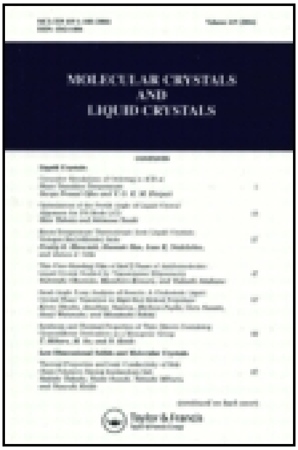

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Efficiency Enhancement Mechanism of Organic Light-Emitting Devices with an Alq_3 Emitting Layer Containing a DPVBi Wide Bandgap Doping Agent

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The efficiency of the organic light-emitting devices (OLEDs) with a tris-(8-hydroxyquinoline) aluminum (Alq$_3$) emitting layer (EML) containing a 4,4-bis(2,2diphenyl vinyl)-1,1-biphenyl (DPVBi) doping agent was significantly enhanced in comparison to that with an Alq$_3$ EML without a DPVBi doping agent. The enhancement of the injection efficiency of the OLEDs with an EML doped with a wide-bandgap doping agent was attributed to a decrease in the trap charge density existing in the EML resulting from the existence of the DPVBi doping agent. The luminescence mechanism of the OLEDs fabricated utilizing an Alq$_3$ EML containing a DPVBi wide-bandgap doping agent is described on the basis of the experimental results.

Keywords: luminescence mechanism; organic light-emitting devices; wide-bandgap doping agent

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I. INTRODUCTION

Organic light-emitting devices (OLEDs) have emerged as potential candidates for applications in full-color flat-panel displays because of their unique advantages of low driving voltage, low power consumption, high contrast, wide viewing angle, low cost, and fast response [1]. Moderate controls of carrier injection and transport for efficient carrier recombination and balance of the electrons and the holes are important for fabricating highly-efficient OLEDs [2], and potential applications of highly-efficient OLEDs have driven extensive efforts to fabricate various kinds of novel device structures [3–5]. Among the various methods for improving the performance of OLEDs, impurity doping is a powerful method for effectively controlling color tuning and for enhancing device efficiency [6–10]. Even though some studies on the enhancement of the efficiency in OLEDs utilizing an emitting layer (EML) containing a smaller-bandgap doping agent have been performed [11–13], studies concerning the efficiency enhancement mechanism in OLEDs with an EML containing a larger-bandgap doping agent have not been reported yet. Furthermore, since the enhancement of the efficiency in the OLEDs utilizing an electron transport layer (ETL) containing a larger-bandgap doping agent has been reported [14], systematic studies on the OLEDs with an EML containing a larger-bandgap doping agent are currently receiving considerable attention because of the possibility of enhancing their efficacies and lifetimes.

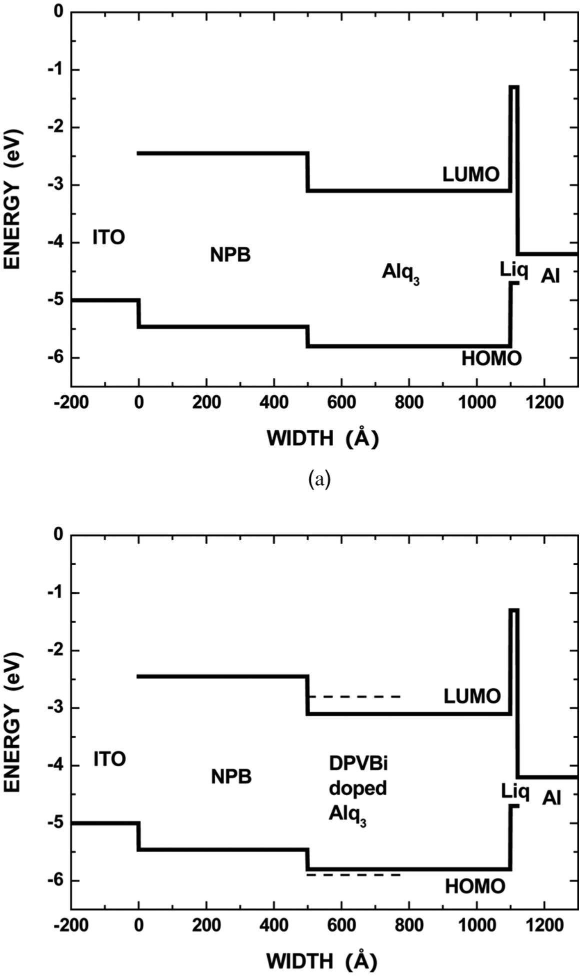
This paper reports data for the electrical and the optical properties of OLEDs fabricated with an EML with and without a wide-bandgap agent and fabricated by using organic molecular beam deposition (OMBD). Current density-voltage, luminescence-voltage, electroluminescence (EL) measurements were carried out to investigate the electrical and the optical properties of OLEDs with a tris-(8-hydroxyquinoline) aluminum (Alq_3) EML with and without a 4,4-bis(2,2diphenyl vinyl)-1,1-biphenyl (DPVBi) agent. Luminescence mechanism for the enhancement of OLED efficiency with an EML with and without a wide-bandgap agent is described on the basis of the experimental results.

II. EXPERIMENTAL DETAILS

The sheet resistivity of the indium-tin-oxide (ITO) thin films on glass substrates used in this study was $30\Omega/\square$. The ITO substrates were cleaned by using acetone and methanol at 60°C for 5 min and were rinsed in de-ionized water thoroughly. The chemically cleaned ITO substrates were then dried by using N_2 gas with a purity of 99.9999%. The two kinds of OLEDs used in this study were fabricated on ITO thin films coated on glass substrates by using OMBD 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) ETL, an Alq_3 (30 nm) EML either with or without a 0.5% DPVBi-doped layer, a *N*,*N*-bis-(1-naphthyl)-*N*,*N*-diphenyl-1,1-biphenyl-4,4-diamine (NPB) (60 nm) hole transport layer (HTL), an ITO (100 nm) anode electrode, and a glass substrate. The Liq layer, acting as an electron injection layer, decreases the driving voltage and increases the power efficiency due to a decrease in the electron injection barrier height [15]. Schematic energy level diagrams of the Al (100 nm)/Liq (2 nm)/Alq_3 (30 nm)/0.5% DPVBi-doped Alq_3 (30 nm)/NPB (40 nm)/ITO (100 nm)/ glass substrate and Al (100 nm)/Liq (2 nm)/Alq_3(60 nm)/NPB (40 nm)/ ITO (100 nm)/glass substrates are shown in Figure 1. After organic and 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).

III. RESULTS AND DISCUSSION

Figure 2 shows the current densities as functions of the applied voltage for the OLEDs with an Alq_3 EML (a) with and (b) without a DPVBi doping agent. The current density of the OLEDs with an Alq_3 EML containing a DPVBi doping agent is larger than that of the OLEDs with an Alq_3 EML. The current density-voltage behavior on the basis of the trap charge limited current (TCLC) is proportional to $(m+1)$th power of voltage [16]. Because the linearly fitted slopes at the applied voltage range between 8 and 15 V are larger than 2, the TCLC current densities at high voltages are dominant. The m values of OLEDs with an Alq_3 EML doped with and without a DPVBi doping agent are 2.8 and 4.6, respectively. The Alq_3 EML containing a DPVBi



(a)

(b)

FIGURE 1 Schematic energy level diagrams of OLEDs with an Alq$_3$ emitting layer (a) with and (b) without a DPVBi doping agent. The LUMO and the HOMO represent the lowest unoccupied molecular orbital, respectively, and the energy level of 0 eV indicates a vacuum level.

doping agent decreases the trap density existing in the Alq$_3$ layer and increases the electron current into the EML.

Figure 3 shows luminances as functions of the applied voltage for the OLEDs with an Alq$_3$ EML (a) with and (b) without a DPVBi doping agent. The operating voltages for the OLEDs with an Alq$_3$ EML with

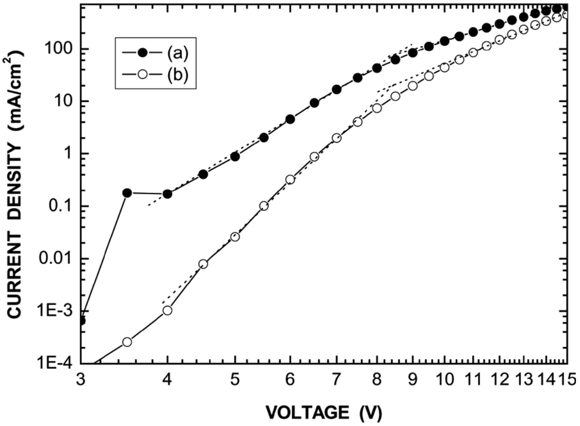


FIGURE 2 Current densities as functions of the applied voltage for OLEDs with an Alq_3 emitting layer (a) with and (b) without a DPVBi doping agent.

and without a DPVBi doping agent for obtaining 100 cd/m^2 luminescence are 6.5 and 8.4 V, respectively. Since the number of the electrons injected into the EML increases due to a decrease in the electron trap density in the OLED with an Alq_3 EML containing a DPVBi doping agent, resulting in an increase of the number of the excitons,

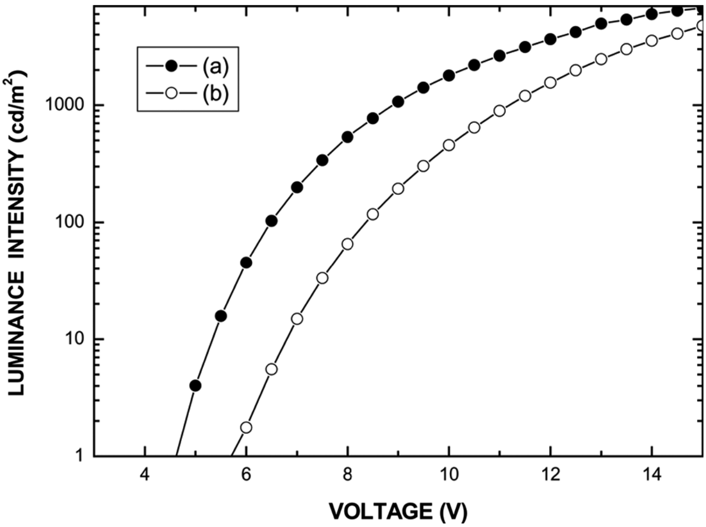
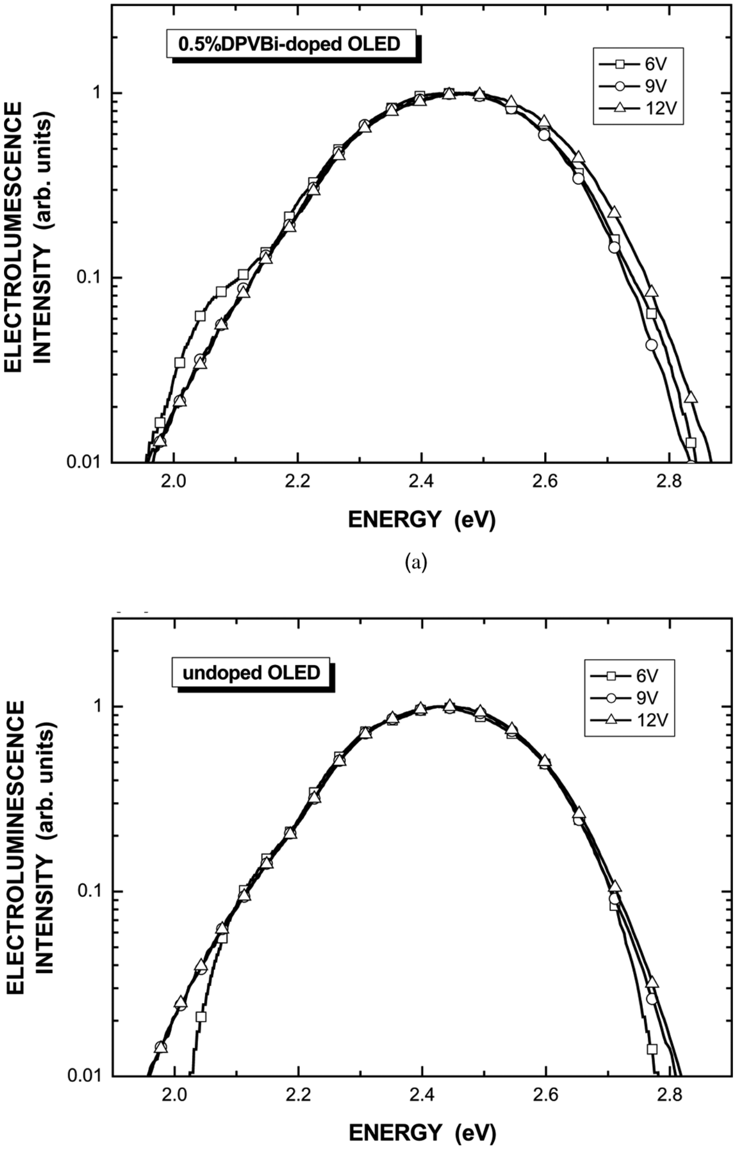


FIGURE 3 Luminance intensity as functions of the applied voltage for OLEDs with an Alq_3 emitting layer (a) with and (b) without a DPVBi doping agent.

the luminance intensity of the OLED with an Alq_3 EML containing a DPVBi doping agent is larger than that of the OLED with an Alq_3 EML. The luminance efficiency of the OLED is significantly improved by using an Alq_3 EML containing a DPVBi doping agent. The significant enhancement of the luminance efficiency of the OLED with an Alq_3 EML containing a DPVBi doping agent in comparison with those of the OLED with an Alq_3 EML originates from the increase of the charge injection. Systematic studies concerning the enhancement in the efficiency and the lifetime of the OLED with an Alq_3 EML containing a DPVBi doping agent will be published elsewhere [17].

Figure 4(a) shows the EL spectra of the OLEDs with an Alq_3 EML containing a DPVBi doping agent at 6, 9, and 12 V, and the dominant peak of Figure 4(a) is 2.44 eV. Since the energy bandgap of the Alq_3 EML is 2.7 eV, the difference between the energy gap of the Alq_3 EML and the dominant peak of the EL spectra is 0.26 eV, which is attributed to an exciton binding energy in the EML. When that the exciton binding energies of the Alq_3 EMLs for two OLEDs are assumed to be the same the exciplex peak formed between the lowest unoccupied molecular orbital of the Alq_3 EML and the highest occupied molecular orbital of the NPB HTL appears at approximately 2.1 eV, as shown in the EL spectrum at 6 V. The observed peak at 2.1 eV for the EL spectrum at 6 V disappears from the spectra at 9 and 12 V. Because the number of exciton formed in the Alq_3 layer containing a DPVBi doping agent increases with increasing bias voltage, the EL peak intensities at 2.7 eV increase. While the recombination magnitude of the exciton at the interface between the NPB and the Alq_3 decreases with increasing bias voltage, the recombination of the exciton at the Alq_3 EML increases. Figure 4(b) shows the EL spectrum of the OLEDs with an Alq_3 EML at 6, 9, and 12 V. The exciplex peak intensity at 2.1 eV for the OLEDs with an undoped EML increases with increasing bias voltage. Because the number of the exciton existing in the NPB HTL increases with increasing bias voltage, the EL intensity around 2.8 eV increases. Therefore, the enhancement of the EL intensity at higher voltage is attributed to an increase in the recombination of the exciton at the NPB and the Alq_3 heterointerface.

Figure 5 show schematic diagrams of the energy level shift in the exciton recombination region due to a variation of the electron trap density for OLEDs with an Alq_3 EML (a) with and (b) without a DPVBi doping agent. The current density-voltage characteristics depict that the electron trap density of the Alq_3 EML containing a DPVBi doping agent is smaller than that of an Alq_3 EML. When the applied voltage for the OLED with the Alq_3 EML containing a DPVBi doping agent increases from 6 to 12 V, the efficiency of the hole transport into the



(a)

(b)

FIGURE 4 Electroluminescence spectra at different bias voltages for OLEDs with an Alq_3 emitting layer (a) with and (b) without a DPVBi doping agent.

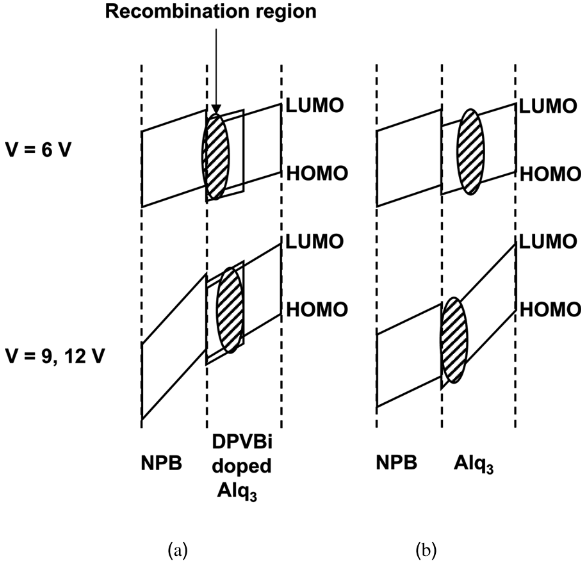


FIGURE 5 Schematic diagrams of the energy level shift in the recombination region for OLEDs with an Alq$_3$ emitting layer (a) with and (b) without a DPVBi doping agent. The LUMO and the HOMO represent the lowest unoccupied molecular orbital and the highest occupied molecular orbital, respectively.

HTL is enhanced. The recombination region of the exciton shifts to inner side of the EML due to the advance of the hole transport. However, the electron injection of the OLEDs with an Alq$_3$ EML under high voltages is enhanced. Therefore, the electron trap density of the OLEDs with an Alq$_3$ EML containing a DPVBi doping agent decreases due to the existence of the DPVBi molecules in the Alq$_3$ EML, resulting in enhancement of the luminance characteristics.

IV. SUMMARY AND CONCLUSIONS

The efficiency of the OLEDs with an Alq$_3$ EML containing a DPVBi doping agent was significantly enhanced in comparison with that of the OLEDs with an Alq$_3$ EML. The enhancement of the efficiency of the OLEDs with an EML containing a wide-bandgap doping agent was attributed to a decrease in the trap charge existing in the EML resulting from the existence of the DPVBi doping agent, which was clarified by the current density-voltage characteristics and electroluminescence spectra. These results indicate that the efficiency of the

OLEDs is dramatically enhanced by utilizing an EML containing a wide-bandgap doping agent.

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