Organic solar cells: Exploring the future and sustainability of clean energy

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Abstract. As a critical technology in renewable energy, organic solar cells play an important role in energy transition and sustainable development. This paper examines the development and significance of organic solar cells in terms of energy demand, environmental requirements, and industrial growth. With the development of China's energy structure adjustment and carbon peak carbon neutral targets, interest in novel energy technologies is growing. The paper then describes the interaction between photons and materials and the electron-hole separation and charge transport mechanism of organic solar cells. In addition, the characteristics and potential applications of organic solar cells with various structures, such as bilayer heterojunction devices, intrinsic heterojunction devices, molecular DA junction devices, and stacked devices, are described in depth. In the outlook section, the paper emphasizes the future potential of organic solar cells, including efficiency enhancements, cost reductions, and integration with energy storage technologies. In conclusion, organic solar cells have tremendous potential in the field of renewable energy, and they are anticipated to lead the energy transition and contribute to sustainable development.

Keywords: energy, cell, environment.

1. Introduction

In a world where environmental concerns have transcended regional boundaries and energy security has become a global imperative, the urgency to embrace renewable energy solutions is unmistakable. The legacy of traditional fossil fuel consumption, marked by ecological degradation and the specter of climate change, has galvanized a concerted quest for alternative energy pathways that promise sustainable growth [1-5]. Amid this transformative landscape, solar energy emerges as a luminous beacon of hope, embodying the potential to revolutionize the way we power our world. Endowed with abundant resources and characterized by emissions that bear no ecological burden, solar energy stands tall among the pantheon of renewable options, offering a compelling route to surmounting the energy conundrum while safeguarding our planet's fragile equilibrium.

Stepping onto this stage of transformative energy solutions, organic solar cell technology has embarked on an odyssey of evolution. Its journey spans from the nascent corridors of laboratory

DOI: 10.54254/2755-2721/85/20240681

experimentation to the bustling avenues of commercial applications, propelling organic solar cells into the spotlight of the clean energy arena. The driving force behind this paradigm shift is the enchanting choreography of the photovoltaic effect – a dance in which photons and semiconductor materials collaborate to awaken the mesmerizing duo of electrons and holes [6,7]. Their harmonious interplay births an electric current, an eloquent testament to the boundless potential that these cells possess. This current, pulsating with energy, holds within its currents the promise to electrify devices, light up homes, and weave the intricate threads of a resilient energy grid.

However, this journey towards harnessing the unbridled potential of organic solar cell technology is no mere sprint; it's a marathon strewn with challenges that demand ingenious solutions. Enabling the full realization of their promise rests upon a relentless pursuit of efficiency enhancement, stability reinforcement, and the reduction of production costs. Beyond this, a sustainable tomorrow mandates a conscientious examination of the environmental footprint woven into their fabrication and processing – a clarion call for innovative strategies that temper issues such as wastewater management and material recycling [8-10]. In laboratories and research hubs, scientists and engineers toil in harmony, unveiling the secrets of new materials, trailblazing methodologies, and holistic paradigms that are poised to shape the trajectory of organic solar cell advancement.

It's in this landscape of innovation and progress that this paper unfurls its mission, an odyssey through the intricacies of design, operational principles, material innovations, and the horizon of future prospects for organic solar cells. By immersing ourselves in the currents of cutting-edge technological innovations, we crystallize our understanding of the profound significance and latent potential organic solar cells offer to the energy ecosystem. Beyond the confines of energy generation, these cells echo the ethos of environmental guardianship, the pillars of sustainable evolution, and the architects of a seamless transition towards an energy-efficient tomorrow. As we venture into an era propelled by renewable energy ideals, organic solar cells stand as the vanguard of innovation, casting their brilliance on the path toward a brighter, more sustainable future.

2. Study on the evolutionary prospects of photovoltaic energy

2.1. Research Background and Significance

New energy development is an inevitable trend and a prerequisite for achieving sustainable development. As socialism with Chinese characteristics enters a new era, new requirements for energy development by the unique historical orientation, promoting the adjustment and optimization of the energy structure and industrial structure, and constructing an environmentally conscious and resource-conserving society have become prevalent trends [11]. In 2021, the State Council released "Opinions on the Complete and Accurate Implementation of the New Development Idea and Doing a Good Job in Carbon Peak and Carbon Neutral Work," which promotes the notion that economic and social development should be green, low-carbon, and resource-efficient. The economic and social development should be based on green and low carbon and efficient utilization of resources. The carbon peak should be implemented in all aspects of economic and social development, focusing on the implementation of the "Ten Actions of Carbon Peak", such as energy green and low carbon transformation actions, green and low carbon science and technology innovation actions, and energy saving, carbon reduction, and efficiency actions, and striving to achieve carbon neutrality by 2050. It aims to attain a non-fossil energy consumption proportion of at least 20%/25%/80% by 2025/2030/2060, respectively. Under the policy requirements of dual-carbon targets and energy structure transformation, new energy sources such as solar and wind power have the benefits of being environmentally friendly, renewable, and resource-rich, making them an essential means of achieving dual-carbon targets and advancing energy structure transformation. The structure of China's energy consumption from 2013 to 2021 is depicted in Figure 1. China's energy development trajectory is evident, as the proportion of renewable and clean energy is rising steadily and will continue to rise.

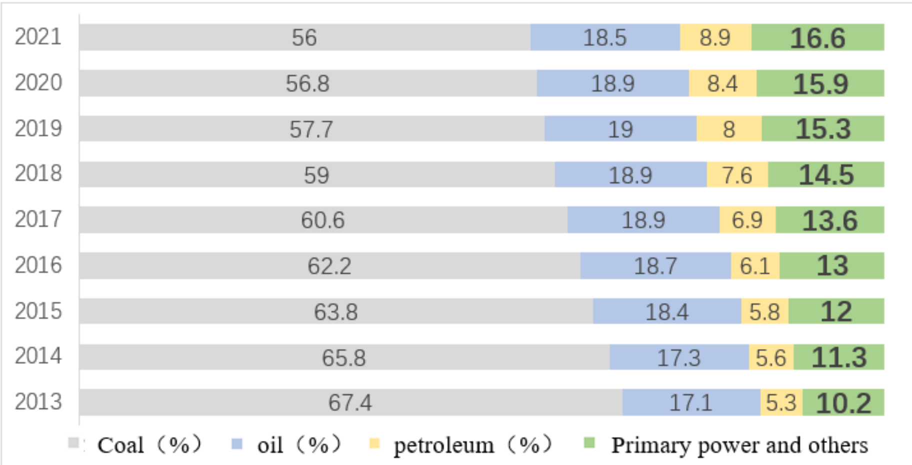

Figure 1. China's energy consumption structure in 2013-2021 (Source: National Bureau of Statistics).

On the other hand, the new energy industry encompasses a broad range of fields and a lengthy industrial chain, which is capital- and technology-intensive. Its development will positively influence the development of other industries in the industrial chain, such as the manufacturing industry, transportation industry, etc., enabling these industries to achieve synchronized technological and scale development and thus form industrial clusters of a certain level. This also means that more employment opportunities will be created and that the economic development of urban and rural areas and the living standards of the population will be enhanced. The new energy industry has a significant economic multiplier [12,13]. The technology diffusion effect is an important force that must be addressed in China's future economic development. The country, businesses, and individuals can all benefit from the new energy wave. In conclusion, the new energy industry is anticipated to become a significant force in national energy development and a substantial driver of economic growth.

There are many kinds of new energy; solar energy has always been a lot of attention. Compared with tidal energy, wind energy, nuclear energy, and other new energy sources, solar energy is widely distributed, huge energy, high security, and mining constraints are small, and to this day, it still has great potential for development. Many researchers are committed to research and development of efficient, new, and practical solar cells; solar cells can be divided into silicon solar cells, organic solar cells, chalcogenide solar cells, etc., according to the use of different materials, of which organic solar cells as a rising star, with good flexibility, easy processing, lightweight, can be printed on a large area and so on, has gradually become a hot spot for research in the field of solar cells, Figure 2 shows the physical picture of organic solar cells.

Figure 2. Organic solar cells prepared in the laboratory (left) and its application (right).

DOI: 10.54254/2755-2721/85/20240681

Over the years, the research in organic solar cells has been deepened layer by layer, the device structure and material types have been constantly introduced, and the energy conversion efficiency has been steadily improved. However, there is still a large gap in its practical application compared with the traditional inorganic solar cells, which is mainly due to the constraints of several problems, such as the organic solar cell conversion efficiency is not high enough, unstable, and poor durability, etc., to further solve these problems, the quality control of the device from the macroscopic point of view must be adjusted from the macro point of view. Quality is regulated in addition to the micro perspective. We must have a more in-depth understanding of the properties of disordered organic semiconductor materials, especially the charge transport problems associated with it.

2.2. Design and working principle of organic solar cells

The design of organic solar cells begins with selecting suitable organic semiconductors. When exposed to light, these substances are typically organic molecules or polymers capable of producing electron-hole pairs. To accomplish highly efficient photovoltaic conversion, designers must consider the material's light-absorbing properties, charge-transfer properties, and stability. In addition, the structure of the cell, including the thickness of the active layer, electrode materials, and interface engineering, is an integral part of the design. Organic solar cells operate based on the photoelectric effect, which converts light energy to electricity. In an organic solar cell, photon energy is absorbed by an organic semiconductor, which excites electron-hole pairs. These electrons and holes are separated within the semiconductor material to create a flow of electrons and holes [14]. When creating an electric current, electrons travel to one cell pole while holes flow to the other. This current circulates in external circuits and can power electronic devices, store energy, or provide energy to a residence. Light energy is converted efficiently into practical electrical energy throughout the process, allowing for energy conversion and utilization.

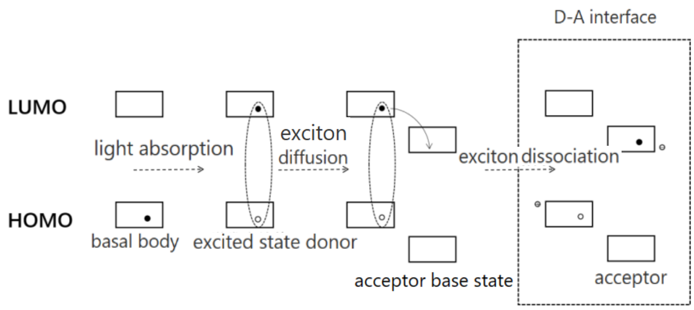

Figure 3. Formation of excitons by photon absorption by the donor material, diffusion of excitons to the DA interface, and the process of exciton dissociation.

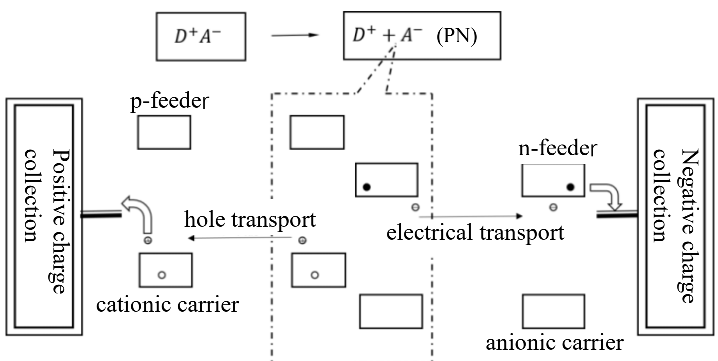

Figure 4. Formation, transport and collection of cation and anion carriers.

Organic solar cells rely on separating electrons and holes within the material, which is achieved by organic semiconductors' energy band structure and electric field effect. The separation of electrons and holes generates a potential difference, which produces a voltage that drives a current through the circuit. Therefore, the design and optimization of organic solar cells focuses on maximizing the efficiency of photon absorption, electron-hole separation, and charge transport to enhance the cell's overall performance. By better comprehending how organic solar cells function, we can better understand their potential application in the clean energy sector and contribute to advancing sustainable energy development (see Figures 3 and 4).

2.3. *Structure of organic solar cells*

There are distinctions in charge transport between organic solar cells with various structures, necessitating a comprehension of the structure of different organic solar cell devices. Typical organic solar cell devices are depicted in Figure 5, including bilayer heterojunction devices, intrinsic heterojunction devices, molecular DA junction devices, and layered devices.

Figure 5(a) depicts the bilayer heterojunction devices, which are simple in structure, have a high energy conversion efficiency, are appropriate for the study of charge transport issues, and are the most important device structures for our research. To improve the charge collection rate of the double-layer heterojunction device, the work function of the anode should correspond to the highest occupied orbital energy level of the donor material, and the work function of the cathode should match the lowest vacant orbital energy level of the acceptor material. The donor and acceptor materials are separated between two electrodes to form a planar-type DA interface. Several stages are required for this device to convert photons into electrons, including exciton generation, exciton diffusion, exciton separation, carrier transport, and carrier collection. The device's driving force for charge separation is primarily determined by the LUMO energy level difference between the donor and the acceptor, i.e., the electronic barrier at the planar-type DA interface. If the electronic barrier at the planar-type DA interface is greater than the exciton's binding energy, the exciton is more likely to dissociate. To increase the efficiency and stability of the cell, the design of suitable bilayer heterojunction devices requires consideration of donor and acceptor materials, energy gap thickness, and width.

As shown in Figure 5(b), the DA interface of the native heterojunction device is distributed throughout the active layer. Carriers in the intrinsic heterojunction device are transported primarily via osmosis. In contrast, carriers in the double-layer heterojunction device are transported with a spatially continuous distribution of donor and acceptor materials as the transport medium, resulting in a lower carrier transport efficiency than that of the double-layer heterojunction device. They are more sensitive to the physicochemical properties of the material due to the transport properties of intrinsic heterojunction devices. Units with electron-donor properties covalently bonded to acceptor small molecules or polymers can form homogeneous bipolar molecular DA junction materials, which can fabricate molecular DA junction devices, as depicted in Figure 5(c). In these devices, light transmission through the DA junction material generates a chemical gradient within the molecule, which powers exciton dissociation and charge transport. The benefit of such DA junction devices is that phase separation between the donor and acceptor materials can be avoided, and the efficacy of charge separation can be enhanced. In contrast to intrinsic heterojunction devices, the increased efficiency of photoinduced charge transfer in molecular DA junction devices is accompanied by an increased probability of charge complexation. Fig. 5(d) depicts the stacked device structure, which consists of two or more unit structures connected in series and is designed to maximize the absorption of the solar spectrum to boost the device's conversion efficiency and open-circuit voltage. The absorption range of organic materials is limited, and the solar spectrum has a wide energy distribution; therefore, a single organic material cannot achieve full coverage of the solar spectrum's energy range; only a portion of the spectral energy is absorbed, and the unabsorbed power will produce thermal effects, thereby affecting the performance of the cell. The key to designing stacked solar cells is locating active unit materials with well-matched lattices, utilizing the different absorption ranges of other materials to increase the

DOI: 10.54254/2755-2721/85/20240681

absorption of the solar spectrum, and giving full play to the characteristics of a single material and the integrity of the device, thereby increasing efficiency and reducing performance degradation.

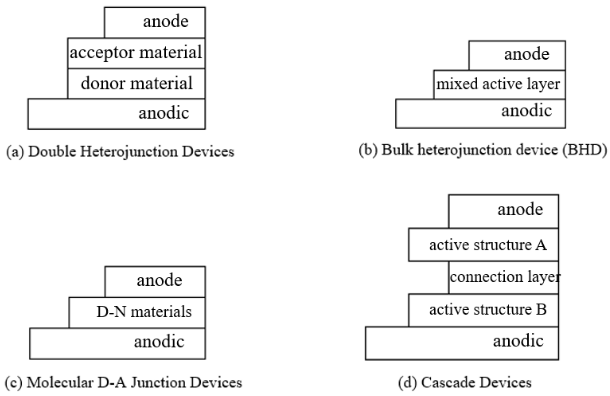

Figure 5. Typical structure of organic solar cells.

Among the above typical organic solar cell device structures, the bulk heterojunction device provides a hole transport channel and an electron transport channel, and after the exciton generates charge transfer, the hole and electron are transported in the donor and acceptor materials, respectively, with a low probability of exciton compounding and high carrier transport efficiency. Its simple and clear structure is very suitable for charge transport analysis. In the double-layer heterojunction device, the selection of the electrode material directly affects the charge carrier collection ability, transparent conductive polymers dominate the anode material, and the cathode material is usually metals and alloys, of which the donor and acceptor materials play the most important roles in the device. The following will be an example of a double-layer heterojunction device, and analyze and study the devices prepared by different donor and acceptor materials.

2.4. Development prospects of organic solar cells

Organic solar cells have excellent development potential. Through the photoelectric effect, photons interact with semiconducting materials to excite electrons and holes, generating an electric current that can be used for electrical devices, residential power supplies, and even connecting to the power grid. The efficiency and cost of organic solar cells are anticipated to increase and decrease in the future, and their adaptability makes them suitable for a wide range of applications, such as wearable devices. At the same time, their eco-friendly properties are compatible with sustainable development. New materials, such as chalcogenide, will also offer new avenues of exploration. In addition, organic solar cells can be combined with energy storage technology to satisfy various energy requirements, and they can be integrated with the smart grid to achieve efficient energy distribution. In conclusion, organic solar cells are anticipated to lead the clean energy transition in the energy sector and substantially contribute to sustainable development.

3. Conclusion

In this paper, the current status and prospects of organic solar cells as a critical technology in the field of renewable energy in the context of energy transition and sustainable development are examined in detail. By analyzing the role of organic solar cells in resolving the energy crisis and mitigating climate change from the perspectives of energy demand, environmental requirements, and industrial development, we can comprehend the significance of organic solar cells in these endeavors. In the meantime, this paper details the working principle of organic solar cells, including photon-material interaction, electron-hole separation, and charge transport mechanism, as well as the characteristics and application prospects of organic solar cells with diverse structures. This paper highlights the potential and possibilities of organic solar cells as it looks to the future of their development. As the global demand for renewable energy rises, organic solar cells are anticipated to improve efficiency, cost reduction, and application expansion significantly. The emergence of novel materials and technological advances will facilitate the development of organic solar cells. In addition, the combination of organic solar cells and energy storage technology, as well as the integration with the smart grid, will promote the application and spread of renewable energy even further. In conclusion, organic solar cells will play an essential role in energy transition and sustainable development as a clean energy technology with great potential. Through continuous research and innovation, organic solar cells are expected to create a cleaner and more sustainable energy future for us.

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