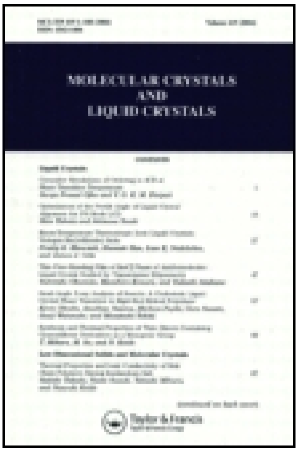

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An OLED Using Cellulose Paper as a Flexible Substrate

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An OLED Using Cellulose Paper as a Flexible Substrate

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Cellulose paper was fabricated and employed as a substrate for flexible organic light-emitting diodes (OLEDs). The performance of the cellulose paper satisfies the criteria for a substrate of an OLED. The visible light transmittance of the cellulose paper was greater than 95% in the visible light wavelength range. After the OLED was fabricated on the cellulose paper substrate through a thermal evaporation method, the OLED exhibited a luminance of 620 cd/m^2 at a driving voltage of 15 V and a current efficiency of 0.85 cd/A. This work suggests that cellulose paper is an environmentally promising substrate material for flexible OLEDs.

Keywords Cellulose paper; flexible; Ni anode; organic light-emitting diodes; transparent

Introduction

Organic light-emitting diodes (OLEDs) have attracted much attention in the past two decades because they provide a fast response, a wide viewing angle, thin display and two dimensional lighting applications [1,2]. Most organic light-emitting diodes are fabricated on a glass substrate and are then encapsulated with metal or glass lids. The glass substrates are fragile, relatively thick, and heavy. Furthermore, it is difficult to form the OLEDs into arbitrary shapes for applications when they are made using a glass substrate. Flexible OLEDs have received much attention in the past decade because of their superior advantages such as their thin thickness, rigidness, and flexibility [3]. Replacing the glass substrate with a plastic substrate can extend the applicability of OLEDs due to the increase in the flexibility. An OLED display using a plastic substrate is thinner and lighter compared to one using a glass substrate. Flexible substrates therefore have a distinct advantage over glass substrates in many applications [4,5].

In this paper, the possibility of employing cellulose paper instead of a plastic substrate as a flexible transparent substrate for OLEDs was investigated. The cellulose paper is made using the most abundant natural polymer on earth. Cellulose is a very suitable material for

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this purpose due to the demand for environmentally friendly and biocompatible products [6, 7]. Cellulose has been utilized in many fields due to its biocompatibility.

Indium tin oxide (ITO) is generally used as a transparent anode for OLEDs because it has good transparency in the visible range and a high work function. However, ITO requires a deposition temperature of over 100°C to ensure it has suitable properties [8]. Therefore, a metal anode which can be deposited without substrate heating is adequate for realizing the OLED on the cellulose paper substrate. Electron-beam evaporated Ni and thermally evaporated Al thin films were used as a semitransparent anode and cathode, respectively. The flexible OLEDs exhibited a luminance of 620 cd/m^2 on the cellulose paper substrates.

Experimental

The cellulose paper was made from a cellulose solution. The cellulose solution was made by dissolving cellulose fibers in an acetone solution with mechanical stirring. The cellulose solution was uniformly coated using a spin coater and dried to fabricate cellulose paper.

The OLEDs were fabricated on the cellulose paper. Ni films were deposited using an e-beam evaporator on the cellulose paper without any barrier layer. The thickness of Ni film was varied from 5 nm to 9 nm. The Ni anode patterns were defined by depositing the Ni film through a shadow mask onto the cellulose paper substrate. After cleaning the substrate, the Ni film was exposed to oxygen plasma before thermal evaporations of the organic and cathode metal layers were carried out. An 80 nm thick N,N′-bis(naphthalene-1-yl)-N,N′-bis(phentl)-benzidine (NPB) layer was deposited on the Ni anode, followed by the deposition of a 60 nm thick tris-(8-hydroxyquinoline) aluminum (Alq_3) layer. After that, 1 nm thick LiF and 100 nm thick Al layers were sequentially deposited on top of the organic layers through a shadow mask. The completed device structures were: cellulose paper/ Ni (5, 7, or 9 nm)/NPB (80 nm)/Alq3 (60 nm)/LiF (1 nm)/Al (100 nm).

The current density-voltage-luminance (J-V-L) characteristics of the devices were measured using computer controlled Keithley 2400 source-measure units and a luminance meter (Minolta LS100). Electroluminescence (EL) spectra were measured using a spectroradiometer (Minolta CS1000). Figure 1 shows a schematic diagram of the completed

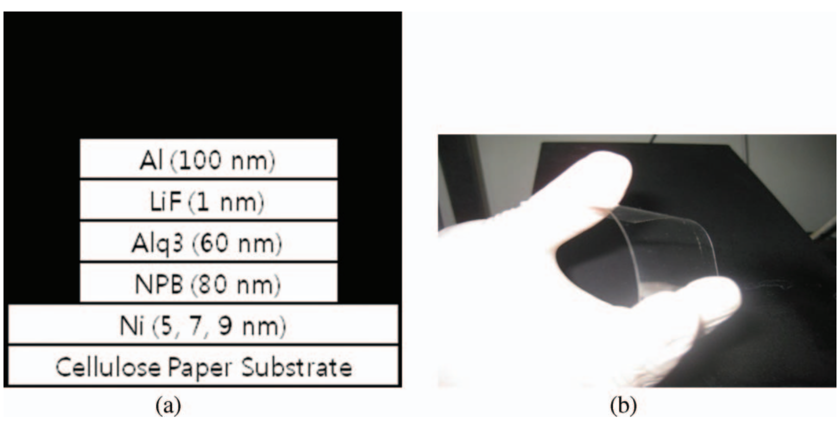

Figure 1. Schematic diagram of the flexible OLEDs fabricated on the cellulose paper substrate and a photograph of the cellulose paper substrate: (a) schematic diagram of the OLEDs; (b) photograph of the cellulose paper substrate.

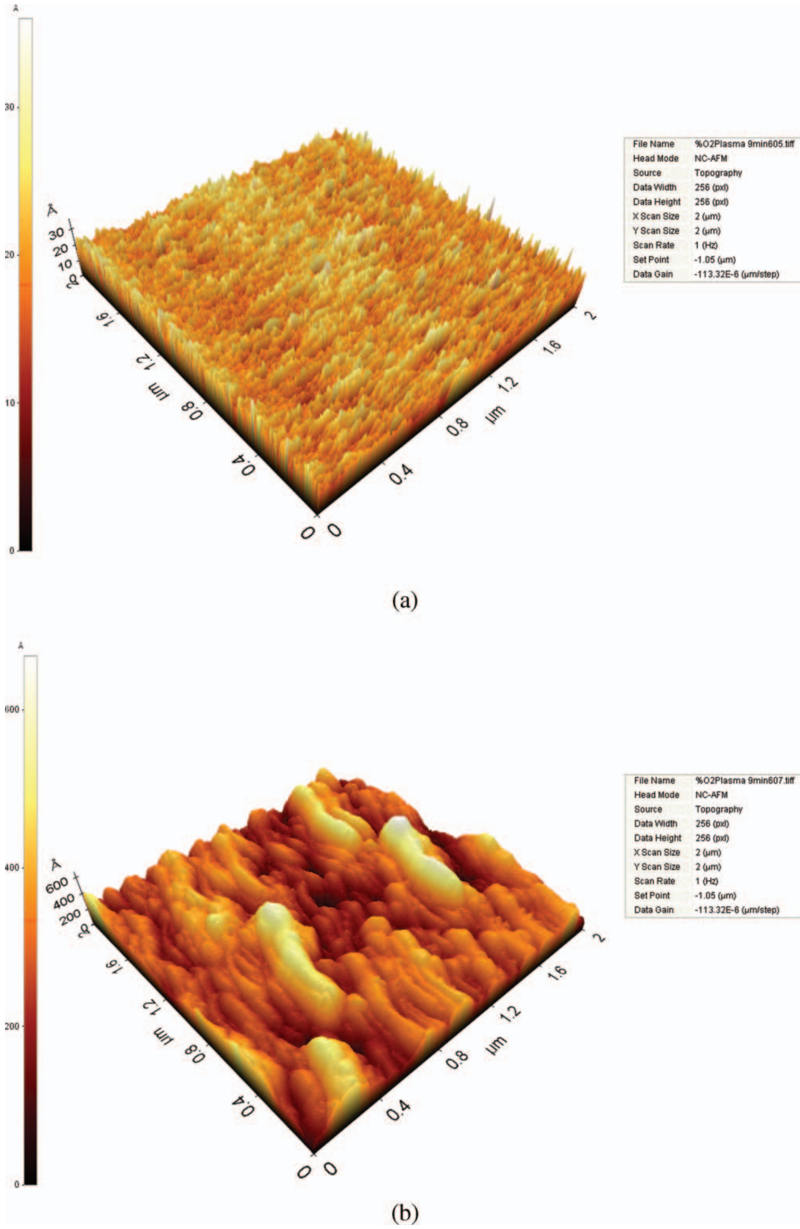

Figure 2. AFM images of cellulose paper and PET film: (a) cellulose paper; (b) PET film.

flexible OLEDs on the cellulose paper substrates and a photograph of the cellulose paper substrate.

Results and Discussion

Figure 2 shows atomic force microscope (AFM) images of wrinkles on the cellulose paper and commercial polyethylene terephthalate (PET) film. For comparison, the surface

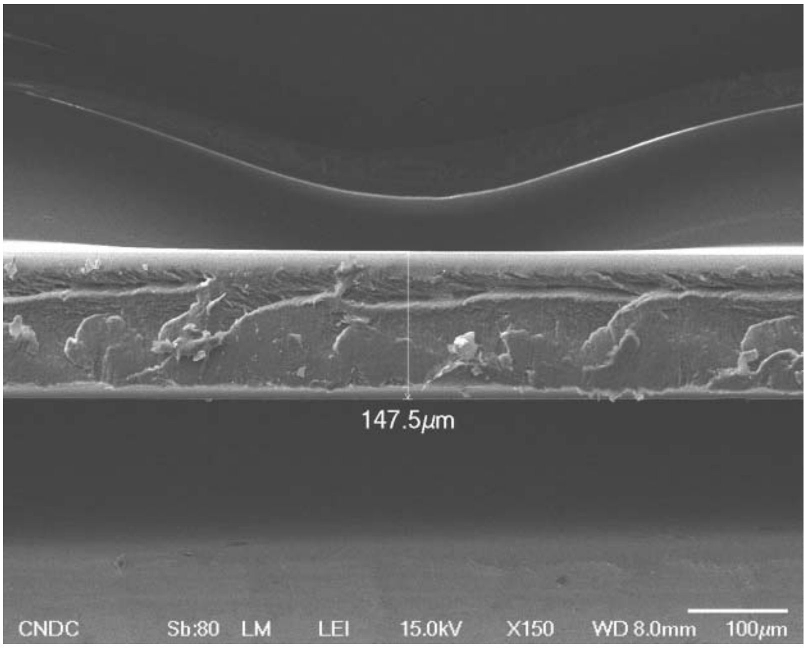

Figure 3. Thickness of the cellulose paper.

morphology of the PET film was investigated. While the root mean square (RMS) value of the surface roughness of the cellulose paper was 3.1 Å, that of the PET film was 11.5 Å. The results indicate that the cellulose paper has better surface roughness properties than the PET film. The thickness of the cellulose paper substrate was about 147.5 μm as shown in the scanning electron microscope (SEM) image in Fig. 3.

The light transmittance of the cellulose paper substrate was measured in the wavelength range from 400 nm to 780 nm by a UV/Visible spectrometer. Figure 4 shows the optical

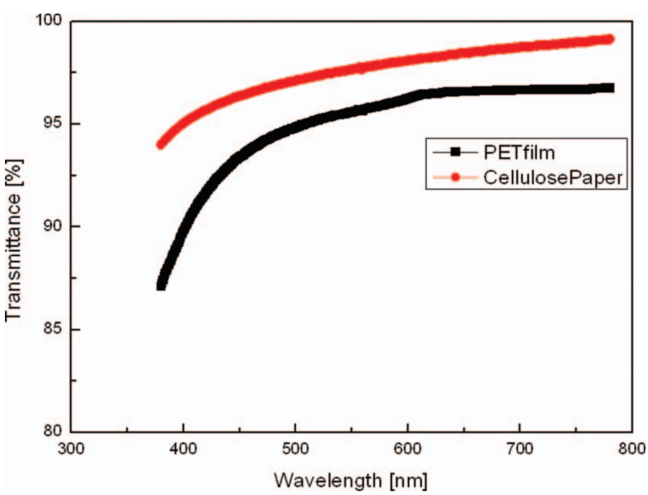

Figure 4. Transmittances of the cellulose paper and PET film.

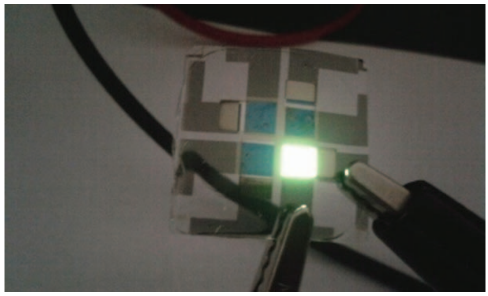

Figure 5. Photograph of an operational OLED on the cellulose paper substrate.

transmittances of the cellulose paper and PET film. The transmittance of the cellulose paper ranged from 95% to 97.6% in the visible light wavelength range. On the other hand, that of the PET film ranged from 90% to 94.5% in the visible light wavelength range. The transmittance of the cellulose paper is higher than that of the PET film. Such a high light transmittance satisfies the transparency criteria of 80% for the OLED substrate [9].

Figure 5 shows an image of a light-emitting OLED fabricated on the cellulose paper. As shown in Fig. 5, a bright image was obtained from the bended OLED. Figure 6 shows current density-voltage curves of flexible OLEDs made using the cellulose paper substrates depending on the thickness of the Ni anode. It can be seen from Fig. 6 that the thicker the Ni film, the higher the current density. The sheet resistance of the anode electrodes reduces as the thickness of the anodes increases. The lower the resistance of the electrodes, the higher the current.

Figure 7 shows luminance-voltage curve for the OLEDs made using the cellulose paper substrates according to the thickness of the Ni film. It can also be seen from Fig. 7 that the thicker the Ni film, the higher the luminance of the device. The maximum luminance of the device with an Ni film thickness of 9 nm fabricated on the cellulose paper substrate was

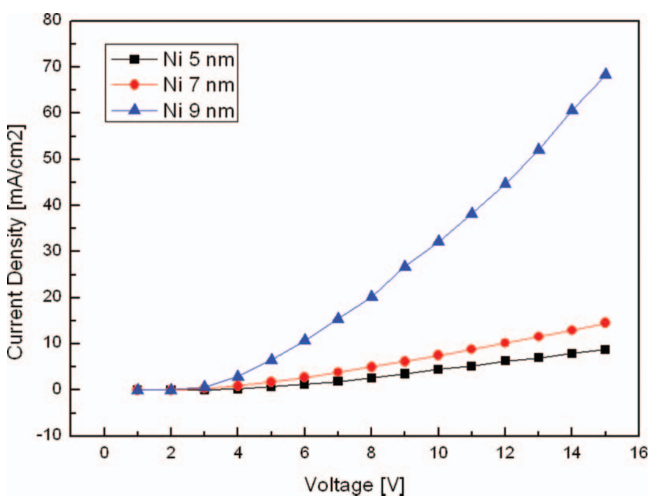

Figure 6. Current density-voltage curve of the flexible OLED fabricated on the cellulose paper substrate.

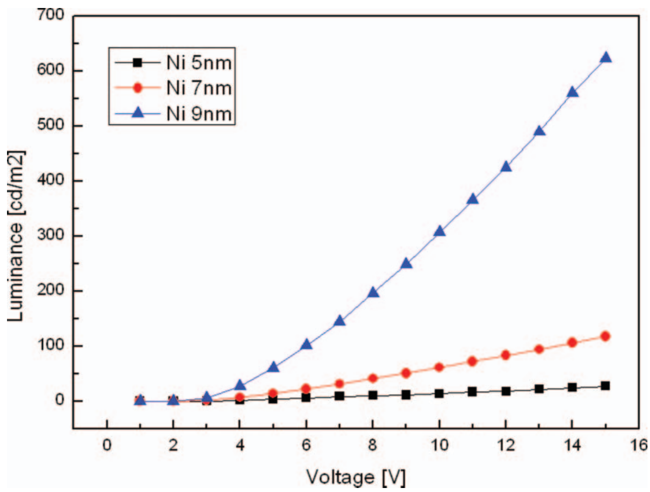

Figure 7. Luminance-voltage curve of the flexible OLED fabricated on the cellulose paper substrate.

about 620 cd/m^2 at an applied voltage of 15 V. The maximum luminance of the device on the cellulose paper is much higher than that of the device on the copy paper substrate [10].

Figure 8 shows the current efficiency of the OLEDs. The current efficiency reached a maximum value of 0.97 cd/A at a current density of 20.2 mA/cm^2. Figure 8 also shows that the thicker the thickness of Ni anode, the higher the current efficiency. When the thickness of the Ni anode is thicker, more holes to form excitons in the emission layer can supply from the Ni anode. This results in increase of the current efficiency of the device. The current efficiency of 0.97 cd/A of the device on the cellulose paper substrate is also much higher than that of 0.085 cd/A of the device on the bacterial cellulose nanocomposite [9].

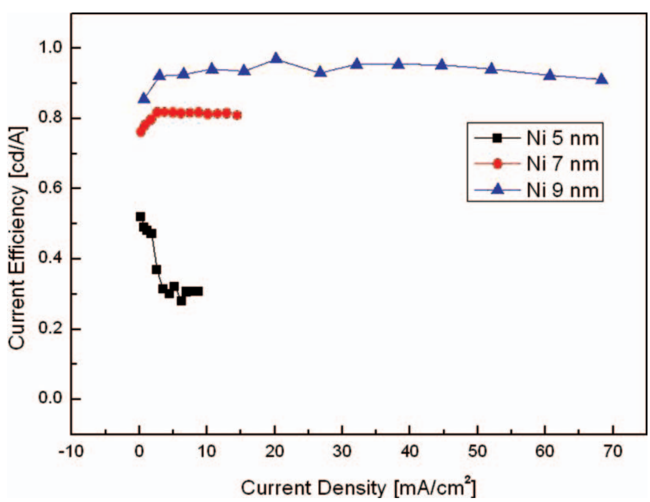

Figure 8. Current efficiency-current density curve of the flexible OLED fabricated on the cellulose paper substrate.

Conclusions

We successfully prepared OLEDs on flexible cellulose paper which was used as a substrate. The cellulose paper possesses appealing features which make it a suitable material for flexible substrates of OLEDs, namely flexibility, a high light transmittance of up to 95–97.6% in the visible light wavelength range (400–780 nm) and a good surface roughness of 3.1 Å. These features satisfied the criteria that must be met by an OLED substrate. Using Ni films deposited on the cellulose paper substrates, we explored flexible OLEDs. The current density-voltage curve of the device exhibited a general diode curve. The flexible OLEDs on the cellulose paper substrate showed a high luminance of 620 cd/m^2. We believe that the device performance can be further improved by coating a barrier layer onto the cellulose paper. This work proves that cellulose paper is a environmentally promising substrate material for flexible OLEDs.

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