Materials and Prospects of Novel Solar Cells

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Abstract. As industrial standards continue to grow, the demand for traditional energy sources is on the rise, the solar energy is clean and non-polluting, renewable energy sources. Solar cells are devices that can convert sunlight directly into electricity. Solar cells have progressively established themselves as a research hotspot sought after by scholars in recent years. This paper summarizes the device structure, principle, development status and problems faced by the traditional silicon crystal solar cells and novel solar cells. In addition, this paper also compares the cost, advantages and disadvantages, and the highest efficiency of these several solar cells, analyzes the advantages of the traditional silicon-based solar cells, and the future development direction of several new solar cells. Finally, this paper concludes that silicon solar cells are still dominant in the market because of their outstanding power conversion efficiency (PCE) and stability. The novel solar cells with thin-film structures have high theoretical conversion efficiency and some other characteristics, so they will hopefully replace the traditional silicon solar cells in the future. However, stability, PCE and cost are currently the main challenges.

1 Introduction

As industrial standards continue to grow, the demand for traditional energy sources is on the rise. Currently, human mainly relies on the consumption of traditional energy sources to generate electricity, resulting in the emission of large amounts of greenhouse gases, thus leading to an increasing greenhouse effect and a continuous deterioration of the human living environment. Therefore, it is urgent to transform the use of energy with the gradual arrival of the energy crisis. For this reason, researchers are looking for new renewable energy sources that can produce electricity and reduce traditional energy consumption without polluting the environment [1].

As a common renewable energy source, solar energy boasts the advantages of being non-polluting, clean and inexhaustible. Efficient exploitation of solar energy is an important measure for solving and alleviating energy and environmental problems, as the conversion of ideal solar energy into electricity for use can greatly reduce mankind's use of traditional energy sources, thereby reducing greenhouse gas emissions and alleviating problems such as energy shortages. Solar cells are devices that can convert sunlight directly into electricity. Based on the above advantages, solar cells have progressively established themselves as a research hotspot sought after by scholars in recent years. Solar cell technology is constantly evolving in order to develop efficient and practical solar cells, and a growing range of solar cell materials is being made available. As of today, solar cell technology is relatively mature, with silicon crystalline solar cells, which are the most technically mature, already being commercialized [1]. Yet, it is difficult to make a major breakthrough in a short time with the shortcomings of silicon-based solar cells. New solar cells with high theoretical conversion efficiencies and simple processes at low cost are entering the vision of researchers, and solar cell technologies based on a variety of new materials are seeing huge breakthroughs. Based on the above analysis, this paper first introduces the principle, structure, current research status and problems faced by several representative solar cell materials, then compares them, analyzes their advantages and disadvantages, and then delivers suggestions for development and an outlook for the future.

2 Silicon-based solar cells

2.1 Single crystalline silicon solar cell

Single crystalline silicon is a non-metallic elemental crystal with quasi-metallic physical properties, a largely intact crystal with a dotted structure and a good semiconductor material with good physicochemical and mechanical properties, which plays an important role in converting solar energy into electricity in solar cells. Single crystalline silicon, which is 99.999% pure in solar cells, is made in a more complex process, from arenaceous quartz → metallurgical silicon → purification and refining → deposition of polysilicon Ingot → single crystalline silicon → silicon wafer cutting [2]. Single crystalline silicon solar cells are the earliest studied and commercially available solar cells and have the most mature technology and highest conversion rates. On 19 November 2022, Chinese companies set the world's highest record PCE for single crystalline silicon solar cell

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of 26.7%, close to the theoretical limit value [3]. The majority of single crystalline silicon solar cells in the commercial range in the market offer photoelectric conversion efficiencies of around 16%.

Although single crystalline silicon solar energy has the highest conversion rate and will be the prevailing material for large-scale applications and industrial production at present and in the future, there are still many drawbacks; its production requires the consumption of large amounts of high-purity silicon material, and single crystalline silicon is cumbersome and expensive to produce and consumes a large amount of electricity, accounting for 54.6% of the total cost of silicon-based solar cells [1]. Large-scale use of single crystalline silicon solar cells can be effectively promoted if the production costs of single crystalline silicon materials can be effectively reduced. In order to reduce the cost of making solar cells and to find an alternative material to single crystalline silicon, polycrystalline silicon materials appeared to the public.

2.2 Polycrystalline silicon solar cell

Compared to single crystalline silicon, polycrystalline silicon is a much less demanding material to produce, using less material and being easier to produce. Processing of polycrystalline solar cells is similar to that of single crystalline solar cells, but at a much lower cost. High purity silicon can be directly melted and calcined to form silicon square ingots, which are then processed to obtain polycrystalline silicon [4]. This reduces production costs and also maintains a high level of performance and stability, making it a key development in recent years. However, the incident photon-to-electron conversion efficiency (IPCE) of polycrystalline silicon solar cells is less than that of single crystalline silicon solar cells because polycrystalline silicon solar cells are affected by various factors such as crystal particle size, morphology, etc. [2]. The highest conversion efficiency of 22.8% for polycrystalline silicon solar cells studied by the German company ISFH is the highest reported so far [5]. However, in large-scale commercial and industrial applications, the actual photovoltaic conversion efficiency is only about 10%, a factor that hinders the development and application of polycrystalline silicon solar cells.

Polycrystalline solar cells can partially replace single crystalline silicon solar cells, but this is highly dependent on silicon and the manufacturing process also need to reach 1100 °C, which requires conventional energy, such as smelting, ingot casting, slicing and adhesive film for manufacturing polycrystalline silicon, which will emit greenhouse gases and pollute the environment [6]. It is worth mentioning that although the cost of single crystalline silicon process accounts for more than 50% of the total cost, it is still a mainstream product in the solar cell market due to its good stability, mature preparation process and high conversion rate advantages. Whereas the laboratory conversion efficiency of silicon based solar cells is close to the theoretical upper limit, it is still a large proportion of the cost price of silicon based solar cells. Therefore, the reduction of cell preparation costs has become the mainstream research direction for silicon based photovoltaic cells in the future.

3 Novel solar cells

All novel solar cells have characteristics such as thin film, relatively high theoretical conversion efficiency, abundant raw materials and Environmental-friendly. With excellent development prospects, the more popular ones are dye sensitized solar cells, organic solar cells, and perovskite solar cells.

3.1 Dye-sensitized solar cells

Dye sensitization is a new type of photoelectrochemical cell derived from photosynthesis. Dye sensitized nanocrystalline solar cells with a photovoltaic efficiency of 7.1% have been on the radar of many researchers and scientists since 1991, when they were manufactured by Professor Gratzel at the Ecole Polytechnique Fédérale de Lausanne) (EPFL) in Switzerland.

The structure of a dye sensitized solar cell is a typical sandwich structure, consisting of three main parts, including the photoanode, the counter electrode and the electrolyte. Photoanodes are generally N-type semiconductor films (e.g. TiO2, ZnO) with porous nanopores loaded with generally ruthenium complexes, pure organic molecules with a specific structure and porphyrin derivative dye sensitizers, whose main role is to emit electrons. Electrolytes between the photoanode and counter electrode are often liquid electrolytes which are mainly used for dye generation and charge transfer, and the liquid electrolyte is often an I^-/I^{3-} redox pair. Platinum is loaded onto conductive glass as a counter electrode to transfer electrons to catalyse the regeneration of redox electrolytes [7].

Dye sensitized solar cells work on the principle that when the visible part of sunlight is absorbed by the light-sensitive dye molecules, the electrons in the dye molecules leap from the ground state to the excited state dye molecules inject electrons rapidly into the conduction band of the porous semiconductor; the electrons injected into the semiconductor conduction band travel from the conductive glass surface to the outer circuit and eventually to the counter electrode; the dye molecules that have lost electrons are oxidized into oxidized dye cations; as the redox potential of the electrolyte pair is lower than the redox potential of the dye molecules, the dye molecules are reduced to the ground state by the redox pair of the electrolyte, facilitating the absorption of electrons again. The oxidized electrolyte is reduced by electrons from the metal electrode and returned to the dye molecule, creating a complete electron transport cycle. Germany, Switzerland, Japan and the USA all have institutions dedicated to the study of dye sensitized solar cells. So far, the highest photoelectric conversion efficiency of 13.5% has been reported by EPFL for dye sensitized solar cells [8]. Nowadays, there are several ways to improve the photovoltaic efficiency, such as ion doping, interfacial modification of nanostructures and the use of other materials to increase the specific surface area and thus improve the light absorption capacity of the dye. Due to the relatively high cost of the metallic electrode platinum, some researchers have replaced the more expensive metallic platinum electrode with a lower cost carbon electrode material to reduce the cost of dye sensitized solar cells [9].

In addition, the stability of dye sensitized cells is also an issue that cannot be ignored. Most dye sensitized solar cells are made with a liquid electrolyte, and although the liquid electrolyte brings the performance advantage of relatively high charge transfer, the organic electrolyte in it has a low boiling point and is prone to volatilization, leading to electrolyte leakage, which reduces the stability and lifetime of the cell. Solid state electrolytes have been studied extensively by a wide range of researchers because of their high stability, but they are flawed by their low electrical conductivity. Up to now, there have been great advances in the field of solid-state electrolytes used in dye sensitized solar cells, but it is a problem that must be solved to increase the efficiency of photovoltaic conversion by further increasing the rate of hole transport [7].

3.2 Organic solar cell

Organic solar cells are an important branch in the field of solar cells because of their light weight, flexible preparation for large areas, simple process and low production costs. In 1958, Kearns and Calvin fabricated the world's first organic solar cell by adding magnesium phthalocyanine between two electrodes with different work functions, and this device achieved a voltage of 200 mV, and since then organic solar energy has been widely researched [10].

In general, the device structure of organic solar cells consists of glass substrates, transparent electrode (ITO, etc.), active layer (blends of electron donor and electron acceptor), metal electrode (Al, Ag, etc.) and buffer layers between the electrode and active layer. The principle of organic solar cells: the acceptor material in the active layer absorbs photons in the incident sunlight that are higher than its band gap energy, and the electrons on the highest occupied molecular orbital (HOMO) energy level are excited to leap to their lowest unoccupied molecular orbital (LUMO) energy level, resulting in electron-hole pairs, after which the electron-hole pairs diffuse to the donor interface, and under the action of the potential difference, the electron-hole pairs dissociate and produce free carriers. Subsequently, the free carriers are transported by the corresponding donor and acceptor materials in the presence of the built-in electric field, collected by the anode and cathode and output to the external circuit, forming a photocurrent [11].

There are many ways to classify organic solar cells, among which they can be divided into fullerene and non-fullerene cells according to the type of acceptor materials in the active layer. In 1985, Curl et al. discovered fullerene materials with unique structures and luminescence [12]. However, as fullerene acceptor materials still have some disadvantages:

(1) the high cost and complexity of preparing derivatives of fullerenes;

(2) weak absorption of visible light;

(3) their tendency to crystallize when subjected to heat, resulting in poor stability [13, 14].

As a result, the PCE of fullerene-based solar cells only reach a maximum of around 12%. Whereas non-fullerene acceptors have the advantages of strong light absorption in the infrared region and easier tuning of spectral energy levels, compared to conventional fullerene receptors, which has been heavily researched in recent years. In the last five years, a variety of non-fullerene acceptor materials have been developed, leading to a significant increase in photoelectric conversion efficiency. In 2020, the conversion efficiency has also reached more than 18% and organic solar cells are entering the non-fullerene era from fullerenes [15]. As yet, however, organic solar cells cannot be widely used on a commercial scale and are still mainly at the laboratory stage, with the main problems they face being: (1) to improve device lifetime. Small area devices can be optimized for more than 10 years, but there is not yet a sufficient amount of research and suitable methods for large area devices; (2) to reduce the cost of commercialization. The cost of the active layer and the electrode material is too high and simple and rational structures for the acceptor and electrode material need to be designed to reduce costs and ensure high efficiency. (3) to improve PCE. It is necessary to focus on the principle of reducing the voltage loss of the device, so that the optimization method of the device can be targeted. Only by improvement in these areas can organic solar cells be used on a large scale [11].

3.3 Perovskite solar cells

Perovskite solar cells are simple to prepare, abundant in raw materials, of low production cost and have excellent photovoltaic performance to meet the commercialization requirements. In 2009, the first perovskite solar cell appeared, with a photovoltaic conversion efficiency of 3.8%, but its device stability was poor, so it did not receive much attention [16]. In 2012, Kim et al. developed a solid electrolyte perovskite cell that improved stability and increased photovoltaic conversion efficiency to 10%. Since then, Perovskite solar cells have attracted wide attention from researchers.

Perovskite solar cells consist of five components: transparent conductive glass electrode layer (ITO, fluorine-doped SnO_2), electron transport layer (e.g., TiO_2, fullerene derivatives), chalcogenide absorber layer (e.g., CH_3NH_3PbI), hole transport layer (e.g. Spiro-OMeTAD) and metal electrode (Au/Ag). The arrangement of the chalcogenide active layer and the charge transport layer can be divided into two types, the orthotropic n-i-p (ETL/chalcogenide absorber layer/HTL) type and the inverted p-i-n (HTL/chalcogenide absorber layer/ETL) type, depending on how the perovskite active layer is sandwiched between the two charge transport layers. The principle of these two types of chalcogenide solar cells is basically similar: the chalcogenide absorbing layer absorbs photons of sunlight with energy greater than its forbidden band width, and the valence band electrons are excited to leap into the conduction band, creating a pair of electron-hole pairs at the same time. Under the effect of the potential difference, electrons and holes diffuse the conduction band and the transport layer of holes in the electron transport layer, respectively, after which the holes are transported to the cathode and the external circuit, forming the external circuit current [17].

Currently, the highest efficiency certified for perovskite solar cells is 25.7%, which is close to that of silicon-based solar cells, making it one of the strongest competitors in the solar cell field [18]. However, perovskite solar cells face a number of challenges if they are to be commercialised on a large scale:

(1)Poor stability. Perovskite materials are extremely sensitive to humidity and temperature and may undergo distortions under conditions such as high temperatures and high humidity, thus losing their light absorption capacity.

(2) Large-area film-forming properties. Most of the perovskite solar cells currently used have an area of only 0.09 cm^2. Large area, high quality perovskite is difficult to prepare, and there is still a gap with commercially available silicon-based solar cells.

(3) Pollution to the environment. Most high-efficiency perovskites contain the element Pb, and the penetration of Pb into the environment can cause pollution, so it is also one of the future research directions for high-efficiency chalcogenide solar cells to get rid of the dependence on Pb elements.

(4) Material costs. In the case of large-scale commercialization, it will be necessary to develop technologies for the production of perovskite modules to reduce costs [19].

4 Comparative analysis

Comparison of the above 5 types of solar cells include the following aspects.

Single crystalline silicon solar cells have the highest photoelectric conversion efficiency, with the highest laboratory record of 26.7%, the most mature technology, and large-scale commercial use, with a life expectancy of about 15-25 years and a cost of 1.04-1.12 Yuan/W, offering excellent performance [20,21]. However, the high purity of the single crystalline silicon required, the cumbersome process and the high power consumption make the cost of single crystalline silicon high, accounting for 54.6% of the total cost.

Polycrystalline silicon solar cells have much lower raw material requirements than single crystalline silicon solar cells, because of the advantages of mature technology, low cost and simple process, the highest laboratory efficiency of 22.8%, cost in 0.73-0.83 Yuan/W, lifetime of 25 years, in the global photovoltaic products used in about 70% [5,20,21]. However, it is only about 10% efficient on a large scale commercial and industrial scale due to the relatively low efficiency of power generation.

Due to the low temperature requirement of the production process, the dye sensitized solar cells are easy to manufacture and have the advantages of low production cost, integrated liquid electrolyte cells, quasi-solid electrolyte cells and high electrical conversion efficiency of over 13%, but they have poor stability and easy volatility of organic solvents. Although the stability of the quasi-solid and solid electrolytes has improved, the low photovoltaic conversion efficiency is a major problem.

Organic solar cells are highly thin and light, transparent, flexible, processible, of low production cost, etc. The current research focuses on non-fullerene organic solar cells, with a maximum laboratory photoelectric efficiency of 18% or more [15]. Yet the main issues are how to improve the photovoltaic conversion efficiency, extend the service life and reduce the cost of commercialization.

Perovskite solar cells offer a high laboratory efficiency of up to 25.7%, close to the highest photoelectric efficiency of silicon-based solar energy, and enjoy low costs, abundant raw materials and simple processes, and have attractive prospects for development. Moreover, it is a current development hit and the current market cost is around 1 Yuan/W for Golden concord nano's perovskite solar cells [21]. However, their poor stability, difficulties in large area film formation, environmental pollution and cost issues have limited their applications.

In summary, in terms of PCE, lifetime and stability, single crystalline silicon and polycrystalline silicon solar cells continue to offer excellent cost performance and will maintain their dominant position in the field of solar cells in the next 10 years. The most promising to become the dominant solar cell is the perovskite solar cell, with the highest IPCE exceeding many polycrystalline silicon solar cells, but problems such as its difficulties in film formation and stability limitations, dependence on Pb, and pollution of the environment limit its development. Compared to others, organic solar cells are high in lightness, transparency and good flexibility. Based on these features, organic solar cells have irreplaceable advantages in indoor photovoltaic and photovoltaic building integration [11]. However, its low stability and photovoltaic efficiency prevent it from being commercially available on a large scale. In addition, the simple structure and long lifetime of dye photosensitive solar cells give them a unique advantage. On balance, its poor stability and low photoelectric conversion efficiency require considerable research to optimize the performance of its electrolyte. In general, most of the new photovoltaic cells currently available are thin, flexible and translucent but feature technologies still only at the laboratory stage, and their cost and area are not yet able to meet the minimum standards for large-scale commercialization and industrialization. Therefore, lower material costs and large-area mass production are currently the main research directions to ensure high conversion efficiency.

5 Conclusion

After the comparison of the various types of solar cells, it is found that the application of solar cells is mainly challenged in terms of energy conversion, cost and stability. Silicon crystalline solar cells, due to their PCE far higher than the other three types of new solar cells, stemming from the stability of silicon solar and excellent photoelectric conversion efficiency, so they will remain dominant in the global solar cell market in the coming 10 years. However, their high power consumption, complex processes, high prices and other factors make it not the ideal solar cell material for the future of mankind. In the long run, new solar cells appear to be more viable, so it is necessary to develop new materials for solar cells to replace traditional silicon crystalline solar cells. However, organic solar cells and dye photovoltaic solar cells are expected to have the highest photoelectric conversion efficiency, while perovskite solar cells should focus on stability. Future research on new solar cells should put emphasis on stability, photoelectric conversion efficiency, and the cost of large-area industrialization. Beyond this, the new solar cells are supposed to play to their respective strengths and characteristics in various fields and scenarios.

There will also be an increasing number of new solar cells, and the technology will become more sophisticated. To replace traditional silicon solar cells, large-scale industrialization and commercialization are the long-term goal for the future, so solar cells should be developed in the direction of high performance, high stability and low cost in addition to the increasingly high requirements for light weight, transparency and intelligence. In the future, the trend is towards the development of the solar cell industry for civilian use and it will no longer be limited to the laboratory research.

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