

DOI: 10.1002/adfm.200500443

Interface Modification to Improve Hole-Injection Properties in Organic Electronic Devices**

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The performance of organic electronic devices is often limited by injection. In this paper, improvement of hole injection in organic electronic devices by conditioning of the interface between the hole-conducting layer (buffer layer) and the active organic semiconductor layer is demonstrated. The conditioning is performed by spin-coating poly(9,9-dioctyl-fluorene-co-N-(4-butylphenyl)-diphenylamine) (TFB) on top of the poly(3,4-ethylene dioxythiophene): poly(styrene sulfonate) (PEDOT:PSS) buffer layer, followed by an organic solvent wash, which results in a TFB residue on the surface of the PEDOT:PSS. Changes in the hole-injection energy barriers, bulk charge-transport properties, and current–voltage characteristics observed in a representative PFO-based (PFO: poly(9,9-dioctylfluorene)) diode suggest that conditioning of PEDOT:PSS surface with TFB creates a stepped electronic profile that dramatically improves the hole-injection properties of organic electronic devices.

1. Introduction

Organic semiconductors are of increasing interest as new materials for electronic devices, owing to their easy processing and potential for low-cost fabrication. Organic light-emitting diodes (OLEDs),^[1,2] field-effect transistors (FETs),^[3] photodiodes, and solar cells^[4] are the electronic applications under the most intense study. One of the fundamental requirements for efficient operation of all-organic electronic devices is the process of carrier injection/extraction from the electrodes into the active region. Poor injection can limit the performance of devices such as OLEDs^[5] and FETs.^[6,7] Poor carrier-extraction properties also limit the organic solar cell's power-conversion efficiency.^[8]

The energy barrier for carrier injection/extraction is determined by the energy difference between the metal work function and the ionization potential/electron affinity of the organic material. Therefore, to optimize the injection properties, electrode materials with work functions that match the electron affinity and ionization potentials of the organic layer are needed.^[9] Several groups have reported results based on methods that modify the electrodes and improve injection properties.^[9–16]

Indium tin oxide (ITO) has been the preferred anode for all organic optoelectronic devices, owing to its optical transparency. However, the work function of ITO is quite low (even after processing methods including special ITO treatments such as plasma or oxygen treatment). One method of increasing the work function of ITO is to include additional engineering at the ITO/organic interface using high-work-function metal oxides or self-assembled monolayers between the ITO and organic material to increase the hole-injection efficiencies.^[10–13] The most common way to improve hole injection/extraction is to incorporate a hole-transporting layer (buffer layer) such as poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) on top of the ITO surface.^[14,15] One of the main features of the buffer layer is that it increases the hole injection from the ITO to the organic layer by increasing the work function of the anode.^[16] Electron injection is also difficult when using Al as a cathode, and hence low-work-function metals such as Mg and Ca and their alloys or alloys such as LiF/Al and CsF/Al have been used to improve electron-injection properties.^[9,17,18] Recently, modification of the cathode interface by incorporation of Ca(acac) (acac = acetyl acetonate) has been shown to improve the device performance of green fluorescent OLEDs.^[19]

Incorporation of polymer-based interlayers with thicknesses of 10–30 nm on top of the PEDOT:PSS layer has been previously reported to improve OLED device performance. In particular, Morgado et al. incorporated a 35 nm layer of poly(*p*-phenylene vinylene) between PEDOT:PSS and the light-emitting polymer (LEP) layer.^[20] Such interlayers can act as an electron-confinement layer for polymer-based LEDs using a blend of poly(9,9-dioctylfluorene) (PFO) and poly(9,9'-dioctylfluorene-*alt*-benzothiadiazole) as the light-emitting layer.^[20] More recently, incorporation of a poly(9,9-dioctylfluorene-co-N-(4-butylphenyl)-diphenylamine) (TFB) interlayer (10 nm) on top of PEDOT:PSS was shown to improve the efficiency and lifetime of polymer-based LEDs.^[21] The im-

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[**] We thank Dr. Dmitry Poplavskyy, Dr. Wencheng Su, and Dr. Pierre Allemand for useful discussions. This work was supported by the Department of Energy (Polymer OLED White Light Development Program; award number DE-FC26-04NT41947).

proved performance was explained on the basis of the inter-layer acting as an exciton-blocking layer, thus preventing luminescence quenching.

Herein, we demonstrate an improvement in the hole-injection properties of organic electronic devices by modifying the interface between the buffer layer and the organic semiconductor (a component of the active region of the electronic device). The modification was performed by first spin-coating a thin film of TFB on top of the PEDOT:PSS buffer layer, followed by washing with neat toluene. The organic-solvent wash leaves only a residue of TFB on the PEDOT:PSS, which we term an “interfacial conditioning effect” to differentiate it from the “interlayer” terminology that has been previously reported in the literature.

2. Results and Discussion

TFB was used to modify the interface between the PEDOT:PSS buffer layer and the electroluminescent conjugated polymer PFO. PFO was chosen as the active component of the diode under study owing to the large barrier for hole injection from PEDOT:PSS to PFO. The ionization potential of PFO is 5.8 eV,^[22] a value which is much higher than the work function of PEDOT:PSS (5.1 eV).^[14] This barrier of 0.7 eV limits the hole-injection properties of the diode. TFB is particularly suitable for use in buffer-layer interface conditioning, since its highest occupied molecular orbital (HOMO) level is around 5.3 eV.^[23] This point is discussed in more detail later in the text. The diode architectures studied are as follows. The control diode is based on ITO/PEDOT:PSS/PFO/Cathode. To investigate the effect of conditioning the PEDOT:PSS on the hole-injection properties of the diode, TFB was spin-coated on top of the PEDOT:PSS buffer layer, followed by an organic solvent wash that results in a TFB residue on the surface of PEDOT:PSS. Al and LiF–Ca–Al were used as the cathodes for hole-only and dual-carrier diodes, respectively. The chemical structure of TFB as well as the device structure with the TFB residue are schematically represented in Figure 1.

Figure 2 shows typical current density–voltage (J – V) curves obtained from the hole-only PFO diodes, prepared with and without the TFB interface conditioning, in linear (Fig. 2b) and log–log (Fig. 2a) plots. Al cathodes were used in the case of

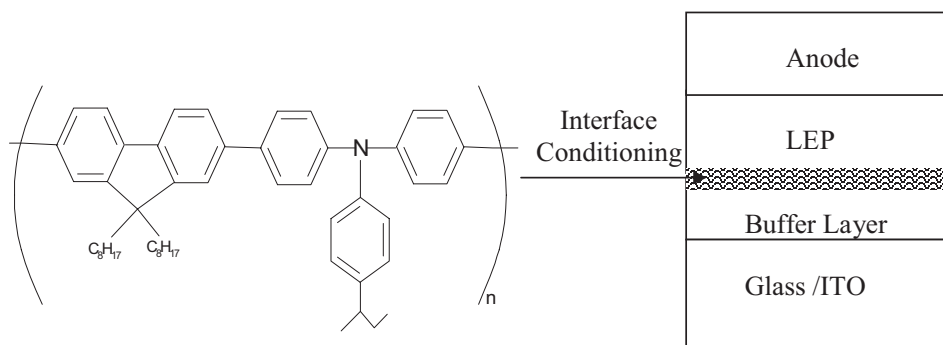


Figure 1. Chemical structure of TFB and a schematic of the device structure with TFB conditioning of PEDOT:PSS.

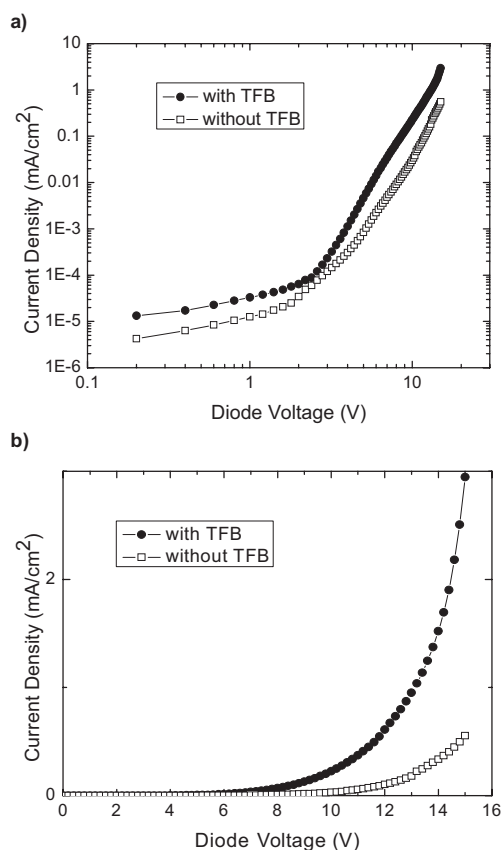


Figure 2. Current density–voltage characteristics of the hole-only diodes under study. The data are plotted in both a) double-log and b) double-linear representations. □: control device, ●: devices incorporating a TFB interfacial layer between PEDOT:PSS and PFO.

hole-only devices, since no electron injection is expected from Al to PFO owing to the difference between the work function of Al (ca. 4.3 eV) and the lowest unoccupied molecular orbital (LUMO) of PFO (ca. 1.9 eV).^[24] This is an important consideration as Brewer et al.^[25] have reported that, in certain cases, hole injection can be enhanced by electron injection. Efficient electron injection can populate trap states close to the PEDOT:PSS/LEP interface causing the potential to drop preferentially at the anode and thus increasing the rate of hole injection.^[25] This mechanism does not apply to the hole-only

devices presented here, as no light emission was observed even at 10 V bias. The J - V data in Figure 2 show an increase in hole current very clearly. Although J - V data typically cannot be used to distinguish changes due to injection from those due to bulk-transport properties, we believe that the large increase in hole current is due to improved injection properties when we consider the way the interface conditioning is applied (see Experimental).

Transient electroluminescence (EL) measurements^[26,27] were performed on dual-carrier devices with a 75 nm thick PFO film to confirm this conclusion. Under the influence of a rectangular voltage pulse applied to the diode, holes and electrons are injected from the opposite electrodes and travel through the PFO layer until they meet and radiatively recombine. A time delay between the onset of the applied voltage pulse and the initialization of the EL signal is related to the transit times of the charge carriers. The transit time t_{tr} is related to the composite electron and hole mobilities μ via Equation 1

$$\mu = d/(Et_{tr}) \quad (1)$$

where E is the applied electric field and d is the thickness of the PFO film.

A typical room temperature (RT) EL transient recorded at $E = 4.8 \times 10^5 \text{ V cm}^{-1}$ is shown in Figure 3a. The t_{tr} estimated from the time delay between the onset of the applied voltage and the appearance of the EL signal is indicated by a dotted line. Figure 3b shows the field dependence of the apparent RT mobility deduced from a sequence of EL transient experiments performed under different bias fields. The mobility data are plotted as a function of the square root of the bias field (corrected for the built-in voltage), in accordance with the expectations of the Poole–Frenkel model.^[28,29] The apparent mobilities measured with the EL transient method show a strong field dependence. Previous reported measurements of the hole mobility of PFO films measured by time-of-flight (ToF) photocurrent measurements^[30] showed a very weak field dependence and non-dispersive hole-photocurrent transients. In contrast, electron mobility has not been measured in PFO by ToF measurements.^[30] The relatively thick films required for ToF measurements and the strong trapping of electron-charge carriers limits the ability of detecting clear electron transients for thick PFO films.

Since the time delay between the onset of the applied voltage pulse and the initialization of the EL signal is related to the t_{tr} of both hole and electron charge carriers, transient EL measurements show the sum of the apparent mobilities (it is not possible to separate electron and hole transport with this technique). At the same time, it is evident that t_{tr} is mainly determined from the fastest carriers. Recent experimental results in the literature indicate that ambipolar transport is an intrinsic property of organic semiconductors.^[24,31,32] However, the measured hole mobilities were always higher than the electron mobilities.^[24,31,32] Thus the EL transient data presented here is influenced by both carriers, and we believe that the fastest carriers for the PFO under study are holes. The strong field dependence in our mobility measurements indicates a strong energetic disorder, which can be attributed to trapping and the

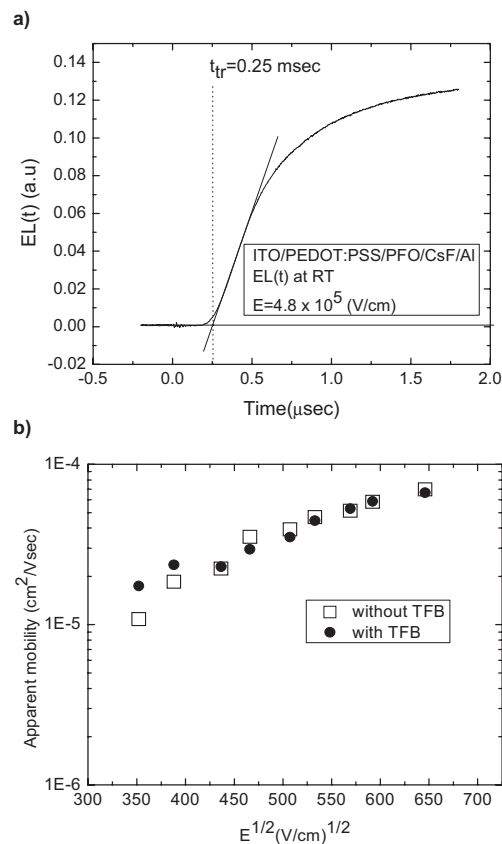


Figure 3. a) Typical EL transient for the PFO diode. The t_{tr} estimated from the time delay between the onset of the applied voltage and the appearance of the EL signal is indicated by a dotted line. b) Field dependence of the mobilities in the dual-carrier diodes under study. The data are plotted as a function of the square root of the external electric field (after accounting for the built-in potential).

purity of the PFO material used in this study. Direct comparison between the data presented here and previously reported results^[30] cannot be given, owing to differences in the material providers, experimental techniques, and the different thicknesses of the films studied.

The EL transient measurements prove that the bulk PFO transport properties were not affected by the TFB interface conditioning, ruling out doping effects due to TFB or the preparation conditions as causes of the observed increase in current density. The strong increase in current density observed for the hole-only devices could be related to an improved hole injection achieved by the TFB residue modifying the interface between the PEDOT:PSS and LEP.

Photocurrent–voltage measurements of the diodes under study were used to further investigate the improvement in hole injection by TFB interface modification. The measurements were performed using a saturated photoconductivity method described in more detail elsewhere.^[32,33] Photocurrent measurements can be used to measure the built-in potential (V_{bi}) and thus the changes in the hole-injection energy barriers. Figure 4a shows the measured photocurrent as a function of diode bias for the dual-carrier PFO diodes, prepared with and with-

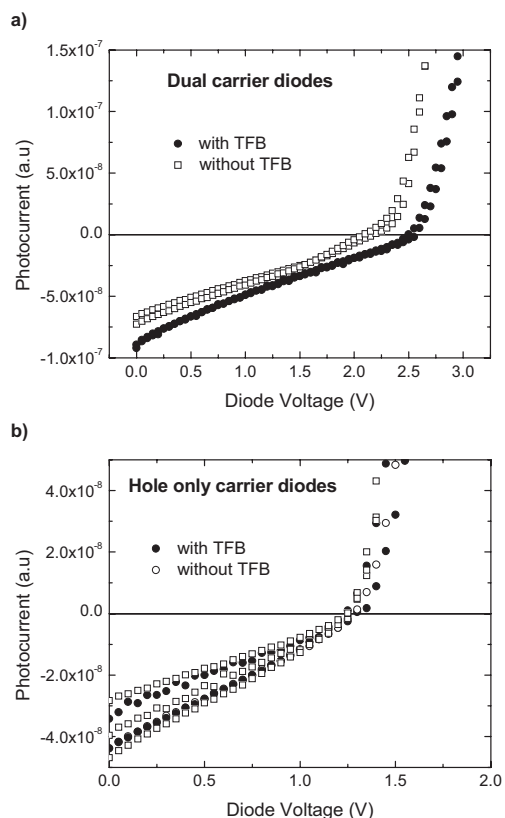


Figure 4. Photoconductivity measurements of the dual carrier diodes under study. a) Dual-carrier diodes. b) Hole-only diodes. □: control devices, ● devices where TFB was used for conditioning the interface between the PEDOT:PSS and PFO.

out TFB interface conditioning. The V_{bi} for the dual-carrier control devices without interface conditioning is about 2.2 V. V_{bi} increases to 2.5 V for the dual-carrier devices where interface conditioning was applied. In contrast to the photocurrent–voltage measurements of the dual-carrier diodes where the V_{bi} appeared to be affected by the TFB interface conditioning, the photocurrent–voltage measurements on hole-only diodes did not show any change in the V_{bi} (Fig. 4b). Even though the reduction in the hole-injection barrier for the dual-carrier diodes by TFB interface modification can signal an altering of the electronic properties of the PEDOT:PSS by TFB, it is unlikely in view of the photocurrent–voltage measurements data based on hole-only devices. Reduction in the hole-injection barrier has been achieved previously by increasing the doping level of the buffer layers.^[34] However, since the TFB used here is undoped, TFB interface conditioning altering the electronic properties of PEDOT:PSS is very unlikely. The underlying mechanism of the observed changes in the V_{bi} for the dual-carrier device by conditioning the PEDOT:PSS with TFB remains unclear. The changes in the dual-carrier device data could be related to electrical-conditioning effects,^[35] or convoluted carrier-injection dependencies where hole injection can be enhanced by electron injection.^[25] Accordingly, the increase in hole current observed for the hole-only devices (Fig. 2) can be attributed to TFB interface modification alter-

ing the surface of the buffer layer, creating a double-step injection profile, and thus reducing the hole-injection barrier between the buffer layer and the organic semiconductor.

Our experimental results clearly show that the effect of improved hole-injection properties arises from altering the surface of the buffer layer by conditioning the PEDOT:PSS layer with the TFB/toluene solution. Therefore, the experimental conditions for the effect of interface conditioning can alternatively be described as a method to treat the surface of buffer layers. The main question that arises for the effect of interface modification is to clarify if the improvement in hole injection is related to the exposure of PEDOT:PSS to TFB or to the organic solvent used in the preparation conditions, such as the toluene used in this particular case. The exposure of PEDOT:PSS to toluene is not believed to affect the electronic properties of PEDOT:PSS, as additional measurements using neat toluene and interface conditioning using PFO did not show any increase in the hole current or improvement on device performance.^[36] Thus, the TFB is responsible for the observed modification of PEDOT:PSS. Further, photoconductivity measurements on hole-only devices with and without TFB interface modification (Fig. 4b) show no difference in V_{bi} , which indicates no altering of the electronic properties of PEDOT:PSS. Hence, the most likely conclusion is that a TFB residue is left on the surface of PEDOT:PSS. The important parameter is the HOMO level of the organic material used for conditioning the PEDOT:PSS. To improve hole injection, the HOMO level of the material used for the conditioning should lie between the HOMO level of the PFO and the work function of the anode.

Molecular-scale engineering of buffer layers has already been reported as a method of fractionating the barrier for hole injection.^[37] Conditioning PEDOT:PSS with TFB can be used as a simple method to form a stepped injection profile in the anode interface, and to provide a double-injection step which strongly improves the hole injection into the active organic semiconductor. Figure 5 schematically illustrates the double-step injection. As mentioned previously, TFB interface modification with the conditions applied in this paper is different from the “TFB interlayer” seen in previous work.^[21] The

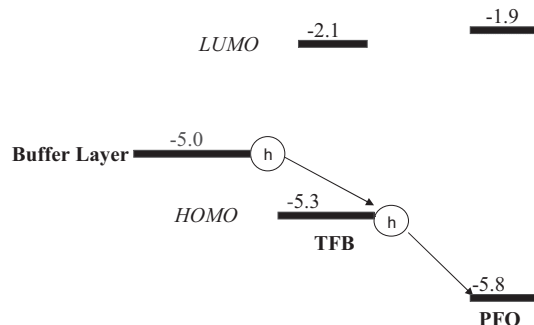


Figure 5. The HOMO and LUMO energy levels of TFB and PFO compared to the work function of PEDOT:PSS buffer layer (all referenced with respect to vacuum). The arrows indicate the stepped electronic profile created by conditioning the PEDOT:PSS with TFB. This provides a double-step injection from the PEDOT:PSS/TFB modified anode into the PFO active layer of the diode.

important parameter for improving the hole injection by conditioning the PEDOT:PSS is the HOMO energy level, and not the hole transporting or exciton blocking properties of the material used. The method of interface conditioning described here can also provide a smoother and more uniform interface between the anode and the active organic semiconductor layer, leading to improved morphology and hole injection.

We note that the J - V characteristics shown in Figure 2 for the hole-only diodes even after the TFB interface conditioning do not exhibit a voltage-squared dependence, indicative of Ohmic hole injection. However a voltage-squared dependence is only expected in the case of trap-free space-charge-limited current (SCLC). The strong field dependence of the mobility measurements presented in Figure 3b clearly indicates trapping effects for the PFO diode under study, since only the trap-free SCLC has a square-type increase in current density as a function of voltage. The J - V data presented here cannot be used to determine whether the injection after the TFB interface modification is Ohmic or non-Ohmic.

The improvement in hole injection by interface modification between the buffer layer and the active organic layer is important for a range of molecular-electronic-device applications, and can be used to improve the device performance in the case of electron-dominant fluorescence-based OLEDs. Conversely, it may harm the performance of hole-dominant OLEDs by further skewing the charge balance in the device. Since the PFO-based OLEDs studied are hole dominant, no improvement in the device performance of the dual-carrier PFO-based diodes was observed. We have previously reported an improvement in the device performance of electrophosphorescence OLEDs by using a TFB interface modification to assist direct hole injection to the phosphorescence emitters.^[36] The improvement is due to enhanced hole injection, leading to better charge balance, and may also shift the recombination zone away from the PEDOT:PSS.^[36] Improving injection properties is also an essential requirement for the construction of electrically pumped laser diodes, and offers potential for high-performance FETs, both of which are areas of major interest for technological applications. Furthermore, poor carrier extraction limits the performance of organic solar cells.^[38] In particular, interface conditioning can be used to improve the hole extraction efficiencies in organic-based solar cells. This will overcome the limitations in the field factor and short circuit current and thus greatly improve the solar cell device performance.

3. Conclusions

Improvement of hole injection in organic electronic diodes by modification of the interface between the buffer layer and the active organic semiconductor layer was demonstrated. Since the TFB used for the interface conditioning is undoped, we rule out the possibility of TFB interface conditioning altering the electronic properties of the underlying buffer layer. We propose that the improvement is due to TFB residue altering the surface of the buffer layer, creating a double-step injection profile, thus resulting in a lowered hole-injection barrier

between the buffer layer and the organic semiconductor. Hole injection from PEDOT:PSS into PFO is drastically improved by TFB interface conditioning of PEDOT:PSS. We believe that this approach can be used as a general method to improve hole-injection properties in a range of organic electronic applications.

4. Experimental

PFO and TFB were purchased from American Dye Sources. PEDOT:PSS used for the buffer layer was purchased from H. C. Starck.

The active organic semiconductor of the diodes under study is a PFO film sandwiched between two injecting electrodes. The anode consists of ITO/glass substrates precoated with a PEDOT:PSS buffer layer. Prior to spin-coating with the PEDOT:PSS buffer layer, ITO was precleaned and UV-ozone treated. After the UV-ozone treatment, a 60 nm PEDOT:PSS layer was spin-coated onto ITO. The PEDOT:PSS layer was baked in a nitrogen environment at 200 °C for 30 min. Pristine PFO solutions were spin-coated on top of the PEDOT:PSS layer inside a glove box with experimental conditions that yield light-emitting layers with thicknesses of around 75 nm and 150 nm for the dual and hole-only carrier diodes, respectively. The PFO layer was then annealed at 130 °C for 30 min. Following the spin-coating step, the samples were transferred into the thermal evaporator in a nitrogen atmosphere. Diodes were then completed by thermal evaporation of shadow-masked aluminum (200 nm) and LiF (2 nm)/Ca (6 nm)/Al (200 nm) top contact for hole-only and dual-carrier diodes, respectively, at a typical pressure of 10^{-6} mbar (1 bar = 10^5 Pa). Following evaporation, the devices were encapsulated with a glass lid and getter. We note that the preparation conditions for the dual-carrier diodes with the conditions described above were not optimized for efficient fluorescence emission. Full details in relation to our experimental setup for the diode characterization by J - V , transient EL, and photoconductivity measurements have been published elsewhere [39].

In the present study, TFB was used for conditioning the interface between the PEDOT:PSS and PFO layer (active region of the diode). TFB was spin-coated inside the glovebox onto a PEDOT:PSS buffer layer from toluene solution and baked at 130 °C for 10 min in a nitrogen environment. Under these conditions, an interlayer thickness of around 10 nm was obtained. To achieve the interface conditioning and prevent mixing of the TFB layer with the active organic layer, we introduced a washing step using toluene on the TFB layer. The term interface modification is used to describe the buffer-layer modification by the exposure of PEDOT:PSS to TFB. Owing to the method followed for interface conditioning, accurate determination of the actual TFB residue on the surface of PEDOT:PSS was not possible using the conventional method of profilometry.

Received: July 12, 2005

Final version: December 2, 2005

Published online: April 10, 2006

- [1] H. Burroughes, D. D. C. Bradley, A. R. Brown, R. N. Marks, K. Mackay, R. H. Friend, P. L. Burn, A. B. Holmes, *Nature* **1990**, *347*, 539.
- [2] R. H. Friend, R. W. Gymer, A. B. Holmes, J. H. Burroughes, R. N. Marks, C. Taliani, D. D. C. Bradley, D. A. Dos Santos, J. L. Bredas, M. L. Logdlund, W. R. Salaneck, *Nature* **1999**, *397*, 121.
- [3] G. Horowitz, *Adv. Mater.* **1998**, *10*, 365.
- [4] G. Yu, K. Pakbaz, A. J. Heeger, *Appl. Phys. Lett.* **1994**, *64*, 3422.
- [5] G. G. Malliaras, J. C. Scott, *J. Appl. Phys.* **1998**, *83*, 5399.
- [6] E. J. Meijer, D. M. de Leeuw, S. Setayesh, E. van Veenendaal, B.-H. Huisman, P. W. M. Blom, J. C. Hummelen, U. Scherf, T. M. Klapwijk, *Nat. Mater.* **2003**, *2*, 678.
- [7] H. Klauk, T. N. Jackson, *Solid State Technol.* **2000**, *43*, 63.

- [8] J. Nelson, *Curr. Opin. Solid State Mater. Sci.* **2002**, *6*, 87.
- [9] D. D. C. Bradley, *Curr. Opin. Solid State Mater. Sci.* **1996**, *1*, 789.
- [10] I. H. Campbell, J. D. Kress, R. L. Martin, D. L. Smith, N. N. Barashkov, J. P. Ferraris, *Appl. Phys. Lett.* **1997**, *71*, 3528.
- [11] Q. Huang, J. Cui, J. G. C. Veinot, H. Yan, T. J. Marks, *Appl. Phys. Lett.* **2003**, *82*, 331.
- [12] W. Hu, K. Manabe, T. Furukawa, M. Matsumura, *Appl. Phys. Lett.* **2002**, *80*, 2640.
- [13] S. Y. Kim, J.-L. Lee, K.-B. Kim, Y.-H. Tak, *Appl. Phys. Lett.* **2005**, *86*, 133504.
- [14] T. M. Brown, J. S. Kim, R. H. Friend, F. Cacialli, R. Daik, W. J. Feast, *Appl. Phys. Lett.* **1999**, *75*, 1679.
- [15] Y. Yang, A. J. Heeger, *Appl. Phys. Lett.* **1994**, *64*, 1245.
- [16] S. Kim, C. Hsu, C. Zhang, H. Skulason, F. Uckert, D. LeCloux, Y. Cao, I. Parker, *J. Soc. Inf. Display* **2004**, *5*, 14.
- [17] Y. Yang, Q. Pei, A. J. Heeger, *J. Appl. Phys.* **1996**, *79*, 2745.
- [18] H. Yang, D. Neher, D. Hertel, T. K. Daubler, *Adv. Mater.* **2004**, *16*, 161.
- [19] Q. Xu, J. Ouyang, Y. Yang, T. Ito, J. Kido, *Appl. Phys. Lett.* **2003**, *83*, 4695.
- [20] J. Morgado, R. H. Friend, F. Cacialli, *Appl. Phys. Lett.* **2002**, *80*, 2436.
- [21] J. Kim, R. H. Friend, I. Grizzi, J. H. Burroughes, *Appl. Phys. Lett.* **2005**, *87*, 023506.
- [22] S. Janietz, D. D. C. Bradley, M. Grell, C. Giebeler, M. Inbasekaran, E. P. Woo, *Appl. Phys. Lett.* **1998**, *73*, 2453.
- [23] M. Redecker, D. D. C. Bradley, M. Inbasekaran, W. W. Wu, E. P. Woo, *Adv. Mater.* **1999**, *11*, 241.
- [24] S. M. Tuladhar, D. Poplavskyy, S. A. Choulis, J. R. Durrant, D. D. C. Bradley, J. Nelson, *Adv. Funct. Mater.* **2005**, *15*, 1171.
- [25] P. J. Brewer, P. A. Lane, J. Huang, A. J. deMello, D. D. C. Bradley, J. C. deMello, *Phys. Rev. B* **2005**, *71*, 205209.
- [26] P. W. M. Blom, M. C. J. M. Vissenberg, *Phys. Rev. Lett.* **1998**, *80*, 3819.
- [27] D. J. Pinner, R. H. Friend, N. Tessler, *J. Appl. Phys.* **1999**, *86*, 5116.
- [28] S. V. Novikov, D. H. Dunlap, V. M. Kenkre, P. E. Parris, A. V. Vannikov, *Phys. Rev. Lett.* **1998**, *81*, 4472.
- [29] H. Bassler, *Phys. Status Solidi B* **1993**, *175*, 15.
- [30] M. Redecker, D. D. C. Bradley, M. Inbasekaran, E. P. Woo, *Appl. Phys. Lett.* **1998**, *73*, 1565.
- [31] S. A. Choulis, Y. Kim, J. Nelson, D. D. C. Bradley, M. Giles, M. Shkunov, I. McCulloch, *Appl. Phys. Lett.* **2004**, *85*, 3890.
- [32] G. G. Malliaras, J. R. Salem, P. J. Brock, J. C. Scott, *J. Appl. Phys.* **1998**, *84*, 1583.
- [33] J. C. Scott, G. G. Malliaras, W. D. Chen, J. C. Breach, J. R. Salem, P. J. Brock, *Appl. Phys. Lett.* **1999**, *74*, 1510.
- [34] M. Gross, D. C. Müller, H.-G. Nothofer, U. Scherf, D. Neher, C. Bräuchle, K. Meerholz, *Nature* **2000**, *405*, 661.
- [35] D. Poplavskyy, J. Nelson, D. D. C. Bradley, *Appl. Phys. Lett.* **2003**, *83*, 707.
- [36] S. A. Choulis, M. K. Mathai, V. Choong, F. So, *Appl. Phys. Lett.* **2005**, *87*, 113503.
- [37] P. K. H. Ho, J.-S. Kim, J. H. Burroughes, H. Becker, S. F. Y. Li, T. M. Brown, F. Cacialli, R. H. Friend, *Nature* **2000**, *404*, 481.
- [38] Y. Kim, S. A. Choulis, J. Nelson, D. D. C. Bradley, S. Cook, J. R. Durrant, *Appl. Phys. Lett.* **2005**, *86*, 063502.
- [39] D. Poplavskyy, W. Su, F. So, *J. Appl. Phys.* **2005**, *98*, 014501.