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Semi-transparent vertical organic light-emitting transistors

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ABSTRACT

Vertical organic light-emitting transistor (VOLET) having an organic light-emitting diode integrated with a vertical thin-film transistor is promising for transparent electronics because the vertical device structure potentially offers a display with a large aperture ratio and a low power consumption. However, making a transparent VOLET has been challenging due to the requirements for all transparent electrodes including fabrication of a porous source electrode for current modulation in the device. Here, we report a semi-transparent VOLET with a large modulation of light emitted through the top and bottom electrodes using a nano-porous indium-tin oxide (ITO) source electrode, a Mg:Ag drain electrode, and an ITO gate electrode. The porous ITO source electrode is not only important for luminance modulation, but the nano-textured film morphology also enhances light extraction from the device. Finally, we show that the off current of the VOLET can be suppressed with an electron transporting layer (C_{60}), leading to a large luminance on/off ratio of 10^4.

1. Introduction

The interests in transparent displays have rapidly increased with the development of smartphones, televisions and wearable devices [1–3]. Due to the requirements of all transparent electronic elements, it is challenging to realize a transparent display on current liquid crystal displays given that neither the backlight module nor the silicon backplane is transparent.

Vertical organic light-emitting transistor (VOLET) that integrates an organic light-emitting diode (OLED) with a vertical thin-film transistor (VTFT) offers advantages for transparent displays [4,5]. First, the combined device architecture saves the space allocated for the driving transistor, allowing a light-emitting display with a higher aperture ratio [6]. Second, due to the short vertical channel, a transistor with a nanoscale channel length is realized, leading to a low power consumption.

For current modulation in vertical transistors, fabrication of a porous source electrode is essential because the gate electric field modulates the drain current via charge injection from the porous electrode. Consequently, making a transparent VOLET would not only require porous electrode fabrication but it also needs all transparent electrodes, and there are limited materials and process options for it. Previously, the porous source electrode for a VTFT has been made with a thin metal layer, such as Al [7–11] or Au [12–15]. However, the porosity relied on the formation of natural pinholes in the metal thin films and the current modulation depended on the oxidation state of the films. Alternatively, a lift-off process was used to make a perforated Au source electrode for a VTFT where a block copolymer film was employed as a mask for the lift-off process [12]; however, the pore size and the shape are difficult to control due to the local phase separation of the block copolymer mask. More importantly, the optical transparency of Al or Au films decreases significantly as the film thickness is over 5 nm [16].

In this work, we report a semi-transparent VOLET by using a porous indium-tin oxide (ITO) source electrode, a Mg:Ag drain electrode, and an ITO gate electrode. Insertion of a phosphorescent OLED in the channel of a VTFT employing the transparent electrodes resulted in a semi-transparent VOLET. Due to the high transmittance (> 70% in the visible spectrum) of the ITO and Mg:Ag electrodes, the VOLET exhibited maximum luminance of 500 cd/m^2 with a large modulation of 10^4 of light emission through the top and bottom electrodes. The porous ITO source electrode not only played a critical role in luminance modulation but the nano-textured ITO film morphology also enhanced light extraction from the device. Finally, we show that the luminance modulation of the VOLET can be tuned by the thickness of the electron transporting layer (C_{60}).

2. Results and discussion

A schematic diagram of the VOLET structure is illustrated in Fig. 1a. ITO was used as both the source and gate electrodes and HfO_2 as a gate insulator of the VTFT. C_{60}/phenyl-C61-butyric acid methyl ester ($PC_{60}BM$) was used as the channel layer of the VTFT. A phosphorescent OLED was sandwiched between the C_{60} layer and the Mg:Ag drain electrode. In the VOLET structure, the most critical element is the

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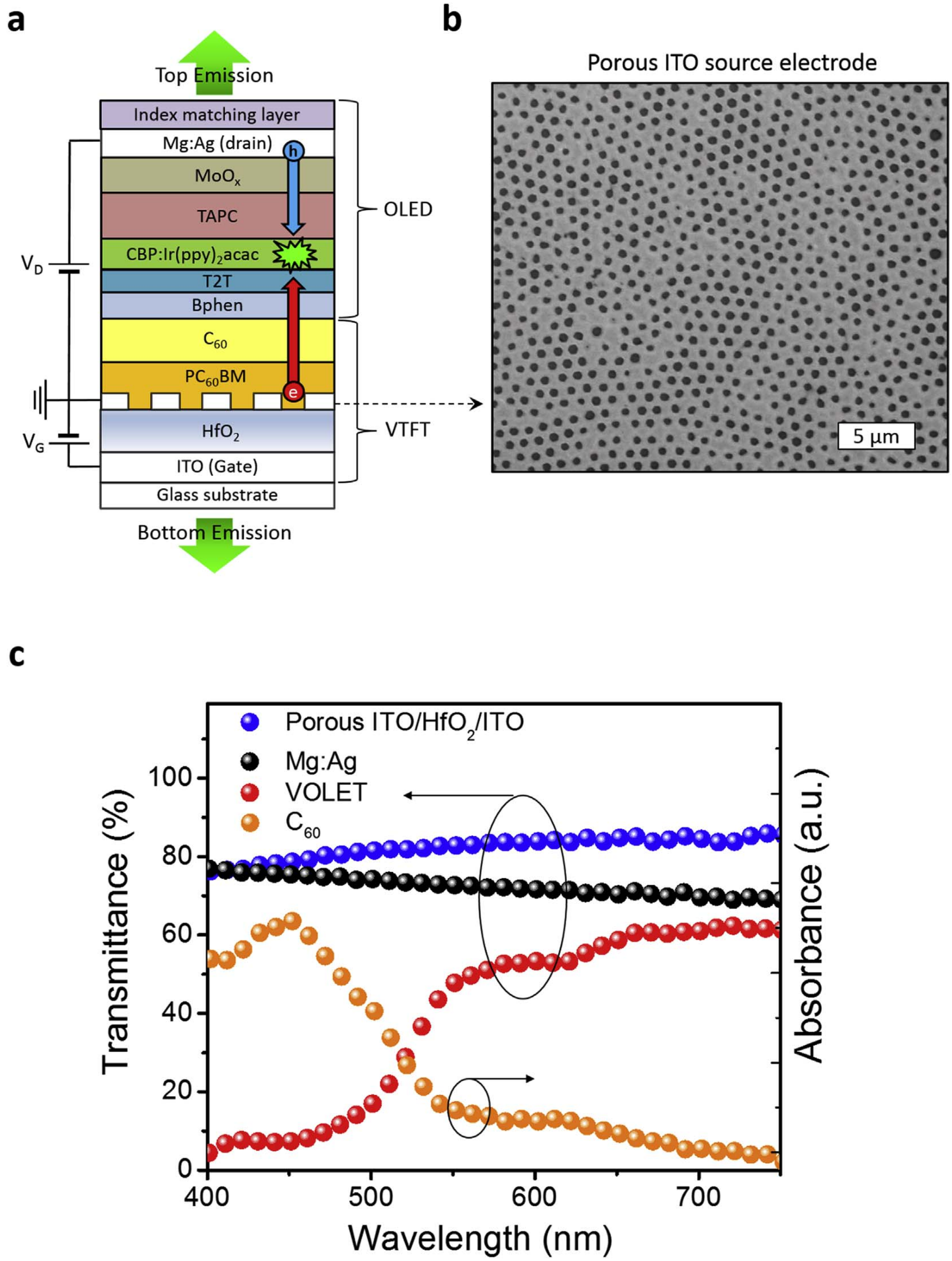

Fig. 1. Schematic description of a semi-transparent VOLET structure. a) VOLET architecture, b) scanning-electron microscope image of the porous ITO source electrode showing around 800 nm pore size with pore-to-pore distance of 1 μm, and c) transmittance of the transparent electrodes and the VOLET. C_{60} absorption spectrum is added to explain the semi-transparency of the VOLET.

porous ITO source electrode which allows the underlying gate electrode to modulate electron injection from the source electrode to the channel layer. In this work, the porous ITO electrode was fabricated by colloidal lithography having a porosity with a pitch of about 1 μm, as shown in the scanning electron microscopy image (SEM) in Fig. 1b. Detailed fabrication of the porous ITO electrode was described in our previous works [5,17]. Here, the VOLET is semi-transparent in the visible spectrum because the fullerene channel layers (C_{60}/$PC_{60}BM$ layers) absorb light with wavelength below 550 nm, rendering the entire VOLET having a transmittance of 50% at 550 nm as shown in Fig. 1c.

Fig. 2a and b illustrate the operation mechanism of a VOLET using a band diagram of the porous ITO region. During operation, the source electrode was grounded and a positive drain bias (V_D) was applied. The solution-processed $PC_{60}BM$ layer plays two important roles in the device operation. First, the porous ITO film had a surface roughness of 90 nm (ITO film thickness) and is partially planarized by the solution-processed $PC_{60}BM$ layer (50 nm), minimizing the possibility of shortings in the OLED. Second, the energy level difference between the lowest unoccupied molecular orbital (LUMO) energy (3.9 eV) of $PC_{60}BM$ and the work-function (4.7 eV) of ITO provides a large