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Title: Mobility and photovoltaic performance studies on polymer blends: effects of side chains volume fraction

Ternary blend of PCBM with two thiophene based poly(*p*-phenylene-ethynylene)-*alt*-poly(*p*-phenylene-vinylene)s (PPE-PPV) consisting of the same conjugated backbone but different types and volume fraction of alkoxy side chains on the phenylene-ethynylene unit, showed better photovoltaic performance as compared to binary blends of the single polymers mixed with PCBM.

As featured in:



See Getachew Adam *et al.*, *J. Mater. Chem.*, 2011, **21**, 2594.

Mobility and photovoltaic performance studies on polymer blends: effects of side chains volume fraction

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Received 13th August 2010, Accepted 4th November 2010

DOI: 10.1039/c0jm02668a

A 1 : 1 mixture of two thiophene based poly(*p*-phenylene ethynylene)-*alt*-poly(*p*-phenylene vinylene)s denoted DO-PThE₁-PPV₂ (**D1**) and MEH-PThE₁-PPV₂ (**D2**), consisting of the same conjugated backbone but different types and volume fraction of alkoxy side chains on the phenylene ethynylene unit, has led to enhanced charge carrier mobility (measured using CELIV technique) as compared to the individual polymers. The resulting ternary blend with PC₆₀BM showed better photovoltaic performance as compared to binary blends from the single polymers mixed with PCBM. This is due to the improved active layer nanomorphology in the ternary system as revealed by AFM studies.

Introduction

Photovoltaic devices based on organic polymers have the potential as low cost renewable energy sources to address the growing global energy needs.^{1,2} Among the various solar cell device architectures, the bulk heterojunction concept has proven to be the most efficient.^{1b,3} This concept is based on ultrafast photo-induced electron transfer from poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) to Buckminsterfullerene (C₆₀)⁴ and the realization of improved performance of the first solar cell of this kind from poly(2-methoxy-5-(3,7-dimethyloctyloxy)-1,4-phenylenevinylene) (MDMO-PPV) : C₆₀ blend.⁵ The concept involves nanoscale self-assembly of heterojunctions by spontaneous phase separation of the donor polymer and the acceptor, which leads to charge-separating heterojunctions throughout the bulk. The resulting photogenerated holes and electrons are then transported to the corresponding electrodes *via* percolating pathways to provide a photocurrent. The high interest for polymer : fullerene based solar cells has triggered the design of a large number of novel conjugated polymeric donor materials such as derivatives of polythiophene, polycarbazole, poly(*p*-phenylene vinylene) (PPV), poly(*p*-phenylene ethynylene) (PPE) and combinations thereof^{6,7} as well as fullerene derivatives as acceptor materials.⁸

To improve the power conversion efficiency donor polymers should have low energy band gap so as to harvest light from most of the solar spectrum; this leads to higher short-circuit current density (J_{SC}) and better overall performance.^{1a,9} In addition to the required band gap and a match of the energy levels of the donor and of the acceptor components, a better nanostructural ordering to get optimized phase separation of both components and an efficient percolation of the photogenerated charges are crucial to improve the power conversion efficiency of organic solar cells.¹⁰ Most studied approaches to improve the nanoscale morphology of the active layer

are (1) thermal annealing,^{11,12} (2) solvent variation,^{13–15} and (3) using additives, like alkyldithiols^{12b,c,16} and diiodoalkanes,¹⁷ in the bulk heterojunction solution. A set of other approaches to efficiently control the active layer morphology has been reported in the literature, such as doping of the polymer with small molecules like triphenylamine,¹⁸ blending the active layer with ionic solid electrolyte (such as polyethylene oxide and LiCF₃SO₃),¹⁹ and ternary blends.

For instance, by using ternary thienothiophene copolymers as a nucleating agent, an enhancement of the degree of crystallization of P3HT in P3HT : PCBM system was observed. This increases the charge carrier transport properties and enlarges the active layer absorption spectrum.²⁰ Electron transporting polymer, poly(9,9-dioctylfluorene-*co*-benzothiadiazole) (F8BT), mixed with PCBM blended with P3HT showed improved efficiency due to enhanced optical absorption, better charge collection and improved charge carrier mobility.²¹ Heeger *et al.* reported on a highly efficient tandem cell achieving an efficiency over 6% by utilizing two p-type conjugated polymers in the two independent active layers to effectively harvest the solar photons.²² A ternary blend bulk heterojunction consisting of two electron donor polymers, MDMO-PPV and P3HT, and PCBM as acceptor showed an improvement of the V_{OC} at a minimum expense of the J_{SC} .²³ In a recent report two donor conjugated polymers, poly[2,6-(4,4-bis(2-ethylhexyl)-4*H*-cyclopenta[2,1-*b*;3,4-*b'*]dithiophene)-*alt*-4,7-(2,1,3-benzothiadiazole)] (PCPDTBT) and a dithiophene-*alt*-benzothiadiazole based polymer, which are capable of absorbing light complementarily in the spectral region covering 400 to 900 nm, were used together with PC₇₁BM to form a ternary blend system. This resulted in an improved photovoltaic performance as compared to the individual polymer : PC₇₁BM blends.²⁴

Here we report on photovoltaic device from ternary blend by mixing PC₆₀BM with two thiophene-containing PPE-PPV based donor polymers having the same conjugated backbone but different alkoxy side chains grafted on the PE-segment, poly{1,4-(2,5-dioctyloxy)-phenyleneethynylene-2,5-thiophenylenevinylene-1,4-[(5-(2-ethylhexyl)oxy)-2-methyloxy]-phenylenevinylene} (DO-PThE₁-PPV₂) (**D1**) and poly{1,4-(5-[(2-ethylhexyl)oxy]-2-methoxy)-phenyleneethynylene-2,5-thiophenylenevinylene-1,4-[(5-(2-ethylhexyl)oxy)-2-methyloxy]-phenylenevinylene} (MEH-PThE₁-PPV₂) (**D2**).²⁵ Their chemical structures are

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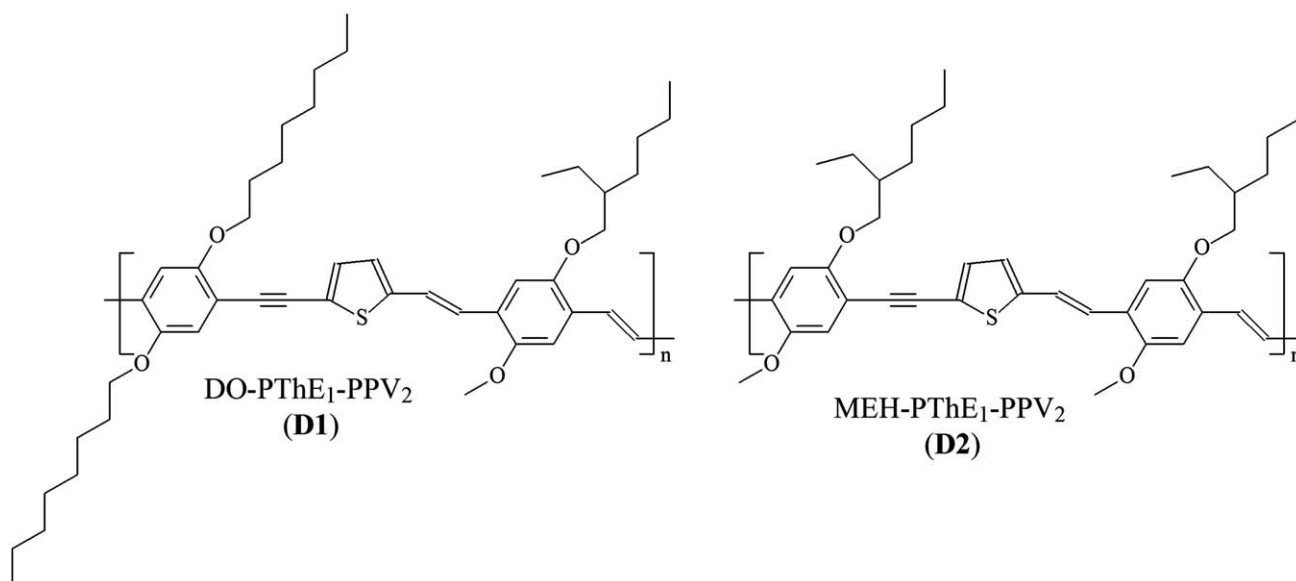


Fig. 1 Chemical structures of the polymers.

displayed in Fig. 1. Systematic variation of the *nature* (linear or branched), *density*, *length* and *position* of alkoxy side chains has been used to tune the supramolecular ordering, the photo-physical, photoconductive, electrochemical, electroluminescent and photovoltaic properties of PPE-PPV based materials.^{26–28} For instance, the lower side chain volume fraction in **D2** than in **D1** leads to higher miscibility between **D2** and PC₆₀BM (1 : 3 ratio) than between **D1** and PC₆₀BM. This, on one hand, increases the donor–acceptor interfacial area, resulting in higher density of photogenerated charges, and on the other hand, fosters the recombination of the photogenerated charges at the same time hampers the percolation paths to the electrodes, which lower both the expected J_{SC} and the FF.²⁵ The mixing of **D1**, **D2** and PC₆₀BM in a ternary system as described in this work resulted in a different active layer nanomorphology than in the individual **D1** : PC₆₀BM or **D2** : PC₆₀BM binary system. Thus higher photovoltaic performance was obtained from the ternary blend system than from the individual binary systems.

Experimental part

The charge carrier transport and recombination strongly influence the photovoltaic performance of solar cells.²⁹ Since semiconducting organic polymers are low mobility materials with low quantum photogeneration efficiency in their pristine phase,³⁰ bulk heterojunction concept is introduced for an efficient charge generation and for a long carrier lifetime.³¹ Time-of-Flight (TOF) technique is usually used to measure the charge carrier mobility in the bulk of the film,³² however, in disordered films with dispersive transport TOF is not well applicable. We have measured the charge carrier mobility of the two polymers and their 1 : 1 mixture using Charge Extraction by Linearly Increasing Voltage (CELIV) technique. This technique has been used to study the charge carrier transport and recombination in various disordered organic and inorganic semiconductors in the past.^{17a,28a,33} CELIV allows us to study the time-dependent, dispersive charge carrier transport in disordered semiconductors

where the carrier mobility is measured directly from the current transients without any assumptions or fitting procedures. The essence of this method is the charge carrier extraction with linearly increasing (triangle-shaped) voltage pulse. If the studied semiconductor is intrinsically pure (undoped) and contains no significant amount of mobile charge carriers, the light pulse is used to photogenerate the charge carriers which are further extracted from the film by increasing voltage. The time-dependent relaxation of photogenerated charge carriers within Density-of-States distribution in disordered media is studied.³⁴ CELIV measures a non-equilibrium charge carrier mobility as opposed to steady state mobility techniques such as space charge limited current (SCLC) or field effect transistor (OFET) measurements.³⁵ Also, Poole–Frenkel type dependence of carrier mobility on electric field is usually seen in disordered films.³⁶ Therefore, the charge carrier mobility is non-constant as a function of electric field and the electric field values, at which the carrier mobility is measured, must be specified.³⁷ The synthesis, electrochemical and photophysical characterizations of **D1** and **D2** are reported elsewhere.²⁵

For CELIV measurements, sandwich-type samples were fabricated as follows: polymers were dissolved in chlorobenzene with a concentration of 10 mg ml⁻¹. The solutions were filtered through a 0.45 μm filter before deposition by drop casting on top of the pre-patterned ITO-covered glass substrates. Bulk charge carrier mobility was measured in thick (>1 μm) films. 30 nm aluminium top electrodes with typical dimensions of 8–10 mm² were evaporated on top of the film in vacuum under 10⁻⁶ mbar. The samples were prepared in air, but after the deposition of top contact films were kept in the nitrogen atmosphere and measured in the cryostat (Oxford Optistat DNV) under vacuum. A variable pulse generator (Agilent 33250A) and the oscilloscope (Tektronix TDS 754C) were used to record the extraction current transients. To control the delay time between voltage and light pulses, an arbitrary pulse (Agilent AG33250A) and a delay function generator (Stanford DG535) were employed. A Nd:YAG laser (Coherent Infinity

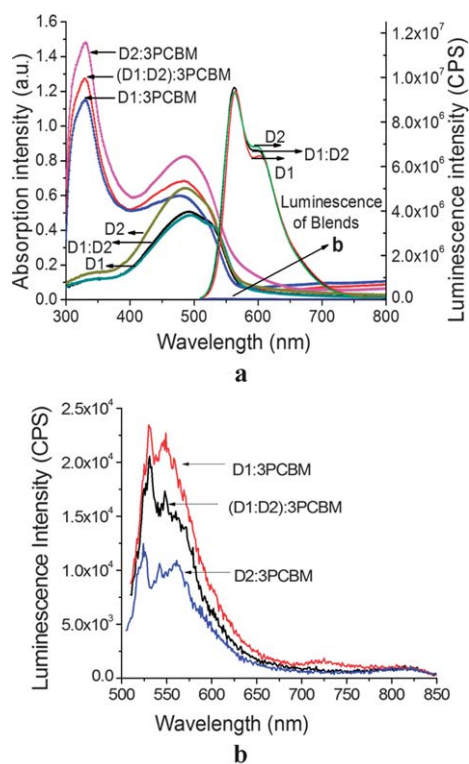


Fig. 2 (a) Thin film absorption and emission spectra of **D1**, **D2** and **D1 : D2** (1 : 1) as well as their blend with PCBM in a 1 : 3 ratio. (b) Enlarged photoluminescence spectra of the blends.

40–100), with a light pulse width of 5 ns, wavelength 355 nm, energy of less than 1 mJ per pulse, was used for the charge carriers photogeneration.

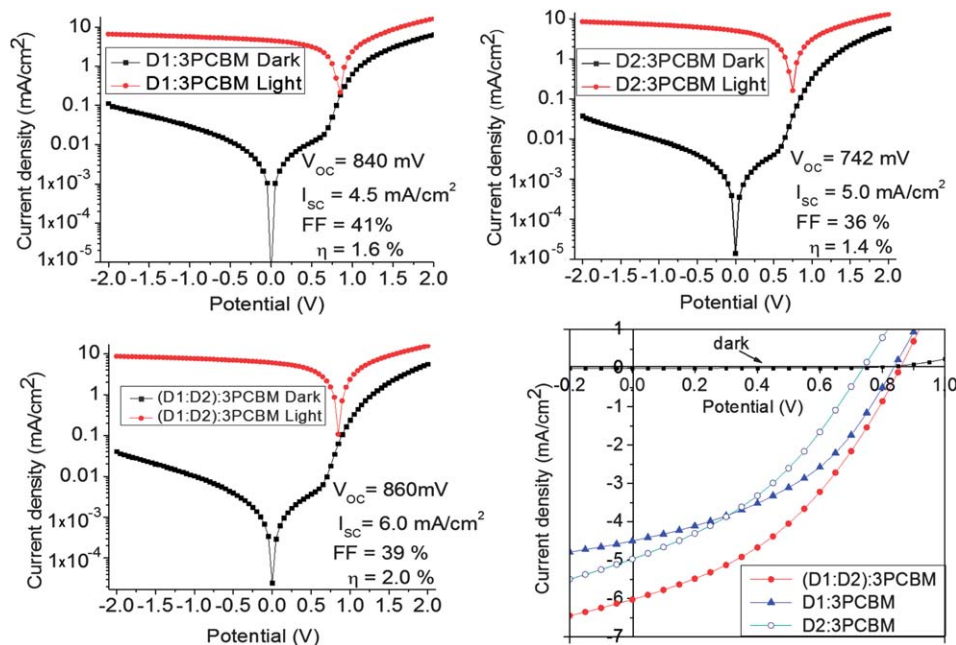


Fig. 3 Current–voltage characteristics of the solar cells made from the ternary blends **D1** : 3PCBM and **D2** : 3PCBM as well as ternary blend **D1** : **D2** : 3PCBM.

For photophysical measurements, the pure polymers (**D1**, **D2**), their 1 : 1 mixture films and their corresponding blend films with PC₆₀BM in a 1 : 3 ratio were prepared from their solution (10 mg polymer) per ml in chlorobenzene by spin coating on glass. After the films were allowed to dry in the glove box for 24 h, optical absorption and photoluminescence measurements were carried out using a Cary (3 G) UV-Vis spectrophotometer and HORIBA JOBIN YVON Fluorescence spectrophotometer, respectively. For the fabrication of bulk heterojunction solar cells, solutions were prepared according to the previous literature^{25a,c} with mixing ratio of 1 : 3 polymer to the acceptor [6,6]-phenyl-C₆₁-butyric acid methyl ester (PC₆₀BM) in chlorobenzene (99%) (ACROS ORGANICS) with a concentration of 40 mg (polymer : PC₆₀BM) per ml stirred overnight. The indium tin oxide (ITO) coated glass substrate was cleaned by ultrasonication successively with glass cleaning detergent helmanex, acetone, isopropanol and deionized water and dried by purging with N₂. Poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate) (PEDOT/PSS) (Baytron PH) stirred overnight and filtered was spin coated from aqueous solution on top of ITO with 2000 rpm to get a film of 80 nm thickness and dried overnight in open air. The polymer : PCBM solutions were then filtered and spin coated on top of PEDOT/PSS film. Then the samples were kept in the glove box dried for 24 h and the top electrode aluminium metal (100 nm) deposition was done by thermal evaporation in vacuum at about 5×10^{-6} bar. Current–voltage (*I*–*V*) characteristics of the devices were measured using a Keithley 236 source measure unit under 100 mW cm⁻² AM 1.5 white light illumination of the solar cell. Incident photon to collected electron efficiency (IPCE) measurements were taken using a optical fiber from 90 W Xenon lamp light source, which is connected to ACTON Spectra Pro150 monochromator and EG & G 7260 DSP Lock in a amplifier to measure the current.

Results and discussion

From thin film absorption and photoluminescence (PL) spectra of **D1**, **D2** and their 1 : 1 blends in Fig. 2, it can be seen that all three entities exhibit almost the same optical features, which is consistent with the previous reports.²⁵ The absorption contribution of PCBM in the binary and ternary blends is viewed by the strong absorption band in the range of 325–390 nm and a kink at 710 nm. It is possible to correlate the intensity of the absorption bands with the volume fraction of the alkoxy side chains, latter acting as *diluting agents* of the photoactive species. The concentration of the photoactive species increases from **D1** : PCBM blend over **D1** : **D2** : PCBM blend to **D2** : PCBM. The highest photoexcited interaction is the blends of **D2** with PCBM (*i.e.* highest miscibility) resulting in the highest photoluminescence quenching in **D2** : PCBM blend, followed by **D1** : **D2** : PCBM blend, then **D1** : PCBM blend as shown in Fig. 2b.

The current–voltage (*I*–*V*) characteristics of the solar cells are given in Fig. 3. Statistical studies were also made in order to ensure the reproducibility of results and the characteristic average values of these solar cells made are shown in Table 1. The *I*–*V* characteristics of the solar cells in Fig. 3 reveal a dark

rectification ratio of approximately 10^3 at ± 2 V. The solar cells made from **D2** : PCBM (1 : 3) showed an average open circuit voltage (V_{OC}) value of 735 mV and that of **D1** : PCBM (1 : 3) showed 842 mV. The average V_{OC} of the ternary blend of 860 mV in contrast is higher than that of the respective binary systems. It is reported that V_{OC} is a function of the HOMO of the polymer and that of the LUMO of the acceptor,^{1b,9} so this result shows that by mixing two polymers of the same backbone but with different side chain volume fraction, the open circuit voltage can be improved.³⁸ When we compare the solar cells made from the individual polymers with PCBM, **D2** : PCBM showed an average short circuit current density (J_{SC}) of 4.9 mA cm⁻² which is higher than that of **D1** : PCBM which showed an average 4.5 mA cm⁻². This trend is consistent with the photoluminescence (PL) spectra of the blends where **D2** : PCBM showed the strongest PL quenching due to more efficient photo-induced electron transfer to the acceptor PCBM as compared to **D1** : PCBM. The highest average J_{SC} of 5.7 mA cm⁻² obtained for the ternary blend is due to its better active layer nanomorphology than the binary blends. The fill factor FF values observed for the ternary blend (40%) are very close to the highest average value of 41% obtained for **D1** : PCBM binary system.

Table 1 The *I*–*V* characteristic results of the solar cells made along with the average values

Blend	Sample no.	Electrode	V_{OC}/mV	$J_{SC}/mA\ cm^{-2}$	FF (%)	η (%)
D1 : PCBM (1 : 3)	1	1	840	4.85	42	1.71
		2	830	4.30	40	1.49
		3	825	4.30	42	1.47
	2	1	850	4.35	43	1.61
		2	855	4.03	43	1.48
		3	836	4.36	41	1.53
	3	1	850	5.06	41	1.74
		2	850	4.61	42	1.67
		3	840	4.50	41	1.58
(D1 : D2) : PCBM (1 : 3)	1	1	885	5.6	41	1.95
		2	865	5.34	40	1.85
		3	855	5.45	39	1.81
	2	1	870	5.59	42	2.04
		2	855	5.57	40	1.91
		3	865	5.52	42	1.79
	3	1	860	6.02	39	2.02
		2	850	5.94	38	1.95
		3	830	6.10	37	1.90
D2 : PCBM (1 : 3)	1	1	745	4.97	38	1.42
		2	730	5.18	36	1.40
		3	710	5.12	37	1.35
	2	1	740	5.06	37	1.41
		2	740	4.97	36	1.35
		3	740	5.04	35	1.35
	3	1	736	4.77	36	1.29
		2	725	4.66	36	1.20
		3	725	4.48	36	1.14

Summary

Average values	Blend		
	D1 : 3PCBM	(D1 : D2) : 3PCBM	D2 : 3PCBM
V_{OC}/mV	842	860	735
$J_{SC}/mA\ cm^{-2}$	4.5	5.7	4.9
FF (%)	41	40	36
η (%)	1.6	2.0	1.3

As can be seen from the incident photon to collected electron efficiency (IPCE) curves in the Fig. 4, the IPCE for the ternary blend is the highest (52% at its maximum) and covers the largest area as compared to the binary blends. At their maximum point **D1** : PC₆₀BM and **D2** : PC₆₀BM showed IPCE values of 40% and 41% respectively. Even though the optical absorption of the two polymers are almost the same a difference in the position of the onsets of the IPCE curves is observed. **D2** : PC₆₀BM blend absorbs strongly at longer wavelengths compared to **D1** : PC₆₀BM blend. The IPCE onset of the ternary blend starts at the longest wavelength as compared to the binary blends. The difference in the IPCE values between the binary blends and the ternary blend is consistent with their difference in short circuit current values. This clearly shows that by mixing the two polymers a new nanomorphology with improved properties is obtained.

The AFM images in Fig. 5 show the nanomorphological differences between the two polymer films **D1** and **D2** and their 1 : 1 mixture from their (1%) solution in chlorobenzene spin

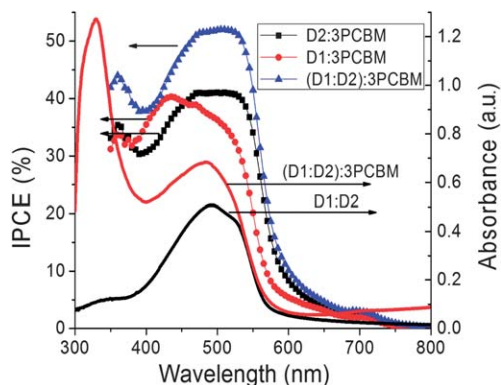


Fig. 4 IPCE of the solar cells from the binary and ternary blend systems together with the absorption spectra of **D1** : **D2** (1 : 1) and **(D1 : D2) : 3PCBM**.

coated on glass. **D1** has a higher roughness around 0.8 nm than that of **D2** which is 0.3 nm, whereas their 1 : 1 mixture shows an intermediate roughness of 0.4 nm. The same trend was observed in their average height where an average value of 2.6 nm was obtained for **D1**, 1.2 nm for **D2** and 1.6 nm for the mixture. As expected, a clear phase separation is observed from AFM picture of **D1** : PCBM blend with a roughness of 4.0 nm and an average height of 10.7 nm, the blend **D2** : PCBM showed a very flat film with a roughness of 0.3 nm and an average height of 1.4 nm due to higher miscibility between **D2** and PCBM. The ternary blend thin film has a roughness 0.5 nm and a height of 2.1 nm which is still flat as compared to **D1** : PCBM but relatively rough as compared to **D2** : PCBM. The increase in J_{SC} and concomitant overall performance of the ternary blend are proposed to be due to optimized phase separation of the ternary blend as compared to the two binary blends, *i.e.* highest phase separation in **D1** : PCBM blend and the highest miscibility in **D2** : PCBM blend.

In Fig. 6 the current extraction transients from CELIV experiment for **D1** and **D2** and their 1 : 1 blend are shown. A typical CELIV current transient presents several important features. The very initial current step $j(0)$ (displacement current) is caused by the geometrical capacity of the sample and it is used to estimate the sample thickness. The following increasing extraction current is caused by the photoconductivity of the sample when the mobile charge carriers are being extracted from the film. As the triangle voltage pulse continues to increase, the majority of charge carriers reach the electrode and the current starts to decrease forming a characteristic extraction maximum from which the carrier mobility (μ) is calculated.³⁸

$$\mu = k \frac{d^2}{At_{\max}^2},$$

where $k = 2/3$ for volume (for thin films) and $K = 2$ for surface photogeneration (for thick films), d is the film thickness, A is the slope of applied rising triangle-shaped voltage pulse. Since the applied electric field in the film is non-constant during the

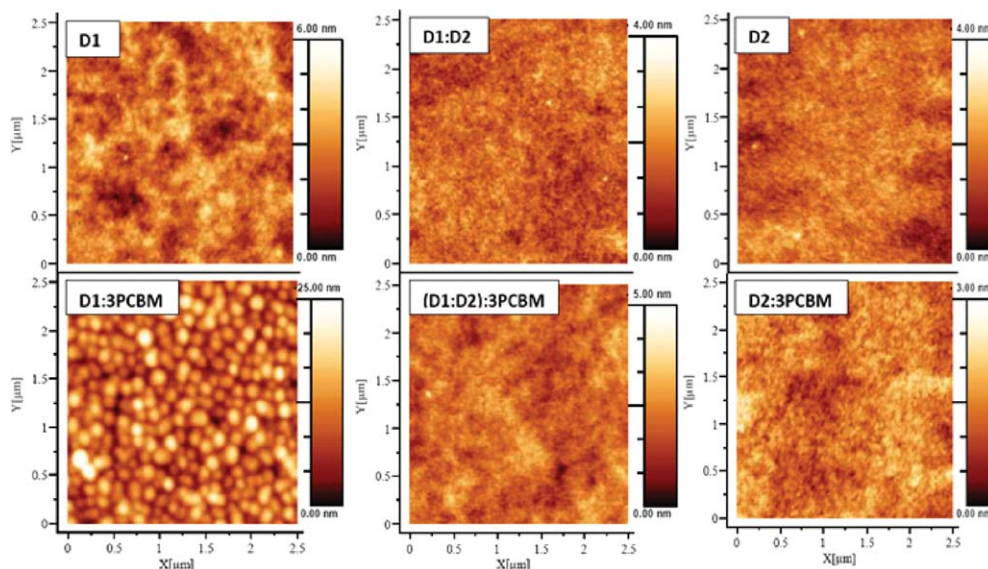


Fig. 5 AFM images of the two polymers and their 1 : 1 mixture films and the corresponding blends with PCBM in a 1 : 3 polymer : PCBM ratio.

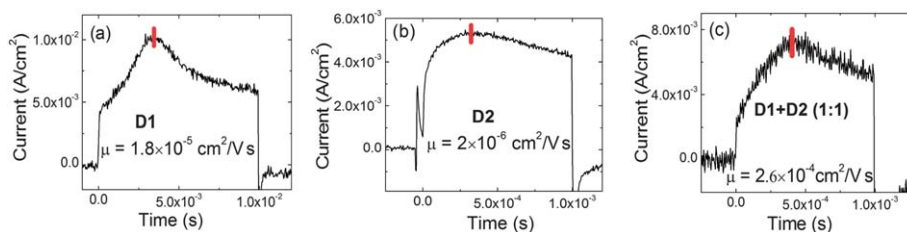


Fig. 6 CELIV extraction current transients are shown for **D1** (a), **D2** (b) and their 1 : 1 blend (c). Vertical bar marks the extraction maximum from which carrier mobility is calculated.

extraction, the electric field at which the carrier mobility is calculated is $E = A \times t_{\text{max}}/d$. The charge carriers are photo-generated with laser pulse of 355 nm since films are undoped with negligible amount of thermally generated charge carriers.

Usually the mobility of fast charge carriers is measured in the blends using time-resolved methods since it dominates the transient photocurrent. However, the photovoltaic performance of solar cells is limited by the slower carrier mobility which is the hole transport in bulk-heterojunction solar cells. We have intentionally measured the carrier mobility in pristine polymers and their 1 : 1 mixture but not in their blends with PCBM in order to find the relation between the carrier mobility and photovoltaic performances. Typical photo-CELIV extraction transients with initial capacitive current step and further extraction maximum are seen in both polymers (**D1**, **D2**) and their 1 : 1 mixture. From the extraction maximum the unequilibrium mobility of photogenerated charge carriers is calculated. Hole mobility in **D1** is $\mu = 1.8 \times 10^{-5} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (at electric field $\approx 18\,000 \text{ V cm}^{-1}$), in **D2** $\mu = 2 \times 10^{-6} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (at electric field $\approx 9400 \text{ V cm}^{-1}$) and in a 1 : 1 blend ratio $\mu = 2.6 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (at electric field $\approx 9600 \text{ V cm}^{-1}$). This CELIV result shows that when the two polymers are mixed they form a new intermolecular arrangement which is favorable to higher charge carrier mobility as compared to the individual polymers. This correlates well with the better photovoltaic performance of the ternary blend as compared to the individual binary blends.

In general, charge carrier transport is determined by the relation between material's chemical structure and film morphology. Surface roughness of polymer films shown in Fig. 5 indicates very little difference. However, the delicate differences in film structure and level of disorder might not be visible from AFM studies of film surface. In the past it has been observed that in contrast to polythiophenes, PPE-PPV structures demonstrate higher charge carrier mobility in the films with less degree of chain stacking.^{27a} Similarly, mixing of two polymers might disturb the chain stacking (since the polymer phase separate when mixed) and results in higher carrier mobilities. Another possible explanation for improved carrier mobility in the blends could be the change in film conductivity or polarizability, for which further studies are required.

Conclusion

Blending of two thiophene-based PPE-PPV polymers having identical conjugated backbone decorated with different volume fraction of hydrophobic alkoxy side chains has led to enhanced

charge carrier mobility and improved photovoltaic performance. This is proposed to be due to favourable intermolecular arrangement as revealed by AFM images.

Acknowledgements

Getachew Adam gratefully acknowledges the scholarship by the Austrian development cooperation (ÖAD). Daniel A. M. Egbe and Getachew Adam are also grateful to the *Deutsche Forschungsgemeinschaft* (DFG) for the financial support in the framework of the priority program SPP1355.

References

- (a) H. Hoppe and N. S. Sariciftci, *J. Mater. Res.*, 2004, **19**, 1924; (b) S. Guenes, H. Neugebauer and N. S. Sariciftci, *Chem. Rev.*, 2007, **107**, 1324; (c) G. Dennler, N. S. Sariciftci and C. J. Brabec, in *Semiconducting Polymers: Chemistry, Physics and Engineering*, 2nd edn, 2007, vol. 1, p. 455.
- A. J. Mozer and N. S. Sariciftci, *C. R. Chim.*, 2006, **9**, 568.
- H. Hoppe and N. S. Sariciftci, *Adv. Polym. Sci.*, 2008, **214**, 1.
- N. S. Sariciftci, L. Smilowitz, A. J. Heeger and F. Wudl, *Science*, 1992, **258**, 1474.
- G. Yu, J. Gao, J. C. Hummelen, F. Wudl and A. J. Heeger, *Science*, 1995, **270**, 1789.
- (a) H. Hoppe, D. A. M. Egbe, D. Mühlbacher and N. S. Sariciftci, *J. Mater. Chem.*, 2004, **14**, 3462; (b) N. Blouin, A. Michaud, D. Gendron, S. Wakim, E. Blair, R. N. Plesu, M. Belletete, G. Durocher, Y. Tao and M. Leclerc, *J. Am. Chem. Soc.*, 2008, **130**, 732; (c) J. H. Tsai, C. C. Chueh, M. H. Lai, C. F. Wang, W. C. Chen, B. T. Ko and C. Ting, *Macromolecules*, 2009, **42**, 1897; (d) J. N. Freitas, A. Pivrikas, B. F. Nowackic, L. C. Akcelrud, N. S. Sariciftci and A. F. Nogueira, *Synth. Met.*, 2010, **160**, 1654.
- (a) D. A. M. Egbe, B. Carbonnier, E. Birkner and U. W. Grummt, *Prog. Polym. Sci.*, 2009, **34**, 1023; (b) J. Chen and Y. Cao, *Acc. Chem. Res.*, 2009, **42**, 1709.
- (a) Y.-J. Cheng, S.-H. Yang and C.-S. Hsu, *Chem. Rev.*, 2009, **109**, 5868; (b) P. Troshin, H. Hoppe, J. Renz, M. Egginger, J. Mayorova, A. Goryachev, A. Pereguov, R. Lyubovskaya, G. Gobsch, N. S. Sariciftci and V. Razumov, *Adv. Funct. Mater.*, 2009, **19**, 779; (c) A. Palmaerts, L. Lutsen, T. J. Cleij, D. Vanderzande, A. Pivrikas, H. Neugebauer and N. S. Sariciftci, *Polymer*, 2009, **50**, 5007.
- (a) C. J. Brabec, A. Cravino, D. Meissner, N. S. Sariciftci, T. Fromherz, M. T. Rispens, L. Sanchez and J. C. Hummelen, *Adv. Funct. Mater.*, 2001, **11**, 374; (b) M. Scharber, D. Mühlbacher, M. Koppe, P. Denk, C. Waldauf, A. J. Heeger and C. J. Brabec, *Adv. Mater.*, 2006, **18**, 789.
- (a) H. Hoppe, T. Glatzel, M. Niggemann, W. Schwinger, F. Schaeffler, A. Hinsch, M. C. Lux-Steiner and N. S. Sariciftci, *Thin Solid Films*, 2006, **511**, 587; (b) C. Y. Yang and A. J. Heeger, *Synth. Met.*, 1996, **83**, 85; (c) X. Yang and J. Loos, *Macromolecules*, 2007, **40**, 1353.
- (a) J. Peet, M. L. Senatore, A. J. Heeger and G. C. Bazan, *Adv. Mater.*, 2009, **21**, 1521; (b) H. Hoppe and N. S. Sariciftci, *J. Mater. Chem.*, 2006, **16**, 45; (c) F. Padinger, R. S. Rittberger and N. S. Sariciftci, *Adv. Funct. Mater.*, 2003, **13**, 1.

- 12 (a) G. Li, V. Shrotriya, Y. Yao and Y. Yang, *J. Appl. Phys.*, 2005, **98**, 043704; (b) L. M. Chen, Z. H. G. Li and Y. Yang, *Adv. Mater.*, 2009, **21**, 1434; (c) N. Y. Canli, S. Günes, A. Pivrikas, A. Fuchsbauer, D. Sinwel, N. S. Sariciftci, O. Yasa and B. Bilgin-Eran, *Sol. Energy Mater. Sol. Cells*, 2010, **94**, 1089; (d) Y. Kim, S. Cook, S. M. Tuladhar, S. A. Choulis, J. Nelson, J. R. Durrant, D. D. C. Bradley, M. Giles, I. McCulloch, C.-S. Ha and M. Ree, *Nat. Mater.*, 2006, **5**, 197.
- 13 (a) A. J. Moule and K. Meerholz, *Adv. Mater.*, 2008, **20**, 240; (b) S. Cook, A. Furube and R. Katoh, *Jpn. J. Appl. Phys.*, 2008, **40**, 1238; (c) F. L. Zhang, K. G. Jespersen, C. Bjorstrom, M. Svensson, M. R. Andersson, V. Sundstrom, K. Magnusson, E. Moons, A. Yartsev and O. Inganas, *Adv. Funct. Mater.*, 2006, **16**, 667; (d) V. Shrotriya, Y. Yao, G. Li and Y. Yang, *Appl. Phys. Lett.*, 2006, **89**, 063505.
- 14 (a) P. Vanlaeke, G. Vanhoyland, T. Aernouts, D. Cheyns, C. Deibel, J. Manca, P. Heremans and J. Poortmans, *Thin Solid Films*, 2006, **511**, 358; (b) G. Li, V. Shrotriya, J. S. Huang, Y. Yao, T. Moriarty, K. Emery and Y. Yang, *Nat. Mater.*, 2005, **4**, 864; (c) V. D. Mihailetschi, H. Xie, B. de Boer, L. M. Popescu, J. C. Hummelen, P. W. M. Blom and L. J. A. Koster, *Appl. Phys. Lett.*, 2006, **89**, 012107.
- 15 (a) Y. Kim, S. A. Choulis, J. Nelson, D. D. C. Bradley, S. Cook and R. Durrant, *Appl. Phys. Lett.*, 2005, **86**, 063502; (b) S. E. Shaheen, C. J. Brabec and N. S. Sariciftci, *Appl. Phys. Lett.*, 2001, **78**, 841.
- 16 (a) A. Pivrikas, P. Stadler, H. Neugebauer and N. S. Sariciftci, *Org. Electron.*, 2008, **9**, 775; (b) J. Ouyang and Y. Xia, *Sol. Energy Mater. Sol. Cells*, 2009, **93**, 1592; (c) J. Peet, J. Y. Kim, N. E. Coates, W. L. Ma, D. Moses, A. J. Heeger and G. C. Bazan, *Nat. Mater.*, 2007, **6**, 496; (d) J. Peet, C. Soci, R. C. Coffin, T. Q. Nguyen, A. Mikhailovsky, D. Moses and G. C. Bazan, *Appl. Phys. Lett.*, 2006, **89**, 252105.
- 17 (a) H. Y. Chen, J. Hou, S. Zhang, Y. Liang, G. Yang, Y. Yang, L. Yu, Y. Wu and G. Li, *Nat. Photonics*, 2009, **3**, 649; (b) Y. Liang, Z. Xu, J. Xia, S. T. Tsai, T. Wu, G. Li, C. Ray and L. Yu, *Adv. Mater.*, 2010, **22**, 135.
- 18 C. H. Yang, J. Qiao, Q. J. Sun, K. J. Jiang, Y. L. Li and Y. F. Li, *Synth. Met.*, 2003, **137**, 1521.
- 19 F.-C. Chen, Q. Xu and Y. Yang, *Appl. Phys. Lett.*, 2004, **84**, 3181.
- 20 R. Bechara, N. Leclerc, P. L ev eque, F. Richard, T. Heiser and G. Hadziioannou, *Appl. Phys. Lett.*, 2008, **93**, 013306.
- 21 (a) Y. Kim, S. Cook, S. A. Choulis, J. Nelson, J. R. Durrant and D. D. C. Bradley, *Synth. Met.*, 2005, **152**, 105; (b) H. Kim, M. Shin and Y. Kim, *J. Phys. Chem. C*, 2009, **113**, 1620.
- 22 J. Y. Kim, K. Lee, N. E. Coates, D. Moses, T.-Q. Nguyen, M. Dante and A. J. Heeger, *Science*, 2007, **317**, 222.
- 23 Y. Kim, M. Shin, H. Kim, Y. Ha and C.-S. Ha, *J. Phys. D: Appl. Phys.*, 2008, **41**, 225101.
- 24 C.-H. Chen, C.-H. Hsieh, M. Dubosc, Y.-J. Cheng and C.-S. Hsu, *Macromolecules*, 2010, **43**, 697.
- 25 (a) A. Wild, D. A. M. Egbe, E. Birckner, V. Cimrova, R. Baumann, U.-W. Grummt and U. S. Schubert, *J. Polym. Sci., Part A: Polym. Chem.*, 2009, **47**, 2243; (b) D. A. M. Egbe, L. H. Nguyen, K. Schmidtke, A. Wild, C. Sieber, S. Guenes and N. S. Sariciftci, *J. Polym. Sci., Part A: Polym. Chem.*, 2007, **45**, 1619; (c) S. G enes, A. Wild, E. Cevik, A. Pivrikas, U. S. Schubert and D. A. M. Egbe, *Sol. Energy Mater. Sol. Cells*, 2010, **94**, 484.
- 26 (a) C. J. Brabec, A. Cravino, G. Zerza, N. S. Sariciftci, R. Kiebooms, D. Vanderzande and J. C. Hummelen, *J. Phys. Chem. B*, 2001, **105**, 1528; (b) R. J. Kline, D. M. DeLongchamp, D. A. Fischer, E. K. Lin, L. J. Richter, M. L. Chabinyc, M. F. Toney, M. Heeney and I. McCulloch, *Macromolecules*, 2007, **40**, 7960; (c) L.-S. Yu and S.-A. Chen, *Adv. Mater.*, 2004, **16**, 744.
- 27 (a) D. A. M. Egbe, S. T urk, S. Rathgeber, F. K uhnl enz, R. Jadhav, A. Wild, E. Birckner, G. Adam, A. Pivrikas, V. Cimrova, G. Kn or, N. S. Sariciftci and H. Hoppe, *Macromolecules*, 2010, **43**, 1261; (b) E. Tekin, D. A. M. Egbe, J. M. Kranenburg, C. Ulbricht, S. Rathgeber, E. Birckner, N. Rehmann, K. Meerholz and U. S. Schubert, *Chem. Mater.*, 2008, **20**, 2727.
- 28 (a) D. A. M. Egbe, E. Tekin, E. Birckner, A. Pivrikas, N. S. Sariciftci and U. S. Schubert, *Macromolecules*, 2007, **40**, 7786; (b) D. A. M. Egbe, C. Ulbricht, T. Orgis, B. Carbonnier, T. Kietzke, M. Peip, M. Metzner, M. Gericke, E. Birckner, T. Pakula, D. Neher and U.-W. Grummt, *Chem. Mater.*, 2005, **17**, 6022; (c) D. A. M. Egbe, C. P. Roll, E. Birckner, U.-W. Grummt, R. Stockmann and E. Klemm, *Macromolecules*, 2002, **35**, 3825.
- 29 (a) A. Pivrikas, N. S. Sariciftci, G. Juska and R. Osterbacka, *Progr. Photovolt.: Res. Appl.*, 2007, **15**, 677; (b) G. Dennler, A. J. Mozer, G. Juška, A. Pivrikas, R.  osterbacka, D. A. Fuchsbauer and N. S. Sariciftci, *Org. Electron.*, 2006, **7**, 229; (c) G. Juška, G. Sliuzys, K. Genevicius, K. Arlauskas, A. Pivrikas, M. Scharber, G. Dennler, N. S. Sariciftci and R.  osterbacka, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2006, **74**, 115314.
- 30 R.  osterbacka, K. Genevicius, A. Pivrikas, G. Juška, K. Arlauskas, T. Kreouzis, D. D. C. Bradley and H. Stub, *Synth. Met.*, 2003, **139**, 811.
- 31 (a) A. Pivrikas, G. Juška, A. J. Mozer, M. Scharber, K. Arlauskas, N. S. Sariciftci, H. Stubb and R.  osterbacka, *Phys. Rev. Lett.*, 2005, **94**, 76806; (b) G. Juška, K. Genevicius, G. Sliuzys, A. Pivrikas, M. Scharber and R.  osterbacka, *J. Appl. Phys.*, 2007, **101**, 114505; (c) G. Juška, K. Arlauskas, G. Sliuzys, A. J. Mozer, N. S. Sariciftci, M. Scharber and R.  osterbacka, *Appl. Phys. Lett.*, 2005, **87**, 222110.
- 32 C. Vijila, A. Pivrikas, H. Chun, C. Zhikuan, R.  osterbacka and C. S. Jin, *Org. Electron.*, 2007, **8**, 8.
- 33 G. Sliuzys, G. Juska, K. Arlauskas, A. Pivrikas, R.  osterbacka, M. Scharber, A. Mozer and N. S. Sariciftci, *Thin Solid Films*, 2006, **224**, 511.
- 34 (a) A. Pivrikas, R.  osterbacka, G. Juska, K. Arlauskas and H. Stubb, *Synth. Met.*, 2005, **155**, 242; (b) A. Pivrikas, G. Juska, K. Arlauskas, M. Scharber, A. Mozer, N. S. Sariciftci, H. Stubb and R.  osterbacka, *Proc. SPIE*, 2005, **5938**, 59380.
- 35 (a) A. J. Mozer, G. Dennler, N. S. Sariciftci, M. Westerling, A. Pivrikas, R.  osterbacka and G. Juška, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2005, **72**, 035217; (b) R.  osterbacka, A. Pivrikas, G. Juska, K. Genevicius, K. Arlauskas and H. Stubb, *Curr. Appl. Phys.*, 2004, **4**, 534; (c) M. Ullah, I. I. Fishchuk, A. Kadashchuk, P. Stadler, A. Pivrikas, C. Simbrunner, V. N. Poroshin, N. S. Sariciftci and H. Sitter, *Appl. Phys. Lett.*, 2010, **96**, 213306.
- 36 A. J. Mozer, N. S. Sariciftci, A. Pivrikas, R.  osterbacka, G. Juška, L. Brassat and H. B assler, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2005, **71**, 035214.
- 37 A. Pivrikas, G. Juška, R.  osterbacka, M. Westerling, M. Viliunas, K. Arlauskas and H. Stubb, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2005, **71**, 125205.
- 38 A. Pivrikas, *Charge Transport and Recombination in Bulk-Heterojunction Solar Cells*, Doctoral thesis,  aboAkademi University, 2006, ISBN 952-12-1786-3.