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Research Highlight

The new era for organic solar cells: polymer acceptors

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Organic solar cells (OSCs) have made fast advance with prominent power conversion efficiencies (PCEs) achieved in non-fullerene OSCs in recent years [1]. Among various types of OSCs, all-polymer solar cells (APSCs) consisting of a polymer donor and a polymer acceptor are promising power sources for portable and wearable electronics due to their intrinsic advantages in device stability and mechanical flexibility [2]. Duan group [3] demonstrated an APSC that maintained 97% of its initial PCE after continuous heating at 65 °C for 300 h, which is much superior to the small molecular acceptor-based OSCs. Kim group [4] compared the mechanical properties of the active layers of APSCs and fullerene acceptor-based OSCs containing the same polymer donor. It was demonstrated that the elongation at the break and toughness of all-polymer blend were 60 and 470 times, respectively, higher than those of polymer:fullerene blend. These advantageous mechanical properties are desirable for practical application of OSCs [5,6]. However, the development of APSCs lags much behind that of small molecular acceptor-based OSCs. In particular, there is a big gap in PCE between APSCs and small molecular acceptor-based OSCs, which is mainly caused by the lack of polymer acceptors with desirable optoelectronic properties and difficulties in morphology control of the active layer.

The first APSC was reported as early as 1995 [7]. After the first PDI polymer acceptor being reported [8], the electron acceptors employed in APSCs were predominated by perylenediimide (PDI) and naphthalenediimide (NDI) based polymers. Among these polymers, N2200 and NDP-V (Fig. 1) are the representative ones, which realized PCEs of 11.8% and 8.6%, respectively [9,10]. Notably, the 11.8% PCE realized by N2200 demonstrated that APSCs can compete with fullerene-based OSCs for the first time [9]. The major drawback of NDI and PDI polymers is their poor light-harvesting capability due to the large torsion angles between NDI/PDI core units and the adjacent units, which limited the short-circuit current density (J_{sc}) of the resulting APSCs. Specifically, NDI polymers usually have very low absorption coefficients ($\approx 3 \times 10^4$ cm^{-1}) in the long wavelength region, and PDI polymers usually exhibit narrow absorption range with absorption onset below 700 nm.

Considerable efforts have been devoted to the development of new polymer acceptors. A few state-of-the-art polymer acceptors beyond NDI and PDI were developed, which can afford >8% PCEs in APSCs (Fig. 1 and Table 1). A fused-ring aromatic diimide polymer, f-BTI3-T, reported by Guo group, gave a PCE of 9.0% in APSCs [11]. Liu group [12] and Huang group [13] reported two B ← N coordinate bond-containing polymer acceptors, PBN-12 and BN-2fT, which offered PCEs of 10.1% and 8.8% in APSCs, respectively. Nevertheless, these polymers have the same disadvantages as NDI and PDI polymers, i.e., narrow absorption range or low absorption coefficients. Specifically, f-BTI3-T and PBN-12 can only absorb photons below 700 nm [11,12], and BT-2fT suffers from low absorption coefficient [13]. Based on dicyanobenzothiadiazole, a strong electron-withdrawing building block, a promising polymer acceptor DCNBT-IDT was developed by Guo group [14], which showed a broad absorption spectrum with an absorption onset at 870 nm and a high absorption coefficient of 6.2×10^4 cm^{-1}. Considering the favorable intrinsic optoelectronic properties of this polymer, though a moderate PCE of 8.3% was attained in this work, higher PCE is conceivable via delicate morphology optimization.

Polymerizing small molecular non-fullerene acceptors is another promising strategy to develop high-performance polymer acceptors for APSCs, which can yield polymer acceptors with very high absorption coefficients (>1.0×10^5 cm^{-1}), since strong intramolecular charge transfer effects exist in the parent small molecular acceptors. This strategy was first proposed by Zhang et al. [15,19] along with the synthesis of a IDIC-derived polymer PZ1 and the demonstration of an efficient APSC with a PCE of 9.2%. After that, a few high-performance polymer acceptors (PFBDT-IDTIC, PF2-DTSi, and PJ1-H) were developed following this strategy and APSCs with PCEs exceeding 10% were realized by several groups [16–18]. Most remarkably, APSCs with a record PCE of 14.4% were reported very recently by Huang group [18], and they used a Y6-derived polymer PJ1-H as the acceptor. Though delivering good PCEs, the photostability of the APSCs with these polymer acceptors needs further evaluation as the photo-oxidation was identified in many non-fullerene small molecular acceptors [20].

Overall, significant progresses have been achieved in the field of APSCs, which are mainly driven by the development of state-of-the-art polymer acceptors. The PCE of 14.4% reported recently has greatly reduced the PCE gap between APSCs and small molec-

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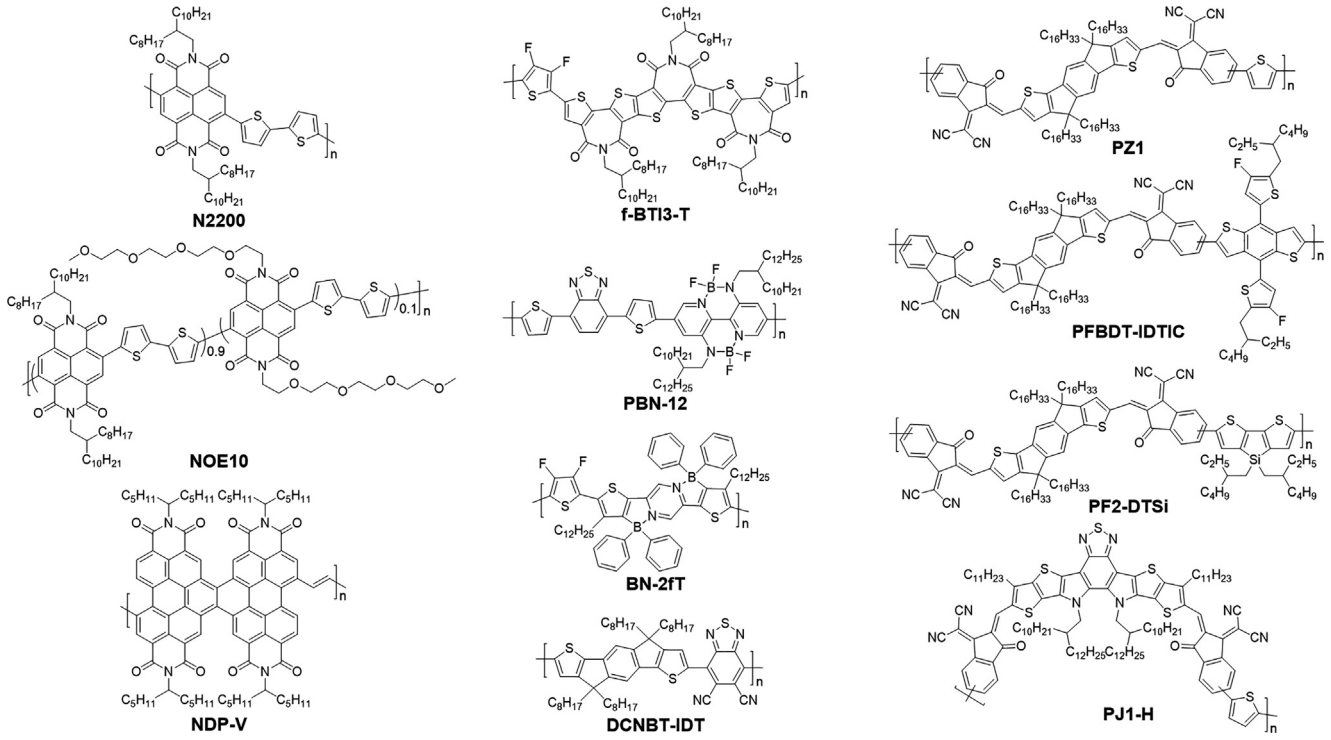

Fig. 1. The chemical structures of state-of-the-art polymer acceptors employed in APSCs.

Table 1
Performance data for binary APSCs based on state-of-the-art polymer acceptors.

Acceptor	Donor	V_{oc} (V) [a]	J_{sc} (mA cm^{-2})	FF [b]	PCE (%)	V_{loss} (V) [c]	Ref.
N2200	PTzBI-Si	0.88	17.6	0.76	11.8	0.57	[9]
NOE10	PBDT-TAZ	0.84	12.9	0.75	8.1	0.61	[3]
NDP-V	PTB7-Th	0.74	17.1	0.67	8.6	0.85	[10]
f-BTI3-T	PTB7-Th	1.03	14.9	0.58	9.0	0.56	[11]
PBN-12	CD1	1.17	13.4	0.64	10.1	0.61	[12]
BN-2fT	PBDB-T	0.93	13.0	0.70	8.8	0.66	[13]
DCNBT-IDT	PBDB-T	0.90	14.2	0.65	8.3	0.53	[14]
PZ1	PBDB-T	0.83	16.1	0.69	9.2	0.72	[15]
PFBDT-IDTIC	PM6	0.96	15.3	0.68	10.3	0.59	[16]
PF2-DTSi	PM6	0.99	16.5	0.66	10.8	0.56	[17]
PJ1-H	PBDB-T	0.90	22.3	0.70	14.4	0.51	[18]

[a] Open-circuit voltage.
[b] Fill factor.
[c] Voltage loss, $V_{loss} = E_g/q - V_{oc}$, where E_g is the bandgap from EQE onset, and q is the elementary charge.

ular acceptor-based OSCs [18]. More importantly, the voltage losses (V_{loss}s) of 0.51 and 0.53 V observed in the APSCs based on DCNBT-IDT [14] and PJ1-H [18] (Table 1) are very close to those observed in high-performance small molecular acceptor-based OSCs [21], suggesting that the theoretical PCE upper limit of APSCs is comparable to that of small molecular acceptor-based OSCs. Therefore, with newly-designed high-performance polymer acceptors matching the polymer donors, delicate morphology optimization, and interface engineering, much higher PCEs can be expected in APSCs. With excellent device stability and mechanical flexibility, APSCs hold bright future in commercialization.

Conflict of interest

The authors declare that they have no conflict of interest.

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