Two-step photolithography to fabricate multilevel microchannels

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In this paper, we study the variation of the thickness of patterned microchannel features in photoresist (PR) by two-step photolithography. The final PR thickness is determined by the thickness and width of the predefined PR pattern in the first-step lithography and the thickness of the spin-coated PR film in the second-step lithography. Thickness variation is demonstrated to be an important consideration within the critical pattern width that the capillary pressure is still dominant for forming the PR film thickness. With this mechanism of two-step photolithography, we demonstrate its ability to form multilevel channel features and its use to fabricate a cross-flow filter with two different pore sizes as a microfluidic application. © 2010 American Institute of Physics. [doi:10.1063/1.3517230]

I. INTRODUCTION

Photolithography is a process routinely used in fabrication of microdevices such as microfluidic devices, microelectronic circuits, and microelectromechanical systems by selectively removing parts of a thin photoresist (PR) film. The early microfluidic devices were fabricated in silicon, quartz, or glass through laborious processes such as chemical etching, reactive ion etching, and thermal bonding. The recent introduction of poly(dimethylsiloxane) (PDMS) for replica molding has revolutionized microfluidics by enabling simplified, faster prototyping with lower production cost and transferring multilevel, complex microfluidic patterns directly into the elastomer through replica molding.^{1,2} Particularly, slant grooves or obstacles fabricated on a linear microchannel have been used for efficient mixing of solutions by using chaotic flows^{3,4} and self-sorting of microbeads and mammalian cells by hydrophoresis.^{5,6} A cross-flow filtration has been also implemented in microchannels with multiple heights, thereby achieving blood plasma separation and white blood cell enrichment.^{7,8}

There are several ways to fabricate master molds for multilevel microchannels, for instance, gray-scale photolithography,⁹ selective overexposure of a PR film to ultraviolet (UV) light,¹⁰ and microtunable elastomeric molds.¹¹ Chen and co-workers⁹ described that the use of microfluidic photomasks that microchannels filled with a light-absorbing dye can produce microfluidic features of multiple heights by altering their opacity according to the dye concentration. Nock and Blaikie¹² developed a similar gray-scale lithography technique with subwavelength patterned photomasks that were fabricated by electron beam lithography and reactive ion etching. Toepke and Kenis¹⁰ showed that selective overexposure of a PR film to UV light can pattern it with features of different heights by using a photomask with masking lines of different widths. Hoffman *et al.*¹¹ developed tunable elastomeric molds consisting of a thin PDMS membrane with sealed cavities that can be pressurized and form microfluidic features of different heights. Although these meth-

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FIG. 1. Schematic drawing of two-step lithography process to fabricate multilevel microchannels.

ods have been successfully demonstrated in a single lithography step, they have some disadvantages such as requirement of costly photomasks or difficulty about wafer-level batch production.

Multistep lithography is one of the simplest ways to fabricate microfluidic features of different heights. Although there is an alignment issue for the fabrication process, it is a routine work that a wafer will go through the lithographic cycle up to several tens of times in fabrication of integrated microelectronic circuits. Many researchers have been studied for formation of a thin liquid film over uneven topography in the aspect of rheology and dynamics of the film formation on microelectronic circuits.^{13–16} Herein we provide the detailed understanding of two-step photolithography for microfluidic applications and its use to fabricate multilevel microchannels and a cross-flow filter with two different pore sizes as a microfluidic application.

II. MATERIALS AND METHOD

A. Two-step lithography

The PR mold for multilevel microchannels was defined on a silicon wafer using two-step photolithography (Fig. 1). The first spin-coating of an UV-curable PR (SU8-2005 or SU8-2010, MicroChem Corp., MA) defined linear features that have different widths ranging from 20 to 600 μm with 200 μm spacing. In the second-step lithography, the PR (SU8-2010 or SU8-2025, MicroChem Corp.) was spin-coated on the previously patterned PR mold and then exposed to UV light through the second photomask that was aligned with respect to the previously developed SU8 patterns. We measured the height of the fabricated microfluidic features using a surface profiler

FIG. 2. Schematic of the PR film profile over a rectangular PR pattern when the centrifugal and capillary forces are balanced.

(Alpha-Step 500, KLA-Tencor Corp., CA). For replica molding, the PDMS mixture of PDMS and its curing agent (the ratio of 10:1) was poured on the PR mold and cured for 3 h in a convection oven at 65 °C for complete cross-linking. To seal the microchannels, we bonded a PDMS layer and a glass slide to each other after brief exposure of oxygen plasma for 30 s.

B. Sample preparation

Fluorescent polystyrene beads with a diameter of 2 μm (Polysciences, Warrington, PA) and nondyed polystyrene beads with a diameter of 6 μm (Polysciences) and 15 μm (Molecular Probes, Eugene, OR) were used to demonstrate the usefulness of the fabricated multilevel microchannel by filtering the beads. The beads were prepared in 2% Pluronic F68 solution (Sigma-Aldrich, St. Louis, MO) with an average concentration of 1.3×10^3 , 3.4×10^2 , and 50 particles/ μl , respectively.

C. Experimental setup

The microchannels were imaged with an inverted microscope (TS100, Nikon Co., Japan) equipped with a charge-coupled device (DS-2 MBWc, Nikon Co.). A syringe pump (Pump 11 Pico Plus, Harvard Apparatus, MA) was used to produce a 1 $\mu\text{l}/\text{min}$ flow through the microchannels.

III. RESULTS AND DISCUSSION

Figure 1 shows a schematic of the two-step lithography process used to pattern the PR with microfluidic features of different heights. During the spin coating of PR over a flat substrate (e.g., the first-step lithography), the centrifugal force that drives PR flow is balanced with the viscous force that resists PR flow, thereby forming a uniform film. During the spin-coating over an uneven substrate (e.g., the second-step lithography), the capillary force begins to act on a PR film and will tend to drive the fluid into the substrate, thus reducing the curvature of the film surface over predefined PR patterns and lowering the film thickness. The capillary pressure P_{cap} generated by the capillary force is proportional to the interfacial tension γ and inversely proportional to the radius of curvature of the air-film interface R (Fig. 2). When $h_f \gg h - h_s$, $w \gg h_f$, and assuming that the film surface over the predefined PR pattern is in semispherical shape, the capillary pressure is given by¹³

$$P_{\text{cap}} = \frac{\gamma}{R} = \frac{8\gamma h_f}{w^2}, \quad (1)$$

where h_f and w are the height and width of the defined PR pattern in the first-step lithography, respectively, h_s is the thickness of the spin-coated PR film on the wafer surface in the second-step lithography, and h is the thickness of the PR film deposited right on the predefined PR pattern. The capillary pressure gradient ∇P_{cap} acting over the PR pattern is estimated by dividing P_{cap} by $w/2$,

FIG. 3. Thickness variation of patterned microchannel features fabricated by two-step photolithography. (a) Optical top-view image of multilevel microchannels molded in PDMS. The first and second coats refer to the first and second PR coating layers, respectively. The layer thicknesses were $h_f = 30.2 \mu\text{m}$ and $h_s = 20.1 \mu\text{m}$. (b) Optical cross-sectional image of the microchannels. (c) Measurements of h vs pattern width. The second layer thickness h_s for all cases was fixed at $20.1 \mu\text{m}$ on average, while the first layer thickness varied from 10.6 to $30.2 \mu\text{m}$. (d) Measurements of h vs pattern width. The second layer thickness h_s for all cases was fixed at $10.8 \mu\text{m}$ on average, while the first layer thickness varied from 4.2 to $10.4 \mu\text{m}$.

$$\nabla P_{\text{cap}} = \frac{P_{\text{cap}}}{w/2} = \frac{16\gamma h_f}{w^3}. \quad (2)$$

The capillary pressure acting on a PR film over a predefined PR pattern increases in a cubic-power manner as the pattern width decreases, thereby lowering the film thickness. Therefore, the two-step lithography process allows to control the height of the final PR patterns by making small adjustments in the width of PR patterns defined for the first-step lithography.

We demonstrated the ability to fabricate multilevel microfluidic features in a single mold by making small adjustments in the width of PR pattern defined in the first-step lithography using two-step lithography process. A $30.2\text{-}\mu\text{m}$ -thick layer of SU8 was deposited and patterned on a silicon wafer to create a master with features of varying widths that eventually create varying heights. The SU8 patterns were formed with a series of linear lines ranging from 20 to $600 \mu\text{m}$ in widths separated by $200 \mu\text{m}$ spacing. A $20.1\text{-}\mu\text{m}$ -thick layer of SU8 was deposited again on the master and then exposed to UV light through the second photomask that was aligned with respect to the previously developed SU8 patterns. Figures 3(a) and 3(b) show PDMS replicas made from the photoresist master in top view and cross-sectional view, respectively. The change in replica feature height relative to PR pattern width results from the intensity of capillary pressure acting on the two sides of uneven topography as mentioned before. The feature heights of PR masters and corresponding coating thicknesses we measured are provided in Figs. 3(c) and 3(d). The capillary pressure acting on a PR film over a predefined PR pattern increases in a cubic-power manner as the pattern width decreases, and linearly increases as the thickness of the PR pattern increases. Since the capillary pressure works for lowering the film thickness, the final feature height of PR masters is determined by the pattern width and the coating thickness in the first-step lithography. This dependence of the capillary pressure on topography allows to control the height of the final PR patterns by making small adjustments in the width of PR pattern defined in the first-step lithography.

The capillary force acting on a PR film over a predefined PR pattern decays as the pattern width increases and is finally overwhelmed by the centrifugal force. The critical pattern width w_c

FIG. 4. Microfluidic cross-flow filter fabricated by two-step photolithography. (a) Schematic of a cross-flow microfluidic filter with three different channel heights of 4.5, 9.8, and 13.2 μm . (b) 2 μm beads entering 4.5- μm -high side-channels from the main channel, sorted from 6 and 15 μm beads. A fluorescence image of 2 μm beads was superimposed on a bright field image. (c) 2 and 6 μm beads entering 9.8- μm -high side-channels from the main channel, sorted from 15 μm beads. (d) 2 μm beads after passing through the 4.5- μm -high side-channels. (e) 2 and 6 μm beads after passing through 9.8- μm -high side-channels. All scale bars are 100 μm .

that the capillary pressure is still dominant for forming the PR film thickness can be calculated by balancing with the centrifugal pressure. The centrifugal pressure gradient ∇P_{cent} generated from the centrifugal force is given by

$$\nabla P_{\text{cent}} = \rho \omega^2 r, \quad (3)$$

where ρ is the density of the PR, ω is the angular velocity, and r is the radial position. The critical pattern width that the centrifugal pressure gradient is equal to the capillary pressure gradient is given by¹³

$$w_c = \left(\frac{16 \gamma h_f}{\rho \omega^2 r} \right)^{1/3}. \quad (4)$$

Assuming γ , h_f , ρ , ω , and r of 40.4 dyn/cm, 20 μm , 1 g/cm³, 210 rad/s (2000 rpm), and 3 cm, respectively, we obtain a value of approximately 210 μm for w_c . Thus, the height of the PR masters is rapidly varied in the width range from 20 to 210 μm within the critical pattern width.

In order to demonstrate the utility of the method for fabrication of multilevel microchannels, we fabricated a cross-flow filter with three different heights (Fig. 4). The SU8 patterns of the side-channels for sorting 2 μm beads were formed in a thickness of 4.5 μm with a series of

linear lines of 20 μm in width. A 9.8- μm -thick layer of SU8 was deposited again and formed the side-channels of 20 μm in width for sorting 6 μm beads. The combination of the depositions finally forms the main channel in a thickness of ≈ 13.2 μm . A bead mixture containing 2, 6, and 15 μm beads was injected into the filter at a flow rate of 1 $\mu\text{l}/\text{min}$. With this filter, we can successfully perform the cross-flow filtration by sorting 2, 6, and 15 μm beads, as shown in Figs. 4(b) and 4(c). The 2 μm beads smaller than the 4.5- μm -high side-channels passed through the side-channels, while 4 and 15 μm beads were all retained in the main channel [Fig. 4(d)]. The 6 μm beads smaller than the 9.8- μm -high side-channels, although still mixed with 2 μm beads, passed through the side-channels, while 15 μm beads were all retained in the main channel [Fig. 4(e)]. The separation selectivity of the 6 μm beads is affected by the majority of 2 μm beads that are still retained in the main channel. The separation selectivity of the 6 μm beads could be further enhanced by employing a perfusion flow to push all the 2 μm beads into the 4.5- μm -high side-channels.⁸ Although we demonstrated a simple cross-flow filter with two different pore sizes, its side-channel thickness can be further varied by the aforementioned mechanism of two-step photolithography, thereby improving the separation capability of the cross-flow filter. In this case, the side-channel thickness can be rapidly varied in the width range from 20 to 130 μm within the critical pattern width of 130 μm . In addition, this fabrication method can be exploited in other microfluidic applications that require multilevel microchannels such as cell trapping,¹⁷ micromixer,^{3,4} and cell separation.⁵⁻⁸

IV. CONCLUSION

This paper provides the detailed mechanism of two-step photolithography for microfluidic applications and shows how to use the mechanism for fabrication of multilevel microchannels. The final PR thickness in two-step lithography is determined by the thickness and width of the defined PR pattern in the first-step lithography and the thickness of the spin-coated PR film in the second-step lithography. The critical pattern width w_c provides a simple means to assess the thickness control range. This simple mechanism allows fabrication of multilevel channels applicable to microfluidic applications such as cell trapping, micromixer, and cell separation.

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