Renewable Energy and the Environment Technical Digest © 2011 OSA

Using localized plasmon resonances to enhance absorption efficiency in thin-film organic solar cells

Khai Q. Le[1,2*], Aimi Abass[3], Bjorn Maes[2,4], Peter Bienstman[2], and Andrea Alu[1]
[1]*Department of Electrical and Computer Engineering, Metamaterials and Plasmonics Research Group, The University of Texas at Austin, Austin, Texas, USA*
[2] *Department of Information Technology, Photonics Research Group, Ghent University-imec, B-9000 Ghent, Belgium*
[3]*Department of Electronics and Information Systems, Solar Cells Group, Ghent University, B-9000 Ghent, Belgium*
[4]*Institut de Physique, Micro- and Nanophotonic Materials Group, University of Mons, B-7000 Mons, Belgium*
[*]*Corresponding author: khai.le@intec.ugent.be*

Abstract: We theoretically investigate the influence of square metallic gratings on the optical absorption of organic solar cells with a thin active layer. We show that excited localized surface plasmon modes may cause strong field enhancement at the interface between the grating and the active layer. This results in broadband absorption enhancement in the active layer. An enhancement of up to 29% has been observed.
OCIS codes:(250.5403), (050.6624), (350.6050)

1. Introduction

Thin-film organic solar cells (OSCs) have attracted intensive research interest due to their potential for low-cost photovoltaic devices [1]. However, the development of these devices is hampered by their low efficiency since the active layer thickness must be smaller than the exciton diffusion length [2]. This causes a limited photon absorption rate. To overcome the diffusion length problem, the concept of bulk heterojunction (BHJ) was introduced [3]. However, even with BHJ the thickness is still restricted to thin films on the order of 200 nm for optimal electronic properties [4]. Above these thicknesses, the energy conversion efficiency drops since free carrier recombination becomes significant [5].
Several techniques have been introduced to improve the optical absorption of OSCs [6-7]. Among those, the use of plasmonic grating structures causing huge absorption enhancement in OSCs has attracted much attention [8]. However, in this proposed device structure, the very thin active layer of around 15 nm may cause big challenges in fabrication. Recently, solar cells with thickness of around 48 nm have been successfully fabricated thanks to advances of nanofabrication techniques [9]. The absorption rate, however, is still quite limited.
In this work, we employ a silver (Ag) periodic grating placed inside the active layer to improve the optical absorption of this thin photovoltaic cell. A strong field enhancement was observed for surface plasmon modes excited at the interface between the grating and the active layer. These localized surface plasmon modes contribute to the improvement of the optical absorption in the active layer.

2. Method

The numerical simulation of light absorption in a solar cell is performed by finite element methods, as implemented in the COMSOL Multiphysics software package. We assume the light illumination on the device as an incident plane wave with frequencies covering the whole solar spectrum. The investigated OSCs are similar to the structure in [9]. All refractive index data is also taken from this reference. To validate the simulation model we compare the calculated optical absorption in the active layer with those obtained by the transfer matrix model (TMM) [9] and the rigorous coupled wave analysis, as implemented in CAMFR [10]. Here, the flat OSC has an active layer thickness of 48 nm. Results are shown in Fig. 1, for a device without grating. It is seen that they are in good agreement as means to confirm the validity of our model.

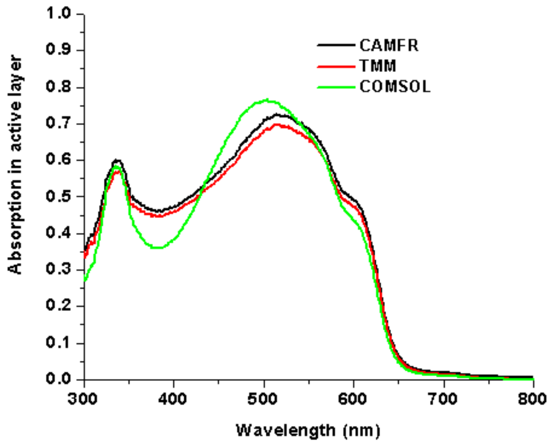

Fig. 1. Optical absorption in the 48 nm thick active layer of the investigated OSC obtained by CAMFR, TMM and COMSOL.

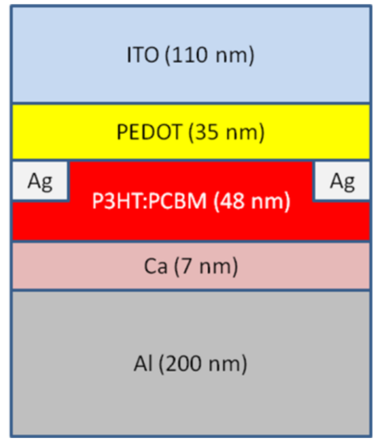

Fig. 2. Cross section of OSC with Ag grating integrated inside active layer

3. Results

We theoretically investigate the influence of 1D Ag gratings on the optical absorption in thin OSCs. The sketch of the device is depicted in Fig. 2. There, the thickness of the poly-3-hexylthiophene:[6,6]-phenyl-C_{61}-butyric acid methyl ester (P3HT:PCBM) active layer is set to 48 nm, the same as in the experimental structure [9]. The complex refractive index of Ag is modeled by the Drude-Lorentz model. Figure 3 shows the calculated absorption in the active layer of the flat OSC, and the one with Ag grating integrated inside the active layer. It is seen that in the wavelength range 380-650 nm a larger integrated absorption caused by the Ag grating is observed. This may lead to broadband absorption enhancement of up to 29%. The optimal absorption enhancement is obtained with the Ag grating having 20 nm height (and width) and 30 nm periodicity (corresponding to a filling factor of 2/3). The enhancement is due to the excitation of localized surface plasmon modes at the interface between the Ag grating and the active layer. Figure 4 shows plots of absorption profile capped at a certain maximum value to show the profile distribution clearly, side stepping the lightning rod effect at the edges of the Ag grating. It is observed that at the wavelength of 350 nm the light is mostly absorbed by the Ag grating, which causes less absorption than the flat cell. However, this only results in negligible loss, as the solar spectrum reaching the ground in the wavelength range below 350nm is already limited. In the wavelength range where it matters, 380-650 nm, the localized surface plasmon modes excited at the interface between the grating and the active layer cause strong field enhancement around the interface. The field is mainly distributed in the active layer rather than inside the metal as we go to longer wavelengths. This results in an improvement in the absorption efficiency of the active layer, particularly around the edges of the metal grating.

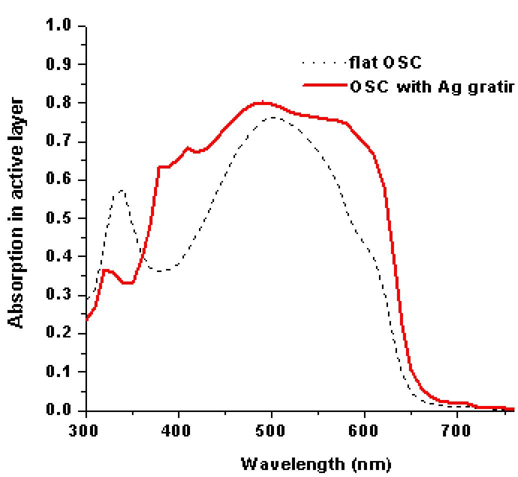

Fig. 3. Absorption in active layer of OSC with and without integrated Ag grating.

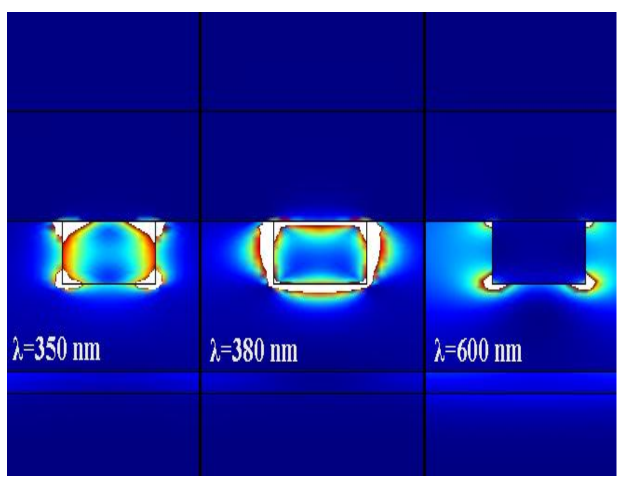

Fig. 4. Absorption profiles (Divergence of the Poynting vector) of OSC at various wavelengths (λ).

4. References

1. H. Hope and N. S. Sariciftci, “Organic solar cells: an overview,” J. Mater. Mater. Res. **19**, 1924-1945 (2004).
2. M. Agrawal and P. Peumans, “Broadband optical absorption enhancement through coherent light trapping in thin-film photovoltaic cells,” Opt. Express 1**6,** 5385-5396 (2008).
3. S. H. Park et al., “Bulk heterojunction solar cells with internal quantum efficiency approaching 100%,” Nature Photon. **3**, 297-302 (2009).
4. G. F. Burkhard, E. T. Hoke, S. R. Scully, and M. D. McGehee, “Incomplete Exciton Harvesting from Fullerenes in Bulk Heterojunction Solar Cells,” Nano Lett. 9, 4037-4041 (2009).
5. T. Soga, Nanostructured Materials for Solar Energy Conversion, Elsevier Science, Amsterdam, 2006.
6. H. Shen, P. Bienstman, and B. Maes, “Plasmonic absorption enhancement in organic solar cells with thin active layers,” J. Appl. Phys. **106**, 073109 (2009).
7. A. Abass, H. Shen, P. Bienstman, and B. Maes, “Angle insensitive enhancement of organic solar cells using metallic gratings,” J. Appl. Phys. **109**, 023111 (2011).
8. C. Min et al., “Enhancement of optical absorption in thin-film organic solar cells through the excitation of plasmonic modes in metallic gratings,” Appl. Phys. Lett. **96**, 133302 (2010).
9. G. F. Burkhard, E. T. Hoke, and M. D. McGehee, “Accounting for interference, scattering, and electrode absorption to make accurate internal quantum efficiency measurements in organic and other thin solar cells,” Adv. Mater. **22**, 3293-3297 (2010).
10. CAMFR, http://camfr.sourceforge.net/