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Novel Donor-Acceptor Polymers based on 7-Perfluorophenyl-6*H*-[1,2,5]thiadiazole[3,4-g]benzoimidazole for Bulk Heterojunction Solar Cells

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Three new fluorinated D–A type conjugated polymers based on a novel building unit 7-perfluorophenyl-6*H*-[1,2,5]thiadiazole[3,4-g]benzoimidazole have been synthesized through Sitlle coupling reaction. The as-prepared polymers exhibit a narrow band gap (from 1.31 to 1.34 eV) and low lying energy levels with the lowest occupied molecular orbital (LUMO) energy levels of -3.95, -3.97 and -4.15 eV, respectively. These polymers exhibit excellent solubility in common organic solvents due to the introduction of perfluorophenyl and long alkyl sidechains. The power conversion efficiency (PCE) of solar cells based on these as-prepared polymers and $PC_{71}BM$ could reach as high as 1.92 %. Our results could provide a simple strategy for designing high performance D-A polymers based on this unit and a potential to further improve their performance.

Introduction

Since the conception of bulk-heterojunction (BHJ) was proposed in 1992, BHJ solar cells have attracted numerous attentions in the past two decades.[1-8] Especially, the power conversion efficiencies (PCEs) of BHJ solar cells based on polymer/fullerene blends are approaching 10% for single-junction cells, which can be attributed to the rapid progress of novel donor-acceptor (D-A) polymers.[9-19] The most charming feature of D-A polymers for BHJ solar cells is the high flexibility in tuning the absorption and frontier molecular orbital energy levels of the objective D-A polymers. Generally, the highest occupied molecular orbital (HOMO) and the lowest occupied molecular orbital (LUMO) energy levels of D-A polymers can be estimated via the HOMO level of the "donor" (D) structural unit and the LUMO level of the "acceptor" (A) unit, respectively. This important feature enables scientists to design and synthesize new polymers with a suitable LUMO level through using specialized acceptors and in coupling with a low bandgap to obtain a high open circuit voltage (V_{oc}) and a high short circuit current (J_{sc}), simultaneously.[17-20] Besides that the aromatic units in D-A polymers can largely determine the photovoltaic performance of the BHJ solar cells, other structural parameters including the peripheral side chains and functional substituents can also have strong influence.[12-24] Under these empirical rules, elaborate design of donors and acceptors can help maintain the upward trend of the device efficiency towards the predicted PCE of 15% for BHJ polymer solar cells.[17,25,26]

Fused aromatics, typically via the annulation of different small aromatic units (e.g., benzene, thiophene, pyrrole, pyridine, etc.), are the most frequently used structural units as donors or acceptors in the D-A polymers for organic electronics.[16-18,25,27,28] Among the reported fused aromatics, D-A polymers based on 2,1,3-benzothiadiazole (BT) have been found with a PCE as high as 10%.[11,13-18, 29-32] Although BT is a strong electron-withdrawing unit, it is still not strong enough to pull LUMO level down to ~ -4.0 eV in D-A polymer, which could have a broad bandgap, an inferior absorption spectrum, and a lower PCE of the resulted solar cells. Therefore, introducing more electron-withdrawing groups into BT units is highly desirable to further increase the PCE of solar cells. Most of recently-reported BT derivatives are summarized in **Chart 1**. Generally, incorporating strong electron-withdrawing units onto BT unit is the most popular strategy. For example, quinoxaline unit has been employed as an electron-withdrawing block to form BT-M1 (Chart 1) through[32-35] a simple synthesis; however, the PCE did not show too much enhancement. Then fluorine atoms were introduced into BT systems as strong electron-withdrawing groups to improve the interaction between polymers:PCBM and electrodes, and the resulted BT-M2 and BT-M3 have become the mostly used units to improve the PCE.[21-24] In order to further increase the electron-withdrawing ability of BT unit, another strategy is to fuse two conjugated five-member-ring heterocycles onto one building unit to generate a novel exceptionally strong acceptor, which can be further employed as construction

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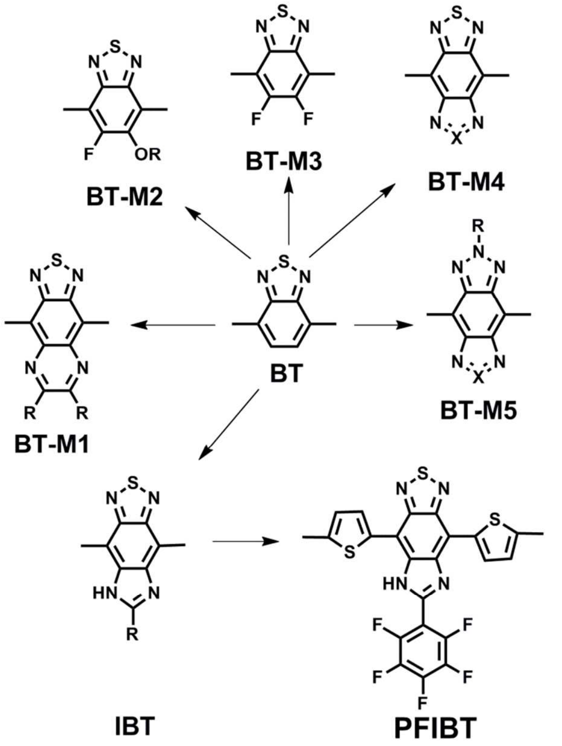
blocks to form low band gap polymers. For example, D-A polymers based on BT-M4 (X = S or Se) show longer wavelength absorptions and deeply LUMO energy levels, and the enhancing PCE.[36-38] If M5 was used, conjugated polymers with BT-M5 have been demonstrated to show good PCE values.[39-41] However, the synthetic procedures of all the above-mentioned monomers are very long and tedious. Therefore, it is urgent to explore other novel strong acceptors, which could be incorporated into BT unit to enhance the PCE of solar cells.

Chart 1. The chemical structures of 2,1,3-benzothiadiazole (BT) and its derivates (X= S or Se)



Herein, we report novel D-A polymers based on 5*H*-imidazo[4,5-f]-2,1,3-benzothiadiazole (IBT) as an acceptor unit, where the imidazole unit is employed to improve the electron affinity. Obviously, IBT unit is a stronger acceptor than BT unit. Moreover, the *N-H···F* intramolecular interactions in the monomer of PFIBT can hinder the rotation of the adjacent thiophene ring and increase the coplanarity and conjugated region in the D-A copolymers, and these interactions can also lower the aromaticity of π-systems to give better charge transport and higher PCEs. Furthermore, another strong electron-withdrawing unit pentafluorophenyl is introduced into benzimidazole unit to further increase the electron affinity and produce a larger conjugated backbone than that of BT unit. The introduction of fluorine atoms is generally believed to improve the solubility and the adhesion to electrodes, and then lower the energy barrier between active layer and electrodes. In addition, the using of fluorine atoms in D-A polymers can also obtain high fill factor (FF), large short-circuit current density (J_{sc}) and high open-circuit voltage (V_{oc}).[21-24] In this paper, we designed and synthesized a novel monomers including 7-Perfluorophenyl-6*H*-[1,2,5]thiadiazole[3,4-g]benzoimidazole **(PFIBT)** units. Three new D-A polymers based on **PFIBT** show good solubility, excellent absorption spectra in the range of 300-800 nm, and deeply LUMO energy levels. In addition, the BHJ solar cells with these polymers as donors have been fabricated and the performance of the as-prepared devices were carefully investigated.

Experimental section

Materials and methods

Compound **1** and **M2**-**M4** (Scheme 1) were prepared according to the reported procedures.[12,42-47] All starting chemicals, unless otherwise specified, were purchased from Alfa Aesar or Sigma-Aldrich and used as received. [6,6]-Phenyl-C_{71}-butyric acid methyl ester ($PC_{71}BM$, >99%, EL device grade) was purchased from Solenne. All solvents were purified by normal procedure before use.

^{1}H Nuclear Magnetic Resonance (^{1}H NMR) spectra were measured at 300 MHz on a Bruker 300 AVANCE III spectrometer with chloroform ($CDCl_3$), *N*,*N*-Dimethylmethanamide (DMF-d_7) or dimethyl sulfoxide (DMSO-d_6) as solvents. UV-Vis absorption spectra were recorded on a Shimadzu 2501 PC spectrophotometer at room temperature. Thermogravimetric analysis (TGA) was performed on a TA Instrument Q500 instrument under a nitrogen atmosphere with a gas-flow rate of 50 mL/min and a heating rate of 10 ℃/min. Gel permeation chromatography (GPC) traces of the samples were monitored on an Agilent 1260 GPC-MDS system fitted with differential refractive index (DRI) and Ultraviolet (UV) detectors using THF as the eluent and linear polystyrenes as the molecular weight standards. Cyclic voltammetry (CV) measurements were carried out with a CHI 604E Electrochemical Workstation (CH Instruments, Shanghai Chenhua Instrument Corporation, China) under an argon atmosphere. The polymer film coated on a Pt plate (working electrode) was scanned at 10 mV/s in an anhydrous dichloromethane solution of tetrabutylammonium hexafluorophosphate (n-Bu_4NPF_6, 0.1 M), with a Pt wire and platinum gauze as the reference and counter electrodes, respectively. The thickness of the polymer film was measured by a KLA Tencor Alpha-Step Surface Profiler.

Fabrication and characterization of polymer BHJs

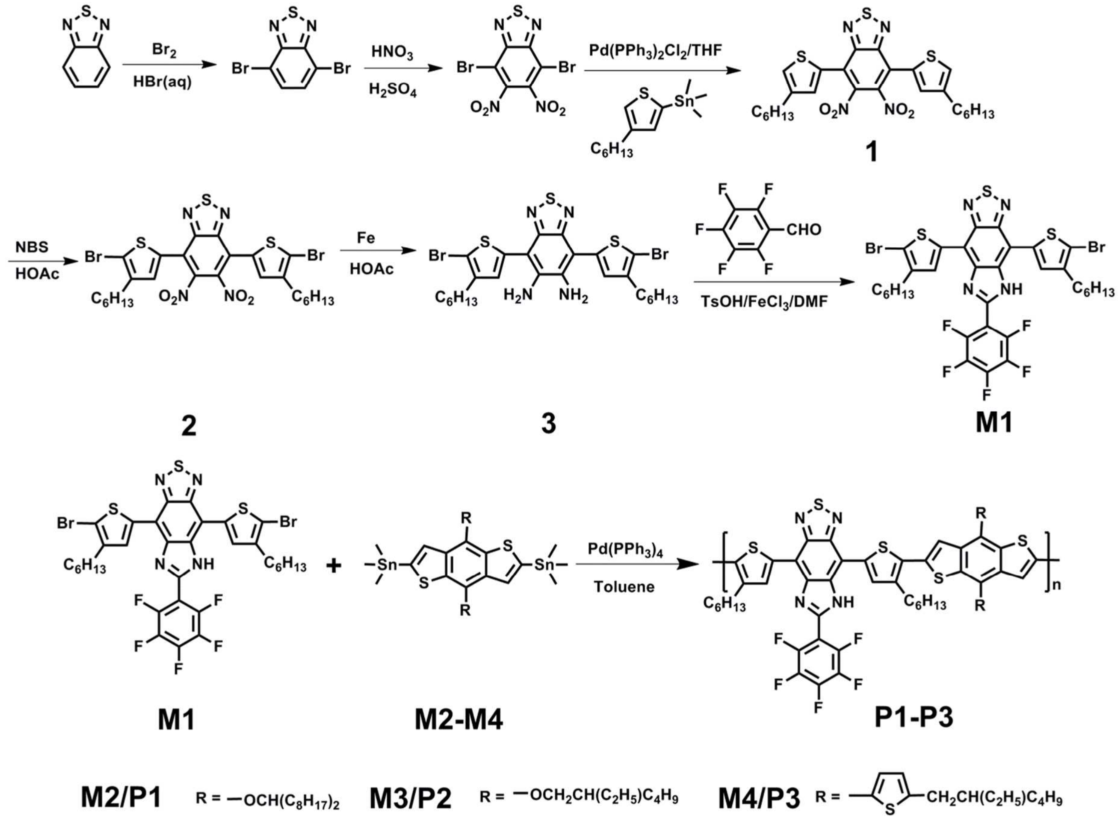
The devices were fabricated with a structure of glass/ITO/PEDOT:PSS/donor:acceptor/PFN/Al. The indium tin oxide coated glass substrates were cleaned sequentially with detergent, DI water, acetone, and isopropyl alcohol and then dried by a nitrogen flow. Before use, the substrate was treated with oxygen plasma. A thin layer of poly(3,4-ethylenedioxthiophene):poly(styrene sulfonate) (PEDOT:PSS) (Baytron P VP AI 4083, filtered at 0.45 μm) was spin-coated (3000 rpm, ca. 40 nm thick) onto ITO surface. After being baked at 150 °C for 20 min, the substrates were transferred into an argon-filled glove box. The active layers were prepared by dissolving polymers and $PC_{71}BM$ at weight ratios of 1:1 (w/w) with a total concentration (20 mg mL^{-1}) in chlorobenzene, and then an active layer was deposited by spin-coating from the solution at a speed of 1500 rpm onto the ITO/ PETDOT:PSS substrates for 40 s. The thickness of each active layer was ~90-100 nm. Finally, a thin layer of PFN were spin-casted on top of active layers and then Al (80 nm) was evaporated to form the top electrode. The effective area of each cell was 4 mm^2 defined by shallow masks. The current density-voltage (*J-V*) curves of photovoltaic devices were obtained by a Keithley 2400 source-measure unit. The devices were measured under AM 1.5 radiation (100 mW cm^{-2}) using an Oriel 96000 solar simulator. The spectral mismatch factor was calculated by comparison of the solar simulator spectrum and the AM 1.5 spectrum at room temperature. External quantum efficiency (EQE) values of the encapsulated devices were measured using a lock-in amplifier (SR810, Stanford Research Systems). The devices were illuminated by monochromatic light from a 150 W xenon lamp passing through an optical chopper and a monochromatic. Photon flux was determined by a calibrated standard silicon photodiode.

Synthesis

*4,7-Bis(5-bromo-4-hexylthiophen-2-yl)-5,6-dinitro-benzo[1,2,5]thiadiazole (**2**)*. Compound **1** (1.12 g, 2 mmol), was dissolved in 30 mL DMF. The resulted solution was heated to 60 °C , and *N*-bromosuccinimide (1.60 g, 9 mmol) was added to the solution in one portion. The mixture was kept at 60 °C for about 12 h until TLC analysis showed no starting material. Then, the mixture cooled to room temperature and was acidified with 2 M HCl solution (300 mL). The as-obtained solution was extracted with ethyl ether for three times. The organic layers were combined and dried Na_2SO_4, and then all solvents were evaporated. The as-resulted mixture was treated with 30 mL hexane and frozen at -15 °C for two days. Orange red crystals were collected, washed with methanol, and dried under a vacuum in a yield of 90% (1.29 g). ^1H NMR (300 MHz, $CDCl_3$): δ (ppm) d 7.17 (s, 2H), 2.62 (t, 4H, J = 7.2 Hz), 1.65-1.55 (m, 4H), 1.37-1.25 (m, 12H), 0.90 (t, 6H, J = 6.9 Hz). ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm), 151.76, 143.42, 138.29, 131.63, 129.09, 120.37, 116.88, 31.56, 29.47, 29.43, 28.75, 22.57, 14.06.

*4,7-Bis(5-bromo-4-hexylthiophen-2-yl)-benzo[1,2,5]thiadiazole-5,6-diamine (**3**)*. Fine iron powder (0.56 g) was added to a stirred solution of 4,7-Bis-(5-bromo-4-hexylthiophen-2-yl)-5,6-dinitro-benzo[1,2,5]thiadiazole (0.72 g, 1 mmol) in acetic acid (25 mL). The mixture was heated to 80 ◦C, stirred for 4 h and then cooled to room temperature. The cooled reaction mixture was poured carefully into 2 N NaOH aqueous solution at 0 °C. The aqueous solution was extracted with diethyl ether three times (3× 50 mL). The combined organic solution was washed with brine, dried over anhydrous Na_2SO_4 and then evaporated to give a dark brown shiny stuff. Hexane (20 mL) was added into this shiny stuff and kept to refrigerator two days. A reddish powder was obtained after dried under

Scheme 1. The synthesis of monomer and polymers



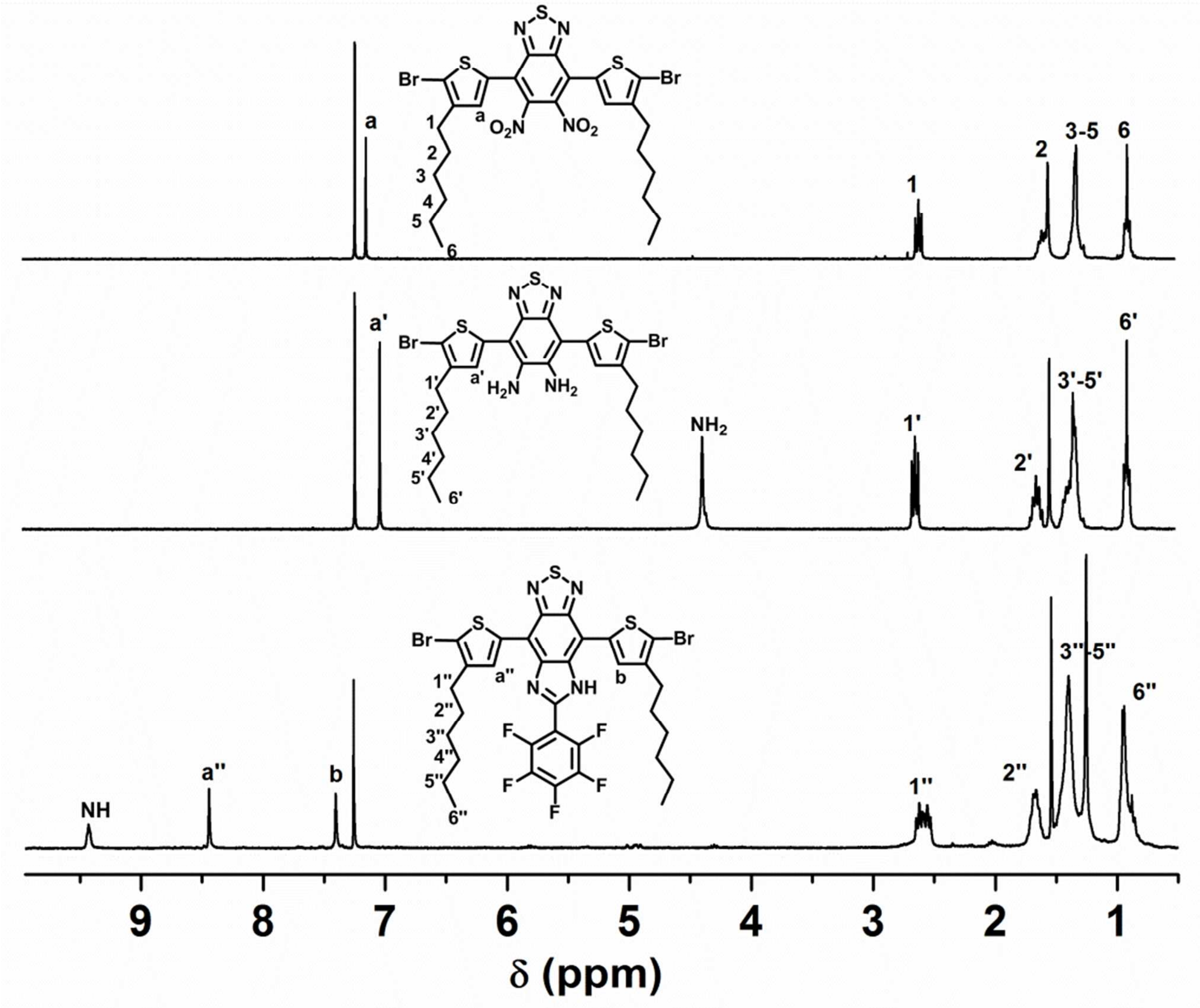


Figure 1. The ^{1}H NMR of compound **2** (top), **3** (middle) and **M1** (bottom) in CDCl$_3$.

vacuum to afford compound 3 (0.59 g, 90 %). ^{1}H NMR (300 MHz, CDCl$_3$): δ (ppm) 7.05 (s, 2H), 4.40 (s, 4H), 2.64 (t, 4H, j = 7.5 Hz), 1.70-1.60 (m, 4H), 1.42-1.25 (m, 12H), 0.90 (t, J = 6.9 Hz). ^{13}C NMR (75 MHz, CDCl$_3$): δ (ppm), 150.44, 142.38, 139.24, 134.79, 129.59, 110.83, 106.87, 31.62, 29.71, 29.69, 29.03, 22.60, 14.09.

*4,10-Bis(5-bromo-4-hexylthiophene-2-yl)-7-(2,3,4,5,6-pentafluorophenyl)-6H-[1,2,5]thiadiazole[3,4-g]benzoimidazole (**M1**)*. 2,3,4,5,6-Pentafluorobenzaldehyde (196 mg, 1 mmol) and compound **3** (410 mg, 0.63 mmol) were thoroughly mixed in DMF (10 mL), and *p*-methylbenzenesulfonic acid (100 mg) was added to the solution, and the mixture was stirred overnight. Then $FeCl_3·6H_2O$ (500 mg) was added in to the solution, and this mixture was heated to 80 °C for 3h. After the solution cooled to room temperature, the reaction mixture was poured into water and extracted with EtOAc (3 ×50 mL), and then washed with brine (3 ×50 mL). After dried by $MgSO_4$, the organic solvent was evaporated under reduced pressure. The crude product was purified by column chromatography (eluent: DCM/hexane = 1:3) to yield **M1** as a purple solid (0.45 g, 85 %). ^{1}H NMR (300 MHz, CDCl$_3$): δ (ppm) 9.43 (s, 1H), 8.44 (s, 1H), 7.41 (s, 1H), 2.65-2.53 (m, 4H), 1.71-1.64 (m, 4H), 1.40-1.26 (m, 12H), 0.95-0.89 (m, 6H). ^{19}F NMR (282 MHz, CDCl$_3$): δ (ppm) -137.25 (d, 2F, J = 19.46 Hz), -148.10 (t, 1F, J = 21.7 Hz), -159.35 (dd, 2F, J = 21.1 Hz, 20.8 Hz).

General procedure of copolymerization by Stille coupling.

The equimolecular amount of **M1** and **M2**-**M4**, and $Pd(PPh_3)_4$ (~1.6 mol%) were dissolved in anhydrous toluene under argon. Argon was bubbled through the solution for 30 min and then the mixture was vigorously stirred at 110 °C under an argon atmosphere for 48 hours. After cooling to room temperature, the mixture was poured into methanol. After washed with methanol, oligomers and catalyst residues were removed by hexane through a Soxhlet apparatus for 24 hours. Then, the product was extracted, by tetrahydrofuran

(THF) for another 24 hours. The THF extract was concentrated and the product was precipitated by methanol, and collected by filtration and dried in vacuum overnight.

P1: **M1** (208.2 mg, 0.25 mmol), **M2** (256.2 mg, 0.25 mmol), $Pd(PPh_3)_4$ (4.5 mg), toluene (3 mL). Black powder, 200 mg, yield 58%. ^1H NMR (300 MHz, $CDCl_3$): δ (ppm): 10.38 (s), 9.08 (s), 8.10-8.01 (m), 7.66-7.60 (m), 7.47 (d), 6.90 (s), 3.07 (s), 2.80-2.75 (m), 2.17 (s), 1.86-1.74 (m), 1.25 (br), 0.91-0.82 (m).

P2: **M1** (208.2 mg, 0.25 mmol), **M3** (193.0 mg, 0.25 mmol), $Pd(PPh_3)_4$ (4.4 mg), toluene (3 mL). Black powder, 208 mg, yield 67%. ^1H NMR (300 MHz, $CDCl_3$): δ (ppm): 10.27 (s), 9.06 (s), 8.12-8.03 (m), 7.68-7.60 (m), 7.43 (d), 6.90 (s), 3.03 (s), 2.80-2.71 (m), 2.16 (s), 1.89-1.72 (m), 1.25 (br), 0.91-0.88 (m).

P3: **M1** (208.2 mg, 0.25 mmol), **M4** (226.1 mg, 0.25 mmol), $Pd(PPh_3)_4$ (4.7 mg), toluene (3 mL). Black powder, 210 mg, yield 66.4%. ^1H NMR (300 MHz, $CDCl_3$): δ (ppm): 10.28 (s), 9.01-8.83 (m), 8.06-7.14 (m), 6.94 (d), 3.79 (t), 2.92-2.59 (m), 1.86-1.27 (m), 0.94 (t)

Table 1. Molecular weights and thermal properties of P1-P3

	M_n/kDa	M_w/kDa	PDI	$T_{d10\%}$/°C
P1	14.1	24.8	1.76	309
P2	14.3	23.4	1.64	360
P3	16.5	30.3	1.85	461

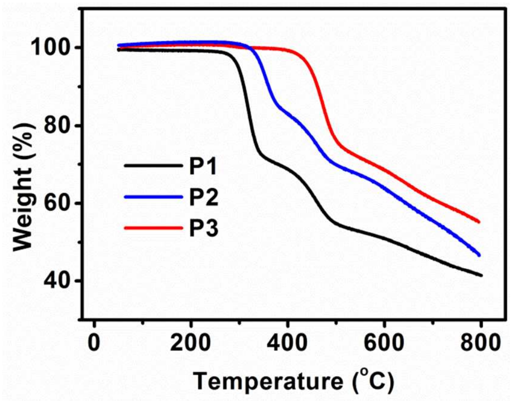


Figure 2. TGA curves of P1-P3 under argon atmosphere at a heating rate of 10 °C min^{-1}.

Results and discussion

Synthesis of monomers and polymers

Scheme 1 shows the synthetic routes that were used to prepare the monomer **M1** and the polymers **P1**-**P3**. Compound **1** was synthesized according to literature.[6,36-38] After treated with NBS, compound **1** was converted into 4,7-Bis(5-bromo-4-hexylthiophen-2-yl)-5,6-dinitro-benzo[1,2,5]thiadiazole (**2**), which was further reduced by iron to form 4,7-Bis(5-bromo-4-hexylthiophen-2-yl)-benzo[1,2,5]thiadiazole-5,6-diamine (**3**). Subsequently, **M1** was prepared through the condensation reaction between **3** and 2,3,4,5,6-pentafluorobenzaldehyde using methylbenzenesulfonic acid and $FeCl_3·6H_2O$ as catalysts and air as an oxidation reagent. **Figure 1** shows the ^1H NMR spectra of compound **2**, **3** and **M1**. The protons on the thiophene group in compound **1** show a single peak with a chemical shift of 7.17 ppm, while the corresponding peak in compound **2** shows a little shift (0.12 ppm) to high field. The peak of amino groups in compound **2** shows a broad peak at 4.40 ppm. Because of the asymmetry from the benzimidazole group in **M1**, two different peaks of the protons on the thiophene are observed at 7.40 and 8.44 ppm; and the proton of benzimidazole ring is observed at 9.43. In addition, the chemical structure of **M1** can also be confirmed by ^{19}F NMR with three group peaks at -137.25, -148.10 and -159.35 ppm. D-A polymers **P1**-**P3** were synthesized through Stille coupling polymerization between **M1** and **M2**-**M4**. The chemical structures of all as-obtained polymers can be confirmed by ^1H NMR spectroscopy. **Table 1** lists molecular weights and thermal decomposition temperature of **P1**-**P3**. The molecular weight and polydispersity index (PDI) were characterized by GPC with calibration against polystyrene standards and THF as an eluant. The number average molecular weights (M_n) of **P1**-**P3** were found to be 14.1, 14.3 and 16.5 kDa, with PDIs of 1.76, 1.64 and 1.85, respectively. The polymers show good thermal stability (See **Figure 2**), as evidenced by its 10% weight-loss temperature ($T_{d10\%}$). **P1**-**P3** show good solubility in common organic solvents such as THF, chloroform and DMF.

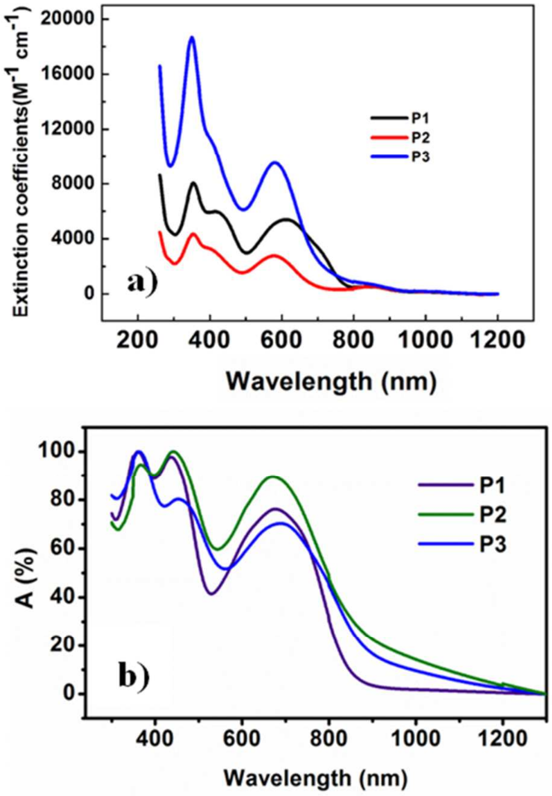


Figure 3. UV-Vis spectra of 6F-BAHP-PC PI in THF solution **(a)** and films (**b**).

Table 2. Optical and Electrochemical Properties of Polymers P1-P3

	λ_{max} (nm) solution	λ_{max} (nm) film	E_g^{opt} (eV)[a]	E_{onset}^{Ox} (V)	E_{onset}^{Red} (V)	HOMO (eV)	LUMO (eV)	E_g^{ec} (eV)[b]
P1	352, 615	360, 437, 671	932	1.21	-0.51	-5.69	-3.97	1.33
P2	352, 576	366, 441, 677	942	1.04	-0.29	-5.52	-4.19	1.31
P3	352, 580	363, 454, 689	925	1.24	-0.53	-5.72	-3.95	1.34

[a] Calculated from the edge of the absorption spectrum of the film. [b] E_g^{ec} = HOMO – LUMO.

Optical and electrochemical properties

The absorption spectra of all polymers in dilute THF solution (1×10^{-5} M of each repeat unit) and as solid films on glass are shown in **Figure 3**, and the data are summarized in **Table 2**. Two main absorption bands at 300-490 nm and 510-800 nm are observed in THF solution of **P1**-**P3**. The bands in the range of 300-490 nm can be attributed to the π-π* transition delocalized along the π-electronic system, whereas the bands in the range of 510-800 nm can be attributed to the strong charge transfer between **IBT** acceptors and **BDT** donors. Generally, the THF solutions of **P1**-**P3** have strong absorptions in the whole range of 300-800 nm, even at the gap of ~500 nm. Compared with the absorption in solution, the absorption peaks of **P1**-**P3** thin films are red-shifted, especially the bands from the charge transfer between donors and acceptors shifted from ~600 nm to ~680 nm, suggesting stronger intermolecular interactions and aggregation in solid states than those in solution. In addition, the polymer films show no obvious absorption edge to ~1300 nm. The optical band gaps of **P1**-**P3**, calculated form the absorption edge in THF solution, are 1.31-1.34 eV. The polymer films show exceptional absorption in the range of 300-900 nm, indicating that the polymers may be good candidates for solar cell applications.

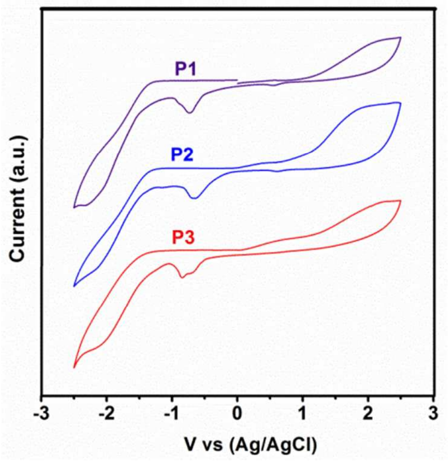


Figure 4. Cyclic voltammograms of P1-P3 films coated on ITO glasses**.**

Electrochemical Properties

Cyclic voltammetry (CV) was used to investigate the redox behaviour of all polymers and to estimate their HOMO and LUMO energy levels. The CV curves of **P1**-**P3** in dichloromethane using a 0.1 M solution of tetrabutylammonium tetrafluoroborate (TBATFB) at 10 mV·s^{-1} are shown in **Figure 4**, and the CV data are summarized in **Table 2**. All the polymers show obvious reduction peaks at -0.74, -0.66 and -0.84 V for **P1**-**P3**, respectively, which are resulted from the strong electron-withdrawing acceptor of **IBT** unit. And the corresponding reduction onsets were located at -0.51, -0.29 and -0.53 V, respectively. Polymers **P1**-**P3** show gradual oxidation peaks and the responding oxidation onsets were observed at 1.21, 1.04 and 1.24 V, respectively. The HOMO and LUMO levels of **P1**-**P3** can be calculated from the oxidation and reduction onset according to the energy level of the ferrocene reference (-4.8 eV versus vacuum level). The deep HOMO levels of these polymers suggest that they can transport holes. These results suggest that these polymers have great potential for the application in solar cells.

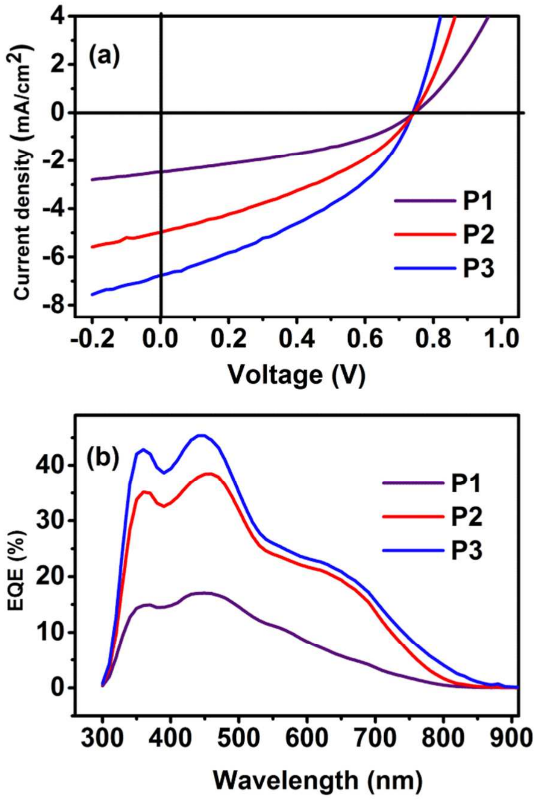


Figure 5. (a) Current density-voltage characteristics of illuminated (AM 1.5G, 100 mW cm^{-2}) polymer solar cells incorporating active layers of polymers/PC71BM; (b) Spectra of EQE spectra of active layers based on polymers/PCBM.

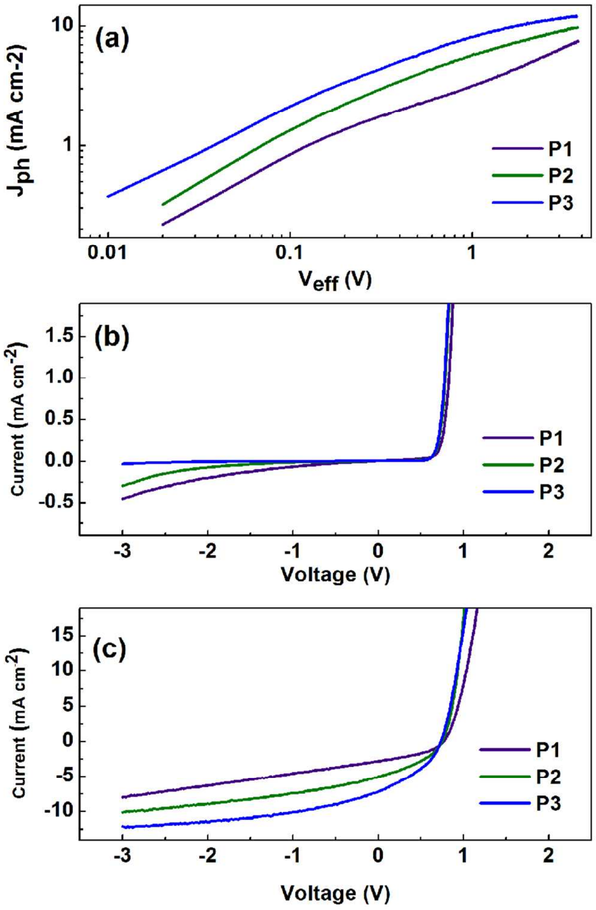


Figure 6. a) Photocurrent density versus effective voltage (J_{ph}-V_{eff}) characteristics for both devices under constant incident light intensity (AM 1.5G, 100 mW cm−2). Dark b) and light c) *J-V* to -3V

Photovoltaic Properties

BHJ photovoltaic devices with **P1**-**P3** as donor materials and $PC_{71}BM$ as an acceptor material have been fabricated with a typical configuration of ITO/PEDOT:PSS/polymers:$PC_{71}BM$/PFN/Al. The weight ratio of polymers vs. $PCBM_{71}$ (1:1) with a total concentration of 20 mg mL^{-1} in chlorobenzene solution was employed to fabricate the devices, and the thickness of the BHJ blend was about ~90 nm. As expected, relatively high V_{oc} in the range of 0.74-0.76 V were observed in all the three polymer:PCBM based BHJ solar cells, consistent with the low-lying HOMO energy levels of **P1**-**P3**. The J_{sc} values for P1-P3 are 2.52, 4.97 and 6.76 mA·cm^{-2}, respectively. The corresponding PCEs of devices based on **P1**-**P3** are 0.82%, 1.35% and 1.92%, respectively. The external quantum efficiency (EQE) spectra of the devices with **P1-P3** are shown in **Figure 5b**. From the EQE spectra, these polymers-based devices exhibit very broad photo-to-current response from 300 to about 900 nm with the highest EQE values of 17%, 38% and 45%, respectively. For the **P1**-, **P2**- and **P3**-based devices, the calculated J_{sc} obtained by the integration of the EQE curves are 2.38, 4.88 and 6.67 mA·cm^{-2}, which show less 5% mismatch compared with the J_{sc} value obtained from the *J-V* curves.

The relationship of photocurrent density (J_{ph}) versus effective voltage (V_{eff}) is employed to investigate the causes of the low device performance of our devices. As shown in Figure 6a, for P1-P3 based devices, the J_{ph} shows a strong field dependence in a large bias and has not saturated even at V_{eff} = 3.8 V. This suggests the devices based on the polymers have low excition dissociation efficiency and low charge transport and collection efficiency with significant geminate and/or bimolecular recombination and/or less efficient interfacial contact, thus low FF and J_{sc}, which is attributed the poor morphology of the photoactive layers, as discussed below. The device based on P3 show more possible tendency to be saturated than that based on P2 and P1. Furthermore, light and dark current (Figure 6b and6c) are measured to confirm the origin of the poor device performance. As shown in Figure 6c, the light current cannot be saturated even at -3V, which suggests the collection of electrons and holes is not effective and the recombination is significant. Combining these measurements and AFM morphology study, we can conclude that the poor morphology leads generation problem and then low PCE.

Table 2. PSC characteristics of the polymers: PCBM BHJ PSCs

Polymers	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	PCE (%)
P1	0.74	2.52	36.0	0.82
P2	0.75	4.97	36.5	1.35
P3	0.76	6.76	38.6	1.92

Morphology study

The morphology of blend films of the polymers with fullerene derivatives plays a vital part on the charge transfer and the efficiency of bulk heterojunction solar cells. Herein, the atomic force microscopy (AFM) was applied to investigate the morphology of the polymer:$PC_{71}BM$ blend films, as shown in Figure 7. The scan size is 5 μm × 5 μm. The root-mean-square (rms) roughness values are 6.64, 0.961 and 0.532 nm for the blend films of **P1**-**P3** with PC71BM, respectively, which suggests that the contact between the active layer and the cathode becomes better from **P1** to **P3**. The blend films of P1-P3 exhibit large phase separation and poor interpenetrating network, which is unfavourable for exciton diffusion/dissociation and charge transport. Moreover, compared with those of **P1** and **P2**, the blend film of **P3** exhibits better interpenetrating networks. As a result, the J_{sc} also becomes larger from **P1** to **P3**. Tuning morphology of active blend films is complex and needs further work focus on it in the future.

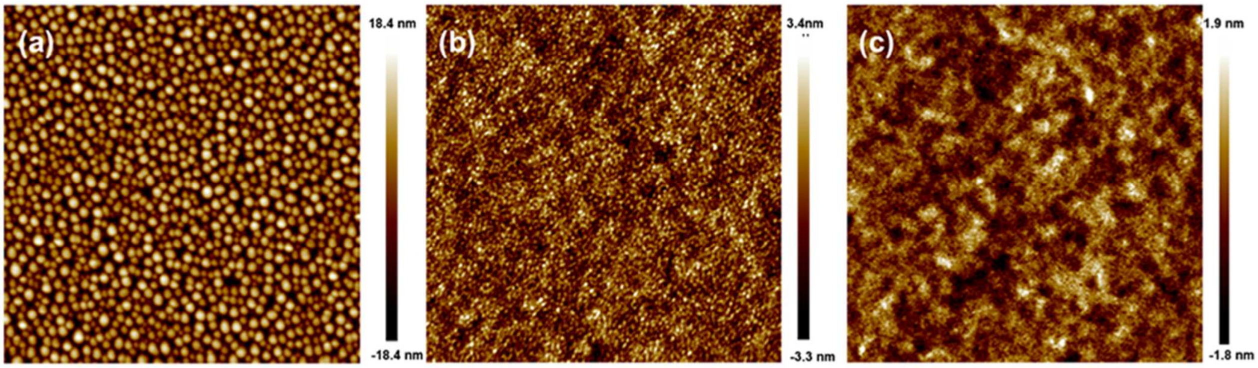


Figure 7. AFM height images of polymers:PC$_{71}$BM, a) P1, b) P2 and c) P3. The areas are 5 μm × 5 μm

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Novel Donor-Acceptor Polymers based on 7-Perfluorophenyl-6*H*-[1,2,5]thiadiazole[3,4-g]benzoimidazole for Bulk Heterojunction Solar Cells

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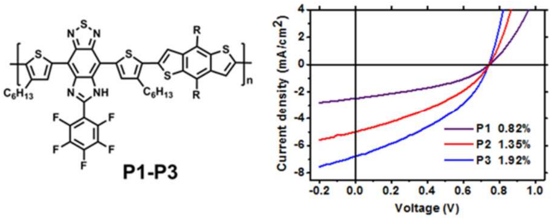

Three polymers with 7-Perfluorophenyl-6*H*-[1,2,5]thiadiazole[3,4-g]benzoimidazole as a building unit were synthesized for BHJ solar cells, and a PCE of 1.92% was obtained.