Light-Material Interactions in Energy Conversion (LMI)
EFRC Director: Harry Atwater
Lead Institution: California Institute of Technology

Mission Statement*: To tailor the morphology, complex dielectric structure, and electronic properties of matter to sculpt the flow of sunlight, enabling light conversion to electrical and chemical energy with unprecedented efficiency.*

The Light-Material Interactions in Energy Conversion Energy Frontier Research Center (LMI-EFRC) is a national resource for fundamental optical principles and phenomena relevant to solar energy conversion, and for design of the optical properties of materials and devices used for energy conversion. The LMI-EFRC features a team of researchers that spans the campuses at California Institute of Technology, Lawrence Berkeley National Laboratory, and University of Illinois at Urbana-Champaign. This Center is a foundational partnership between scientific world leaders in optical properties of matter with internationally recognized experts in photovoltaic energy conversion and innovators in the design and fabrication of novel electronic and photonic materials. We are creating new methods and architectures for complex photonic materials for solar energy conversion, including metamaterials, transformation optics, plasmonics, photonic crystals and other dielectric spectrum-splitting and light-trapping elements. These structures span dimensions ranging from the greater-than-wavelength scale to the subwavelength scale, and as a result, the LMI-EFRC has fostered a world-leading capability for fabrication of complex three-dimensional photonic nanostructures and light absorbers.

Objectives

- Design an optical system for full spectrum photon conversion via optically independent multijunction solar converter architectures to greatly enhance the efficiency of photovoltaic energy conversion.
- Define the limits of absorption and spontaneous emission in optical materials, yielding principles for design of ultrathin photovoltaic cells with scaling of light absorbers to nanoscale dimensions, enabling advances in photovoltaic conversion efficiency and reduced material utilization.
- Establish fundamental transformation optics principles for light absorption and emission in complex metamaterial structures.
- Develop light-driven material synthesis processes that enable energy conversion materials to develop their own complex architectures in response to illumination conditions and tailor light absorption in dielectric materials with complex architectures.

Selected Accomplishments to Date

- Developed flexible concentrator photovoltaics based on microscale crystalline silicon solar cells embedded in downshifting luminescent waveguides, increasing power output by greater than 300%.
- Discovered that to maximize photovoltaic conversion efficiency, photon emission from the solar cell should be maximized. Theoretical results led to Alta Devices' world record 27.6% efficient flat plate single-junction GaAs solar cell in 2011 (now 28.8% in 2012), exceeding the previous record by 2%.
- Developed high quality silver nanoparticle and indium tin oxide inks for direct ink writing of conductive microelectrodes, transparent planar microgrids, and three-dimensional structures.
- Synthesized ordered silicon microwire arrays for photovoltaics that achieve up to 95% peak absorption and up to 85% absorption of day-integrated, above-bandgap direct sunlight.
- Demonstrated the first optoelectronically active photonic crystal light-emitting diode in an epitaxial, single-crystal GaAs photonic crystal with light-emitting heterostructures.

Center Research Team and Scientific Organization

The faculty involved in the LMI-EFRC span five academic departments (Applied Physics, Chemistry, Materials Science, Electrical Engineering and Mechanical Engineering) in the three institutions Caltech, Berkeley and Illinois. The LMI-EFRC is organized scientifically into four Research Groups:

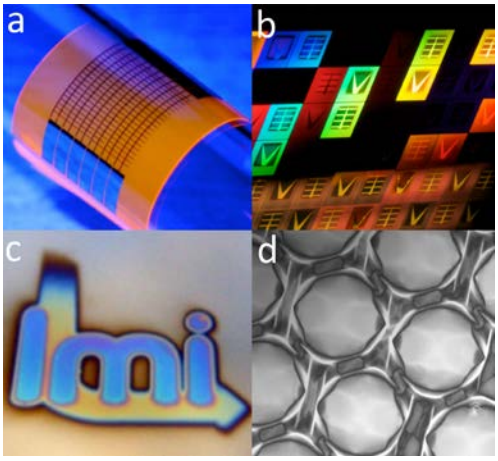

Figure 1. Representative LMI-EFRC research efforts: **(a)** down-shifting luminescent concentrator with micro solar cells, **(b)** large-area nanostructured plasmonic solar cells in amorphous silicon, **(c)** refractive index design via porous etching of silicon, **(d)** three-dimensional GaAs photonic crystal light emitting diode.

RG-1 Full Spectrum Photon Conversion: Designing photonic materials and structures with controlled optical properties for efficient conversion of the entire solar spectrum via up-conversion, down-conversion, down-shifting, and spectrum splitting.

RG-2 Optics for Spontaneous Emission and Absorption Enhancement: Investigating dielectric, metallic, and semiconductor light-trapping structures for enhancing absorption in photovoltaics and emission in light-emitting devices. Initial work from RG-2 has identified new optical designs for light trapping beyond the ray optical limit, using both scattering structures and also by exploiting internal photon recycling via spontaneous emission (Figure 2).

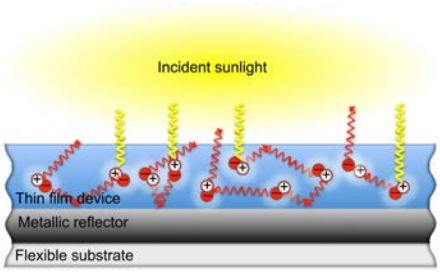

Figure 2. Illustration of photon recycling in a thin film solar cell. This concept discovered by RG-2 researchers motivated the design of Alta Devices' world record solar cell.

RG-3 Transformation Optics for Photovoltaics: Implementing a new approach to photovoltaic absorber design using optical focusing by transformation optics. Transformation optics provides a novel way to control the propagation of light using metamaterials – ordered artificial structures with features smaller than the wavelength.

RG-4 Complex Architecture and Self-Architected Absorbers: Developing photonic structures with preferential morphological and physical orientation of nanostructures on the macroscale for photovoltaic absorption. Complex semiconductor structures such as photonic crystals and silicon microwire arrays give rise to unusual optical properties not found in conventional bulk or thin film solar absorbers. Additionally, we are investigating light-driven synthesis of materials, using light as a tool to control the spatial scale for ordering in complex absorbers.

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