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 to offer 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 four 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 Harris, Fan, Cui and Brongersma, have a project entitled “Toward high-efficiency thin film solar cells combining multi-junctions and nano-scale light management” in which they specifically address the development of practical, ultra-thin single crystalline GaAs, AlGaAs and c-Si solar cell structures, as well as AlGaAs/c-Si tandem cells. They thus far, have developed a wafer bonding and lift-off process and obtained GaAs thin film cells with thicknesses on the order of hundreds of nanometers, which enabled the study of nanophotonic light management on ultra-thin film solar cells. This novel cell architecture yields an extremely high-quality planar junction, which

avoids the fundamental, significant V_{oc} and efficiency degradation in traditional nanostructured junction solar cells. A high efficiency Si solar cell with 5μm thickness and TiO selective contact was designed and fabricated. This represents a crucial step forward toward realizing a III-V/Si multi-junction cell. Combining all these developed techniques, nano-structured thin film multi-junction solar cells can be achieved. Such a cell would significantly increase solar cell array efficiency, while minimizing cost increases by developing very thin-film cell structures that are enabled by nanostructuring and light management. Success in demonstrating a high-efficiency, low-cost cell will drastically reduce the cost of solar energy conversion systems as measured in dollars/Watt, and ultimately enable much greater penetration of photovoltaics into the energy market in the industrialized world.

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 project, the Brongersma group has demonstrated that flat optical elements can be realized that redirect and trap light as well as concentrate light for concentrated solar photovoltaics. They optimized the size, shape and arrangement of the dielectric scatterers. The aim is to apply these metasurfaces to thin (5-50 μm) single-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 μm with an AM1.5 conversion efficiency over 20%. If successful, this 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 (c. 0.25 $/Wp) this project would present a major step forward in Si solar cell technology.

Professor's William Chueh and Nick Melosh are working on "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. The team will address these shortcomings by designing earth-abundant, oxide-based heterojunction photoanodes that can operate at temperatures significantly above ambient. These oxide-based PECs aim to capture excess thermal energy resulting from the absorption of intense concentrated sunlight, which is normally discarded. In the first one and half years of this work, substantial progress in demonstrating the strong performance enhancement with temperature and optical concentration in iron oxide and bismuth vanadate photoelectrode in liquid electrolytes has been made. A solid-state electrolysis cell operating between 300 and 600 °C has been developed. This result lays the foundation towards high efficiency solid-state PECs operating beyond room temperature.

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 achieving efficiencies over 18% in the case of the CIGS-perovskite tandem. As the

reliability of the perovskite material remains the greatest technical risk in commercialization of perovskite photovoltaics, the team has made several important discoveries regarding instabilities of the perovskite to electrical bias and illumination. In particular, they have found that perovskite solar cells in planar architectures typically exhibit hysteresis with voltage, and a decline in performance under steady-state conditions that can be reversed by forward biasing the device. These observations are consistent with electromigration of ions within the device during operation. They have also found that larger bandgap perovskites incorporating mixed halides, such as $CH_3NH_3Pb(I_{1-x}Br_x)_3$, generally undergo a halide segregation process under illumination. This produces domains with a smaller bandgap than the starting material and limits the open circuit that can be achieved by these materials. Previously the $CH_3NH_3PbI_3$ perovskite was shown to be highly sensitive to moisture. The group has developed 2-dimensional perovskite materials incorporating hydrophobic organic cations that have greatly improved the moisture resistance, with no degradation products observed after 46 days of moisture exposure.