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# Improved performance of organic light-emitting diode with vanadium pentoxide layer on the FTO surface

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**Abstract**

Vanadium pentoxide layer deposited on the fluorine-doped tin oxide (FTO) anode by vacuum deposition has been investigated in organic light-emitting diode (OLED). With 12nm optimal thickness ofV2O5, the luminance efficiency is increased by 1.66 times compared to the single FTO-based OLED. The improvement of current efficiency implies that there is a better charge injection and better control of hole current. To investigate the performance of OLED by the buffer layer, V2O5 films of different thicknesses were deposited on the FTO anode and their J–V and L–V characteristics were studied. Further analysis was carried out by measuring sheet resistance, optical transmittance and surface morphology with the FE-SEM images. This result indicates that the V2O5 (12nm) buffer layer is a good choice for increasing the efficiency of FTO-based OLED devices within the tunneling region. Here the maximum value of current efficiency is found to be 2.83 cd/A.

**Keywords.** Tunneling effect; charge injection; organic light-emitting diode; FE-SEM; optical transmittance.

## 1. Introduction

Organic light-emitting diodes (OLEDs) have been the topic of intensive research because of their low cost, lightweight and flexible displays [1,2]. As a result, OLEDs are currently the most advanced devices in the field of organic electronics. However, to further enhance the power efficiency of OLEDs, it is crucial to develop a more optimized device architecture. Especially, improving the injection of charge carriers from the electrode to the emitting layer is significantly important to achieve highly efficient OLEDs. The interface between the organic layer and the electrodes plays a significant role in the performance of OLED because it determines the efficiency of the device by controlling the flow of charge from the electrode into the light-emitting layer [3]. The insertion of a buffer or hole injection layer between the anode and hole transport layer (HTL) is one of the simple and effective methods to improve the performance of the device. The relatively high hole injection barrier between the electrode and the organic hole transport layer can be overcome by inserting buffer layers such as transition metal oxide [4,5], small organic molecule [6] and conducting polymers [7–9] because the presence of such hole injection layers reduce the energy barrier at the interface and enhanced the hole injection tendency into the organic layers and also improve the surface roughness of the electrode surface which directly affects the device performance. Inorganic insulating buffer layers such as LiF [10], Al2O3 [11], SiO2 [12] and MoO3 [13] were reported in the literature. Zhang et al [14] calculated the J–V characteristics of OLEDshaving a uniform buffer layer based on the WKB approximation. Lu and Yokoyama [15] reported hole block effect due to the insertion of Ta2O5 and HfO2 buffer layers, whereas other reports showed the apparent enhancement of hole injection with the insertion of various buffer layers such as LiF [10], SiO2 [12], WO2.5 [16], etc. Vanadium pentoxide (V2O5) has also been used to modify the anode surface to enhance hole injection [17,18] due to its suitable value of work function. Fluorine-doped tin oxide (FTO), though more cost-effective than the ITO, is not widely used to fabricate OLEDs because its transparency is less than ITO [19]. There are published reports that indium has a tendency to diffuse into the emissive layer under device operation [20], which may in

turn influence the quantum efficiency and lifetimes of OLEDs. In addition, it is known that the performance of ITO-based OLEDs is highly dependent on the chemical condition of the ITO electrode. On the other hand, in the case of FTO anode, no indium is present which eliminates the possibility of indium diffusion into the emissive layer in the OLED. The chemical composition, as well as the work function of FTO, was independent of the cleaning methods employed [21] which is not the case with ITO. This indicates that FTO is more stable to oxidation than ITO. It has also some advantages as it is not classified as dangerous for carriage or supply and not hazardous to the environment. Also for the FTO anode, no risk or safety phrases are necessary. Therefore, some material of intermediate layers such as PEDOT: PSS and sulphonated polyaniline can be used to effectively reduce the potential barrier for FTO-based OLED [22,23]. In this work, we report an OLED that was fabricated on FTO-coated glass and optimize it by using bilayer anode at various thicknesses of V2O5 film.

## 2. Experimental details

All devices were fabricated on FTO-coated glass and thermally deposited Al was used as the cathode. The FTO glass was cleaned in an ultrasonic bath of acetone and isopropanol for 15 min and the deposition was carried out at a pressure less than $5 \times 10{-}5$ torr. All the organic and inorganic layers were evaporated at a deposition rate higher than 10 Å/s. All the devices were fabricated by using the thermal vacuum evaporation unit and the corresponding film thicknesses were recorded by the thickness monitor (Model DTM-10). Sheet resistance and optical transmittance were measured by four probes and UV–Visible double beam spectrophotometer unit. The current-voltage luminescence characteristics of the fabricated OLEDs were measured by digitally controlled source-meter and luminance meter unit. All tests are performed in air at room temperature without any encapsulation and all materials are purchased from Sigma-Aldrich and used without further purification.

## 3. Result and discussion

We have fabricated the standard OLEDs using V2O5 as a hole injection layer (HIL), N,N————————————-bis(3-methylphenyl)- N,N————————————(phenyl)-benzidine (TPD), tris(8-hydroxy quinolinato) aluminium (Alq3) and lithium fluoride (LiF) are used as the hole transport layer, emitting layer and the electron transport layer respectively and compared the J–V–L characteristics of OLEDs with different thicknesses of HIL and also that of HIL-free OLED. Without LiF electron injection layer it is difficult for the electron to be injected from Al cathode to the Alq3 layer, as the dissociation of the alkali halide into the organic layer leads to the enhancement of electron injection. The structures of the bottom light-emitting diodes used in this study are: Device A: FTO/TPD (40nm)/Alq3 (50nm)/ LiF (5nm)/Al (110nm) Device B: FTO/V2O5 (4nm)/TPD (40nm)/Alq3 (50nm)/LiF (5nm)/Al (110nm) Device C: FTO/V2O5 (8nm)/TPD (40nm)/Alq3 (50nm)/LiF (5nm)/Al (110nm) Device D: FTO/V2O5 (12nm)/TPD (40nm)/Alq3 (50nm)/LiF (5nm)/Al (110nm) Device E: FTO/V2O5 (16nm)/TPD (40nm)/Alq3 (50nm)/LiF (5nm)/Al (110nm) The current-voltage and the luminance–voltage characteristics of OLED having configuration FTO/V2O5 (varying thickness)/TPD (40nm)/Alq3 (50nm)/LiF (5nm)/Al (110nm) are shown in figures 2a and 2b respectively. To study the influence of the variation of thickness of V2O5 on luminance, we kept thickness of all layers constant except for V2O5 layer, which was varied between 4 and 16 nm. It is found that when the thickness of the buffer continuously increases, current density decreases. This indicated that this interlayer has the direct effect of blocking the hole current by controlling the flow of positive charge carrier. On the other hand, a good EL device should posses high luminance efficiency. In our work, it is found that the device with 12nm V2O5 buffer layer has the highest efficiency of 2.83 cd/A compared to the other OLED devices. Therefore, current efficiency increases compared to the device without a buffer layer (1.70 cd/A). With the increasing thickness of the buffer layer, it is observed that there is a gradual increase of efficiency of the devices. This is due to the better enhancing of positive charge carrier injection by the high thickness of oxide layer [24]. This improvement in efficiency is because of the proper balancing of charge carrier injection. This interlayer also prevents the diffusion of metal and oxygen into the organic layer from the anode and hence reduces the probability of electrical breakdown of the device. From the literature it is known that the mobility of electron is lower in electron transport layer than the mobility of holes in the hole transport layer [25]. As a result, there is an accumulation of positive charge carrier at the interface of HTL/ETL layer. Therefore, to enhance the efficiency of the device, we should either decrease the positive charge carrier mobility or increase the negative charge carrier mobility. In our case we balance the mobility of positive charge carrier by using V2O5 buffer layer between the FTO and TPD layer.

In other words, this oxide layer can help in preventing the accumulation of excess holes in the luminance layer, thus increasing the probability of electron–hole pair combination. Initially, when the thickness of V2O5 is very small, mobility of the positive charge carrier is significantly increased due to the tunnelling of charge carrier from the FTO surface of the TPD layer. This effect is associated with the high value of current density and luminance of the device along with the lower threshold voltage. After that when we increase the thickness of the buffer layer continuously, it is found that both value of current density and luminescence of the devices decreases. This may be due to the reduction of tunnelling effect between the anode and hole transport layer. From the characteristic graphs shown in figures 2a and 2b, it is clear that although the values of current density and luminance are decreased, the efficiency improved continuously with the increasing thickness of the buffer layer. In our work, maximum efficiency is provided by Device 4 which is better than the earlier reported result [22,23]. Here, the optimized thickness of the buffer layer is found to be 12 nm. After that, efficiency of the device decreases due to the more reduction of tunnelling effect when the thickness of the buffer layer increases. The initial increase of luminance may also be due to the minimization of crystal defects due to the presence of oxide layer at the interface region of FTOand TPD layer. Also, when we placed the V2O5 layer between the anode and the hole transport layer, then there is a high tendency for the positive charge carrier to inject into the organic layer from a high energy level compared to that without any buffer layer as shown in figure 1a. Some trap may exist in the hole transport layer which should trap the holes before they come to the light emitting region. When the holes are injected relatively from a higher energy level then the probability of their trapping is decreased. This is reason because of which the device efficiency is more in buffer layer devices than without any buffer layer within the charge tunnelling region. Figure 3a represents the variation of current efficiency of the OLED devices with respect to their applied voltage. In this figure, it is clear that Device 4 shows the maximum efficiency

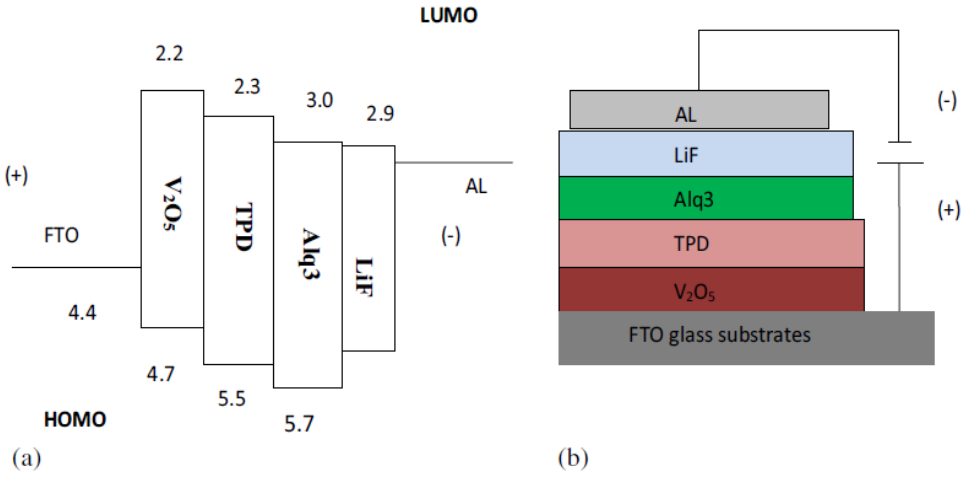



Figure 1. (a) Energy level alignment of OLED structure and (b) schematic representation of OLED structure.

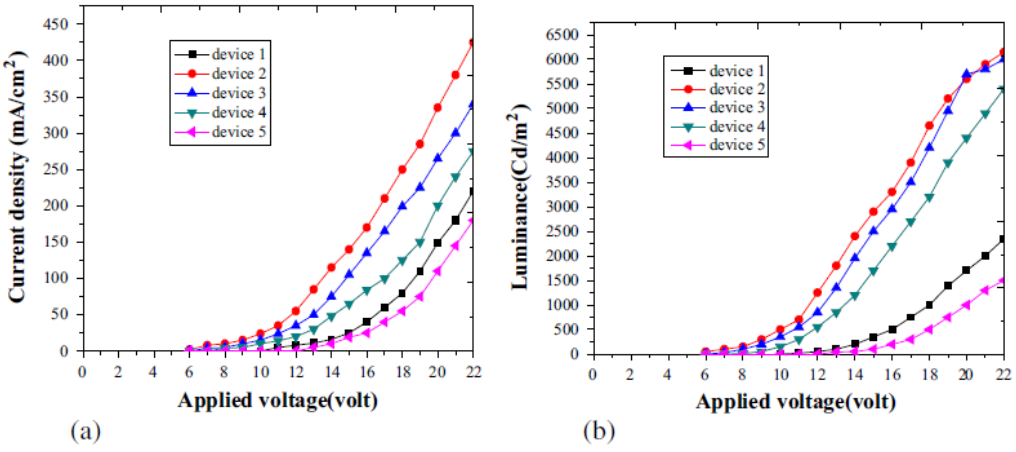



**Figure 2.** (**a**) Graph of voltage vs. current density and (**b**) graph of voltage vs. luminance.

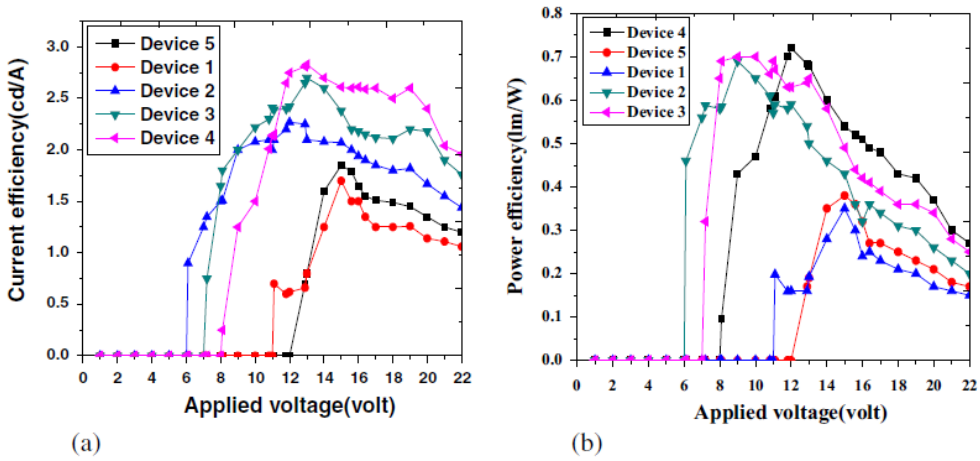
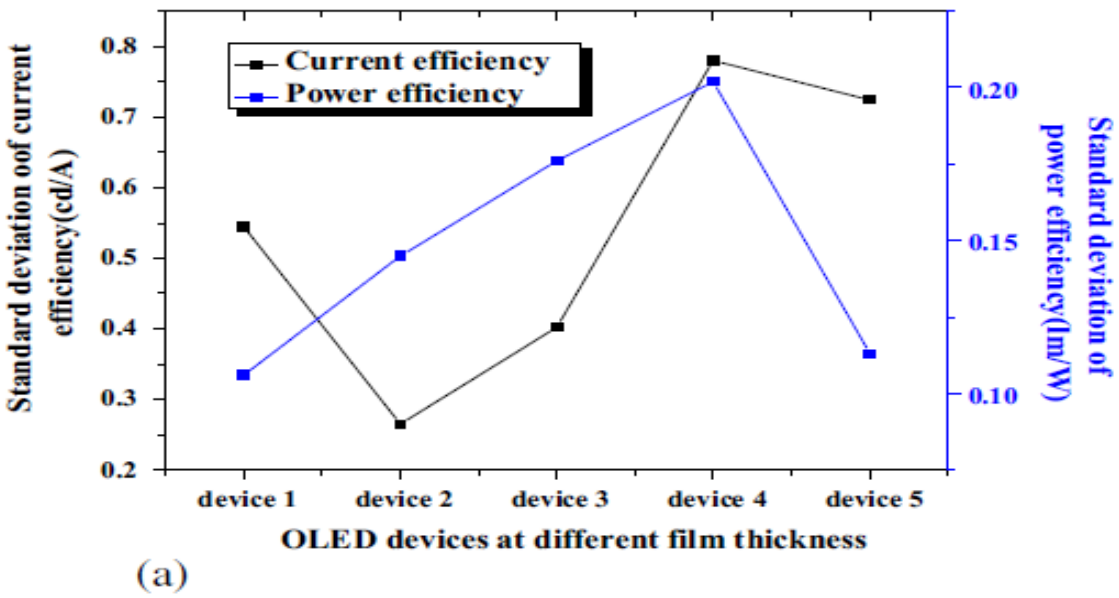



**Figure 3.** (**a**) Graph of voltage vs. current efficiency and (**b**) graph of voltage vs. power efficiency.

whereas Device 1 has lower efficiency. This situation is directly linked with the proper charge injection process, i.e. exciton formation probability. Initially, when the thickness is very low, the charge tunnelling process is slightly enhanced. But when we increase the thickness, this process tends to be more enhanced because of which we get better device efficiency in our devices. This effect is maximum at the optimized thickness of 12nm (Device 4) where we get the highest efficiency of 2.83 cd/A. This implies that when the thickness of the buffer layer is 12 nm, then there is a more balanced positive charge carrier injection on a negative charge from both the electrode side of the OLED device. But after that, the optimized thickness efficiency decreases. This is due to the reduction of charge carrier tunnelling at a higher thickness of the buffer layer from the anode to the hole transport layer.

Similarly, the variation of power efficiency vs. applied voltage for all the devices is shown in figure 3b which Device 4 shows the highest value where the maximum balance of holes and electron injection takes place. As a result, less energy is consumed at the anode and the hole transport interface layer. It is found that the power efficiency (η) and current efficiency (γ ) are depending on each other and their relation can be given by eq. (1) considering the Lambertian emission pattern [26].



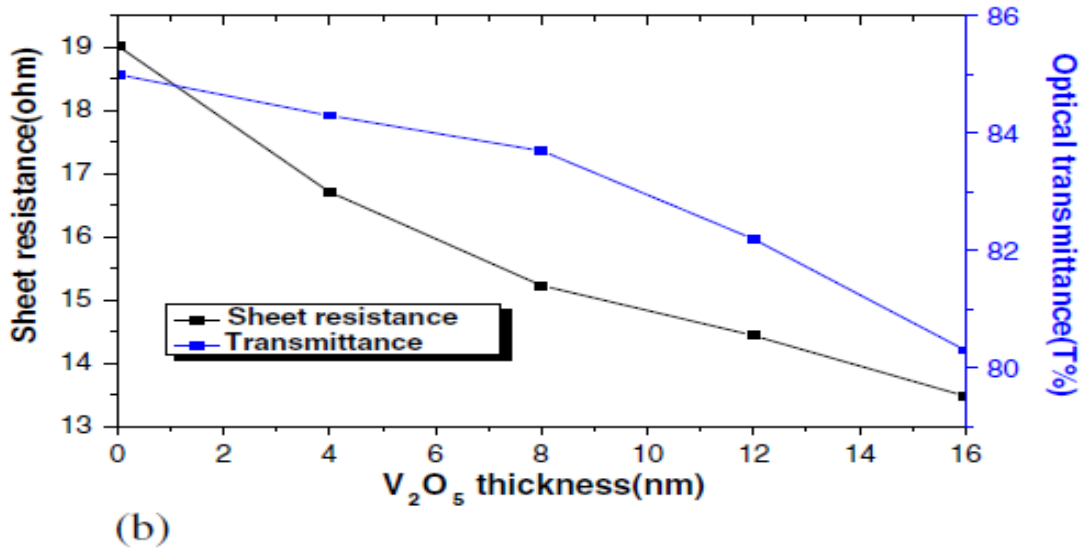



**Figure 4.** (**a**) Graph of standard deviation of OLED at different thicknesses of V2O5 and (**b**) graph of variation of sheet resistance and transmittance with V2O5 thickness

## 4. Conclusion

OLEDs based on the structure of FTO/V2O5/TPD/ Alq3/LiF/Al has been systematically studied. From this we conclude that excessively thick V2O5 films lead to higher turn-on voltage, thus degrade the current efficiency. For Alq3 and TPD-based device configurations, a buffer layer of V2O5 at the critical thickness leads to more current efficiency. This result revealed that there is an optimum thickness of the buffer layer at which the maximum OLED current efficiency can be achieved. In this case, the optimum thickness of 12 nm V2O5 buffer layer has resulted in 1.66 times enhancement in current efficiency compared to the bare FTO anode. For maximum current efficiency, the thickness of LiF, Alq3, TPD and V2O5 are 5, 50, 40 and 12nm respectively. In this configuration, a luminance of 5400 cd/m2 is obtained at a current density of 275mA/cm2.

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