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The Sustainable Development Trend, Progress and Challenge of Solar Cells

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Abstract: The current development of solar cells indicates that this field is experiencing rapid technological progress and market expansion. Various types of solar cells, from traditional silicon-based ones to emerging thin-film, dye-sensitized, perovskite, and organic solar cells, are constantly being developed to improve efficiency, reduce costs, and meet different application needs. While silicon-based solar cells remain one of the most mainstream types on the market, researchers are exploring third-generation photovoltaic devices such as multi-junction series cells, intermediate band gap cells, multiple exciton-generating cells hot carrier cells thermal-light photovoltaic solar cells to further bolster efficiency and reduce costs. These new solar cell technologies theoretically offer higher conversion efficiency and are anticipated to replace traditional silicon-based ones in the future. Advancements in the technology of solar cells mainly involve continuous progress and innovation in materials' development structural design manufacturing processes-from early silicon-based designs to today's thin-film arrays. Each generation is developed with the goal improving efficiency lowering costs; subsequently leading to recent developments in organic and perovskite arrays currently under exploration creating a final product at a lower price. At present, current attention within development primarily lies towards material components advancement efficiency maximization. Cost reduction strategies large scale production Although faced with certain obstacles; through consistent research proving their overwhelming effectiveness; implications for widespread use suggest performance. Overall prospects within Solar energy appear limitless.

Keywords: Solar Cells; Sustainable Development; Challenge.

1. Introduction

From the perspective of technological progress, the variety and efficiency of solar cells have improved significantly over the past few decades. Due to their excellent thermal properties and high efficiency, solar cells have gained attention [1, 2]. New materials and methods have since been created, including perovskite solar cells, organic solar cells and thin-film solar cells made of copper indium gallium selenide (CIGS), and these new technologies have shown huge potential in boosting the efficiency of solar cells and reducing costs. Perovskite solar cells are widely regarded as strong contenders for the next generation of low-cost, high-efficiency photovoltaic technologies due to their cost-effectiveness and high efficiency. The increasing demand in the market is also a crucial factor in driving the advancement of solar cells. In light of the global energy crisis and growing environmental awareness, there is a rising need for renewable energy. As a clean and sustainable energy source, the market demand for solar energy continues to escalate [3]. In addition, the price of solar cells is gradually decreasing, making the cost of electricity in many regions more competitive with traditional energy sources [4]. Currently, various factors significantly influence the efficiency and performance of solar cells, such as the band gap of materials, the generation and composite mechanism of electron-hole pairs, the interface state, and the device structure. The open circuit voltage (VOC) of organic solar cells (OSCs) is impacted by the donor-receptor material system, with the effective band gap (Egeff) typically considered as the upper limit of VOC [5]. Furthermore, the disparity between the open circuit voltage and optical band gap (Eg)e in organic solar cells serves as an important parameter for determining its performance [6]. It is evident that in order to enhance organic solar cell efficiency, there is a need to further reduce the gap between Eg and VOC. Additionally, I would like to discuss challenges encountered in developing solar cells while also highlighting advancements made by scientists at each stage of their research (each generation of solar cells) and explaining ongoing development obstacles we are working to overcome.

2. First Generation Cell

It is a huge breakthrough and development in the battery field since modern times. It is mainly based on monocrystalline silicon and polysilicon materials. The development of these cells marked the preliminary stage of photovoltaic technology, and they have an important place in history as they were the first type of solar cell to be commercialized.

2.1. Monocrystalline silicon of the solar cells

Monocrystalline silicon solar cells are made of extremely pure silicon, which is cut from large ingot by a technique called the Czochralski process. While this process does require a significant amount of energy to purify the silicon and can be costly, monocrystalline silicon solar cells are widely praised for their high efficiency. However, due to the expensive materials and manufacturing processes involved, this type of solar cell is not suitable for mass production.

2.2. Polycrystalline silicon solar cells

It is made from small pieces of silicon crystals that are melted and cast into ingots, which are then cut into sheets. Compared to monocrystallion silicon, polysilicon costs less, but the efficiency is usually slightly lower than monocrystalline silicon. The majority of the crystalline silicon used in the first generation of solar cells was relatively efficient, but it was highly expensive to purify the silicon. In addition to this, the primary drawbacks of the initial solar cell generation include material defects, interface defects, electron-hole pair recombination, thermal stability and humidity stability problems, and limited spectral response range. These defects limit the performance and efficiency of solar cells, so further research and improvement measures are needed to overcome these problems. The initial focus of solar cell applications was primarily on utilizing silicon materials to convert solar energy into electricity. These included the use of monocrystalline silicon, polysilicon, and amorphous silicon solar cells, which were among the earliest forms of photovoltaic technology. The primary applications for these first-generation solar cells were in electricity production, space exploration, portable power, indoor photovoltaic systems, and various other fields. Although the first generation of solar cells has made remarkable progress in terms of technology and applications, they also face some challenges, such as high cost, relatively low efficiency, and environmental impact. With the development of new materials and technologies, more efficient and lower cost solar cells may emerge in the future to meet the growing global energy demand.

3. The Second Generation of Solar Cells

3.1. Composition

It is mainly based on thin-film manufacturing technology, which has lower materials coats and less materials requirements than the first generation of monocrystalline silicon and polysilicon. These characteristics make the second generation of solar cells have a significant reduction in cost. The second generation of solar cells marks an important stage in the advancement of photovoltaic technology, and the thin film manufacturing process that serves as the foundation for this generation of solar cells. Compared to the first generation of monocrystalline and polysilicon based solar cells, the second one achieves significant cost reductions due to their low-temperature manufacturing process and fewer material requirements [7].

3.2. Hydrogenated Amorphous Silicon (a-Si: H)

In second-generation solar cells, it is one of the most mature thin-film technologies currently in development, although there are inherent problems with photoinduced degradation, which limits further improvements in its efficiency. However, by optimizing the structure and materials, such as the successful deposition of hydrogenated nancrystalline silicon (nc-Si:H) films at high deposition rates using RF PECVD technology with high pressure and high power, has shown potential in improving stability and reducing degradation [8].

3.3. The Defects of the Second Generation Solar Cells

3.3.1. Material and Structural Inhomogeneity

The Kesterite CZTS-SE solar cells exhibit structural inhomogeneity as a result of the limited-phase stability of their quaternary phases and defects. This lack of uniformity may cause fluctuations in local open-circuit voltage and high levels of carrier recombination, ultimately impacting the performance and repeatability of the device [9].

3.3.2. Effects of Point Defects and Imporities

Bi_2S_3 solar cells' intrinsic point flaws restrict their photovolatic efficiency, such as S-vacancies and S-gaps, which create deep defect levels in the band gap, resulting in non-radiative recombination of electron-hole carries and a shortened minority carrier lifetime [10].

3.3.3. Defects in lead iodide (PbI_2)

Lead iodide (PbI_2) is a precursor and a common residue as one kind of lead halide perovskite solar cells. Defects such as iodine vacancies and iodine gaps created during the synthesis process can affect the energy alignment and efficiency of the solar cell [11]. These defects from defective energy levels in the band gap that become storage or absorption centers for electron/hole carries.

Challenges facing second-generation solar cells include material and structural inhomogeneity, the effects of point defects and impurities, defects in lead iodide, dislocations in polycrystalline silicon solar cells, non-radiative recombination, electroactive traps, and metastable defects. The existence of these problems has seriously affected the performance and stability of solar cells.

3.4. Production Process of the Second Generation

The production progress of the second generation solar cells mainly focuses on improving efficiency and reducing costs. The second generation of solar cells include amorphous silicon hydride (a-Si:H), cadmium telluride (CdTe) and copper indium gallium selenium ($Cu(In,Ga)Se_2$ or CIGS) thin film solar cells [8]. These materials achieve higher stability efficiency by optimizing the structure and thickness. In terms of efficiency, solar cells of a-Si:H, CdTe and CIGS materials have reached the maximum efficiency of 9.134%, 20.776% and 23.03% respectively [12]. In addition, for $Cu(In,Ga)Se_2$ solar cells, research is also exploring how to trigger the development of the next generation through new strategies.In terms of cost, the goal is to reduce production costs by improving the manufacturing process and using more economical materials. In addition, some emerging technologies are being studied to for improving the performance, like quantum dot(QD) and multi-quantum well (MQW) solar cells, which are expected to increase efficiency to 24.8% and 25.8% [13]. At the same time, hybrid solar cells that combine conjugate polymers and semiconductor nanocrystals, also show good development prospects.

In brief, the second-generation solar cells have made significant progress in enhancing efficiency and reducing costs. Furthermore, future research will continue to explore novel materials and technologies in order to achieve even higher performance and wider applications. Thank you for considering these points.

4. The Third Generation of Solar Cells

This technology is based on a solution of semiconductor organic macromolecules, inorganic nanoparticles, or a combination of the two. These innovative technologies encompass polymers such as fullerenes, mixed polymers, and perovskite solar cells, all of which have significantly enhanced photovoltaic conversion efficiency. The aim of third-generation solar cells is to surpass the Shockley-Queisser limit and achieve high power conversion efficiency at a low production cost.

4.1. Categories of Third Generation Solar Cells

Dyesensitized solar cells, perovskite-based solar cells, organic photovoltaic cells, quantum dot solar cells, and series solar cells are examples of third-generation solar cell types. These solar cells use a variety of materials and technologies to maximize the sunlight spectrum range, which improves power conversion efficiency. Currently, perovskite solar cells are the strongest contender in the third generation of solar cells due to their rapid technological growth and significant improvement in photoelectric conversion efficiency from 3.9 percent in 2009 to 25.8 percent in 2021 [14].

Third generation solar cells can be divided into several main categories: organic-fullerene solar cells, hybrid polymer solar cells, perovskite solar cells, quantum dot solar cells, and multi-junction solar cells. In addition, there are a number of other technologies and concepts that are being explored, as multiple exciton solar cells, hot carrier solar cells, and dye-sensitized solar cells. Each of these technologies has its own advantages and challenges and requires further research and development to achieve commercial breakthroughs.

The objective of the third generation of solar cells' development is to surpass the efficiency and cost effectiveness of traditional silicon-based solar cells, while providing a wider spectrum absorption capacity and higher energy conversion efficiency [15]. Despite some technical and environmental challenges, with continued research and innovation, third-generation solar cells are expected to make an important contribution to future renewable energy solutions.

4.2. Main Problems

4.2.1. Long-term Stability Issues

Although third-generation solar cells have made significant advances in efficiency, their long-term stability remains a major challenge. Perovskite solar cells are prone to degradation under the influence of ultraviolet light and humidity, while organic solar cells face photooxidation and electron capture problems, resulting in polymer conjugated structure destruction and bleaching.

4.2.2. Cost Issues

Third-generation solar cells are made to have a high power conversion efficiency at a cheap production cost, yet, in practical applications, the commercialization of these new technologies still faces cost issues. Especially for those solar cells that require complex manufacturing processes or use expensive materials, the cost may be higher than traditional silicon-based solar cells [16].

4.2.3. Environmental Impact

Although solar cells are a clean and renewable energy technology, the environmental impact of their production and disposal needs to be further studied and improved. For example, certain materials can be harmful to the environment, so more environmentally friendly alternative materials and technologies need to be developed.

5. Further Trends

5.1. Continuous Improvement of Lithium-ion Battery Technology

Although lithium-ion battery technology is very mature, there is still room for further improvement. This includes improving energy density, optimizing costs, safety, and power capabilities. Research on new electrode materials and solid electrolytes is ongoing to achieve these goals.

5.2. Reduction of Battery Cost

Although lithium-ion batteries are already relatively low in cost, further reducing the cost is still an important research direction. This includes developing low-cost synthesis methods, optimizing materials and manufacturing processes, among others.

5.3. Solid-state Battery Development

Solid-state batteries are seen as a logical follow-up to lithium-ion batteries, which use solid-state electrolytes instead of traditional liquid electrolytes, promising to solve some of the current safety and performance problems faced by lithium-ion batteries. However, the commercialization of solid-state batteries still faces uncertainties in material selection, component concepts, and production routes.

5.4. Battery Recycling and Reuse

With the increasing use of batteries, battery recycling and reuse has become an important issue. By recovering the internal chemical composition and reusing it, the life cycle of the battery can be extended while reducing the environmental impact.

5.5. Exploration of Next-generation Battery Technology

In addition to lithium-ion batteries, researchers are also exploring other types of battery technology, such as aluminum-based secondary batteries, sodium-ion batteries, and sulfide-based batteries. These new technologies are designed to reduce material costs, increase energy density and environmental sustainability.

6. Conclusion

In conclusion, the solar cell development is not limited to the notable improvement in cost and efficiency, but also in the innovation of materials and technologies, the growth of global solar energy utilization, and the provision of environmentally friendly energy solutions. Despite many challenges, enhancing materials can lead to a large increase in solar cell performance, optimizing device structure, and controlling details in the manufacturing process. For example, by placing selective reflectors around solar cells, the optimal material band gap can be transferred to lower energy levels, enabling greater efficiency. In short, the current performance gap of solar cells is mainly determined by the material band gap, interface state, device structure and other factors. By deeply studying these factors and taking corresponding optimization measures, it is expected to achieve higher solar cell efficiency in the future. But together, these achievements have promoted the wide application and sustainable development of solar cells around the world.

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