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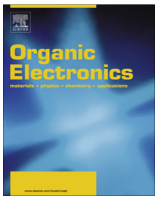

High-speed operation in printed organic inverter circuits with short channel length

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ABSTRACT

We have demonstrated fast operation of printed organic inverter circuits. We employ a soluble organic semiconducting material which has high field-effect mobility and ink-jet printed source/drain electrodes with short channel length. Appropriate concentration of the semiconducting solution and modification layer of source/drain electrodes improve both mobility and on/off ratio. The fabricated transistors with a short channel length (4 µm) exhibit excellent mobility (1.2 $\text{cm}^2/\text{V s}$), high on/off ratio (>10^5) and operational stability. The diode-load inverter with a narrow channel and low parasitic capacitance operate at 8 kHz at 20 V. These results will lead to significant progress in applications of printed organic circuits.

1. Introduction

Applied research on organic electronics is accelerating with the aim of developing low-cost flexible devices that have large areas. Organic materials have two significant advantages. They possess intrinsic mechanical flexibility due to loose Van der Waals bonds between their organic molecules. In fact, ultra-flexible electronics have been demonstrated [1,2]. Another advantage is solubility in organic solvents; this makes organic materials more suitable than inorganic materials for printing processes. Organic devices can also be used to realize new kinds of electrical devices; besides flexible displays [3–5], these include large-area sensors [6–8] and flexible radio-frequency identification (RFID) tags [9,10]. Moreover, there are several reports on organic integrated circuits such as inverters [11–13], ring oscillators [14–16], flip-flops [17], and four-input multiplexers [18]. However, the characteristics of these circuits will have to be improved before they can be put to commercial use.

Specifically, operating speed is an issue for organic circuits. Here, the operating frequency is largely dependent on the channel length, i.e., [19]

$$f_t = \frac{\mu_{\text{eff}}(V_{\text{GS}} - V_{\text{TH}})}{2\pi L[L + 2(L_{\text{C}} + L_{\text{ext}})]} \quad (1)$$

where f_{T} is cutoff frequency, μ_{eff} is effective charge-carrier mobility, V_{GS} is gate-source voltage, V_{TH} is threshold voltage, L is channel length, L_{C} is contact length, and L_{ext} is extended contact length. Eq. (1) clearly indicates that both a short channel length and high effective mobility can provide fast operation of integrated circuits. Although organic integrated circuits with channel lengths of less than 5 µm and operating frequencies above 1 MHz [20,21] have been reported, their source/drain electrodes were fabricated with conventional thermal evaporation and photolithography processes, not printing.

In the case of source/drain electrodes formed by a printing process, the channel length is generally longer than those fabricated by photolithography because of the lack

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of positioning accuracy and spread of the printed ink. Though there are several reports on printed organic thin-film transistor (TFT) devices with short channel lengths (less than 10 μm) [22–24], the estimated field-effect mobility was only 0.1 cm^2/V s because of the large contact resistance (R_C). Furthermore, the operation speeds of printed integrated circuits with such short-channel-length TFT devices have yet to be reported. It is thus very important to investigate the operational speeds of printed organic TFT devices with high field-effect mobility and short-channel-length transistors and to evaluate the dynamic responses of integrated circuits using these devices.

In this study, we fabricated inverter circuits based on printed organic TFT devices using a high mobility organic semiconductor materials and short channel lengths. We investigated two ways of improving the transistor characteristics: optimization of the organic semiconductor concentration in a solution (ink) and a self-assembled monolayer (SAM) treatment of the source/drain electrodes. We found that the electrical performance of the organic TFT devices strongly depended on the concentration of the semiconducting solution. We obtained high-quality organic semiconductor film from an optimized solution and realized organic TFT devices with a short channel length (less than 10 μm) that had high mobility (1.2 cm^2/V s), high on/off ratio (>10^5), and high operational stability. These OTFT devices led to a significant improvement in the dynamic response of the inverter circuits.

2. Experimental

Fig. 1(a) and (b) shows a schematic illustration and photograph of a fabricated bottom-gate, bottom-contact organic TFT device. These devices were fabricated by evaporating Al onto a glass substrate to form a 30-nm-thick gate electrode. A 440-nm-thick cross-linked poly-4–vinylphenol (PVP) (Mw ~ 25,000, Sigma Aldrich Co.,) layer was then prepared. PVP and poly(melamine-co-formaldehyde) (Sigma Aldrich Co.) as a cross-linking agent were mixed in propylene glycol monomethyl ether acetate (PGMEA). The solution was deposited by spin-coating onto the gate electrodes and dried at 150 °C for 1 h. Silver nanoparticle ink (NPS-JL, Harima Chemicals) was patterned with an ink-jet printer (Fujifilm Dimatix, model DMP2831) to form the source/drain electrodes. The droplets were deposited with a dot-to-dot spacing of 60 μm. During the inkjet patterning process, the substrate temperature was maintained at 60 °C. After the printing process, the substrates were heated at 120 °C for 1 h to sinter the printed silver nanoparticles. The self-assembled monolayer (SAM) treatment for source/drain electrodes was prepared by immersing the substrates in a 5 mM propanol solution of pentafluorobenzenethiol (PFBT) for 5 min at room temperature. The substrates were then rinsed with pure propanol and blown dry with nitrogen. The SAM treatment changed the work function of the printed silver source/drain electrodes from 4.7 eV to 5.4 eV (see Fig. S1). Then, a 1 wt% solution of fluoropolymer (DuPont™, Teflon® AF 1600,) in Fluorinert™ (3M™ FC-43) was used as a bank layer and printed by using dispenser equipment (Musashi Engineering, Image Master 350 PC) that included a three-axis table and an air dispenser, both of which were computer-controlled to dispense and pattern the solution. 200-nm-thick fluoropolymer bank layers were printed at a patterning speed of 20 mm/s and discharge pressure of 7 kPa, and they were subsequently cured at 40 °C for 5 min in air. The bank size was 2000 μm × 1000 μm. Finally, a mesitylene-based formulation for the organic semiconducting layer (Merck, lisicon® S1200) [25–28] with a deep ionization potential of 5.4 eV was drop-casted into the bank layers. The volume of each droplet was 1 μl for all devices. After deposition,

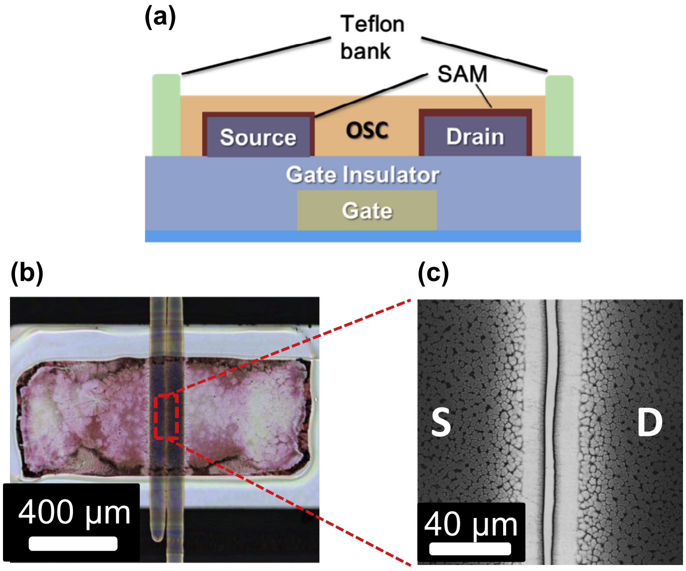

Fig. 1. Organic TFT devices with printed electrodes. (a) Illustration of a fabricated organic TFT device. (b) Photograph of the organic TFT device. (c) Photograph of the source/drain electrodes.