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 offers a practical solution to smooth supply intermittency over time periods of several hours.

Photoelectrochemical 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 organic and inorganic thin films, one in (photo-assisted) thermionic systems, one in high-efficiency thermo-photovoltaic conversion, and one in photoelectrochemical production of hydrogen.

Professor Zhenan Bao is developing a carbon nanotube (CNT)-based transparent electrode technology for photovoltaic applications. Her research includes the development of an experimental method to selectively separate metallic from semiconducting nanotubes and to control the morphology of the metallic nanotube network to optimize both the film transparency and the sheet conductivity. This progress report includes, among others, recent results on the fabrication of smooth and robust single-wall CNT films on polymers and on improved mechanisms to achieve the absorption of CNTs on functionalized surfaces.

Professors Nicholas Melosh and Zhi-Xun Shen are investigating a novel photon-enhanced thermionic concept that combines photon- and thermal-excitation in a semiconductor material to increase the efficiency of thermionic electron emission compared to current systems. So far, the investigators determined the key material parameters and device geometries to achieve the established theoretical efficiency limits, and built a new surface preparation and characterization chamber that can provide detailed control and measurement of material performance.

Professors Shanhui Fan and Peter Peumans from Stanford University in collaboration with Professor Paul Braun from University of Illinois at Urbana-Champaign are developing a thermo-photovoltaic (TPV) device capable of achieving solar-to-electric energy conversion efficiencies higher than the Shockley-Queisser limit for single-junction solar cells. The main components of the system consist of photonic crystals designed to absorb electromagnetic energy over the entire solar spectrum and reemit light at energies close to and above the bandgap of a single junction photovoltaic cell. This year's progress report describes continued progress towards the development of high-efficiency cell designs and of the experimental setup for fabricating and measuring such devices.

Professors Gavin Conibeer and Martin Green of the University of New South Wales, Professor Jean-François Guillemoles of IRDEP, France, Professor Tim Schmidt 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 the 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. Due to differences in the starting times of the various sub-contracts under this multi-institutional collaboration, this year's progress report already includes the final report by Professors Marti and Luque on their theoretical studies of the fundamental energy transfer mechanisms between hot electrons and phonons and on the experimental setup requirements for the physical characterization and the measurement of the performance of hot carrier devices.

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 or Ag 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, and the practicability of realizing devices with a large number of junctions. Recent progress on both nanowire-based transparent electrodes is described as well as their integration into a CIS-based working device.

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 (plasmonic) 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. In this progress report, the authors describe how they used full-field electromagnetic simulations to optimize the "nanoring" geometry of the plasmonic resonator antenna against spectral splitting and electromagnetic field concentration; the methods that they developed to fabricate the antenna; and their setups for the construction of fully working devices.

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 nanocrystalline 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. Last year, non-periodic plasmonic structures with optimal broadband light absorption were modeled and are now being experimentally validated. Also, light-trapping back-reflector using periodic plasmonic nanostructures were demonstrated, resulting in enhanced absorption and photocurrent in prototype InGaN cells.

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. Recent research demonstrated the highly-controlled fabrication of Si nanorod-based photocathodes and their integration with a proton conductive membrane, and the deposition of stable metal catalysts. Also, much progress was done in the development of novel biological and bio-inspired catalyst systems.