Surface Plasmon Enhanced Efficiency of Organic Solar Cells using Transparent Ag Nanowire Electrodes

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Surface plasmon resonance (SPR) in metallic nanostructures offers a promising way to enhance the power conversion efficiency (PCE) of organic solar cells as it exhibits strongly enhanced electromagnetic fields in the vicinity of metal, which can lead to high optical absorption of the organic semiconductors. In this work, we demonstrate about 35% enhancement of the PCE of the organic thin film solar cell using periodic Ag nanowire electrodes fabricated by nanoimprint lithography as compared to that using conventional ITO electrode. Ag nanowire electrode is employed as a standalone transparent electrode, and the incident light resonantly excites surface plasmon modes between the Ag grating electrode and a thick Ag cathode. The SPR of the Ag nanograting enhances the optical field intensity between the two metal electrodes and the light absorption of the organic thin film leading to enhancement of the PCE.

The period and thickness of Ag nanowire electrodes investigated in this work are 220 nm and 40 nm, respectively. Two sets of Ag nanowire electrodes with different line-width (95 nm and 55 nm) are prepared based on our initial simulation results that showed different field enhancement factors for the Ag nanogratings with different duty cycles. Simulation based on rigorous coupled wave analysis and the measurement of extinction spectra of the Ag nanowire samples with a multilayer organic materials of PEDOT (30nm), CuPc (16nm), C_{60} (26nm), and BCP (8nm) showed distinct enhancement over the wavelength range between 550nm and 650nm as compared with samples made on regular ITO electrode.

Several devices were fabricated to investigate the dependence of the optical field enhancement by the SPR on the organic layer thicknesses in a given Ag nanowire geometry. The measured I-V characteristics showed similar Voc and FF for all devices, while the behavior of the short-circuit current (J_{sc}) provided clear evidence of the SPR-induced enhancement in the devices made with Ag electrodes. Overall, the Jsc of the ITO device decreases with reducing organic layer thickness because of the lower absorption of the incident light energy by the thinner layers. In sharp contrast, the Ag devices showed enhanced J_{sc} as the organic layer thickness decreases. Moreover, the measured external quantum efficiency (EQE) of devices using Ag nanowires showed a peak enhancement around 570nm, and the enhancement becomes stronger and covers a wider wavelength range with reducing organic layer thickness. Specifically, a 2.5 fold EQE enhancement was achieved at ~ 570nm for the organic layer thickness of 80 nm resulting in about 35 % overall PCE enhancement in case of the device with 55nm line-width Ag electrode in comparison with devices using ITO. Simulation work for optimal device structure which can further enhance the PCE is currently underway. These results show that the use of transparent plasmonic Ag nanowire electrode has the potential to realize low cost and high efficiency organic solar cells.

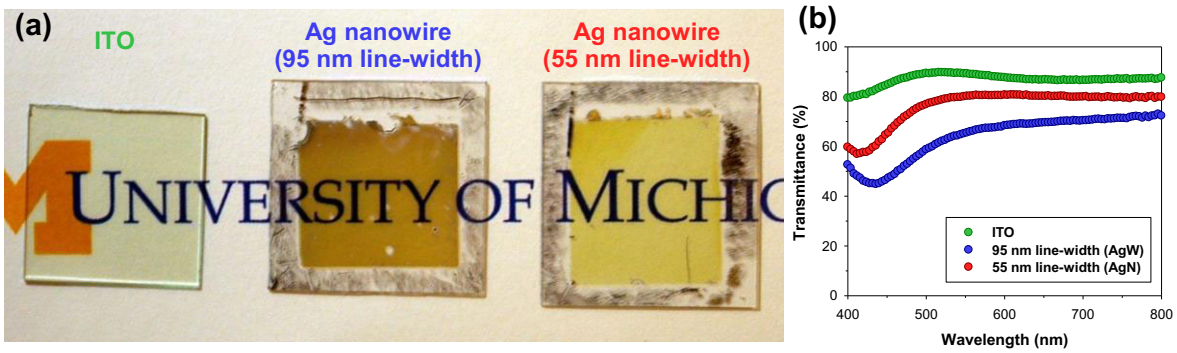

Figure 1. (a) Photograph of the conventional ITO, Ag nanowires with line-width of 95 nm (AgW) and 55 nm (AgN), respectively. (b) The optical transmittance of ITO (green), AgW (blue) and AgN (red) electrode, respectively.

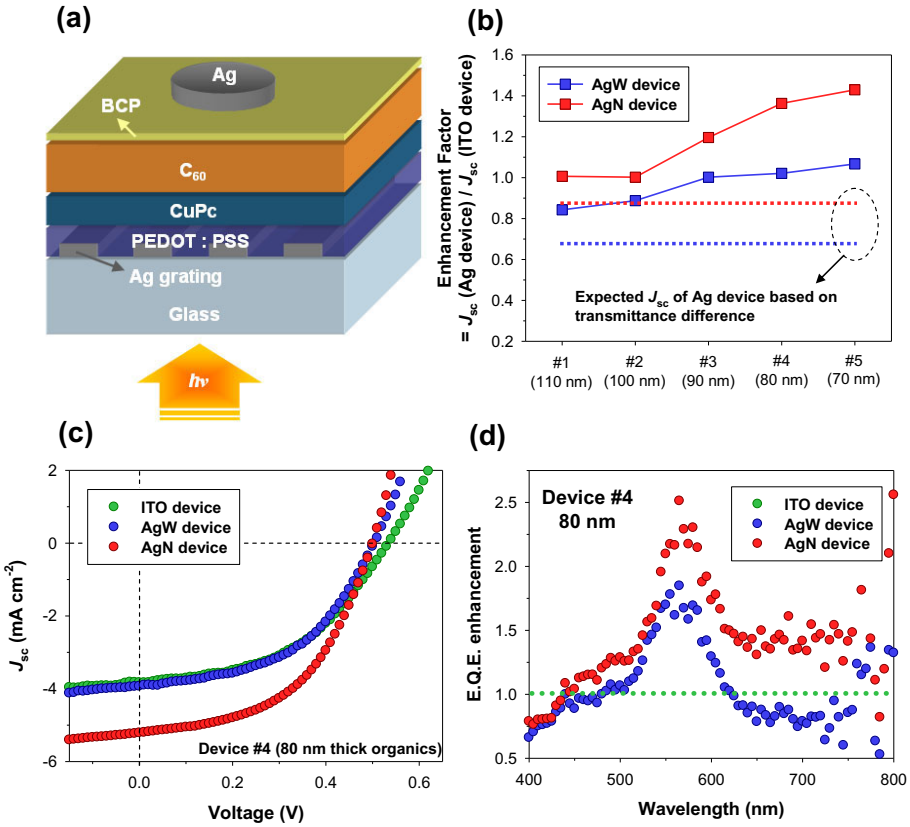

Figure 2. (a) Schematic of the fabricated small molecular weight organic solar cells. Several devices were fabricated and characterized with different total organic thickness ranging from 110 nm to 70 nm with 10 nm step, which correspond to the device number from 1 to 5. The thickness of the PEDOT and BCP was fixed at 30 nm and 8 nm, respectively, for all fabricated devices. The total thickness was controlled by changing the thickness of CuPc and C_{60}. Each device has following CuPc and C_{60} thickness. Device #1 (CuPc: 28 nm, C_{60}: 44 nm), Device #2 (CuPc: 25 nm, C_{60}: 35 nm), Device #3 (CuPc: 20 nm, C_{60}: 32 nm), Device #4 (CuPc: 16 nm, C_{60}: 26 nm), and Device #5 (CuPc: 12 nm, C_{60}: 20 nm). (b) Enhancemnet factor of the J_{sc} vs. total organic layer thickness, extracted by normalizing the J_{sc} of Ag devices with that of the ITO device. I-V (c) and EQE (d) curve of the device #4 showing the highest enhancement of the PCE