

Award number: DE-SC0002368

Recipient: *University of California Santa Barbara, Santa Barbara, CA 93106*

Project title: Mechanistic Studies of Charge Injection from Metallic Electrodes into Organic Semiconductors Mediated by Ionic Functionalities

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Period of performance: 09/14/2009-09/14/2013

Final report date: 12/14/2013

Distribution limitations: None

Total approved budget amount: \$900,000.00

## **Executive summary:**

Metal-organic semiconductor interfaces are important because of their ubiquitous role in determining the performance of modern electronics such as organic light emitting diodes (OLEDs), fuel cells, batteries, field effect transistors (FETs), and organic solar cells. Interfaces between metal electrodes required for external wiring to the device and underlying organic structures directly affect the charge carrier injection/collection efficiency in organic-based electronic devices primarily due to the mismatch between energy levels in the metal and organic semiconductor. Environmentally stable and cost-effective electrode materials, such as aluminum and gold typically exhibit high potential barriers for charge carriers injection into organic devices leading to increased operational voltages in OLEDs and FETs and reduced charge extraction in photovoltaic devices. This leads to increased power consumption by the device, reduced overall efficiency, and decreased operational lifetime. These factors represent a significant obstacle for development of next generation of cheap and energy-efficient components based on organic semiconductors.

It has been noticed that introduction of organic materials with conjugated backbone and ionic pendant groups known as conjugated poly- and oligoelectrolytes (CPEs and COEs), enables one to reduce the potential barriers at the metal-organic interface and achieve more efficient operation of a device, however exact mechanisms of the phenomenon have not been understood. The goal of this project was to delineate the function of organic semiconductors with ionic groups as electron injection layers. The research incorporated a multidisciplinary approach that encompassed the creation of new materials, novel processing techniques, examination of fundamental electronic properties and the incorporation of the resulting knowledgebase into development of novel organic electronic devices with increased efficiency, environmental stability, and reduced cost.

During the execution of the project, main efforts were focused on the synthesis of new charge-bearing organic materials, such as CPEs and COEs, and block copolymers with neutral and ionic segments, studies of mechanisms responsible for the charge injection modulation in devices with ionic interlayers, and use of naturally occurring charged molecules for creation of enhanced devices. The studies allowed PIs to demonstrate the usefulness of the proposed approach for the improvement of operational parameters in model OLED and FET systems resulting in increased efficiency, decreased contact resistance, and possibility to use stable metals for fabrication of device electrodes. The successful proof-of-the-principle results potentially promise development of light-weight, low fabrication cost devices which can be used in consumer applications such as displays, solar cells, and printed electronic devices. Fundamental mechanisms responsible for the phenomena observed have been identified thus advancing the fundamental knowledgebase.

### **Summary of the project accomplishments**

- An extensive study program has been completed in order to determine the fundamental mechanisms behind enhancement of the charge carriers injection at metal-organic interface by interlayers of conjugated molecules with ionic functionalities. The work included synthesis of novel CPE and COE materials, characterization of nanoscale morphology and structure of interfacial layers, electrical and optical characterization of devices. (As proposed initially).
- Novel COEs and CPEs have been synthesized and evaluated for the use in charge injection interlayers using surface imaging and electrical characterization techniques. (As proposed initially)
- Creation of interfacial dipole layer and ions redistribution were investigated as potential mechanisms for the phenomenon observed (As proposed initially). The former effect was found predominant in thin layers and the latter one – in thick interlayers. However, both effects can take place simultaneously.
- Enhanced operation of OLEDs and FETs have been shown using charge injection layers cast from non-conjugated “green”, naturally occurring charged molecules, such as DNA. Ambipolar operation of DNA-enhanced FET has been demonstrated (Not in the initial proposal but stems logically from the COE- and CPE-based work).

### **Summary of the project activities**

Activities through this program have been focused primarily on four major research areas: understanding mechanisms responsible for the charge carriers injection in OLEDs, synthesis of novel CPEs and COEs, synthesis of block copolymers with neutral and charged segments, and the use of biologically derived polyelectrolytes for improving the performance in organic electronic devices. The most relevant findings and activities are summarized below.

#### **Synthesis and Characterization of Conjugated Oligoelectrolytes**

COEs seemed to be a very promising class of materials for use in ionic interlayers for improvement of charge injection at the metal-organic interface. If compared to CPEs, they exhibit zero molecular weight dispersion and are easier to synthesize and purify. Nevertheless, our studies of the interlayers' structure by means of the scanning probe techniques indicated that morphology of the ionic material layer is highly inhomogeneous due to dewetting effects that leads to poorly reproducible device performance and make the fabrication process sensitive to the fabrication techniques. Aggregation and layer formation processes in COEs have been studied in details in optically active molecules using various characterization and nanoscale imaging techniques. Novel COE molecules have been studied and characterized for application in optoelectronic devices as well. Major findings relevant to the synthesis and characterization of COE which resulted in journal publications are summarized below:

1) Chen, Z.; Dang, X. D.; Gutacker, A.; Garcia, A.; Li, H. P.; Xu, Y. H.; Ying, L.; Nguyen, T.-Q.; Bazan, G. C., *Reconstruction of Conjugated Oligoelectrolyte Electron Injection Layers. Journal of the American Chemical Society* 2010, 132, 12160-12162.

It was determined that the unusual topography observed with COE interlayers atop electroluminescent semiconducting layer is the result of dewetting. COEs are intrinsically hydroscopic and can, if not handled properly, lead to incorporation of water, an increase in the polarity of the interlayer and dewetting from the hydrophobic electroluminescent layer. Motion of molecules at the interface takes place to produce large features not observed with as-cast layers without COE. No such effect takes place with CPEs because of the much higher energy required for motion (intrinsic solid state viscosity) of macromolecular systems. These findings led us to focus more tightly on the development of materials that do not exhibit surface reconstruction processes.

2) Ortony, J. H.; Chatterjee, T.; Garner, L. E.; Chworos, A.; Mikhailovsky, A.; Kramer, E. J.; Bazan, G. C., *Self-Assembly of an Optically Active Conjugated Oligoelectrolyte. Journal of the American Chemical Society* 2011, 133, 8380-8387.

The combination of hydrophobic and highly polar structural components within the COE structure is akin to those of common surfactants. We found that that molecular aggregation in water leads to increased fluorescence lifetimes, coupled with hypsochromic shifts, and larger two-photon absorption cross sections. Liquid atomic force microscopy (AFM) and cryogenic transmission electron microscopy (cryo-TEM) were used to image these aggregates and to confirm that planar molecules stack to form nanocylinders above a critical aggregation concentration. Finally, small-angle neutron scattering (SANS) was used to quantify the aggregate dimensions *in situ*. Comparison of the results highlights that a hydrophilic mica surface used to image via liquid AFM and the high concentrations required for cryo-TEM facilitate the propagation of the cylinders into long fibers. SANS experiments are consistent with equivalent molecular packing geometry but with lower aspect ratios. Such a study makes it possible to understand the evolution of optical properties as a function of concentration and aggregation and the general geometric features of the resulting supramolecular structures. These features translate to the morphology of the interfacial layers, as obtained immediately after solution deposition.

3) Zalar, P.; Pho, T. V.; Garcia, A.; Walker, B.; Walker, W.; Wudl, F.; Nguyen, T.-Q., *Optical and Charge Transport Properties of Water/Alcohol-Soluble Quinacridone Derivatives for Application in Polymer Light Emitting Diodes. Journal of Physical Chemistry C* 2011, 115, 17533-17539.

The optical and charge transport properties of four COEs based on quinacridone salts were characterized and used as electron injection layers in OLEDs. Increased alkyl chain length leads to a higher degree of aggregation in solution and greater order in the solid state. The bulky

counterion, tetraphenylphosphonium, affects molecular packing. As a consequence, the electron mobilities of the sodium salts are two orders of magnitude higher than their tetraphenylphosphonium analogues due to the greater degree of intermolecular charge transport afforded by the smaller size. The charge-transport characteristics of these materials affect the device performance. One of the COE compounds is shown to improve the efficiency of the devices even better than the commonly used barium cathode in the control device. We also demonstrated the versatility of COEs as electron injection materials by testing its function with a blue emissive small molecule. Quinacridone salts are a promising class of COEs that could easily find applications in places where CPEs have previously been successful. However, for this class of material, the synthesis is much simpler, they can be easily purified and produced in large quantities.

### **Characterization of Conjugated Polyelectrolytes**

Several series of organic electronic devices have been fabricated using CPEs with variable ionic functionalities and conjugated backbones. Their performance has been evaluated to uncover effects of ionic interlayers on the charge injection and transport. The device characterization data were correlated with the chemical structure of CPE and the charged layer's morphology. From these experiments, we have gained substantial understanding of the charge injection mechanism of OLEDs utilizing CPEs as charge injection layers. The insertion of charged or polar groups between the cathode and the CPE results in a positive interfacial dipole that effectively lowers the work function of the cathode,<sup>i</sup> increases the built-in electric field within the device<sup>ii,iii</sup> and results in a lowering of injection barrier heights at the interface.<sup>iv,v</sup> The permanent dipole presumably forms via self-assembly and alignment of the polymer at the interface.<sup>vi</sup> This mechanism is observed for devices utilizing a thin layer of CPEs as an electron injection layer. It should be noted, however, that the orientation and dynamics of charged groups at the metal/polymer interface remain to be characterized. For devices with a thick layer of CPE, ion movement and redistribution within the CPE layer lead to screening of the internal electric field and a lowering of the electron injection barrier.<sup>vii,viii,ix</sup> There is also no limitation that forbids both processes to occur concurrently. Major findings relevant to characterization of CPE interlayers and determination of their mechanism of action which resulted in journal publications are summarized below:

4) Garcia, A.; Bakus, R. C.; Zalar, P.; Hoven, C. V.; Brzezinski, J. Z.; Nguyen, T.-Q., *Controlling Ion Motion in Polymer Light-Emitting Diodes Containing Conjugated Polyelectrolyte Electron Injection Layers. Journal of the American Chemical Society* 2011, 133, 2492-2498.

New conjugated polyelectrolytes were prepared with the specific role of serving as study subjects that probe the effect of side group substitution on the rate of ion transport within the interfacial layer. It was found that despite the introduction of polar oligo(ethyleneoxide) pendant groups, the rate of ion motion did not increase substantially, relative to those CPEs with non-

polar alkyl groups. However, it was found that by applying an external bias at temperatures above the glass transition temperature, followed by cooling (still above  $T_g$ ) one can lock the ion distribution so to effectively eliminate the turn-on time associated with electric field distribution within the device. It is worth mentioning that these types of devices can be described by one of the two mechanisms (ion redistribution, instead of dipolar layer/tunneling) and the devices include a relatively thick CPE layer.

5) Lin, C. Y.; Garcia, A.; Zalar, P.; Brzezinski, J. Z.; Nguyen, T.-Q., *Effect of Thermal Annealing on Polymer Light-Emitting Diodes Utilizing Cationic Conjugated Polyelectrolytes as Electron Injection Layers*. *J. Phys. Chem. C* 2010, 114, 15786-15790.

Thermal annealing is a common post deposition technique used to modify the morphology of organic semiconductors inserted within device configurations. In this study, we identified an undesirable chemical transformation at high temperatures (180 °C) that reduces the ionic component of CPEs. Pendant ammonium functionalities are lost presumably via a Hofmann elimination mechanism. The loss of intrinsic charge and ionic properties results in dramatic shift of the turn-on voltage of the annealed devices. By pre-annealing and post-annealing experiments, we propose that the thickness of injection layers influences the preferred operating mechanisms for electron injection in multilayer PLEDs. These results are important for long term applications of PLEDs with CPE interlayers in lighting and display technologies.

6) Seo, J. H.; Namdas, E. B.; Gutacker, A.; Heeger, A. J.; Bazan, G. C., *Solution-Processed Organic Light-Emitting Transistors Incorporating Conjugated Polyelectrolytes*. *Advanced Functional Materials* 2011, 21, 3667-3672.

This effort provides the first demonstration of improved performance of *p*-type organic light emitting transistors (OLETs) by introducing a CPE layer and symmetric high work function source and drain metal electrodes. The OLET comprises a tri-layer film consisting of a hole transporting layer, an emissive layer, and a CPE layer as an electron injection layer. The thickness of the CPE layer is critical for achieving good performance and provides an important structural handle for consideration in future optimization studies. We also demonstrated for the first time, good performance solution-processed blue-emitting OLETs. These results further demonstrate the simplification of device fabrication and improved performance afforded by integrating CPE interlayers into organic optoelectronic devices.

### **Synthesis of New CPE Materials**

Synthesis of novel CPE materials was focused on the development of materials for the charge injection interlayers with optimal performance which is ensured by good charge transport properties and processability resulting in the desired morphology of the interlayer. Also, ionic species were used for tuning of OLED emission color and modulate electronic properties of the material use in OLED emissive layer. Publications relevant to this effort are summarized below:

7) Henson, Z. B.; Zhang, Y.; Nguyen, T.-Q.; Seo, J. H.; Bazan G. C., *Synthesis and Properties of Two Cationic Narrow Band Gap Conjugated Polyelectrolytes*. *Journal of the American Chemical Society* 135 (11), 4163-4166 (2013).

Cationic CPEs containing a backbone with alternating electron rich and electron poor moieties, and therefore narrow band gap characteristics, were designed and synthesized. A remarkable observation is that, unlike the neutral counterparts, the CPE containing BIm<sub>4</sub> counteranion exhibits n-type behavior within an FET device configuration. It is interesting to note that such transport is not observed with the bromide species. Moreover, a set of analytical experiments was consistent with n-type behavior not being due exclusively due to interfacial phenomena. For example, if one simply includes a thin layer of the n-type CPE atop the neutral precursor, no n-type behavior is observed. Thus, the combination of backbone and electrostatic field from the ionic layer leads to an organization of structural units that is appropriate for electron motion.

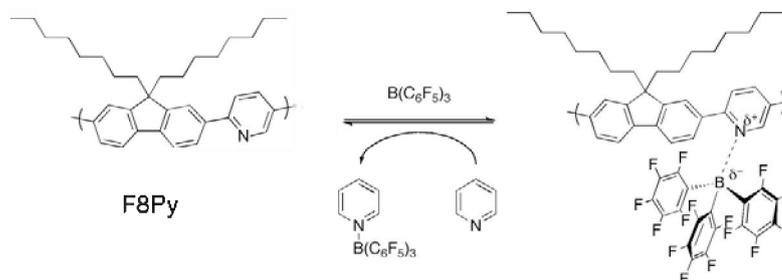
8) Ying, L.; Zalar, P.; Collins, S. D.; Chen, Z.; Mikhailovsky, A. A.; Nguyen, T.-Q.; Bazan, G. C., *All-Conjugated Triblock Polyelectrolytes*. *Advanced Materials* 2012, 24, 6496-6501.

All-conjugated triblock polyfluorenes with well-defined molecular weights and low polydispersities were synthesized via chain-growth Suzuki-Miyaura polymerization. Ionization of pendant alkylbromide chains by pyridine affords amphiphilic triblock polyelectrolytes with neutral/charged/neutral or charged/neutral/charged segments. The immiscible blocks lead to aggregation in polar and nonpolar solvents, and to complex surface morphologies depending on the polarity of the substrate. More configurationally stable chains are observed in more polar media, as determined by the observation of  $\beta$ -phase-like characteristics. Energy transfer studies indicate that the polymer chains are aggregated, even under dilute conditions, and that this aggregation is favored for the triblock species with higher hydrophobic content in more polar media. However, the composition, nuclearity and general structural characteristics of these multi-chain species remain poorly understood. These triblock structures work efficiently as electron injection layers in PLEDs and the resulted device efficiencies are similar to those achieved using the less stable Ba/Al cathode.

9) Zalar, P.; Henson, Z. B.; Welch, G. C.; Bazan, G. C.; Nguyen, T.-Q., *Color Tuning in Polymer Light-Emitting Diodes with Lewis Acids*. *Angewandte Chemie-International Edition* 2012, 51, 7495-7498.

This contribution points out a completely new and possibly general method for fine tuning PLED emission. The simple mixing of a Lewis basic electroluminescent conjugated polymer with a Lewis acid allows the absorption and PL properties of the parent polymer to be modified in a simple chemical step, see Scheme 1. Interestingly, solutions and films containing F8Py-B(C<sub>6</sub>F<sub>5</sub>)<sub>3</sub> adducts exhibit significantly longer excited state lifetimes and larger quantum yields than the native F8Py. PLEDs were successfully fabricated by using F8Py and F8Py-

$B(C_6F_5)_3$  adducts as the emissive layer. The EL spectra shift to longer wavelengths as the fraction of polymer bound to  $B(C_6F_5)_3$  is increased. When 0.10 monomer equiv of  $B(C_6F_5)_3$  is added, the emission of the pristine F8Py polymer at 426 nm is completely suppressed, resulting in an EL with a  $\lambda_{max}$  of 509 nm. The  $LE$ - $J$  characteristics of devices were not significantly influenced by the formation of F8Py- $B(C_6F_5)_3$  adducts, however,  $J$ - $V$  and  $L$ - $V$  characteristics were shifted to higher voltages. These shifts can be readily rationalized in the context of increasing hole-injection barriers as the HOMO level of the F8Py film is decreased with increasing presence of F8Py- $B(C_6F_5)_3$  adducts. The use of alternative hole injection electrodes is anticipated to circumvent this feature. Lewis acid-base interactions therefore provide a straightforward way to modulate optoelectronic properties in PLEDs without influence on the device external quantum efficiency. This strategy should translate well to other organic electronic applications in which fine-tuning of energy levels are important for device operation or performance.



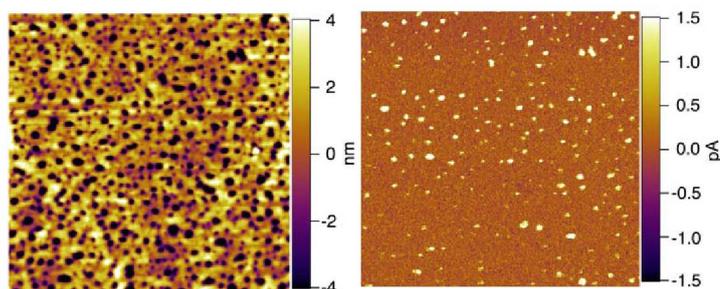
**Scheme 1.** Reversible adduct formation between Lewis acidic  $B(C_6F_5)_3$  and Lewis basic F8Py in solution.

### DNA as charge injection layer

Besides using synthetic materials, we have been successfully using natural materials such as DNA as charge injection layers in OLEDs and OFETs. Much of the motivation came as a result of the mechanistic proposal that certain devices are improved by only the presence of a thin dipole layer between the metal electrode and organic layer. Use of naturally occurring and renewable molecules is justified by the growing demand for “greener” chemistry and renewable materials. We have studied the effects of DNA extracted from salmon fishing industry as waste products.<sup>xixi</sup> With the help of DNA injection interlayers we were able to improve operation of OLEDs and OFETs. In the latter case, ambipolar device operation has been demonstrated which indicated that certain materials can be used for improvement of injection of both electron and holes due electric field-induced reorientation of the interfacial dipole. This finding is important because it allows for fabrication of ambipolar devices with simplified structure.

10) Zalar, P.; Kamkar, D.; Naik, R.; Ouchen, F.; Grote, J. G.; Bazan, G. C.; Nguyen, T.-Q., *DNA Electron Injection Interlayers for Polymer Light-Emitting Diodes. Journal of the American Chemical Society* 2011, 133, 11010-11013.

In collaboration with scientists at Air Force Research Laboratory (Materials and Manufacturing Directorate), we demonstrated that DNA can significantly improve PLED efficiencies utilizing poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) electroluminescent layers. Introduction of the DNA interlayer beneath Al leads to an increase in efficiency from  $6.5 \times 10^{-3} \pm 2.3 \times 10^{-3}$  cd/A to  $0.80 \pm 0.15$  cd/A. Comparison of the  $J$ - $V$  characteristics of the MEH-PPV/DNA/Al and MEH-PPV/Al devices shows that the DNA layer facilitates electron injection. Device temporal response can be accommodated more easily within a mechanistic framework where ion motion only plays a minor role in modifying the injection barriers. We proposed therefore that a dipole layer is formed which modifies the effective work function of Al. AFM experiments show that the deposition of DNA does not lead to a homogenous film, but instead one finds a web-like morphology. Such features are anticipated under circumstances where there is poor wetting with the hydrophobic underlayer and are consistent with the previous work with COEs described above. Conductive AFM scans show that DNA also serves as a hole-blocking layer; with current observed only within the areas corresponding to the “pinholes” in Figure 2. Since a thick DNA layer is anticipated to be insulating toward both electrons and holes, we propose that the electrons are most reasonably injected into the MEH-PPV within the thinnest portions of interlayer.

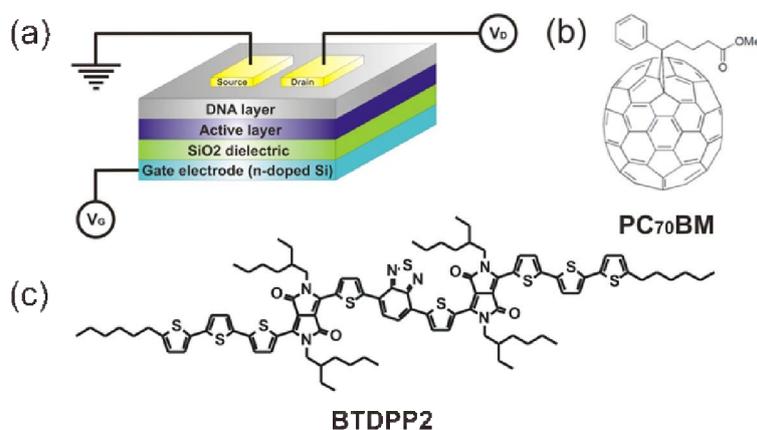


**Figure 2.** Morphology (left) and current (right) measurements of MEH-PPV/DNA surfaces. The voltage in the current measurements is +5 V. The rms roughness is 2.8 nm. The size of the images is  $2 \mu\text{m} \times 2 \mu\text{m}$ .

11) Zhang, Y.; Zalar, P.; Kim, C.; Collins, S.; Bazan, G. C.; Nguyen, T.-Q., *DNA Interlayers Enhance Charge Injection in Organic Field-Effect Transistors. Advanced Materials* 2012, 24, 4255-4258.

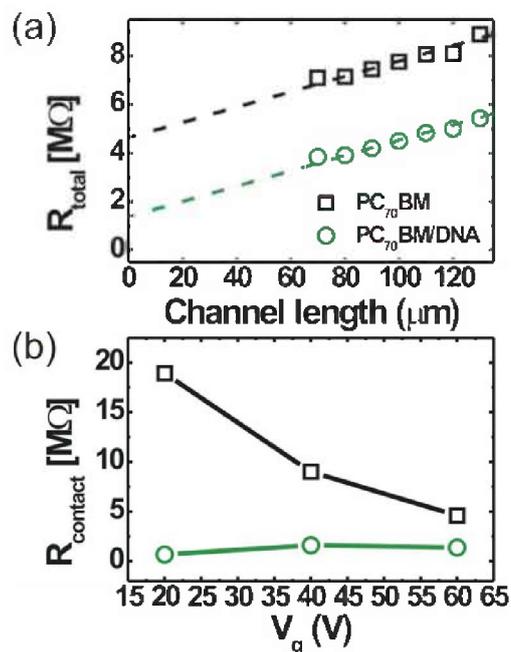
Following the successful demonstration of DNA interlayer function in OLEDs, we established that the incorporation of appropriate DNA interlayers leads to improvements in the  $n$ -type transport of PC<sub>70</sub>BM and ambipolar transport in BTDP2 OFET devices, see Figure 3. We attribute these observations to improved charge injection at the Au/organic interface. The field-

effect electron mobility for PC<sub>70</sub>BM devices is enhanced by a factor of two, together with a reduced contact resistance (from 19 MΩ to 0.7 MΩ, at  $V_g = 20$  V). Additionally, ambipolar BTDPP2 OFETs using the DNA layers show a factor of three and four increase in both the electron *and* hole mobilities, respectively. Since there is no indication of ion motion within the DNA layer, it appears that the simultaneous improvement of hole and electron injection is due to the dipole layer formed by DNA, which can change orientation in response to the polarity of the applied  $V_g$ . From a broader perspective, it has also been demonstrated that biomaterials such as DNA have a place within traditional organic semiconductor device structures where synthetic materials have previously been well established.



**Figure 3.** (a) Device structure and chemical structures of (b) PC<sub>70</sub>BM and (c) BTDPP2.

Similarly, DNA layers were used to control charge carriers injection in OFETs (Figure 3). By inserting them beneath the Au contact, the contact resistance of PC<sub>70</sub>BM FETs was reduced by 27 times at a gate bias of 20 V (Figure 4). Also, effective electron and hole mobilities of ambipolar BTDPP2 transistors are increased by one order of magnitude with a reduction of the threshold voltage from 12 to 6.5 V. By evaluating transient operation of DNA-enhanced devices, it was concluded that formation of an interfacial dipole was responsible for the observed enhancement of the device performance. We hypothesize that orientation of the dipole can be reversed by the polarity of the applied gate bias thus enabling improvement of ambipolar devices.



**Figure 4.** (a) Total channel resistance versus channel length of the PC<sub>70</sub>BM device using DNA along with the control device at  $V_g = 60$  V. (b) Contact resistance of these two devices as a function of gate bias.

12) Y. Zhang, M.F. Wang, S.D. Collins, H.Q. Zhou, H. Phan, C. Proctor, A. Mikhailovsky, F. Wudl, T.Q. Nguyen, *Enhancement of the Photoresponse in Organic Field-Effect Transistors by Incorporating Thin DNA Layers*, *Angewandte Chemie* 53 (11), 244-249 (2014).

Tunable photoresistivity of OFET materials allows applications in light-sensitive optoelectronics including photodetectors, light-induced switches, light-triggered amplifiers, and image sensors, *etc.* In comparison to conventional OFETs that are operated in the darkness, organic phototransistors (OPT) require both satisfactory charge transport and high photoresponse to render the detection mechanism. We investigated effects of DNA interlayer on the photoresponse of solution-processed *n*-type OPTs and lateral diodes. The active layer is based on a new fullerene chromophore 1-(3-carboxypropyl)-1-phenyl[6,6]C<sub>61</sub> (PCBA) incorporated with disperse-red dyad, denoted as PCBDR that features an absorption in the range of 400~600 nm (Figure 5(a-c)). By incorporating the DNA interlayer, a considerable increase in the photocurrent is observed leading to a photosensitivity exceeding  $10^3$  upon irradiation (Figure 5(d)). The increased photocurrent is rationalized by the combined results of the modified electron injection and enhanced exciton dissociation at the PCBDR/metal interface. The surface potential on PCBDR determined by Kelvin probe force spectroscopy shows a higher response to irradiation upon incorporation of DNA that indicates increased density of surface charge carriers. The enlarged photoresponse and surface carrier density are both rationalized by the dipole interaction

at the PCBDR/DNA interface. Our results demonstrate a possibility of incorporating biomolecules into organicoptoelectronics for light-detecting applications.

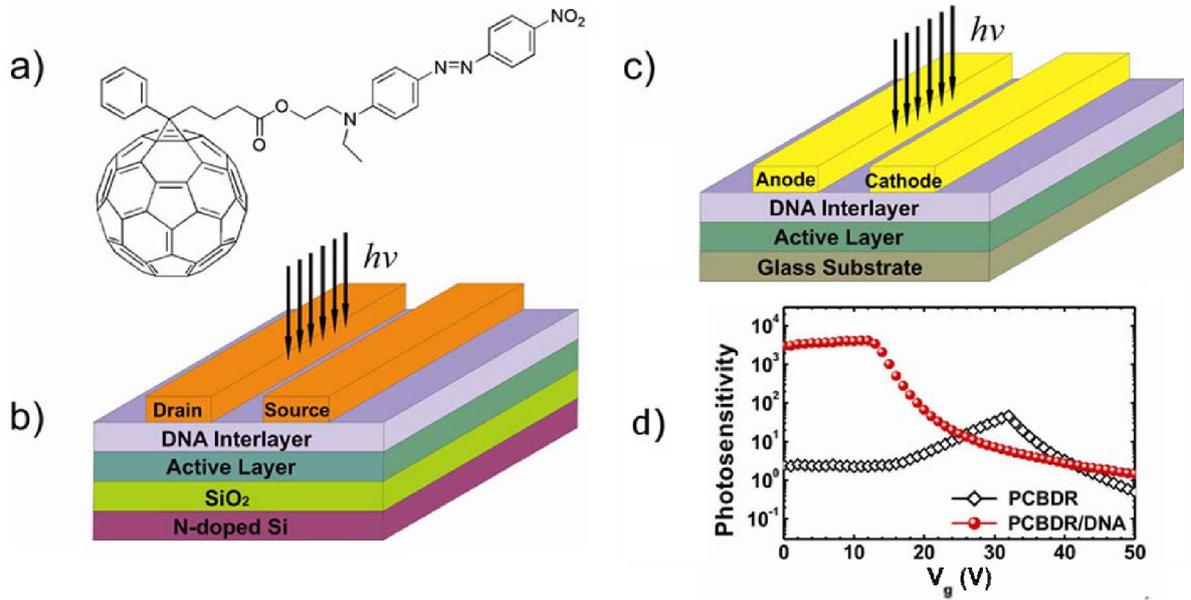


Figure 5. (a) Chemical structure of PCBA; Architectures of OPTs (b) and planar photodiodes (c) with DNA interlayer; (d) Photosensitivity spectra of OPTs with and without DNA interlayer.

Products:

Publications resulting from the project:

1. Z. Chen, X. D. Dang, A. Gutacker, A. Garcia, H. P. Li, Y. H. Xu, L. Ying, T. Q. Nguyen and G. C. Bazan, Reconstruction of Conjugated Oligoelectrolyte Electron Injection Layers, *Journal of the American Chemical Society* 132 (35), 12160-12162 (2010).
2. C. Y. Lin, A. Garcia, P. Zalar, J. Z. Brzezinski and T. Q. Nguyen, Effect of Thermal Annealing on Polymer Light-Emitting Diodes Utilizing Cationic Conjugated Polyelectrolytes as Electron Injection Layers, *Journal of Physical Chemistry C* 114 (37), 15786-15790 (2010).
3. A. Garcia, R. C. Bakus, P. Zalar, C. V. Hoven, J. Z. Brzezinski and T. Q. Nguyen, Controlling Ion Motion in Polymer Light-Emitting Diodes Containing Conjugated Polyelectrolyte Electron Injection Layers, *Journal of the American Chemical Society* 133 (8), 2492-2498 (2011).
4. J. H. Ortony, T. Chatterjee, L. E. Garner, A. Chworos, A. Mikhailovsky, E. J. Kramer and G. C. Bazan, Self-Assembly of an Optically Active Conjugated Oligoelectrolyte, *Journal of the American Chemical Society* 133 (21), 8380-8387 (2011).
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6. P. Zalar, D. Kamkar, R. Naik, F. Ouchen, J. G. Grote, G. C. Bazan and T. Q. Nguyen, DNA Electron Injection Interlayers for Polymer Light-Emitting Diodes, *Journal of the American Chemical Society* 133 (29), 11010-11013 (2011).
7. P. Zalar, T. V. Pho, A. Garcia, B. Walker, W. Walker, F. Wudl and T. Q. Nguyen, Optical and Charge Transport Properties of Water/Alcohol-Soluble Quinacridone Derivatives for Application in Polymer Light Emitting Diodes, *Journal of Physical Chemistry C* 115 (35), 17533-17539 (2011).
8. L. Ying, P. Zalar, S. D. Collins, Z. Chen, A. A. Mikhailovsky, T. Q. Nguyen and G. C. Bazan, All-Conjugated Triblock Polyelectrolytes, *Advanced Materials* 24 (48), 6496-6501 (2012).
9. P. Zalar, Z. B. Henson, G. C. Welch, G. C. Bazan and T. Q. Nguyen, Color Tuning in Polymer Light-Emitting Diodes with Lewis Acids, *Angewandte Chemie-International Edition* 51 (30), 7495-7498 (2012).
10. Y. Zhang, P. Zalar, C. Kim, S. Collins, G. C. Bazan and T. Q. Nguyen, DNA Interlayers Enhance Charge Injection in Organic Field-Effect Transistors, *Advanced Materials* 24 (31), 4255-+ (2012).

11. Z. B. Henson, Y. Zhang, T. Q. Nguyen, J. H. Seo and G. C. Bazan, Synthesis and Properties of Two Cationic Narrow Band Gap Conjugated Polyelectrolytes, *Journal of the American Chemical Society* 135 (11), 4163-4166 (2013).
12. A. Sharenko, C.M. Proctor, T.S. van der Poll, Z.B. Henson, T.Q. Nguyen, G.C. Bazan, A High-Performing Solution-Processed Small Molecule: Perylene Diimide Bulk Heterojunction Solar Cell, *Advanced Materials* 25 (32), 4403-4406 (2013).
13. Y. Zhang, M.F. Wang, S.D. Collins, H.Q. Zhou, H. Phan, C. Proctor, A. Mikhailovsky, F. Wudl, T.Q. Nguyen, Enhancement of the Photoresponse in Organic Field-Effect Transistors by Incorporating Thin DNA Layers, *Angewandte Chemie* 53 (11), 244-249 (2014).

### **Presentations:**

US-China Workshop on Nanostructured Materials for Global Energy and Environmental Challenges, Suzhou City, Jiangsu Province, China, October 17-18, 2009

NSF Workshop on Macromolecular, Supramolecular and Nanochemistry, Washington DC, June 14-15, 2010

Electronic Processes in Organic Materials, Gordon Research Conference, Mount Holyoke Third Workshop with Imperial College, Santa Barbara, CA, September 2010

US-China Workshop on Energy and Environment, Beijing, China, September 18-23, 2010

Workshop with South China University of Technology, Guangzhou, China, October 2010.

Department of Chemistry, Cambridge University, United Kingdom, November 2010.

Pacificchem 2010, Honolulu, Hawaii, December 15-20, 2010

ICB Army-Industry Collaborations Conference, Santa Barbara, CA, February 2011.

Materials Research Society Spring Meeting, San Francisco, CA, April 2011.

Nanyang Technological University, Singapore, April 2011.

Plextronics, April 23, 2011

International Symposium on Functional pi-Electron Systems, Beijing, China, October 2011.

ICB Conference, Santa Barbara, California, February 2012.

Gordon Research Conference on Organic Electronics, Lucca, Italy, May 2012.

International Union of Pure and Applied Chemistry (IUPAC) Photochemistry Conference, Coimbra, Portugal, July 2012 (*Plenary Lecture*).

Presentation at DoE BES office Department of Materials Research Principle Investigators Conference. July 2012, Annapolis, MD.

Symposium on Soft Matter & Polymer Science, Ho Chi Minh City, Vietnam, November 4, 2012

Summer School on "Organic Electronics", Biarritz, France, May 28 - June 1, 2013

Center for Nano Science and Technology@PoliMi, Istituto Italiano di Tecnologia, Milan, Italy,

September 23, 2013

Department of Chemistry, University of Bari, Italy, October 01, 2013

**Collaborations:**

Air Force Research Laboratory (Materials and Manufacturing Directorate). Development of OLEDs and OFETs with enhanced charge injection by DNA interlayers.

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