Improving organic photovoltaic cell efficiency with enhanced charge-transfer recovery by incorporating local field enhancement of sub-bandgap infrared light

T.A. Hendriks, M.A. Sefunc, L.J.A. Koster, S.M. Garcia-Blanco, Member IEEE

1 University of Twente, Optical Sciences group, MESA+ Institute for Nanotechnology, P.O. Box 217, 7500 AE Enschede, The Netherlands, e-mail: t.a.hendriks@student.utwente.nl

2 Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands, e-mail: l.j.a.koster@rug.nl

Illuminating organic solar cell active materials with infrared light, ranging from 0.3 to 1.25 eV, has shown to be a potential way of enhancing solar cell efficiency due to enhanced charge-transfer state recovery. This paper focuses on the fabrication and application of plasmonic nanostructures in organic solar cells to give local field enhancement within these wavelengths.

Aluminum gratings and nanorods are investigated to give local field enhancement at 0.58 eV to enhance charge-transfer state recovery and improve photovoltaic cell performance. This work encompasses a first practical application combining plasmonics and sub-bandgap light to enhance charge-transfer state recovery.

Introduction

In view of the global need for clean energy, using solar energy to generate electricity is one of the more promising solutions [1]. However, the efficiency of photovoltaic devices is low in general and even lower for the less expensive ones such as organic photovoltaic devices (OPVs). Furthermore, not all wavelengths are equally absorbed and parts of the solar spectrum (mainly the lower energies) are not even utilized. Different strategies to trap light within the cell to improve its absorption have been proposed, such as stacking multiple active layers absorbing at different spectral bands [2], placing concentrators or lenses in front of the devices [2] and introducing small particles which either produce local field enhancement or increase scattering within the active layer of the device [3]. Such strategies benefit most the intrinsically thin photovoltaic cells such as OPVs [4].

Organic solar cells have an active layer wherein two different materials (the donor and the acceptor) form an interface where excitons (electron-hole pairs generated by a photon with energy above the bandgap of the donor material) can dissociate into weakly interacting charge-transfer states (CT-states). After dissociation of the CT-state the electron and hole (charge separated (CS) states) travel towards their respective electrode to generate current. The selection of materials together with the interface morphology has huge impact on the performance of OPVs. The efficiency of these devices is still low. The highest reported efficiency for a tandem organic solar cell is 12% [11] whereas the highest reported efficiency for an inorganic solar cell (triple junction of InGaP/GaAs/InGaAs) is 44.4 ± 2.6% [5].

The lower efficiency of OPVs can be mainly attributed to trapped states. At the interface of donor and acceptor, CT-states occur, increasing the recombination rate. Sufficient
Energy is needed to overcome the trap and let charges diffuse towards their respective electrode. Enhanced dissociation of CT-states into separate charges has been investigated by using “pump-probe” mechanics [6]. Typically, the lowest unoccupied molecular orbit (LUMO) levels of the donor and acceptor should be chosen such that sufficient excess energy permits dissociation of the CT-states [7]. This choice in LUMO levels limits the open-circuit output voltage of the OPV with the subsequent loss of efficiency.

In [6] an infrared laser (3 μm) is used as probe to push electrons or holes from their trapped state and help them diffuse from the interface. Infrared excitation between 0.3 – 1 eV has been claimed to repopulate “hot” CT-states, increasing the chance to evolve to separated charges (SC-states) [6].

In this work we propose to utilize plasmonic nanostructures to enhance the absorption of infrared photons with energies in the 0.3 – 1 eV range [present in the solar spectrum as shown in Fig. 1 (b)] to help the dissociation of CT-states into CS-states, increasing current output and allowing for smaller LUMO-offset choices, thereby increasing open-circuit output voltage [8], [9]. This paper will focus on the design, fabrication and preliminary results of fabrication of such plasmonic structures.

**Finite difference time domain (FDTD) simulations**

Given the wavelength range targeted in this work (2.0 – 2.4 μm), aluminium exhibits a good performance. Since aluminium is relatively low cost and it is already sometimes present as back electrode in the fabrication of OPVs [10], it was selected in this study as the material for the nanostructures.

Figure 2(a) shows the layer structure of the device considered in this work. It consists of a 180 nm thick layer of indium tin oxide (ITO), a 60 nm thick layer of PEDOT:PSS, a 200 nm layer of P3HT:PCBM and a 360 nm aluminium layer that acts as back electrode.
Square aluminium particles were placed in contact below the ITO. Both the dimensions and periodicity of the particles were investigated to obtain maximum enhancement at the wavelength of 2135 nm (0.58 eV).

In the simulations, a plane wave source was placed 260 nm above the ITO and periodic symmetric and anti-symmetric boundary conditions were utilised to reduce computation time. Non-uniform mesh setting with additional mesh regions in the ITO layer (20 nm), the P3HT:PCBM layer (20 nm) and around the aluminium particle (10 nm) were implemented. Sweeps of the particle parameters: height (10 – 80 nm), width (50 – 600 nm), length (400 – 800 nm) and periodicity (both in x and y direction (1.5 – 2.5 μm) were performed.

Enhancement was calculated as the power [measured with the monitor shown in Fig. 2 (a)] inside the active material on a device with aluminium particle divided by the power on a structure without particle. This ratio is shown in Fig. 3. It was found that a square particle of 560 nm wide and 60 nm high performed best in an array of 2x2 μm. Enhancement up to a factor of 2.82 in the infrared region (peak at 2135 nm) is found. A decrease in the amount of light absorbed in the visible range (an average decrease of 0.926) is also observed. This is undesirable but can be expected due to the shadowing effect of the aluminium particles.

Fabrication

The fabrication process based on electron-beam lithography followed by lift-off is currently being developed to experimentally realize the designed nanostructures. Figure 2 (b) shows a scanning electron microscope (SEM) picture of a fabricated structure. As it can be clearly seen, further optimization is needed to produce nanostructures with the targeted dimensions.
Conclusion

Preliminary simulation results show modest enhancement of the amount of light coupled into the active material at around 2135 nm. It was shown that fabrication is possible. However, optimization is needed to reach the right particle size. Other lower-cost fabrication methods are also being evaluated, such as direct-laser writing and nano-imprint lithography.

Acknowledgements

L.J.A.K. acknowledges support by a grant from STW/NWO (VENI 11166).

References