Advances and Promises of Photovoltaic Solar Cells

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Abstract. Photovoltaic devices have attracted enormous attention in recent decades. Except for silicon, a traditional photovoltaic material, a lot of new technologies have emerged for a reduction in costs and application in flexible devices. To present a relatively comprehensive view of such devices, this paper summarized the newest researches and challenges faced by different materials respectively. To be more specific, the general working principles of photovoltaic devices are explained initially and then the development of several typical solar cells are introduced, including silicon, Copper indium gallium selenide (CIGS), organic, and perovskite cells, followed by a brief introduction of their fabrication processes. This paper aims to help with advances in manufacturing methods or device structures to improve solar cell efficiency through the analysis of the progress in the corresponding fields.

1. Introduction
As a lack of energy becomes an increasingly severe problem around the world, the value of solar energy stands out as it is clean and sufficient [1-3]. Therefore, making the most of solar energy is critical to ease the energy crisis. And how to convert solar energy directly to electricity has been a popular researching subject in recent years [4-6]. Since 1975 different kinds of solar cells have been researched and new devices are created all the time as shown in Figure 1 [7]. Among various solar cells, silicon solar cells are the earliest reported, and their technologies are the most mature. Silicon is an outstanding semiconductor material that is the most researched and its corresponding physics theories as well as fabrication processes are the most developed. Until now, such devices have achieved the highest efficiency of 27.6%. However, the devices, especially those with single crystal silicon, require huge costs and complicated fabrication processes. Besides, they cannot be compatible with flexible substrates, which limits their applications in flexible equipment and wearable devices. Under such situation, film solar cells have attracted the attention of researchers due to their low manufacturing cost and the practicality of producing flexible devices. In fact, thin-film technologies are among the earliest research subjects. After about 45 years of development, the efficiency of Copper indium gallium selenide (CIGS) thin film solar cells has been reached 23.4%. Additionally, a lot of researches have been conducted on other photovoltaic materials including dye-sensitized cells, organic cells and perovskite cells. Taking perovskite as an example, the efficiency of such devices has been reached 25.5% in less than ten years.

In this review, working principles of photovoltaic devices are explained at first, followed by introductions of the newest progress in the corresponding fields. Then the development of silicon, CIGS, organic and perovskite solar cells are introduced in details. This paper is expected to deepen people’s understanding of photovoltaic fields and help them to enter these fields through this work.
2. Working principles of photovoltaic devices

2.1 Basic structures
Structures of solar cells can be divided into two categories, p-n type and p-i-n type. The former one is basic, mainly consisting of a P-N junction. A typical example of such type is a silicon solar cell. For the latter type, it can also be n-i-p, depending on the order of n and p. Figure 2(a) presented an n-i-p structure. In this configuration, n stands for an electron transporting layer (ETL), p represents a hole transporting layer (HTL) and i refers to active materials which are sandwiched between ETL and HTL (absorber). Electrodes are located on ETL and under HTL, with conductive glass (ITO or FTO) functioning as the bottom electrode [1]. Besides, glass is the substrate on which solar cells are manufactured considering the tiny scale of the cells. Perovskite and organic solar cells are good instances of this configuration.

2.2 General working principle
The basic working principle of solar cells is based on the photovoltaic effect. Converting solar energy into electricity consists of two necessary processes. The first is the generation of photo-carriers and the second is the collection of such carriers. To be more specific, when the light is incident on semiconductor materials such as silicon and perovskite, if the photon energy is greater than or equal to the bandgap of the material, the photon would be absorbed, exciting electrons in the valence band to jump to the conduction band, as shown in Figure 2(b) (process 1). This is the generation of electrons and holes. Following this, carrier transportation is driven by the built-in electric field. It should be noted that this stage is different for distinct structures of solar cells. For p-n type, electrons are transported to the n region and holes to the p region. Then the two kinds of carriers diffuse to front metal and back metal respectively, after which electric current can be generated when the device is connected to external circuits. While for the p-i-n type of structure, electrons and holes are transported as described in Figure 2(b). The electrons and holes both diffuse to the interface between absorber and ETL (or HTL). Characteristics of ETL and HTL are that ETL only allows electrons to pass through it and prevents holes, vice versa for HTL. Thus, electrons are transported to ETL (process 3) and collected by the top electrode (process 4). Similarly, holes are transported to HTL (process 5) and collected by the bottom electrode (process 6). The aforementioned physical processes of transporting holes and electrons are the conversion from sunlight to electricity. However, unfavorable processes can also occur including recombination of electrons and holes (process 2). When the absorber materials have some pin-holes,
ETL and HTL might contact each other directly and recombination is serious in such case as presented in process 7 [1].

![Figure 2](image-url)  
**Figure 2.** Basics of solar cells (a) n-i-p structure of a solar cell [1]. (b) working principle of n-i-p structure [1]. (c) I-V curve of a solar cell [4]. (d) equivalent circuit of a solar cell [3].

According to the working principle, a conclusion can be drawn in terms of factors affecting the efficiency of solar cells. Firstly, for absorption of photons, materials on top of the absorber should allow enough light to pass through it, absorption coefficients of absorber materials and spectrum of light absorbed should be considered. Reflection of light on the surface of solar cells should also be reduced. Secondly, for transportation of carriers, lower carrier binding energy of semiconductor materials is beneficial to separation of electrons and holes. Diffusion length that exceeds absorber thickness is also required. Charge transporting characteristics of ETL and HTL materials should be considered that the lowest unoccupied molecular orbital (LUMO) of ETL matches the bottom of semiconductor conduction band and highest occupied molecular orbital (HOMO) of HTL matches the top of semiconductor valence band in order to transmit carriers more efficiently [4]. Thirdly, the recombination of carriers should be prevented as much as possible. As mentioned before, the compactness of the absorber is of great significance because the pin-hole of the absorber may cause direct contact between ETL and HTL. Besides, higher charge mobility of the light-absorbing layer can give rise to a longer diffusion length of carriers. For example, organic semiconductor materials are highly dependent on morphology that orderly morphology means high charge mobility [4]. Ohmic contact between electrodes and semiconductor materials reduces interface recombination as well. Additionally, extraction of carriers by electrodes can also be taken into consideration.

### 2.3 Parameters of photovoltaic devices

When solar cells are tested on standard lighting conditions, radiation intensity is 1000 W/m² (AM 1.5) and temperature is 25±2°C, some important parameters to judge quality of a solar cell can be obtained through current versus voltage curve shown in Figure 2(c) [2]. The parameters include photon-to-electron conversion efficiency (PCE), open circuit voltage (V_{oc}), short circuit current density (J_{sc}), external quantum efficiency (EQE) and fill factor (FF). The most significant one is PCE which describes the ability of solar cells to convert incoming light into electricity. All factors summarized in 1.2 can affect PCE.

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PCE = \frac{V_{mp} J_{mp}}{P_{in}} = \frac{V_{oc} J_{sc} FF}{P_{in}} \tag{1}
\]
Where, $V_{oc}$ is the maximum output voltage of the solar cell. Fermi energy level difference between the n-type material and the p-type material, defect density of the absorber layer, contact between the absorber and the interface of the transmission layer and the contact between the transmission layer and the electrode can determine $V_{oc}$. $J_{sc}$ is the maximum number of photo-carrying fluids produced by solar cells per unit area, Bandgap width, intensity of incident light, thickness of absorber and transmission of carriers influence the value of $J_{sc}$. To be more specific, narrower bandgap, wider range of absorbed light, thicker absorber, and stronger absorption capacity are preferred. EQE reflects the absorption capacity of solar cells to a single wavelength of light, which has a similar meaning to PCE. Absorption of light plays an important role in affecting this parameter. In other words, solar cell response to various wavelengths of incident light is the key. The equation for it is

$$EQE = \frac{\text{the number of carriers}}{\text{the number of incoming photons}} \quad (2)$$

Fill factor (FF) reflects the state of the device as a diode and $0<FF<1$. When FF is closer to 1, the performance of solar cells is better. Device series resistance and parallel resistance influence FF, which can be analyzed in the equivalent circuit of a solar cell shown in Figure 2(d) [3]. Small series resistance and large parallel concatenation resistance cause larger FF. The equation is

$$FF = \frac{V_{mp}}{I_{mp}} \frac{J_{sc}}{V_{oc}} \quad (3)$$

Additionally, stability can be represented by factors such as solar cell life. Semiconductor material stability including internal ion migration and defect density affect such parameter.

3. Popular solar cells under research

As shown in Figure 1, several types of solar cells are focused in scientific fields, such as perovskite solar cells, organic solar cells, CIGS solar cells and silicon solar cells. The following sections give a closer observation of such devices.

3.1 Silicon solar cells

Silicon is sufficient in the earth’s crust and relatively easy to be purified for industry. Thus, it is widely used in fabrication of solar cells. After a long period of researches, its highest efficiency is 27.6%. The atomic structure of a silicon atom is shown in Figure 3(a) with covalent bonds between atoms [3]. Figure 3(b) shows the absorption coefficient of silicon solar cells, reflecting a good absorption capability within a certain range of wavelengths [8]. As shown in Figure 3(c), a recent trend in researches of solar cells is the integration of silicon solar cells and redox flow batteries to construct a solar flow battery (SFB) [9]. SFB solar cells are promising in stand-alone solar home systems with convenience and efficiency. Besides, researchers also make breakthroughs in pure silicon solar cells as depicted in Figure 3(d). Researchers from Hanergy Thin Film Power Group, Chengdu R&D Center and Beijing University of Technology reported a certified efficiency of up to 25.11% for silicon heterojunction (SHJ) solar cells on a full-size n-type M2 monocrystalline-silicon (c-Si) wafer (total area, 244.5 cm2). An ultra-thin intrinsic a-Si:H buffer layer was introduced on the c-Si wafer surface. $V_{OC}, I_{SC}$ and FF were significantly improved, among which FF contributed the most for the increase of cell efficiency [10].
Figure 3. Silicon solar cells (a) atomic structure of silicon atom [3]. (b) absorption coefficients vs wavelengths [8]. (c) Configuration of traditional silicon solar cell and SFB solar cell [9]. (d) IV curve of a high efficiency silicon solar cell [10].

3.2 CIGS solar cells
The researches of Copper indium gallium selenide (CIGS) thin film solar cells began in 1975. Such a device can obtain an efficiency of 23.4% recently. CIGS has a structure shown in Figure 4(a), consisting of Cu, In or Ga and Se atoms [11]. CIGS has several merits including an ideal bandgap and high absorption rate of visible lights. Therefore, although only the p region (CIGS) is the main part of the cell structure to absorb light and generate carriers, the device can achieve comparable efficiency as silicon. In addition, Figure 4(b) shows another feature of the cell structure that the band match of CIGS and the material on top of it can affect carrier transportation [11]. If the top of conduction band is higher than the top of CIGS conduction band, carriers can be more easily transported. Besides, IV curve of a high efficiency CIGS solar cell is shown in Figure 4(c). The efficiency of 23.35% was achieved by researchers from the University of Electronic Science and Technology of China. State-of-the-art Cd-free Cu(In,Ga)(Se,S)₂ (CIGSSe) solar cells with Zn(O,S,OH)ₓ/Zn₀.₈Mg₀.₂O double buffer layers, deposited by a combination of chemical bath deposition and atomic layer deposition techniques were applied. Through this approach, Vᵪₒ was increased by approximately 15 mV, and FF as well as Iᵪₑ were improved. The minority carrier lifetime (τ) was also elongated, implying reduction in carrier recombination [12]. In practical applications, CIGS plays an important role in flexible devices which has expanded applications such as mobile power and installation over uneven surfaces (shown in Figure 4(d)). Nevertheless, the flexible CIGS faces some challenges in fabrication. For example, flexible substrates can negatively affect the doping level of CIGS [13].
3.3 Organic solar cells

The Organic solar cells were studied from 2001 and their highest efficiency to date is 18.2%. The organics used in the devices are mainly Fullerene (Figure 5(a) [4]) and some non-fullerene materials have been applied recently. Figure 5(b) shows the processes to generate photocurrent in a polymer–fullerene solar cell. The general working principle can be applied to most of the steps, while a special point needs attention. In each electron-hole pair (excitons), there is a strong Coulomb force between the two kinds of carriers. Thus, they have to diffuse to the interface between donor and acceptor to be separated. Besides, when electrons reach the acceptor and holes reside on the donor, they may still be bound, requiring a polaron pair dissociation step (process (4) in Figure 5(b)) [14].

As fullerene costs much money in manufacturing and its ability to absorb light is weak although it has merits in carrier transmission and control morphology. Therefore, non-fullerene gradually replaces fullerene as acceptor for its easy production and strong ability to absorb light. The development of organic solar cells is depicted in Figure 5(c) [5]. The IV curve of the most efficient organic solar cell is shown in Figure 5(d). Researchers from several universities and National Center for Nanoscience and Technology in China developed a D-A copolymer donor D18 based on a fused-ring acceptor unit DTBT. D18 has a high hole mobility of $1.59 \times 10^{-3}$ cm$^2$ V$^{-1}$ s$^{-1}$. The D18:Y6 solar cells gave a PCE of 18.22%, which is the highest efficiency achieved from organic solar cells to date [15].
3.4 Perovskite solar cells

Study of perovskite solar cells started around 2013. Despite the short period of time, this type of equipment has made great achievements, with a maximum conversion efficiency of 25.5%. Although it is a short period of time, great achievements have been achieved that the highest conversion efficiency of such devices is 25.5%. At first, perovskite can be represented as ABX₃ and it is a tetragonal crystal as shown in Figure 6 (a) [1]. Such material stands out in semiconductor materials because it has a high absorption rate of light and a long diffusion length. Absorption coefficients of perovskite compared to other materials are shown in Figure 6 (b) [6]. From this figure, it is clear that perovskite can absorb a wide range of light. Additionally, perovskite solar cell has two types of structure, meso-hole structure, and flat structure. The meso-hole material carrier is more easily collected because of titanium dioxide. But lots of experiments prove that even without TiO₂, the flat structure can also perform well. The highest efficiency of 25.4% is posted in Figure 6 (c) [16]. Such efficiency was achieved by researchers from MIT and Korean institutions through enhanced charge carrier management. First, they developed an electron transport layer with an ideal film coverage, thickness and composition by tuning the chemical bath deposition of tin dioxide (SnO₂). Second, they decoupled the passivation strategy between the bulk and the interface, leading to improved properties, while minimizing the bandgap penalty. In forward bias, their devices exhibited an electroluminescence external quantum efficiency of up to 17.2% and an electroluminescence energy conversion efficiency of up to 21.6%. As solar cells, they achieved a certified power conversion efficiency of 25.2%, corresponding to 80.5% of the thermodynamic limit of its bandgap. However, perovskite has some defects that it is not stable enough. In other words, it can be easily affected by environmental factors such as light, moisture, temperature and oxygen (Figure 6 (d)) [17]. In humid environments, hydrated compound and high ion mobility of perovskite are a matter of worry. In a dry atmosphere, chemical reactions with oxygen and Pb-O bonds should be concerned. Light can cause photo-induced ion migration, trap state formation and phase segregation. And high temperature can lead to phase transition or separation, decomposition, ion diffusion and inhibition of charge transport.
Figure 6. Perovskite solar cells (a) The structure of perovskite [1]. (b) Absorption coefficient of several photovoltaic materials [6]. (c) I-V curve of the most efficient perovskite solar cells [16]. (d) Stability study of perovskite solar cells [17].

4. A brief introduction of solar cell fabrication processes

4.1 Crystal solar cell
Silicon solar cell is a typical crystal solar cell with mature manufacturing technologies. Therefore, in a lot of university courses related to photovoltaic devices, fabrication of a silicon solar cell in laboratory is an important part. In the laboratory, the experiment consists of three main parts: silicon wafer cleaning, PN junction formation and metal contact construction. Through the whole procedures, personal protective equipment is of great significance. Wafer cleaning is performed in general unless the silicon wafer is brand new vacuum packed. Such a step is to remove surface contamination of wafers such as organic residues and oxides. Following this, the wafer is doped and the dopant is diffused to form PN junction. Finally, metal masks designed primarily in software are attached to the front and back side of the wafer. The above procedures are used to fabricate a basic silicon solar cell. Practical production generally performs additional steps including formation of anti-reflection coating or texture on the wafer surface.

In fact, the fabrication of silicon solar cells is expensive and complicated, which requires strict conditions such as high temperature. This prevents further development of the solar cells and thus encourages researches of improving manufacturing technologies and developing solar cells applying other semiconductor materials.

4.2 Thin film solar cells
Perovskite solar cell is a kind of thin film solar cells, which can be produced through a variety of methods. In general, the key in fabrication is the mixture and reaction of inorganic and organic salts on a specific substrate to produce perovskite film. Common processes to manufacture a perovskite solar cell are as follows. Firstly, the filtered perovskite precursor solution is spin-coated on the substrate which is selected in advance (for instance, NiOx), using one-step solution spin coating method. The spin coating parameters should be set including time and revolution. Then the sample is annealed on a hot plate at a certain temperature for a certain time to form the perovskite film, followed by passivation of the film.
Second step is to prepare ETL through the solution spin coating method. Finally, metal such as silver is evaporated as electrodes [2].

5. Conclusion
This paper reviews the characteristics and trends of solar cells based on the articles published in recent years. In summary, this paper shows two types of solar cell structures, general working principles and related parameters, as well as the development of perovskite, organic, CIGS and silicon solar cells. These findings could be good references for basics of solar cells. In addition, the results could be helpful to predict prospects of solar cells to reduce the negative effects of insufficient energy and environmental problems.

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