

Donor Polymers in All polymer Organic Solar Cells

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Abstract. This article introduces the background and foundation, design and structure, manufacturing technology, efficiency of All-polymer organic solar cells (all-PSCs). The article lets you learn about the latest development of All-PSCs. First, All-PSCs can reduce optical losses compared to other organic solar cells. Secondly, studying the active layer's morphology can enhance the conversion efficiency of All-PSCs. Thirdly, developing receptor materials can also improve the conversion efficiency of All-PSCs. Therefore, this paper mainly studies the active layer's morphology and the development of new receptor material. It also shows the latest development of all PSCs and the latest conversion efficiency from these two aspects. Finally, this article mainly focuses on all PSC-S, by finding the latest materials to achieve higher conversion efficiency of all PSCs. The potential for integrating all-PSCs into a wider range of applications, including wearable technology and building-integrated photovoltaics, presents an exciting avenue for research and innovation. Furthermore, nanostructuring and molecular engineering advancements could unlock new pathways to surpass the current efficiency thresholds, setting the stage for all-PSCs to become a cornerstone in the renewable energy landscape.

Keywords: Active Layer Morphology, Polymer Receptors, Organic Solar Cells.

1. Introduction

All-PSCs represent promising frontier in renewable energy technology, offering a potential solution to the challenges faced by traditional solar cells. Unlike conventional photovoltaic systems that typically combine polymers and small-molecule organic materials, all-polymer OSCs exclusively consist of polymeric components for both the electron donor and acceptor materials, as shown in Figure 1. This unique design characteristic contributes to their remarkable flexibility, enhanced stability, and potential for large-scale, cost-effective production.

The driving force behind the growing interest in All-Polymer OSCs lies in their distinct advantages over other solar cell technologies. Their all-polymer composition allows easy processing via solution-based techniques, enabling fabrication of lightweight, flexible, and semi-transparent devices. This attribute paves the way for innovative applications, including integration into wearable electronics, curved surfaces, and windows, thereby expanding the potential market for solar energy harvesting.

Moreover, using all-polymer materials in OSCs offers inherent mechanical robustness and chemical stability advantages compared to mixed systems. These characteristics are crucial for solar cells' long-term performance and durability, especially when exposed to varying environmental conditions. This enhanced stability is a key factor driving research efforts to commercialize All-Polymer OSCs for practical applications.

However, despite their numerous advantages, All-Polymer OSCs face challenges related to achieving high power conversion efficiencies and optimizing their device architecture. Scientists and researchers are actively exploring novel polymer designs, morphology control strategies, and interface engineering techniques to overcome these hurdles and enhance the overall performance of these solar cells.

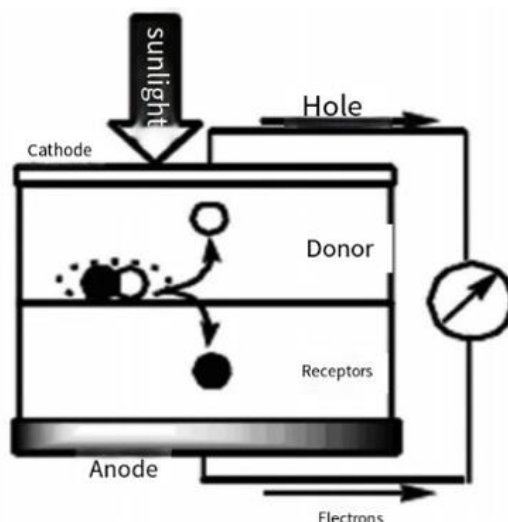


Fig 1. Structure of all-PSCS [1].

2. Design and Structure

The principle of working of the polymer organic solar cell involves using organic semiconductor materials. The operations of all PSCS are based on photovoltaic effect: if sunlight strikes the cell's surface, the photosensitive dye within the organic semiconductor absorbs photons. The jump of electrons from the valence band to the conduction band leads to the formation of electron-hole pairs. These electrons, and holes are separated within the cell's internal electric field. A polymer organic solar cell typically comprises two material layers—an electron donor and an electron acceptor.

Upon separation, Electrons that move to the electron donor layer are negatively charged; in the same book, holes went to the electron acceptor layer. This process is facilitated by the electric field established within the cell, influenced by material structure and cell design. This field guides the movement of electrons and holes towards respective electrodes, where electrons accumulate at one electrode, and holes gather at the other.

Ultimately, these accumulated electrons generate a current flow in an external circuit, transmitting energy through the connected circuit, thereby converting solar energy into usable electrical energy.

Organic solar cells, compared to traditional silicon-based ones, offer flexibility and lightweight advantages, albeit with typically lower efficiency. Consequently, scientists continuously research to boost the structure and performance of the materials to increase these solar cells' efficiency and stability.

All-PSCs are a type of solar cell that utilize all-organic materials for the electron donor and electron acceptor. They typically consist of several key components:

The active layer comprises two types of organic semiconductors – one acts as the donor and the other is the acceptor (typically fullerene derivative or non-fullerene acceptor). This layer facilitates the absorption of light and the generation of electron-hole pairs [2].

2. Electrodes: Usually made of conductive materials like indium tin oxide or other conductive oxides of transport, which allow light to pass through. They facilitate the extraction of electrons and holes generated in the active layer.

3. Interfacial Layers often present both active layer and the electrodes, these layers used to improve contact and efficiency of charge extraction at the active layer.

4. Encapsulation: Encapsulation layers are typically made of glass or high-barrier plastic films to protect the active layers from moisture and oxygen.

The device's performance and efficiency rely on the selection and optimization of materials, the device architecture, and the fabrication methods employed. Improving the efficiency often involves enhancing the absorption of light, charge carrier mobility, and reducing energy losses through optimization of the active layer's morphology. And also the interfaces within the device [3].

3. Active Layer Morphology and New Materials for Polymer Receptors

All-PSC is a novel energy device prepared by mixing the polymer electron acceptor with a conjugated polymer electron donor. Compared to traditional small-molecule acceptors, All-Polymer acceptors exhibit broader and stronger absorption in the visible light range. Moreover, their more modifiable molecular structure enables effective modulation of material absorption spectra, molecular energy levels, and crystallinity. Additionally, All-PSCs display superior photothermal stability and mechanical properties compared to small-molecule acceptors. Therefore, developing efficient All-PSCs holds profound significance in furthering the practical application of organic solar cells [4].

All-PSCs' energy conversion (PCE) efficiency has consistently lagged behind other types of organic solar cells. Achieving higher conversion efficiency requires high-performance n-type polymers. To obtain high-performance n-type polymers, the primary reliance lies on the design and chemical synthesis of highly electron-deficient acceptors with optimized spatial structures and electronic properties. In recent years, researchers' exploration for high-performance organic semiconductors has sparked a resurgence of two renowned molecules, naphthalene diimide (NDI) and perylene diimide (PDI), in organic electronics. This resurgence has significantly enhanced the n-type performance of polymer semiconductor materials.

Another novel high-performance organic semiconductor employs benzothienophene imide (BTI), developing a series of high-performance polymer semiconductors based on BTI, as shown in Figure 2. Compared to NDI and PDI, the thiophene ring within the BTI molecule exhibits higher chemical reactivity and significantly reduced steric hindrance, presenting an unprecedented opportunity to expand and optimize its chemical structure. A range of (semi) ladder-type organic semiconductors has been successfully synthesized using a fused-ring strategy. This illustrates the device's performance in organic transistors and All-PSCs equivalent to polymers derived from NDI and PDI.

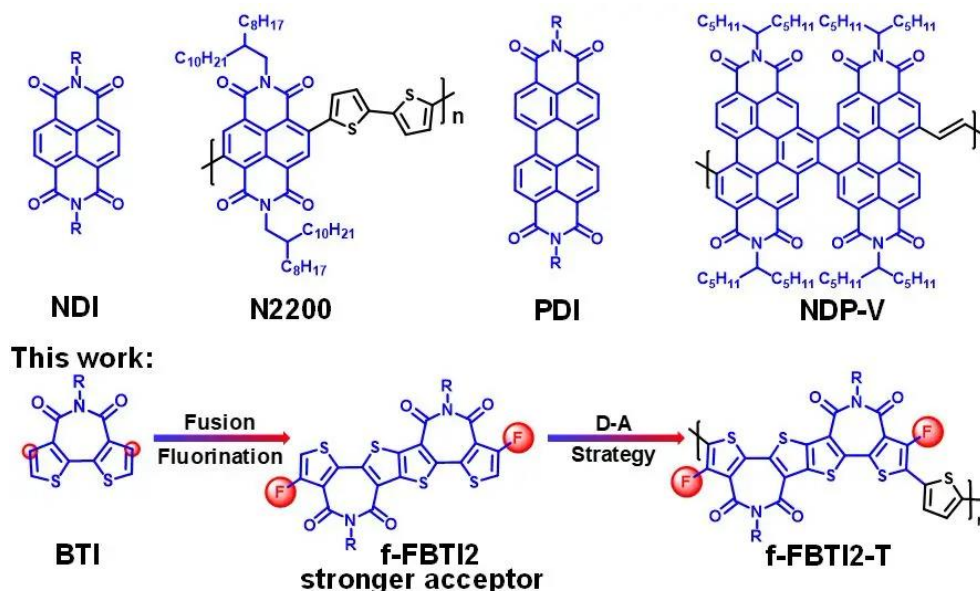


Fig 2. (Top) The structures of NDI and PDI and the n-type polymer acceptor with the best performance at present, and (bottom) the strategy to design a monomer f-FBTI2 and the n-type polymer semiconductor of corresponding [5].

This layer is made up of two organic semiconductor materials that are used to absorb sunlight and generate electron-hole pairs. As shown in Figure 3, we can observe sunlight incident on the active layer at different angles. The left part of the Figure compares the surface topography of two different solar cells. When combined the images in the lower right corner, we can infer that solar cells with this morphology reduce optical losses. Therefore, it is essential to study the active layer's morphology and determine more suitable films to increase the conversion efficiency of whole all PSCs.

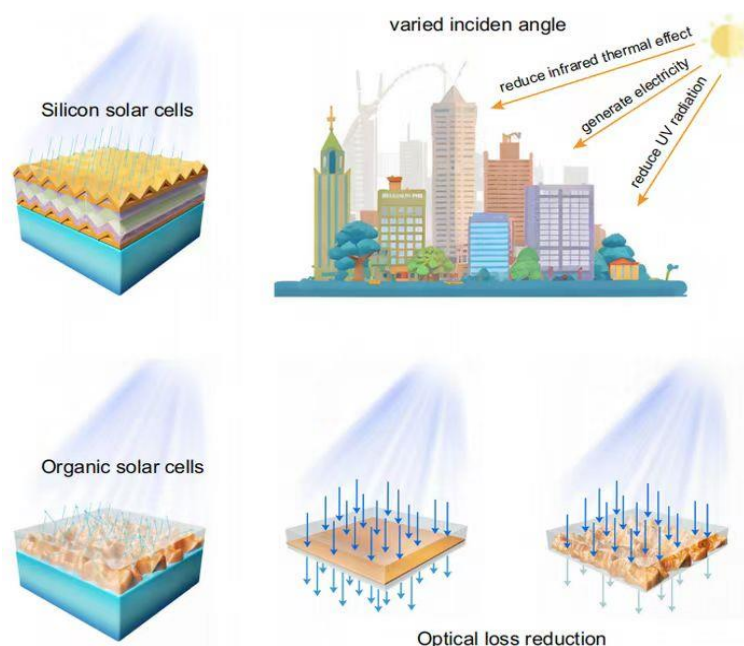


Fig 3. The left image compares surface topography between silicon and organic solar cells, while the lower right image illustrates how this topography reduces light loss in organic solar cells. The upper right diagram shows that this surface structure of OSCs are more appropriate for city environments [6].

The design of efficient and stable all-PSCs requires polymer acceptor materials with narrow band gap and strong absorption, but such materials are relatively rare. As a result, the PCE of all-PSCs lives far behind small molecule photovoltaic systems. Therefore, exploring new polymer acceptor materials and studying new methods for the active layer of morphology have become important strategies to further improve the performance of all PSCs.

In thin-film organic photovoltaics, thin films usually refer to the active layer, significantly affecting the photovoltaic performance of all-polymer solar cells (all-PSCs). This layer is made up of two organic semiconductor materials that are used to absorb sunlight and generate electron-hole pairs. Like this image, we can see sunlight incident on the active layer from different angles. The surface topography of two different solar cells is compared the left half of the image, and combined with the image in the corner, we can see that OSCs with this topography of surface reduce the light loss in organic solar cells. Therefore, it is key to find a more suitable film by studying the active layer's morphology to improve the conversion efficiency of all-PSC [7].

In 2023, Li, S et al. found a new polymer acceptor material, PY-2CI, through an end-group chlorination strategy. The structure of this material is shown in Figure 4, and it was found that the acceptor material has good spectral complementarity with the PY-1S1Se acceptor material. Therefore, if PY-2CI is added as the third part into PY-1S1Se and the component ratio is finely adjusted to construct a ternary system, the ability of the all-polymer active layer to capture sunlight can be improved. PY-1S1Se: Compared with PY-1S1Se films, PY-2CI blends have higher electron mobility, crystalline coherence length, photoluminescence quantum yield and increased exciton diffusion length, which is beneficial to inhibit non-radiative charge recombination in ternary blends. Through the study of morphology, the introduction of PY-2CI enhanced the orderliness of molecular accumulation and solidified the microstructure of the blend. Finally, as shown in Figure 1B, the optimal PCE for ternary all-PSCs was significantly higher than that for binary systems (16.5% and 14.8%), reaching a record 18.2%. Further studies have shown that ternary all-PSCs exhibit better operational stability than binary systems due to increased glass transition temperature, maintaining 77.5% of the initial efficiency after 3000 hours of continuous light exposure. This work opens up a promising prospect for accelerating the development of all polymer systems through a ternary strategy.

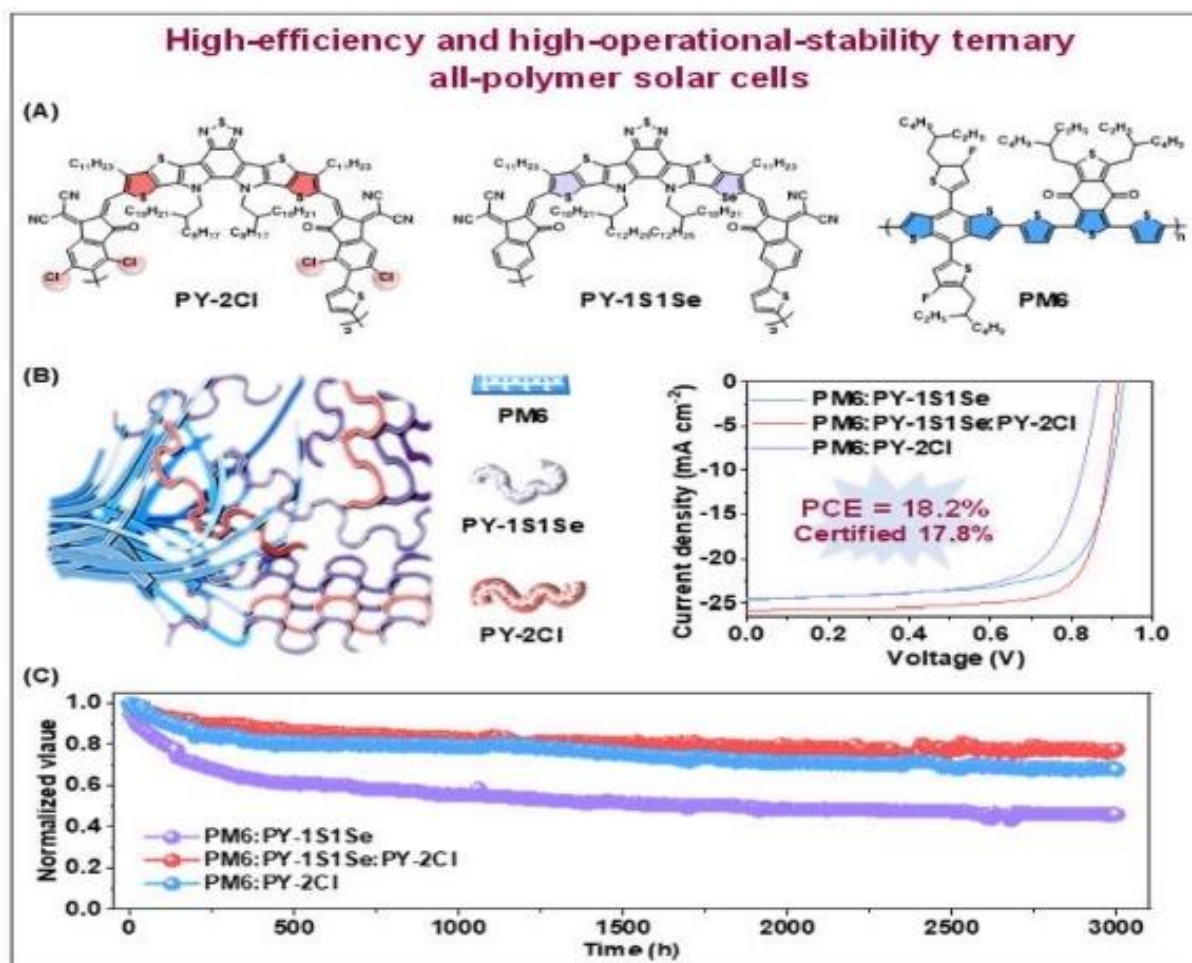


Fig 4. (1) Chemical structure, (2) phase diagram and performance curve, (3) stability curve of ternary all-polymer system [8].

4. Efficiency

In organic photovoltaics, the term "thin film" typically refers to the active layer, significantly influencing the performance of all-polymer solar cells (all-PSCs). This layer comprises two organic semiconductor materials that absorb sunlight and generate electron-hole pairs. Distributed photovoltaics in everyday settings capture sunlight at varying angles throughout the day. There is a pressing have to develop solar cells with a wide incidence angle to reduce space requirements [9].

Due to the high molecular weight of long conjugated main-chain molecules and polymer acceptors, controlling the active layer's morphology in all-PSCs is relatively challenging. Therefore, an appropriate nanoscale interpenetrating network is achieved. The key to high-performance all-PSCS is orderly molecular packing and good molecular orientation. Full polymer solar cells exhibit significantly stratified morphologies through newly developed sequential processing, promoting the conversion from excitons to charge carriers.

The combination of nanoscale fibrillar donor-acceptor networks and micrometer-scale light-trapping structures has yielded an efficiency of 19.06% (certified at 18.59%), marking the highest efficiency achieved to figures for all-PSCs. In addition, the micrometer-scale morphology also work hard to achieving a larger incident angle for light absorption. The power gain from the stratified morphology is 30% higher than flat devices. These promising findings suggest that all-PSCs and stratified features are really suitable for commercially distributed photovoltaics because of their reduced placement requirements.

The practical applications of polymer organic solar cells are vast, primarily due to their flexibility and lightweight nature.

1. **Wearable Technology:** Their flexibility allows integration into clothing, accessories, and wearable devices. They can power sensors, displays, and other functionalities in smart garments, fitness trackers, providing continuous power without relying on traditional batteries.

2. **Portable Electronics:** Organic solar cells can charge small portable electronics like smartphones, portable speakers, and outdoor gear (camping equipment, backpacks, etc.). They offer a convenient means to utilize solar energy while on the move.

3. **Building Integration:** when these cells are embedded into building materials. For instance, windows or rooftops to generate electricity within structures. By integrating them into architectural elements, buildings can partially rely on renewable energy, promoting sustainable construction practices.

4. **IoT Devices and Sensors:** In the realm of IoT and smart technology, these cells power sensors, tags, and other low-power electronic devices used in smart packaging, environmental monitoring, agriculture (crop monitoring), among various industries demanding wireless and sustainable energy solutions.

5. **Emerging Applications:** Ongoing research explores novel applications for these solar cells, including flexible displays, solar-powered vehicles (drones, small vehicles), and integrated power sources in remote or developing regions.

While their efficiency may not match traditional silicon-based solar cells, the adaptability and flexibility of polymer organic solar cells make them attractive in scenarios where conventional rigid solar panels aren't practical. Continuous research aims to enhance their efficiency, durability, and cost-effectiveness, expanding their application across industries and everyday technologies [10].

5. Conclusion

All-PSCs have vast prospects for development in the future. With the increasing demand for renewable energy sources and growing environmental consciousness, these solar cells exhibit significant developmental trends and prospects. Firstly, there is a drive towards performance enhancement as scientists and engineers continually refine the material design and production processes of all-PSCs to enhance their conversion efficiency. Secondly, there's a focus on commercialization, where the advantages of being lightweight, thin, flexible, and cost-effective position all-polymer solar cells for potential large-scale commercial production in the future. Lastly, there's an emphasis on environmental friendliness, as all polymer solar cells are manufactured using organic materials, making their production process comparatively more environmentally friendly than that of other solar cells. Overall, all-polymer OSCs possess extensive market potential and scientific research opportunities, continuing to be a significant component in the field of renewable energy in the future.

Looking forward to the future, All-PSCs have broad development prospects. With the increasing demand for renewable energy and increasing environmental awareness, all-PSCs has shown significant development trends and prospects. First, as scientists and engineers continue to improve the design of materials and production of all-PSCs, their conversion efficiency will continue to increase, and so will their performance. Second, it is important to commercialize, i.e. lightweight, thin, flexible and cost-effective all-polymer solar cells that could be used for potential large-scale commercial production in the future. Finally, there is environmental friendliness, as all polymer solar cells are manufactured using organic materials, making their production process comparatively more environmentally friendly than other solar cells. Overall, All-PSCs have wide market potential and scientific research opportunities and will continue to be a key part of the renewable energy sector.

First, the all-PSCs can reduce the light loss rate compared with other OSCs. Secondly, studying the active layer's morphology can improve the All-PSCs' conversion efficiency. And thirdly, the conversion efficiency of all-polymer solar cells can also be improved through the research and development of acceptor materials.

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