Ultrathin, High-Efficiency, Broad-Band, Omni-Acceptance Organic Solar Cells Using New Plasmonic Cavity with Subwavelength Hole Array

Stephen Y. Chou* and Wei Ding
NanoStructure Laboratory, Department of Electrical Engineering
Princeton University, Princeton, New Jersey 08544 (chou@princeton.edu)

Three central challenges in solar cells are high light coupling into solar cell, high light trapping and absorption in a sub-absorption-length-thick active layer, and replacement of indium-tin-oxide (ITO) transparent electrode used in thin-film devices. Here, we present fabrication and demonstration of a new ultra-thin high-efficiency solar cell (SC) structure, termed "Plasmonic cavity with subwavelength hole-array (PlaCSH) SC". The new SC offer solutions to all three issues with unprecedented performance, including high, broadband, and omni acceptance (nearly angle and polarization independence) in light absorption and trapping, leading to nearly doubling of the normal incident power conversion efficiency (PCE) and tripling of the total PCE in cloudy day [1].

An optimized PlaCSH-SC comprises a ultrathin plasmonic cavity structure of a metal-mesh electrode with subwavelength hole-array (MESH) (Au 30 nm thick) which is light transmissive and replaces ITO, a metal back electrode, and in-between a photovoltaic active layer of P3HT/PCBM (85 nm thick, 1/3 average absorption-length) plus of two thin buffer layers (Fig. 1).

The MESH of 200 nm period, 180 nm hole-diameter and 20 nm spacing was fabricated by nanoimprint, and lift-off of gold on 4" fused silica substrates, with the MESH covered entire wafer. The nanofabrication shows high nanopatterning fidelity (Fig. 1b).

Experimentally, the PlaCSH-SCs have achieved (1) light coupling-efficiency/absorptance as high as 96% (average 90%), broadband, and Omni acceptance (light coupling nearly independent of both light incident angle and polarization); (2) an external quantum efficiency of 69% for only 27% single-pass active layer absorptance (at 500nm wavelength); leading to (3) a 4.4% power conversion efficiency (PCE) at standard-solar-irradiation, which is 52% higher than the reference ITO-SC (identical structure and fabrication to PlaCSH-SC except MESH replaced by ITO), and also is among the highest PCE for the material system that was achievable previously only by using thick active materials and/or optimized polymer compositions and treatments; and (4) in harvesting scattered light, the Omni acceptance can increase PCE by additional 81% over ITO-SC, leading to a total 175% increase (i.e. 8% PCE).

Furthermore, we found that (a) after formation of PlaCSH the light reflection and absorption by MESH are reduced by 2 to 6 fold from the values when it is alone; and (b) the sheet resistance of a 30 nm thick MESH is 2.2 ohm/sq or less–4.5 fold or more lower than the best reported value for a 100 nm thick ITO film, giving a lowest reflectance-sheet resistance product.

The PlaCSH structure is applicable to many other thin film solar cells and is scalable to roll-to-roll manufacturing, opening up many new applications in other fields.

[1] S. Y. Chou, and W. Ding, Opt. Express. A60, Vol. 21, No. 21. (2013).

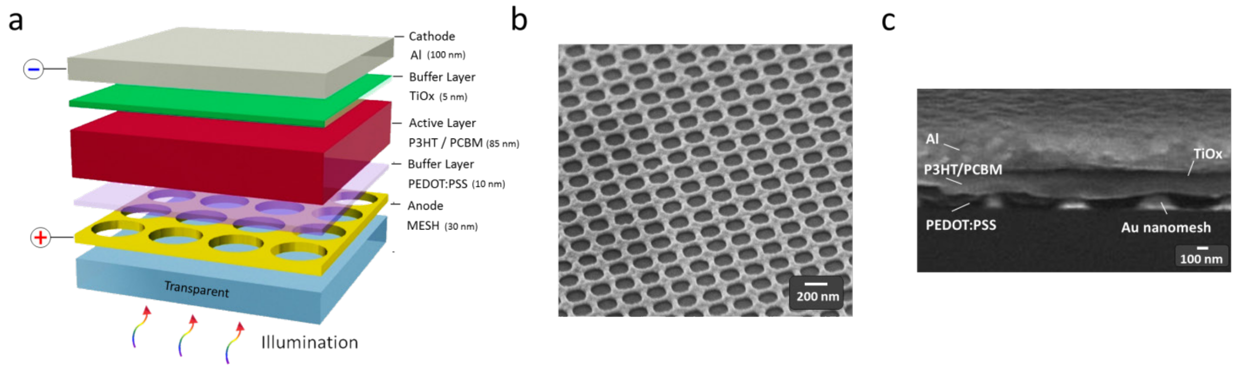

Fig. 1. Plasmonic Cavity with Subwavelength Hole-array (PlaCSH) Solar Cell. (a) Schematic. PlaCSH consists of Au Metallic Electrode with Subwavelength Hole-array (MESH) and a Al backplane, sandwiches P3HT/PCBM, TiOx, and PEDOT:PSS layers between the two electrodes. (b) Tilt-view scanning electron micrograph (SEM) of MESH. (c) Cross-sectional SEM of PlaCSH-SC.

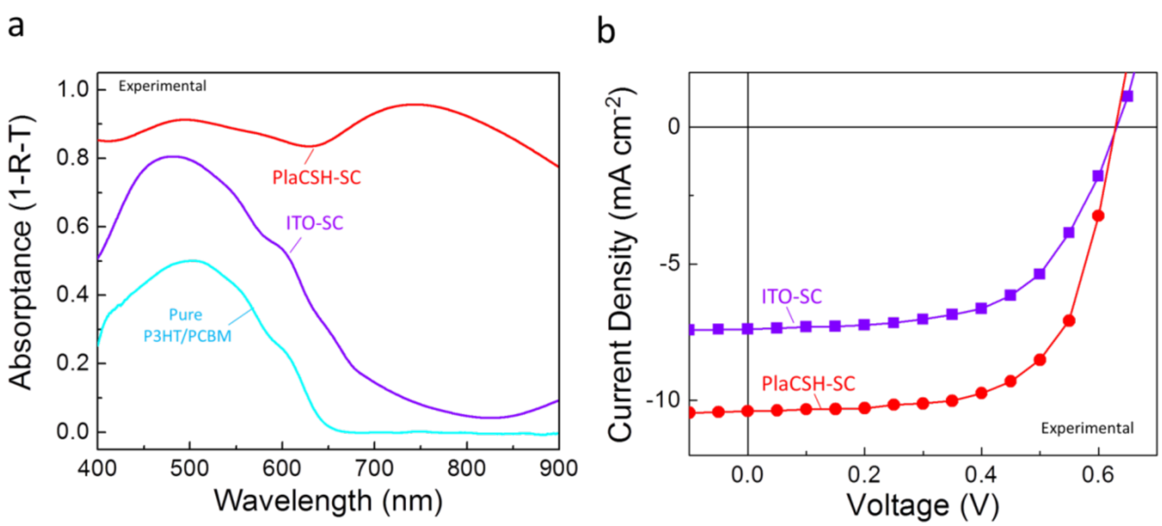

Fig. 2. Optical and electrical properties of PlaCSH Solar Cell. (a) Absorptance Spectrum (1-Reflectivity-Transmittance) of PlaCSH based solar cell, ITO based solar cell and pure active layer P3HT/PCBM on glass. (b) J-V characteristics under AM 1.5G solar illumination of organic solar cells (OSCs) fabricated with PlaCSH as well as conventional ITO electrodes.