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Fabrication and characterization of sub-500 nm channel organic field effect transistor using UV nanoimprint lithography with cheap Si-mold

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ABSTRACT

P-type poly (3-hexylthiophene) (P3HT) organic field effect transistors (OFETs) with channel length down to 500 nm were fabricated. The gold source and drain electrodes were patterned using UV-based nanoimprint lithography and a lift-off process. To reduce mold costs, an opaque silicon nanoimprint-mold was used instead of expensive quartz molds for UV-nanoimprint. This new technique, called non-transparent UV-nanoimprint lithography, can be applied due to the impact of indirectly propagating light. Finally, the electrical performance of OFETs was tested. However, the OFETs with short channels show inhibited saturation ability and a weak gate control. The reasons for this short channel effect were discussed.

1. Introduction

In recent years, rapid developments of organic electronics in low-cost applications have been observed. Many organic semiconductors are solution processable, which enables the use of the "Ink-Jet-Print" technique to fabricate devices directly on flexible, large-area polymer substrates [1,2].

Organic field effect transistors (OFETs) as basic elements have been widely investigated. Many OFETs are applied in cheap passive tags of a radio-frequency-identification (RFID) system [3–6]. To be compatible to the transponder, the organic circuits should be able to be operated in MHz regime [6]. This is a great challenge for OFETs due to the much lower charge carrier mobility μ in organic semiconductor thin films. Besides the switching frequency, the current density I_D of OFETs should be guaranteed to drive more passive elements in a system. Reducing the channel length is a promising way to fulfill both of the demands above. For a high clock speed, the cut-off frequency f_c of OFET scales approximately with $\mu V_D L^{-2}$, meanwhile, the saturation current density I_D scales with L^{-1} [7]. For a hole mobility of $\mu = 0.1\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$, which is typical for P3HT, a channel shorter than 1 µm is needed to reach a theoretic f_c at about 10 MHz [8].

To achieve sub-micron channels, pattern techniques with excellent resolution as well as low-cost character are required. Nanoimprint lithography (NIL) is intensively used in these fields due to its relative low equipment costs for sub-λ structure patterning, its high available aspect ratios [9] and a very broad material spectrum for resists and substrates [10,11]. The UV-based NIL is used in this work due to its thinner residual layers, smaller resist viscosities, smaller imprint pressures and lower process temperature compared to other imprint techniques like hot-embossing [12].

2. Non-transparent-UV-NIL

For normal UV-NIL, transparent quartz molds are required to enable the light traveling through it and arrive into the UV-curing resist. However, the quartz mold is usually difficult to be patterned and therefore much expensive. To reduce the mold costs, an opaque silicon mold is used in this work as proposed elsewhere [21]. This non-transparent UV-NIL (NT-UV-NIL) is usable in many commercial UV-NIL machines, where the light comes from the source above the mold. The indirect exposure is realized via specular and diffuse reflection of the light between the substrate and the chuck (Fig. 1). However, the silicon mold blocks most of the primary light. To accelerate the UV-curing process, higher doses and a suitable ratio of the mold size to the transparent substrate thickness are required to ensure an acceptable throughput.

3. Manufacture of silicon mold

The OFETs driving current I_D depends on the ratio of channel width W to channel length L [7]. To increase the current,

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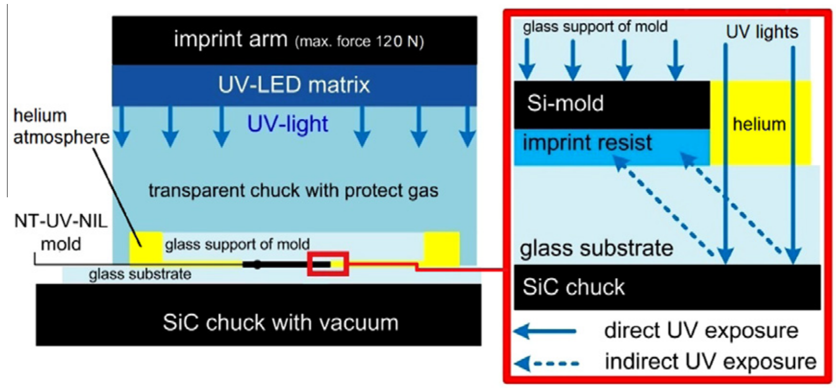

Fig. 1. Representation of the UV-exposure system of the NPS 300 UV-NIL imprinter. The red frame in left corresponds to the zoom-in chart in right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

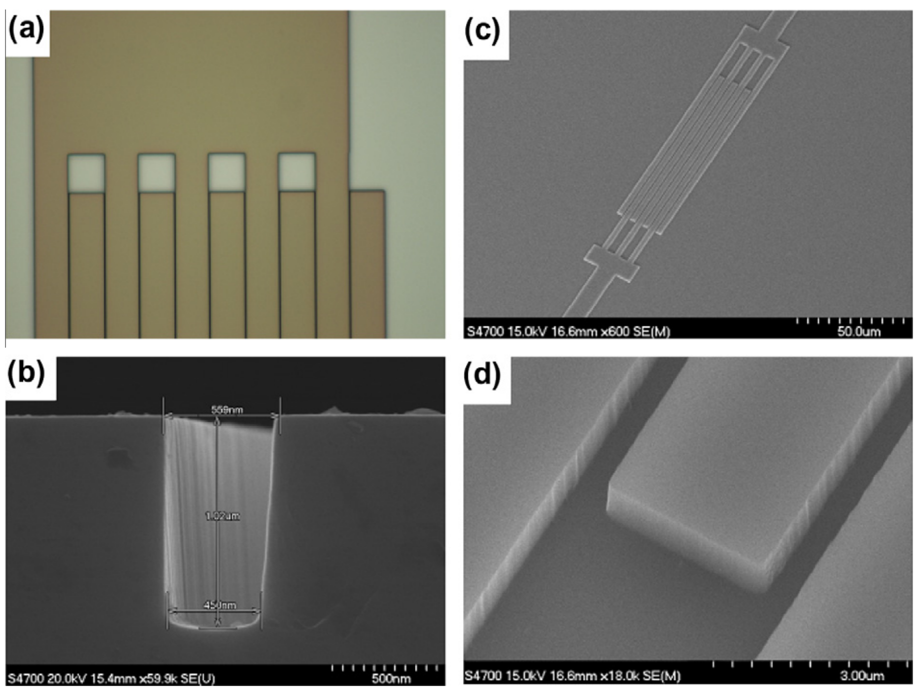

Fig. 2. OFETs-Si-mold. (a) overview of ten micron wide source and drain electrodes with 500 nm channel; (b) cross section of (a); (c) overview of three micron wide source and drain electrodes with 500 nm channel; (d) zoom in view of (c).

comb-electrodes (Fig. 2a) with *W* of 1350 µm and *L* down to minimal 500 nm were designed.

We used i-line lithography (λ = 365 nm) to transfer the layout into a photo resist layer. Subsequently, reactive ion etching (RIE) was used to pattern the Si-mold. For a NIL-mold, the tilt angle of the sidewalls of the features must be kept close to 90° but never exceed that. Otherwise it would complicate or even prevent the demolding after imprint. We used 25 sccm SF_6 and 85 sccm C_4F_8 gas mixtures with a RF-power of 800 W to etch the silicon mold about 1000 nm deep. A deep reactive ion etching tools with ICP source (ASE, Surface Technologies Systems in UK) was used. With these RIE parameters, for a 1 µm deep etching shifts the sidewall about 55 nm. The sidewall angle was calculated to be about 87° and was very suitable for imprint (Fig. 2b).

4. Fabrication of OFETs

To achieve a homogenous and thin residual resist layer, a commercial NIL instrument NPS 300 (Fig. 1) with an accurate optical calibration system (Smart Equipment Technology) was used. The maximal exposure intensity of the UV-light at the wavelength of 365 nm of this machine is about 50 mW/cm^2.

The surface of the Si-mold should be modified with an anti-sticking layer (ASL) in order to reduce the surface energy and ensure a defect free demolding. In this work, 1H,1H,2H,2H-perfluoro-decyltrichlorosilane (FDTS) (CAS-No. 78560-44-8, from ABCR GmbH) was applied.

Most of the commercially available UV-NIL resists, for instance, mr-UV-Cur21SF from micro resist technology GmbH Berlin Germany, dissolve in organic solutions like acetone very difficult due to the UV-polymerization and the meanwhile generated cross-links between polymer chains, which transforms the resist into a highly networked status and providing a sufficient mechanic hardness. However, this performance inhibits the lift-off process after NT-UV-NIL process. In most of other publications, people report about the bi-layer architecture for UV-NIL using an easy dissoluble scarifying underlayer [13]. However, this bi-layer resist structure always results in a thicker residual layer due to the relative soft under layer.