Vertical organic light emitting transistor

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The authors demonstrate a vertical organic light emitting transistor achieved by stacking a capacitor on top of an organic light emitting diode (OLED). This unique device has dual functions, emitting light as an OLED and switching current as a transistor. When the capacitor is under bias, the storage charges on the thin electrode shared by two cells modulate the charge injection of the OLED active cell, hence controlling the current flow and subsequently tuning the light emission. Due to the vertical integration, this device can be operated at low voltage, which provides a solution for OLED display applications. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2778751]

Organic electronic devices, such as organic/polymer light emitting diodes[1,2] (OLEDs/PLEDs), organic field effect transistors,[3,4] and memory devices[5–7] have attracted considerable attention in recent years. Recently, organic light emitting transistors (OLET), a class of multifunctional devices integrating the light source within the traditional transistors, show several applications in highly integrated organic optoelectronic devices.[8–10] Due to the inherent low carrier mobility in organic materials, the traditional lateral structure transistors show low current output even at high working voltages.[11,12] Ma and Yang reported an organic transistor utilizing a vertically stacked structure to achieve promising performance.[13] In this letter, we demonstrate a vertical organic light emitting transistor (VOLET). This unique device exhibits dual functions, emitting light as an OLED and switching current as a transistor.

The VOLET device contains two cells: the capacitor and the light emitting cells [Fig. 1(a)] joined by a common electrode. This middle thin and rough electrode is defined as the common-source electrode (*S*), which plays a vital role in our device. The top electrode and the bottom electrode are defined as the gate electrode (*G*) and drain electrode (*D*), respectively. Light emitting polymer (LEP) is used as an active layer between the source and drain electrodes. In this work, aluminum (work function of 4.2 eV) is used as the source electrode to ensure the large injection barrier between the LEP and the source electrode, preventing the injection of electrons at zero gate voltage. LiF serves as a dielectric layer to provide a high capacitance.[14]

The Indium Tin Oxide (ITO) glass (soda lime glass, polished) used as drain electrode was purchased from Colorado Concept Coatings LLC (Catalog No. 00104). Its surface roughness was around 1 nm rms. A 5 nm film of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) was spin coated onto the ITO electrode, serving as the hole injection layer. The substrate was then placed on a hot plate for 60 min at 120 °C. After the heating process, the substrate was transferred into a dry box and then 80 nm of green fluorine-containing copolymer (5BTF8), consisting of 5 wt % poly(9,9-dioctylfluorene-co-benzothiadiazole) and 95 wt % poly(9,9-dioctylfluorene), was applied as the active and light emitting layers. The sample was then transferred into a vacuum chamber for thermal evaporation processes. A thin aluminum film (17 nm) was deposited onto the organic cell surface as the source electrode. The lithium fluoride layer (120 nm thick) followed as the gate dielectric layer, and then the gate aluminum electrode deposition took place. The pressure for thermal deposition processes was held below 4×10^{-6} torr. In this letter, all devices were examined with an ambient relative humidity of 45% using an Agilent 4155C precision semiconductor parameter analyzer in continuous sweep mode. Light intensities were measured using a silicon photodiode (1.0×1.0 cm^2) in reverse bias (0.1 V). Device images were taken with a digital camera.

Figure 1(b) shows the output characteristics of the VOLET device. The transistor action has a near 0.4 mA output current and a 10^2 on/off ratio (the ratio of the source-drain current I_{SD} with and without gate bias). The light emission of a VOLET [shown in Fig. 1(c)], measured by the photocurrent from an optical sensor, has the same tendency indicated in Fig. 1(b): the gate bias controls not only the current flow but also the light intensity. In addition, the photocurrent from the optical sensor indicates that light emission can be observed from the active layer when the gate bias (V_G) is slightly over 2 V. The result is similar to the turn-on voltage of a regular OLED using the same LEP, but with a low work function electron injection electrode such as calcium. This observation suggests that the electron injection barrier of the VOLET can be significantly lowered by gate modulation.

Figure 2 illustrates our device viewed from the front. A series of pictures were taken with constant source-drain bias (V_{SD}) and increasing gate bias at 2 V/scan step. When V_G was at 0 V bias [Fig. 2(b)], the whole device area was dark. Neither the camera nor the eyes could sense light emission from the device. However, when we raised the V_G to 2 V, a faint green light was observed at the same V_{SD} [Fig. 2(c)]. As we kept increasing the V_G step by step to 6 V, the intensity of the green light became stronger and stronger [Figs. 2(c)–2(e)]. It is worth mentioning that in order to ensure a perfect overlap, all VOLET electrodes were arranged in increasing size beginning with the smallest area gate, the slightly larger source, and the transparent drain which has the largest area. The center dark area shown in Fig. 2(b) delineates the surface area of the source electrode of the VOLET. The gate electrode is below the source electrode and is not visible in this figure. The images [Figs. 2(c)–2(e)] clearly

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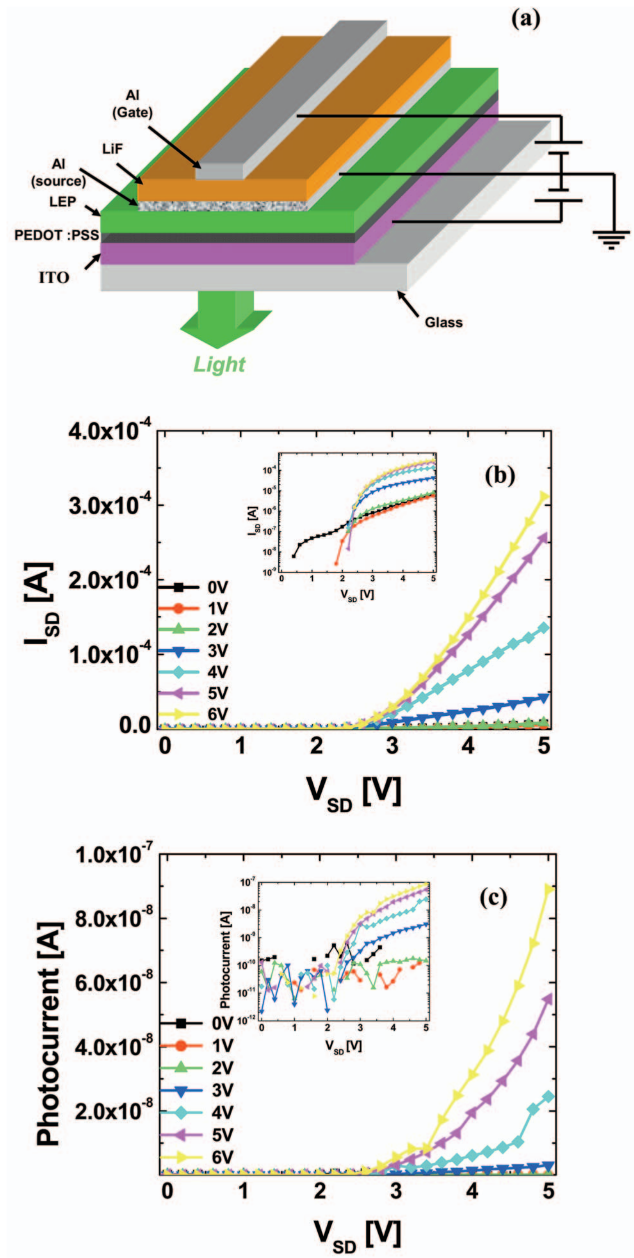

FIG. 1. (Color) Device structure and performance of the vertical organic light emitting transistor. (a) The configuration of the proposed device structure. The common source electrode is connected to the ground. (b) Output characteristics of the same device tested in ambient condition. (c) Photodiode current as a function of source-drain voltage.

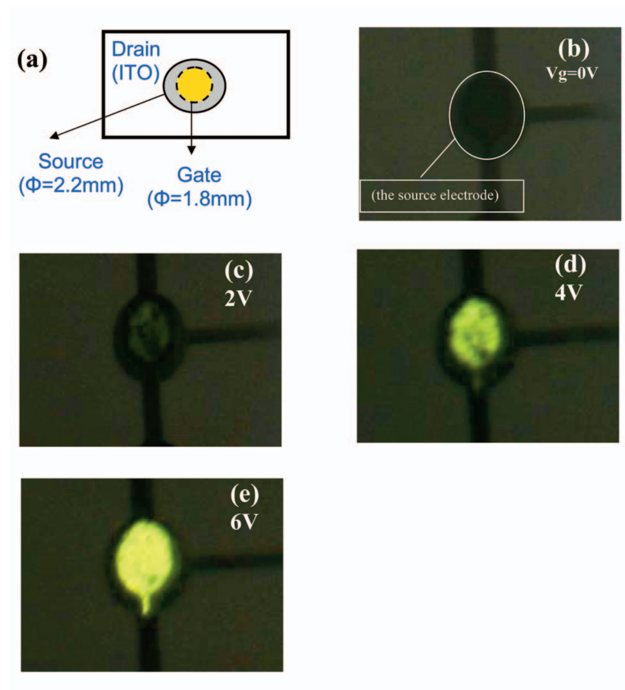

FIG. 2. (Color) The photographic images of a VOLET with different gate biases at constant source-drain bias (5 V). (a) The diagram of the shape and arrangement of the drain-source-gate electrodes. The gate bias increases from 0 to 6 V in 2 V steps in the following figures: (b) 0 V, (c) 2 V, (d) 4 V, and (e) 6 V.

indicate that the emission area is exactly the same shape, size, and position as those of the gate electrode. This set of images provides direct evidence that the light emission of our device is modulated by the gate electrode.

The most prominent concept concerning the VOLET's operation is the control of charge injection which could be modulated by the gate bias. This is achieved by choosing a metal for source electrode with a work function significantly below the lowest unoccupied molecular orbital (LUMO) of the organic semiconductor, which creates a significant charge injection barrier. Once the barrier becomes lower, under the gate bias, electrons can easily inject into the LEP and recombine with holes injected from the drain electrode forming photons. One critical problem associated with the device operation mechanism is how the gate bias influences the charge injection of the source/organic contact. As described in Ref. 13, a thin, rough, and partially oxidized source electrode is the key element required for VOLET. It is also observed that the modification behavior vanishes after a certain source electrode thickness.[15] From the cross-sectional transmission electron microscope (TEM) images (Fig. 3) of the thin source electrode, we believe that this thin source electrode consists of quasidiscontinuous aluminum grains which are surrounded by aluminum oxide domains. The discontinuous aluminum film even allows the polymer film to contact the dielectric layer (LiF) of the capacitor cell directly. When the gate is biased, the discontinuous metal film allows the inducing charges forming at the metal/Al-oxide interface to modulate the charge injection barrier between the source/polymer interfaces. Moreover, because of the direct contact of the polymer film and the LiF layer, the Li^+ or F^- ions may dope into the polymer under certain gate bias and change the in-

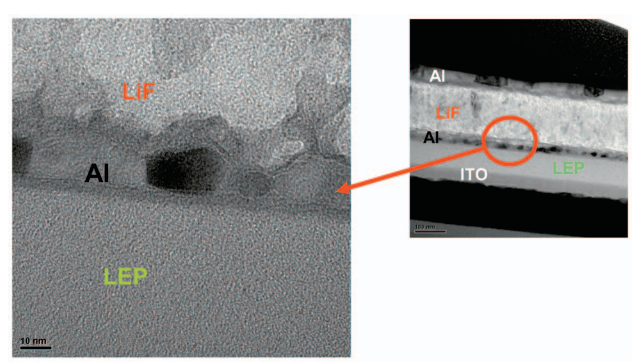

FIG. 3. (Color) Cross-sectional TEM images of the VOLET. Note the granular structure of the Al film located at the center of the left figure. This is the source electrode. It was realized that its morphology is important to the operation of the device.

jection barrier.[16] These effects disappear when the metal aluminum grains cover the whole surface. The excess free electrons in the metallic aluminum shield the influence of the induced charges by the screening effect and the uniform film blocks the drift of ions. This explanation is consistent with our x-ray/ultraviolet photoemission spectroscopy results showing that the gate bias induces charges at thin source electrode surface and changes the energy alignment at the source/organic interface.[15]

Based on the evidence obtained from our experiments, we propose an operating mechanism for the VOLET. In PLEDs, photons are the results of radiative recombination of the electron-hole pairs (excitons) in the light emitting materials. Therefore, efficient and balanced electron and hole injections is crucial for PLEDs with high performance. In the VOLET, as mentioned previously, when the gate is off ($V_G=0$), the electron current is very low because of the high injection barrier height between the Fermi level of source electrode (Al) and the LUMO of the LEP. The electrons and holes are imbalanced at this operating condition. By turning on the gate bias, with the proper polarity, the energy level alignment between source electrode and organic material changes, and the electron injection barrier is lowered. Thus, higher and balanced electron-hole injection is achieved even at low source-drain bias. As a result, excitons are formed more efficiently in the LEP and stronger light emission can be observed. It is worth mentioning that PLED (or OLED) are dual carrier devices. When one type of carrier dominates the current (for example, the holes), it actually hinders further charge injection due to the charging effect of the polymer layer. However, when dual carriers are balanced, or close to balance, carriers radiatively recombine and this charging effect will be significantly reduced. As a result, a much higher injection current is expected.[17,18]

In summary, by interface engineering and by using a LEP as the active layer, we have demonstrated a vertical organic light emitting transistor. The light emission of this device can be controlled by modulating the gate bias. This device combines dual functions, a switching transistor and a light emitting unit, into one device. Based on the structure demonstrated here, similar devices with different semiconductor and electrode materials can be made. For instance, by choosing different organic semiconductors as the active layer, we could make devices emit different colors. This device has promising applications in organic displays and electronic paper. For display applications, it is anticipated that this device can significantly reduce the number of transistors required to fabricate the active matrix display. Furthermore, investigation of this device has provided us a better insight into the working mechanism of the VOFET since the light emitted from the active layer is directly related to the carrier injected from the source.

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