Vanadium pentoxide modified polycrystalline silicon anode for active-matrix organic light-emitting diodes

X. L. Zhu, J. X. Sun, H. J. Peng, Z. G. Meng, M. Wong, and H. S. Kwok[a)]
Center for Display Research and Department of Electrical and Electronic Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, People's Republic of China

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Recently, polycrystalline silicon (*p*-Si) has been demonstrated to be an efficient anode for organic light-emitting diode (OLED) [X. L. Zhu, J. X. Sun, H. J. Peng, Z. G. Meng, M. Wong, and H. S. Kwok, Appl. Phys. Lett. **87**, 083504 (2005)]. In this letter, we show that, by depositing an ultrathin vanadium pentoxide (V_2O_5) layer on the *p*-Si anode, the performance of the OLED can be greatly improved. Detailed x-ray photoelectron spectroscopy study shows that strong band bending occurs at the *p*-Si/V_2O_5 interface, leading to much stronger hole injection. This modified *p*-Si anode can be integrated with the active *p*-Si layer of thin-film transistors in active-matrix OLED displays. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2099520]

Organic light-emitting diodes (OLEDs) have attracted wide attention due to their potential application in flat-panel displays.[1–4] Indium tin oxide (ITO) is the most widely used anode in OLEDs because of its high conductivity and transparency. Recently, the use of polycrystalline silicon (*p*-Si) thin film as an alternative semitransparent anode for bottom-emitting OLEDs has been proposed and demonstrated.[1] It is well known that *p*-Si is used as the active layer in thin-film transistors (TFTs) for active-matrix OLED (AMOLED) displays.[5,6] Replacing ITO with *p*-Si as the anode allows the elimination of at least one mask for fabricating an 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 improvements in production yield.

Unfortunately, the work function of the *p*-Si (in the range of 4.7–5.1 eV) 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 can be added.[1] Surface modification of the *p*-Si film can also be employed. Nanometers of high work function metal oxides, such as AgO_x,[7] NiO_x,[8] IrO_x,[9] have been proven to be good modification layers for anodes of OLEDs. V_2O_5 is a *p*-type semiconductor[10] with a high work function of above 5.4 eV.[11] It has also been reported as an efficient modification layer of ITO anode to enhance holes injection.[12]

In this letter, we demonstrate that by depositing an ultrathin V_2O_5 layer, significant enhancement in holes injection from *p*-Si anode can be achieved. X-ray photoelectron spectroscopy (XPS) analysis indicates that the higher work function of V_2O_5 than *p*-Si anode leads to an increase in *p*-Si surface band bending. Thus, the barrier for holes injection from *p*-Si anode to the hole transport layer (HTL) is decreased. We show that the performance of OLEDs with V_2O_5 layer is greatly improved compared with those using bare *p*-Si without V_2O_5 modification. Interestingly, it is also better than the ITO anode device due to the existence of a microcavity effect.

The *p*-Si anode used in the present study is as same as the one described in our previous report.[1] It is made on low-temperature oxide coated Corning 1737 glass by the process of metal-induced crystallization.[6] This *p*-Si (~50 nm) film has a sheet resistance of about 200 Ω/□. There is about 2–3 nm of native oxide on the *p*-Si. This oxide layer can, in principle, be used to block the diffusion of dopants in *p*-Si into the organic layer. The *p*-Si substrates were cleaned with acetone, ethanol, and deionized water sequentially, and dried in an oven.

The optical properties of this *p*-Si layer have been studied and reported previously.[1] Basically, the transmittance of the *p*-Si film varies from 65% to 35% from 450 to 800 nm. This variation in transmittance has to be compensated in a full color device. At the green wavelength used in the present study, the absorption is about 7.5% and the reflectivity is about 42%. Thus microcavity effect is expected to be present.

The OLED was prepared in a chamber with a base pressure of 1.6×10^{-4} Pa. Prior to organic layers deposition, 3 nm of V_2O_5 was evaporated with a tantalum boat. The organic layers consisted of 50 nm 4,4-bis[*N*-(1-naphthyl)-*N*-phenyl-amino]biphenyl (NPB) as the HTL, 50 nm tris-(8-hydroxy quinoline) aluminum (Alq_3) as the electron transport layer and emissive layer. Bilayer of LiF/Al was used as the efficient electrons injection cathode. The structure of the device is *p*-Si/V_2O_5 (~3 nm)/NPB (50 nm)/Alq_3 (50 nm)/LiF (1 nm)/Al (100 nm). For comparison, another two devices were fabricated. These two devices had the same structure as the one described earlier, except that *p*-Si without V_2O_5 coating and ITO coated with V_2O_5 were used as the anodes, respectively.

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. The XPS measurements were carried out with PHI 5500 surface analysis system using a monochromatic Al $K\alpha$ x-ray source with a photon energy of 1486.6 eV. The

[a)]Electronic mail: eekwok@ust.hk

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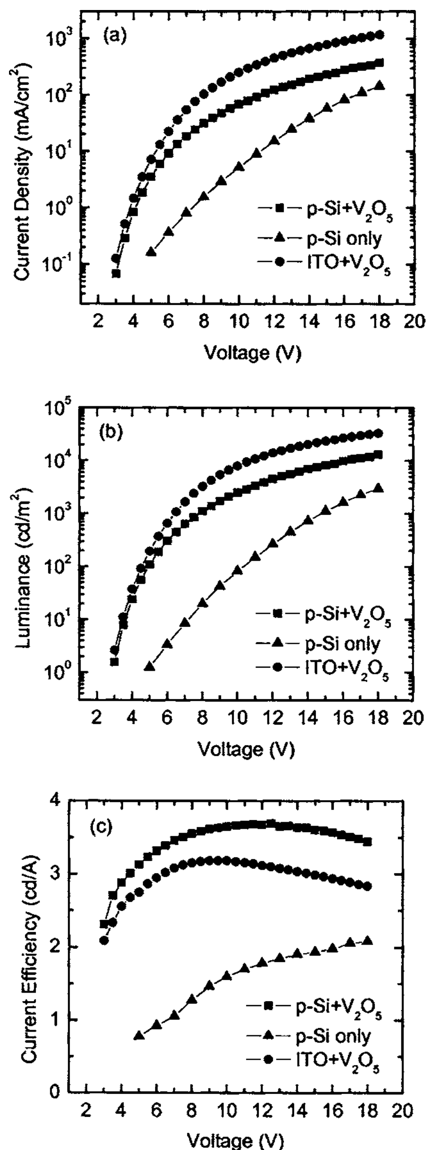

FIG. 1. (a) *J-V*, (b) *L-V*, and (c) current efficiency characteristics of devices with p-Si/V_2O_5, p-Si only, ITO/V_2O_5 anodes.

XPS spectra were referenced to C 1*s* peak (248.8 eV).

Figures 1(a) and 1(b) give the *J-V* and *L-V* characteristics of the devices with p-Si/V_2O_5, p-Si, and ITO/V_2O_5 anodes. It can be seen that, due to the sheet resistance difference of ITO (~25 Ω/□) and p-Si (~200 Ω/□), although the work functions of p-Si and untreated ITO are similar, the device with ITO/V_2O_5 anode exhibited better *J-V* and *L-V* performance than the one with p-Si/V_2O_5 anode. With the same applied voltage, the current density and the luminance of the device with p-Si/V_2O_5 anode are much larger than those of the device with p-Si only anode. With V_2O_5 layer modification, the turn-on voltages (defined as the voltage required for the luminance of 1 cd/m^2) dramatically decreased from 5 to 2.9 V.

The reduction in operation voltage can be explained by a lowered barrier for holes injection from p-Si to the highest occupied molecular orbits of the HTL. Figure 2 shows the core-level Si 2*p* XPS spectra of p-Si and p-Si/V_2O_5. The peak of bulk silicon is located at ~99 eV. Another smaller peak ~103 eV is associated with the oxide state of silicon. The peak from the p-Si/V_2O_5 surface shows a shift of about −0.3 eV with respect to the one from the p-Si surface. It is known that the valence-band edge has a fixed energy difference from the Si 2*p* core level, independent of the Fermi-level (E_F) position. Thus, the difference in the Si 2*p* level reflects a difference in the valence-band maxima (VBM) relative to E_F.[13,14] In other words, the core-level shift corresponds to an upward shift of VBM relative to E_F. The band-bending situation is schematically shown in Fig. 3(b). In addition to band bending, the work function will increase according to the value of $\Delta\Phi=\Phi_2-\Phi_1$. As a result, the barrier for hole injection is decreased.[9,15]

The current efficiency versus voltage of the three devices in the normal direction are shown in Fig. 1(c). It can be seen that the maximum current efficiency for p-Si/V_2O_5 device (~3.7 cd/A) is about two times larger than that of the p-Si only device (~2.0 cd/A). The existence of V_2O_5 increases the holes injection to HTL, correspondingly increases the excitons at the interface of NPB/Alq_3. Comparing with the device with ITO/V_2O_5, the higher current efficiency in the normal direction of the p-Si/V_2O_5 device is primarily attributed to microcavity effect.[16,17] The EL angular distributions of the ITO anode and p-Si anode devices are calculated by a straightforward optical model and are shown in Fig. 4.[17] The emission pattern of ITO anode device is approximatively

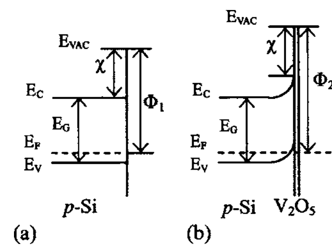

FIG. 3. Schematic energy band diagram for (a) p-Si surface (b) p-Si surface capped with V_2O_5 layer. E_F, E_{VAC}, E_C, E_V, E_G, χ, and Φ denote Fermi level, vacuum level, conduction-band minimum, valance-band maximum, band gap, electron affinity, and work function, respectively.

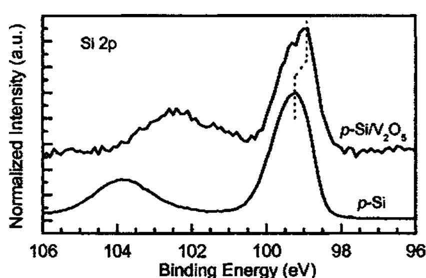

FIG. 2. Core-level Si 2*p* XPS spectra measured on p-Si and p-Si/V_2O_5 (3 nm) surfaces.

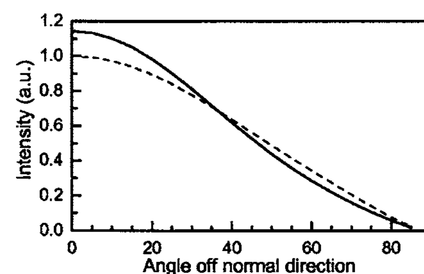

FIG. 4. Angular distribution of the EL intensity of the device with p-Si anode (solid line) and ITO anode (dashed line).

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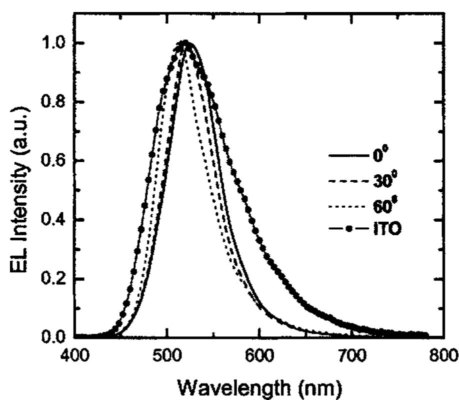

FIG. 5. EL spectra of device using p-Si/V_2O_5 anode at different viewing angles and EL spectrum of device using ITO/V_2O_5 anode in the normal direction.

Lambertion, while the device with p-Si anode shows enhancement in the normal direction.

Another manifestation of the microcavity effect is spectral narrowing of the light output. Figure 5 shows the measured EL spectra of the device with p-Si/V_2O_5 anode at different viewing angles and the EL spectra of the device with ITO/V_2O_5 anode in the normal direction. It can be seen that the EL spectra of the p-Si/V_2O_5 device are considerably narrower than those of the ITO/V_2O_5 device. These results are obviously due to the existence of microcavity effects caused by the reflection from the p-Si anode.[17,18] It is interesting to note that the angular shift of the emission color in the p-Si device is quite small, and the color purity is excellent.

In summary, we have demonstrated that an ultrathin V_2O_5 layer can effectively enhance hole injection from a p-Si anode. Compared with the device with p-Si only, the J-V and L-V characteristics are significantly improved. For the standard Alq_3/NPB OLED used in this study, the turn-on voltage decreased from 5 to 2.9 V and the maximum current efficiency increased from ~2.0 to ~3.7 cd/A. Similar improvement should be observed in other OLEDs of different colors.

It is expected that some other approaches for ITO surface modification can also be used for p-Si. The modified p-Si anode is 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. Recently it is shown that p-type metal oxide semiconductor TFT is sufficient for device integration on the AMOLED panel. Hence, the total number of masks needed in an integrated AMOLED device with p-Si as the anode can be less than 6. This is a tremendous reduction in processing time and cost. The only problem with the p-Si anode is its wavelength-dependent reflectivity. However, since red-green-blue OLEDs have different efficiencies anyway, such wavelength dependence can easily be compensated.

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