Voltage Reduction of Organic Light-Emitting Device (OLED) with an n-type Organic Material and a Silver Cathode

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ABSTRACT

In this paper, a 1.85V reduction in driving voltage of an OLED is presented by using an alkali-metal doped electron transport layer (ETL) and a silver (Ag) cathode. Such an ETL is composed of 2,9-dimethyl-4,7-diphenyl 1,10-phenanthroline (BCP) doped with Cseium (Cs) to increase the conductivity of the organic material and achieve ohmic contact at the ETL/cathode interface regardless the work function of the cathode material. Ag is used to replace the conventional aluminum as the cathode material due to its lower electrical resistivity and optical absorption in visible range. In our devices, the drive voltage was reduced by 1.45V when using MD technique only. When we change the cathode material from Al to Ag, the driving voltage has a further of 0.4V reduction. In those devices, current efficiency is around 3.3 to 4.1 cd/A at 100 mA/cm^2.That corresponds to an improvement of 53.36% in power efficiency at 10 mA/cm^2.

Keywords: OLED, Organic, Metal-doped, silver cathode.

1. INTRODUCTION

Optoelectronics devices like display, solar cell and optical sensor composed of organic materials exhibit the advantages of easy fabrication, flexible substrate capability and potentially low cost [1], [2]. However, the driving voltage of such a device is about three to four times larger than that of a semiconductor light-emitting diode (LED) although a semiconductor LED is much thicker than an OLED device. Since the bandgap of the organic material is wide, the carrier concentration of such a material is quite low [3]. The carrier mobility is also limited by the amorphous structure that is typically six to eight orders of magnitude lower than that in semiconductor material [4]. It leads to the high resistivity and hence high driving voltage of a device. Such a high driving voltage increases the power consumption that decreases the efficiency. On the other hand, the wasted power generates heat and decreases the operation lifetime of such a device [5].

To lower down the driving voltage of an OLED, alkali metal atom was used to dope into the organic materials of the electron transport layer (ETL) that is called metal dopant (MD) technique [6], [7]. The alkali metal exhibits low work function and easily releases an electron that increases the carrier concentration and decreases the resistivity of the MD layer. In choosing the alkali metal materials, we use the heavy atom, Cesium (Cs), doped into the organic

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ETL materials, 2,9-dimethyl-4,7-diphenyl 1,10- phenanthrolin (BCP). Cs is a large atom among the alkali ones and it is harder to diffuse under the electric field than the small atom, like lithium. It decreases the metal quenching effect after long term operation and hence increases the lifetime [8]. Due to the incorporation of the metal atoms, the interface of the ETL and cathode is modified from Schottky to ohmic contact regardless the cathode materials. That means we do not need to use the electron injection layer (EIL) material, like LiF, to enhance the electron injection ability from the cathode to ETL. Such an ohmic contact property also increases the flexibility in choosing the cathode material. Here, we propose to use silver (Ag) to replace the common used cathode material aluminum (Al) since Ag has lower electrical resistivity and less optical absorption in visible range. To investigate the electrical property of the n-doping layer, we fabricated a series of electron-only device with different metal contact and found that the material can form ohmic contact in all our trials. With increasing metal dopant concentrations, we found that the conductivity increases rapidly, saturates and then decreases. The first increase results from carrier concentration increase. However, carrier transport in such a material is dominated by hopping process assisted by electrical field. Further increase in Cs atom does not increase the hopping ability. On the other hand, further increase in concentration means too many "free" electrons in this material that impedes the hopping process. The lowest resistivity we achieved was $3.14*10^5\ \Omega$-cm while the Cs: BCP ranged between 5:1 and 1:13.

By using MD/Al and MD/Ag as the ETL/cathode, we fabricated OLED devices and it has a 2.3 and 3.5 V reductions in driving voltage as compared with a conventional LiF/Al device, respectively. Hole transport layer (HTL) material usually exhibits higher mobility and higher conductivity than that of the ETL. That results in the carrier imbalanced in such a device. We also found that in our metal dopant devices, the higher current efficiency is obtained with a lower driving voltage device. That indicates the carrier is more balanced in such a device. Lifetime experiments were also conducted for studying the reliability issue. The experiments are represented in section 2. The results and the related discussions are shown in section 3. Conclusions are drawn in section 4.

2. EXPERIMENTS

In all of our experiments, the deposition process was carried in a batch-type multi-source chamber. The base pressure was about 1×10^{-7} torr. Typically, the deposition rate was controlled at 0.1 nm/sec. Electron only devices were fabricated with the structures of organic layer sandwiched by silver (Ag) electrode. The organic layer is composed of 2,9-dimethyl-4,7-diphenyl 1,10- phenanthroline (BCP) doped with Cseium (Cs) of different concentration. For OLED device fabrication, we used ITO glass substrate of low sheet resistivity (10 Ohm/sqr) and flat surface roughness (Ra<1 nm). The size of active region in our test pixel was 0.5 cm x 0.5 cm. Before organic deposition, O_2 plasma treatment was used to clean the ITO surface and increase the ITO work function. In our control devices, we used N,N'-diphenyl-N,N'-bis(1-napthyl)-1,1'-biphenyl-4,4'-diamine (NPB) as the hole transporting layer (HTL) material and tris-(8-hydroxyquinoline) aluminum (Alq3) as the emitting layer (EML) material. In our control device, Alq3 is also used as the ETL material. LiF of 0.7 nm in thickness was used for more efficient electron injection between the ETL and the aluminum cathode. The thickness of the aluminum cathode was 100 nm. For the metal dopant devices, Cs:BCP with the concentration of 1:9 was used as the ETL materials. The Ag cathode with the thickness of 100 nm was then evaporated. The thickness of the HTL, EML and ETL were 45, 27.5, and 27.5 nm, respectively. Device structures are shown in Fig. 1. After organic and metal depositions, devices were well encapsulated in the glove box with O_2 and H_2O concentrations below 1 ppm. Device performances were characterized with Keithley 2400 for the current-voltage measurements and with PR705 photometers for the brightness measurements. These instruments were connected to a personal computer and controlled by labview software.

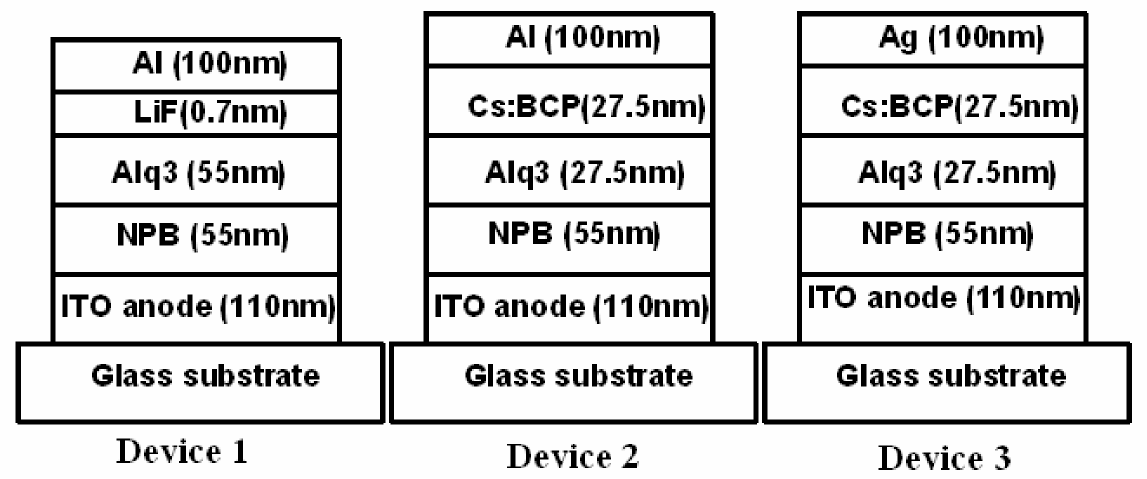

Fig. 1 Device structures of a convnetional device and two metal dopant devices.

3. RESULTS AND DISCUSSIONS

Fig. 2 shows the resistivity values of electron only devices with different Cs concentration which is deduced from the J-V characteristics. It has been shown that J-V curves is always linear that means the contact between cathode and MD layer is always ohmic [9]. We can clearly see that there is a large process window, and the lowest resistivity of Cs-doped BCP is 1:9 by volume ratio.

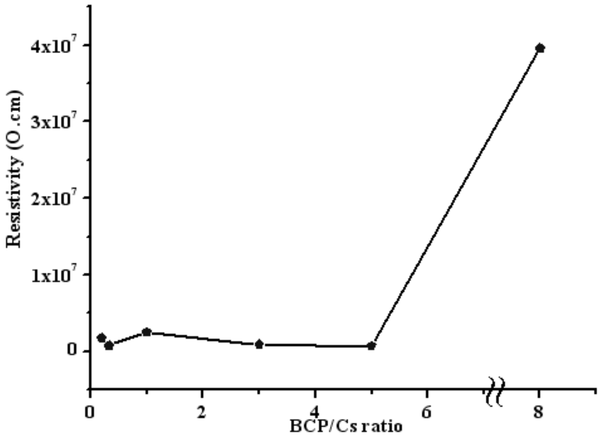

Fig. 2 Risistivity with different dopant concentration.

Fig. 3 shows the current-voltage characteristics of different samples. Device 1 is our control device and exhibits lowest current density under the same driving voltage among all the samples. With replacing the ETL as the MD layer, we can see that the driving voltage is reduced by 2V. Using Ag to replace the Al as the cathode material, the driving voltage has another 1V reduction.

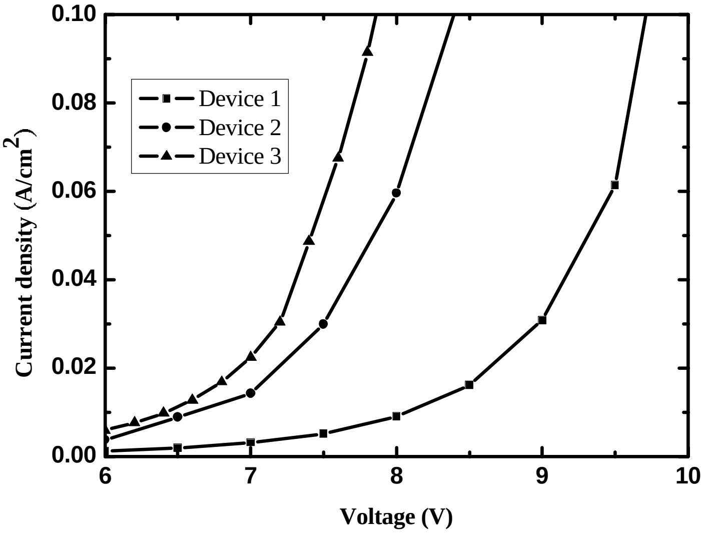

Fig. 3 Comparison of current density versus voltage curves.

Figure 4 shows dependence between current efficiency (cd/A) and injection current density. Since there are many metal atoms (or ions) inside the metal dopant ETL, the strong absorption within this layer is one of the major concern for such a technique. We can see that in Fig. 4 the devices 2 and 3 also have higher brightness than device 1

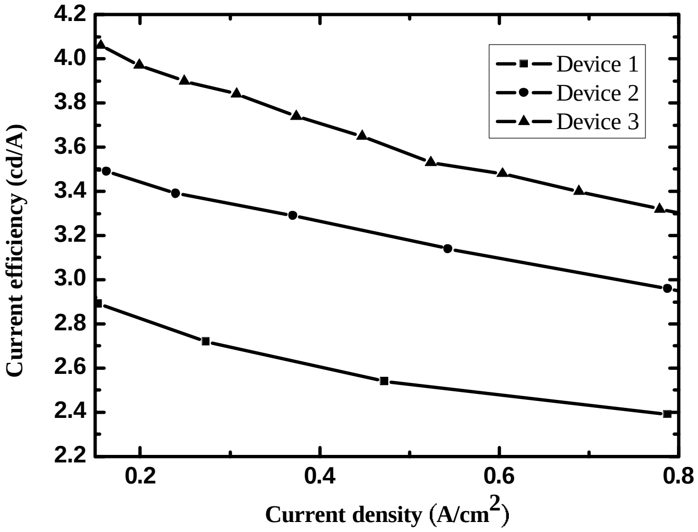

Fig. 4 Comparison of efficiency versus current density.

under the same current density. We did not observe the metal atom (or metal ion) quench effect in our devices with the EML thickness of 25 nm. On the other hand, we can see that the current efficiency is higher in the metal dopant devices. In OLED devices, hole mobility of HTL is usually much higher than electron mobility of ETL. Hence, the conductivity of HTL is much higher than that of ETL. When a voltage is applied on the device, voltage drop is mainly on the ETL. At the same time, there are more holes than electrons near the emission center. That means the carrier is not balanced in this interface. That results in low current efficiency and shorter lifetime. Here, the use of metal dopant ETL increases the carrier concentration and conductivity. It also helps to balance the electrons and holes distribution near the interface. Not only the driving voltage is decreased, current efficiency is also increased in our metal dopant case. We can also see that device 3 exhibits higher current efficiency than device 2. It results from the higher reflectivity and lower absorption of the Ag cathode.

Fig. 5 shows the results of the acceleration lifetime test. The initial brightness of this test is set at 10000cd/m^2 under DC constant current driving. Under this condition the temperature of the glass side is around 40 ℃ hence the temperature at the device side and inside the device may be much higher than this temperature. We can see that our control device, device 1, has shorter lifetime. The half lifetime can be estimated under such a high brightness is 14.5 hours by extrapolating the data. Device 3 exhibits a half-life of 24 hours although the Tg of the metal dopant host is low. We attribute this to the higher power efficiency of the metal dopant devices. Due to less heat generated, the degradation speed is also slow down.

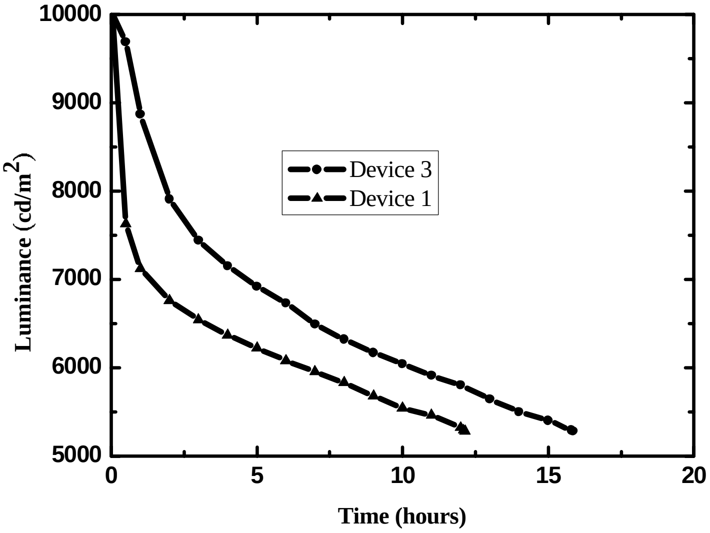

Fig. 5 Accelerated lifetime test of devices.

4. SUMMARY

In summary, we have shown device performance of an OLED with metal dopant technique that can effectively increases the carrier concentration of the ETL and decreases the driving voltage of a device. The interface between the ETL and cathode is also modified that results in an ohmic contact rather than a schottky barrier regardless the cathode materials due to the alkali metal dopant. When using Ag as the cathode material, lower ohmic loss and less optical absorption can be observed. Driving voltage and higher current efficiency is achieved. We choose cesium doped into BCP as the ETL material. The heavy alkali metal atom decreases the effects of metal ion diffusion from the ETL to EML and inhibits the quenching effects after long-term operation as compared with the use of the light alkali metal, lithium. It hence increases the operation lifetime. For devices with metal ETL, not only the driving voltage is decreased, higher current efficiency is also achieved due to better charge balance. A 70% increase in lifetime was observed in our Cs:BCP device. The increasing lifetime suggested that Cs did not diffuse into emission layer and the devise is stable.

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