Laser Assisted Lift-Off Process as a Organic Patterning Methodology for Organic Thin-Film Transistors Fabrication

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Abstract
Organic thin-film transistors (OTFTs) based on a semiconducting polymer have been fabricated using an organic patterning methodology. Laser assisted lift-off (LALO) technique, ablating selectively the hydrophobic layer by an excimer laser, was used for producing a semiconducting polymer channel in the OTFT with high resolution. The selective wettability of a semiconducting polymer, poly (9-9-dioctylfluorene-co-bithiophene) (F8T2), dissolved in a polar solvent was found to define precisely the pattering resolution of the active channel. It is demonstrated that in the F8T2 TFTs fabricated using the LALO technique and is applicable for the larger area display.

1. Introduction
The potential of organic thin-film transistors (OTFTs) is a low-cost alternative to a mainstream amorphous silicon-based technology for electronic applications, for example, devices in large-area format such as displays, electronic papers, and sensors, radio frequency identification tags, and smart cards [1–6]. In contrast to traditional silicon-based devices that require expensive and complicated fabricating processes at high temperature [7], organic based devices on large substrates including plastic substrates involve relatively simple processes [8, 9]. Up to date, many soluble polymeric materials have been used for fabricating the OTFTs in backplane electronics for large area displays. Oligothiophenes [10], poly (3-hexylthiophene) (P3HT) [11, 12], and fused heterocyclic compounds [13] have been shown to possess physical and electrical properties that are suitable for the OTFTs applications. Especially, the regioregular P3HT shows high field-effect mobility (0.01～0.1 cm^2/Vs) and reasonable on/off ratios (>100 in air and 10^6 in an inert atmosphere) [14, 15].
Although such soluble semiconducting polymers have generally yielded the OTFTs with high mobility, they suffer from the limited patterning capability. Except for recent works on patterned active layers [17, 18], the whole coverage of the semiconducting polymers have been routinely prepared for the polymeric OTFTs. Therefore, one of the critical issues for fabricating high performance polymeric OTFTs is how to pattern the semiconducting polymer layer for the active channel region and to reduce the leakage current associated with the formation of conductive paths between the pixels. Moreover, the precise patterning is very important to eliminate high resistive and capacitive parasitics of leakage current sources at the insulator/semiconductor interface and to remove cross talks from interconnects [9, 19].
Several existing patterning technologies are inkjet printing [17, 18], screen printing [20], micromolding [21], electron-beam lithography [22], and spin coating followed by photolithography [23]. The traditional photolithography is a high-resolution method of patterning but it is rather complex and not simply applicable for soluble organic materials. Screen printing is inexpensive but is not able to routinely manufacture fine features (<100 μm). Although inkjet printing is very useful for soluble semiconductors to manufacture the OTFTs, it is limited due to the incompatibility between the material in the print head

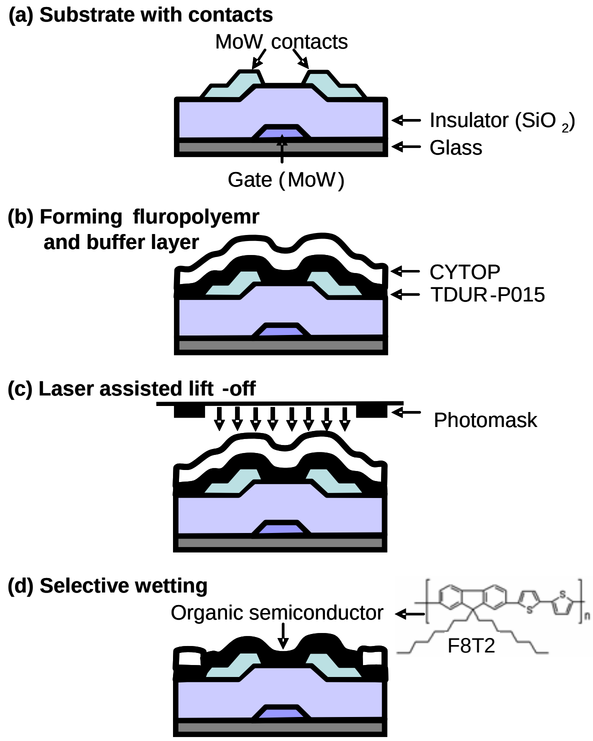

Fig. 1. The fabrication processes of low leakage OTFTs using the LALO technique: (a) source and drain contacts of MoW (100 nm) were prepared on an oxide substrate, (b) the fluropolymer and the photo-absorption buffer layer were then formed by spin casting to control the selective wettability on the substrate, (c) the substrate was treated by the LALO through a photomask, and (d) a polar solution of the soluble semiconducting polymer (1 wt%) was completely wetted by spin casting on only hydrophilic regions.

and the organic solvent dissolving the organic semiconductor.

In this work, we report on the laser assisted lift-off (LALO) technique, ablating selectively the hydrophobic layer by an excimer laser, which was employed for fabricating low leakage polymeric OTFTs using the selective wetting capability. A direct laser ablation of the polymer by optical radiation, in particular, from an excimer Laser [24, 25], has been often used for high resolution patterning in large area devices, several problems such as the particle contamination and the damage of the underlayer remain to be solved. In contrast, the LALO technique we developed concerns only the selective ablation of the hydrophobic layer instead of the semiconducting polymer layer for an active channel. In this case, only the selective wettability of a semiconducting polymer

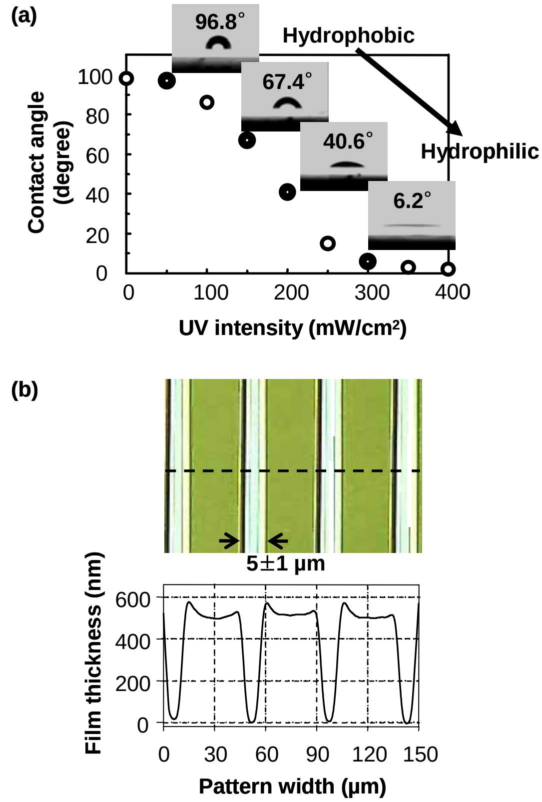

Fig. 2. (a) The contact angle of a xylene drop on the CYTOP film as a function of the UV intensity and (b) the optical micrograph of high resolution hydrophilic regions (≈ 5 µm) patterned by the LALO.

of poly (9-9-dioctylfluorene-co-bithiophene) (F8T2) dissolved in a polar solvent, created by the LALO on the substrate, plays an essential role to define precisely the active channel region. This leads directly to the reduction of the current leakage and the excellent electrical properties of soluble polymeric OTFTs with high resolution features. Moreover, this approach has an advantage for producing an array of OTFTs in large area over existing patterning techniques.

2. Experiments

The key process is to create the selective wettability on the substrate by the LALO technique to apply simple spin casting of the soluble semiconducting polymer in large area. Fig. 1 shows the underlying concept of creating the selective wettability on a fluorine based polymer film of the CYTOP (Asahi Glass, Co.) by the LALO through a quartz photomask. Since the bare CYTOP has no absorption band in the deep UV wavelength (≤248 nm) [26], a photo-absorption buffer layer of the TDURP015 (Tokyo Ohka Kogyo, Co.) with an absorption band at the 248 nm wavelength was prepared below the CYTOP to carry out the ablation of a fluropolymer film by the LALO as shown in Fig. 1(b). In the presence of the UV irradiation at about 300 mW/cm^2, the lift-off of the two layers, the CYTOP and the TDUR-P015, was promoted as shown in Fig. 1(c). This means that the hydrophilic region with the LALO and the hydrophobic region without the LALO were produced as shown in Fig. 1(d). As a consequence, the CYTOP film patterned by the LALO has the selective wettability on the surface.

3. Results

We examine the change in the wettability with varying the UV intensity during the LALO process. The contact angle (θ_{CA}) of a xylene drop on the CYTOP film as a function of the UV intensity is shown in Fig. 2(a). In the low UV intensity range, the CYTOP surface is essentially hydrophobic ($\theta_{CA} \approx 97$ º). As the UV intensity increases, the CYTOP surface becomes hydrophilic ($\theta_{CA} \approx 6$ º). This means that our LALO technique is a simple and powerful tool of controlling the wettability. Moreover, high resolution hydrophilic regions (≈ 5 μm) patterned by the LALO are shown in Fig. 2(b). Clearly, the LALO technique, ablating selectively the hydrophobic layer by an excimer laser, indeed produces a high resolution active channel of the OTFT. This enables us to fabricate bottom-contact polymeric OTFTs based on the F8T2 [27] by the LALO. The solvent used for dissolving the F8T2 was xylene which has a contact angle of 96.8 º on the CYTOP layer before the LALO. Note that the contact angle decreases and reaches 6.2 º as the LALO is proceeded. As a result, a polar solution of the F8T2 (1 wt%) becomes completely wet and exists in only hydrophilic regions of the substrate as shown in Fig. 1(d).
The device performances of our fabricated OTFTs with a channel length of 20 μm and a channel width of 1800 μm were measured using the Keithley 4200 semiconductor characterization system in air at room temperature. The drain current (I_D) characteristics as a function of the drain voltage (V_D) are shown in Fig. 3(a) for several gate voltages (V_G) of 0 V, −10 V, −20 V, −30 V, and −40 V. The results clearly show the linear and saturated regimes that are typical features of a field-effect transistor. Transfer characteristics are shown in Fig. 3(b). The transfer curve in the saturated regime follows a nearly square form of the gate bias except for the high voltage range
where the bias stress effect is involved [3]. From the plot of the square root of the drain current ($I_D^{1/2}$) versus the gate voltage for fixed drain voltage of −40 V, the field-effect mobility (μ) of our OTFT in the saturation regime is estimated as 9.1×10^{-4} cm^2/Vs. Here, we used the following relationship in the saturation regime.

$$I_D = (W/2L)\, \mu C_i (V_G - V_T)^2$$

where W denotes the channel width, L the channel length, C_i the insulator capacitance per unit area, and VT the extrapolated threshold voltage. It was found that the threshold voltage is about −2 V and the on/off ratio is larger than 10^3. The output characteristics showed good saturation behaviors, clean saturation currents but the current flow of charge carrier is low with 10^{-9}A current level. This is the contact resistance of MoW and surface trap charge. But it would be enable to fabricate of high-performance OTFTs through substrate surface chemistry [28, 29].

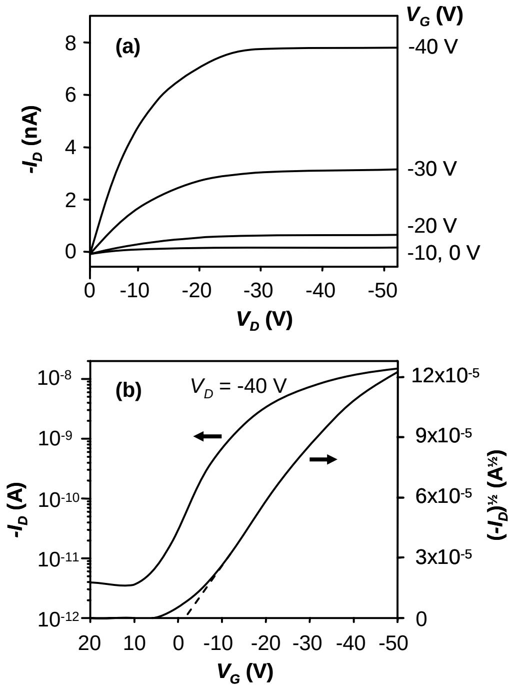

Fig. 3. (a) I_D versus V_D as a function of V_G in the OTFT with the channel length of 20 μm and the channel width of 1800 μm and (b) I_D and $I_D^{1/2}$ versus V_G at $V_D = -40$ V used for calculating the field-effect mobility and the current on/off ratio.

4. Conculsion

We demonstrated a polymeric OTFT by the LALO technique using the concept of the selective wettability. The measured field-effect mobility of the F8T2 soluble semiconducting polymer was about 9.1×10^{-4} cm^2/Vs in the saturation regime, the current on/off ratio of the F8T2 OTFT was of the order of 10^3, and the threshold voltage was about −2 V. The LALO technique presented here would be applicable for most soluble semiconducting polymers that are used for fabricating OTFTs in organic electronics and flexible displays. Finally, the concept of the selective wettability created by the LALO plays an essential role in precisely patterning polymeric active channels with high resolution for the larger area display.

5. Acknowledgment

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