Mechanical Testing of OPVs using Flextrode: An ITO-Free, Transparent, Polymer-Based Electrode

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Abstract:

Organic photovoltaic (OPV) cells may offer a means to rapidly produce low-cost devices by printing thin films onto plastic substrates in ambient conditions. Indium-tin oxide (ITO) is the standard electrode for OPVs, but is brittle, prohibitively expensive, and not scalable. Flextrode, a transparent, flexible electrode composed of conductive polymers, was recently developed as a move towards cheaper materials with better mechanical properties than ITO. This project investigated effects of mechanical strain on the cohesion and function of the flextrode layer as part of an OPV. Films on a plastic substrate were deformed to varied strains, while monitoring film behavior with an optical microscope. Changes in surface morphology were characterized with optical and atomic force microscopy to determine the strain tolerance of the films. Additionally, *in situ* measurements of conductivity and photovoltage during tensile tests determined the effect of strain on the functionality of the layers. Flextrode proved to be a mechanically robust alternative to ITO that resists cracking up to a 25% strain with minimal loss of conductivity.

Introduction:

Organic photovoltaics is a recently developed field that uses polymers in electron donor-acceptor pairs to harness the photoelectric effect. OPVs offer solutions to a number of the limitations of silicon cells. For instance, they may be mass-produced at much lower cost due to cheap starting materials and simple fabrication processes. In addition, the light weight and flexibility is compatible with easy transport and deployment, and wearable electronics applications. However, OPV research still faces a number of hurdles in reliability and power conversion efficiency (PCE). OPV efficiency lags behind that of traditional cells, and they degrade due to environmental stressors, further lowering PCE. In addition, the cells must withstand stresses from deformation of the plastic substrate. Heretofore, adhesive and cohesive strength of OPVs has been low, causing mechanical failure. Flextrode, a polymer based, printed electrode, was developed as an alternative to ITO, which is brittle and plagued by many of the limitations of silicon cells. Prior work has characterized its fabrication and electrical properties [1]; this project investigated the tensile strain tolerance of a flextrode based OPV and the films that comprise it.

Methods:

The films of interest are printed sequentially onto the plastic substrate: beginning with only flextrode and zinc oxide electron transport layers (ETL), followed by active layer, then the conductive polymer hole transport layer (HTL), and finally the complete device. Samples were prepared with one, two, or three layers and each was incrementally strained by tensile loading. The resulting the changes in surface morphology were characterized using optical and atomic force microscopy (AFM). Electrical measurements were also taken to determine the functionality of the cells under strain. The resistance of the flextrode layer and photocurrent generated by the full device were measured during tensile tests using a multimeter.

Results and Discussion:

Cohesive cracking due to strain was characterized with AFM in order to determine the robustness of the individual films. Table 1 shows the strain at which cracks were first detected (crack onset) and at which they propagated

Table 1:

Cell Layer	Crack onset (% Strain)	Cracks through (% Strain)
HTL (PEDOT:PSS)	No cracking	Delamination at 15 %
Active (P3HT:PCBM)	6	30
ETL (ZnO)	5	10
Flextrode (PEDOT:PSS)	25	30

Table 1: Strain tolerance of films.

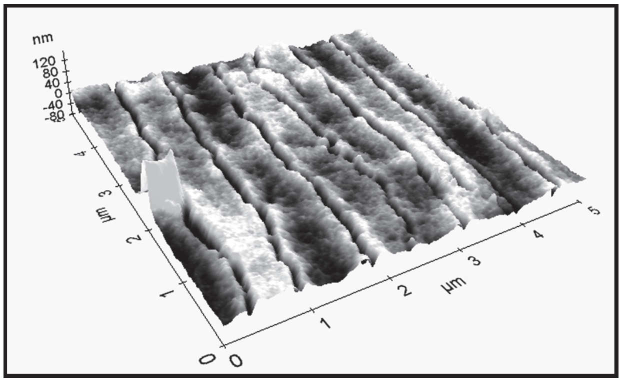
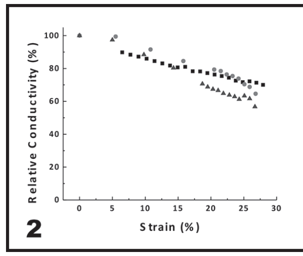


Figure 1: AFM image cracked ETL on flextrode at 20% strain (60-80 nm cracks).



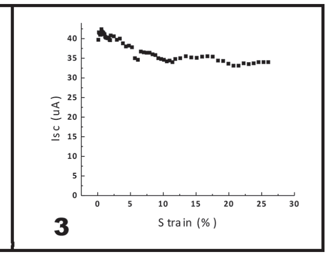


***Figure 2, left:** Conductivity measurements of flextrode during tensile testing.* ***Figure 3, right:** Photocurrent (I_{sc}) measured as a function of strain.*

through the film (cracks through). Delamination of the HTL due to poor adhesion to the underlying active layer was found to be the first cause of total device failure. Onset of surface cracking of the active layer occurred at 6% strain, but the devices continued to function despite this. Figure 1 shows surface cracking of the ETL on flextrode in a 5 µm square AFM topography image. Before straining, the surface was very smooth with 3-5 nm surface features; crack depth, width, and density increased with greater strain. Flextrode was shown to be mechanically robust to 25% strain. This is nearly an order of magnitude above the strain tolerance of ITO, which begins to crack at 3% strain [2].

The changes in surface morphology were correlated with the functionality of the films. Strain slightly decreased the conductivity of the flextrode layer, as shown in Figure 2, but it retained 75% of its function at 25% strain. The layer had not failed catastrophically even by 60% strain, a deformation that requires kilonewtons of force.

Next, function of the full devices under strain was tested by photocurrent measurements, the results of which are shown in Figure 3. Background effects interfered with quantitative measurements, but qualitative trends were apparent. At strains less than five percent (comparable to operating conditions), cracks reclose and function is restored upon relaxation. The full device retains functionality to 25% strain. Though crack onset in the active layer at 6% strain causes some decrease in output, the complete cell is able to withstand deformations well beyond those expected in service.

Conclusions:

Though OPVs face a number of challenges before they are market-ready, we have shown flextrode-based devices to be quite robust towards tensile strain. Surface morphology of the films was characterized with AFM to determine onset of cohesive cracking, and this was correlated with film functionality. Flextrode tolerated an order of magnitude higher strain than conventional ITO, retaining 75% of its original conductivity at 25% strain. Though the active layer begins to crack at 6% strain, actual device failure was caused by delamination of the HTL. Straining cells decreased their PCE, but the device continued to function at 25% strain, far beyond normal operating conditions. Flextrode is therefore shown to be a viable replacement for ITO, and more compatible with the fabrication process and applications of OPVs. Improvement of adhesion at the active layer-HTL interface will improve cells' mechanical durability, a critical step in realizing the potential of OPVs.

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References:

[1] Frederik C. Krebs, 2009, 93, 4, 394-412.
[2] Mora, et al. Electronic Materials Letters 2010, 10, 1033.