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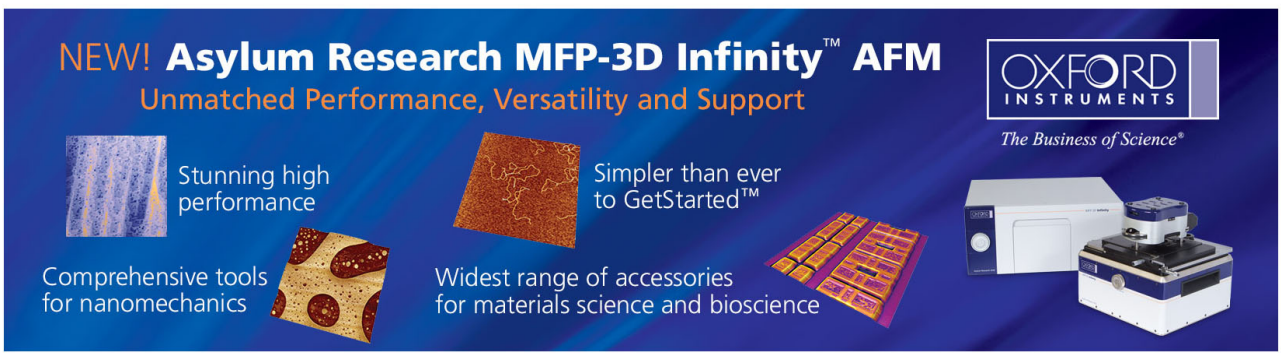

Organic thin-film transistors with color filtering functional gate insulators

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We developed color filtering functional organic thin-film transistors exhibiting both high field-effect mobilities and color-filtering ability. The conventional colorant inks were utilized as the materials for the color filter/dielectric multifunction layers. In order to improve the electrical performance, a high dielectric polymeric insulator, poly(2,2,2-trifluoroethyl methacrylate), was introduced to modify the surface of the dielectric layer. Further, the Commission Internationale de L'Eclairage chromaticity coordinates were (0.64, 0.34), (0.36, 0.54), and (0.14, 0.15) for red, green, and blue devices, respectively, covering 49.2% National Television Systems Committee standard. This work represents one potential example for multifunctional organic electronics. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2966365]

Organic electroactive materials have received much attention recently because they could offer low-cost approaches, such as low temperature and printing methods, for the manufacture of electronic products.[1] Additionally, the devices made of organic compounds have great potential for applications on flexible electronics such as smart cards, radio-frequency identification tags, and paperlike displays.[2–8] On the other hand, from the viewpoint of the value structure of printing technology, it is necessary to reduce the number of printing steps to fabricate truly low-cost products.[1] Therefore, to accomplish printed electronics, one rather promising approach is to use a multifunctional material (ink) as the common component of different devices in parallel in a certain electronic system.[1] For example, the polymer material, poly(3,4-ethylenedioxythiophene):poly(styrenesulphonate) (PEDOT:PSS), could be used as the active material for electrochemical transistors, electrochromic displays, push-button input devices, and batteries in a system-on-a-sheet label.[9] As a result, only one step is required to print the PEDOT:PSS layer for all the devices in the electronic label. Herein, we reported organic thin-film transistors (OTFTs) with an additional function of color filtering. The colored polymer insulators not only serve as the dielectric materials for field-effect transistors, which could be the driving circuits, but also as color filters for liquid crystal displays (LCDs). This work represents one potential example for multifunctional organic electronics. Further, since color filters significantly contribute the bulk of material cost, integrating color filters and gate insulators is also an effective method for reducing the overall cost of LCDs.

Typical colorant inks are composed of dispersants, nanosized pigments, styrene, acrylic acid, and azo-bisisobutyronitrile. To achieve multiple functions, we further introduced a polymeric material, poly(2,2,2-trifluoroethyl methacrylate) (PTFMA) (Fig. 1), whose dielectric constant (κ) is equal to 6.0, to modify the surface of the color filters.[10] The PTFMA layer smoothes the surface of the color filters, facilitating the crystallization of the semiconducting molecules, pentacene, and its higher dielectric constant helps to induce more field-effect charges, increasing the output current and driving capability. The molecular structure of PTFMA is similar to that of polymethyl methacrylate (PMMA) (Fig. 1). Although PMMA has excellent film formation properties, the low dielectric constant of PMMA (κ =2.7) (Ref. 11) usually results in lower output current. Therefore, we replaced the hydrogens on the terminals of the side chains with trifluoromethyl (CF_3) groups. Owing to its high polarity, the CF_3 group increased the dielectric constant from 2.7 to 6.0. As a result, the use of PTFMA could increase the capacitance of the dielectric insulators. Further, from the viewpoint of optical properties, PTFMA has limited absorption in the visible regime. Therefore, the absorption spectra and the corresponding Commission Internationale de L'Eclairage (CIE) chromaticity coordinates of the multilayer insulators remain unchanged.

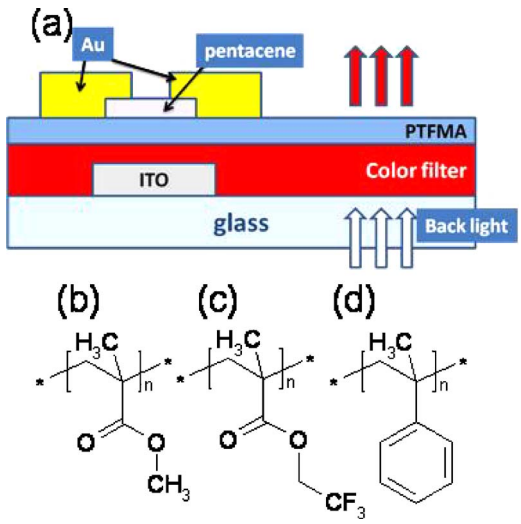

FIG. 1. (Color online) (a) The cross sectional illustration of the OTFT with a bilayer colored dielectric insulator consisting of a commercial color filter and PTFMA. (b) Chemical structure of PTFMA. (c) Chemical structure of PMMA. (d) Chemical structure of PαMS.

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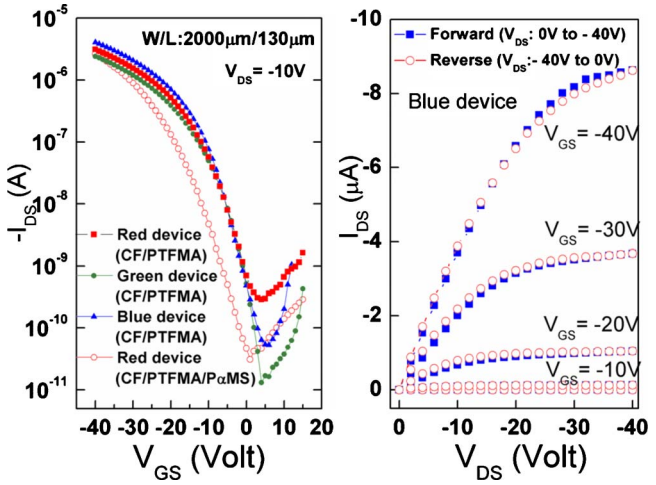

FIG. 2. (Color online) (a) The transfer and (b) output characteristics of the color filtering functional devices.

The cross section of the OTFTs in this work is illustrated in Fig. 1. The devices were fabricated on indium tin oxide (ITO) patterned glass substrates. The 100 nm thick ITO was used as the gate electrodes. Commercial colorant inks (Everlight Chemical Industrial Corporation) (Ref. 12) were spin coated on the substrates. The colored films were subsequently cured at 90 °C for 15 min and then at 230 °C for 40 min. The PTFMA dissolved in propylene glycol monomethyl ether acetate (9.0 wt %) was spin coated on the as-prepared color filters and then cured at 100 °C for 1 h. For some devices, an additional layer of poly(α-methylstrylene) (PαMS) (5 nm) was further coated from toluene solutions (0.1 wt %). After the preparation of the dielectric layers, pentacene was thermally evaporated on the insulators as the semiconductors of the devices. Finally, gold was thermally deposited as the source (S) and drain (D) electrodes through a shadow mask. The channel length (L) and width (W) of the pentacene OTFTs were 130 and 2000 μm, respectively. The devices with a metal-insulator-metal structure, consisting of the dielectric layers sandwiched between ITO and Al, were used for capacitance measurements. The calculated dielectric constants were 3.5, 4.7, and 4.0 for red, green, and blue dielectric layers, respectively. The capacitance measurements were conducted with a HP 4284A Precision LCR meter. The transmittance spectra were obtained by a PerkinElmer Lambda 650 spectrometer. The CIE coordinates were measured by a ConoScope (Autronic-Melchers, GmbH). The film thickness and roughness were measured using a DI 3100 series atomic force microscope (AFM). The electrical characteristics of the OTFTs were measured with a Keithley 4200 semiconductor parameter analyzer in a light-shielded ambient environment.

Initially, the colorant materials were used directly to serve as the dielectric layers. However, limited field effect and larger hysteresis were observed. The poor device performance was probably owing to the high polarity of the surface. On the other hand, after the modification in PTFMA, hysteresis was inhibited and larger output current was obtained. Figure 2(a) show the transfer characteristics of color filtering OTFTs at room temperature. The extracted motilities in the saturation region following the conventional field effect model were 0.31, 0.21, and 0.42 cm^2/V s for red, green, and blue devices, respectively. On-off current ratios for all

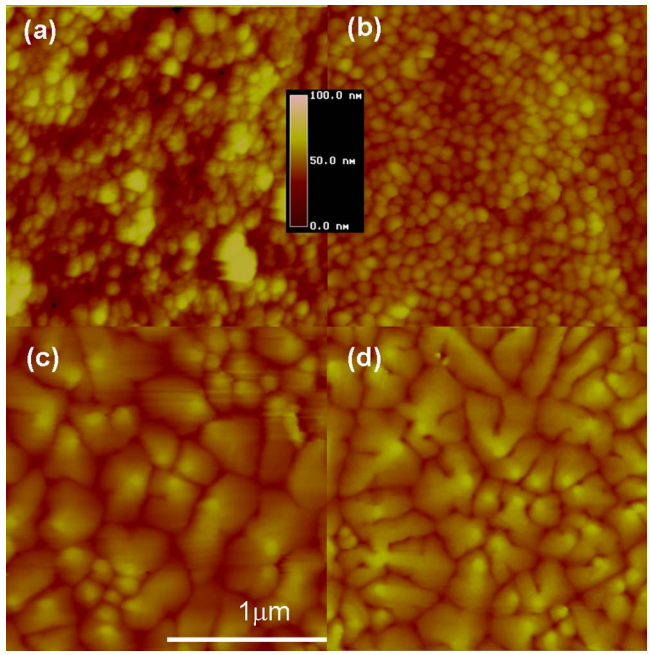

FIG. 3. (Color online) (a) The AFM image of the surface of the red color filter. The surface morphology of the pentacene layers on (b) the red color filter, (c) the red color filter/PTFMA insulator, and (d) the trilayer red color filter/PTFMA/PαMS insulator.

the devices were around 10^5. We also discovered that the red device modified with a second thin layer of PαMS layer had an even higher mobility ($\sim$0.51 $cm^2\,V^{-1}\,s^{-1}$) [Fig. 2(a)]. Further, Fig. 2(b) shows the typical output characteristics of colored devices (with a blue colored dielectric insulator in this case). Apparently, when the gate voltage was reversely swept, very limited hysteresis was observed, suggesting very stable device characteristics.

To further identify the function of the buffer layer, PTFMA, the surface morphologies of the colored films and the pentacene thin films on different dielectric surfaces were examined by AFM. The typical AFM images are displayed in Fig. 3. The surface of the color filters was quite rough, as shown in Fig. 3(a). Therefore, pentacene molecules were not able to grow well on the rough surface. The grain size of pentacene on the neat color film was very small, thereby leading to poor device performance [Fig. 3(b)]. The grain boundaries might trap great amount of charges, limiting charge transport and resulting in significant hystresis. On the other hand, the grain size on the surface of the PTFMA modified bilayer insulator became larger [Fig. 3(c)]. The PTFMA significantly smoothed the surface and further changed the surface energy of the colored film, facilitating the crystallization of pentacene molecules. Further, for the devices with trilayer insulators, pentacene also grew well on PαMS. [Fig. 3(d)]. The more "compact" grains of the pentacene film probably reduced the density of charge traps at the grain boundaries, leading to even higher device mobility [Fig. 2(a)]. The nonpolar nature of PαMS might improve the crystal growth of pentacene.[13] The results of the morphology study were consistent with the aforementioned electrical characteristics.

Since the light absorption of organic materials increases with the film thickness, thick color filter layer usually have better filtering performance. On the other hand, the capacitance of the gate dielectric decreases with the increasing in-

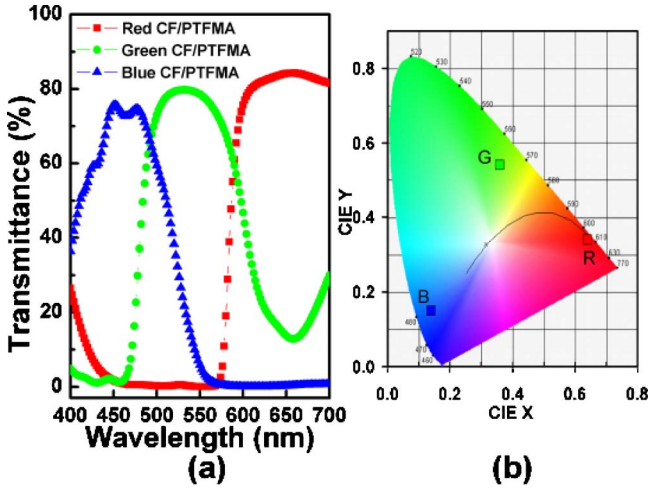

FIG. 4. (Color online) Optical properties of red, green, and blue functional OTFTs: (a) The transmission spectra and (b) CIE 1931 coordinates.

sulator thickness. The smaller capacitance would lead to lower density of field-effect charge carriers and, therefore, higher operating voltages. As a result, the optimum thicknesses of red, green, and blue colorant films with PTFMA bilayer were 1.36, 1.20, and 1.37 μm, respectively. Figure 4(a) shows the transmission spectra of these colored devices. The light transmitted through ITO glasses, the color filtering, and the PTFMA layers. Since PTFMA has limited absorption in the visible regime, the absorption spectra were almost unchanged after the addition of the PTFMA layer. Figure 4(b) shows the corresponding CIE coordinates, which were (0.64, 0.34), (0.36, 0.54), and (0.14, 0.15) for red, green, and blue devices, respectively, covering 49.2% National Television Systems Committee (NTSC) standard. From the above results, it is proved that the devices not only have high electrical performance, but also have satisfied optical properties.

In summary, we demonstrated color filtering OTFTs with multilayer gate insulators exhibiting high field effect mobilities, on-off current ratios, as well as color filter functions. The PTFMA polymer smoothed the surface of the colored films and improved the crystallization of pentacene molecules, thereby enhancing the device performance. This study provides an alternative approach to integrate gate insulators and color filters in LCDs. Finally, the current work also represents one practical example for multifunctional organic electronics.

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