Thermally Activated Delayed Fluorescence vs Room Temperature Phosphorescence by Conformation Control of Organic Single Molecules†

Przemyslaw Data,^{a,b,c*} Masato Okazaki^d, Satoshi Minakata^d and Youhei Takeda^{d*}

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

DOI: 10.1039/x0xx00000x

www.rsc.org/

The time-resolved photophysical analysis of a multi-colour-changing mechanochromic luminescent compound has been disclosed, which reveals distinct different emission paths to boost TADF and RTP of the emitter depending on its molecule conformations. Furthermore, by making the use of the obtained knowledge here, we also present the possibility to control the emission colors by regulating the population of conformers formed inside the emissive layer using solution process, and this technique was applied to fabricate emissive layers of OLED devices.

Introduction

Organic compounds that can efficiently harvest triplet excitons and convert into light as either thermally activated delayed fluorescence (TADF)¹ or room-temperature phosphorescence (RTP)² have emerged as promising candidates for the next-generation emitting materials to realize efficient organic light-emitting diodes (OLEDs). Especially, since the rediscovery of TADF effect in OLED emitters,³ a number of new organic TADF emitters have been developed,¹ and some of them have already broken the theoretical maximum external quantum efficiencies (EQEs) of 20%.⁴

On one hand, pursuing new aspects of TADF and RTP-active organic materials would offer us tremendous opportunities to expand materials' perspective and utility.⁵ In this line, recently, we have developed a TADF-active multi-colour-changing mechanochromic luminescent (MCL)⁶ organic molecular material (**1**, Figure 1),⁷ which drastically change emission colors (yellow, red, and orange) in response to various external stimuli such as a mechanical force, heat, and solvent vapor (Figure 1). Most importantly, the MCL behavior was rationally correlated with its specific conformers (i.e., **1_Y**: quasi axial-quasi axial (ax-ax), **1_R**: quasi equatorial-quasi equatorial (eq-eq), and **1_O**: quasi axial-quasi equatorial (ax-eq) rather than molecular packing. Nevertheless, the dynamic photophysics of these different-colour-emitting phases of the MCL material have not been exploited, and it is surprising that there is a single report

on such study.⁸ If the relationship between the detailed photophysics of MCL materials and specific conformer-enriched phases is revealed, it would be possible to not only probe conformational information of the MCL materials in the films of one's interest but also tune emission properties by controlling the population of specific conformers with a single component material.

Herein we disclose the time-resolved photophysical profiles of the MCL- and TADF-active donor-acceptor-donor (D-A-D) organic material **1** (Figure 1),⁷ using specific conformer-enriched solids **1_Y**, **1_R**, and **1_O**, to explain the differences in emission properties from the viewpoint of conformation. Most importantly, depending on the dominant conformers, the RTP or TADF processes were distinctly observed. Moreover, we present the possibility of using solution process in order to form a particular conformer-enriched thin emitting layers to tune emission colors, which was also applied to fabrication of OLED devices. By making the use of this knowledge, more strategic

Figure 1 Investigated molecule PTZ-DBPHZ (**1**) and the relationship between MCL properties and conformers.

^a Faculty of Chemistry, Silesian University of Technology, Ks. M. Strzody 9, 44-100 Gliwice, Poland E-mail: Przemyslaw.Data@polsl.pl

^b Physics Department, Durham University, South Road, DH1 3LE, Durham, UK

^c Centre of Polymer and Carbon Materials, Polish Academy of Sciences, M. Curie-Skłodowskiej 34, 41-819 Zabrze, Poland

^d Department of Applied Chemistry, Graduate School of Engineering, Osaka University, Yamdaoka 2-1, Suita, Osaka 565-0871, Japan

† Electronic Supplementary Information (ESI) available: experimental details, additional photophysics results. See DOI: 10.1039/x0xx00000x

approaches for designing efficient TADF- and/or RTP-based OLED devices may be developed in the future.

Experimental Methods

The procedure for the synthesis of PTZ-DBPHZ (**1**) and the formation of respective conformers can be found in the previous work.⁷ The solvents, toluene (TOL), acetonitrile (ACN), dichloromethane (DCM), and tetrahydrofuran (THF) were purchased from Sigma Aldrich (analytical grade). They were used without further purification. Steady-state photophysical measurements were performed in dilute solutions, with UV-Visible absorption spectra taken upon a UV-3600 Shimadzu spectrophotometer and emission spectra taken upon a Jobin Yvon Horiba Fluoromax 3 and Fluoromax 2. The emission spectra were calibrated for detector efficiency using instrument specific company calibration files. Time-resolved photophysical measurements were conducted according to previously described procedures.⁹ The excitation source for all temperature dependent/ time-resolved measurements was the 3rd harmonic of a Nd:YAG laser (355 nm) (Ekspla SL312 and Q-Spark A50). Solid-state thin films used in this analysis were prepared to form 1% w/w ratio in zeonex[®] or a 10% w/w ratio in CBP, spin coated from respective solvent onto clean quartz substrates at 90 °C on a hotplate until dry and then dried in vacuum oven for 12 h to be sure all solvent particles were removed. There was no spectra change between samples dried on hotplate and additionally dried in vacuum oven. OLEDs were fabricated by spin-coating / evaporation hybrid method. Hole injection layer (Heraeus Clevis HIL 1.3N) and emitting layer were spin-coated, whereas electron transport layer (TPBi) and cathode (LiF/Al) were evaporated. Devices of 4 x 2, 4 x 4, 2 x 1 mm pixel size were fabricated. OLED devices were fabricated using pre-cleaned indium-tin-oxide (ITO) coated glass substrates after ozone plasma treatment with a sheet resistance of 20 Ω cm⁻² and ITO thickness of 100 nm. Heraeus Clevis HIL 1.3N was spun-coated and annealed onto a hotplate at 200 °C for 3 min to give 45 nm film.

Results and discussion

Photophysics of the organic solids **1_Y**, **1_O**, and **1_R**

As described in our previous paper,⁷ yellow-emissive (**1_Y**), red-emissive (**1_R**), and orange-emissive (**1_O**) organic solid samples were reproduced by recrystallizing PTZ-DBPHZ (**1**) from CHCl₃/*n*-hexane (**1_Y**) and CH₂Cl₂ (**1_O**), and by grinding **1_Y** (or **1_O**) with a pestle and mortar (**1_R**), respectively. These samples are assumed to be enriched with conformers of ax-ax, eq-eq, and ax-eq, respectively.⁷ In general, the most promising TADF molecular design is perpendicular D-A scaffold,^{1,3,10} and this perfectly matches with the geometry of eq-eq conformation of **1**. However, in reality, we can have a mixture of conformers of **1** in OLED devices, and it is difficult to predict which conformer (i.e., ax-ax, ax-eq, or eq-eq) is the most influential one in fabricated device. Time-resolved spectroscopic analysis of organic solids under vacuum at room

Figure 2 Time-resolved photoluminescence spectra of solids (a) **1_Y** (ax-ax), (b) **1_O** (ax-eq), and (c) **1_R** (eq-eq) at different delay time and comparison with their steady state fluorescence emission (SS FL); (d) photoluminescence decay of respective samples.

temperature allows for revealing their complicated photoluminescence profiles, which involve emissions from a localized singlet excited state ¹LE,¹¹ a charge-transfer excited state ¹CT, and longest-lived mixed emissions from the triplet excited states (Figure 2). It should be very important to note that in **1_Y** (enriched with ax-ax conformer) the most dominant component is prompt emission, which resembles steady-state photoluminescence spectrum (SS FL dotted line, Figure 2a), whereas in **1_O** (enriched with eq-ax conformer) and **1_R** (enriched with eq-eq conformer) the more dominant is delayed component. The steady-state spectra overlap with the delayed component for both **1_O** (ax-eq) and **1_R** (eq-eq) (Figure 2b and c, respectively). Moreover, the prompt emission of **1_Y** seems to be a multicomponent emissive state, at 1.1 ns we observe emission from one ¹LE and at 5.7 ns the emission is mixed of ¹CT emission and another ¹LE which looks close to the steady state emission (SS FL).

What is also important from a comparison of the properties of different conformers is that we directly observed a bathochromic shift of both singlet and triplet emissions to lower energies as the number of equatorial units increased. The singlet level was shifted much more than triplet, probably due to the increased spin-orbital coupling (SOC) effect of charge-transfer state (¹CT) in equatorial conformation. As for the time-decay profiles, we clearly observed different processes for each sample: in the case of **1_Y** (ax-ax), short-lived prompt emissions (τ_1 1.03 ns (62%), τ_2 4.25 ns (31%), τ_3 22.67 ns (7%)), and long-lived phosphorescence (τ_1 0.15 μ s (82%), τ_2 2.32 μ s (18%)) were observed, whereas in the case of **1_R** (eq-eq) a prompt but longer-lived emissions (τ_1 5.72 ns (42%), τ_2 38.42 ns (58%)) and a strong delayed emission (TADF) (τ_1 0.20 μ s (34%), τ_2 0.98 μ s (66%)) followed by phosphorescence were observed. More interestingly, in the case of **1_O** (ax-eq), we observed the mixed

features of ax-ax and eq-eq conformers: the prompt time decay (τ_1 3.16 ns (55%), τ_2 27.13 ns (45%)) resembles that of **1_Y** and the long-lived time decay (τ_1 0.27 μ s (38%), τ_2 2.06 μ s (62%)) resembles that of **1_R**, which also support the mixed conformer of ax-eq (Figure 2d).

For closer inspection of the effect of the conformational difference in photophysical properties, the temperature dependence of the emission profiles for ax-ax (**1_Y**) and eq-eq (**1_R**) conformers were investigated (Figure 3). Firstly, what is important to understand is the main difference between delayed fluorescence and phosphorescence process. Nowadays, even when the emission spectra are recorded at very low temperature (e.g., <100 K), it is difficult to distinguish between phosphorescence and delayed fluorescence, mainly because of the very small ΔE_{ST} gap.¹¹ Strong ¹CT emission resulted from a large SOC causes the overlap of emission spectra, and thereby they are undistinguishable. This is found in many literatures, where ¹CT emission is used as phosphorescence emission. To overcome this problem, the measurement of emissions at a different temperature is necessary. With the rise of temperature, the delayed fluorescence intensity should rise as well. Conversely, if the

emission comes from the triplet excited state (phosphorescence), the intensity should drop. From this main assumption, it could be concluded that mid-range microsecond region (0.3–20 μ s) of ax-ax (**1_Y**) decay is related with mixed emission of delayed fluorescence and phosphorescence with the domination of phosphorescence (Figure 3a), while for eq-eq (**1_R**) conformer, it is mostly related with delayed fluorescence (Figure 3b). The long-lived component (>10 μ s) is from the phosphorescence emission. At low temperature (80 K), the emission from the ¹LE state for ax-ax conformer is observed with maxima around 530 nm (Figure 3c), where for eq-eq conformer we observed mainly emission from the ¹CT state. It is also surprising that the ax-ax conformer is in a locked state at low temperature and there is no emission from a charge transfer excited state (¹CT) at the low temperature. When the temperature rises (Figure S1), the mixed ¹CT emission was observed above 110 K, but still the ¹LE was observed at 290 K. The eq-eq conformer (**1_R**) behaves in a classical way of perpendicularly twisted TADF molecules.¹⁰ From this observation, it could be concluded that RTP was boosted in ax-ax and TADF was in eq-eq, which is consistent with the recent report by Bryce et al.¹²

To briefly summarize the observed results, the illustrative scheme for photophysical mechanisms for each conformers are shown in Figure 4. In the ax-ax, the prompt fluorescence (PF) irradiates from the ¹LE state, whereas the phosphorescence derives from the ³LE state generated through the inter-system crossing (ISC) from the ¹CT state (Figure 4a). Since the ¹CT level is much above the ³LE, the thermally activated reverse ISC (RISC) less likely to occur, leading the irradiation of phosphorescence. In contrast, within the perpendicular eq-eq conformation, due to the separated HOMO/LUMO electronic configuration, the ΔE_{ST} is quite narrow (Figure 4b). In conjunction with vibrations of the electron donors, the RISC is accelerated to yield TADF. With the mixed type conformer (i.e., ax-eq), the ΔE_{ST} is slightly larger than that of eq-eq, thereby leading to less efficient TADF (Figure 4c).

Figure 4 Photophysical mechanism mechanisms in a) ax-ax, b) eq-eq, and c) ax-eq conformer.

Figure 3 Photoluminescence decays of (a) ax-ax and (b) eq-eq conformers at different temperature; time-resolved photoluminescence spectra at different delay time for (c) ax-ax and (d) eq-eq conformers at temperature 80 K and (e) ax-ax and (f) eq-eq conformers at temperature 290 K.

According to the abovementioned conclusion, our attention turned to tailoring emission colors from the same molecule by setting a proper conformation of the molecule in the solid state. But the problem is how to control the conformation in the solid states. It is well known that solvent molecules interact with compounds and they could be even contained in the crystal lattice to offer sufficient voids that can vary the population of conformers. To check if the solvent could setup the proper conformer or to set the majority of one conformer inside solid materials, firstly the 1% of **1** in zeonex® polymer matrix from DCM, TOL, and THF were deposited on quartz substrates by solution process. The photoluminescence transient decays and time-resolved spectra difference were clearly observed (Figure 5). At 5.7 ns, the lowest energy of fluorescence emission was from the layer deposited using DCM, where highest from TOL (Figure 5b). Interestingly, there is no direct relationship between emission energy and the solvent polarity. Nevertheless, there is a significant influence of the solvent on the emission profiles as the results of conformation population change in the deposited compound. This was also clearly supported by the observation that evaporation of solutions under a reduced pressure gives a mixture of different color solids, depending on the solvents used. Of course, it cannot be fully excluded the possibility that the residual solvents affect the emission profiles through dipole-dipole interaction and spin-orbital coupling by these experiments. Both layers deposited from TOL and THF solutions showed strong DF processes, whereas in the layer from DCM did not (Figure 5a).

The same approach was applied with a proper host material (CBP), which was used for fabricating OLED devices by thermal evaporation process in the previous research.⁷ We deposited thin films by spin coating the solutions of 10% of **1** in CBP on quartz substrates from ACN, DCM, TOL, and THF (Figure 6). Like

for zeonex layers, here we again observed a strong influence of the solvents on the PL profiles inside the emissive layer. In this case, much clearer influence of solvent polarity on the emission profiles. Importantly, the layer deposited from TOL, which has the lowest polarity among the tested solvents, exhibited the lowest emission energy (Figure 6d): both of short-lived components and the long-lived one are shifted ca. 0.1 eV to the lower energy regime, when compared to the layers deposited from more polar solvents. More importantly, the emissions from the layers deposited from THF and DCM showed single Gauss-type emissions (Figure 6b and c), whereas in the case of the film made from ACN solution we observed dual emission (Figure 6a). This would suggest that at least two conformers coexist in the layer. From these results, we postulate that the more polar solvents increase the population of the axial conformer in the films. Both of the solvent DCM and THF allowed the dominance of ax-eq conformer in the layer, whereas in the case of ACN we obtained a mixture of ax-ax and ax-eq conformers, which correspond to the energy difference observed in pure conformers (Figure 2 and 3). TOL allowed to form a mixture of eq-eq and ax-eq conformers (Figure 6d).

As the proof of concept, we fabricated OLED devices and compared the effects of respective solvents on EL properties (Figure 7). Four devices were fabricated through depositing an emissive layer on the top of PEDOT:PSS by a solution process, and one device was made by thermal evaporation using previously described process.⁷ Devices [ITO | HIL (PEDOT:PSS 1.3 N) (45 nm) | 10% **1** in CBP (20 nm) – DEV_{ACN}, DEV_{DCM}, DEV_{THF}, DEV_{TOL}, DEV_{EV} | TPBi (50 nm) | LiF (1 nm) | Al (100 nm)] were produced with the use of the described materials, methods and respective solvents (Figure 7). The devices showed a low turn-on voltage at around 2.7 V (Figure 7b). The highest external efficiency (EQE) was marked by evaporated devices (16 %,

Figure 5 (a) Photoluminescence decay of 1% **1** in zeonex film deposited from different solvents; time-resolved photoluminescence spectra of 1% **1** in zeonex deposited from different solvents at (b) 5.7 ns, (c) 56 μs, and (d) 12.6 ms delay time.

Figure 6 Time-resolved photoluminescence spectra of 10% **1** in CBP deposited from (a) ACN, (b) DCM, (c) THF, and (d) TOL, and respective OLED device electroluminescence spectra.

DEV_{EVP}). The efficiencies of spin-coated devices are usually lower than those fabricated through evaporation method, but there is always a possibility to achieve higher efficiency through further device optimization. The highest efficiency was achieved for a device in which the emissive layer was deposited from TOL, and the EQE was around 12%, which is quite good for solution-based OLED devices.¹³ Slightly lower efficiency was obtained for the emissive layer deposited from THF (Figure 7d). The lowest efficiency (5.2%) was obtained from a device with an emissive layer deposited from a DCM solution, but this could be affected by poor layer morphology. Nevertheless, all devices had decent luminance (more than 1,000 cd/m²). Although the highest luminance (28,642 cd/m²) was achieved with the fully evaporated device, the spin-coated devices based on THF and TOL deposited emissive layer attained higher luminance than 23,000 cd/m² (Figure 7c). Most importantly, we observed the change in the emission spectra using different solvents to deposit emissive layer (Figure 7a) ranging from $\lambda_{\max}$ 587 nm – 625 nm, independent of solvent polarity. This nicely provides us with the proof of the concept of controlling conformation ratio inside the emissive layer to tune emission colors. From the comparison of all the PL data, it could be concluded that the evaporated layer has a dominant number of ax-eq conformer rather than eq-eq, which would benefit from the highest TADF contribution. This also explains why the device efficiency is lower than the theoretical limit of the compound in the CBP matrix. We also tried to use thermal evaporation deposition rate of the emitter from 0.1 Å/s up to 10 Å/s to increase-decrease the amount of eq-eq conformer inside the layer, but we have not observed such influence. The solution process was the only way we could observe the change in the conformation of the emitter in the emissive layer.

Figure 7 (a) comparison of electroluminescence spectra, (b)–(d) Characteristics of OLED devices fabricated using emitters and host presented in this work.

Conclusions

To summarize, we investigated the photophysics of multi-color-changing MCL materials **1** using different color emissive solid samples and revealed the effect of conformers in their photophysical properties. Depending on the conformers dominated in the solids, different photophysical processes, i.e., TADF and RTP, were boosted. This would provide us deeper insights of MCL materials. Not only that, we proofed the possibility of controlling emitter conformations by choosing the proper solvents for spin coating of the emissive layer. This would offer us opportunities to enhance the efficiency of an OLED device and give a new role of solution process technique in the OLED fabrication in the future.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The partial work cited herein was supported by a Grant-in-Aid for Scientific Research on Innovative Areas “ π -System Figuration: Control of Electron and Structural Dynamism for Innovative Functions” (JSPS KAKENHI Grant Number JP15H00997 & JP17H05155, to YT) from the MEXT (Ministry of Education, Culture, Science and Technology, Japan), and by the Research Grants from the Japan Prize Foundation, the Iketani Science and Technology Foundation, and the Research Encouragement Grants and the Continuation Grants for Young Researchers from the Asahi Glass Foundation (to YT). We would like to thank prof. Andrew Monkman for consultation. P.D. kindly acknowledges the support received from the First Team program of the Foundation for Polish Science co-financed by the European Union under the European Regional Development Fund, project no. First TEAM 2017-4/32. YT and PD acknowledge the EU’s Horizon 2020 for funding the OCTA project under grant agreement No 778158.

Notes and references

- For reviews on TADF materials, see: (a) Y. Tao, K. Yuan, T. Chen, P. Xu, H. Li, R. Chen, C. Zheng, L. Zhang and W. Huang, *Adv. Mater.*, 2014, **26**, 7931–7958; (b) M. Y. Wong and E. Zysman-Colman, *Adv. Mater.*, 2017, **29**, 1605444; (c) Z. Yang, Z. Mao, Z. Xie, Y. Zhang, S. Liu, J. Zhao, J. Xu, Z. Chi and M. P. Aldred, *Chem. Soc. Rev.*, 2017, **46**, 915–1016; (d) F. B. Dias, T. J. Penfold and A. P. Monkman, *Methods Appl. Fluoresc.*, 2017, **5**, 012011.
- For reviews on RTP, see: (a) S. Mukherjee and P. Thilagar, *Chem. Commun.*, 2015, **51**, 10988–11003; (b) M. Baroncini, G. Bergamini and P. Ceroni, *Chem. Commun.*, 2017, **53**, 2081–2093; (c) H. Yuasa and S. Kuno, *Bull. Chem. Soc. Jpn.*, 2018, **91**, 223–229; (d) A. Forni, E. Lucenti, C. Botta and E. Cariati, *J. Mater. Chem. C*, 2018, **6**, 4603–4626.
- (a) H. Uoyama, K. Goushi, K. Shizu, H. Nomura and C. Adachi, *Nature*, 2012, **492**, 234–238; (b) F. B. Dias, K. N. Bourdakos, V. Jankus, K. C. Moss, K. T. Kamtekar, V. Bhalla, J. Santos, M. R. Bryce and A. P. Monkman, *Adv. Mater.*, 2013, **25**, 3707–3714.

- 4 For selected TADF-based OLEDs exceeding 20% EQEs, see: (a) Y. J. Cho, K. S. Yook and J. Y. Lee, *Adv. Mater.*, 2014, **26**, 4050–4055; (b) S. Hirata, Y. Sakai, K. Masui, H. Tanaka, S. Y. Lee, H. Nomura, N. Nakamura, M. Yasumatsu, H. Nakanotani, Q. Zhang, K. Shizu, H. Miyazaki and C. Adachi, *Nat. Mater.*, 2015, **14**, 330–336; (c) D. R. Lee, M. Kim, S. K. Jeon, S.-H. Hwang, C. W. Lee and J. Y. Lee, *Adv. Mater.*, 2015, **27**, 5861–5867; (d) Y. Seino, S. Inomata, H. Sasabe, Y.-J. Pu and J. Kido, *Adv. Mater.*, 2016, **28**, 2638–2643; (e) P. Rajamalli, N. Senthilkumar, P. Gandeepan, P.-Y. Huang, M.-J. Huang, C.-Z. Ren-Wu, C.-Y. Yang, M.-J. Chiu, L.-K. Chu, H.-W. Lin and C.-H. Cheng, *J. Am. Chem. Soc.*, 2016, **138**, 628–634; (f) T. Ohsawa, H. Sasabe, T. Watanabe, K. Nakano, R. Komatsu, Y. Hayashi, Y. Hayasaka and J. Kido, *Adv. Opt. Mater.*, 2019, **7**, 1801282.
- 5 For a review on TADF/RTP multifunctional materials, see: P. Dada and Y. Takeda, *Chem. Asian J. Early View* (doi: 10.1002/asia.201801791).
- 6 For reviews on MCL materials, see: (a) Y. Sagara and T. Kato, *Nat. Chem.*, 2009, **1**, 605–610; (b) A. Pucci, R. Bizzarri and G. Ruggeri, *Soft Mater*, 2011, **7**, 3689–3700; (c) Z. Chi, X. Zhang, B. Xu, X. Zhou, C. Ma, Y. Zhang, S. Liu and J. Xu, *Chem. Soc. Rev.*, 2012, **41**, 3878–3896; (d) Y. Sagara, S. Yamane, M. Mitani, C. Weder and T. Kato, *Adv. Mater.*, 2016, **28**, 1073–1095; (e) C. Wang and Z. Li, *Mater. Chem. Front.*, 2017, **1**, 2174–2194.
- 7 M. Okazaki, Y. Takeda, P. Data, P. Pander, H. Higginbotham, A. P. Monkman and S. Minakata, *Chem. Sci.*, 2017, **8**, 2677–2686.
- 8 R. Pashazadeh, P. Pander, A. Bucinskas, P. J. Skabara, F. B. Dias and J. V. Grazulevicius, *Chem. Commun.*, 2018, **54**, 13857–13860.
- 9 P. Pander, P. Data and F. B. Dias, *J. Vis. Exp.* 2018, **142**, e56614.
- 10 P. Data, P. Pandor, M. Okazaki, Y. Takeda, S. Minakata and A. P. Monkman, *Angew. Chem. Int. Ed.*, 2016, **55**, 5739–5744.
- 11 F. B. Dias, J. Santos, D. R. Graves, P. Data, R. S. Nobuyasu, M. A. Fox, A. S. Batsanov, T. Palmeira, M. N. Berberan-Santos, M. R. Bryce and A. P. Monkman, *Adv. Sci.*, 2016, **3**, 1600080.
- 12 C. Chen, R. Huang, A. S. Batsanov, P. Pander, Y.-T. Hsu, Z. Chi, F. Dias and M. R. Bryce, *Angew. Chem., Int. Ed.*, 2018, **57**, 16407–16411.
- 13 (a) T. Huang, W. Jiang and L. Duan, *J. Mater. Chem. C*, 2018, **6**, 5577–5596; (b) H. J. Kim, C. Lee, M. Godumala, S. Choi, S. Y. Park, M. J. Cho, S. Park and D. H. Choi, *Polym. Chem.*, 2018, **9**, 1318–1326.