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Near infrared electron acceptors with a photoresponse beyond 1000 nm for highly efficient organic solar cells

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Abstract

Developing near infrared (NIR) organic semiconductors is indispensable for promoting the performance of organic solar cells (OSCs), but addressing the trade-off between voltage and current density thus achieving high efficiency with low energy loss is still an urgent challenge. Herein, NIR acceptors (H1, H2 and H3) with a photoresponse beyond 1000 nm were developed by conjugating dithienopyrrolobenzothiadiazole to 2- (5,6-difluoro-3-oxo-2,3-dihydro-1H-inden-1-ylidene)malononitrile *via* varied alkyl thiophene bridges. It was found that the linear outward chains in thiophene bridges could mitigate both the conformation disorder of H3 and the electronic disorder of the PBDB-T:H3 blends, which could help to form a favorable blend morphology, facilitating highly efficient photoelectric conversion in the resultant OSCs. As a result, devices based on PBDB-T:H3 achieve a high efficiency of 13.75% with a low energy loss of 0.55 eV, which is one of the highest efficiencies and the lowest energy loss among OSCs with an optoelectronic response near 1000 nm. This work provides a new design strategy towards NIR acceptors for efficient OSCs and future exploration of functional optoelectronics.

Introduction

Organic solar cells (OSCs) have nowadays exceeded a power conversion efficiency (PCE) of 17%.^{1–8} Though this is promising, it is still very necessary to develop organic semiconductors with a broad optical response towards solar spectra for sufficient photon energy harvesting.^{9–12} In addition, to develop functional optoelectronics, such as visually transparent OSCs, multi junction devices, near infrared (NIR) photodetectors etc., there is also a strong need to develop outstanding narrow bandgap materials.^{13–16}

Recent progress made in NIR non-fullerene acceptors (NFAs) with absorption edges located at 1000 nm has promoted the development of OSCs. For instance, IEICO-4F10

with an indaceno[1,2-b:5,6-b']dithiophene core and an alkoxythiophene bridge is widely used in transparent or tandem OSCs. When it pairs with polymer donor PTB7-Th, a PCE of 12.8% is achieved.¹⁷ To broaden the absorption of acceptors, fused terthieno[3,2-b]thiophene (6T) has been developed for NIR NFAs, such as 6TIC, F8IC and IXIC-2Cl,^{18–20} wherein IXIC-2Cl-based devices obtain a PCE of 12.2%.²⁰ The NIR acceptor CO₈DFIC, a successful example created by introducing an oxygen atom into the 6T core, presents a PCE of 12.16% and a high shortcircuit current density (J_{sc}) of 26.12 mA cm⁻² in binary OSCs.²¹ By employing CO₈DFIC in the rear subcell of tandem devices, a champion PCE of 17.3% has been obtained.⁵

Nevertheless, to achieve a high photovoltaic efficiency is still the main challenge faced by narrow bandgap molecules, because low energy NIR photons, in addition to photon-to-electron conversion, are also inclined to photothermic conversion through the non-radiative relaxation of organic materials.²² In fact, most of the open-circuit voltage (V_{oc}) values obtained from OSCs based on the narrow bandgap materials reported so far are generally below 0.7 V (Table S1†). That is, the energy loss in such OSCs tends to exceed 0.6 eV. The trade-off between V_{oc} and J_{sc} arises commonly in OSCs utilizing narrow bandgap materials. Interestingly, newly developed Y-series acceptors (Y6 and its derivatives)^{23–28} maintain relatively deep highest occupied molecular orbital (HOMO) levels when the optical bandgap is narrowed, which enables OSCs to achieve a high efficiency with a low energy loss. The absorption edge of Y-series acceptors is generally located at 930 nm.⁴ In this case, further exploration of molecular design for narrow bandgap acceptors is indispensable, in which the trade-off between V_{oc} and J_{sc} in OSCs dealing with NIR photons must be addressed. It is the key not only to achieving a high PCE of OSCs, but also to developing new functional optoelectronics.

In this work, three narrow bandgap acceptors (H1, H2 and H3, as shown in Fig. 1) with a photoresponse beyond 1000 nm were developed by conjugating the dithienopyrrolobenzothiadiazole (DTPBT) core to 2-(5,6-difluoro-3-oxo-2,3-dihydro-1H-inden-1-ylidene)malononitrile (DF-IC) through alkyl thiophene bridges. Interestingly, in addition to tuning the optoelectronic properties through the DTPBT unit, it was

found that the alkyl chains in the thiophene bridges play a crucial role in optimizing the photovoltaic performance of the derived OSCs. That is, the acceptors with outward alkyl chains have clear advantages in OSCs over those with inward chains with the same skeletons, and the linear type is superior to the branched. H3, the one possessing linear outward chains, achieves a high PCE of 13.75% with a low energy loss of 0.55 eV when paired with polymer donor PBDB-T, which is one of the highest efficiencies among OSCs with an optoelectronic response near 1000 nm.

Compared with H1 (edge-on orientation) and H2 (mixed edge-on and face-on orientation), H3 exhibits a dominant face-on orientation with a close p-p stacking distance of 3.50 Å, because the alkyl chains close to the terminal DF-IC have a substantial influence on the conformation and solid stacking of the molecules. H3 could form a favorable morphology in bulk heterojunction blends facilitating efficient exciton dissociation, charge transport and mitigated recombination, thus achieving the highest external quantum efficiency (EQE) response among the three studied acceptors. Energy loss analysis proves that the PBDB-T:H3 based devices exhibit the lowest energy loss among the three types of devices. Besides, an extremely low Urbach energy (E_U) of 23.3 meV was calculated, indicating the low electronic disorder of the molecular solid. This means, through alkyl chain tuning, both the conformation disorder of H3 and the electronic disorder of the H3 based blends have been mitigated, which enables highly efficient photoelectric conversion in the resultant OSCs. As a result, the new design of the NIR NFAs appears to be reasonably successful in addressing the trade-off between the V_{oc} and J_{sc} of the OSCs, thus realizing a high PCE with a low energy loss. This work provides a new design strategy towards NIR acceptors for efficient OSCs and future exploration of functional optoelectronics.

Results and discussion

Synthesis and characterization

Fig. 1 (a) Chemical structures of the acceptors H1, H2, and H3 and a schematic representation of the molecular orientation. (b) An energy surface scan of rotamers in H1, H2 and H3. (c) UV-vis absorption spectra of the acceptors in CHCl₃ solution and film.

The synthetic routes for the three acceptors are displayed in Scheme S1.[†] We first obtained the brominated DTPBT,^{29,30} which was then connected to the alkyl thiophene through Stille coupling. Final products were obtained by Knoevenagel condensation. As depicted in Fig. 1, H1 and H3 have linear alkyl chains in the thiophene bridges with different positions, while H2 has branched outward chains. Detailed synthesis information and structure characterizations can be found in the ESI.[†] The three acceptors possess good solubility in common solvents such as dichloromethane, chloroform and chlorobenzene.

As depicted in Fig. 1, we found that the transition from an edge-on orientation to a face-on orientation of the acceptors is realized through tuning the alkyl chains (the morphology characterization will be discussed hereafter). H1 exhibits a dominant edge-on orientation while H3 shows a dominant face-on orientation, and the two types coexist in H2. Density functional theory (DFT) calculations based on the B3LYP/6-31G(d) level were conducted to investigate the chemical geometry of the acceptors.

As shown in Fig. S1,[†] slightly twisted backbones and alkyl chains attached to the pyrrole rings are the two main factors that prevent the over-aggregation of acceptors for suitable domain sizes.²³ In addition, from the energy scans of rotamers consisting of thiophene and DF-IC (Fig. 1b), it is revealed that the outward alkyl chains could certainly help to inhibit the stereo-isomerization caused by single-bond rotation.

The optical properties of the three acceptors were characterized by UV-vis spectroscopy (Fig. 1c and S2e[†]). H2 and H3 appear to have similar maximal peaks located at 753 nm and 757 nm in chloroform solutions. The numerical value for H1 blue-shifts to 730 nm. When converted into films, the maximal peaks are red-shifted by 136 nm, 104 nm and 123 nm for H1, H2 and H3, respectively. All three acceptors possess almost the same absorption edges of 1016 nm with narrow optical bandgaps calculated to be 1.22 eV. Among them, H3 presents the most obvious absorption aggregation shape, revealing dominant J-aggregation, while the aggregation behavior is more complex in the H1 and H2 films, which is related to the fact that the linear outward chains could suppress conformation disorder, thus affecting its solid state as well as the device performance as discussed in the following.^{31,32}

Cyclic voltammetry was carried out to measure the energy levels and the related results are displayed in Fig. S2.[†] All three acceptors with different alkyl chain substituents exhibit similar lowest unoccupied molecular orbital (LUMO) and HOMO levels. Compared with H1 and H2, H3 has slightly down-shifted energetics. As previously reported, narrowing the energy level offsets between the donor and acceptor is an effective way to reduce energy loss for high device performance if the charge separation remains efficient.^{33–36} Based on the above mentioned contents, we selected the wide bandgap polymer PBDB-T as the donor, which possesses a complementary absorption and small HOMO level offsets to these acceptors.

Photovoltaic properties

Fig. 2 (a) A schematic illustration of the inverted device structure. (b) J - V curves and (c) EQE curves of the OSCs based on PBDB-T:H1, PBDB-T:H2, and PBDB-T:H3 blend films. (d) A comparison of PCE values among the representative narrow bandgap materials (the optical bandgap is below 1.30 eV, Table S1†).

Table 1 Photovoltaic parameters of OSCs based on different acceptors.

Active layer	V_{oc} (V)	J_{sc} (mA cm ⁻²)	J_{cal}^a (mA cm ⁻²)	FF	PCE ^b (%)
PBDB-T:H1	0.784	16.81	16.09	0.53	6.89
	(0.782 ± 0.004)	(16.62 ± 0.22)		(0.53 ± 0.01)	(6.79 ± 0.16)
PBDB-T:H2	0.781	24.40	23.50	0.69	13.15
	(0.776 ± 0.004)	(24.24 ± 0.22)		(0.69 ± 0.01)	(13.05 ± 0.16)

	0.006)	0.17)		0.00)	0.07)
PBDB-T:H3	0.757	25.84	25.78	0.70	13.75
	(0.759 ±	(25.54 ±		(0.70 ±	(13.62 ±
	0.003)	0.24)		0.00)	0.10)

^a Integrated current densities from EQE curves. ^b Average PCEs from 20 devices.

Devices with an inverted structure (Fig. 2a) of ITO/ZnO/active layer/MoO₃/Ag were fabricated to characterize the photovoltaic properties. The device fabrication and characterizations are provided in the ESI. Current density–voltage (J – V) curves of the PBDB-T:H1, PBDB-T:H2 and PBDB-T:H3 blends are displayed in Fig. 2b and S3.† Detailed photovoltaic parameters are summarized in Tables 1 and S3.† In the case of the small V_{oc} differences, PBDB-T:H1 based devices exhibit the lowest PCE of 7% due to the comparatively poor J_{sc} and fill factor. On the other hand, for H2 and H3, which possess outward alkyl chains in thiophene bridges, the corresponding devices demonstrate a much higher J_{sc} thus showing average PCEs over 13%. Notably, PBDB-T:H3 based devices achieve the highest PCE of 13.75% among the three acceptors, indicating that alkyl chain mediating is crucial for device performance and the best choice is the linear outward chains in these cases.

EQE spectra are displayed in Fig. 2c. OSCs based on acceptors with outward alkyl chains (H2 and H3) appear to show much higher responses than that of the inner one (H1). The integrated J_{cal} values from the EQE curves are 16.09 mA cm⁻², 23.50 mA cm⁻² and 25.78 mA cm⁻² for PBDB-T:H1, PBDB-T:H2 and PBDB-T:H3, respectively, close to those from the J – V curves. Compared with the previously reported narrow bandgap materials with an optical bandgap below 1.30 eV (Fig. 2d), H1 and H3 show the best performance in OSCs among long wavelength spectrum response systems. In addition, the V_{oc} values could reach higher than 0.75 V, which is quite outstanding since most of the V_{oc} in OSCs based on reported narrow bandgap materials are below 0.7 V (Table S1†), revealing a favorable performance in reducing energy losses.

Energy loss analysis

Fig. 3 (a) Energy loss diagram of different parts. (b) FTPS curves of the devices with the PBDB-T:H1, PBDB-T:H2, PBDB-T:H3 blends. (c) The EQE_{EL} of the devices at various injection currents. (d) The calculated Urbach energy based on the exponential fits to the tail of the EQE spectra. (e) A comparison of energy loss in the three types of devices.

Table 2 Detailed energy loss of OSCs based on different acceptors.

Active layer	E_g (eV)	qV_{oc} (eV)	E_{loss} (eV)	qV_{oc}^{SQ} (eV)	ΔE_1 (eV)	qV_{oc}^{rad} (eV)	ΔE_2 (eV)	ΔE_3 (eV)	$EQE_E \times 10^{-3}$ (%)	Exp. $qV_{oc}^{non-rad}$ (eV)
PBDB-T:H1	1.34	0.78	0.56	1.08	0.26	1.03	0.05	0.25	3.69	0.26
PBDB-T:H2	1.34	0.78	0.56	1.08	0.26	1.03	0.05	0.25	5.23	0.26
PBDB-T:H3	1.31	0.76	0.55	1.05	0.26	1.01	0.04	0.25	3.78	0.26

Detailed investigations were conducted to probe the energy losses of these OSCs (Fig. 3a).^{37,38} Equations are described in the ESI. E_g is obtained from the Fourier transform photocurrent spectroscopy (FTPS)-EQE curve (Fig. 3b). The values are 1.34 eV, 1.34 eV and 1.31 eV for the PBDB-T:H1, PBDB-T:H2 and PBDB-T:H3 blends (Fig. S4[†]), respectively. Detailed energy loss data are summarized in Table 2. All three blends show an identical ΔE_1 of 0.26 eV, which is unavoidable under the Shockley–Queisser limit.³⁹ So far, some articles have demonstrated that introducing more halogen atoms can indeed reduce nonradiative loss.^{7,40} In contrast, the non-radiative losses (ΔE_3 or Exp. $q\Delta V_{oc}^{non-rad}$ as calculated from the EQE_{EL} curve, Fig. 3c) in our systems are similar, which could be attributed to the same skeletons constructed by the same atoms of the three acceptors. Obviously, the difference exists in ΔE_2 (Fig. 3e). Compared with the PBDB-T:H1 and PBDB-T:H2 blends, the PBDB-T:H3 blends appear to have a steeper absorption edge, and the ΔE_2 is estimated to be as low as 0.04 eV. Usually, in disordered semiconductors, the existence of localized states could extend the bandgap thus shifting the absorption edge. The optical absorption coefficient ($\alpha(E)$) in the low photon energy range follows the Urbach rule^{41,42} of eqn (1):

$$\alpha(E) = \alpha_0 e^{\frac{E-E_g}{E_U}} \quad (1)$$

where α_0 is the optical absorption coefficient at the band edge and E is the photon energy. The Urbach energy could characterize the degree of the absorption edge smearing due to the disorder caused by structural peculiarities as well as that induced by external factors. For the PBDB-T:H1 and PBDB-T:H2 blends, E_U is 24.5 meV and 24.7 meV, while for the PBDB-T:H3 blends, it is 23.3 meV (please see Fig. 3d and detailed calculations are shown in the ESI[†]). The electronic disorder of OSCs based on PBDB-T:H3 is low, indicating that the linear outward alkyl chains may be suitable for suppressing electronic disorder and reducing ΔE_2 .^{43,44} In addition, we find that PBDB-T:H3 blends with the lowest electronic disorder exhibit efficient charge separation

(discussed in the following), which is in accordance with the literature.^{45,46}

Charge separation, transport and recombination

Fig. 4 Colour plots of the TA spectra of (a) neat H3 film and (b) PBDB-T:H3 blend film under 750 nm excitation. (c) Representative TA spectra of the PBDB-T:H3 blend film at indicated delay times. Grey circle: the TA spectrum of the neat H3 film excited by 750 nm for comparison. (d) TA kinetics of the PBDB-T:H1, PBDB-T:H2 and PBDB-T:H3 blends showing the hole transfer process.

In order to study the hole transfer process in these three blends, which is a vital step for solar cell operation, we performed femtosecond transient absorption (TA) spectroscopy measurements. The excitation wavelength of 750 nm was selected here to excite only acceptors without exciting donors. The TA results of all the pristine acceptors and blend films are displayed in Fig. 4, S5 and S6.† The primary absorption

peaks for different acceptors and donors are well separated in the spectral domain, therefore, both the spectral and temporal characteristics of hole transfer dynamics can be extracted. The color plots of the TA spectra of pristine H3 and PBDB-T:H3 blend film after 750 nm excitation are shown in Fig. 4a and b, respectively. A few representative TA spectra at indicated delay times of the PBDBT:H3 blend film and a TA spectrum from neat H3 film (gray circles) for comparison are shown in Fig. 4c. The bleach peaks at 850 nm appear in both the neat H3 film and PBDB-T:H3 blend film, corresponding to the stimulated emission and ground state bleach of the absorption transition in H3 due to photoexcitation. With the decay of the H3 bleach peak at 700–930 nm, a few clear bleach peaks at 550–650 nm appear in the TA spectrum of the PBDB-T:H3 blend film. These peaks at 550–650 nm match very well with the absorption features of the PBDB-T films. The TA results of the PBDB-T:H1 and PBDB-T:H2 blend films are shown in Fig. S6,[†] showing a similar spectral evolution. The ground state bleach kinetics of PBDB-T in blends reflect the hole transfer and electron–hole recombination processes after photoexcitation. The kinetics for the three different acceptor blends are shown in Fig. 4d. All three blends show similarly ultrafast rising kinetics, with a half-life time of 0.6 ps, corresponding to the hole transfer process. Notably, PBDB-T:H1 shows a very fast recombination after the ultrafast hole transfer process, leading to inefficient charge generation, which is in line with its poor device performance.

Charge recombination was also investigated by employing J – V properties as a function of light intensity (P_{light}) (Fig. S7[†]). The relationship between V_{oc} and P_{light} could be described as $V_{\text{oc}} \propto nkT/q \ln(P_{\text{light}})$ (k is the Boltzmann constant, T is the temperature and q is the elementary charge, a larger n value means a greater component of monomolecular recombination). The correlation between J_{sc} and P_{light} could be described as $J_{\text{sc}} \propto P_{\text{light}}^{\alpha}$ (the closer the α value is to 1, the greater the component of bimolecular recombination). As a result, the PBDB-T:H1 blends exhibit the greatest monomolecular recombination, which is consistent with the TA kinetics result. Both monomolecular recombination and bimolecular recombination are mitigated comparatively in the PBDB-T:H3 blends.

To investigate the charge transport after charge separation, the space-charge-limited

current (SCLC) method was utilized to examine the charge carrier mobility in the blend films (Fig. S7†). The PBDB-T:H3 blends possess the highest electron mobility (μ_e) of $4.22 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and the highest hole mobility (μ_h) of $3.37 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. In contrast, values for PBDB-T:H1 blends are the lowest with μ_e of $1.00 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and μ_h of $2.05 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. For the PBDB-T:H2 blends, μ_e is $3.49 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and μ_h is $2.67 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. Besides, the pristine electron mobilities of the acceptors are calculated as $1.12 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $2.87 \times 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $3.34 \times 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for H1, H2 and H3, respectively. Combined with the above, it is found that though charge separation is fast in the PBDB-T:H1 blends, the situations of charge recombination and charge transport are less favorable, which may lead to the lower EQE response. Through tuning the alkyl chain, acceptors with outward alkyl chains exhibit higher mobility in blends, which is related to the molecular orientation and packing discussed in the morphology characterization below.

Blend morphology

Fig. 5 2D GIWAXS images of (a) H1, (b) H2, (c) H3 neat films and (d) PBDB-T:H1, (e) PBDB-T:H2, (f) PBDB-T:H3 blends. GIWAXS intensity profiles of the corresponding (g) neat films and (h) blends along the in-plane (dotted lines) and out-of-plane (solid lines) directions.

To study the surface morphology, atomic force microscopy (AFM) characterization was conducted (Fig. S8[†]), PBDB-T:H3 blends exhibit smooth and homogeneous surfaces with the lowest root-mean-square roughness. Grazing-incidence wide-angle X-ray scattering (GIWAXS) characterization was performed to investigate the molecular orientation and packing (Fig. 5 and S9, Table S2[†]).⁴⁷ In neat acceptor films, H3 possesses an obvious π - π stacking peak at $q_z = 1.80 \text{ \AA}^{-1}$ ($d = 3.50 \text{ \AA}$) in the out-of-plane

(OOP) direction, indicating a dominant face-on orientated molecular stacking, which is beneficial for vertical charge transport. There are two scattering peaks observed in the in-plane (IP) direction at $q_r = 0.272 \text{ \AA}^{-1}$ ($d = 23.1 \text{ \AA}$) and $q_r = 0.375 \text{ \AA}^{-1}$ ($d = 16.8 \text{ \AA}$), suggesting the existence of an additional structure order beyond lamellar stacking in the IP direction. In contrast, for H1, two orders of lamellar peaks are observed in the OOP direction at $q_z = 0.305 \text{ \AA}^{-1}$ ($d = 20.6 \text{ \AA}$) and $q_z = 0.635 \text{ \AA}^{-1}$ ($d = 9.89 \text{ \AA}$), while the π - π stacking peak is located at $q_r = 1.82 \text{ \AA}^{-1}$ ($d = 3.45 \text{ \AA}$) in the IP direction. This suggests that H1 molecules are predominantly edge-on oriented. H2 shows the mixture of face-on and edge-on orientation in the neat film with lamellar and π - π peaks identified in both the IP and OOP directions (detailed data are shown in Table S2[†]). H3 exhibits the favorable face-on orientation and highly ordered molecular stacking in the neat film, which could be attributed to the conformation modulation by fine-tuning the alkyl chains. When blended with PBDB-T, all the three blends show obvious lamellar peaks in the IP direction and a strong π - π stacking signal in the OOP direction, and among them, the PBDB-T:H3 blends exhibit the strongest intensity and the closest π - π stacking with $q_r = 1.77 \text{ \AA}^{-1}$ ($d = 3.55 \text{ \AA}$). These results are consistent with the observations in the aforementioned characterizations. In particular, the tuning of the alkyl chains could certainly affect the molecular orientation and help to form ordered stacking, which would result in an efficient photoelectric conversion process for high device performance.

Conclusions

In summary, three narrow bandgap acceptors H1, H2 and H3 with a photoresponse beyond 1000 nm were synthesized by conjugating DTPBT to DF-IC *via* varied alkyl thiophene bridges. Through the characterizations of the intrinsic material properties and device performance, we revealed that the alkyl chains in the thiophene bridges substantially affect the photovoltaic performance of the derived OSCs. The acceptors with outward alkyl chains have clear advantages over those with inward chains with

the same skeletons, wherein the linear outward chains could mitigate both the conformation disorder of H3 and the electronic disorder of the PBDB-T:H3 blends. The PCE of 13.75% with a low energy loss of 0.55 eV for the PBDB-T:H3 blends based OSCs is one of the highest efficiencies and the lowest energy loss among OSCs with an optoelectronic response near 1000 nm. As a result, the new design of NIR NFAs appears to be reasonably successful in addressing the trade-off between the V_{oc} and J_{sc} of the devices, thus enabling a high PCE with a low energy loss of OSCs with broad absorption.

Author contributions

C. He, C.-Z. Li and H. Chen conceived the idea. C. He designed the experiments and performed the chemical synthesis and properties characterization of the acceptors. Y. Li (Yaokai Li) performed the device fabrication, device measurements and data collection. Y. Liu and F. Zhang contributed to the FTPSEQE and EL measurements and analysis. Y. Li (Yuhao Li) and X. Lu performed the GIWAXS measurements and analysis. G. Zhou and H. Zhu carried out TA measurements and analysis. C. He drafted this paper. All the authors commented on the final paper. C.-Z. Li and H. Chen supervised the project.

Conflicts of interest

There are no conflicts to declare.

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