Ultrathin Foldable Organic Light-Emitting Diodes with High Efficiency

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Abstract

We demonstrated ultrathin foldable organic light-emitting diodes (OLEDs) by using dielectric-metal-dielectric (DMD) electrode and polyvinyl alcohol (PVA) substrate. The DMD containing a thin metal layer suppresses waveguide mode formation and help efficiency improvement, and the spin-coated PVA film forms an ultrathin substrate for OLEDs ~ 1 μm.

Author Keywords

OLEDs; thin film electrodes; FTCs; high transmittance; flexible OLEDs; foldable OLEDs; PVA film.

1. Objective and Background

There has been a great deal of attention in flexible and foldable displays recently (1, 2). Organic light-emitting diodes (OLEDs) are promising light sources for such applications since organic molecules are cost effective, simple to process, and have intrinsic property of high flexibility, which is essential to impart bending and folding capability to the displays (3).

Our previous works showed that the ultrathin Ag alloy is highly flexible and can even enhance outcoupling efficiency of OLEDs by suppressing waveguide mode formation (4, 5). Ag alloy with two adjacent dielectric layers, called dielectric-metal-dielectric (DMD) electrode, is more widely used in many applications since DMD forms ultrasmooth surface and is compatible with the conventional OLED structure and fabrication processes (6-8).

Highly flexible OLEDs are achieved by replacing ITO with DMD along with extremely thin flexible substrate. Therefore, it is important to investigate optical property of OLEDs with DMD in terms of light outcoupling efficiency and its validity on ultrathin flexible substrate.

In this work, we conducted modal analysis of DMD based OLEDs and showed that DMD can suppress waveguide mode formation, similar to that using bare Ag alloy electrode, therefore enhancing device efficiency. Also, we showed that ultrathin PVA film supporting DMD OLEDs can help achieve ultrathin flexible OLEDs, reaching ~ 1 μm in total thickness, realizing foldable OLEDs. Extremely thin substrate is the key for highly flexible and foldable displays, and we demonstrated that our ultrathin OLEDs can be folded and still operate well.

2. Results and Discussion

Theoretical analysis for waveguide mode elimination: Figure 1a shows a schematic illustration of the DMD based OLED, which can be regarded as an optical waveguide. Organic layer was assumed to be 120 nm neat CBP layer. Two lowest order waveguide modes are transverse electric (TE_0) and magnetic (TM_1) modes. Here only the effective index (n_{eff}) of TE_0 is shown, while TM_1 mode cannot be supported under this condition. The waveguide mode reaches cutoff when n_{eff} becomes smaller the refractive index of the glass substrate, n_{glass} = 1.5. The significance of reaching waveguide cutoff is that emitted light in OLED is no longer trapped within the waveguide, leading to improved light extraction efficiency. Figure 1b shows that the thickness of the Cu-Ag in DMD at cutoff reduces with increased negative permittivity, indicating that metals with larger negative permittivity can effectively suppress waveguide mode formation at sub-10 nm thickness. However, ITO having much higher refractive index than n_{glass} increases modal confinement in the waveguide.

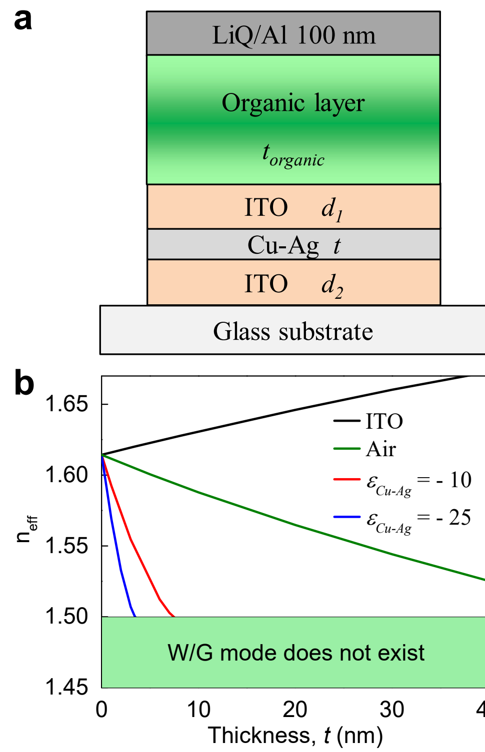

Figure 1. (a) Schematic illustration of a DMD OLED. (b) Effective index of TE_0 mode as a function of Cu-Ag thickness with varied refractive index. d_1 and d_2 are fixed to 40 nm. ITO or Air indicates ITO or air refractive index instead of Cu-Ag in DMD.

The typical organic layer thickness ($t_{organic}$) in OLEDs is less than 150 nm to ensure good electrical property and charge balance. We ensured the cutoff condition still allows sufficient $t_{organic}$ to make practical OLEDs with DMD. Figure 2 shows organic layer at cutoff conditions of TE_0 and TM_1 modes with varied d_1 and d_2 of DMD. 150 nm organic thickness is indicated by the traces with red circles in Fig. 2. As one can see, TM_1 mode has thicker organic cutoff since it is a higher order mode than TE_0 mode.

Considering the cutoff thickness shown in Fig. 2 and also electrical characteristics, we fabricated DMD with $d_1 = d_2 = 40$ nm in this work, which gives organic layer thickness of ~ 90 nm to reach waveguide cutoff condition. At this $t_{organic}$, only emitted light at the very short wavelength is slightly guided, whereas light at longer wavelength is not guided in DMD OLED and therefore can be extracted.

 ISSN 0097-996X/21/5201-0289-$1.00

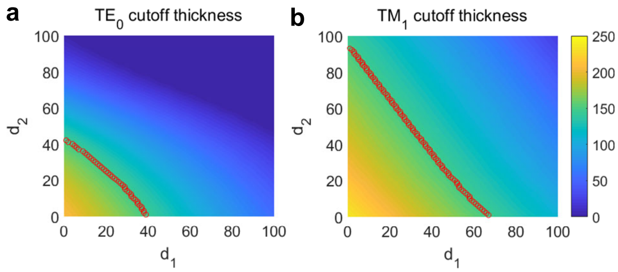

Figure 2. Cutoff organic thickness with varied top (d_1) and bottom (d_2) dielectrics of DMD for (a) TE_0 and (b) TM_1 modes. $t_{organic}$ = 150 nm is indicated with red circles.

Spectral power distribution in OLEDs: Spectral power distribution from dipole source in OLEDs with ITO and DMD as anodes was investigated and shown in Figs. 3a and 3b, respectively (9). The device structure for the calculation is the same as that in Fig. 1a, where the organic layer consists of 5 nm MoO_3 / 40 nm TAPC / 20 nm emissive layer (EML) / 50 nm TPBi. EML was assumed to be neat CBP layer. Both TE_0 and TM_1 modes are strongly confined along the entire wavelength range in the ITO based OLED, but the DMD device only supports these guided modes at short wavelength with little amount of power. As a result, the suppression of the waveguide modes in the DMD OLED can lead to higher external quantum efficiency (EQE) than the ITO device.

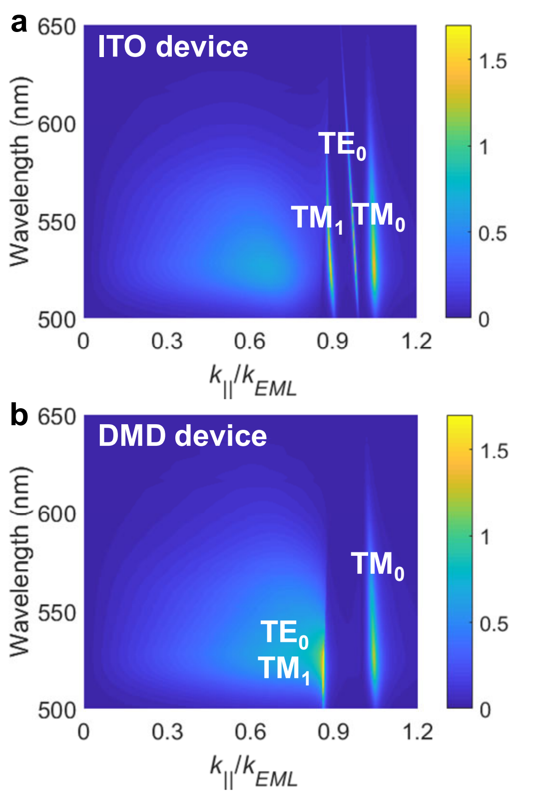

Figure 3. Spectral power distribution in (a) ITO and (b) DMD OLEDs. Each mode is denoted in the figures. $k_{||}$ and k_{EML} are wavenumbers in the propagating direction and in the transverse direction, respectively.

Electric or magnetic field profiles: We plotted electric or magnetic field profile of each mode in Fig. 4. Fields generated in ITO and DMD OLEDs are displayed in black and red curves, respectively. Figure 4a shows TM_0 mode, which is strongly confined at the metal interface in both devices. Figures 4b and 4c show TE_0 and TM_1 modes, which are dielectric mode and have larger field portion at the waveguide core region. One can see that the TE_0 and TM_1 modes are very loosely confined in the DMD OLED compared to the ITO device, which is consistent with Fig. 3.

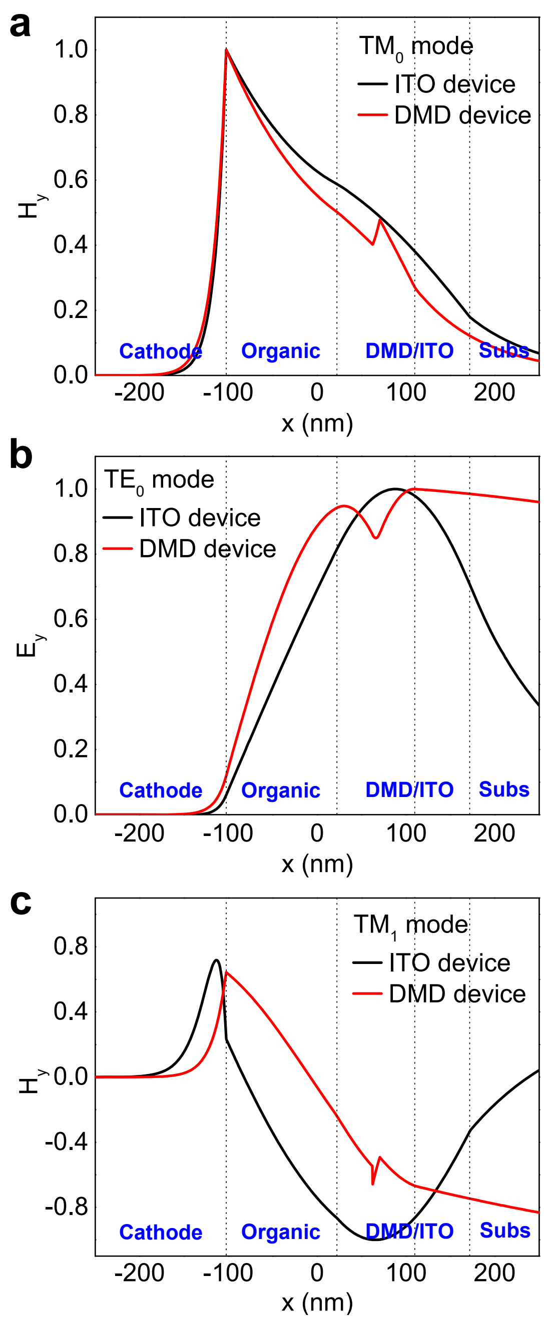

Figure 4. Electric or magnetic field profile of (a) TM_0, (b) TE_0, and (c) TM_1 modes in ITO and DMD OLEDs. TM_0 mode is plasmonic mode, and TE_0 and TM_1 modes are waveguide modes. Each field profile includes either ITO or DMD in each device.

Figure 5e shows fraction of light energy distributed in each mode. Around 15% of the energy was transferred to the waveguide mode and lost in the ITO device, whereas only small portion of the energy was transferred to waveguide mode in the DMD OLEDs due to modal cutoff and the corresponding suppressed waveguide mode energy increased energy fractions of other modes, especially the substrate mode.

It is essential to have low sheet resistance of an electrode for OLEDs and large area display applications. We compared DMD and ITO considering both waveguide mode portion and its sheet resistance. Figure 5b shows that DMD can achieve low sheet resistance and waveguide mode portion simultaneously.

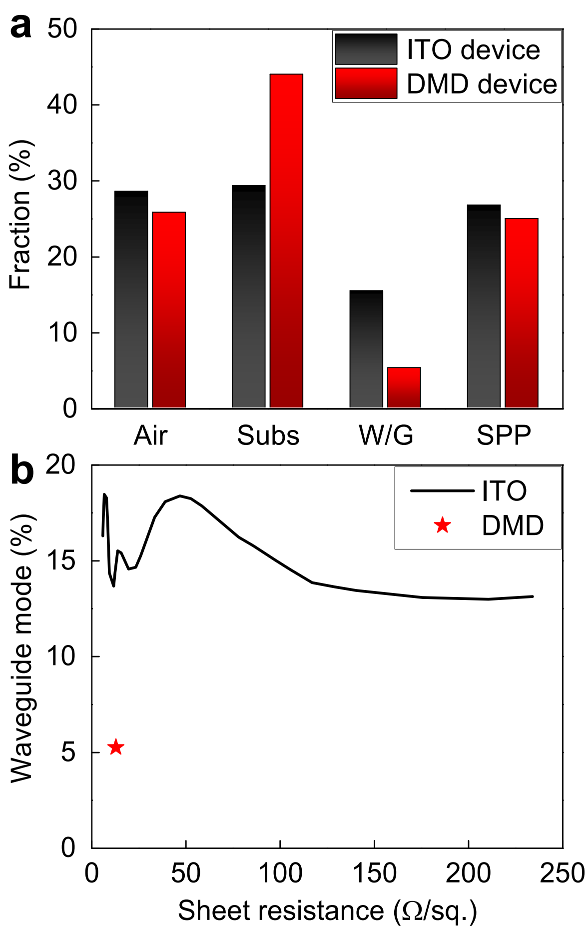

Figure 5. (a) Fraction of energy distributed to each mode in ITO and DMD OLEDs. (b) Relation between waveguide mode portion and sheet resistance of the electrode in ITO and DMD OLEDs, which was obtained by varying ITO thickness.

OLED performances: ITO and DMD OLEDs were fabricated based on the parameters given in the previous section. Figure 6a shows measured EQE – current density characteristics. The two devices showed very similar EQE without using any outcoupling methods. However, DMD based OLED showed larger improvement when the substrate mode was extracted by using index-matching fluid (IMF), which results from the removal of the guided mode within OELD layer. The efficiency enhancement shown in this figure was consistent with the calculation in Fig. 4, where DMD OLED has higher substrate mode portion due to waveguide mode suppression.

Measured current density – voltage characteristic plotted in Fig. 6b, which showed that the ITO and DMD OLEDs have almost the same electrical properties. Since dielectric layers adjacent to Ag alloy film act as an antireflective coating, the DMD OLED has very similar emission spectrum compared to the ITO OLED as shown in Fig. 6c.

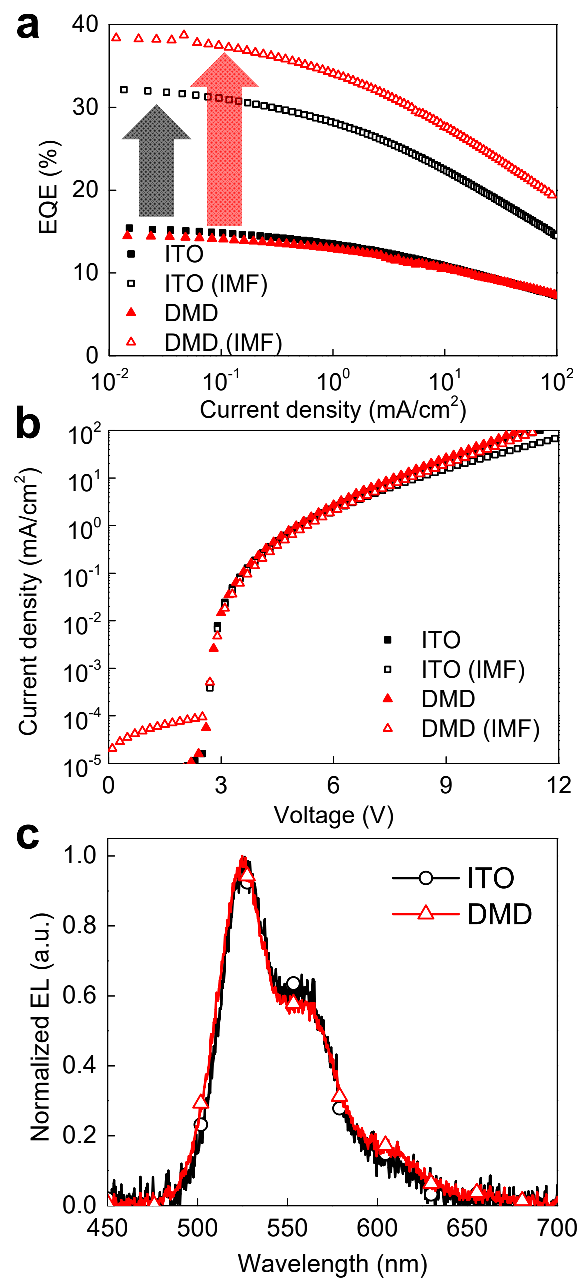

Figure 6. (a) EQE – *J* and (b) *J* – *V* characteristics of ITO and DMD OLEDs. IMF was used to extract the substrate mode. (c) Measured spectra of ITO and DMD OLEDs.

Figure 7 shows flexible DMD OLED made on a thin PVA substrate. Solution processed PVA substrate was first spin-coated on a Si substrate, then DMD electrode and organic layers were thermally deposited on PVA/Si substrate. Then, PVA substrate was detached from the Si substrate. The resulting DMD OLED on PVA film was ~ 20 μm and had good flexibility, and also emit strong green light as shown in Fig. 7b.

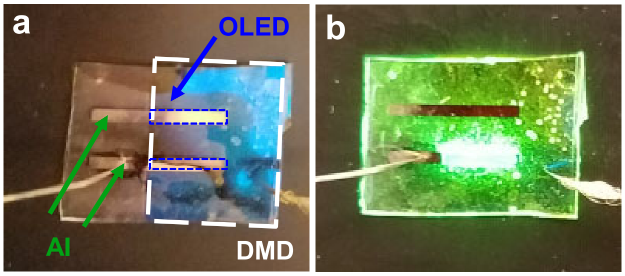

Figure 7. Flexible OLEDs on PVA substrate ~ 20 μm. Pictures of the detached flexible OLED (a) before and (b) after turn-on.

Thinner substrate enables smaller bending radius and even folding of the OLED. Ultrathin substrate can reduce rigidity and strain exerted on the device layers (10, 11). Figure 8 shows ultrathin DMD OLED made on ultrathin PVA substrate of ~ 1 μm thickness. Figure 8 shows that DMD based OLED on the ultrathin PVA substrate can even be bent along the razor blade. Importantly, the OLED can be completely folded as shown in Fig. 8. Figures 8b and 8c show that the folded DMD OLED still operates very well.

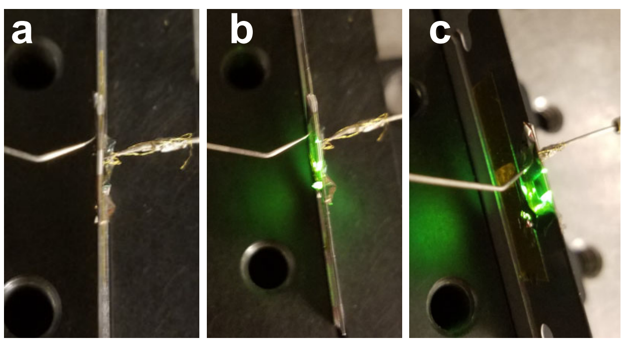

Figure 8. Pictures of foldable OLED (a) before and (b,c) after turn-on. Folded OLED illuminates strong light.

3. Conclusion

In this work, we conducted optical analysis of OLEDs with DMD electrode and showed that DMD can also suppress waveguide mode formation and enhance outcoupling efficiency of OLEDs. We showed that the high efficiency DMD OLEDs can be achieved on ultrathin flexible PVA substrate. We demonstrated ultrathin foldable OLEDs ~ 1 μm that operates very well even when it is bent around thin razor blade.

4. Impact

This work shows that the DMD electrode containing a Cu-Ag film can effectively suppress waveguide mode formation and enhance outcoupling efficiency. We made detachable ultrathin flexible and foldable OLEDs that can operate even when it is folded around very thin razor blade. This work may provide important insight to flexible display industry.

5. Acknowledgements

The authors thank to Zenithnano Inc. for the support and Lurie Nanofabrication Facility at the University of Michigan.

6. References

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