Effects of dielectric capping layer in the phosphorescent top emitting organic light emitting diodes

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Keywords : Top emission OLEDs, Microcavity, Dielectric capping layer, Cavity length

Abstract

Effects of a dielectric capping layer on the luminous characteristics of top emitting organic light emitting diodes (TOLEDs) have been analyzed using a classical electromagnetic theory. Special attention was given to the influence of the cavity length on the effectiveness of the capping layer. The luminance characteristics of the TOLEDs influenced by the combined effects of the cavity length and the capping layer thickness. Furthermore, these combined effects also modify the emission spectrum and pattern of the TOLEDs, which result in the improvement of total luminance of the device, but no significant change in the device out-coupling efficiency.

1. Introduction

Recently, top emission organic light emitting diodes (TOLEDs) are being used for small size active matrix OLED (AMOLED) due to the high fill factor, large aperture ratio, and high luminous efficiency.[1-3] Since most of TOLEDs have two metal mirrors consisting of reflective metal anode and semi transparent top cathode, they show strong microcavity effects. This microcavity effect influences various light output characteristics of TOLEDs such as spectral distribution and angular light output pattern. As results, TOLEDs have strong angular dependence and their emission pattern is usually does not show Lambertian distribution.[3] These optical effects are sometimes a drawbacks in the application to a flat panel display due to the none Lambertian emission pattern and the difficulty of spectrum control. To resolve them and to enhance luminous efficiency, the dielectric capping layer deposited on top of thin metal cathode is proposed.[4-9] Major effects of capping layer are enhancement of light outcoupling efficiency and angle dependent spectral distribution through modification of interference effect. Riel et.al demonstrated that the angular intensity distribution can be tuned and the light out coupling is enhanced simply by varying the optical thickness of inorganic dielectric layer deposited on top of the cathode.[4, 5] Q. Huang et. al showed experimentally the enhancement of maximum current efficiency by a factor of 1.38 and explained that the efficiency enhancement is mainly due to the improvement of outcoupling efficiency by changing the optical structure of the devices with the organic capping layer.[7, 8]

Most of the reports up to now have investigated the effects of dielectric capping layer when the total thickness of organic layer in the device is fixed. In this paper, we investigated the influence of the thickness of organic layer (equivalent to cavity length of microcavity structure) on the effect of the dielectric capping layer in phosphorescent top emitting organic light emitting diodes (TOLEDs). To analyze the effects, we calculated 0 degree luminous intensity, angle dependent intensity distribution and device out coupling efficiency as a function of cavity length and capping layer thickness with or without capping layer using classical electromagnetic theory.

2. Theory

The classical electromagnetic theory has been applied to the optical modeling and calculation of the TOLEDs.[10-12] In classical theory, the radiating molecules is modeled as a classical oscillating dipole and the radiation fields in the layered media are described by a dyadic Green's function or Hertzian vector approach that has been applied to OLEDs. From the theory, the normalized damping rate of

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oscillating electric dipoles is proportional to the dissipated power of the dipole.[13] Therefore, we calculate the normalzed damping rate of dipole radiator in 1D microcavity as a function of wavelength. Of course, the capping layer thickness and cavity length are included in the 1D optical microcavity structures as a parameter. From the classical theory, the radiated power from dipole radiator at each wavelength is given by

$$R(\lambda,t,d) = \int_0^{\infty} \mathrm{Re}[S(u,\lambda,t,d)]du \quad (1)$$

where, $R(\lambda,t,d)$ is the radiated power from dipole radiators as a function of wavelength of λ, cavity length of d, capping layer thickness of t. S is electromagnetic fields, which was affected by an optical environment. $\mathrm{Re}[S]$ is the real part of S and u is parallel component of wavenumber of emissive layer k. The electromagnetic field coupled to various optical modes can be classified with parallel component of wave-number u. If $0 \le u \le k_{air}$, the electromagnetic fields will be coupled to radiate mode (escaping to the air). To characterize capping effect with cavity-length, we derived three emission characteristics from the eq.(1) for analysis; i) 0 degree spectrum and luminous intensity, ii) angle dependent intensity distribution, iii) device out-coupling efficiency. To define the 0 degree spectrum and luminous intensity, the angle dependent radiated power from dipole is defined as,

$$U(\lambda,\theta,t,d) = \mathrm{Re}[S(k_{air}\sin\theta,\lambda,t,d)]k_{air}\cos\theta/\pi \quad (2)$$
$$0 \le \theta \le 90^{\circ}$$

where U is the wavelength dependent radiated power at the viewing angle θ. In eq(2), 0 degree spectrum can be calculate by setting the viewing angle zero. From eq. (2), calculated luminous intensity was defined as follows:

$$L(t,d) = \int_{400}^{700} I_{pl}(\lambda)\cdot U(\lambda,0^{\circ},t,d)\cdot V(\lambda)d\lambda \Big/ \int_{400}^{700} I_{pl}(\lambda)\cdot V(\lambda)d\lambda \quad (3)$$

where $V(\lambda)$ is the spectral eye-sensitivities. I_{pl} is normalized photo-luminescent (PL) spectrum. In the optical model, PL is equivalent to an intrinsic radiated spectrum of dipole radiators in the microcavity structure. Optimized device which has the highest optical light output will be characterized at the maximum L. By integrating eq.(2) of all visible wavelength, the second optical character, angle dependent intensity, can be calculated. Therefore angle dependent intensity is represented as

$$U_{tot}(\theta,t,d) = \frac{\int_{400}^{700} I_{pl}(\lambda)\,\mathrm{Re}[S(k_{air}\sin\theta,\lambda,t,d)]k_{air}\cos\theta d\lambda}{\int_{400}^{700} I_{pl}(\lambda)d\lambda} \quad (4)$$

where U_{tot} is the total radiated power from dipoles at the viewing angle. From eq. (4), angle dependent emission patterns can be calculated. Lastly, the out-coupling efficiency (or light extracted efficiency) which is defined as the ratio of the total emitted light to the surface emitted light from dipole radiator is described as follows:

$$\eta_{out}(t,d) = \frac{\int_{400}^{700} I_{PL}(\lambda)\int_0^{k_{air}} \mathrm{Re}[S(u,\lambda,t,d)]\; du d\lambda}{\int_{400}^{700} I_{PL}(\lambda)\int_0^{\infty} \mathrm{Re}[S(u,\lambda,t,d)]\; du d\lambda} \quad (5)$$

where η_{out} is light out-coupling efficiency. In eq(5), the optical performance of TOLEDs relate to external quantum efficiency can be demonstrated for various cavity length of d and capping layer thickness of t. Next section, we will discuss the effect of capping layer for different cavity length and the optical behavior of TOLEDs from theoretical results, which calculated by eq. (2) – (5).

3. Result and discussion

The device configuration for analysis is illustrated in Fig. 1. The devices have iridium tris(phenylpyridine) ($Irppy_3$)– based green double emission layer (D-EML) and organic/inorganic hybrid p-i-n structure for effective charge transport. This p-i-n structure is originated from the technology native to our group.[14] In this study, cavity length is modulated by changing the thickness of p-doped HTL up to 200 nm. The organic material, 1,1,-bis [(di – 4 - tolylamino) phenyl] cyclohexane (TAPC), is employed as the dielectric capping layer on top of the semi-transparent metal cathode to analyze capping effect in the p-i-n TOLEDs. The emission zone is assumed to be located at the interface between D-EMLs as a dipole sheet.

Figure 2 shows the relative luminous intensity as a function of cavity length for uncapped devices. Luminous intensity is dramatically changed as the cavity length varies. It is expected because the emission zone shift from node to antinode of the standing wave of the cavity as the thickness of the hole transporting layer changes in the devices emission spectrum is affected by the cavity length

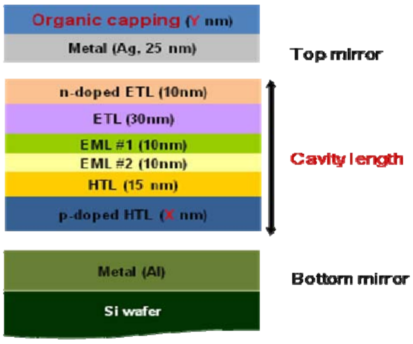

Fig. 1. Schematic diagrams of device model for theoretical study.

represented in the inset of Fig. 2. The inset of Fig. 2 depicts a set of normalized EL spectra of the devices for selected cavity lengths of 100–130 nm. The device with cavity length of 120 nm shows the EL spectrum with the peak positioned at 540 nm wavelength, which is known as the peak position giving the maximum luminous efficiency of TOLEDs.[8]

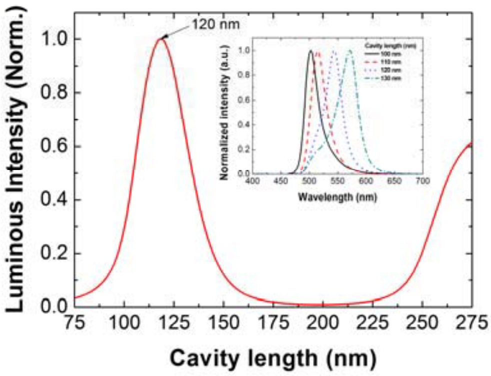

Fig. 2. Calculation results of normalized luminous intensity as a function of cavity length for uncapped device. The inset shows the calculated EL spectrum for selectecd cavity length.

Fig.3 shows the calculation results of normalized luminance as a function of cavity length and capping layer thickness for the emission from Ir(ppy)$_3$. It clearly shows that the optimum thickness of the capping layer in the TOLEDs varies with the change of the cavity length within the devices. To further investigate the cavity length-dependent capping layer effects on the device, the enhancement factors of the luminance (defined as the ratio of the maximum luminance with and without the capping layer) are calculated and plotted in Fig. 4. The enhancement factor notably increases when the cavity length is large than 115 nm. It is interesting to note that the luminance of the uncapped devices shows the maximum value at the cavity length of 120 nm and then decreases with the increase of the cavity length.

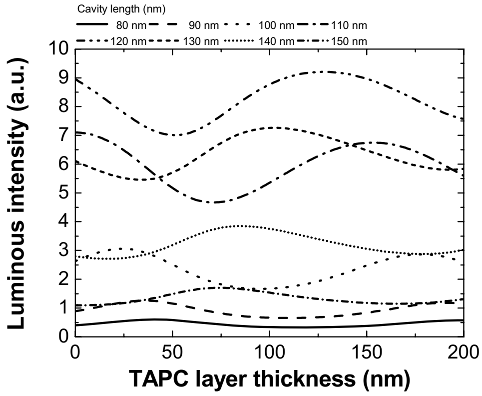

Fig. 3. Calculation results of luminous intensity as a function of capping layer thickness and cavity length.

Additionally, the large enhancement factor (capping effect) of TOLEDs can only be obtained for the uncapped devices with large cavity length, namely, uncapped TOLEDs far from the optimized lcavity length. In other words, if the uncapped device has already reached the maximum luminance (antinode position at the standing wave, Fig.2), no enhancement of the luminance of the devices can be obtained by the capping layer. Luminance was enhanced only when

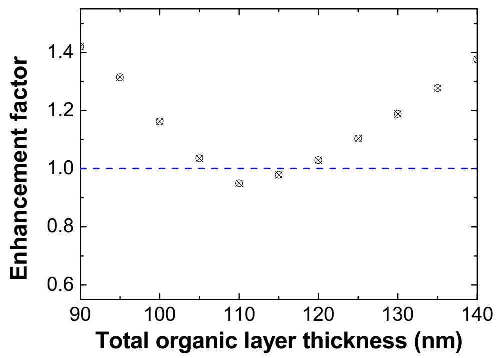

Fig. 4. The enhancement factor which define as the ratio of the maximum luminous intensity with and without the capping layer

the device without the capping layer has the cavity length far from the optimum one. Larger the deviation from the optimum cavity length is larger enhancement is obtained by the capping layer.

To further understand the effect of capping layer in the TOLEDs, the relative luminance intensity and out-coupling efficiency of the devices are calculated and displayed in the Fig. 5(a) and 5(b), respectively. The luminance intensity of the TOLEDs varies significantly with the change of the capping layer and the cavity length. In contrast the out-coupling efficiency of the devices is significantly affected by the cavity length, but in less extent by the capping layer. Further calculation exhibited that the angle dependence of emission spectrum and intensity of TOLEDs are seriously affected by the capping layer. These results indicates that the enhancement of luminance of the TOLEDs by the capping layer is originated from the modulation of the emission spectrum and pattern of the devices rather than the increase of total light output from the device.

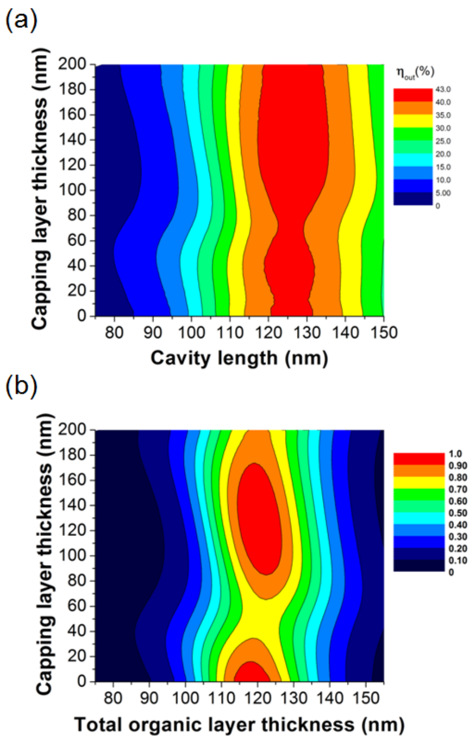

Fig. 5. Calculation results of (a) device out coupling efficiency and (b) luminous intensity as a function of cavity length and capping layer thickness.

4. Summary

We investigated effect of the dielectric capping layer when devices have variety of cavity length. Based on our results, effect dielectric capping layer which contributed to enhancement of luminous intensity was increased or decreased with different cavity length. Additionally, the luminous intensity of the TOLEDs varied significantly with the change of the capping layer and the cavity length. In contrast, the out-coupling efficiency of the devices was also significantly affected by the cavity length, but less affected by the capping layer. Therefore, the outcoupling efficiency and total emission efficiency from the top electrode was not significantly affected by the capping layer. Thereby Enhancement of luminous intensity by a capping layer was achieved not from the improvement of outcoupling efficiency but from modification of spectrum and emission pattern with capping layer thickness.

Acknowledgement

This work was supported by a grant from the Ministry of Knowledge Economy of Korea Government through the center for OLED.

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