Synthesis and Semiconducting Characteristics of the BF₂ Complexes of Bisbenzothiophene-Fused Azadipyrromethenes

Wanle Sheng,^{†,§} Fei Chang,[†] Qinghua Wu,[†] Erhong Hao,[†][©] Lijuan Jiao,^{*,†}[©] Jie-Yu Wang,^{*,‡}[©] and Jan Pei^{*,‡}[©]

[†]Laboratory of Functional Molecular Solids, Ministry of Education; School of Chemistry and Materials Science, Anhui Normal University, Wuhu 241002, China

[‡]Beijing National Laboratory for Molecular Sciences, College of Chemistry, Peking University, Peking 100871, China [§]Department of Chemistry, BengBu Medical College, Bengbu 233030, China

Supporting Information

ABSTRACT: A novel type of dibenzothiophene [b]-fused core-expanded azaBODIPYs were obtained through an efficient post-functionalization of tetrabrominated azadipyrromethenes, using CuI-catalyzed cyclization, followed by BF₂ complexation. These dyes show nearly planar skeletons, strong NIR absorption with maximum peaks up to 733 nm, and remarkable low-lying LUMO level of -4.15 eV. The field-effect transistor based on **1b** exhibits bipolar transport properties, with the highest electron and hole mobilities up to 0.012 and 0.046 cm² V⁻¹ s⁻¹, respectively.

B oron-complexed azadipyrromethenes (azaBODIPYs, Figure 1),¹ as an emerging class of near-infrared (NIR) organic dyes, play important roles in the traditional applications of dyes including chemosensors,² noninvasive bioimaging reagents,³ and photosensitizers.⁴ On the other hand, their strong NIR absorption, low optical band gaps, high thermal stability/photostability, low-lying lowest unoccupied molecular orbital (LUMO), and the large planar and highly electron-deficient conjugation skeleton with large dipole moment are ideal features for the organic optoelectronics application.⁵ However, the semiconducting properties of BODIPYs, especially azaBODIPYs, have rarely been studied and they generally exhibited very low carrier mobilities, despite the above favorable features.^{6–8}

Lately, the fusion of aromatic ring(s) onto the pyrrolic position(s) of the (aza)BODIPYs to form the so-called *a*-, or *b*-fused (aza)BODIPYs (Figure 1) has successfully formed large and extended π -structures with red-shifted absorptions and large absorption coefficients.^{9,10} However, synthetic methods to annulated azaBODIPYs with aromatic rings at their peripheral positions are limited. One elegant example is the synthesis of [*a*]-ring-fused azaBODIPYs using phthalonitrile as the starting material (see Figure 1). The product, thiophene-substituted benzo-fused azaBODIPY **A**, showed strong intermolecular π - π interactions in the solid state, and was used as π -functional materials with good electron mobility.^{8b} Compared with *a*-fusion, *b*-fusion is more effective to narrow the HOMO-LUMO gap, while maintaining a low-lying LUMO. The latter is the key to the stability toward air oxidation.¹¹ Thus, [*b*]-ring-fused azaBODIPYs could be





Figure 1. (Top) Chemical structures of parent (aza)BODIPYs, [a]and [b]-fused (aza)BODIPYs, and thiophene substituted benzo-[a]fused azaBODIPYs A. (Bottom) The construction of bisbenzothiophene [b]-fused azaBODIPY in this work.

promising π -architectures for organic optoelectronic application. However, the [b]-ring-fused azaBODIPYs were very limited, because of the synthetic challenges. In this paper, dibenzothiophene [b]-fused azaBODIPYs were successfully developed for the first time, using tetrabrominated azadipyrromethenes. We report the characterizations via X-ray analysis, optical spectroscopy, and density functional theory (DFT)

```
Received: November 19, 2019
```

Organic Letters

calculations, as well as the preliminary investigation of their electronic properties by organic field-effect transistors (OFETs).

Organic conjugated molecular-containing benzothiophene units have wide applications in organic electronics.¹² Recently, the Yoshikai group has successfully synthesized sulfurembedded π -conjugated systems by using 2,2'-diiobiaryls and sulfur powder under the catalysis of CuI.¹³ Inspired by this, the tetrabrominated BF₂-complexed azadipyrromethene 4b has been chosen first to try the reaction with sulfur powder by using CuI as a catalyst in dimethylformamide (DMF). Compound 4b was prepared by direct bromination of compound 4a with bromine (see the Supporting Information for details). This coupling reaction under 130 °C for 24 h indeed realized the desired ring fusion; however, only BF2 removed product of the expected 1a was isolated in a low yield. Thus, tetrabrominated azadipyrromethene 2a was used directly in this coupling reaction, and the desired product 1a was isolated in 77% yield after the BF2 complexation of intermediate 7 (see Scheme 1). Azadipyrromethene 2 was





synthesized in high yields by bromination of azadipyrromethene **3** with 2 equiv of bromine. Compound **1b** containing didodecyloxy groups on the aryl groups at the 1,7-positions was also synthesized by the same method in 80% yield, which showed enhanced solubility in common organic solvents. Compounds **1a** and **1b** were characterized by ¹H NMR, ¹³C NMR, and high-resolution matrix-assisted laser desorption ionization—time of flight mass spectroscopy (MALDI-TOF MS).

The molecular structure of 1a was also determined via single-crystal X-ray diffraction (Figure 2). The C₄S five-



Figure 2. Single-crystal structure of **1a**, with thermal ellipsoids shown at 30% probability: (a) top view, (b) dimer in one unit, and (c) crystal packing structure. The hydrogen atoms in the structure were omitted for clarity.

membered rings were constructed by the formation of the sulfur bridge between the pyrrole and the phenyls at 3,5positions. The C-S bond lengths (1.669–1.737 Å) in 1a are shorter than the typical C–S single bond length (1.82 Å), which probably denotes that the S atoms are conjugated with both the azaBODIPY core and the phenyl rings. The small dihedral angle $(1.5^{\circ}-4.3^{\circ})$ between the two pyrroles and the central six-membered ring indicated that the parent skeleton has only been slightly distorted, which may be affected by the steric and crystal packing factors. After incorporation into the benzothiophene group, the pyrrolic rings still maintain a weak aromaticity with a NICS(0) value of -2.1. The newly formed thiophene rings exhibit a moderate aromaticity with a NICS(0)value of -5.0. The molecular orbitals of 1a are fully delocalized over the entire backbone, similar to those of compound 4c, but their energy levels are completely different (Figure 3). The HOMO and LUMO energy levels of 1a are -5.36 eV and -3.31 eV, which are 0.09 and 0.23 eV lower than those of 4c, respectively. The band gap of compound 1a is 0.14 eV less than that of 4c, mainly due to the remarkably lowered LUMO energy level.

The optical spectra of the target compounds 1a, 1b, and azaBODIPY 4c have been studied in toluene (Figure 4, as well as Table S1 in the Supporting Information). Compound 4c exhibits typical spectral properties of azaBODIPY, with a maximum absorption peak at 657 nm and the corresponding emission maximum at 683 nm ($\phi = 0.25$). After the cyclization, the absorption bands of compounds 1a and 1b undergo significant red shifts to 600–800 nm, with the maximum absorption peaks at 715 and 733 nm for 1a and 1b, respectively. The extinction coeffient values of the ring-fusion compounds 1a and 1b reach 73 300 and 84 700 M⁻¹ cm⁻¹, which are greater than that of 4c (56 300 M⁻¹ cm⁻¹). Similar



Figure 3. DFT-calculated NICS(0) values (in ppm), molecular orbitals and energy diagrams of compound **4c** (left) and **1a** (right). H = HOMO; L = LUMO.



Figure 4. Absorption (Abs) and fluorescence (FL) spectra of compounds 1a, 1b, and 4c in toluene (5 \times 10⁻⁶ M).

red shifts in the fluorescence spectra were also observed. In toluene, **1a** and **1b** showed the maximum emission peaks at 796 and 804 nm, respectively. Similar photophysical properties were obtained in chloroform and THF (see Figures S2–S4 and Table S1 in the Supporting Information). Slight blue shifts of absorption maxima and increased Stokes shifts were found in a polar solvent (THF). Although the fusion increased the rigidity of molecular skeleton, both compounds **1a** and **1b** show low fluorescence ($\phi < 0.01$) in the test solvents. In further study, under irradiation with broadband light (>600 nm), both BODIPYs **1a** and **1b** can efficiently generate singlet oxygen, which was trapped by 1,3-diphenylisobenzofuran (DPBF) (see Figure S5 in the Supporting Information), indicating that their singlet excited states may be transformed to triplet states, to some extent, through intersystem crossing.

Cyclic voltammetry (CV) was used to investigate the electrochemical properties of 1a and the reference compound 4c (Figure S6 in the Supporting Information), which were

measured in CH₂Cl₂ with *n*-Bu₄NPF₆ as the supporting electrolyte and saturated calomel electrode (SCE) as the reference electrode. In comparison with the nonfused azaBODIPY **4c**, the [*b*]-fused **1a** showed a reversible oxidation wave at only a slightly more positive potential (1.22 and 1.26 V vs SCE, respectively). However, the reversible reduction wave exhibited a much less negative potential by 0.20 V (reduction waves are at -0.24 and -0.44 V vs SCE, respectively). The HOMO and LUMO energy levels of **4c** were thus estimated by redox waves to be -5.62 and -3.96 eV, respectively. In contrast, the HOMO and LUMO energy levels of **1a** reduced to -5.66 and -4.15 eV, respectively. The electrochemical band gap of **1a** narrows to 1.51 eV, mainly resulting from the diminution of the LUMO energy level. These results are in

Letter

good agreement with the results from theoretical calculations. The LUMO levels (-4.15 eV for 1a) of these dibenzothiophene[b]-fused azaBODIPYs observed above are even lower than those of many perylene bisimides, which are representative *n*-type semiconducting materials.¹⁴ Furthermore, in the crystal packing structure (Figure 2), the two molecules of 1a are arranged into a reverse face-to-face packing in a unit due to the dipole-dipole interaction. The center and the vertical distances between the two intermolecular faces are 4.40 and 3.75 Å, respectively, indicating that there are strong intermolecular interactions between two molecules. The axes of the two molecules are not parallel, with a dihedral angle (9.5°) of B-N-B'-N'. Therefore, the dipole interaction between these two molecules cannot be canceled in the unit, which will increase the interaction between the units to form a more-ordered arrangement. Each unit is arranged in a "herringbone" packing model with slipped π stacks along the b-axis. Overall, it shows a double glyph pattern. This packing model is rather rare and may have potential applications in organic electronics.15

The semiconducting properties for compound 1b were thus investigated using a field-effect transistor (FET). A top-gate/bottom-contact device architecture (TG/BC) was used to fabricate OFETs. The conducting layer was deposited by spin-coating the toluene solution (4 mg/mL) of 1b onto a patterned Au/SiO₂/Si substrate. After thermal annealing of the film at 140 °C for 5 min, a well-ordered film was obtained with an interlayer distance of ~4.0 nm (see Figure 5, as well as Figures S7 and S8 in the Supporting Information). The perfluorinated CYTOP polymer was used as a dielectric layer by spin-coating, and an aluminum layer was thermally evaporated as the gate electrode.

Interestingly, the OFET devices exhibited bipolar charge transport characteristics when tested under ambient conditions, (Figure 5), which were not found previously for BODIPY- and azaBODIPY-based small molecular semiconductors. The highest electron mobility of 0.012 cm² V⁻¹ s⁻¹ with current on/off ratios of ~10 and threshold voltage (V_T) values of 73 V, and the highest hole mobility of 0.046 cm² V⁻¹ s⁻¹ with current on/off ratios of ~70 and threshold voltages of $V_T = -55$ V were observed. This charge transport property was better than most of the reported BODIPY- or azaBODIPY-derived small molecular semiconductors.⁶⁻⁸ The performance of the devices may be further improved by optimization of the device fabrication.

In summary, we report a novel type of core-expanded azaBODIPY dyes, annulated with five-membered thiophene rings between their 3,5-aryls and 2,6-positions. These dibenzothiophene[b]-fused azaBODIPYs were obtained



Figure 5. (a) AFM images for 1b films prepared from toluene solution. Panel (b) shows the height profile for the red line horizontally traversing the micrograph in panel (a). (c) Transfer characteristics of the thin-film FET device.

through an efficient post-functionalization of tetrabrominated azadipyrromethenes, using CuI-catalyzed cyclization, followed by BF₂ complexation. These resultant π -extended benzothiophene [b]-fused azaBODIPYs with a nearly planar skeleton, show strong, red-shifted absorption in NIR region with maximum absorption peaks up to 733 nm. The ordered molecular packing structure and the remarkably stabilized LUMO energy level of -4.15 eV indicate the potentially good electron transport ability. The field-effect transistor fabricated by solution process using 1b exhibits interesting bipolar transport properties, with the highest electron and hole mobilities up to 0.012 and 0.046 cm² V⁻¹ s⁻¹, respectively. This work here indicate that annulated azaBODIPYs could be highly promising semiconductors, because of their NIR absorption, large planar π -extended structure, deep LUMO level, and good stability. Structural versatility of annulated azaBODIPYs is currently under investigation.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.orglett.9b04142.

Experimental detail, additional spectra, Cartesian coordinates, and the DFT-optimized structure (PDF)

Accession Codes

CCDC 1548795 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

AUTHOR INFORMATION

Corresponding Authors

*E-mail: jiao421@ahnu.edu.cn (L. Jiao).

*E-mail: jieyuwang@pku.edu.cn (J.-Y. Wang). *E-mail: jianpei@pku.edu.cn (J. Pei).

ORCID 💿

Erhong Hao: 0000-0001-7234-4994 Lijuan Jiao: 0000-0002-3895-9642 Jie-Yu Wang: 0000-0002-1903-8928 Jan Pei: 0000-0002-2222-5361

Author Contributions

The manuscript was written through contributions of all authors.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work is supported by the National Nature Science Foundation of China (No. 21672007, 21871006, 21722201, 21790360), and National Key R&D Program of China (No. 2017YFA0204701). The DFT calculations have been done on the supercomputing system in the Supercomputing Center of USTC.

REFERENCES

(a) Ge, Y.; O'Shea, D. F. Chem. Soc. Rev. 2016, 45, 3846.
 (b) Burgess, K.; Loudet, A. Chem. Rev. 2007, 107, 4891.
 (c) Ulrich, G.; Ziessel, R.; Harriman, A. Angew. Chem., Int. Ed. 2008, 47, 1184.
 (d) Lu, H.; Mack, J.; Yang, Y.; Shen, Z. Chem. Soc. Rev. 2014, 43, 4778.
 (e) Boens, N.; Verbelen, B.; Ortiz, M. J.; Jiao, L.; Dehaen, W. Coord. Chem. Rev. 2019, 399, 213024.
 (f) Sawazaki, T.; Shimizu, Y.; Oisaki, K.; Sohma, Y.; Kanai, M. Org. Lett. 2018, 20, 7767.
 (g) Wang, Z.; Cheng, C.; Kang, Z.; Miao, W.; Liu, Q.; Wang, H.; Hao, E. J. Org. Chem. 2019, 84, 2732.

(2) (a) Boens, N.; Leen, V.; Dehaen, W. Chem. Soc. Rev. 2012, 41, 1130. (b) Shi, W.-J.; Lo, P.-C.; Ng, D. K. P. Dyes Pigm. 2018, 154, 314. (c) Zatsikha, Y. V.; Didukh, N. O.; Swedin, R. K.; Yakubovskyi, V. P.; Blesener, T. S.; Healy, A. T.; Herbert, D. E.; Blank, D. A.; Nemykin, V. N.; Kovtun, Y. P. Org. Lett. 2019, 21, 5713. (d) Stacko, P.; Muchova, L.; Vitek, L.; Klan, P. Org. Lett. 2018, 20, 4907. (e) Ramos-Torres, Á.; Avellanal-Zaballa, E.; Prieto-Castañeda, A.; García-Garrido, F.; Bañuelos, J.; Agarrabeitia, A. R.; Ortiz, M. J. Org. Lett. 2019, 21, 4563.

(3) (a) Kowada, T.; Maeda, H.; Kikuchi, K. Chem. Soc. Rev. 2015, 44, 4953. (b) Patalag, L. J.; Ulrichs, J. A.; Jones, P. G.; Werz, D. B. Org. Lett. 2017, 19, 2090. (c) Wu, D.; Daly, H. C.; Grossi, M.; Conroy, E.; Li, B.; Gallagher, W. M.; Elmes, R.; O'Shea, D. F. Chem. Sci. 2019, 10, 6944. (d) Kolemen, S.; Akkaya, E. U. Coord. Chem. Rev. 2018, 354, 121.

(4) (a) Zhao, J.; Xu, K.; Yang, W.; Wang, Z.; Zhong, F. Chem. Soc. Rev. 2015, 44, 8904. (b) Turksoy, A.; Yildiz, D.; Akkaya, E. U. Coord. Chem. Rev. 2019, 379, 47. (c) Kamkaew, A.; Lim, S. H.; Lee, H. B.; Kiew, L. V.; Chung, L. Y.; Burgess, K. Chem. Soc. Rev. 2013, 42, 77. (5) (a) Bessette, A.; Hanan, G. S. Chem. Soc. Rev. 2014, 43, 3342. (b) Chen, J. J.; Conron, S. M.; Erwin, P.; Dimitriou, M.; McAlahney, K.; Thompson, M. E. ACS Appl. Mater. Interfaces 2015, 7, 662. (c) Klfout, H.; Stewart, A.; Elkhalifa, M.; He, H. ACS Appl. Mater. Interfaces 2017, 9, 39873. (d) Kyeong, M.; Lee, J.; Lee, K.; Hong, S. ACS Appl. Mater. Interfaces 2018, 10, 23254.

(6) (a) Popere, B. C.; Della Pelle, A.; Thayumanavan, S. *Macromolecules* 2011, 44, 4767. (b) Usta, H.; Yilmaz, M. D.; Avestro, A.-J.; Boudinet, D.; Denti, M.; Zhao, W.; Stoddart, J. F.; Facchetti, A. *Adv. Mater.* 2013, 25, 4327. (c) Debnath, S.; Singh, S.; Bedi, A.; Krishnamoorthy, K.; Zade, S. S. *J. Phys. Chem. C* 2015, 119, 15859. (d) Singh, S.; Chithiravel, S.; Krishnamoorthy, K. *J. Phys. Chem. C* 2016, 120, 26199. (e) Squeo, B. M.; Gregoriou, V. G.; Han, Y.; Palma-Cando, A.; Allard, S.; Serpetzoglou, E.; Konidakis, I.;

Letter

Organic Letters

Stratakis, E.; Avgeropoulos, A.; Anthopoulos, T. D.; Heeney, M.; Scherf, U.; Chochos, C. L. J. Mater. Chem. C 2018, 6, 4030.

(7) (a) Singh, S.; Venugopalan, V.; Krishnamoorthy, K. Phys. Chem. Chem. Phys. 2014, 16, 13376. (b) Ozdemir, M.; Choi, D.; Kwon, G.; Zorlu, Y.; Cosut, B.; Kim, H.; Facchetti, A.; Kim, C.; Usta, H. ACS Appl. Mater. Interfaces 2016, 8, 14077. (c) Ozdemir, M.; Choi, D.; Zorlu, Y.; Cosut, B.; Kim, H.; Kim, C.; Usta, H. New J. Chem. 2017, 41, 6232. (d) Huaulmé, Q.; Sutter, A.; Fall, S.; Jacquemin, D.; Lévêque, P.; Retailleau, P.; Ulrich, G.; Leclerc, N. J. Mater. Chem. C 2018, 6, 9925.

(8) (a) Ho, D.; Ozdemir, R.; Kim, H.; Earmme, T.; Usta, H.; Kim, C. ChemPlusChem **2018**, 84, 18. (b) Li, F.; Chen, Y.; Ma, C.; Buttner, U.; Leo, K.; Wu, T. Adv. Electron. Mater. **2017**, 3, 1600430.

(9) (a) Jean-Gérard, L.; Vasseur, W.; Scherninski, F.; Andrioletti, B. Chem. Commun. 2018, 54, 12914. (b) Ni, Y.; Wu, J. Org. Biomol. Chem. 2014, 12, 3774. (c) Wang, J.; Wu, Q.; Wang, S.; Yu, C.; Li, J.; Hao, E.; Wei, Y.; Mu, X.; Jiao, L. Org. Lett. 2015, 17, 5360. (d) Zhou, Z.; Zhou, J.; Gai, L.; Yuan, A.; Shen, Z. Chem. Commun. 2017, 53, 6621. (e) Descalzo, A. B.; Xu, H.; Xue, Z.; Hoffmann, K.; Shen, Z.; Weller, M. G.; You, X.; Rurack, K. Org. Lett. 2008, 10, 1581. (f) Hayashi, Y.; Obata, N.; Tamaru, M.; Yamaguchi, S.; Matsuo, Y.; Saeki, A.; Seki, S.; Kureishi, Y.; Saito, S.; Yamaguchi, S.; Shinokubo, H. Org. Lett. 2012, 14, 866. (g) Zhao, N.; Xuan, S.; Zhou, Z.; Fronczek, F. R.; Smith, K. M.; Vicente, M. G. H. J. Org. Chem. 2017, 82, 9744. (h) Miao, W.; Feng, Y.; Wu, Q.; Sheng, W.; Li, M.; Liu, Q.; Hao, E.; Jiao, L. J. Org. Chem. 2019, 84, 9693. (i) Jiang, X.-D.; Liu, X.; Fang, T.; Sun, C.; Xiao, L. Tetrahedron Lett. 2018, 59, 546. (j) Bessette, A.; Auvray, T.; Désilets, D.; Hanan, G. S. Daltton Trans 2016, 45, 7589.

(10) (a) Lu, H.; Shimizu, S.; Mack, J.; Shen, Z.; Kobayashi, N. Chem. - Asian J. 2011, 6, 1026. (b) Liu, H.; Mack, J.; Guo, Q.; Lu, H.; Kobayashi, N.; Shen, Z. Chem. Commun. 2011, 47, 12092. (c) Gresser, R.; Hummert, M.; Hartmann, H.; Leo, K.; Riede, M. Chem. - Eur. J. 2011, 17, 2939. (d) Zheng, W.; Wang, B.; Li, C.; Zhang, J.; Wan, C.; Huang, J.; Liu, J.; Shen, Z.; You, X. Angew. Chem., Int. Ed. 2015, 54, 9070. (e) Sheng, W.; Zheng, Y.-Q.; Wu, Q.; Wu, Y.; Yu, C.; Jiao, L.; Hao, E.; Wang, J.-Y.; Pei, J. Org. Lett. 2017, 19, 2893. (f) Sheng, W.; Cui, J.; Ruan, Z.; Yan, L.; Wu, Q.; Yu, C.; Wei, Y.; Hao, E.; Jiao, L. J. Org. Chem. 2017, 82, 10341. (g) Cui, J.; Sheng, W.; Wu, Q.; Yu, C.; Hao, E.; Bobadova-Parvanova, P.; Storer, M.; Asiri, A. M.; Marwani, H. M.; Jiao, L. Chem. - Asian J. 2017, 12, 2486.

(11) (a) Wakamiya, A.; Murakami, T.; Yamaguchi, S. Chem. Sci.
2013, 4, 1002. (b) Ni, Y.; Zeng, W.; Huang, K.; Wu, J. Chem. Commun. 2013, 49, 1217. (c) Shimogawa, H.; Mori, H.; Wakamiya, A.; Murata, Y. Chem. Lett. 2013, 42, 986.

(12) (a) Gao, J.; Li, R.; Li, L.; Meng, Q.; Jiang, H.; Li, H.; Hu, W. Adv. Mater. 2007, 19, 3008. (b) Takimiya, K.; Shinamura, S.; Osaka, I.; Miyazaki, E. Adv. Mater. 2011, 23, 4347. (c) Chen, L.; Xia, P.; Du, T.; Deng, Y.; Xiao, Y. Org. Lett. 2019, 21, 5529.

(13) Wu, B.; Yoshikai, N. Angew. Chem., Int. Ed. 2015, 54, 8736.

(14) (a) Li, C.; Wonneberger, H. Adv. Mater. 2012, 24, 613.
(b) Zhan, X. W.; Facchetti, A.; Barlow, S.; Marks, T. J.; Ratner, M. A.; Wasielewski, M. R.; Marder, S. R. Adv. Mater. 2011, 23, 268.
(c) Chen, S.; Slattum, P.; Wang, C.; Zang, L. Chem. Rev. 2015, 115, 11967.

(15) (a) Wang, C.; Dong, H.; Hu, W.; Liu, Y.; Zhu, D. Chem. Rev. **2012**, 112, 2208. (b) Dong, H.; Fu, X.; Liu, J.; Wang, Z.; Hu, W. Adv. Mater. **2013**, 25, 6158.