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Independently controllable stacked OLEDs with high efficiency by using semitransparent Al/WO$_3$/Ag intermediate connecting layer

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Abstract
A high efficiency organic light-emitting device (OLED) has been fabricated by using a vertical stack of two OLED units connected by Al/WO$_3$/Ag. In the stacked OLEDs, each unit can be independently biased. It is found that the introduction of WO$_3$ between Al and Ag enhances the electroluminescent (EL) efficiency by 3.7 cd A$^{-1}$ for the top emissive unit. Meanwhile, the EL efficiency of the stacked OLED with the Al/WO$_3$/Ag interconnecting electrode is improved by 6 cd A$^{-1}$ with respect to the case of using Al/Ag as the connecting electrode. Our results indicate that Al/WO$_3$/Ag is an excellent kind of connecting structure for the fabrication of independently controlled high efficiency stacked OLEDs.

1. Introduction
Since Shen et al [1] and Burrows et al [2] reported a unique vertically stacked pixel architecture which allows for independent tuning of colour and intensity, many independently controllable and uncontrollable stacked (or tandem) structures have been studied in order to fabricate organic light-emitting devices (OLEDs) with high efficiency [3–10]. In stacked OLEDs, the intermediate connection layer plays a critical role in modifying the device performance. For the independently controllable stacked OLEDs, the intermediate connecting structure should simultaneously function as an anode for one unit and as a cathode for another unit. To realize the simultaneous function, at present a semitransparent metal layer or a transparent indium-tin oxide (ITO), such as Mg:Ag/indium zinc oxide [1], CuPc/indium tin oxide (ITO) [11] and LiF/Ca/Ag [12], is generally used. However, the potential thin film damage due to sputtering of ITO and the transmission problem of the thin metal electrodes may limit the improvement of the device performance. Therefore, it is desirable to develop the intermediate controllable metal electrodes with the aim of not only improving the transmission but also enhancing the efficiency of the stacked OLEDs.

In this paper, a new configuration of the interconnection structure of Al/WO$_3$/Ag is used to fabricate independently controllable integrated OLEDs. It is found that the insertion of WO$_3$ between Al and Ag improves the transmission of the connecting layer, and enhances the microcavity effect, which contributes to the improvement of the electroluminescent (EL) efficiency of the top unit in the stacked OLEDs as compared with that of the stacked OLEDs using Al/Ag. In addition, the emission spectra of the top and bottom units of the Al/WO$_3$/Ag OLEDs are narrowed as compared with that of the one using Al/Ag and the integrated OLEDs using ITO as the interconnecting layer [1, 2].

2. Experiment
In order to compare the role of Al/WO$_3$/Ag with Al/Ag as the intermediate connecting layer, two OLEDs were fabricated.
that the $J$–$B$–$V$ characteristics of the bottom units of devices A and B are approximately the same as that of the control device C. The current density of the bottom OLED of device A is lower than that of device B at the same applied voltage as shown in figure 2. In addition, the current efficiency of the bottom OLED of device A is slightly better than device B. These results are attributed to the insert of WO3 [13].

For the $J$–$B$–$V$ characteristics of the top units, there is an evident difference between devices A, B and the control device C. The current densities of the top OLED of both devices A and B are higher than that of device C. Besides, the current density of the top OLED of device A is also higher than that of device B as shown in the figure 2. Generally, the current density enhancement should be due to the increase of hole injection. For the former case, the enhancement should be related to the MoO$_3$ buffer layer on top of Ag. For the latter case, this should be attributed to the utilization of WO$_3$ inset layer between Al and Ag, due to the modifying effect of the oxide layer on the metal Al, which is similar to the reports from Lee [14] and Meyer et al [15]. The enhancement of the current injection makes the current efficiency of device A higher than that of device B to some extent.

To clearly compare the performance among the devices, the current density–brightness–voltage ($J$–$B$–$V$) characteristics of the top and bottom units of device A. For comparison, the $J$–$B$–$V$ characteristics of each unit of devices B and C are also shown in figure 2. It can be seen
Al/Ag, the solid lines denote Al/WO3/Ag and the dashed lines
denote Al/Ag.

of dispersion losses due to the utilization of WO3 between
and efficiency should be partially attributed to the improvement
for device B from the top unit. The enhancement in brightness
efficiency of device A from the top unit are much higher than
brightness and efficiency. As we can see, the brightness and
efficiency of device A from the top unit are much higher than
for device B from the top unit. The enhancement in brightness
and efficiency should be partially attributed to the improvement
density–current efficiency characteristics of the stacked device A
between Al and Ag narrows the EL spectrum further, indicating
that the Al/WO3/Ag possesses a more effective microcavity
confinement role than the Al/Ag. Furthermore, it can be clearly
seen that the microcavity effect does not produce obvious
angular dependence in the emissive spectrum of the bottom
units of devices A and B. The top units of devices A and B show
strong angular dependence, as shown in figures 5(b) and (d);
however, the angular dependence in device A is different from
that in device B. For device A, the emissive spectra gradually
narrow as the viewing angle increases whereas they gradually
widen with the increase of viewing angle in device B. This
indicates that the cavity effect of the Al/WO3/Ag film is
different from that of the Al/Ag film. The Al/WO3/Ag has
the most effective optical confinement role, which should be
favourable for the improvement of device efficiency.

Besides functioning as an effective intermediate connecting
unit, the Al/WO3/Ag can function as a charge generation
layer for stacked OLED devices, which also leads to higher
EL efficiency as compared with the Al/Ag OLED as shown
in figure 6. For instance, at a current density of 80 mA cm−2,
the brightness and current efficiency arrive at 19 900 cd m−2
and 25.1 cd A−1 for the Al/WO3/Ag stacked device, respecti
whereas the brightness and current efficiency arrive at
14 500 cd m−2 and 18.4 cd A−1 for the Al/Ag stacked device,
respectively. In addition, the brightness and current efficiency
of the stacked devices are about the sum of the brightness
and efficiency of the bottom and top unit devices, and
the stacked device A shows higher brightness and current
efficiency than the stacked device B, as shown in figure 6.
Again, using the case of current density of 80 mA cm−2 as
an example, the bottom and top units of device A emit
with the brightness of 12 535 cd m−2 and 8100 cd m−2
and the efficiency of 15.4 cd A−1 and 9.7 cd A−1, respectively,
whereas the bottom and top units of device B emit with
the brightness of 12 882 cd m−2 and 5300 cd m−2 and the
efficiency of 15.2 cd A−1 and 6.0 cd A−1, respectively, and
the control device C emits with the brightness of 12 470 cd m−2
and the efficiency of 15 cd A−1. It can be seen that the
current efficiency of the stacked device A (25.1 cd A−1) is
close to the sum of the brightness of the corresponding bottom
(15.4 cd A−1) and top (9.7 cd A−1) unit devices; however,
the current efficiency of the stacked device B (19.1 cd A−1) is
lower than the sum of the efficiency of the corresponding bottom
(15.2 cd A−1) and top (6 cd A−1) unit devices. This further
confirms that the Al/WO3/Ag structure is better than the Al/Ag
structure as the middle electrode in the stack devices. It should
be noted that the bottom emitting units in the stacked OLEDs
have the same emission characteristic as the control device, i.e.
no degradation in the device performance.

4. Conclusion

In summary, the Al/WO3/Ag structure is proposed to function
as the intermediate connecting electrode for independent
controllable two-unit integrated OLEDs. As compared
with the integrated OLEDs using Al/Ag as the intermediate
Figure 5. Normalized EL spectra of devices A, B and C: (a) the EL spectra of the bottom unit of device A and control device C and inset of (a) EL spectra of A bottom unit at various viewing angles, (b) EL spectra of A top unit, (c) EL spectra of B bottom unit and (d) EL spectra of B top unit.

Figure 6. Current density–brightness characteristics and current density–current efficiency characteristics of the stacked device A from top unit (down triangle), bottom unit (up triangle) and total device (square) and device B from top unit (left triangle), bottom unit (diamond) and total device (circle).

connecting electrode, both the top and the bottom units of the Al/WO3/Ag integrated OLED and the whole integrated device have higher current efficiency. The explanations have also been discussed. In addition, the change in the emission wavelength with viewing angle, due to the microcavity effect, of the top unit in the stack OLED with the Al/WO3/Ag electrode is smaller than that of the top unit in the stacked OLEDs using the Al/Ag electrode. The concept of introducing an oxide layer in between metal layers can be applied to other bilayer metal structures. Furthermore, such a connecting structure can be easily fabricated by simple thermal evaporation, and can be easily applied for fabricating real-time colour-tunable stacked OLEDs by changing the external bias, thus realizing high resolution, independently addressable, stacked red–green–blue pixels for application of colour displays.

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References


