2025 International Conference on Advanced Mechatronics and Intelligent Energy Systems

Advancements in Organic Solar Cells: Non-Fullerene Acceptors, Ternary Blends, and Other Improvements

AIPCP25-CF-AMIES2025-00096 | Article

Advancements in Organic Solar Cells: Non-Fullerene Acceptors, Ternary Blends, and Other Improvements

Minghao Shen

Electrical Electronic Engineer, University of Glasgow, University of Electronic Science and Technology of China, Chengdu 611730, China

2022190501011@std.uestc.edu.cn

Abstract. In modern epoch, organic solar cells (OSCs) have arisen significant attention because it can solve urgent challenges for renewable energy because they are cost effective and flexible. They also have great potential to be manufactured in a large scale. However, OSCs have faced challenges such as efficiency, stability, and scalability. These demerits hindered their commercialization. Recent advancements in materials science have led to significant improvements in the performance of OSCs, especially through the development of non-fullerene acceptors (NFAs), ternary blend systems, and other novel improvements. NFAs are proved to be brilliant by providing better energy level alignment, enhanced charge separation, and broader absorption spectra. All these merits have boosted a significant increase in the power conversion efficiency (PCE) of OSCs. Ternary blend systems which combined two types of electron acceptors alongside a single donor polymer have further improved device performance by optimizing the morphology of the active layer. Silver nanowire (AgNW) electrodes which can offer improved transparency, conductivity and flexibility have also shown promise in enhancing light absorption and device performance. Furthermore, the combed-shaped Active blends can also enhance the stability and efficiency. This paper reviews these cutting-edge technologies and discusses their impact on OSC performance. The paper will also provide deep insights into the future directions for further enhancing the efficiency, stability, and scalability of OSCs.

INTRODUCTION

The increasing demand for renewable energy has driven an urgent need for high level solar energy technologies. Among all the solutions, organic solar cells (OSCs) show their potential to the scientists and quickly gain attention of them. OSCs is researched to be a very good option of all types of solar cells due to their potential for low-cost production, lightweight construction, and mechanical flexibility. Traditional solar cells are rigid, and they require complicated process which need high energy. OSCs can be fabricated using cutting edge techniques. This advantage makes them suitable for a variety of applications. These applications include flexible electronics, wearable devices, and large-scale solar panels [1].

However, as the technology is not mature now, there are several challenges which have limited their extensive use. One of the main issues is their low power conversion efficiency (PCE) compared to silicon-based solar cells. Another obstacle is the stability of OSCs. Organic materials are prone to degradation when exposed to environmental factors so that more actions should be taken to protect the OSCs [1].

In the past few years, several innovations have shown that OSCs have the potential to conquer these challenges. Scientists and researchers are trying their best to improve both the efficiency and stability of OSCs. Among these innovations, the paper chooses the most important ones to introduce. They are non-fullerene acceptors (NFAs), ternary blend systems, silver nanowire electrode and combs-shaped blends [2] [3] [4] [5].

This paper aims to review basic information of these innovations and explore the future and applications of these cutting-edge technologies. We are eager to find a way to enhance the performance of OSCs. For the main context, we will discuss the mechanisms behind these developments and highlight key examples of successful implementations. An outlook into future research directions aimed at further improving OSC efficiency, stability, and scalability is also included in this paper.

NEWEST RESEARCH OF OSCS

As the paper have mentioned above the OSCs have great future. Thus, the primary challenge is to achieve the high-power conversion efficiencies (PCEs). This index is the vital and crucial factor for practical applications. Actually, for OSCs it is the most important factor to be assessed. To enhance this index, substantial advancements have been made to conquer all the barriers of technologies. The next part of this paper will include NFAs, ternary blend systems, AgNWs electrode and combs-shaped blend system are introduced respectively in sequence.

NON-FULLERENE ACCEPTORS (NFAS) IN ORGANIC SOLAR CELLS

Non-fullerene acceptors (NFAs) are the main solution to improve the performance of OSCs. Fullerene-based acceptors such as PCBM were widely used in early generations of OSCs due to their stability and good electron-accepting properties [2]. However, fullerene derivatives have big limitations that hinder the performance of OSCs. These limitations include poor energy level alignment with certain donor materials, narrow absorption spectra and difficulties in achieving optimal morphology in the active layer [2]. To overcome these problems, people began to develop new kinds of electron acceptors which can solve the problems mentioned above.

NFAs have shown to be good alternatives to the traditional fullerene acceptors. These acceptors have the following advantages [2] [3]. Broader absorption spectrum of NFAs leads to harvest more sunlight and greater photocurrent. NFA has better energy level alignment with the donor so that the charge transfer and separation between donor and acceptor are enhanced. With higher charge mobility in NFA and less recombination loss, more charge can be collected at the electrode [2] [3].

One of the most successful NFA is Y6. Y6 has achieved very good performance in OSCs. The PCE of the device based on Y6 exceeds 18%, which is much higher than that of the device based on fullerne-based acceptors [2]. The reason why Y6 can achieve high efficiency is that Y6 has good charge transport property and can extend the absorption range in near infrared region to harvest more light [2]. Besides, Y6 is very stable under ambient condition and can be used in commercial device [2].

Zhang et al. (2020) [2] compared the performance of the OSCs based on traditional fullerene acceptors and the OSCs based on NFA. The performance of the latter is better than that of the former in both efficiency and stability. In addition, the NFA based devices are more resistant to the impact of the environment. The operational lifetime of the device based on NFA can be greatly extended by UV and oxygen, which are the main factors that cause the degradation of the device.

TERNARY BLEND SYSTEMS

The ternary blend system combines two electron acceptors with a donor polymer. In the past few years, this new combination system has become a powerful strategy for improving OSC performance. In traditional blending systems, phase separation usually occurs in the active layer that forms large domains. This phenomenon hinders charge transfer and reduces efficiency. The ternary blend system solves this problem by creating a better distribution of donor and acceptor materials. It can improve the shape of the active layer and enhance charge transfer [5] [6].

The ternary system also allows for more precise adjustment of the energy level of the active layer. In addition, ternary blends can utilize the complementary properties of fullerene and non-fullerene receptors [5].

A key benefit of ternary blends is that they can help scientists minimize composite losses to the greatest extent possible. Composite loss is a major indicator of OSC. By adjusting the morphology of the active layer and improving charge transfer, ternary blends reduce the possibility of charge carriers recombining before reaching the electrode. Scientists have taken advantage of this advantage and fully utilized them, resulting in PCE exceeding 18%, which is a fairly high value for this type of OSC [5].

In the recent study, Soyeong Jeong et.al (2023) used ternary blend system with NFAs in the combination with traditional FAs. They obtained higher PCE in comparison to the binary system devices. In this way, they showed that it is possible to combine the best features of both fullerene and non-fullerene acceptors in ternary blend system and have more efficient and stable OSCs [5]

SILVER NANOWIRE ELECTRODES IN ORGANIC SOLAR CELLS

Another important example of innovation in organic solar cell (OSC) technology is the application of silver nanowire (AgNW) electrodes (Figure 1). Compared to traditional indium tin oxide (ITO) electrodes, AgNW provides a better choice. Old designs are often expensive and difficult to scale to large-scale applications. AgNW has flexibility and conductivity. Therefore, this new solution provides an exciting way to overcome the aforementioned challenges, particularly in flexible and large-scale solar cell applications [4].

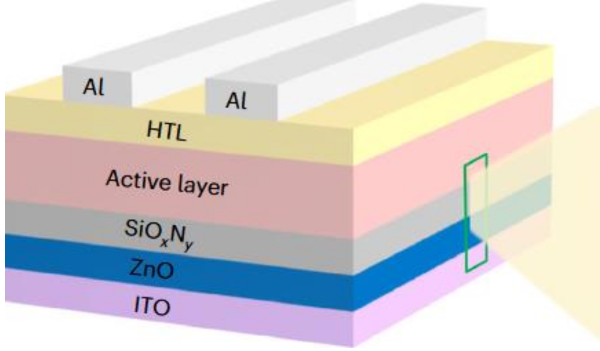

FIGURE 1. Schematic of the inverted organic solar cells [4]

A study by Bowen Liu et al. (2022) explored the use of AgNW electrodes in OSCs. Their work clearly showed that they could significantly enhance the device performance by using the AgNW as electrodes rather than traditional solutions [4]. The Y6-based organic photovoltaic devices are an exact good fit OSCs for AgNWs. Their findings highlighted the potential of AgNW-based OSCs to outperform traditional ITO-based devices in several key areas. These good characteristics include light absorption, charge transport and mechanical flexibility [4].

Another important advantage of AgNWs is that this material does not cost much. In contrast when we look at ITO, the high cost of indium has been a significant barrier to the large-scale production of OSCs with ITO electrodes. Looking to the other side, the silver is more abundant and less expensive than indium. That is why AgNWs are more sustainable and cost-effective. AgNWs can be processed using solution-based techniques. The technology about inkjet prints and roll-to-roll process which makes them suitable for large area production at a lower cost [4].

There is still some work to be done to achieve the long-term stability of the AgNW-based electrodes in OSCs. Even if AgNWs are relatively stable, the overall stability of the device has to be tested in real-world conditions. The stability of the devices in the presence of moisture, oxygen, and UV radiation must be tested carefully. The durability and resistance of AgNW electrodes to environmental degradation are the targets of the current research. In addition, more improvements in the manufacturing processes will be needed to achieve more consistent performance in large-scale production [4].

Despite these challenges, AgNW-based OSCs look very promising for the future of OPVs. The newest research even reaches over 25% PCE by using AgNW in combination with SnO_x [7]. The advantage of AgNWs in the production of OSCs lies in the improvement of efficiency and mechanical flexibility of the cells, as well as the cost-effectiveness and scalability of the technology for large area production. As the research continues and the stability and scalability of the AgNW electrodes improve, this innovation will certainly find a place in the commercial production of flexible and efficient organic solar cells.

COMB-SHAPED ACTIVE BLENDS FOR IMPROVED EFFICIENCY AND THERMAL STABILITY

In the new generation of organic solar cell (OSC) in recent years, the most advanced and promising work is the formation of comb-shaped active blends. The new active blend has greatly improved the performance of efficiency and thermal stability of OSC [8]. In 2022, Yin et al. used comb-shaped active layers to control the morphology of active blend. This method could solve the key problems of phase separation and thermal stress stability, which are often seen in traditional bulk heterojunction (BHJ) OSCs [8].

The comb-shaped active blend system takes donor polymer (PM6) and non-fullerene acceptor (BTP-eC9) (Figure 2) [8]. The active blend was prepared by LBL method to form a unique comb-shaped structure. The unique comb-shaped structure can control the donor/acceptor interface, which further reduces the recombination loss and enhances the charge transport. The comb-shaped morphology could also control the crystallinity and order of active layer, which further improved the stability and performance of device [8].

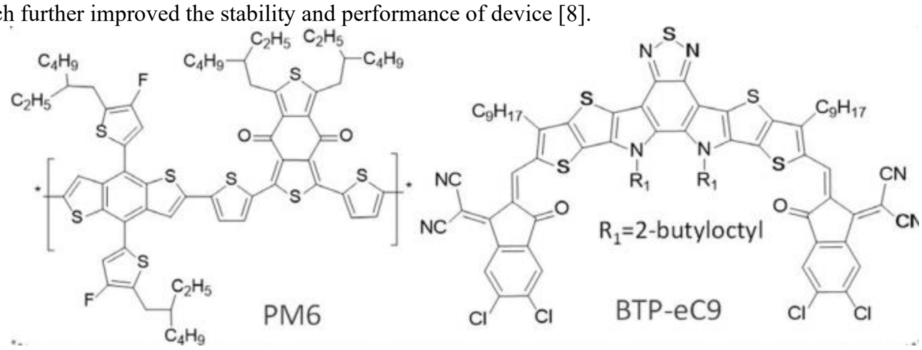

FIGURE 2. Chemical structure of polymer donor PM6 and non-fullerene acceptor BTP-eC9 [8]

In the aspect of performance, the device based on comb-shaped active blend obtained an improved PCE of 17.13%, while the PCE of traditional BHJ system was 16.05% [8]. More importantly, the thermal stability of comb shaped OSCs was greatly improved. When the device was thermal stress at 85oC, the device based on comb-shaped active blend was still 93% of initial performance after 9h in nitrogen atmosphere. While the device based on BHJ system only kept 51% of initial performance [8]. The significant improvement of thermal stability is due to the enhanced morphology of comb-shaped active blend. The comb-shaped active blend could control the morphology of active layer, which further suppressed the phase separation and structure damage under heat. The traditional BHJ OSCs would suffer from the problems of phase separation and structure damage under thermal stress, which would lead to the decrease of device performance [8]

The enhanced thermal stability is crucial for the commercialization of OSCs. It is vital because it ensures that the devices will perform reliably over long periods even under harsh environmental conditions. By addressing both efficiency and thermal stability, the comb-shaped blend system shows the potential for creating long-lasting, high-performance organic photovoltaics. It is this advancement that paves the way for more durable and commercial OSCs. They can be integrated into a wide range of applications, from flexible solar panels to large-area energy-harvesting systems thanks to the combs-shaped blend systems.

Yin et al. led a work which highlight the importance of shape control in optimizing OSC performance and stability. By combining the unique properties of the donor and acceptor materials with advanced processing techniques, the comb-shaped active blend system represents a significant step forward in the development of efficient and stable OSCs [8].

CHALLENGES AND SOLUTIONS

There are also several hard barriers which must be conquered by our scientists. In the next part of this paper, we will introduce the challenges and the corresponding solutions for them.

MATERIAL STABILITY

Material stability is one of the most critical challenges to commercialize OSCs and it is often the first characteristic that scientists will focus to improve. The semiconductors used in OSCs are extremely more vulnerable to degradation when exposed to environmental factors. During the research, some of the factors such as moisture, oxygen, and ultraviolet (UV) radiation are seen to be the most dangerous for OSCs [9]. This degradation leads to a decline in the efficiency of the devices over time, limiting their operational lifetime and their commercial viability.

To mitigate this issue, researchers have searched the whole planet for more stable ingredients. Non-fullerene acceptors (NFAs) have shown superior resistance to environmental degradation compared to traditional fullerene-based acceptors. Materials like Y6 have demonstrated excellent stability under UV exposure and oxygen, making them highly promising for use in OSCs [2]. For P3HT: PCBM OSCs, scientists use ZnO ETL battery to improve the stability [10]. It can be expected that the stability of OSCs can be improved a lot in the future.

EFFICIENCY STUFF

Although the efficiency of OSCs has improved over the past decade, the technology still lags behind traditional silicon-based solar cells because of efficiency stuff. It is hard to enhance the PCE of OSCs even if the resources are almost all consumed to pursue high efficiency of OSCs. The situation is caused because of the narrow absorption spectra of the materials used in OSCs. This seriously limit their ability to capture sunlight and convert it into electrical energy efficiently. Moreover, it is truly hard for researchers to find new materials which fit for the OSCs' need.

The development of NFAs with broader absorption spectra has been a good strategy to address this limitation. By extending the absorption range into the near-infrared region, NFAs can capture a broader portion of the solar spectrum. Thus, they can help increasing photocurrent generation. Moreover, the combination of ternary blend systems has been shown to further enhance light absorption rate and charge separation. Furthermore, the integration of AgNW electrodes, which enhance light absorption through plasmonic resonance, is another promising solution that improves the overall efficiency of OSCs [4] [7].

DEVICE ARCHITECTURE

Device Architecture is both vital and essential for obtaining good device performance. In traditional bulk heterojunction (BHJ) architectures, phase separation in the active layer can lead to the formation of large domains that decrease charge transport and lead to recombination losses. This greatly affects the efficiency of the devices.

There are also new architectures such as the advanced device architecture with comb-shaped active layer, in which case the morphology of active layer is improved, and the charge transport property of device is enhanced. The comb-shaped blend system not only has an optimal donor/acceptor interface and could avoid the phase separation, but also can lead to an enhanced efficiency and thermal stability of OSCs. In addition, if the organic materials and perovskite materials are used in the hybrid architectures, it may also be a promising architecture to achieve high efficiency and stability as well as to overcome the limitation of traditional OSC [6] [11].

SCALABILITY AND MANUFACTURING

Scalability is one of the most important problems in the commercialization of OSCs. Because of the high cost and complicated process, the current fabrication process methods such as thermal evaporation and sputtering cannot be applied in the large-scale manufacturing process. It is also hard to obtain the uniform coating over a large area.

If there are the processing techniques which can solve the above main problems of scalability and manufacturing such as roll-to-roll printing, the scalability of OSCs will be solved. Roll-to-roll printing can continuously and highly throughput process the flexible OSCs and has the advantage of low cost. It is highly applicable to the large area production and can be a scalable method to fabricate the flexible and lightweight solar cells at low cost. Besides, the low cost and abundant materials such as AgNWs and NFAs can also be used to fabricate the flexible organic solar cells at low cost and further solve the scalability problem. A special PFFBT4T-2OD Ternary blend system has been used in the semitransparent organic solar cells, which lead to an average transmittance about 25.0% and the color rendering index larger than 90 and achieved brilliant manufacturing of OSCs [12].

CONCLUSION

In conclusion, scientist have made a great progress on OSCs in recent years, which are attributed to the rapid development of materials science, device architecture and fabrication technique. The NFAs have greatly improved the PCE of OSCs and now the devices can reach over 18%. There are some advantages of NFAs, such as a wider absorption spectrum, better energy level alignment and more stability in environmental stress, which have accumulated to improve the performance of OSCs. Besides, ternary blend system can optimize the morphology of the active layer and save recombination losses. The use of AgNWs as transparent conductive electrode in the fabrication of organic solar cells has also shown great potential for improving the performance of the devices. Compared with the traditional ITO electrode, AgNWs electrode has many advantages, such as better flexibility, a higher transmittance due to the plasmonic resonance effects on the nanowires, and lower production expenses. Moreover, the scalability of AgNWs based organic solar cells, combined with the roll-to-roll print technique which optimized the process of fabrication, can further solve the scalability problem, and make the organic solar cells a more commercially available option for large-scale energy harvesting.

However, there are still many issues that the OSCs need to overcome before they can be widely implemented in commercial devices. These include material stability under environmental conditions, long-term device operation stability, and still better efficiencies. In addition, the device architecture needs to be improved to reduce phase separation and promote charge transport. Finally, scalable, and low-cost fabrication processes need to be developed to satisfy the requirements of large area devices. Given the advantages of OSCs, it is likely that future research will concentrate on the development of new materials with both high efficiency and improved stability, as well as the optimization of device architectures.

If we can combine OSCs with perovskite solar cells and make them a good fit, the combination may provide a new route to furtherly improve the efficiency and stability of organic photovoltaics. Meanwhile, the advancement of scalable fabrication techniques and low-cost materials will also help reduce the production cost of OSCs. As a new generation of solar cells, organic solar cells have the potential to become an important technology in the renewable energy field. They are flexible, low cost and scalable. All these good features make them ideal for a variety of applications from flexible solar panels to wearable devices. If the efficiency, stability, and scalability of OSCs continue to improve, these innovative solar cells will definitely be helpful for solving our energy problems and building a sustainable energy future.

REFERENCES

1. M. Hiramoto, S. Izawa, eds., Organic Solar Cells: Energetic and Nanostructural Design ISBN 978-981-15-9112-9, ISBN 978-981-15-9113-6 (2021).
2. W. Zhang, Y. Zhang, Z. Liu, et al., Chemical Reviews 120, 8590-8609 (2020).
3. S. Ashagre, A. K. Ogundele, J. N. Ike, et al., Journal of Polymer Science 2025, 0, 1 – 10 (2025).
4. B. Liu, O. J. Sandberg, J. Qin, Y. Liu, S. Wilken, N. Wu, X. Yu, J. Fang, Z. Li, R. Huang, W. Zha, Q. Luo, H. Tan, R. Österbacka, C. Q. Ma, Nature Photonics 19, 195 – 203 (2025).
5. F. Werlinger, C. Segura, J. Martínez, I. Osorio-Roman, et al., Energies 16, 5868 (2023).
6. C. Xie, C. Xiao, J. Fang, C. Zhao, W. Li, Core/shell AgNWs@SnOx electrodes for high performance flexible indoor organic solar cells with >25% efficiency, Nano Energy 107, 108153 (2023).
7. Z. Yin, Q. Wang, H. Zhao, H. Wang, N. Li, W. Song, 17.13% Efficiency and Superior Thermal Stability of Organic Solar Cells Based on a Comb-Shape Active Blend, Energy Environ. Mater. 6, e12443 (2022).
8. C. Flores, Y. L. Casallas-Moreno, A. Sacramento, et al., Materials Research Express 11, 125103 (2024).
9. G. Grancharov, M.-D. Atanasova, R. Kalinova, R. Gergova, et al., Molecules 26, 6890 (2021).
10. W. Chen, Q. Zhang, Recent progress in non-fullerene small molecule acceptors in organic solar cells (OSCs), J. Mater. Chem. C 5, 1275 – 1302 (2017).
11. L. Duan, H. Yi, Z. Wang, Y. Zhang, F. Haque, B. Sang, R. Deng, A. Uddin, Sustainable Energy & Fuels 3, 2456-2463 (2019).