# Transient electroluminescence of white organic light-emitting diodes with blue phosphorescent and red fluorescent emissive layers

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## 1. Introduction

Organic semiconductors have attracted considerable attention due to their simple and low-cost processes and potential electronic and optoelectronic applications. Organic light-emitting diodes (OLEDs) utilizing fluorescent dyes or conducting polymers are capable of emission over a wide visible range, high efficient, and require only a low driving voltage. OLEDs have been realized which have a long lifetime and excellent durability for flat-panel display applications. There are some requirements of OLEDs for use not only in display applications but also as various light sources.

Employing phosphorescent materials exhibits high efficiencies because breaking the spin conservation rule indicates that both the singlet and triplet excitons contribute to emission. However, the response time of phosphorescent materials such as Ir complexes is slower than that of fluorescent ones due to their long emission lifetime.

In this study, we studied the transient characteristics of white OLEDs with blue phosphorescent and red fluorescent materials as the emissive layers by applying the voltage pulsed on the devices. Utilizing the different transient characteristics between the fluorescent materials and Ir complexes, emission color has been successfully tuned by varying the applied pulse width and frequency. We discussed the transient electroluminescence of OLEDs and the application of the white OLEDs that enabled to control the emission color by applying the various voltage pulses on devices.

## 2. Experimental

Figure 1 shows the two types of device structures used in this study. The substrate was degreased with solvents and cleaned in a UV ozone chamber. The typical device of device A consisted of an indium-tin-oxide (ITO) - coated glass substrate, 4,4'-bis[N-(1-napthyl)-N-phenyl-amino]biphenyl  $(\alpha$ -NPD) transporting hole layer, bis[(4,6-difluorophenyl)-pyridinato-N,C<sup>2'</sup>](picolinate) iridium(III) (FIrpic) doped in 4,4'-bis (9-carbazolyl)-2,2'-dimethyl-biphenyl (CDBP) phosphorescent emissive layer, bis(2-methyl-8-quinolinato)-4-(phenylphenolato)aluminum (BAlq) buffer layer, 4-(dicyanomethylene)-2-i-propyl-6-(1,1,7,7-tetramethyljulolidyl-9-enyl)-4*H*-pyran (DCJTI) doped in tris(8-hydroxyquinoline)aluminum (Alq<sub>3</sub>) fluorescent emissive layer and BAlq hole blocking layer, terminated with a 0.5 nm-thick lithium fluoride (LiF) and Al/Ag electrodes cathode. The doping concentrations of FIrpic and DCJTI were fixed at 5 vol% relative to the host of CDBP and Alq<sub>3</sub>, respectively. The device B consisted of Alq<sub>3</sub> with a DCJTI partial doping layer as a fluorescent emissive layer.

The layer structure was fabricated by organic molecular beam deposition on ITO-coated glass substrates to form the EL devices at a background pressure of about 10<sup>-5</sup> Pa. The organic materials were placed in separate Knuden cells, heated to their sublimation temperature, and subsequently deposited onto the substrate. The layer thickness of the deposited material was monitored in situ using an oscillating quartz thickness monitor. The cathode consisted of LiF (0.5 nm)/Al/Ag was deposited in vacuum at a chamber base pressure of about 10<sup>-4</sup> Pa. Finally, the device was covered with a glass plate and encapsulated by epoxy resin in an argon gas atmosphere to prevent oxidation of the cathode and the organic layer. The active area was 4 mm<sup>2</sup>.

The electroluminescent (EL) spectra were measured using a photonic multichannel spectral analyzer (Hamamatsu Photonics, PMA-11). The current density-voltage- luminance (J–V-L) characteristics were obtained using a 2000 multimeter (Keithley), a regulated DC power supply (Kenwood, PW36-1.5AD) and a luminance meter (Minolta, LS-100). The transient EL measurements were performed by applying square-wave voltage pulses generated by an HP8114A source (Agilent). The optical pulse was observed using a photomultiplier tube detector (Hamamatsu Photonics). The EL response and voltage were simultaneously digitized by a Sony Tektronix TDS3054 oscilloscope. All of the measurements were carried out at room temperature.



Fig. 1. Device structures used in this study.

#### 3. 3. Results and discussion

Figure 2 shows the typical EL spectra of the devices B with various thicknesses of  $\alpha$ -NPD layer related with a red

fluorescent emission. The EL spectra of devices with a DCJTI partial doping layer at the  $\alpha$ -NPD/Alq<sub>3</sub> interface was mostly attributed to the fluorescence of DCJTI. This result indicates excitons are confined within the narrow region of  $\alpha$ -NPD/Alq<sub>3</sub> interface. For the devices with X = 10 and 20 nm-thick  $\alpha$ -NPD layer, the red emission from DCJTI was mainly observed. While, the OLEDs with 3 and 5 nm-thick  $\alpha$ -NPD layer had higher blue emission base on FIrpic than those with 10 and 20 nm-thick  $\alpha$ -NPD layer. This is because the electron injection from the red emission layer to the blue emission layer of FIrpic was suppressed by increasing the thickness of  $\alpha$ -NPD layer.



Fig. 2. Typical EL spectra of the devices B with various thicknesses of  $\alpha$ -NPD layer related with red fluorescent emission.

The J–V-L characteristics for two types of devices are presented in Fig.3. The luminance increased significantly in the forward bias direction above a threshold voltage of approximately 4 V. The maximum luminances of more than  $6,000 \text{ cd/m}^2$  and  $20,000 \text{ cd/m}^2$  were obtained from device A and B, respectively. Device A exhibited the white emission with the Commission Internationale de L'Eclairage (CIE) coordinate of (0.33, 0.35) at applied voltage of 12V under the pulse width of 5 ms and frequency of 100 Hz. While, for device B, the CIE coordinate of (0.35, 0.43) was obtained due to the green emission from Alq<sub>3</sub> at applied voltage of 15V under the pulse width of 10 µs and frequency of 1 kHz.

The dye doping method is practically important because it is easy to improve their performance such as color tunability, efficiency and device lifetime. This method is also effective to obtain high-speed optical pulses from OLEDs. The fluorescence lifetime of the dye is one of the determining factors for generating the high-speed optical pulses. The response time of phosphorescent OLEDs is slower than that of fluorescent OLEDs due to their long emission lifetime. Figure 4 shows applied voltage dependence of the rise and decay times of OLEDs with FIrpic and DCJTI as an emissive dopant, respectively. The devices were driven at a 1 ms period and duty ratio of 1/100 pulse. The rise and decay times of red OLED with DCJTI as an emissive dopant were faster than that of blue OLED with FIrpic. For OLEDs, the rise time was slower than the decay time. The rise time of red OLED was almost ten times faster than that of blue OLED. Therefore, the EL spectra of both device A and B were red-shifted with increasing the frequency from 100 Hz and 100 kHz because the blue emission from FIrpic decreased for higher frequency due to the slower rise and decay times. Utilizing the different transient characteristics between Ir complex and the fluorescent material, emission color has been successfully tuned by varying the applied pulse width and frequency. For device A, the spectra were changed from white emission to red emission with the CIE coordinate of (0.6, 0.34) by varying the applied pulse width and frequency. For device B, the CIE coordinate of (0.46, 0.4) was obtained.



Fig. 3. J-V-L characteristics for two types of devices.



Fig. 4. Applied voltage dependence of the rise and decay times of OLEDs with FIrpic and DCJTI as an emissive dopant, respectively.

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