

Blue Flexible Transparent Organic Light-Emitting Devices

Takayuki Uchida, *Member, IEEE*, Makoto Wakana, Masahiro Yahata, Somsak Dangtip, Tanakorn Osotchan, Toshifumi Satoh, and Yutaka Sawada

Abstract—Blue transparent organic light-emitting devices (TOLEDs) and blue flexible OLEDs (FOLEDs) have been fabricated on glass and plastic films, respectively. We have also fabricated blue flexible transparent OLEDs (FTOLEDs) having both flexibility and transparency by using indium–tin–oxide:cesium (ITO:Cs) as a cathode. A Cs-incorporated ITO electrode is useful for the fabrication of not only a TOLED on a glass substrate but also a flexible TOLED on a plastic film.

Index Terms—Transparency, transparent organic light-emitting device (TOLED), flexible organic light-emitting device (FOLED), cesium compound, flexible structures, plastic films.

I. INTRODUCTION

ORGANIC light-emitting devices (OLEDs) have received significant attention in recent years because of their potential application in full-color flat-panel displays. In particular, the transparency of the constituent organic thin films with respect to visible radiation allows the fabrication of transparent OLEDs (TOLEDs) [1]. This unique characteristic of OLEDs can be exploited in vertically stacked color displays, top emission displays, and multiphoton-emission (MPE) displays, provided transparent contacts are fabricated for both surfaces of the device.

It is also possible to fabricate flexible displays [2]. We have already developed green flexible transparent OLEDs (FTOLEDs) that have both flexibility and transparency when they are turned off [3]. In this study, we fabricated blue OLEDs on a flexible plastic substrate having transparent electrodes (anode and cathode) without a metal layer.

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II. EXPERIMENTS

Blue OLEDs are fabricated on a glass or a polyethylene naphthalate (PEN) film substrate coated with an indium–tin–oxide (ITO) layer having a sheet resistance of $10 \Omega/\text{sq}$. The thicknesses of the base glass and the PEN film are 1 mm and $125 \mu\text{m}$, respectively. A 70-nm-thick film of poly(styrenesulfonate)/poly(2,3-dihydrothieno(3,4-b)-1,4-dioxin) (PEDOT-PSS) or a 30-nm-thick film of 4,4',4''-Tris(N-3-methylphenyl-N-phenyl-amino)-triphenylamine (m-MTDATA) was spin-coated or evaporated on the ITO layer to enhance hole injection in OLEDs respectively. Next, a 30-nm-thick film of bis[N-(1-naphthyl)-N-phenyl]benzidine (NPB) or 4,4'-bis(2,2-diphenyl-ethen-1-yl)diphenyl (DPVBi) [4], [5] was evaporated on the ITO layer, followed by the evaporation of a 30-nm-thick film of 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP). A metallic cathode comprising an Al alloy doped with Li (0.2 wt%) is used. As a transparent cathode, a 200-nm-thick ITO:Cs film was deposited by radio frequency (RF) magnetron sputtering by introducing Cs vapor during the sputtering process [4].

For evaluation purposes, the optical transmission spectra of the OLEDs were measured using a UV-VIS-NIR scanning spectrophotometer (UV3100PC, Shimadzu). The luminance-voltage (L - V) characteristics of the OLEDs were measured using an organic EL luminous efficiency measuring instrument (EL-1003, Precise Gauges, with a 2400-V source, Keithley).

III. RESULTS AND DISCUSSION

1) *Blue OLED With Metallic Cathode:* Before investigate the device of FTOLEDs, we fabricated and measured the OLED on glass substrate and film substrate. Fig. 1 shows the L - V characteristics of the blue TOLED fabricated on glass and film substrates. The inset figure also shows the luminance efficiency-current density characteristics of the blue TOLED.

The turn-on voltage (at $1 \text{ cd}/\text{m}^2$) of (b) the film substrate device is lower than that of (a) the glass substrate device. The maximum luminance of (a) the glass substrate device is approximately three times that of (b) the film substrate device. The luminance efficiency of both the devices is identical, having a value of $1.5 \text{ cd}/\text{A}$ at a low current density. In the case of using film substrate, the efficiency rapidly decreases in comparison with (a) a glass substrate device. This difference in behaviors appears to be dependent on the difference in the crystallization states (polycrystal ITO on glass, amorphous ITO on film) of ITO deposited on the upper surface of the substrate and not on the materials comprising each substrate.

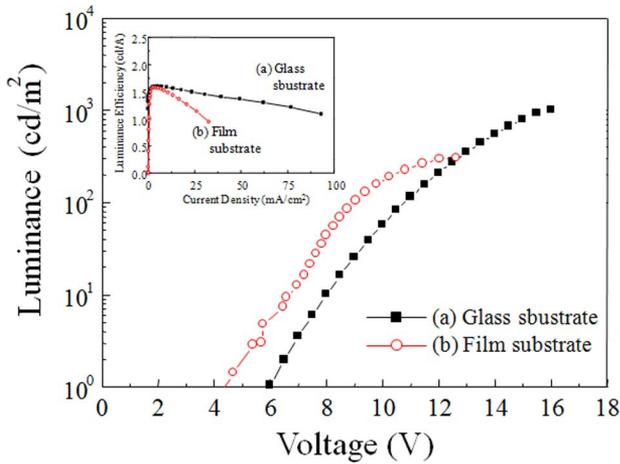


Fig. 1. L - V characteristics of blue TOLED fabricated on glass and film substrates. Inset figure: Luminance efficiency-current density characteristics of blue TOLED. Substrate/ITO/m-MTDATA(30 nm)/NPB (30 nm)/BCP (30 nm)/Al-Li (40 nm)/Al (100 nm), Substrate = (a) Glass. (b) Film.

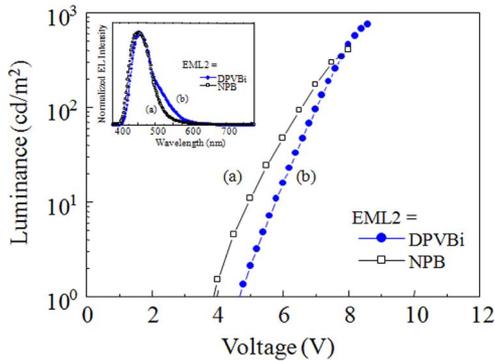


Fig. 2. L - V characteristics of blue FOLED fabricated on film substrate. Inset figure: Emission spectra of blue FOLED. Film/ITO/PEDOT-PSS (70 nm)/EML1/EML2/BCP (30 nm)/Al-Li (40 nm)/Al (100 nm) EML1/EML2 = (a) [NPB/NPB] (30 nm) and (b) NPB (40 nm)/DPVBi (40 nm).

Fig. 2 shows the L - V characteristics of the blue FOLED fabricated on a film substrate. In this case, PEDOT-PSS was used as HIL. The inset figure shows the emission spectra of the blue FOLEDs. Each spectrum corresponds to an EL spectrum that is almost the same as the photoluminescence (PL) spectrum of the blue FOLEDs. When DPVBi is used as EML, the emission peak exhibits a shoulder at 530 nm.

Fig. 3 shows the luminance efficiency-current characteristics of blue FOLED fabricated on a film substrate. When NPB/DPVBi is used as EML, the efficiency is found to be approximately 2.8 cd/m^2 (at 4.8 mA/cm^2).

2) *Blue Flexible TOLED With Transparent Cathode:* We fabricated a blue flexible TOLED (FTOLED) that has both flexibility and transparency. Fig. 4 shows the optical transmittance of the blue FTOLED. The inset of the figure shows an image of the blue FTOLED with a pixel turned off.

The image (KOUGEI logo) behind the TOLED is visible when pixel is turned off. The optical transmittance of the blue FTOLED in the visible region is 59%. A drop in transmittance observed at a short wavelength is attributed to the absorption of the PEN film. The ITO:Cs electrode is slightly brown in color.

Fig. 5 shows the L - V characteristics of the blue FTOLED fabricated on a plastic film. The inset figure on the left shows the

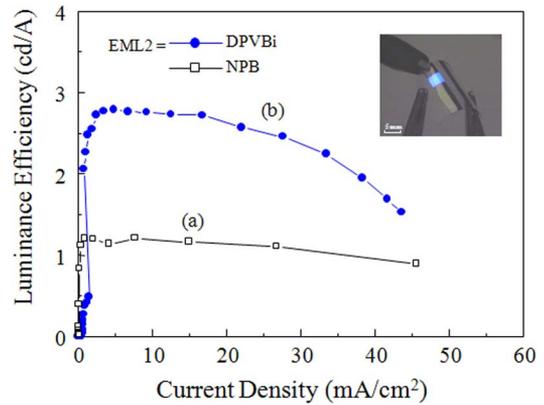


Fig. 3. Luminance efficiency-current characteristics of blue FOLED fabricated on a film substrate. Inset figure: A photograph of blue FOLEDs. Film/ITO/PEDOT-PSS (70 nm)/EML1/EML2/BCP (30 nm)/Al-Li (40 nm)/Al (100 nm). EML1/EML2 = (a) [NPB/NPB] (30 nm) and (b) NPB (40 nm)/DPVBi (40 nm).

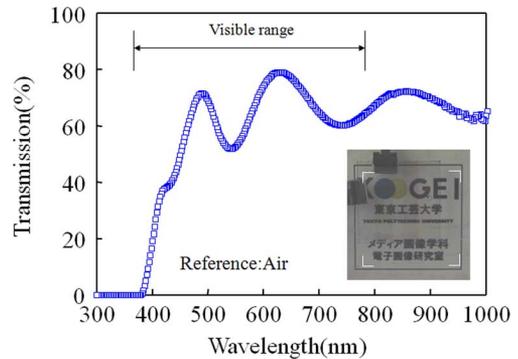


Fig. 4. Optical transmittance of blue FTOLED fabricated on a plastic film with a pixel turned off. Inset figure: Blue FTOLED with a pixel turned off. Film/ITO/PEDOT-PSS (70 nm)/NPB (40 nm)/DPVBi (40 nm)/BCP (30 nm)/ITO:Cs (200 nm).

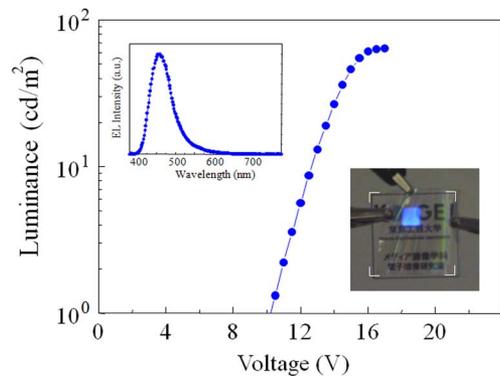


Fig. 5. L - V characteristics of blue FTOLED fabricated on a plastic film. Inset figure (left): Emission spectrum of blue FTOLED. Inset figure (right): Image of blue FTOLED with a pixel turned on. Film/ITO/PEDOT-PSS (70 nm)/NPB (40 nm)/DPVBi (40 nm)/BCP (30 nm)/ITO:Cs (200 nm).

emission spectrum of the blue FTOLED. Blue emission materials have a wider energy bandgap than green and red emission materials. Therefore, it is difficult to fabricate blue emission materials because of poor electron injection at the transparent cathode (not metal) of wide-bandgap materials having high device efficiency.

When the device not employ the alkali metal doping, FTOLED indicate low characteristics with less than 0.1 cd/A .

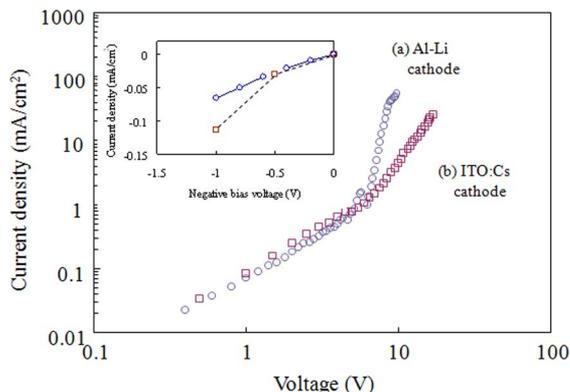


Fig. 6. ($\ln V - \ln J$) characteristics of blue FOLED with (a) metal cathode and (b) transparent cathode. Inset figure: Negative-voltage-current-density characteristics of devices (a) and (b). Film/ITO/PEDOT-PSS (70 nm)/NPB (40 nm)/DPBVi (40 nm)/BCP (30 nm)/cathode.

The electron injection characteristics of FTOLEDs are improved by using ITO:Cs as the cathode with a luminance efficiency of 0.3 cd/A (at 18 mA/cm²). However, the luminance efficiency of the FTOLED (transparent cathode) was ten times lower than that of the FOLED (metal cathode).

Fig. 6 shows the negative-voltage-current-density ($\ln V - \ln J$) characteristics of the blue FOLED with metal cathode (a) and blue FTOLED with transparent cathode (b). Before emission, the $J - V$ characteristics of each device are ohmic. After emission, the slopes of the $J - V$ characteristics of devices (a) and (b) were significantly different. In the case of electron injection from transparent conducting oxides (TCOs) to lowest unoccupied molecular orbital (LUMO) level for organic EML is necessary for improvement such like the Cs-incorporated ITO or alkali metal doped organic buffer layer.

We must take into account not only the effects of carrier injection but also the damages caused by the sputtering deposition of the transparent cathode. These damages were estimated by the $J - V$ characteristics before emission. Most of the characteristics are identical; however, the current density is high when the ITO:Cs cathode is used. Severe damages were estimated by the current density at negative bias. These characteristics are shown in the inset of Fig. 6. This result also indicates that some damages or carrier traps exist in organic films.

Conventional structures having a low work function metal are employed. These devices require encapsulation to drive in air and they can employ an Al-Li or Mg-Ag cathode. Even though the devices were encapsulated, their performance gradually degraded due to oxidation [7], [8].

The ITO:Cs film can include a variety of cesium compounds, such as cesium carbonate (Cs₂CO₃), cesium hydroxide (CsOH), and cesium oxide (Cs₂O). An oxide generally exhibits a high work function, and it is believed that its electron injection characteristics are weak. However, an improvement in the electron-injection characteristics is achieved when ITO:Cs films are used instead of films without Cs.

Recently, it has been reported that titanium dioxide (TiO₂) is an important electron-injection layer [9]. In addition, a several-nanometers-thick layer due to the spin coating of cesium

compounds on TiO₂ acts as a hole-blocking unit having high efficiency and high stability in air [10].

In this study, we have fabricated blue FTOLEDs that have both transparency and flexibility by using ITO:Cs as a cathode and by using a low work function of the ITO electrode by introducing Cs vapors during the RF magnetron sputtering process. This method is useful for the fabrication of not only a TOLED on a glass substrate, but also for an FTOLED on a plastic film.

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