Testing Organic Solar Cells on the Nanoscale:

Using Photoconducting Atomic Force Microscopy to Probe Structure-Property-Performance Relationships in Organic Photovoltaics

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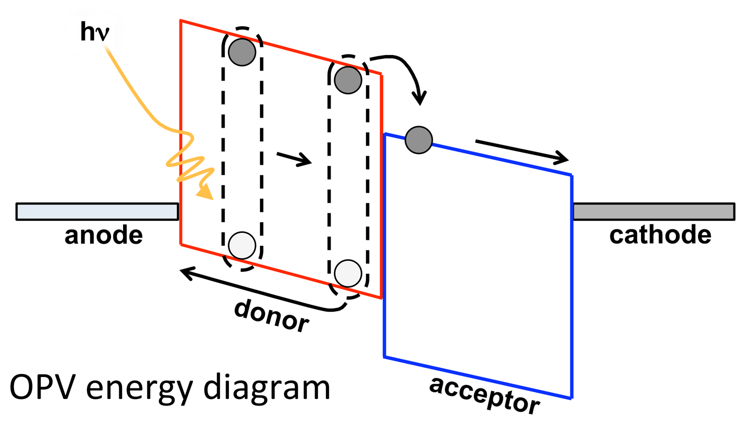
Introduction

Organic photovoltaics (OPVs) are a promising energy technology because of their potential to be produced at low cost via solution processing onto lightweight and flexible substrates (see image on right).



OPV energy diagram

OPVs consist of a thin (~ 100 nm) film made up of a network of two organic materials with dissimilar electronic properties such that one behaves as an electron donor and the other as an electron acceptor. This film is then sandwiched between two electrodes.

The diagram to the left shows an energetic diagram of the processes occurring in an OPV: photon absorption, exciton diffusion, charge separation, and charge transport and collection.

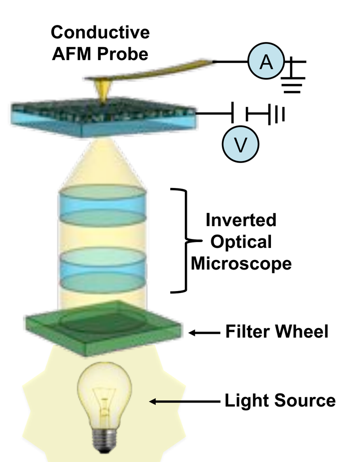


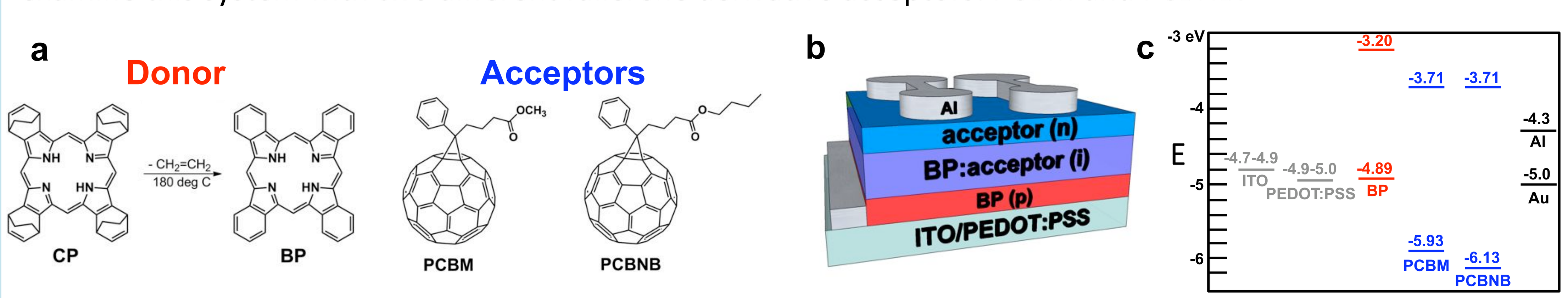
Diagram of pc-AFM setup

Photoconducting atomic force microscopy (pc-AFM) allows for these processes to be directly probed on the nanoscale, the length scale on which they occur.

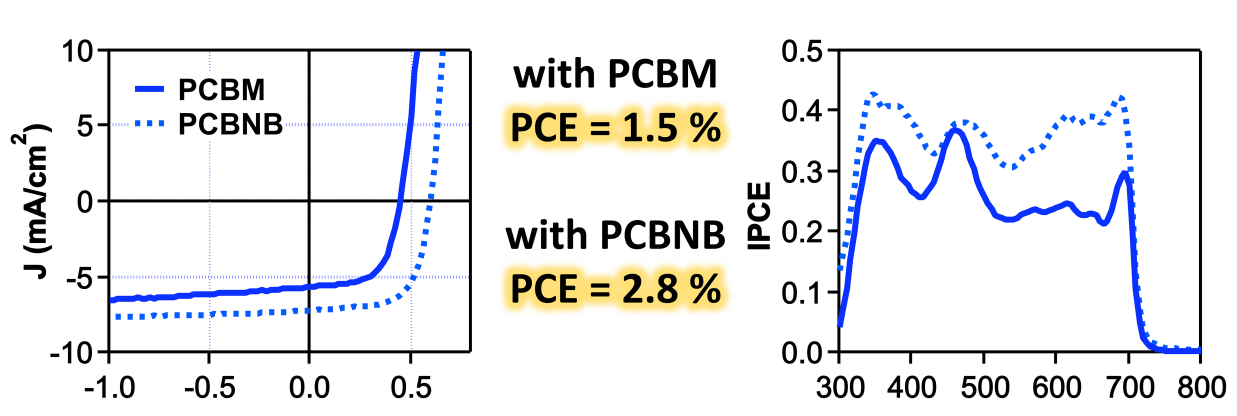
This study utilizes pc-AFM as a nanoscale analog to bulk solar cell testing. A conductive AFM probe measures the active layer morphology and photocurrent simultaneously, resolving nanoscale morphological features that either benefit or undermine the device performance.

The System

In this study,[1] we examine a multilayer p/i/n OPV system utilizing the donor material benzoporphyrin (BP).[2] We examine this system with two different fullerene derivative acceptors: PCBM and PCBNB.



(a) structures of BP precursor (CP), BP, PCBM and PCBNB. Solution processed thin films of CP are thermally converted to BP, rendering them insoluble, thus allowing solution processing of additional layers atop the p-layer. (b) schematic device structure and (c) energy levels of the donor, acceptors, and relevant electrode materials.



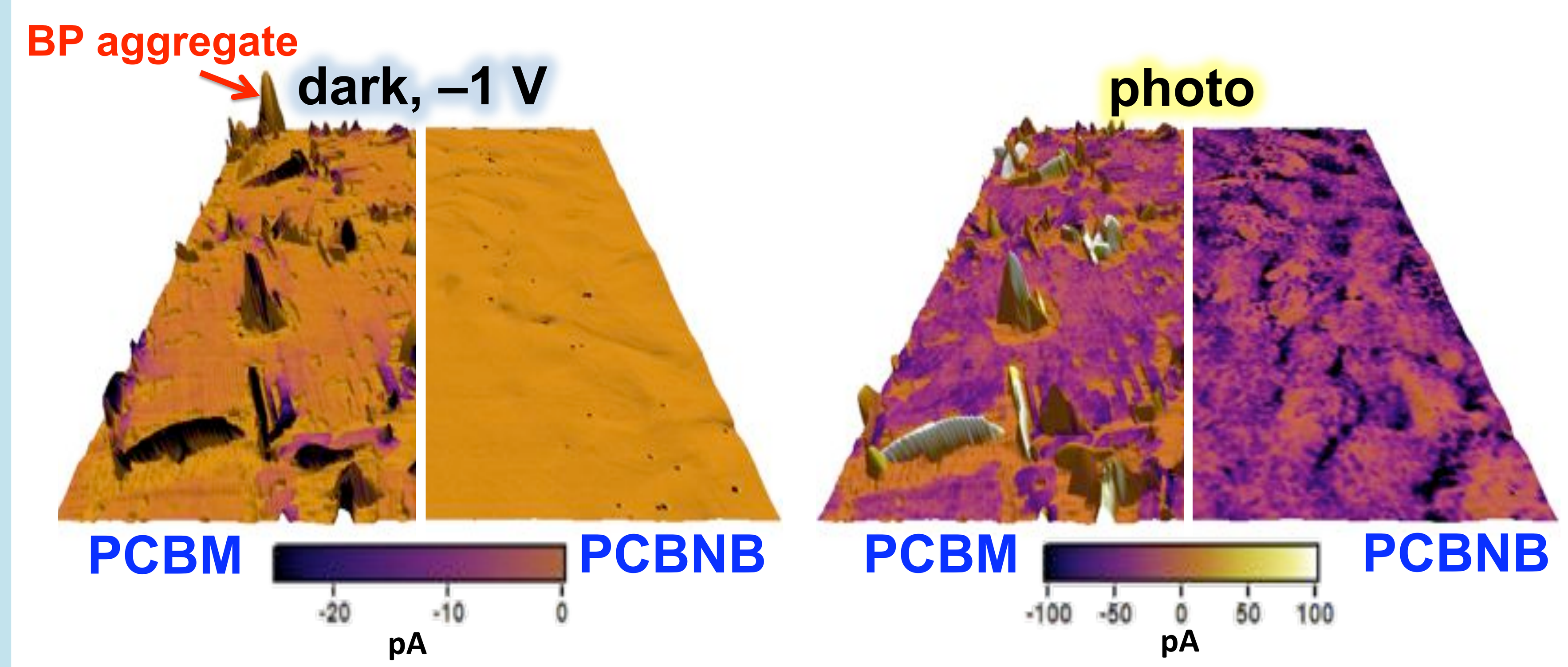
Bulk current-voltage (*J-V*) curves collected at AM 1.5 conditions (left) and incident photon to collected electron (IPCE) spectra (right) for p/i/n devices with PCBM (solid) and PCBNB (dashed), with the overall power conversion efficiencies (PCEs) of the two systems (center).

Using a p/i/n device architecture, devices using PCBNB outperform those containing PCBM, despite the similar frontier energy levels of PCBM and PCBNB, thus indicating that nanoscale morphology influences the device performance. In this study, we characterize each layer by c-AFM and pc-AFM in order to understand why they perform differently.

c-AFM/pc-AFM Study

i-layer

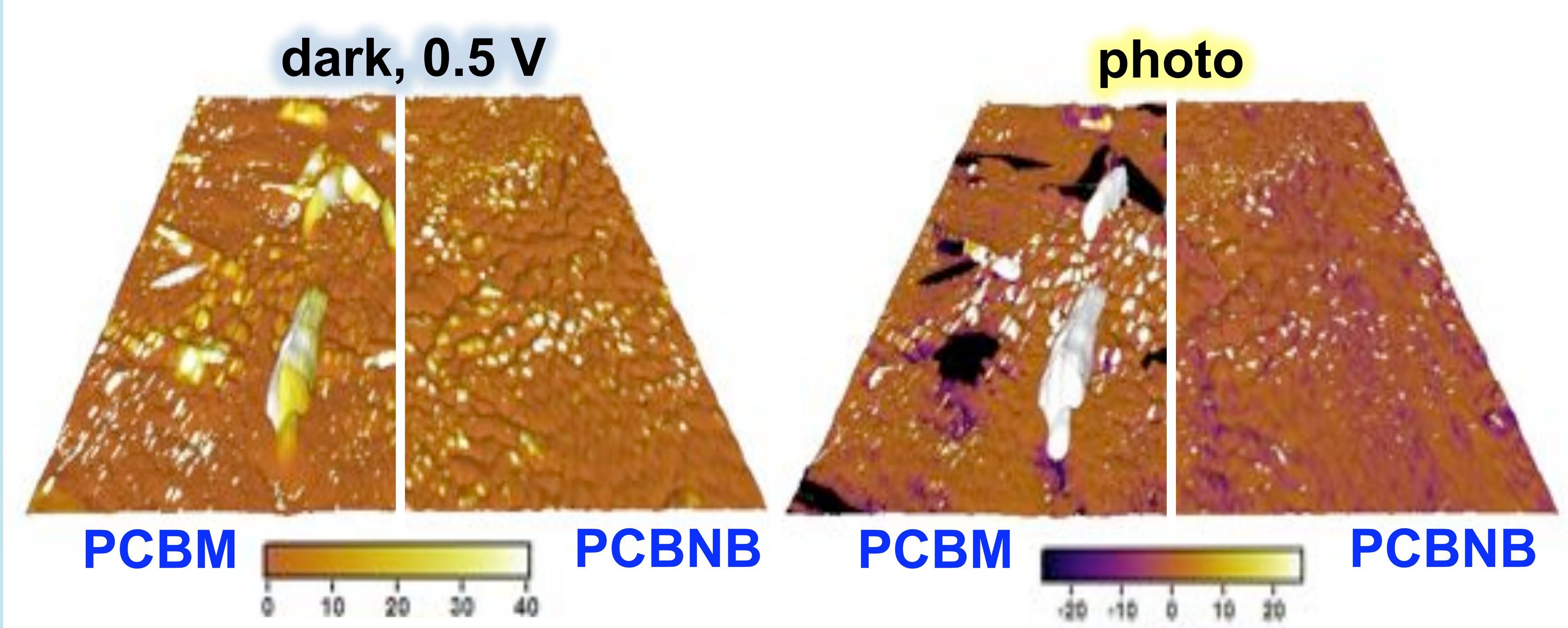
The i-layer consists of a phase separated blend of BP and acceptor atop the p-layer. The i-layer with PCBM is highly textured with large aggregates on the surface. From the high dark current and positive photocurrent, these large aggregates are identified as ordered donor-rich domains that extend from the substrate to the surface of the film. These BP aggregates are not observed in the i-layer films with PCBNB.



c-AFM topography depicted in 3D with dark current at – 1 V bias (left set) and photocurrent (right set) color overlaid of p/i films with the device structure: glass/ITO/PEDOT:PSS/BP/BP:acceptor. Each image is 5 × 10 µm.

n-layer

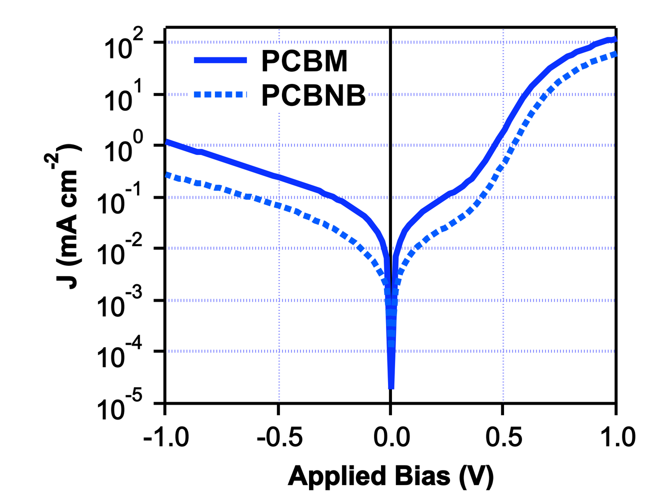
The n-layer is a neat layer of acceptor cast atop the i-layer. In films with PCBM, the n-layer partially covers the BP aggregates in the i-layer, resulting in both exposed and slightly buried BP aggregates. These BP aggregates once again exhibit high dark current, whereas these features are absent in films with PCBNB. Additionally, in films with PCBM, the photocurrent varies in magnitude and sign over the surface of the film.



c-AFM topography depicted in 3D with dark current at 0.5 V bias (left set) and photocurrent (right set) color overlaid of p/i/n films with the device structure: glass/ITO/PEDOT:PSS/BP/BP:acceptor/acceptor. Each image is 2.5 × 5 µm.

From Nano to Macro

In devices with PCBM, the high dark current of the BP aggregates in c-AFM measurements is consistent with the higher leakage current in bulk p/i/n OPVs. This correlation illustrates the connection between our nanoscale characterization and bulk device performance.



Bulk *J-V* curves collected under dark conditions for p/i/n devices with PCBM (solid) and PCBNB (dashed).

Conclusions

Via conductive and photoconductive AFM, we have found that p/i/n devices utilizing PCBM as the acceptor possess large donor-rich aggregates that contribute to leakage current. These features were not found in devices containing PCBNB, thus providing insight as to why devices with PCBNB exhibited higher OPV performance.

References

1. Guide et al *Adv. Mater.* 2011, 23, 2313-2319.

2. Matsuo et al *J. Am. Chem. Soc.* 2009, 131, 16048-16050.

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