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 seven ongoing projects in the solar area that fall across the areas of organic and inorganic thin films, (photo-assisted) thermionic systems, nanoscale light-management and photo electrochemical production of hydrogen.

Professors Mike McGehee and Alan Sellinger of Stanford University began a 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. In the past year, significant progress in the discovery of the mechanisms underlying how devices prepared with new electron acceptor materials generate free charges that contribute to photocurrent has been made. The researchers have entered into an arrangement with Sigma-Aldrich, which will scale up the promising electron acceptor

and make it available to the community for purchase and testing. The highest efficiency solution-processed bulk heterojunction solar cells prepared without the use of fullerene derivatives have utilized one particular material, 4,7-bis(4-(N-hexylphthalimide) vinyl)benzo[c]1,2,5-thiadiazole, termed HPI-BT. With further improvements in the synthetic preparation of the material and processing conditions, device efficiencies as high as 3.7%, have been achieved. This may be one of the highest efficiencies for solution processed organic solar cells that do not contain fullerene derivatives. Preliminary device lifetime testing results show that OPVs using the HPI-BT electron acceptor are quite long, and this aspect will be looked at further.

Professor Zhenan Bao's project has 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. Work in the last year focused on improving the sorting of semiconducting carbon nanotubes and the enhancement of the conductivity and transparency of carbon-based electrodes. A high-yield method to selectively disperse semiconducting CoMoCAT (CO disproportionation on Co-Mo Catalysts) single-walled carbon nanotubes (SWNTs) with regioregular poly (3-alkylthiophenes) polymers is described. Additional experimental and modeling results obtained by these researchers provide a better understanding for future rational design of polymers for sorting SWNTs.

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. Using a suite of analytic calculations, electrodynamic simulations, this project has: predicted the expected photovoltaic efficiency improvements with realistic upconverters; improved existing upconversion processes by precisely controlling photonic and electronic processes; and developed cost-effective upconverting electrodes that can convert near-infrared light to visible light and extract current from solar cells. This innovation in upconverter materials design has yielded record-efficiency upconverting layers, and ongoing work is aimed at incorporating these materials into research and commercial solar cells.

Professor James Harris, Shanhui Fan, Yi Cui, and Mark Brongersma are working on light management in multijunction 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 wafer bonding and lift-off process for a GaAs/Si device on Si, which can be bonded to a glass or metal substrate. They have successfully demonstrated lift-off

of GaAs solar cells with sub-micron thickness. Also demonstrated are: a novel nano-window GaAs solar cell that achieved 17% efficiency and the highest V_{oc} (~1 V) in any nanostructure solar cell; a novel thin-film double junction solar cell; the V_{oc} advantage of thin film solar cell with a 5□m thick Si solar cell, which achieved 10% efficiency, and the highest V_{oc} of 640mV for any Si solar cell under 30um thick.

Professor Brongersma has a project that began in 2012 on Dielectric Metasurfaces for Light Trapping in High-efficiency Low-cost Silicon Solar Cells. In this very recently started project (subcontracts to FOM and CalTech are currently being put in place), these researchers are introducing for the first time the concept of dielectric metasurfaces, in which the coupling between dielectric scatterers with optimized shape, size and periodic architecture is engineered to optimize light trapping. They aim to apply these metasurfaces to thin (5-50 □m) crystalline silicon solar cells that are made using commercially available lift-off and layer transfer techniques. Numerical simulations show that it is feasible to realize dielectric-metasurface-enhanced single crystalline Si solar cell thinner than 20 □m with an AM1.5 c
will demonstrate a highly efficient silicon solar cell that can be made at low silicon materials cost. As the cost of silicon is a major cost factor in conventional wafer scale Si solar cells (□0.25 $/Wp) this pr
technology. Dielectric metasurfaces can be made onto any solar cell surface using large-area inexpensive soft-imprint lithography.

Professor's William Chueh and Nick Melosh are working on a project entitled, Maximizing Solar-to-Fuel Conversion Efficiency in Oxide Photo-electrochemical Cells Using Heat and Concentrated Sunlight. The goal is to substantially increase the solar-to-fuel conversion efficiency in photoelectrochemical cells (PECs) by using heat and intense light from concentrated solar radiation. In the first six months of this work, substantial progress has been made in demonstrating the strong performance enhancement with temperature and optical concentration in iron oxide photoelectrodes in liquid electrolytes. This result lays the foundation towards elevated temperature, high efficiency solid-state PECs.

Professor Mike McGehee and Professor Hemamala Karunadasa have a project entitled, Novel Inorganic-organic Perovskites for Solution Processable Photovoltaics. These researchers have already fabricated 4-terminal hybrid tandem solar cells, which comprise of a semi-transparent perovskite solar cell stacked on top of a CIGS or silicon solar cell. The semi-transparent perovskite solar cells have power conversion efficiencies of over 12%. When combined with commercial-grade CIGS solar cells and some silicon solar cells, the tandem produces more power than the CIGS or silicon solar cell by itself. The toxicity of lead and the stability of perovskite materials containing CH_3NH_2 to moisture are significant challenges that may need to be overcome in order to commercialize perovskite hybrid tandem solar cells. Future work will be aimed at functionalizing the organic groups in these materials to improve their moisture resistance. Perovskite materials based on germanium as well as bismuth to replace lead will be investigated as well as one-step deposition methods for forming continuous films of perovskites, which may result in improved film quality and device performance. These processes also avoid

the multi-step conversion process of forming the perovskite and high-temperature vapor annealing steps, which may be less suitable for large-scale manufacturing.