Highly Efficient Top-Emitting Electrophosphorescent Organic Light-Emitting Devices

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Abstract

We present both a theoretical analysis and experimental data to show that electrophosphorescent top-emitting organic light emitting-devices (TOLEDs) with a reflective anode and a transparent cathode can be more efficient than the equivalent state-of-the-art bottom-emitting electrophosphorescent OLEDs (PHOLEDs^{TM}). The lifetime of devices with transparent cathodes are shown to approach that of the corresponding bottom-emitting devices.

1. Introduction

Organic light-emitting devices (OLEDs) [10] hold great promise as the next-generation display technology. One of the remaining challenges in manufacturing active-matrix OLED displays is the requirement for a backplane that provides constant, uniform drive current. The pixel and driver circuitry need to compensate for the initial non-uniformities of the low-temperature poly-silicon thin film transistors (TFTs) or the threshold-voltage-shift of the amorphous silicon TFTs [4,9]. Most pixel designs incorporate more than two transistors along with a conventional bottom-emitting OLED [4,5]. This can significantly diminish the aperture ratio, forcing the OLED to operate at a high luminance level, reducing lifetime. One solution is to build top-emitting OLEDs (TOLEDs) over a planarized backplane [2,3]. However, up until recently, it was commonly held that TOLEDs are less efficient than their bottom-emitting counterpart, such that any gain in aperture ratio must be large enough to offset the efficiency loss. In this paper, we demonstrate both theoretically and experimentally that TOLEDs can be more efficient than the corresponding bottom-emitting OLEDs.

2. The TOLED Microcavity

In a conventional bottom-emitting OLED fabricated on a glass substrate, 50-80% of the light emission is lost to waveguiding modes in the glass, indium-tin-oxide (ITO) and organic layers. The decay paths of excitons after they are formed in the OLED cavity can be categorized as follows:

$$W_{TOT} = W_R + W_{ET} + W_{NR} \qquad (1)$$
$$W_R = W_{ext} + W_{sub} + W_{IO}$$

where W_{TOT}, W_R, W_{ET} and W_{NR} denote the total, the radiative, the exciton-cathode energy transfer, and the non-radiative rates of decay, respectively. The rate of radiative decay, W_R, is the sum of the decay rates into the external, substrate waveguided and ITO/organic waveguided modes, W_{ext}, W_{sub} and W_{IO}. The external quantum efficiency, η_{EL}^{ext}, can be written as:

$$\eta_{EL}^{ext} = \gamma\, r_{st} \left(W_{ext} / W_{TOT} \right) \qquad (2)$$

where γ is the number of exciton forming events per electron flowing through the OLED, and r_{st} is the portion of excitons capable of radiative recombination. One way to increase the out-coupling is to employ shaped substrates to convert waveguided light into external modes, thereby increasing the numerator (W_{ext}) in eq. 2 [7].

Another approach to increase the out-coupling efficiency is to reduce the denominator (W_{TOT}) in eq. 2, for example, by inserting a low index-of-refraction aerogel layer (t = 50 μm, n ~ 1.03) between the ITO and the glass substrate (Fig. 1a) [11]. The ITO/organic layers are too thin to support more than a handful of modes by themselves. Waveguiding in the glass substrate is eliminated since the large angle modes experience total internal reflection at the ITO/aerogel interface. Consequently, η_{EL}^{ext} is

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significantly enhanced, with W_{sub} and W_{IO} either eliminated or suppressed. An increase in η_{EL}^{ext} by a factor of 1.8 from insertion of the aerogel layer was reported [11].

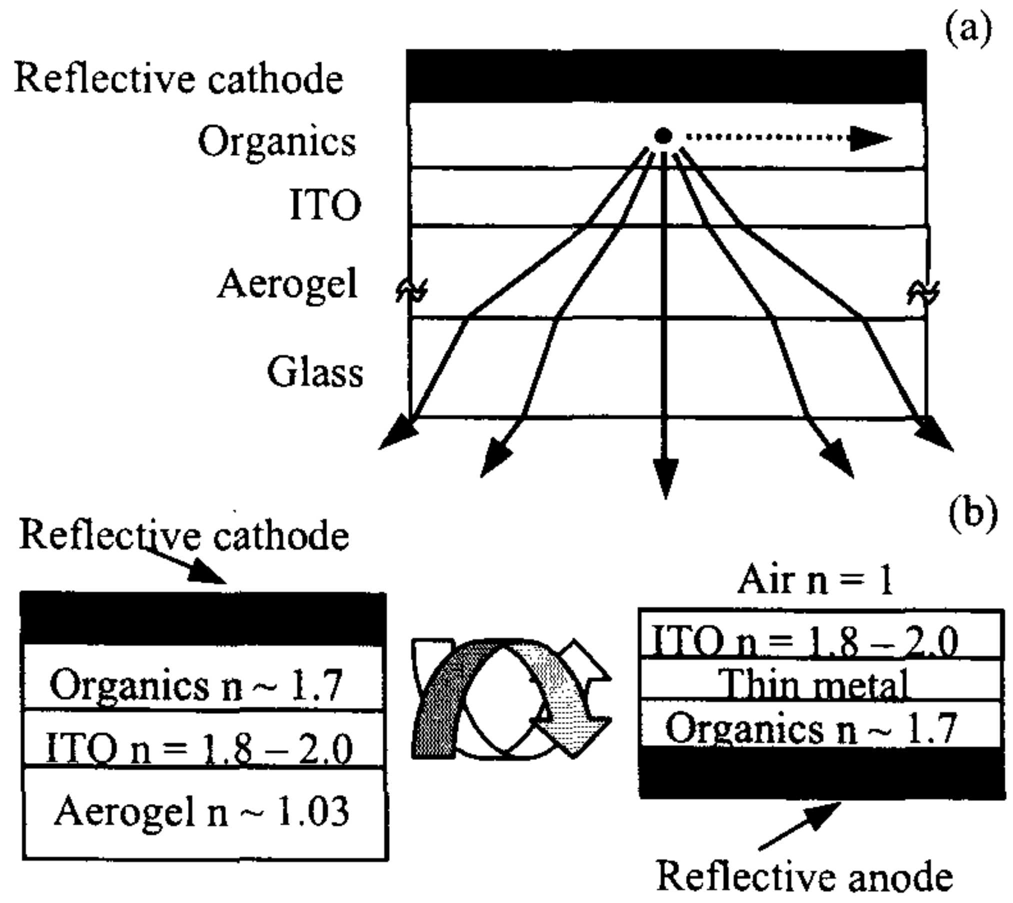

Figure 1 a) Light emission in an OLED on aerogel/glass substrate. The waveguided modes (dashed line) in the ITO/organic layer are suppressed (adapted from Ref. 11). b) Comparison of microcavity of the OLED in part a) with that of a TOLED: neglecting the thin metal film in TOLED and the difference between the refractive indices of aerogel and air, the two structures are identical.

Table 1 External (ext), substrate-waveguided (sub), and ITO/organic-waveguided (I/O) modes in bottom-emitting (BE) OLEDs and TOLEDs. Waveguiding modes confined in the thin ITO/organic layers are suppressed.

Mode	Mode angle	BE, on glass	BE, on aerogel	TOLEDs
Ext	$\theta_o < \sin^{-1} 1/n_{org}$	Un-affected	Un-affected	Un-affected
Sub	$\sin^{-1} 1/n_{org} < \theta_o < \sin^{-1} n_{glass}/n_{org}$	Un-affected	Sup-pressed	Sup-pressed
I/O	$\theta_o > \sin^{-1} n_{glass}/n_{org}$	Sup-pressed	Sup-pressed	Sup-pressed

The microcavity structures of the OLED on aerogel and the TOLED are compared in Fig. 1. The microcavity terminates in the aerogel layer because of its thickness and porosity. Neglecting the optical density of the thin metal layer and the difference between the refractive indices of air and aerogel, the microcavity of the OLED on aerogel is replicated in the TOLED, upside down. So in theory, TOLEDs with reflective anodes and transparent cathodes enjoy the same boost in efficiency as OLEDs on aerogel due to suppression of the waveguiding modes, thus TOLEDs can be more efficient than the equivalent bottom-emitting OLEDs on glass substrates (Table 1).

3. Experimental

Top-emitting, bottom-emitting and transparent OLEDs were fabricated as follows. The reflective anodes for TOLEDs were 160 Å ITO on Ag. The organic layers were: copper phthalocyanine (CuPc, 100-200 Å) as the hole injection layer, 4,4'-bis[N-(1-napthyl)-N-Phenyl-amino] biphenyl (α-NPD, 300 Å) as the hole transport layer, 4,4'-N,N'-dicarbazole-biphenyl (CBP, 300 Å) doped with *fac* tris (2-phenylpyridine) iridium [$Ir(ppy)_3$, 6 wt%] as the emitting layer, aluminum(III) bis (2-methyl-8-quinolinato) 4-phenylphenolate (BAlq, 100 Å) as the blocking layer, and tris-(8-hydroxyquinoline) aluminum (Alq_3, 400 Å) as the electron transport layer, all deposited by conventional vacuum thermal deposition at pressures less than $5x10^{-7}$ torr and nominal deposition rates of 1-3 Å/s [1]. The transparent compound cathodes of the TOLEDs consisted of 200 Å Ca deposited by vacuum thermal evaporation, followed with 800 Å ITO by sputter deposition [2,3]. The TOLEDs were encapsulated with a 1.1 mm soda lime cover glass. Equivalent bottom-emitting OLEDs with the same organic layer and were LiF (10 Å)/Al cathodes were fabricated on ITO coated glass for comparison [6]. Transparent OLEDs with the same organic layers were also fabricated on ITO coated glass. Mg:Ag/ITO were used as the compound cathodes in the transparent OLEDs used in the lifetime studies.

The reflectivities and transmissivities of various anodes and cathodes were measured with a Varian Cary 100 UV-Vis spectrophotometer. The electroluminescence was measured with a Photoresearch PR705 spectrophotometer, and the J-V-L characteristics were measured with a Keithley 236 source measure unit and a calibrated Si photodiode. All devices showed green EL emission from $Ir(ppy)_3$ that peaks at approximately 515 nm.

4. Results and Discussion

The emission intensity of TOLEDs depends strongly on the top ITO layer thickness due to microcavity effects. Both experimental data and modeling indicate that 800 Å is the optimal ITO thickness for these $Ir(ppy)_3$ based TOLEDs. This work is published elsewhere [8].

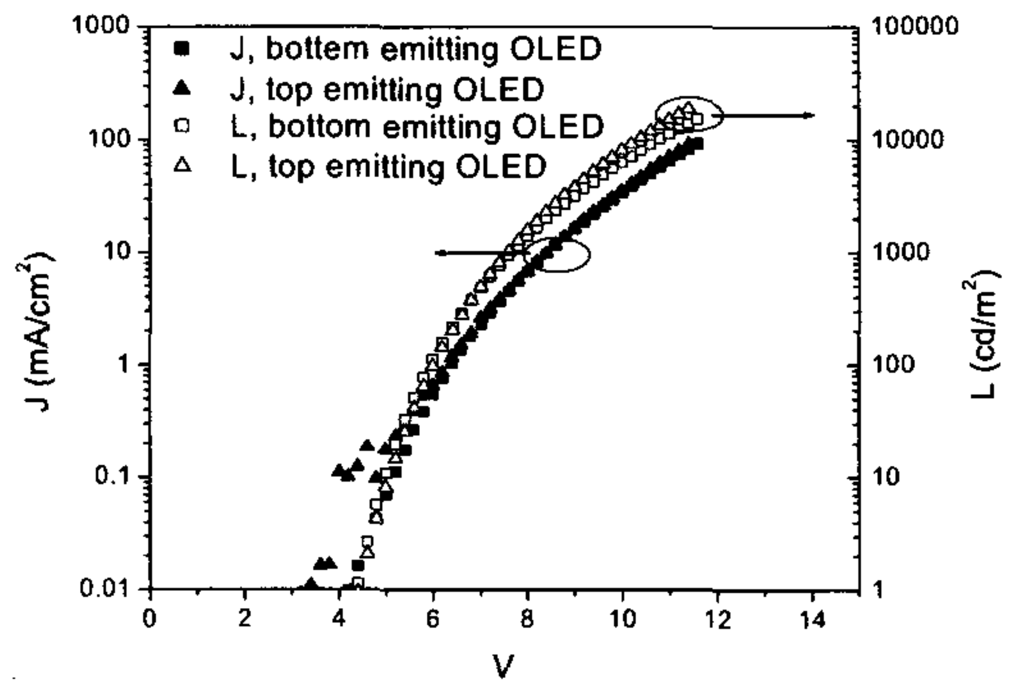

Figure 2 J-V-L curve of a TOLED compared with that of a bottom-emitting OLED. The luminance of the TOLED is measured through the cover glass. [8]

The J-V-L characteristic of the TOLED with an Ag/ITO anode and a Ca/ITO cathode is compared with that of a state-of-the-art OLED with the same organic layers, ITO anodes and LiF/Al cathodes in Figure 2. The J-V curves are identical within measurement uncertainties, while the TOLED has a slightly higher luminous efficiency. The OLED and TOLED reach 100 cd/m^2 at 5.9 V and 6.0 V, respectively. At 10 mA/cm^2 the luminance is 2030 cd/m^2 for the OLED and 2310 cd/m^2 for the TOLED (through the cover glass), i.e., 15% higher. The transmissivity of glass/Ca (200 Å)/ITO (800 Å) is 62.8% at λ = 515 nm [~ the peak of $Ir(ppy)_3$ emission], much less than the transmissivity of 89.9% for the ITO coated glass. The reflectivity of the Ag/ITO anodes is 85.5% at λ = 515 nm, again less than that of the Al cathodes at 88.5%. Overall, the electrodes of the bottom-emitting OLEDs are more reflective/transmissive than those of the TOLEDs. Therefore, the enhanced luminance in TOLEDs can only be attributed to the more favorable microcavity structure.

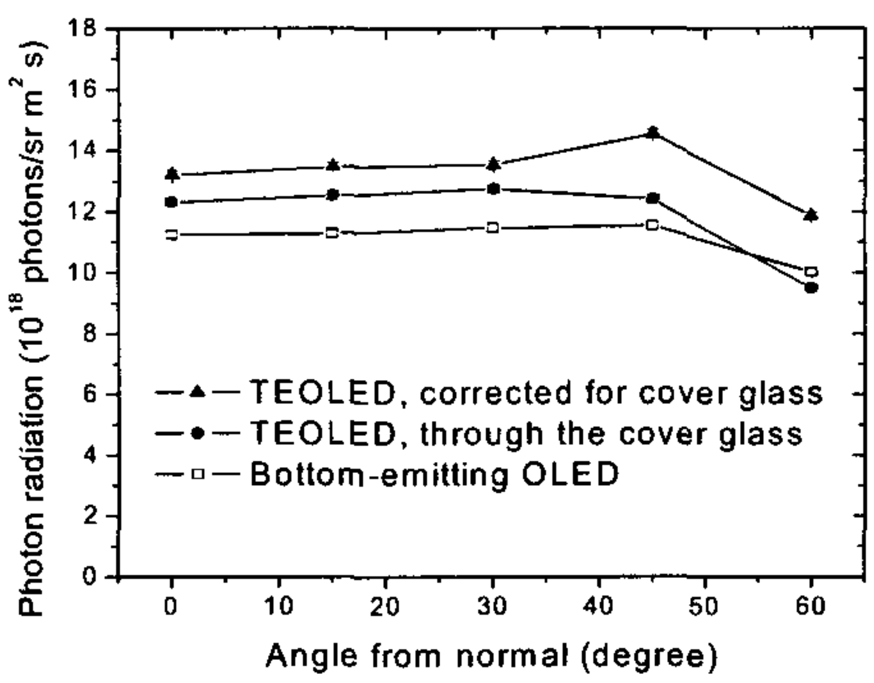

Figure 3 Photon radiation vs. far-field angle, all data was taken at J = 10 mA/cm^2. [8]

The far-field photon radiation from these devices was measured directly with a Photoresearch PR705 spectrophotometer. Due to the relative size of the devices and the focal spot of the spectrophotometer this measurement could be carried out reliably only up to a far-field angle of 60° from normal. Figure 3 shows the angular dependence of photon radiation for the TOLED (through the cover glass), the same TOLED corrected for the cover glass, and the corresponding bottom-emitting OLED. In accordance with our predictions, photon radiation is higher in these TOLEDs even uncorrected for the cover glass. There is only weak angular dependence which indicates that the emissions are approximately Lambertian in this angular range. Estimating the integrated photon flux by the formula $\Sigma I(\theta)\sin(\theta)\Delta\theta$, where $I(\theta)$ is the photon radiation at angle θ, the uncorrected and corrected TOLED were found to emit 4.2% and 20.8% more photons than the OLED in the forward 120° cone, respectively.

Figure 4 shows DC life-testing results of a typical long-lived bottom-emitting OLED and a transparent OLED with a Mg:Ag/ITO based compound cathode. The initial luminance is 600 cd/m^2 for both devices. In the case of the transparent OLED, it is the sum of the emission from both sides. The current density through the transparent OLED is slightly higher due to absorption in the Mg:Ag layer. The bottom-emitting OLED is projected to reach a half-life of 8000 hours, and that of the transparent OLED is slightly less due to the higher current density used.

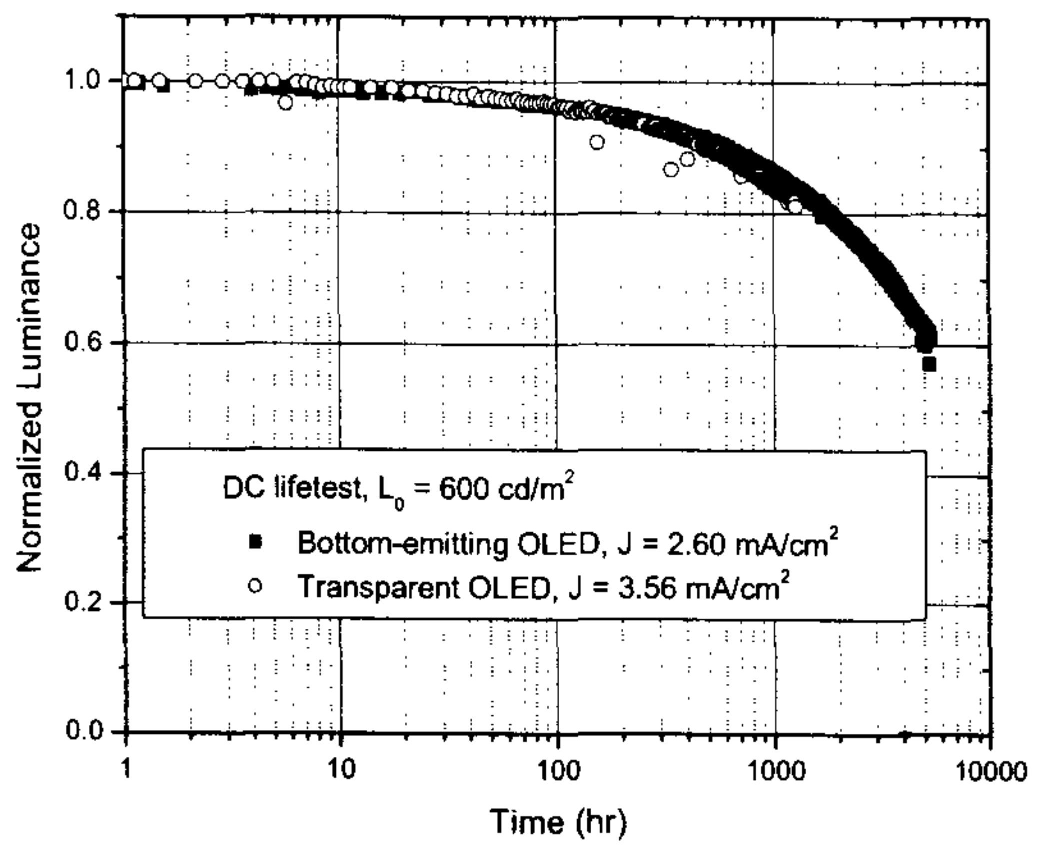

Figure 4 DC lifetime of a bottom-emitting OLED and a transparent OLED with Mg:Ag/ITO cathode.

5. Conclusions

We presented arguments based on a microcavity theory that TOLEDs can be more efficient than the corresponding bottom-emitting OLEDs. These theoretical predictions were confirmed by fabricating highly efficient TOLEDs based on Ag/ITO anodes and Ca/ITO transparent compound cathodes that emit 20.8% more photons in the forward 120° cone than corresponding OLEDs. Finally, we demonstrated a transparent OLED with Mg:Ag/ITO compound cathode whose lifetime approaches that of a typical long-lived bottom-emitting OLED. Based on these results, active matrix OLED displays employing TOLEDs should have higher efficiency and longer lifetime in addition to the advantage of an enhanced aperture ratio as compared with conventional bottom-emitting AMOLED display designs.

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7. References

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