Final Report – Molecular Solar Cells

Investigators

Peter Peumans, Assistant Professor, Electrical Engineering; Shanbin Zhao, Jung-Yong Lee, Whitney Gaynor, Albert Liu, Soojin Kim, Seung Bum Rim, Junbo Wu, Mukul Agrawal, Uraib Aboudi, Graduate Researchers, Stanford University.

Abstract

We have focused on developing architectures and processing methods for organic solar cell device architectures that allow high efficiency solar cells to be built with organic materials despite the shortcomings of these materials. Using low-cost, laminatable transparent electrodes, we demonstrated multi-terminal multijcuntion cells that have the highest efficiency potential of all organic solar cell device architectures. Substantial progress was also made in light management using shaped substrates. Finally, progress was also made in understanding the physics of organic solar cells with an accurate model for recombination.

Introduction

Organic solar cells are attractive because of their potential for very low-cost photovoltaics. Despite their promise, the efficiency of organic solar cells is still too low for applications in primary energy generation. We are developing device architectures that overcome the fundamental limits of organic materials to reach power conversion efficiencies >10%.

An important reason for the low efficiencies of organic solar cells is our limited understanding of the physics that governs these devices. Unlike in inorganic solar cells, electrons and holes in organic semiconductors are strongly attracted to each other, leading to strong exciton binding energies (which necessitates the use of donor-acceptor junctions) and strong correlated motion between electrons and holes even after the excitons are dissociated, which leads to *geminate* recombination.

Background

Over the last few years, enormous progress has been made in increasing the efficiency of singla-junction organic solar cells, with recent record cells achieving 8% power conversion efficiencies (the records were at ~4% when this project was started). Many researchers now think that single junction organic solar cells have nearly reached their full potential. Future advances will come from multijunction architectures, one of our focus areas.

It has also become clear that light management approaches to increasing the efficiency have become a high priority. The best cells to date do a great job of separating charges, but do not absorb all the light. This has also been a focus area of our research project.

Finally, it deserves mentioning that there are now credible long lifetime demonstrations for organic solar cells with lifetimes extending up to 30 years (extrapolated) in a recent report from Heliatek.

Results

We briefly discuss our results in the areas of new device architectures, light management and fundamental physics of organic solar cells.

Multi-Terminal Multijunction Organic Solar Cells

To achieve efficiencies approaching 15%, which will likely be required for organic solar cells to become a competitive solar cell technology, multijunction approaches are necessary. The traditional method to make a multijunction cell entails connecting the subcells in series, which requires current matching and limits the design options. We've shown that by inserting intermediate transparent electrodes, higher efficiencies can be obtained with simpler device designs, as shown in Fig. 1. The 3-cell series-connected cell has a potential of 11.2%, while the 2-cell multi-terminal cell has a potential of 12.3%.

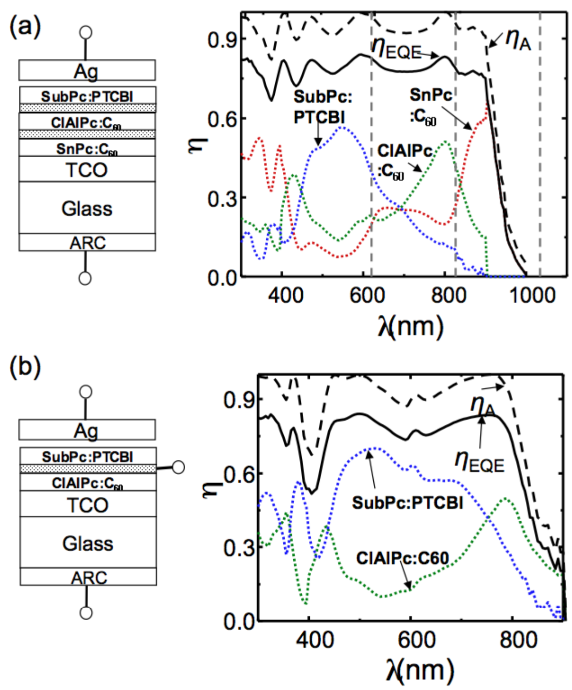

Figure 1: The efficiency potential of a traditional 3-cell series-connected multijucntion cell (a) and a 2-cell multi-terminal multijunction cell (b).

We had developed technology for laminating higjh-performance, solution-processed transparent electrodes built from Ag nanowires onto organic solar cells. These transparent electrodes are equal in performance to the best metal-oxide transparent conductors and come out of a research collaboration between Prof. Cui and Prof. Peumans' groups. Using such a laminated transparent electrode, we demonstrated a multi-terminal multijunction organic solar cell, as shown in Fig. 2. The overall conversion efficiency is

3% due to a limitation of the materials used. The front cell is a P3HT:PCBM polymer cell while the back cell is a small-molecular weight CuPc/C_{60} cell.

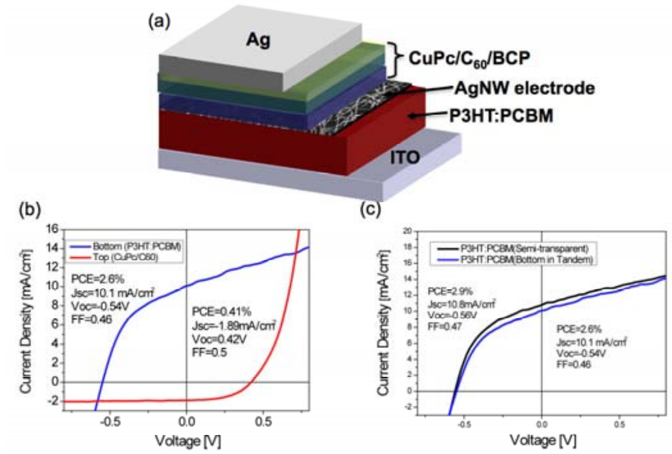

Figure 2: (a) Schematic of the device. (b) IV curves of the two subcells. They can be measured independently because of the multi-terminal architecture. (c) IV curves of the polymer front cell with and without back cell.

Light Management

We had shown early on in the research project that a simple V-shaped light trap is very effective at increasing the light absorbing abilities of an organic solar cell. The central idea is that light is allowed to bounce several times off the thin active layers to increase the probability that the light is absorbed.

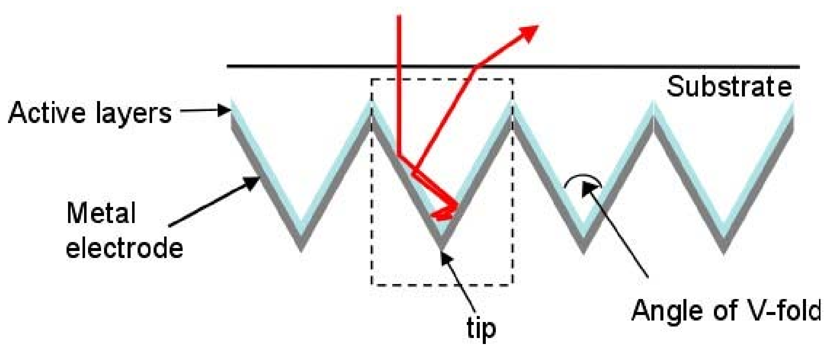

Figure 3: Schematic of the V-shaped device architecture for increased light absorption.

We have completed a full theoretical investigation of this approach and have recently demonstrated that this approach is effective for today's best cells in a collaboration with Prof. McGehee. For example, the efficiency of a 5.2% PCDTBT:PCBM cell was increased to 7.3%. Using this approach, we anticipate that 10% efficient organic solar cells will be demonstrated in the near future.

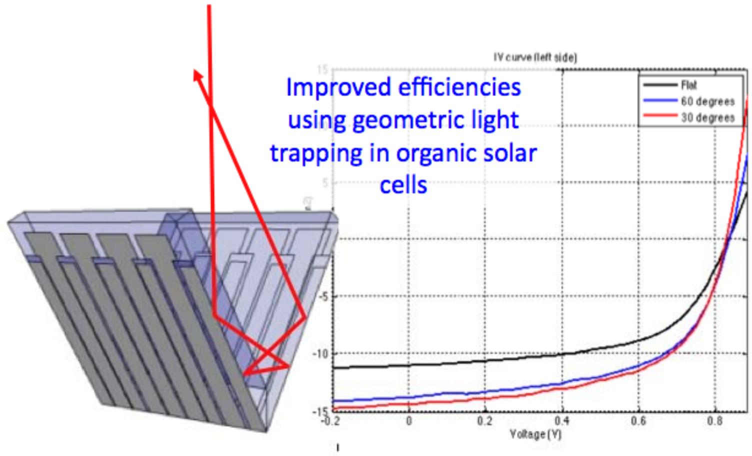

Figure 4: Schematic of the V-shaped geometry used and IV curves for a flat cell (control, black) and cells in a V-shape, showing the increase in photocurrent. The efficiency increased from 5.2% to 7.3%.

Modeling of Recombination in Organic Solar Cells

Recombination of carriers is a major efficiency bottleneck in organic solar cells, especially bulk heterojunction solar cells. Dark current-voltage measuremtns are in essence a probe of recombination rate as a function of carrier density. We have used dark IV measurements as a function of temperature to probe this process and developed a simple model that explains both the temperature and carrier-concentration dependence. The model results are compared to experimental data in Fig. 4.

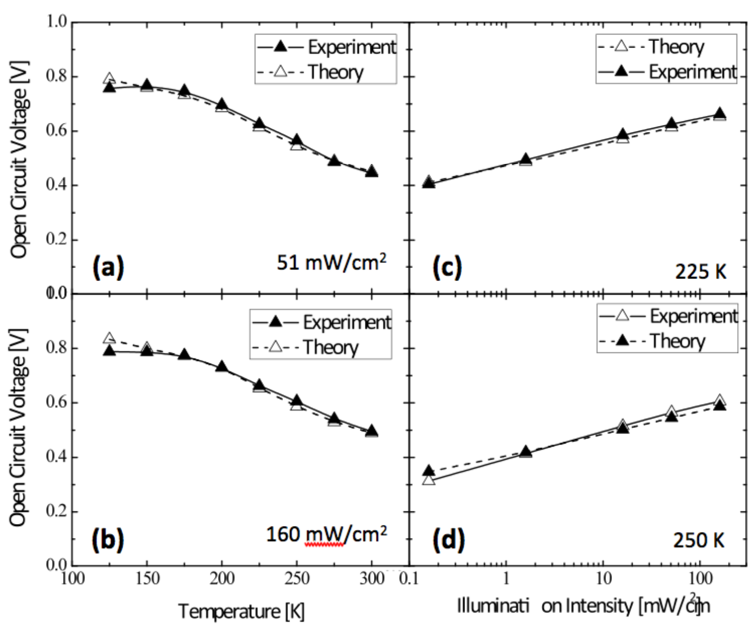

Figure 5: Modeled and measured open circuit voltage as a function of temperature and light intensity for a CuPc/PTCBI bilayer system.

We also studied the charge separation process in simple bilayer systems. This process is strongly field and temperature-dependent. The field at the donor-acceptor interface is determined by the unintentional doping concentration in the donor and acceptor, but can be tuned by freezing out the free carriers using low-temperature measurements. By combining capacitance-voltage and photocurrent-voltage measurements at low temperatures with kinetic Monte Carlo simulations, a good agreement between experiment and theory was obtained.

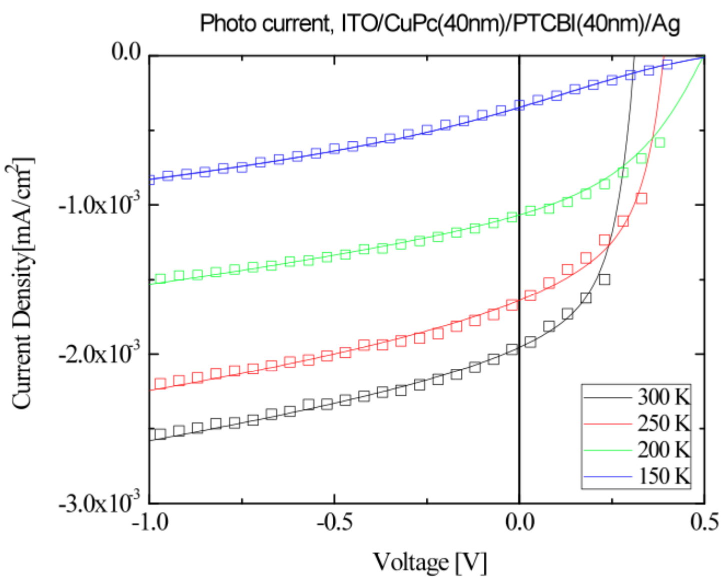

Figure 6: Modeled and measured photocurrent as a function of voltage and temperature. The model is a kinetic Monte Carlo model that correctly models the Coulomb interaction between electrons and holes as they are attempting to escape from each other.

Conclusions

In conclusion, a multi-terminal multijunction cell architecture with very high efficiency potential was developed and demonstrated by applying a novel solution-processed transparent electrode. A new light management technique that significantly enhances the efficiency of the best organic solar cells was demonstrated and is likely to lead to 10%-efficient organic solar cells if the very best materials available today are used. Finally, accurate models for carrier recombination and dissociation were developed.

Publications

1. J. Wu, H.A. Becerril, Z. Bao and P. Peumans, "Organic solar cells with solution-processed graphene transparent electrodes," Appl. Phys. Lett. **92**, 263302 (2008).
2. M. Agrawal and P. Peumans, "Broadband optical absorption enhancement through coherent light trapping in thin-film photovoltaic cells," *Optics Express* **16**, 5385-5396 (2008).
3. Liu, S. Zhao, S.-B. Rim, M. Koenemann, P. Erk and P. Peumans, "Control of electric field strength and orientation at the donor-acceptor interface in organic solar cells," *Advanced Materials* **2008**, 1065-1070 (2008).
4. S. Zhao and P. Peumans, "Geminate recombination at organic semiconductor heterojunctions," submitted.

5. S.-B. Rim, S. Zhao, S.R. Scully, M.D. McGehee and P. Peumans, "An effective light trapping configuration for thin-film solar cells," *Applied Physics Letters* **91**, 243501 (2007).
6. W. Gaynor, J.-Y. Lee and P. Peumans, "Fully Solution-Processed Inverted Polymer Solar Cells With Laminated Nanowire Electrodes," ACS Nano, Vol. 4 (1), 30-34 (2010).
7. J.-Y. Lee, S. T. Connor, Y. Cui and P. Peumans, "Semitransparent Organic Photovoltaic Cells with Laminated Top Electrode", Nano Letters, Vol. 10 (4), 1276-1279 (2010)
8. S.B. Rim and P. Peumans, "An analysis of light trapping configurations for thin-film solar cells based on shaped substrates," accepted in J. Appl. Phys.
9. S. Zhao and P. Peumans, "Simulations of carrier dynamics in bulk heterojunction organic solar cells," in preparation
10. W. Gaynor, G. Burkhard, M. D. McGehee, and P. Peumans, "A High-Performance Composite Solution-Processed Indium Tin Oxide Replacement for Optoelectronic Devices", submitted.
11. A. Liu, C. Stoessel, L. Boman, C. Niu, J. Miller and P. Peumans, “High-speed toll-to-roll vacuum deposition of organic solar cells,” submitted to Appl. Phys. Lett.
12. S. Zhao, S.B. Rim and P. Peumans, “Field and temperature-dependent photocurrent generation in bilayer organic donor/acceptor solar cells,” submitted to Adv. Mater.
13. S. Zhao and P. Peumans, “An accurate microscopic model for the dark current and open-circuit voltage of organic solar cells,” submitted to Adv. Mater.

Contacts

Prof. Peter Peumans: ppeumans@stanford.edu