Organic Optoelectronics for Renewable Energy

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Organic photovoltaic (PV) cells

Traditional PV cell technologies based on inorganic semiconductors produce clean electricity at a cost per kWh that is nearly an order of magnitude higher than that of electricity generated by fossil fuel combustion. Organic PV cells have recently attracted considerable attention because of their potential to substantially reduce the cost of solar electricity by lowering the cost of the substrate, materials, processing and installation. While the power conversion efficiency of organic PV cells has increased steadily since their inception to the current state-of-the-art of 3-4%, it still falls far below that achieved in crystalline silicon (η_P~24%). Organic PV cells remain therefore uneconomical as an energy source. Our short-term research efforts focus on developing device architectures and fabrication methods for organic PV cells with power conversion efficiencies exceeding 10%. Our long-term goal is to render organic photovoltaics the cheapest known option for electric energy production.

Concrete projects being pursued are:

Multijunction cells: We have demonstrated that transparent metal nanoclusters contacts allow organic PV cells to be stacked in series, resulting in an increased in power conversion efficiency over single junction devices [1]. The use of thinner individual cells and the ability to adjust the absorption edge of each individual cell, allow efficiencies closer to the thermodynamic limit to be achieved. This approach is also used to construct very-high-efficiency inorganic PV cells but requires careful control over the multilayer growth. Organic materials are inherently advantageous in this respect since heterostructure growth does not require lattice matching. We are now exploring the limits of this approach through the use of novel materials (low bandgap, band offset tuning), device modeling, growth studies, and material and device characterization.

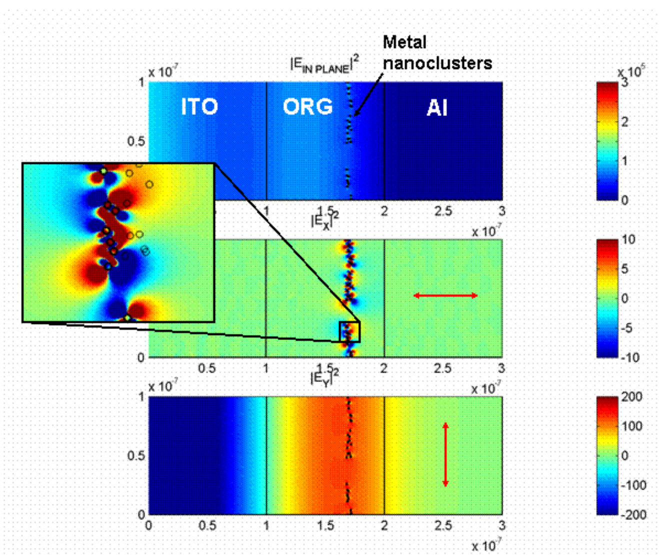

Fig. 1: Finite-element model of the enhanced optical absorption due to a random array of 10Å diameter Ag clusters in an organic thin film.

Nanoscale optical design: The presence of noble metal nanoclusters in organic films enhances the linear optical absorption of the organic material (Fig. 1), leading to a concomitant increase in the power conversion efficiency of a thin PV cell. We have developed a quantitative understanding of this effect [2] and are exploring strategies to exploit this effect to a larger extent. We will focus on reducing unwanted excitation quenching using thin dielectric insulators shells and on optimizing the nanoscale organization of the metal structure for optimal absorption enhancement. In addition, we have discovered that the use of aperiodic dielectric stacks embedded in the substrate can lead to a 50% increase in power conversion efficiency by realizing broadband resonant cavities matched to the solar spectrum, leading to further enhancements of the optical absorption. In this project, we will use electromagnetic and device modeling, optimization techniques, dielectric multilayer stacks, nanoscale metal patterning and device growth and fabrication. As a part of this effort, we are constructing a dedicated computing architecture for very-large-scale electromagnetic simulations using the finite-difference time-domain (FDTD) method.

Composite systems: We are investigating the use organic composites and hybrid systems consisting of nanocomposites of inorganic nanocrystals (TiO_2, CdSe), large molecules (carbon nanotubes, polymers) and small molecular weight organic materials. These systems exhibit a wider tuning range and can be used in combination with the above approaches to achieve higher efficiencies. We will further improve the quantitative models we have developed [3] and explore vapor phase deposition techniques [4]. In contrast to wet deposition techniques (spin coating, ink jet printing, dip coating), a vapor phase technique would afford the incorporation of these advanced materials into more complex multilayer structures and stacked devices with full control over the nanoscale morphology through kinetic control. An aerosol deposition tool currently under development in our laboratory (Fig. 2) allows for the deposition of inorganic nanoclusters, very large molecules, polymers and small molecular weight materials and is scalable to roll-to-roll type processing. High performance devices can be fabricated by layering the various materials using this entirely dry process. Furthermore, the ability to deposit virtually any nanostructured material allows for the realization of complete PV cells, including a passivation layer, in a single reactor, leading to very-low-cost manufacturing.

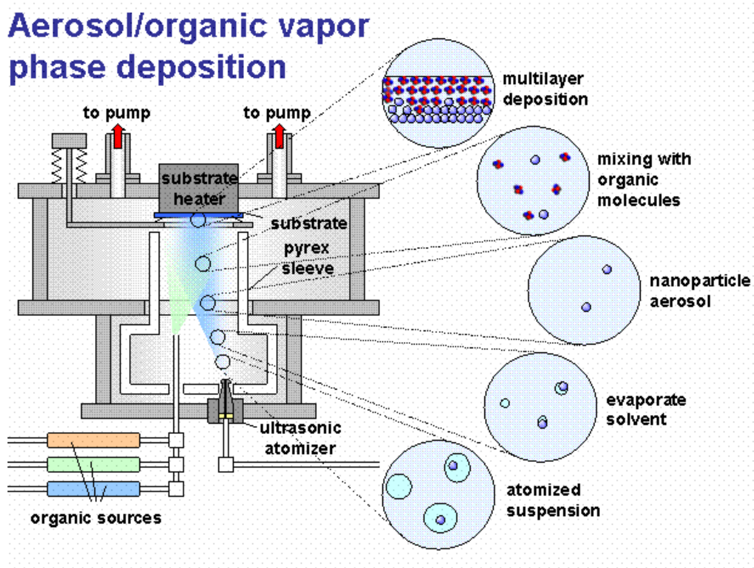

Fig. 2: Combined aerosol/organic vapor phase deposition system.

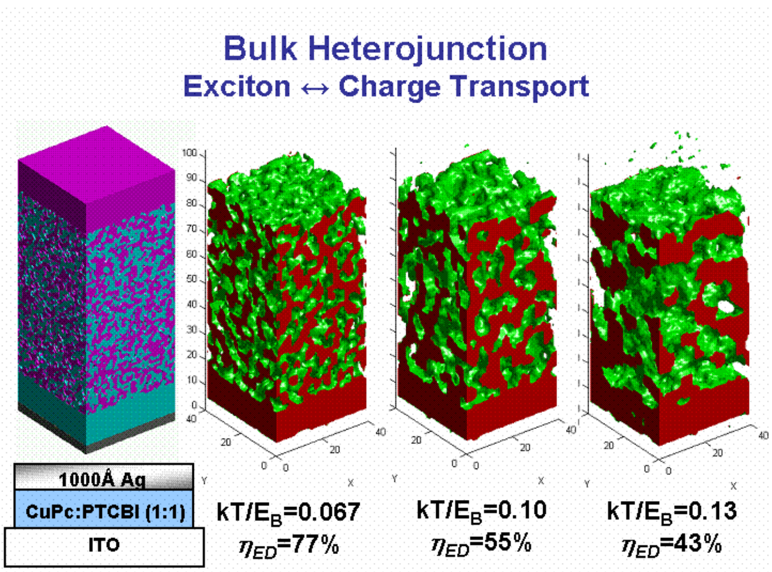

Fig. 3: Simulation of phase separation in a binary mixture resulting in a bulk heterojunction donor-acceptor photovoltaic cell.

Device modeling: A hierarchy of models across multiple length scales, from molecular dynamics models to continuum device models (see Fig. 3), is used to verify the developed insights and design better structures.

Other PV-related research projects: the evaluation of new materials for increased exciton diffusion lengths and lower bandgaps, the integration of photosynthetic antenna systems into organic PV cells, organic PV cell lifetime, the effect of source material purity on the performance and lifetime of organic PV cells, innovative form factors for organic PV cells (e.g. lightweight PV cells on textile fiber), innovative fabrication techniques (e.g. vapor jet printing), p and n-type doping for increased V_{OC}.

Low-cost, high-efficiency inorganic microconcentrator solar cells

We have developed a technique that allows us to “stretch” a semiconductor wafer to 1000x its original size. This is achieved by cutting specially designed patterns into the wafers using micromachining techniques. The result is an array of micro-solar cells, automatically spread out and wired over a large area. In combination with a microconcentrator sheet, these arrays exhibit high efficiencies at very low cost.

Very-high-efficiency solid-state organic light sources

In 1997, lighting was responsible for 8% (1775 billion kg) of the worldwide CO_2 emission and costed $230 billion [5]. Efficient light-emitting diode (LED) based solid state white lighting systems have a significant potential to reduce GHG emission. Organic LEDs (OLEDs) are a promising white light source that can be manufactured at low cost and in novel, practical form factors (e.g. tiles, flexible foil). While state-of-the-art white OLEDs approach the efficiency of fluorescent lighting, 80% of the generated photons remain unused because of total internal reflection in the substrate, waveguiding and plasmon polariton emission. Using dielectric stacks and metal nanostructures, the angular and spectral distribution of the photon density of states can be altered to inhibit emission into these lossy modes, resulting in large efficiency gains and white-emitting devices with wall-plug efficiencies exceeding those of fluorescent lighting by a factor of two or more.

Collaborations

We work closely with research groups in Chemistry, Chemical Engineering and Material Science and Engineering for an integral approach to the above projects. This research will be supported by the Stanford Organic Electronics Laboratory (SOEL), a central state-of-the-art organic electronics research facility currently being built by the group of Prof. Peumans.

References:

[1] P. Peumans, A. Yakimov, and S.R. Forrest, *J. Appl. Phys.* **93**, 3693 (2003).
[2] B. Rand, P. Peumans, and S.R. Forrest, accepted for publication in *J. Appl. Phys*.
[3] P. Peumans, S. Uchida, and S.R. Forrest, *Nature* **425**, 158 (2003).
[4] M. Shtein, P. Peumans, J. Benziger, and S.R. Forrest, *J. Appl. Phys.* **93**, 4005 (2003).
[5] E. Mills, in *Proceedings from the 5th International Conference on Energy-Efficient Lighting, May 2002, Nice, France*.