Material Innovations and Scalable Manufacturing for Next-Generation Advanced Organic Photovoltaics

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Abstract. Organic photovoltaics (OPVs), representing a novel paradigm in photoelectric conversion technologies, have garnered substantial interest within the renewable energy sector. These technologies, leveraging organic molecules or polymers for photon absorption and subsequent electricity generation, stand in contrast to traditional silicon-based solar cells. OPVs offer distinct advantages, including flexibility, lightweight construction, and cost-effective production, rendering them adaptable across diverse application contexts. Nonetheless, when juxtaposed with their silicon-based counterparts, the efficiency and longevity of OPVs remain areas necessitating further exploration and enhancement. Recent advancements have been achieved through meticulous material design, process refinement, and interface engineering, collectively contributing to the augmented efficiency and durability of OPVs. Looking ahead, it is anticipated that ongoing technological evolution and innovation will position organic solar cells and photovoltaics as pivotal components in the sustainable energy landscape, offering novel avenues to address the energy crisis and ameliorate the impacts of climate change.

Keywords: Organic Electronics; Organic Photovoltaics; Advanced Materials.

1. Introduction

Organic photovoltaics (OPVs) are a relatively new and interesting sector in the realm of renewable energy. OPVs are solar cells that convert sunlight into electrical energy by using organic materials as active layers, such as molecules and polymers. Compared to traditional silicon-based solar cells, OPVs provide a variety of advantages, such as flexibility, low weight, transparency, and cheap manufacturing costs. Typically, the organic components of OPVs are compounds or polymers with special properties, such as strong electron-donating or electron-accepting abilities. These materials are arranged in thin sheets and placed between two electrodes (a transparent anode and a metal cathode) to form the basic building block of an OPV cell.

OPVs may be divided into two primary groups according to the structural makeup of the organic elements they use. One type of organic material mix known as Bulk-Heterojunction (BHJ) OPVs combines many different organic materials to create a special donor or acceptor structure. This configuration is essential for the effective movement of charges inside the cell, which greatly improves charge carrier mobility and, in turn, cell performance. Alternatively, Single-Material OPVs make use of organic materials that possess strong electron-donating and electron-accepting properties. The materials are arranged in a deliberate manner into different configurations, such as organic semiconductor layers or molecular wires, with the goal of increasing the mobility of charge carriers and enhancing the overall performance and efficiency of the cell [1].

In addition, OPVs offer flexibility, cost-effectiveness, and environmental sustainability—significant improvements over conventional solar technology. Because they can be produced on flexible substrates like plastic or metal foils, lightweight, bendable solar panels may be made that are appropriate for a variety of uses, such as building facades and portable electronics. Because OPVs are easier to make and need lower temperatures than traditional solar cells, their manufacturing technique significantly reduces production costs, increasing the accessibility of solar energy. Furthermore, the fact that OPVs are made of recyclable, non-toxic organic materials highlight their environmental advantages and establishes them as a more environmentally friendly option in the solar energy industry.

The development and improved efficiency of organic solar cells, which have benefits over their conventional silicon-based equivalents including flexibility, transparency, and reduced production costs, depend heavily on material innovation. The development of high-performance organic materials is crucial to achieving the full potential of organic solar cells and improving their performance. This entails investigating new compounds and polymers that possess potent electron-donating and electron-accepting capabilities to enhance charge carrier transit and boost the photovoltaic effect. Furthermore, the meticulous engineering of molecular structures and their self-assembly is critical for fabricating high-efficiency organic solar cells. Techniques like molecular self-assembly and layer-by-layer deposition are instrumental in creating well-organized organic films with customized properties, crucial for enhancing charge carrier mobility, minimizing energy losses, and boosting cell efficiency [2]. Furthermore, the efficiency and longevity of organic solar cells are greatly influenced by the choice of electrode materials and cell designs. Cutting-edge electrode materials and designs can improve charge collection, reduce energy losses, and improve overall cell performance. To advance organic solar cell technology, this all-encompassing approach to material innovation emphasizes the significance of both the creation of novel organic compounds and the tactical engineering of cell components.

This article will discuss the material selection for the organic solar market that is documented in organic photovoltaics, as well as the process and comparison with earlier technologies, in light of recent advancements. It will also go over possibilities and problem-solving techniques.

2. Current State of Materials in Organic Solar Cells

2.1. Fundamentals and Properties of Materials in Organic Solar Cells

Multiple layers are used in the fabrication of organic solar cells. electrodes, intermediate layers, and active, or photovoltaic, layer. The active layer is composed of two electrodes and a photo absorbing layer. Interfacial middle layers improve the efficiency of charge transfer.

OPVs exhibit several advantageous characteristics, notably their amenability to solution processing, which positions them as prime candidates for roll-to-roll fabrication and large-scale production. The deposition of OSCs from the solution can be executed via two distinct methodologies [3]. The donor and acceptor materials can first be deposited independently, resulting in a bilayer device design with low miscibility. An alternative is to synthesize a mixture of acceptor and donor materials in a single solution, which is then deposited via vapor processing or solution-based methods to create a bulk heterojunction. Spin coating, which is frequently related to solution processing, is well known for its capacity to generate consistent, consistently thin coatings across a limited area. On the other hand, OPVs may be used with a range of scalable deposition methods, including slot die coating, bar coating, and blade coating, which emphasizes their adaptability and potential for broad use.

2.2. Novel Donor Materials for Organic Solar Cells

Recent advancements in donor materials have significantly contributed to the progress in organic solar cells (OSCs), particularly through the development of polymeric and small molecule donors. Polymeric donors such as PBDB-T, PM6, and PM7, which follow a conjugated alternating copolymer structure with a D–π–A configuration, incorporate an electron-donating unit, benzodithiophene (BDT), and an electron-accepting unit, benzodithiophenedione (BDD). These materials have been instrumental in the advancement of Y-series non-fullerene acceptors (NFAs), with PM6, in particular, standing out as a benchmark material in organic photovoltaic research due to its exceptional performance, reliability, and broad commercial availability [4].

Small molecule donors (SMDs) for OSCs, featuring a linear A−π−D−π−A structure, include a BDT unit as the central electron-donating core, flanked by electron-accepting terminal groups such as cyanoester or rhodanine derivatives, and oligothiophenes modified with alkyl chains serving as π-bridges. This configuration facilitates efficient charge transport and energy level optimization. Strategies such as halogenation have shown promise in enhancing intermolecular interactions through noncovalent bonds, thereby improving the energy alignment between donor and acceptor materials and boosting photovoltaic efficiency. Additionally, alkyl-chain modulation, applied to either the side chain of the central core or along the structure, plays a crucial role in optimizing photovoltaic cell efficiency (PCE) performance [5]. These material innovations underscore the dynamic nature of research in organic solar cells, highlighting the importance of molecular engineering and strategic modifications in pushing the boundaries of photovoltaic performance and opening new avenues for future advancements in OSC technology.

3. Material Innovation and Modification Strategies

3.1. Materials Engineering

Organic solar cells' effective solar energy conversion depends on their ability to absorb light. Consequently, enhancing the light-absorbing materials' absorption spectrum range and intensity is a crucial step in raising the effectiveness of organic solar cells. A conjugation system and structural modifications can be made to increase the absorption capacity of materials that absorb light. Additionally, increasing the efficiency of organic solar cells also requires refining the band structure. It is possible to increase the mobility of electrons and holes, decrease charge recombination, and raise the battery's photoelectric conversion efficiency by modifying the band structure.

Enhancing the light absorption performance of molecules is crucial for optimizing the efficiency of photovoltaic materials. This can be achieved by incorporating groups with strong light-absorbing properties, such as conjugated systems and aromatic rings, into the molecular structure, thereby significantly improving the molecule's capacity to capture light. Additionally, adjusting the conjugation length of a molecule plays a pivotal role in influencing electron movement and the absorption spectrum, which in turn optimizes the photoelectric performance of the material [6].

Furthermore, the optimization of electron affinity and mobility is essential for enhancing the performance of photovoltaic devices. By integrating electron acceptors and donors within the molecular framework, it is possible to fine-tune the electron affinity, facilitating improved electron mobility [7]. Ensuring the electron transport channel within the molecule is ordered and continuous is also vital, as it minimizes the scattering loss of electrons, thereby enhancing the overall efficiency of electron transport and contributing to the improved performance of photovoltaic materials.

3.2. Interface Engineering

Appropriate functional molecules are introduced on the surface of the electrode material to change the energy level structure of the electrode-photoactive layer interface and improve the efficiency of charge separation. The surface modifier is used to regulate the energy level distribution at the interface between the electrode and photoelectric active layer, reduce the energy level shift, and improve electron transport efficiency. The effective path of charge transfer is increased by interface engineering and interface modification, and the uneven thickness of the electrode interface layer is reduced. The transfer rate and stability of the interface are improved by controlling the lattice matching and crystal orientation of the material interface. The energy level difference of charge at the material interface can be reduced, thus reducing charge recombination.

3.3. Hybrid Materials

The introduction of suitable interface materials between the electron transport layer and hole transport layer, such as electron transport interface material and hole transport interface material, helps improve the charge extraction efficiency. Further, the introduction of quantum dots can extend the spectral range and enhance the absorption of light [8]. The energy band structure of quantum dots can be regulated to make them selectively respond to different wavelengths of light and improve the photoelectric conversion efficiency. Inorganic nanoparticles such as titanium dioxide can also be used to enhance light absorption. The size and shape of these nanoparticles can be adjusted to optimise the absorption of specific wavelengths of light.

4. Fabrication and Processing Techniques

Solution processing methods play a vital role in the fabrication of organic solar cells, offering a range of techniques for efficient and precise material deposition. Inkjet printing, a non-contact digital printing technology, stands out for its high-resolution and high-precision capabilities, enabling accurate material deposition across various layers, thereby enhancing manufacturing efficiency and material utilization. Flexographic printing, known for its high-speed continuous operation, is particularly suited for printing on films and flexible substrates, making it a cost-effective choice for organic solar cell production [9].

Offset printing technology, ideal for large-scale continuous printing, supports high-speed and efficient manufacturing of organic solar cells. Advances in printing equipment and materials have broadened the application of offset printing in organic solar cell production.[5] Spin coating, another widely used technique ensures even coating of solutions on surfaces by rotating the substrate, facilitating uniform thin film coatings essential for organic solar cells. Spray coating, a method that saves materials and covers large areas uniformly, shows promise for the mass production of organic solar cells, highlighting its potential for scalability [9].

The scalability of production, however, faces challenges, particularly in terms of manufacturing costs and sustainability. The high manufacturing cost of organic solar cells, attributed to material expenses, complex production processes, and limited production volumes, poses a significant hurdle. Innovations in process optimization, automation, and the development of cost-effective organic semiconductor materials, coupled with large-scale production, are essential for cost reduction. Emphasizing sustainable materials and environmentally friendly manufacturing processes remains a crucial direction for the industry.

Transitioning from laboratory-scale to commercial-scale production introduces challenges related to accommodating higher production speeds, larger line sizes, and maintaining consistent product quality. Innovations in efficient printing and coating technologies, such as electronic printing and continuous printing, aim to enhance production efficiency. The development of standardized production processes and quality control systems is vital to ensure product consistency, marking a significant step toward the commercial viability of organic photovoltaics.

5. Challenges and Opportunities

5.1. Hybrid Materials

OPV technology, while promising for its flexibility and lightweight properties, faces significant challenges in stability and longevity compared to inorganic semiconductor materials. Organic materials are inherently more fragile and susceptible to environmental factors such as light, humidity, and oxygen, which can detrimentally affect the performance and service life of solar cells. To address these issues, advancements in organic semiconductor materials are crucial, including the design of more stable molecular structures and the incorporation of protective layers or stabilizers to enhance the durability and lifespan of the cells.

The development of multilayer battery structures presents a potential solution to improve the efficiency of OPVs. Different materials within these structures possess unique absorption characteristics for various wavelengths of light, allowing for the design of multi-layered architectures where each layer targets a specific wavelength. This approach not only improves spectral utilization but also enables the conversion of solar energy across a broader spectral range, thereby enhancing the overall efficiency of the solar cells [10].

Furthermore, the inherent flexibility and lightness of organic semiconductor materials make OPVs particularly suitable for innovative applications such as wearable devices. The simple production process, which allows for printing on flexible substrates, and the transparency of these materials facilitate their integration into textiles and other flexible, wearable forms. Similarly, flexible thin-film solar cells, utilizing materials like polymer films and thin-film silicon, offer advantages in terms of weight, flexibility, and transparency, making them ideal for incorporation into clothing or wearable accessories.

The integration of solar materials into textiles represents a growing trend, aiming to create solar-charged clothing or accessories. These textile-integrated solar materials often feature conductive fibers or coatings, enabling the generation of electrical energy and connectivity to batteries or devices. Exploring perovskite organic hybrid cells combines the benefits of perovskite and organic solar cells to leverage their complementary absorption characteristics. This hybrid approach allows for a wider spectral range of light absorption, improving the efficiency of photoelectric conversion through spectral compensation [10]. Although perovskite solar cells may face stability challenges, especially under prolonged use or in harsh environments, their combination with the more flexible and stable organic solar cells can enhance the overall stability of the system. This synergy not only improves performance but also offers greater design flexibility for creating flexible, transparent, or translucent solar installations, expanding the possibilities for integrating solar technology into a variety of applications.

5.2. Suggestions

To enhance commercial viability and overcome market entry barriers for OPV technology, several strategic approaches can be adopted. Firstly, increasing the efficiency of OPVs is paramount. This involves the research and development of new organic semiconductor materials, alongside optimizing cell design and manufacturing processes to boost photoelectric conversion efficiency. Enhancements in battery structure and material combinations are also crucial to broaden the light absorption range and improve electron transport efficiency. Addressing the stability of organic solar cells for long-term use is another critical strategy. Enhancing the durability and longevity of these cells can be achieved through better material selection, advanced packaging technologies, and effective moisture protection measures. These improvements are essential for solving the stability issues that have historically limited the appeal of OPVs.

Reducing manufacturing costs is vital for making OPVs more competitive. Streamlining the manufacturing process and adopting large-scale, cost-effective production techniques can significantly lower the costs associated with organic solar cell production. Exploring innovative material preparation methods, such as printing and solution processing, can further enhance production efficiency and reduce expenses. Establishing industrial partnerships is a strategic approach to accelerate the advancement and application of OPV technology. Collaborations with companies, research institutions, and government agencies can foster technological innovation, sharing the burden of research and development costs, and speeding up the commercialization process. Lastly, addressing recyclability and environmental concerns is essential for promoting the sustainable development of OPVs. Emphasizing the recyclability and environmental friendliness of materials from the product design stage can contribute to the sustainable production and recycling of these solar cells, aligning with global efforts toward environmental sustainability.

By focusing on these strategies, the organic photovoltaic industry can overcome existing challenges, enhancing the technology's market entry and commercial success, and paving the way for a more sustainable and efficient solar energy future.

6. Conclusion

In conclusion, further support is needed for the development of organic solar cells for use in OPVs, even if they have faced a number of obstacles. A concentrated approach to material selection is required due to the critical role that material efficiency plays in the conversion of photons into electricity, which is at the center of this analytical step. Engineers must develop novel, solution-processable electrode materials to address these issues. They also need to improve the overall stability of OPVs, reduce the performance disparity between the PCEs of individual cells and modules, and close the performance gap. Furthermore, the creation of scalable roll-to-roll production procedures and the design of OPV packaging schemes that use a range of materials are essential. With these coordinated efforts, it is anticipated that OPVs will become commercially viable in the upcoming years, representing a major advancement in the field of renewable energy technology.

Authors Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

References

[1] Kranthiraja K, Gunasekar K, Kim H, et al. High-performance long-term-stable dopant-free perovskite solar cells and additive-free organic solar cells by employing newly designed multirole π-conjugated polymers. Advanced Materials, 2017, 29(23): 1700183.

[2] Li W, Ye L, Li S, et al. A high-efficiency organic solar cell enabled by the strong intramolecular electron push–pull effect of the non-fullerene acceptor. Advanced Materials, 2018, 30(16): 1707170.

[3] Lin Y, Magomedov A, Firdaus Y, et al. 18.4% organic solar cells using a high ionization energy self-assembled monolayer as hole-extraction interlayer. ChemSusChem, 2021, 14(17): 3569-3578.

[4] Zheng Z, Awartani O M, Gautam B, et al. Efficient charge transfer and fine-tuned energy level alignment in a THF-processed fullerene-free organic solar cell with 11.3% efficiency. Advanced Materials, 2017, 29(5): 1604241.

[5] Sun J, Ma X, Zhang Z, et al. Dithieno [3,2-b:2,3-d] pyrrole fused nonfullerene acceptors enabling over 13% efficiency for organic solar cells. Advanced materials, 2018, 30(16): 1707150.

[6] Welch G. Organic Photovoltaics: An Introduction. Retrieved on: 24th Feb 2024, Retrieved from: https://www.ossila.com/pages/organic-photovoltaics-introduction.

[7] Su Y W, Lan S C, Wei K H. Organic photovoltaics. Materials Today, 2012, 15(12): 554-562.

[8] Lowrie W, Westbrook R J E, Guo J, et al. Organic photovoltaics: The current challenges. The Journal of Chemical Physics, 2023, 158(11).

[9] Sharma V V, Landep A, Lee S Y, et al. Recent advances in polymeric and small molecule donor materials for Y6-based organic solar cells. Next Energy, 2023: 100086.

[10] Basha B, Mubashir T, Tahir M H, et al. Designing of novel organic semiconductors materials for organic solar cells: A machine learning assisted proficient pipeline. Inorganic Chemistry Communications, 2023, 153: 110818.