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Abstract

Small-molecule photovoltaic cells using diindenoperylene (DIP) as new donor material in combination with the fullerene C₆₀ as electron acceptor are demonstrated. In addition to the successful application in planar and bulk heterojunction devices a comprehensive analysis including structural studies, the determination of the energy level alignment and electrical transport investigations is given, stressing the correlation between growth conditions, film morphology and device performance. Due to pronounced crystallinity and large surface area of DIP films grown at elevated temperature exceptionally high fill factors of almost 75 % are

achieved in planar heterojunction cells. Bulk-heterojunctions exhibit large-scale phase separation forming to a bicontinuous network of both molecular species which enables efficient exciton dissociation and charge carrier transport. The high ionization potential of DIP and the favorable energy level alignment with the fullerene C₆₀ yield large open circuit voltages close to 1 V and comparable power conversion efficiencies of about 4 % in both cell architectures.

1. Introduction

Energy conversion utilizing organic semiconductors in photovoltaic cells has been under investigation since the 1970s.^[1] After poor success with metal-organic Schottky junctions, a seminal step towards more efficient organic photovoltaic cells (OPVC) was made by Tang in 1986,^[2] who laid the foundation for effective exciton-dissociation with the invention of the donor-acceptor heterojunction concept. Since then, many different approaches for increasing the power conversion efficiency have been proposed: Amongst others, the realization of bulk heterojunctions (BHJ) from solution processed polymer-fullerene mixtures,^[3,4] which reduces the exciton diffusion bottleneck by creating an interpenetrating network of donor and acceptor materials, has proven extremely successful. In recent years power conversion efficiencies under simulated sunlight conditions exceeding 7 % have been achieved.^[5, 6, 7] In spite of its obvious advantage to facilitate exciton dissociation and charge carrier generation, which is otherwise limited by small exciton diffusion length in organic semiconductors, the BHJ concept, however, also has some disadvantages: Blends of electronically different materials often show reduced charge carrier mobility, as compared to the neat electron and hole transporting materials^[8,9], and enhanced recombination losses, leading to reduced fill factor (FF) and open circuit voltage (V_{OC}) in solar cells.^[10, 11]

In the area of molecular OPVC materials, which are in the focus of this work, bulk-

heterojunctions have been realized with a number of different donor-acceptor combinations.

Classical examples are the metal-phthalocyanines (Pc), such as CuPc or ZnPc, pentacene or oligothiophenes as donors in combination with C₆₀ as acceptor or perfluorinated analogues of

these donor molecules.^[12,13,14,15] However, due to the afore mentioned limitations regarding

charge transport in organic semiconductor blends (see e.g. the detailed studies on CuPc:C₆₀

mixtures in field-effect transistors^[9] and diodes^[8,16]), molecular BHJ cells usually exhibit

significantly smaller layer thickness and thus less light absorption as compared to their

polymeric counterparts. Consequently, the planar heterojunction (PHJ) remains a viable

alternative in the context of small molecule OPVCs, in particular, since these materials are

deposited from the vapor phase which allows for preparing well-defined multilayer structures.

The optimization of deposition parameters, like substrate temperature and evaporation rate,

allows growing films with higher crystallinity, resulting in better transport of both charge

carriers and excitons, which in turn is the prerequisite for utilizing larger layer thickness for

improved light harvesting. Additionally, since recombination in PHJ is limited to the narrow

interfacial region (or the contacts), these cells have the potential for higher fill factors in

comparison to BHJ solar cells.

Besides optical absorption as well as transport and recombination properties, a decisive

parameter is the open circuit voltage (V_{OC}) of a solar cell, which is given by the splitting of

the quasi-Fermi levels of electrons and holes under illumination. It has been shown

convincingly for polymeric solar cells that there is a direct relation between V_{OC} and the

energy-level offset at the donor-acceptor heterojunction, i.e. in first order approximation the

difference between the highest occupied molecular orbital (HOMO) level of the donor and the

lowest unoccupied molecular orbital (LUMO) level of the acceptor or, if the exciton binding

energy is considered, the energy of the intermolecular charge transfer state resulting from

exciton dissociation.^[17] The importance of this restrictive aspect can be demonstrated using the example of the wide-spread material system C₆₀/CuPc, where many of the traditional small molecule solar cells are based on. In spite of advantages such as efficient light harvesting due to the high absorption coefficient of CuPc over a broad spectral range, as well as the large acceptor strength of the fullerene^[18], the overall quantum efficiency is to some extent limited by the low open circuit voltage not exceeding 0.6 V.^[19,20,21,22] The reason for this limitation can be found in the small intermolecular HOMO-LUMO gap of only ca. 1 eV.^[23]

In this paper we present photovoltaic cells based on the new donor material diindenoperylene (DIP) in combination with the fullerene C₆₀ as acceptor. The chemical structure of DIP and the absorption spectra of DIP and C₆₀ are depicted in **Fig. 1**. DIP has been shown to exhibit almost balanced transport of electrons and holes along the *c'* direction in single crystals^[24] and remarkably high exciton diffusion lengths of up to 100 nm^[25] – although the magnitude of the exciton diffusion length and its unique determination in thin films is still under discussion.^[26,27,28] It was further reported that DIP exhibits exceptionally high structural order in evaporated thin films, with molecules standing almost upright with their long axis aligned parallel to the surface normal on inert substrates.^[29] This, in turn, confirms the large exciton diffusion length as there is a correlation between structural coherence length and exciton diffusion length.^[30] Moreover, it was shown that these films exhibit a high hole mobility of up to 0.1 cm² V⁻¹ s⁻¹ in field-effect transistor geometry, i.e., parallel to the substrate surface.^[31] To our knowledge, however, DIP has not yet been investigated in photovoltaic cells. Only recently, a similarly constructed aromatic molecule, tetraphenyldibenzoperiflanthene (DBP), was used in planar heterojunction OPVCs exhibiting an open-circuit voltage of 0.9 V and power conversion efficiencies of up to 3.6 %, ^[32] but no correlations to film morphology, energy level alignment and transport properties are available for this material. High values for

V_{OC} (close to 1 eV) were also achieved using low bandgap oligothiophenes (DCVnT) as donor material when combined with C_{60} as acceptor.^[33,34] Even higher open circuit voltages reaching 1.5 V have been obtained when blending suitable electron-donating and accepting polymers, however, often showing low fill factors.^[35,36,37, 38]

In the following we will discuss the influence of the substrate temperature during film growth on the morphology and structural ordering of DIP films on solar cell relevant substrates.

Thereafter, we will present results on the energy level alignment in photovoltaic cells with C_{60} as acceptor and demonstrate how this affects the electrical characteristics of single junctions both in the dark and under illumination before comparing the performance of planar and bulk heterojunction cells under simulated sunlight conditions.

2. Morphological and structural investigation

For materials with short exciton diffusion length the morphology is a crucial parameter as it determines on the one hand the magnitude of the photoactive volume where excitons can be efficiently dissociated. On the other hand, even in a blend with large interfacial area the successful formation of percolation paths in the donor and acceptor material is a prerequisite for efficient charge carrier collection towards the electrodes.^[39] Furthermore, transport properties of both excitons and charges are strongly correlated to the crystalline order of the involved materials. We have therefore grown DIP films at different substrate temperatures and investigated their morphological and structural properties in neat films as well as in heterostructures covered with C_{60} and in blends where DIP and C_{60} were coevaporated.

Figure 2 shows the surface topography (from atomic force microscopy (AFM)) of 50 nm thick DIP films evaporated on tin-doped indium oxide (ITO)-coated glass substrates covered with a hole injection layer of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), which were heated to different temperatures during evaporation. We note that all PEDOT:PSS films heated to different temperatures showed smooth, featureless topography

as probed by AFM. The surface of DIP grown on the unheated substrate (Fig. 2a) indicates growth of small islands with about 80 nm in diameter. When heating the substrate to 100 °C during evaporation the surface morphology changes to a cohesive microstructure with extended crystallites (Fig. 2c). More importantly, the DIP film grown at 100 °C has a large surface area which is expected to be favorable for solar cells. DIP films evaporated at an intermediate substrate temperature of 60 °C show a surface morphology that appears in between those evaporated on the unheated and the 100 °C substrate (Fig. 2b). Evaporating C₆₀ on top of these DIP films yields small C₆₀ domains with diameters of about 25-30 nm which are adapting to the underlying morphology of the DIP film (Fig. 2e-g). Coevaporation of both materials (with the substrate at 100 °C) leads to a spongiform basic structure (Fig. 2d) composed of large interconnected features resembling the neat DIP film grown at 100 °C as well as smaller crystallites on top (see enlarged figure 2h) reminiscent of C₆₀ grown on top of DIP. This observation already points to phase separation in the coevaporated film which will be confirmed in the following. An additional indication for phase separation in the coevaporated film is given by the absorption spectrum of the mixed film (Fig. 1), which resembles an additive superposition of the individual spectra even though roughness and reflection have not been taken into account.

In order to detect crystalline order and quantitatively determine the spatial coherence length of the observed structures, X-ray diffraction (XRD) measurements were performed. In specular diffraction the momentum transfer \mathbf{q} is parallel to the surface normal (i.e., $\mathbf{q} = (0,0,q_z)$, see sketch in **Fig. 3**, thus probing the electron density profile along that direction. Bragg peaks are analyzed by means of the peak centre position q_z and the full width at half maximum of the peak, Δq_z . The corresponding lattice spacing is determined as $d = 2\pi/q_z$, whereas a lower limit for the domain size is given by $D = 2\pi/\Delta q_z$.^[40] Figure 3 shows X-ray reflectivity data of neat DIP films (40 nm), bilayered structures of C₆₀ (20 nm) atop of DIP (20 nm) and mixed films

substrates. The DIP films and the mixed C₆₀:DIP layers were deposited at substrate temperatures of 25 °C and 100 °C, respectively. For all samples, Bragg reflections at $q_z = 0.378 \text{ \AA}^{-1}$ associated with a DIP lattice plane spacing of $d_{\text{DIP}} = 16.6 \text{ \AA}$ are observed. From this it is deduced that crystalline domains with DIP molecules standing almost upright are formed on PEDOT:PSS/ITO (tilt angle $\Phi \approx 17^\circ$,^[41] denoted as σ -phase^[29,40]) as schematically sketched in Fig. 3. The upright standing arrangement of the DIP molecules is consistent with the low absorption coefficient of neat DIP films (see Fig.1), as the transition dipole moment of the fundamental molecular absorption is aligned along the long molecular axis and thus unfavorably oriented for efficient absorption of light under normal incidence. DIP Bragg reflections from films evaporated at 100 °C are more intense compared with films grown at room temperature, which is a clear evidence for higher crystallinity.

In contrast to previous studies on neat C₆₀ films evaporated on PEDOT:PSS/ITO^[16] the XRD spectra of C₆₀ evaporated on DIP (grown at substrate temperatures of 25 °C and 100 °C) show comparatively pronounced Bragg reflections of C₆₀ at $q_z \approx 0.775 \text{ \AA}^{-1}$ superimposed with the DIP(002) reflection. This exceptional behavior may be attributed to improved growth properties of C₆₀ on top of the well ordered DIP structure. Laue oscillations around the DIP(001) Bragg reflections of the neat DIP film and the C₆₀/DIP bilayer structure are clear evidence for coherently ordered domains, whose magnitude correspond to the whole DIP layer thickness in both cases. Mixed DIP:C₆₀ layers show the same DIP Bragg peak positions as neat DIP, which confirms the appearance of phase separation in coevaporated films. However, there is no measurable C₆₀ Bragg reflection in the blends, which indicates low out-of-plane order for C₆₀ crystallites. Nevertheless, the comparably narrow width Δq_z of the DIP(001) Bragg peak in the mixture corresponds to a coherence length of $D \approx 45 \text{ nm}$, which is approximately equal to the entire layer thickness, indicating that crystalline DIP domains

extend throughout the whole film. This is in full agreement with AFM measurements (cf.

Fig. 2) depicting the blend of DIP and C₆₀ as cohesive structures of DIP with small C₆₀ crystallites in between. Further details including grazing incidence X-ray diffraction data are given in section A of the Supporting Information.

3. Electronic structure

DIP and C₆₀ thickness dependent UPS (ultraviolet photoelectron spectroscopy) investigations of sample structures as they are used in OPVCs were performed in order to assess the energy level alignment in these devices. Two different commercially available PEDOT:PSS containing formulations were used: Clevios™ P AI4083 (designated as PEDOT:PSS) and Clevios™ HIL1.3 (designated as HIL1.3) providing two hole injection layers (HIL) with different work functions (see below). Specifically, the material sequences (i) C₆₀/DIP/PEDOT:PSS, (ii) C₆₀/DIP/HIL1.3 and (iii) C₆₀:DIP(codeposited)/PEDOT:PSS were chosen. While (i) and (iii) allow to compare energy levels in PHJ and BHJ structure, (ii) allows the determination of the positive pinning level of DIP and the electronic structure at the interface to the hole extracting electrode in the pinning regime,^[42] because HIL1.3 has a higher work function as compared to the standard PEDOT:PSS (see also section B of the Supporting Information).

Fig. 4a and **b** show thickness dependent UPS spectra (only one monolayer and one multilayer spectrum are shown for clarity) of the planar heterojunction (PHJ) interface of C₆₀/DIP formed on PEDOT:PSS, with an initial conducting polymer work function of 4.9 eV (secondary electron cut-off (SECO) spectra in Fig. 4a). The deposition of DIP on PEDOT:PSS does not change the sample work function, i.e., no interfacial dipole is formed, indicating that energy level pinning of DIP does not yet occur at this electrode work function. No sample work function change is observed at the C₆₀/DIP interface as well, i.e., vacuum level alignment at this donor/acceptor interface is valid. From the valence region spectra

(Fig. 4b) we infer that the low binding energy (BE) onset of the DIP HOMO directly at the interface (1.6 nm coverage) to PEDOT:PSS and for the multilayer (10 nm coverage) is at the same distance from the Fermi-Energy E_F , with a value of 0.45 eV. This value corresponds to the hole injection barrier at the electrode-donor interface and, adding the sample work function of 4.9 eV, yields a DIP ionization energy of 5.35 eV. The valence spectra for C_{60} on 10 nm DIP/PEDOT:PSS show that the low BE onset of the acceptor HOMO is at 1.50 eV, both for the C_{60} mono- and multi-layer. Consequently, the HOMO offset between the donor DIP and the acceptor C_{60} at this interface is 1.05 eV.

The energy level alignment at the C_{60} /DIP interface is unchanged when using the high work function HIL1.3 as electrode, i.e., vacuum level alignment prevails and the HOMO offset is 1.05 eV (see section B of the Supporting Information). However, the interface energetics between HIL1.3 and DIP are markedly different from DIP/PEDOT:PSS. Upon DIP deposition the sample work function changes from 5.70 eV (pristine HIL1.3) to 4.9 eV (see Supporting Information). This observation is consistent with pinning of the DIP energy levels due to the high initial work function of HIL1.3. Because the work function of multilayer DIP on both PEDOT:PSS and HIL1.3 is identical (4.9 eV), we can conclude that this is the critical substrate work function for energy level pinning of DIP.^[42] We note that the work function of both HILs, in particular PEDOT:PSS, depends critically on the residual water content in the conductive polymer film; with decreasing water content, e.g., induced by film annealing in vacuum, the work function increases up to 5.6 eV.^[43] Therefore, it is reasonable to argue that DIP/PEDOT:PSS contacts in devices fabricated at elevated substrate temperatures exhibit lower contact resistance. The energy level structure at C_{60} /DIP/HIL interfaces is schematically summarized in **Fig. 5a**, where the energy levels highlighted in red only occur when HIL1.3 is used. The C_{60} /DIP interface energetics relevant for PHJ devices are identical for both PEDOT:PSS formulations. Assuming a transport gap for C_{60} of 2.3 eV^[44] and for DIP of

2.5 eV^[45], the offset between the DIP HOMO and the C₆₀ LUMO is 1.25 eV, which is an estimate of the maximum achievable open circuit voltage in OPVCs.^[46]

In Fig. 5b we show the energy level alignment for bulk heterojunction C₆₀:DIP, obtained by co-deposition of donor and acceptor material (1:1 ratio) on PEDOT:PSS. The energy levels are almost identical to the PHJ case, only the low BE onset of the HOMO level of C₆₀ is found 0.1 eV closer to E_F, as inferred from a fitting routine of the mixed film UPS spectra by summation of pristine C₆₀ and DIP spectra (Fig. 5c). Consequently, the HOMO offset for the BHJ is 0.95 eV, and the offset between the DIP HOMO and the C₆₀ LUMO is 1.35 eV. Thus, compared to the intermolecular HOMO-LUMO gap of the planar configuration (1.25 eV) similar values for V_{OC} are expected in PHJ and BHJ solar cells.

4. Electrical characterization - dependence on growth conditions

To demonstrate the importance of film growth conditions, we investigated the current-voltage (*j*-*V*) characteristics of nominally planar heterojunctions between DIP (grown at different substrate temperature) and C₆₀ evaporated on top (with the underlying DIP film then kept at room temperature). This allows for a direct comparison between film morphology and the resulting electrical properties in a solar cell architecture. The structure of the investigated PHJ cells is Al(100nm)/ LiF (lithium fluoride, 0.5nm)/ C₆₀(80nm)/ DIP(50nm)/ PEDOT:PSS/ ITO, with DIP evaporated at substrate temperatures of 25 °C, 60 °C, and 100 °C.

Figure 6 shows the *j*-*V* characteristics for the cells in dark (dashed lines) and under one sun simulated AM1.5G solar illumination (solid lines). In the following discussion we focus on the shape of the *j*-*V* characteristics in the forward bias regime. A detailed analysis with regard to photovoltaic properties of planar and bulk heterojunction solar cells will be the subject of section 5. All different substrate temperatures yield short circuit current densities (*j*_{sc}) in the range between -0.8 and -1.2 mA cm⁻² and V_{OC} between 0.85 V and 0.92 V. The *j*-*V* characteristics of the device where DIP was grown at room temperature are strongly affected

by an S-shape behavior, i.e. they show a decrease of the current close to the open-circuit

voltage, which will reduce the fill factor in a solar cell, and also very low current above V_{OC} .

This feature decreases continuously when heating the substrate to higher temperatures during DIP deposition and vanishes completely for the device with DIP grown at 100 °C.

The occurrence of the undesired S-shape in the current-voltage characteristics under illumination is correlated to suppressed forward currents being apparent already in the dark j - V characteristics, as displayed in Fig 6b on a semi-logarithmic scale.

The forward-bias characteristics can be fitted (solid lines) using the modified Shockley equation:^[47]

$$j = j_s \left\{ \exp \left[\frac{e(V - jR_s)}{nkT} \right] - 1 \right\}, \quad (1)$$

where j_s is the reverse-bias saturation current density, n the ideality factor, e the electron charge, R_s a series resistance, k Boltzmann's constant, and T the temperature. The slope of the j - V characteristics in the exponential regime depends on j_s and the ideality factor n . In our devices we find an ideality factor of about 1.5 for the planar heterojunction diode with DIP evaporated at a substrate temperature of 100 °C. For the other substrate temperatures the determination of n is difficult due to the presence of the leakage currents. The most noticeable difference in the dark j - V characteristics, however, is the continuous decrease of the series resistance R_s when the substrate temperature during DIP evaporation is raised. Thus, R_s decreases by almost three orders of magnitude from 42 kΩ at room temperature to 55 Ω at 100 °C substrate temperature, causing the systematic decline of the S-shape in the j - V curves until complete vanishing at 100 °C.

S-shaped solar cell characteristics have recently gained more and more attention in the literature and are commonly ascribed to energetic injection and extraction barriers between the photoactive layer system and the electrodes.^[48,49,50] In the present case, the S-shaped

characteristics are clearly connected to the growth temperature of the DIP layer. Together with the arguments given in the previous section for a reduction of the hole injection barrier on heated PEDOT:PSS and DIP layer thickness variations (not shown here) it indicates the decisive role of charge carrier injection and transport in DIP, which are both drastically improved when the substrate is heated to 100 °C.

5. Application of DIP in solar cells

The applicability of DIP as donor material has already been demonstrated in the previous section, although the focus was more on the transport behavior of DIP films evaporated at different substrate temperatures. For a detailed analysis of photovoltaic properties the device stack using DIP and C₆₀ as photoactive materials was extended by an additional exciton blocking material bathocuproine (BCP). The beneficial effect of BCP on solar cell performance has been demonstrated by various studies, all describing its property to prohibit quenching of excitons at the electrode and to act as diffusion barrier for Al and as protection layer to eliminate the creation of Al-induced defect states in C₆₀.^[51,52,53]

Planar as well as planar-mixed heterojunction (PM-HJ) devices with different thicknesses of the organic layers have been fabricated and compared to each other. The PM-HJ is a combination of a strict planar heterojunction and a mixed layer bulk-heterojunction within the same structure and is known to unify the benefits of both concepts.^[54] Thus, it takes maximum advantage of the unhindered charge carrier collection properties of neat organic layers, and the improved exciton dissociation properties of films consisting of a mixture of donor and acceptor materials. The exact layer sequences of the investigated PHJ solar cells (device **A** and **C**) and the PM-HJ cells (device **B** and **D**) are given in **Fig. 7a**. According to the above discussed electrical properties of C₆₀/DIP heterojunctions dependent on different substrate temperatures, the investigation of photovoltaic properties is restricted to cells where DIP and mixed C₆₀:DIP films were deposited on substrates heated to 100 °C.

The obtained current density-voltage (j - V) characteristics under one sun simulated AM1.5

illumination are shown in Fig. 7b and the corresponding photovoltaic parameters are

summarized in **Table 1**. In general, all four devices show almost identical open-circuit voltage

V_{OC} slightly above 0.9 V and differ only in their short-circuit currents j_{SC} and fill factors (FF).

The short-circuit currents are considerably higher in the PM-HJ solar cells (devices **B** and **D**)

as compared to the corresponding PHJ structures (devices **A** and **C**). Excitons which are

created in the mixed layer are always in proximity of a donor-acceptor interface and can thus

easily be dissociated. Furthermore, excitons created in the adjacent layer of neat DIP may also

contribute to the photocurrent, as the layer thicknesses of 5 and 15 nm are well below the

exciton diffusion length.^[25]

Successful realization of the bulk heterojunction concept requires the formation of percolation

pathways inside the mixed film, which is necessary for efficient charge carrier transport. From

the morphological and structural analysis of mixed C₆₀:DIP films (see section 2) it can be

deduced that both materials exhibit phase separation in the blend and form percolation paths

for both carrier types. However, the decrease in j_{SC} from device **B** to **D** demonstrates the

limits of the bulk heterojunction concept: with the increase in layer thickness, recombination

losses due to the presence of both phases in close proximity exceed the gain in absorption

efficiency and finally reduce j_{SC} .^[55,56]

Comparing the PHJ devices **A** and **C**, j_{SC} is markedly increased from device **A** to device **C**

due to the larger film thicknesses of DIP and C₆₀ in device **C**, leading to improved absorption

of incoming light and exciton generation. The essential requirement for this enhancement is

the high crystallinity and the concomitant large exciton diffusion length of DIP, facilitating

efficient charge carrier dissociation and collection, respectively, even for enlarged film

thickness.

The second parameter, in which the investigated cells differ in a characteristic way, is the fill factor. Both PHJ cells have a higher FF than the PM-HJ devices, at least at high light intensities (further details are given in section C of the Supporting Information) and in particular for the thick PHJ device **C** it reaches exceptionally high values exceeding 74 % at one sun. This is - to the best of our knowledge - one of the highest fill factors observed for organic small molecule solar cells. It indicates highly efficient charge carrier transport towards the electrical contacts with little recombination losses^[56] - despite of comparatively thick layers - as well as unhindered charge carrier extraction without energetic barriers.^[12,48] The fill factors of both PM-HJ cells are significantly below the values of device **C**, peaking at light intensities of about 10 mW cm^{-2} (device **B**: 58 %, device **D**: 55 %). Inherently higher bulk recombination and lower carrier mobility in the mixed layer probably limit charge collection efficiency and thereby the FF of these devices.^[10,11]

As already mentioned, all devices reach open circuit voltages in excess of 0.9 V at one sun simulated AM1.5 illumination (see also section C of the Supporting Information). Thereby the V_{OC} of device **C** is slightly higher than for the other three devices. It is remarkable that the PM-HJ devices **B** and **D** reach almost the same values as the best PHJ device, while pure bulk-heterojunction devices (not shown here) have lower V_{OC} (0.6 - 0.7 V). This can be seen as a further advantage of the hybrid PM-HJ concept over the BHJ device: in the latter V_{OC} may be limited by the built-in voltage V_{BI} , because recombination of charge carriers at the interface between an electrode and the mixed layer immediately sets in as soon as the applied voltage exceeds V_{BI} .^[48] The neat donor and acceptor layers encompassing the mixed layer in the PM-HJ cell suppress this direct recombination and thus enable V_{OC} to reach values as high as for PHJ devices.

The comparison of different device architectures shows that power conversion efficiency around $\eta_{PCE} \approx 4 \%$ can be reached with a hybrid planar-mixed heterojunction structure with

BCP as exciton blocking layer. Nevertheless, the hybrid PM-HJ cell suffers from transport losses in the mixed layer, which limit the FF to values not exceeding 53 % at one sun. As compared to this PM-HJ structure, the lower current in the planar heterojunction cells is almost completely compensated by their extremely high FF achieving equally high power conversion efficiency.

Finally, we would like to discuss the performance of the investigated cells in comparison to C₆₀/CuPc, which is a widely used prototype small molecule OPVC system.^[20,45,57,58,59] For that purpose we have put together solar cell parameters obtained by us on C₆₀/CuPc devices fabricated and measured under comparable conditions (see **Table 1**, lines 5 and 6).

The most prominent difference is the open-circuit voltage being only about 0.5 V for C₆₀/CuPc cells. Theoretically the maximum value of V_{OC} is related to the difference between the HOMO energy of the donor and the LUMO level of the acceptor, minus the binding energy of the dissociated, geminate electron-hole pair.^[46] Comparing the energy level alignment for C₆₀/DIP cells as discussed in section 3 and as reported by us in Ref. [23] for C₆₀/CuPc one comes to the conclusion that both from the point of view of the HOMO-LUMO gap at the DA interface as well as the built-in voltage, resulting from the differences in the effective electrode work functions, C₆₀/DIP cells are expected to have an open-circuit voltage that is approximately larger by 0.5 V – fully consistent with the experimentally observed numbers.

Regarding the short-circuit currents both types of C₆₀/CuPc cells are clearly ahead of the corresponding DIP based devices, however, this is simply related to the larger absorption coefficient of CuPc (peak value 20.6 μm^{-1} ^[45]) and the better spectral coverage in the long wavelength range (bands in the range 550-780 nm^[45]). Given the fact that the maximum absorption coefficient of DIP in the visible spectral range (420-580 nm) is about four times

lower than for CuPc, the reduction of the photocurrent (by only about 25 %) for DIP cells is remarkably small and points towards very good carrier collection.

The lower fill factors for C₆₀/CuPc are indicative for stronger recombination losses in this material system. This can be ascribed to a significantly lower hole mobility in neat CuPc as compared to DIP^[31,60] and to a further reduction of the mobility in C₆₀:CuPc blends due to the small scale phase separation (see Ref. [45]). By contrast, the morphology of the DIP phase in both architectures (PHJ and PM-HJ) is characterized by large, cohesive crystalline structures, allowing for favorable transport properties and thus less recombination losses.^[61]

6. Conclusions

In conclusion, we have presented a comprehensive analysis of the new donor material diindenoperylene (DIP) in combination with the fullerene C₆₀ ranging from growth studies and energy level alignment via electrical transport properties and finally to its successful application in organic solar cells. Our studies emphasize the crucial influence of the substrate temperature during DIP film growth on the morphology and thus the overall performance of DIP based photovoltaic cells. Growth at elevated temperature leads to the formation of a cohesive network of crystalline DIP domains, yielding a large surface area that can be covered with C₆₀ molecules in planar heterojunctions, or to a phase separated bicontinuous network in bulk-heterojunctions when DIP and C₆₀ are coevaporated. Favorable film morphology together with high crystalline order allows for improved transport properties of both excitons and charges in photovoltaic cells. The main advantage of DIP can be found in its high ionization potential and the favorable energy level alignment with both the PEDOT:PSS electrode and the C₆₀ acceptor leading to high open circuit voltages of up to 0.93 V under 100 mW cm⁻² simulated AM1.5G illumination. Simply stacked PHJ devices – devoid of doped transport layers - yield remarkably high fill factors up to 74 % and a power conversion efficiency close to 4 %.

For future work, it will be important to improve the absorption properties of films

incorporating DIP as donor material while keeping its good transport properties and favorable energy level alignment with C₆₀. One promising strategy might be found in modifying the orientation of the molecules: Achieving flat lying DIP molecules (so-called λ -phase^[40]) could yield an increase in the absorption coefficient by a factor of ~ 6 ^[62] holding a large potential for further increasing solar cell efficiencies. Furthermore, the combination with a second donor-acceptor system absorbing in the longer wavelength range in a tandem cell could boost power conversion efficiencies to application relevant values.^[63,64,65,66]

7. Experimental

Photovoltaic cells were fabricated on commercially available photolithographically structured tin-doped indium oxide (ITO)-coated glass substrates (Merck, sheet resistance per square $< 10 \Omega$) which were subsequently cleaned in ultra sonic bath with acetone and isopropanol prior to processing. An oxygen plasma treatment was implemented to improve wettability for the aqueous suspension of the intrinsically conducting polymer poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS in a ratio of 1:6 by weight, purchased from H.C. Starck as Clevios™ P AI4083). The polymer was deposited via spin coating, and annealed at 125 °C for 45 minutes under ambient conditions.

DIP (purchased from W. Schmidt Institut für PAH-Forschung) and C₆₀ (purchased from Creaphys) have been twice purified by vacuum gradient sublimation prior to use, while BCP (purchased from Acros Organics) was used as-received. Materials were sequentially grown by vacuum thermal evaporation at base pressures of 10^{-6} - 10^{-7} mbar with the following rates: DIP (0.5 Ås^{-1} in neat film, 0.3 Ås^{-1} in blend), C₆₀ (0.5 Ås^{-1} in neat film, 0.3 Ås^{-1} in blend), BCP (0.2 Ås^{-1}), LiF (0.2 Ås^{-1}), and Al (1 Ås^{-1}). The metal cathodes (typically 1000 Å thick) were evaporated through a shadow mask resulting in solar cells with an area of 4 mm². The

entire cell preparation as well as the electrical measurements has been performed without air exposure; i.e. under inert gas atmosphere or in vacuum.

Current-voltage characteristics were recorded using a source measure unit (Keithley 236 SMU) in dark and under illumination with a solar simulator (Oriel 150W with AM 1.5G filters). The illumination intensity was approved by a calibrated silicon reference cell (RERA systems, PV Measurement Facility, Radboud University Nijmegen, area $1 \times 1 \text{ cm}^2$).

Nevertheless, as the perfect homogeneity of the light beam cannot be guaranteed, the power conversion efficiency of our OPVCs with an area smaller than the reference cell might be slightly overestimated. Furthermore, the measured photocurrents have not been corrected for spectral mismatch.

Absorption spectra were obtained from transmission measurements of organic films grown on transparent substrates using a Varian Cary 50 UV-Vis spectrophotometer with a spectral range from 280 to 1000 nm. AFM measurements were performed using a Thermo Microscopes Autoprobe CP-Research in non-contact mode. X-ray reflectivity measurements were conducted on a GE/Seifert X-ray diffractometer ($\text{Cu K}\alpha_1$ radiation, multilayer mirror, and double bounce compressor monochromator). Grazing incidence X-ray diffraction measurements were performed on the X04SA beamline at the Swiss Light Source, Paul Scherrer Institut, Villigen, Switzerland (12 keV photon energy). X-ray scattering, AFM, and optical absorption measurements were performed under ambient conditions on solar cell relevant substrates.

Ultraviolet photoelectron spectroscopy (UPS) measurements were performed at the endstation SurICat at the synchrotron radiation source BESSY II - HZB. Spectra were recorded with a hemispherical energy analyzer (resolution set to 100 meV) with 35 eV photon energy. The secondary electron cut-off (SECO) was recorded with the sample biased at -10 V to clear the analyzer work function. By repeated measurements performed with the samples kept in dark

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 and with additional visible light illumination we established that sample charging did not occur. Two different hole injection layers were used in the UPS experiments: Clevios™ P AI4083 (designated as PEDOT:PSS) and Clevios™ HIL1.3 (designated as HIL1.3) as a PEDOT-containing dispersion for HILs provided by H.C. Starck [67]. Both hole injection layers were deposited on cleaned ITO via spin coating, and annealed at 200 °C for 5 minutes under ambient conditions. Samples were introduced subsequently into UHV conditions where deposition of C₆₀ and DIP followed (substrates at room temperature), from resistively heated crucibles with evaporation rates of ca. 1 Å min⁻¹. The film thickness was monitored with a quartz crystal microbalance. Sample transfer between preparation chamber (base pressure < 3×10⁻⁸ mbar) and analysis chamber (base pressure 1×10⁻¹⁰ mbar) was done without breaking UHV conditions.

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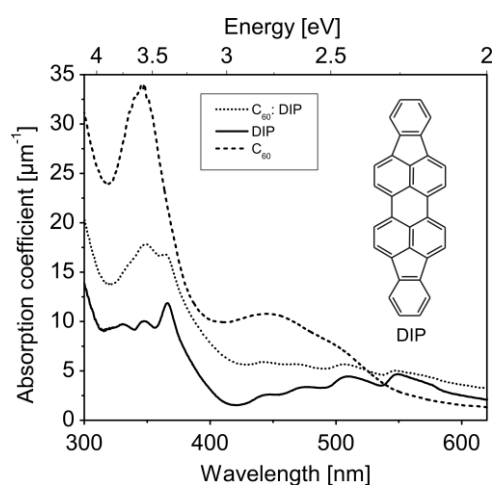


Figure 1. Absorption spectra of neat films of DIP and C_{60} and a coevaporated C_{60} :DIP film (mixing ratio 1:1 by weight). The spectra are calculated from transmission measurements on transparent substrates. The inset shows the molecular structure of DIP.

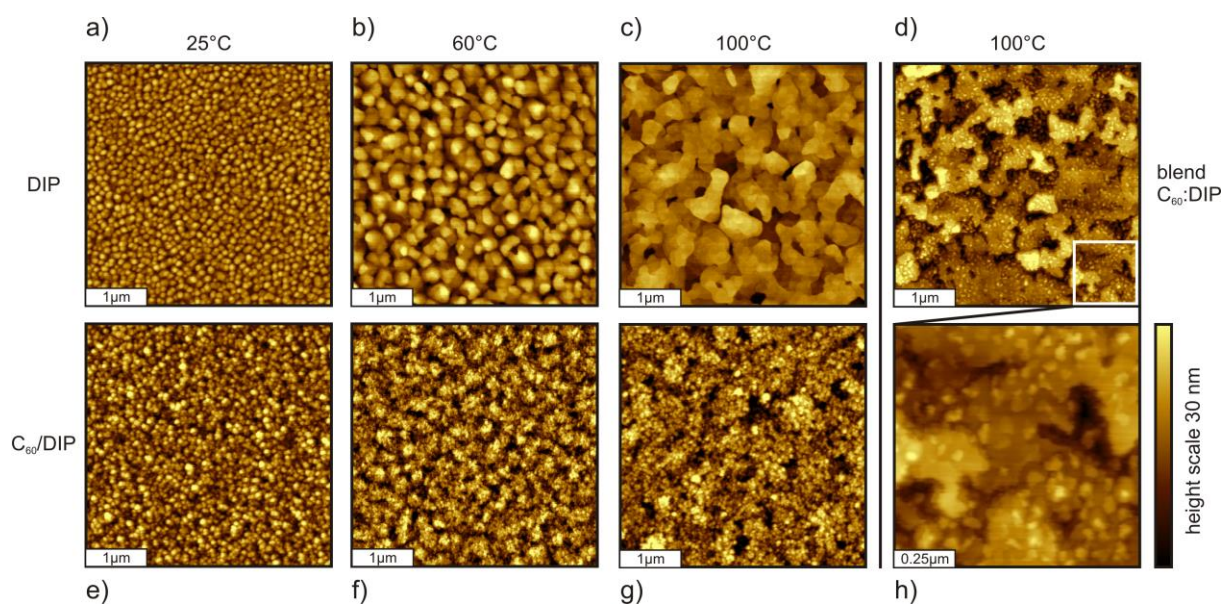


Figure 2. (upper row) AFM images of DIP films (50 nm) on PEDOT:PSS/ITO, evaporated at substrate temperatures of a) 25 °C b) 60 °C and c) 100 °C. (lower row) C_{60} (80 nm) on DIP (50 nm)/PEDOT:PSS/ITO, with DIP evaporated at the same substrate temperatures as in the upper row. d) AFM image of C_{60} :DIP blend (mixing ratio 1:1, 50 nm)/DIP (5 nm) on PEDOT:PSS/ITO evaporated at substrate temperature of 100 °C with magnification in h).

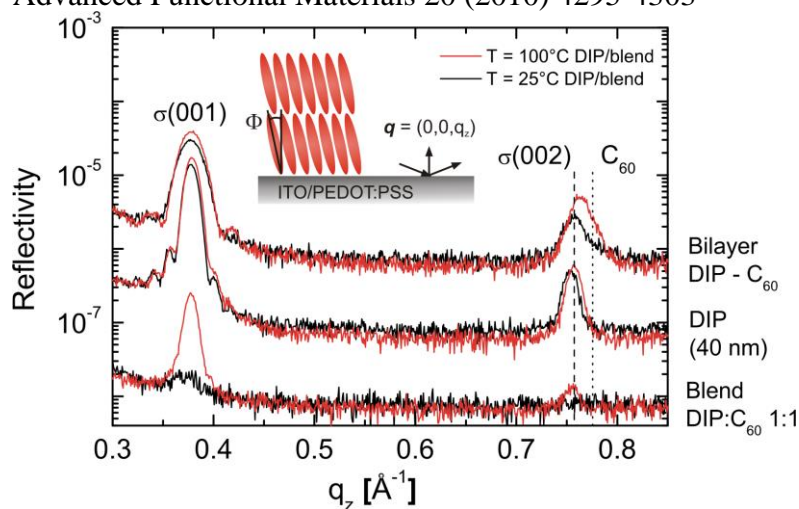


Figure 3. Out-of plane X-ray reflectivity of DIP(40 nm) on PEDOT:PSS/ ITO, C₆₀(20 nm)/ DIP(20 nm) on PEDOT:PSS/ ITO and mixed layers of C₆₀:DIP(40 nm, mixing ratio 1:1) on PEDOT:PSS/ ITO, grown at different temperatures as indicated in the diagram. The inset shows the scattering geometry for the specular scans and a sketch of the σ -phase of DIP molecules, stacked with their long axis essentially perpendicular to the substrate (tilt-angle $\Phi \approx 17^\circ$ with respect to the surface normal).

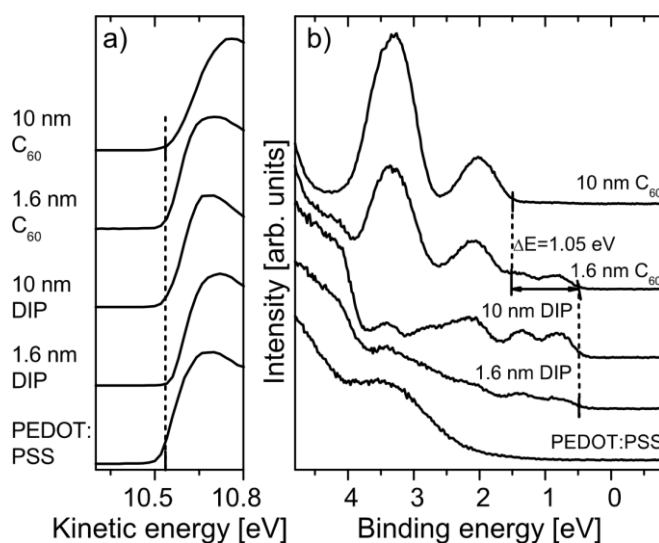


Figure 4. Ultraviolet photoelectron spectra of PEDOT:PSS/ITO substrates with different coverage of DIP and C₆₀ on top of 10nm DIP. Secondary electron cutoff (SECO) spectrum a) and valence region spectrum b).

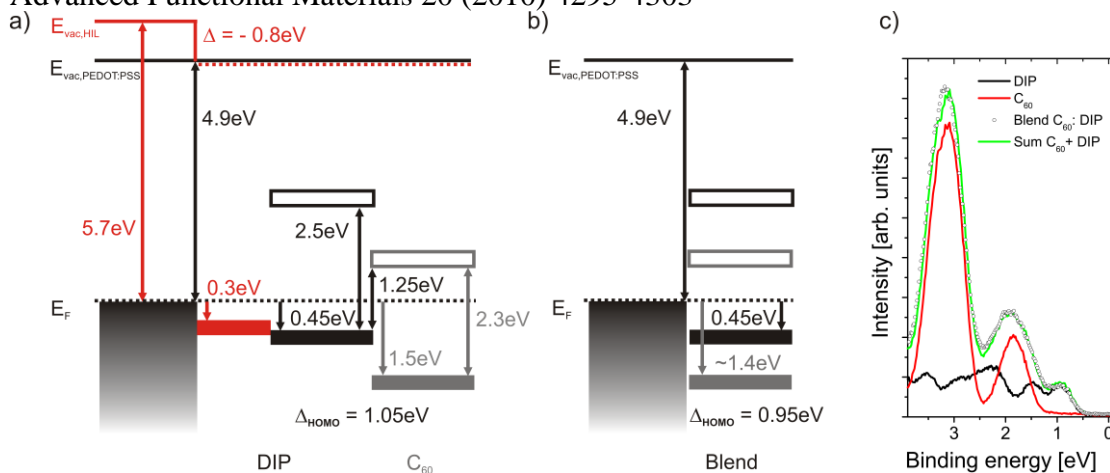


Figure 5. Schematic energy level diagrams for a) the PHJ C₆₀/DIP/HIL with PEDOT:PSS or HIL1.3 as hole injection layer and b) the corresponding BHJ. The levels marked in red only occur for the HIL1.3. c) Valence region spectra for C₆₀, DIP and the mixed film C₆₀:DIP compared to a summation of the pristine C₆₀ and DIP spectra.

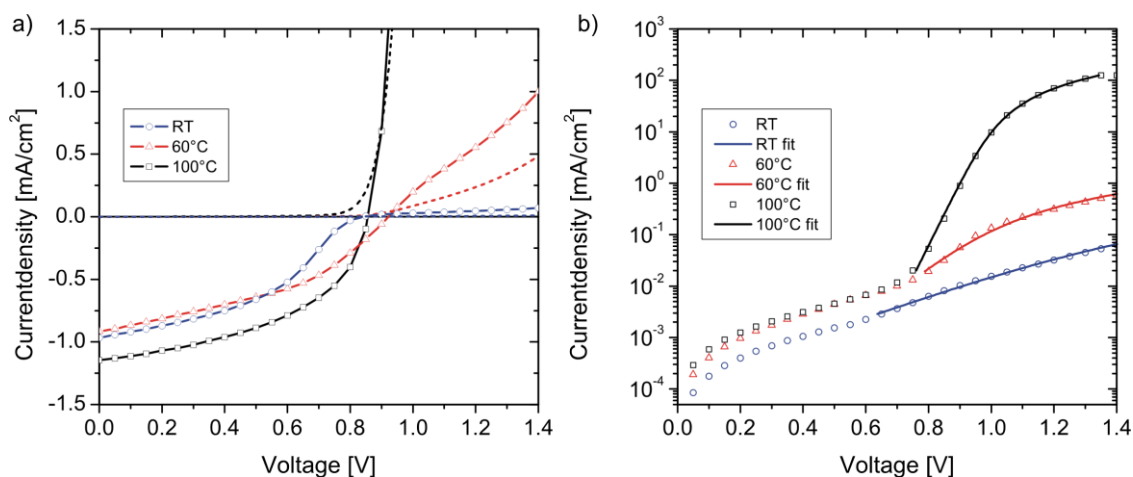


Figure 6. Current density vs. voltage (*j*-*V*) characteristics of PHJ diodes. The device structures are Al(100 nm)/ LiF(0.3 nm)/ C₆₀(80 nm)/ DIP(50 nm)/ PEDOT:PSS/ ITO. During DIP evaporation the substrates were heated to different temperatures (RT, 60 °C, 100 °C). a) *j*-*V* characteristics in the dark (dashed lines) and under simulated AM 1.5G illumination at 100 mW cm⁻². b) Logarithmic plot of the dark *j*-*V* characteristics (open circles). The solid lines are fits to the *j*-*V* characteristics based on the modified diode equation.

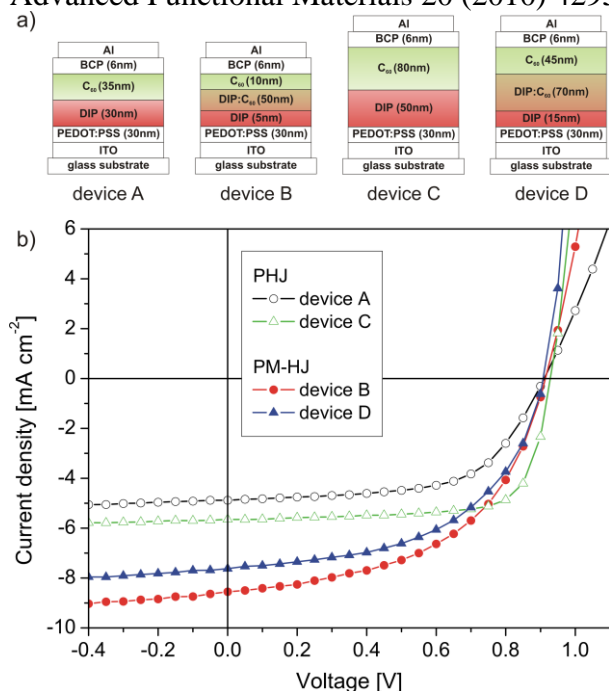


Figure 7. a) PHJ solar cell architecture of samples **A** and **C**, and PM-HJ architecture of samples **B** and **D**. b) Current density vs. voltage (j - V) characteristics of devices with different architecture (see a) measured under AM 1.5G illumination. During DIP evaporation (as neat or blended film) the substrates were heated to 100 °C.

Table 1. Solar cell parameters of devices with different architecture as obtained from the j - V characteristics shown in Fig. 7. V_{OC} : open circuit voltage, j_{SC} : short circuit current density, FF: fill factor, η_{PCE} : power conversion efficiency. For comparison, characteristic values for $C_{60}/CuPc$ cells taken from Ref. [45] are given.

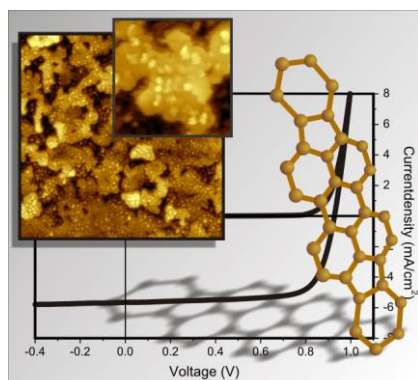
Device	Architecture	V_{OC} [V]	j_{SC} [mA cm ⁻²]	FF [%]	η_{PCE} [%]	Reference
A	PHJ	0.91	-4.8	60.4	2.7	This work
B	PM-HJ	0.91	-8.4	51.9	4.1	This work
C	PHJ	0.93	-5.7	74.3	3.9	This work
D	PM-HJ	0.91	-7.5	53.1	3.7	This work
CuPc/ C_{60}	PHJ	0.54	-7.3	52.6	2.3	[45]
CuPc/ C_{60}	PM-HJ	0.49	-10.6	33.4	1.8	[45]

Small-molecule solar cells are demonstrated using diindenoperylene as new donor material. Due to high crystallinity and large surface area of DIP films grown at elevated temperature as well as favorable energy level alignment with the fullerene C₆₀ as acceptor, large open circuit voltage close to 1 Volt and exceptionally high fill factors of almost 75 % are achieved, leading to power conversion efficiencies of 4 %.

Organic Solar Cell, Thin Films, Diindenoperylene

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High fill factor and open circuit voltage in organic photovoltaic cells with diindenoperylene as donor material



A. Morphological and structural investigation

In-plane (grazing incidence) X-ray diffraction data (**Fig. S1a**) show several C_{60} Bragg reflections in the C_{60} /DIP bilayers confirming the presence of a crystalline C_{60} layer on DIP. In addition, also for the C_{60} :DIP blend, weaker individual C_{60} and DIP Bragg reflections are present, revealing a certain degree of phase separation between both materials. All in-plane DIP reflections belong to the σ -phase.^[1] C_{60} Bragg reflections can be assigned either to the hcp or fcc structure.^[2] **Figure S1b** shows rocking scans on the (001) reflections of different DIP-films on PEDOT:PSS/ITO revealing that the mosaicity of the DIP grains is below 3° .

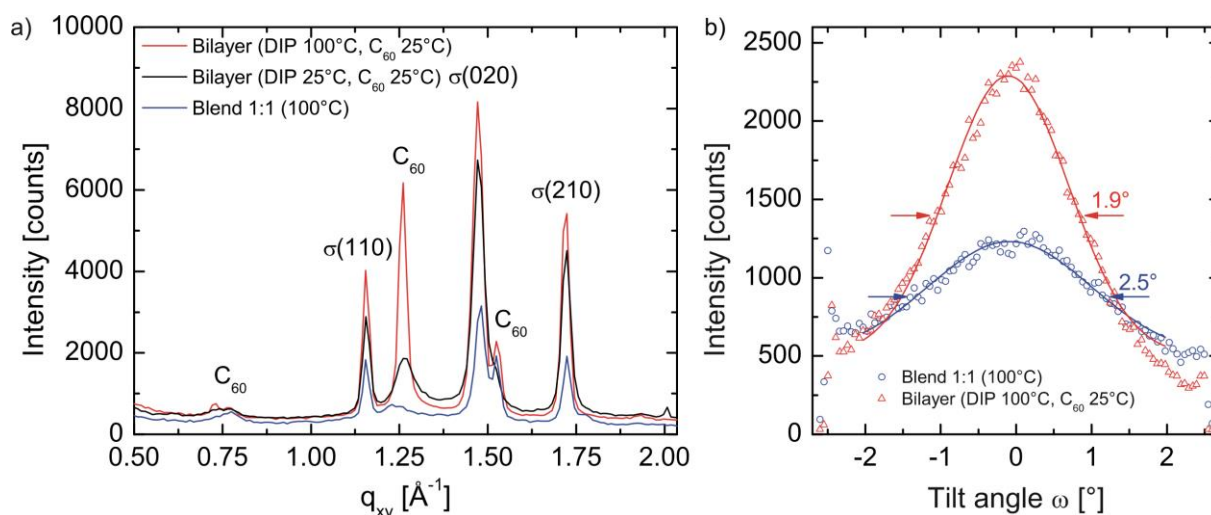


Figure S1. a) In-plane grazing incidence X-ray diffraction data of two C_{60} (20 nm)/DIP(20 nm) bilayers on PEDOT:PSS/ITO grown at substrate temperatures of 100 °C and 25 °C and a mixed layer of C_{60} :DIP(40 nm, mixing ratio 1:1) on PEDOT:PSS/ITO (grown at a substrate temperature of 100 °C). b) Rocking scans on the DIP (001) reflections of a C_{60} (20 nm)/DIP(20 nm) bilayer and a mixed layer of C_{60} :DIP(40 nm, mixing ratio 1:1) on PEDOT:PSS/ITO grown at a substrate temperature of 100 °C.

B. Electronic structure

The interface energetics between HIL1.3 and DIP are markedly different from DIP/PEDOT:PSS. Upon DIP deposition the sample work function changes from 5.70 eV (pristine HIL1.3) to 4.9 eV (**Fig. S2a**), which is reached for 3.2 nm DIP coverage, and

remains constant for higher DIP coverage. This observation is consistent with pinning of the DIP energy levels due to the high initial work function of HIL1.3.^[3] The work function reduction saturates after completion of the first two DIP monolayers, and the interface dipole of -0.8 eV is caused by positive charges residing on interfacial DIP molecules.^[4] The charge transfer at the interface directly impacts the position of the low BE onset of the HOMO level. For 1.6 nm DIP coverage it is 0.30 eV below E_F , and for multilayers it is constant at 0.45 eV (see inset in **Fig. S2b**). This can be assigned to the presence of DIP cationic species (positive polarons) at the interface to HIL1.3, i.e., the DIP/HIL1.3 contact can be considered as ohmic due to charge transfer doping of DIP. In spite of the differences at the hole injecting contact, the energy level alignment at the C_{60} /DIP interface is unchanged when using the high work function HIL1.3 as electrode (**Fig. S2b**), i.e., vacuum level alignment prevails and the HOMO offset is 1.05 eV.

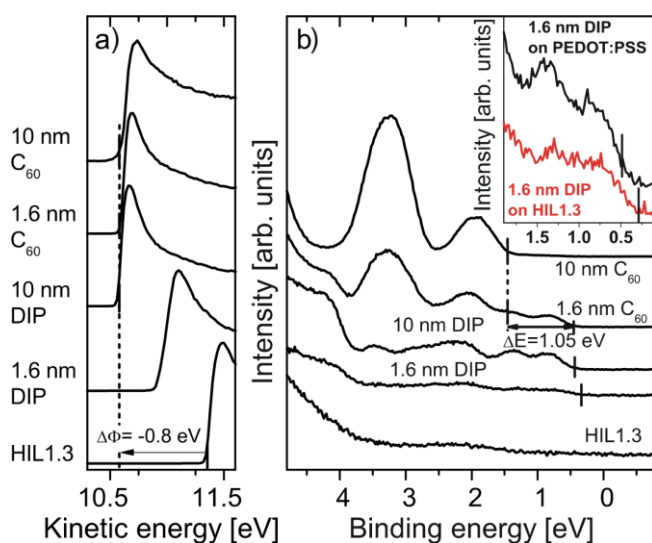


Figure S2. Secondary electron cutoff (SECO) spectrum a) and valence region spectrum b) for C_{60} /DIP/HIL1.3.

C. Application of DIP in solar cells

In addition to the data presented in the main text, we have also investigated solar cell characteristics of different device structures as function of light intensity. The PHJ cell incorporating thin photoactive layers (device **A**) starts with very poor FF (see **Fig. S3a**) at low

light intensity and is increasing towards higher illumination – but stays markedly below the values obtained for the thicker PHJ device **C**. According to the previously discussed rough morphology of DIP evaporated on a heated PEDOT:PSS/ITO substrate, a thin film of 30 nm DIP will be composed of isolated crystallites which might not be well connected. This assumption is based on growth studies by other groups,^[5] reporting on two-dimensional island growth and non-closed DIP films up to thicknesses in between 10 and 20 nm. Evaporating a thin layer of C₆₀ (35 nm) on top might result in incomplete coverage of DIP by C₆₀ and thus continuous pathways of both materials between the electrodes, which manifests itself in transport losses and reduced FF. Increasing both layer thicknesses in device **C** yields complete coverage of the rough DIP underlayer with a relatively smooth C₆₀ layer (cf. Fig. 2 in main text) thus avoiding these losses. The short circuit currents (see **Fig. S3b**) follow a power law $j_{sc} \propto I^\alpha$ with an exponent α very close to one, indicating monomolecular recombination kinetics. The light intensity dependence of the open circuit voltage is expected to show a weak (logarithmic) light intensity dependence which is indeed observed for all devices, except for the thin PHJ (see **Fig. S3c**). As discussed above, unfavorable morphology may be the reason for the low V_{oc} at low illumination in the latter case.

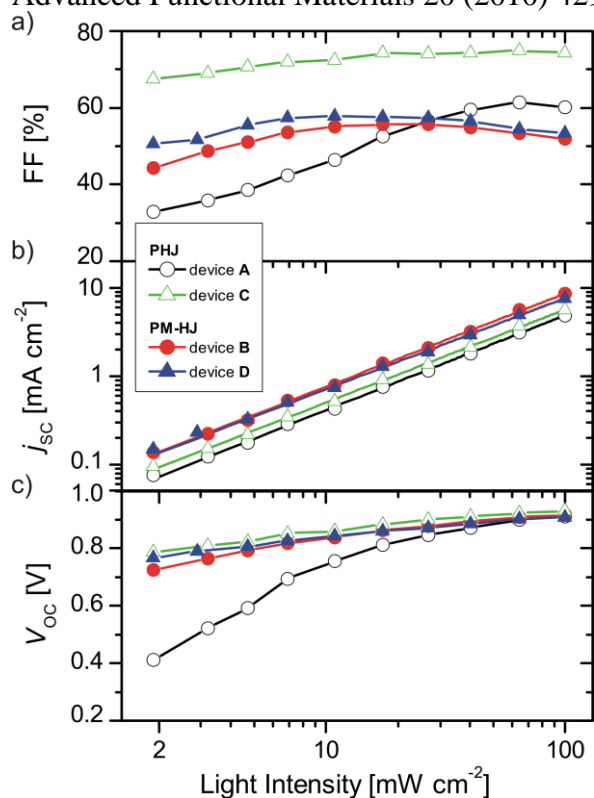


Figure S3. Development of a) the fill factor (FF), b) the short circuit current density (j_{sc}) and c) the open circuit voltage (V_{oc}) with intensity for devices **A-D**.

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