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Bottom contact ambipolar organic thin film transistor and organic inverter based on C_{60}/pentacene heterostructure

S.D. Wang [a,*], K. Kanai [b], Y. Ouchi [b], K. Seki [c]

[a] Research Center for Materials Science, Nagoya University, Furocho, Chikusa-ku, Nagoya 464-8602, Japan
[b] Department of Chemistry, Graduate School of Science, Nagoya University, Furocho, Chikusa-ku, Nagoya 464-8602, Japan
[c] Department of Chemistry, Graduate School of Science and Institute for Advanced Research, Nagoya University, Furocho, Chikusa-ku, Nagoya 464-8602, Japan

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Abstract

We report on the fabrication and characterization of the bottom contact organic thin film transistor and inverter based on a heterostructure of C_{60} on pentacene. The transistor shows ambipolar transport characteristics with high electron and hole mobilities of 0.23 $cm^2\,V^{-1}\,s^{-1}$ and 0.14 $cm^2\,V^{-1}\,s^{-1}$, respectively. Both the n-channel in C_{60} and the p-channel in pentacene are stable in N_2 atmosphere. After exposure to air, the n-channel is completely degraded whereas the p-channel keeps working. The inverter exhibits typical transfer characteristics, which are interpreted by the distribution of the accumulated electrons and holes depending on the bias conditions. The combination of the high performance and the bottom configuration of our devices suggests a potential way to fabricate organic complementary circuits without patterning of organic materials.

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1. Introduction

Organic thin film transistors (OTFTs), with advantages of low-cost, flexibility and large-area capability, are attractive for numerous applications including switching devices for various displays [1] and components for organic integrated circuits [2]. Most OTFTs reported so far exhibit either n-type or p-type behavior [1,3], and electron and hole mobilities as high as 0.5 $cm^2\,V^{-1}\,s^{-1}$ and 1.5 $cm^2\,V^{-1}\,s^{-1}$ have been demonstrated in fullerene (C_{60})-based [4] and pentacene-based [5] transistors, respectively. However, development of organic complementary technology, where both n-type and p-type transistors are incorporated, is essential for achieving efficient organic integrated circuits with low power dissipation, good noise immunity and high operational stability. There are two approaches to this goal. One is

* Corresponding author. Fax: +81 52 789 2944.
E-mail addresses: dong@mat.chem.nagoya-u.ac.jp, trueccfs@hotmail.com (S.D. Wang).

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to incorporate separate n-type and p-type transistors by electrical connection [2,6–8]; the other is to realize ambipolar charge transport in a single transistor. The latter has superiorities for device fabrication such as operation at both positive and negative voltages and simplicity of circuit design. Recently solution-processed ambipolar OTFTs and organic inverters using interpenetrating blends [9–11] or small-bandgap polymer [9] have been reported. As for organic small molecules, OTFTs based on a heterostructure, first reported by Dodabalapur et al. [12], have exhibited ambipolar transport characteristics [13–15]. The heterostructure consists of two active layers, one of which is n-type organic semiconductor and the other is p-type. Thus both electron and hole can be accumulated depending on the gate bias. Nevertheless, the carrier mobility in the ambipolar bilayer transistors is quite low (10^{-6}–10^{-3} $cm^2\,V^{-1}\,s^{-1}$) compared with those in the corresponding n-type or p-type transistors, and efforts to improve the mobility are still needed.

Recently Kuwahara, Kubozono and co-workers reported ambipolar transistors based on C_{60}/pentacene heterostructure with relatively high electron and hole mobilities (10^{-3}–10^{-2} $cm^2\,V^{-1}\,s^{-1}$) [16,17]. In their devices, however, no ambipolar behavior could be observed with the top and bottom contact configurations, and only devices with the middle contact configuration, which is equivalent to a top contact for pentacene and a bottom contact for C_{60}, have shown ambipolar transport characteristics after annealing in high vacuum (HV). The middle contact configuration requires electrode patterning after the deposition of pentacene. Since pentacene is dissolved to many solvents, photolithographic etching cannot be employed on already deposited pentacene film, making such configuration not practical in device manufacturing [18,19]. Furthermore, the vacuum annealing process also limits the practicability for real device fabrication.

In this paper we report the fabrication of transistors based on C_{60}/pentacene heterostructure with bottom contact configuration, which is very similar with that in Ref. [16], whereas the in situ measurements of our devices in HV have shown significantly different results. Clear ambipolar transport characteristics were observed in the bottom contact devices without any annealing treatment, while the electron and hole mobilities reached the order of 0.1 $cm^2\,V^{-1}\,s^{-1}$. A bottom contact inverter was also successfully fabricated by incorporating two C_{60}/pentacene ambipolar transistors. Such devices have advantages that (1) the patterning of the electrodes can be carried out before the deposition of organic materials, and (2) the simple sequential deposition of the two organic materials after electrode patterning completes the device fabrication without annealing. The devices work in N_2 atmosphere as well, demonstrating the possibility of utilizing this bottom contact configuration in practical devices.

2. Experimental

The heavily doped silicon (Si) wafers with 1 μm silicon dioxide (SiO_2) layers, purchased from Photo Precision Co., Ltd., were used as the substrates. The Si and SiO_2 act as the gate electrode and the gate dielectric, respectively. The gold (Au) electrodes, with thickness of 50 nm, were deposited by thermal evaporation through a shadow mask on the substrate pre-cleaned by the sequential ultrasonic bath of acetone and ethanol. The channel length and channel width were 0.1 mm and 2 mm, respectively. All the electrodes were connected to vacuum electrical feedthroughs before the deposition of organic films. Commercially available pentacene and C_{60} (TCI Co., Ltd.) were used as received. The organic materials were sublimated by quartz cells in a HV system, where the base pressure was about 6×10^{-5} Pa and two quartz crystal microbalances are installed. Both of the microbalances were calibrated by UV–visible absorption measurements of deposited films dissolved in solution. One of the microbalances (fixed) was used to monitor the films deposition, and the other one (movable) was used in advance for setting the tooling factor of the fixed one. The deposition rates of both materials are 0.1–0.2 Å/s. Both the transistor and the inverter were fabricated by the successive deposition of 10 nm pentacene and 20 nm C_{60} on the Au patterns, with two terminals (drain and source, see Fig. 1) for the transistor, and with three terminals (supply, output and ground, see Fig. 6) for the inverter. The in situ electrical measurements were performed at room temperature just after the fabrication.

3. Results and discussion

3.1. Bottom contact ambipolar OTFTs with C_{60}/pentacene and pentacene/C_{60} heterostructures

Fig. 2(a) and (b) shows the drain current (I_D) versus drain voltage (V_D) characteristics of a bottom contact transistor with an active layer of 20 nm C_{60}