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High efficiency and low power consumption in active matrix organic light emitting diodes

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Abstract

Phosphorescent full color 2.2 inch quarter common intermediate format (QCIF) active matrix organic light emitting diodes (AMOLED) have been developed for mobile phone application. Red and green phosphorescent emitters have been adopted as light emitting components and the efficiency of the AMOLED as measured was enhanced up to 10.9 cd/A at a white brightness of 100 cd/m^2. The power consumption of the AMOLED was reduced below 200 mW due to high efficiency and low driving voltage.

1. Introduction

In recent years active matrix organic light emitting diodes (AMOLED) have attracted great attention due to its advantages such as light weight, short response time, low driving voltage, wide color gamut, wide viewing angle, high brightness and low power consumption. Especially, the power consumption of AMOLED can be reduced below 200 mW compared with 240 mW for AMLCD if high efficiency organic materials are used. Power consumption of AMOLED is closely related with the light efficiency and operating voltage of light emitting components. Highly efficient EL materials give low power consumption for AMOLED because they can reach required brightness at a low current level. It is essential to improve the light efficiency to fabricate a low power consuming AMOLED.

Efficiency of the OLEDs mainly depends on the material efficiency and device structure [1]. In general, light emitting efficiency of OLEDs can be expressed by the following relation:

$$\eta_{ext} = \eta_o \eta_{ex} \phi_p \gamma$$

where η_{ext} is the external quantum efficiency of OLEDs, η_o the out-coupling efficiency which is assumed to be 20% for a glass substrate with refractive index of 1.5 and organic layer with refractive index of 1.7 [2,3]. η_{ex} is the fraction of total exitons formed which result in radiative transition, which is about 0.25 for fluorescent EL materials and 1 for phosphorescent materials. γ is the fraction of opposite charges which combine to form the exiton, which is less than 1 in most cases. ϕ_p is the intrinsic quantum efficiency for radiative decay. η_o is typically dependent on structural factors such as refractive index, organic layer thickness and ITO thickness, while η_{ex}, ϕ_p and γ are closely

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connected with material properties as well as structural factors.

Several approaches have been pursued to maximize the device efficiency from material point of view. Phosphorescent EL materials are very effective to increase the light emitting efficiency of OLEDs because they use the triplet state of an organic molecule for light emission. Phosphorescence is distinguished from fluorescence in that fluorescence emits light from only singlet state, while phosphorescence uses both singlet and triplet state for light emission [4–7]. Therefore, theoretical maximum internal quantum efficiency for phosphorescence reaches 100% compared with 25% for fluorescence. Adachi et al. reported nearly 100% internal quantum efficiency in phosphorescent OLED using bis(2-phenylpyridine)iridium(III) acetylacetonate doped into 3-phenyl-4-(1′-naphthyl)-5-phenyl-1,2,4-triazole [8]. Maximum external quantum efficiency of 20% and luminous power efficiency of 60 lm/W were achieved in the phosphorescent devices. Ikai et al. obtained maximum external quantum efficiency of 19.2% and peak power efficiency of 70 lm/W using starburst perfluorinated phenylenes as a hole blocking layer [9]. However, there have been no reports about the application of phosphorescent material to real AMOLED panels.

In this work, the efficiency and power consumption of the AMOLED fabricated using phosphorescent light emitting materials will be discussed. The optimization of the R, G, B structure for the high efficiency and low power consumption was investigated.

2. Experimental

The AMOLED structure used in this work is shown in Fig. 1. The organic electroluminescent materials were deposited on low temperature polysilicon TFTs with aperture ratio of 32%. The EL layers were made up of a hole injection layer, a hole transport layer, a light emitting layer, a hole blocking layer, an electron transport layer from ITO side. Lithim fluoride (LiF)/aluminum double layer was adopted as a cathode for the AMOLED. Charge transport layers including a hole injection

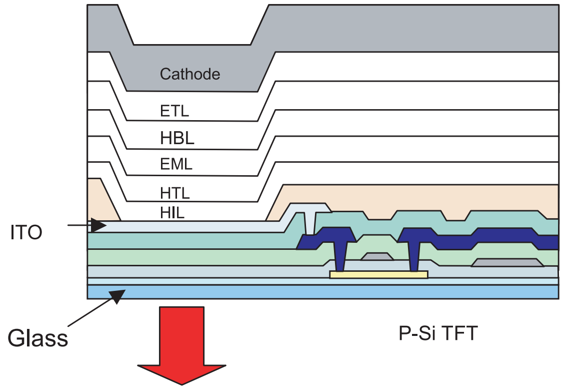

Fig. 1. Schematic diagram of AMOLED structure. (This figure is available in color, see the on-line version.)

layer (HIL), hole transport layer (HTL), hole blocking layer (HBL) and electron transport layer (ETL) were introduced as common layers for RGB and RGB light emitting layers were deposited separately using a fine metal shadow mask. A starburst type amine material, 1,3,5-tris(*N*,*N*′-bis-(4,5-methoxyphenyl)-aminophenyl)-benzol (TDAPB) was used as a hole injection material at a thickness of 50 nm and a hole transport material was 4,4′-bis[*N*-(1-naphthyl)-*N*-phenylamino]biphenyl (NPB, 30 nm). 4,4′-*N*,*N*′-dicarbazole-biphenyl (CBP, 30 nm) was a host for the light emitting layer and bis(2-phenylquinoline)iridium tetramethylheptanedione and *fac* tris(2-phenylpyridine)iridium ($Ir(ppy)_3$) were used as dopants for red and green light emitting layers, respectively. Biphenoxy bi(8-quinolinato)aluminum (Balq, 5 nm) was used as a hole blocking layer and tris(8-quinolinato)aluminum (Alq_3, 20 nm) was used as an electron transport layer. The TFT substrates were cleaned with deionized water in an ultrasonic bath for 30 min and washed with boiled isopropyl alcohol. The substrates were baked for 60 min at 180 °C after cleaning and were treated with UV–ozone for 15 min. All organic materials and metal cathodes were deposited in a high vacuum chamber (10^{-7} Torr).

Current density (I)–voltage (V)–luminance (L) characteristics of the OLED were measured with PR 650 spectrometer and the lifetime results of the RGB devices were obtained at a constant current mode at a brightness of 600, 800 and 400 cd/m^2 for RGB, respectively.

3. Results and discussion

The pixel driver for the AMOLED was composed of two p-type thin film transistors (TFT) and one storage capacitor. The schematic diagram of the pixel driver is shown in Fig. 2. The switching TFT (T1) is employed to select a specified pixel and transfer data through data line. The data is stored in storage capacitor (Cst) during one period. The currents injected to organic luminescent emitting diode is adjusted by a driving TFT (T2). Detailed experimental procedure for the TFT substrates preparation will not be described here. Detailed specification for the 2.2 inch AMOLED is summarized in Table 1.

The optimization of the EL structure for full color OLED was carried out using optical simulation. The light emitting layer was assumed to be a point source and the refractive index of the organic layer was assumed to be 1.7. Blue color index is very sensitive to the thickness of the common organic charge transport layer, especially ETL, while red and green color index is insensitive to the thickness. Therefore, the EL structure optimization was focused on blue color. The optical simulation results for efficiency and color index of blue are shown in Fig. 3 according to the thickness of ETL and HTL. The blue color area which reflects the color coordinates gives a maximum value at low ETL thickness and at a thickness of 1200 Å. On the other hand, the luminance shows a maximum value at a thickness range between 400 and 600 Å. Considering these two results, the thickness of the ETL layer which includes EML, HBL and ETL should be in the range between 400 and 600 Å to get a large color gamut and a luminance efficiency. The thickness of the HTL layer had little effect on the color coordinates and luminance compared with ETL thickness.

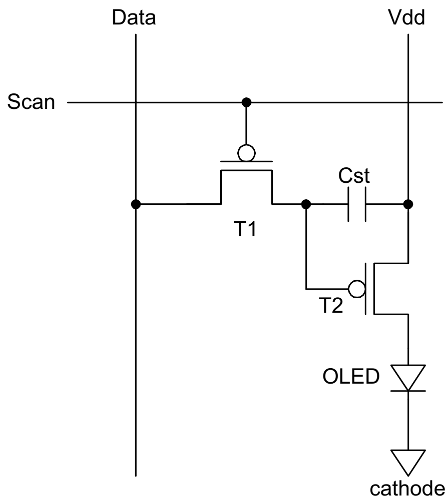

Fig. 2. Schematic diagram of drive pixel diode.

Table 1
Specification of the 2.2 inch AMOLED

Display size	2.2 inch quarter common intermediate format
Pixel number	176 (RGB)×220
Pixel pitch	66×198 μm (128 ppi)
Aperture ratio	32%
Gray scale	64
TFT mobility (μ)	88–89 $cm^2/V\,s$
Color coordinates	(0.31, 0.32)
Power consumption	200 mW

Based on the simulation results, the thickness of the organic layer and dopant concentration were optimized. Common charge transport layers were used for RGB colors. Phosphorescent dopant concentration for the red and green was 12% and 5%, respectively, and fluorescent dopant concentration for the blue was 3%. The IVL data for the red, green and blue are summarized in Table 2. The operating voltage for the RGB at white 100 cd/m^2 was lower than 6 V for all three colors and luminance efficiency was 10, 22.2 and 6.8 cd/A for RGB colors, respectively. The efficiency of the red and green was quite high compared with blue because phosphorescent dopants which use both singlet and triplet state for light emission were adopted as light emitting components. The color coordinate of the white was (0.31, 0.32) and white luminance efficiency was 10.9 cd/A, which is higher than any other data reported in the literature [10,11]. The power efficiency of the white was 6.8 lm/w. The introduction of the phosphorescent material in red and green colors resulted in a high efficiency in AMOLED and device structure optimization gave low operating voltage for the devices. The color gamut of the device was 60% at white 100 cd/m^2 condition.

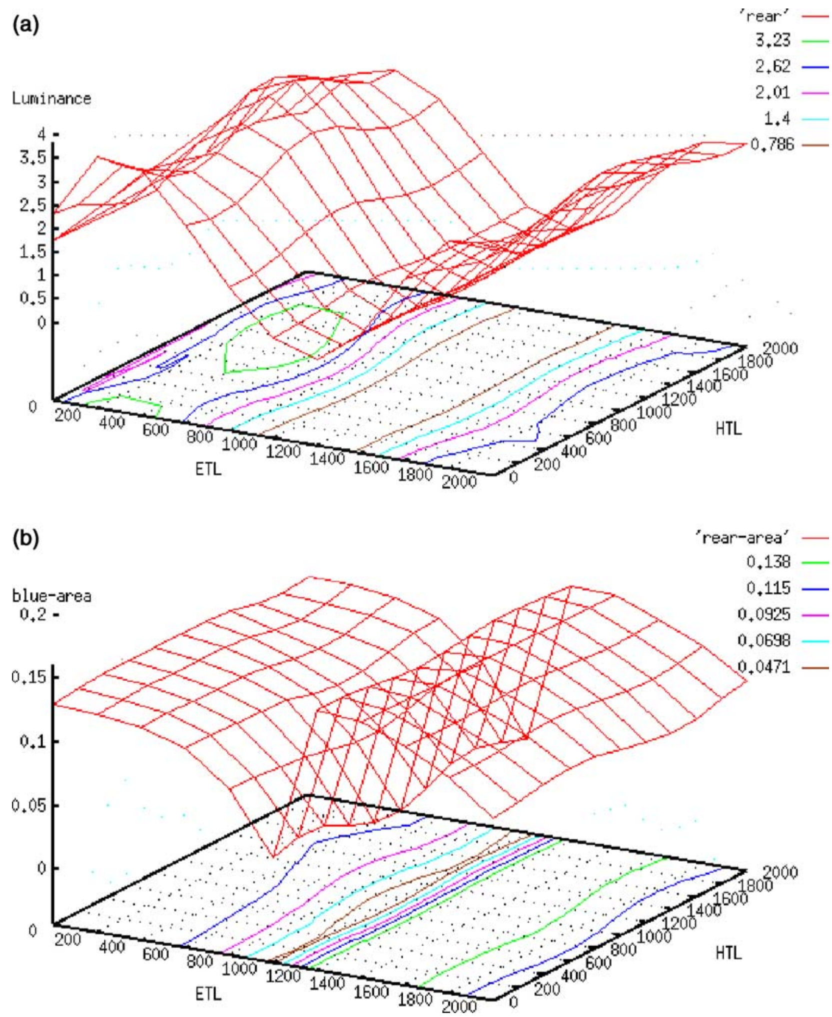

Fig. 3. Optical simulation result for luminance (a) and color index (b) of blue material according to HTL and ETL thickness. (This figure is available in color, see the on-line version.)

Table 2
IVL characteristics of the RGB colors

Color	Red	Green	Blue	White
Efficiency (cd/A)	10.0	22.2	6.8	10.9
CIE	(0.63, 0.37)	(0.28, 0.62)	(0.14, 0.16)	(0.31, 0.32)

The power consumption of the phosphorescent device was reduced considerably because the luminance efficiency was higher than 10 cd/A and the driving voltage was lower than 6 V. The power consumption of the device at 100 cd/m^2 with 30% pixel on was less than 200 mW compared with 350 mW for fluorescent display. The relative contribution of fluorescent blue color for the power consumption in phosphorescent AMOLED was almost 50% for the total device power consumption because of low efficiency of blue emitter. Therefore, the power consumption of AMOLED can be reduced significantly if high efficiency blue phosphorescent dopant is adopted as a blue emitter.

The lifetime curves of RGB colors were plotted in Fig. 4. The lifetime of RGB was measured at white 100 cd/m^2 condition, which corresponds to 600, 800 and 400 cd/m^2 for RGB, respectively. The lifetime of phosphorescent materials is greatly dependent on the hole and electron charge balance and the distribution of the recombination region in light emitting layer. Therefore, the control of the thickness of charge transport layers is critical to the lifetime of the phosphorescent materials. In particular, the thickness of electron transport layer and hole blocking layer is important for the lifetime and efficiency. Thick electron transport layer and hole blocking layer lead to the increase of luminance efficiency, but poor lifetime. The optimum thickness for the lifetime did not correspond to the optimum structure for the luminance and efficiency. The lifetime of red and green phosphorescent materials for the optimized device structure by allowance for lifetime and efficiency is expected to be over 10,000 h at required brightness. In addition, the lifetime of fluorescent blue is also expected to be 10,000 h. These results indicate that the red and green phosphorescent materials can secure stable operation of the OLED as well as high efficiency for mobile phone application. The picture for the 2.2 inch AMOLED using red and green phosphorescent materials is shown in Fig. 5. The peak luminance of the device was over 300 cd/m^2.

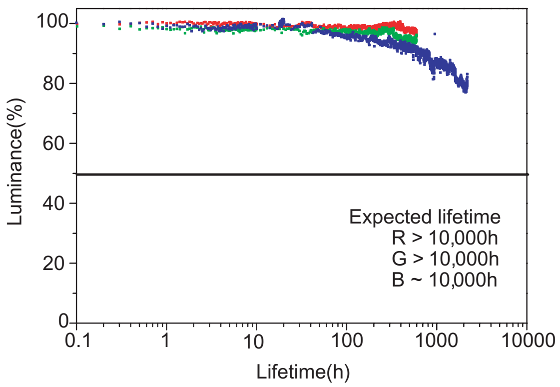

Fig. 4. Lifetime of RGB colors at required brightness. (This figure is available in color, see the on-line version.)

Fig. 5. Picture for the 2.2 inch AMOLED. (This figure is available in color, see the on-line version.)

4. Conclusion

2.2 inch AMOLED was developed successfully using phosphorescent red and green dopants in light emitting layer. The introduction of phosphorescent materials gave high efficiency of 10.9 cd/A for white color and driving voltage of lower than 6 V, which resulted in the low power consumption of less than 200 mW at white 100 cd/m^2. In addition, the lifetime of the phosphorescent materials was extended over 10,000 h at the required brightness by optimizing device structure.

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References

[1] M.A. Baldo, D.F. O'Brien, Y. You, A. Shoustikov, S. Sibley, M.E. Thompson, S.R. Forrest, Nature (London) 396 (1998) 151.
[2] N.C. Greenham, R.H. Friend, D.D.C. Bradley, Adv. Mater. 6 (1994) 491.

[3] G. Gu, D.Z. Garbuzov, P.E. Burrows, S. Vankatsh, S.R. Forrest, M.E. Thompson, Opt. Lett. 22 (1997) 396.
[4] D.F. O'Brien, M.A. Baldo, M.E. Thompson, S.R. Forrest, Appl. Phys. Lett. 74 (1999) 442.
[5] M.A. Baldo, M.E. Thompson, S.R. Forrest, Pure Appl. Chem. 71 (1999) 2095.
[6] M.A. Baldo, D.F. O'Brien, M.E. Thompson, S.R. Forrest, Phys. Rev. B 60 (1999) 14422.
[7] M.A. Baldo, S. Lamansky, P.E. Burrows, M.E. Thompson, S.R. Forrest, Appl. Phys. Lett. 75 (1999) 4.
[8] C. Adachi, M.A. Baldo, M.E. Thompson, S.R. Forrest, J. Appl. Phys. 90 (2001) 5048.
[9] M. Ikai, S. Tokito, Y. Sakamoto, T. Suzuki, Y. Taga, Appl. Phys. Lett. 79 (2001) 156.
[10] J.L. Sanford, E.S. Schlig, Society for Information Display 2001, San Jose, USA, 2001, p. 376.
[11] N. Komiya, R. Nishikawa, M. Okuyama, T. Yamada, Y. Saito, S. Oima, K. Yoneda, H. Kanno, H. Takahashi, G. Rajeswaran, M. Itoh, M. Boroson, T.K. Hatwar, in: EL 2000, Hamamatsu, Japan, 2000, p. 347.