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 systems viable and competitive on a large scale include: enhancing the performance of these systems through increased efficiency of energy conversion and use of materials that are stable and durable over the long term; reducing the 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.

The overall energy conversion efficiencies of photovoltaic devices that can be achieved have increased steadily in the past decade through enhanced photon absorption and charge transport. Continuous development of novel device concepts, materials, and fabrication processes has contributed to lowering the cost of solar power and hence to making it more competitive. 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 above 15%. Organic solar cells are at an earlier stage of development with efficiencies currently ranging from ~6% for polymeric heterojunctions to 10% for 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 addresses the issue of supply intermittency common to other renewable sources. The conversion of solar energy into chemical fuels, and particularly hydrogen, is another way of circumventing supply intermittency.

Recognizing the importance of solar energy for building a low GHG global energy portfolio, GCEP has been increasing its efforts in this area. To date GCEP has awarded six research projects in organic and inorganic thin films and one in bioelectricity.

Professor Michael McGehee is developing ordered nanostructured photovoltaic devices that may be fabricated using reel-to-reel coating machines. This research may lead to devices that will a) efficiently split excitons and carry charge to electrodes, b) have improved packing of the molecules in the organic semiconductor to enhance its ability to carry charge, and c) have a modified organic-inorganic interface to prevent recombination of electrons and holes.

Professors Fritz Prinz and Arthur Grossman are exploring the possibility of capturing electricity directly from living biological cells by inserting nanoscale electrodes into the cells' chloroplasts. Generation of bioelectricity will occur by exploiting the electrical potential difference created by the photosynthetic process in the chloroplast. This will be achieved by placing the anodic electrode in the stroma of the chloroplast and the cathodic electrode in the lumen.

Professors Stacey Bent, James Harris and Michael McGehee are applying atomic layer deposition (ALD) techniques to the fabrication of photovoltaics using nanostructured inorganic semiconductor composites. This approach is intended to increase the photon absorption of inorganic thin films by using the multiple junction concept and by increasing the optical path of light through the device by controlling the cell geometry at the nanoscale. As ALD deposition is applicable to high-throughput fabrication, this technology could potentially lead to low cost photovoltaics with good energy conversion efficiencies.

Professors Mark Brongersma, Peter Peumans, and Shanhui Fan are developing organic multijunction photovoltaic cells that use metal nanoscale features to enhance both photon absorption and charge transport. Transparent high-sheet-conductivity nano-patterned metal films are being used as conductors allowing parallel sub-cell connection, and metal nanostructures are being embedded in the active layers to enhance the photon absorption and charge separation efficiency.

Professors Martin Green and Gavin Conibeer of the University of New South Wales, Australia, are working on an innovative photovoltaic device based on integrating low-cost polycrystalline silicon thin films with higher bandgap semiconducting materials. These materials are synthesized using silicon quantum dots embedded in a matrix of silicon oxide, nitride, or carbide to produce two- or three-cell tandem stacks. At the nanoscale, quantum confinement increases the effective bandgap of silicon and enhances absorptivity due to the formation of a quasi-direct bandgap. A significant increase in the efficiency of silicon-based thin films is anticipated without adding appreciably to large-volume manufacturing costs per unit, thus decreasing installed system costs.

Professors Zhenan Bao and Michael McGehee are developing novel organic materials to be used in bulk heterojunction photovoltaics. The properties of these semiconducting polymers will be customized to increase the photon absorption efficiency in the IR spectrum (by reducing their optical bandgap), and to enhance the exciton transport (by generating, upon photoexcitation, triplet states that exhibit longer lifetimes than singlet states).

Professor Peter Peumans is developing organic photovoltaics (OPVs) based on intrinsically stable conjugated molecules to address the durability issue of OPVs. High conversion performance will be achieved both by enhancing the absorptivity of the small molecules in the visible and near IR spectra and by enhancing exciton diffusion and charge transport in bulk heterojunctions through structural engineering. For this purpose, multiple deposition and post-treatment techniques will be explored to optimize the nanoscale morphology of self-organized bulk-heterojunctions.