RESEARCH HIGHLIGHTS

Journal of Semiconductors
(2021) 42, 080202
doi: 10.1088/1674-4926/42/8/080202

Polymer acceptors for all-polymer solar cells

Xiaofei Ji[1], Zuo Xiao[2], Huiliang Sun[1, †], Xugang Guo[1, †], and Liming Ding[2, †]

[1]Department of Materials Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China

[2]Center for Excellence in Nanoscience (CAS), Key Laboratory of Nanosystem and Hierarchical Fabrication (CAS), National Center for Nanoscience and Technology, Beijing 100190, China

Citation: X F Ji, Z Xiao, H L Sun, X G Guo, and L M Ding, Polymer acceptors for all-polymer solar cells[J]. *J. Semicond.*, 2021, 42(8), 080202. http://doi.org/10.1088/1674-4926/42/8/080202

Bulk-heterojunction polymer solar cells (PSCs) as a clean and renewable energy resource have attracted great attention from both academia and industry[1–20]. Recently nonfullerene PSCs based on polymer donors (PDs) and small molecule acceptors (SMAs) have achieved remarkable success with the power conversion efficiencies (PCEs) over 18%[21–26]. Among various PSCs, all-polymer solar cells (all-PSCs) consist of PDs and polymer acceptors (PAs), showing unique merits including superior stability and mechanical robustness. However, the development of all-PSCs lag behind SMAs-based PSCs due to the scarcity of high-performance PAs[6].

The first all-PSCs can be traced back to 1995[27]. However, only ten years later, aromatic-imide-based PAs got achievements in all-PSCs. After the first report of perylene diimide (PDI) PA named PDI-DTT[28] by Zhan *et al.* in 2007 (Fig. 1, Table 1), PDI and naphthalene diimide (NDI) derivatives began to dominate PAs. Among them, a NDI-based copolymer PNDIOD-T2 (a.k.a. N2200) opened a new era for PAs research[29, 30]. With tailored PDs and device engineering[5, 31], steady progress has been achieved in all-PSCs based on N2200 and its derivatives. A PCE of 11.76% was realized in 2020[32]. However, a major drawback for PDI and NDI PAs is their low absorption coefficient in the NIR region due to the steric-hindrance-induced large torsion angles between NDI/PDI core and co-units, thus limiting the short-circuit current density (J_{sc})[33, 34]. Moreover, their low LUMO energy levels led to relatively low open-circuit voltage (V_{oc}). Other electron-deficient building blocks like diketopyrrolopyrrole (DPP), isoindigo (IID), bithiophene imide (BTI), thieno[3,4-c]pyrrole-4,6-dione (TPD) and B←N bridged bipyridine (BNBP) unit were also explored for PAs[35]. BTI derivative SPA2 and BNBP derivative PBN-12 were the representatives, affording 9.21% and 10.07% PCEs with >1 V V_{oc} in all-PSCs, respectively[36, 37]. However, these acceptors suffer from the same defects as NDI and PDI PAs. Specifically, SPA2 and PBN-12 show weak light-harvesting capability with absorption onsets below 700 nm. In this regard, Guo *et al.* developed a strong electron-withdrawing building block 5,6-dicyano-2,1,3-benzothiadiazole (DCNBT)[38, 39]. PAs based on DCNBT show narrow bandgap (1.28 eV) with high absorption coefficient in the NIR region. A PCE of 12.1% was achieved in a recent work[38]. Higher efficiencies from DCNBT-based PAs are anticipated through further morphology and device optimization.

In 2017, the strategy of "polymerizing SMAs" was proposed by Zhang *et al.*[40] SMAs were introduced as electron-deficient building blocks to construct new-generation PAs. These polymerized SMAs (PSMAs) not only inherit the merits like narrow bandgap, strong absorption and tunable energy levels from SMAs, but also present good film-forming capability and photostability of the polymers[41]. The first PSMA named PZ1 was synthesized by copolymerizing IDIC-C16 with thiophene unit, showing a high extinction coefficient (>10^5 cm^{-1}) and yielding a PCE of 9.19% in all-PSCs[40]. Afterwards, a wide variety of SMAs and different conjugated linkage units were selected to tune the physicochemical and photovoltaic properties of PSMAs. A few high-performance PSMAs were designed and synthesized by several groups, enabling all-PSCs with PCEs over 14% (Fig. 1)[42]. Notably, the widely used end groups in SMAs are a mixture of two isomers with similar polarity, thus resulting in isomeric issues in PSMAs. This brings a negative effect to the batch-to-batch reproducibility of the PSMAs, leading to a large deviation in device performance. Luo *et al.*[43] reported a regioregular PSMA named PY-IT by using isomerically pure end groups, which enabled the PCE of all-PSCs exceeding 15% for the first time, significantly higher than its regiorandom counterparts. The higher performance resulted from enhanced absorption, more balanced charge transport and favorable morphology. Fu *et al.*[44] synthesized a new regioregular PSMA PZT-γ by replacing the benzothiadiazole moiety with benzotriazole. The PZT-γ-based all-PSCs exhibited a high PCE of 15.8%. To improve the electron mobility of PAs, Guo *et al.*[45] combined "polymerizing SMAs" and "acceptor–acceptor" (A–A) strategies to develop a new PSMA L14 by copolymerizing the distannylated BTI with a brominated SMA. The A–A type backbone renders L14 an enhanced electron mobility. L14 achieved an efficiency of 14.3%, which is a record value for all-PSCs based on A–A type PAs. The success of PSMA-based binary all-PSCs triggered the further exploration of efficient ternary all-PSCs. An impressive work is the incorporation of a B←N-based PA into PM6:PY-IT host blend by Liu *et al.*[46]. A PCE of 16.09% was achieved due to an optimal morphology and reduced nonradiative energy loss in ternary cells. Very recently, Min *et al.* reported a 17.2% efficiency from ternary all-PSCs with two well-compatible PSMAs[47].

Overall, remarkable progress has been made in all-PSCs in terms of materials diversity and device performance. Over 17% PCEs have been demonstrated. In addition, the energy losses in the devices can reach 0.5 eV or less, indicating that

Correspondence to: H L Sun, sunhl@sustech.edu.cn; X G Guo, guoxg@sustech.edu.cn; L M Ding, ding@nanoctr.cn

Received 3 MAY 2021.

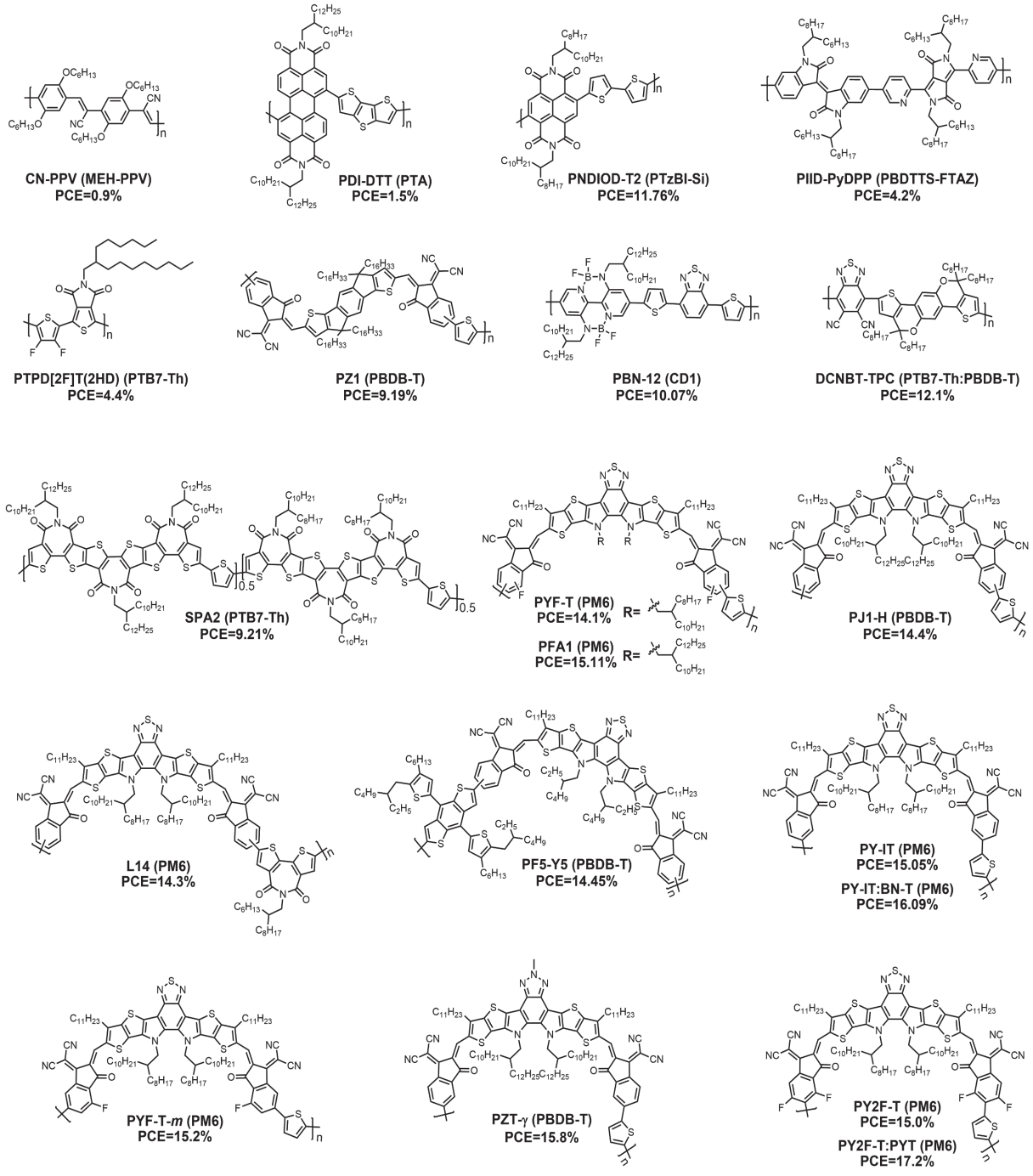

Fig. 1. High-performance polymer acceptors. (Note: the names in the parentheses indicate the polymer donors.)

Table 1. Performance data for the polymer acceptors.

Acceptor	Donor	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	PCE$_{max}$ (%)	Ref.
PDI-DTT	PTA	0.63	4.2	39.0	1.5	[28]
N2200	PTzBI-Si	0.88	17.62	75.78	11.76	[32]
SPA2	PTB7-Th	1.02	15.16	59.4	9.21	[36]
PBN-12	CD1	1.17	13.39	64.0	10.07	[37]
DCNBT-TPC	PTB7-Th:PBDB-T	0.81	21.9	68.3	12.1	[38]
PZ1	PBDB-T	0.83	16.05	68.99	9.19	[40]
L14	PM6	0.96	20.6	72.1	14.3	[45]
PY-IT	PM6	0.933	22.30	72.3	15.05	[43]
PZT-γ	PBDB-T	0.896	24.7	71.3	15.8	[44]
PYT:BN-T	PM6	0.955	22.65	74.3	16.09	[46]
PY2F-T:PYT	PM6	0.90	25.2	76.0	17.2	[47]

the theoretical limit is comparable to that of SMA-based cells. It should be noted that all-polymer blend films typically show poor nanoscale phase separation due to the long and intertwined polymer chains, thus leading to low FFs. Hence, more efforts in developing narrow bandgap PAs with high electron mobility and optimizing film morphology should be made.

Acknowledgements

We thank the Natural Science Foundation for Distinguished Young Scholars of Guangdong Province (2021B1515020027), the National Natural Science Foundation of China (21801124 and 21774055) and Shenzhen Science and Technology Innovation Commission (JCYJ20180504165709042). L. Ding thanks the National Key Research and Development Program of China (2017YFA0206600) and the National Natural Science Foundation of China (51773045, 21772030, 51922032, 21961160720) for financial support.

References

[1] Guo X, Facchetti A. The journey of conducting polymers from discovery to application. Nat Mater, 2020, 19, 922
[2] Armin A, Li W, Oskar J S, et al. A history and perspective of non-fullerene electron acceptors for organic solar cells. Adv Energy Mater, 2021, 11, 20003570
[3] Tong Y, Xiao Z, Du X, et al. Progress of the key materials for organic solar cells. Sci China Chem, 2020, 63, 758
[4] Duan C, Ding L. The new era for organic solar cells: non-fullerene small molecular acceptors. Sci Bull, 2020, 65, 1231
[5] Duan C, Ding L. The new era for organic solar cells: polymer donors. Sci Bull, 2020, 65, 1422
[6] Duan C, Ding L. The new era for organic solar cells: polymer acceptors. Sci Bull, 2020, 65, 1508
[7] Duan C, Ding L. The new era for organic solar cells: small molecular donors. Sci Bull, 2020, 65, 1597
[8] Xiao Z, Yang S, Yang Z, et al. Carbon-oxygen-bridged ladder-type building blocks for highly efficient nonfullerene acceptors. Adv Mater, 2019, 31, 1804790
[9] Tang A, Xiao Z, Ding L, et al. ~1.2 V open-circuit voltage from organic solar cells. J Semicond, 2021, 42, 070202
[10] Guan W, Yuan D, Wu J, et al. Blade-coated organic solar cells from non-halogenated solvent offer 17% efficiency. J Semicond, 2021, 42, 030502
[11] Pan W, Han Y, Wang Z, et al. Over 1 cm^2 flexible organic solar cells. J Semicond, 2021, 42, 050301
[12] Li X, Xu J, Xiao Z, et al. Dithieno[3',2':3,4;2'',3'':5,6]benzo[1,2-c][1,2,5]oxadiazole-based polymer donors with deep HOMO levels. J Semicond, 2021, 42, 060501
[13] Xiao Z, Liu F, Geng X, et al. A carbon-oxygen-bridged ladder-type building block for efficient donor and acceptor materials used in organic solar cells. Sci Bull, 2017, 62, 1331
[14] Xiao Z, Jia X, Ding L. Ternary organic solar cells offer 14% power conversion efficiency. Sci Bull, 2017, 62, 1562
[15] Wang T, Qin J, Xiao Z, et al. A 2.16 eV bandgap polymer donor gives 16% power conversion efficiency. Sci Bull, 2020, 65, 179
[16] Xiong J, Jin K, Jiang Y, et al. Thiolactone copolymer donor gifts organic solar cells a 16.72% efficiency. Sci Bull, 2019, 64, 1573
[17] Wang T, Qin J, Xiao Z, et al. Multiple conformation locks gift polymer donor high efficiency. Nano Energy, 2020, 77, 105161
[18] Qin J, Zhang L, Xiao Z, et al. Over 16% efficiency from thick-film organic solar cells. Sci Bull, 2020, 65, 1979
[19] Liu L, Liu Q, Xiao Z, et al. Induced J-aggregation in acceptor alloy enhances photocurrent. Sci Bull, 2019, 64, 1083
[20] Liu J, Liu L, Zuo C, et al. 5H-dithieno[3,2-b:2',3'-d]pyran-5-one unit yields efficient wide-bandgap polymer donors. Sci Bull, 2019, 64, 1655
[21] Jin K, Xiao Z, Ding L. 18.69% PCE from organic solar cells. J Semicond, 2021, 42, 060502
[22] Liu Q, Jiang Y, Jin K, et al. 18% efficiency organic solar cells. Sci Bull, 2020, 65, 272
[23] Cui Y, Yao H, Zhang J, et al. Single-junction organic photovoltaic cells with approaching 18% efficiency. Adv Mater, 2020, 32, 1908205
[24] Zhan L, Li S, Xia X, et al. Layer-by-layer processed ternary organic photovoltaics with efficiency over 18%. Adv Mater, 2021, 33, 2007231
[25] Jin K, Xiao Z, Ding L. D18, an eximious solar polymer!. J Semicond, 2021, 42, 010502
[26] Qin J, Zhang L, Zuo C, et al. A chlorinated copolymer donor demonstrates a 18.13% power conversion efficiency. J Semicond, 2021, 42, 010501
[27] Yu G, Heeger A J. Charge separation and photovoltaic conversion in polymer composites with internal donor/acceptor heterojunctions. J Appl Phys, 1995, 78, 4510
[28] Zhan X, Tan Z, Domercq B, et al. A high-mobility electron-transport polymer with broad absorption and its use in field-effect transistors and all-polymer solar cells. J Am Chem Soc, 2007, 129, 7246
[29] Yan H, Chen Z, Zheng Y, et al. A high-mobility electron-transporting polymer for printed transistors. Nature, 2009, 457, 679
[30] Guo X, Watson M D. Conjugated polymers from naphthalene bisimide. Org Lett, 2008, 10, 5333
[31] Zhu P, Fan B, Ying L, et al. Recent progress in all-polymer solar cells based on wide-bandgap p-type polymers. Chem Asian J, 2019, 14, 3109
[32] Zhu L, Zhong W, Qiu C, et al. Aggregation-induced multilength scaled morphology enabling 11.76% efficiency in all-polymer solar cells using printing fabrication. Adv Mater, 2019, 31, 1902899
[33] Sun H, Wang L, Wang Y, et al. Imide-functionalized polymer semiconductors. Chem Eur J, 2019, 25, 87
[34] Sun H, Tang Y, Koh C W, et al. High-performance all-polymer solar cells enabled by an n-type polymer based on a fluorinated imide-functionalized arene. Adv Mater, 2019, 31, 1807220
[35] Yang J, Xiao B, Tang A, et al. Aromatic-diimide-based n-type conjugated polymers for all-polymer solar cell applications. Adv Mater, 2019, 31, 1804699
[36] Sun H, Liu B, Yu J, et al. Reducing energy loss via tuning energy levels of polymer acceptors for efficient all-polymer solar cells. Sci China Chem, 2020, 63, 1785
[37] Zhao R, Wang N, Yu Y, et al. Organoboron polymer for 10% efficiency all-polymer solar cells. Chem Mater, 2020, 32, 1308
[38] Feng K, Wu Z, Su M, et al. Highly efficient ternary all-polymer solar cells with enhanced stability. Adv Funct Mater, 2020, 31, 2008494
[39] Shi S, Chen P, Chen Y, et al. A narrow-bandgap n-type polymer semiconductor enabling efficient all-polymer solar cells. Adv Mater, 2019, 31, 1905161
[40] Zhang Z, Yang Y, Yao J, et al. Constructing a strongly absorbing low-bandgap polymer acceptor for high-performance all-polymer solar cells. Angew Chem Int Ed, 2017, 56, 13503
[41] Zhang Z, Li Y. Polymerized small-molecule acceptors for high-performance all-polymer solar cells. Angew Chem Int Ed, 2021, 60, 4422
[42] Liu W, Xu X, Yuan J, et al. Low-bandgap non-fullerene acceptors enabling high-performance organic solar cells. ACS Energy Lett, 2021, 6, 598
[43] Luo Z, Liu T, Ma R, et al. Precisely controlling the position of bromine on the end group enables well-regular polymer acceptors for all-polymer solar cells with efficiencies over 15. Adv Mater, 2020, 32, 2005942

[44] Fu H, Li Y, Yu J, et al. High efficiency (15.8%) all-polymer solar cells enabled by a regioregular narrow bandgap polymer acceptor. J Am Chem Soc, 2021, 143, 2665
[45] Sun H, Yu H, Shi Y, et al. A narrow-bandgap n-type polymer with an acceptor-acceptor backbone enabling efficient all-polymer solar cells. Adv Mater, 2020, 32, 2004183
[46] Liu T, Yang T, Ma R, et al. 16% efficiency all-polymer organic solar cells enabled by a finely tuned morphology via the design of ternary blend. Joule, 2021, 5, 914
[47] Sun R, Wang W, Yu H, et al. Achieving over 17% efficiency of ternary all-polymer solar cells with two well-compatible polymer acceptors. Joule, 2021, 5, 1548

Xiaofei Ji got her PhD degree from Nankai University in 2020. She is now a postdoc in Xugang Guo Group at Southern University of Science and Technology (SUSTech). Her research focuses on the design and synthesis of interfacial materials for organic/perovskite solar cells.

Zuo Xiao got his BS and PhD degrees from Peking University under the supervision of Prof. Liangbing Gan. He did postdoctoral research in Eiichi Nakamura Lab at the University of Tokyo. In March 2011, he joined Liming Ding Group at National Center for Nanoscience and Technology as an associate professor. In April 2020, he was promoted to be a full professor. His current research focuses on organic solar cells.

Huiliang Sun received his PhD from Changchun Institute of Applied Chemistry, Chinese Academy of Sciences in 2017. He was a joint postdoc with Prof. Xugang Guo at SUSTech and Prof. Junwu Chen at South China University of Technology from 2017 to 2019 and a visiting postdoc in Henry Yan Group at Hong Kong University of Science and Technology from 2019 to 2020. Currently, he is a research assistant professor at SUSTech. His research focuses on the design and synthesis of polymer semiconductors and their application in solar cells.

Xugang Guo joined Mark D. Watson Group at the University of Kentucky in 2006 and obtained his PhD in Chemistry in 2009. From 2009 to 2012, he carried out his postdoctoral training with Profs. Tobin J. Marks and Antonio Facchetti at Northwestern University. Currently, he is a full professor in Department of Materials Science and Engineering at SUSTech. His research interests include synthesis and application of organic and polymeric semiconductors.

Liming Ding got his PhD from University of Science and Technology of China (was a joint student at Changchun Institute of Applied Chemistry, CAS). He started his research on OSCs and PLEDs in Olle Inganäs Lab in 1998. Later on, he worked at National Center for Polymer Research, Wright-Patterson Air Force Base and Argonne National Lab (USA). He joined Konarka as a Senior Scientist in 2008. In 2010, he joined National Center for Nanoscience and Technology as a full professor. His research focuses on innovative materials and devices. He is RSC Fellow, the nominator for Xplorer Prize, and the Associate Editors for Science Bulletin and Journal of Semiconductors.