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High-resolution conductive patterns fabricated by inkjet printing and spin coating on wettability-controlled surfaces

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ABSTRACT

In this study, we develop a simple and low-cost surface wettability patterning based on soft lithography processes such as nano-imprint lithography (NIL) and micro-contact printing (μCP) to fabricate high-resolution conductive patterns using two different solution processes: inkjet printing and spin coating. An epoxy-based photoresist layer was imprinted by an elastomeric stamp during the NIL process to produce negative micro-structures in the epoxy-based photoresist layer. To form surface wettability contrast, a hydrophobic fluorocarbon film was transferred onto the top surface of the imprinted epoxy-based photoresist layer using μCP. The epoxy-based photoresist layer was UV-treated before the μCP process in order to increase surface wettability contrast; the hydrophilic imprinted patterns surrounded by hydrophobic surfaces were fabricated in the epoxy-based photoresist layer. After printing Ag ink on the imprinted epoxy-based photoresist layer, high-resolution printed line array and square spiral patterns with line width and gap distance of several micrometers can be fabricated with an aid of high surface wettability contrast. Even though well-defined high-resolution conductive patterns with electrical resistivity lower than 6 μΩ cm can be obtained regardless of the solution processes, inkjet printing seems more efficient from the viewpoint of the amount of ink used in each solution process. The surface wettability patterning suggested in this study is expected to be used in the fabrication of high-resolution conductive patterns in printed electronics.

1. Introduction

A photolithography process has been widely used to fabricate high-resolution patterns in various electronic industries. Even though submicron-sized patterns can be produced, this conventional fabrication process has serious disadvantages: complexity of multiple step process, hazardous waste and expensive vacuum facilities. In this perspective, considerable research has gone into fabricating high-resolution patterns using solution processes to replace photolithography in printed electronics [1–4]. Traditional solution processes used in graphic industries have been proposed to print conductive pattern directly on a substrate using metallic inks such as gold, copper, and silver nanoparticle inks in printed electronics. Among the solution processes, drop-on-demand inkjet printing is the most promising technique on account of its simplicity, minimal waste of materials and flexibility [5–9].

The resolution of inkjet-printed patterns is largely influenced by nozzle size and ink spreading on a substrate because liquid droplets ejected from a nozzle come into contact with the substrate during inkjet printing process. Even though the smaller nozzle size (smaller initial droplets) results in the enhanced resolution, there is a limit to reducing nozzle diameter due to the clogging problem. Surface wettability of a solid substrate is a critical factor in determining the ink spreading. The size of printed features is mainly changed depending on the surface wettability [10–12]. A hydrophobic surface can help to print high-resolution patterns due to smaller ink spreading. However, dewetting of printed liquids occurs on the hydrophobic surface, leading to degradation of pattern quality or no formation of desired patterns. Accordingly, inkjet printing is facing challenges to produce high-resolution conductive patterns.

To overcome these problems, it has been suggested that ink is printed onto a patterned surface with wettability contrast [13–17]. Both hydrophilic and hydrophobic regions are defined on the substrate before printing process. The printed liquids are repelled from the hydrophobic region and thus selectively placed on the hydrophilic region. As a result, self-aligned high-resolution printed patterns can be obtained. There have been attempts to produce high-resolution patterns using inkjet printing and surface wettability contrast. Sirringhaus et al. confined the spreading of ink droplets on a polyimide surface with controlled surface wettability [18]. Wang et al. investigated the dewetting of conducting polymer inks on patterned SiO_2 substrates with a fluorinated self-assembled monolayer [19]. The surface of pre-deposited electrode was modified to be hydrophobic so that the subsequently overprinted electrode was repelled and then self-aligned from the first electrode [20]. Kawahara et al. produced hydrophobic grid patterns with a line width of 75 μm and a pitch of 2 mm by inkjet printing

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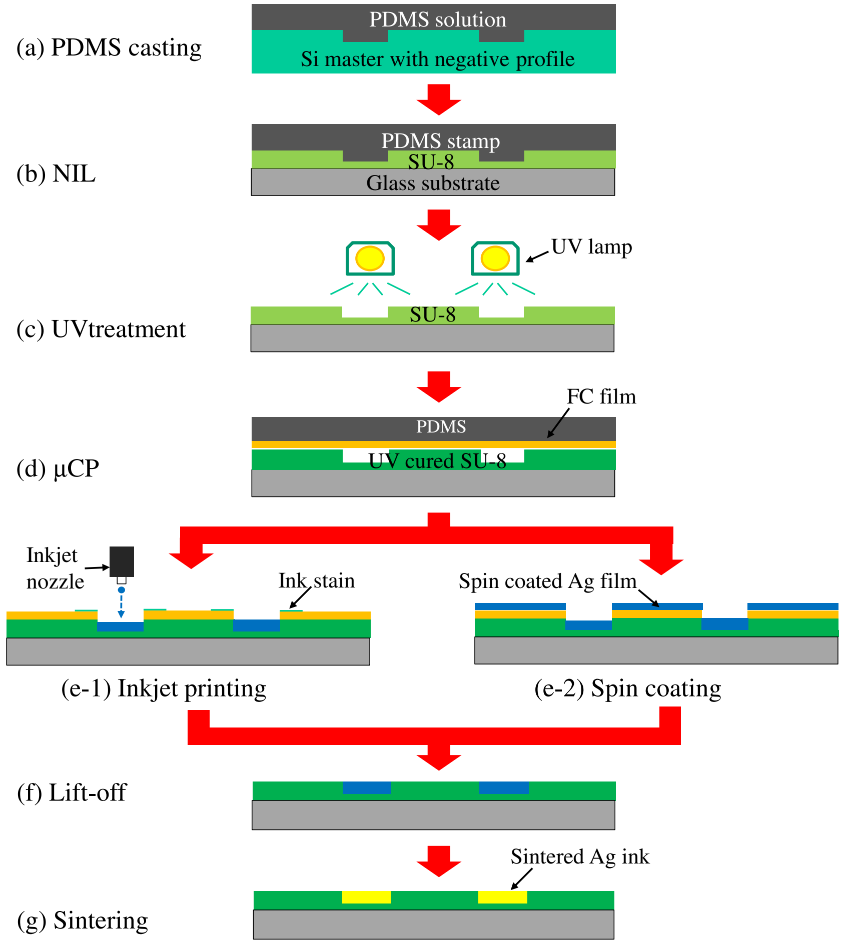

Fig. 1. Fabrication process of a high-resolution conductive pattern using soft lithography and various printing techniques.

hydrophobic polystyrene lines for the fabrication of organic electrochromic display pixel [21]. However, most previous works have focused on the formation of relatively simple and small-sized source and drain electrodes with narrow channel length for the inkjet-printed thin film transistors. Complicated and expensive processes such as photolithography, electron-beam lithography and plasma treatment were also involved to form surface wettability contrast. In addition, for the fabrication of complicated-shaped, high-resolution patterns, the inkjet-printed droplets need to be accurately positioned on desired locations with a minimized position error, which could not be easily implemented for practical use.

Thus, we have developed a simple, economical, and effective way of surface wettability patterning to produce complicated-shaped, high-resolution patterns (e.g., line array and square spiral patterns) without an accurate positioning of printed ink, for the implementation of electronic components such as interdigitated electrodes, inductor coils and thin film transistors. Such patterned surface with wettability contrast was simply achieved with a help of soft lithography processes in which surfaces are micro-structured and chemically modified using nano-imprint lithography (NIL) [22,23] and micro-contact printing (μCP) [24], respectively. To evaluate the feasibility of surface wettability patterning for the fabrication of high-resolution conductive pattern, not only inkjet printing but also spin coating were utilized to deposit conductive ink on the patterned surface.

During the NIL process, a photosensitive, epoxy-based SU-8 layer was pressed by a micro-structured elastomeric stamp to fabricate negative micro-structures: line array and square spiral patterns with line width and gap distance of several micrometers. The imprinted SU-8 layer was then UV-treated to make the surface hydrophilic. To create surface wettability contrast, a hydrophobic fluorocarbon (FC) film was transferred onto the top surface of the SU-8 layer through μCP. As a result, the imprinted SU-8 layer where the imprinted part is hydrophilic and the top surface of the SU-8 layer is hydrophobic was fabricated. Ag nanoparticle ink was inkjet-printed and spin-coated on the imprinted SU-8 layer with surface wettability contrast. After the spreading of printed ink inside the hydrophilic region, the FC film was peeled off by a lift-off process using wet chemistry to remove ink stains which were not moved to the hydrophilic region and still remained on the FC film. The effect of printing variables such as the number of inkjet-printed droplets and spin coating speed on the formation of high-resolution printed patterns was investigated. For each printing process, the resulting morphology and electrical resistivity of printed patterns were finally examined.

2. Experimental details

2.1. Soft lithography process

In this study, patterned surface with wettability contrast was fabricated using soft lithography techniques such as NIL and μCP. A Si master was patterned using photolithography process. A poly(dimethylsiloxane) (PDMS) replica of the patterned Si master was made via molding process for use as a stamp during the NIL process because PDMS stamps do not need any surface treatment for easy stamp detachment due to its inherent low surface energy. The 1:10 (vol/vol) mixture of the PDMS curing agent (Sylgard 184, Dow Corning) and base (Sylgard 184, Dow Corning) was de-gassed in a vacuum chamber to remove internal cavities because air bubbles are usually generated and then trapped in the