Electrical and optical characteristics of phosphorescent organic light-emitting device with thin-codoped layer insertion

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ABSTRACT

In this paper, we demonstrated the changes of electrical and optical characteristics of a phosphorescent organic light-emitting device (OLED) with tris(phenylpyridine)iridium $Ir(ppy)_3$ thin layer (4 nm) slightly codoped (1%) inside the emitting layer (EML) close to the cathode side. Such a thin layer helped for electron injection and transport from the electron transporting layer into the EML, which reduced the driving voltage (0.40 V at 100 mA/cm^2). Electroluminescence (EL) spectral shift at different driving voltage was observed in our blue OLED with [(4,6-di-fluoropheny)-pyridinato-N,C$^{2'}$]picolinate (FIrpic) emitter, which came from the recombination zone shift. With the incorporation of thin-codoped $Ir(ppy)_3$, such EL spectral shift was almost undetectable (color coordinate shift (0.000, 0.001) from 100 to 10,000 cd/m^2), due to the compensation of $Ir(ppy)_3$ emission at low driving voltage. Such a methodology can be applied to a white OLED which stabilized the EL spectrum and the color coordinates ((0.012, 0.002) from 100 to 10,000 cd/m^2).

1. Introduction

Typically, the emitting layer of a phosphorescent organic light-emitting diode (OLED) consists of a phosphorescent dopant and a host material [1]. A phosphor dopant determines the emission wavelength. For example, [(4,6-di-fluoropheny)-pyridinato-N,C$^{2'}$]picolinate (FIrpic), tris(phenylpyridine)iridium $Ir(ppy)_3$, and tris(2-phenylquinoline-C2,N')iridium(III) $(Ir(2-phq)_3)$ are common phosphor for blue, green, and red emission, respectively [2]. In these materials, heavy metal (such as Ir, Pt, and Os) are needed to provide efficient spin-orbital coupling, which mixed the singlet and triplet state [3]. A basic requirement of the host material is the high triplet state, which did not quench the excitons emitted from dopant material. Efficient energy transfer from host to dopant material is preferred [4]. Due to the short range of Dexter energy transfer, dopant concentration in a phosphorescent OLED is higher than that in a fluorescent OLED [5]. Besides, it was also found that phosphors actually played certain role in electrical properties, such as carrier injection, transport, and trapping [6]. In some cases, even though the energy transfer was not efficient, dopant material can act as a carrier trap in a matrix for light emission [7]. And the

dopant material can be also used as a carrier transporter [8], which in turns changed the electrical characteristics, to lower the driving voltage and improve the charge balance for higher efficiency.

In this paper, we used an ultrathin (4 nm) and slightly-doped (1%) $Ir(ppy)_3$ partially doped inside the emitting layer (EML) at the interface with electron transporting layer (ETL) to facilitate the electron injection of a blue phosphorescent OLED, based on FIrpic as the dopant material [9]. Due to the better electron injection, driving voltage decreased. Electroluminescence (EL) spectra shifted under different driving voltages was observed, which came from the emission zone shifted from the cathode to anode side with higher driving voltage. With the insertion of the $Ir(ppy)_3$, such green emission can compensate EL shift which resulted in a stable spectra under different driving voltage. Such a methodology was also applied to a white phosphorescent OLED to stabilize EL spectral shift with different driving voltages.

2. Experiments

Our OLED was fabricated on glass substrates coated with indium-tin oxide (ITO) tin film, which was used as the anode. Before organic thin film deposition, ITO was treated by O_2 plasma to increase the workfunction, which facilitated hole injection and decreased the driving voltage. Then, the substrate was sent into a

vacuum chamber for organic and cathode stack by thermal deposition. Device encapsulation was done directly after thin film process inside the glove box with O_2 and H_2O less than 1 ppm. A cover glass was used with UV resin on the peripherals, which was assembled with device and cured by UV. Electrical and optical measurements were carried out by Keithley 2400 source meter and Minolta CS-1000, connected to a personnel computer and controlled by software. Different voltage was provided to the device and the current was recorded by the source meter. Simultaneously, the EL spectra was recorded. Hence, the luminance-current density-voltage (L–J–V) characteristics can be obtained.

Table 1 showed our OLED recipe. We use N,N′-diphenyl-N,N′-bis(1-napthyl)-1,1′-biphenyl-4,4′-diamine (NPB), N,N′-dicarbazolyl-3,5-benzene (mCP), and 3-(Biphenyl-4-yl)-5-(4-tert-butylphenyl)-4-phenyl-4H-1,2,4-triazole (TAZ) as the hole transporting layer (HTL), exciton blocking layer (EBL), and ETL, respectively, with the thickness of 50, 10, and 30 nm. LiF and Al with the thicknesses of 1.2 and 100 nm were used as the electron injection layer (EIL) and cathode. Blue phosphorescent OLED was used as our backbone with FIrpic emitter. In devices 1 and 2, host materials were hole-transporting mCP and electron-transporting TAZ, respectively. Fig. 1 showed the molecular structures and device architecture, together with the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels of the organic materials used in this study. To improve the charge balance, double EML (DEML) structure (mCP/TAZ) was employed in device 3. In device 4 and 5, a thin and light-doped Ir(ppy)$_3$ layer was co-doped in the EML close to the ETL with the thickness of 2 and 4 nm, respectively. Device 6 was a white OLED, based on device 3, with co-doped 7.5 nm Ir(2-phq)$_3$ (1%) inside the EML close to the EBL. Devices 7 and 8 are similar to device 5 with the insertion of 7.5 and 5 nm Ir(2-phq)$_3$, respectively.

For understanding electron injection and transport characteristics of CL and FIrpic doped in TAZ matrix, three electron only devices (EODs) were fabricated to exclude the effects of holes, excitons, and photons. The EOD structure was: Al (50 nm)/LiF (1.2 nm)/TAZ-1 (30 nm)/X (15 nm)/TAZ-2 (30 nm)/LiF (1.2 nm)/Al (100 nm). "X" represents: 1. TAZ, 2. TAZ:FIrpic (15%), and 3. TAZ:FIrpic (15 nm) with 4-nm light doped Ir(ppy)$_3$ inside TAZ:FIrpic and close to the TAZ-2 layer.

3. Results and discussions

3.1. Ir(ppy)$_3$ compensation layer in blue phosphorescent OLED

Fig. 2(a) showed the J-V characteristics of devices 1–5. Device performances were listed in Table 2. Compared the OLEDs with mCP, TAZ, and mCP/TAZ (devices 1, 2, and 3, respectively) as the EML hosts, one can see that the driving voltages was lowest (11.04 V at 100 mA/cm^2) for the DEML case (device 3), compared to single EML cases (11.05 V and 11.83 V at 100 mA/cm^2 for mCP- and TAZ-based OLED, corresponding to devices 1 and 2,
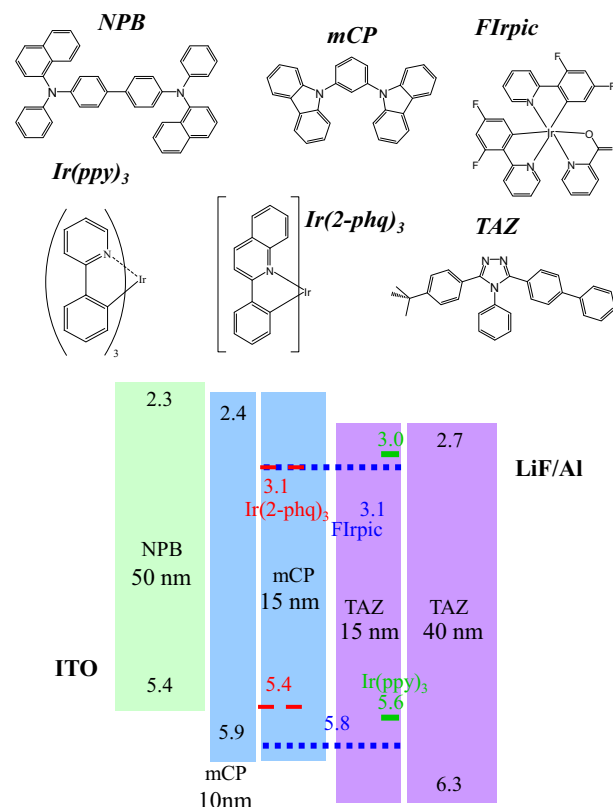

Fig. 1. Molecule structures and energy levels of organic materials.

respectively), due to better charge balance and the increase of the recombination current, which also resulted in higher current efficiency and external quantum efficiency (EQE) (as shown in Fig. 2(b) and (d), and Table 2) [10]. In devices 4 and 5, when inserting the compensation layer (CL), Ir(ppy)$_3$, in TAZ:FIrpic, the driving voltage decreased (10.92 V and 10.64 V at 100 mA/cm^2, respectively) compared to device 3 as shown in Table 2, although the layer was so thin (2 and 4 nm) and the dopant concentration was so low (1%). As shown in Fig. 3, J–V characteristics of EODs was used for understanding FIrpic and CL effects to electron injection and transport in TAZ host. For the pure TAZ case, the voltage at 100 mA/cm^2 was lowest (9.19 V). When FIrpic was added into the TAZ matrix, the voltage at 100 mA/cm^2 increased by 1.01 V to 10.20 V, because FIrpic acted as an electron trap in TAZ host and there were lots of electrons accumulating at the EML/ETL interface. It increased space charge density, impeded further electron injection, and hence increased the driving voltage [11]. When adding CL at this interface, the driving voltage at 100 mA/cm^2 decreased to 9.44 V. As shown in Fig. 1, LUMO value of Ir(ppy)$_3$ (3.0 eV)

Table 1
Layer structures of the OLED.

Device	HTL NPB	EBL mCP	EML (B: 15% FIrpic, G: 1% Ir(ppy)$_3$, R: 1% Ir(2-phq)$_3$)				ETL TAZ	EIL LiF	Cathode Al
1	50 nm	10 nm	B:mCP (30 nm)				30 nm	1.2 n	100 nm
2			B:TAZ (30 nm)						
3			B:mCP (15 nm)		B:TAZ (15 nm)				
4			B:mCP (15 nm)		B:TAZ (13 nm)	BG:TAZ (2 nm)			
5			B:mCP (15 nm)		B:TAZ (11 nm)	BG:TAZ (4 nm)			
6			BR:mCP (7.5 nm)	B:mCP (7.5 nm)	B:TAZ (15 nm)				
7			BR:mCP (7.5 nm)	B:mCP (7.5 nm)	B:TAZ (11 nm)	BG:TAZ (4 nm)			
8			BR:mCP (5 nm)	B:mCP (10 nm)	B:TAZ (11 nm)	BG:TAZ (4 nm)			