High-efficiency, Large-area and Color-stable Flexible Organic Light-emitting Diodes using an Ultra-thin Metal Electrode

Cheng Zhang[1], Qingyu Huang[1,2], Qingyu Cui[1], Chengang Ji[1], Zhong Zhang[1], Suling Zhao[2] and L. Jay Guo[1*]

1. Department of Electrical Engineering and Computer Science, University of Michigan-Ann Arbor, MI, 48105, USA
2. Institute of Optoelectronics Technology, Beijing Jiaotong University, Beijing, 100044, China
*Email: guo@umich.edu

Large-area and flexible organic light emitting diodes (OLEDs) have numerous applications in display and solid-state lighting. One of their key components is flexible transparent electrode (FTE), whose requirements are not well satisfied by the traditional ITO-based ones. In this work, we report on a high-performance FTE based on an ultra-thin Ag film, which has high optical transmittance, good electrical conductivity over large areas, robust mechanical flexibility, as well as long-term stability. The FTE is prepared by adding a proper amount of Ni during Ag deposition. The incorporation of Ni atoms sufficiently suppresses the 3D growth mode of Ag atoms, and consequently, ultra-thin (<10 nm), smooth (roughness <1 nm), highly conductive (sheet resistance <20 Ω sq^{-1}), and chemically stable Ag films are prepared on flexible substrates (figure 1).

The ultra-thin Ag based FTE is then employed in large-area flexible OLEDs, whose device structure is shown in figure 2a. Control devices are fabricated on ITO coated glass substrates. Current-voltage-luminance (I-V-L) characteristics of the OLEDs are shown in figure 1b. The Ag based OLED exhibits almost twice maximal luminance than ITO based device (16265 cd/m^2 vs. 9905 cd/m^2). Also, the Ag based OLED demonstrates a peak current efficiency (CE) up to 13.47 cd/A and a corresponding external quantum efficiency (EQE) of 4.25%. In contrast, ITO based OLED shows lower maximal CE and EQE of 10.4 cd/A and 3.17%, respectively (figure 2c). The enhanced efficiency of the Ni-doped Ag OLED is attributed to its improved light out-coupling capability, especially by eliminating the trapped emission light in the high-index ITO layer. In addition, the Ni-doped Ag based OLEDs exhibit almost identical emission spectra even at a very large angle, making them desirable for practical applications (figure 2d).

A large area (1.5 cm by 1.5 cm) OLED with the contour shape of the University of Michigan logo is shown in figure 2e. The device is on a flexible PET substrate, and the photo is taken when device is bent with a radius of 0.5 inch. The OLED gives both bright and uniform light over the entire emission area. In addition, the OLED demonstrates an extraordinary bending stability, and maintains its 70% current efficiency even after 1200 times of bending (figure 2f).

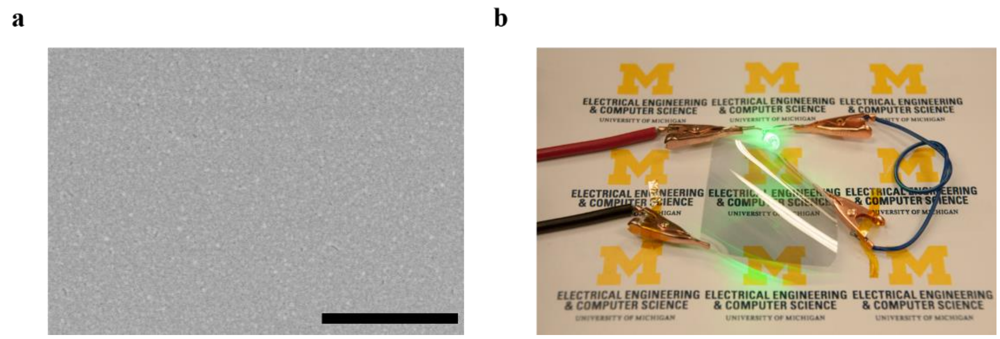

Figure 1: (a) SEM picture of a 7 nm Ni-doped Ag film on fused silica substrate, which exhibits a very smooth surface morphology. In contrast, pure Ag at such a thickness is dis-continuous. The scale bar is 500 nm; (b) Picture of a Ni-doped Ag film on PET substrate, which is utilized as a FTE in a demo circuit that lights up a green LED.

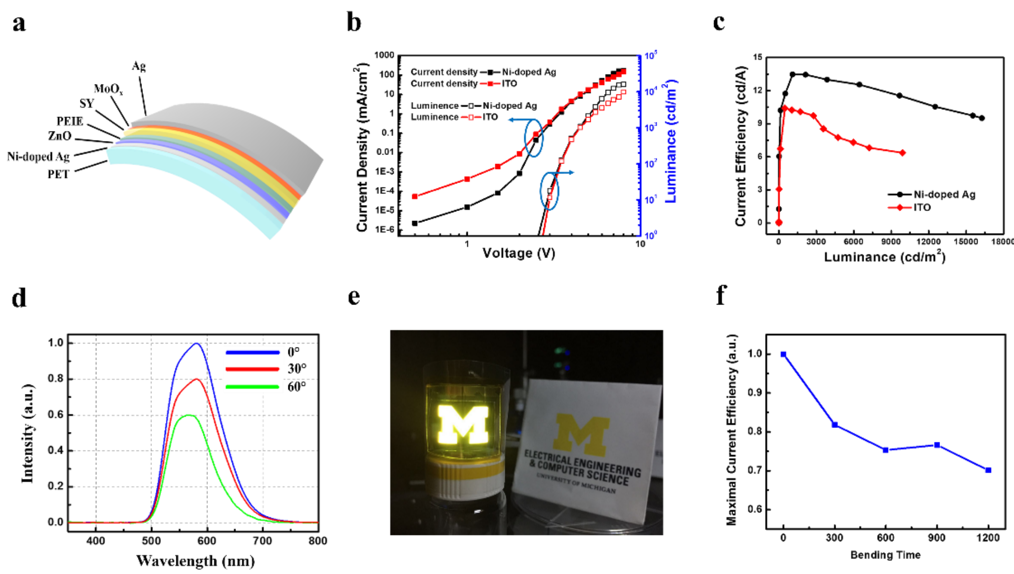

Figure 2: (a) Schematic drawing of the OLED, which consists of stacking layers of PET substrate/ Ni-doped Ag (8 nm)/ ZnO nanoparticle (15 nm)/ PEIE (20 nm)/ Super Yellow (70 nm)/ MoO_x (8 nm)/ Ag (100 nm); (b) Measured I-V-L curves of the thin Ag and ITO based OLEDs. The Ni-doped Ag based OLED exhibits about twice maximal luminance than its ITO-based counterpart; (c) Measured current efficiencies of the thin Ag and ITO based OLEDs; (d) Measured emission spectra at different viewing angles of the Ni-doped Ag based OLED. The device exhibits almost identical emission spectra up to very large viewing angles; (e) A 1.5 cm by 1.5 cm area OLED with the contour shape of the University of Michigan logo. The device gives both bright and uniform light over the entire emission area. (f) The maximal current efficiency of Ni-doped Ag based OLED as a function of bending cycles. The device demonstrates an extraordinary bending stability, and maintains its 70% current efficiency even after 1200 times of bending.