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The real anode and the electrons-pump-layer of OLED

FANGCONG WANG[a,b,*], HAIXIA LI[c], PENG CHANG[a,b]
[a]*Key Laboratory for Magnetism and Magnetic Materials of the Ministry of Education*
[b]*Institute of microelectronics, School of physical science and technology, Lanzhou University, Lanzhou, 730000, People's Republic of China*
[c]*Institute of Modern Physics, Chinese Academy of Science, Lanzhou, 730000, People's Republic of China*

The widely used anode for organic light emitting devices (OLED) is ITO/metal/ITO or ITO/insulated layer which could improve the performance of OLED than which only ITO as anode could, while the contribution of such multilayer anode to improve device performance is still poorly understood. A number of mechanisms were proposed for this kind of anode, some different mechanism is given by us here which are demonstrated by the next experiments. The metal plays the role of real anode for OLED and the insulated layer such as LiF, Al_2O_3, Ta_2O_5, SiO_xN_y, TiO_2, and ZnS contributes as the electrons-pump-layer.

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1. Introduction

Organic light-emitting devices (OLED) have been intensively investigated in the past years as promising candidates for full-color, flat panel displays [1] because of their prominent advantages such as in fabrication and convenience in application [2]. Therefore, tremendous efforts have been made toward improving the device performance, including the lower operation voltage, the higher brightness, the higher luminance efficiency etc. It was known that the performance of OLED depends heavily on the efficiency of carrier injection and their recombination, which generate molecular excitions [3, 4]. In order to achieve maximal efficiency, more carrier injection into the emission layer is a must in the device. Up until now, there are several approaches to increase the number of injected electrons including modification of the cathode contact or electron transport layer have been known to improve carriers injection, transmitted and recombination [5, 6]. Dramatic improvement was achieved by using of a thin interlayer between the cathode and the organic layer. This layer is such as the inorganic LiF [7], CsF [8], NaCl [9], NaF [10], Al_2O_3 [11], SiO_2, Si_3N_4, MgO etc. The most widely used electron-injection-layer (EIL) is the LiF layer, which is known to form an excellent interface for electron injection into OLED (with ~1nm thick LiF). Another several approaches to increase the number of injected holes and improve the performance of OLEDs by also using of a thin interlayer between the anode and the devices such as metal/ITO [12, 13, and 14], LiF [15], Al_2O_3 [16], Ta_2O_5 [17], SiO_xN_y [18], TiO_2 [19], ZnS [20], while the contribution of the interlayer in improving device performance is still poorly understood. A number of mechanisms were proposed for metal/ITO, such as the obviously decreasing the total sheet resistance and increasing the injected holes [12, 13, and 14], while for LiF [15], Al_2O_3 [16], Ta_2O_5 [17], SiO_xN_y [18], TiO_2 [19], ZnS [20] which are all insulated layer, it is poorly understood how do they work.

In this letter we demonstrate the contribution of such an interlayer which can significantly improve the device performance.

2. Experiments and discussion

In our experiments, the structure of ITO (50nm)/Ag (2~20 nm)/ITO (50 nm) with different Ag thickness were fabricated. After the routing cleaning procedure of ultrasonicating the ITO coated glass in organic solvents, deionized water and dried, different Ag thickness was deposited, and then 50 nm ITO was deposited too. Fig. 1 shows the sheet resistances of the investigated multilayer.

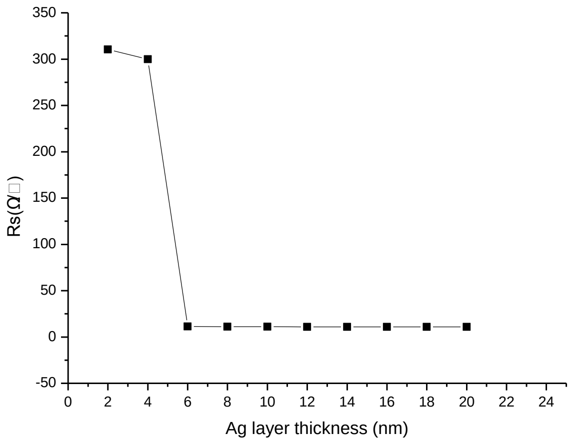

Fig. 1. The sheet resistance R_s data as a function of Ag layer thickness for ITO/Ag/ITO structure.

Assuming that the total resistance results from three resistance of single layers coupled in parallel it is possible to calculate the specific resistivity:

$$\frac{1}{R} = \frac{2}{R_{ITO}} + \frac{1}{R_{Ag}} \quad (1)$$

Eq. (1) holds for double ITO layer of equal resistances. Fig. 1 shows that total sheet resistance does not change obviously since the thickness of Ag layer reaches 6nm. It is the same size of sheet resistance for 6nm to 20nm Ag interlayer which means that the current from the four-point probe system goes through both sides of Ag layer 3nm. If the thickness of Ag layer is higher than 6nm, current goes through only both sides of 3 nm Ag layer, no more goes through the central Ag layer. So the total sheet resistance is the same size from 6nm to 20 nm Ag layer, it is called Skin Effect. 6nm Ag layer is enough for OLED to lower cost.

The sheet resistance of single 50 nm ITO is 300Ω/□, 600Ω/□ for single 100 nm ITO, while 11Ω/□ for multilayer ITO (50 nm)/Ag (Thickness is higher than 6nm)/ITO (50 nm). Using Eq. (1), the sheet resistance of Ag layer (Thickness is higher than 6 nm) could be calculated and the result is 11.42Ω/□, which is most close to the total sheet resistance of multilayer. It means that the sheet resistance of Ag layer plays a decisive role for the total sheet resistance, even if the sheet resistance of both sides of ITO layer changes, the total sheet resistance could change a little.

It is assumed that the Ag Layer is the real anode for OLED.

It is well known that only Ag layer for anode of OLED and not any interlayer between anode and organic layer, the performance of such OLED is mostly poor. The contribution of LiF [15], Al_2O_3 [16], Ta_2O_5 [17], SiO_xN_y [18], TiO_2 [19], ZnS [20] is demonstrated by the next experiments.

Next experiments is that the structure of ITO (40Ω/□)/LiF (0, 0.5nm, 1 nm, 1.5 nm, and 2 nm)/TPD (30nm)/Alq_3 (100 nm)/Al (100 nm) with different LiF thickness were fabricated. Fig. 2 shows the curve of efficiency-current density.

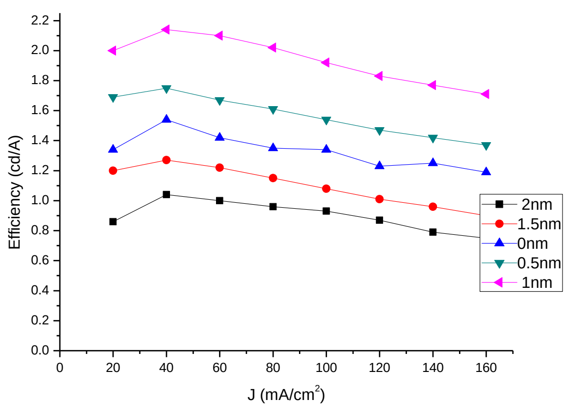

Fig. 2. The efficiency data of OLED as a function of LiF layer thickness for ITO/LiF structure.

Compared to ITO layers, ITO/LiF samples shows improved efficiency with the thickness of LiF is 1nm and 0.5 nm, and deteriorated with the thickness of LiF is 1.5 nm and 2 nm. For example, with 1nm LiF, efficiency improves by over 1.5 times without LiF.

Usually it is thought holes come from anode, and electrons come from cathode. While it is well known that this kind of material of TPD, Alq_3 etc is organic semiconductors, and holes and electrons are both carriers. The materials of Ag, Au, and Cu etc as real anode are metals, holes could not be injected or transmitted to organic layer during metals, and holes only exist in semiconductors including organic semiconductors. So it is reasonable that electrons are transmitted from organic layers to LiF (also as Al_2O_3, Ta_2O_5, SiO_xN_y, TiO_2, ZnS layers) and pumped from LiF to anode by strengthened electric field around F^-. At the same time, it is thought that holes are injected to the organic layer like TPD here.

The LiF layer has a lot of dangling bonds, like Al_2O_3 [16], Ta_2O_5 [17], SiO_xN_y [18], TiO_2 [19], ZnS [20], so a lot of anions F^- and cations Li^+ are close to the ITO anode after LiF is deposited to the ITO layer. Fig. 3 shows the distributed dangling F^- and Li^+, once a bias is given to the OLED, electric field line is uneven distributed like Fig. 3 shows, then the electric field will be weaken somewhere the electric field line is sparse around Li^+, and strengthen somewhere the electric field line is dense around F^-.

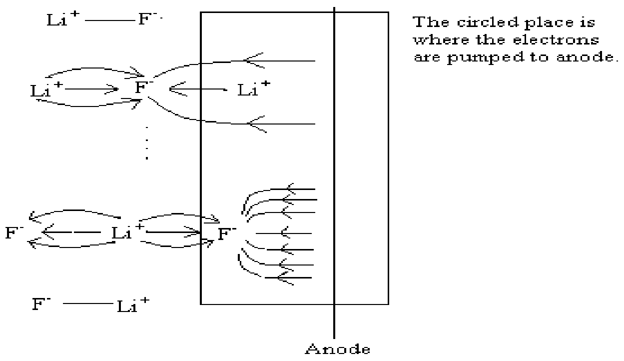

Fig. 3. The schematic diagram shows two kinds of dangling bonds, Li^+ ions and F^- ions. The electric field is strengthened around F^- ions, and the electric field is weakened around Li^+ ions when a bias is given. It means that numbers of electrons could be pumped from F^- ions to anode.

Around the place where the electric field is weakened around Li^+ ions, fewer electrons are injected from the ITO anode. The place where the electric field is strengthened around F^- ions, more electrons are injected from the ITO anode. The consequent is that the electrons injection is enhanced where the electric field is strengthened around F^- and the electric field line is from anode to F^-, and the performance of OLED is improved.

The LiF layer is insulate (the dielectric constant of LiF is 9.036 at 300 K) [21], while the LiF layer could not only enhance the electrons injection but also transport the injected electrons into the organic layer such as TPD layer. Fig. 2 shows an experiment fact is that the optimized thickness of LiF is ~1nm. The lattice constant of LiF is 4.0279Å. The 1 nm LiF layer is about 2.5 times of the lattice constant, it means that only 2 or 3 elements (including Li and F) between the emitting layer and the cathode, Fig. 3 shows.

It could be the non-linear positive correlation between the number of electrons which could penetrate the LiF layer (Electrons could penetrate any ultra thin layer regardless of how much the dielectric constant or anything else is in TEM. The only determining factor is the radius of ions and electric field between the ions) and the thickness of LiF layer and the number of the elements in the LiF layer from one side to another [22, 23], it means if the thickness of LiF layer is higher or the ions is slightly more or the radius of ions is slightly larger than the Li^+ and F^-, the number of electrons which could penetrate the LiF layer and reach the organic layer will extremely lower, then the performance of OLED is lower too. So the optimized thickness of LiF is 1nm. So it is much effective to improve the performance of OLED inserting a LiF layer or other layers, such as Al_2O_3 [16], Ta_2O_5 [17], SiO_xN_y [18], TiO_2 [19], ZnS [20] etc, and they are assumed as electrons-pump-layer by anode which anode could pump electrons from.

It is upper mentioned that only metal like Ag layer for anode of OLED and not any interlayer between anode and organic layer the performance of such OLED is mostly poor. While only ITO layer could play the role of anode of OLED well, because the whole ITO layer is separated into two layers, the layer is close to organic contributes as electrons-pump-layer, and the left contributes as the real anode. Only Ag layer as anode of OLED, no electrons-pump-layer exists, not much more electrons could be pumped from organic layer, so performance of OLED with only Ag layer is worse than that of OLED with only ITO(It plays both roles of real anode and electrons-pump-layer). This also could metal here is the real anode of OLED.

3. Conclusion

ITO/metal/ITO and other kinds of structure of anodes are most widely used in OLED, here it is demonstrated that the real anode is the metal layer which plays a decisive role for the total sheet resistance even if the sheet resistance of both sides of ITO layer changes, the total sheet resistance could change a little. The experiments of using the structure of ITO/LiF demonstrate that the contribution of LiF layer is electrons-pump-layer, not the holes-injection-layer or holes-buffer-layer, since holes only exist in semiconductors including organic layers.

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*Corresponding author: wangfangcong@gmail.com