Fuzzy-junction organic light-emitting devices

C.-W. Chen, T.-Y. Cho, and C.-C. Wu
Department of Electrical Engineering, Graduate Institute of Electro-Optical Engineering, and Graduate Institute of Electronics Engineering, National Taiwan University, Taipei, Taiwan 10617, Republic of China

H.-L. Yu and T.-Y. Luh
Department of Chemistry, National Taiwan University, Taipei, Taiwan 10617, Republic of China

(Received 20 May 2002; accepted for publication 1 July 2002)

A “fuzzy-junction” organic light-emitting device (OLED) containing a graded organic–organic interface is reported. Such graded junction is effectively produced utilizing interdiffusion through an ultrathin interfacial fusing layer sandwiched between two functional layers. With a glass transition temperature ($T_g$) lower than remaining layers, this fusing layer permits smooth interdiffusion and mixing of neighboring layers by annealing above its $T_g$. With appropriate material combinations, fuzzy-junction OLEDs thus prepared exhibit both reduced voltage and enhanced emission efficiency in comparison with conventional abrupt-junction devices. As an instance, a green fluorescent OLED with such fuzzy junction shows a high peak power efficiency of ~20 lm/W, substantially higher than ~14 lm/W of a corresponding abrupt-junction device. © 2002 American Institute of Physics.

[DOI: 10.1063/1.1502912]
above $T_g$ of DPSVB (but still $< T_g$'s of others) could cause the interdiffusion of neighboring layers through it and consequently the fusing of the initially separated $\alpha$-NPD and Alq layers [Fig. 1(b)]. This has been confirmed by effective resonant energy transfer between $\alpha$-NPD and Alq in photoluminescence (PL) studies of doped devices. As a result, the hole-blocking property is bypassed and device emission is altered from blue of $\alpha$-NPD to green of Alq, making the device a “programmable” one. In this work, we find that by making DPSVB as thin as tens of angstroms, the fusing caused by this interfacial fusing layer can actually enhance device performance beyond that of a conventional $\alpha$-NPD/Alq device. Since the interdiffusion of $\alpha$-NPD, DPSVB, and Alq is expected to cause blurring of the abrupt junction and to give a region of graded compositions of these three compounds between pure $\alpha$-NPD and pure Alq regions, we have therefore named this type of device a “fuzzy-junction” OLED. Owing to the additional “fusing” step, after the device deposition, the completed structures were subject to annealing at elevated temperatures under dry nitrogen atmosphere to complete the fabrication of the fuzzy-junction device.

Figures 2(a) and 2(b) compare the $I-V-L$ and the efficiency characteristics of a conventional $\alpha$-NPD/Alq device and a corresponding fuzzy-junction device (with DPSVB 10 Å, annealing at 80 °C, 3 min). Both devices showed the same Alq electroluminescence (EL) spectra. However, the fuzzy-junction device exhibited substantially reduced voltage and enhanced efficiency (1.6%, 5 cd/A vs 1.3%, 4 cd/A for the conventional device), resulting in higher brightness at a given voltage and improved power efficiency [4.1 lm/W vs 3.3 lm/W at the peaks, Fig. 2(d)]. Although not shown, it has to be mentioned that characteristics of conventional devices with or without similar annealing were also examined and were found nearly identical, ensuring that the device enhancement was due to fusing rather than some other annealing effect. Furthermore, as shown in Fig. 2(b), the fuzzy-junction device exhibits highly rectified $I-V$ characteristics (rectification ratio $\sim 10^8$) as in the conventional device, indicating that the fuzzy junction brings no detrimental effects on these characteristics. Both devices show identical onset voltage of $\sim 2$ V, yet the fuzzy junction gives steeper $I-V$ and $L-V$ characteristics [Fig. 2(b)], leading to reduced operation voltage.

The device enhancement due to the fuzzy junction applies to devices with emissive dopants as well. Figure 2(c) shows the $I-V-L$ and efficiency characteristics of the C545 T-doped (1 wt% in the first 300 Å of Alq) conventional device and fuzzy-junction device (DPSVB 10 Å, annealing at 80 °C, 3 min). Both devices exhibit pure green emission of C545T [inset of Fig. 2(d)]. The fuzzy-junction device shows a substantially higher maximum efficiency than the conventional one ($\sim 4.5\%$, 16.3 cd/A vs $\sim 3.4\%$, 12.3 cd/A). It is also noteworthy that the efficiency of the fuzzy-junction device rises sharply to its efficiency maximum at $\sim 2.5$ V and stays rather constant beyond. In contrast, the efficiency of the conventional device still rises gradually beyond 3 V until a maximum is finally reached at $\sim 8.5$ V. Together with reduced operation voltage, enhanced efficiency gives the fuzzy junction a remarkably high power efficiency of 19.5 lm/W at the peak (with a few cd/m²) and 14 lm/W at 100 cd/m² (vs 13.5 lm/W at the maximum and 8 lm/W at 100 cd/m² for the conventional device), as shown in Fig. 2(d). Such improvements in turn-on characteristics and power efficiency are of particular significance to the active-matrix OLED displays, in which OLEDs are driven near device onset.

Since the present scheme makes use of interdiffusion capability of organic glasses, one may be concerned about thermal stability of fuzzy-junction devices. However, after extended annealing (80 °C, >60 min) of DPSVB fuzzy-junction devices, they exhibited almost identical characteristics as those shown previously, showing no indication of degradation. Such thermal stability may suggest that the interdiffusion induced by an interfacial layer at an elevated temperature is self-limiting. That is, initially in pure DPSVB, $T_g$ is low and interdiffusion is feasible. With interdiffusion and mixing, the concentration of DPSVB declines, leading to a rise of local $T_g$ and eventually suppression of further diffusion. In recent years, there is also a trend of employing high-$T_g$ materials in OLEDs to extend opera-
TIONAL TEMPERATURE RANGE. 11 To test whether interfacial fusing can be applied to such high-$T_g$ systems, we replaced $\alpha$-NPD and DPSVB with higher-$T_g$ hole-transport TATE ($T_g \sim 150 ^\circ C$) and hole-blocking BCP ($T_g \sim 80 ^\circ C$), respectively. Since $T_g$ of the fusing layer is raised, the fusing temperature required correspondingly increases to 120 °C (but still $< T_g$’s of other materials). Figure 3 compares the $I-V-L$ and efficiency characteristics of the conventional TATE/Alq device (triangles) and a TATE/BCP/Alq fuzzy-junction device (circles). Inset: efficiency vs voltage for the above two devices.

To acquire further insight of present fuzzy-junction devices and its differentiation from conventional ones, we have also fabricated the following devices with codeposited mixed layers to mimic the situation of fuzzy junction:

(1) ITO/PEDT/$\alpha$-NPD 375 Å/$\alpha$-NPD:DPSVB (5:1 wt, 25 Å)/Alq:BCP (5:1 wt, 25 Å)/Alq 575 Å/LiF/Al, (II) ITO/PEDT/$\alpha$-NPD 375 Å/$\alpha$-NPD:BCP (5:1 wt, 25 Å)/Alq:BCP (5:1 wt, 25 Å)/Alq 575 Å/LiF/Al, (III) ITO/PEDT/$\alpha$-NPD 375 Å/$\alpha$-NPD:Alq:DPSVB (5:5:2 wt, 50 Å)/Alq 575 Å/LiF/Al, (IV) ITO/PEDT/$\alpha$-NPD 375 Å/$\alpha$-NPD:Alq (1:1 wt, 50 Å)/Alq 575 Å/LiF/Al. All these devices have a 50 Å codeposited mixed region between pure HTL ($\alpha$-NPD) and pure ETL (Alq) and all show pure EL of Alq. Figure 4 compares the $I-V$ and efficiency characteristics of these devices with those of the conventional and fuzzy-junction devices in Fig. 2(a). It is noticed that codepositing HTL and ETL only as in device (IV) does not provide for efficiency enhancement as compared to the conventional abrupt-junction device, consistent with previous reports. 7,9 On the other hand, from the efficiency enhancement observed for devices I–III, it appears that mixing hole-blocking materials (DPSVB or BCP) near the junction is responsible for efficiency enhancement in present fuzzy-junction devices and for the difference in performance from previous mixed-layer devices. 7,9 Meanwhile, the fuzzy junction induced with a hole-blocking fusing layer has the further advantage of substantial voltage reduction, compared to mixing hole-blocking materials simply by codeposition. Although detailed mechanisms require further investigation, it is currently speculated that the graded composition and the hole-blocking compounds mixed near the fuzzy junction subtly affect the scenario of carrier injection/transport, and distributions of carriers and electric fields near the junction, together contributing to overall device enhancement.

In summary, we report a “fuzzy-junction” OLED, in which the graded organic–organic interface is effectively produced by a functional interfacial fusing layer. The ultra-thin interfacial fusing layer has lower $T_g$ than remaining layers such that annealing the structure with a temperature above its $T_g$ causes the fusing (mixing) of neighboring layers, forming a fuzzy junction. The fuzzy-junction OLEDs exhibit both reduced operation voltage and enhanced emission efficiency in comparison with conventional abrupt-junction devices. This approach may be generalized to appropriate material combinations and to various organic–organic interfaces in a heterostructure OLED to obtain desired or optimized device characteristics.

The authors would like to acknowledge financial support from National Science Council (Grant No. NSC 90-2215-E-002-025) and Ministry of Education (Grant No. 89-N-FA01-2-4-2) of the Republic of China.


FIG. 3. Comparison of $I-V$ ( ), $L-V$ ( ), and $L-V$ ( ) characteristics of a conventional TATE/Alq device (triangles) and a TATE/BCP/Alq fuzzy-junction device (circles). Inset: efficiency vs voltage for the above two devices.

FIG. 4. Comparison of $I-V$ and efficiency characteristics of devices I ( ), II ( ), III ( ), IV (*) with those of the conventional device (Δ) and the fuzzy-junction device (○) in Fig. 2(a).