Tandem Organic Light-Emitting Devices Having Increased Power Efficiency

Liang-Sheng Liao[1] and Kevin P. Klubek
Research Laboratories, Eastman Kodak Company, Rochester, NY 14650, U.S.A.
[1]TEL: 01-585-588-8462, e-mail: liang-sheng.liao@kodak.com.

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Abstract

Tandem organic light-emitting diodes (OLEDs) do not always improve power efficiency over their conventional OLED counterparts. When a tandem OLED utilizes optimized EL units, increased power efficiency can only be achieved if the intermediate connector in the device has excellent charge injection capability.

1. Introduction

Tandem organic light-emitting diodes (OLEDs) can have improved current efficiency, brightness, and operational lifetime compared to conventional OLEDs.[1–14] A tandem OLED is constructed by vertically stacking several individual electroluminescent (EL) units, each typically including a hole-transporting layer (HTL)/light-emitting layer (LEL)/electron-transporting layer (ETL), and with each EL unit then being connected by an intermediate connector (or a connecting unit). The tandem OLED is operated by driving all of the EL units inside the device in series using a single power source.[1–14] For a tandem OLED having N EL units (N > 1), the current efficiency can be about N times as high as that of a conventional OLED (i.e., containing only one EL unit between electrodes) because N EL units instead of just one EL unit contribute to light emission. Therefore, at a specific current density, a tandem OLED can achieve a luminance about N times as high as that of a conventional OLED while maintaining about the same lifetime. Alternatively, a tandem OLED needs only about 1/N the current used in a conventional OLED to obtain the same luminance, which results in an operational lifetime N times that of a conventional OLED.

As is known, it is critical to achieve improved power efficiency for OLEDs to be best utilized in commercial applications. While current efficiency, brightness, and operational lifetime for tandem OLEDs are already superior compared to conventional OLEDs, power efficiency may potentially be improved as well. In this work we investigated different organic/metal, organic/metal-oxide, and organic/organic intermediate connectors to demonstrate their effects on the power efficiency of the tandem OLEDs.

2. Experimental

The organic materials used in this work were KODAK OLED Materials: HT1, GH1, EK-BH109, GD1, and EK-GD403. The other organic materials were 4,7-diphenyl-1,10-phenanthroline (Bphen), 2,3,5,6-tetrafluoro-7,7,8,8-tetracyanoquinodimethane (F_4-TCNQ), and 1,4,5,8,9,11-hexaazatriphenylene hexacarbonitrile (HAT-CN), which were synthesized in the research laboratories of Eastman Kodak Company. The inorganic materials used in this work were: Li, Al, Ag, MoO_3, and V_2O_5.

All OLEDs (including conventional and tandem structures) were fabricated on ~1.1-mm-thick glass substrates precoated with a transparent indium-tin oxide (ITO) conductive layer having a thickness of ~22 nm and a sheet resistance of ~70 Ω/square. The detailed substrate cleaning process, device fabrication method, and EL measurements of the devices are described elsewhere.[14]

The schematic device structures of both conventional and tandem OLEDs are shown in Fig. 1. The organic layers, i.e., HTL/LEL/ETL/electron-injecting layer (EIL), between the modified ITO anode and the aluminum cathode in the conventional OLED in Fig. 1(a), are defined as an EL unit. Two EL units connected in series by an intermediate connector and sandwiched between the anode and cathode form a tandem OLED as shown in Fig. 1(b).

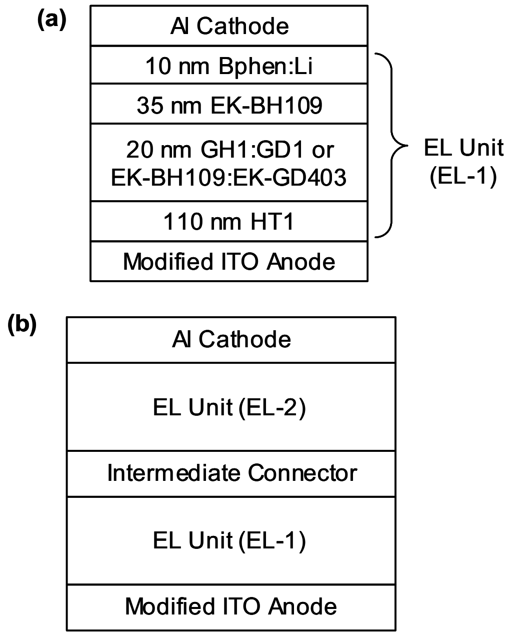

Fig. 1. Schematic structure of (a) a conventional OLED and (b) a tandem OLED.

Six different intermediate connectors were investigated, with each falling into one of three categories, i.e., of organic/metal, organic/metal-oxide, and organic/organic, and each is listed in Table 1.

TABLE 1. Intermediate Connectors

1	15 nm Bphen:1 vol% Li/3 nm Al
2	15 nm Bphen:1 vol% Li/3 nm Ag
3	15 nm Bphen:1 vol% Li/3 nm MoO_3
4	15 nm Bphen:1 vol% Li/3 nm V_2O_5
5	15 nm Bphen:1 vol% Li/ 10 nm HT1:4 vol% F_4-TCNQ
6	15 nm Bphen:1 vol% Li/10 nm HAT-CN

Two sets of light-emitting devices, Set-A (A-0 to A-6) and Set-B (B-0 to B-6), were fabricated. A-0 is a conventional device having the following structure: "Anode/110 nm HT1/20 nm GH1:1 vol% GD1/35 nm EK-BH109/10 nm Bphen:1 vol% Li/Al." Devices A-x (x = 1–6) are tandem devices corresponding to the aforementioned intermediate connectors and having the following structure: "Anode/EL-1/Connector-x/EL-2/Al," wherein both EL-1 and EL-2 are the same as the EL unit in A-0 except that the thickness of the HT1 layer in EL-2 is adjusted to achieve a maximal optical out-coupling, such that the central distance between the two LELs is kept at about 150 nm (which is equivalent to an optical path of a half-emitting wavelength). Set-B (B-0 to B-6) is the same as Set-A except that the LEL (20 nm GH1:1 vol% GD1) in Set-A has been changed into "20 nm EK-BH109:6 vol% EK-GD403" for Set-B.

3. Results and Discussion

Shown in Fig. 2 is the EL performance of Set-A devices.

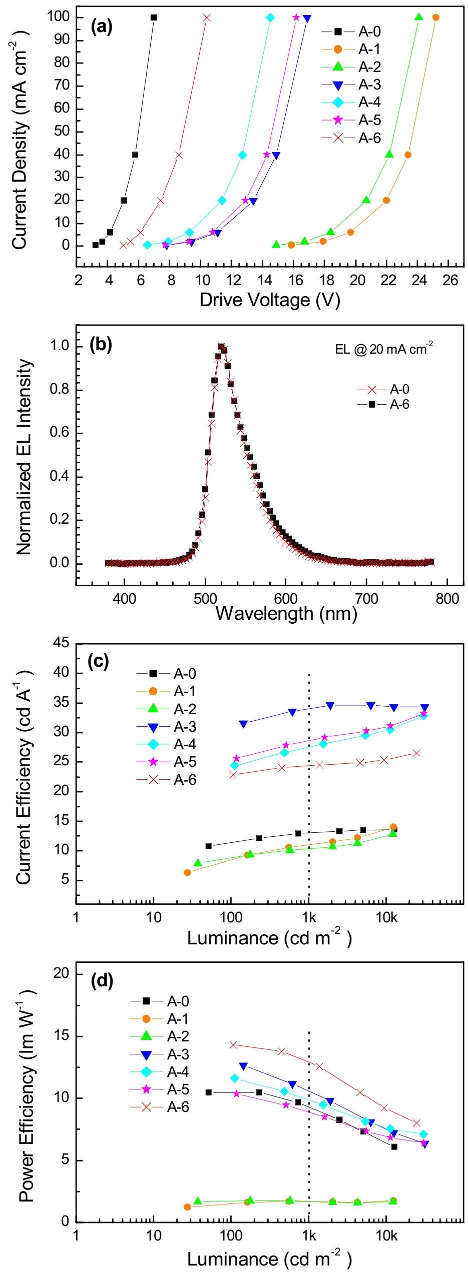

Fig. 2. Electroluminescence performance of Set-A devices.

The current-voltage (J-V) characteristics shown in Fig. 2(a) indicate that different intermediate connectors result in different drive voltages for the tandem OLEDs. Fig. 2(b) compares the EL spectra between A-0 and A-6 tested at 20 mA/cm^2. No significant peak narrowing and shifting occur in A-6 compared to A-0. Fig. 2(c) plots current efficiency vs. luminance and this shows that current efficiency is at least doubled for any device containing an organic/metal-oxide or organic/organic intermediate connector. Shown in Fig. 2(d) are the plots of power efficiency vs. luminance for the devices. This figure indicates that all of the tandem OLEDs, except A-1 and A-2, have a power efficiency higher than or comparable to that of the conventional OLED (A-0).

It is clear from the data presented in Fig. 2 that there is no advantage in using an organic/metal bilayer as the intermediate connector. We suspect that a high charge injection barrier forms due to the metal layer in the intermediate connector, resulting in high voltage and lower power efficiency. This proposition is supported by viewing the EL images shown in Fig. 3 of the emitting surfaces of the tandem devices. Devices A-3–A-6 have uniform emission across the device surface, whereas devices A-1 and A-2 have emission occurring predominantly at the edges and through some micro shorting pinholes. We attribute these two EL images to the inferior charge injection capability of Connectors 1 and 2.

As shown in Fig. 2(d), with the exception of the metal related intermediate connectors, the other types of intermediate connectors achieve increased or comparable power efficiency for the tandem OLEDs vs. the conventional OLEDs. However, this is not always the case. We found that if a tandem OLED is fabricated based on a conventional OLED (or an EL unit) that has low current efficiency and low external quantum efficiency (EQE), increased power efficiency can be easily achieved. However, if a tandem OLED is fabricated based on a conventional OLED (or an EL unit) that has high current efficiency and high EQE, increased power efficiency can only be achieved if its intermediate connector has excellent charge injection capability. In order to illustrate the importance of both the EL unit and the intermediate connector and their combined effect on power efficiency improvements, we measured the EL characteristics of Set-B devices and present their EL performance in Fig. 4.

Similar to Fig. 2(a), the J-V characteristics shown in Fig. 4(a) also indicate that different intermediate connectors result in different drive voltages for the tandem OLEDs. Fig. 4(b) compares the EL spectra between B-0 and B-6 tested at 20 mA/cm^2. No significant peak narrowing and shifting occur in B-6 compared to B-0. Fig. 4(c) plots current efficiency vs. luminance and shows extremely high current efficiency (57 cd/A) from device B-6. Fig. 4(d) plots power efficiency vs. luminance for the devices. Unlike Fig. 2(d), Fig. 4(d) shows that only B-6 has achieved a higher power efficiency than that of device B-0. For example, at 1000 nits, the power efficiency of B-6 is 31 lm/W, which is about 50% higher than that of device B-0.

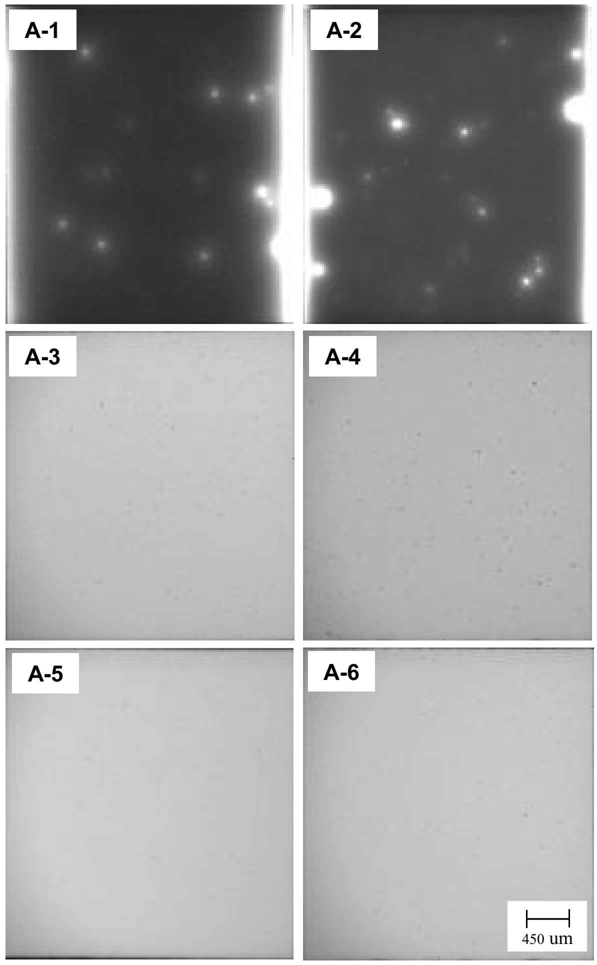

Fig. 3. Electroluminescence image of Set-A devices.

One of the advantages of a tandem OLED is that the intermediate connector may provide a balanced charge injection toward the two adjacent EL units. In Set-A devices, A-0 has relatively low efficiency (13.5 cd/A, 3.7% EQE at 20 mA/cm^2). This means that the charge recombination might not be well balanced. Therefore, the tandem OLEDs based on this EL unit can easily achieve an improved recombination balance resulting in improved power efficiency. However, in Set-B devices, B-0 has relatively high efficiency (21 cd/A, 5.9% EQE at 20 mA/cm^2), implying that charge recombination in the EL unit has already been well balanced. Therefore, only an intermediate connector with excellent charge injection capability along with a negligible voltage drop across it (such as Connector-6) can achieve increased power efficiency.

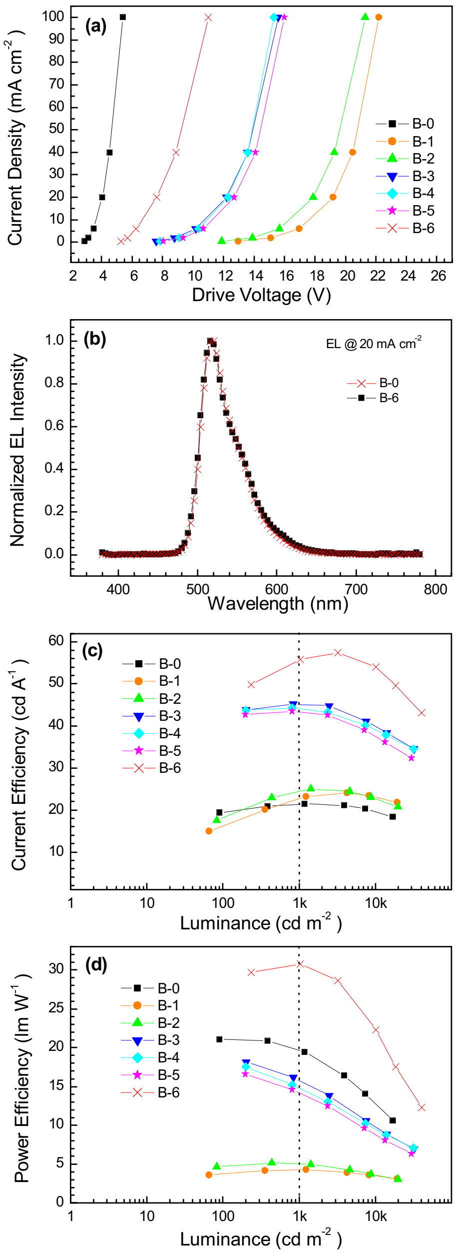

Fig. 4. Electroluminescence performance of Set-B devices.

4. Summary

It has been demonstrated that increased power efficiency cannot be achieved from a tandem OLED having an organic/metal intermediate connector. Power efficiency improvements depend greatly on both the EL unit and intermediate connector. Intermediate connectors possessing excellent charge injection capability along with a negligible voltage drop work best. Of the intermediate connectors that were investigated in this work, we find that the one consisting of a Li-doped Bphen layer and a HAT-CN layer exhibits the best power efficiency improvement for the tandem OLEDs.

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