

# ChemComm

Accepted Manuscript



This is an *Accepted Manuscript*, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

*Accepted Manuscripts* are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this *Accepted Manuscript* with the edited and formatted *Advance Article* as soon as it is available.

You can find more information about *Accepted Manuscripts* in the [Information for Authors](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the [Ethical guidelines](#) still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this *Accepted Manuscript* or any consequences arising from the use of any information it contains.



ChemComm

COMMUNICATION

## Fullerene-free small molecule organic solar cells with high open circuit voltage of 1.15V

Received 00th January 20xx,  
Accepted 00th January 20xx

Wang Ni, § <sup>a,b</sup> Miaomiao Li, § <sup>a,b</sup> Bin Kan, <sup>a,b</sup> Feng Liu, <sup>c</sup> Xiangjian Wan, <sup>\*a,b</sup> Qian Zhang, <sup>a,b</sup> Hongtao Zhang, <sup>a,b</sup> Thomas P Russell <sup>c,d</sup> and Yongsheng Chen <sup>\*a,b</sup>

DOI: 10.1039/x0xx00000x

www.rsc.org/

**A new small molecule named DTBTF with thiobarbituric acid as terminal group were designed and synthesized as acceptor for organic photovoltaic application.. DTBTF exhibits strong absorption in the visible region, and relatively high lying LUMO energy level (-3.62 eV). All-small-molecule organic solar cells based on DR3TSBDT:DTBTF blend films show a considerable PCE of 3.84% with a high  $V_{oc}$  of 1.15 V.**

Organic photovoltaics (OPVs) are considered as promising candidates for the production of renewable energy with advantages such as solution processability, low cost, light weight and flexibility.<sup>1</sup> Power conversion efficiencies (PCEs) over 10% have been achieved for single junction organic solar cells with bulk heterojunction (BHJ) architecture with fullerene derivatives as acceptors.<sup>2</sup> The rapid progress is mainly ascribed to the development of new electron-donor materials including polymers and small molecules.<sup>3</sup> With the advantages of high electron mobility and high electron affinity, fullerene derivatives are the most commonly used electron acceptors in organic solar cells.<sup>4</sup> However, these fullerene derivatives also have some disadvantages such as weak absorption in the visible region, difficulty in tuning energy levels and high cost in synthesis. Therefore, recently more and more attention has been given to design and synthesis of non-fullerene electron acceptor materials including polymers and small molecules.<sup>5</sup> PCEs over 6% have been achieved for the devices based on polymer donor materials and non-fullerene electron acceptor materials.<sup>6</sup> It is worth to note that nearly all the fullerene-free

based devices employed polymers as donor materials.<sup>5a, 7</sup> In comparison with polymer materials, small molecules offer several advantages such as well-defined structure and therefore less batch-to-batch variation, easier energy level control, etc.<sup>3b, 8</sup> Even with those advantages of small molecule based devices, it is interesting to note that fullerene-free all-small-molecule organic solar cells were relatively rare studied and PCEs over 3% have been achieved.<sup>9</sup>

It is most accepted that open-circuit voltage ( $V_{oc}$ ) depends on the difference between the highest occupied molecular orbital (HOMO) energy level of the donor material and the low lying lowest unoccupied molecular orbital (LUMO) level of the acceptor material,<sup>10</sup> and an off-set energy of 0.3 eV between the LUMO level of donor and acceptor materials could provide efficient exciton dissociation.<sup>11</sup> In order to maximize the  $V_{oc}$ , it is satisfying that the LUMO energy level of the electron acceptor is as high as possible while still guaranteeing for efficient electron transfer from the donor to the acceptor material. For many reported efficient small molecule donor materials such as *p*-DTS(FBTTh<sub>2</sub>)<sub>2</sub> and DR3TSBDT,<sup>12</sup> the LUMO energy levels are around -3.3 eV, indicating a relatively big off-set energy of ~0.6 eV between the LUMO levels of these small molecule donors and PC<sub>71</sub>BM (~ -3.90 eV for LUMO<sup>4</sup>). Thus there is enough space for up-shift of the LUMO energy level to achieve higher  $V_{oc}$ , thus further improving the PCE of small molecule organic solar cells. In addition, the energy loss ( $E_{loss}$ ), which is the loss in energy of the  $V_{oc}$  relative to the optical band gap ( $E_g$ ), defined as  $E_{loss} = E_g - qV_{oc}$ , is an important parameter to evaluate the  $V_{oc}$  of BHJ organic solar cells.<sup>13</sup> The minimum  $E_{loss}$  is suggested to be 0.6 eV, and the corresponding  $V_{oc}$  is often considered as the maximum achievable  $V_{oc}$ .<sup>11</sup>

As one type of donor-acceptor (D-A) type small molecules, A-D-A small molecules have been demonstrated to be efficient photovoltaic materials in the past years.<sup>14</sup> In our previous works, we have demonstrated that choosing terminal acceptor units with suitable electron withdrawing ability could obtain desirable LUMO energy levels. Herein, we designed and synthesized an A-D-A small molecule electron acceptor

<sup>a</sup> State Key Laboratory and Institute of Elemento-Organic Chemistry, Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), School of Materials Science and Engineering, Nankai University, Tianjin 300071, China  
Email : xjwan@nankai.edu.cn, yschen99@nankai.edu.cn.

<sup>b</sup> Key Laboratory of Functional Polymer Materials and the Centre of Nanoscale Science and Technology, Institute of Polymer Chemistry, College of Chemistry, Nankai University, Tianjin, 300071, China

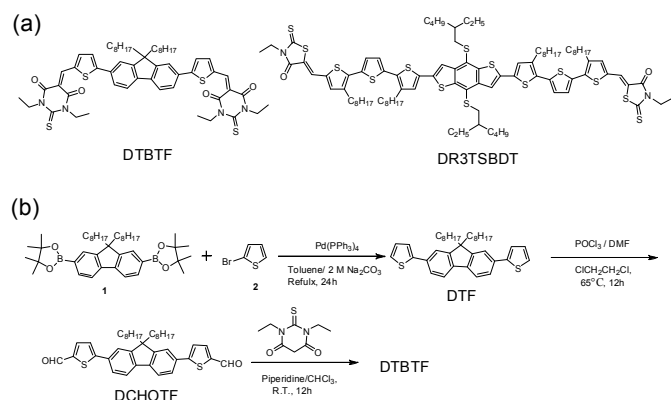
<sup>c</sup> Materials Science Divisions, Lawrence Berkeley National Lab, Berkeley 94720, United States.

<sup>d</sup> Department of Polymer Science and Engineering, University of Massachusetts, Amherst 01003, United States.

† Electronic Supplementary Information (ESI) available: Details of synthesis and characterization of DTBTF, TGA, AFM, SCLC.]. See DOI: 10.1039/x0xx00000x  
§ W. Ni and M.M. Li contributed equally to this work.

## COMMUNICATION

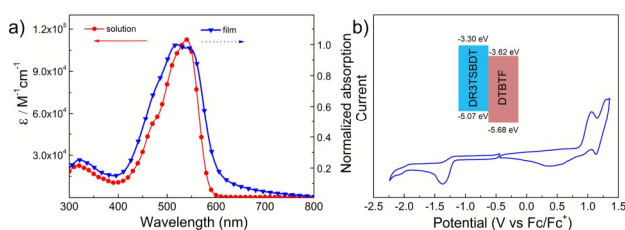
Journal Name



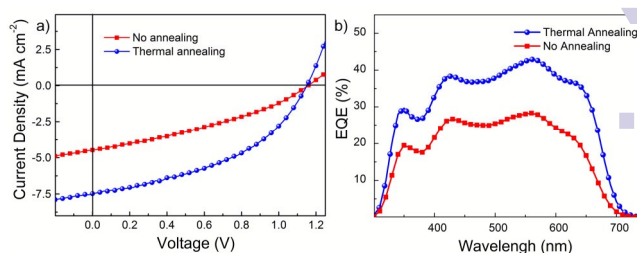
**Fig. 1** a) Chemical structures of DTBTF and DR3TSBDT, b) synthetic route of DTBTF.

material named DTBTF (**Fig. 1a**) with weak electron-donating unit fluorene as central building block and strong electron-withdrawing unit thiobarbituric acid as the terminal. The new small molecule exhibited strong absorption in the visible region, a deep HOMO (-5.68 eV) and relatively ideal LUMO energy level (-3.62 eV). All-small-molecule organic solar cells based on our reported small molecule donor DR3TSBDT (**Fig. 1a**) and the new electron acceptor DTBTF exhibited a PCE of 3.84% and an impressively high  $V_{oc}$  of 1.15 V which is among the highest  $V_{oc}$  values reported for single junction organic solar cells. The devices based on DTBTF as acceptor showed a low energy loss of only 0.59 eV, indicating that nearly maximum achievable  $V_{oc}$  for DR3TSBDT based BHJ organic solar cells was realized. The results demonstrate that DTBTF is a promising acceptor material for achieving high-performance fullerene-free organic solar cells.

The synthetic route of DTBTF is shown in **Fig. 1b**. DTF was synthesized using Suzuki coupling between 1 and 2. The intermediates of dialdehyde DCHOTF was obtained by Vilsmeier-Haack reaction. The target molecule DTBTF were then prepared by Knoevenagel condensation of DCHOTF with thiobarbituric acid. The details are shown in Supporting Information. The new molecule exhibits good solubility in common organic solvents, such as dichloromethane, chloroform, tetrahydrofuran, etc. Thermogravimetric analysis (TGA) indicates that DTBTF exhibits excellent thermal stability up to 350 °C under  $N_2$  atmosphere (**Fig. S1**). The UV-Vis absorption spectra of DTBTF in chloroform and in thin film are shown in **Fig. 2a**. DTBTF in chloroform ( $10^{-6}$  M) shows an absorption peak at 540 nm with a maximum absorption



**Fig. 2** a) Absorption spectra of DTBTF in chloroform solution and as-cast film, b) Cyclic voltammogram of DTBTF in a dichloromethane solution of 0.1 mol L<sup>-1</sup> Bu<sub>4</sub>NPF<sub>6</sub> with a scan rate of 100 mV s<sup>-1</sup>.



**Fig. 3** a) Characteristic current density versus voltage ( $J-V$ ) curves of DR3TSBDT:DTBTF based devices without and with thermal annealing; b) The external quantum efficiency (EQE) curves of the DR3TSBDT:DTBTF based devices without and with thermal annealing.

coefficient of  $1.12 \times 10^5$  M<sup>-1</sup> cm<sup>-1</sup>. The DTBTF film casted from chloroform shows a blue-shifted maximum absorption peak at 520 nm, and a broad absorption band from 300 to 620 nm. The optical band gap of DTBTF is 2.03 eV estimated from the onset of the film absorption spectrum.

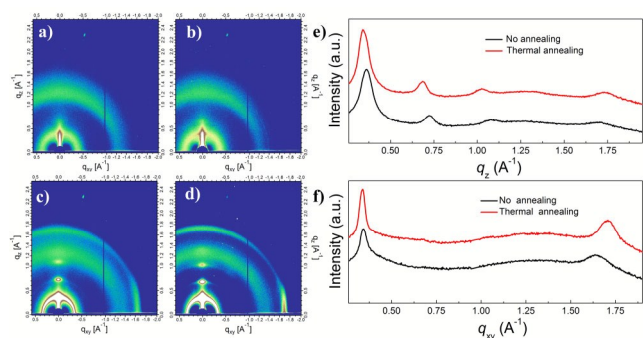
The electrochemical properties of DTBTF were investigated by cyclic voltammetry with ferrocene/ferrocenium of the (Fc/Fc<sup>+</sup>) redox couple (4.8 eV below the vacuum level) as the internal calibration. As shown in **Fig. 2b**, the HOMO and LUMO energy levels of DTBTF, which are -5.68 eV and -3.62 eV, respectively, are estimated based on the onset oxidation potential and the onset reduction potential of the redox curves. Both the HOMO offset and LUMO offset between DR3TSBDT and DTBTF were large enough for photoinduced hole and electron transfer, respectively.<sup>11</sup> Due to the higher LUMO energy level compared to PC<sub>71</sub>BM, an improved  $V_{oc}$  could be expected by using DTBTF as the electron acceptor material.

BHJ organic solar cells were fabricated using DR3TSBDT as the electron donor material and DTBTF as the electron acceptor material with a device structure of glass/ITO/PEDOT:PSS/DR3TSBDT:DTBTF/PDIN/Al, using the conventional solution spin-coating process. PDIN is a perylene diimide derivative, developed as cathode interlayer by Li *et al.*,<sup>15</sup> and its structure is shown in **Fig. S2**. The optimized devices parameters of  $V_{oc}$ ,  $J_{sc}$ , FF and PCE are summarized in **Table 1**, and more performance data under various conditions are shown in **Table S1** and **S2**. The optimized D/A weight ratio of DR3TSBDT:DTBTF is 1:0.5. The current density-voltage ( $J-V$ ) curves of the devices (with D/A weight ratio of 1:0.5) with different treatments measured under 100 mW cm<sup>-2</sup> simulated sunlight illumination are shown in **Fig. 3a**. The device without

**Table 1** Device performance parameters of the BHJ solar cells based on DR3TSBDT:DTBTF (1:0.5, w/w) blend films.

Post treatment	$V_{oc}$ [V]	$J_{sc}$ [mA cm <sup>-2</sup> ]	FF	PCE [%] <sup>a,b</sup>
No annealing	1.15	4.51	0.34	1.65±0.11 (1.76)
Thermal annealing	1.15	7.42	0.45	3.64±0.20 (3.84)

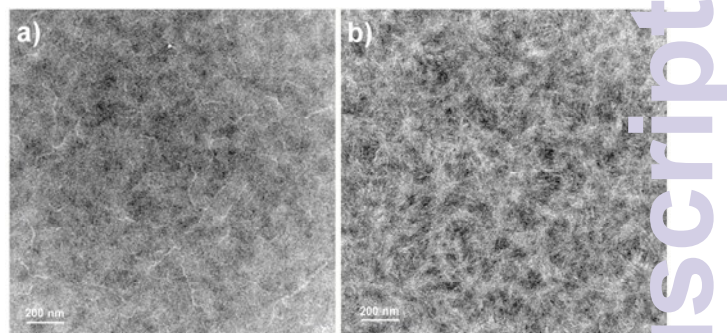
a) Average values from 30 devices, b) The best PCEs are provided in parentheses.



**Fig. 4** GIWAXS images of (a, b) DTBTF pure films and (c, d) DR3TSBDT:DTBTF blend films. (a, c) The films without post-treatment. (b, d) The films with thermal annealing. (e) Out-of-plane line-cuts of GIWAXS patterns for the DR3TSBDT:DTBTF blend films. (f) In-plane line-cuts of GIWAXS patterns for the DR3TSBDT:DTBTF blend films.

post-treatment showed a PCE of 1.76%, with a  $V_{oc}$  of 1.15V, a  $J_{sc}$  of 4.51 mA cm<sup>-2</sup> and a FF of 0.34. After thermal annealing at 100 °C for 10 min, the performance was significantly improved to a PCE of 3.84%, with a  $V_{oc}$  of 1.15 V, a  $J_{sc}$  of 7.42 and a FF of 0.45. The devices with DTBTF as electron acceptor exhibited much higher  $V_{oc}$  (1.15 V) than the devices with PC<sub>71</sub>BM as electron acceptor (with  $V_{oc}$  of 0.96 V).<sup>12b</sup> The higher  $V_{oc}$  could be attributed to the high-lying LUMO energy level of DTBTF. Furthermore, the  $E_{loss}$  is 0.59 eV, calculated from the difference between the optical band gap of DR3TSBDT and the  $qV_{oc}$ . Since the minimum  $E_{loss}$  is suggested to be 0.6 eV and the corresponding  $V_{oc}$  is also often considered as the maximum achievable  $V_{oc}$  in the BHJ organic solar cells, replacing PC<sub>71</sub>BM with non-fullerene acceptor DTBTF in OPV devices could almost realized the maximized  $V_{oc}$  for DR3TSBDT based BHJ organic solar cells. External quantum efficiency (EQE) spectra of the OPV devices are shown in **Fig. 3b**. The DR3TSBDT:DTBTF blend film with thermal annealing showed broad photo-to-current response from 300 to 700 nm with the maximum value of 41% at 560 nm. The calculated  $J_{sc}$  obtained by integration of the EQE curves were 4.41 and 7.06 mA cm<sup>-2</sup>, respectively, for the devices without and with thermal annealing, respectively, which showed a 2~5% mismatch compared with the  $J_{sc}$  values obtained from the *J-V* curves.

The hole and electron mobilities of the BHJ blend films were measured using the space-charge limited current (SCLC) method with device structures of ITO/PEDOT:PSS/DR3TSBDT:DTBTF/Au and Al/DR3TSBDT:DTBTF/Al, respectively (**Fig. S3**). For the devices without annealing, the hole and electron mobilities were 6.70×10<sup>-5</sup> cm<sup>2</sup>V<sup>-1</sup>S<sup>-1</sup> and 1.91×10<sup>-5</sup> cm<sup>2</sup>V<sup>-1</sup>S<sup>-1</sup>, respectively. After thermal annealing, the hole and electron mobilities increased to 1.14×10<sup>-4</sup> and 4.13×10<sup>-5</sup> cm<sup>2</sup>V<sup>-1</sup>S<sup>-1</sup>, respectively. The microstructural features of the pure DTBTF films and DR3TSBDT:DTBTF blend films with different treatments were investigated by two dimensional (2D) grazing-incidence wide-angle X-ray scattering (GIWAXS) (**Fig. 4**). The pure DTBTF films showed weak (100) diffraction peak at 0.39 Å<sup>-1</sup>, corresponding to interchain distance of 16.1 Å, indicating poor molecular packing in the solid state. For the blend film without annealing,



**Fig. 5** TEM images of DR3TSBDT:DTBTF blend films (a) without annealing and (b) with thermal annealing.

both (h00) and (010) reflections of DR3TSBDT were observed. After thermal annealing, the reflection intensity of both (h00) and (010) was strengthened, which indicates that a more ordered structure was formed after thermal annealing treatment. In addition, from photoluminescence (PL) spectra of the pure and blend films (**Fig. S5**), Compared with the DR3TSBDT:DTBTF blend film without annealing, the DR3TSBDT:DTBTF blend film with thermal annealing exhibited a decreased PL emission, indicating the enhancement of intermolecular interaction between the donor and acceptor. The enhanced intermolecular interaction and more ordered packing in the blend film with thermal annealing could promote charge separation and transport, thus higher  $J_{sc}$ .

The morphologies of the blend films were investigated by atomic force microscopy (AFM) and transmission electron microscopy (TEM). From AFM images (**Fig. S4**), the blend films without and with thermal annealing are smooth and uniform with low root-mean-square (RMS) roughness of 0.78 and 1.05 nm, respectively. The TEM images clearly showed the differences between the morphologies of the blend films with different treatments. As shown in **Fig. 5**, the blend film without post-treatment showed poor interpenetrating networks of the donor and acceptor phases. After thermal annealing, the blend film exhibited clear phase separation, and obvious fiber like crystalline structures. The better morphology could increase charge transport efficiency, thus resulting in higher  $J_{sc}$ . However, the large domains with size of ~120 nm in the blend film which is much larger than the ideal exciton diffusion length (10~20 nm),<sup>16</sup> would lead to serious charge recombination, thus inferior FF and relatively low EQE response. It is believed that higher PCEs could be expected through further efforts focused on device optimization to improve the  $J_{sc}$  and FF in the future.

In conclusion, a new A-D-A small molecule electron acceptor DTBTF containing a central fluorene unit as the central block unit and thiobarbituric acid as the end-capping groups was designed and synthesized. The introduction of electron withdrawing group thiobarbituric acid could finely tune the LUMO energy level of the acceptor molecule. The new molecule DTBTF exhibited strong absorption in the visible region and a high LUMO energy level compared to PCBM. The devices based on the DR3TSBDT:DTBTF blend film exhibited a PCE of 3.84% and a  $V_{oc}$  as high as 1.15 V with a low energy loss of only 0.59 eV. The

results indicate that the OPV performance of fullerene-free all-small-molecule organic solar cells could have great improvement room if desirable  $J_{sc}$  and  $FF$  could be obtained simultaneously. We demonstrate that the A-D-A molecules could serve as not only good donors but also good acceptors. Through careful molecule design and device optimization, fullerene-free all-small-molecule organic solar cells would achieve better performance in the near future.

The authors gratefully acknowledge the financial support from MoST (2014CB643502), NSFC (51373078, 51422304 and 91433101), PCSIRT (IRT1257) and Tianjin city (13RCGFGX01121). TPR and FL were supported by Polymer-Based Materials for Harvesting Solar Energy (PhaSE), an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Basic Energy Sciences under award number DE-SC0001087.

## Notes and references

- (a) A. J. Heeger, *Chem. Soc. Rev.*, 2010, **39**, 2354-2371; (b) F. C. Krebs, *Sol. Energy Mater. Sol. Cells*, 2009, **93**, 394-412.
- (a) Z. He, B. Xiao, F. Liu, H. Wu, Y. Yang, S. Xiao, C. Wang, T. P. Russell and Y. Cao, *Nat Photon*, 2015, **9**, 174-179; (b) B. Kan, M. Li, Q. Zhang, F. Liu, X. Wan, Y. Wang, W. Ni, G. Long, X. Yang, H. Feng, Y. Zuo, M. Zhang, F. Huang, Y. Cao, T. P. Russell and Y. Chen, *J. Am. Chem. Soc.*, 2015, **137**, 3886-3893; (c) C. Liu, C. Yi, K. Wang, Y. Yang, R. S. Bhatta, M. Tsige, S. Xiao and X. Gong, *ACS App. Mater. Inter.*, 2015, **7**, 4928-4935; (d) J.-D. Chen, C. Cui, Y.-Q. Li, L. Zhou, Q.-D. Ou, C. Li, Y. Li and J.-X. Tang, *Adv. Mater.*, 2015, **27**, 1035-1041; (e) S. Zhang, L. Ye, W. Zhao, B. Yang, Q. Wang and J. Hou, *Sci. Chin. Chem.*, 2015, **58**, 248-256.
- (a) L. Ye, S. Zhang, L. Huo, M. Zhang and J. Hou, *Acc. Chem. Res.*, 2014, **47**, 1595-1603; (b) Y. Lin, Y. Li and X. Zhan, *Chem. Soc. Rev.*, 2012, **41**, 4245-4247; (c) G. Dennler, M. C. Scharber and C. J. Brabec, *Adv. Mater.*, 2009, **21**, 1323-1338; (d) Y. Li, *Acc. Chem. Res.*, 2012, **45**, 723-733; (e) J. E. Coughlin, Z. B. Henson, G. C. Welch and G. C. Bazan, *Acc. Chem. Res.*, 2013, **47**, 257; (f) C. D. Wessendorf, G. L. Schulz, A. Mishra, P. Kar, I. Ata, M. Weideler, M. Urdanpilleta, J. Hanisch, E. Mena-Osteritz, M. Lindén, E. Ahlswede and P. Bäuerle, *Adv. Energy Mater.*, 2014, **4**, 1400266; (g) A. C. Stuart, J. R. Tumbleston, H. Zhou, W. Li, S. Liu, H. Ade and W. You, *J. Am. Chem. Soc.*, 2013, **135**, 1806-1815.
- Y. He and Y. Li, *Phys. Chem. Chem. Phys.*, 2011, **13**, 1970-1983.
- (a) Y. Lin and X. Zhan, *Materials Horizons*, 2014, **1**, 470-488; (b) A. a. F. Eftaiha, J.-P. Sun, I. G. Hill and G. C. Welch, *J. Mater. Chem. A*, 2014, **2**, 1201-1213. (c) J. E. Anthony, *Chem. Mater.*, 2011, **23**, 583-590; (d) P. Sonar, J. P. Fong Lim and K. L. Chan, *Energy Environ. Sci.*, 2011, **4**, 1558-1574.
- (a) Y. Lin, J. Wang, Z.-G. Zhang, H. Bai, Y. Li, D. Zhu and X. Zhan, *Adv. Mater.*, 2015, **27**, 1170-1174; (b) J. Zhao, Y. Li, H. Lin, Y. Liu, K. Jiang, C. Mu, T. Ma, J. Y. Lin Lai, H. Hu, D. Yu and H. Yan, *Energy Environ. Sci.*, 2015, **8**, 520-525; (c) Y. Zhong, M. T. Trinh, R. Chen, W. Wang, P. P. Khlyabich, B. Kumar, Q. Xu, C.-Y. Nam, M. Y. Sfeir, C. Black, M. L. Steigerwald, Y.-L. Loo, S. Xiao, F. Ng, X. Y. Zhu and C. Nuckolls, *J. Am. Chem. Soc.*, 2014, **136**, 15215-15221; (d) Y.-J. Hwang, B. A. E. Courtright, A. S. Ferreira, S. H. Tolbert and S. A. Jenekhe, *Adv. Mater.*, 2015, **27**, 4578-4584; (e) J. W. Jung, J. W. Jo, C.-C. Chueh, F. Liu, W. H. Jo, T. P. Russell and A. K. Y. Jen, *Adv. Mater.*, 2015, **27**, 3311-3317; (f) H. Li, Y.-J. Hwang, B. A. E. Courtright, F. N. Eberle, S. Subramaniyan and S. A. Jenekhe, *Adv. Mater.*, 2015, **27**, 3266-3272; (g) D. Sun, D. Meng, Y. Cai, B. Fan, Y. Li, W. Jian, L. Huo, Y. Sun and Z. Wang, *J. Am. Chem. Soc.*, 2015, **137**, 11156-15221.
- S. M. McAfee, J. M. Topple, I. G. Hill and G. C. Welch, *J. Mater. Chem. A*, 2015, DOI: 10.1039/C5TA04310G.
- Y. Chen, X. Wan and G. Long, *Acc. Chem. Res.*, 2013, **46**, 2645-2655.
- (a) O. K. Kwon, J.-H. Park, D. W. Kim, S. K. Park and S. Y. Park, *Adv. Mater.*, 2015, **27**, 1951-1956; (b) A. Sharenko, C. M. Proctor, T. S. van der Poll, Z. B. Henson, T.-Q. Nguyen and G. C. Bazan, *Adv. Mater.*, 2013, **25**, 4403-4406; (c) Z. Tang, B. Liu, A. Melianas, J. Bergqvist, W. Tress, Q. Bao, D. Qian, C. Inganäs and F. Zhang, *Adv. Mater.*, 2015, **27**, 1900-1907. (d) Y. Zhang, Y. Xiao, Y. Xie, L. Zhu, D. Shi and C. Cheng, *Org. Electron.*, 2015, **21**, 184-191; (e) J. A. Mikroyannidis, P. Suresh and G. D. Sharma, *Synth. Met.*, 2010, **160**, 932-938; (f) G. D. Sharma, P. Suresh, J. A. Mikroyannidis and M. M. Stylianakis, *J. Mater. Chem.*, 2010, **20**, 561-567.
- H. Zhou, L. Yang and W. You, *Macromolecules*, 2012, **45**, 607-632.
- D. Veldman, S. C. J. Meskers and R. A. J. Janssen, *Adv. Funct. Mater.*, 2009, **19**, 1939-1948.
- (a) T. S. van der Poll, J. A. Love, T.-Q. Nguyen and G. C. Bazan, *Adv. Mater.*, 2012, **24**, 3646-3649; (b) B. Kan, Q. Zhang, M. Li, X. Wan, W. Ni, G. Long, Y. Wang, X. Yang, H. Feng and Y. Chen, *J. Am. Chem. Soc.*, 2014, **136**, 15529-15532.
- (a) W. Li, K. H. Hendriks, A. Furlan, M. M. Wienk and R. A. J. Janssen, *J. Am. Chem. Soc.*, 2015, **137**, 2231-2234; (b) K. Gao, L. Li, T. Lai, L. Xiao, Y. Huang, F. Huang, J. Peng, Y. Cao, F. Liu, T. P. Russell, R. A. J. Janssen and X. Peng, *J. Am. Chem. Soc.*, 2015, **137**, 7282-7285.
- W. Ni, X. Wan, M. Li, Y. Wang and Y. Chen, *Chem. Commun.*, 2015, **51**, 4936-4950.
- Z.-G. Zhang, B. Qi, Z. Jin, D. Chi, Z. Qi, Y. Li and J. Wang, *Energy Environ. Sci.*, 2014, **7**, 1966-1973.
- (a) X. Yang, J. Loos, S. C. Veenstra, W. J. H. Verhees, M. M. Wienk, J. M. Kroon, M. A. J. Michels and R. A. J. Janssen, *Nano Lett.*, 2005, **5**, 579-583; (b) C. M. Proctor, M. Kuik and T.-Q. Nguyen, *Prog. Polym. Sci.*, 2013, **38**, 1941-1966.