Room-temperature deposition of thin-film indium tin oxide on micro-fabricated color filters and its application to flat-panel displays

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Abstract — Direct deposition of indium tin oxide (ITO) thin film on color filters is of practical use in the fabrication of state-of-the-art flat-panel displays. Room-temperature dc magnetron sputtering of thin-film ITO and issues related to the integration of ITO-on-glass panels containing micro-fabricated color filters and other functional materials have been investigated. The resulting polycrystalline ITO exhibited good adhesion to the underlying color filters, as well as good optical transparency and high electrical conductivity. Application of this ITO deposition technology to color liquid-crystal and organic light-emitting diode displays will also presented.

Keywords — *Indium tin oxide, color filter, room-temperature dc magnetron sputtering.*

1 Introduction

Color rendition is a basic requirement of high-quality information and entertainment displays. Combining filters of primary colors with a white-light emitter is one common approach to realizing color displays. This technique is widely used in liquid-crystal displays (LCDs). It is also being applied to organic light-emitting-diode (OLED) displays.[1–8]

For voltage-driven LCDs, color filters (CFs) are generally coated on indium tin oxide (ITO) electrodes,[1] resulting in a CF/ITO/substrate structure. For an active-matrix display, the substrate may contain thin-film transistors (TFTs). The added CF thickness results in a reduction in response speed. Though this can be compensated by increasing the driving voltage, it will lead to higher power dissipation. Alternatively, CFs are fabricated on an opposite substrate containing the ITO counter electrodes,[2] but this requires a larger alignment margin between the respective substrates containing the CFs and the TFTs. To enable both minimal driving voltage and alignment margin, it would be advantageous to form ITO directly over CFs on a TFT substrate. For current-driven OLED displays, it is a requirement that the ITO anode be directly connected to the OLEDs.[4–9] This implies that the CFs must be fabricated under the ITO for conventional bottom-emitting white-light-based color displays.

For improved CF registration, and hence also display resolution, it is best to form the CFs using micro-fabrication techniques. This is commonly done using photo-definable organic CF pre-cursor materials. If ITO were to be formed on such CFs, it would be imperative that the ITO formation temperature be low and the adhesion between the ITO and the CF be good.

ITO deposited using magnetron sputtering at a substrate temperature of 300–350°C[10] has been shown to exhibit good physical and micro-patterning properties. However, this temperature range is significantly higher than the CF processing temperature of 230°C.[10] Though a process of fabricating ITO on CF at a low substrate temperature of 200°C[10,11] has been reported for display applications, no discussion on issues relating to micro-patterning of such ITO has been given. After comparing the edge profiles of ITO obtained using both acid-based etching and photoresist-based lift-off, the latter was adopted because of its significantly better characteristics. However, because of the very low tolerance temperature of the conventional photoresist used as the lift-off mask, near-room-temperature deposition of ITO was required.

Presently reported are the room-temperature dc magnetron sputtering of thin-film ITO and resolution of issues relating to the integration of ITO-on-glass panels containing micro-fabricated CFs and other functional materials. The resulting polycrystalline ITO exhibits good adhesion to the underlying CFs, as well as good optical transparency and high electrical conductivity. Application of this ITO deposition technology to color LC and OLED displays was demonstrated.

2 Experimental

2.1 Micro-fabrication of CFs

Corning 1737 was used as the glass substrates. The initial cleaning procedure consisted of an organic solvent soak in MS2001 at 70°C for 5 minutes to remove dust and organic surface contaminants. De-ionized (DI) water rinse was followed by 180°C oven bake dry for 10 minutes. HMDS prime for 10 minutes was performed to further dehydrate and to form on the surface a thin layer of adhesion promoter. The substrate was then ready for CF preparation.

The procedure outlined below was repeated three times to obtain filters for the red (R), green (G), and blue (B) primary colors. Negative-tone, ultra-violet (UV) sensi-

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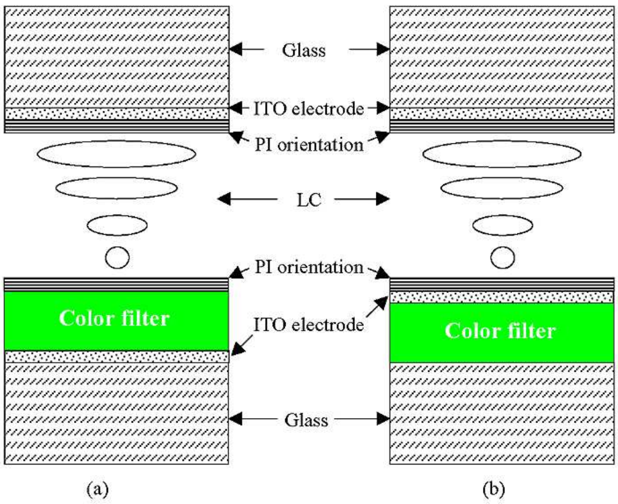

FIGURE 1 — Liquid-crystal cells with rear panels consisting of (a) CF/ITO/glass and (b) ITO/CF/glass.

tive organic CF precursor blend was spin-coated on the substrate and soft baked on a 110°C hot plate for 3 min. UV-exposed CF was developed in a 1:100 potassium hydrogen (KOH):DI water solution. Post-bake was done in an 180°C oven for 10 min. The spin speeds for the R, G, and B blends were 500, 600, and 500 rpm, respectively. After all three CFs were formed, an extended oven bake at 180°C for 6 hours was performed for more complete polymerization and to smooth out the edges of the CFs. The latter would improve the step coverage of the subsequently sputtered ITO electrode.

2.2 Lift-off patterning and room-temperature sputter deposition of ITO

For active-matrix LCDs or OLED displays, the ITO electrodes are connected to the source/drain junctions of the TFTs through an intermediate metallic (usually aluminum) interconnection. Since the KOH developer attacks aluminum (Al), it is not desirable to have the Al exposed during the preparation of the CFs. Consequently, a process was designed to open contact holes to Al only after the complete preparation of the CFs.

The contact opening process started with a 10-min HMDS prime. This was followed by the spin-coating of a 1-µm-thick HPR204 positive photoresist. After a 110°C hotplate soft-bake for 3 min, the photoresist was exposed before soaking for 1 min in an FHD-5 developer. Following 120°C oven post-bake for 20 min, etching was done in a "777" solution for 12 min to open the contact holes through both the CF and the silicon dioxide insulation layer covering the Al. The photoresist was subsequently removed in MS2001 at 70°C, with no observable degradation to the CFs.

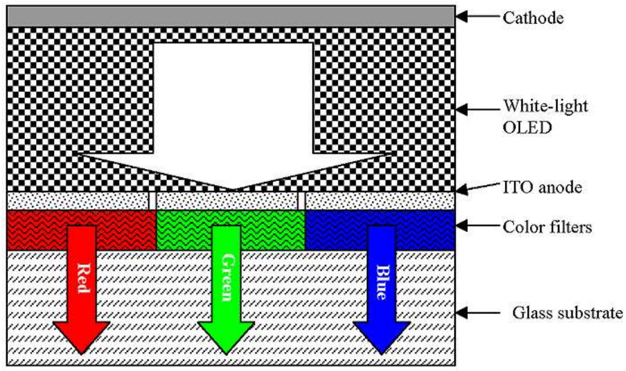

FIGURE 2 — Schematic diagram of a color display based on color filters and white-light-emitting OLED.

After the preparation of a 1-µm-thick AZ-1518 sacrificial lift-off mask, ITO was deposited using dc magnetron sputtering in an AJA ATC1200 sputtering machine. The separation between the 2-in. target and the substrate was 15 cm. The base pressure was ~5 µTorr. The process gas, pressure, power, and deposition time were 1:100 oxygen:argon mixture, 10 mTorr, 120 W, and 30 min, respectively. These are optimized conditions for good optical transparency and low electrical resistance. The adhesion of ITO to CF was found to be strong enough for the subsequent lift-off process in an ultrasonic acetone bath.

2.3 Preparation of displays

Two types of twisted-nematic LCDs (TN-LCDs) were constructed for comparison, with the same front panels consisting of commercial ITO glass coated with the same polyimide (PI) orientation layer but different relative placements of CF and 180-nm dc magnetron-sputtered ITO on the rear panels (Fig. 1). The cell gap was 7 µm and the LC was 88Y1104. The resolution of the color display was 60 × RGB × 80.

For OLED displays with the same resolution (Fig. 2), the R, G, and B CFs were prepared on MIUC-TFT[12,13] active-matrix substrates. No additional black matrix was necessary, as it was implemented by overlapping adjacent CFs: green on red, blue on green, and red on blue. 180-nm ITO was formed as the OLED anodes. The ITO was treated in a UV/ozone atmosphere for 5 min prior to the formation of the OLEDs, the constituent layers[14] of which are a 20-nm CuPc anode buffer layer, a 50-nm rubrene-doped TDP hole-transport layer, a 60-nm Alq_3 electron-transporting and light-emitting layer, an ~1-nm LiF electron-injection layer, and a 150-nm Al cathode. The display was packaged in a nitrogen glove box.

3 Results and discussion

A photograph and a scan obtained using a surface profilometer of the micro-fabricated CFs are shown in Figs. 3 and 4,

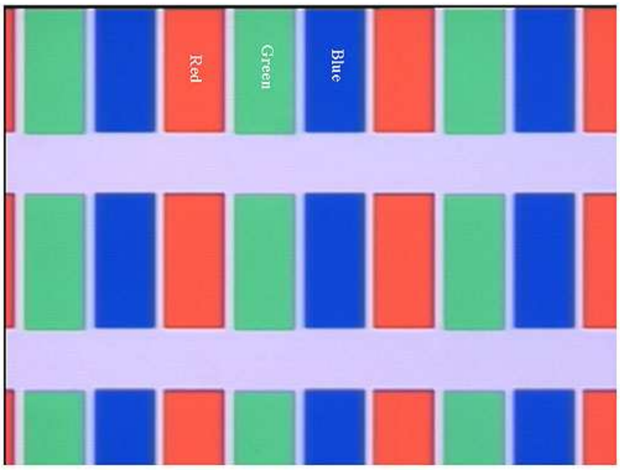

FIGURE 3 — Photograph of micro-fabricated red, green, and blue color-filter array.

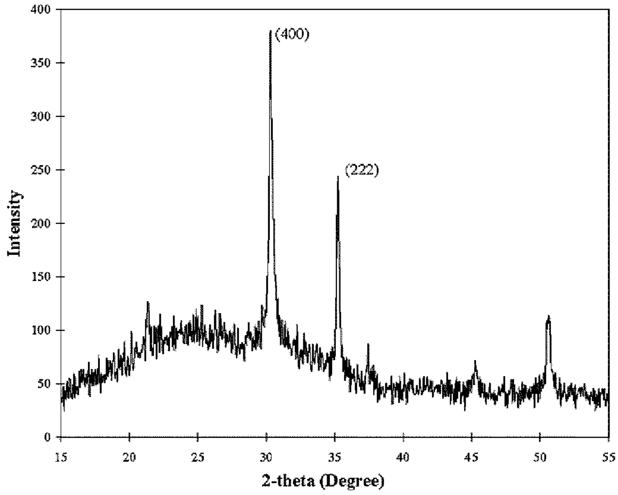

FIGURE 5 — XRD spectrum of room-temperature dc magnetron sputtered ITO on color filters.

respectively. The respective thickness of the R, G, and B CFs is 990, 1100, and 1050 nm. The slope of the edge was reduced from 60° to 30° after the 180°C 6-hour extended hard-bake. This results in improved ITO step coverage in regions between adjacent CFs.

The micro-structure of ITO grown directly over CFs was studied using x-ray diffraction (XRD). Two peaks at 30.8° and 35.3° (Fig. 5) were observed. These correspond respectively to the (400) and (222) orientations of ITO. Therefore, the films grown using the optimized condition as mentioned in section 2.2 was polycrystalline. Calculated using the half-width of the (400) peak, the average grain size for ITO both on glass and on CF was about 90 nm.

The roughness of the ITO was characterized using an atomic-force microscope (AFM) and the results are shown in Fig. 6. At 50 nm, this roughness is acceptable for making LCDs, resulting in workable AMOLED panels. However, the roughness needs to be further reduced as it may be detrimental to the longer-term reliability of the AMOLED panels. The optical transmission of 180-nm-thick ITO on glass is shown in Fig. 7. Using a bare glass substrate as a reference, the respective transmittance of the ITO thin film was measured to be 93.3%, 96.7%, and 91.3% at wavelengths of 450 nm (B), 530 nm (G), and 630 nm (R). The transmittances are slightly lower than those of the ITO[14] deposited using rf/dc magnetron sputtering at 200°C. The rougher surface and the lower transmittance are the present trade-offs of using room-temperature-deposited ITO.

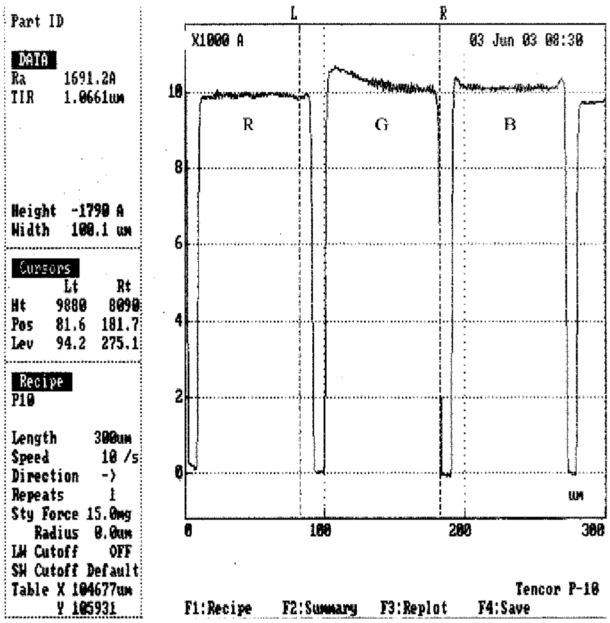

FIGURE 4 — Surface profilometer scan of R, G, B CFs after extended hard-bake.

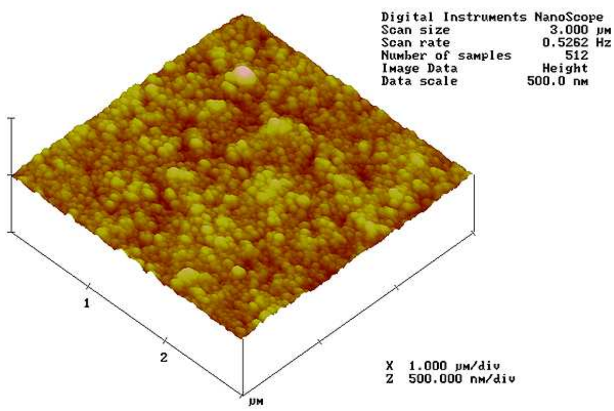

FIGURE 6 — AFM image of room-temperature dc magnetron sputtered ITO on color filters.

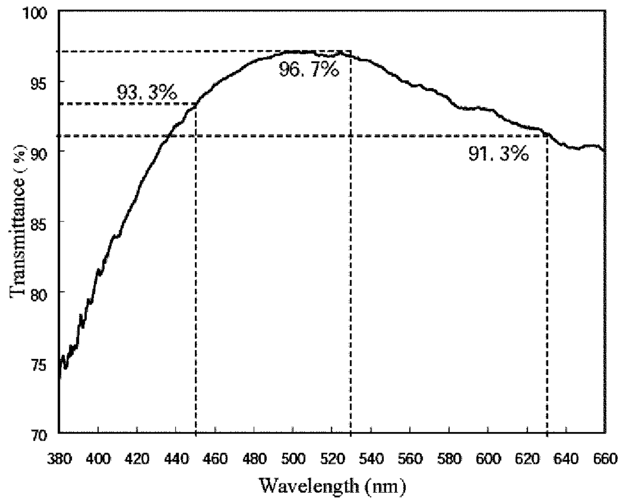

FIGURE 7 — Transmittance spectrum of room-temperature dc magnetron sputtered ITO on glass.

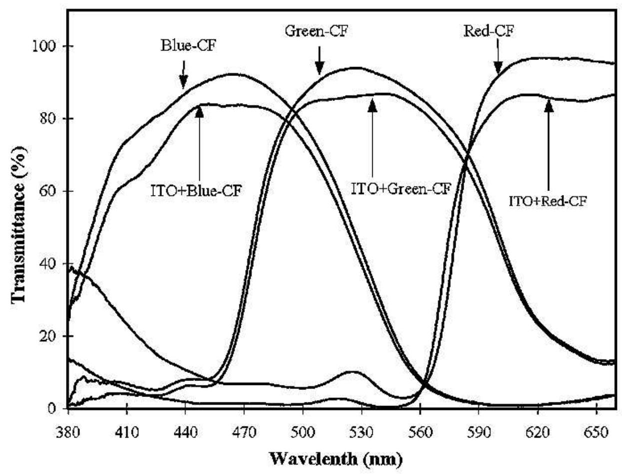

FIGURE 9 — Comparison of the transmittance spectra of red, green, and blue color filters and the same filters covered by ITO.

Though the 220-μΩ-cm resistivity of the room-temperature ITO is higher than the 140–160-μΩ-cm resistivity of ITO deposited at higher temperatures, it is usually not a problem for active-matrix panels. This is because signals are generally routed through metal-based interconnections.

A photograph of a CF array covered by patterned ITO and the corresponding transmittance spectrum are given in Figs. 8 and 9, respectively. The transmittance for the three ITO/CF stacks is reduced to ~85% of a bare glass substrate.

4 Display characteristics

The room-temperature ITO on CF technology has been applied to self-scanned active-matrix LCDs (Fig. 10). The row and column drivers were implemented using simple D-type flip-flops. The transmittance–voltage (T–V) characteristics of two types of LCDs are shown in Fig. 11. To achieve a given transmittance, a smaller bias voltage is required for a display with ITO-on-CF than for that with CF-on-ITO. The shift (δV) is about 0.2 V in the transition region. This reduction is attributed to the elimination of the voltage drop across the CF. For a respective LC cell gap (d_{LC}) and CF thickness (t_{CF}) of 7 and 1 μm, respective LC dielectric constant (ε_{LC}) and CF dielectric constant (ε_{CF}) of 4.1 and 3.24, δV can be estimated by using

$$\delta V = V_{LC}\,\frac{\varepsilon_{LC}/d_{LC}}{\varepsilon_{CF}/t_{CF}} \approx 0.26\ \mathrm{V},$$

where V_{LC} = 1.5 V is the approximate voltage required to achieve a 50% LC transmittance. The calculated value is close to the measured value of 0.2 V.

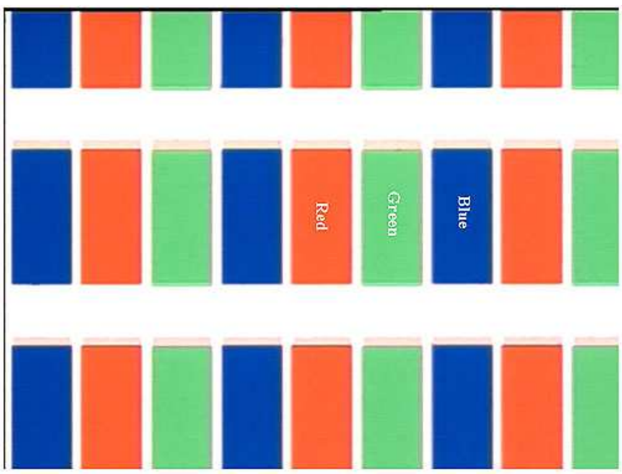

FIGURE 8 — Photograph of a CF array covered by patterned ITO.

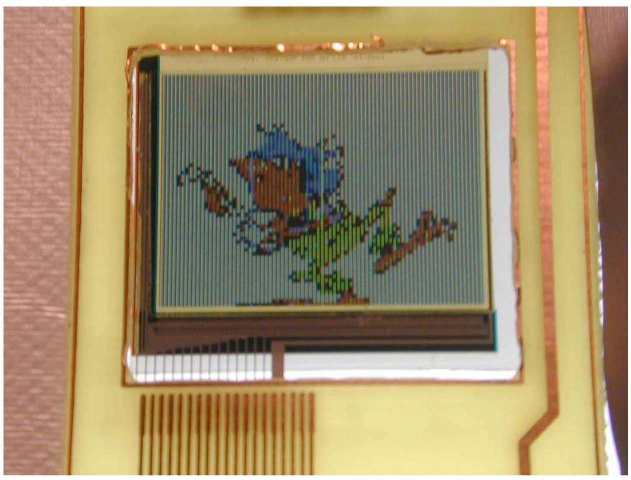

FIGURE 10 — Photograph of an image displayed on MIUC polycrystalline-silicon TFT AMLCD utilizing the technology of room-temperature dc magnetron sputtered ITO on color filters.

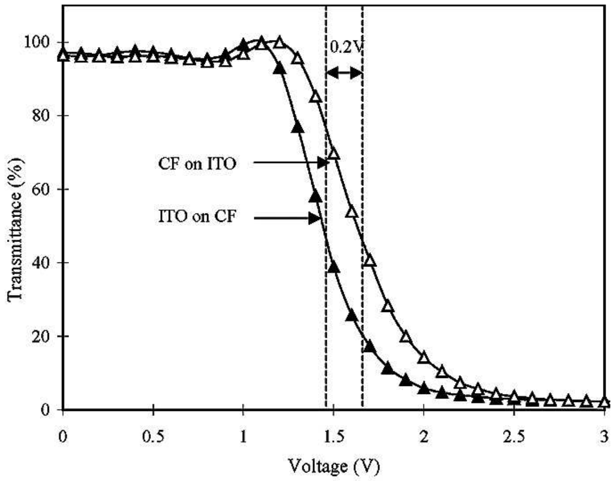

FIGURE 11 — Transmittance–voltage characteristics of LCDs with the two different rear panels.

The applicability of this ITO-on-CF technology to OLED displays is demonstrated using the results shown in Fig. 12, in which the spectra of a "bare" green emitter and the emission from the same emitter transmitted through a green CF are compared. The action of the filter is clearly visible. Shown in Fig. 13 are the luminance–current characteristics of bare and filtered OLEDs. If the impact of the color filter on the transmittance was accounted for, it can be inferred that the emission efficiency of the OLED constructed using ITO-on-CF was not degraded, compared to that of a bare one constructed on glass.

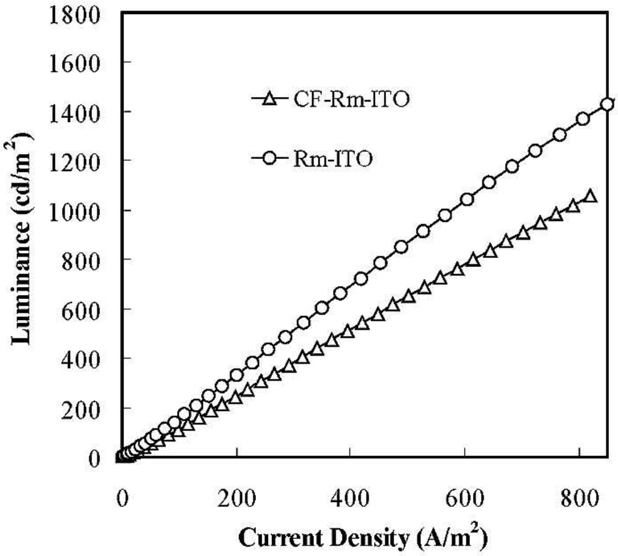

FIGURE 12 — Emission spectra of OLEDs fabricated on room-temperature dc magnetron sputtered ITO on glass and on CF/glass.

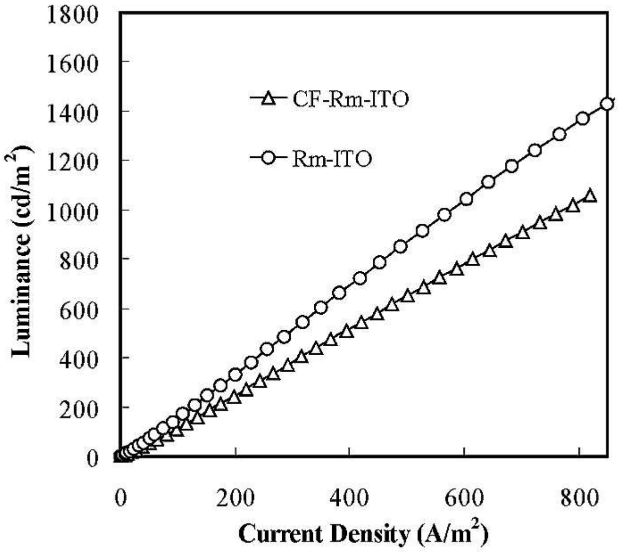

FIGURE 13 — Luminance–current-density characteristics of OLEDs fabricated on room-temperature dc magnetron sputtered ITO on glass and on CF/glass.

5 Conclusions

Room-temperature dc magnetron sputtering of ITO is compatible with micro-fabricated color filters and other functional materials. The resulting polycrystalline ITO exhibits good adhesion to the underlying color filters, as well as good optical transparency and high electrical conductivity. Application of this ITO deposition technology to color LCDs and OLEDs has also been demonstrated. A smaller bias voltage was required for a LCD with ITO-on-CF than for that with CF-on-ITO to achieve a given transmittance. The emission efficiency of an OLED constructed on ITO-on-CF was not degraded compared to that of a bare one constructed on glass.

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