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Design and Fabrication of Pure Green Color Microcavity Organic Light Emitting Device

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A pure green microcavity organic light emitting device (MOLED) was designed and fabricated with an emission peak of 552 nm and the full width at half maximum (FWHM) of 24 nm. The maximum luminous efficiency and luminance are 8.4 cd/A at 13 V and 35000 cd/m^2 at 21 V for the MOLED, and 3.2 cd/A at 18 V and 27000 cd/m^2 at 25 V for the normal noncavity OLED. The luminous efficiency, voltage and current density are 6.3 cd/A, 7 V and 1.6 mA/cm^2 for the MOLED, and 2.4 cd/A, 12 V and 4.2 mA/cm^2 for the noncavity OLED at the luminance of 100 cd/m^2. The CIE 1931 chromaticity coordinates of the MOLED at the normal direction is (0.35, 0.62), which shows purer green emission comparing with that of the noncavity OLED (0.36, 0.46). [DOI: 10.1143/JJAP.45.9224]

KEYWORDS: microcavity, OLED, efficient, green emission, pulse color

1. Introduction

Organic light-emitting devices (OLEDs) are very attractive as a new technology for applications in low cost and high brightness flat panel displays.[1–4] For full color display applications, it is very important to obtain pure red, green and blue light in OLEDs. While emission spectra of most organic materials are very broad due to the vibronic sidebands and the strong inhomogeneous broadening of the transitions.[3,4] In order to obtain saturated colors, organic materials with narrow spectrum band such as rare-earth complexes have been used in OLEDs.[5,6] Unfortunately the electroluminescence (EL) properties of those devices so far are not stable.

An optical microcavity is a structure with one or more spatial dimensions on the order of an optical wavelength.[7] In the past few years, Optical cavity has been introduced to normal OLED in order to improve extraction efficiency and purity.[8–10] When placing emitters of light in microcavities, there is expected to be a spectral and spatial redistribution of the emission due to the weak coupling effects of the microcavity. As a result, the spectrum would be narrowed and the emission pattern be non-lambertian determined by the cavity resonance. Microcavity structures can modify the spontaneous properties of the materials inside due to the alteration of the optical mode density within it. Although strong cavity effects were also expected to involve in EL properties of microcavity OLED (MOLED), the reported EL properties such as luminance and luminous efficiency were not satisfying so far.[12–14] One reason is that design of MOLED comes down to refractive indices of multi organic materials, most of which are estimated. The other may be due to the reality that optical quality of distributed Bragg reflectors (DBRs), indium tin oxide (ITO) films and metal films such as phase information, is not easy to obtained. While the phase of a cavity is one of key factors that determines cavity length along with the emission peak, and position of emitted dipoles in a cavity field, which ulteriorly determines luminance and luminous efficiency of a device. In this paper, we report an optimized DBR and cavity structure, based on which an efficient pure green light EL emission device was obtained.

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2. Microcavity Design

The MOLED has a structure of glass/DBR/ITO (139 nm)/4,4-bis[*N*-(1-naphthyl)-*N*-phenyl-amino]biphenyl (NPB) (74 nm)/tris(8-hydroxyquinoline) aluminum (Alq_3):Rubrene (23 nm)/Alq_3 (40 nm)/MgAg (150 nm). NPB was used as the hole transport layer (HTL). Rubrene doped Alq_3 was used as the emitter layer (EML), and Alq_3 as the electron transport layer (ETL). ITO is the anode. MgAg mirror serves as cathode. The DBR consists of 2(1/2) pairs of quarter-wavelength thickness Ta_2O_5 and SiO_2 dielectric layers, and is designed to have a maximum reflectance of 73% at the Bragg wavelength of 550 nm. Ta_2O_5 is the high-index material with a refractive indices n_H of 2.1 and thickness of 65 nm. SiO_2 is the low-index material with a refractive indices n_L of 1.46 and thickness of 94 nm.

Compared with the OLED, MOLED is based on a Fabry–Perot structure in which cavity layers made of the organic materials are surrounded by a DBR on one side, and a metal MgAg mirror on the other side. The resonant wavelength λ_0 of the MOLED is determined by the Fabry–Perot peak condition:[11]

$$\frac{4\pi}{\lambda_0}\sum_i n_i d_i \cos\left[\arcsin\left(\frac{\sin\theta}{n_i}\right)\right] - \varphi_1 - \varphi_2 = 2m\pi \quad (1)$$

where φ_1 and φ_2 are the phase shifts on reflection from the DBR and metal mirror. The third term of the eq. (1) defines the phase thickness of the cavity layers. n_i and d_i are the refractive indices and thicknesses of the cavity layers, θ is the detection angle, and m is an integer. Phase change φ_1 of the DBR is multiples of π at the Bragg wavelength. Phase change of the metal MgAg mirror in the normal direction can be expressed by

$$\phi_m = \arctan\left(\frac{2n_{Alq_3}k_{MgAg}}{n_{MgAg}^2 + k_{MgAg}^2 - n_{Alq_3}^2}\right) \quad (2)$$

where n_{Alq3} is the refractive index of the Alq_3 film, and n_{MgAg} and k_{MgAg} are the real and imaginary parts of the refractive index of the MgAg mirror. The measured refractive indices of ITO, Alq_3, and NPB are 1.98, 1.72, and 1.81 at 550 nm, respectively. The phase of the cavity layers in the normal direction is shown in Fig. 1. The phase change of MgAg is calculated according to eq. (2). In this case, the calculated Φ_m is 2.39 rad, corresponding to a phase

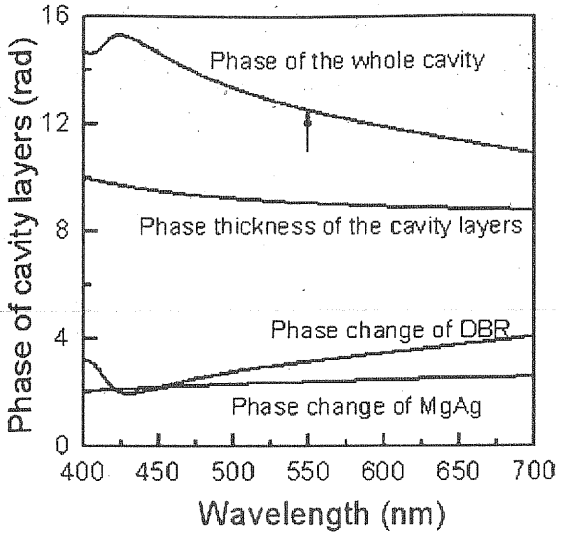

Fig. 1. Phase of cavity layers.

distance of $|\lambda(\pi - \Phi_m)|/4\pi \approx 34\,\text{nm}$ at the metal mirror. It shows that the phase change of MgAg mirror and DBR mirror varies almost linearly within the visible spectral region. The phase change of DBR was calculated by a transfer matrix method, which is also used for analyzing the optical performance of MOLED.[15] The optical thicknesses of Alq_3, NPB, and ITO layer were designed to form a λ (550 nm) cavity. According to eq. (1), the calculated total phase of the cavity is 4π at 550 nm nearby. The refractive index and electrical field distributions in MOLED are shown in Fig. 2. In the design the interface 1 between NPB and Alq_3:Rubrene layers, near where the excitons are formed, is positioned at a optical distance of $\lambda/4$ from the cathode. So the exciton forming zone is around the antinode of the confined cavity field as shown in Fig. 2.

3. Experimental Procedure

The DBR and ITO were grown on a glass substrate by electron-beam evaporations. The organic films and the metal MgAg (under rate ratio 10 : 1) cathode were deposited by vacuum evaporation. EML was formed by co-evaporation of the Alq_3 and Rubrene materials in a deposition rate of 100 : 2. To make comparison, a reference noncavity OLED was fabricated on an ITO-coated glass substrate under the same conditions. Typical active areas were $2 \times 2\,\text{mm}^2$. Refractive indices of the materials used were measured by spectroscopic phase modulated ellipsometer (UVISEL). The photoluminescence (PL) and EL spectra, driven by a DF1730SB5A DC stabilized voltage supply, were measured with a Hitachi spectrophotometer F-4500 in the normal direction from the device surface. The luminance was measured on a ST-86LA screen luminance meter. The transmittance spectra were measured on a Shimadzu dual-wavelength/double-beam recording spectrophotometer UV-3000.

4. Results

The transmittance spectrum of the DBR is shown in Fig. 3 together with the PL spectra of NPB, Alq_3:Rubrene film and the cavity at the excitation wavelength of 355 nm. The emission spectrum of Alq_3:Rubrene is a broad band with the peak of 555 nm and a full width at half maximum (FWHM) of 100 nm, the emission of which comes mainly from Rubrene molecules. The DBR has a maximum reflectance of 73% near the PL peak of Alq_3:Rubrene film. The PL spectrum of the microcavity shows a narrow band emission at 552 nm, which comes from the resonant mode of the cavity and is in good agreement with the designed wavelength. Another PL peak of the microcavity around 450 nm is due to the emission of NPB molecules.

The MOLED has a turn-on voltage of 4 V. The measured EL spectra at 8 V with and without a microcavity in the normal direction are shown in Fig. 4. The EL of the noncavity OLED has the same spectral shape as its PL. The EL peak of the MOLED is at 552 nm and the FWHM is narrowed to 24 nm. The simulated EL spectrum of the MOLED in the normal direction, also shown in Fig. 4, was

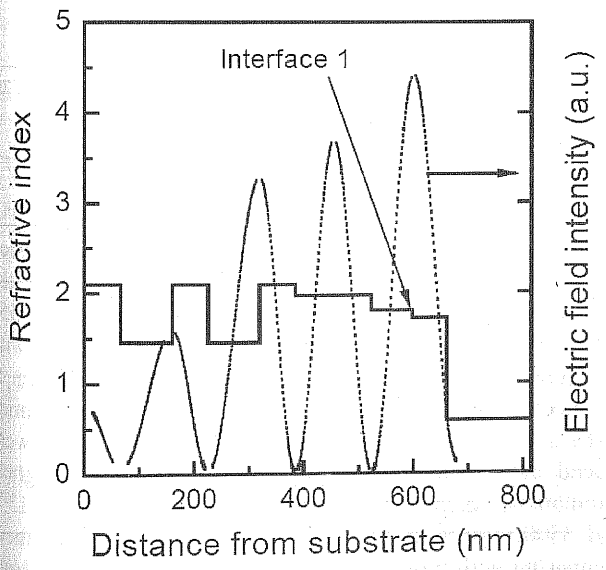

Fig. 2. Refractive index distribution and electric field in MOLED.

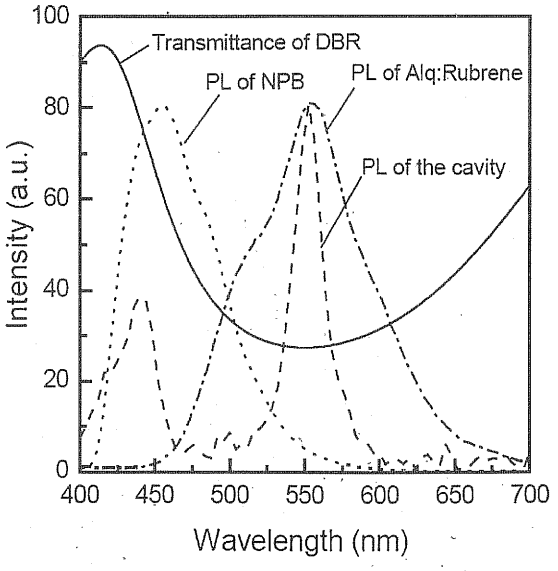

Fig. 3. Transmittance spectrum of the dielectric mirror (line), and PL spectra of NPB film (dot), Alq_3:Rubrene film (dash dot) and the MOLED (dash).

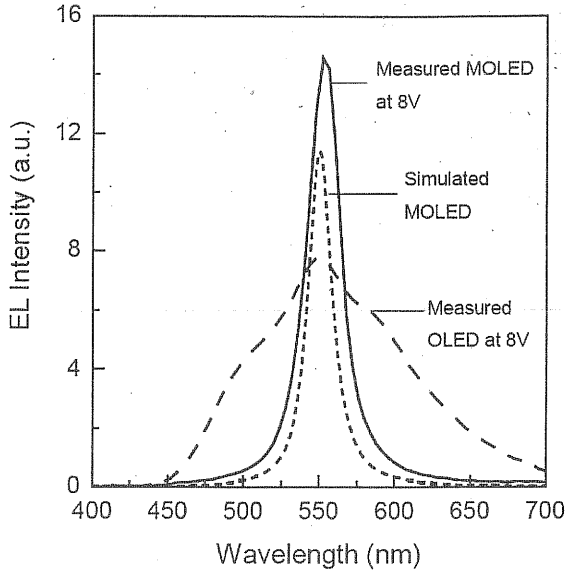

Fig. 4. EL spectra of the MOLED and the noncavity OLED in the forward direction.

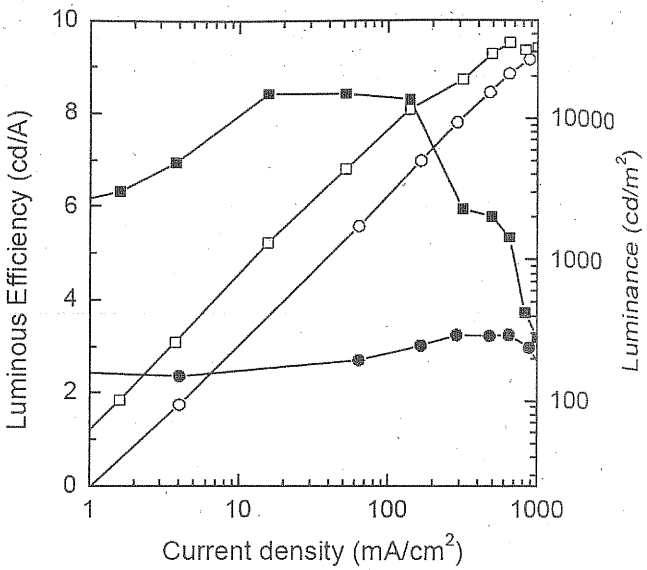

Fig. 5. Dependence of luminous efficiency (solid square: MOLED; solid circle: OLED) and luminance (open square: MOLED; open circle: OLED) on current density.

calculated approximately by the following equation based on classical optics:[7]

$$|E_{cav}(\lambda)|^2 = \frac{(1-R_d)\left[1+R_m+2\sqrt{R_m}\cos\left(\frac{4\pi z}{\lambda}\right)\right]}{1+R_mR_d-2\sqrt{R_mR_d}\cos\left(\frac{4\pi L}{\lambda}\right)}|E_n(\lambda)|^2 \quad (3)$$

where z is the effective distance between the interface 1 and the metal mirror, R_d and R_m are the reflectances of the DBR and metal mirrors, respectively. L is the total optical thickness of the microcavity, and $|E_n(\lambda)|^2$ is the free space EL intensity at λ. In this case, the z includes not only organic layers between the interface 1 and the metal mirror, but also the phase distance of 34 nm resulting from the phase change at MgAg interface. The measured reflectance of MgAg mirror is about 75% at 550 nm. The calculated FWHM of the EL spectrum is 18 nm. The experimentally observed spectrum is a little wider than the simulated one. The reason is due to the light emitting area $2 \times 2\,mm^2$ is so big that light from cavity in different directions can reach the detection window of spectrometer.

Figure 5 shows the dependence of luminous efficiency and luminance on current density of the OLED and MOLED. For the MOLED device, the maximum luminance in the normal direction was 35000 cd/m^2 obtained at 21 V, and the maximum efficiency is 8.4 cd/A at 13 V. While for the noncavity OLED the maximum luminance and efficiency are 27000 cd/m^2 at 25 V and 3.2 cd/A at 18 V, respectively. At the typical luminance of 100 cd/m^2, the luminous efficiency, voltage and current density are 2.4 cd/A, 12 V and 4.2 mA/cm^2 for the noncavity OLED and 6.3 cd/A, 7 V and 1.6 mA/cm^2 for the MOLED, respectively. It can be seen that by introducing the microcavity to OLED the efficiency was improved greatly. Figure 6 shows the CIE-1931 chromaticity coordinates of the EL emission in the normal direction from the MOLED and noncavity OLED. The emission color is pure green with a CIE coordinate of

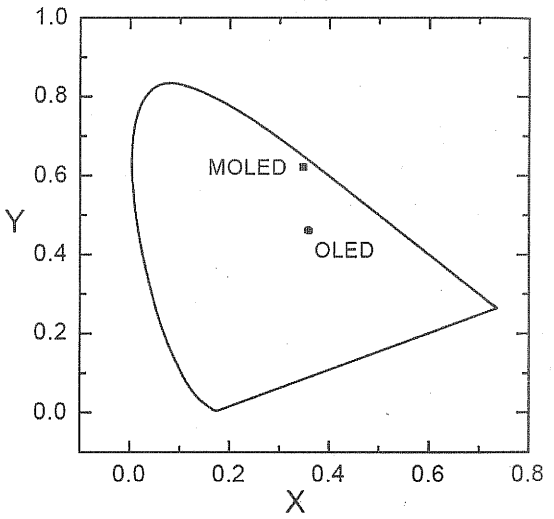

Fig. 6. CIE chromaticity diagram, with the coordinates of the spectra from both the MOLED and the noncavity OLED.

(0.35, 0.62) for the microcavity device, instead of (0.36, 0.46) for noncavity device.

5. Conclusions

We have studied the microcavity effects on OLED. The normal noncavity OLED has a broad free space emission spectrum spanning the range of 450–650 nm, while the MOLED shows a narrowed spectrum with the peak at 552 nm and FWHM of 24 nm, which is in good agreement with the theoretical simulations. By calculating the distribution of the electric field of the microcavity, which were assummed to be at the interface of the Alq_3:Rubrene and NPB, were placed at the antinode of the electric field. The highest luminous efficiency and luminance of 8.4 cd/A at 13 V and 35000 cd/m^2 at 21 V for the MOLED were obtained, comparing with those of 3.2 cd/A at 18 V and 27000 cd/m^2 at 25 V for the noncavity OLED. The results show that the

MOLED is potential to improve the emission efficiency and luminance. The microcavity device has a pure green light emission with the CIE chromaticity coordinate of (0.35, 0.62) comparing with the noncavity one of (0.36, 0.46).

Acknowledgments

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