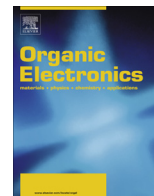




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## Enhancement of out-coupling efficiency due to an organic scattering layer in organic light-emitting devices

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### ABSTRACT

Organic light-emitting devices (OLEDs) with an organic scattering layer (OSL) were fabricated to enhance their out-coupling efficiencies. The OSL was formed through a crystallization process at room temperature after deposition in a vacuum. The luminances of the OLEDs with an 1,3-bis(cabazol-9-yl)benzene (mCP), a 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP), or a 4,7-diphenyl-1,10-phenanthroline (BPhen) OSL were 2.16, 2.13, and 2.11 times higher than that of the OLED without an OSL due to an increase in the scattering effect at the interface between the glass substrate and the OSL. The current efficiencies of the OLEDs with a mCP, a BCP, or a BPhen OSL were increased by 14.8%, 15.8%, and 14.8% compared to that for the OLED without an OSL. The OSL films in the OLEDs decreased the intensity of the wave-guided light, resulting in enhanced light extraction.

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### 1. Introduction

Organic light-emitting devices (OLEDs) have been a subject of considerable interest due to their important applications in flexible displays and in light sources with fast response and self-emission characteristics. In spite of excellent advantages of OLEDs, their light-extraction efficiency is relatively low in comparison with their internal quantum efficiency, which has reached 100% due to the utilization of phosphorescent organic materials [1–7]. The light extraction efficiency of conventional OLEDs is below 20% because of total internal reflection at the organic/organic interface or the organic/inorganic interface. Various methods for achieving high-efficiency OLEDs fabricated with scattering layers have been employed to reduce the extraction losses. Organic materials with a low glass transition temperature ( $T_g$ ) have been reported to crystallize under different conditions, resulting in a rough surfaces [8,9], and those materials can be used as a scattering layer to improve the light extraction efficiency in OLEDs. The crystallized organic scattering layers (OSLs), which are formed on the outside of the OLEDs, enhance the light extraction of the OLEDs by reducing the intensity of the wave-guided light in the substrates or the transparent electrodes [10]. The OSLs are formed by crystallizing pre-evaporated organic layers under ambient conditions. The

crystallized OSL at the interface between the substrate and air increased the light extraction efficiency of the OLEDs. Even though some works on enhancement of the light extraction in OLEDs have been performed [11–17], very few studies concerning enhancement of the out-coupling efficiency in OLEDs with an organic scattering layer (OSL) have been reported [17]. Furthermore, because the structural formation of the crystalline grains in organic layers was significantly affected by the glass transition temperature and the material type, systematic investigations about enhancement of the out-coupling efficiency of the OLEDs containing various kinds of OSLs with a low glass transition temperature were necessary to clarify the relation between the structural formation of the crystalline grains for the OSLs and the enhancement of the extraction efficiencies for the OLEDs.

This paper reports data for the enhancement of the out-coupling efficiency in OLEDs fabricated utilizing various kinds of OSLs with a low glass transition temperature. Atomic force microscopy (AFM), optical microscopy, and transmission electron microscopy (TEM) measurements were carried out in order to investigate the surface and the microstructural properties of the 1,3-bis(cabazol-9-yl)benzene (mCP), 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP), and 4,7-diphenyl-1,10-phenanthroline (BPhen) films. Current density–voltage–luminance ( $J$ – $V$ – $L$ ) measurements were performed to investigate the electrical and the optical properties of the OLEDs with and without an OSL. The luminance of the OLEDs was observed as a function of the viewing angle to evaluate the light extraction.

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2. Experimental details

The OLEDs used in this study were fabricated on indium-tin-oxide (ITO)-coated glass substrates with a sheet resistance of 15 ohm/square and a thickness of 150 nm. The ITO-coated glass substrates were cleaned in acetone and methanol at 25 °C for 20 min by using an ultrasonic cleaner and were rinsed in de-ionized water thoroughly. After the chemically-cleaned ITO-coated glass substrates had been dried by N<sub>2</sub> gas with a purity of 99.99%, the surfaces of the ITO-coated glass substrates were treated with an ultraviolet-ozone treatment for 20 min at room temperature. The organic layers and the electrodes were deposited on the ITO-coated glass substrates at a substrate temperature of 25 °C and a system pressure of 8.0 × 10<sup>-7</sup> Torr. The OLEDs had the following structure starting from the bottom layer: N,N'-bis-(1-naphthyl)-N,N'-diphenyl-1'-biphenyl-4,4'-diamine (NPB) as a hole transport layer (HTL), tris(4-carbazoyl-9-ylphenyl)amine (TCTA) as an exciton blocking layer, tris(phenylpyridine)iridium (Ir(ppy)<sub>3</sub>)-doped N,4,4'-bis(-carbazoyl)-1,1'-biphenyl (CBP) as an emitting layer (EML), and a BPhen as an electron transport layer (ETL). The evaporation rate of the organic layers and the metal layer was 2 Å/s.

The crystallization of the organic films was observed by using an optical microscope (S39A, Microscopes Instrument) and a polarizing microscope (BX51, Olympus). The current density–voltage (J–V) characteristics were measured on a programmable electrometer with built-in current and voltage measurement units (M6100, McScience). The luminance–voltage (L–V) characteristics and the electroluminescence (EL) spectra were measured by using a spectroradiometer (CS-1000, Minolta). The atomic force microscope (AFM) measurements were performed by using the XE-100 system (PSIA).

3. Results and discussion

Fig. 1 shows (a) a schematic diagram of an OLEDs with a BPhen OSL and (b) the corresponding energy band diagram for green phosphorescent OLEDs. The Ir(ppy)<sub>3</sub> molecules in the CBP layer acted as an efficient green phosphorescent dopant, and the TCTA layer blocked the excitons generated from the CBP layer, providing an optimized structure for the OLEDs. Fig. 1(c) shows the structures of the organic materials used in this work. The mCP, the BCP, and the BPhen films with Tg's of 55, 82, and 62 °C were deposited on glass substrates. While the as-deposited mCP, BCP, and BPhen films were in an amorphous state, the organic films gradually became crystallized when exposed to air [18]. The crystallized organic films deposited on the glass substrates might decrease the amount of wave-guided light in OLEDs by scattering at the interface between the glass substrate and the crystallized organic layer.

Fig. 2 shows AFM images of the vacuum-evaporated mCP, BCP, and BPhen films exposed for 3 h in vacuum and of the mCP, BCP, and BPhen films exposed for 30 h under ambient conditions. After the mCP, BCP, and BPhen films had been subjected to evaporated in a vacuum of 10<sup>-7</sup> Torr, they were left in a vacuum of 10<sup>-2</sup> Torr for 3 h, as shown in Fig. 2(a)–(c). The surface roughnesses of these mCP, BCP and BPhen films were approximately 0.643, 23.408, and 18.215 nm, respectively. The increases in the surface roughnesses of the films originated from the strong cohesion between the organic molecules. The surface roughnesses of the films gradually increased with increasing deposition time due to the aggregation of organic molecules. The surface roughnesses of the mCP, BCP and BPhen films after 30 h of exposure to air were approximately 1.097, 24.038, and 18.880 nm, respectively. Even

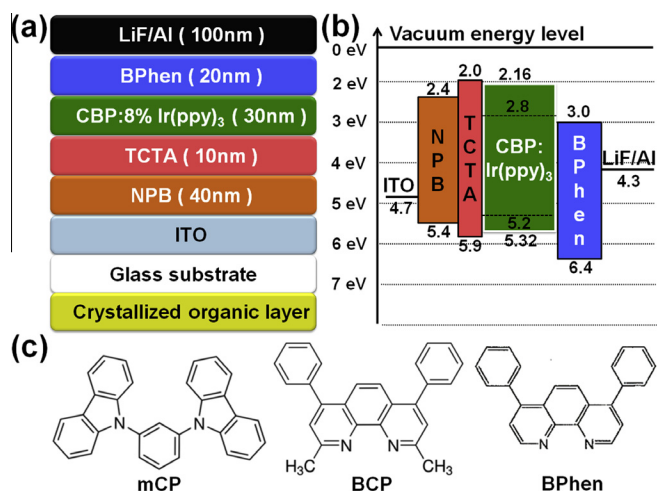


Fig. 1. (a) Schematic diagram of an OLED, (b) energy band diagram, and (c) molecular structures.

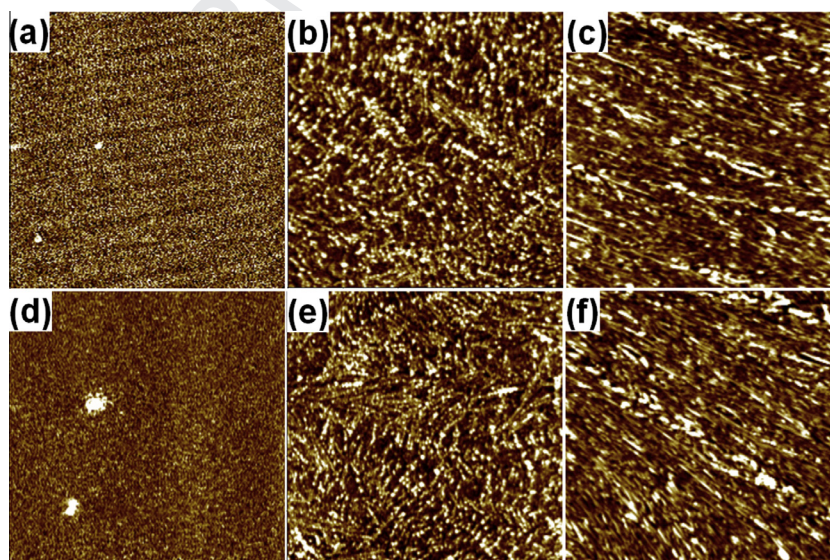


Fig. 2. Atomic force microscopy images of vacuum-evaporated (a) mCP, (b) BCP, and (c) BPhen films exposed for three hours in a vacuum, and (d) mCP, (e) BCP, and (f) BPhen films exposed for 30 h under ambient conditions. The scan areas are 25 × 25 μm<sup>2</sup>.

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