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Inverted top-emitting organic light-emitting diodes using transparent conductive NiO electrode

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Abstract

We report on a top-emitting organic light-emitting device (TE-OLED) using a thermally evaporated and semi-transparent NiO film as a top-electrode. Our TE-OLED was fabricated, basically taking the reverse sequence for the fabrication of a conventional bottom-emitting organic light-emitting device (BE-OLED). Since the resultant sheet resistance of our NiO was high (8 kΩ/□) and its transmittance was only 50%, the resulting luminance (∼150 cd/m^2) and injection current (∼50 mA/cm^2) of our TE-OLED were much inferior to those of the BE-OLED device. However, its top-emitting was clearly observable and is thus concluded that our TE-OLED using thermally evaporated NiO, is quite promising if the NiO is controlled to have lower sheet resistance than the present value.

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Keywords: Top-emitting organic light-emitting device (TE-OLED); Semi-transparent NiO; Thermally evaporated; Bottom-emitting organic light-emitting device (BE-OLED)

1. Introduction

Organic light-emitting devices (OLEDs) have extensively been studied and developed for the last decade due to their potentials for more modern flat-panel display applications [1–3]. Most of the OLEDs have used indium tin oxide (ITO) films deposited on glass for their transparent cathode, which is a bottom electrode. Then, generated light should be emitted through the ITO glass. This type of emission is called ''bottom-emitting'' but now ''top-emitting'' OLEDs have became necessary, which is a device emitting the light through a top transparent electrode [4–7]. The top-emitting type devices should eventually be prepared along with thin film transistors (TFTs) (as OLED drivers) for the accomplishment of active matrix OLED display [7–9]. Whether the utilized organic materials are small molecules or polymers, the

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top emitting type of OLEDs is important although its realization is difficult. Not many top emitting OLEDs have been reported yet [4–7], but also other transparent oxides than ITO have rarely been studied for the top or bottom electrode. In the present paper, we have initially investigated thermally evaporated NiO as a transparent top electrode and report on its possibility for the electrode of the top-emitting OLEDs.

2. Experiment

Indium tin oxide (ITO) glass, of which the thickness and sheet resistance were 100 nm and 40 Ω/□, respectively, was used to fabricate a conventional bottom-emitting OLED (BE-OLED) as shown in Fig. 1(a). Anode lines (width = 2 mm) were patterned on the ITO glass and the surface of the ITO glass was cleaned with acetone, methyl alcohol, and de-ionized water prior to the deposition of organic films. The organic films were deposited using a thermal crucible in a vacuum chamber with a base pressure of 1×10^{-6} Torr at a substrate temperature of 25 °C [room temperature (RT)]. The *N*,*N*′-diphenyl-*N*,*N*′-bis (3-methylphenyl)-[1,1′-biphenyl]-4,4′-diamine (TPD) (purity 99%, Aldrich Chem. Co.) was initially deposited by thermal evaporation on ITO glass with a fixed deposition rate of ∼0.15 nm/s at the crucible temperature of 160 °C. The tris-(8-hydroxyquinoline) aluminum (Alq_3) (purity 99.995%, Aldrich Chem. Co.) was subsequently deposited on TPD with ∼0.2 nm/s at the crucible temperature of 180 °C by employing thermal evaporation. The thicknesses of TPD and Alq_3 were fixed to 50 nm. All the film thicknesses were monitored by a quartz crystal oscillator. Al cathode lines (width = 2 mm) were patterned by thermal evaporation using a shadow mask, finally to form 2 mm × 2 mm pixels for OLED.

For our top-emitting organic light-emitting devices (TE-OLED), we patterned the Al cathode lines (width = 2 mm) on the cleaned glasses first, before sequentially evaporating Alq_3 and TPD under the same deposition conditions as those for the BE-OLED. Finally, the semi-transparent 100 nm thick NiO anode lines were deposited by thermal evaporating NiO powders. The sheet resistance and transmittance of the NiO film were measured to be as high as 8 kΩ/□ and 50%, respectively. Fig. 1(b) shows the schematic structure of our TE-OLED.

Current–voltage (*I*–*V*) and luminance–voltage (*L*–*V*) measurements were made to analyze the electrical and light-emitting performances of the BE-OLEDs and TE-OLEDs. We used a KEITHLEY 236 source-measure unit (SMU) and a candela meter (PR650) for the *I*–*V* and *L*–*V* measurements, respectively. For the electroluminescence (EL) intensity and spectra of our OLED pixels, we used a charge-coupled device (CCD) array spectrometer (Acton Research Co.).

3. Results and discussion

Fig. 2 shows the electroluminescence spectra of the BE-OLED and TE-OLED using ITO and thermally evaporated NiO, respectively. Their peak positions were identical, found at 520 nm (green). The EL intensity of the BE-OLED (applied voltage = 17 V)

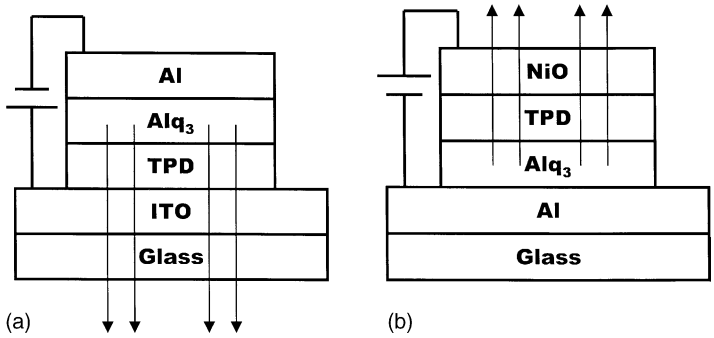

Fig. 1. Schematic cross-sections of our conventional (a) BE-OLED and (b) TE-OLED.

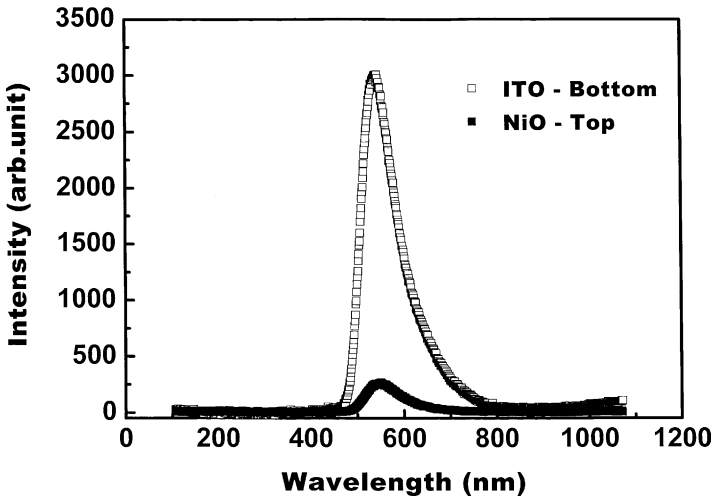

Fig. 2. Electroluminescence spectra obtained from BE-OLED (ITO-bottom, applied with 17 V) and TE-OLED (NiO-top, applied with 40 V).

was about 10 times higher than that of the TE-OLED (applied voltage = 40 V). Their luminance–voltage plots are also displayed at Fig. 3. As expected from Fig. 2, the luminance from the TE-OLED (maximum ~150 cd/m^2) is ~10 times lower than that of the BE-OLED. Since 100 nm thick NiO film has only 50% of transmittance in the visible range of 400–700 nm while the ITO film with the same thickness does over

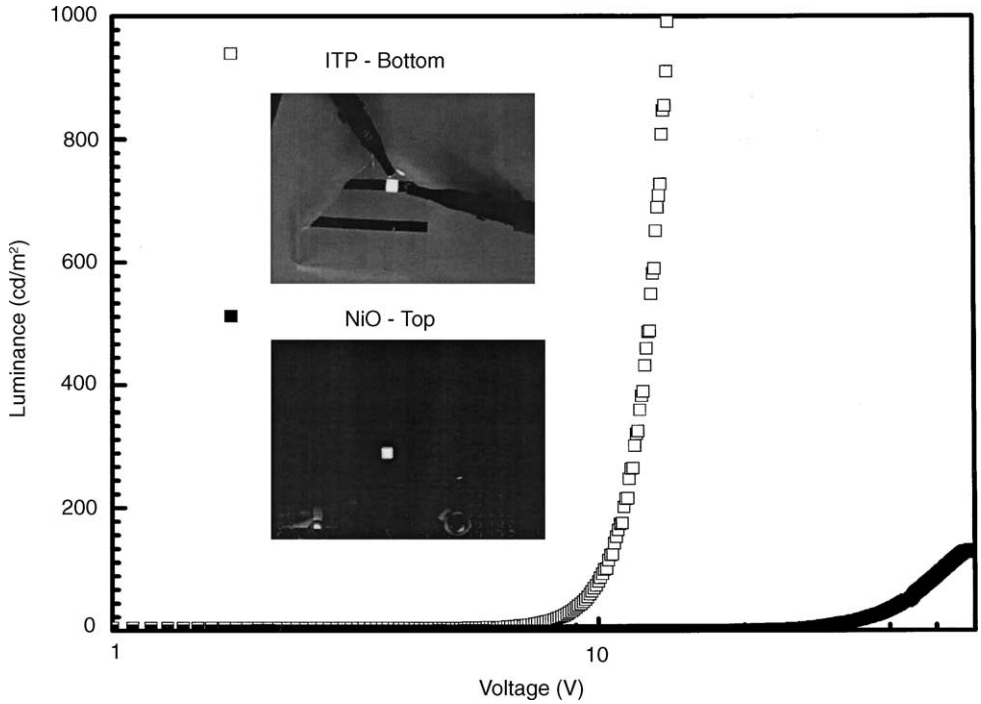

Fig. 3. Luminescence–voltage (*L–V*) plots obtained from BE-OLED (ITO-bottom) and TE-OLED (NiO-top) Insets are pictures taken from the BE-OLED (ITO-bottom, applied with 17 V) and TE-OLED (NiO-top, applied with 40 V).

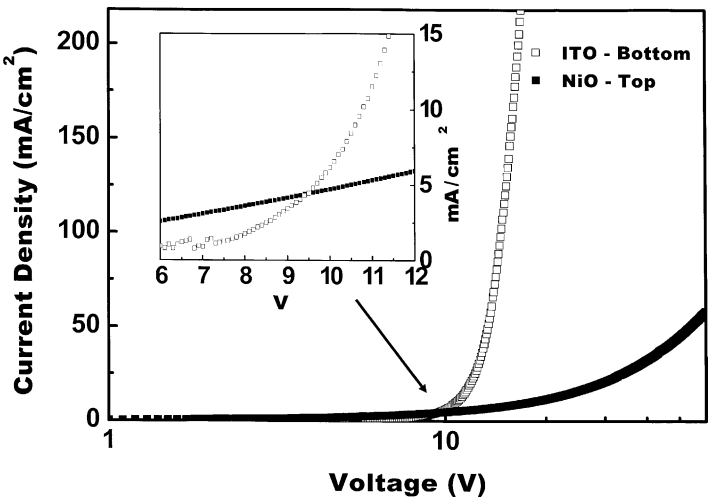

Fig. 4. Current-density–voltage (J–V) plots obtained from the BE-OLED (ITO-bottom) and TE-OLED (NiO-top) Inset is a magnified and linear-scaled part (6–12 V range) of the J–V plots, showing the large leakage current from the TE-OLED.

90% in the same photon range, the luminance obtained from the TE-OLED is basically inferior to that from the BE-OLED. In spite of such inferiority, the EL picture taken from the TE-OLED using charge-coupled device camera was very clear at least (the TE-OLED case was taken by the camera at a high voltage of 40 V. See the inset pictures).

Fig. 4 displays current-density–voltage curves obtained from the BE-OLEDs and TE-OLEDs. Since the sheet resistance of the NiO film (8 kΩ) is 2 order of magnitude higher than that of the ITO, the hole injection from the NiO is much more difficult than the injection from the ITO. The injection current density was only about 50 mA/cm^2 at 50 V. This can be a main reason, why our TE-OLED exhibits some visible luminance after attaining at a higher voltage and its luminance intensity is much weaker than that of the BE-OLED. (We all know that the luminance comes from the electron–hole recombination.) Furthermore, the NiO which should be actually p-type degraded semiconductor probably generates more resistance-involved heat during biasing than the ITO electrode. The generated heat also inhibits our TE-OLED from efficiently emitting the light.

It is of interest to note that the injection current at 10 V is about the same (to be 5 mA/cm^2) for the both BE-OLED and TE-OLED devices (see the inset of Fig. 4) while their resulting luminance is very different to each other (Fig. 3). No luminescence was observed from our TE-OLED at the 10 V despite some current flowing while a luminance of ∼80 cd/m^2 was measured from the conventional BE-OLED. It is inferred that any trap-involved leakage current irrelevant to the electron–hole recombination also exists in p-NiO film during biasing.

In the present moment, it has been found that the TE-OLED is much inferior to the BE-OLED in efficiency. However, it is quite prospective that a well-developed NiO with a higher conductivity may solve the heat-induced problems and the leakage problems as well. Hence, it is concluded that our attempt to obtain a TE-OLED using thermally evaporated NiO is promising and valuable.

4. Conclusion

In summary, we have prepared a TE-OLED device using a thermally evaporated and semi-transparent NiO film as a top-electrode. Since the sheet resistance of our NiO was very high and its transmittance was only about 50%, the resulting luminance and injection current of our TE-OLED were much inferior to those of the BE-OLED device. However, its top-emitting was clearly observable and is thus concluded that our TE-OLED using thermally evaporated NiO is quite promising if the NiO is controlled to have much lower sheet resistance than the present value.

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