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Non-fullerene polymer acceptors based on perylene diimides in all-polymer solar cells

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ABSTRACT

All-polymer solar cells (All-PSCs) have attracted a lot of attention in the recent years due to broad absorption spectra, adjustable chemical structures, high morphological stability, better donor-acceptor compatibility and better mechanical durability. This review summarizes the recent development of perylene diimides (PDI)-based electron acceptors used in all-PSCs because these polymers are promising candidates. The photovoltaic performances of non-fullerene polymer acceptors were compared, and the structure-performance relationship was discussed when the same donor material was used.

1. Introduction

Over the past two decades, organic solar cells (OSCs) have attracted a lot of attention, which is mainly because of the following advantages: light weight, low cost, easy processing and flexibility [1–3]. The active layer in single-junction OSCs is sandwiched between two electrodes. The active layer consists of donor (p-type) materials and acceptor (n-type) materials. So many efforts have been made to design novel and efficient donor and acceptor materials in order to pursuit high power conversion efficiency (PCE) [4,5]. Great progress has been achieved mainly based on fullerene derivatives as the acceptor materials because fullerene derivatives exhibit good solubility in organic solvents (such as chloroform, chlorobenzene, dichlorobenzene, etc.), high electron affinity and high electron mobility [6–9]. Various efficient acceptors based on fullerene are synthesized, such as phenyl-C61-butyric acid methyl ester ($PC_{61}BM$), phenyl-C71-butyric acid methyl ester ($PC_{71}BM$) and Indene-C_{60} bisadduct (ICBA), etc. [10–12]. Nevertheless, these materials have some inherent shortcomings: limited tunability of chemical structure and energy levels; low light absorption capacity in the visible and infrared spectra; high cost and poor mechanical adaptability [13–15]. Therefore, it is necessary to find new alternative acceptor materials to solve these problems.

Non-fullerene electron acceptors (NFA) can be divided into two categories, small molecules [16,17] and polymer acceptors [18–25]. Non-fullerene acceptors are attracting more and more attentions because of their advantages, such as: broad absorption spectra, adjustable chemical structures and better stability. PCE over 14% [26,27] has been achieved by taking advantages of non-fullerene small molecules. While, the PCE values of OSCs based on polymer acceptors just exceeded 10% [28]. Compared with small molecules, polymer electron acceptors own additional merits: the higher morphological stability and better donor-acceptor compatibility [29–31]. Because the polymer acceptor was intrinsically more ductile than the small molecular acceptors and could better entangle with the other polymer chains with strengthened interfaces [32]. Therefore, it is of great significance to realize the efficiency breakthrough in all-polymer solar cells (All-PSCs), consisting of a polymer donor (P_D) and a polymer acceptor (P_A). Perylene diimides (PDI) have been widely used to construct non-fullerene acceptor materials, either small molecules or polymers, because there are two electron-withdrawing imide groups in PDI structure, which results in high electron affinity. Moreover, the highly extended π-conjugated system gives rise to strong inter-molecular interaction that increases the electron mobility. But the photovoltaic performance of PDI-based P_A materials is still lagged behind. Although amide [33–35], imide [28,31,36] or B→N units [23,37–39] have been widely used to construct P_A, only PDI-based P_A materials in recent years and P_A materials with similar structures in the early stage were included in this mini review.

Some excellent reviews are recommended for readers to know the development of the non-fullerene P_A materials in the early stage [32,40–42]. In order to study the structure-performance relationship, the photovoltaic performance of non-fullerene P_A was discussed when the same donor material was used. This review is divided into three parts according to the structural feature of these P_A: (1) copolymerized with a variety of electron-rich (donor) units, (2) copolymerized with various electron-deficient (acceptor) units and (3) side-

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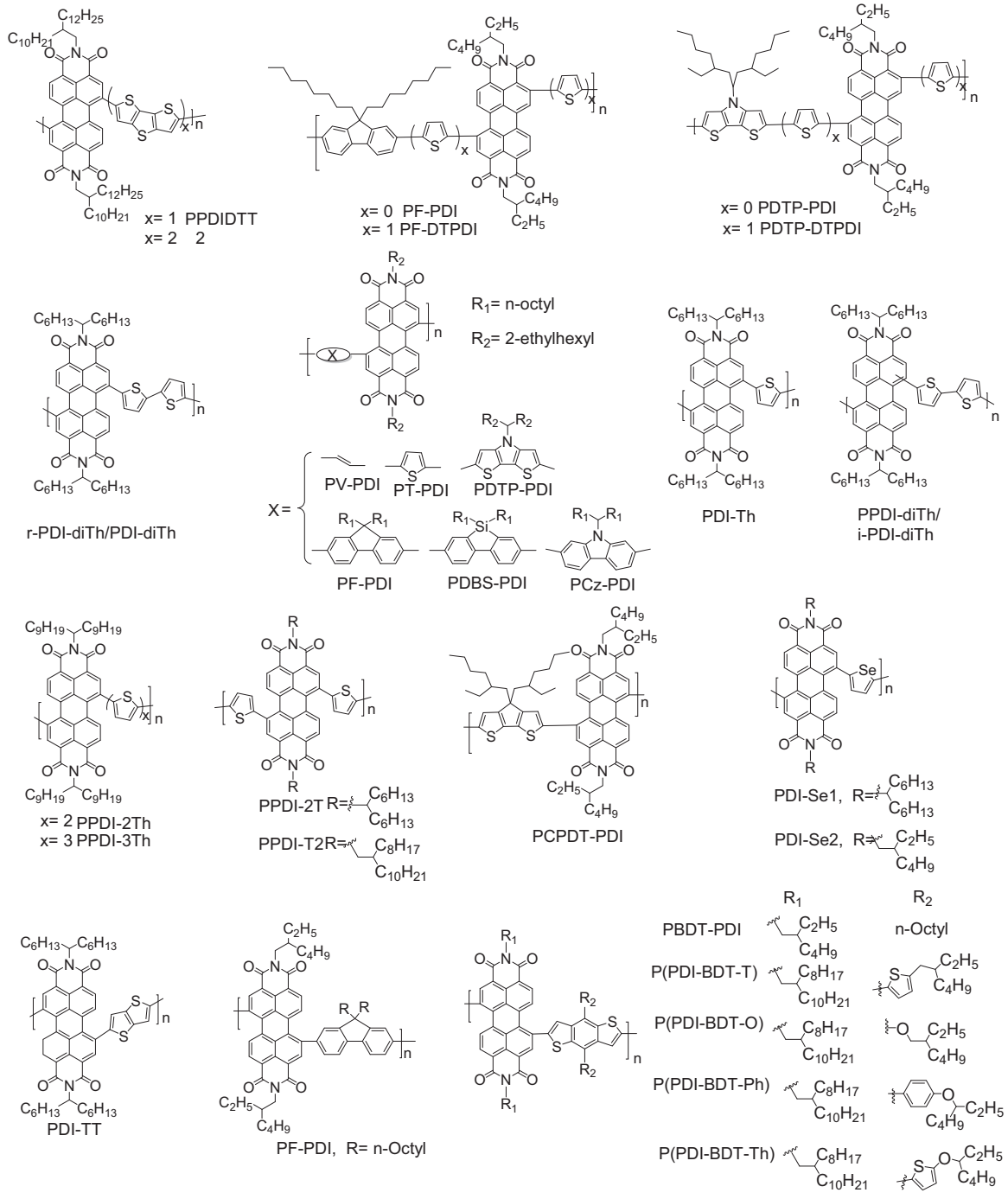

Fig. 1. PDI-based polymer acceptors copolymerized with variety of common electron-rich (donor) units.

chain engineering. Additionally, morphology and energy loss were discussed briefly for readers to understand other challenges or chances in making breakthrough in all-PSCs. Structures of the donor materials mentioned in this review were exhibited in Fig. 6. We hope that this review might shed a light on design novel and efficient polymer acceptors in the future.

2. Copolymerized with variety of electron-rich (donor) units

In 2007, Zhan et al. creatively synthesized the first PDI-based P_A, namely PPDIDTT (as shown in Fig. 1). This is a precedent in the development of NFA materials. Blended with a polythiophene derivative (polymer 1, as seen in Fig. 6) as donor, a power conversion efficiency (PCE) of 1% was achieved [43]. Since then, donor-acceptor (D-A) alternating copolymers based on PDI become one kind of promising non-fullerene candidates. This is because dibromo-PDI can be easily obtained [44–47], which could be copolymerized with a wide variety of electron-rich (donor) units to fine-tune the optoelectronic properties of the P_A. The donor segments include vinylene (V), thiophene (Th), dithieno[3,2-b:2',3'-*d*]pyrrole (DTP), fluorene (F), dibenzosilole (DBS), carbazole (Cz), bithiophene (DT), selenophone (Se), thieno[3,2-b] thiophene (TT), bithienyl-benzodithiophene (BDT) and so on.

When the donor segment in P_A was extended to two dithienothiophene (DTT), P_A 2 was synthesized. Compared to PPDIDTT, P_A 2 had higher frontier molecular orbital energy levels. The lowest unoccupied molecular orbital (LUMO) level and the highest occupied molecular