Research Progress and Prospect of Translucent Organic Ohotovoltaic Cells

Yuhan Fu *

School of Chemical Engineering, East China University of Science and Technology, Shanghai, China

* Corresponding Author Email: 1807050219@stu.hrbust.edu.cn

Abstract. Translucent organic photovoltaic cells, as a branch of photovoltaic cells, are an important part of society towards green, clean, sustainable and renewable development. Not only has it become a hot spot in academia in research, but also has its potential in many aspects such as photovoltaic building integration. And with the development of devices, its performance has also been continuously improved. Therefore, this paper aims to review the development history of organic photovoltaic cells and translucent organic photovoltaic cells, analyze the advantages and disadvantages of their devices, and explore the hot spots and development trends of today's scientific research to help people who first contact or rarely contact the field of translucent organic photovoltaic cells. Thus more quickly and comprehensively understand and grasp the development trend and prospect of translucent organic photovoltaic cells. Through literature review, this paper lists the development process of translucent organic photovoltaic cells, and introduces the current application scenarios of translucent organic photovoltaic cells with examples. The first part of this paper is a general overview of organic photovoltaic cells; The second part discusses the research progress of translucent organic photovoltaic cells, and discusses the core elements of the development of translucent organic photovoltaic cells. The third part is a detailed discussion of the application of translucent organic photovoltaic cells, proving their market value and the necessity of research, so as to rationally and objectively analyze translucent organic photovoltaic cells from different types of horizontal photovoltaic cells and vertical time scales.

Keywords: Organic photovoltaic cells; translucent; materials.

1. Introduction

With the rapid development of science and technology, the energy problem is not only a scientific and technological problem, but also a social problem. Coal, oil and natural gas still occupy the dominant position of energy consumption structure for a long time [1], but the problems of environmental pollution and resource depletion cannot be avoided. At the same time, the demand for carbon neutrality and carbon peaks is also raised. Therefore, people are gradually turning their attention to renewable green and clean energy, including solar energy, wind energy, water energy, etc[2].

Green and clean new energy mainly includes geothermal energy, wind energy, water energy, solar energy, tidal energy and so on. Among these renewable energy sources, solar energy occupies an important position. The advantages of solar energy are: (1) abundant and huge solar energy resources, the sun irradiates to the earth every second equivalent to the energy released by burning 5 million tons of coal, and for human beings, solar energy is inexhaustible; (2) Solar energy covers a wide range and is not subject to regional restrictions; (3) Solar energy is clean and pollution-free. Photovoltaic cells are divided into five categories according to the type of semiconductor: silicon-based solar cells, compound semiconductor solar cells, dye-sensitized solar cells, perovskite solar cells and organic solar cells. The earliest to enter the public field of vision is also the earliest made of monocrystalline silicon solar cells, whose energy conversion efficiency is 6%. Subsequently, crystalline silicon photovoltaic cells, that is, monocrystalline silicon or polysilicon photovoltaic power generation, have gradually become popular and successfully commercialized. Then the second generation photovoltaic cells, the third generation photovoltaic cells and organic photovoltaic cells have gradually become the focus of research. At present, the highest power conversion efficiency of organic photovoltaic cells has been certified by more than 18% [3]. Although there is still a gap in the efficiency of organic photovoltaic cells compared with the former, compared with the shortcomings of the former production process is complex, raw materials are rare, and the cost is high, the raw materials of organic photovoltaic cells are rich, the preparation process is simple, the texture is soft, and can be large-scale production by rolling to rolling and other processing methods. Translucent organic photovoltaic cells inherit these advantages on the basis of the above, but also has the characteristics of translucent. This can be applied not only in buildings and greenhouses, but also in areas such as laminated battery structures. However, there are still shortcomings and defects in photoelectric conversion efficiency, carrier lifetime and device stability of organic photovoltaic cells. However, how to improve organic photovoltaic cells, such as improving the efficiency of organic photovoltaic cells, increasing carrier life, improving device stability, etc., is still a hot topic of research.

At present, most research groups focus on the improvement of materials and structures to improve the performance of organic photovoltaic cells, such as the transparency optimization of the top electrode, device stability optimization, preparation process optimization, etc., but there is a lack of more systematic and complete literature review to sort out the above contents, and the literature review in this field is relatively blank. In order to fill the research gap in this field, this article focuses on the discussion of translucent organic photovoltaic cells, one of the new energy sources. The structure, related parameters and working principle of organic photovoltaic cells are summarized. After that, this paper will discuss the research progress of translucent organic photovoltaic cells from three perspectives: material design, photovoltaic design and electrode design. Further, to discuss the research hotspot and current situation of translucent organic photovoltaic cells, and analyze the application prospect of translucent organic photovoltaic cells, in order to provide detailed reference materials and theoretical support for this field.

2. Overview of Translucent Organic Ohotovoltaic Cells

2.1. Background

The research of organic photovoltaic cells began in 1959 with the report of H.Kallmann and M. ope, and the device with single crystal anthracene as the active layer between the two electrodes entered the field of vision of researchers, but at that time its photoelectric conversion efficiency was extremely low, only 2×10^{-6} [4]. For a long time after this, the efficiency of organic photovoltaic cells did not make a great breakthrough. The principle of the metal-insulation-semiconductor structure used in the device is to drive the dissociation of excitons in the device through the work function difference between the two electrodes. But the most obvious problem with the device is that this weak driving force does not dissociate excitons enough, thus limiting the upper limit of photoelectric conversion efficiency.

In 1986, Dr. Deng Qingyun made a breakthrough by introducing heterojunctions into device structures. He used phthalocyanine as the donor and perylene as the acceptor to prepare organic photovoltaic devices, achieving a photoelectric conversion efficiency of close to 1%[5]. The D/A heterojunction structure can be said to be a major breakthrough in the field of OPV, because there is a difference in the lowest empty orbital energy level between the donor and acceptor layers between the two electrodes, allowing excitons to separate more efficiently at the interface between the donor and acceptor layers. However, due to the influence of light absorption in the active layer of the device, exciton generation is not only limited by the interface between the donor layer and the acceptor layer, but also because the interface area is limited, which hinders the separation of excitons, resulting in a strong electrostatic coupling of charges.

In order to improve the shortcomings of organic photovoltaic devices, the structure of organic photovoltaic cells is constantly optimized, from double heterojunction to bulk heterojunction, active layer material design is constantly updated, from fullerene derivatives to non-fullerene receptors. The research of organic photovoltaic cells is maturing, and gradually moving toward mass production and marketization.

2.2. Working Principle of Organic Photovoltaic Cells

The photovoltaic effect is the key to the photoelectric conversion of photovoltaic cells. According to this effect, under the irradiation of light, the electron hole pair is excited into excitons, separated by the action of electrostatic potential energy, and transferred to the electrode, resulting in the electromotive force. Therefore, the working principle of organic photovoltaic cells and crystalline silicon cells is basically the same, but the differences in the composition and material selection of the two make the actual mechanism is not the same. The core of the crystalline silicon cell is the mixed monocrystalline silicon. The core of organic photovoltaic cells is the photosensitive active layer. The structure of organic photovoltaic cells such as active layers will be discussed in the next section. The working principle of organic photovoltaic cells discussed in this section can be divided into four parts:

(1) Photon absorption and exciton production: when external light is injected, the active layer absorbs specific photons. The absorption is based on the fact that the photon energy of the incident light is greater than or equal to the band gap width of the donor material. After that, the electrons on the donor surface absorb energy, transition from the HOMO to the LUMO orbital, and the electron vacancy forms a hole, and the corresponding hole and the electron are electrostatic coupled to form an electron hole pair, namely exciton. However, the binding capacity of excitons is larger, between 0.3-0.5eV.

(2) exciton diffusion: A large number of excitons formed in the material reach the donor-acceptor interface through diffusion due to concentration differences. But in general, in organo-organic semiconductor materials, excitons have a limited and short diffusion distance, between 10-20nm. Therefore, only when the distance of the exciton to the donor-acceptor interface is within the diffusion range of the exciton can it dissociate to form holes and electrons. Instead, excitons recombine, releasing energy by emitting light and heat.

(3) exciton dissociation: When the exciton diffuses to the donor-acceptor interface, the exciton will dissociate under the action of the energy level difference between the donor and the acceptor materials, becoming a hole and an electron. The resulting electrons will be transferred to the LUMO energy level of the acceptor material, while the holes will remain in the HOMO energy level of the donor material.

(4)Transport and collection of electrons and holes: the resulting electrons and holes will attract electrons to the cathode and holes to the anode under the action of the electric field of the device's built-in electrode, and the external circuit will generate current.

2.3. Structure of Organic Photovoltaic Cells

An organic photovoltaic cell is a device that converts light energy into electrical energy. Its common device structure takes the single-section device most commonly used in the laboratory as an example, which can be divided into 5 parts, the shape of the device is similar to a sandwich, from the outside to the inside are: positive and negative electrodes, two interface modification layers, namely the electron transport layer and the hole transport layer, and an active layer.

Positive and negative electrodes: The two electrodes are located on the outermost sides of the organic photovoltaic device. In order to ensure the normal and efficient operation of the photovoltaic cell, one pole of the photovoltaic cell will be used as a transparent electrode with high optical transparency. In traditional organic photovoltaic cell devices, indium tin oxide (ITO) glass with high transparency and good conductivity is often used as the anode to collect holes. The other pole will act as the role of reflecting light, with extremely high reflectivity, usually using high-reflectivity metal aluminum or silver as a cathode, collecting electrons and achieving secondary absorption of light.

Interface modification layer: The interface modification layer will modify the corresponding Cathode and anode electrodes to achieve selective transport of electrons and holes. In the traditional organic photovoltaic cell device structure, the anode ITO is often modified by PEDOT:PSS as a buffer layer, which helps to reduce the electron capture between the anode and the active layer, and makes the active layer material better spread. The cathode was modified with low work function (WF) metals Ca and Ba.

In the above example, the organic photovoltaic cell device structure is called a forward device. In this device, the acidity of PEDOT: PSS will corrode the ITO [6] of the anode, and low work function metals are easily corroded by oxygen and moisture. The above factors seriously affect the efficiency and stability of organic photovoltaic cells, and shorten the life of photovoltaic cells. The reverse device is to invert the forward device, usually using low-WF zinc oxide modified cathode ITO, ITO no longer collects holes, but collects electrons; the hole transport layer is usually molybdenum trioxide (MoO3) with high WF. The above changes make the reverse device have better stability.

Active layer: The active layer is the core of organic photovoltaic cells, and organic materials are usually selected as the active layer to achieve photon absorption and conversion. Due to the narrow absorption spectrum of a single organic material, it is impossible to cover the solar spectrum in a large range. In order to make greater use of sunlight per unit area, a method is developed to superposition organic photovoltaic devices with multiple active layers with different band gaps perpendicular to the base direction, thus forming a classification of the number of active layers: laminated devices and single-section devices.

Among the active layer materials, the bulk heterojunction has the best device performance in organic photovoltaic cells. In the bulk heterojunction, the acceptor solution and donor solution are mixed, and the resulting biconcontinuous interpenetrating network structure has natural advantages, and the large specific surface area is helpful for exciton dissociation. However, the collection of electrons and holes by the anode and cathode electrode is more advantageous in the planar heterojunction. Therefore, layer-by-layer devices that combine planar heterojunctions and bulk heterojunctions have become the focus of research.

3. Development Status and Research Hotspots

Because of its soft texture, light quality, flexible material selection, low-cost large-area printing and preparation advantages, organic photovoltaic cells are popular in the academic community, while in the market compared with other photovoltaic cells are also very competitive. In addition to inheriting many advantages of organic photovoltaic cells, translucent organic photovoltaic cells also have the advantage of absorbing other wavelengths of light through visible light and converting it into electricity. Therefore, translucent organic photovoltaic cells are highly valuable in the fields of BIPV integration in buildings (BIPV)[7], agricultural greenhouses, vehicles, portable electronic devices, etc. and these applications will be discussed in section 3. And translucent organic photovoltaic cells in the market-oriented, towards the popularization and cutting-edge academic research on the emergence of many problems, exposed many defects, organic photovoltaic cells structure and material optimization is still in progress. The following will discuss the development status and research hotspots of translucent organic photovoltaic cells.

3.1. Development Status

Translucent photovoltaic cells in the concept, should have a good selection of different wavelengths of light transmittance, the ultraviolet light and near-infrared light fully absorbed and efficiently converted into electricity. At the same time, the horizontal comparison of the inorganic semiconductor as the core of the translucent photovoltaic cells, translucent organic photovoltaic cells because of its optical property adjustment flexible characteristics, in the translucent photovoltaic cells stand out. It will balance the absorption and transmission of visible light according to the actual situation, in order to meet the market demand and more full use of light energy.

In 2006, Yang reported based on the P3HT: PC61BM as the active layer of translucent organic photovoltaic cells, using ITO|Cs2CO3|3HT: PC61BM V205|Au (12 nm) or ITO, with gold and ITO as the top electrode material, the energy conversion efficiency reached 0.52% and 0.85%. In 2011, Colsmann et al. reported that the device based on PSBTBT: PC71BM as the active layer has a color rendering index (CRI) of up to 86, showing good color rendering capability. In 2017, Zhan et al.

reported on the device based on IHIC and PTB7-Th system, the energy conversion efficiency exceeded 9.77%, and the visible light transmittal (AVT) reached 36% [8-10].

The research enthusiasm for translucent organic photovoltaic cells has never waned, and it is constantly innovating. When it comes to the development of translucent organic photovoltaic cells, the key lies in the optimization of all aspects of its design, which is mainly in three aspects: material, electrode and optical design.

3.1.1. Active layer material

The design of active layer materials mainly focuses on the selection and proportional regulation of donor materials and acceptor materials, and the introduction of narrow band gap materials to match different band gap materials, so as to achieve a balance between photovoltaic conversion efficiency and AVT. Achieve light transmittance of 380-750nm wavelength and make full use of other wavelengths of light.

In terms of receptor materials, it is mainly divided into fullerene materials and their derivatives and non-fullerene receptors. Since fullerene receptors were reported to be used in organic photovoltaic cells in 1995[11], the photovoltaic conversion efficiency of fullerene receptors was much higher than that of non-fullerene receptors at first. However, on the one hand, fullerene receptors have many shortcomings, such as narrow spectral range and low light absorption coefficient. On the other hand, the selection of non-fullerene receptor building units is wide and new materials are continuously synthesized, and the photovoltaic conversion efficiency continues to break through. Since most of the energy in the solar spectrum is concentrated in the near-infrared light band, and the conversion efficiency of non-fullerene small molecule receptors in this band is excellent, which makes non-fullerene receptors become one of the focuses of research. For example, in 2019, Zou et al. synthesized a non-fullerene material, Y6 [12], which is known as a star small molecule receptor. As soon as it was reported, it received high attention from the academic community and was designed as a device with structure ITO|Al(Ac)3|PM6:Y6|MoO3|Ag in 2020, with photovoltaic conversion efficiency up to 12.41% and AVT up to 25.33%[13]. Similarly, in terms of donor materials, the focus of scientific research is also focused on narrow band gap donor materials, the pursuit of both strong near-infrared light absorption capacity and strong visible light transmission capacity. While considering the bandgap and absorptive capacity of donor and acceptor materials, factors such as material solubility and carrier mobility are some of the directions of optimization.

3.1.2. Electrode design and optimization

The translucent top electrode should have a suitable energy level, a good collection ability for carriers, excellent electrical conductivity, visible light transmittance, non-visible light reflection ability, especially near infrared light, and other factors are included in the design and optimization considerations, while the physical and chemical properties of the material and whether the preparation process has an impact on the active layer are also considered.

In 2006, Yang et al. reported for the first time the use of 12nm ultra-thin metal film gold (Au) as a translucent electrode and the inverted structure of ITO|Cs2CO3|P3HT:PC61BM|V2O5|Au(12nm) to reveal the prelude to the study of translucent organic photovoltaic cells. In the report, light is injected from ITO and Au electrodes, and the photovoltaic conversion efficiency is 0.85% and 0.52%, respectively. The difference in efficiency is mainly due to the stronger reflection ability of Au electrodes to light, and therefore, the reflection ability of non-visible light, especially near-infrared light, is one of the important factors in the design[8]. Ultra-thin metal film metal has also entered the field of vision of researchers, but at that time, the ultra-thin metal film still faced the problems of poor electrical conductivity, low AVT and poor color rendering performance. In 2013, Schubert et al. reported that Ca, Al and Au were deposited on the surface of an ultra-thin metallic silver Ag film as a translucent top electrode, thereby improving the conductivity of the electrode. In 2015, Shen et al reported that photovoltaic devices with the structure of ITO|TiO2|PSBTBT:PC60BM|WO3|Ag| photonic crystal (n-layer WO3|LiF) enhanced AVT and color rendering performance by selectively reflecting light in ultraviolet and infrared bands and maintaining transmittance to visible light [14,15].

Subsequent metal oxide electrodes, conductive polymer electrodes, silver nanowire electrodes, carbon nanotubes and graphene electrodes all play an important role in the electrode materials of translucent organic photovoltaic cells, and each of the four has its advantages and disadvantages.

3.2. Research Hotspots

In the previous development status of translucent organic photovoltaic cells, it can be clearly concluded that the development of translucent organic photovoltaic cells revolves around the balance between photovoltaic conversion efficiency and visible light transmittance, and develops two sub-problems of design and optimization of active layer and translucent electrode. The problems and difficulties arising from the extension of these two sub-problems and the implementation of the actual market mass production are the so-called research hotspots, including but not limited to the regulation and preparation of color photovoltaic cells through optical design, the exploration of non-fullerene materials, and the research of improving the stability of devices.

3.2.1. Device stability optimization

As a large-scale application of organic photovoltaic cells to civilian applications in the future, the stability of its device structure is an unavoidable problem. With the continuous breakthrough of its energy conversion efficiency, the topic of stability has gradually become a hot research topic. How to improve the stability of organic photovoltaic cells, mainly to overcome the inherent instability of organic photovoltaic devices, light, temperature and air on the stability of the device. The performance of organic photovoltaic cells will gradually decrease during the process of the morphology of the active layer and the diffusion of each layer material. The light will degrade the device by photochemistry and photophysics. At the same time, organic photovoltaic cells have to face continuous high temperature when working, but their thermal stability cannot be adapted to the operating temperature of the parts; In addition, the water and oxygen in the air will diffuse into the device, and the corrosion and oxidation of the device will accompany this process. For example, the commonly used hole transport layer PEDOT: PSS has been studied to diffuse into the active layer through molecular thermal motion, affecting the efficiency [16].

3.2.2. Research and development of color translucent organic photovoltaic cells

With the development of photovoltaic cells and the commercialization of photovoltaic cells, BIPV has gradually entered the public's vision. In the design of BIPV, translucent organic photovoltaic cells as an important part, not only provide power supply value, at the same time, in order to meet the needs of BIPV for different occasions of transmitted light color, produce neutral color and color translucent photovoltaic cells division. The development of color translucent photovoltaic cells can meet the needs of designers in the BIPV market and related industries, but also provide aesthetic value to the public. As a part of life and art, there is great potential for development. For example, in 2014, Lin et al reported a color device with Ag|NPB|Ag as the cathode electrode with Fabry-Perot cavity structure. This micro-cavity structure can prepare translucent organic photovoltaic devices of various colors by adjusting the thickness of dielectric layer NPB [17].

3.2.3. Deficiencies, defects and the key to development

Different from the development of organic photovoltaic cells, the key to the development of translucent organic photovoltaic is to find a balance between energy conversion efficiency and AVT and CRI. Therefore, the commercial large-scale application of translucent organic photovoltaic cells in AVT must reach the threshold of 25%. In addition, this key also leads to the need for electrical conductivity and transparency of the top electrode and the need for efficient near-infrared light absorption, visible light transmission and stability of the active layer material. Even at the moment of full development and obvious efficiency improvement, the aesthetic demand for translucent organic photovoltaic cell color has become the focus of research. And the mapping is people's pursuit of various needs. It is also in the process of meeting the needs, in the mass production is still in the early stages, which exposed many problems. For example, the device stability as a research focus, the problem that the laboratory preparation process cannot match the large-scale actual production, the problem of material production cost. For example, in the production of high-efficiency devices, its small area (~0.04cm^2), the production process has highly toxic halogenated solvents and other problems limit its development.

4. Application and prospect

As mentioned above, translucent organic photovoltaic cells as a device with great market potential, its inherent advantages, such as the visible light through and absorption of invisible light, photoelectric conversion, in this will not be repeated. As a new type of photovoltaic technology, it will complement the advantages of other photovoltaic cells. At the same time, the solution of many environmental problems is imminent, which is also an external factor to promote the development and application of photovoltaic cells. Among them, translucent organic photovoltaic cells have the advantages of soft texture and visible light transmission, and have wide application possibilities in agricultural greenhouses, BIPV, transportation vehicles and portable electronic equipment. The following will discuss the application of translucent organic photovoltaic cells.

4.1. Applications

Unlike traditional power generation equipment, the energy of photovoltaic cells comes from green solar energy, which is in line with the increasing demand for clean energy in social development. Because of their advantages, translucent organic photovoltaic cells will provide aesthetic value while facilitating life as a power generation device. As a result, it is constantly moving towards the market in the construction field and wearable electronic devices. The following will take agricultural greenhouses and BIPV as examples to explain.

4.1.1. Photovoltaic agricultural greenhouses

Photovoltaic agricultural greenhouse as a new greenhouse, its surface will be covered by photovoltaic devices, without affecting the growth of crops at the same time, make full use of the crop does not need to convert light into electricity storage. For example, ultraviolet light, which usually has a certain harmful effect on crop growth, can be collected and converted into electricity by translucent organic photovoltaic cells. Through the combination of photovoltaic cells and agricultural greenhouses, the formation of solar room type photovoltaic agricultural greenhouses, simple photovoltaic agricultural greenhouses, plus solar module type plastic agricultural greenhouses, agricultural greenhouses four forms. It provides advantages for the utilization of light energy resources, crop growth and economic benefits [18]. In the future, energy self-sufficiency may be satisfied; Environmental control will improve the quality of agricultural products; Make full use of land resources to realize the versatility of agriculture.

4.1.2. Photovoltaic Building Integration (BIPV)

Translucent organic photovoltaic cells in the future BIPV, indoor photovoltaic, wearable electronic devices and other fields will be involved, and BIPV will be one of the main application directions, used in architectural glass, automotive glass, high-rise glass curtain wall and other aspects. Buildings account for 40% of global energy consumption, mostly for artificial lighting, heating and cooling [19], and photovoltaic cells will act as power generation devices to offset some of the energy consumption. Therefore, photovoltaic building materials with different functions emerge endlessly, "photovoltaic curtain wall", "photovoltaic sunshade", "photovoltaic shed", reflecting the development of solar photovoltaic in the field of BIPV [20].

4.2. Outlook

Compared with the history of the entire development of photovoltaic cells, translucent organic photovoltaic cells are still an emerging technology. There are still many obstacles to its development. On the one hand, the device is coated on a large area, and it still faces the challenge of how to realize ultra-thin interface processing. On the other hand, it is the problem of improving the stability of the device, such as how to achieve the challenge of optical stability. Although the development of translucent organic photovoltaic cells is difficult, but with the continuous breakthrough of its technology, the pace of marketization has never stopped, and the road to the application of translucent organic photovoltaic cells is still a long way to go.

5. Conclusion

Through the research and discussion of the above content, the development of translucent organic photovoltaic cells from the past to the future, each step taken, including the development status, research hotspots, application prospects, etc., all around a topic, to grasp the concept of translucent organic photovoltaic cells as a whole. Among them, in the first part, the grasp of the development of organic photovoltaic cells, as well as the discussion of its working principle and device structure, these as the preparatory work discussed below, is the skeleton of the whole translucent organic photovoltaic cells. Then, whether it is the development and hot spots of the second part, or the direction and trend of its future market, all of which are inseparable from the photovoltaic device in the photovoltaic conversion efficiency and AVT balance between the control of this core, as a basic concept, linked to the entire translucent organic photovoltaic cell system; As the ultimate goal and driving force of development, it constantly generates new concepts and research hotspots, introduces new technologies and stimulates market potential. It is precisely because of the continuous emergence of new concepts and new technologies that it is extremely important to summarize the development of translucent organic photovoltaic cells by means of bibliometric methods, as a link between beginners or those with less contact and the academic frontier in this area. However, this does not mean that this article is perfect enough, limited time cannot make this paper fully understand all the literature in the relevant field, and limited space cannot make this paper to do everything. Therefore, if the academic is the deep sea, this paper is just a piece of floe ice, the future still requires and expects people to explore more deeply in this field.

References

[1] Golledge N R, Nicholas R. Golledge E D K, Gomez N, et al. Global environmental consequences of twenty-first-century ice-sheet melt .Nature. 2019, 566(7742): 65-72

[2] Ma Limei, Wang Junjie. Energy transformation and renewable energy innovation - based on empirical study of the multinational data. Journal of Zhejiang Academy of Social Sciences, 2021 (04): 21-30.

[3] Li C, Zhou J, Song J, et al. Non-fullerene acceptors with branched side chains and improved molecular packing to exceed 18% efficiency in organic solar cells.Nature Energy. 2021, 6(6): 605-13.

[4] Kallmann H, Pope M. Photovoltaic effect in organic crystals. Journal of Chemical Physics, 1959, 30(2): 585-586.

[5] Tang CW. Two-layer organic photovoltaic cell. Applied Physics Letters, 1995, 48: 183-185.

[6] Nakno K, Tajima K. Organic planar hetero junctions: From models for interfaces in bulk heterojunctions to high-performance solar cells. Advanced Materials. 2017, 29(25):1603269.

[7] Sorgato M J, Schneider K, Ruther R. Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing fa ade and rooftop materials in office buildings in a warm and sunny climate. Renewable Energy, 2018, 118: 84-98.

[8] Li G, Chu C W, Shrotriya V, et al. Efficient inverted polymer solar cells [J]. Applied Physics Letters, 2006, 88(25): 253503.

[9] Colsmann A., Puetz A., Bauer A., et al. Efficient semi-transparent organic solar cells with good transparency color perception and rendering properties. Advanced Energy Materials. 2011, 1(4): 599-603.

[10] Wang W, Yan C Q, Lau T K, et al. Fused hexacyclic nonfullerene acceptor with strong near-infrared absorption for semitransparent organic solar cells with 9.77% efficiency. Advanced Materials. 2017, 29(31).

[11] Yu G, Gao J, Hummelen J C, et al. Polymer photovoltaic cells: enhanced efficiencies via a network of internal donor-acceptor heterojunctions. Science. 1995, 270(5243): 1789-91.

[12] Yuan J, Zhang Y, Zhou L, et al. Single-junction organic solar cell with over 15% efficiency using fused-ring acceptor with electron-deficient core. Joule. 2019, 3(4): 1140-51.

[13] Bai Y M, Zhao C Y, Shi R K, et al. Novel cathode buffer layer of Al(acac)(3)enables efficient, large area and stable semi-transparent organic solar cells. Materials Chemistry Frontiers. 2020, 4(7): 2072-80.

[14] Schubert S, Meiss J, Müller-Meskamp L, et al. Improvement of transparent metal top electrodes for organic solar cells by introducing a high surface energy seed layer. Advanced Energy Materials, 2013, 3(4): 438-443.

[15] Yu W, Jia X, Long Y, et al. Highly efficient semitransparent polymer solar cells with color rendering index approaching 100 using one-dimensional photonic crystal. ACS Applied Materials & Interfaces, 2015, 7(18): 9920-9928.

[16] Chen Y H., Chen C W., Huang Z Y., et al. Organic solar cells: microcavity-embedded, colour-tuneable, transparent organic solar cells. Advanced Materials, 2014, 26(7): 1129.

[17] [17] Franke R, Maennig B, Petrich A, et al. Long-term stability of tandem solar cells containing small organic molecules. Solar Energy Materials and Solar Cells, 2008, 92(7): 732-735.

[18] Guo Wenhua. Photovoltaic agricultural greenhouse planting technology applications. Agricultural machinery use and maintenance, 2022 (9): 133-135.

[19] Li DHW, Lam TNT, Wong SL, Tsang EKW. Lighting and cooling energy con sumption in an open plan office using solar film coating. Energy 2008; 33(8): 1288e97.

[20] Zhu Chaofeng, Zhao Zhenmin, Sun Yuqing, et al. Organic photovoltaic cells in the building integrated photovoltaic application and prospects. Journal of guangxi university (natural science edition), 2023 (6): 13.