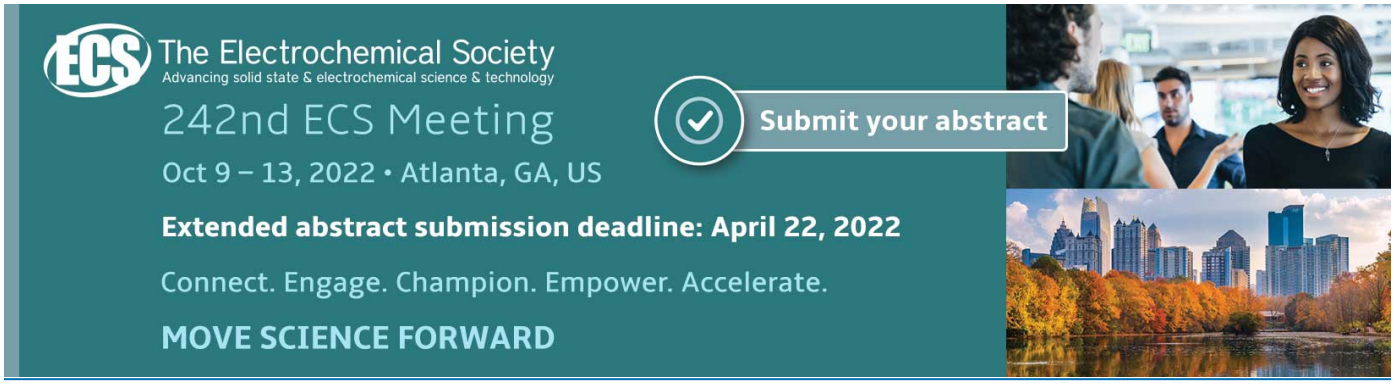
Progress on Organic Solar Cells: A Short Review



Progress on Organic Solar Cells: A Short Review

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Abstract Thin film organic solar cells have emerged as a replacement to inorganic solar cells based on silicon. Organic solar cells offer several advantages compared to silicon-based devices. In the last 10 years, concentrated research attempts towards accomplishing the mandatory power conversion efficiency of 10 % and environmental stability of the device still remain a main challenge. In order to influence the efficiency, polymers are frequently utilized to fabricate the absorber and buffer layers. Also, binary and tenary polymer blends have been devised to influence the performance in micro/nanostructures. In addition, the advantages of organic solar cells for realistic application, and potential solutions are also considered.

Keywords: Buffer layer**;** organic solar cells; power conversion efficiency; polymer.

1. Introduction

Presently, solar cell efficiencies is an utmost limiting factor in the commercialization of this devices (Abodunrin *et al.,* 2018). The quest for improved energy supply has led to the development of various technologies. Some these technologies have been proven to detrimental to life form. For example, the fossil fuel generator is the most used in developing country. This technology has contributed significantly to the global carbon print. The nuclear energy technology is still in use in most parts of the globe (Tsokos, 2010). The main shortcoming of nuclear energy technology is the toxic radioactive waste. Radioactive waste includes solid, liquid or gas material that consists of a radioactive nuclear substance. This waste can lead to air, land and water pollutions if not properly managed. The renewable energy technology has received huge patronage based on the global resolution to promote the sustainable development goal (SDG) number 7 i.e., provision of clean energy. Among the renewable energy options, the solar energy is the most prominent due to the availability of the sun in sizeable parts of the globe. There solar devices that are used to convert solar to useable energies. Some of the solar devices include solar collector, solar heater, photovoltaic, thermovoltaic, solar storage fluids etc. The photovoltaic technology is the most used among the renewable energy options.

The photovoltaic had improved since 1954 when the first photovoltaic was invented by Calvin Souther Fuller, Daryl Chapin and Gerald Pearson (Tsokos, 2010). Most photovoltaic devices readily referred to as solar cells, which are semiconducting device. Solar cells are grouped into first, second and third generation cells. Unfortunately, the solar device has gone through several modifications due to the bid to optimize its technology. This paper is a short review that is meant to discuss on the progress and shortcoming of photovoltaic device.

2. Progress on Organic solar cells

Organic solar cells are classified into three types namely: single, bilayer and bulk heterojunction organic solar cell. The single-layer OSCs are the easiest structure of organic solar cells (Kesinro *et al.,* 2019). The simplest structure for OSCs is based on single layer of organic material. They are fabricated by embedding a layer of the conjugated polymer between two conducting electrodes. The primary arrangement of a single layer device is displayed in Figure 2.5(a). it comprises of an organic absorber medium sandwiched amid indium tin oxide (ITO) and aluminum electrodes. The main limitation encountered for this device is its small thickness of the absorber medium at roughly 10 - 20 nm allowing

merely a minor ration of the incident light to be absorbed by the device for power conversion (Kalyani & Dhoble 2018).

The bilayer OSC has two separate organic layers sandwiched between the electron and hole collecting layer followed by the conducting electrodes. Figure 2.5 (b) displays the fundamental structure of the device. Exciton separation occurs at the interface between the donor and acceptor. The workfunction of the electrodes to form better ohmic contacts are modified by the electron and hole collecting layers. Better electron affinity and ionization potentials is exhibited by the acceptors compared to the donors. The donor layer absorbs the incident photon, and electrons in the donor material are agitated from the highest occupied molecular orbital (HOMO) level to lowest unoccupied molecular orbital (LUMO) level, forming excitons. Lastly, bulk heterojunction OSC has a photoactive (absorber) layer which is a polymer blend. The blend is normally made by combining electron donor and acceptor polymers which is then inserted between the electrodes. (Kalyani & Dhoble 2018).

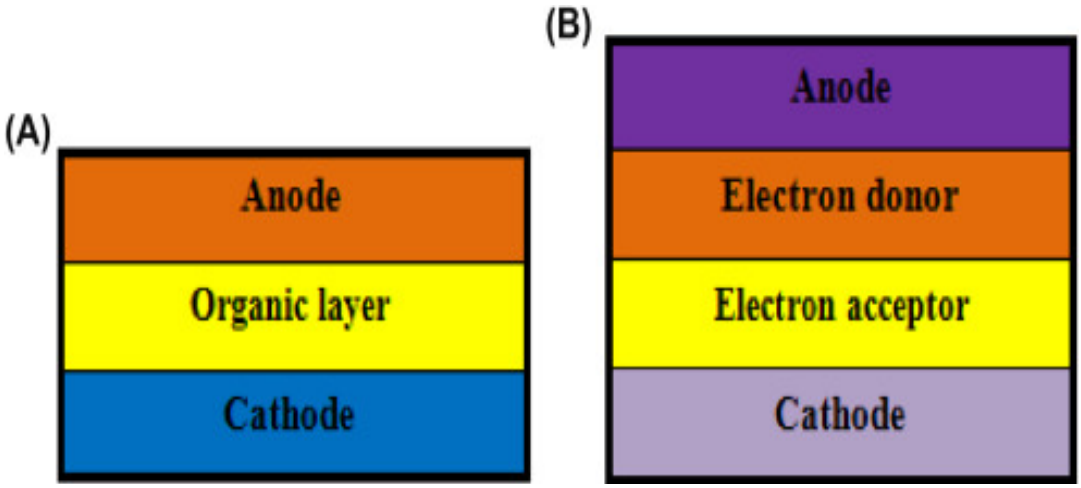

Figure 1: Organic solar cells: (a) single layer and (b) bilayer (Kalyani & Dhoble, 2018)

Recently, in order to achieve absorption across a wide spectrum, tandem OSCs based on PTB7: $PC_{70}BM$ and PDPPSDTPS: $PC_{60}BM$ as absorber materials was proposed by Kumar *et al.* (2019). The introduction at the top and bottom subcells with silver (Ag) nanospheres and effectively enhanced the absorption and performance of the device in comparison to the reference OSC without nanoparticles. The improvement in the PCE of ~15.4 %, in comparison to 12.25 % attained by the reference device is attributed to the introduction of plasmonic nanoparticles and the wide spectrum absorption band of the absorber materials.

3. Bulk Heterojunction Organic Solar Cells (BHJ-OSCs)

The structure of BHJ-OSC is a multilayer structure where each layer can be created by an individual fabrication technique. In this device structure, the photoactive (absorber) medium is a combination of donor and acceptor polymers. These polymers are dissolved in a solvent system to form the absorber layer which is an important component of the BHJ-OSC. Also, in the BHJ-OSC bicontinous interpenetrating networks are formed which increases the border between the donor and acceptor is vital for the necessary separation of excitons. A schematic diagram for BHJ-OSC is displayed in Figure 2.8. Additionally, massive input of results based on BHJ-OSC has been published over the past decade due to the encouraging results that have been attained by this device structure (Wolf, Cruciani, Labban & Beauiuge, 2015).

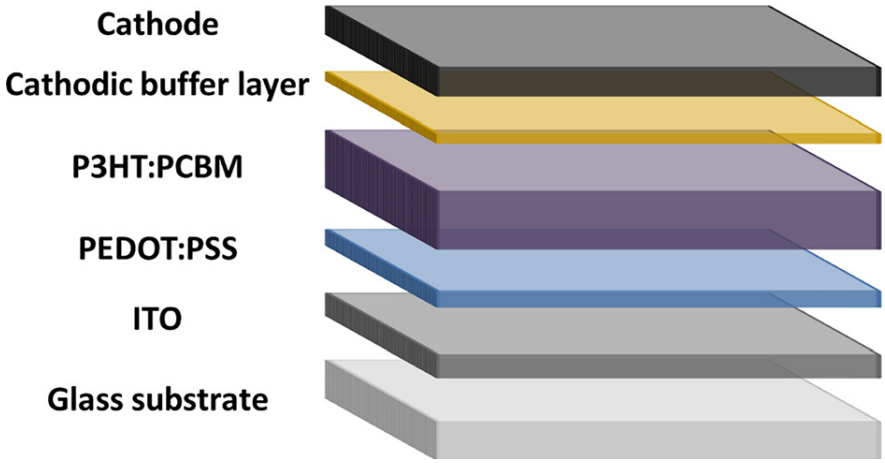

Figure 2: Schematic diagram of BHJ organic solar cell (Berger & Kim, 2018)

3.1 Photoactive (Absorber) Layer

The absorber layer is a very crucial part of device, and it is made up of a donor/acceptor blend mixture. The absorber coating is included between the anode and cathode. Excitons are created in the absorber medium after the absorption of photon. After the generation of excitons, they diffuse in the absorber medium to the donor/acceptor barrier where they are separated into the electron and hole carriers. The carriers are then transferred to their separate electrodes to generate photocurrent provided there is no recombination of the carriers. Therefore, the synthesis of the photoactive layer is essential for excitons separation and device performance (Hou, Xiao, Han, & Lin, 2019) The traditional acceptors and derivatives used are based on their prominent electron affinity, long electron diffusion and quick carrier separation include the fullerene (C_{60}, $PC_{60}BM$, and $PC_{70}BM$). However, there are numerous polymer donors available compared to acceptors. Nevertheless, medium or low bandgap, high carrier mobility, and good solubility are the conditions a good donor polymer ought to satisfy (Yao, He, Zhang, Li, Zhang, & Hou, 2016).

3.2 Donor Polymers

Donor polymers are rich in electrons and are used in donating electrons in the absorber layer in BHJ-OSCs. Polythiophenes, thienthiopene and 2, 1, 3 - benzothiadiazole (BT) shown in Figure 2.9 are the common donor polymers used in the formulation of the absorber medium in OSCs. The attraction in polythiophenes and its derivatives has intensified high research curiousity for photovoltaic applications. P3HT molecules, a derivative of polythiophene, has often been utilized in assembly of OSCs. As a consequence, the blend of P3HT and fullerene counterparts have produced efficient and stable devices based on organic semiconductor both on glass and flexible substrates (Sun *et al.,* 2014).

However, the conjugated polymers with 4,7-di(thiophene-2-yl) benzo[c]-[1,2,5]-thiadiazole (DTBT) building block, especially, poly[*N*-9′-heptadecanyl-2,7-carbazole-*alt*-5,5-(4′,7′-di-2-thienyl-2′,1′,3′ benzothiadiazole) (PCDTBT), have attained extra research concentration in OSCs, which has translated in better performances documented so far in OSCs (He *et al.,* 2015). Based on device performances reported using different donor polymers, thieno [3,4-*b*] thiophene-*alt*-benzodithiophene (PTB7) reported an efficiency as high as 10 %, which sees it as the most successful donor polymer in OSCs.

3.3 Acceptor Polymer

Several derivatives of C_{60} known as fullerenes were produced to affect the polymer solubility in familiar solvents. The most general C_{60} derivatives are [6, 6]-phenyl-C_{61}-butyric acid methyl ester ($PC_{60}BM$), [6, 6]-phenyl-C_{71}-butyric acid methyl ester ($PC_{70}BM$) ($PC_{71}BM$) which are soluble in organic solvents. Though, derivatives of (C_{60} and C_{70}) in Figure 2.10 have been utilized in fabricating high performing OSCs over the years. $PC_{70}BM$ has entertained tremendous consideration due to its improved optical absorption in the visible range (Ganesamoorthy, Sathiyan, & Sakthivel, 2017). The four main roles of the acceptors in OSCs are as follows:

i. Light absorption: Although donors absorb photons and generate excitons, acceptors can also absorb photons to produce excitons and contribute to the photocurrent. Complementary absorption between donors and acceptors can, therefore, be an effective method of increasing light harvesting (Ganesamoorthy *et al.,* 2017).
ii. Exciton dissociation: The excitons generated under illumination move to the donor-acceptor interface and detach into holes and electrons. The driving force for the separation of the excitons comes from the difference in energy between the donor HOMO and acceptor LUMO (Ganesamoorthy *et al.,* 2017).
iii. Electron transport: After the dissociation of excitons, the electrons are moved to the cathode through the acceptor channels. As a result of the limited lifetime (nanoseconds to microseconds) of the carriers, the mobility of the acceptor should be high enough to ensure that the electron can be transported to and extracted by the cathode within its lifetime, otherwise, recombination between the hole and electron will occur (Ganesamoorthy *et al.,* 2017).
iv. Morphology control: Morphology control of the absorber medium is a crucial issue in bulk heterojunction (BHJ) OSCs. As a result of their dissimilarity, donor and acceptor materials tend to aggregate with homogeneous molecules and separate from heterogeneous molecules, resulting in spontaneous phase separation (Ganesamoorthy *et al.,* 2017).

4. Operational Principle of Bulk Heterojunction Organic Solar Cell

It has been identified that four primary steps describe the working principle of BHJ-OSCs. These stages which consist of: photon absorption and creation of exciton (electron-hole pairs); diffusion of exciton and separation; transport and collection of carriers (Rafique *et al.,* 2018). The donor material absorbs the incident light in the absorber layer. After the absorption of photons, excitons are created and it is affirmed that to generate excitons, the balance between donor (HOMO) and acceptor (LUMO) should exist between 0.1 to 1.4 eV. However, excitons are separated into holes and electrons after diffusing to interface between the donor and acceptor where necessary potential energy drop separates them. The free carriers move towards their respective electrodes through the bicontinous pathway after separation while avoiding recombination. Also, losses are encountered during these stages which include absorption loss due to spectral difference, thermalization loss, limiting the overall performance of the device (Siddiki, Li, Galipeau & Qiao, 2010).

5. Solvent Additives

The general efficiency of BHJ-OSCs is mostly established by the morphology of the photoactive medium (Jackson, Savoie, Marks, Chen & Ratner, 2015). There have been a number of approaches to enrich the morphology of the photoactive medium for instance post-thermal annealing, solvent annealing and additives. The additive method has shown to be the mainly utilized for BHJ-OSCs with fullerene acceptors (Tran, Kim, Park & Cho, 2018). They tend to change the solubility of one or both, components, or the mutual miscibility between the donor and acceptor. Octanedithiol (ODT), diiodooctane (DIO), diphenyl ether (DPE) and chloronaphthalene (CN) are typical processing additives for BHJ-OSCs. Recent studies on the effects of solvent additives (ODT, DIO, CN, and DPE) indicated that DPE readily forms optimized BHJ morphologies for five key polymer: fullerene blends (Lee *et al.,* 2017). As a result of their elevated boiling point and selective solubility, the formation of the photoactive film is strongly influenced by the introduction of additives. By delaying the solidification of one component (often the fullerene derivative), the second component can form more ordered structures. Two essential guides in choosing host solvent and additive are: (1) the electron donor and acceptor molecules most be highly soluble in host solvents due to high solubility, and (2) the solvent additives are typically less volatile with higher boiling points than host solvents.

Foertig *et al.* (2014) examined the effect of introducing DIO additive in the photoactive medium composed of PTB7 and $PC_{71}BM$. It results obtained indicate an improvement in device performance by weakening of the bimolecular recombination, due to significant morphology changes in the photoactive layer. In similar vein, Choi *et al.* (2015) utilized DPE to improve the morphology of DT-PDPP2T-TT: $PC_{71}BM$ absorber medium with a thickness of up to 300 nm, thereby increasing PCE from 3.2% to 9.5%. Similarly, Araujo *et al.* (2019) researched the influence of DIO additive on performance of BHJ-OSC using PTB7-Th: $PC_{71}BM$ blend as the photoactive medium. Pure chlorobenzene as a solvent or mixed with DIO were used in fabrication of the devices. It was evident that the consequence of DIO in the photoactive layer improved its morphology, leading to improvement in the conduction process, and reduction of recombination coefficient.

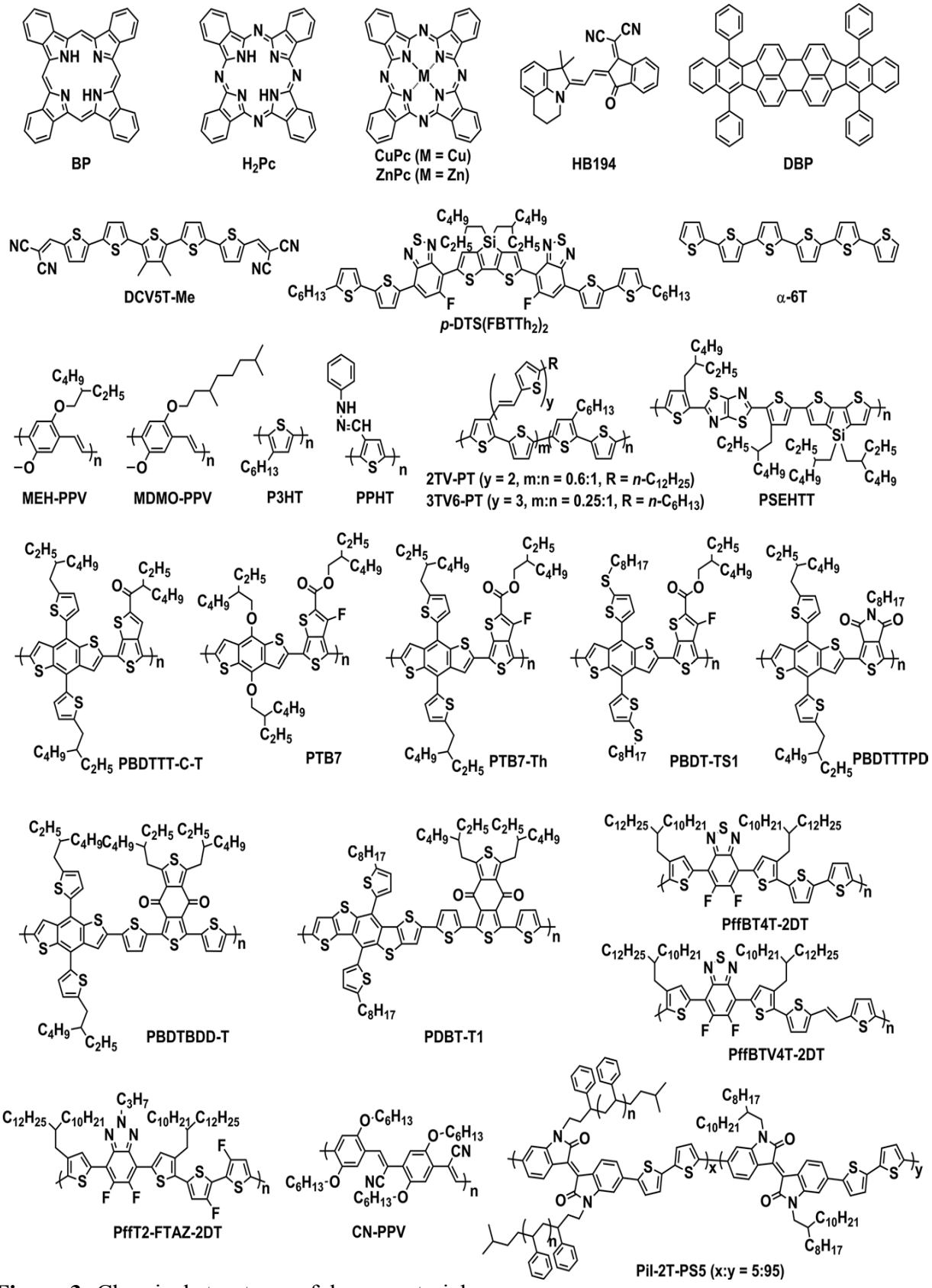

Figure 3: Chemical structures of donor materials.
Source: Wang & Zhan (2017)

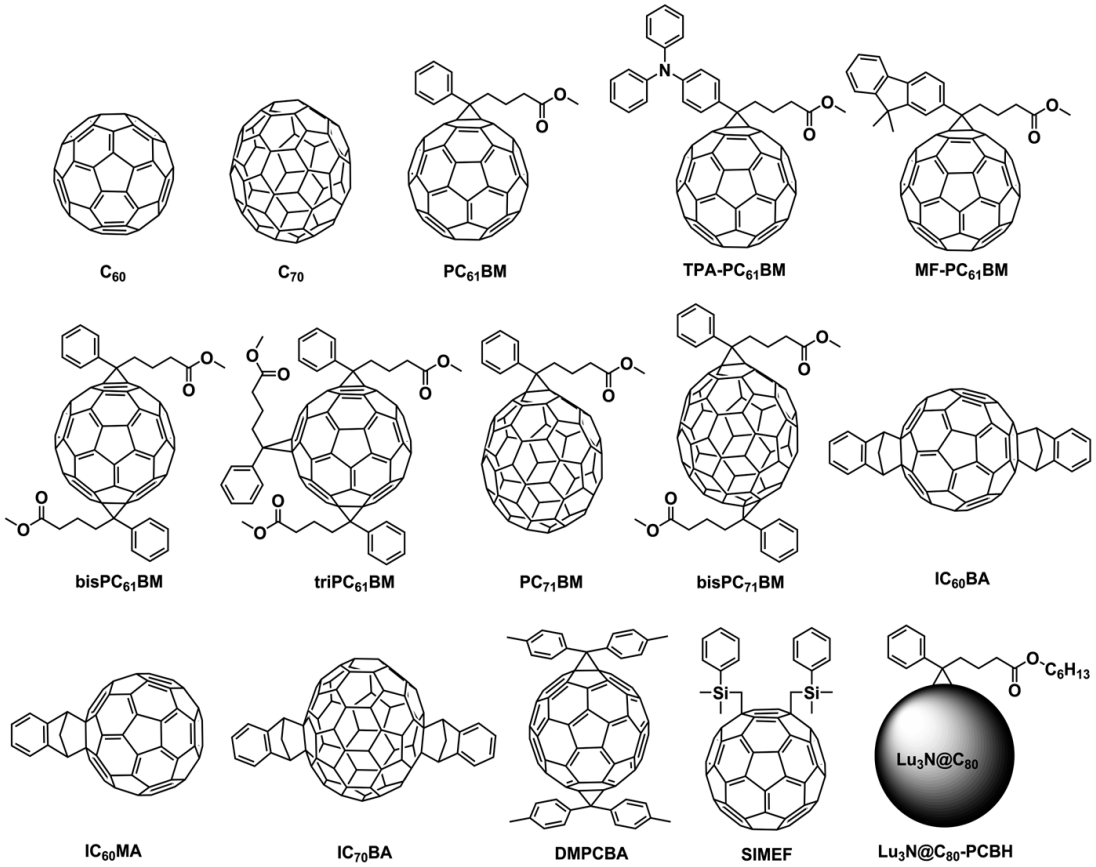

Figure 4: Fullerene-based acceptor molecules in OSC (Wang & Zhan 2017)

Consequently, enhancement of the generated photocurrent is possibly due to the breaking up of $PC_{71}BM$ clusters and improved infusion into the PTB7-Th polymer matrix, enabling separation of charge-transfer states at donor/acceptor interfaces. Zheng *et al.* (2018) attained an efficiency of 9.5 % using PTB7: $PC_{70}BM$ photoactive layer in OSC by introducing binary solvent additives of DPE and DIO. Results reported showed that the combination of additives improved the crystallinity of the donor (PTB7) using DPE and improved $PC_{70}BM$ distribution using DIO. Similarly, Khan *et al.* (2019) examined the effects on the morphology and overall performance using electron transport layer based on ZnO nanoripple and DIO. PTB7 Th: $PC_{71}BM$ constitute the absorber blend and it is asserted that using ZnO nanoripples and DIO enabled the growth of continuous network of donor and acceptor. Also, the device demonstrated better current density (J_{sc}) and PCE of 15.57 mA cm^{-2} and 8.20 % respectively.

Conclusion

In the quest to achieve favorable production cost at the same time appreciable power conversion efficiency, OSCs have presented considerable advantages. The ability to tune the chemical properties, light weight as well as easy fabrication are some of the advantages presented by OSCs. Although, inorganic molecules based solar cells have exhibited higher power conversion efficiency and environmental stability, several advancements have been attained towards the realization in OSCs. The possibility to obtain high performance in OSC can be attained by using highly effective absorber materials and the use of inverted device structure in organic solar cells involving tandem architecture. In OSC, the polymers are generally utilized as the absorber layer to induce the light harvesting efficiency and performance of devices. The key to fulfilling the highly effective OSC is to design the new polymers with narrow bandgap and appropriate energy level arrangement.

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