Nanostructured Metal-Organic Composite Solar Cells

Investigators
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Abstract
This project aims at realizing a high efficiency organic photovoltaic device using the multijunction concept and metal nanoscale features to enhance the overall cell performance. In particular, transparent high-sheet-conductivity nanopatterned metal films are being developed for use as transparent conductors allowing parallel subcell connection, and metal nanostructures are being embedded in the active layers to enhance the photon absorption and charge separation efficiency. This year we experimentally demonstrated increases in photocurrent by 20% to 30% related to the incorporation of metallic nanostructures. We have also generated simple engineering models for the design of the optimum metallic nanostructures. We found that metallic antennas can simply be described as Fabry-Perot cavities for surface plasmon-polariton waves. In parallel, we have continued our design of transparent metallic contacts using nanopatterning techniques. We have now designed deep-subwavelength apertures supporting propagating plasmonic modes that cover the entire solar spectrum.

Introduction

Organic-based solar cells have high potential to reduce the cost of photovoltaics. Low-cost active materials, high-throughput reel-to-reel deposition technologies, and application versatility makes them very likely to become competitive against inorganic thin-film devices. However the power conversion efficiency of organic photovoltaics (OPV) is still too low. This project aims at realizing a high efficiency organic devices by exploiting the unique optical properties of metal to realize high-sheet-conductivity and virtually transparent contacts. It also aims at optimizing the use of metal nanostructures in the active layers to enhance the photon absorption and charge separation efficiency.

Background

The performance of organic photovoltaics has been improving relatively quickly in the last few years. However this technology is still facing major fundamental limitations towards higher efficiency and stability that need to be overcome for it to be competitive with inorganic thin-film solar cells. This project proposes an innovative cell design to increase the efficiency of organic photovoltaics: a stack of organic/inorganic heterojunctions with embedded nanostructured metal features to improve the overall cell performance. The stack design is a high potential route to increase the light absorption efficiency of photovoltaics. The splitting of the solar spectrum through complementary absorption by different cells with specifically designed bandgaps minimizes thermal losses and increases the overall photon conversion efficiency.

Results

During the last year, progress has been made several research directions outlined below. We developed new methods to include solution-synthesized metal nanoparticles into an organic solar cell without exposing the organic materials to solvents. The basic method was developed earlier under Peumans' Molecular Solar Cells GCEP grant for the inclusion of inorganic structures into organic solar cells. This method was then applied to include gold nanoparticles and nanorods at the active interface of simple bilayer organic solar cells, leading to an enhancement of their efficiency.

The physical mechanism behind the enhancement is a local concentration of the optical electric field, as shown in Fig. 1. In the future, specifically designed metal structures may be used to further increase the efficiency gains. Developments in the design of the metallic structures that provide maximum field enhancements will be discussed later in this report.

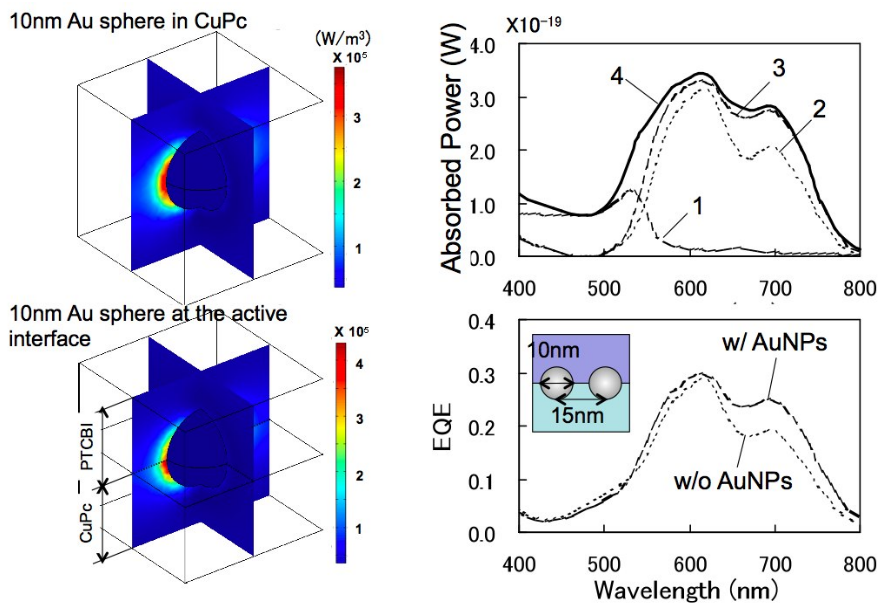

Figure 1: The presence of a 10nm-diameter gold nanosphere in an organic matrix leads to increased optical absorption (top) and increased device performance (bottom) according to finite-element simulations.

Our experimental results agree with the simulation results of Fig. 1, with an increase in photocurrent by 20% to 30%, as shown in Fig. 2. As far as we know, this is the first demonstration of the use of metal nanoparticles to enhance the performance of organic solar cells using near-field effects.

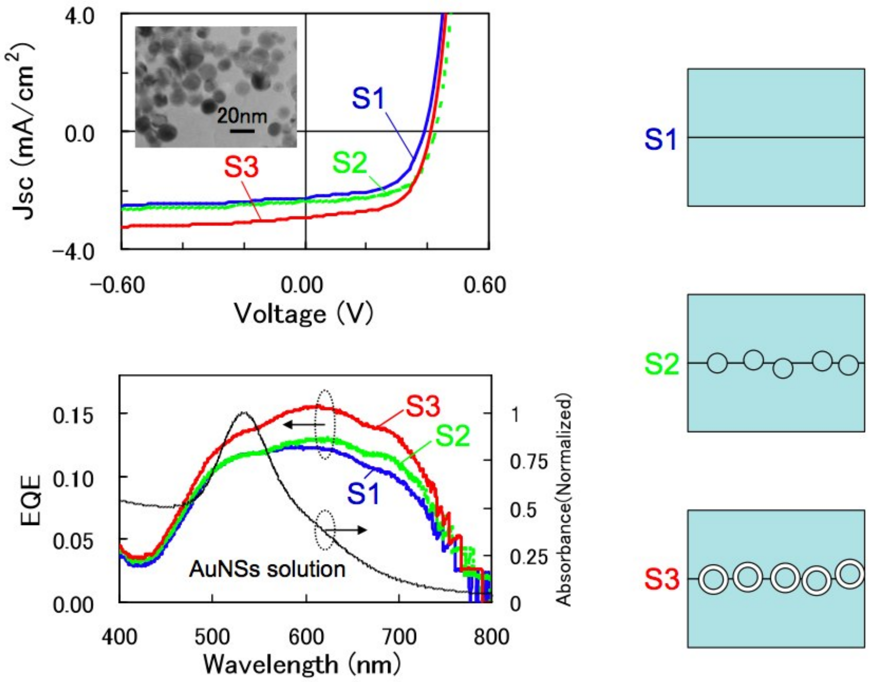

Figure 2: (Top) Increase in photocurrent for a bilayer cell when metal nanparticles are included at the interface between the donor and acceptor of a simple bilayer organic solar cell. S1 is a control device without metal nanoparticles, S2 is a device with metal nanoparticles coated with an alkanethiol and S3 is a device in which a thin wide-bandgap coating was used to further electrically isolate the nanoparticles from the organic matrix. (Bottom) Increase in external quantum efficiency.

In order to further optimize the light concentration ability of metallic nanostructures we have derived inspiration from microwave antenna structures. Such structures enable a very strong light-matter interaction when the metal antenna length equals half the free space wavelength ($\lambda_0/2$). Due to the difference in the optical behavior in the microwave and visible frequency regimes, we found that nanoscale metallic antennas need to be a substantially shorter than half the free space wavelength of light. In the visible regime, we found that metallic rods act as tiny Fabry-Perot cavities for (short range) surface plasmon-polariton waves that bounce back and forth between the antenna ends. For this reason, maximum field enhancements can be attained when the metallic antennas are approximately half of the surface plasmon-polariton wavelength ($\lambda_{SPP}/2$). This effect is seen in Figure 3, which shows the calculated field intensity enhancements at the ends of 50 nm thick metallic strip antennas for different illumination wavelengths and antenna lengths.

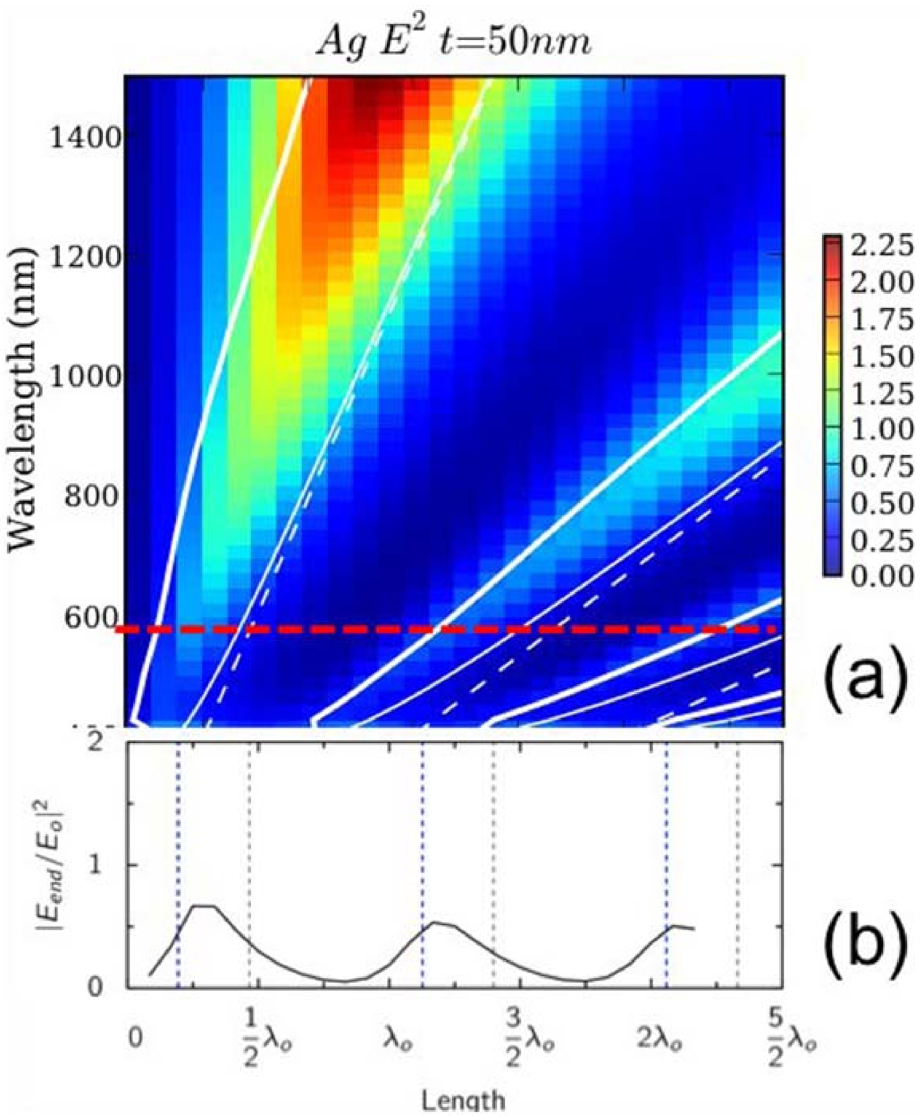

Figure 3: (a) Field intensity enhancements at the terminal ends of a metallic stripe antenna as a function of the antenna length and the illumination wavelength. (b) A cross-section of the field intensities at a wavelength of 580 nm. High field intensities are attained when the length of the antenna is close to $0.5(n+1)\lambda_{spp}$, where λ_{spp} is the surface plasmon-polariton wavelength and n is an integer. Note that resonances occur at significantly shorter antenna lengths than is the case for microwave antennas, which would resonate at $0.5(n+1)\lambda_0$, where λ_0 is the free space wavelength.

In parallel, we have continued our design of transparent metallic contacts using nanopatterning techniques. We have now designed deep-subwavelength apertures supporting propagating plasmonic modes that cover the entire solar spectrum. We have performed a detailed study of the interactions of various pathways in light transport through perforated metal thin film.

In the microwave frequency, an aperture has a long-wavelength cutoff – it does not support a propagating mode when the diameter of the aperture is smaller than approximately half the wavelength of incident light. Consequently the transmission through a single sub-wavelength aperture is very poor.

It is commonly assumed that the same cut-off behavior persists in sub-wavelength apertures at optical frequencies. Consequently, significant research is focused on using arrays of sub-wavelength apertures in a metal film, where the surface plasmon modes on the top and bottom surface are used to enhance transmission. Such a mechanism, however, suffers from a very small transmission bandwidth.

Again, it is important to note that the material properties of metals are very different in the optical frequency range. Exploiting such properties, we were able to show sub-wavelength apertures in the optical frequency in fact always support propagating modes, regardless of how small the hole is. Building upon this insight, with the support of GCEP program, we have undertaken a systematic study to further improve the transmisson efficiency and bandwidth of single sub-wavelength aperture, and in understanding the complex interplay that occurs in the array of sub-wavelength apertures.

We now have numerical design, showing broad-band transmission through a specifically designed sub-wavelength aperture. The key idea is to use an additional dielectric rod at the center, to drastically enlarge the bandwidth of the propagating modes. The figure below shows the transmission spectrum for three different apertures, as can be seen, the use of a dielectric rod at the center of aperture significantly broaden the transmisson spectrum. Assuming a plasmonic wavelength of 200 nm, the improved design has a pass band that extends from infrared to the visible wavelength range, making them potentially suitable for solar applications.

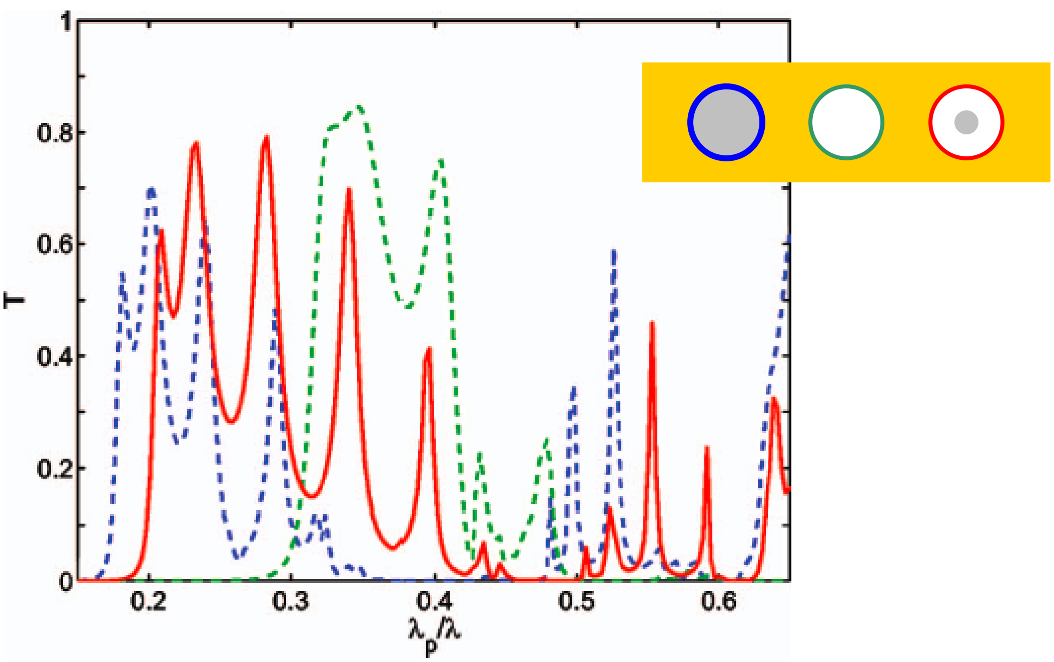

Figure 4:. Transmission spectra for three different apertures shown in the inset. The green line is for an aperture with air inside. The blue line is for an aperture filled with dielectric. And the red line is for an aperture with a dielectric rod at the center. Notice that the structure with a dielectric rod in the center results in significant broadening of the passband of the structure.

Progress and future plans

This year, we have obtained our first very promising results on our solar cells that show that plasmon-enhancements can be attained. We have also made significant progress in the development of metallic nanoantennas and transparent contacts. We will continue our efforts to generate transparent metal contacts. We believe there are still substantial opportunities for further engineering of single aperture structures. The group velocity of the mode, for example, can be further increased by to reduce the loss in the apertures. The significant Fabry-Perot oscillation in the passband may also be smoothed out with better impedance matching. We are well on our way towards a single nanoaperture, as well as aperture arrays, that support high transmission over the entire solar bandwidth. We also plan on verifying the Fabry-Perot model for our metallic antennas experimentally and then we will incorporate the optimized antennas into our PV cells to see whether further enhancements in photocurrent can be attained. If successful, the transparent metal contacts and antennas will significantly enhance solar cell performance and offer increased competitiveness of OPV for clean energy production compared to routes that ultimately lead to green house gas emissions. In order to have a global impact, methods for efficient scaling of this technology will have to be explored in the future.

Publications

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