RESEARCH HIGHLIGHTS

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Engineering fibrillar morphology for highly efficient organic solar cells

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The power conversion efficiency (PCE) for single-junction organic solar cells (OSCs), wherein the photoactive layer is a typical bulk-heterojunction containing donor and acceptor materials, has surpassed 19%[1–4]. The advance is ascribed to the development of Y-series non-fullerene acceptors (NFAs)[5, 6] and polymer donors[7–13], and the refined control of the blend film morphology. The design of donor or acceptor structures is to achieve optimal energy level alignment or to broaden the absorption range, thereby improving charge generation and maximizing photon capture. The organic semiconductors exhibit low dielectric constants and strong electron localization, leading to the generation of Frenkel excitons. Additionally, the organic semiconducting materials (OSMs) display a relatively low charge carrier mobility associated with the formation of polarons and charge carrier trap centers, which harm the transport and extraction of charge carriers. The photovoltaic performance of OSCs depends on the electronic structure of the active materials, molecular stacking, phase separation, and miscibility regulation. Therefore, how to control the nanoscale phase separation to realize optimal morphologies in photoactive layers is quite critical for OSCs.

Benefiting from previously developed star polymer donors and Y-series NFAs, including D18, PM6 and L8-BO (Fig. 1), the optimal bicontinuous network morphology has been achieved by manipulating domains and crystallinity of the blend films. Such morphological structures are advantageous for minimizing energy losses and enhancing charge carrier generation, thus enhancing the power output of OSCs. Liu *et al*. constructed a bicontinuous network with nanofibril aggregates in PM6:Y6 and D18:Y6 films by using solvent vapor annealing, achieving PCEs of 16.53% and 17.98% in single-junction OSCs, respectively[14]. This achievement can be attributed to the formation of bundled nanofibril structures in the blend films after solvent annealing, which can facilitate charge transport and reduce charge recombination.

Liu *et al*. devised ternary OSCs based on PM6:D18:L8-BO, giving a PCE of 19.6%. The incorporation of polymer crystallization and NFA fibril assembly yielded a dual-fibril network[15]. Wang *et al*. further used a solid additive to make fine fibril-like morphology, leading to a PCE of 19% for D18:L8-BO binary system[16]. Similarly, Hou *et al*. introduced a second polymer donor or highly volatile additives to regulate the aggregation behavior in the blend films with PBQx-TCl or PBQx-TF, yielding a PCE over 19%[17, 18].

All-polymer solar cells (all-PSCs) with high performance also face the difficulty of constructing bicontinuous fibril-like network in the active layer. Hou *et al*. introduced PM6 with high molecular weight into the blend of PBQx-TF:PY-IT, realizing a precise adjustment of the bicontinuous network. This adjustment resulted in a short π–π stacking distance, and all-PSCs based on PBQx-TF:PM6:PY-IT offered a PCE of 18.2%[19]. Liu *et al*. employed a combined strategy with solid additive, thermal annealing and solvent annealing to control polymer crystallization and film surface structure. This approach yielded a highly crystalline and bicontinuous network, greatly enhancing the exciton dissociation and charge carrier transport. All-PSCs based on PM6:PY-IT achieved a PCE over 19%[20].

The above studies emphasize the significance of morphology optimization in OSCs. With appropriate donor and acceptor materials, trying to attain an optimal fibril-like morphology is one of the foremost strategies for improving OSC performance.

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References

[1] Wei Y N, Chen Z H, Lu G Y, et al. Binary organic solar cells breaking 19% via manipulating the vertical component distribution. Adv Mater, 2022, 34(33), 2204718

[2] Zhou M W, Liao C T, Duan Y W, et al. 19.10% efficiency and 80.5% fill factor layer-by-layer organic solar cells realized by 4-bis(2-thienyl)Pyrrole-2, 5-dione based polymer additives for inducing vertical segregation morphology. Adv Mater, 2023, 35(6), 2208279

[3] Chen T Y, Li S X, Li Y K, et al. Compromising charge generation

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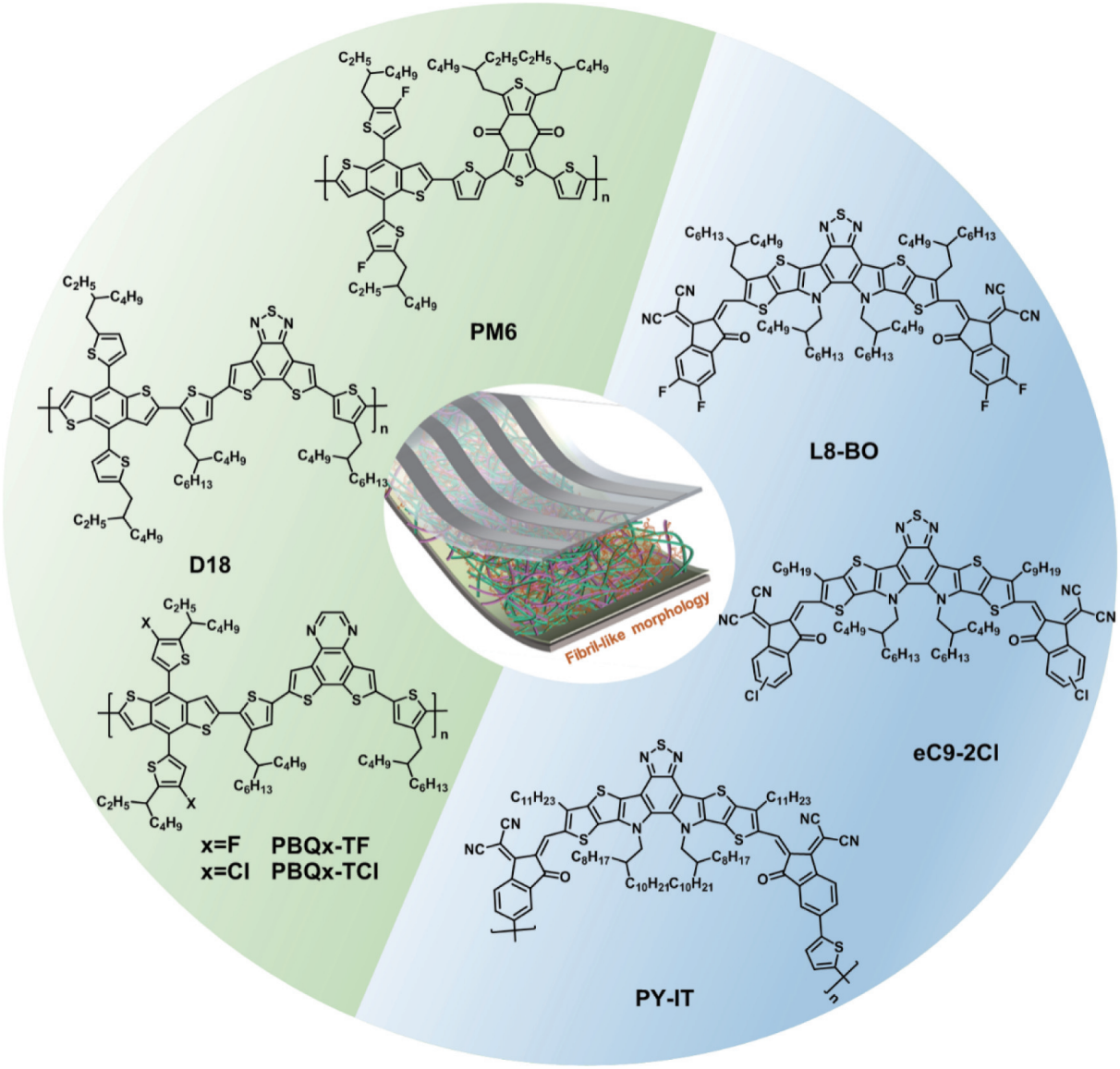

Fig. 1. (Color online) Chemical structures for the star donors and acceptors.

and recombination of organic photovoltaics with mixed diluent strategy for certified 19.4% efficiency. Adv Mater, 2023, 35(21), 2300400

[4] Ma R J, Yan C Q, Yu J S, et al. High-efficiency ternary organic solar cells with a good figure-of-merit enabled by two low-cost donor polymers. ACS Energy Lett, 2022, 7(8), 2547

[5] Zhang G C, Lin F R, Qi F, et al. Renewed prospects for organic photovoltaics. Chem Rev, 2022, 122(18), 14180

[6] Cao J M, Yi L F, Ding L M. The origin and evolution of Y6 structure. J Semicond, 2022, 43(3), 030202

[7] Liu Q S, Jiang Y F, Jin K, et al. 18% efficiency organic solar cells. Sci Bull (Beijing), 2020, 65(4), 272

[8] Cao J M, Nie G G, Zhang L X, et al. Star polymer donors. J Semicond, 2022, 43(7), 070201

[9] Meng X Y, Jin K, Xiao Z, et al. Side chain engineering on D18 polymers yields 18.74% power conversion efficiency. J Semicond, 2021, 42(10), 100501

[10] Jin K, Xiao Z, Ding L M. D18, an eximious solar polymer! J Semicond, 2021, 42(1), 010502

[11] Jin K, Xiao Z, Ding L M. 18.69% PCE from organic solar cells. J Semicond, 2021, 42(6), 060502

[12] Qin J Q, Zhang L X, Zuo C T, et al. A chlorinated copolymer donor demonstrates a 18.13% power conversion efficiency. J Semicond, 2021, 42(1), 010501

[13] Zhou J, Li D H, Wang L, et al. Bicontinuous donor and acceptor fibril networks enable 19.2% efficiency pseudo-bulk heterojunction organic solar cells. Interdiscip Mater, 2023, 2(6), 866

[14] Su Y L, Zhang L, Ding Z C, et al. Carrier generation engineering toward 18% efficiency organic solar cells by controlling film microstructure. Adv Energy Mater, 2022, 12(19), 2103940

[15] Zhu L, Zhang M, Xu J Q, et al. Single-junction organic solar cells with over 19% efficiency enabled by a refined double-fibril network morphology. Nat Mater, 2022, 21(6), 656

[16] Li D H, Deng N, Fu Y W, et al. Fibrillization of non-fullerene acceptors enables 19% efficiency pseudo-bulk heterojunction organic solar cells. Adv Mater, 2023, 35(6), 2208211

[17] Bi P Q, Wang J Q, Cui Y, et al. Enhancing photon utilization efficiency for high-performance organic photovoltaic cells via regulating phase-transition kinetics. Adv Mater, 2023, 35(16), 2210865

[18] Wang J Q, Wang Y F, Bi P Q, et al. Binary organic solar cells with 19.2% efficiency enabled by solid additive. Adv Mater, 2023, 35(25), e2301583

[19] Ma L J, Cui Y, Zhang J Q, et al. High-efficiency and mechanically robust all-polymer organic photovoltaic cells enabled by optimized fibril network morphology. Adv Mater, 2023, 35(9), 2208926

[20] Zeng R, Zhu L, Zhang M, et al. All-polymer organic solar cells with nano-to-micron hierarchical morphology and large light receiving angle. Nat Commun, 2023, 14(1), 4148

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