Proceedings of the 2023 International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/23/20230664

Comparison and evaluation of different types of solar cells

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Abstract. Solar energy is commonly seen as a sustainable and clean energy source that can help reduce fuel pollution and address the growing energy demand of mankind due to the rapidly increasing population. Solar energy can be transformed into thermal heat and electrical power through the processes of photothermal and photoelectric conversion. Over the years, research has resulted in a range of solar cells based on photovoltaics, which can be classified into three generations. The first and second generations have been widely adopted in public infrastructure, enterprises, and homes as crucial sources of clean energy. Despite advances, there are still issues like low efficiency, high cost, instability, and manufacturing technology that prevent solar cells from taking the lead in energy supplement and replacing conventional fuel sources. In this paper, the advantages, disadvantages, current state, and future trends of the various solar cells, in particular those based on perovskite, will be discussed.

Keywords: solar cell, perovskite solar cell, sustainable energy, power efficiency.

1. Introduction

The sun sends a copious amount of heat and radiation to our planet Earth every day, known as solar energy. In 2012, the sun is said to send almost four million exajoules(1 EJ = 10^{18} J) of energy toward the earth every year, of which 50,000 exajoules are said to be easily harvestable [1]. As conventional fossil resources like coal oil and gas are running out, certain conflicts and commercial wars broke out for the limited resource. New technology based on solar energy is promising to solve such problems with an adequate energy supply. Another major advantage of solar energy is that it is eco-friendly and renewable. The rapidly growing global population has resulted in a range of social and economic challenges, including the need to balance energy consumption and environmental protection, particularly in several developing countries. It is alleged that the generation of energy from traditional carbon fuels like coal and gas pollutes the air, water, and soil, resulting in acid rain, hindering agricultural productivity, and destroying forested areas. However, renewable technology plays an important role in many developing countries and can alleviate the harmful results caused by conventional fossil fuels. A desirable and advantageous source of renewable energy is solar energy because of its high availability and accessibility for the general public. It is abundant in supply, making it a reliable and long-lasting source of energy [2]. The direct conversion of solar energy to heat and electricity is made possible by thermal sensors and photovoltaic cells, which are solar energy's predominant applications and key competitive advantages. Additionally, compared with current production technologies, the solar cell requires substantially fewer human expenditures, which implies minimal maintenance and no supervision. The solar cell also produces no noise during operation

DOI: 10.54254/2755-2721/23/20230664

compared to other pumping devices [2,3].

There are three generations of solar cell innovation and development. The initial wave of solar cells is composed of crystalline solar cells made from silicon wafers. The greatest benefit of these cells is their high power conversion efficiency(PCE). On the other hand, high efficiency can be realized at the cost of high expense in manufacture because highly purified silicon wafers are required. Thin film solar cells, or the second generation of solar cells, appeared with much lower expenses and a slightly lower yield than first-generation solar cells, which have received an explosion of interest in both academia and industry. Moreover, the materials chosen for the second generation are more varied and flexible without the restriction of crystal. Dye-sensitized, polymer-based, concentrated, and nanocrystal-based solar cells comprise third-generation cells, most of which are still in the research phase and have not yet been commercialized due to their current efficiency, stability, and lifespan not yet meeting commercial standards [3]. However, theoretically, this new generation of solar cells can offer a satisfactory PCE and is promising to resolve the energy supply problem. Recently, perovskite solar cells (PSCs) have become a topic of great interest among researchers due to their remarkable development and considerable enhancement of their PCE. A long-lasting and durable perovskite solar cell with solid-state construction was initially reported to have a high PCE of 9.7%, which increased to an impressive 17.9% within just two years [4]. This success exceeds that of any other solar cell. Figure 1 displays a classification of three different solar cell generations.

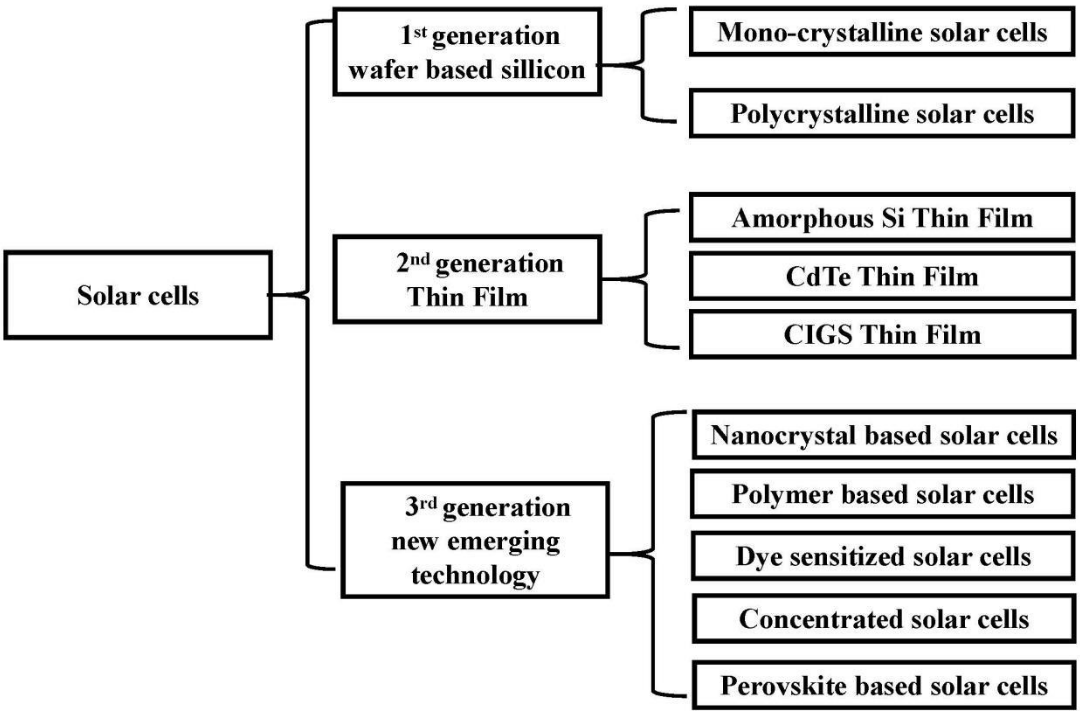

Figure 1. Classification of the three solar cell technology generations.

Solar cells operate by harnessing the energy of light through a three-step process. First, light is absorbed to create load vectors, i.e., electrons (n-type) and holes (p-type). Second, divide charge carriers. Finally, collect the charge carriers at the electrodes, which produces a potential contrast across the p-n junction. This voltage difference, generated by visible radiation, can be utilized to perform work [2]. With photovoltaic (PV) technology, solar energy is able to be directly converted into direct current, and then into alternating current by an inverter. A variety of elements have an impact on PV cells' efficiency, such as temperature, sunlight exposure, dust, and inverters [3]. As temperature rises, the efficiency of conversion diminishes. This is mainly due to the increased concentration of carriers, which causes greater rates of internal carrier recombination. This paper aims to give a review of three generations of solar cells, especially perovskite cells, followed by evaluations

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and prospects of different kinds.

2. Solar cells in different generations

2.1. First generation of solar cells

Crystalline silicon wafer-based solar cells are the first generation of solar cells, which may be classified as silicon-based monocrystalline and multi-crystalline solar cells. Monocrystalline solar cells are typically produced using the Czochralski process, which requires precise manufacturing techniques, resulting in a relatively high cost for this type of solar cell. However, its high efficiency is a major competitive edge over most other kinds of solar cells. In some special tasks, such as the tasks in the space, high efficiency speaks louder than cost. Monocrystalline solar cells are usually black in color, as this helps to enhance their light absorption capabilities [5]. The highest confirmed PCE for single crystal solar cells is claimed to be as high as 26.1% and can be higher as 27.6% with a concentrator system [6]. Polycrystalline silicon solar cells are created by combining various crystals. Cooling a graphite-filled mold is essential for these cells, making them more cost-effective than monocrystalline ones. Multicrystalline solar cells have achieved a confirmed maximum PCE of 23.3%, which is slightly lower than that of single-crystal cells [6].

2.2. Second generation of solar cells

Second-generation solar cells are built on the foundation of thin-layer PV technology. The light-absorbing layer of silicon-wafer cells is around 350 micrometers thick, whereas thin-film cells have a layer that is only 1 micrometer thick [7]. Thin-layer cells are more cost-effective than silicon wafer cells, but the efficiency of the former is lower. Thin-film cells can be broadly categorized into three main families: amorphous silicon, CdTe, and CIGS. The highest confirmed PCE for each type is reportedly 13.8%, 23.3%, and 23.4%, respectively [3,6]. Low-temperature process can be implemented for amorphous silicon cells, thus permitting flexible substrates, such as low-cost polymer to be used. During manufacturing, the reverse side of the substrate is coated with doped silicone [3]. Amorphous silicon cells' major drawback is their instability and relatively low efficiency.

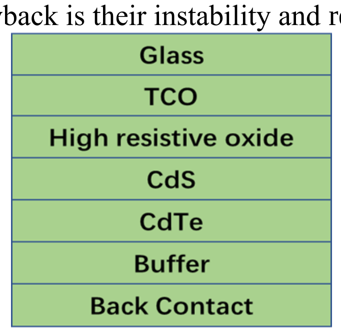

Figure 2. Schematic of CdTe solar cell[8].

Compared to other thin-layer solar cells, CdTe is more cost-effective and economically viable. The manufacturing process for CdTe-based solar cells typically involves two main steps. Firstly, with polycrystalline materials used, the cells are synthesized and glass is usually selected as the substrate. Secondly, the cells go through a deposition process, in which the substrate is coated with multiple layers of CdTe using economical techniques [3]. However, there is a debate over the use of cadmium in these cells. Several people believe that environmental issues have been caused by the toxic properties of cadmium. and their recycling can be highly expensive [2,5]. On the other hand, there are some who argue that at least when it comes to acute exposure, CdTe is less toxic than elemental cadmium. Additionally, in 2015, CdTe Photovoltaic modules have been suggested as the most eco-friendly among other current uses of cadmium [5]. Figure 2 displays an illustration of a CdTe solar cell.

The copper-indium-gallium-selenium (CIGS) solar cells bear the name of the four elements used in their construction. In order to manufacture these solar cells, a glass or plastic backing is deposited with a thin layer of CIGS. The front and back electrodes are to collect current [5]. CIGS can be deposited on a flexible substrate due to their thin layers and developments in low-temperature deposition, which are advantageous for generating highly pliable and lightweight solar panels [5].

2.3. Third generation of solar cells

There are still testing and research needs for third-generation solar cells, which include dye-sensitized, polymer-based, nanocrystal-based, and concentrated solar cells [3]. Dye modules are used between the different electrodes to form the dye-sensitized solar cells, which are composed of a dye sensitizer, a redox mediator a semiconducting electrode, and a counter electrode. The advantages of these cells are low cost, flexibility, transparency, and simple conventional process methods, such as printing. The biggest challenge is deterioration and stability which still need research and improvements. The highest confirmed PCE of these cells is claimed to be 13% [6].

Thin functional layers that are connected in sequence comprise polymer-based solar cells, which have polymer substrates [9]. The function principle of polymer solar cells is known as PV effects, which is the same as other cells [2].

Nano-technology-based solar cells come in three types: quantum dot, hybrid organic, and dye-sensitized solar cells [10], among which the first ones are usually referred to as nanocrystal-based solar cells [3]. Quantum dots are clusters of semiconductors at the nanoscale, possessing remarkable optoelectronic properties that can be modified by quantum physical effects dependent on the size of the cluster [10]. The combination of different sizes of the quantum dot can expand the absorption spectrum, enhancing efficiency. In addition, quantum dots possess remarkable optoelectronic properties that make them well-suited for use in solar cells. They are capable of inducing multiple electron-hole pairs with a single photon of the solar spectrum, whereas conventional solar cells can only generate one electron-hole pair per photon, resulting in lower electricity output and efficiency [10]. The highest confirmed efficiency of quantum dots solar cells is 18.1% [6]. A diagram of a QD layer appears in figure 3.

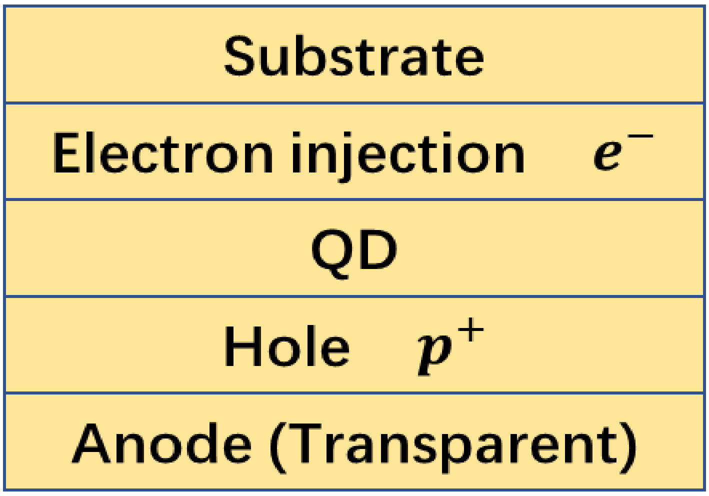

Figure 3. A diagram of the QD layer [11].

Concentration solar cells are designed to collect tremendous solar energy and concentrate it onto a small area with a specific arrangement of large mirrors and lenses [12]. The concentration system can combine with several kinds of cells, like single-crystal silicon and multijunction solar cells. In the last several years, there has been a growing belief that multijunction solar cells represented the future of high-efficiency solar technology, and subsequent developments have largely supported this view. It was claimed that multijunction solar cells enjoyed the highest confirmed conversion efficiency as high as 47.6% in 2022 [6]. Figure 4 displays a diagram of a concentrated solar cell.

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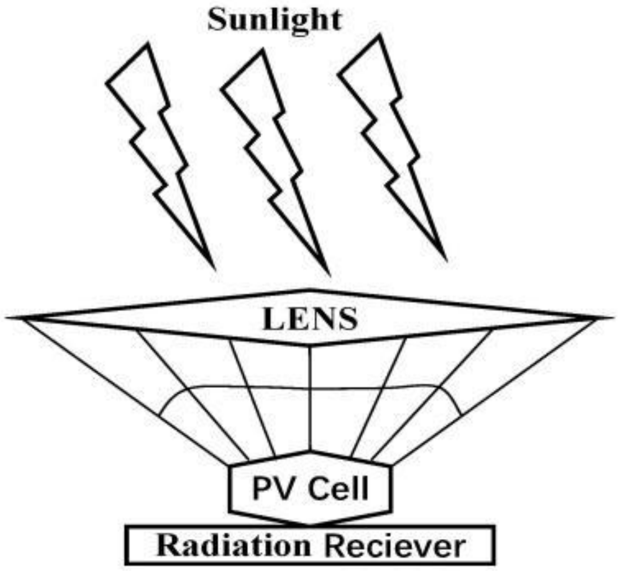

Figure 4. Diagram of a concentrated solar cell [3].

2.4. Perovskite solar cells

These cells emerge as a new kind of solar cells in the third generation with tremendous potential for their boost in power conversion efficiency within a decade. Perovskite materials have several benefits, such as high carrier mobility, high extinction coefficients, and small band gaps [13]. Moreover, PSCs are appealing due to their straightforward fabrication process and financial reasons. PSCs were first reported in 2009 using liquid electrolytes, but they had low efficiency, only 3.81%. In 2012, liquid electrolytes were substituted for spiro-OMeTAD, resulting in a surprising increase in efficiency to 9.7% [14]. After carrying out extensive research that revealed the hidden mechanism responsible for exceptionally high PCE and a range of manufacturing methods for perovskite films, the PCE of PSCs surged significantly from 9.7% to 20.1% within two years [13]. The highest confirmed efficiency of PSCs is claimed to be 25.7% [6]. In the past several years, most research on PSCs has focused on improving their efficiency, however, studies on their stability, which is a primary factor hindering their commercial use, have lagged behind.

Perovskite is defined by the formulation of ABX_3, in which A and B are cations and X is an anion that is generally halogenated such as Cl, Br, and I. Organometric halide $MAMX_3$(MA: CH_3NH_3, M: Pb or Sn, X: Cl, Br or I) is a crucial material for perovskite solar cell production, which has received significant attention in recent research. $CH_3NH_3PbI_3$ and $CH_3NH_3SnI_3$ are common materials used, with a direct band gap of 1.50-1.55 eV [15]. For panchromatic absorption, however, a bandgap of about 1.55eV is insufficient because the wavelength of absorption is only 800nm [4]. There are two techniques to modify the band gap. (1)Cation MA can be replaced by other organic cations. Despite the change can not modify the band gap directly, it can alter the M-X-M angle and band length which can tune the band gap. (2)Directly mutate the M-X bond with the replacement of M or X. For instance, when Sn^{2+} partially substitutes the Pb^{2+}, band gap adjustments could range from 1.55 eV to 1.17 eV, which indicates that the band gap can be any value between 1.55 eV and 1.17 eV as long as the proper ratio of Pb^{2+} to Sn^{2+} is satisfied. The principle of this method is to change the M-X connection can directly affect the valence band's highest and the conduction band's lowest [4,15]. A schematic figure of the perovskite crystal structure is depicted in figure 5.

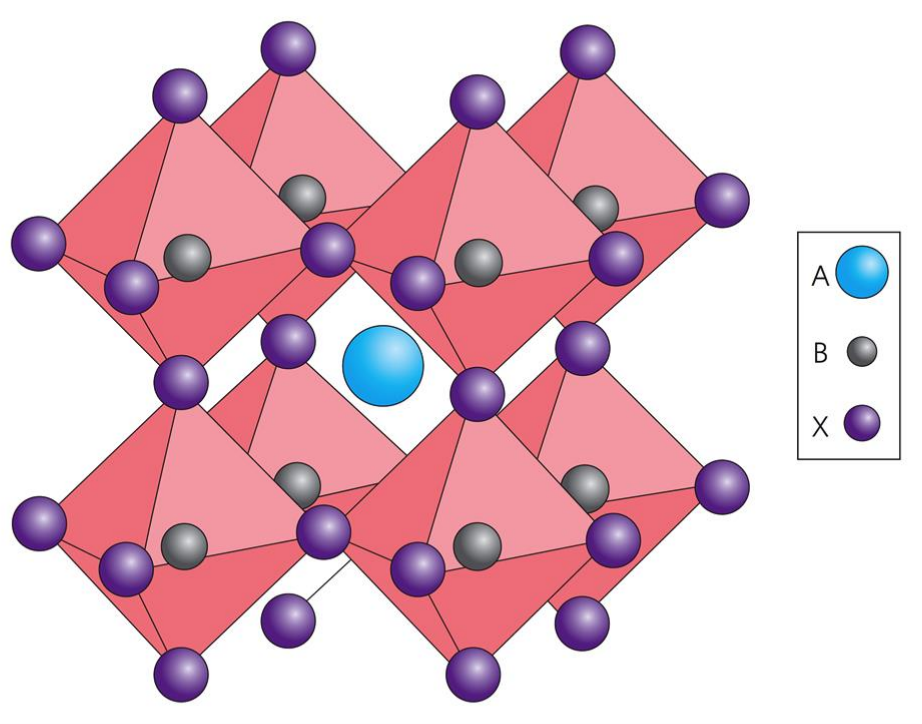

Figure 5. Cubic perovskite crystal structure [16].

There are two main layouts for perovskite solar cells: n-i-p and p-i-n with mesopore or planar heterojunction. Cells such as n-i-p, also known as conventional cells, are built with a sequence of glass, transport conductive oxide layers (TCO), electronic transport layer (ETL), perovskite, hole transport layer (HTL), and metal. On the other hand, the inverted cells, also known as p-i-n type cells, are constructed with a layer sequence of glass, TCO, HTL, perovskite, ETL, and metal. It should be noted that the layer sequence is inverted between the two types of cells. It is worth mentioning that TiO_2 (titanium dioxide) is crucial for augmenting the efficiency of PSCs, which may increase carrier concentration and decrease the working function of the Indium Tin Oxide (ITO) electrode [13]. However, the existence of TiO_2 is associated with corrosion happening in the PSCs which does harm the stability of cells and finally decreases the efficiency. The researchers used Al_2O_3 as an alternative to TiO_2, which is beneficial in improving the stability of solar cells.

The preparation methods of perovskite film include solution processing techniques and vapor deposition techniques. Despite the latter technique can process a more uniform surface, the solution processing techniques are dominant due to their lower cost and suitability for mass production. The solution processing techniques can be divided into sequential deposit techniques into one or two steps [15]. In terms of morphology control, which is an essential factor influencing the efficiency of cells, the one-step method performs better [15]. In order to put PSCs into commercial utilization, there are two open issues required to be further studied and solved: long-term stability and J-V hysteresis. The instability of PSCs might be attributed to UV light, solution process, temperature, oxygen, and moisture [13]. As an abnormal behavior observed in the photocurrent-voltage (J-V) curves of perovskite materials, the J-V hysteresis is possibly attributed to three potential factors: imbalanced charge collection rates, ion migration, and ferroelectricity [15].

3. Evaluation and prospect

Table 1 provides a comparison of the various types of solar cells. The first-generation (crystalline silicon) solar cells enjoy a relatively high PCE of 26.1%. However, the cost of production is high due to the need for pure crystalline silicon. On the contrary, 2nd generation solar cells are more commercially viable with a slightly lower efficiency due to the use of low-temperature and

DOI: 10.54254/2755-2721/23/20230664

conventional manufacturing processes. This allows for the use of more flexible and cost-effective materials in the construction of solar cells. However, certain environmental concerns require further discussion and detailed regulations due to the presence of toxic cadmium used to produce affordable CdTe thin-layer solar cells. At present, third-generation solar cells exhibit promising potential for achieving high conversion efficiency at a lower cost through advanced manufacturing technologies. For example, with a concentration system applied, multijunction solar cells can reach the highest power conversion efficiency of 47.6%. PSCs show a rapid improvement in efficiency within a decade. However, further research is still required to fully explore their capabilities, such as issues of J-V hysteresis and instability of PSCs still need exploration, which are decisive factors to put these cells into commercial use.

As for the market proportion of different solar cells, crystalline silicon solar cells account for over 90% of the world's solar panel output, with thin-film solar cells accounting for the remaining 10% as of 2021 [3]. Despite the fact that crystalline silicon solar cells will continue to retain a sizable market share in the future due to their established foundation, third-generation solar cells are expected to gradually replace them and provide higher conversion efficiency at a lower cost. In particular, perovskite exhibits excellent power conversion efficiency while being very cost-effective in terms of materials [4].

Table 1. Evaluation and comparison of different solar cell technologies.

Solar Cell Technology	Highest Confirmed PCE (%)	Advantage	Disadvantage	Current State
Mono-crystalline	26.1	Relatively high efficiency	The expensive and precise man-ufacturing process	Account for over 90% of the global solar panel market
Poly-crystalline	23.3			
Amorphous	13.8	Economically feasible	Unstable and low efficiency	Account for the remaining 10% of the global solar panel market
CdTe	23.3		Toxic Cd	
CIGS	23.4			
Nanocrystal	18.1	Promising to realize high efficiency at a low cost with the advanced manufacturing process	Efficiency and stability issues haven't reached the commercial standard	More demonstrations are required to be put into commercial use
Dye-sensitized	13			
Multijunction with concentration	47.6			
Perovskite	25.7	Potential in high efficiency	J-V hysteresis and instability	

4. Conclusion

Solar energy is a significant and promising form of sustainable energy that has vast energy supplement capabilities and various applications. For instance, solar photovoltaic systems for electricity generation can be grid-connected or used in buildings, transportation, and remote locations. The first-generation solar cells are crystalline silicon-based solar cells that offer high efficiency due to their well-established research foundation and mature production technology. In addition, these cells are durable, long-lasting, and require minimal maintenance, thus dominating the global solar panel market. However, their expensive cost and limited flexibility are major disadvantages. The second generation of solar cells, made from materials such as amorphous CeTd and CIGS, has taken the majority of the remaining market as they meet the economic demand and are suitable for installation in areas with high radiation like deserts. Emerging third-generation solar cells aim for higher efficiency, cost-effectiveness, and sustainability, although further demonstrations are needed especially for the domain of durability, manufacturing, stability and lifespan. These cells include nanocrystal, dye-sensitized, perovskite solar cells. Perovskite solar cells, for example, are highly efficient, yet research must overcome issues with J-V hysteresis and long-term stability in order for them to be put into commercial use. There is a need for fundamental research to help solve such problems. The solar cells

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market has a promising future as the world increasingly adopts renewable energy sources, and various government policies and incentives support the development of clean energy technology. The trend of solar cell development is towards more efficient, cost-effective, and sustainable technologies. As perfect theory and advanced process technologies emerge, the first two generations of solar cells should be gradually replaced by third-generation solar cells.

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