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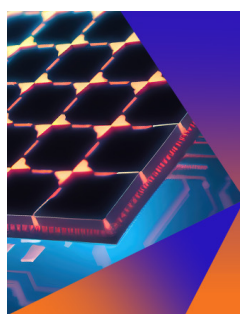


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High-efficiency top-emitting organic light-emitting devices

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Based on theoretical arguments that top-emitting organic light-emitting devices (TOLEDs) can be more efficient than equivalent bottom-emitting devices, we fabricated TOLEDs comprising reflective anodes and transparent compound cathodes that emit 20.8% more photons in the forward 120° cone than equivalent bottom-emitting OLEDs. Device optimization by tuning the thickness of the top indium–tin–oxide layer according to a microcavity model is also reported. © 2002 American Institute of Physics. [DOI: 10.1063/1.1523150]

Organic light-emitting devices (OLEDs)¹ are ideal for flat panel display applications due to their full color gamut and thin form factor. OLEDs utilizing phosphorescent dopants (PHOLEDsTM) are especially promising for displays in mobile electronic devices because of their low power consumption.² Active-matrix drive is required for high information content OLED displays. Because OLEDs are current-driven devices, one of the remaining technological challenges in bringing to market an active-matrix OLED display is a backplane design that provides a constant, uniform drive current. As in general there are nonuniformities in the as-fabricated threshold voltage and mobility of low-temperature polysilicon thin film transistors (TFTs), and bias stress induced threshold-voltage-shifts in amorphous silicon TFTs,^{3,4} uniformity compensation is required in either the pixel or driver circuitry. Most solutions incorporate three, four, or more TFTs within each pixel. This significantly diminishes the aperture ratio in displays employing conventional bottom-emitting OLEDs, forcing the OLEDs to operate at a higher luminance level, reducing lifetime.^{2,5} One solution to maintain a larger aperture ratio is to build top-emitting OLEDs (TOLEDs)^{6–8} over a planarized backplane. However, to date TOLEDs have demonstrated less efficiency than their bottom-emitting counterparts, so that to justify using TOLEDs in an active-matrix OLED display, the gain in aperture ratio must be large enough to offset any efficiency loss. In this letter, we demonstrate both theoretically and experimentally that TOLEDs can be more efficient than corresponding OLEDs.

In a conventional 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.⁹ The fraction of internally generated photons that are emitted externally is determined by the *relative* decay rates into the external and waveguiding modes as represented by the relationship between the internal and external quantum efficiencies (η_{EL}^{int} and η_{EL}^{ext} , both are photon/electron):

$$\eta_{EL}^{ext} = \eta_{EL}^{int} (W_{ext}/W_R) = \eta_{EL}^{int} [1 - (W_{sub} + W_{IO})/W_R] \quad (1)$$

where W_R , the total radiative decay rate, is the sum of the decay rates into the external, substrate waveguided, and ITO/organic waveguided modes, W_{ext} , W_{sub} , and W_{IO} .

One way to increase the outcoupling is to insert a low index-of-refraction aerogel layer ($t=50\text{ }\mu\text{m}$, $n\sim 1.03$) between the ITO and the glass substrate [Fig. 1(a)].¹⁰ In a conventional OLED, there is a high density of waveguiding modes in the glass substrate due to its thickness. After insertion of the aerogel layer, these modes no longer exist because of the total internal reflection at the ITO/aerogel interface. Instead, all waveguiding modes exist in the thin ITO/organic layers that have a very low mode density. According to quantum mechanics, the emitted photon must be in one of the allowed cavity modes, so a low mode density corresponds to a low decay rate.¹¹ W_{ext} , which remains unchanged, now represents a much greater portion of W_R , resulting in a large enhancement in η_{EL}^{ext} [Eq. (1)].¹² An increase in external emission by a factor of 1.8 from insertion of the aerogel layer was reported.¹⁰ The optical microcavity structure (as manifested in the refractive indices) of the OLED with the aerogel layer is compared side by side with that of a TOLED in Fig. 1(b). The microcavity of the OLED terminates in the aerogel layer due to its thickness and porosity. We find that the optical microcavity structure of the OLED is replicated in the TOLED, the optical density of the thin metal layer in the TOLED cathode and the difference between the refractive indices of air and aerogel being negligible. We therefore expect the same suppression of the waveguiding modes in TOLEDs as in OLEDs with aerogel layers, so that TOLEDs *can* be more efficient than the equivalent bottom-emitting OLEDs on glass substrates.

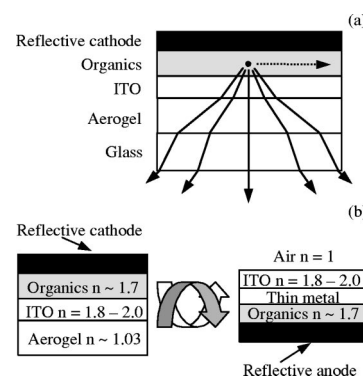


FIG. 1. (a) Light emission in an OLED on aerogel/glass substrate. The waveguided modes (dashed line) in the ITO/organic layer are suppressed (adapted from Ref. 10). (b) Comparison of the OLED in part (a) with a TOLED: neglecting the thin metal film in TOLED and the difference between the refractive indices of aerogel and air, the two structures are identical.

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To verify these theoretical predictions, TOLEDs were fabricated using two different anode/cathode combinations. In the first set of experiments, anodes consisting of a reflective metal over-coated by a thin Ni layer were deposited by *e*-beam evaporation onto glass substrates. The TOLEDs were defined by 5 mm² square openings in a layer of photoresist. The material system used throughout this letter was one based on 4,4'-N,N'-dicarbazole-biphenyl (CBP) doped with *fac* tris(2-phenylpyridine) iridium [Ir(ppy)₃] that had demonstrated high efficiency and stability.^{2,13} The TOLEDs were fabricated by sequentially depositing layers of copper phthalocyanine (CuPc, 200 Å) as the hole injection layer, 4,4'-bis[N-(1-naphthyl)-N-phenyl-amino] biphenyl (α -NPD, 300 Å) as the hole transport layer, 300 Å CBP doped with 6 wt % of Ir(ppy)₃ as the emitting layer, aluminum(III) bis(2-methyl-8-quinolino)4-phenylphenolate (BALq, 100 Å) as the hole blocking layer, and tris-(8-hydroxyquinoline) aluminum (Alq₃, 400 Å) as the electron transport layer. These devices were fabricated by conventional vacuum thermal deposition. During organic deposition, the chamber pressure was less than 5×10^{-7} Torr and the deposition rates were nominally 1–3 Å/s. The transparent compound cathodes in the first set of TOLEDs consisted of a 100 Å layer of Mg:Ag (25:1 by weight) and an overlaying ITO layer.⁶ The second set of TOLEDs consisted of Ag/ITO (160 Å) anodes, the same organic layers and Ca (200 Å)/ITO (800 Å) transparent compound cathodes.¹⁴ The TOLEDs were encapsulated with a 1.1 mm soda lime cover glass.¹⁵ Equivalent bottom-emitting OLEDs of the structure soda lime glass/ITO(1300 Å)/CuPc (100 Å)/NPD (300 Å)/CBP:Ir(ppy)₃ (6% wt, 300 Å)/BALq (100 Å)/Alq₃ (400 Å)/LiF (10 Å)/Al similar to that reported previously¹³ were fabricated for comparison. 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, and the *J*–*V*–*L* characteristics were measured with a Keithley 236 source measure unit and a calibrated Si photodiode.

It is well known that the emission characteristics of OLEDs can be accurately described by a model based on wave interference in multilayer thin films.¹⁶ Previous work to improve device performance has concentrated on optimizing the organic layer thickness which is the easiest parameter to adjust in the bottom-emitting structure.¹⁷ The TOLEDs and OLEDs share the same organic layers which were optimized for high efficiency and long lifetime in the bottom-emitting structure. In the TOLED, the dominant reflective interface on the cathode side is not the organic/cathode interface but the ITO/air interface that has a larger refractive index mismatch [Fig. 1(b)]. It follows that microcavity effects in TOLEDs are highly sensitive to the top ITO layer thickness giving them additional design flexibility. The luminance efficiency (η_{LE}) in the normal direction as a function of the top ITO layer thickness in the first set of TOLEDs is examined in Fig. 2. The experimental data show a peak η_{LE} of 19 cd/A at a drive current density of 10 mA/cm² at an ITO thickness of 800 Å. At an ITO thickness of 480 Å, η_{LE} falls 21% to 15 cd/A; and at an ITO thickness of 1120 Å η_{LE} falls 37% to 12 cd/A. The absorption of ITO in this thickness range differs by $\sim 1\%$; therefore, the difference in efficiency

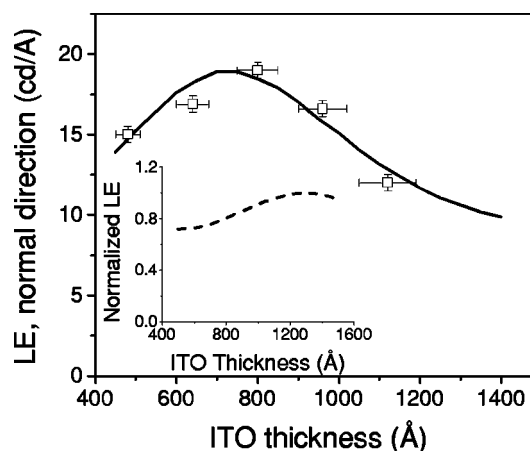


FIG. 2. Comparison of measured and calculated luminance efficiency in the normal direction vs thickness of the ITO layer in TOLED cathode. The TOLED structure is reflective metal/thin Ni/CuPc/NPD/CBP:Ir(ppy)₃/BALq/Alq/Mg:Ag/ITO. The TOLED model results (solid line) were scaled to give the best fit to the data (squares) which were taken at $J = 10$ mA/cm². Inset: normalized luminance efficiency vs ITO layer thickness in the OLED anode [glass/ITO/CuPc/NPD/CBP:Ir(ppy)₃/BALq/Alq/LiF/Al].

is due entirely to microcavity effects. These large variations demonstrate the importance of optimizing the top ITO layer in TOLEDs. The model result was scaled to give the best fit to the experimental data and the agreement was excellent (Fig. 2). The inset of Fig. 2 shows how the luminance efficiency of the OLED varies with the thickness of the ITO layer in the anode. There is a clear peak at 1300 Å, but the peak-to-trough variation is smaller than that in TOLEDs which is a consequence of the smaller index mismatch between ITO and glass.

Ignoring the difference in injection barriers of various cathodes/anodes, one expects the highest device efficiency to be achieved with a highly reflective anode and a highly transparent cathode. To this end, we fabricated TOLEDs with Ag/ITO (160 Å) anodes and Ca (200 Å)/ITO (800 Å) cathodes. The transmissivities of glass/Mg:Ag (100 Å)/ITO (800 Å) and glass/Ca (200 Å)/ITO (800 Å) are 54.9% and 62.8% at $\lambda = 515$ nm [$\sim$ the peak of Ir(ppy)₃ emission], respectively. They are much less than the transmissivity of 89.9% for commercial ITO (1300 Å) coated glass (Applied Films Co., Boulder, CO) at the same wavelength. The reflectivities of the reflective metal/thin Ni and Ag/ITO anodes for TOLEDs are 60.2% and 85.5% at $\lambda = 515$ nm, respectively, while that of the Al cathodes for OLEDs is 88.5%. Overall, the OLEDs have a sizable advantage over the TOLEDs in terms of the transmissivity/reflectivity of the electrodes. The *J*–*V*–*L* characteristic of the TOLED with an Ag/ITO anode and a Ca/ITO cathode is compared with that of an OLED with the same organic layers, ITO anode and LiF/Al cathode¹³ in Fig. 3. The *J*–*V* curves are identical within measurement uncertainties, while the TOLED has slightly higher luminance efficiency. The OLED and TOLED reach 100 cd/m² at 5.9 and 6.0 V, respectively. At 10 mA/cm² the luminance is 2030 cd/m² for the OLED and 2310 cd/m² for the TOLED (through the cover glass), i.e., 15% higher. While the Ca/ITO cathode needs to be further characterized, the identity of the two *J*–*V* curves provides phenomenological evidence that the difference in luminance originates from

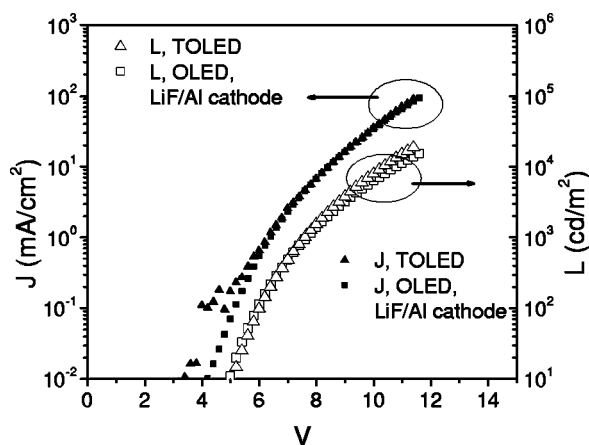


FIG. 3. J - V - L curve of a TOLED [Ag/ITO/CuPc/NPD/CBP:Ir(ppy)₃/BAlq/Alq/Ca/ITO, triangles] compared with an OLED with a LiF/Al cathode [glass/ITO/CuPc/NPD/CBP:Ir(ppy)₃/BAlq/Alq/LiF/Al, squares].

microcavity effects rather than improved charge injection or carrier balance.

The most unequivocal data indicating that the TOLED is more efficient than the corresponding OLED is from a direct measurement of the far-field photon radiation. Due to the relative size of the devices and the focal spot (1°) of the PR705 spectrophotometer this measurement could be carried out reliably only up to a far-field angle of 60° from normal. Figure 4 shows the angular dependence of photon radiation for a TOLED (through the 1.1 mm soda lime cover glass), the same TOLED corrected for the effect of the cover glass,¹⁸ and a corresponding OLED. There is only a weak angular dependence which indicates that the emission profiles are approximately Lambertian in this angular range. Estimating the integrated photon flux by the formula $\sum I(\theta)\sin(\theta)\Delta\theta$, $\theta=0, 15, \dots, 60^\circ$, where $I(\theta)$ is the photon radiation at angle θ , the uncorrected and corrected TOLED are found to emit 4.2% and 20.8% more photons than the OLED in the forward 120° cone, respectively.¹⁹

The inset of Fig. 4 shows the Commission Internationale de l'Eclairage (CIE) coordinates of the emission color of the TOLED and OLED as a function of the far-field angle. The color of the OLED is constant while the TOLED shows a drop in the CIE x coordinate with increasing viewing angle, corresponding to a small blue-shift in the spectrum. This is not expected to be a problem in display applications.

In conclusion, we presented arguments based on a microcavity theory that TOLEDs can be more efficient than the corresponding OLEDs. The thickness of the top ITO was identified as a key parameter for optimization. Finally, we confirmed our theoretical predictions by fabricating highly efficient TOLEDs based on Ag/ITO anodes and Ca/ITO cathodes that emit 20.8% more photons in the forward 120° cone than corresponding OLEDs. 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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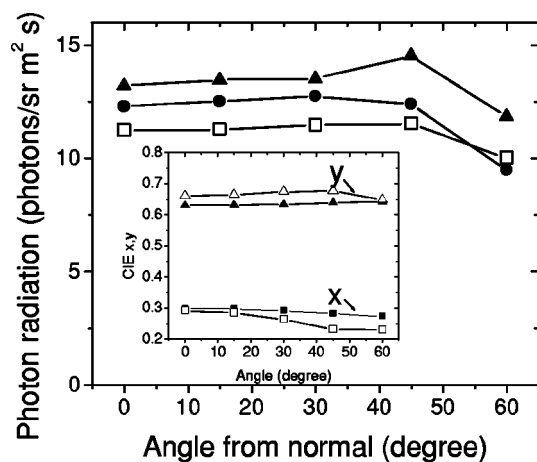


FIG. 4. Photon radiation vs far-field angle. Open squares: OLED with LiF/Al cathode; solid circles: TOLED [Ag/ITO/CuPc/NPD/CBP:Ir(ppy)₃/BAlq/Alq/Ca/ITO] through the cover glass; solid triangles: the same TOLED corrected for the effect of the cover glass. Inset: CIE coordinates vs far-field angle. Open squares and triangles: CIE x and y for the OLED; solid squares and triangles: CIE x and y for the TOLED through the cover glass. All data were taken at $J = 10$ mA/cm².

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- ¹⁸The correction factor is arrived at by comparing the measured emission from a similar TOLED with and without the cover glass.
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