Flexible Transparent Organic Light-Emitting Diodes with Suppressed Waveguide Modes

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Abstract

We developed high efficiency transparent organic light-emitting diodes (TOLEDs) with ultrathin metal electrodes. The modal calculation showed that our TOLED does not support waveguide mode, leading to potentially trapped-energy free device. This high efficiency TOLEDs do not require complex modal outcoupler but only high-quality metal thin film.

Author Keywords

OLEDs; transparent OLEDs; flexible OLEDs; thin metal films; FTCs; high transmittance; antireflection coatings.

1. Objective and Background

There has been growing interest in transparent and flexible displays in the market recently. Organic light-emitting diodes (OLEDs) are great candidates for future transparent/flexible displays since organic semiconductors are transparent in visible wavelength region, intrinsically flexible, cost-effective, and easy to process (1).

Finding an appropriate conductor that is highly transmissive and flexible with low sheet resistance (R_{sh}) is one of the most important aspects for high performance transparent OLEDs (TOLEDs). Indium tin oxide (ITO) is widely used in the conventional TOLEDs due to its high transparency and simple fabrication. However, conventional TOLEDs made with oxide-based electrodes such as ITO or indium zinc oxide (IZO) require sputtering process, which easily damages underlying organic molecules and impact device performances (2, 3). Additionally, from optics perspective, ITO-based TOLEDs trap significant amount of light inside the device in the form of waveguide mode, leading to poor device performances (4). This light trapping issue becomes more severe when ITO or IZO becomes thicker to ensure low R_{sh}. Therefore, it is necessary to develop highly transparent and flexible conductors, which are conductive and also reduce the amount of light trapping.

In this work, we conducted systematic modal analysis of TOLEDs and showed that the trapped light can be completely liberated by using ultrathin metal electrodes for both anode and cathode. The TOLEDs in this work were fabricated without sputtering process for the top electrode, which helped avoid potential material damage that frequently occurs in the top ITO based TOLEDs. Due to the intrinsically low R_{sh} of metal, our TOLEDs showed very conductive current – voltage characteristics even at an ultrathin thickness of electrode. The absence of metal oxide-based material in TOLEDs helped achieve high flexibility and transparency at the same time. This work shows that ultrathin metal-based electrodes are good candidates for future transparent/flexible displays.

2. Results and Discussion

Theoretical modal analysis of waveguide: Generated light in OLEDs excites several waveguide modes, and thicker the organic stacks the greater number of the guided modes (5). Organic layer used in conventional TOLEDs create two waveguide modes, fundamental transverse magnetic (TM_0) and electric (TE_0) modes. Effective index of such waveguide mode (n_{eff}) was calculated to analyze its behaviors in TOLEDs. The waveguide mode with lower n_{eff} is more loosely guided in a device, and the formation of the mode is eventually suppressed when n_{eff} is smaller than refractive index of the glass substrate with n_{glass} = 1.5. Figure 1 shows the cutoff condition of the organic layer thickness ($t_{organic}$) for each mode.

Figure 1a and 1b shows n_{eff} of TM_0 and TE_0 modes, respectively. Ag alloy used for this calculation is Cu-seeded Ag film (7 nm Ag deposited on 1 nm Cu seed layer, R_{sh} = 13.5 Ω/sq.). Extremely small refractive index of Ag reduces the effective refractive index of waveguide core and reduces modal confinement of the waveguide mode. The cutoff thickness of the organic stack is 130 for 8 nm Ag alloy, i.e. the TM_0 mode cannot be excited up to $t_{organic}$ = 130 nm in TOLEDs with 8 nm Ag alloy as electrodes. The TE_0 mode, which has smaller n_{eff} than TM_0, shows wider range of $t_{organic}$ for modal cutoff, meaning that TE_0 mode also disappears when TM_0 mode does not exist in a device. For traditional ITO based devices, however, even at $t_{organic}$ = 0, both waveguide modes still exist, resulting in large energy waste.

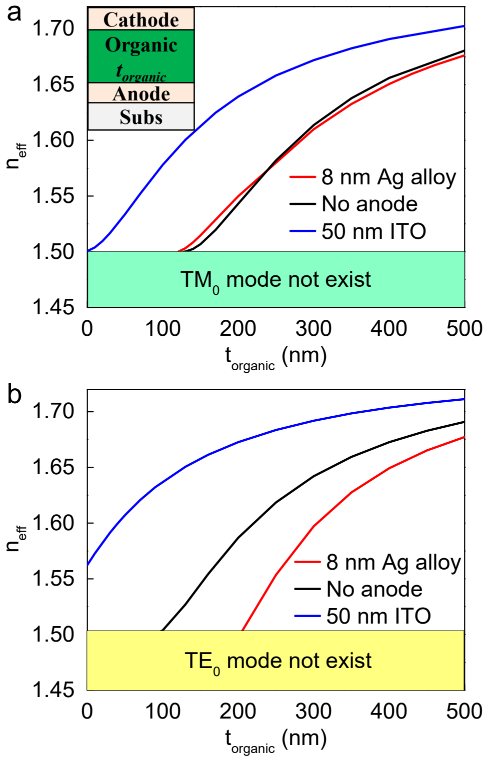

Figure 1. Calculated effective indices of (a) TM_0 and (b) TE_0 modes as functions of organic layer thickness. The inset shows a waveguide used for calculation. Anode and cathode are either 50 nm ITO or Ag alloy. Ag alloy film increases the cutoff thickness, indicating that the Ag film suppresses formation of the waveguide mode.

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Power distribution in TOLED: Power distribution to each mode in TOLEDs with ITO or thin metal electrode is shown in Fig. 2. The calculated structure is anode (ITO or Ag alloy) / 5 nm MoO_3 / 40 nm TAPC / 20 nm EML / 50 nm TPBi / cathode (ITO or Ag alloy), where EML was assumed to be CBP neat layer for the calculation.

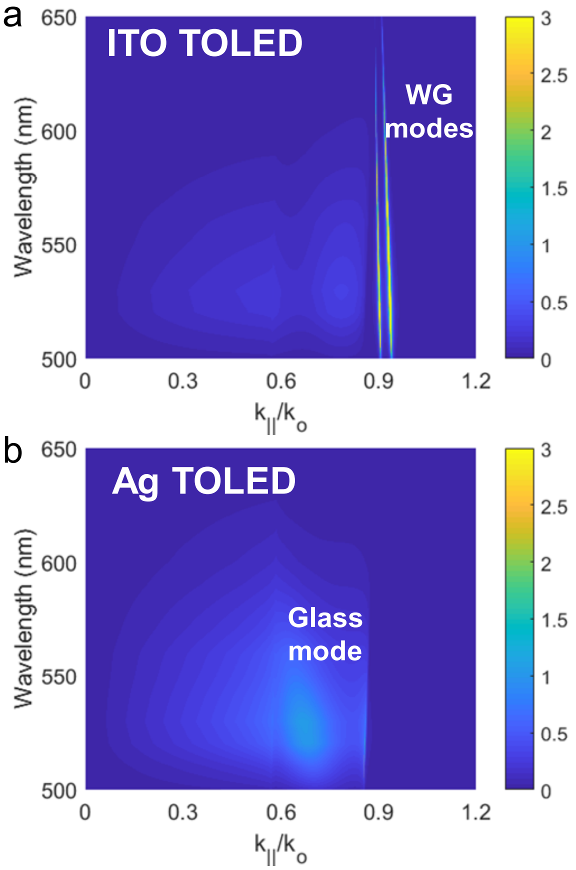

Figure 2. Spectral power distributions of TOLEDs based on (a) ITO and (b) Ag alloy. Power distribution in the form of waveguide (WG) and glass modes are denoted in the figures. Two strong waveguide modes are observed in the ITO TOLED, but not in the Ag alloy based TOLED. $k_{||}$ and k_o are the wavenumbers in horizontal direction and of the EML, respectively.

Figure 2 shows that power distribution of the substrate mode portion significantly increased in the Ag TOLED, whereas the ITO TOLED has large waveguide mode portion. Both TM_0 and TE_0 modes are excited in the ITO device but do not exist in the Ag TOLED. The Ag TOLED showed higher power in the glass mode as compared to the ITO device. The suppression of the two guided modes in the Ag alloy TOLED could lead to higher external quantum efficiency (EQE) than the ITO counterpart by extracting the glass mode from microlens array or index matching media.

Transmittance of cathode and TOLED: The ultrathin Ag alloy film for the bottom electrode of TOLED was obtained by a 1 nm thick Cu seed layer, which makes sufficient nucleation sites to produce a smooth and continuous Ag film. The thin transparent metal cathode was obtained by 15 nm Al film. Relatively thicker Al was used to guarantee continuous film on organic molecules, which leads to relatively low transmittance as shown in Fig. 3 Interestingly, the transmittance of the entire TOLED stack is higher than the bare Al film. This is because the adjacent organic materials in OLED function as effective anti-reflective (AR) layer for the Al cathode.

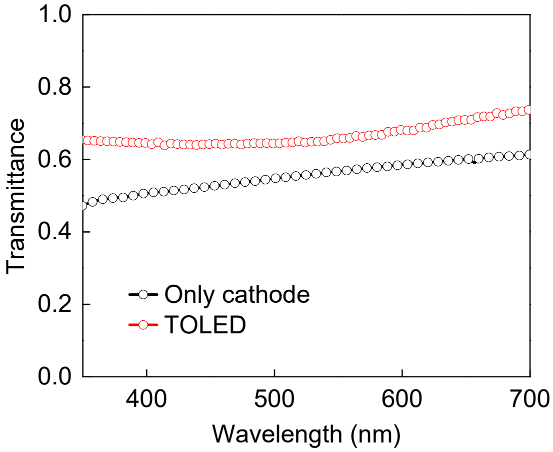

Figure 3. Measured transmittance of 15nm Al cathode and the complete TOLED. Organic materials adjacent to thin metal films act as AR coating, increasing transmittance of the device.

OLEDs performances: TOLEDs with ultrathin metal electrodes were fabricated. Figure 4a shows a device structure of the fabricated TOLEDs, which was made on a glass substrate. LiQ and MoO_3 are electron and hole injection layers, and TPBi and TAPC are electron and hole transporting layers. Emissive layer is CBP with 10% $Ir(ppy)_2acac$.

Figure 4b shows measured EQE versus current density characteristic. The bottom and top emissions were measured separately. The bottom Cu-Ag electrode is only 6 nm with smooth morphology made by the E-Beam evaporation, which leads to minimal optical loss. In contrast, the relatively thick Al for the top cathode has higher attenuation of emission to the top side, lowering EQE measured from the top. Since the deposited organic material has more coarse morphology compared to the commercial plane glass substrate, the top cathode requires thicker margin to form a continuous film, compared to the bottom electrode, which eventually lowers the top EQE of TOLED.

Figure 4c shows the measured current density—voltage characteristics of the TOLED. The electrical property of an TOLED does not change by replacing ITO with ultrathin metal films. The ultrathin Ag film has sheet resistance of less than 20 Ω/sq.. To achieve similar conductivity, ITO electrode will need to be much thicker, which not only traps more light but also severely affects the flexibility of the device. Overall, the results in this section showed that the ultrathin metal electrodes can lead to high performance TOLED due to waveguide mode suppression and suitability for flexible applications of TOLEDs.

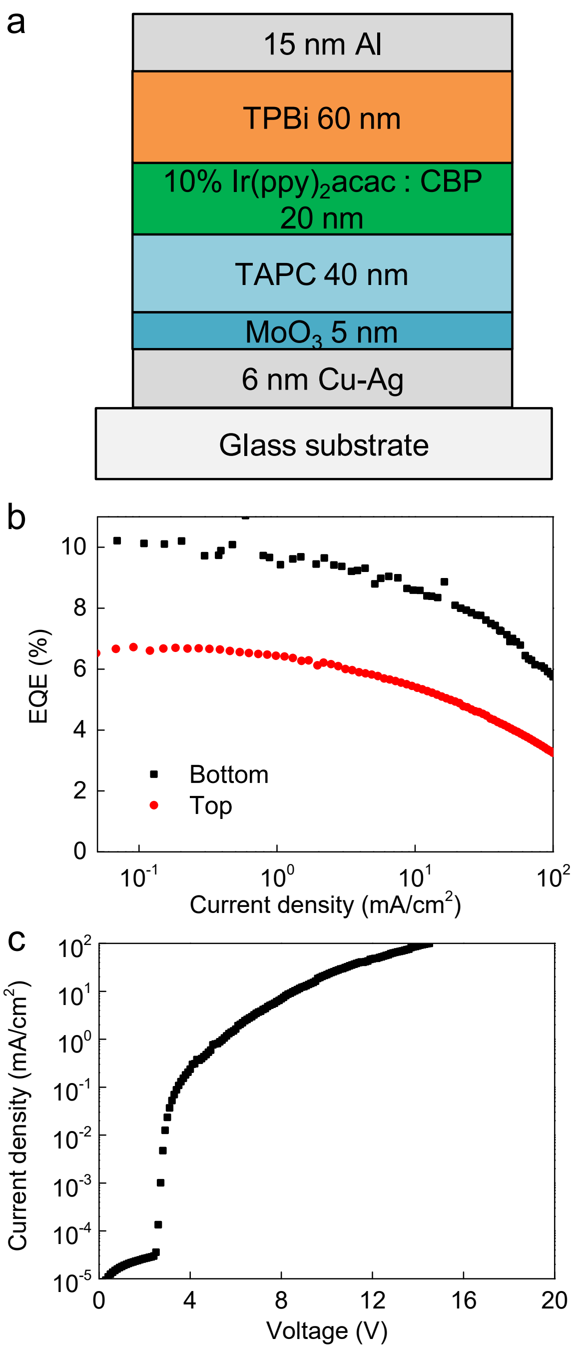

Figure 4. Device performances of Ag alloy based TOLED. (a) Device structure of OLEDs made in this work. (a) EQE – current density and (b) current density – voltage characteristics of Ag TOLEDs. Bottom and top electrodes are 6 nm Cu-Ag and 15 nm Al, respectively. Bottom and top emissions were measured separately.

Figure 5 show measured bottom and top emission spectra of the TOLED. The bottom emission is very similar to the one from pure emitter molecule, $Ir(ppy)_2acac$, and the top emission shows slight broadening. This difference is currently under further investigation.

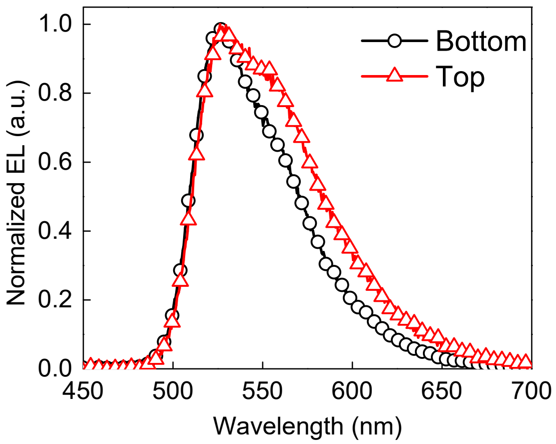

Figure 5. Measured spectra of Ag TOLED. Bottom and top side emissions were separately measured. Top emission has slightly broader spectrum compared to the bottom counterpart.

The bottom and top electrodes used in our TOLED investigated in this work are very thin and transparent. Figure 6 shows pictures of the fabricated TOLED in off and on states. In the off-state letters behind the TOLED sample is clearly visible. Figure 6b shows bright light illumination from the TOLED when it is turned on. An interesting feature observed in Fig. 6b is that the entire substrate is glowing when the device is on, indicating that the significant amount of light is in the glass mode, which is the consistent result with Fig. 2b.

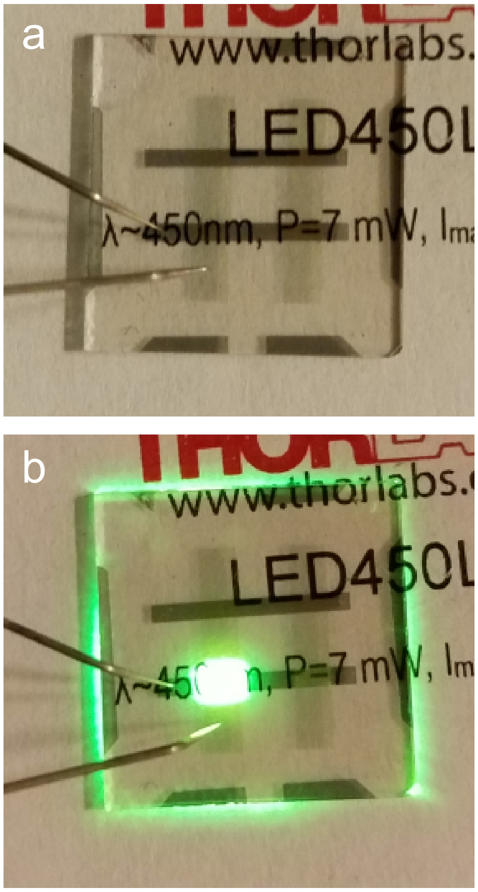

Figure 6. Picture of the fabricated Ag TOLED. Pictures of TOLED (a) at rest and (b) under operation. Strong light emission from top side is observable. The entire glass substrate is glowing due to large amount of light in the glass substrate.

3. Conclusion

Liberation of the trapped light is one of the biggest problems in TOLED since thick ITO electrodes capture significant amount of emission energy in the waveguide mode. Ultrathin metal electrodes can reduce the waveguide core thickness below the cutoff thickness thus effectively suppress the formation of the waveguide mode. The top metal electrode can be made by thermal evaporation for our TOLED, which does not generate damage on organic molecules during the deposition process, which is very challenging in ITO-based TOLEDs. We showed that TOLED has very high transmittance with the help of the AR effect. This flexible and high efficiency TOLED will be versatile in a variety of display applications.

4. Impact

Significant portion of light is trapped inside a device in conventional TOLED in the form of waveguide mode. This work shows that ultrathin metal electrodes can effectively suppress the primary guided modes and transfer the corresponding energy to the glass substrate, potentially achieving an OLED free from trapped energy in a device. The TOLED developed in this work can outcouple waveguide mode without introducing complex outcoupling structure to the device. Ultrathin metal electrodes in the TOLED can made by simple thermal evaporation technique, which does not damage organic molecules unlike ITO-based TOLEDs. The TOLED has high transparency and excellent flexibility, which can be a good candidate for high efficiency display products in industry.

5. Acknowledgements

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