Plasmonic Photovoltaics

Investigators

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Abstract

We summarize first results from our recently initiated plasmonic photovoltaics three year GCEP project. We have made progress in two key areas: 1) we have performed an theoretical analysis of the power absorption and scattering from plasmonic solar cells and 2) we have developed a fabrication method for quantum dot-based plasmonic solar cells. The theoretical analysis employs full field electromagnetic simulation of power absorption of sunlight into guided photonic and plasmonic modes of a plasmonic solar cell with silicon and gallium arsenide absorber layers.

Introduction

The plasmonic photovoltaics project is a joint Caltech-Stanford-Utrecht/FOM research program which exploits recent advances in plasmonics to realize high efficiency solar cells based on enhanced absorption and carrier collection in ultrathin film, quantum wire and quantum dot solar cells with multispectral absorber layers. The program has three key focal points:

1) design and realization of plasmonic structures to enhance solar light absorption in ultrathin film and low-dimensional inorganic semiconductor absorber layers; this is the largest area of effort for the proposed effort;
2) synthesis of earth-abundant semiconductors in ultrathin films and low-dimensional (quantum wire and quantum dot) multijunction and multispectral absorber layers;
3) investigation of carrier transport and collection in ultrathin plasmonic solar cells.

Background

Since 2001, there has been an explosive growth of scientific interest in the role of surface plasmons in optical phenomena including guided-wave propagation and imaging at the subwavelength scale, nonlinear spectroscopy and 'negative index' metamaterials[1,2]. The unusual dispersion properties of metals enable excitation of propagating surface plasmon modes both near and away from the plasmon resonance. At frequencies near the plasmon resonance frequency, the excited localized resonant modes in nanostructures access a very large range of wavevectors over the visible and near infrared frequency range. Both resonant and nonresonant plasmon excitation allow for light localization in ultrasmall volumes in metallodielectric structures[3].

To date, little systematic, comprehensive thought has been given to the question of how plasmon excitation and light localization might be exploited to our advantage in high efficiency photovoltaics. The goal of the current plasmonic photovoltaics project is to change that. Conventionally, photovoltaic absorbers must be optically 'thick' to enable nearly complete light absorption and photocarrier current collection. They are usually semiconductors whose thickness is several times the optical absorption length. For silicon, this thickness is greater than 50 microns, and it is several microns for direct bandgap compound semiconductors, and high efficiency cells must have minority carrier diffusion lengths several times the material thickness. Thus solar cell design and material synthesis considerations are strongly dictated by this simple optical thickness requirement.

Dramatically reducing the absorber layer thickness could significantly expand the range and quality of absorber materials that are suitable for photovoltaic devices by, e.g., enabling efficient photocarrier collection across short distances in low dimensional structures such as quantum dots or quantum wells, and also in polycrystalline thin semiconductor films with very low minority carrier diffusion lengths. This is especially important to enable effective utilization of earth-abundant semiconductor absorbers (e.g. Cu_2O, Fe_2O_3, Zn_3P_2, β-$FeSi_2$, $CaSi_2$), for which the state of electronic materials development is not as advanced as for Si. For absorber layers with good surface passivation, the ability to diminish the solar cell base thickness via plasmonic design yields an increase in cell open circuit voltage, in addition to enhancing carrier collection.

Results

In the first stages of our recently initiated project, we have developed a wavevector decomposition method for full-field electromagnetic simulations that enables us to analyze the sunlight power absorbed in each allowed mode of plasmonic solar cells as well as accounting for light scattered during the incoupling process. Simulations at all wavelengths across the AM 1.5 solar spectrum were performed as a function of solar radiation incidence angle, metal particle size, shape, and spacing. We have also performed simulation for various PV cell thicknesses to assess the potential role and benefits of using metallic nanostructures for thicker cells.

We have also developed fabrication processes suitable for making quantum dot plasmonic solar cells utilizing CdSe and Si quantum dot absorbers. The CdSe quantum dots are fabricated in our laboratory via colloidal synthesis techniques. Si quantum dots offer the opportunity for tunable spectral absorption throughout the visible and near infrared region of the solar spectrum with high quantum efficiency. However Si quantum dots are relatively weak light absorbers and thus may potentially benefit significantly from plasmon-enhanced absorption to improve the power conversion efficiency of a photovoltaic device with Si quantum dot absorber layer.

In the coming months we will report on the results of mode-dependent absorption in plasmonic solar cells, and fabricate our first round of CdSe and Si quantum dot solar cells. In addition, we will develop a baseline process for crystalline Si thin film solar cells with plasmonic light absorbers.

Fig. 1: Photos taken at the kick off meeting for the joint CalTech, Stanford, AMOLF\Utrecht research program on Plasmonic Photovoltaics funded by GCEP.

In February, the research partners in the plasmonic photovoltaics project from Caltech, the FOM Institute\Utrecht, and Stanford held a joint workshop from February 5-8, 2008 at both Caltech and subsequently at Stanford to kick off the GCEP research program (see Figure 1). This valuable meeting allowed the graduate students and postdocs working on the project to be introduced to each other and identify common issues as well as coordinate future research plans. Future in-person meetings of the principal investigators are scheduled in July, 2008 and the student and postdoc team members will meet approximately every 3 weeks by videoconference to coordinate efforts.

Progress

The design of plasmonic photovoltaic devices has the potential to dramatically reduce photovoltaic absorber layer thicknesses and thus also cell cost and the material resource consumption per Watt of manufactured photovoltaic devices. Plasmonic photovoltaic design principles are general and widely applicable to a range of photovoltaic device technologies.

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