High efficiency OSCs by simultaneous plasmon-optical and -electrical effects from plasmonic asymmetric modes

Organic solar cells (OSCs) have the advantages of low-cost, non-toxic and easy to scale up etc., which are promising to address the energy issues. However, the OSC efficiency is still low to meet the commercialization criteria. The tradeoff between the optical absorption length and exciton diffusion length hinders to achieving high absorption of the active layer. The optimal thickness of active layer is usually around two hundred nanometers, the inefficient light absorption of the ultra-thin active layer results in a lower power conversion efficiency (PCE). Therefore, increasing the optical absorption of active layer is of critical importance for high performance OSCs.

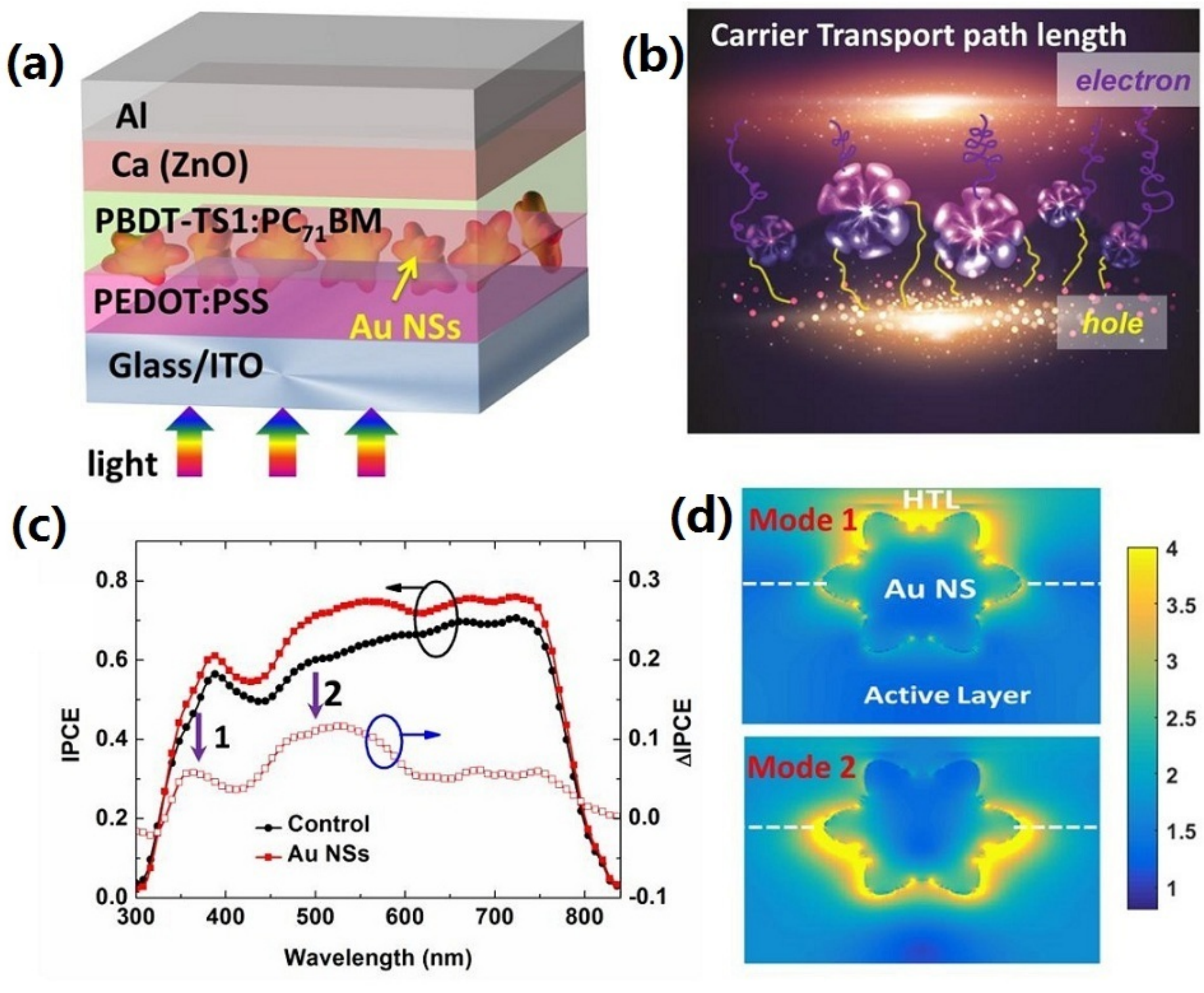

Fig. 1. (a) Schematic structure of OSC device; (b) Illustration of the transport path of electron and holes to respective electrodes; (c) IPCE spectra of the OSCs without and with gold nanostars (Au NSs); (d) Near field distribution of the two plasmonic asymmetric modes.

The plasmonic effects of the metallic nanostructures (MNs) are capable of concentrating the incident light into the subwavelength region with an amplified intensity up to ten or even hundreds of times, which favors the increment of the optical absorption of active layer. In last decade, there are extensive studies of improving the active layer absorption with MN plasmonic resonances. However, the plasmonic resonances are typically narrow bandwidth which can only promote active layer absorption at regional wavelength of visible region. To increase the active layer absorption over a broadband spectra, it has proposed to incorporate various MNs in active layer or simultaneously in the carrier transport layer and active layer. The above recipes are complicate for experimental implementation which are not practical for commercialize applications. Therefore, achieving the wideband plasmonic resonance with a simple and feasible method are desirable for plasmonic OSCs.

In this study, the gold nanostars (Au NSs) with geometrically designed size have been incorporated in between the hole transport layer (HTL, PEDOT:PSS) and active layer (PBDT-TS1:$PC_{71}BM$). The excited plasmonic asymmetric modes substantially improve the optical and electrical properties of OSCs resulting in a significant PCE increment.

For the plasmon-optical effects, the Au NSs are located in between the HTL (PEDOT: PSS) and active layer (PBDT-TS1:$PC_{71}BM$) through the geometrical design. The asymmetric electromagnetic environment (i.e. dielectric constant) enable the excitations of the plasmonic asymmetric modes. Through analyzing the theoretical and experimental results, the plasmonic asymmetric modes are the wide band resonances in the visible region, which enhance the active layer absorption over a wide bandwidth. The mechanisms of the increased active layer absorption are attributed to the energy transfer induced by the excited plasmonic asymmetric modes. The previously energy dissipated in the electron transport layer has transferred to the active layer and become the photocurrent. Therefore, the energy transfer raised by the excited plasmonic asymmetric modes is the in-depth reason of absorption enhancement in active layer.

For the plasmon-electrical effects, the mobility of holes in the active layer (1.18×10^{-3} cm^2 v^{-1} s^{-1}) is one order of magnitude smaller than that of the electrons (6.56×10^{-2} cm^2 v^{-1} s^{-1}). The electrons and holes would easily become the accumulated space charges due to the imbalance extractions. After incorporating Au NSs, the plasmonic asymmetric modes relocate the exciton generation region from the middle of active layer to the vicinity of HTL. The transport path length of the hole-to-anode is shortened while the transport path length of the electron-to-cathode becomes longer. The better balanced extractions of the electrons and holes eliminate the space charge and improve the OSC electrical properties. In addition, the impedance spectroscopy uncovers that the incorporated Au NSs also favor the reduction of the transport resistance in HTL.

Finally, due to the simultaneously plasmon-optical and -electrical effects by the plasmonic asymmetric modes of Au NSs, the PCE can reach 10.5% for Au NSs incorporated OSCs.

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