Progress of Physical Vapor Deposition's Application in the Field of Solar Cells

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Abstract. Solar cells are devices that convert solar energy into electricity, and the research on their performance is of great importance to relieving energy shortage. Physical Vapor Deposition (PVD) is a common technology used to enhance the performance of thin films on the surface of solar cells. This article comprehensively explains the application of PVD in the field of solar cells. It first introduces PVD's basic principles and categories, which include vacuum evaporation, sputtering, and ion plating. Then, PVD's specific application in different types of solar cells, such as monocrystalline silicon cells, polycrystalline silicon cells, thin-film cells, and perovskite solar cells, are discussed in detail. Its advantages in improving cell performances, such as improving photo-electric conversion efficiency and enhancing stability, are also analyzed. Meanwhile, the discussion covers the process parameter control, equipment characteristics, challenges faced, and future development trends of PVD in the preparation of solar cells. Research shows that PVD offers effective methods to improve solar cells' performance and reduce their cost with its unique advantages in thin film preparation. It holds broad prospects for the future development of the solar energy industry.

Keywords: Physical vapor deposition; Solar cells; Photo-electric conversion efficiency; Thin film preparation; Solar industry.

1. Introduction

With the continuous rise of the global population, traditional fossil fuel reserves are becoming scarce. It is estimated that global oil reserves are available for about 54 years, while natural gas about 48 years, and coal about 140 years. As a result, people have an urgent need to develop new energy. In 2024, the proportion of global new energy power generation exceeded 40%, with solar power generation accounting for about 20%. As a renewable clean energy, solar power features almost inexhaustible, so its status in the field of energy is gradually rises. Solar cells are the key devices to convert solar power into electricity, and its performance and manufacturing cost are the focus of research. Physical Vapor Deposition (PVD), a common thin film preparation technology, has broad application prospects in solar cells. It helps to improve solar cell performance and to reduce manufacturing costs. Currently, PVD technology is frequently used to prepare perovskite solar cells, heterojunction cells and TOPcon cells. The global market scale of photovoltaic PVD equipment is expected to exceed 15 billion yuan.

This article aims to discuss the principle of PVD technology and solar cells, analyze the current research process of solar cells and the application prospect and challenges faced of PVD.

2. The Development of Solar Cell Performance

It took decades for the efficiency silicon-based solar cells to improve from 1% to 6%. After the 21th century, the efficiency of solar cells constantly increased and gradually exceeded 25%. It is estimated that each 1% increase in the average efficiency of photovoltaics can reduce the cost per kilowatt-hour by 5%-7%. So improving solar cells efficiency is always the research focus [1]. Solar cells can be generally divided into three categories. The first generation refers to monocrystalline silicon and polycrystalline silicon cell. Its technology is relatively mature and its efficiency is 20% to 25%. The second generation refers to thin-film cells, such as CdTe cells and CIGS cells. Its cost is lower and can be produced on a large scale. Its efficiency is about 20%, a little lower than silicon cells. The third generation refers to emerging technology cells, such as perovskite solar cells, quantum dot solar cells, and tandem cells. It has a higher efficiency. For instance, the single-junction perovskite cell studied by Hainan University achieved an efficiency of 27.32%, and the silicon-perovskite tandem solar cell developed by LONGi achieved a conversion efficiency of 34.85%, both breaking world records [1]. However, the third-generation solar cells are still at the initial development stage, which faces several challenges before large-scale production.

3. The Principles and Advantages of PVD Technology

3.1. Vacuum Evaporation

Vacuum evaporation is a process where evaporated materials are heated in a vacuum environment, causing their atoms or molecules to vaporize and escape, and then condense into a film on the substrate surface. As an early developed PVD technology, it features mature technology, easy equipment, high evaporation efficiency, and various materials to choose [2]. Its disadvantages are poor film adhesion, low density, and the lack of suitable materials for depositing high melting-point materials (such as tungsten, molybdenum, niobium, etc.) [3].

3.2. Sputtering

Sputtering coating is a process where the target material is placed on the cathode. By imposing electric field on plasma, high-energy ions can bombard the target material and sputter atoms or molecules off the surface of the target material, which are then deposited onto the substrate surface. Magnetron sputtering is a method that utilizes a magnetic field to improve sputtering efficiency based on traditional sputtering process. It has become a mainstream process in the current coating industry [4]. Sputtering features a wide range of target materials, high film adhesion and high density, which meet the demand of large-scale industrialization.

3.3. Ion Plating

Ion plating is a technique where materials are ionized through arc discharge under a vacuum environment, and then accelerated and deposited onto the surface of a substrate under the influence of an electric field to form a film. It features high coating quality, uniformity and density. However, it costs a lot and the equipment is complex. So it has unique advantages in situations where high film performance is required [5].

3.4. Comparative Analysis

Comparing three PVD technologies, ion plating has the highest adhesion, as shown in table 1. followed by sputtering, and then vacuum evaporation. The film density of vacuum evaporation is lower than the other two. The porosity of the film is higher during vacuum evaporation at low temperatures. The deposition speed decreases from high to low as follows: vacuum evaporation, sputtering, and ion plating.

Table 1. Comparison of Three PVD Technologies

PVD technology	Adhesion	Film density	Film porosity
Vacuum evaporation	relatively bad	low	high at low temperatures
Sputtering	relatively good	high	low
Ion plating	good	high	low

4. The Application of PVD in the Field of Solar Cells

4.1. Crystalline Silicon Solar Cell

In crystalline silicon solar cells, PVD technology can be applied to prepare various thin films and metal electrodes, etc.

Anti-reflection coating can reduce the reflection of light at the surface of solar cells, allowing more sunlight to be absorbed, thus improving the photoelectric conversion efficiency. Relying on PVD technologies like magnetron sputtering, the thickness and reflectivity can be precisely controlled to obtain an anti-reflection coating with high purity and optical performance (such as alumina anti-reflection coating) [6].

A heterojunction (HJT) cell is a battery based on N-type monocrystalline silicon. Transparent conductive oxide (TCO) coating exists on both sides of the battery. PVD is the key process to prepare it. With PVD, TCO coating of high light transmittance, conductivity and density can be made. For instance, the commonly used indium tin oxide (ITO) thin film is made with it.

Producing HJT cells with PVD costs low and has mature process. Suzhou Maxwell Technologies Co., Ltd. collaborated with SunDrive to develop HJT cells with an efficiency of up to 26.4% by integrating PVD into TCO preparation process [7]. Jinchen Renewable Energy Laboratory also combined PECVD technology with PVD technology to develop HJT cells with an efficiency of 25.35% [8].

4.2. Thin Film Solar Cells

In CIGS thin-film solar cells, PVD technology is one of the mainstream processes for producing the back electrode and light absorption layer.

Since the molybdenum back electrode is located at the bottom of CIGS cell, CIGS layer is directly deposited on it, which requires the back electrode to have good conductivity, adhesion and does not chemically react with CIGS layer [9]. There is mature process to deposit molybdenum thin films on flexible substrates through magnetron sputtering.

In the production of light absorption layer, co-evaporation and post-sputtering selenization methods are frequently used. Co-evaporation can evaporate four elements, copper, indium, tin, and gallium on a substrate at the same time. It can obtain high-quality thin films with controllable composition, realize the V-shaped distribution of calcium concentration. The absorption layer produced by the sputtering has lower efficiency, but the process is simple and suitable for large-scale industrial production [9].

4.3. Perovskite Solar Cells

The conductive electrode material for perovskite solar cells is also indium tin oxide, which can be produced by Magnetron sputtering. PVD evaporation technology can be used to prepare electron transport layers, hole transport layers, and perovskite film layers. High-quality Perovskite film can be obtained by controlling temperature and pressure during the PVD process [10]. Compared with traditional high-temperature processes, PVD has a lower temperature requirement and better scalability, which is suitable for large-scale production [10].

Qian Yicheng utilized PVD to passivate perovskite solar cells, significantly enhancing its energy conversion efficiency [11]. In recent years, the collaboration of PVD and atomic layer deposition (ALD) has become new research direction. For example, Jiangsu Leadmicro Nano Technology Co., Ltd. developed PVD plus ALD equipment. It utilizes ALD to ensure the density and uniformity of tin oxide films and uses PVD to ensure the film width. This achieved reliable uniform film formation on a large scale and boosts the industrialization of perovskite solar cells [12].

5. Challenges and Prospects

5.1. Challenges Faced

Although PVD has significant advantages in the field of solar cells, its application still faces several challenges. Firstly, PVD equipment requires high investment, especially those high precision ones, which restricts its popularization among small and medium-sized enterprises. Then, uniform deposition over a large area remains a technical challenge, especially for batteries with complex structures like tandem batteries. It requires further improvements in process parameter and equipment design. What's more, issues of low target utilization rate and material waste during the PVD process need to be addressed by improving the target material structure, sputtering process, and recycling technology.

5.2. Future Development Trends

To further enhance the performance of solar cells and reduce costs, the combination of PVD with other film preparing technologies (such as solution method or CVD) will become mainstream. Meanwhile, the introduction of new types of materials will broaden the appliance of PVD, improve film quality, enhance photo-electric conversion efficiency and stability. Furthermore, benefiting from the rapid development of artificial intelligence, PVD equipment can evolve towards intelligence in the future. AI algorithms helps to optimize process parameters and achieve real-time monitoring and automatic adjustment of film quality.

6. Conclusion

Rely on its precise control ability and broad applicability in thin film preparation, PVD has become one of the indispensable key technologies in the field of solar cells. PVD makes great contributions to improving photo-electric conversion efficiency, enhancing thin film performance and promoting industrialization. This article introduces the basic principle of PVD, discusses its application in solar cells and looks ahead to its future development direction. Despite challenges like high cost, uniformity and low usage rate, its combination with ALD and CVD, innovations in target materials and intelligent development of production equipment will provide continuous impetus for the efficient and green development of solar cells. Though traditional single-junction solar cells have theoretical limit of efficiency, people should try to constantly innovate technology to approach the limit. In the future, it is possible for PVD to make larger achievements in the field of new types of solar cells and make great contribution to global energy transition.

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