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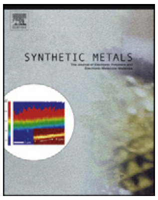

Improved performance of Si-based top-emitting organic light-emitting device using MoO_x buffer layer

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ABSTRACT

Highly efficient Si-based top-emitting organic light-emitting device (TOLED) using MoO_x buffer layer is demonstrated. With tris(8-hydroquinoline) aluminum as emitting and electron-transport layer, the *p*-Si/MoO_x based TOLED shows a maximum luminous efficiency of 1.1 cd/A and a power efficiency of 0.68 lm/W, which are almost double those (0.64 cd/A and 0.34 lm/W) of *p*-Si/SiO_2 based TOLED. Moreover, in comparison with the widely used thermally grown SiO_2 buffer layer, MoO_x can be deposited by conventional evaporation technology and thereby simplifying fabrication process.

1. Introduction

Squeezing light out of Si has been attracted considerable attention for revolutionizing Si-based optoelectronic applications [1]. However, Si has indirect bandgap and thus quite inefficient band-to-band radiative electron–hole recombination. In recent years, the research interest of Si-based light emission is focused on the combination of Si and organic electroluminescence (EL) [1,2]. This hybrid technology gains many advantages such as no lattice mismatch between Si and organic materials, simple fabrication process, and good compatibility with modern Si technology [2,3]. In the early pioneering works [2–4], the efficiency of Si-based organic light-emitting device (OLED) is extremely low and the reasons for the poor performance remain unclear. Since Qin et al. [5] reported highly efficient Si-based top-emitting OLED (TOLED) using au ultra-thin buffer layer of thermally grown SiO_2, intensive investigation of Si-based TOLED has been carried out and received increasing attention thereof [6–9]. Nowadays, researchers become more optimistic about Si-based TOLED, because this will open up an alternative route to the integration of optical devices with Si chips, including active matrix OLED (AM-OLED) displays.

Generally, two methods are widely used for realizing Si-based TOLED: (i) Si is directly used as anode, and (ii) Si coated with metal is used as electrode. For the latter, the metal determines carrier-injection characteristics and thereby device performance, while the Si only served as a substrate. For the former, the Si properties play a key role in determining the electro-optical characteristics. This structure allows the elimination of at least one mask for fabricating an AM-OLED, which simplifies the fabrication process and reduces manufacturing cost.

In Si-based TOLED, it is well established that the surface modification of Si is indispensable to improve device efficiency [4–5,8–10]. Buffer layers (e.g., $FeCl_3$, V_2O_5, MoO_x and WO_3) have been used in OLED with indium-tin-oxide (ITO) anode may also be employed for tuning carrier-injection characteristics of Si anode. MoO_x is superior to other choices of buffer layer in several respects: [11] (i) easy handling compared with the corrosive and optically absorbing $FeCl_3$; (ii) nontoxicity and high transmittance in comparison with V_2O_5; (iii) moderate evaporation temperature (much

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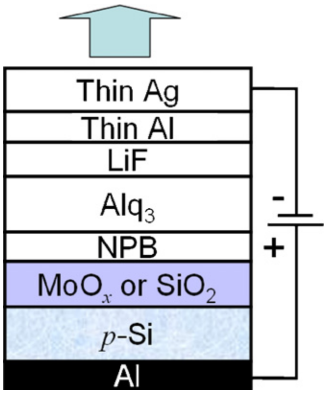

Fig. 1. Schematic structure of Si-based TOLEDs.

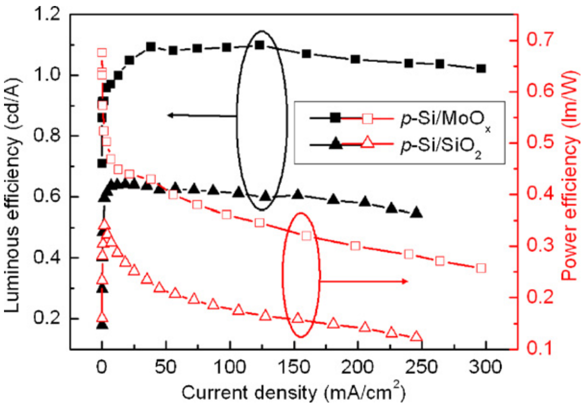

Fig. 2. η_J–J and η_P–J characteristics of p-Si/MoO$_x$ and p-Si/SiO$_2$ devices.

lower than WO$_3$) facilitates deposition process. On the other hand, most reported Si-based TOLEDs are realized using SiO$_2$ buffer layer [3,5–10]. SiO$_2$ must be obtained from other additional equipment, which will increase the cost and create contamination. In this article, we report the improved performance of Si-based TOLED using MoO$_x$ buffer layer.

2. Experimental details

The p-Si wafer with (1 0 0) orientation and electrical resistivity of 10 Ω cm was served as substrate and anode. Al ohmic contact was formed in the backside. The TOLED was fabricated on the front side of Si under a vacuum of 3×10^{-4} Pa. MoO$_x$ (2 nm) as a buffer layer and N,N'-bis(naphthalen-1-yl)-N,N'-bis(phenyl) benzidine (NPB, 60 nm) as a hole-transport layer were deposited subsequently, followed by 50 nm tris(8-hydroquinoline) aluminum (Alq$_3$) as an emitting and electron-transport layer. Trilayer LiF (0.3 nm)/Al (3 nm)/Ag (18 nm) semitransparent cathode [12] was deposited and patterned through a shadow mask to define the emitting area. Another Si-based TOLED using thermally grown SiO$_2$ (~2 nm) [5,6] as buffer layer was also fabricated for comparison. Fig. 1 shows the schematic structure of Si-based TOLEDs. We refer to the p-Si-based TOLED with MoO$_x$ (or SiO$_2$) buffer layer as p-Si/MoO$_x$ (or p-Si/SiO$_2$) device. The layer thickness of deposited materials was monitored *in situ* using an oscillating quartz thickness monitor. The deposition rate for organic materials was ~1 Å/s. The current–voltage–luminance (I–V–L) characteristics were measured with a Keithley 2400 Source Meter and a Minolta LS-110 Luminance Meter. The EL spectra were measured using a PR-650 Spectra Scan. Contact potential difference measurements were carried out as depicted in our early works [13].

3. Results and discussion

Fig. 2 shows the luminous efficiency–current density (η_J–J) and power efficiency–current density (η_P–J) characteristics of p-Si/MoO$_x$ and p-Si/SiO$_2$ devices. It can be seen that the p-Si/MoO$_x$ device shows a maximum luminous efficiency of 1.1 cd/A and a power efficiency of 0.68 lm/W, which are almost double those (0.64 cd/A and 0.34 lm/W) of p-Si/SiO$_2$ device. This indicates that MoO$_x$ is more efficient than SiO$_2$ for enhancing device efficiency. We also noted that the luminous efficiency (0.64 cd/A) of p-Si/SiO$_2$ device is slightly lower than that (~0.8 cd/A) of reported p-Si/SiO$_2$ based TOLEDs with the same organic layers [6,9]. Such difference may be resulted from the following two factors: (i) the reported efficiency in literatures [6,9] is obtained using p-Si anode with an optimized resistivity (40 Ω cm), and (ii) the difference in semitransparent cathode, i.e., the transmittance of LiF (0.3 nm)/Al (3 nm)/Ag (18 nm) semitransparent cathode is ~30% [12] while that of Yb (4 nm)/Au (15 nm) is ~60% [6]. However, the maximum luminous efficiency (1.1 cd/A) and power efficiency (0.68 lm/W) of p-Si/MoO$_x$ device are much higher than those (~0.8 cd/A and ~0.3 lm/W) of reported p-Si/SiO$_2$ based TOLEDs with the same organic stacks [5,6,9]. This indicates that MoO$_x$ is an efficient buffer layer for tuning hole-injection characteristics of Si anode.

The J–V and L–V characteristics are depicted in Fig. 3 which clearly demonstrates that p-Si/MoO$_x$ and p-Si/SiO$_2$ devices exhibit the same trend of J–V–L characteristics. This implies that the hole-injection characteristics from p-Si anode to NPB can be effectively controlled via the buffer layer of MoO$_x$ just like via SiO$_2$. But MoO$_x$ is superior to SiO$_2$ in enhancing luminance and reducing driving voltage [Fig. 3].

It is well known that the work function (WF) of Si anode plays a key role in tuning carrier-injection characteristics and thus carrier balance within device [4,10]. To clarify the contribution of MoO$_x$ and SiO$_2$ to the improvement of device performance, we measured the relative WFs of p-Si/MoO$_x$ and p-Si/SiO$_2$ as a function of standing time after surface treatment [Fig. 4]. It is clear that MoO$_x$ and SiO$_2$ modification can considerably enhance the WF of p-Si anode (enhanced by ~0.6 eV). The enhanced WF results in reduction of hole-injection barrier-height, which promotes carrier balance and improves device efficiency. On the other hand, heavily doped Si usually exhibits metallic properties. With the passivation of an ultrathin buffer layer, the modified-Si shows semiconductor properties which play a crucial role in tuning carrier-injection characteristics in Si-based TOLED [3,10]. In other words, the interfacial electronic structure of anode contact with the organic layer (NPB in this study) is an important factor controlling the hole injection [4]. SiO$_2$ is an insulating material, the semiconductor properties of

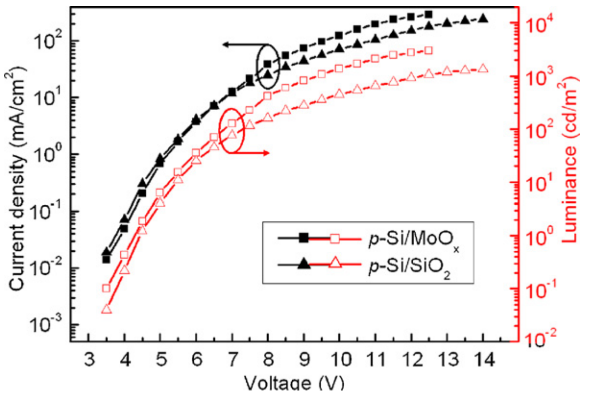

Fig. 3. J–V and L–V characteristics of p-Si/MoO$_x$ and p-Si/SiO$_2$ devices.

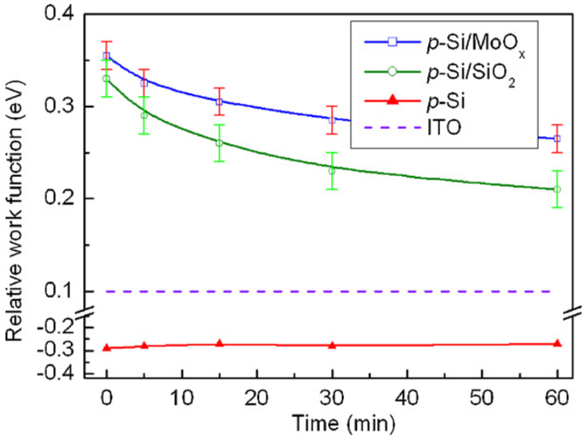

Fig. 4. The relative WFs of *p*-Si/MoO$_x$ and *p*-Si/SiO$_2$ as a function of standing time after surface treatment. The characteristics of ITO and *p*-Si (without treatment) are also incorporated for comparison.

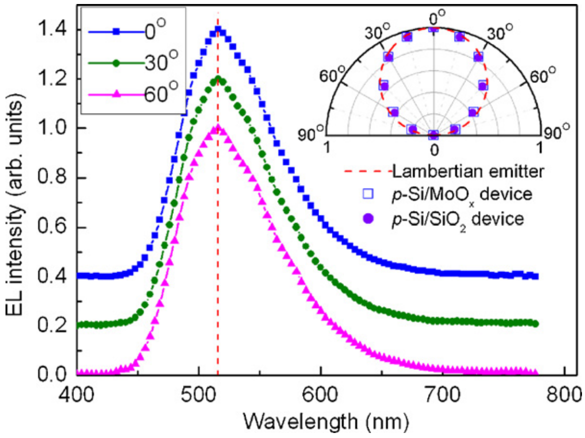

Fig. 5. EL spectra (normalized) of *p*-Si/MoO$_x$ device at viewing angles of 0°, 30° and 60°. For clarity, some curves have been shifted vertically. (Inset) The polar plots of emission intensities (normalized to the 0° intensities) of *p*-Si/MoO$_x$ device compared with *p*-Si/SiO$_2$ device and Lambertian emitter.

SiO$_2$-passivated Si are resulted from the trade-off between metallic Si and insulating SiO$_2$ [6,9]. While MoO$_x$ is a semiconductor material with appropriate WF and superior hole-injection ability [11], the hole-injection characteristics can be predominantly controlled by MoO$_x$ itself. The difference in surface electronic structure of *p*-Si/MoO$_x$ and *p*-Si/SiO$_2$ may account for the difference of device performance. The *p*-Si/MoO$_x$ device shows higher current density in comparison with *p*-Si/SiO$_2$ device at the same voltage (>6 V) [Fig. 3], as both devices share the same cathode and organic stacks, the higher current density indicates an enhanced hole injection. Furthermore, the luminance of *p*-Si/MoO$_x$ device is much higher than that of *p*-Si/SiO$_2$ device [Fig. 3], suggesting the enhanced hole injection contributes to better carrier balance and thereby promoting device efficiency. Therefore, MoO$_x$-modification is proven to be more favorable to improving EL performance. The WFs of *p*-Si/MoO$_x$ and *p*-Si/SiO$_2$ decrease slightly with the increase of standing time after surface treatment [Fig. 4]. This is due to the surface electronic structures of *p*-Si/MoO$_x$ and *p*-Si/SiO$_2$ are influenced by the ambient conditions. Further studies are required to clarify the detailed mechanism. In addition, MoO$_x$ is deposited under high vacuum condition which is free from contamination. This to great extent contributes to the improvement of device performance.

Fig. 5 shows the measured EL spectra (normalized) of *p*-Si/MoO$_x$ device at viewing angles of 0°, 30° and 60° off the surface normal. It can be seen that the EL spectra do not show blueshift with the increase of viewing angles. In the forward direction, the EL spectrum peaks at 516 nm with a full-width at half-maximum of 88 nm, giving green emission with Commission Internationale d'Eclairage (CIE) color coordinates of (0.278, 0.549). With increasing viewing angles, the CIE color coordinates show negligible variation. For example, at the viewing angle of 60° off the surface normal, the CIE color coordinates only shift to (0.280, 0.529). In addition, the polar plots of emission intensities (normalized to the 0° intensities) of *p*-Si/MoO$_x$ and *p*-Si/SiO$_2$ devices are almost Lambertian distribution [inset in Fig. 5]. All these phenomena indicate that *p*-Si/MoO$_x$ device exhibiting weak microcavity effect as a result of low reflectivity of Si.

4. Conclusions

MoO$_x$ and SiO$_2$ modification can considerably enhance the WF of *p*-Si anode, which accounts for the excellent EL performance of Si-based TOLED. MoO$_x$ is proven to be more efficient than SiO$_2$ in improving device performance, the efficiencies of *p*-Si/MoO$_x$ device are almost double those of *p*-Si/SiO$_2$ device. Moreover, MoO$_x$ can be deposited by conventional evaporation technology, which simplifies the fabrication process and thus reduced manufacturing cost.

Acknowledgements

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