

Research On Current Situation and Future Outlook of Solar Cells

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Abstract:

Solar energy, as a clean and sustainable energy source, is regarded as one of the key technologies for renewable energy. Solar cells as the core of photovoltaic technology, can directly convert light energy into electricity through the photovoltaic effect without emitting greenhouse gases during operation, which played a significant role in energy security and environmental protection. This paper systematically reviews the research progress of solar cell technology through literature research, focusing on the working principles, technical characteristics, and application status of crystalline silicon cells, thin-film cells, and emerging perovskite cells. The study finds that crystalline silicon cells dominate the market due to their high conversion efficiency (22%-24%) and stability, but the production process of crystalline silicon can be energy-intensive, and its material is sensitive to temperature. In contrast, thin-film cells have advantages in material consumption and manufacturing energy consumption, but its efficiency improvement faces several bottlenecks and the market thin-film solar is facing remains relatively narrow. Perovskite cells exhibit extremely high efficiency potential (photoelectric conversion rate exceeding 29%), but the material stability problems and lead leakage risks have hindered the commercialization process of perovskite cells. Additionally, the paper explores the role of energy storage technologies, intelligent management systems, and material optimization in promoting the future development of solar technology.

Keywords: solar cells, crystalline silicon, perovskite, thin-film, p-n junction.

1. Introduction

In recent years, with the improvement of production and living standards, the demand for energy has

continued to grow. As one of the most important energy sources, fossil fuels are struggling to meet the increasing demand. At the same time, the environmental damage caused by fossil fuel consumption is

concerning, such as the fact that fossil fuel combustion is one of the main sources of greenhouse gases. Therefore, finding renewable energy solutions has become an urgent task. In 2015, the United Nations proposed 17 Sustainable Development Goals (SDGs), among which Goals 7 and 13 mentioned “ensuring access to affordable, reliable, sustainable, and modern energy for all” and “taking urgent action to combat climate change and its impacts.” Against this backdrop, solar energy is widely regarded as one of the solutions [1].

Solar cells are at the forefront of applying this energy technology. As the cornerstone of photovoltaic technology, they can directly convert sunlight into electricity through the photovoltaic effect without emitting greenhouse gases that drive climate change during operation. In addition to climate benefits, solar energy also contributes to energy security, such as reducing air pollution and creating jobs in the renewable energy sector. However, to fully realize the potential of solar energy, challenges such as intermittency, land use, and material sustainability must be addressed.

Since Bell Labs developed the first practical silicon solar cell in 1954, solar photovoltaics have gradually evolved from a niche technology to a mainstream energy source. According to statistics, the installed capacity of solar cell projects is expected to reach a milestone of over 1 terawatt in the future. The cost of solar modules also significantly reduces over the past decade, which making solar energy the cheapest source of electricity in many regions. This cost reduction, combined with policy incentives and technological advancements, has made solar energy a key enabler of sustainable development.

Research on solar cells has also made significant progress in recent years, with efficiency records for different technologies being continuously broken. With the latest record, the dominant crystalline silicon technology has made great strides, the average component efficiency was 20.3%, and the record efficiency was 26.7% [2]. In contrast, new high-efficiency solar cells, such as wide-band-gap perovskite cells combined with silicon bottom cells, have achieved efficiencies of over 29.15% [3].

Despite these advancements over the decades, solar cells still face several challenges. The construction of solar systems often involves high initial costs. Although the price of solar modules has dropped significantly in recent years, as mentioned earlier, the cost of inverters and other supporting equipment remains high, posing a considerable financial burden for individual users and small to medium-sized enterprises, which may affect their willingness to invest. Additionally, the power generation efficiency of solar systems is highly dependent on natural conditions. During cloudy or rainy weather or at night, solar irradi-

ance drops significantly, leading to a noticeable reduction in power generation. This instability is particularly pronounced in regions with large climate fluctuations or during winter, making it difficult for solar power to provide a stable and continuous electricity supply [4].

Furthermore, specific solar cell technologies face their own obstacles. For example, in terms of stability and durability, perovskite and organic solar cells are prone to material degradation when exposed to environmental stress over long periods. Lead-containing perovskite cells also pose potential lead leakage risks [5], which could threaten ecosystems and human health. This necessitates the development of more effective encapsulation technologies and environmentally friendly materials as solutions. These factors collectively hinder the transition of new solar technologies from the laboratory to the market. To address these challenges, researchers continue to explore solar technologies [6].

This paper provides a comprehensive review of existing solar cell technologies, with a focus on their working principles and classifications. The study aims to fill the academic gap in comparative analyses of different solar cell technologies and incorporates dimensions such as efficiency, cost, stability, and material sustainability into a unified framework for analysis.

2. Working Principles of Solar Cell Technology

As solar energy becomes increasingly important, solar cell technology has gained prominence. Solar cell technology, also known as photovoltaic technology, is a method of directly converting solar radiation into electricity using semiconductors with the photovoltaic effect. Compared to other methods of converting solar energy into electricity, photovoltaic technology offers higher overall efficiency and is a widely applicable renewable energy technology.

Solar cells operate based on the photovoltaic effect, where semiconductor materials absorb photons and generate electron-hole pairs, which are then separated under an internal electric field to produce electricity. This process mainly involves three steps: light absorption, carrier generation, and charge collection. The conversion efficiency depends on the semiconductor's bandgap.

A solar cell is a p-n junction device that converts light energy into electricity through the p-n junction of semiconductor materials. As shown in Fig. 1, the n-type region provides negatively charged electrons from donor impurity atoms, while the p-type region produces positively charged holes from acceptor impurity atoms.

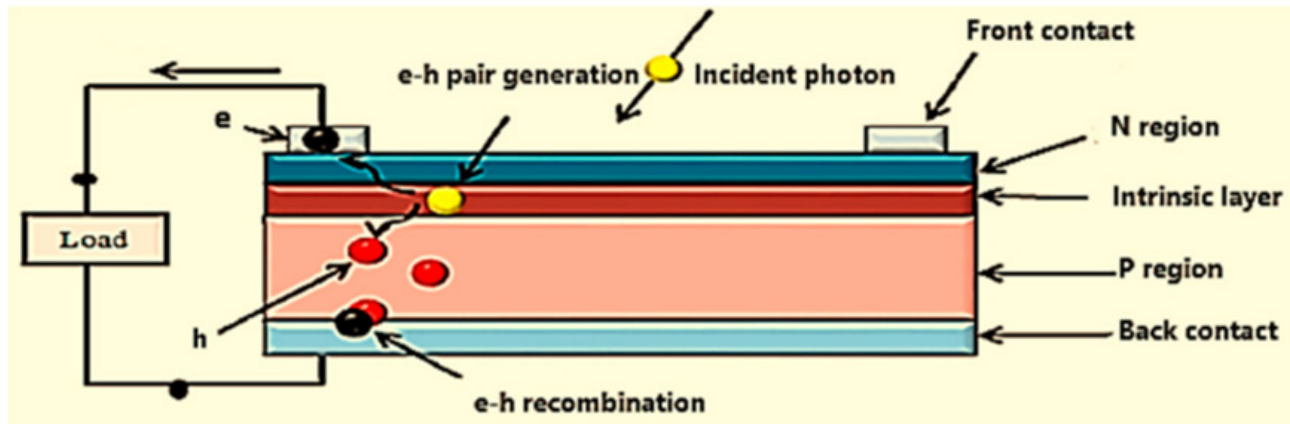


Fig. 1 A p-n junction PV cell [7]

In the photovoltaic effect, when the energy of incident photons ($E=h\nu$) exceeds the bandgap width (E_g) of the semiconductor material, the photon energy causes electrons in the valence band (E_v) to jump to the conduction band (E_c), while simultaneously creating holes in the valence band. If the photon energy exceeds the bandgap, the excess energy is converted into the kinetic energy of electrons or holes, while the remaining energy is dissipated as heat. Subsequently, the photogenerated carriers separate in the external photovoltaic circuit, holes are extracted through the p-type region and electrons through the n-type region, completing circuit transmission before recombination. Finally, the separated electrons drive the external circuit to perform work. It is worth noting that to ensure effective current generation before recombination, the n-type region is typically designed to be thinner than the p-type region to shorten the electron transmission path [7].

3. Literature References

3.1 Crystalline Silicon Solar Cells

Most traditional solar cells are made of silicon. In fact, 95% [8] of the world's solar cells are made of silicon, and most manufacturers prefer silicon for producing solar panels for the commercial market. One of the main reasons is that silicon is abundant in most regions of the world, making it more accessible than other solar cell materials. Crystalline silicon cells are mainly divided into monocrystalline and polycrystalline silicon cells, differing in their silicon wafer fabrication processes. Monocrystalline silicon is prepared using the Czochralski method and has a complete crystal structure, while polycrystalline silicon is produced by directional solidification, resulting in more grain boundary defects but lower costs. Like most solar cells mentioned earlier, crystalline silicon cells operate

based on the photovoltaic effect using a p-n junction. When the photon energy exceeds the bandgap of silicon, electron-hole pairs are generated and separated under the internal electric field to form a current.

The main advantages of crystalline silicon solar cells are reflected in three aspects. First, compared to other competing products, crystalline silicon cells have higher conversion efficiency, as mentioned earlier, with commercial module average efficiencies reaching 20.3%. Second, monocrystalline silicon, as the primary material, exhibits excellent stability, featuring large diameters, relatively low impurity defect concentrations, more uniform distribution, low cost, and high efficiency. Third, silicon is abundant in the Earth's crust, ensuring a stable supply of raw materials.

However, this technology also has significant drawbacks. For example, crystalline silicon solar cells require high-purity raw materials and involve complex production processes. Mainstream methods such as the Czochralski process are energy-intensive, with silicon melting at 1414 °C, requiring heating to this high temperature to melt and prepare it for further processing.

Crystalline silicon cells are also sensitive to temperature. While they can convert up to about twenty percent of incident sunlight into electricity, the remaining unconverted or reflected sunlight may raise the surface temperature of the cell components, affecting heat dissipation. Quantifying power loss due to temperature through temperature coefficients, the actual power output may deviate from the rated capacity by up to 10% [9].

Crystalline silicon solar cells are widely used not only in common household and commercial applications but also in off-grid systems in remote areas due to their reliability and low maintenance costs. For example, crystalline silicon solar panels have been installed in earthquake observation stations in several locations in China, such as in Sheshan, Zhejiang Heng Lake, and Dayangshan. Data

tests have shown stable performance under various weather conditions. On sunny days, the cells can store excess energy in batteries, while on cloudy days, cells can still support load operations with the help of storage systems [10].

3.2 Thin-Film Solar Cells

Thin-film solar cells (TFSCs) have become one of the most promising technological routes for ground and space photovoltaic applications due to their highly flexible device structures and manufacturing processes. This technology exhibits significant diversity: in terms of substrate selection, flexible or rigid substrates can be used, compatible with metal or insulating materials; in terms of fabrication processes, various thin-film deposition techniques such as physical vapor deposition (PVD), chemical vapor deposition (CVD), electrochemical deposition (ECD), and plasma deposition can be employed; in terms of device structure design, the materials and thicknesses of functional layers such as contact layers, buffer layers, absorption layers, and reflection layers can be precisely adjusted to optimize photoelectric performance. This multi-dimensional customizability provides broad engineering design space for improving device performance. However, when scaling up laboratory-optimized processes to large-area

device production, the complexity of the processes and the coupling effects of various parameters increase significantly, requiring stricter process control systems and more comprehensive manufacturing quality management standards [11].

Compared to crystalline solar cells, thin-film materials have much lower absorption coefficients, as shown in Fig. 2. During preparation, thin-film materials require less silicon. Beyond reduced material consumption, thin-film solar technology has significant energy-saving advantages over traditional crystalline silicon photovoltaic production. The energy consumption in the manufacturing process of thin-film solar cells is much lower than that of crystalline silicon technology, making it more environmentally friendly overall. However, thin-film manufacturing processes may still emit greenhouse gases such as nitrogen oxides or fluorine-containing compounds due to high-temperature heating or chemical reactions [12].

While crystalline silicon technology is widely used in large-scale construction projects, thin-film solar cells are favored in small-device industries such as pocket calculators and sports watches due to their lightweight and thin characteristics. Although these industries still rely on thin-film solar cells, demand remains sluggish due to stagnant component efficiency [13].

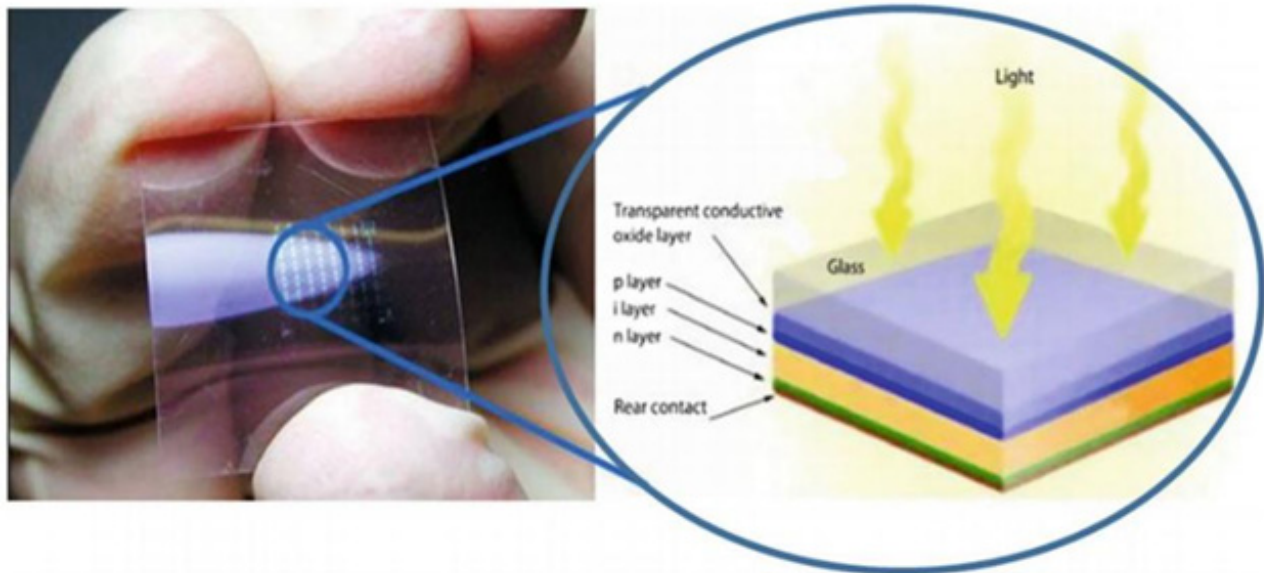


Fig. 2 Thin-film semiconductors and their specific layers [13]

3.3 Emerging Solar Cells

The field of emerging solar cells is still in its growth stage. In recent years, perovskite solar cells have become a topic of increasing interest. Currently, perovskite materials used for solar cells are mainly divided into metal halides and

organic compounds. It is worth noting that the term “perovskite” originally referred to the mineral calcium titanate (CaTiO_3) but has since been extended to describe a class of materials with a similar CaTiO_3 crystal structure. These materials typically have the chemical formula ABX_3 , where the A-site is usually occupied by organic cations

such as CH_3NH_3^+ , coordinating with 12 X anions to form a cubic octahedral framework; the B-site is occupied by metal cations such as Pb^{2+} , exhibiting six-coordination to form octahedral centers; and the X-site consists of halogen anions such as I^- . This unique crystal structure, with its stable octahedral close packing, endows the material with excellent properties such as high light absorption coefficients, low carrier recombination rates, and high carrier mobility. As show in Fig.3; by precisely adjusting the composition ratios of A, B, and X-site ions, the photoelectric properties of the material can be directionally optimized, providing important design insights for improving the conversion efficiency of perovskite solar cells [14].

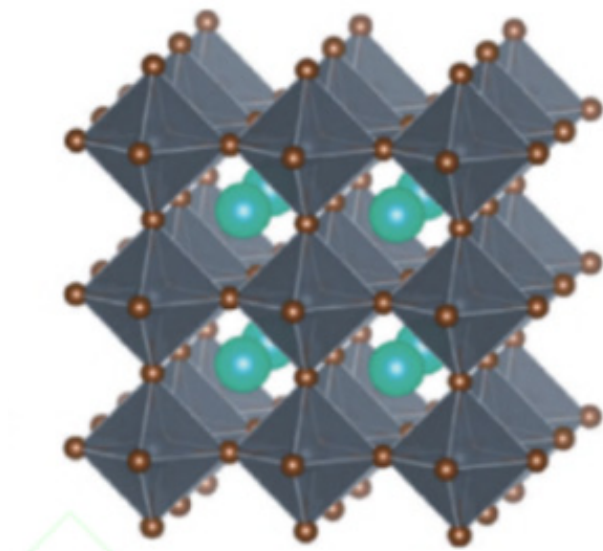


Fig. 3 The 3D perovskite crystal structure diagram [14]

Over the past decade, the highest photoelectric conversion efficiency of perovskite cells has surpassed that of crystalline silicon cells, showing potential for commercialization. Halide perovskite materials are not only suitable for solar cells due to their high sensitivity and fast response but are also widely used in various optoelectronic devices such as light-emitting diodes, field-effect transistors, and photodetectors.

3.4 Outlook

Based on current trends, the future development of solar cell technology will continue to diversify, improve in efficiency, and incorporate intelligence. For crystalline silicon solar cells, future research will likely focus on further reducing manufacturing costs and improving energy conversion efficiency. This can be achieved by optimizing crystal preparation processes and developing new doping technologies to address the high material purity require-

ments and energy consumption during production. At the same time, combining crystalline silicon and thin-film technologies could be a future direction, as this approach may reduce silicon usage while maintaining high photoelectric conversion efficiency.

Additionally, most solar systems face the challenge of significantly reduced photoelectric conversion rates at night or in regions with large climate variations. Developing new energy storage materials and intelligent energy management systems can effectively address the intermittency of solar power generation. Introducing artificial intelligence technology can also enable intelligent operation, maintenance, and fault prediction for photovoltaic systems, significantly improving reliability and power generation efficiency.

4. Conclusion

This paper's systematic study of solar cell technologies reveals that current photovoltaic technology has formed a landscape dominated by crystalline silicon cells, supplemented by thin-film cells, with rapid development in emerging cells. Crystalline silicon cells occupy the mainstream market due to their high efficiency and stability but face challenges in cost reduction and temperature sensitivity. Thin-film cells have advantages in materials and processes but need to overcome efficiency bottlenecks to expand their market. Emerging cells like perovskites show great potential, but their industrialization is still constrained by material stability and fabrication processes.

Therefore, in the future, the industry must strengthen fundamental research to deepen the understanding of the relationship between material structure and performance. Emphasis should be placed on industry-academia-research collaboration to accelerate the translation of laboratory achievements into practical applications. At the same time, the study highlights the lack of lifecycle assessments for materials in the field, which could help promote the green and sustainable development of photovoltaic technology.

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