

Modification of polycrystalline silicon as efficient anode for active-matrix organic light-emitting diodes

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Abstract

The effects of different modification methods for polycrystalline silicon (*p*-Si) on the performance of *p*-Si anode OLEDs have been studied. UV-ozone treatment of *p*-Si improved the device performance with suitable UV time, while O₂ plasma treatment led to deterioration. By depositing ultra-thin high work function metal oxides, such as V₂O₅ and MoO₃, on *p*-Si anode, the performance of OLEDs was greatly improved compared with those using bare *p*-Si as anode and competitive with that of the conventional devices with ITO anode. This modified *p*-Si anode can be integrated with the active *p*-Si layer in active-matrix OLED (AMOLED) displays with a reduction of at least one mask in the fabrication process.

Introduction

Organic light-emitting diodes (OLEDs) have attracted wide attention due to their potential application in flat panel displays [1-3]. Indium tin oxide (ITO) is the most widely used anode in OLEDs because of its high conductivity and transparency. Many approaches have been proposed for modifying the ITO surface to improve holes injection. Commonly used methods include UV ozone treatment [4], O₂-plasma treatment [5], and CF_x coating [6]. In addition, it has been shown that coating ITO with some oxides, such as Pr₂O₃ [7], NiO [8], VO_x [9], greatly enhances the hole injection efficiency.

Recently, we have proposed the use of polycrystalline silicon (*p*-Si) thin film as an alternative semitransparent anode for bottom-emitting OLEDs [10]. It is well-known that *p*-Si is used in the fabrication of thin-film transistors (TFT) for AMOLED displays [11-13]. Replacing ITO with *p*-Si as the anode allows the elimination of at least one mask for fabricating

AMOLED. Indeed the *p*-Si anode and the active *p*-Si source-drain of the TFT can be the same layer. Thus, fewer processing steps will be required. This will present considerable savings in manufacturing cost and perhaps improvements in production yield.

Unfortunately, the work function of the *p*-Si (~4.7eV) is not amenable to efficient holes injection for OLED. There are several ways to overcome this difficulty, similar to ITO. For example, a *p*-doped intermediate hole injection layer (HIL) [10] can be added. Surface modification to the *p*-Si can also be attempted. In this paper, we demonstrated different modification methods for the *p*-Si anode to improve the device performance. For UV-ozone treatment, some improvement was achieved if the UV time was suitable. While, no improvement was obtained with O₂ plasma treatment, on the contrary, some deterioration was observed, for example, there was very large leakage in the devices with the O₂ plasma treatment *p*-Si anode. By depositing ultra-thin high work function metal oxides, such as V₂O₅ and MoO₃, on the *p*-Si anode, remarkable improvement of device performance was achieved which was attributed to great enhancement in holes injection from *p*-Si anode.

Experiment Details

The *p*-Si anode used in the present study is made by the process of metal-induced-crystallization (MIC). However, other types of *p*-Si, in particular, laser annealed *p*-Si, should work as well. The MIC *p*-Si was fabricated as follows. First low pressure chemical vapor deposition (LPCVD) was used to deposit 100nm of low temperature oxide (LTO) on a Corning 1737 glass substrate. It was then followed by LPCVD of 50nm of a-Si. Then nickel was sputtered onto the a-Si and annealed to give the MIC *p*-Si. Finally, boron ions at the

dose of $4 \times 10^{15} \text{ cm}^{-3}$ were implanted at 40keV into the MIC *p*-Si. The sheet resistance of this *p*-Si was measured by four Point Kelvin-probes to be $\sim 200 \Omega/\square$. There was about 2-3 nm of native oxide on top of the *p*-Si. This oxide layer could in principle be used to block the diffusion of boron into the organic layer.

The *p*-Si substrates were cleaned with standard ITO clean process and treated by UV-ozone or O₂ plasma. In another case, the *p*-Si without any surface treatment, but 3nm V₂O₅ or MoO₃ were deposited on it by thermal evaporation in high vacuum chamber prior to organic layers deposition. All the devices consisted of an organic stack layer of 4,4-bis[*N*-(1-naphthyl)-*N*-phenyl-amino]biphenyl (NPB) (50nm)/ tris-(8-hydroxyquinoline) aluminum(Alq₃)(50nm). NPB is served as holes transport layer (HTL) and Alq₃ is electron transport layer (ETL) as well as emissive layer. Multilayer of lithium fluoride (LiF) capped with aluminum (Al) was used as an effective cathode.

The current density-voltage (J-V) and luminance-voltage (L-V) characteristics of these devices were measured simultaneously with a semiconductor parameter analyzer (HP4145B) and a silicon photodiode calibrated by Photo Research PR650 spectrometer. The electroluminescence (EL) spectra were measured with the PR650. All measurements were carried out under ambient atmosphere without device encapsulation.

Results and discussion

A. Optical characteristics of *p*-Si anode

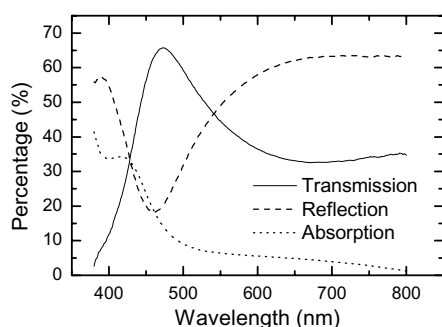


FIG. 1. Optical transmission, reflection, absorption of glass/LTO/*p*-Si.

The optical transmission, reflection and absorption spectra of glass/LTO/MIC *p*-Si are shown in Fig. 1.

Obviously the optical properties of the substrate will greatly affect the emission characteristics of the OLED devices. It can be seen that the MIC is relatively transparent throughout most of the visible spectrum, varying from 60% in the blue to 35% in the red. This reflectivity will affect the micro-cavity effect in the OLED. This variation has to be taken into account and compensated in designing full color RGB devices.

B. Effects of surface treatment

Fig. 2 (a), (b) show the J-V, L-V characteristics of the OLEDs with UV-Ozone and O₂ plasma treated *p*-Si anodes respectively. Compared to the device using untreated *p*-Si anode, the device with 15-minutes UV treated *p*-Si anode exhibits a much lower operation voltage and a much higher current efficiency (4.5 cd/A vs. 2 cd/A, inset of Fig. 2 (b)). When increasing the treatment time to 20 minutes, the device operation voltage increased but still with a higher EL efficiency of 4.5 cd/A. These results indicate that the UV-ozone treatment can remove the carbon contaminants on the *p*-Si surface resulting in holes injection enhancement. When the UV time is too long, *p*-Si will be oxidized. The thick oxidized *p*-Si (SiO_x) will increase the driving

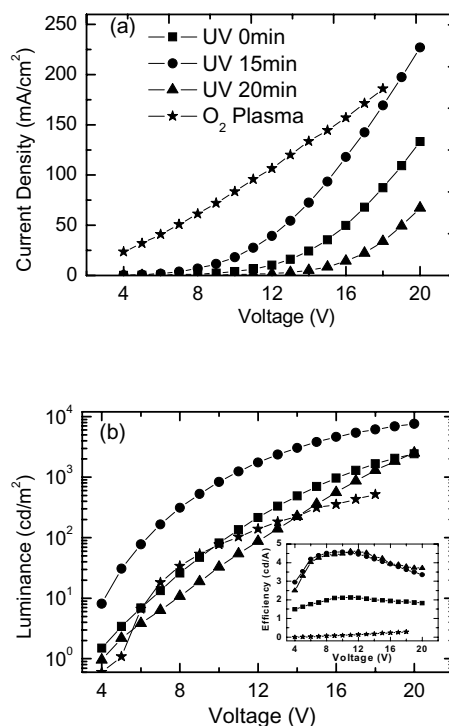


FIG. 2. (a) J-V, (b) L-V characteristics of devices with untreated, UV ozone treated, and O₂ plasma treated *p*-Si anodes. Inset: current efficiency.

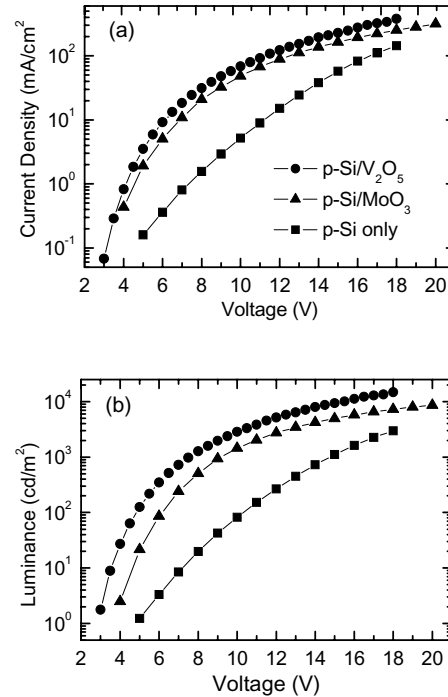
TABLE I. Performance of OLEDs with *p*-Si only, *p*-Si/V₂O₅, *p*-Si/MoO₃ anodes

Anode	Turn on voltage (V)	Voltage (V) at 20mA/cm ²	Voltage (V) at 1000cd/m ²	Maximum efficiency (cd/A)
<i>p</i> -Si	5.0	12.5	14.6	2.0
<i>p</i> -Si/V ₂ O ₅	2.9	7.3	7.5	4.2
<i>p</i> -Si/MoO ₃	3.5	8.0	9.2	3.0

voltage, leading to worse OLEDs performance. According to the plasma treatment, the current of the device is much larger than that of the device with untreated *p*-Si anode and linearly increased with applied voltages increased. It is obvious that there is very large leakage current. It is known that if use Si as OLED electrodes, a thin film of SiO_x is necessary inserted at the interface [14, 15]. Without the ultra-thin SiO_x layer, there will be large leakage current and no light can be observed. In the case of O₂ plasma treatment, the plasma will somewhat damage the ultra-thin SiO_x leading to deterioration of the device performance.

C. Effects of metal oxides modification

Fig. 3 shows the J-V and L-V characteristics of the devices with *p*-Si, *p*-Si/V₂O₅ and *p*-Si/MoO₃ anodes. From Fig. 3 (a), it can be seen that the current density of the device using V₂O₅ or MoO₃ modified *p*-Si anode is much larger than that of the device using *p*-Si only anode. This can be understood since the high work function of V₂O₅ and MoO₃ decreases the barrier for holes injection from the *p*-Si anode to the high occupied molecular orbital (HOMO) of NPB. Additionally, because the work function of V₂O₅ is a little higher than that of MoO₃, the device with V₂O₅ modified *p*-Si anode shows better performance than the one with MoO₃ modified *p*-Si anode. The turn-on voltages (defined as the voltage required for the luminance of 1 cd/m²) are 5V, 2.9V and 3.5V for the devices with *p*-Si, *p*-Si/V₂O₅ and *p*-Si/MoO₃ anodes, respectively (shown in Table I). The voltages needed to achieve the brightness of 1000 cd/m² are 7.3V and 8V respectively for the *p*-Si/V₂O₅ and *p*-Si/MoO₃ devices, much lower than that (12.5V) of the one using *p*-Si only

**FIG. 3.** (a) J-V, (b) L-V characteristics of devices with *p*-Si only, *p*-Si/V₂O₅, *p*-Si/MoO₃ anodes.

anode. The maximum current efficiency for *p*-Si/V₂O₅ device (~ 4.2 cd/A) is over 2 times larger than that of the *p*-Si only device (~ 2.0 cd/A). These results indicate that the ultra-thin V₂O₅ or MoO₃ can greatly enhance the holes injection to HTL and increase the excitons formed at the interface of NPB/Alq₃.

The manifestation of micro-cavity effect is the angular dependence of the light output [16]. Shown in Figure 4 are the EL spectra of device with V₂O₅ coated *p*-Si anode at different viewing angles. It can be seen that the EL spectra are slightly blue shift with increasing viewing angle. These results are obviously due to the existence of the micro-cavity effect caused by the reflection from the *p*-Si anode [17].

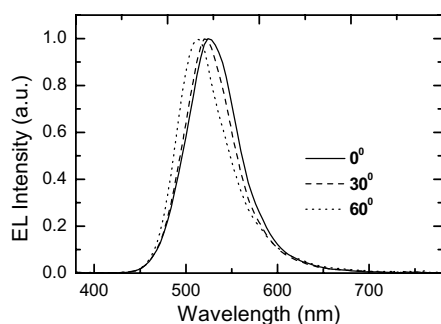


FIG. 4. EL spectra of device using *p*-Si/V₂O₅ anode at different viewing angles

Conclusions

In summary, we have investigated different modification methods include surface treatment and inserting thin films of metal oxides for *p*-Si anode. Some improvement was achieved with suitable UV ozone exposure time. O₂ plasma treatment somewhat damaged the *p*-Si surface leading to the deterioration in the device performance. While, ultra-thin high work function metal oxides, such as V₂O₅ or MoO₃ on the *p*-Si anodes can effectively enhance the holes injection from the *p*-Si anode. Compared with the device with *p*-Si only anode, the J-V and L-V characteristics were significantly increased, the turn-on voltage decreased from 5 V to 2.9V and the maximum current efficiency increased from ~2.0 cd/A to ~4.2 cd/A. The effectively modified *p*-Si anode will be a good candidate for integrating the OLED with the TFT in AMOLED fabrication. At least one ITO mask can be eliminated, with additional processing steps reduced.

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