27.4: Top-emitting Organic Light-Emitting Diode using Nanometer Platinum Layers as Hole Injector

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Abstract

Top-emitting organic light emitting diodes (Top-OLED) were made with platinum (Pt) and praseodymium oxide (Pr_2O_3) as the anode buffer. ITO on thin Al was used as the transparent cathode. Efficient Top-OLED were obtained with a microcavity design. It was found that this Top-OLED was highly non-Lambertian. It emitted 10% more photons than conventional bottom-emitting-OLED after integration over all angles.

1. Introduction

Organic light-emitting diode (OLED) [1] is challenging liquid crystal display (LCD) as an alternative flat-panel display technology because of its ease of manufacturing and its all solid-state nature. As well, its faster switching speed and being self-emitting with a wider viewing angle are quite useful in applications.

While passive matrix OLED can be applied to small displays, active matrix OLED, consisting mostly of thin film transistors (TFT) on glass, are needed for higher information content displays [2,3]. Active matrix displays also have lower average drive currents compared to passive matrix displays. Since the lifetime of an OLED is approximately inversely proportional to the driving current, active matrix OLED therefore in principle should have longer lifetimes than passive ones.

Because OLED display is a current driven device, so more than two transistors are needed to drive each pixel [3,4]. Some pixel designs have even more transistors per pixel due to the need to reduce sensitivity to transistor characteristics. Thus the aperture ratio of active matrix OLED is significantly diminished, if the device employs the conventional bottom-emitting design. This is not desirable as it limits the resolution of the display and increases the current loading of the OLED. The lifetime is also reduced [5].

Top-emitting organic light-emitting diodes (Top-OLED) will eliminate the problem of reduced aperture ratio for TFT on glass displays [6]. With a top emitting structure, the TFT can be hidden below the organic emitting layers. Aperture ratio in the 90% range can be achieved in principle. Such Top-OLED is also required for displays fabricated on opaque substrates such as on silicon [7-9]. Even for passive matrix OLED, a Top-OLED structure will allow the use of non-transparent or even absorbing substrates.

Top-OLED theoretically can also have higher emission efficiency because of the accompanying microcavity effect, which eliminates substrate waveguide loss [10,11]. However, Top-OLEDs fabricated on silicon, or coated aluminum on silicon are less efficient than conventional bottom-emitting [7-9]. Since the efficiency of OLED is sensitively dependent on the nature of the electrodes [12-14], the low emission efficiency is probably due to the lack of a good anode.

It has been reported that thin platinum (Pt) film [15] and thin praseodymium oxide (Pr_2O_3) film [16] can improve the hole injection of OLED. In this paper, we report a Top-OLED design using nanometer thick Pt(15Å) and Pr_2O_3(10Å) coated on n-type silicon or on pre-coated Al glass as anode. This Top-OLED is based on copper (II) phthalocyanine (CuPc) as the organic buffer layer, N,N'-diphenyl-N,N' bis(3-methylphenyl-1,1'-biphenyl-4,4'-diamine (TPD) as the hole transport layer, tris-8-hydroxyquinoline aluminium (Alq_3) as an emitting/electron-transport layer, and LiF(10Å)/Al(150 Å)/ITO(800 Å) as the cathode. This structure was found to be an efficient Top-OLED, with an emission efficiency higher than that of a conventional bottom emitting OLED.

The cathode is the same as a conventional device and consists of LiF and Al. In the Top-OLED however, the Al is made very thin and current conduction is enhanced by an additional thick layer of ITO, in order to make the cathode semi-transparent. It was found that efficient Top-OLED could be obtained with such a design. This Top-OLED was highly non-Lambertian due to the microcavity effect. It emitted 10% more photons than conventional bottom-emitting-OLED after integration over all angles.

2. Top-emitting OLED Fabrication

The starting substrates were heavily doped n-type silicon (device Type S) or Al (100nm) coated on glass (device Type G). The sequence of pre-cleaning prior to loading into the evaporation chamber consisted of ultra-sonic DI water soaking for 30mins, oven bake-drying for 1-2hrs and UV/O_3 illumination for 9mins [17].

Nanometer thick Pt and Pr_2O_3 were sequentially evaporated using 99.99% pure Pt wire and Pr_2O_3 powder loaded in resistively heated evaporation cells. The deposition rate was 0.01-0.03nm/s. After the evaporation, the samples were subjected again to DI water rinse and UV/O_3 treatment.

The constituent organic layers for the OLED were next deposited using thermal vacuum evaporation of commercial grade CuPc, TPD and Alq_3 powders. The base pressure in the evaporator was ~8μTorr. The deposition rates of the organic thin films were 0.2-

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0.4nm/s. The anode consisted of Pt(1.5nm)/ Pr_2O_3(1nm). The cathode consists of 0.1nm lithium fluoride (LiF) topped with 15nm aluminum (Al) then DC sputtered with 80nm ITO. The deposition rates of LiF, Al and ITO were 0.02-0.05nm/s, 1-1.5nm/s, and 0.05nm/s, respectively. Film thicknesses were determined *in situ* using a crystal monitor.

Three types of OLEDs were fabricated for comparison:

Type C: Glass/ITO(75nm)/CuPc(20nm)/TPD (40nm)/Alq_3(50nm)/LiF(1nm)/ Al(150nm).

Type S: n-type Si/ Pt(1.5nm)/ Pr_2O_3(1nm)/CuPc /TPD/Alq_3/LiF(1nm)/Al(15nm)/ITO(80nm).

Type G: Glass/ Al(100nm)/ Pt(1.5nm)/Pr_2O_3(1nm) /CuPc/TPD/ Alq_3/LiF/Al/ITO.

Type C is a control device, while Type S and G are the new structures under test. Unless specified otherwise, the thickness values of the various films in device Types S and G are the same as those of the corresponding films in the Type C control conventional bottom-emitting diode sample. The structures of the OLEDs are shown in Fig. 1.

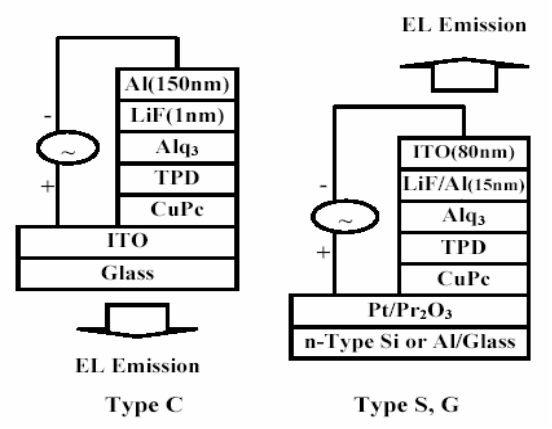

Figure 1. Schematics of the T-OLED structures studied, Type C is the control

The devices were characterized in room ambient and temperature without further encapsulation. EL intensity was measured using a PR650 SpectraScan spectrophotometer. Current-voltage (I-V) characteristics were measured using a Advantest R6145 DC Voltage Current Source and Fluke 45 Dual Display Multimeter.

3. Results

The luminance-current density (*L-J*) and voltage-current density (*V-J*) characteristics of Types S, G and C diodes are shown in Fig. 2.

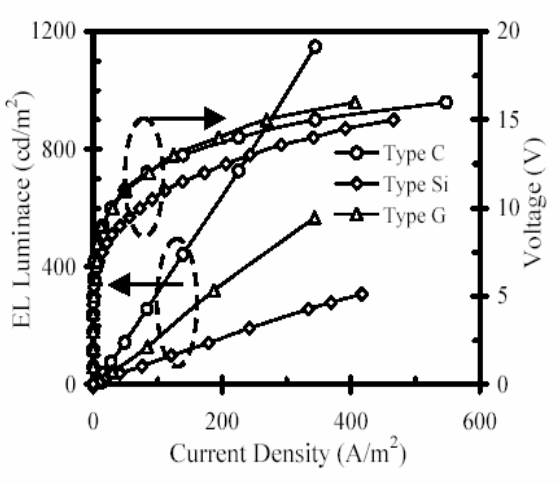

Figure 2 The EL Luminance (L) in normal direction Current Density (J) –Voltage (V) characteristics of the T-OLED and conventional bottom emitting OLED

Compared to those of the Type C reference diode, it can be seen that the voltage (*V*) at the given current curve is decreased slightly. This is the result of enhancement of hole injection by the Pt and Pr_2O_3 layers [15,16]. We attempted to measure the resistance of the 1.5nm and 2.5nm thickness of Pt film on glass. They were too large to be measured using the four-point sheet resistance analyzer. Hence the 1.5nm thick Pt is an insulator along the OLED surface. This is important in device fabrication as the coated 1.5nm Pt on the TFT should not short out the TFT across different pixels. We have also fabricated similar Top-emitting diodes without the Pt and Pr_2O_3 layers. The resulting diodes are only weakly emitting, especially using Al film as the anode.

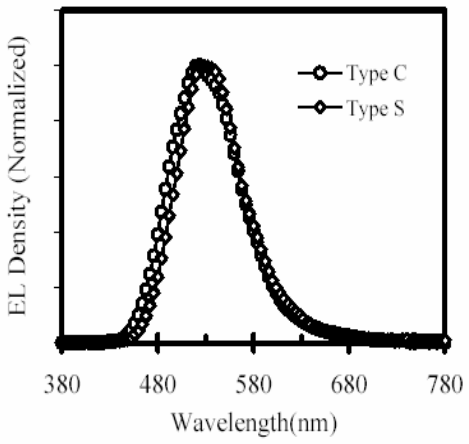

Figure 3. EL Spectra of Type S and C OLED

The measured luminance *L* at a given current density is decreased for Type S and G diodes as compared with Type C in the normal direction. Type S has the lowest luminance. This is true only in the normal direction, and is due to the microcavity effect. For Type S and G devices, both the top and bottom electrodes are

reflecting. The bottom anode mirrors have reflectivities of around 45% and 90%, for Si and Al, respectively. Both devices have the same top cathode layers consisting of a thin layer metal and an ITO layer. The reflectivity of this top layer is about ~50%. Depending on the device thickness, this reflectivity generally causes a lower luminance in the normal direction of devices Type S and G as compared with the conventional Type C device. The lowest luminance of Type S is caused by lower reflectivity of the bottom Si layer as well.

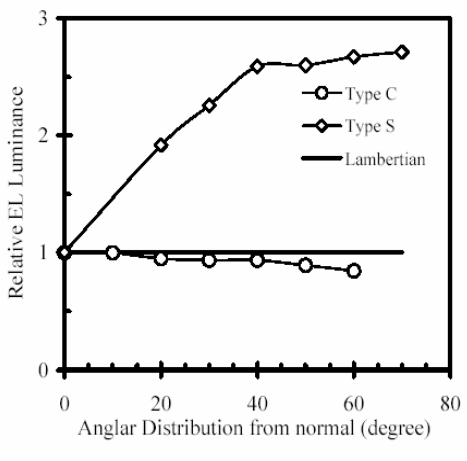

Figure 4. Angular distribution of the emission of the T-OLED and conventional bottom emitting OLED

Fig. 3 shows the EL emission spectra of Type C, S devices in the normal direction. It can be seen that the spectrum of Type S becomes narrower comparing to conventional bottom-emitting-OLED Type C. This is indicative of the microcavity effect [17, 18]

Since Top-OLED shows a strong microcavity effect, it is important to measure the angular dependence of the output. Fig. 4 shows the angular dependence of the luminance for the Top-OLED as compared to the conventional bottom-emitting-OLED. The data are normalized with respect to the value measured from normal direction. The Lambertian distribution is also plotted for comparison. The emission profile of Type C device is close to Lambertian as expected. The *3.3-cd/A* current efficiency and *1.1-lm/W* power efficiency of our conventional bottom-emitting-OLED were calculated using a Lambertian distribution. These are results obtained without any doping and are comparable to literature values.

However, from Fig. 4, it can be seen that there is a strong angular dependence for the emission of the Type S Top-OLED studied. There is much stronger emission at large angles. We believe that the strong angular dependence is due to the lower waveguiding loss in the Top-OLED. For the conventional device, there is around 80% light lost to the waveguiding modes in the glass interface [10]. However, the light from a top-emitting-OLED is extracted after passing through an ultrathin metal film and a thin ITO cap layer. The thin layer is effective for reduction of waveguide modes. Our calculation shows that only the zero-order waveguide mode remains in the ITO layer. So more light is coupled out of the OLED.

To estimate the integrated photon flux out of the diode, we use the formula:

$$F = \sum \alpha L(\theta) \sin(\theta) \Delta\theta \qquad (1)$$

where α is a wavelength dependent constant, $L(\theta)$ is the luminance at the angle θ. After integration, it is found that the Top-OLED emits 10% more photons than conventional bottom-emitting-OLED. Thus, not only have we fabricated a top emitting OLED, we have also improved the photon extraction efficiency of the device.

4. Conclusion

Through the use of nanometer platinum (Pt) and praseodymium oxide (Pr_2O_3), top-emitting-OLED based on CuPc/TPD/Alq_3 have been investigated. It was found that this new Top-OLED has a strong microcavity effect. Measurements show that Top-OLED emits 10% more photons than conventional bottom-emitting-OLED at the forward 140° cone. This device should be useful for active matrix OLED using either transparent or opaque substrates.

5. Acknowledgements

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6. References

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