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Microcavity Effect in Compliance with Interference of Light in Alq_3 Based Top-Emission Organic Light-Emitting Diodes

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Since top-emission organic light-emitting diodes have a structure of microcavity, there is a change in emission spectrum compared to that of noncavity such as a full width at half maximum and peak wavelength of the spectrum. Optical properties of top-emission organic light-emitting diodes were studied depending on an organic layer thickness and view angle. A structure of the manufactured device was Al(100 nm)/TPD/Alq_3/LiF(0.5 nm)/Al(2 nm)/Ag(30 nm). An Al(100 nm) and LiF(0.5 nm)/Al(2 nm)/Ag(30 nm) were used as an anode and semitransparent cathode, respectively. A thickness of hole injection layer of N,N′-diphenyl-N,N′-bis(3-metylphenyl)-1,1-biphenyl-4,4′-diamine (TPD) was varied from 40 nm to 70 nm, and that of an emission layer of tris(8-hydroxyquinoline) aluminum(III) (Alq_3) was varied from 60 nm to 110 nm. At each device, a thickness ratio of TPD and Alq_3 layer was kept to be about 2:3. It was observed that the emission spectrum of top-emission organic light-emitting diodes shows a microcavity effect when the organic layer thickness and view angle were varied. This microcavity effect of the device was analyzed in terms of theoretical interpretation based on an interference of light. Through these analyses, we were able to understand a shift of peak wavelength in spectrum, and deduce a refractive index and a thickness of organic layer. These deduced values are in agreement with known values.

Keywords Alq_3; interference; microcavity; spectrum; top emission

1. Introduction

Organic light-emitting diodes (OLEDs) are the devices where the emission spectrum is close to that of natural light. Currently, an application of OLEDs is moving from small-sized display to large-sized display markets. People concerns on next generation display such as flexible display, electronic paper, both-side emission device with a use of organic materials [1].

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Electroluminescent phenomenon was discovered by Helfrich et al. in organic semiconductor anthracene single crystal in 1963 [2], but there was less concern on this phenomenon because of high operating voltage and low efficiency. In 1987, Tang and VanSlyke in Eastman Kodak reported efficient organic light-emitting diodes using bilayer device structure [3]. The OLEDs generate light by a recombination process of electrons and holes injected from a cathode and an anode. They have advantages in low operation voltage, low power consumption, fast response time, high efficiency, and *etc*. [4,5]. Because of these advantages, currently lots of researches are going on.

Yokoyama reported optical potential applications of microcavity effect in 1992 [6]. In 1994, Dodabalapur *et al.* reported microcavity effect out of organic light-emitting diodes, where the emission spectrum from the device can be controlled even with one emission layer. One of the advantages of microcavity effect is that it is able to generate various colors having narrow width in spectrum [7,8]. Emission spectrum of top-emission organic light-emitting diodes is mostly determined by organic/electrode materials, thickness of organic layer, and device structure. If a reflectivity of the electrode used in the device is relatively high, microcavity effect affects on the emission spectrum of the device [9–11].

In this paper, optical properties of top-emission organic light-emitting diodes were studied depending on a thickness of organic layer and view angle. They were quantitatively analyzed in terms of theoretical interpretation based on an interference of light.

2. Experimental Details

Device was manufactured in a structure of Al(100 nm)/TPD(x nm)/Alq_3(y nm)/LiF(0.5 nm)/Al(2 nm)/Ag(30 nm), as shown in Figure 1. A 100 nm thick Al layer was used as an anode. On top of the evaporated Al layer, hole-transport layer of N,N′-diphenyl-N,N′-di(m-tolyl)-benzidine (TPD) was thermally deposited to a thickness ranging from 40 nm to 70 nm. An emission layer of tris(8-hydroxyquinoline) aluminum (Alq_3) was thermally deposited to a thickness from 60 nm to 110 nm. Here, a thickness ratio of TPD and Alq_3 layer was kept to be about 2:3, and a total the organic layer thickness was made to be 100 nm, 120 nm, 140 nm, 160 nm, and 180 nm. A LiF(0.5 nm)/Al(2 nm)/Ag(30 nm) layer was used as a semitransparent

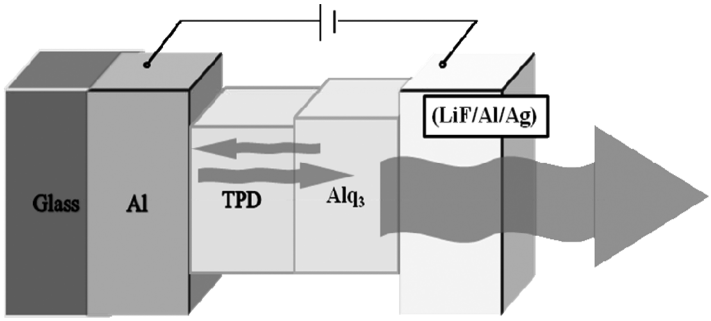

Figure 1. Device structure of top-emission organic light-emitting diodes. Al and LiF/Al/Ag were used as an anode and semitransparent cathode, respectively.

cathode, and its transmittance in visible region is about 40%. Evaporation was performed at 2×10^{-5} torr, and deposition rate of organic materials was 0.5~1.0 Å/s, and that of electrode was 0.5~5 Å/s. An active area of the device was made to be $3 \times 5\,mm^2$.

In order to measure the angular dependent emission spectrum of the device, the device was located at the center of rotation stage inside a black box. Emission spectrum of the device was measured by rotating the stage with 10° step at a luminance of $100\,cd/m^2$.

Electrical and optical characteristics were measured using Keithley 236 source-measure unit and Keithly 617 electrometer at room temperature. And emission spectrum was measured using Ocean Optics USB20000.

3. Results and Discussion

Light generated in top-emission organic light-emitting diodes propagates through a medium by reflection and refraction at the interfaces. Simplified picture of propagation of light is shown in Figure 2. Light rays in air transmitted through a semitransparent cathode cause interference. A condition for a constructive interference is the following.

$$2nd\cos\phi = m\lambda_p \quad (m = \pm 1, \pm 2, \ldots) \tag{1}$$

Here, n is a refractive index of organic layer, d is a distance between two electrodes, ϕ is an incident angle of the light ray coming out from the organic layer to the air, λ_p is a peak wavelength of light where the constructive interference is formed, and m is an order number. And a relationship between the incident angle ϕ and refractive angle θ traveling between two media satisfies the Snell's law. That is,

$$n\sin\phi = \sin\theta \tag{2}$$

For a normal incidence of light which comes out directly above the device (that is $\phi = 0°$), when the order number m is 1, Eq. (1) becomes

$$2nd = \lambda_p \tag{3}$$

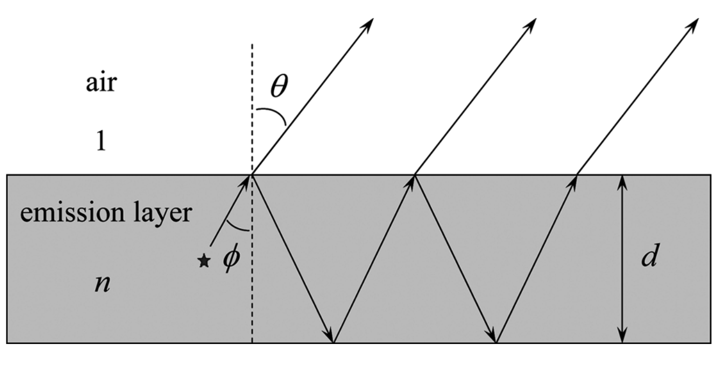

Figure 2. Schematic picture of propagation of light through a medium by reflection and refraction at the interfaces.

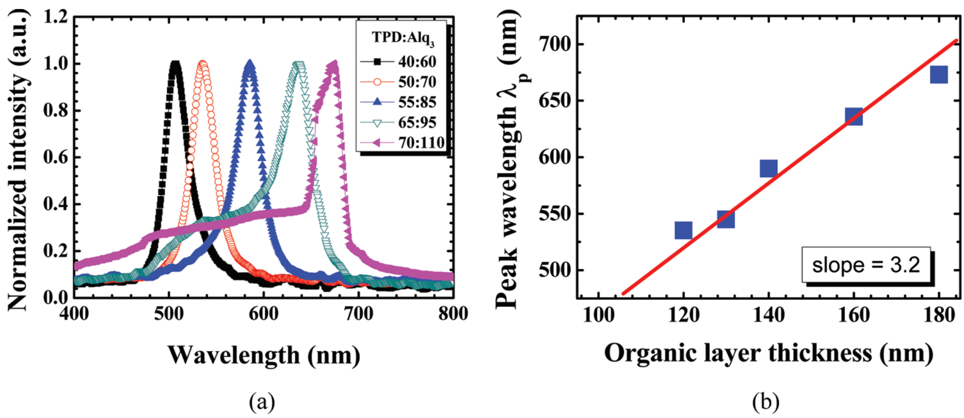

Figure 3. (a) Organic layer thickness-dependent emission spectrum measured at $\theta = 0°$, and (b) peak wavelength of the spectrum as a function of organic layer thickness.

Figure 3(a) is the emission spectra coming out normally right above the top-emission organic light-emitting diodes when a thickness of organic layer was varied from 100 nm to 180 nm. Total thickness of TPD and Alq_3 layer was made to be 100 nm, 120 nm, 140 nm, 160 nm, and 180 nm. As shown in the figure, peak wavelength of the spectrum for 100 nm thickness is 505 nm. And as the organic layer thickness increases, the peak wavelength of the spectrum shifts to a longer wavelength. Figure 3(b) is a graph showing the peak wavelength as a function of organic layer thickness, obtained from Figure 3(a). It shows a linear relationship as expected in Eq. (3). From a slope of this straight line, a refractive index of 1.6 was obtained. Since it is known that a refractive index of these organic layer is 1.6~2.1, our result is in agreement with a reported value.

Figure 4(a) shows the angular dependent emission spectra out of the device for the organic layer thickness of 140 nm (TPD 55 nm and Alq_3 85 nm). Here, an angle θ is the angle from the normal direction as shown in Figure 2. Namely, $\theta = 0°$ means a direction perpendicular to the device plane. As shown in the figure, the peak

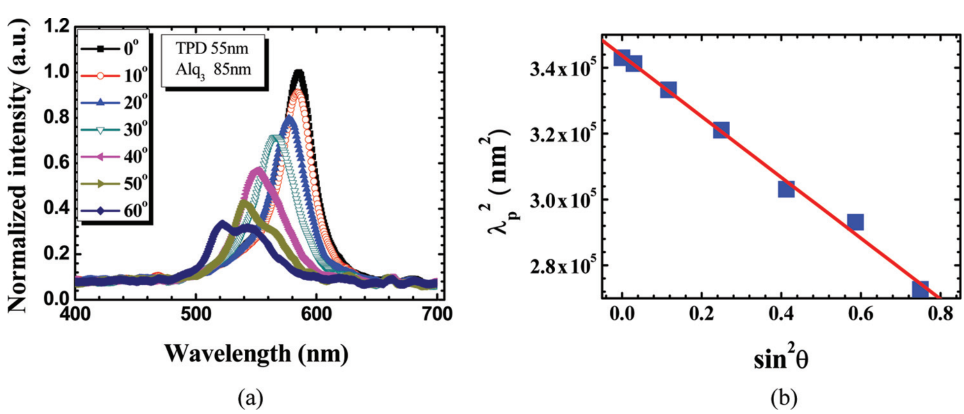

Figure 4. (a) Angular dependence of emission spectra for 140 nm thick organic layer device, and (b) a graph between λ_p^2 and $\sin^2\theta$.

wavelength of the spectrum for $\theta = 0°$ is 580 nm. As the view angle increases, the peak wavelength shifts to a shorter wavelength. To understand these behaviors, we can apply the following relation derived from Eqs. (1) and (2). For $m = 1$,

$$\lambda_p^2 = (2nd)^2 \left(1 - \frac{\sin^2\theta}{n^2}\right) \tag{4}$$

In order to verify a validity of Eq. (4), a graph relating λ_p^2 and $\sin^2\theta$ is plotted in Figure 4(b). As shown in the figure, it shows a linear relationship as expected in Eq. (4). From the slope and y-intercept of this straight line, a refractive index n and a thickness d of the organic layer are able to be obtained. The obtained value of refractive index n is 1.9, and thickness d is 150 nm. These values are reasonably close to the known values within 10% uncertainty.

Using a theory of interference of light, we were able to understand a shift of the peak wavelength depending on the organic layer thickness and view angle in top-emission organic light-emitting diodes. However, this simplified constructive interference condition only supports a behavior of peak wavelength. To understand a behavior of full width at half maximum of the spectrum, a reflectivity of the electrodes must be considered together. These considerations are being under conducted.

4. Conclusion

Microcavity effect in compliance with interference of light was quantitatively studied in Alq_3 based top-emission organic light-emitting diodes depending on a thickness of organic layer and view angle. It was found that as the thickness of organic layer of the device increases, the peak wavelength shifts to a longer wavelength. And also, as the view angle increases, the peak wavelength shifts to a shorter wavelength. These behaviors were able to be understood with a simple theory of interference of light. Through this theoretical approach, estimated refractive index and a thickness of organic layer were in agreement with known values.

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