29.3: Very Bright and Efficient Top-Emitting OLED with Ultra-Thin Yb as Effective Electron Injector

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Abstract

Very bright and efficient top-emitting organic light-emitting diodes (TOLEDs) using an ultra-thin ytterbium (Yb) layer capped with a semitransparent Ag layer as the effective electron-injection cathode were demonstrated. TOLED with Yb/Ag cathode exhibited lower operation voltage and higher power efficiency, as compared to the one with commonly used Ca/Ag cathode. With bis(2-phenylpyridine)iridium [$(ppy)_2Ir(acac)$] as the phosphorescent dopant, the Yb/Ag based TOLED showed a current efficiency of 88 cd/A and a power efficiency of 67 lm/W, considerably greater than those (56 cd/A and 44 lm/W) obtained from the corresponding bottom-emitting one. The good performance of these TOLEDs is attributed to the efficient electrons injection from the Yb/Ag cathode as well as a micro-cavity effect.

1. Introduction

OLEDs have attracted much interest due to its potential application in flat-panel displays [1-3]. Conventional bottom-emitting OLEDs require transparent substrates. The pixel aperture ratio will be limited by the transistors integrated on the substrate. In order to achieve high-resolution displays, top-emitting OLEDs are desirable since the transistors can be buried underneath the OLEDs [4, 5]. Additionally, TOLEDs are needed for opaque substrates such as crystalline silicon or flexible stainless steel [6, 7].

In TOLEDs, the (semi-) transparent top cathodes play an important role for achieving good device performance. Many attempts have been made to develop proper top cathodes [8-10]. Transparent conducting oxides, such as indium tin oxide (ITO) [8], deposited by sputtering, are always used as the transparent cathodes in TOLED. However, the sputtering process can cause serious damage to the organic layers. Semi-transparent metals by thermal evaporation are therefore more suitable as the top cathode in TOLED [9, 10]. Among various metals, semitransparent Ag is considered as a good candidate for the cathode of TOLEDs because of its low absorption and high stability. However, the work function of Ag (~4.6eV) is too large for efficient electrons injection. So an electron injection layer is necessary for electrons injection enhancement using Ag cathode.

The electron injection layers should have the proper thickness for efficient electrons injection as well as lowest light absorption [9, 10]. So far, Ca [10-11] and ultra-thin LiF/Al [9, 12], which have low work function, are two commonly used electrons injection layers for Ag cathode. Ytterbium (Yb) has a lower work function (2.6eV) than Ca (2.9eV) and LiF/Al (3.1eV) and is believed to be a good electron injection layer for Ag cathode.

In this paper, we demonstrated an efficient TOLED on silicon substrate with an ultra-thin Yb layer capped with a semitransparent Ag layer as the effective electron-injection cathode. In comparison with the TOLED using Ca/Ag cathode, Yb/Ag based TOLED shows a much lower operation voltage and higher power efficiency. With $(ppy)_2Ir(acac)$ used as the emissive phosphorescent dopant, the Yb/Ag based TOLED shows a maximum current efficiency of 88 cd/A and a peak power efficiency of 67 lm/W, much greater than those (56 cd/A and 44 lm/W) obtained from the corresponding bottom-emitting one.

2. Experiment

All the TOLEDs are fabricated on a (100) crystalline silicon substrate coated with 70 nm sputtered Al. A 300 nm wet oxidized SiO_2 layer was inserted between the silicon substrate and the Al layer for insulation. The Al layer was patterned to form stripes with conventional photolithography. This patterned Al layer was used as the reflective anode for the TOLEDs. A reference bottom-emitting OLEDs is also fabricated on 75nm ITO (with a sheet resistance of 25 Ω/ □) coated glass substrate. All the substrates are cleaned with standard clean procedure prior to other layers deposition. All the other layers of the devices were finished by thermal evaporation in a high-vacuum chamber with a base pressure of about 1.6×10^{-4} Pa.

In our study, two sets of devices were fabricated. The first set of devices were TOLEDs fabricated on Al coated silicon substrate. A metal oxide, V_2O_5, and NPB (4,4-bis[*N*-(1-naphthyl)-*N*-phenyl-amino]biphenyl) are co-depostied at a molar ration of about 4:1 to form a mixed layer having a thickness of 10nm acting as hole injection layer (HIL)[13]. Then 45nm NPB as hole transport layer (HTL) was deposited, followed by 50nm Alq_3 (tris-(8-hydroxyquinoline) aluminum) as electron transport layer (ETL) and emitting layer (EML). Thereafter, the bi-layer semi-transparent cathode, Yb(2nm)/Ag(20nm) or Ca(5nm)/Ag(20nm), and additional 50nm Alq_3 as index-matching layer were deposited sequentially [9]. The second set of devices have the configurations of ITO/MoO_x (2nm)/ NPB (40nm)/ CBP (7wt% $(ppy)_2Ir(acac)$) (30nm)/BCP(15nm)/Alq_3 (30nm)/LiF/Al and Al /MoO_x (2nm) /NPB (40nm)/CBP (7wt% $(ppy)_2Ir(acac)$) (20nm)/ BCP(10nm)/ Alq_3 (30nm)/Yb(2nm)/Ag(20nm)/Alq_3(50nm), respectively. Here the 2nm MoO_x was achieved by thermal evaporating MoO_3 used as HIL for ITO and Al [14] anode. Here, NPB and Alq_3 were HTL and ETL respectively. CBP denotes 4,4'-bis(carbazol-9-yl)-biphenyl as the host material for the emissive phosphorescent dopant $(ppy)_2Ir(acac)$) and BCP denotes 2,9-Dimethyl-4,7-diphenyl-1,10-phenanthroline as the hole block layer (HBL).

The current density-voltage (J-V) and luminance-voltage (L-V) characteristics of these devices were measured simultaneously with parameter analyzer (HP4145B) and a silicon photodiode

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calibrated by Photoresearch PR650 spectrometer. The EL spectra were measured with the PR650 spectrometer.

3. Results and Discussion

A. Optical characteristics of Yb/Ag

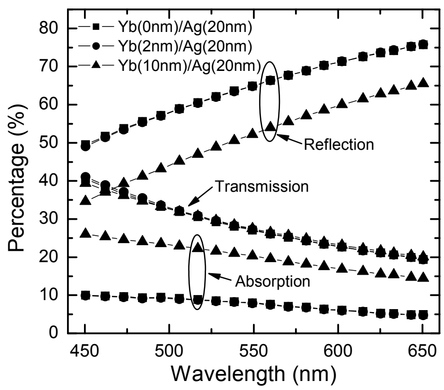

FIG. 1. Optical transmission, reflection, absorption of Yb(*x* nm)/ Ag (20nm) films.

Fig. 1 shows the optical transmission, reflection and absorption spectra of Yb(*x* nm)/Ag (20nm) with different Yb thickness. It can be seen that the optical property of the film with 2nm Yb almost the same as that of Ag-only film. While when the thickness of Yb increased to 10nm, although there is no obvious change in the transmission, the reflection greatly decreases, correspondingly, the absorption of the film greatly increases. The higher absorption will reduce the micro-cavity effect, resulting in efficiency lowering [15]. The effects of Yb thicknesses on the electron injection ability of Yb/Ag cathode have also be evaluated by varying the Yb thickness and it is found that the injection ability is independent on Yb thickness [16]. According to above analysis, ultra thin Yb (2nm) was used in our study.

B. Electrons injection enhancement by Yb/Ag cathode

The devices fabricated on Al coated silicon substrate has the configuration of Al/V_2O_5:NPB (4:1) (10nm)/ NPB(45nm)/ Alq_3 (50nm) / Yb(2nm) or Ca(5nm)/Ag(20nm)/Alq_3(50nm).

The key results of the TOLEDs with Yb/Ag cathode and Ca/Ag cathode are listed in Table I. It can be seen that the turn-on voltage (defined as the voltage to achieve 1cd/m^2) of the device using Yb/Ag cathode is 0.7V lower than that of the one with Ca/Ag cathode. Similarly, the Yb/Ag cathode based device can achieve a current density of 20mA/cm^2 and a brightness of 1000cd/m^2 at 8.1V and 7.5V, respectively. While the corresponding voltages of Ca/Ag based device are 8.9V and 8.4V, respectively.

Fig. 2 (a) gives the J-V-L characteristics of the two devices. It is obvious that the Yb/Ag based device shows a lower driving voltage, and at the same applied voltage, it shows a higher brightness. Correspondingly, the power efficiency is much higher than that of the Ca/Ag based one (Fig. 2 (b)). The maximum

TABLE I. Performance of TOLEDs with different cathodes

Devices	V_{on} @ 1cd/m^2 (V)	V @ 20mA/cm^2 (V)	V@ 1000cd/m^2 (V)	$\eta_{J\max}$ (cd/A)	$\eta_{P\max}$ (lm/W)
Ca/Ag	3.9	8.9	8.4	8.3	3.5
Yb/Ag	3.2	8.1	7.5	8.5	4.5

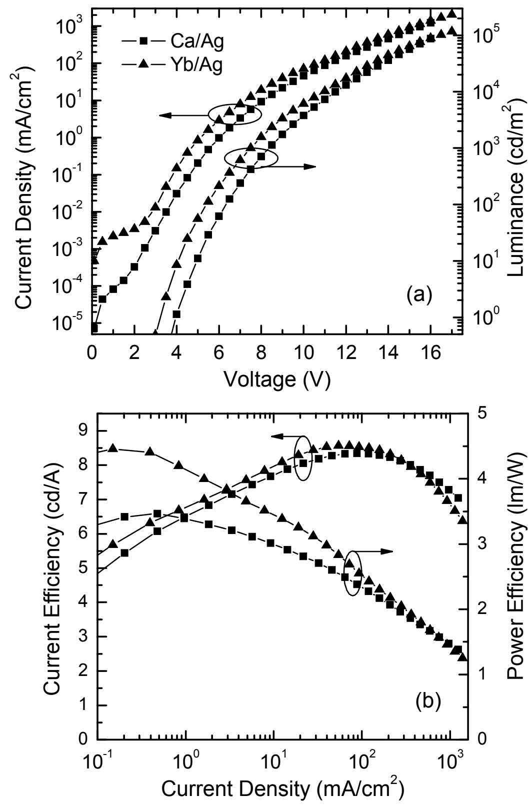

FIG. 2. (a) J-V-L and (b) efficiency characteristics of the TOLEDs with Ca/Ag cathode and with Yb/Ag cathode.

power efficiency of the TOLED with Yb/Ag cathode is about 4.5lm/W higher than that of the Ca/Ag based device (3.5lm/W). These improvements are predominately attributed to the lower work function of Yb (2.6eV) compared to that of Ca (2.9eV), which can provide much more electrons injection. The results also suggest that the 2nm Yb was an effective electron injector for electron injection.

The two TOLEDs both show a maximum current efficiency above 8-cd/A, and achieve very high brightness above 1x10^5-cd/m^2 at 17V. This performance is much better than that of the reported Alq_3-emitter based bottom-emitting OLED. This is partially because there is micro-cavity effect existed in the TOLEDs induced by the highly reflective anode and semitransparent cathode [17-19]. The EL spectra of the two devices in the normal direction are shown in Fig. 3. It can be seen that there is almost no difference in the two EL spectra. This indicates the optical properties of Yb(2nm)/Ag(20nm) and

Ca(5nm)/Ag(20nm) are almost the same, which result in a similar interference effect and therefore the same out coupling spectra. This result also confirms that the improved performance of Yb/Ag based device as compared to Ca/Ag based one is attributed the electrons injection improvement only.

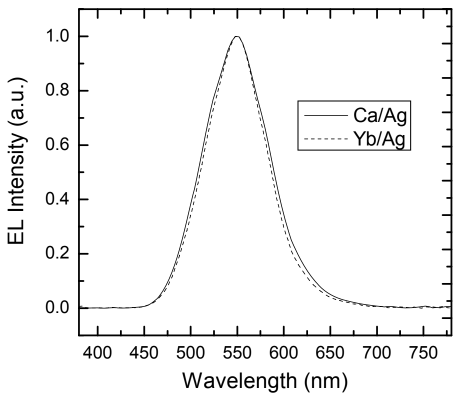

FIG. 3. Normal emission spectra of the TOLEDs with Ca/Ag cathode (solid line) and with Yb/Ag cathode (dashed line).

C. Efficiency enhancement with micro-cavity effect

In this section, two devices based on phosphorescent emission are compared. One is bottom-emitting with ITO anode and conventional LiF/Al cathode. The other one is a top-emitting with reflective Al anode and semitransparent Yb(2nm)/Ag(20nm) cathode. They have the same organic functional layers except that in order to achieve effective micro-cavity effect enhancement, the emissive layer and HBL are thinner in the top-emitting one.

Fig. 4 (a) shows the measured EL spectra of the Yb/Ag cathode based top-emitting OLEDs at different view angles and the EL spectrum from the bottom-emitting device with ITO anode. It is obvious that there are some variations in the EL spectra of the TOLED at different view angles. Evidently, there is strong micro-cavity effect in the TOLED, induced by the reflectivity of Yb/Ag cathode. With a careful choice of the organic layer thicknesses, the [15], the color shift can be minimized and acceptable as standard green.

The J-V-L and efficiency characteristics of these two devices are compared in Figs. 4 (b) and (c), respectively. It can be seen that the J-V characteristics of the two devices are quite similar, although Al /MoO_x is inferior for holes injection as compared to ITO /MoO_x [14]. This is because the top-emitting device has a 10nm thinner emissive layer and 5nm thinner HBL. With same current density, Yb/Ag based top-emitting device can achieve much higher luminance. For example, at 20mA/cm^2, the top-emitting device can achieve a luminance of about 11,700-cd/m^2, which is much higher than 7,400-cd/m^2 for the LiF/Al based bottom-emitting device. These results can be attributed to the enhancement of the coupling efficiency induced by micro-cavity effect. So the top-emitting devices can achieve a maximum current efficiency of 88-cd/A and a maximum power efficiency of 67-lm/W, much higher than those (56-cd/A and 44-lm/W) obtained from the bottom-emitting device.

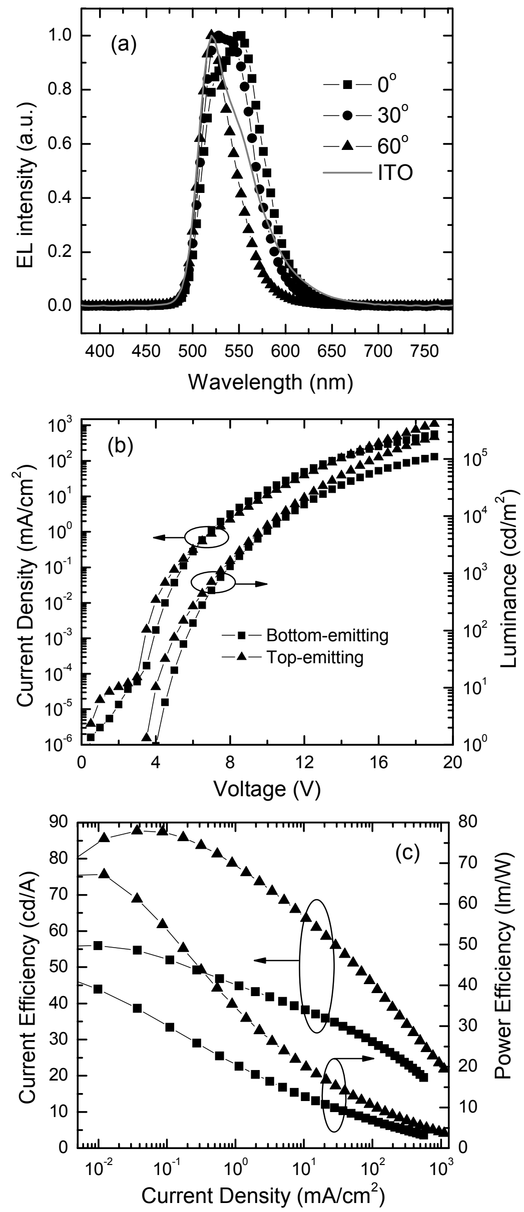

FIG. 4. (a) EL spectra of Yb/Ag based top-emitting device at different viewing angles in comparison with that from bottom-emitting device. (b)J-V-L characteristics of the top- and bottom-emitting devices. (c) Current and power efficiency comparison.

4. Conclusions

In summary, very bright and efficient TOLEDs using ultra-thin Yb (2nm) capped with a semitransparent Ag layer as the cathode have been demonstrated. In comparison with the TOLED using Ca/Ag cathode, Yb/Ag based TOLED shows a much lower operation voltage and a higher power efficiency. With $(ppy)_2Ir(acac)$ as the emissive phosphorescent dopant, combining with the micro-cavity effect enhancement, the Yb/Ag based TOLED gives a maximum current efficiency of 88-cd/A and a peak power efficiency of 67-lm/W, which are much greater than those (56 cd/A and 44 lm/W) obtained from the corresponding bottom-emitting device.

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