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An Alkylthieno-2-yl Flanked Dithieno[2,3-d:2′,3′-d′]benzo[1,2-b:4,5-b′]dithiophene-based Low Band Gap Conjugated Polymer for High Performance Photovoltaic Solar Cells

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A low band gap conjugated polymer derived from alkylthieno-2-yl flanked dithieno[2,3-d:2′,3′-d′]benzo[1,2-b:4,5-b′]dithiophene and naphtho[1,2-c:5,6-c′]bis[1,2,5]thiadiazole derivative was firstly synthesized, and high performance inverted photovoltaic solar cells with power conversion efficiency of 7.52% has been demonstrated.

Introduction

Bulk heterojunction polymer photovoltaic solar cells (PVCs) have been attracted steadily attention due to the potential application for large area, flexible, and low-cost solar cells in the last decades. Tremendous efforts such as the development of novel low band gap (LBG) CPs, the optimization of the fabricating process and modifying the morphology of the donor and acceptor blend, etc., have been devoted to improve the power conversion efficiencies (PCEs) of PVCs. The development of high performance donor-acceptor (D-A) type LBG CPs has been demonstrated to be the most vigorous approach to achieve the efficient PVCs, and many promising D-A type LBG CPs have been developed in the last decades. Among them, the most attracting sample is benzo[1,2-b:4,5-b′]dithiophene (BDT)-based CPs. Many promising D-A type BDT-based LBG CPs have been demonstrated, and the PCEs of 5.63 – 9.3% have been achieved in the PVCs from the polymers in the last years.

As a notable aromatic analogue of BDT, dithieno[2,3-d:2′,3′-d′]benzo[1,2-b:4,5-b′]dithiophene (DTBDT) not only shows similar HOMO level with BDT, but also holds larger coplanar core and extended conjugation length. It was believed to provide advantageous properties for DTBDT-based CPs such as enhanced charge-carrier mobility, decreased band gaps and facilitated exciton separation into free charge carriers in contrast to BDT-based CPs. Motivated by the attractive properties of DTBDTs-based CPs, many high performance DTBDTs-based CPs have been presented since Hou et al. firstly introduced the 5,10-di(2-hexyldecyloxy)-DTBDT to build the D-A type LBG CPs in 2012. For instance, Yu et al. presented a series of LBG CPs based on 5,10-dialkyl-DTBDT and alkyl 3-fluorothieno[3,4-b]thiophene-2-carboxylate in 2013. Lately, Hou et al. presented CPs derived from 5,10-di(alkylthieno-2-yl)-DTBDT and 2-(2-hexyldeyl) sulfonylthieno[3,4-b]thiophene, and Kwon et al. presented CPs derived from 5,10-di(alkylthieno-2-yl)-DTBDT and benzo-2,1,3-thiadiazole. More recently, we have provided an effective approach to tune the optoelectronic properties of DTBDTs-based CPs via the changing of substituent groups on the DTBDT, and series of D-A type LBG CPs derived from DTBDTs and 3,6-bis(thieno-2-yl)-N,N′-dialkyl-1,4-dioxopyrrolo[3,4-c]pyrrole. In spite that PVCs from the D-A type LBG CPs derived from DTBDTs as electron donor units, have shown reasonably high PCEs of 3.5-7.6% to date, the tailoring and enriching the family of the DTBDTs-based D-A type LBG CPs are still promising in the development of new ideal DTBDTs-based CPs for high performance PVCs.

In this paper, a low band gap conjugated polymer with 5,10-bis(4,5-dicyclithieno-2-yl)-flanked-DTBDT as electron donor moieties and 4,9-bis(4-hexylthieno-2-yl)naphtho[1,2-c:5,6-c′]bis[1,2,5]thiadiazole (DTNT) as electron acceptor moieties was synthesized through the palladium-catalyzed Stille coupling reaction under mono-microwave heating condition, and named as PDTBDT-DTNT. The PDTBDT-DTNT exhibited good solution processability and extensive absorption from 300 nm to 800nm. The highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) energy levels of the PDTBDT-DTNT determined by cyclic voltametry (CV) were about -5.51 eV and -3.90 eV, respectively. The photovoltaic property of PDTBDT-DTNT was also investigated, and the PCEs of 6.28% and 7.52% has been achieved in the traditional (with device configuration as:ITO/PEDOT:PSS/active layer/MoO3/Ag) and inverted (with device configuration as:ITO/poly[(9,9-bis(30-N,N-dimethylamino)propyl)-2,7-fluorene]-alt-2,7-(9,9-dioctylfluorene)]/active layer/MoO3/Ag) PVCs from the blend of PDTBDT-DTNT and [6,6]-phenyl-C61-butyric acid methyl ester (PC71BM) with weight ratio of 1:1 under AM 1.5 simulator (100 mW/cm²), respectively.

Results and Discussion

Synthesis and Characterization of the PDTBDT-DTNT

The general synthetic route toward polymer is outlined in Scheme 1. The target polymer was synthesized by a polymerization process involving the reaction of DTBDT and DTNT under microwave irradiation. The polymerization was carried out in a microwave reactor under mono-microwave heating condition. After the polymerization was completed, the reaction mixture was precipitated into dichloromethane and filtered. The crude polymer was purified by dissolving in dichloromethane and precipitating into diethyl ether. The purified polymer was then dried under vacuum.

The optical properties of the polymer were studied by UV-Vis spectroscopy. The absorption spectrum of the polymer showed a broad absorption band ranging from 300 nm to 800 nm. The band gap energy was calculated using the Tauc’s relation, and the result was found to be 1.6 eV, which is typical for LBG CPs.

The electrochemical properties of the polymer were studied by cyclic voltammetry (CV). The HOMO level of the polymer was determined to be -5.51 eV, while the LUMO level was determined to be -3.90 eV. These results indicate that the polymer has a high charge carrier mobility and a large band gap, which is ideal for solar cell applications.

The photovoltaic properties of the polymer were studied by fabricating bulk heterojunction polymer solar cells (BHJ-PSCs) with the device configuration of ITO/PEDOT:PSS/active layer/MoO3/Ag. The PCEs of the devices were determined to be 6.28% and 7.52%, respectively, for the devices using ITO/PEDOT:PSS/active layer/MoO3/Ag and ITO/poly[(9,9-bis(30-N,N-dimethylamino)propyl)-2,7-fluorene]-alt-2,7-(9,9-dioctylfluorene)]/active layer/MoO3/Ag, respectively. These results indicate that the polymer has high efficiency as an electron donor material in BHJ-PSCs.
Scheme 1. Synthetic route of PDTBDT-DTNT

4,9-bis(5-bromo-4-hexylthieno-2-yl)naphtho[1,2-c:5,6-c]bis[1,2,5]thiadiazole (BrDTNT) were synthesized as the procedure reported in the references. The structures of the monomers were confirmed by $^1$H NMR and elemental analyses before use. The PDTBDT-DTNT was synthesized with 1 and BrDTNT through the palladium-catalyzed Stille coupling reaction under mono-microwave heating condition. Subsequently, the polymer was end-capped with 2-tributylstannyliophene and 2-bromo-thiophene to remove bromo and trimethylstannyl end groups. The $^1$H NMR (400 MHz, CDCl$_3$) spectrum of the copolymer exhibited broad NMR signals at ca. 8.87, 8.17, 7.25-7.15, 3.08-2.97, and 2.30-0.90 ppm (Fig 1).

The 8.87 and 8.17 ppm correspond to the aromatic H atoms of DTNT rings in the copolymer backbone, and 7.25-7.15 ppm correspond to the aromatic H atoms on the I rings in the copolymer backbone. We also monitored the $^1$H NMR signal at 3.08-2.97 ppm belonging to the α-H atoms of alkyl on I and DTNT. $^1$H NMR spectrum of the copolymer confirmed that the copolymer is right on target alternating molecular structures containing 5,10-di(4,5-didecylthieno-2-yl)dithieno[2,3-d:2′,3′-d′][benzo[1,2-b:4,5-b′]di-thiophene and 4,9-bis(4-hexylthieno-2-yl)naphtho[1,2-c:5,6-c]bis[1,2,5]thiadiazole. The number-average molecular weight of the PDTBDT-DTNT determined by GPC in tetrahydrofuran (THF) with polystyrene standards, is about $M_n = 26,400$ g/mol with PDI of 2.35. The decomposed temperature ($T_d$) of PDTBDT-DTNT in chloroform solution and solid thin film (a), electrochemical property of PDTBDT-DTNT (b)
5% weight-loss) of the PDTBDT-DTNT is about 423.6°C (See ESI†, SFig 1).

Optical and electrochemical property of PDTBDT-DTNT

The UV-Vis absorption spectra of PDTBDT-DTNT in chloroform solution and solid thin film were monitored on a UV-2550 spectrophotometer, and presented in Fig 2a. As shown in Fig 2a, the PDTBDT-DTNT exhibits three absorption peaks at 350 nm, 493 nm and 733 nm with two shoulder absorption peaks at around 466 nm and 670 nm in chloroform solution. The PDTBDT-DTNT in solid thin film shows similar absorption spectrum except that the absorption peak at around 350 nm is decreased and the absorption peak at around 493 nm is increased in contrast to those for the absorption of PDTBDT-DTNT in solution. The optical band gap ($E_g$) of PDTBDT-DTNT estimated from the onset of absorption edge in solid thin film is about 1.58 eV (Fig 2a).

The electrochemical behaviour of the polymer film was investigated by cyclic voltammetry in a nitrogen-saturated solution of 0.1 M tetrabutylammonium hexafluorophosphate in acetonitrile with glass carbon and Ag/AgNO$_3$ electrode as the working and reference electrode, respectively. All scans were performed at a scan rate of 0.1 V/s. The oxidation potential of PDTBDT-DTNT was observed at around 0.50 eV, and the reduction potential was observed at around -1.12 eV (Fig 2b). The $E_{1/2}$ of ferrocene/ferrocenium (Fc/Fc$^+$) was observed at 0.09 V vs Ag/Ag$^+$. The HOMO and LUMO energy levels were estimated from the onset of the oxidation and reduction waves, respectively, and the value of 5.1 eV vs vacuum was used for Fc/Fc$^+$, i.e., HOMO = $-E_{oxygen} - 0.09 + 5.1$ eV and LUMO = $-E_{oxygen} - 0.09 + 5.1$ eV. Thus, the HOMO and LUMO levels were $-5.51$ eV and $-3.9$ eV, respectively. The electrochemical gap (1.61 eV) is slightly higher than the optical one (1.58 eV) which was determined from the onset band gap wavelength of PDTBDT-DTNT in thin film. A comparison between the two gaps not only provides further support to the validity of considering the redox potentials and absorption maxima for a correct evaluation of energy gaps, but also gets involved in the exciton binding energy of conjugated polymers.

Charge transporting property of PDTBDT-DTNT

To investigate the influence of the extended coplanar core and conjugation length of the 5,10-di(4,5-didecylthieno-2-yl)-DTBDT units on the hole mobility of PDTBDT-DTNT, the hole mobility of PDTBDT-DTNT was determined by applying the space-charge limited current (SCLC) model. The hole mobility was found to be $8.28 \times 10^{-5}$ cm$^2$ V$^{-1}$ s$^{-1}$ for PDTBDT-DTNT in comparison to $3.0 \times 10^{-3}$ cm$^2$ V$^{-1}$ s$^{-1}$ for PDDBT-DTNT. Because the PDTBDT-DTNT hold similar molecular weight and side alkyl chains as compared with the PDDBT-DTNT derived

Photovoltaic property of PDTBDT-DTNT

Figure 3. $I$–$V$ characteristics of the SCLC measurement of PDTBDT-DTNT from 4,8-di(4,5-didecylthieno-2-yl)-BDT and DTNT, except that the coplanar core and conjugation length of 5,10-di(4,5-didecylthieno-2-yl)-DTBDT is larger than that for 4,8-di(4,5-didecylthieno-2-yl)-BDT. The higher hole mobility of PDTBDT-DTNT probably contributes the larger coplanar core area and extended conjugation of 5,10-di(4,5-didecylthieno-2-yl)-DTBDT.

The PDTBDT-DTNT, as the electron donor materials for PVCs, was employed in PVCs with device configuration of ITO/PEDOT: PSS/active layer/Ca/Al (traditional PVCs), and PC$_{71}$BM as the electron acceptor materials. The weight ratios of PDTBDT-DTNT and PC$_{71}$BM were varied from 1:1 to 1:1.5 and then up to 1:2. The devices were characterized under AM 1.5 simulator (100 mW/cm$^2$). The PCEs of the traditional PVCs were varied from 5.30% to 4.13% and dropped to 3.16% with the open...
photoconverted current efficiency (IPCE) curves (Fig 4b), the absorption of photons etc, thus to improve the reduction of bimolecular recombination, and enhance the advantages such as the vertical phase separation, and the enhancement of the morphologies of the blend films from PDTBDTvDTNT and PC71BM could induce rougher surface and larger D0A interfaces of the films of PDTBDTvDTNT (See ESI†, SFig 3 and SFig 4), thus lead much higher consistency of photovoltaic results. To modify the PVCs from PDTBDT-DTNT, the optimization of the morphologies of the blend films from PDTBDT-DTNT/PC71BM via the induction of 1,8-Diiodooctane (DIO) in the fabrication of the devices were implemented, and the weight ratio of PDTBDT-DTNT and PC71BM was varied from 1:1 to 1:1.5 and then up to 1:2. It could be found that the optimal weight ratio of PDTBDT-DTNT and PC71BM was 1:1.

To modify the PVCs from PDTBDT-DTNT, the optimization of the morphologies of the blend films from PDTBDT-DTNT/PC71BM via the induction of 1,8-Diiodooctane (DIO) in the fabrication of the devices were implemented, and the weight ratio of PDTBDT-DTNT and PC71BM was fixed at 1:1. Similar to the results in the reported works, the PCEs of PVCs from PDTBDT-DTNT/PC71BM was clearly increased while 3% (V\textsubscript{DIO}: V\textsubscript{chlorobenzene} 3:100) of DIO was added to the solution of PDTBDT-DTNT/PC71BM (W:W, 1:1) in chlorobenzene solution. And PVCs with PCEs of 6.28%, V\textsubscript{oc} of 0.70V, J\textsubscript{sc} of 14.98 mA/cm\textsuperscript{2} and FF of 60.0% were achieved (Table 1, Fig 4a). The results from AFM and TEM measurements of blend films of PDTBDT-DTNT/PC71BM (W : W, 1:1) indicated that the using of DIO could induce rougher surface and larger D-A interfaces of the films of PDTBDT-DTNT/PC71BM (See ESI†, SFig 3 and SFig 4), thus lead much higher J\textsubscript{sc} and FF and enhance the PCEs of the corresponding PVCs. According to the incident-light induced current density (IPCE) curves (Fig 4b), the integral current density values (J\textsubscript{lab} Table 1) of the devices are 14.18 mA/cm\textsuperscript{2}, 15.16 mA/cm\textsuperscript{2} and 17.08 mA/cm\textsuperscript{2}, respectively. The deviations between the integral current density and the J\textsubscript{sc} read from the J-V measurement are within 3%, indicating the consistency of photoovoltaic results.

In recently, it has been demonstrated that the inverted PVCs may take advantages such as the vertical phase separation, reduction of bimolecular recombination, and enhancement of absorption of photons etc, thus to improve the J\textsubscript{sc} and FF of the inverted PVCs. To further modify the PVCs from PDTBDT-DTNT/PC71BM, the inverted PVCs with the devices configuration as ITO/PFN/ PDTBDT-DTNT/PC71BM (W:W, 1:1)/MoO\textsubscript{3}/Ag were also fabricated and characterized. As shown in Fig 4a and Table 1, the V\textsubscript{oc} of the inverted PVCs were slightly decreased in contrast to that for the traditional PVCs (0.70 V vs 0.65 V), and the J\textsubscript{sc} and FF of the inverted PVCs were increased about 16.9% and 10% (17.51 mA/cm\textsuperscript{2} vs 14.98 mA/cm\textsuperscript{2}, 66.0% vs 60.0%) in contrast to those for traditional PVCs. As the inverted structure harvest more photons from solar spectra than the traditional PVCs (Fig 5a, calculated by One Dimensional Transfer Matrix Formalism (TMF)), and the calculated J\textsubscript{sc} of the inverted PVCs was increased about 10% as compared with those for traditional PVCs (Fig 5b), the enhancement of the J\textsubscript{sc} for the inverted PVCs should mainly be attributed to the increase of the more photons from solar spectra in contrast to the traditional PVCs. On the other hand, although we did not achieved to monitor the desirable vertical phase separation like of the relative enrichment of the acceptor materials (PC71BM) at bottom surfaces and the reduction of acceptor materials (PDTBDT-DTNT) at the top interfaces of the inverted PVCs at this stage, the enhancement of the FF and the remaining part of the increase of J\textsubscript{sc} for the inverted PVCs might be attributed to the exhibiting favourable vertical phase separation of the inverted PVCs.

<table>
<thead>
<tr>
<th>Device configuration</th>
<th>Active layer</th>
<th>DIO (%a)</th>
<th>V\textsubscript{oc} (V)</th>
<th>J\textsubscript{sc} (mA/cm\textsuperscript{2})</th>
<th>J\textsubscript{ FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional PVCs</td>
<td>PDTBDT-DTNT/PC71BM (1:1)</td>
<td>0</td>
<td>0.70</td>
<td>14.50</td>
<td>14.18</td>
<td>52.50</td>
</tr>
<tr>
<td>Traditional PVCs</td>
<td>PDTBDT-DTNT/PC71BM (1:1.5)</td>
<td>0</td>
<td>0.70</td>
<td>11.43</td>
<td>-</td>
<td>51.63</td>
</tr>
<tr>
<td>Traditional PVCs</td>
<td>PDTBDT-DTNT/PC71BM (1:2)</td>
<td>0</td>
<td>0.70</td>
<td>10.33</td>
<td>-</td>
<td>43.68</td>
</tr>
<tr>
<td>Inverted PVCs</td>
<td>PDTBDT-DTNT/PC71BM (1:1)</td>
<td>3</td>
<td>0.70</td>
<td>14.98</td>
<td>15.16</td>
<td>60.0</td>
</tr>
</tbody>
</table>

Figure 5. Distribution of absorbed AM 1.5G photon flux density inside the active layer (a) and The calculated J\textsubscript{sc} of conventional and inverted PVCs from PDTBDT-DTNT/PC71BM (W:W, 1:1) with assuming average IQE of 85% (b).
Conclusions

In this paper, a low band gap conjugated polymer with 5,10-Bis(4,5-didecylthiieno-2-yl)-flanked-DTBDT as electron donor units and 4,9-bis(4-ethylthieno-2-yl)naphtho[1,2-c:5,6-c]bis[1,2,5]thiadiazole (DTNT) as electron acceptor units, was synthesized through the palladium-catalyzed Stille coupling reaction under mono-microwave heating condition, and named as PDTBDTvDTNT. The chemical structure, molecular weight and optoelectronic properties etc of PDTBDTvDTNT were characterized by gel permeation chromatography (GPC), \textit{H} NMR, UV-Vis absorption spectra and cyclic voltammetry (CV) etc. The photovoltaic property of PDTBDTvDTNT was also investigated, and the PCEs of 6.28% and 7.52% has been achieved in the traditional and inverted PVCs from the blend of PDTBDTvDTNT and [6,6]-phenyl-C$_{71}$-butyric acid methyl ester(PC$_{71}$BM) with weight ratio of 1:1 under AM 1.5 simulator (100 mW/cm$^2$), respectively.

Experimental Section

Materials

All reagents, unless otherwise specified, were obtained from Aldrich, Acros and TCI Chemical Co., and used as received. All the solvents were further purified under a nitrogen flow. 2,7-bis(trimethylstannyl)-5,10-di(4,5-didecylthiien-2-yl)dithieno[2,3-d:2′,3′-d′]benzo[1,2-b:4,5-b′]dithiophene (I) 36 and 4,9-bis(5-bromo-4-ethylthieno-2-yl)naphtho[1,2-c:5,6-c]bis[1,2,5]thiadiazole (BrDTNT) 25 were synthesized as the procedures reported in references, and characterized by \textit{H} NMR and FAB-MS before use. Poly((9,9-bis(30-(N,N-dimethylamino)propyl)-2,7-fluorene)-alt-2,7-(9,9-diobetylfluorene)) (PFN) 20 were prepared and characterized by the procedure as reported reference.

General Methods

\textit{H} NMR spectra were recorded on a Bruker DRX 400 spectrometer operating at 400 MHz and were referred to tetramethylsilane. FAB-MS were obtained on VG ZAB-HS. The polymerization reactions were carried on a mono-microwave system (NOVA, PreeKem Scientific Instruments Co.) Analytical GPC was performed using a Waters GPC 2410 in tetrahydrofuran (THF) relative to polystyrene standards. Elemental analyses were performed on a Vario EL Elemental Analysis Instrument (Elementar Co.) Thermal gravimetric analysis (TGA) was conducted on a TGA 2050 (TA instruments) thermal analysis system under a heating rate of 10 °C/min and a nitrogen flow rate of 20 mL/min. UV-visible absorption spectra were measured on a UV-2550 spectrophotometer (Shimadzu, Co.). The cyclic voltammetry (CV) of the PDTBDTvDTNT was measured on CHI 660 electrochemical workstation (Shanghai Chenhua Co.) at a scan rate of 50 mV/s with a nitrogen-saturated solution of 0.1 M tetraubuthylammonium hexafluorophosphate (Bu$_4$NPF$_6$) in acetonitrile (CH$_3$CN) with glass carbon and Ag/AgNO$_3$ electrode as the working and reference electrode, respectively. Tapping-mode atomic force microscopy (AFM) images were obtained using a NanoScope NS3A system (Digital Instrument). Transmission electron microscopy (TEM) images were obtained using JEM-2100F FIELD EMISSION ELECTRON MICROSCOPE (JEOL).

Preparation and Characterization of the Photovoltaic Solar Cells

A patterned indium tin oxide (ITO) coated glass with a sheet resistance of 10–15 Ω/square was cleaned by a surfactant scrub, followed by a wet-cleaning process inside an ultrasonic bath, beginning with de-ionized water, followed by acetone and isopropanol. After oxygen plasma cleaning for 5 min, a 40 nm thick poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) (Baymer Baytron 4083) anode buffer layer was spin-casted onto the ITO substrate and then dried by baking in a vacuum oven at 80 °C overnight. The active layer, with a thickness in the 70–80 nm range, was then deposited on top of the PEDOT:PSS layer by spin-casting from the chlorobenzene solution containing PDTBDTvDTNT/PC$_{71}$BM (W/W, 1:1, 1:1.5 and 1:2) with and without DIO. Then a 8 nm calcium and a 100 nm aluminium layer were evaporated with a shadow mask under vacuum of (1–5)×10$^{-5}$ Pa. The overlapping area between the cathode and anode defines a pixel size of device of 0.1 cm$^2$. The thickness of the evaporated cathode was monitored by a quartz crystal thickness/ratio monitor (SI-TM206, Shenyang Scienti Co.). Except for the deposition of the PEDOT:PSS layers, all the fabrication processes were carried out inside a controlled atmosphere in a nitrogen drybox (Etelux Co.) containing less than 1 ppm oxygen and moisture. The power conversion efficiencies (PCEs) of the resulting polymer solar cells were measured under 1 sun, AM 1.5G (Air mass 1.5 global) condition using a solar simulator (XES-7051, San-El Electric Co.) with irradiation of 100 mW/cm$^2$. The current density–voltage (J–V) characteristics were recorded with a Keithley 2400 source-measurement unit. The spectral responses of the devices were measured with a commercial EQE/incident photon to charge carrier efficiency (IPCE) setup (7-SCSspecIII, Beijing 7-star Opt. In. Co.). A calibrated silicon detector was used to determine the absolute photosensitivity.

Synthesis of PDTBDTvDTNT

A mixture of toluene (6 mL) and N,N-dimethylformamide (DMF, 0.5 mL) was added to a 55 mL microwave tube containing 2,7-bis(trimethylstannyl)-5,10-di(4,5-didecylthiien-2-yl)dithieno-[2,3-d:2′,3′-d′]benzo[1,2-b:4,5-b′]dithiophene (271.1 mg, 0.2 mmol), 4,9-bis(2-bromo-4-ethylthieno-2-yl)naphtho[1,2-c:5,6-c]bis[1,2,5]thiadiazole (146.9 mg, 0.2 mmol), Pd(dba)$_2$ (2.0 mg) and tris(3-methoxynaphthyl)phosphine (4 mg) in a glove box with moisture and oxygen under 1 ppm. Then the tube was subjected to the following reaction conditions in a mono-microwave reactor: 120 °C for 5 min, 140 °C for 5 min and 160 °C for 20 min. At the end of polymerization, the polymer was end-capped with 2-trityltystannyliiophene and 2-bromo-thiophene to remove bromo and trimethylstannyl end groups. The mixture was then poured into methanol. The precipitated material was collected and extracted with ethanol, acetone, hexane and toluene in a Soxhlet extractor. The solution of the copolymer in toluene was condensed to 20 mL and then poured into methanol (500 mL). The precipitation was collected and dried under vacuum overnight (yield: 75%). $M_w$ = 26,400g/mol with a polydisperse index (PDI) of 2.35. \textit{H} NMR (CDCl$_3$, 400 MHz), 8.87, 8.17,
Acknowledgements

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Notes and references

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Graphical Abstract

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Solar Cells

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Yuancheng Zhu, c Chunyan Yang, a Hongbin Wu, b and Yong Cao b

A low band gap conjugated polymer with alkylthieno-2-yl flanked
dithieno[2,3-d:2′,3′-d′]benzo[1,2-b:4,5-b′]dithiophene as electron donor
moieties and naphtho[1,2-c:5,6-c]bis[1,2,5]thiadiazole derivative as electron
acceptor moieties, was firstly synthesized and characterized, and high
performance inverted photovoltaic solar cells with power conversion efficiency
of 7.52% has been demonstrated.