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Experimental and Simulation Improvement of ITO Thin Films Applied to Flat Areas of Displays

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Abstract: Transparent conductive indium tin oxide (ITO) thin films were used as electrode of organic light emitting diodes (OLED's), flat panel display devices, and thin film solar cells due to its high electrical conductivity and high transparency in the visible light wavelength range. In this investigation, the electrical, structural, and optical properties of these films were examined. The resistivity of the ITO film electrode was calculated based on the sheet resistance R_s measured by the standard four-point probe technique at room temperature. A low resistivity of 2.2×10^{-4} Ω·cm and an average transmittance of more than 92% was measured in the visible range. A typical value of work function for the ITO, calculated from the optical spectra used in all our experiments, was 4.8 eV and surface roughness of approximately 15 nm for a Super-smooth ITO films of about 150 nm thick. Modeling of the ITO optical properties is presented and compared to experimental data. The modeled transmission and reflection spectra of ITO thin films on glass are in a good agreement with measured data. A lower resistivity and better spectra selectivity is a measurement of the quality and potential use of Indium Tin oxide for the application as transparent electrode of organic light-limiting diodes. OLED's based on optimized ITO films were fabricated and tested. It was found that the surface roughness and work function of ITO films are very important to enhance the stability and efficiency of OLED's. For electro-optical characteristics, the fabricated OLED gave a power efficiency of 50 lm/W at 40 cd/m^2, 3.4 Volts and 55 cd/A.

Key words: ITO thin films, optical transmission, organic light emitting diode (OLED), Mat lab modeling, simulation.

1. Introduction

In recent years, there has been an increase in the number of applications of ITO thin films, due to their unique optical, electrical and mechanical properties which are different to those of bulk material. Indium tin oxide (ITO) is an n-type transparent semiconductor with a wide band gap (E_g = 4 eV). These properties have led them to play an irreplaceable and increasing role in many areas of today's very demanding and rapidly developing technology, especially in the electronic displays and optical industries [1-3].

Interest in transparent films with an oxide layer such as indium tin oxide (ITO) has increased due to its excellent electrical and optical properties for a wide range of applications including heat-reflecting mirrors [4], the field of flat panel displays [5] antireflection coatings [6], organic light-emitting diodes [7], and gas sensors [8], and as transparent electrodes in solar cells [9].

The major concerns for ITO deposition are as follows:

- Low specific resistivity (< 150 μΩ·cm);
- High uniformity across the substrate;
- Low particle contamination;
- Low manufacturing costs.

There are several deposition techniques to grow ITO thin films including chemical vapor deposition [10, 11], magnetron sputtering [12, 13], evaporation [6, 14], spray pyrolysis [15], sol-gel [16] and pulsed laser ablation [10, 17]. The resulting ITO thin films exhibit low resistivity (ca. 4.2×10^{-4} Ω·cm) and high optical transmittance in the visible region (ca. 90%); and band gap of 4.78 eV), deposited on a glass substrate.

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2. Experiment

Commercial ITO-coated glasses deposited by RF magnetron sputtering from an ITO target (99.99%, In_2O_3:SnO_2 = 9:1) were used as received from the supplier. Prior to device fabrication, the (0.7 mm thick) glass substrates coated with 150 nm thick Indium-Tin-Oxide (ITO), were cut into 1" by 1" squares. The substrates were cleaned by sonication with detergent, rinsed with deionised water for 20 minutes, dried in the oven at 120 °C for outgassing, and finally subjected to oxygen plasma.

Immediately after plasma treatment, the substrates were transferred via a nitrogen-filled glove box system for the deposition of organic materials and then cathode layers.

The dendrimer/TCTA blends were typically spin-coated onto the substrates from 5-10 g/L solution in toluene at 100 to 4,000 rpm to give a 20 to 50 nm thick films, and dried in a nitrogen atmosphere at 180 °C for 20 min. The coated substrates were then transferred to the Spectros vacuum evaporator (KJ Lesker) and a layer of a hole blocking/electron transporting material 1, 3, 5-tri (phenyl-2-benzimidazole)-benzene (TPBI): (30-80 nm), 1.2 nm of Lithium Floride (LiF) and 100 nm of Aluminum (Al) cathode were deposited sequentially. Quartz oscillators monitored film thickness *in situ*. A typical device structure is shown in Fig. 1.

After all the film depositions, the OLED's devices were encapsulated in a nitrogen-filled glove box with glass including getter inside to protect the OLED's from oxygen and water vapors. Fig. 2 shows the organic devices fabricated on ITO substrates and then encapsulated with glass lid.

The surface morphology and roughness of the ITO films were observed using Atomic Force Microscopy (AFM) in tapping mode. The optical transmittance and reflectance measurements were performed with an UV/Visible spectrophotometer.

3. Results

3.1 Optical Properties

Fig. 3 represents the absorption in the visible wavelength range from 300 nm to 800 nm of a 150 nm thick ITO thin films. All deposited films showed low absorption less than 2%.

Fig. 4 shows the measured and simulated transmission and reflectance characteristics of ITO film deposited on glass. The films showed a high transmittance of 94.5% in the visible wavelength range. The data were then interpolated using Mat lab built-in functions Interp [18] in the wavelength range of 300-1,000 nm.

The modeled transmission and reflection spectra of ITO thin films on glass are in good agreement with measured data.

Modeling of the optical and electronic performance

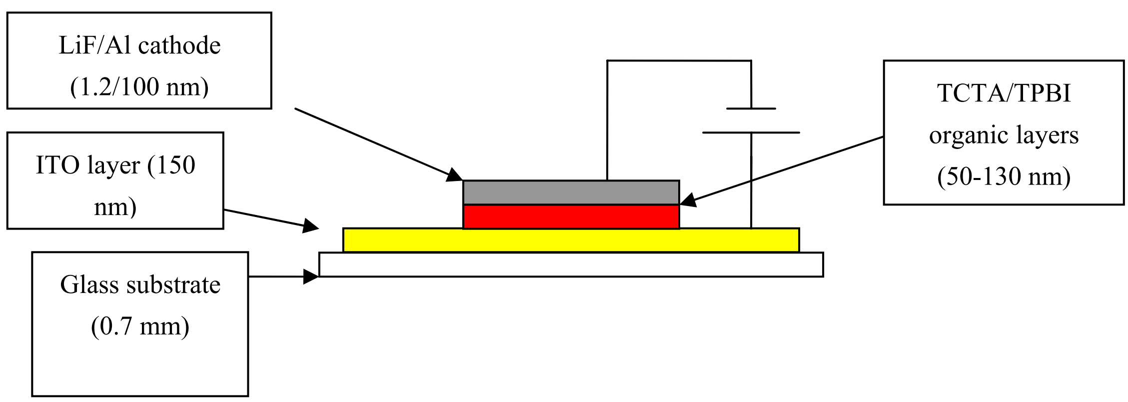


Fig. 1 A cross-sectional view of OLED device structure.

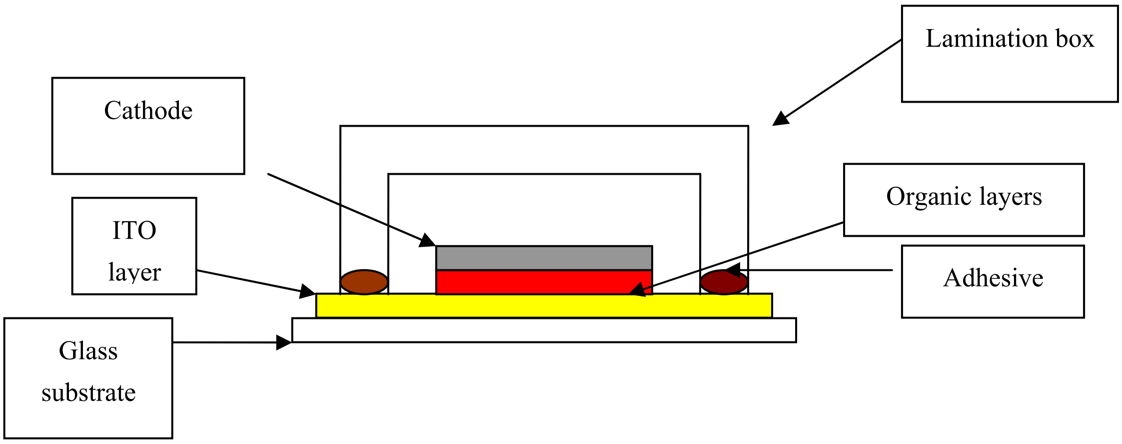


Fig. 2 A cross-sectional view of an encapsulated OLED showing the adhesive layer which incorporates moisture in the device structure.

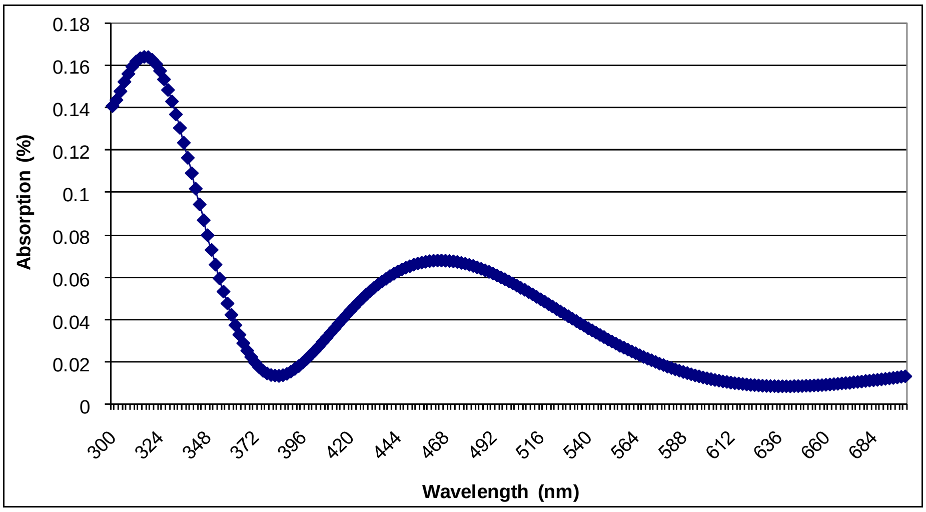


Fig. 3 The absorption spectrum of OLED in the visible region range.

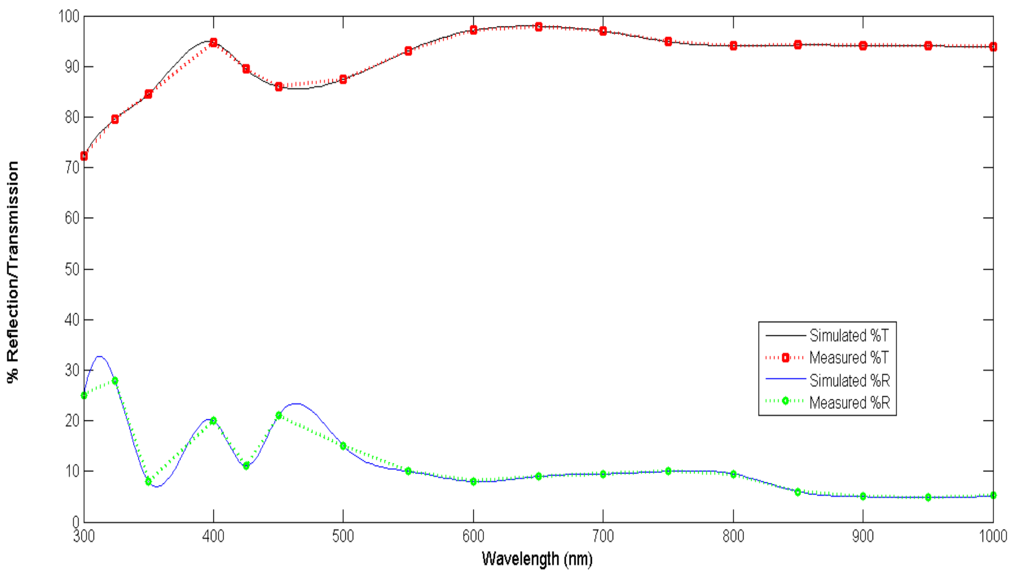


Fig. 4 The modeled/measured transmission and reflection spectra of ITO thin films on glass.

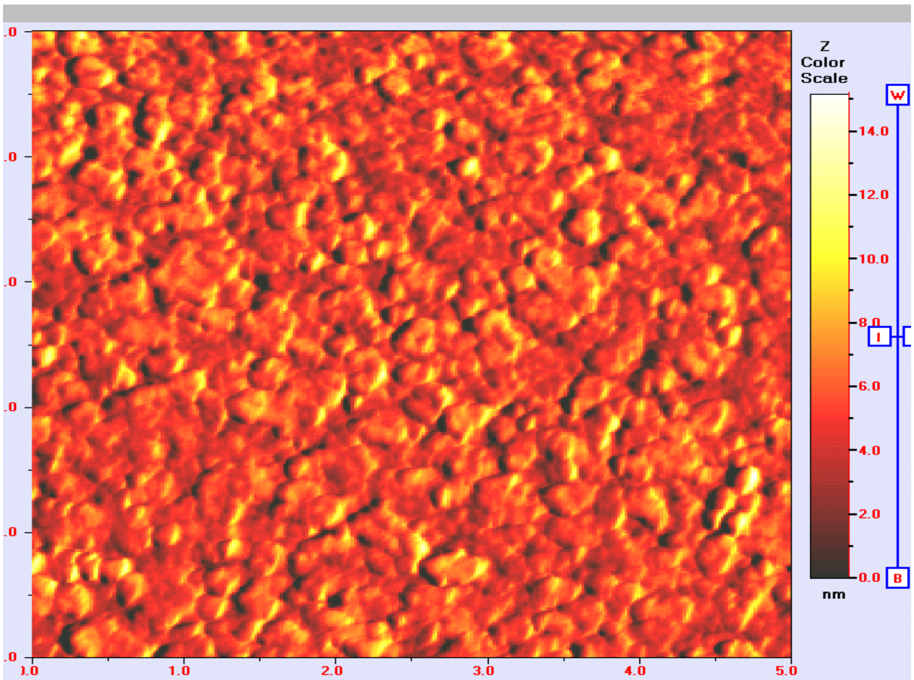


Fig. 5 AFM morphology of ITO films.

of OLED's organic layers, is under investigation now and it will be compared to experimental data for a set of device structures and presented in the near future.

3.2 Resistivity

The sheet resistance R_s of the ITO films was measured using a four-point probe method at room temperature. By assuming that the thickness of the films was uniform, the resistivity ρ of the films was calculated from the simple equation $\rho = R_s d$, where d is the ITO film thickness. A low resistivity of (2.25×10^{-4} $\Omega \cdot$cm) was measured for the 150 nm thick ITO films at ambient temperature.

3.3 Atomic Force Microscopy

3.3.1 Indium Tin Oxide Anode

Fig. 5 shows the morphology of ITO films with small grain sizes of (5-7 nm). Fig. 6 shows AFM images of the surface roughness of ITO films. It shows a surface roughness of approximately 15 nm. The surface roughness and work function of ITO films are very important to enhance the stability and efficiency of OLED's. All functional organic layers which act as injection, transportation and emission layers are deposited on ITO, so surface morphology of ITO is directly transferred to them and uneven interface is not desirable for the efficiency and stability of OLED. It shows a surface roughness of approximately 15 nm. Typical properties and results obtained for the ITO films were presented in Table 1.

3.3.2 Aluminum Cathode

Atomic Force Microscopy (AFM) was also used to find surface roughness and grain sizes of the deposited Al metal films used as a cathode in the OLED's. Fig. 7 shows the surface morphology and the roughness of Al films. Images are provided below at 40 µm magnification for Aluminum films. The deposited film surfaces were mainly smooth and dense for all the Aluminum cathode films used, and showed fine crystalline structure, with grain sizes at ambient temperature in the range of 5-6 nm. Smooth and dense Aluminum cathode would enhance its chemical stability, especially when used in long term operation of OLED's. Fig. 8 shows the measured and simulated reflectance spectra of the Aluminum thin films (120 nm thick) in the range 300-1,100 nm. The films showed high reflectance higher than 90% in the visible range.

The measured data were then interpolated using MATLAB built-in functions interp. Typical properties and results obtained for the Aluminum films used as a cathode were presented in Table 2.

The modeled reflection spectrum of Al thin films deposited on glass showed in the Fig. 9 are in good agreement with measured data.

3.4 OLED Device Fabrication and Characterization

The ITO thin films were used as anodes for OLED devices made onto glass substrates. The device structure consisted of Al (120 nm thick) as the cathode,

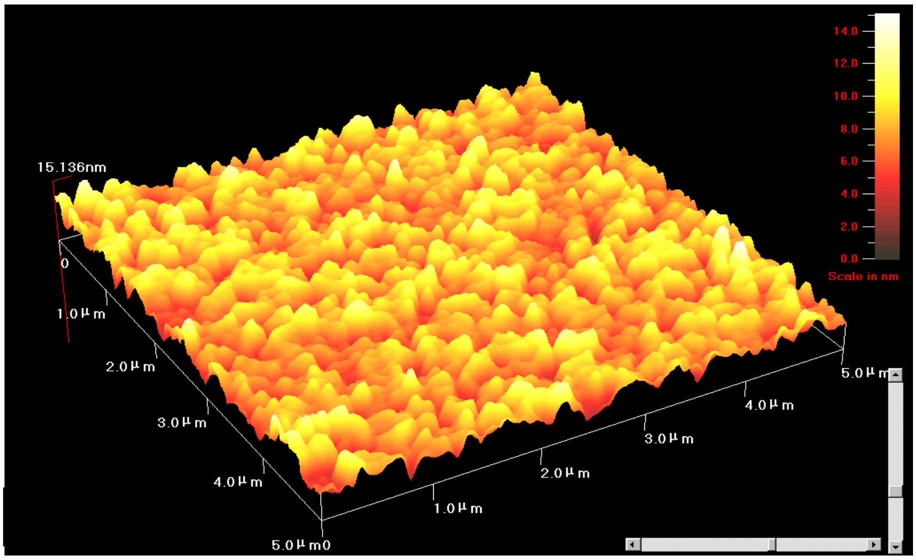


Fig. 6 Shows the surface roughness (~15 nm) of 150 nm thick ITO films.

Table 1 Typical properties and results obtained for the ITO films.

Property	Results
Transmittance (%)	94.5
Optical band gap (eV)	4.8
Sheet resistance (Ω/square)	15
Resistivity (Ω·cm)	2.25×10^{-4}
Surface roughness (nm)	2.5
Grain sizes (nm)	5-7

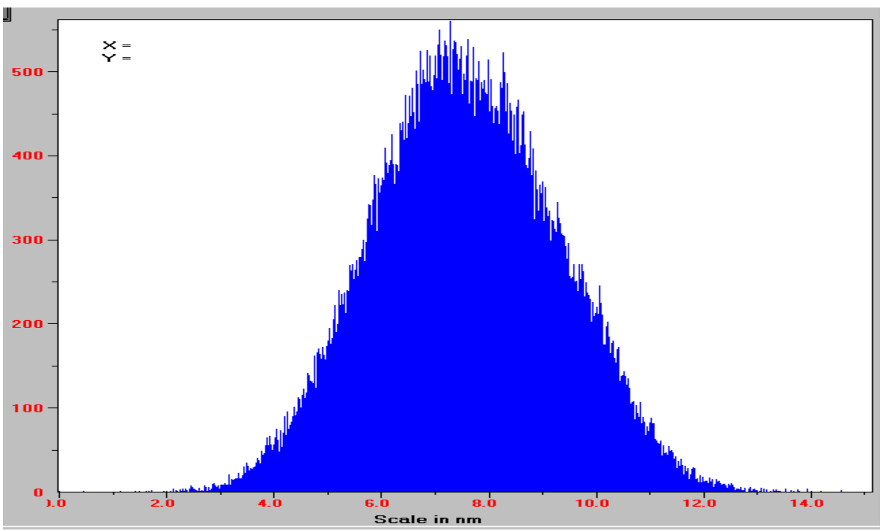
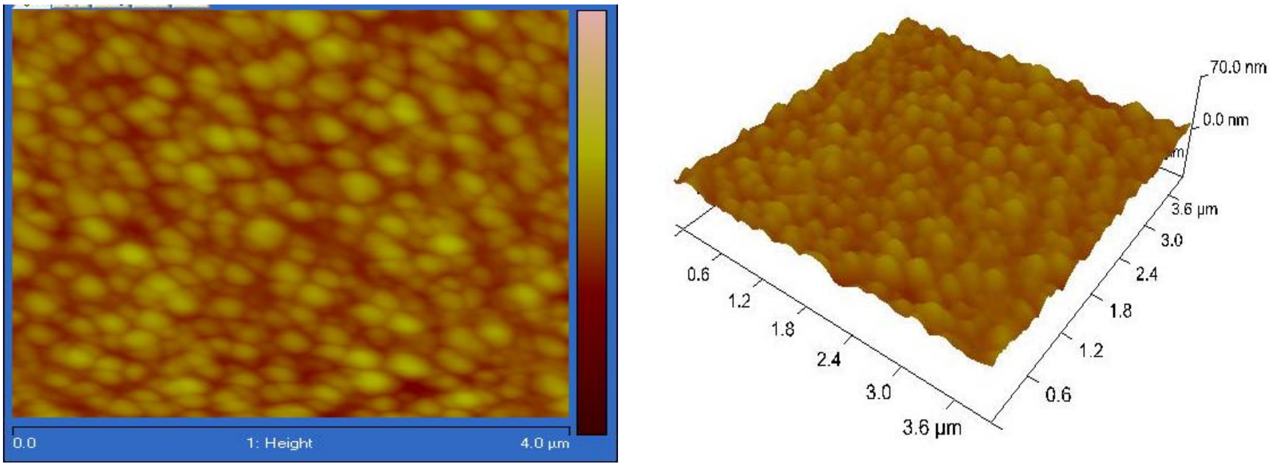


Fig. 7 AFM images of the average surface roughness of ITO films.



(a) (b)

Fig. 8 (a) The surface of Al film used as a cathode with small grains and (b) roughness of the film.

Table 2 Typical properties and results obtained for the Aluminum films

Property	Results
Reflectance (%)	93-94
Optical band gap (eV)	3-4.6
Sheet resistance (Ω/□)	22.5
Resistivity (Ω·cm)	2.7×10^{-6}
Surface roughness (nm)	7-10
Grain sizes (nm)	5-6

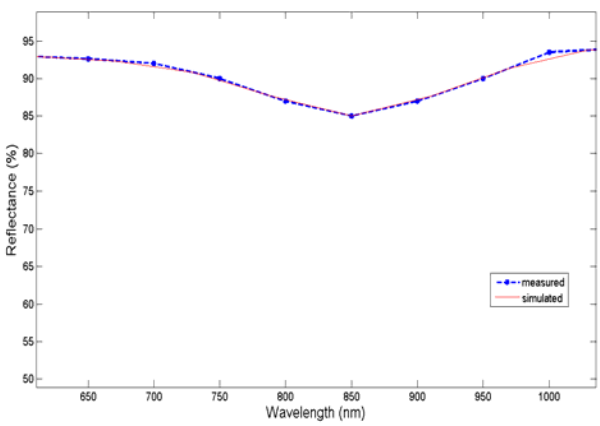


Fig. 9 The modeled/measured reflection spectrum of Al thin films on glass.

an ultra thin LiF layer, TPBI as the luminous layer and TCTA as the hole transport layer. The device was tested for electro-optical characteristics. The results of electro-optical testing are presented in Fig. 10.

The CIE coordinates for the emission are x = 0.31 y = 0.64 and stay virtually unchanged at high luminance, calculated from the electro luminescence (EL spectrum), which suggested that the device can emit

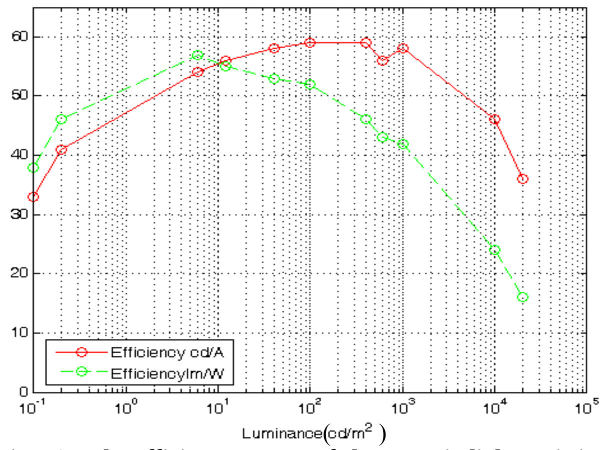


Fig. 10 The efficiency curves of the organic light emitting diode.

green light. A power efficiency of 50 lm/W is achieved for these structures at 40 cd/m^2, 3.4 V, and 54 cd/A. At a luminance of 10,000 cd/m^2, the power efficiency was found to stay at 20 lm/W [18, 19].

4. Summary

In summary, this paper presents the fabrication of an OLED's device with highly transparent and conducting ITO thin films as an anode. An ITO thin film with low resistivity (ca. 2.2 × 10^{-4} Ω·cm) and high visible-light-transmittance (ca. 90%; band gap, 3.71 eV) can be achieved on film using high-temperature rf magnetron sputtering, while maintaining high efficiency of the optimized OLED's. The Super-smooth ITO films obtained here are applicable to various optoelectronic devices such as organic light emitting diodes. The modeled transmission and reflection spectra of ITO thin films (150 nm thick) on glass are in good agreement with measured data.

The optimized thickness of the evaporated Al cathode was determined to be in the range 100-120 nm. Meanwhile, the OLED based on both optimized electrodes, has the turn-on voltage (2.8 Volts) which was defined to be the minimum voltage at which electroluminescence was visually detected. The higher luminous efficiency and low operating voltage are very important factors in increasing the lifetime of the OLED device.

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