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Enhanced Luminance Efficiency from Organic Light-Emitting Diodes with 2D Photonic Crystal

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1. Introduction

Organic light emitting diodes (OLEDs) are one of the most promising light sources for the next-generation flat panel displays because the OLED have some potential, such as low-voltage operation, high-speed response and high luminance. The external quantum efficiency for the OLEDs depends on the internal quantum efficiency and the light extraction efficiency. The high internal quantum efficiency has been achieved by the phosphorescent OLEDs [1,2]. On the other hand, the light extraction efficiency is generally estimated to be about 20 %. The OLEDs with 2D photonic crystals (PCs) have been proposed in order to improve the light extraction from the OLED [3-5]. The OLEDs with the SiO_2/SiN_x PC between the indium-tin-oxide (ITO) anode and the glass substrate achieved increases in the extraction efficiency of over 50% [3,4]. On the other hand, for the OLED with ITO-patterned PCs, the enhancement of a luminance efficiency of 50 % has been realized as compared to the device without PC under a constant electric power density.

In this study, we have investigated the effect of the PCs on the optical properties for the OLED in detail and demonstrated the enhanced light extraction from the OLED with the PC. To investigate the PC lattice constant dependence, the PC structures with various periods were fabricated using electron-beam (EB) lithography.

2. Experimental

Figure 1 shows the illustration of the fabricated OLED with the PC. The fabrication process is as follows. We fabricated the circular hole in the deposited SiO_2 on the glass substrates by EB lithography and dry-ion etching. In order to flatly fill the circular hole in the SiO_2 layer, the SiN_x layer over 400 nm in thick was deposited by the reactive sputtering. Then, the deposited SiN_x layer was etched to adjust the vertical distance between the PC and the emission layer of the OLED. In this study, the total thickness of SiO_2 and SiN_x was about 210 nm. The PC structures had square lattices with lattice constants a = 320, 340 and 360 nm. The values of the lattice constants were determined from the results of the numerical calculation. The first or second lowest mode on the Γ point of the dispersion relation for the PC with these lattice constants is estimated to be in the spectrum width from the OLED. The ratio of the radius of the SiN_x circular cylinder to the lattice constant was about 0.35. The ITO layer was deposited by rf-sputtering. The subsequent processes were the same as those for conventional OLEDs. The OLED structure consists of ITO (150 nm), α-NPD (50 nm), Alq_3 (60 nm) and the metal cathode of LiF (0.5 nm)/Al (100 nm). The samples were encapsulated with epoxy and a glass in N_2 atmosphere. The OLEDs with the SiO_2/SiN_x PC of various lattice constant and with unpatterned SiO_2 layer as a reference device were fabricated on the same glass substrates. The ITO for each OLED on the same substrate was separated to individually derive the OLEDs. The OLEDs had an emission area of 400 μm × 400 μm. The electric and optical properties for the fabricated OLEDs were measured in air at room temperature.

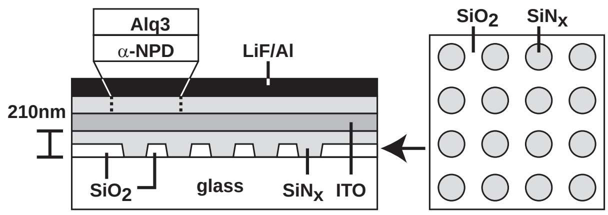

Fig. 1 Illustration of the fabricated OLEDs with the SiO_2/SiN_x PC.

3. Results and discussion

Figure 2(a) shows *I-V* characteristics of the OLED with and without the PC. The lattice constant of the PC was 360 nm. The *I-V* curve for the OLED with the PC shifted to the lower voltage. This may be because the carrier injection from the ITO is improved by the roughness of ITO layer in the OLED with the PC. Figure 2(b) shows the relationship of the luminance and efficiency to the current density. The luminance was measured in the normal direction to the sample surface. The luminance curve for the OLED with the PC had a larger gradient than that of the OLED without the PC. Therefore the OLED with the PC provided the higher luminance efficiency. The luminance efficiency for the OLED with and without the PC at a current of 10 mA/cm^2 was 3.54 cd/A and 3.00 cd/A, driven at voltages of 7.3 V and 8.0 V, respectively. This result shows that the 18% improvement in the luminance efficiency was achieved.

We measured the electroluminescence (EL) spectra for the PC with various lattice constants. The spectra in the normal direction for a = 320 nm, 340 nm and 360 nm at a current density of 10 mA/cm^2 are shown in Fig. 3 with the

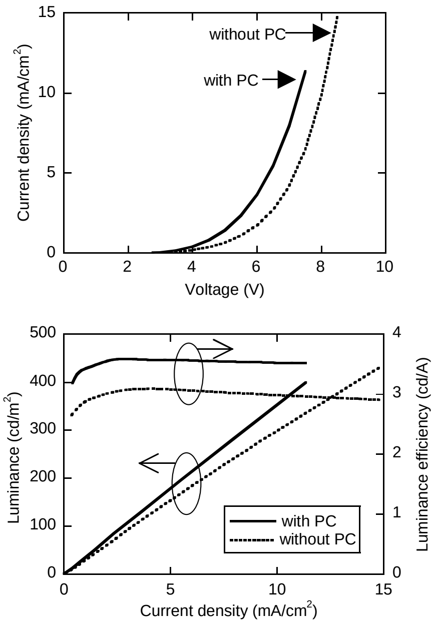

Fig. 2 (a) Current density versus voltage for the OLED with and without the PC. (b) Luminance and efficiency to current density. The lattice constant of the PC was 360 nm.

spectra for the sample without the PC. The results show that the spectra depend on the lattice constant of the PC and the integrated intensity for the OLEDs with the PC is larger than that of the OLED without the PC. The integrated intensity ratios of the OLED with the PC to that without the PC are 1.27 for a = 320 nm, 1.26 for a = 340 nm and 1.23 for a = 360 nm, respectively.

In order to clarify the influence of the PC, the ratios of the EL spectra for the OLED with the PC to that for the OLED without the PC are shown in Fig. 4. Two intensity peaks are clearly observed in each spectrum. The values of the ratio at the peaks were about 2.0. These peaks shifted to higher wavelength with the lattice constant maintaining a ratio of about 2.0. The normalized frequencies at the two peaks are 0.59±0.01 and 0.54±0.01 for the three samples with the different lattice constant. The behavior of the peak shift clearly shows that the PC causes the EL intensity peaks.

The enhancement of the EL intensity over 100% at a wavelength is larger as compare with the results in Ref. 4, although the SiO_2/SiN_x PC structure in this study is similar to that in Ref. 4. This larger enhancement is likely attributed to the shorter distance between the PC layer and the organic emission layer, and the appropriate lattice constant of the PC.

4. Conclusions

We fabricated the OLEDs with the SiO_2/SiN_x PC of various lattice constants. The lattice constant dependence of the EL spectra revealed that the enhanced EL spectra are attributed to the PC structure. We obtained enhancement in the EL intensity over 100% at a wavelength and the luminance efficiency of about 18% under a constant current density.

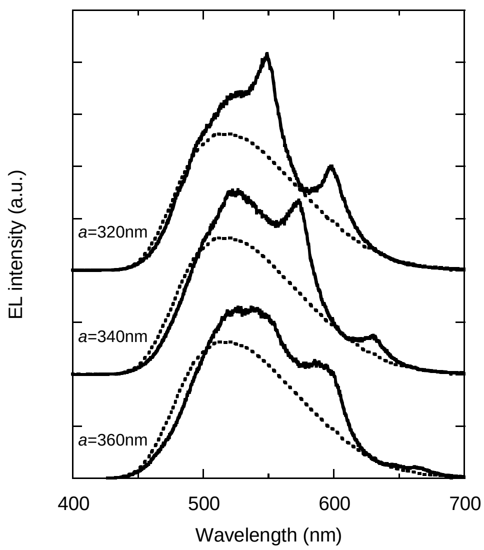

Fig. 3 EL spectra for the OLED with the PC of a = 320 nm, 340 nm and 360 nm (solid lines) and without the PC (dotted lines).

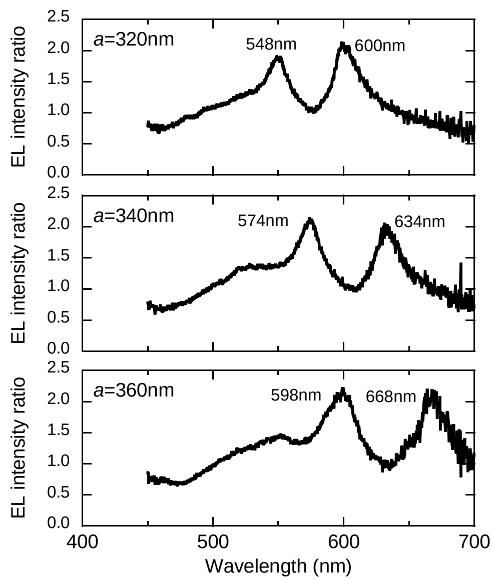

Fig. 4 Ratios of the EL spectra of the OLEDs with the PCs to that of the OLED without the PC.

Acknowledgements

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