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Outcoupling EfficiencyImprovement of Planar OLED Devices with Square-based Microlenses

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Keywords: Microlens, efficiency, optical emitting spectrum, CIE coordinate.

ABSTRACT

In this paper, analysis of outcoupling efficiency improvement and optical characteristics of organic light-emitting devices (OLEDs) attached with square-based microlens arrays are presented. A square-based microlens array, having a base length of 35.4 μm and a fill factor of 89.6%, increases the luminous current efficiency and outcoupling efficiency of the OLED device by 42% and 47%, respectively. Optical properties of the OLED device, such as optical emitting spectrum and CIE coordinate, have also been investigated when attached with microlens arrays having different fill factors.

INTRODUCTION

Recently, flat panel displays (FPDs) have become increasing common in a variety of areas of daily life. Use of the technology can be seen in mobile phones, personal digital assistants (PDAs), computer monitors and televisions. The development trends for these devices are aimed toward increasing energy-saving properties of the units, decreasing unit weight and screen thickness, and emphasizing environmental friendliness. With these requirements in mind, liquid crystal displays (LCDs) seem to be the main-stream products used to produce from small to large-sized FPDs.

General speaking, the LCDs are composed of its primary liquid crystal display panel, a backlight module, an electrical system, and various mechanical supports. Since liquid crystal molecules act as a light valve or light switch for the light that is emitted perpendicular to the display panel, the extraction of light from the backlight becomes highly important. The backlight module itself, which includes a cold-cathode fluorescent lamp (CCFL), a light guide plate, a reflector film, diffuser films and prism sheets, is primary light source for the display panel. The diameter of the CCFL is currently no smaller than a few millimeters. Therefore, efforts have been made to minimize the total thickness of the backlight module while at the same time improving the module's luminous current efficiency normal to its surface.

When organic light-emitting devices (OLEDs) are used to replace the backlight modules entirely for use in the LCD, the preliminary goal is to improve luminous current efficiency perpendicular to the emitting surface. There are essentially two ways to increase device efficiency. The first method is to increase the internal quantum efficiency of the OLEDs, which is typically achieved by modifying the thin-film structure in the devices. The second way is to enhance outcoupling coefficient of the device. Because the refractive indices of both the glass and plastic substrates of the OLEDs are approximately 1.5, only about 20-40% of the internal emitted light would be released from the device surface [Lu et al, 2001]. There is thus a large margin for improvement of the outcoupling coefficient of the device. For this reason, extensive research has currently been focused on this topic [Lin et al, 2000; Möller et al, 2002; Choi et al, 2004; Wei et al, 2004, 2006; Peng et al, 2005].

To increase outcoupling coefficient of the OLED, microlens arrays [Möller et al, 2002; Choi et al, 2004; Wei et al, 2004, 2006; Peng et al, 2005] show good results and do almost not alter the optical emitting spectrum of the OLED. However, there are few studies to systematically discuss the influence of microlenses

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on the optical properties of the OLED. Therefore, outcoupling efficiency improvement of the OLED attached with microlens arrays will be studied. The effect of the fill factor of microlens arrays on the other optical properties of the OLED will also be discussed.

BACKGROUND

The luminous current efficiency (E) of a planar OLED device is defined as

$$E = B / J = BA / I \qquad (1)$$

where B, J, A, I are the luminance, current density, active area and current of the OLED, respectively. If the driving current and the active area of the OLED are kept the same, the luminance ratio of the OLED device with microlenses (B_{lens}) to that without microlenses (B_0) should equal the ratio of its luminous current efficiency,

$$B_{lens} / B_0 = E_{lens} / E_0 \qquad (2)$$

where E_{lens} and E_0 are the luminous current efficiencies of the OLED with and without microlenses, respectively.

EXPERIMENTAL

Microlens arrays are made by the combination of photolithography, thermal reflow, molding and UV forming techniques. The process flow for the duplication of microlens arrays is depicted in Figure 1. First, a 4-inch p-typed, test grade (100) silicon wafer is used as a substrate. Second, the photoresist AZ P4620 is spun on the wafer and through photolithography process to make square plates, having a length and thickness of 35.4 and 8.9 μm, respectively. Third, these plates are put on a hot plate that is set at a temperature much higher than the glass transition temperature of these plates. They are left at this temperature for an extended period of some tens hours to transform into the shape of microlenses. Fourth, liquid poly-dimethylsiloxane (PDMS) mixed with its hardener is poured onto the wafer and put in a vacuum oven to be thermally cured. Fifth, the PDMS mold with a microlens array on the mold surface is released by peeling off the wafer and photoresist patterns. Sixth, UV-hardening epoxy OG152 is spin coated on the PDMS mold and then exposed to a specified dose of UV radiation to harden the epoxy. Finally, a free-standing epoxy film with the duplicated microlens array on the film surface is formed after separating the mold from the film.

The luminance of the OLED device without microlenses is first measured as a reference. The refractive-index-matched silicon oil with a refractive index of ~1.5 is then used to reduce the reflection between the OLED and microlens array. All the microlens arrays are attached in turn on the same OLED device. In this study, all the experiments were carried out with the same driving current density and voltage for the OLED with and without microlenses.

For the outcoupling efficiency measurement, the device is attached on a rotational stage. The luminance is then measured at different viewing angles from 0° to 80°. The outcoupling efficiency of the device can be obtained by integration of the luminance intensity times sinθ over θ, where θ is the viewing angle.

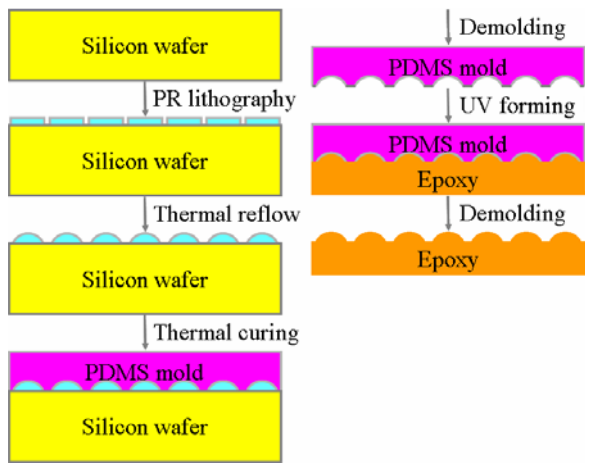

Fig. 1 Schematics of the process flow for the duplication of microlens array.

A source meter (Keithley 2400) is used to supply and monitor the driving current and voltage for the OLED. A spectroradiometer (Minolta CS-1000A) is focused on the active area of the OLED device to measure its luminance, optical emitting spectrum and CIE coordinate.
The base length and gap distance between adjacent photoresist plates (before thermal reflow) are measured using a surface profiler (Alpha-Step 500). The height of the microlenses is analyzed with a scanning electron microscope (Hitach S3500).

RESULTS AND DISCUSSIONSc

When the green OLED device without microlens arrays is driven at a luminance of ~700 cd/m^2, the peak wavelength and full width at half maximum (FWHM) of the optical emitting spectrum are 516 and 95.3 nm, respectively. The CIE coordinate of this OLED device is (0.2741, 0.5324).

The arrangement of microlens array is illustrated in Figure 2. In this study, the fill factor is defined as the ratio of the total area of the base surface of microlenses to the active area of the OLED device. Thus, the relationship among the fill factor (F), the base length (L) and the gap distance (d) can be formulated as follows:

$$F = \left(\frac{L}{L+d} \right)^2 \tag{3}$$

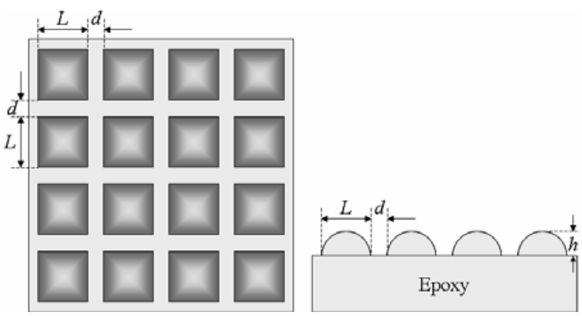

Fig. 2 The arrangement of a microlens array.

A typical duplicated free-standing epoxy film with a square-based microlens array, having a fill factor of 60% and a base length of 35.4 μm, on its surface is shown in Figure 3.

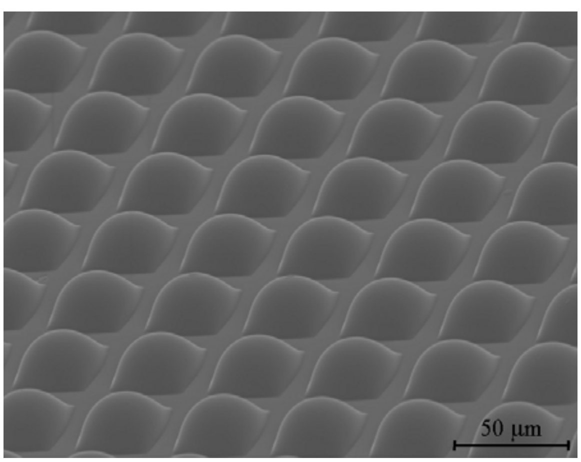

Fig. 3 Microphotograph of a square-based microlens array (tilt: ~60°).

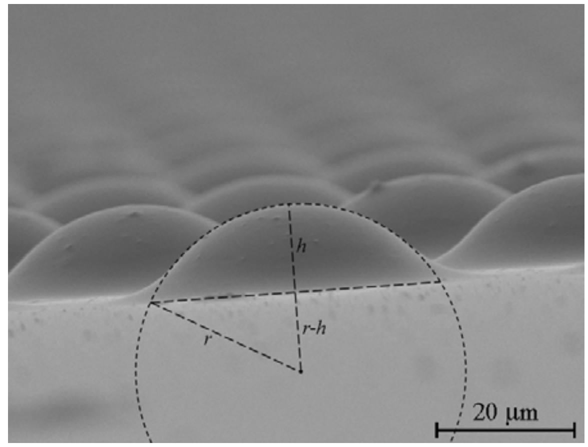

Fig. 4 Schematics of the determination of the height and radius of curvature of a microlens.

Since the height and profile are difficult to measure with commercial surface profilers, for this study they are measured with a scanning electron microscope (SEM). The height (h) and radius of curvature (r) of microlenses are analyzed by curve fitting the microlens contour obtained from the SEM microphotograph, as shown in Figure 4. The height and radius of curvature are 12.9±0.2 and 22.5±0.3 μm by averaging 10 different microlenses.

The variation of the luminance ratio with the fill factor is illustrated in Figure 5 and Table 1. The luminance can be improved by 42% when the OLED is attached with microlens array having a fill factor of 89.6%. It can be found that the luminance ratio increased linearly with the fill factor for the OLED device attached with microlens arrays. This trend is similar to previous works [Wei et al, 2004, 2006]. Analyzing the data in Figure 4, a proportional relationship between the luminance ratio and the fill factor of microlenses can be formulated:

$$B_{lens} / B_0 = k_1 F + k_2 \tag{4}$$

where k_1 is the slope in this curve and k_2 is a constant.

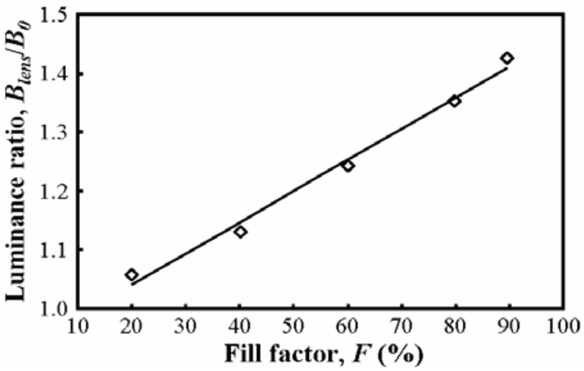

Fig. 5 The relationship between the luminance ratio and the fill factor for microlens arrays.

Table 1 The luminance ratio (or the ratio of luminous current efficiency) and the ratio of outcoupling efficiency of the OLED device attached with microlens arrays having various fill factors.

F	B_{lens}/B_0 (E_{lens}/E_0)	η_{lens}/η_o
no microlens	1	1
20.0%	1.06	1.13
40.1%	1.13	1.25
60.0%	1.24	1.36
79.9%	1.35	1.41
89.6%	1.42	1.47

The ratio of the luminous current efficiency of the OLED device with and without microlens arrays is also derived which is proportional to the fill factor of microlenses from Equations (2) and (4):

$$E_{lens} / E_0 = k_1 F + k_2 \quad (5)$$

If the absorption of the duplicated film integrated with the refractive-index-matched silicon oil is zero, k_2 will be unity. Equation (5) can then be rewritten as

$$\frac{E_{lens} - E_0}{E_0} = k_1 F \quad (6)$$

Thus, k_1 is the enhancement factor of the luminous current efficiency of the OLED device when the emitting surface of the device is fully occupied with microlenses.

The ratio of the outcoupling efficiency of the OLED device with microlens array to that of the OLED device without microlenses is described in Table 1. The ratio of outcoupling efficiency increases with increasing the fill factor of the duplicated microlens array. That is, microlens array can effectively improve the outcoupling efficiency of the OLED device. The outcoupling efficiency of the OLED device can be enhanced up to 47% when attached with microlens array having a fill factor of 89.6%.

The optical emitting spectrum of the OLED device with the microlens array is depicted in Figure 6. The OLED device with microlenses of a greater fill factor is shown to possess a more significantly blue shift since the microlenses cancel out the effect of the waveguiding mode and out-couple the light with shorter wavelengths.

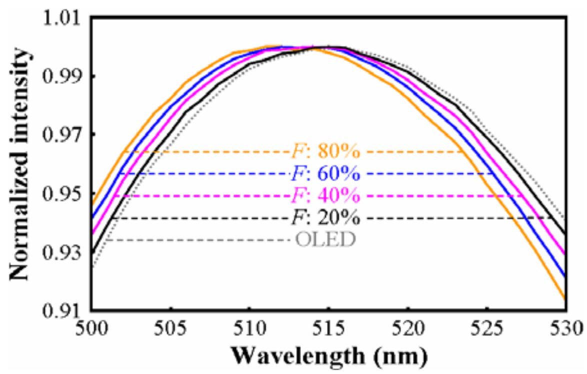

Fig. 6 The optical emitting spectra of the OLED device attached with microlens arrays having different fill factors.

The shift of the peak wavelength ($\Delta\lambda_{peak}$), defined as the difference of the peak wavelength between the optical emitting spectrum of the OLED device with and without microlens arrays, decreases linearly with increasing the fill factor of microlenses, as seen in Figure 7. The difference of the FWHM (ΔFWHM) between the optical emitting spectrum of the OLED device with and without microlens arrays also linearly decreases when the fill factor of microlens arrays increases. That is, the emitting color not only shifts towards blue, but the OLED device also shows a slightly purer color when attached with microlens arrays that have a greater fill factor.

Analyzing the data in Figure 7, proportional relationships among the $\Delta\lambda_{peak}$, ΔFWHM and the fill factor of microlenses can be formulated:

$$\Delta\lambda_{peak} = k_3 F + k_4 \quad (7)$$

$$\Delta FWHM = k_5 F + k_6 \quad (8)$$

where k_3 and k_5 are the slops , and k_4 and k_6 are constants in these two curves, respectively. If there are no microlenses on the duplicated films (F = 0), k_4 and k_6 should approach zero. Therefore, k_3 and k_5 are the shift of peak wavelength and the difference of the FWHM between the OLED device fully covered with and without microlenses, respectively.

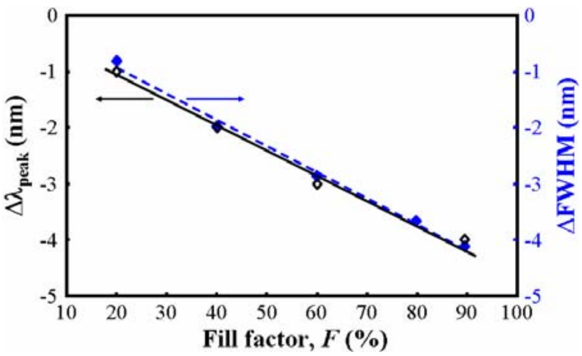

Fig. 7 The variations of the $\Delta\lambda_{peak}$ and the ΔFWHM with the fill factor of microlenses.

The difference of the CIE indices (ΔCIE-X and ΔCIE-Y) between the OLED device with and without microlenses is described in Figure 8. Though the ΔCIE-X decreases linearly with the fill factor of microlenses, the variance is miniscule. Initially, the ΔCIE-Y remains almost constant at a fill factor less than 40%, then decreases with further increasing the fill factor of microlenses; however, the variance is also minimal.

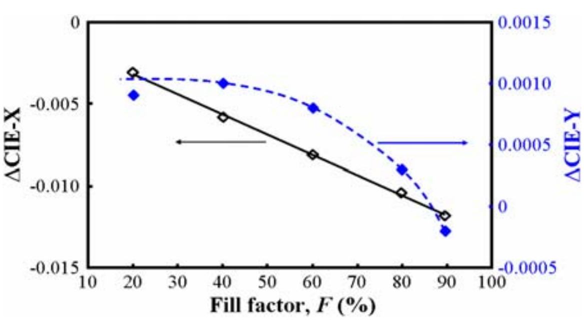

Fig. 8 The variations of the ΔCIE-X and ΔCIE-Y with the fill factor of microlenses.

Therefore, the luminous current efficiency normal to the OLED device surface can be improved by attaching microlen arrays. The higher the fill factor of microlenses, the more improvement the OLED device. In addition, the variation of the optical properties of the OLED device due to the attachment of microlens arrays can be ignored for the backlight applications.

CONCLUSIONS

The luminous current efficiency normal to the OLED surface increases linearly with the fill factor of microlenses. The outcoupling efficiency of the OLED device also increases with increasing the fill factor of microlens array. The $\Delta\lambda_{peak}$ and ΔFWHM of the optical emitting spectrum of the OLED device also decrease linearly with increasing the fill factor of microlenses. Though both the ΔCIE-X and ΔCIE-Y decrease with increasing the fill factor of microlenses, their variations are extremely small for the backlight applications. Therefore, the microlens array with a high fill factor is preferred to be attached on the OLED device to increase its luminous current efficiency.

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REFERENCES

Lu, M.-H., and Sturm, J. C., “External coupling efficiency in planar organic light-emitting devices”, *Appl. Phys. Lett.*, Vol. 78, pp. 1927-1929 (2001)

Lin, L., Shia, T. K., and Chiu, C.-J., “Silicon-processed plastic micropyramids for brightness enhancement applications”, *J. Micromech. Microeng.*, Vol. 10, pp. 395-400 (2000)

Möller, S., and Forrest, S. R., “Improved light out-coupling in organic light emitting diodes employing ordered microlens arrays”, *J. Appl. Phys.*, Vol. 91, pp. 3324-3327 (2002)

Choi, H. W., Liu, C., Gu, E., McConnell, G., Girkin, J. M., Watson, J. M., and Dawson, M. D., “GaN micro-light-emitting diode arrays with monolithically integrated sapphire microlenses”, *Appl. Phys. Lett.*, Vol. 84, pp. 2253-2255 (2004)

Wei, M.-K., and Su, I-L., “Method to evaluate the enhancement of luminance efficiency in planar OLED light emitting devices for microlens array”, *Opt. Exp.*, Vol. 12, pp. 5777-5582 (2004)

Peng, H., Ho, Y. L., Yu, X.-J., Wong, M., and Kwok, H.-S., “Coupling efficiency enhancement in organic light-emitting devices using microlens array-theory and experiment”, *J. Display Technol.*, Vol. 1, pp. 278-282 (2005)

Wei, M.-K., Su, I-L., Chen, Y.-J., Chang, M., Lin, H.-Y., and Wu, T.-C., “The influence of a microlens array on planar organic light-emitting devices”, *J. Micromech. Microeng.*, Vol. 16, pp. 368-374 (2006)

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以方底微透鏡增益平面發光二極體元件外部耦合效率之研究

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摘 要

本論文分析貼附方底微透鏡陣列之有機發光元件，其外部耦合效率的增益與光學特性，本研究使用底部邊長 35.4 µm 以及充填比例 89.6 %之方底微透鏡陣列，可分別提昇有機發光二極體元件之光電效率 42 % 以及外部耦合效率 47 %。此外，貼附不同充填比例微透鏡陣列之有機發光二極體元件，其光學特性，如發射光譜和 CIE 座標也在探討之列。