BAPVC Annual Project Report

Project Title: Solar Cell Efficiency Enhancement via Light Trapping in Resonant Dielectric Structures

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Summary:

During the current project period, we focused on light trapping in CIGS and Si thin film solar cells with resonant nanostructures and photonic crystal superlattices. Electromagnetic simulations using rigorous coupled wave analysis (RCWA) and finite difference time domain (FDTD) methods were employed to optimize light trapping in arrays of trapezoidal nanostructures, and photonic crystal superlattices patterned in thin-film Si slabs combined with dielectric texturing. Optical simulations of nanostructured CIGS showing that absorber layers thinned by nearly 50% can absorb nearly 98% of the optical power absorbed in conventional thick CIGS cells. Coupled optical and device transport simulations in amorphous Si solar cells demonstrated interactions between the optical modes excited by different light trapping structures with the defect morphology in a-Si cells. The results indicate that different light trapping structures yield significantly different cell internal quantum efficiencies for similar nominal cell electrical device designs.

Key Accomplishments:

Using electromagnetic simulations, we have found significant enhancements in the photocurrent density for very thin (200 nm thick) crystalline Si slabs patterned with light trapping structures comprised of photonic crystal 'superlattices' combined with a randomly textured dielectric incoupler (Figure 1b). This combination greatly increases light incoupling to the optical modes of very thin crystalline Si devices, enhancing absorption. Experimentally, we have demonstrated the ability to pattern a-Si thin films with superlattice photonic crystal structures using nanoimprint lithography techniques. Additionally, we have demonstrated the ability to successfully nanoimprint features in silica sol gel and transfer patterns by etching. As a separate light trapping mechanism, the group designed subwavelength-scale nanoresonators with a crossed trapezoid shape incorporated into the active layer of thin film Si solar cells.

We have also experimentally demonstrated a trapezoidal-shaped Mie resonator structure that exhibit polarization-independent, angle-insensitive, spectrally broadband enhanced absorption with 4-fold increase in photocurrent compared to 220 nm thick bare Si film using that yield broadband absorption, illustrated in Fig. 1c.

In a third effort, we showed that by making use of 'natural' light trapping structures in CIGS thin films that are inherent microstructural features of the layer growth and cell fabrication, film thickness can be thinned by nearly 50% with minimal loss (2%) in absorption (Figure 1d).

Using coupled optical and electrical simulations for an amorphous Si solar cell, we showed that localized defects interact with the photonic design, producing a significantly different spectral response compared to homogeneous material without localized defects. Figure 2 shows a simulated n–i–p a-Si:H solar cell with vertical recombination active internal surfaces (RAIS) indicated by the dashed lines.

Future Work: We will focus on extending the coupled optical and electrical device simulation method to crystalline Si and CIGS solar cells that incorporate light trapping structures, and we will demonstrate integration of optimized nano-imprinted structures into a device.

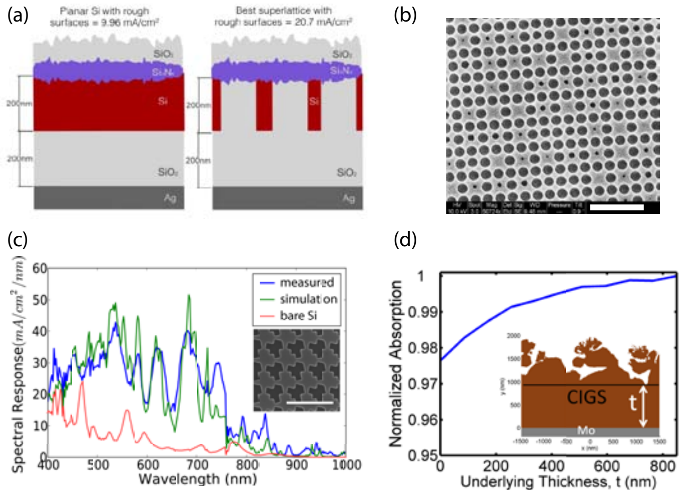

Figure 1: (a) The best superlattice with a roughened surface has more than 2 times the absorbed current as a planar film of the same thickness with the same surface. (b) Scanning electron microscope image of a Si wafer patterned with one of the photonic crystal superlattices from this study. (c) The spectral photocurrent enhancement measured on nanostructured Si with trapezoid cross-sections (inset) reveal 4-fold increase compared to bare Si film without nanostructures. (d) The integrated absorption in CIGS films weighted by the AM1.5 spectrum shows a minimal decrease with the thickness of the CIGS underlying the nanostructured portion of the layer.

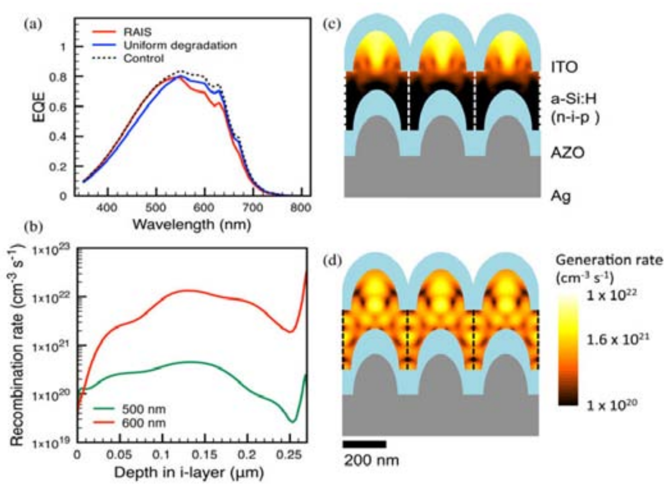

Figure 2: Under 500 nm illumination, the EQE for the control and localized defect (RAIS) structures exhibit very small deviations from one another, while at 600 nm, the localized defect EQE is significantly degraded due to stronger optical absorption in the defect geometry.

Publications:

1. "Silicon Solar Cell Light-Trapping Using Defect Mode Photonic Crystals", Kelsey A. Whitesell, Dennis M. Callahan, and Harry Atwater, Physics, Simulation, and Photonic Engineering of Photovoltaic Devices II, edited by Alexandre Freundlich, Jean-Francois Guillemoles, Proc. of SPIE Vol. 8620, 86200D · © 2013 SPIE DOI: 10.1117/12.2005450
2. Light trapping in ultrathin silicon photonic crystal superlattices with randomly-textured dielectric incouplers, Dennis M. Callahan, Kelsey A. W. Horowitz, and Harry A. Atwater, Optics Express 21 pp 30315-30326.

Presentations:

1. 2/19/14 – Distinguished Lectures on Metamaterials (DLM), "Plasmonics and Metamaterials for Photonics and Solar Energy Conversion," Seoul, South Korea
2. 2/14/14 – American Association for the Advancement of Science 2014 Annual Meeting (AAAS Meeting, "Ultrahigh Efficiency Photovoltaic Structures," Chicago, IL
3. 2/2/14 – seminar at King Abdullah University of Science and Technology (KAUST), "Light Material Interactions for High Efficiency Solar Energy Conversion," Jeddah, Saudi Arabia
4. 1/21/14 – Dorn Lecture at Northwestern University, "Tunable and Quantum Plasmonic Materials," Evanston, IL
5. 12/3/13 – Fall Materials Research Society Conference, "GaAs/Si and GaInP/Si Wire Photovoltaic and Photoelectrochemical Devices," Boston, MA
6. 12/2/13 – Fall Materials Research Society Conference, "Full Spectrum Ultrahigh Efficiency Thin Film Photovoltaics," Boston, MA
7. 12/2/13 – Fall Materials Research Society Conference, "Manipulating Photon Emission and Scattering in High Efficiency Solar Cells," Boston, MA
8. 11/12/13 – Directors Colloquium at Los Alamos National Laboratory, "Light Material Interactions for High Efficiency Solar Energy Conversion,"Los Alamos, NM
9. 11/4/13 – OSA Congress Renewable Energy and the Environment, "Dielectric Light-Trapping Structures for Ultrathin Silicon and Gallium Arsenide Solar Cells", Tucson, AZ
10. 10/17/13 – University of Pennsylvania Materials Science and Engineering Colloquium, "Light Material Interactions in Solar Energy Conversion," Philadelphia, PA
11. 10/12/13 – Van Vlack Lecture at University of Michigan, "The exciting past, turbulent present and abundant future of solar energy conversion," Ann Arbor, MI
12. 10/11/13 – Van Vlack Lecture at University of Michigan, "Tunable Nanophotonic Materials," Ann Arbor, MI
13. 10/7/13 – Rio Grande Symposium, "Photonic Materials for Solar Energy Conversion at the Thermodynamic Limit,"Albuquerque, NM
14. 9/17/13 – Japan Society of Applied Physics – Materials Research Society Joint Symposia (JSAP MRS), "Nanostructured Photonic Materials for Ultrahigh Efficiency Solar Energy Conversion," Kyoto, Japan
15. 9/13/13 – National Taiwan University, "Photonic Materials for Solar Energy Conversion at the Thermodynamic Limit,"Taipei, Taiwan
16. 7/9/2013 – InterSolar North America Conference, "It's Radiative: Photonic Design of High Efficiency Cells and Modules," San Francisco, CA

17. 6/19/2013 – IEEE Photovoltaic Specialists Conference, plenary speaker "Full Spectrum High Efficiency Photovoltaics,"Tampa, FL
18. 6/6/2013 – UCSD Physics Colloquium, "Tunable Nanophotonic Materials," San Diego, CA
19. 3/21/2013 – Ulsan Institute of Science and Technology (UNIST), "Photonic Materials for Solar Energy Conversion at the Thermodynamic Limit", Ulsan Korea.
20. 3/18/2013 – American Physical Society March Meeting, Nanomanufacturing for Solar Energy Applications, Baltimore MD.