Material and Application of Semitransparent Organic Solar Cells

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Abstract. Semitransparent organic solar cells (ST-OSCs) harness abundant solar energy while transmitting visible light via the modification of layer structures and materials considering their characteristics and cost-effectiveness. Besides electrodes and charge transport layers, the key to determining the cell performance is the active layer structuralized as separate donor and acceptor layers or in bulk heterojunction (BHJ). Although bilayer cells can be optimized by modifying the layer thickness, interpenetration is preferred due to a shorter exciton diffusion length. In BHJ, non-fullerene acceptors gain the most benefits over fullerene derivatives and metal-related compounds due to the controllable absorption spectra and higher operation lifetime. Donors are made of conjugated polymers because of their electric conductivity and tunable properties. Till now, the power conversion efficiency (PCE) has reached 15% and the average visible transmittance (AVT) has exceeded 30%, showing an improvement in cell operation that encourages constructional, agricultural and bioelectronic applications. Properties and fabrication of present products such as building-integrated photovoltaics (BIPVs) and greenhouse rooftops, and health monitors, are analyzed. Future products such as emergency tents and heartbeat detectors have been explored to vitalize the market. Further commercialization requires attempts to overcome the tradeoff between PCE and AVT and enhance cell stability.

Keywords: Semitransparent organic solar cells, donor-acceptor material, building-integrated photovoltaics.

1. Introduction

Anthropogenic activities including the combustion of fossil fuels and car engines, contribute to negative environmental impacts, in which the enhanced greenhouse effect is the most serious, trapping more long-wave radiation from escaping. This has led to a 1.15℃ warming in 2022 compared to the pre-industrial stage and an accelerated warming rate of at least 1.5℃ by 2030, encouraging people to seek alternative energy sources or make use of the excessive heat [1]. Solar cells stand out as a popular method to generate power by utilizing solar energy. They can be classified into organic and inorganic ones. Organic solar cells (OSCs) or organic photovoltaics (OPVs) outweigh the inorganic ones due to their cheap cost of production and tunable mechanical properties. Among them, semitransparent ones allow visible light to pass through and absorb radiation in other wavelengths.

Since the first organic photoelectric conversion using magnesium phthalocyanine dye in 1958, OSCs have been refined in structures and materials to capture maximum sunlight and raise the power conversion efficiency (PCE), such as the invention of heterojunction cells to improve the diffusion length of excitons in 1986 (PCE=1%), the discovery of C60 as an excellent charge acceptor in 1992 (PCE = 2.9%), and the progress in strengthening the absorption of visible light by tuning bandgaps using non-fullerene acceptors after 2013 (PCE = 13%). At present, PCE has already surpassed 18% [2] contributed by a ternary blending strategy in a single-junction OSC.

The prevalence of organic photovoltaics is due to the capability of organic chemicals to select different wavelengths of absorption spectrums in OPVs, shedding light on the development of semitransparent OPVs (ST-OPVs) or semitransparent OSCs (ST-OSCs) which transmit visible spectrum but absorb UV and IR radiation to generate power. Because of this unique characteristic, ST-OSCs have gained strong potential for building-integrated photovoltaics (BIPVs), such as being installed on windows, rooftops, and facades attached to high-rise buildings and households that are largely exposed to more intense sunlight, and night vision equipment owing to the ability of ST-OSCs to absorb near-infrared spectrum and convert it to visible light. The daily availability of ST-OSCs demonstrates that addressing the global warming issue is not only confined to factories but also enables people to care for the Earth individually. Though with great significance, the fabrication of ST-OSCs has not been deeply developed probably because of the challenge to strictly control the absorbed or transmitted spectrums. So far, most of the research groups have concentrated on the modification of semitransparent organic photovoltaics based on a specific application or a certain property to be improved, creating a need to categorize and summarize diversified features behind the detailed products.

In order to clarify the current development of ST-OPVs and give personal outlooks, this review focuses on introducing dominant structures (bulk heterojunction and bilayer) of semitransparent organic solar cells including materials in different component layers, such as $PC_{61}BM$, $PC_{71}BM$, IT-IC, and 2PACz for acceptors, and PCE-10, TQ1, and PIDT-PhanQ for donors. In addition, major utilizations of ST-OSCs are linked to the properties required and potential future products are suggested. Here, challenges and possible ways to increase the efficiency and the transparency level are proposed to inspire more effective energy absorption via ST-OSCs.

2. Principle, Structure and Materials

2.1. Working Principle

The OSCs absorb incoming photons that are then attracted by electrons, forming excitons. They diffuse to the interface layer between the donor and acceptor and dissociate into electrons and holes. To separate charges, the acceptor material with a slightly higher energy than the HOMO level is constructed to let electrons that tend to fall to lower energy migrate to the acceptor first since they are physically closer in distance. Holes migrate to the anode and electrons flow to the cathode under the influence of an electric field, forming a loop of positive and negative charges, powering the cell. Fig. 1 illustrates the science behind solar cell operation.

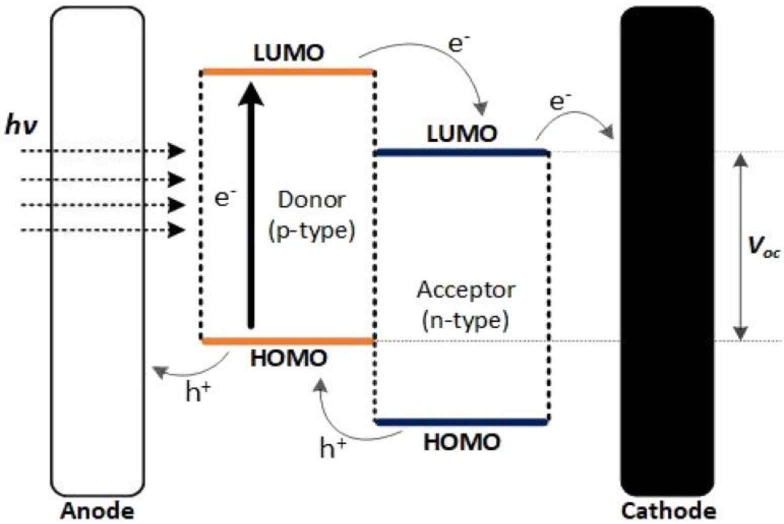

Fig. 1 Working principle of OPV [3]

A semitransparent organic solar cell generally contains top and back electrodes, with an electron-transport layer and a hole-transport layer in between. Fig.2 shows the typical arrangement of layers in a semitransparent organic solar cell. A substrate made of indium tin oxide (ITO) or glass is attached to the anode. A photoactive layer is inserted between the two charge-transport layers, in which donor and acceptor materials can either be blended to form a bulk heterojunction (BHJ) cell or be separated as bilayer cells. The fabrication of the photoactive layer is the key to promoting the efficiency of solar cells. To further improve the performance of the solar cell, an optical filter can be deposited on top of the cathode to enhance the visible light transmission and an antireflection coating can cover on top of the ITO/glass substrate that directly exposes to the Sun [4]. In this way, minimized reflection rate and maximum energy absorption can be ensured. The materials used for each layer are elaborated below.

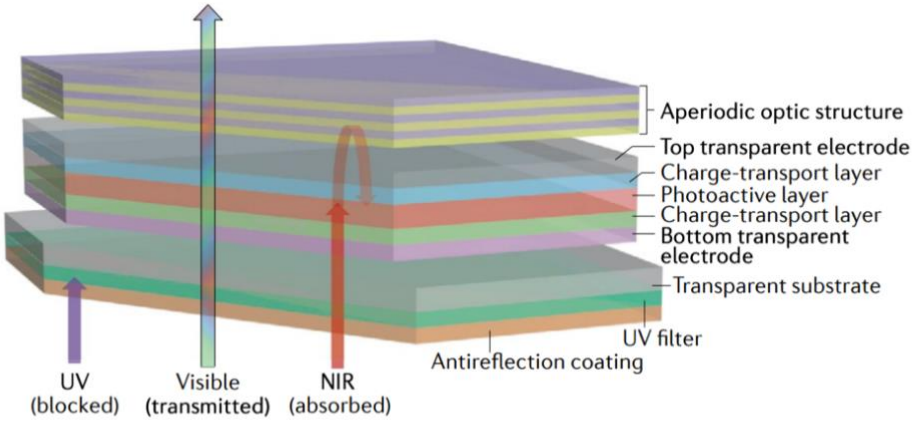

Fig. 2 Structure of a typical ST-OPV device [4]

2.2. Top and Back Electrodes

The development of top and back electrodes is still ongoing with plenty of innovations and creativity. In order to achieve high and well-balanced transmittance and conductivity in the visible light spectrum, the anode and cathode of semitransparent OPVs should be transparent to transmit light to the active layer. The anode and cathode are usually a transparent conductive surface receiving the incident light and a metal layer respectively, but new types of electrodes consisting of metal nanowires, ultrathin metal electrodes, transparent conductive polymers, carbon nanotubes and graphene, are constantly emerging to satisfy diversified demands. ITO has still been a dominant choice for anode material due to its efficiency at harvesting solar energy. As studied by Huang's team, the ITO transparent electrode works well to transfer charges because of its O-Cs dipole layer providing the strong ability to donate electrons [5]. This indicates that the dipole moment of molecules is able to tell the strength of electron-donating abilities, providing more detailed qualitative clues for deducing appropriate electrode materials. Nevertheless, ITO consumes as much as 90% of energy during manufacturing processes, raising the need for ITO-free electrodes.

Alternatively, metals possess high conductivity and minimization of bandgaps. In 2010, transparent silver nanowire electrodes were reported by Hu et al [6]. The high transmittance, excellent robustness and flexibility made it the best ITO substitute on plastic substrates for flexible electronics and solar cells. Moreover, the research group proved that the conductivity of the Au coating was enhanced as the junction resistance was reduced. This suggests that scientists started to consider the significance of the interconnections between layers to increase the sensitivity of electrodes. Besides silver, gold was discovered in January 2023 by Duan et al. to be suitable for highly transparent metal front electrodes which owe an average visible transmittance (AVT) of over 95% and a PCE of 10.14% [7]. To improve the durability and reduce the manufacturing cost, ultra-flexible thin metal electrodes in June 2023 by Lee et al. with a thickness below 10 nm were designed [8]. Compared to the past experiments that engaged in the environmental and operational aspects of ultra-flexible electrodes applied for sensors and biomonitors, Lee's group identified the demand for modifying the transparency rate of thin metal electrodes for building-integrated photovoltaics and solar energy harvesting.

However, the inevitable degradation of the metal electrode when encountering moisture, oxygen, heat, light, and mechanical stress led to its instability, encouraging the replacement with carbon or transparent conducting oxides. In 2012, Kim et al. developed top electrodes with laminated free-standing carbon nanotubes [9]. They can directly contact the OSCs without carrier substrate and possess little leakage currents without any smoothing layers, showing long-term stability and a low possibility of being damaged. In addition, metal and carbon allotropes can be combined to tune the transport property. Ultra-thin silver consisting of fullerene as an electrode in a PIDT-PhanQ:$PC_{71}BM$ system has been reported by Chueh et al., which redistributed the incident light intensity and created a favorable interface for organic and metal layers [5]. With the decreasing silver thickness and increasing PCE, this experiment shows that the hybridization of metal and other chemical compounds enables better performance in the solar cell compared to pure metal or carbon.

2.3. Charge-transport Layers

After the absorbance of photons, electrons and holes travel through the electron transport layer (ETL) and hole transport layer (HTL) respectively and form pairs as excitons. Here, the charge transport layers are the key to minimizing charge loss and maintaining high transparency for the light to reach the active layer. Poly(3,4-ethylenedioxythiophene)polystyrene sulfonate (PEDOT:PSS) and ZnO are widely used for transport layers. The popularity of PEDOT:PSS owes to the perfect interaction with the top electrode. When attached to the ITO transparent top electrode, the PEDOT:PSS HTL can exert force on ITO and stick to it. This function improves the performance and transmittance of the ITO electrode. For ITO and ultra-thin silver as electrodes, using PEDOT:PSS can reduce the silver surface roughness by enabling good wettability for the deposition of silver atoms. When the top and back electrodes are made of silver nanowires, PEDOT:PSS HTL can promote surface smoothness without influencing the transparency level by inserting it between the bottom silver layer and the ZnO layer.

2.4. Photoactive Layer

The photoactive layer is in the middle of the cell between the two charge transport layers for electrons and holes to dissociate. It includes donor materials and acceptor materials that are essential to make a difference in PCE and AVT. They can be arranged in different structures, namely single-junction, bilayer, bulk heterojunction (BHJ) and tandem solar cells. In particular, the commonly applied bilayer and bulk heterojunction cells and their related donor-acceptor materials are discussed below due to their distinct properties and progress.

2.4.1 Bilayer solar cells

In bilayer solar cells, the active layer has the donor and acceptor materials in two respective layers, deposited together by solution-based methods like spin-coating. The electrons and holes separate when flowing through the accepting sublayer and the donating sublayer correspondingly in the active layer. In 2020, Song et al. found out effective methods to optimize and increase the PCE of the semitransparent OPV using a bilayer structure, with PCE-10 as the electron-donating layer and IEICO-4F as the electron-accepting layer [10]. This is contributed by the increase in thickness of the IEICO-4F acceptor, which absorbs little visible light but strong near-infrared radiation to maintain the AVT without affecting the separated donor layer. Whereas in a BHJ structure, the overlapping of donor and acceptor materials causes the donor absorption vulnerable to any modifications of the acceptor, leading to a tradeoff between PCE and AVT. The above implies that the bilayer solar cells provide scientists access to a preferred efficiency value by altering the thickness of the donor or accepting layer, which does not apply to BHJ cells with a mixture of donor and acceptors.

2.4.2 Bulk heterojunction (BHJ) solar cells

The chance for excitons in bilayer cells to separate into electrons and holes only occurs when excitons move to the interface between the donor and acceptor, which shows a far less possibility for exciton diffusion, decreasing its charge transfer rate. Hence, other than the fabrication in the thickness of the active layer, heterojunction solar cells play a more important role in current research. The major reason is that the blending of donor and acceptors significantly shortens the diffusion length of excitons, so that less voltage is needed for them to separate and travel smoothly. Inevitably, the intriguing properties of BHJ structures need sophisticated modification of materials, making it more expensive than bilayer cells to be fabricated, but the increasing abundance of exploration in BHJ manufacturing methods will surely lower the cost in the future.

The choice of acceptor and donor materials is essential to guarantee the performance of OSCs. For the acceptor, fullerene and its derivatives have long been intriguing the transparent organic photovoltaics (TOPV) market because of their accessibility and efficient charge transport abilities. Fullerene derivatives' high electron affinity provides them enough energy to withdraw electrons from donors. C_{60}, $PC_{61}BM$, $PC_{71}BM$ and others have been utilized.

However, it is difficult to tune the absorption spectra in fullerene-based acceptors, leading to the investigation of small-molecule and non-fullerene acceptors (NFAs) that enable the near-infrared (NIR) absorption, obtain high transparency and tunable optic and electronic properties, and reduce energy loss. For instance, IT-IC, IEICO and IEICO-4F are low-bandgap acceptors commonly used in bulk heterojunction OSCs. Research teams have attempted various methods to lower the energy difference by either decreasing the LOMO level or raising the HOMO level. For example, IT-IC synthesized by Lin et al. contains 2-(3-oxo-2,3-dihydroinden-1-ylidene)malononitrile (INCN) groups at the end of the molecule [11]. The strong electron-withdrawing ability of one carbonyl and two cyano groups in INCN lowered the LUMO level to about -3.8eV and a bandgap of 1.6eV. This progress not only paved the way for the use of fullerene-free acceptors in semitransparent OPVs but also showed the significance of end-capping groups in small-molecule acceptors to determine the energy difference and modify the absorption spectra to increase the stability of ST-OPVs. The end-capping groups demonstrated their effectiveness in perylene diimide (PDI) NFA acceptors as well. Alkoxy groups and chlorine substitutions increase the electron-withdrawing strength, enhance the charge distribution and thus reduce the electron-hole binding energy, eventually achieving an energy loss below 0.6eV [4].

Donor materials in OPV cells are conjugated polymers, including PCE-10, TQ1, and PNDI-T10. This is because conjugated polymers can be engineered to possess a low ionization energy, easier to donate electrons. For semitransparent OPVs, the requirement in the transparency level creates the need for electron donors to have narrow spectral widths, a small binding energy and a more efficient NIR absorption. Interestingly, the fabrication of donor materials to achieve high efficiency is based on the modification of end groups as well, resembling the mechanism of enhancing the performance of acceptor materials. In 2012, the low-bandgap polymer PBDTT system (poly-thienylbenzodithiophene) was reported to be a good choice for weak donors5 due to the attachment of thiophene moieties end groups instead of the original oxygen atoms to the benzodithiophene unit, lowering the HOMO and LUMO energy levels. Moreover, the chlorine substitution in PCE-10 NIR polymer donor is able to stabilize HOMO and LUMO levels and increase the efficiency and potential difference in the open circuit, solving the problem of the tradeoff between voltage loss and quantum efficiency for polymers with low bandgap energies [4].

Donor and acceptor materials cannot be discussed separately since the increase in PCE requires careful design to let them interpenetrate. In 2019, Xia et al. reported 11% PCE and 30% AVT with PCE-10:IEICO-4F active layer [12]. In 2021, Yao et al. used PM6:Y6 donor-acceptor as the active layer to reach a PCE of 7.46% [13]. Although the efficiency is not so competitive, PM6 donor content is lowered to increase the AVT to 36.4%, demonstrating the ability to promote AVT by decreasing the percentage of donor contents. To date, it is still challenging to balance the absorption efficiency and the visible light transmittance. A 15.2% PCE has been developed in 2022 using a small-molecule acceptor 2PACz with low-donor content, despite the fact that the AVT is less than 20% [14]. Considering the specific applications and the unique property of the transparency of organic solar cells, 50% AVT is a favorable criterion to commercialize the ST-OPVs into the market, showing the need to level up the light transmittance while conserving the PCE. Besides AVT, the PCE of semitransparent organic photovoltaics is still not catching up with non-transparent OPVs which already exceed 18% PCE in single-junction cells, illustrating the major direction of future research to be focused on the performance of both AVT and PCE.

3. Performance and Application

All efforts dedicated to the improvement of electrode, transport layer and donor-acceptor materials are to impact the performance of ST-OPVs, with different properties required for various application fields.

3.1. Construction Use

Semitransparent OPVs have high transmittance of visible light and good power-generating ability, contributing to their utilization in households and high-rise buildings as building-integrated photovoltaics (BIPVs). ST-OPVs can be attached to the walls of skyscrapers which have great exposure to sunlight or be directly used as power-generated windows that have been already under development. As sunlight is incident on the solar window, visible light is transmitted due to its semitransparency and invisible spectrum such as ultraviolet and near-infrared radiation are absorbed. Compared to smart window blinds that are prevalent in the solar market at present, solar windows are more aesthetic because of the direct sunlight absorption of the window itself without the need for an extra cover outside the window. By introducing non-fullerene acceptors and Bragg reflectors to enhance the visible light transmittance and the reflectance of NIR radiation, the solar window achieves power-producing ability as well as heat insulation [15]. The rising convenience comes at the price of a higher performance of the solar cell, which is the balance between PCE and AVT, becoming one of the reasons why BIPVs using ST-OPVS are still under research and development. Typically, those ST-OPVs for building walls and windows are all very large for people inside buildings and households to have a broader sight and see clearly. Although the large cell size increases the absorption intensity by allowing more light to pass through in unit time, the wider entrance needs more power generation while more visible light is transmitted. In this case, it may be not easy to maintain the PCE. Though it is currently not possible to increase the PCE to a superior level, the challenge can be relieved by reducing the powered surface area.

As a result, ST-OPVs may be appropriate for individual use such as the cover on the cloth of tents, especially emergency tents. The covering solar cell of the tent should be flexible, bendable and thin to be packed up, thus making ST-OPVs the favorable choice. When interacting with solar radiation, visible light is not absorbed so that people inside the tent can see the outdoor environment to catch up with the current situation if adventurers are lost in unknown locations with unsafe geological features such as mountains and cliffs. After UV and NIR radiation are absorbed during the day, the solar energy can be converted to electricity to power the light connected to the ST-OPVs with external circuits in the tent. Light sources are usually not provided in mountains, cliffs and deserts, so the ability of emergency tents to generate electricity would solve the problem of darkness and enable night vision. Since the tent surface does not have a size as big as windows or building walls and the electricity consumption for emergencies is not that much compared to daily usage, a lower PCE is acceptable. Therefore, ST-OPV products for emergency use widen the solar market and possess a promising future for commercialization due to the necessity of emergency tools for every household and the ease of mass production via roll-to-roll printing.

3.2. Agricultural Use

The potential for ST-OPVs to be utilized for agriculture is based on simultaneous energy saving and plant photosynthesis in greenhouses. The operation of a greenhouse consumes a lot of energy in heating, cooling, artificial lighting, and ventilation to properly control the inner conditions such as temperature and humidity to elongate the growing season and diversify the categories of vegetation. Hence, the greenhouse has better gain the ability to power itself to achieve a more environmentally friendly development. Ideally, semitransparent or transparent organic photovoltaics are installed on the rooftops of greenhouses so that the allowance of visible light transmittance induces photosynthesis for plants to grow, while the UV and NIR radiation supplies the energy to power up the greenhouse. Organic solar cells are more competitive relative to inorganic ones due to the tunable bandgaps and the expected advantages of ST-OPVs. First, ST-OPVs have great mechanical strength and flexibility to withstand various weather conditions. The manufacturing process, roll-to-roll printing, has already been in large-scale application in factories, ensuring the low cost of production. Moreover, ST-OPVs would not impact crop growth since the non-toxic materials are selected for inner layers in solar cells, contrasting with inorganic or metal solar cells that are very likely to have some extent of toxicity that will affect the soil and water quality inside the greenhouse.

Currently, a strategy for achieving a net energy balance in greenhouses using OSCs has been developed depicted according to Fig.3. The PCE has reached 13.08% for semitransparent OSCs and a plant growth factor of 24.7% [16]. One drawback during the promotion of PCE is that the photosynthesis process may become less efficient because the solar cell's absorption spectrum will overlap with the radiation range for photosynthesis. This suggests future manipulation of ST-OPVs in agricultural use to focus on improving the selectivity of the absorption spectrum.

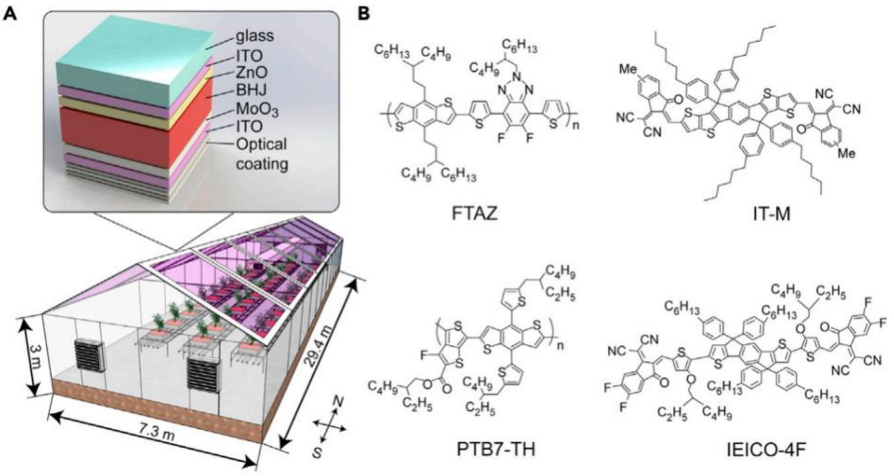

Fig. 3 Structure of OSCs in greenhouses [17]

(A). Macroscopic view of the greenhouse with OSCs installed and the layers of OSCs

(B). Materials in the photoactive layer

Not only can semitransparent OPVs be utilized in greenhouse rooftops, but also be adapted into other agricultural processes for power generation. The watering carts used for plant irrigation become one of the examples. The watering machine can be covered with semitransparent organic solar cells on top as a protection shell to absorb UV and NIR radiation to power up the irrigation process so that no external energy sources are needed. Due to the semitransparency, the plant growth processes would not be interrupted with the shell on top of the watering devices. This may shed light on possible future research directions on the agricultural aspect of ST-OPV applications.

3.3. Bioelectronics

Semitransparent organic solar cells are gradually being utilized in health science as well, for example, biological sensors and neural interfaces. In this case, scientists must be very careful about the choice of materials considering whether it creates short or long-term side effects to patients. Organic materials stand out due to their mechanical properties similar to the natural tissues in human bodies so that organic compounds can be adapted more quickly. Therefore, OSCs deal with the rising demand for self-powered health monitoring devices, increasing the convenience for patients in daily life. Some extent of transparency is required for patients and medical staff to see the skin clearly to observe biological symptoms in case the absence of visible light might cause unexpected skin color fading or skin diseases.

The photoactive layer inside the cell usually contains conductive polymers due to the benefits below. Firstly, mechanical and chemical properties can be easily adjusted. For example, extending the conjugated chain lengths and altering end-capping groups of polymers enable the modification of the electronegativity values to tune the bandgap. If oxygen or nitrogen atoms are introduced to create polar bonds, electrons are now less averagely distributed and become concentrated in the partially negative side, decreasing the electron mobility, increasing the bandgap. From another perspective, if double bonds emerge when polar atoms or groups are added to the original polymers, the pi-bonds provide freedom for electrons to flow below and above the bond axis, increasing the electron mobility, reducing the energy gap. Hence, the modification of end-capping groups of polymers gives scientists multiple directions to either enhance or suppress the performance of monitoring devices, but the ultimate goal is to fit with the human bodies and achieve high-efficiency self-powered equipment. Moreover, conductive polymers enable low-temperature processing, especially suitable for people living in ambient conditions. The most important feature of conductive polymers inside OSCs is the high ion mobilities, which means ions can move freely through the public area created by overlapped pi-bonds in the conjugated carbon chain to conduct electricity and transport charges. This also creates one of the similarities of OSCs with the body, that they both transport charges. In this way, diagnostic devices can detect similar chemical signals inside the body to sense any unusual behaviors; therapeutic devices would be able to transfer electric signals back into the body to deliver medical treatment. As a result, ion mobility is the essential reason why conductive polymers are effective for bioelectronics.

The power conversion efficiency is considered in bioelectronics as well, which comes into play as sensitivity. In other words, an acceptable health monitoring device in the market should be highly sensitive to transfer or receive chemical signals, suggesting the requirement of a large surface area of polymer materials to attach to charges so that more molecules are received in unit time. Compared to inorganic solar cells which are in the closely packed structure of metallic lattices that do not allow ions to penetrate, organic materials have loosely connected polymers for ions to move. In the current investigation, an efficiency of 7.9% was reached in 2017 by Jinno et al. with ultra-flexible organic solar cells coated with elastomers on both sides. It remained 80% of the initial efficiency after roughly 2 hours of water immersion [18]. The water-resistant ability suggests wearable electronics to be applied in daily usages, not only for medical diagnosis or treatment. For instance, people who are fond of scuba diving may be equipped with semitransparent bioelectronic devices on their arms or hands to monitor their heart rate during regular diving exercises. The transparency enables them to see the health data underwater. Nevertheless, the long-term stability of ST-OPVs is necessary to be enhanced to prevent efficiency degradation and prolong the lifetime of bioelectronics.

Overall, three major application fields of semitransparent OPVs are illustrated with product examples, market development, expected properties, some manufacturing techniques and future focus. The above information is summarized in the Table 1.

Table 1. Summary of performance and application of ST-OPVs

Application	Properties	Fabrication method	Existing Products	Future Focus
Construction	High flexibility Low thickness Light weight High efficiency Low reflection	Roll-to-roll large-area printing	Smart window blinds Solar windows in households, office buildings and cars	Emergency tent covers
Agriculture	Water resistance Low brittleness High efficiency No toxicity High absorbance selectivity	Roll-to-roll large-area printing	Rooftop covers of greenhouses	Irrigation equipment
Bioelectronics	High flexibility High malleability Low thickness Light weight High sensitivity Good compatibility	Slide-coating system [19]	Health monitoring devices Vital signs tracking Therapeutic apparatus	Heart rate tracking in sports

4. Conclusion

Under the rising severity of global warming, the utilization of solar energy has long been fascinated by scientists who have investigated possible methods to harness and select different wavelengths of the electromagnetic spectrum for different applications. Among them, semitransparent organic photovoltaics are beneficial due to the accessibility of organic materials, ensuring mass production and cost-effectiveness. Semitransparent organic solar cells consist of an ITO/glass substrate, cathode and anode, charge transport layers attached on each electrode and the photoactive layer in between. ITO has been a popular choice for transparent top and back electrodes, but the huge energy consumption is inevitable. Thus, alternatives such as metal nanowires and ultra-flexible thin metal electrodes have been developed. The degradation issue of metals can be solved by replacing them with carbon and its derivatives. Electron and hole transport layers usually consider conductive polymers like PEDOT:PSS and metal oxides like zinc oxide as suitable materials. The photoactive layer largely determines the overall performance of ST-OSCs. The donor and acceptor materials can be arranged in a bilayer or bulk heterojunction structure. Different approaches to optimize the two structures have been testified to be effective, but BHJ solar cells generally outweigh the bilayer cells due to the reduction in exciton diffusion length. Non-fullerene acceptors and conjugated polymer donors interpenetrate. Their properties can be tuned by modifying the end groups of polymers to improve the PCE, opening the ST-OPV market for commercial and residential, and agricultural use. A highly flexible, ultrathin and lightweight semitransparent solar cell is usually attached to walls or inlaid as solar windows due to the large-area outer shell exposure rate of buildings. To cope with the efficiency problem, ST-OPVs can cover the emergency tents which do not need large amounts of power. Due to their environmental friendliness, ST-OPVs appear on greenhouse rooftops to simultaneously generate power and let plants photosynthesize. In the future, the electricity converted may be used to power watering carts and other agricultural equipment. The good conformability, high flexibility and ion mobilities of organic materials made ST-OPVs favorable for wearable electronic devices. Not only are they able to be applied in health science, but they are also able to monitor heartbeat rate during daily sports exercise.

Despite the in-depth research and development on a lab scale, it is still challenging for ST-OPV products to enter the market due to several unsolved troubles. The first and foremost is the balance between visible light transmittance and power conversion efficiency. For BIPVs, although a PCE of approximately 20% has been developed, an AVT of at least 50% is required for commercialization, which has not been achieved yet, suggesting the need to improve spectrum selectivity and raise the awareness of the significance of the optical coating behind the solar cell surface to increase the visible transparency, enhance the NIR absorption and provide desirable color. Apart from the challenge of enhancing operating efficiency, cell instability leads to a shorter lifetime and color degradation. Possible solutions include the introduction of more electronegative end groups in non-fullerene acceptors to decrease photooxidation, and the modification of interfaces between electron-hole transport layers and active layers. The increasing smoothness of the interfaces can reduce current leakage and improve thermal stability. Future research is required to illustrate the effectiveness of these methods and confront the challenges. In a word, semitransparent organic solar cells play an important role in establishing a sustainable environment. As various layers in the photovoltaics are more sophisticatedly fabricated, the efficiency and transparency will surely be enhanced. The low cost and possibility of relatively matured fabrication techniques guarantee the bright future of ST-OPVs and encourage the introduction of new blood into the field.

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