



Color temperature tuning of white organic light-emitting diodes via spatial control of micro-cavity effects based on thin metal strips



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ABSTRACT

White organic light-emitting diodes (WOLEDs) are one of the most promising technologies to realize future solid-state lighting with high power efficiency, broad and adjustable spectral coverage, and area emission for more effective and natural illumination. In this work, we report a new method of tuning the correlated color temperature (CCT) of WOLEDs via spatially controlling the degree of the micro-cavity effect in an OLED. Varying the width of thin Ag strips deposited on top of a transparent electrode leads to changes in both intensity and phase of reflection at the anode, hence significantly altering emission spectra of proposed WOLEDs. CCT of the implemented WOLEDs span a wide range, from 3000 K to 8000 K, demonstrating that our proposed approach helps to meet the need for lighting with various CCTs.

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1. Introduction

Organic light-emitting diodes (OLEDs), an emerging thin film light-emitting device which has been extensively studied recently, are primarily being adopted commercially in small-sized mobile displays, owing to their excellent dynamic contrast ratio and thin panel thickness. While conventional fluorescent tubes and market-pioneering white inorganic light-emitting diodes are currently holding most of the market share in the lighting industry, white OLEDs (WOLEDs) could be a very competitive candidate due to their unique advantages, including the freedom in tuning emission spectra by a wide selection of molecular emitters [1–4], more natural illumination quality arising from areal source emission instead of linear/point source emission, tunability in both angular emission profile [5–7], and color properties [8–10] that aid engineers to easily meet various needs for various lighting applications. It has also been shown that the emission color of OLEDs can be tuned dynamically, e.g. by application of an AC bias to an OLED with tandem device architecture [P.E. Burrows et al., Color-tunable organic light-emitting devices, Appl. Phys. Lett. 69

(1996) 2959; Z. Shen et al., Three-color, tunable, organic light-emitting devices, Science 276 (1997) 2009–2011; M. Fröbel et al., Get it white: color-tunable AC/DC OLEDs, Light: Sci. Appl. 4(2) (2015) e247]. The correlated color temperature (CCT), which is closely related to the relative amount of blue emission in white spectrum, is of special interest in designing WOLEDs with multiple reports [11–13] supporting significant physiological impacts of blue emission in lightings on human beings.

In this work, we report a method to control micro-cavity effects in WOLEDs by using a spatially patterned thin silver (Ag) layer on top of transparent indium tin oxide (ITO) electrode as the bottom anode. We have previously demonstrated that spatially patterned thin Ag layers can provide an effective way in both tuning the degree of micro-cavity resonance in green OLEDs without the need to carefully design the optical structures of devices, and also in decreasing sheet resistance of the ITO electrode owing to the excellent conductivity of the Ag layer [14]. While most of the previous works on cavity properties of OLEDs were performed by modifying the ‘vertical’ optical structure of stacks [15–18], our approach is more independent of the internal optical structures and is mostly governed by the simple ratio of Ag area covered on top of ITO electrodes. Here, we have adopted this strategy to blue phosphorescent OLEDs and to two-color WOLEDs, and finally to three-color WOLEDs, thus demonstrating the wide applicability of our

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approach and the possibility to easily tune the CCT of WOLEDs from warm white of 3000 K to cool white of 8000 K.

2. Experimental

A series of phosphorescent OLEDs based on *p-i-n* doped structures were fabricated with the following configuration [14,18]: ITO (90 nm)/striped Ag layer (20 nm)/*p*-layer/1,1-bis[(di-4-tolylamino)phenyl]cyclohexane (TAPC) (10 nm)/emissive layer (EML)/2-(diphenylphosphoryl)spirofluorene (SPPO1)/*n*-layer/Al(cathode, 100 nm), as shown in Fig. 1. For the *p*-type hole injection/transport layer, we used 30-nm-thick films of *N,N,N,N'*-tetrakis(4-methoxyphenyl)-benzidine (MeO-TPD) doped with 2 wt% of the Novaled dopant *p*-type 2 (NDP-2, Novaled AG, Dresden). For the *n*-type electron injection and transport layer, we used 40 nm of cesium (Cs)-doped bathophenanthroline (BPhen), with conductivity comparable to that of the *p*-layer. The 10-nm-thick layer of TAPC and the 10-nm-thick layer of SPPO1 were used as the electron and hole blocking layers, respectively, to confine charge carriers and excitons within the EML. For Group A (Blue OLEDs), the 10-nm thick blue EML consists of two host materials 4,4',4''-tris (*N*-carbazolyl)-triphenylamine (TCTA) (5 nm) and 2,6-bis(3-(carbazol-9-yl)phenyl)pyridine (26DCzPPy) (5 nm), doped with 7, and 10% of the phosphorescent emitter iridium(III) bis(4,6-(difluorophenyl)pyridinato-*N,C2'*)picolate (Flrpic), respectively. To fabricate white OLEDs (Group B: 2-color WOLED; and Group C: 3-color WOLED), an *x* nm thick red EML of 6 wt% bis(2-methyl-dibenzo-[f,h]quinoxaline) (acetylacetonate) iridium(III) (Ir(MDQ)₂(acac))-doped TCTA and a *y* nm thick orange EML of 6 wt% bis(2-(9,9-dihexylfluorenyl)-1-pyridine) (acetylacetonate) iridium(III) (Ir(dhfp_y)₂(acac))-doped TCTA were inserted between two blue EMLs. (Group B: (*x*, *y*)=(1.0, 0), Group C: (*x*, *y*)=(1.0, 1.0)), respectively.

An additional 20-nm-thick striped Ag layer was deposited on top of the ITO anode, which will be discussed in detail later. These Ag strips might result in visual non-uniformity especially when observers are in close proximity: however, for practical lighting applications, this issue might not be a significant problem since the visual acuity (i.e. spatial resolution) limit of the human eye does not allow observers to distinguish a 0.35 mm-wide line pair at a distance of 1 m as we described previously [14].

The overall active area of a single OLED device was 6.7 mm². All OLEDs were fabricated by thermal evaporation of the different materials onto ITO-coated structured glass substrates in an ultra-high vacuum (UHV) chamber (Kurt J. Lesker Co.) at a base pressure of approximately 10⁻⁷ mbar. The devices were encapsulated immediately after preparation under nitrogen atmosphere using epoxy glue and glass lids. For OLED characterization, we utilized a source measure unit (Keithley 2400) to obtain current–voltage data, while a spectrometer (INSTRUMENT SYSTEMS GmbH CAS140) and a calibrated silicon photodiode (Hamamatsu) were used to simultaneously measure the luminance and spectral radiant intensity in the forward direction.

3. Results and discussion

Fig. 1(a) shows the full device structure of the Group A blue phosphorescent OLEDs, the Group B 2-color system and the Group C 3-color system WOLEDs studied in this work. All three configurations share the identical *p-i-n* structure with *p*-doped hole transport layers and *n*-doped electron transport layers for reduced driving voltage. The Group A blue OLED has a double emission layer for reduced roll-off. The emission layers of the Group B 2-color system WOLED and the Group C 3-color system WOLED incorporate ultrathin (1 nm) red/orange emission layers in

between the blue double emission layers to achieve combined white emission [19]. Each group has 4 different device configurations – devices without any Ag covering the ITO anode (labeled as A1, B1 and C1), devices with 20 nm-thick Ag stripes that are 100 μm-wide and have 200 μm spacing in between (A2, B2 and C2), devices with 20 nm-thick Ag strips that are 200 μm-wide with 200 μm spacing in between (A3, B3 and C3), and devices with 20 nm-thick Ag fully covering the ITO anode (A4, B4 and D4) as shown in Fig. 1(b). Ag strips were directly deposited onto ITO and patterned through shadow masks. The areal ratio of the Ag strips directly affected the overall transmittance and reflectance of the anode, thus changing the device properties. Fabricated devices were analyzed individually to obtain current density–voltage–luminance (*J-V-L*) graphs, and the data for Groups A, B and C are plotted in Fig. 2(a–c), respectively.

The *J-V* curves show that devices in the same group exhibit similar current densities at the same voltage, indicating that the hole transport layers doped with the NDP2 dopant successfully established ohmic contacts to both ITO and Ag [20], which allows us to attribute any difference in the characteristics of the different devices to optical effects. Forward luminance and current efficiency values of all devices were measured at a driving voltage of 5.5 V or at a current density of 3 mA/cm² as summarized in Table 1. Hence, differences in the luminance values in forward direction directly resulted in different current efficacies as shown in Fig. 3.

Without the Ag layer, a current efficacy of 18.5 cd/A was observed at a driving current of 10 mA/cm² for device A1, and 18.6 cd/A for A2, 18.2 cd/A for A3, 17.2 cd/A for A4 as the areal ratio of the 20 nm-thick Ag layer increased from 0 to 1/3 (A2), 1/2 (A3) and 1 (A4). This slight change in current efficacy from device A1 to A4 is not only due to change in emission intensity itself but also due to change in emission spectrum, which will be discussed in detail later. For the 2-color WOLEDs in Group B and the 3-color WOLEDs in Group C, this change is more severe: Devices B1 and C1, which have no Ag layer, exhibited efficacies of 20.0 cd/A and 21.3 cd/A. A gradual increase in the area of the Ag layer lead to efficacies of 17.6 cd/A (B2), 16.9 cd/A (B3), 12.7 cd/A (B4), and 19.5 cd/A (C2), 18.6 cd/A (C3), 12.2 cd/A (C4). The fact that the current efficacy decreases despite the increasing micro-cavity effect (owing to the Ag layer) can only be understood by considering the change in the electroluminescence (EL) spectra, which are shown in Fig. 4.

The EL spectra of the devices under study were measured in forward direction at a fixed driving current of 1 mA. As shown in Fig. 4 (a), Device A1 exhibited a typical EL spectrum of Flrpic, with a dominant emission peak at 475 nm accompanied by a shoulder peak around 500 nm. As the area of the Ag layer increases, the cavity resonance wavelength placed near 490 nm raises the shoulder emission peak of Flrpic and increases the overall radiant intensity at the forward direction. Another factor to be noticed is that the higher cavity finesse due to increased reflectivity of the bottom electrode narrowed down the width of the EL spectra as well, leading to a reduced green component and hence decreased luminous intensity and current efficacy. The EL spectra of devices in Groups B and C with two-color and three-color system WOLEDs are shown in Fig. 4(b and c). The red and orange emission from the ultrathin emission layers with Ir(MDQ)₂(acac) and Ir(dhfp_y)₂(acac) dopants are clearly visible in Devices B1 and C1, with emission peaks located near 600 nm and 560 nm. The intense longer wavelength emission compared to the Flrpic emission results in relatively low CCTs (warm white) of 3130 K for Device B1 and 2980 K for device C1. As we increased the areal ratio of Ag layer in the same manner as for devices in Group A, a cavity modification almost identical to the one that occurred to Devices A1–A4 took place. This again leads to an increase in the Flrpic shoulder emission peak

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