Enhancement of the luminous efficiency of organic light-emitting diodes utilizing a wide-bandgap impurity doped emitting layer

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Abstract

The electrical properties of organic light-emitting devices (OLEDs) with wide-bandgap impurity-doped emitting layers (EML) were investigated. While the luminous efficiency of OLEDs with a NPB or a DPVBi-doped Alq_3 EML did not vary significantly with the current density, that of the OLEDs with a BCP-doped Alq_3 EML changed dramatically.

1. Introduction

Potential applications of organic light-emitting devices (OLEDs) in promising next-generation flat-panel displays have driven extensive efforts to enhance lifetimes and efficiencies [1-2]. OLEDs have emerged as promising candidates for potential applications in the fabrication of full-color flat-panel displays with high efficiencies because they have the unique advantages of fast response, low power consumption, wide viewing angle, high contrast, and large flexibility [3, 4]. However, in comparison with other competitive displays, OLEDs have inherent problems, due to their relatively low efficiencies and short lifetimes, for applications. After an electroluminescent (EL) device using a single organic layer had been introduced, various kinds of the OLED structures were introduced to enhance the efficiencies of OLEDs. Among the various methods for improving the performance of OLEDs, smaller bandgap impurity doping and phosphorescence doping were powerful methods for enhancing device efficiency [5-7]. Even though some studies on the enhancement of the efficiency in OLEDs utilizing an emitting layer (EML) doped with smaller-bandgap impurities were performed [8, 9], systematic studies concerning the efficiency enhancement mechanism in OLEDs with an EML doped with larger-bandgap impurities have not been reported yet.

This communication reports data for the dependence of the electrical and the optical properties on the wide-bandgap impurity-doped EMLs in OLEDs. Current density-voltage, luminescence-voltage, luminescence efficiency-current density, and power efficiency-voltage measurements were carried out to investigate the electrical and the optical properties of OLEDs with a tris-(8-hydroxyquinoline) aluminum (Alq_3) emitting layer doped with *N*,*N*-bis-(1-naphthyl)-*N*,*N*-diphenyl-1,1-biphenyl-4,4-diamine (NPB), 4,4-bis(2,2diphenyl vinyl)-1,1-biphenyl (DPVBi), or 2,9-dimethyl-4,7diphenyl-1,10-phenanthroline (BCP) impurities. The luminescence mechanism and origin of the variation in the efficiencies of the OLED with EMLs doped with various wide-bandgap impurities are described on the basis of the experimental results.

2. Experimental

The sheet resistivity of the indium-tin-oxide (ITO) thin films on glass substrates used in this study was 30 Ω/square. The ITO substrates were cleaned by using sonication of acetone, methanol, and distilled water at 60°C for 15 min. The chemically cleaned ITO substrates were kept for 48 h in isopropyl alcohol. After the chemically cleaned ITO substrates had been dried by using N_2 gas with a purity of 99.9999%, the surfaces of the ITO substrates were treated with an oxygen plasma for 2 min at an O_2 pressure of approximately 2×10^{-2} Torr. The three kinds of OLEDs used in this study were fabricated on ITO thin films coated on glass substrates by using organic molecular beam deposition with effusion cells and shutters. The OLEDs consisted of the following structures from the top: an Al (100 nm) cathode electrode, a lithium quinolate (Liq) (2 nm) electron injection layer, an Alq_3 (30 nm) electron transport layer (ETL), an Alq_3 (30 nm) emitting layer (EML) doped with 1% DPVBi, 1% NPB, or 1% BCP [10, 11], a NPB (50 nm) hole transport layer (HTL), an ITO (100 nm) anode electrode, and a glass substrate. The Liq layer, acting as an electron injection layer, causes the driving voltage to decrease and the power efficiency to increase due to a decrease in the electron injection barrier height [12]. Schematic diagrams of the Al (100 nm)/Liq (2 nm)/Alq_3 (30 nm)/1% DPVBi-doped Alq_3, 1% NPB-doped Alq_3, or 1% BCP-doped Alq_3 (30nm)/NPB (50 nm)/ITO (100 nm)/glass substrate are shown in Fig 1. After the organic and the metal depositions, the OLED devices were encapsulated in a glove box with O_2 and H_2O concentrations below 1 ppm. A desiccant material consisting of barium-oxide powder was used to absorb the residue moisture and oxygen in the encapsulated device. The organic layers were deposited at a substrate temperature of 27°C and a system pressure of 5×10^{-8} Torr. The deposition rates of the organic layers and the metal layers were approximately 0.1 and 0.5 Å/s, respectively. The deposition rates were controlled by using a quartz crystal monitor. The size of the emitting region in the pixel was 5 mm × 5 mm. The current-voltage characteristics of the OLEDs were measured on a programmable electrometer with built-in current and voltage measurement units (model 236, Keithely). The brightness was measured by using a brightness meter, chroma meter CS-100A (Minolta).

3. Results and discussion

Figure 2 (a) shows the current density-voltage characteristics of the OLEDs with NPB-doped Alq_3 EML, DPVBi-doped Alq_3 EML, and BCP-doped Alq_3 EMLs. While the energy gaps of the DPVBi, the NPB, and the BCP molecules are larger than that of the Alq_3 EML, the positions of the lowest unoccupied molecular orbital (LUMO) and the highest occupied molecular orbital (HOMO) levels of the molecular impurities are different, as shown in Fig. 1. The LUMO level of the DPVBi impurity is higher than that of the Alq_3 EML, and the HOMO level of the DPVBi of the DPVBi is lower than that of the

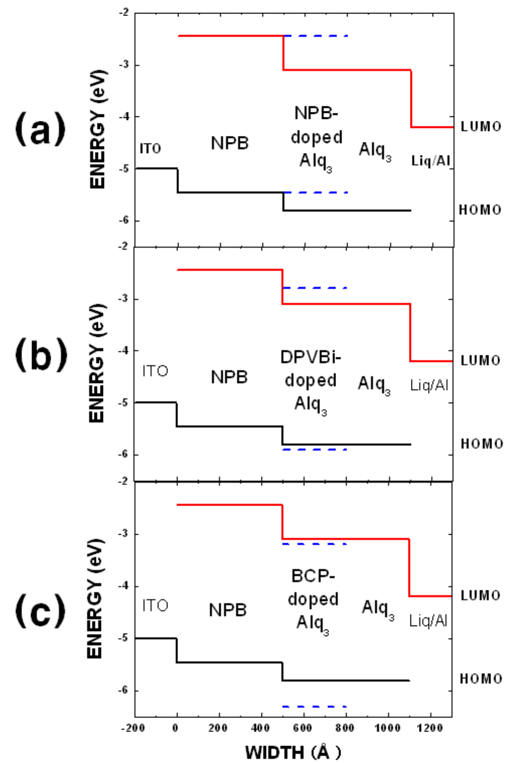

Fig. 1. Schematic energy level diagrams of OLEDs with an Alq_3 emitting layers doped with (a) NPB, (b) DPVBi, and (c) BCP impurities. The LUMO and the HOMO represent the lowest unoccupied molecular orbital and the highest occupied molecular orbital, respectively, and the energy level of 0 eV indicates a vacuum level.

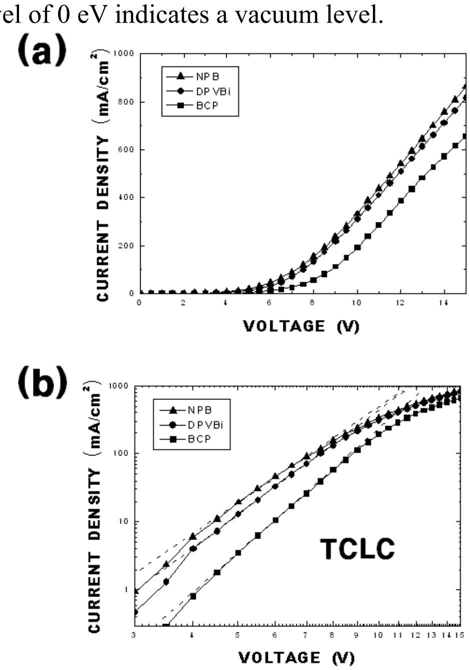

Fig. 2. (a) Current densities and (b) logarithmic current density as functions of the applied voltage characteristics for OLEDs with Alq_3 emitting layers doped with NPB, DPVBi, and BCP impurities. The TCLC represents the trap-charge-limited-current region.

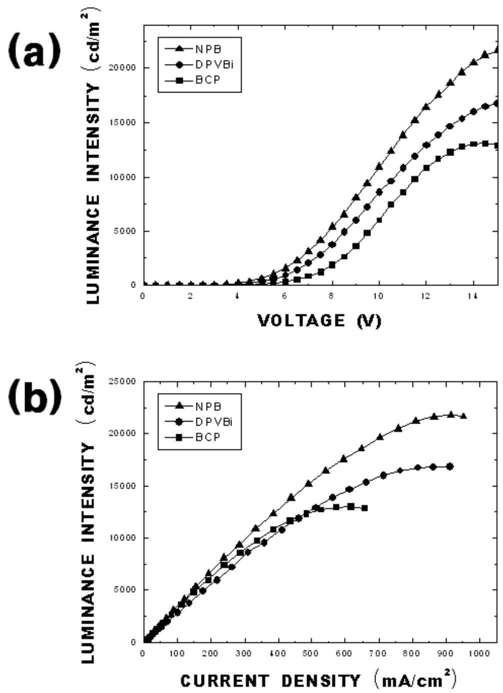

Fig. 3. (a) Luminance intensities as functions of the applied voltage and (b) luminance intensities as functions of the current density characteristics for OLEDs with Alq3 emitting layers doped with NPB, DPVBi, and BCP impurities.

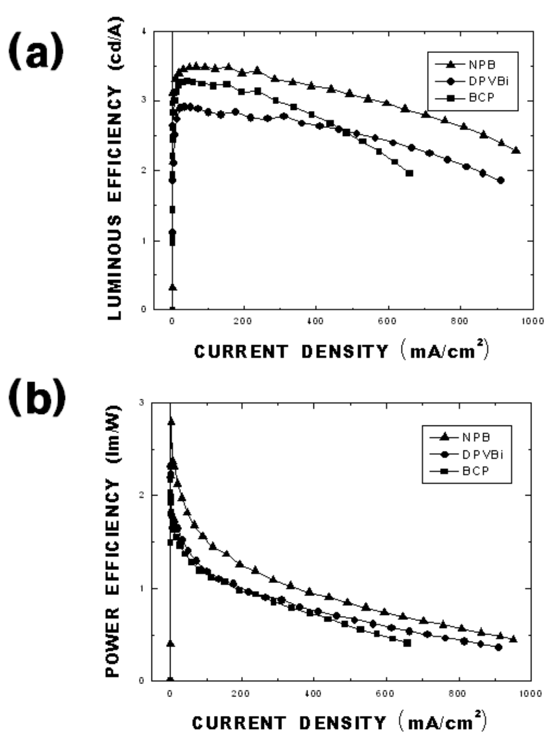

Fig. 4. (a) Luminous efficiencies as functions of the current density and (b) power efficiencies as functions of the current density characteristics for OLEDs with Alq3 emitting layer doped with NPB, DPVBi, and BCP impurities.

Alq_3. While the LUMO and the HOMO levels of the NPB impurity are higher than those of the Alq_3 EML, those of the BCP impurity are lower than those of the Alq_3 EML. Because the LUMO and the HOMO levels of the impurities doped into the EMLs are different, the electron or hole trap densities in the EMLs are different, resulting in variations in the injection and the luminance efficiencies. The current density for OLEDs with a NPB-doped Alq_3 EML at the same voltage is higher than that of OLEDs with a DPVBi- or a BCP-doped Alq_3 EML. When the linear scale graph is transformed into a logarithmic scale, the graph can be fitted as a function of V^{m+1}, where m is related to the trap density [13]. Figure 2 (b) shows logarithmic scale plots of the current density-voltage characteristics and the fitted lines. The m values, determined from the slopes of the fitting lines of the double logarithmic current density-voltage characteristics for OLEDs with NPB-, DPVBi-, and BCP-doped Alq_3 EMLs in the trap-charge-limited-current region, are approximately 3.7, 4, and 5, respectively. The trap density of BCP-doped OLEDs is larger than that of DPVBi- or NPB- doped OLEDs. While the electron trap for the OLEDs with BCP-doped Alq_3 EMLs is shallow, the corresponding hole trap is very deep. While trap levels for the OLEDs with DPVBi-doped Alq_3 EMLs do not exist, deep hole trap levels for OLEDs with NPB-doped Alq_3 EMLs exist. While the injection efficiency of OLEDs with wide-band-gap impurity-doped EMLs is significantly affected by the existence of shallow trap levels, the corresponding deep trap levels do not significantly affect the charge transport in the organic layers.

Figure 3 shows (a) luminance-voltage and (b) the luminance-current density characteristics for OLEDs with NPB-, DPVBi-, and BCP-doped Alq_3 EMLs. Among the three samples, the luminance of the NPB-doped OLEDs is the highest, and the corresponding turn-on voltage is the lowest. However, the luminance of the BCP-doped OLEDs at low current densities is higher than that of the DPVBi-doped OLEDs, which originates from the existence of shallow trap levels in the OLEDs with BCP-doped Alq_3 EMLs. The electrons trapped in the EML at a low current density do not seriously interrupt the electron transport from the ETL, and they assist the hole transport existing in the interface between the HTL and the EML. The formation probability of the exciton in the EML increases due to an increase in the number of trapped electrons. When the trap levels in the EML are almost occupied with increasing current density, and the trap charges severely prevent any increase in the charge injection. The decrease in the charge injection impedes an increase in the luminance, resulting in a saturation of the constant luminance. The saturation of the luminance is attributed to the existence of shallow trap levels in the EML. Even though the OLEDs with BCP-doped Alq_3 EMLs contain many shallow traps in the EML, the NPB- or DPVBi-doped OLEDs accommodate few shallow traps. Therefore, the luminance saturation is related to the shallow-trap-level density, as shown in Fig. 3 (b).

The luminous efficiency-current density and the power efficiency-current density characteristics for OLEDs with NPB-, DPVBi-, and BCP-doped Alq_3 are shown in Figs. 4 (a) and (b), respectively. The luminous and the power efficiencies of NPB-doped OLEDs are the highest among the samples. The enhancement of the efficiency for OLEDs with NPB-doped Alq_3 EMLs, in comparison with OLEDs with DPVBi-doped Alq_3 EMLs, originates from the higher hole mobility of the NPB [14]. The hole for the OLEDs with a NPB-doped Alq_3 EML penetrates into the deeper side of the EML, and the probability of exciton formation increases. The efficiency of BCP-doped OLEDs at low current densities are higher than that of DPVBi-doped OLEDs. The enhancement of the efficiency at low current densities is due to the existence of shallow trap levels in the BCP-doped Alq_3 EML. The variation of the luminous and the power efficiencies are in reasonable agreement with the results of Fig. 3 (b). While the shallow electron traps in EMLs at low current densities increase the electron-hole recombination probability, the filled shallow traps in EMLs at high current densities decrease the electron injection. While the efficiency of OLEDs with BCP-doped Alq_3 EMLs at low current densities is higher than that of OLEDs with DPVBi-doped Alq_3 EMLs, the corresponding efficiency at high current densities is lower.

4. Summary

The electrical and the optical properties of OLEDs fabricated with various wide-bandgap impurity-doped EMLs were investigated. The wide-bandgap impurity-doped Alq_3 EML acted as shallow or deep traps in the OLEDs. While the efficiency of an OLED with a NPB- or DPVBi-doped Alq_3 EML was not significantly affected by the current density, that of an OLED with a BCP-doped Alq_3 EML was dramatically changed. The significant enhancement of the efficiency of an OLED with a NPB-doped EML in comparison with the efficiency of an OLED with a DPVBi- or a BCP-doped Alq_3 EML was attributed to a decrease in the shallow traps existing in the EML resulting from the an increase in the hole mobility. These results can help in understanding the dependence of the electrical and the optical properties on wide-bandgap impurity-doped EMLs in OLEDs.

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