Double External Quantum Efficiency/Light Extraction and Widen Viewing Angle of Organic Light-Emitting Diodes with New Plasmonic Cavity with Subwavelength Hole Array (PlaCSH)

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One major challenge in light emitting diode (LED) is the light extraction, and another is to replace the transparent ITO electrode in organic LEDs. [1-2] Here, we report a proposal and the first experimental demonstration of a new LED structure with a subwavelength plasmonic cavity, that, compared to the reference LEDs of the same structure except no plasmonic cavity, (a) increases total external quantum efficiency (EQE) 93%, (b) has widen viewing angle by 7% (from angle-FWHM 116^o to 124^o), and (c) replaces the ITO using a thin light transmissive metallic-mesh electrode of subwavelength holes (MESH).

An optimized PlaCSH-LED has a ultrathin plasmonic cavity that comprises a 15 nm thickness Au MESH as the front electrode, a 100 nm thick Al (LiF) film as the back electrode, and in-between 100 nm thick light emitting layer (poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) for electron transport and polystyrenesulfonic acid (PEDOT:PSS) for hole transport) (Fig. 1a). The PlaCSH-LEDs have a similar structure as a PlaCSH solar-cell [3] except different active materials and cavity length. And they were fabricated on a glass substrate (0.5 mm thick) with the MESH facing the substrate.

The MESHs of sub-wavelength pitch (200 nm) were fabricated by nanoimprint lithography on 4" glass substrates with nanopatterns over entire substrate area, and by deposition and lift-off of Au. SEMs show the MESH's hole shape is close to square with round corners and smooth edges, and that the MESH is uniform over large area (Fig. 1b).

The measurements (Fig. 2a) show that all-direction-EQE is 2.35 % in PlaCSH-LED of 180 nm diameter holes -- 93 % higher than ITO-LED (1.35 %). The near doubling in the total EQE is primarily due to better light radiation by the PlaCSH, which acts as an antenna for the light. The EQE doubling should be independent of the light emitting active materials, hence a much higher absolute EQE can be achieved when the current active materials are replaced by high internal quantum efficient materials (Note the use of the current active materials was for simple processing).

Furthermore, we found that PlaCSH has widened the LED's viewing angle. Fig. 2(b,c) shows that PlaCSH-OLEDs have not only an EQE enhancement, but also a larger angle-FWHM of 124^o compared with ITO-OLED (angle FWHM of 116^o), which give advantages for certain applications.

Compared with ITO, the 180 nm diameter hole MESHs also have higher conductivity (< 4 ohm/sq) –2.5 times better and high transmission (80 %), and is more flexible, lighter and cheaper.

The design of PlaCSH LEDs can be extended to other LED' materials (organic and inorganic), and its fabrication is scalable to roll-to-roll and wallpaper size for low-cost applications.

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[2] Z. B. Wang, M. G. Helander, J. Qiu, D. P. Puzzo, M. T. Greiner, Z. M. Hudson, S. Wang, Z. W. Liu and Z. H. Lu, Nature Photonics. 5. 753-757 (2011).
[3] S. Y. Chou, and W. Ding, Opt. Express. A60, Vol. 21, No. 21. (2013).

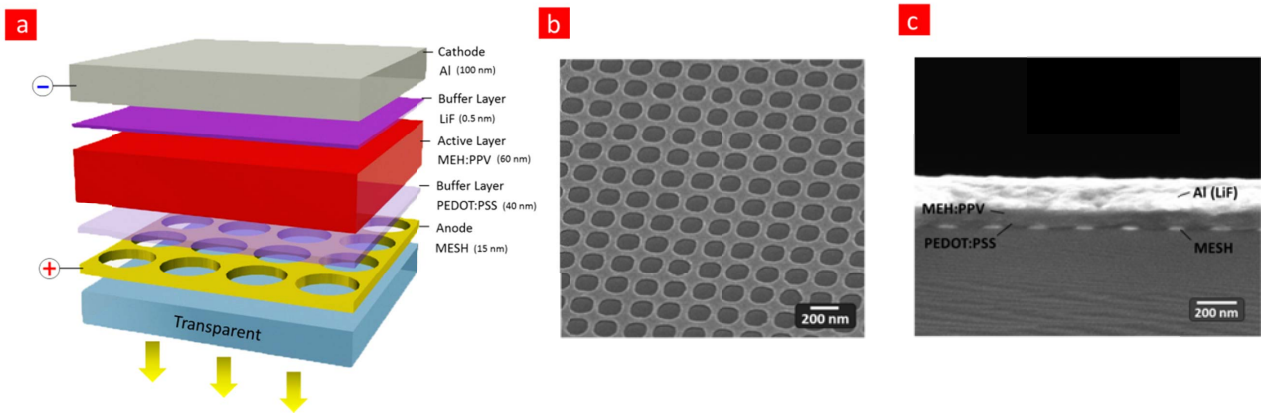

Fig. 1. Organic Light Emitting Diode (LED) with Plasmonic Cavity with Subwavelength Hole-array (PlaCSH). (a) Structure schematic of PlaCSH-LED consisting of a top metallic (Au) electrode with subwavelength hole-array (MESH), an back electrode (Al), and in between thin layers of MEH-PPV, LiF, and PEDOT:PSS; (b) tilt-view SEM of MESH; (c) cross-sectional SEM of PlaCSH-LED.

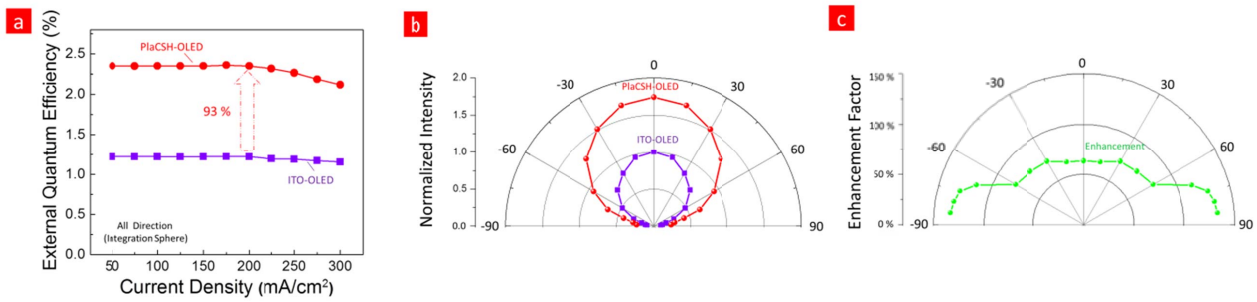

Fig. 2. External Quantum Efficiency enhancement (EQE) with PlaCSH structure (a) and Far field Luminescence Intensity distribution (b) and enhancement (c). Compared with ITO-OLED (EQE = 1.22 %), PlaCSH-OLED has an enhancement to 93 % (EQE = 2.35 %). From the angle distribution (b) and enhancement (c), PlaCSH-OLED has a normal direction power density enhancement of 63 %, overall enhancement around 90 % and larger angle FWHM of 124^{o} compared with ITO-OLED (angle FWHM of 116^{o}).