ChemComm

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: C. Tan, J. Gorman, A. Wadsworth, S. Holliday, S. Subramanian, S. A. Jenekhe, D. Baran, I. McCulloch and J. Durrant, *Chem. Commun.*, 2018, DOI: 10.1039/C7CC09123K.

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 [author guidelines](#).

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, outlined in our [author and reviewer resource centre](#), 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.

Journal Name

COMMUNICATION

Barbiturate End-Capped Non-Fullerene Acceptors for Organic Solar Cells: Tuning Acceptor Energetics to Suppress Geminate Recombination Losses.

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

DOI: 10.1039/x0xx00000x

www.rsc.org/

Ching-Hong Tan^a, Jeffrey Gorman^b, Andrew Wadsworth^a, Sarah Holliday^{*c}, Selvam Subramaniyan^d, Samson A. Jenekhe^d, Derya Baran^e, Iain McCulloch^{a, e}, James R. Durrant^{*a}

We report the synthesis of two barbiturate end-capped non-fullerene acceptors and demonstrate their efficient function in high voltage output organic solar cells. The acceptor with the lower LUMO level is shown to exhibit suppressed geminate recombination losses, resulting in enhanced photocurrent generation and higher overall device efficiency.

Non-fullerene acceptors (NFAs) are attracting increasing interest for organic solar cell (OSC) applications due to their low synthesis costs, chemical tunability, high power conversion efficiencies and stabilities. In particular, the higher LUMO levels of some NFAs relative to more widely used fullerene acceptors have been shown to yield OSCs with higher output voltages.¹⁻⁴ However the efficiency of organic solar cells employing NFAs have typically been limited by relatively modest external quantum efficiencies (EQEs) for photocurrent generation – with peak EQEs typically in the range 50-65%.^{3, 5-8} Very recently, a few studies have reported higher EQEs, but have not explored fully the origin of the enhanced EQEs they reported.^{1, 2, 9, 10} In this study, we address the role that geminate recombination of photogenerated charges play in limiting the EQE of NFA-based OSCs, and show that these losses can be suppressed by judicious tuning of acceptor LUMO level.

Of the non-fullerene acceptor motifs developed recently, calamitic acceptor-donor-acceptor (A-D-A) type structures have shown particular promise as a molecular design template for low band gap, highly modular materials that deliver high efficiencies.^{3, 11, 12} Extended, fused ring core systems such as indacenodithienothiophene (IDTT)^{13, 14} and indacenodithiopheno-

indacenodithiophene (IDTDT)¹⁵ have been shown to be particularly effective as the electron-rich core moiety. Despite the high efficiency of these NFA materials, they often lack the synthetic simplicity that is advantageous for commercial scale-up.¹⁶ By contrast, cross-coupled, fluorene-cored materials provide particularly promising scope for structural and optoelectronic diversification via relatively simple, low cost synthetic routes^{11, 17, 18}. Coupling units such as benzothiadiazoles and thiophenes onto this core provides a modular approach to acceptor design, as incorporating different units can effectively tune optical and electronic character. Moreover by end-capping with rhodanine¹⁴, barbiturate,^{19, 20} malononitrile²¹, indenemalononitrile¹³ and indandione²² derivatives, the molecular optoelectronic and morphological properties can be modified further.²³ Here we compare two fluorene based non-fullerene acceptors that are synthesised in two steps from commercially available precursors. Both acceptors comprise a thiophene-fluorene-thiophene triad, end-capped with either the barbiturate derivative 1,3-dimethylbarbituric acid (FTB) or 1,3-diethyl-2-thiobarbituric acid

(FTTB) (Figure 2). Thiocarbonyl substitution has emerged as a promising means of controlling the optoelectronic properties in

Figure 1: a) Synthetic scheme of FTB and FTTB, b) UV-vis absorption spectra of FTB and FTTB solutions and films, c) First heating and cooling differential scanning calorimetry (DSC) cycle of FTB and FTTB films at a scan rate of 5 °C min⁻¹.

^a Department of Chemistry and Centre for Plastic Electronics, Imperial College London SW7 2AZ London, United Kingdom.

^b Cavendish Laboratory, University of Cambridge, CB2 1TN, United Kingdom.

^c Department of Materials Science and Engineering, University of Washington, Seattle, WA 98195, United States of America.

^d Departments of Chemical Engineering and Chemistry, University of Washington, Seattle, Washington 98195-1750, United States

^e Physical Sciences and Engineering Division, KAUST Solar Centre (KSC), King Abdullah University of Science and Technology (KAUST), Thuwal, 23955-6900, Kingdom of Saudi Arabia.

Electronic Supplementary Information (ESI): See DOI: 10.1039/x0xx00000x

COMMUNICATION

Journal Name

organic semiconducting materials.^{24, 25} However, the effect of this functional group remains poorly understood, and currently there are no studies regarding thiocarbonyl substitution in the context of small molecule acceptors. In this work, two NFAs with carbonyl and thiocarbonyl functionalised barbiturate derivatives are compared directly in order to investigate the effect of this group on the optoelectronic and device properties. Both acceptors were blended with a medium-band gap donor polymer **PSEHTT**, which has successfully been utilised in non-fullerene OSCs.^{26, 27}

The synthetic schemes for **FTB** and **FTTB** are shown in Figure 1a, and described in greater detail in the SI. In brief, Suzuki coupling of 9, 9-dioctylfluorene-2, 7-diboronic acid pinacol ester with 2-bromo-5-formylthiophene yields the aryl dialdehyde intermediate. Knoevenagel condensation of this intermediate with 1,3-dimethylbarbituric acid yields the final product **FTB**, whilst condensation with 1,3-diethyl-2-thiobarbituric acid yields **FTTB**. Due to commercial availability of the barbiturate precursors, methyl groups were incorporated for **FTB** while ethyl groups were used in the case of **FTTB**. Studies are underway to explore the influence of alkyl groups and thiocarbonyl substitution independently on the materials properties. As demonstrated by the DFT (B3LYP/6-31G*) structural optimizations shown in Figure S5, both acceptors exhibit a similar, slightly twisted molecular structure due to torsion between the fluorene and thiophene units, but with slightly bulkier ethyl groups in the case of **FTTB**.

Figure 1b shows the UV-vis absorption spectra of the **FTB** and **FTTB** solutions and neat films. The solutions yield a pronounced absorption band 400–600 nm with maximum extinction coefficients of $7.7 \times 10^4 \text{ M}^{-1}\text{cm}^{-1}$ and $8.9 \times 10^4 \text{ M}^{-1}\text{cm}^{-1}$ for **FTB** and **FTTB** respectively (Table S1), both higher than for PC₆₀BM within the visible region ($0.5 \times 10^4 \text{ M}^{-1}\text{cm}^{-1}$)¹⁸, making them suitable for photon harvesting applications such as OSCs. The **FTTB** spectrum is red-shifted by about 30 nm compared to **FTB**, signifying a lower optical band gap. Both materials show a ~20–30 nm absorption red shift from solution to film.

Figure 2: a) A graphic representation of the LUMO and HOMO levels calculated by cyclic voltammetry (CV) and optical band gap (refer ESI) and b) chemical structures of PSEHTT, FTB and FTTB, c) Device J-V characteristics and d) External quantum efficiency (EQE) of FTTB:PSEHTT (red) and FTB:PSEHTT (blue) systems.

Differential scanning calorimetry (DSC) was carried out on **FTB** and **FTTB** films (Figure 1c). **FTB** shows a higher melting

transition with a peak at around 230°C compared to **FTTB** (180°C), consistent with **FTB**'s higher planarity and the increased intermolecular interactions that are expected from its less bulky methyl groups. In addition, the DSC scan for **FTB** shows a small exothermic crystallization transition at 140°C which is not observed in **FTTB** above glass transition temperatures (120°C and 130°C for **FTB** and **FTTB** respectively), consistent with the XRD data before and after annealing (refer to SI). We note that ordering of **FTB** molecules is almost entirely repressed in blend after annealing as confirmed by XRD and UV-vis absorption data (Figure S10).

The thin film electrochemical characteristics of the two acceptors and **PSEHTT** donor polymer were investigated by cyclic voltammetry (CV) combined with E_g^{opt} , derived from the UV-vis absorption spectra of neat films, to estimate their HOMO and LUMO energy levels, as illustrated in Figure 2a (refer to Table S1, Figure S6–8 for details). **FTTB** has a deeper HOMO (–5.8 eV) and LUMO (–3.7 eV) levels than **FTB** (–5.7 eV and –3.5 eV respectively), which can be attributed to the more polarizable nature of the C=S bond compared to C=O, making the thioketone a stronger acceptor group. Consistent with previous studies, thioketone substitution is observed to have a more significant effect on the LUMO energy, resulting in a slightly reduced optical bandgap.^{24, 25} This stronger acceptor group creates larger LUMO-LUMO and HOMO-HOMO offsets between **PSEHTT** and **FTTB** (0.4 eV and 0.6 eV respectively) compared to **FTB** in blends (0.2 eV and 0.5 eV respectively), corresponding to higher driving forces for charge separation in devices employing **FTTB**.

OSCs were fabricated in an ITO/ZnO/**PSEHTT**: **Acceptor** /MoO₃/Ag inverted architecture and their J-V curves were measured under 100 mWcm^{–2} simulated AM1.5G illumination (Figure 2b). Device performance was optimised by varying the blend ratios, concentrations, solvent and annealing temperatures (refer to Table S2 and S3). For **PSEHTT**:**FTTB** devices, optimised conditions (1:2 blend ratio in 10 gL^{–1} CB solvent without annealing), yielded a PCE of up to 7.2%. Similar optimised conditions were found for **PSEHTT**:**FTB** leading to a PCE of up to 5.4%. The higher efficiency of the **FTTB** devices results from higher photocurrent generation (13.5 mAcm^{–2} compared to **FTB** 8.9 mAcm^{–2}), offset in part by a lower open circuit voltage (0.98 V vs 1.13 V). We note that both processing additives and thermal annealing lowered the device efficiency, due mainly to the reduced J_{SC}. The higher V_{OC} of the **FTB** devices is consistent with its higher LUMO level. We focus herein rather on the cause of the difference in photocurrent density which results in the higher PCE for **FTTB** devices.

The higher photocurrent obtained for **FTTB** devices compared to **FTB** was confirmed by external quantum efficiency (EQE) as shown in Figure 2c. Whilst **FTB** devices exhibited a modest maximum EQE (54%), a maximum EQE of 84% was attained for **FTTB** devices, comparable to some of the highest values reported for polymer:fullerene systems (we note drop off in EQE for $\lambda > 550 \text{ nm}$ is due to lower sample absorption).^{28–31} Both blends showed similar absorption maxima, indicating that this difference in EQE values does not arise from differences in light harvesting.

Photoluminescence quenching (PLQ) was employed to investigate whether the higher EQE values for the **PSEHTT:FTTB** devices could result from more efficient exciton separation. For a selective excitation of **PSEHTT** (Figure S11), **PSEHTT:FTTB** blends showed modestly higher PLQ than **PSEHTT:FTB** relative to neat **PSEHTT** films (96% vs 85%). Analogous data were collected for acceptor PLQ employing acceptor excitation, showing 95% and 89% PLQs for **FTTB** and **FTB** blends respectively (Figure S12). These data are consistent with the higher energy offsets between **PSEHTT** and **FTTB** increasing the efficiency of exciton separation. However, the difference in PLQ between the two blends (6%) is too small to explain the 30% difference in maximal EQEs between **FTTB** and **FTB** devices.

Blend mobilities were measured using the space-charge limiting current (SCLC) method (Figure S13 and S14). Electron and hole mobilities for **PSEHTT:FTB** and **PSEHTT:FTTB** blends were both found to be similar. The electron mobility ranged from $3\text{--}6 \times 10^{-5} \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ while the hole mobility ranged from $7\text{--}8 \times 10^{-5} \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ for both systems. It thus appears unlikely that the difference in EQE values derives from differences in charge transport between the two blends.

Figure 3: fs-TA spectra of a) **PSEHTT:FTB** and b) **PSEHTT:FTTB** films. c) fs-TA kinetics of **PSEHTT** exciton in neat and in blend (deconvoluted) systems and d) Deconvoluted polaron generation and decay in **PSEHTT:FTB** and **PSEHTT:FTTB** employing an excitation wavelength of 650 nm at a density of $2 \mu\text{mol cm}^{-2}$ in N_2 atmosphere

Ultrafast transient absorption data were employed to investigate further the charge generation process in the two blends, adopting a selective **PSEHTT** excitation at 650 nm, as shown in Figure 4. Both blends show an initial photoinduced absorption maximum at $\sim 1300 \text{ nm}$, assigned by comparison to neat film data (Figure S15) to **PSEHTT** exciton absorption. At longer time delays this exciton absorption is replaced by a narrower absorption band peaking at 1050 nm , assigned to **PSEHTT** polaron absorption.³² Figure 4c shows the kinetics of **PSEHTT** exciton signal decay in neat **PSEHTT** (assigned primarily to non-radiative decay to ground) and both the **FTB** and **FTTB** blend films, determined following by deconvolution of the exciton and polaron spectra (see SI for details). The **PSEHTT** exciton decay time accelerates from $\sim 35 \text{ ps}$ in the neat polymer film to 5.2 and 1.3 ps in the blends with **FTB** and **FTTB**

respectively. These data are in reasonable agreement the PLQ data, confirming efficient exciton separation in both blends, with this **PSEHTT** exciton separation being modestly more efficient in blends with **FTTB**.

Figure 4d shows kinetics of **PSEHTT** polaron generation and decay, again determined by deconvolution of the transient spectra shown in Figures 4a and 4b. The rise of the polaron absorption is in reasonable agreement with the exciton decay kinetics plotted in Figure 4c. We also note the appearance of significant polaron absorption within our instrument response ($\sim 300 \text{ fs}$), also apparent as a reduction in the initial exciton absorption intensity in both blend films relative to neat **PSEHTT**. It is striking that this **PSEHTT** polaron absorption is longer lived for the **FTTB** blend than for **FTB** blend. For the **FTTB** blend, a modest (20%) decay of polaron absorption within the timescale of our measurement (6 ns) is observed with a decay half-life of 1.5 ns . By contrast, in the **FTB** blend, this decay is both larger in amplitude (40%) and faster ($\sim 650 \text{ ps}$). Further TAS data were collected as a function of excitation intensity to determine whether these decays resulted from geminate or non-geminate recombination processes (Figure S16). For the **FTB** blend the decay was observed to be intensity independent, indicating that the decay originates from a geminate recombination process. By contrast, some intensity dependence was observed for the **FTTB** blend, indicating that the (in any case more modest) decay in this blend originates in part from non-geminate losses. It can thus be concluded that the **PSEHTT:FTB** blend shows substantially higher geminate recombination losses than the **PSEHTT:FTTB** ($\leq 20\%$ vs 40%). Such geminate recombination losses, assigned to recombination to ground of interfacial, bound electron-hole pairs,³³ primarily impact on the efficiency of photocurrent generation in organic solar cells. It is apparent that this difference in geminate recombination losses between the two blends is sufficient to be the largest cause of the higher EQE values, and therefore higher PCEs obtained for **PSEHTT:FTTB** devices relative to **PSEHTT:FTB** devices. Based on the bulkier Et group in **FTTB** that inhibits crystallization, as well as the absence of any crystalline diffraction peaks in the unannealed films of either acceptor, it is unlikely that higher geminate recombination losses for **PSEHTT:FTB** result from differences in film morphology (increased crystallinity can reduce exciton separation efficiency but typically suppresses geminate recombination losses). Instead, the suppression of geminate recombination losses for **PSEHTT:FTTB** can be more reasonably assigned to the $\sim 0.2 \text{ eV}$ larger energetic offset driving charge separation in this blend compared to **PSEHTT:FTB**, consistent with several studies reporting that larger energy offsets can suppress the geminate recombination of bound charge pairs at organic donor/acceptor interfaces.³³

In summary, two simple non-fullerene acceptors **FTB** and **FTTB** were synthesised with different barbituric acid functionalised end groups to explore the potential of the carbonyl and thiocarbonyl derivatives in the context of small molecule acceptors. While the higher-lying LUMO of the barbituric acid analogue **FTB** benefited the open circuit voltage, yielding an impressive V_{oc} of 1.13 V in blends with

PSEHTT, photocurrent generation was only modestly efficient in these devices (maximal EQE of 54%), leading to PCE of up to 5.4%. Substitution of the 1,3-dimethyl barbiturate derivative in **FTB** for the more electron withdrawing thiocarbonyl derivative N-ethyl thiobarbiturate, in **FTTB** resulted in a 0.2 eV deeper LUMO and red-shifted absorption. This lower LUMO resulted in a slightly reduced device V_{oc} of 0.98 V, which was more than compensated by an increase in maximal EQE to 84%, leading to an increase in overall device efficiency to up to 7.2%, comparable to the highest reported to date for binary PSEHTT based NFA systems.²⁶ The increase in EQE is shown to result primarily from a suppression of geminate recombination losses in **PSEHTT:FTTB** blends relative to **PSEHTT:FTB**, attributed to the lower **FTTB** LUMO and HOMO levels which increase the energy offsets, and in turn drive more efficient dissociated charge generation in these devices. Detailed morphological studies would be needed to fully characterise the effect of differences in phase separation on device performance with these materials. In addition, future studies should explore the use of other donor polymers that can further reduce the geminate recombination losses. The results shown herein demonstrate that tuning the optoelectronic properties of calamitic non-fullerene acceptors utilising carbonyl and thiocarbonyl functionalised barbituric acid based end groups is simple and effective strategy to optimise the performance of organic solar cells employing such non-fullerene acceptors.

Notes and references

The authors acknowledge KAUST for the funding (OSR-2015-CRG4-2572) and KAUST Center Competitive Fund. CH thanks MyBrainSc for PhD scholarship. SAJ and SS acknowledge funding under US NSF (CBET-1435912).

- H. Bin, L. Gao, Z.-G. Zhang, Y. Yang, Y. Zhang, C. Zhang, S. Chen, L. Xue, C. Yang, M. Xiao and Y. Li, *Nature Communications*, 2016, **7**.
- H. Bin, Z.-G. Zhang, L. Gao, S. Chen, L. Zhong, L. Xue, C. Yang and Y. Li, *Journal of the American Chemical Society*, 2016, **138**, 4657-4664.
- W. Chen and Q. Zhang, *Journal of Materials Chemistry C*, 2017, **5**, 1275-1302.
- W. Zhao, D. Qian, S. Zhang, S. Li, O. Inganas, F. Gao and J. Hou, *Advanced Materials*, 2016, **28**, 4734-4739.
- T. Earmme, Y.-J. Hwang, S. Subramaniyan and S. A. Jenekhe, *Advanced Materials*, 2014, **26**, 6080-6085.
- H. Kang, W. Lee, J. Oh, T. Kim, C. Lee and B. J. Kim, *Accounts of Chemical Research*, 2016, **49**, 2424-2434.
- F. Fernandez-Lazaro, N. Zink-Lorre and A. Sastre-Santos, *Journal of Materials Chemistry A*, 2016, **4**, 9336-9346.
- F. Jin, G. Ding, Y. Wang, J. Yuan, W. Guo, H. Yuan, C. Sheng, W. Ma and H. Zhao, *The Journal of Physical Chemistry C*, 2017, DOI: 10.1021/acs.jpcc.7b03001.
- Z. Li, K. Jiang, G. Yang, J. Y. L. Lai, T. Ma, J. Zhao, W. Ma and H. Yan, *Nature Communications*, 2016, **7**, 13094.
- L. Gao, Z.-G. Zhang, L. Xue, J. Min, J. Zhang, Z. Wei and Y. Li, *Advanced Materials*, 2016, **28**, 1884-1890.
- C. B. Nielsen, S. Holliday, H.-Y. Chen, S. J. Cryer and I. McCulloch, *Accounts of Chemical Research*, 2015, **48**, 2803-2812.
- N. Liang, W. Jiang, J. Hou and Z. Wang, *Materials Chemistry Frontiers*, 2017, **1**, 1291-1303.
- Y. Lin, J. Wang, Z.-G. Zhang, H. Bai, Y. Li, D. Zhu and X. Zhan, *Advanced Materials*, 2015, **27**, 1170-1174.
- S. Holliday, R. S. Ashraf, A. Wadsworth, D. Baran, S. A. Yousaf, C. B. Nielsen, C.-H. Tan, S. D. Dimitrov, Z. Shang and N. Gasparini, *Nature Communications*, 2016, **7**, 11585.
- Y. Li, X. Liu, F.-P. Wu, Y. Zhou, Z.-Q. Jiang, B. Song, Y. Xia, Z.-G. Zhang, F. Gao, O. Inganas, Y. Li and L.-S. Liao, *Journal of Materials Chemistry A*, 2016, **4**, 5890-5897.
- S. Holliday, Y. Li and C. K. Luscombe, *Progress in Polymer Science*, 2017, **70**, 34-51.
- M. Li, Y. Liu, W. Ni, F. Liu, H. Feng, Y. Zhang, T. Liu, H. Zhang, X. Wan, B. Kan, Q. Zhang, T. P. Russell and Y. Chen, *Journal of Materials Chemistry A*, 2016, **4**, 10409-10413.
- S. Holliday, R. S. Ashraf, C. B. Nielsen, M. Kirkus, J. A. Röhr, C.-H. Tan, E. Collado-Fregoso, A.-C. Knall, J. R. Durrant, J. Nelson and I. McCulloch, *Journal of the American Chemical Society*, 2015, **137**, 898-904.
- P. Sullivan, G. E. Collis, L. A. Rochford, J. F. Arantes, P. Kemppinen, T. S. Jones and K. N. Winzenberg, *Chemical Communications*, 2015, **51**, 6222-6225.
- W. Ni, M. Li, B. Kan, F. Liu, X. Wan, Q. Zhang, H. Zhang, T. P. Russell and Y. Chen, *Chemical Communications*, 2016, **52**, 465-468.
- K. Wang, Y. Firdaus, M. Babics, F. Cruciani, Q. Saleem, A. El Labban, M. A. Alamoudi, T. Marszalek, W. Pisula, F. Laquai and P. M. Beaujuge, *Chemistry of Materials*, 2016, **28**, 2200-2208.
- K. N. Winzenberg, P. Kemppinen, F. H. Scholes, G. E. Collis, Y. Shu, T. Birendra Singh, A. Bilic, C. M. Forsyth and S. E. Watkins, *Chemical Communications*, 2013, **49**, 6307-6309.
- O. P. Lee, A. T. Yiu, P. M. Beaujuge, C. H. Woo, T. W. Holcombe, J. E. Millstone, J. D. Douglas, M. S. Chen and J. M. J. Fréchet, *Advanced Materials*, 2011, **23**, 5359-5363.
- D. Gendron, F. Maasoumi, A. Armin, K. Pattison, P. L. Burn, P. Meredith, E. B. Namdas and B. J. Powell, *RSC Advances*, 2017, **7**, 10316-10322.
- S. Lévesque, D. Gendron, N. Bérubé, F. Grenier, M. Leclerc and M. Côté, *The Journal of Physical Chemistry C*, 2014, **118**, 3953-3959.
- Y.-J. Hwang, H. Li, B. A. E. Courtright, S. Subramaniyan and S. A. Jenekhe, *Advanced Materials*, 2016, **28**, 124-131.
- H. Li, T. Earmme, G. Ren, A. Saeki, S. Yoshikawa, N. M. Murari, S. Subramaniyan, M. J. Crane, S. Seki and S. A. Jenekhe, *Journal of the American Chemical Society*, 2014, **136**, 14589-14597.
- Y. Liu, J. Zhao, Z. Li, C. Mu, W. Ma, H. Hu, K. Jiang, H. Lin, H. Ade and H. Yan, *Nature Communications*, 2014, **5**, 5293.
- V. Vohra, K. Kawashima, T. Kakara, T. Koganezawa, I. Osaka, K. Takimiya and H. Murata, *Nature Photonics*, 2015, **9**, 403-408.
- Y. Liang, Z. Xu, J. Xia, S.-T. Tsai, Y. Wu, G. Li, C. Ray and L. Yu, *Advanced Materials*, 2010, **22**, E135-E138.
- S. C. Price, A. C. Stuart, L. Yang, H. Zhou and W. You, *Journal of the American Chemical Society*, 2011, **133**, 4625-4631.
- S. Shoaee, S. Subramaniyan, H. Xin, C. Keiderling, P. S. Tuladhar, F. Jamieson, S. A. Jenekhe and J. R. Durrant, *Advanced Functional Materials*, 2013, **23**, 3286-3298.
- S. D. Dimitrov and J. R. Durrant, *Chemistry of Materials*, 2014, **26**, 616-630.