Introduction to Solar Energy Conversion

Solar energy represents the largest energy input into the terrestrial system. Despite its relatively low power density, this resource could potentially satisfy the global energy demand on its own. The challenges that need to be addressed to make solar energy viable and competitive on a large scale include: enhancing the performance of solar energy conversion systems through increased efficiency and use of durable materials; reducing the material, fabrication, and installation costs so that these systems can be deployed at a large scale; and overcoming the intermittent nature of the resource to allow supply to meet demand at all times.

Photovoltaic energy conversion efficiency has increased steadily in the past decade through enhanced photon absorption and charge transport. Moreover, continuous development of novel device concepts, materials, and fabrication processes has contributed to lowering the cost of solar power. Thin-film solar cells are regarded as a promising route for low-cost energy conversion. Inorganic thin films are relatively mature technologies with record efficiencies around 20%. Organic solar cells are at an earlier stage of development with efficiencies reaching around 11% for polymeric heterojunctions and dye-sensitized cells. Further research in thin-film technologies is required to increase their efficiency up to the thermodynamic limits, to enhance their stability, and to further reduce their fabrication cost.

Solar thermal technologies are appropriate for large-scale energy production and can be combined with thermal energy storage systems, which offers a practical solution to smooth supply intermittency over time periods of several hours.

Photo electrochemical systems are another option under investigation to circumvent the intermittency issue of solar power. They hold the promise to efficiently harvest solar energy and convert it into chemical fuels with a single, potentially low-cost device. This conversion strategy allows for the carbon-free – or even carbon-negative when CO_2 is used as a feedstock – synthesis of fuels for electricity and/or transportation, and provides a solution to the intermittency problems without requiring the use of ancillary energy storage systems to match supply and demand.

Currently, GCEP has five ongoing projects in the solar area that fall across the areas of organic and inorganic thin films, (photo-assisted) thermionic systems, high-efficiency thermo-photovoltaic conversion, and photo electrochemical production of hydrogen.

Professors Zhenan Bao, Michael Toney, and Alan Aspuru-Guzik began a project in 2010 aimed at a pathway towards breakthrough performance solar cells by rational organic semiconductor material design. This project combines the molecular design and device fabrication expertise of Bao, theoretical simulation expertise of Aspuru-Guzik, and the structural characterization expertise of Toney. The large distributed computing power of IBM’s World Community Grid (WCG) that this project employs allows the rational design of organic semiconductors for solar cells from a completely new angle. Many achievements have been made so far including the development of high efficiency and polymer/polymer solar cell, and the precise molecular packing structures for thin films of pentacene, TIPSE-pentacene, and a series of fluorine-bithiophene oligomers from grazing incidence X-ray diffraction (GIXD) data combined with numerical fitting has been determined. This development is important for structure-property relationship studies because it allows us to understand organic semiconductor packing on substrates that are directly used for device fabrication.

Professors Mike McGehee and Alan Sellinger of Stanford University began a new project in 2010 aimed at investigating advanced electron transport materials for application in organic photovoltaics (OPVs). The objectives of the proposed work are to design, prepare and characterize a family of new advanced electron transport materials from simple, minimal step, high yield, and inexpensive synthetic processes for application in OPVs.

Professor Bao has a second project with the goal of developing an all carbon-based solar cell. This project focuses on taking advantage of the potential of carbon-based materials to form an all-carbon solar cell. Bao has demonstrated an all-carbon solar cell employing single walled carbon nanotubes (SWNTs) in conjunction with fullerenes as the active junction, and single walled carbon nanotubes and graphene oxide as the electrodes. Ongoing work is aimed at engineering a more efficient solar cell by optimization of material processing specifically the sorting of semiconducting SWNTs of various diameters as well as moving towards the formation of an interpenetrating bulk heterojunction of the donor and acceptor layers.

Professors Jennifer Dionne and Alberto Salleo are working on upconverting electrodes for improved solar energy conversion. They are developing an electrode that consists of colloidally synthesized silver nanowires decorated with upconverter-doped dieletric nanoparticles. This ongoing work will allow the optimization of the upconverting nanoparticles and the nanorod/nanoparticle geometry.

Professor James Harris, Shanhui Fan, Yi Cui, and Mark Brongersma are working on light management in mutlijunction solar cells. Their project is aimed toward achieving high-efficiency thin film solar cells that combine multi-junctions and nano-scale light management. A number of achievements have been made to date including the development of a computational tool for the detailed balance analysis of nanophotonic structures, elucidation of the physics of open-circuit voltage enhancement by analyzing the angular and spectral distribution of the cell’s absorption spectrum, and the demonstration of a novel nano-window GaAs solar cell that achieved 17% efficiency, and highest Voc (~1V) in a nanostructured solar cell.