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Letter

Electrical responses of short-channel organic transistor prepared by solution-processed organic crystal wire mask

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ABSTRACT

We report a formation of a solution-grown single crystal wire mask for the fabrication of short-channel organic field-effect transistor with enhanced dynamic response time. The various channel length, ranging from submicrometer to a few micrometers, were obtained by controlling the concentration of solution and processing conditions. We fabricated *p*- and *n*-channel bottom-contact organic field-effect transistors using pentacene and PTCDI-C_{13}, respectively, and static and dynamic electrical characteristics of the devices were investigated. The highest and average field-effect hole mobility values were found to be 0.892 $cm^2/V\,s$ and 0.192 $cm^2/V\,s$, respectively. The load type inverter based on the short-channel transistor connected with a 2 MΩ resistor showed a clear switching response when square wave input signals up to 1 kHz were applied at $V_{DD} = -60$ V.

1. Introduction

The organic field-effect transistor (OFET) has been receiving tremendous interest as an active element in electronic applications [1–3]. The OFET's performance can be engineered by either the appropriate selection of material components or the optimization of the device structure and dimensions. The device's operation speed is a critical factor for high-density integrated circuits. The switching speed is described using the cut-off frequency (f_c) which is represented as $f_c = \frac{\mu V_{GS}}{2\pi L^2}$, where μ, V_{GS}, and L are the mobility, gate-source voltage, and channel length, respectively [4]. The enhancement of the switching speed of devices can be achieved by increasing μ, or reducing L. To increase μ is relatively difficult due to the limited charge carrier properties of an organic semiconductor. Therefore, reducing L is a better strategy to achieve an OFET with high speed. Various approaches have been developed to fabricate a device with a short L. Electron beam lithography (EBL) is typically used to fabricate a short-channel in many research environments because of its high resolution and useful design tool (maskless lithography) [5]. Austin and Chou reported a 70 nm-channel-length polymer OFET using nanoimprint lithography [6]. Li et al. developed a spin-coating-induced edge template and ink-jet printing method for the short-channel polymer field-effect transistor [7]. Scheiner et al. reported an under-etching technique in combination with low-resolution lithography and a peel-off process [8]. Pyo et al. demonstrated a submicrometer-channel-length OFET created by atomic force microscopy lithography [9]. In addition, embossing [10], microcontact printing [11], and various inkjet printing techniques [12] have been developed for short-channel fabrication. However, these techniques require high-cost equipment and relatively complicated processes. Thus, the development of a low-cost and simple fabrication process is one of the major concerns for realization of the short-channel OFET. In an attempt to scale down the channel length without high-cost equipment, Jiang et al. introduced an organic ribbon mask technique [13] using "H"-type anthracene derivative organic ribbon prepared

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by the physical vapor transport technique. But it is still required the use of specific equipment under controlled conditions. In addition, most of the devices with short channels are based on a silicon dioxide (SiO_2) gate dielectric rather than a polymer dielectric that shows better compatibility with flexible substrates. In this paper, we present a low-cost and simple short-channel fabrication method using a solution-processed organic crystal wire mask grown directly on a polymer gate dielectric. We demonstrate short-channel OFETs based on polymer dielectric with good static and dynamic operational stability. Furthermore, we also fabricated load-type inverters and examined their dynamic electrical characteristics.

2. Experimental

A fabrication process for bottom-gate, bottom-contact OFETs with short channels is represented in Fig. 1. A cross-linked poly(4-vinylphenol) (PVP-CL) dielectric (C_i = 57.8 pF/mm^2) was formed over an indium thin oxide (ITO)-coated glass substrate as shown in Fig. 1(a). On top of the dielectric, a solution of 0.025 wt% of *N*,*N*′-dioctyl-3,4:9,10-perylene tetracarboxylic diimide (PTCDI-C_8) in *o*-dichlorobenzene (*o*-DCB) was dropped on a capillary tube (3 cm length and 1.2 mm diameter) placed on top of the dielectric layer, and then the substrate was transferred to a hot plate and baked at 70 °C for 1hr to form an aligned PTCDI-C_8 crystal wire (Fig. 1(b)–(d)) that is used as a mask for the short-channel formation. The width of the wire was in the range of 0.8–2.2 μm. In our previous communication [14], we investigated the molecular orientation and structure of the PTCDI-C_8 crystal using 2-dimensional grazing incidence X-ray diffraction (2D-GIXD) and found that the PTCDI-C_8 crystal wire had a directionally grown single crystalline nature. A 30 nm-thick gold was deposited using thermal evaporation (Fig. 1(e)) over the PTCDI-C_8 crystal wire, followed by removing the wire by spraying acetone to peel-off the wire along with Au, as shown in Fig. 1(f) and (g). Finally, 50 nm-thick pentacene (*p*-type) and 40 nm-thick *N*,*N*′-ditridecyl-3,4,9,10-perylenetetracarboxylicdiimide (PTCDI-C_{13}) (*n*-type) was deposited using thermal evaporation to complete the short-channel OFET fabrication (Fig. 1(h)). The optical microscope images of each process are shown in the inset of the figure.

3. Results and discussion

Fig. 2 shows optical microscope (Olympus BX51) and atomic force microscope (AFM) (Nanoscope IIIa, Digital Instruments) images of the short-channel. The channel length varies slightly, ranging from submicrometer to a few micrometers according to the PTCDI-C_8 crystal width, which can easily be engineered by varying the solution concentration and heating temperature (a)–(c). The channel length and depth were reconfirmed by AFM imaging (d), which shows that the depth of the channel is 27 nm, almost the same as the initial thickness of the gold layer, indicating that there is no loss of Au layer during the process. The AFM images of pentacene and PTCDI-C_{13} deposited on the channel region are shown in Fig. 2(e) and (f), respectively. Typical dendritic and ellipsoidal grains are observed for pentacene and PTCDI-C_{13}, respectively. The similar morphologies of pentacene and PTCDI-C_{13} are also observed on the PVP-CL polymer dielectric [15,16].

Fig. 3 shows output (I_{DS} *vs.* V_{DS}) and transfer (I_{DS} *vs.* V_{GS}) characteristics of representative short-channel pentacene ((a) and (b)) and PTCDI-C_{13} OFETs ((c) and (d)) measured under ambient conditions using a semiconductor parameter analyzer (HP 4156A). In low V_{DS} region of the output curves, suppression in charge injection from Au electrode

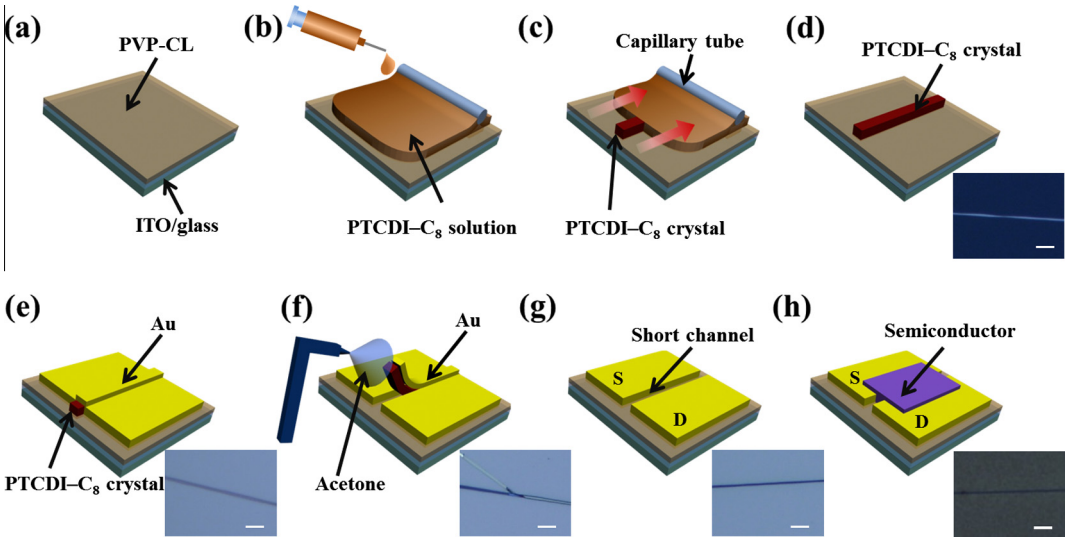

Fig. 1. The formation procedure of short-channel OFET using a solution-processed organic crystal wire mask. (a) PVP-CL layer formation on glass substrate, (b) dropping PTCDI-C_8 solution onto the capillary tube, (c) crystal wire formation from the edge of the solution drop, (d) formed PTCDI-C_8 crystal wire mask on the substrate, (e) Au deposition, and (f) crystal wire removal by spraying acetone, (g) formation of channel, and (h) organic semiconductor deposition to form field effect transistor. The insets show optical microscope images of each process, and the scale bar is 10 μm.