-evaporation method has been widely used. GaAs thin-film preparation includes epitaxial growth by metalorganic chemical vapor deposition (MOCVD) and electrodeposition; the former is the mainstream preparation process, which can achieve rapid and precise synthesis, but the raw materials are expensive and have extremely high safety requirements.

Starting from the properties of the above mainstream thin-film materials, this paper analyzes the characteristics of films produced by different processes and the future improvement directions of the mainstream processes.

The advantages of CdTe thin-film solar cells are mainly reflected in low production cost, low temperature coefficient, and excellent low-light performance. CdTe has a direct bandgap of approximately 1.45 eV, which is very close to the theoretical optimal value. Combined with an absorption coefficient on the order of $10^4\sim 10^5\text{ cm}^{-1}$, a film only 1 μm thick can absorb 99% of visible light, thus giving it a relatively high theoretical conversion efficiency. The temperature coefficient of the cell is about $-0.20\%/^{\circ}\text{C}$, which is significantly better than that of crystalline silicon ($-0.45\%/^{\circ}\text{C}$), demonstrating better power generation stability in harsh environments such as high-temperature and humid regions. However, CdTe has a strong self-compensation effect, making it difficult to achieve effective p-type heavy doping. Currently, the open-circuit voltage only reaches 75.8% of its theoretical value, leaving considerable room for efficiency improvement. At the same time, the CdS window layer absorbs sunlight with wavelengths below 515 nm, causing blue light loss and limiting further increases in short-circuit current [1].

The most prominent advantage of CIGS thin-film solar cells is their light absorption coefficient of up to 10^5 cm^{-1} , and by adjusting the Ga/In ratio, the bandgap can be continuously tuned in the range of 1.0–1.7 eV, providing a flexible material basis for spectral matching optimization and graded bandgap structure design [4]. In addition, CIGS cells have strong radiation resistance and good low-light performance, and can be fabricated on flexible substrates such as stainless steel or polyimide, offering unique advantages in building-integrated photovoltaics (BIPV), portable mobile energy, and IoT devices. However, the fabrication of CIGS cells involves precise synergistic control of multiple elements, with a complex phase diagram and significant interfacial coupling effects between functional layers; even minor compositional deviations can significantly degrade device performance [4]. Although CIGS module efficiency has reached 19.2%, limited by the uniformity of deposition equipment and the stability of complex process flows, commercial module efficiency remains around 16%, leaving a considerable gap from laboratory levels.

GaAs thin-film solar cells are made from compound semiconductors synthesized at high temperatures, exhibiting good temperature tolerance, slow photoelectric conversion degradation, and long service life, and are primarily used in aerospace and space power applications. Flexible GaAs thin-film cells use polyimide or ultra-thin stainless steel as substrates, with thicknesses of only 0.05–0.1 mm and a bending radius of less than 1.5 cm, making them suitable for power generation on the surfaces of micro-satellites, space probes, and unmanned aerial vehicles [3]. Due to the limited reserves of gallium on Earth, the manufacturing cost of GaAs cells is extremely high. In four-junction GaAs cells, there is a lattice mismatch issue; the approximately 2.15% mismatch between the InGaAs subcell and the GaAs substrate introduces strain energy in the epitaxial layer, and excessive dislocation density can degrade material quality and drastically reduce conversion efficiency [3]. In addition, substrate lift-off technology faces two major problems—slow lift-off rates and susceptibility to epitaxial layer damage—which limit the feasibility of mass production of thin-film cells.

2. Preparation processes for CdTe thin films

2.1. Vacuum evaporation method

The vacuum evaporation process uses CdTe as the sole evaporation source, heating it in a vacuum environment to sublimate and deposit onto a low-temperature substrate to form a thin film. The overall reaction process can be expressed as $\text{CdTe(s)} \rightleftharpoons \text{Cd(g)} + \text{Te(g)}$. During deposition, substrate temperature, substrate surface condition, and vacuum level all affect film quality; defects that typically form require heat treatment of the film to address. The defects in films prepared by vacuum deposition mainly originate from deposition rate and substrate properties, while vacuum level has no significant effect on film quality [5].

2.2. Electrodeposition method

The electrodeposition process utilizes an electrolytic cell to deposit Cd onto the cathode, thereby obtaining CdTe thin films, where the electrolyte contains Cd^{2+} as the Cd source and the cathode material is mostly tellurium oxide. The specific process is divided into potentiostatic deposition and galvanostatic deposition; the former yields more uniform films and is therefore more widely used. Potentiostatic deposition requires first determining the deposition potential of Cd^{2+} ions, thereby maintaining a suitable potential at the working electrode to achieve selective deposition. The advantage of electrodeposition lies in its ability to obtain the target product at low temperatures by controlling parameters such as potential and the type of working electrode, while also ensuring purity. Currently, the electrodeposition process can prepare CdTe thin films at 70 °C, and laboratory cell efficiencies have exceeded 15% [6].

2.3. Magnetron sputtering deposition

Magnetron sputtering deposition uses a CdTe compound target or Cd/Te dual targets, utilizing plasma ionized from the atmosphere to bombard the target, sputtering target atoms to deposit onto the substrate to form CdTe thin films. Magnetron sputtering is a low-temperature process, easy to control, and very suitable for preparing large-area films while ensuring film uniformity and stability. However, due to the suppression of target ion transport by the space electric field and the decrease in electroactivity caused by high-energy ion sputtering, the deposition rate and film quality of

magnetron sputtering are lower than those of the close-spaced sublimation process, resulting in lower conversion efficiencies for the fabricated cells. Some researchers have found that replacing the target with nanostructured CdTe helps improve cell efficiency [7].

2.4. Close-spaced sublimation (CSS)

CSS, as the mainstream industrial preparation method for CdTe thin films, has a principle essentially similar to vacuum evaporation, but the distance between the substrate and the evaporation source is much smaller, and gases such as Ar and O₂ are introduced to ensure stable atomic transport, which not only allows regulation of the grain size of the film but also conducts heat from the evaporation source to the substrate, maintaining an appropriate temperature difference [8]. As a high-temperature method, CSS maintains the evaporation source temperature above 600 °C, ensuring a certain evaporation rate while also compensating for substrate temperature; the substrate temperature is also as high as 500 °C, which facilitates the diffusion of deposited atoms on the substrate surface to obtain large grains and reduce defect formation.

3. Preparation processes for CIGS thin films

3.1. Co-evaporation method

The co-evaporation method is a process in which the four elements Cu, In, Ga, and Se are deposited separately. According to the deposition steps, it can be divided into one-stage, two-stage, and three-stage methods, among which the three-stage method is the most commonly used because it facilitates the control of the spatial distribution of elements and the thickness of each layer. In the three-stage method, the entire evaporation process is carried out in a Se atmosphere: the first stage typically involves co-evaporating In/Ga onto the substrate to form a precursor layer; the second stage co-evaporates Cu and Se, aiming to form a Cu-rich phase in the precursor layer, which drives the growth of fine grains into dense CIGS crystals and forms a conductive chalcopyrite structure; the third stage again co-evaporates In/Ga to form a Cu-poor phase, which stabilizes the chalcopyrite structure while effectively suppressing carrier recombination at the interface due to its high resistance characteristics.

3.2. Selenization of metal precursor layers

In this process, a Cu–In–Ga precursor layer is first sputter-deposited onto the substrate, followed by high-temperature selenization in a H₂Se atmosphere to form CIGS crystals. This selenization process enables uniform film distribution and is suitable for large-area film deposition. However, the toxic H₂Se gas used in the selenization process is one of the factors restricting its production, and currently no better alternative exists. In addition, the prolonged high-temperature environment of the selenization process can easily cause material loss; moreover, the lower reactivity of Ga and In compared to Se leads to local segregation of Ga, resulting in a bandgap distribution that deviates from the ideal profile and is detrimental to carrier separation [4].

4. Preparation processes for GaAs thin films

4.1. Metalorganic chemical vapor deposition (MOCVD)

MOCVD is a process for growing thin films on a substrate through chemical reactions, typically using gases containing Ga and As elements, such as trimethylgallium (TMG) and arsine (AsH_3), to epitaxially grow GaAs films on a high-temperature substrate. Most researchers believe that reactant molecules first adsorb onto adjacent reaction sites on the substrate surface, then react, ultimately forming the GaAs lattice. In the MOCVD process, the flow ratio of TMG to AsH_3 significantly affects the film properties, and the resulting films contain carbon residues, mainly from the decomposition of the methane byproduct [9]. The advantage of MOCVD lies in its ability to controllably prepare high-quality GaAs films, while its disadvantages are the extremely high production cost and stringent safety requirements.

4.2. Potentiostatic co-deposition method

In electrochemistry, co-deposition refers to the process in which two or more ions are discharged and deposited on the cathode. In the laboratory, Ga and As_2O_3 are commonly dissolved in hydrochloric acid to prepare the electrolyte, and a conductive glass is used as the cathode. By adjusting the pH value, concentration, and working voltage of the electrolyte, approximate co-deposition of Ga^{3+} and As^{3+} can be achieved, and the two elements spontaneously form GaAs compounds after deposition [10]. The morphology and performance of films prepared by potentiostatic co-deposition are highly dependent on the selected deposition voltage; films with good monochromaticity can be obtained, but the crystallinity is relatively low, requiring annealing treatment to optimize the optoelectronic properties.

5. Development directions of mainstream processes

5.1. Close-spaced sublimation

The improvements in close-spaced sublimation focus on breaking through the uniformity bottleneck in large-area production and enhancing material quality. One important future direction for CSS is to develop more precise and controllable deposition methods, such as achieving uniform preparation of CdSeTe alloy films through alternating deposition of CdSe and CdTe layers followed by annealing [11]. Another direction is to control the performance of the CdTe source material by optimizing the oxygen atmosphere to address its oxidation degradation issues, as well as to develop new processes such as rapid ultra-high-temperature diffusion to improve film quality.

5.2. Co-evaporation method

The core of improving the co-evaporation method lies in the ultimate control over the microstructure and composition of the material. The conventional three-stage co-evaporation process has already been able to achieve "V"-shaped or "W"-shaped bandgap gradients by adjusting the elemental deposition rates at each stage [8]. In the future, more precise synergistic control of process parameters such as Ga element gradient, Ag alloying, and alkali metal post-deposition treatment (PDT) will be key to improving open-circuit voltage and fill factor [12]. An important direction for co-evaporation is compatibility with the fabrication process of perovskite top cells. The research focus will be on how to uniformly deposit perovskite layers on rough CIGS surfaces using co-

evaporation and how to resolve interfacial issues. Recently, the team of Hou Yi at the National University of Singapore reported a perovskite/CIGS tandem solar cell fabricated entirely by co-evaporation, achieving an efficiency of 23.1%.

5.3. Metalorganic chemical vapor deposition

The improvement direction for MOCVD is very clear: to reduce the high manufacturing cost while maintaining its excellent optoelectronic performance. The core future direction is to develop ultra-high growth rate MOCVD technology to increase equipment throughput, shorten process cycles, and reduce precursor consumption, thereby fundamentally lowering manufacturing costs. Studies have achieved growth rates exceeding 280 $\mu\text{m/h}$, with the absorber layer growth time for single-junction GaAs cells being less than 1 minute while still maintaining an efficiency of 24.5% [13]. In addition, directly growing GaAs thin films on flexible substrates using MOCVD is also a key technology for achieving lightweighting and expanding applications.

6. Conclusion

This paper examines the strengths, weaknesses, and preparation methods of CdTe, CIGS, and GaAs thin films, while comparing the performance of films from typical processes and discussing future optimizations. Overall, the three thin-film cell technologies each have their own strengths: CdTe dominates the ground power station and BIPV markets with its low-cost advantage; CIGS targets differentiated applications with its tunable bandgap and flexible potential; and GaAs serves high-end fields such as aerospace with its ultimate efficiency. In the short term, they are difficult to replace each other. Compared with other processes, CSS for CdTe is relatively simple; by controlling the distance between the substrate and the evaporation source and the oxygen-containing atmosphere pressure, large-sized dense grains can be obtained, making it suitable for large-scale production. Among CIGS preparation processes, the three-stage co-evaporation method facilitates the control of elemental spatial distribution and layer thickness, forming a dense and stable chalcopyrite structure that effectively improves cell optoelectronic performance. Although the selenization method can also prepare large-area CIGS films, it currently inevitably uses toxic H_2Se gas, and suffers from material loss due to high temperatures and Ga segregation, making it not the optimal choice. MOCVD can prepare high-quality GaAs films, but the raw materials are expensive, there is carbon residue, and stringent safety controls are required. The potentiostatic co-deposition method has lower cost, but the film crystallinity is poor and requires annealing optimization. The improvements of the mainstream processes for the three materials are summarized as follows: close-spaced sublimation is dedicated to improving large-area coating uniformity through modified system design, and achieving more precise control of film quality by developing alternating deposition processes and rapid ultra-high-temperature diffusion technologies; the co-evaporation method focuses on process optimization, developing doping technologies such as $(\text{Ag,Cu})(\text{In,Ga})\text{Se}_2$ alloying to enhance cell performance, while promoting compatibility with perovskite top-cell fabrication processes; MOCVD focuses on developing ultra-high growth rate technology to reduce costs, while actively exploring direct growth on flexible substrates to achieve lightweighting and low-cost applications. These results can provide references for the preparation of solar cell thin films and also point out some processes that urgently need improvement.

References

- [1] Liyun, M., Ganhua, F., Min, G., Tao, Y., Liusha, X., Xuejun, Q., & Yuanjin, C. (2022). Journal of the Chinese Ceramic Society, 50(8), 2305-2312.
- [2] Nianguan, Y., & Shanli, W. (2010). CIGS3 present status and developing trend of Cu-In-Ga-Se thin film solar cell. Nonferrous Metal Materials and Engineering, 31(1), 14-18.
- [3] Xin, W., Bin, L., Xianglei, S., Lihua, Z., Lijie, S., Bo, W., & Xunchun, W. (2023). Research on fabrication of high-efficiency multi-junction flexible thin-film gallium arsenide solar cells. In Proceedings of the 17th Shanghai Aerospace Science and Technology Forum and the 2022 Annual Academic Conference of the Shanghai Society of Astronautics (pp. 23-33). Shanghai Institute of Space Power Sources.
- [4] Xinyi, S., Yexiang, X., Yuhao, Z., Zongyan, Z., Dianyu, E., & Jiain, C. (2026). Research progress on key fabrication technology of copper indium gallium selenide thin-film photovoltaic devices. Jiangxi Metallurgy, 1-16.
- [5] Salavei, A., Rimmaudo, I., Piccinelli, F., et al. (2013). Influence of CdTe thickness on structural and electrical properties of CdTe/CdS solar cells. Thin Solid Films, 535, 257-260.
- [6] Ojo, A. A., & Dharmadasa, I. M. (2005). 15.3% efficient graded bandgap solar cells fabricated using electroplated CdS and CdTe thin films. Solar Energy, 2016, 136, 10-14.
- [7] Kang, Y., Park, N. G., & Kim, D. (2005). Hybrid solar cells with vertically aligned CdTe nanorods and a conjugated polymer. Appl Phys Lett, 86, 113101.
- [8] Major, J. D., Proskuryakov, Y. Y., Durose, K., et al. (2010). Control of grain size in sublimation-grown CdTe, and the improvement in performance of devices with systematically increased grain size. Solar Energy Mater Solar Cells, 94(6), 1107-1112.
- [9] Hengtai, Z. (1975). Process exploration for GaAs epitaxial film growth using TMGa and AsH₃. Microelectronics(1), 1-8.
- [10] Jing, L. (2012). Electrosynthesis and characterization of nano gallium arsenide thin films by electrodeposition method (Master's thesis, Taiyuan University of Technology).
- [11] Jundt, P., Zywitzki, O., Modes, T., Baitule, S., Arndt, R., Späth, B., & Siepchen, B. (2026). Formation of configurable uniform CdSeTe thin films by close-space sublimation deposition of multiple alternating CdSe and CdTe layers. Science and Technology of Advanced Materials, 27(1).
- [12] Witte, W., Gutzler, R., Paetel, S., & Hariskos, D. (2026). Measures to improve wide-bandgap Cu(In, Ga)Se₂ solar cells by industry-relevant in-line co-evaporation. Solar, 6(3), 27.
- [13] Lang, R., Klein, C., Ohlmann, J., Dimroth, F., & Lackner, D. (2024). Review on ultrahigh growth rate GaAs solar cells by metalorganic vapor-phase epitaxy. Journal of Vacuum Science & Technology A, 42(2), 020801.