Engineering The Solar Energy Future: Mechanisms, Materials, and Manufacturing

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The amount of sunlight energy that reaches the earth's surface in one hour exceeds annual worldwide energy consumption. Harnessing just a small fraction of the solar resource offers an unprecedented opportunity to revolutionize global energy systems. During this presentation, I will discuss the scientific breakthroughs and technological innovations required for the effective collection, conversion, and storage of solar energy. The properties of solar photons, state-of-the-art approaches to harvest them, and the requirements for terawatt-scale deployment will be provided. Nanostructured photovoltaic devices will serve as an archetypal future technology and the speaker's research in this area included where appropriate. Scientific and engineering challenges that open new opportunities for interdisciplinary research will be highlighted.

While solar radiation is abundant, it is also diffuse, broadband, and intermittent; properties that constrain all aspects of solar energy research and development. Immense land areas are required to achieve power generation levels on par with already existing infrastructure, especially in the industrialized world. This necessitates energy conversion schemes and manufacturing techniques that are highly efficient and scalable, respectively. The broad spectral nature of sunlight further requires the most efficient designs to parse photons of different frequency (e.g. ultraviolet, visible, and infrared). The diurnal cycle and general variability of terrestrial sunlight also demand that any solar energy converter be paired with storage. Two schemes will be contrasted in this regard: solar-to-electric and solar-to-fuels. The first category consists of solar thermal as well as solar photovoltaic approaches, both of which require storage. The direct conversion of photons to chemical bonds promises seamless integration with present-day liquid fuel systems, but success in this area remains limited. In general, a portfolio of technologies should be anticipated in the long-term as all approaches are not suitable for all geographic locations and end-user applications.

A discussion of the physical mechanisms, materials requirements, and manufacturing necessities for truly transformative photovoltaic technologies (e.g. solar wallpaper) will comprise the core of this presentation. Fundamental phenomena and governing principles, spanning atomic to macroscopic length scales and femto to microsecond time scales, will be emphasized within the context of rational device design.

- <u>Mechanisms:</u> An efficient photovoltaic device must absorb incident light as well as extract photogenerated charge carriers. Four loss mechanisms – incomplete absorption, thermalization, recombination, and thermodynamic loss – limit the theoretical energy conversion efficiency of a traditional device with a single absorption threshold (i.e. band gap) to 44%. However, recent advances in the understanding of semiconductor photophysical processes, predominantly in nanoscale systems, open new avenues to limit these losses.

- <u>Materials:</u> Gaining the synthetic dexterity required to control physical processes in nanoscale semiconductors is a grand challenge in materials science. State-of-the-art fabrication techniques cannot currently achieve the structural and chemical precision necessary to harness advanced photogeneration mechanisms. Crystal structure, dopant/impurity incorporation, and surface termination must be robustly engineered at the atomic through nanometer length scales.

- <u>Manufacturing:</u> The high-throughput fabrication of a complete device will require advances in our ability to assemble composite materials with micro to nanoscale internal dimensions across macroscopic areas. Distinct classes of materials and their interfaces must be designed to effectively deliver photons, rapidly extract charge carriers, and ensure long-term stability under standard operating conditions.