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Effects of transparent bottom electrode thickness on characteristics of transparent organic light-emitting devices

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We conduct both simulation and experiment studies of impacts of simultaneously varying the thicknesses of transparent bottom electrodes and semi-transparent top thin metal electrodes on optical characteristics (e.g., transmission, reflection) and efficiencies of transparent organic light-emitting devices (OLEDs). For the thickness range of both electrodes studied, the total electroluminescent (EL) efficiencies (including both bottom and top emission), EL spectra, and emission patterns remain similar; yet the ratio of top to bottom emission would be modulated by the semi-transparent top metal electrode thickness. The thickness of the transparent bottom electrode has weak effects on the efficiencies of top/bottom/total emission, but it does have definite effects on optical transmission/reflection spectra (e.g. peak/valley wavelengths). Meanwhile, the thickness of semi-transparent top metal electrodes mainly affect magnitudes of the optical transmission/reflection. Transmissive/reflective hues and appearances of the transparent OLEDs can thus be tuned by the thicknesses of bottom/top electrodes. Overall, we demonstrated efficient transparent green phosphorescent OLEDs exhibiting a high peak transmittance of up to 81% and rather high total external quantum efficiencies of up to 21–21.5% (corresponding to a total current efficiency of 80–82 cd/A and total power efficiency of 95–99 l m/W), among the highest (if not the highest) for planar transparent OLEDs using no other optical out-coupling structures. By varying the thicknesses of transparent bottom electrodes and semi-transparent top metal electrodes, the ratio of top to bottom emission, and the transmissive or reflective hues/appearances of transparent OLEDs in the off state can be tuned, yet without sacrificing total EL efficiencies or changing their EL colors/patterns. Such tunable optical characteristics of transparent OLEDs may find some interesting applications.

1. Introduction

Transparent organic light-emitting devices (OLEDs) are one of the most fascinating developments of OLED technologies in recent years due to their various possible interesting applications [1–8]. Possible applications of transparent OLEDs could range from transparent (see-through) displays, transparent (see-through) lighting panels, head-mounted displays, smart windows for architectural or advertising purposes, to navigation/warning displays on car windshields [1–8].

One of the most feasible and widely adopted configurations for implementing transparent OLEDs is to use thin and semi-transparent metal top electrodes to replace thick and opaque metal top electrodes in conventional OLED structures [5–11]. With such a device configuration, to reduce the optical absorption loss and to modulate reflection properties of the thin semi-transparent metal electrodes for tuning/optimizing transparency and optical out-coupling efficiencies of devices, further coverage of thin semi-transparent metal electrodes with appropriate transparent capping layers had also been widely adopted and studied [5–11]. In addition, the adjustment of organic layer thicknesses had also been generally studied for tuning/optimizing optical and efficiency characteristics of transparent OLEDs [5–11]. Overall, external quantum efficiencies (EQEs) and transparency nowadays achieved with such a transparent OLED configuration are still largely

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significantly lower than 20% and 70%, respectively [5–13], and thus require further improvement.

Although the influences of the thicknesses of thin semi-transparent metal electrodes, capping layers, and even organic active layers on optical characteristics (e.g., transmission) and electroluminescent (EL) efficiencies of transparent OLEDs had been previously extensively investigated, yet we notice that the influence of the thickness of the transparent bottom indium tin oxide (ITO) electrode has not been carefully examined. In this work, we conduct both simulation and experiment studies of impacts of simultaneously varying the thicknesses of transparent bottom electrodes and semi-transparent top electrodes on optical characteristics (e.g., transmission, reflection) and efficiencies of transparent OLEDs. Results show that for the thickness range of both electrodes studied, the total EL efficiencies (including both bottom and top emission) remain similar and yet the ratio of top to bottom emission would be varied (mainly by the semi-transparent top metal electrode thickness). In addition, it is found that the transparent bottom ITO electrode thickness has significant effects on the optical transmission/reflection spectra (e.g., peak/valley wavelengths), while the semi-transparent top metal electrode thickness mainly affects magnitudes of the optical transmission/reflection. As a result, we demonstrated efficient transparent green phosphorescent OLEDs exhibiting broad optical transmission bands with a high peak transmittance of up to 81% and tunable hues, and rather high total EQE of up to 21–21.5% (corresponding to a total current efficiency of 80–82 cd/A and total power efficiency of 95–99 l m/W), among the highest (if not the highest) for planar transparent OLEDs using no other optical out-coupling structures.

2. Experiments

As shown in Fig. 1, the devices for both simulation and experiment studies in this work were green phosphorescent OLEDs having the general structure of: glass substrate/ITO anode (X nm)/HATCN (5 nm)/TAPC (60 nm)/CBP:Ir (ppy)$_2$acac 8 wt% (20 nm)/B3PYMPM (50 nm)/LiF (0.6 nm)/Al (1 nm)/thin Ag cathode (Y nm)/NPB capping (70 nm). ITO and Al/Ag served as the anode and

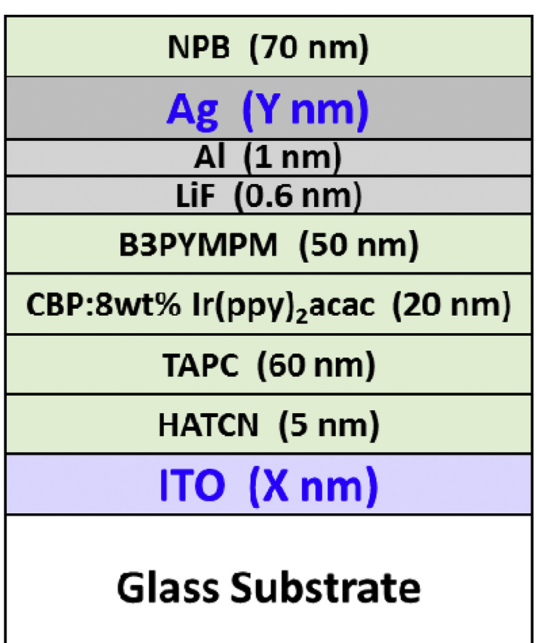

Fig. 1. The device structure for both simulation and experiment studies in this work.

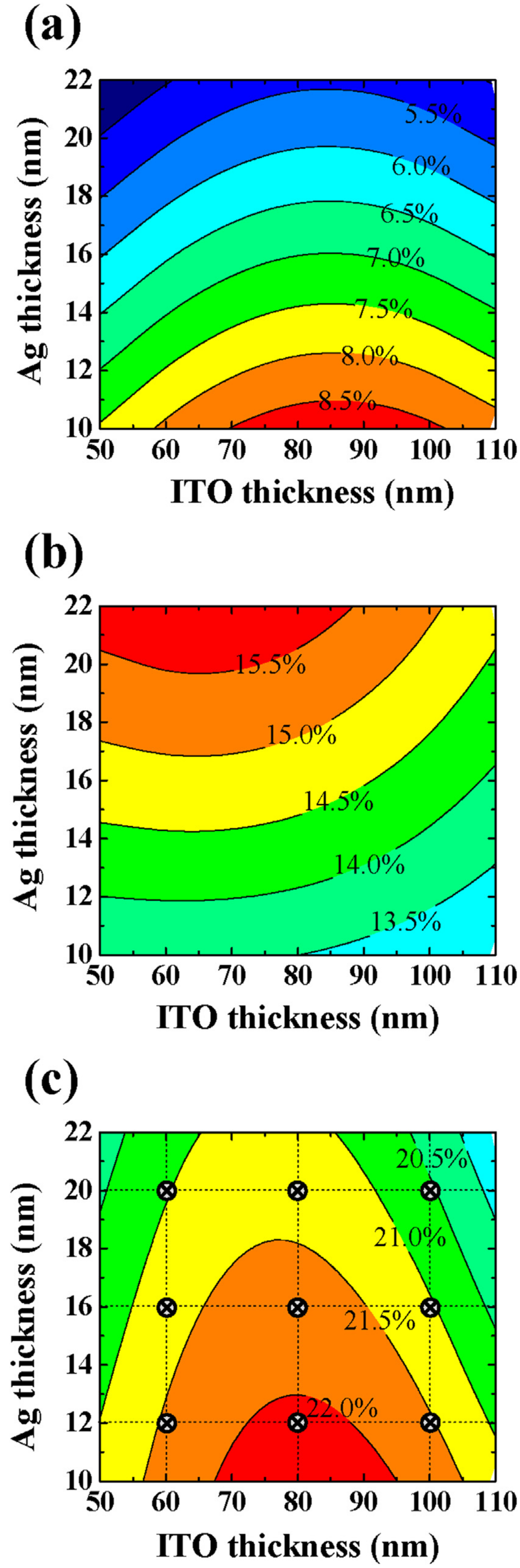

Fig. 2. Calculated optical out-coupling efficiency for (a) top emission, (b) bottom emission, and (c) total emission (top + bottom emission) of the transparent OLEDs as a function of the bottom ITO electrode thickness and the top semi-transparent Ag thickness. Fabricated and tested 3 × 3 experiment devices having varied combinations of ITO thicknesses (60, 80 and 100 nm) and Ag thicknesses (12, 16, and 20 nm) are marked in Fig. 2(c)).