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 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. Currently, GCEP has nine ongoing projects in organic and inorganic thin films and one in photochemical production of hydrogen.

Professors Stacey Bent, James Harris, and Michael McGehee are applying atomic layer deposition (ALD) techniques to the fabrication of thin-film photovoltaics using nanostructured inorganic semiconductor composites. This approach is intended to both increase photon absorption by increasing the optical path of light through the device and decrease charge transport inefficiency through the control of the absorber morphology 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, 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.

Professors Nate Lewis, Harry Gray, and Harry Atwater of the California Institute of Technology are developing an integrated device for producing hydrogen directly from sunlight. The proposed device is composed of a conductive membrane that has both the role of absorbing the solar radiation and supporting the initial charge separation. Electrons and holes are directed to different sides of the membrane, where two specifically designed organic catalysts assist water reduction and oxidation half-reactions.

Professors H.-S. Philip Wong, Peter Peumans, Mark Brongersma, and Yoshio Nishi are working on a new nanowire-based multijunction device. The two key components of the proposed design are a metallic nanostructured electrode serving as light concentrator and spectral filter, and the absorbing material consisting of an array of vertically aligned nanowire-shaped *p-n* junctions with different bandgaps. The metal substrate can split the incident broadband solar spectrum and localize spectral energy in different spatial locations coinciding with the location of nanowires with the optimized bandgap. This challenging concept offers multiple advantages such as the use of low-cost and abundant materials, and parallel connection of the multijunction subcells.

Professor Harry Atwater of the California Institute of Technology, Professor Mark Brongersma of Stanford University, and Professor Alfred Polman of the Foundation for Fundamental Research on Matter (FOM), The Netherlands, are applying plasmonic technologies to enhance the performance of nanocrystal semiconductor-based thin film photovoltaics. Nanopatterned metallic films are utilized as transparent electrodes and light concentrators to allow the use of poor electron transport materials – such as low-dimensional semiconductor structures – in very thin (10-100nm) layers of photoactive material. This project also explores potential designs of omnidirectional absorbers that can be integrated into the cell as built-in tracking systems to further enhance cell efficiency.

Professors Gavin Conibeer and Martin Green of the University of New South Wales, Professor Jean-François Guillemoles of IRDEP, France, Professor Nicholas Ekins-Daukes of the University of Sidney, and Professors Antonio Marti and Antonio Luque of the Instituto de Energía Solar, Spain, are developing a proof-of-concept device of a hot carrier solar cell using abundant and non-toxic nanostructured materials. The project addresses all main scientific and technological aspects of such a concept, including the reduction of hot carrier thermalization in the main absorber, the development of selective energy contacts, and the integration of all components into a working device.

Professors Alberto Salleo, Yi Cui, and Peter Peumans are investigating a novel low-cost concept for inorganic multijunction solar cells. The proposed concept uses solution-processed absorbers made of colloidal semiconductor nanocrystals and ZnO nanowire network-based transparent conductors as an alternative to established technologies based on brittle and high-cost transparent metal oxide films. The overall approach offers advantages such as large flexibility in the choice of active materials, easy control of subcell bandgap using quantum-confinement effects, practicability of realizing devices with a large number of junctions.