SIMPLY FABRICATED PRECISE MICROFLUIDIC MIXER WITH RESIST FLOW PATHS SEALED BY AN ACRYLIC LID

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Abstract: A microfluidic mixer was simply and easily fabricated using 380-μm thick patterns of negative resist SU-8 as flow paths and sealing the paths by an acrylic lid plate. The SU-8 was mainly composed of epoxy resin, and it was hardened by the baking after the development. Because the too narrow flow paths were not practical, the target width of the flow-path was set at 30-100 μm. The aspect ratio limit for 1:1 line-and-space patterns increased when the pattern width became large and the lower numerical-aperture or higher F-number projection lens was adopted. The maximum aspect ratio for line-and-space patterns with a width of 26-53 μm was 6.5-8, corresponding to the pattern width and the numerical aperture. After snail-shape flow-path groove patterns were successfully fabricated, the resist block was covered by an acrylic lid plate and sealed using screws. After microtubes were attached to the entrance and exit holes, red and blue colored waters were injected into the two entrance tubes. As a result, two waters were mixed while passing through the snail-shape paths, and dark purple water was ejected from the exit. It was successfully verified that the easily and simply fabricated microfluidic mixer actually worked well.

1 INTRODUCTION

Among a lot of biodevices, microfluidic reactor, mixer and other modules used for sensing and analyzing are the most important and useful devices. For this reason, various fabrication methods of microfluidic devices are proposed. For example, fine grooves are mechanically cut on the surfaces of slide-glasses or quartz plates. Glassy materials are chemically stable and not reactive. Accordingly, they are suitable for the materials to fabricate chemical-use devices. However, because the glassy materials are fragile, it is difficult to make dense and deep grooves. Moreover, it takes a long time to machine the materials.

In most cases, microfluidic devices mentioned above are thrown away after once they are used. Accordingly, they should be easily fabricated with a low cost. For this reason, various fabrication methods using the technologies for applying to Micro Electro Mechanical Systems (MEMS) are developed. Most of MEMS microfluidic devices directly use the resists such as poly-dimethyl-siloxane (PDMS) (Lien, 2008) (Lei, 2008) (Casquillas, 2008), SU-8 (Tsai, 2006) (Yang, 2007) and poly-methyl-methacrylate (PMMA) (Nugen, 2009) as flow paths. Some of the proposed devices used the combination of the plural resists (Kontakis, 2009) (Lo, 2008) (Ho, 2008).

On the other hand, similar flow paths are also formed by etching silicon or glass substrates using the resist patterns printed by lithography as the etching masks (Avram, 2008) (Eun, 2008).

However, because most of the proposed methods require complicated long processes, high fabrication costs are anticipated. For this reason, a simple and easy but highly accurate and useful fabrication method of microfluidic devices is investigated here.

Dense and deep microfluidic patterns are printed using thick SU-8 resist films mainly composed of epoxy resin. It is not difficult to print high-aspect patterns if the appropriate projection exposure conditions are selected. Therefore, good flow paths are fabricated by a simple lithography process. Once the resist is sufficiently baked, it is hardened and works like normal plastics. Accordingly, the baked resist patterns are effectively used as flow paths of throw-away microfluidic devices.

In this paper, investigation on the thick resist patterning process is shown, and the aspect ratio

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limit for 1:1 line-and-space patterns is clarified correlating with the numerical aperture (NA) of the projection lens. In addition, a precise microfluidic mixer is actually fabricated. Two colored waters are successfully mixed using the fabricated device.

2 PATTERNING CONDITIONS

In this research, negative SU-8 100 (MicroChem Corp.) was used as a resist. Referring to the material composition description provided by the supplier, SU-8 is composed of Epoxy Resin of 35-75%, Gamma Butyrolactone of 20-60%, Mixed Tryarylsulfonium/Hexafluoroantimonate Salt of 3.5%, and Propylene Carbonate of 1-5%. Patterning process conditions used in the experiments are shown in Table 1. The SU-8 was coated on copper-clad plastic substrates and silicon wafers in thicknesses between 65-420 nm. Thick films were obtained by double or triple repetitions of resist coating and baking.

The copper-clad plastic substrates were used because various electrode patterns are easily formed, if necessary. Moreover, metals are directly electroplated on them for fabricating the injection molds. On the other hand, silicon wafers were used to observe the cross sections of patterns by snapping them along the crystal direction.

Table 1: Patterning conditions of SU-8.

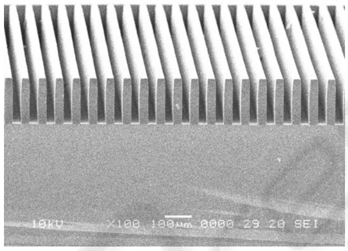
Process	Condition
Pre-bake	Step1: 20 min at 65°C in an oven Step2: 50 min at 95°C in an oven
Exposure	1/19 low-NA projection exposure, 4-10 min
Development	Dip in SU-8 developer, 5-40 min Rinse in 2-propanol, 1-2 min

Resist patterns were printed using a handmade simple exposure system (Hirota, 2003). The specifications are shown in Table 2. The system uses a camera lens as a projection lens, and the numerical aperture or the F-number is controllable.

It was clarified that the maximum aspect ratio depended on the F-number, and the larger the F-number was, the higher aspect ratio was obtained. When the patterns were printed under various F-number conditions, the highest aspect patterns shown in Fig. 1 were printed (Horiuchi, 2008).

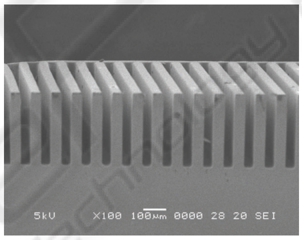
Table 2: Specifications of the exposure system.

Item	Specification
Light source	Ultra-violet lamp, LS-140UV (Sumita Optical Glass) Wavelength: 290-440 nm
Projection lens	Camera lens (Yashika), F=2.8-16
Reduction ratio	1/19
Field size	2.2 mm square
Wafer stage	X and Y: ±6.5 mm, Z: ±5mm



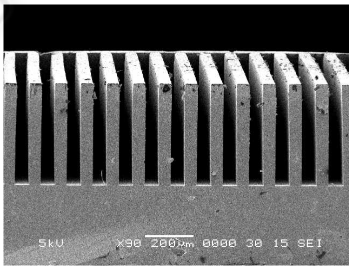
F-number: 5.6
Width: 31.6μm
Thickness: 170μm
Aspect ratio: 5.4

(a)



F-number: 8
Width: 42.1μm
Thickness: 300 μm
Aspect ratio: 7.1
A little resist remains at the bottom.

(b)



F: 11.2
Width: 52.6μm
Thickness: 420 μm
Aspect ratio: 8.0

(c)

Figure 1: High aspect patterns obtained under various F-number conditions.

The critical factor deciding the aspect ratio was not the pattern collapse but the depth-of-focus (DOF) for securing sufficient image contrast throughout the resist thickness. The pattern collapse was prevented by giving sufficient exposure dose, as shown in Fig. 2. The highest aspect ratio for 1:1 line-and-space patterns became as shown in Fig. 3, and they were 6.5-8.0 for F-numbers of 5.6-11.2, respectively.

Because the high aspect ratio was obtained for the quite large patterns compared with the critical-size patterns, the redundancy to print the fluid-path patterns was considered.

The pattern width w to obtain the highest aspect ratio experimentally changed as shown in Table 3, depending on the resolution R and the DOF of the projection optics. Here, DOF_c is the DOF for the patterns with the critical width R, and they were calculated by equations (1) and (2). The central wavelength λ was assumed to be 365 nm. NA is the numerical aperture of the projection lens. The constants k_1 and k_2 were assumed to be 0.7 and 1.0.

$$R = k_1 \frac{\lambda}{NA} = 0.7 \frac{\lambda}{NA} = 0.7 \times 2\lambda F = 1.4\lambda F. \qquad (1)$$

$$DOF_c = k_2 \frac{\lambda}{NA^2} = \frac{\lambda}{NA^2} = 4\lambda F^2. \qquad (2)$$

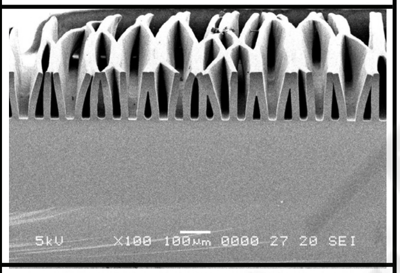
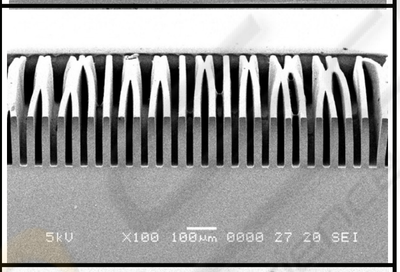
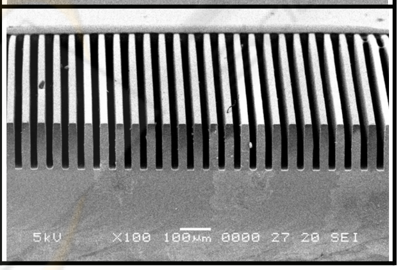
Exposure time	26-µm line-and-space patterns (170-µm thick resist)
5 min	
6 min	
7 min	

Figure 2: Pattern collapse prevention by giving a large exposure dose. F-number is 5.6.

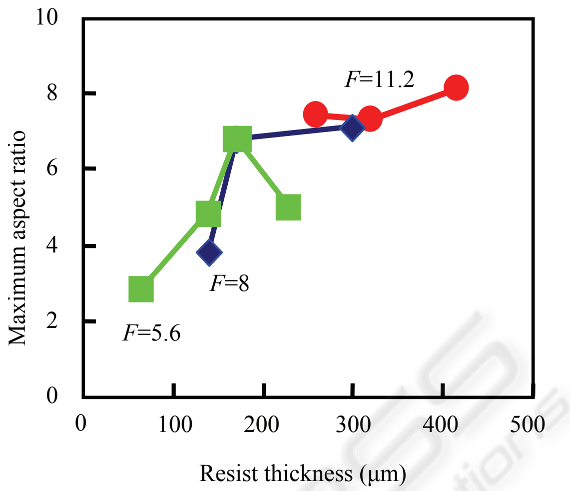


Figure 3: Maximum aspect ratio dependence on resist thickness and F-number.

From the calculated resolution limit R and the pattern width w for obtaining the highest aspect ratio, w/R was also calculated, as shown in Table 3. The ratio w/R was almost constant without depending on the F-number.

Table 3: Resolution versus pattern width and thickness for obtaining the highest aspect ratio.

F-number	5.6	8	11.2
NA	0.089	0.063	0.045
R (µm) (Calculated)	2.86	4.09	5.72
DOF_c (µm) (Calculated)	45.8	93.4	183
w (µm) (Experimental)	26.3	42.1	52.6
Resist thickness (µm)	170	300	420
Aspect ratio	6.5	7.1	8.0
Ratio w/R	9.2	10.3	9.2
DOF_w (µm) (Calculated)	421	962	1680

Although the DOF_c for the critical size pattern was calculated above, DOF_w for the patterns with a width of above w was far larger. Because the first-order diffraction light angle from the periodical patterns with a large width of w is R/w times smaller than that from the critical-size periodical patterns, the DOF_w for the patterns with a width of w is multiplied by w/R. Therefore, DOF_w is calculated as shown in Table 3. It was known that the DOF_w was sufficiently deep for printing such high-aspect patterns in thick resist films. This performance is caused by the utilization of the low-NA or large F-number projection optics.

It was considered that too narrow flow paths were irrelevant to fabricate practical microfluidic devices. From the experience, minimum flow-path width for fluids such as water and alcohol was estimated to be 30-100 μm. For this reason, considering the resolution redundancy, F-number of 5.6 was selected to fabricate an actual microfluidic device. Under this condition, patterns with 26.3-36.8 μm were printed well with a considerable exposure time margin, as shown in Fig. 4. Patterning characteristics for wider line-and-space patterns with a width of 105 μm were also investigated. Figure 5 shows the results. Nice patterns were obtained for long exposure time of up to twice longer than the time for obtaining the nominal width patterns, and groove patterns much narrower than the nominal width were obtained for the long exposure time.

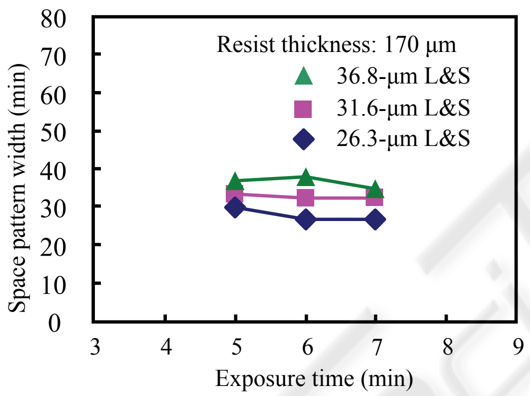


Figure 4: Stable space-pattern-width controllability of narrow high-aspect patterns.

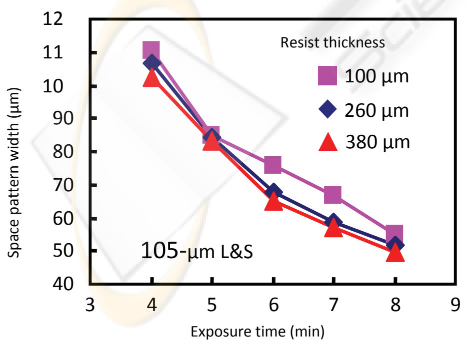


Figure 5: Change of large space pattern width depending on the exposure time and resist thickness.

3 REPLICATION OF MICRO-MIXER RESIST PATTERNS

Considering the results obtained in the previous chapter, actual microfluidic mixer patterns with a snail-shape were printed using 380-μm-thick SU-8. Printed patterns were shown in Fig. 6, and the groove widths at the Y-shape entrance and the confluent throat were measured as shown in Fig. 7.

Because the groove-width change became smallest and the clearest pattern profiles were obtained, 9 min was the optimum exposure time. Bird's eye view of the resist patterns at the entrance and the exit are shown in Fig. 8. Printed patterns had vertical and sharp sidewalls. The groove width and the aspect ratio at the Y-shape entrance were 73μm and 5.2, respectively, when the exposure time was 9 min. The vertical confluent groove had a width of 135 μm and aspect ratio of 2.8.

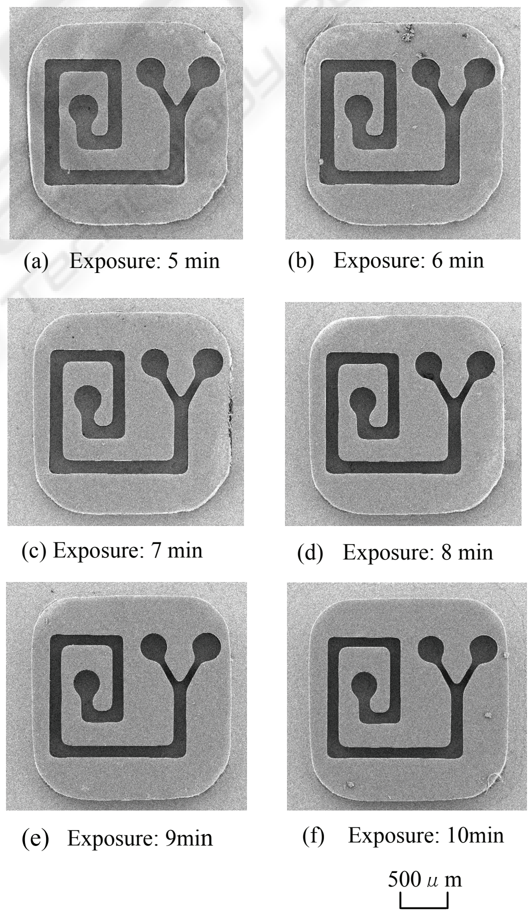


Figure 6: Micro-mixer patterns fabricated under various exposure-dose conditions.

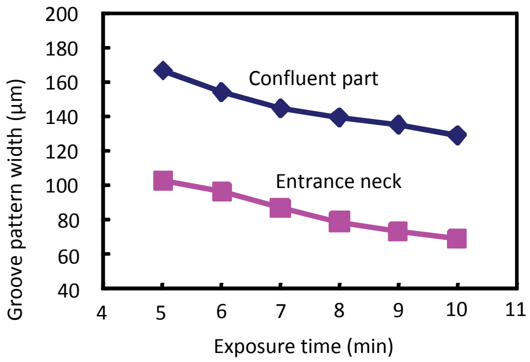
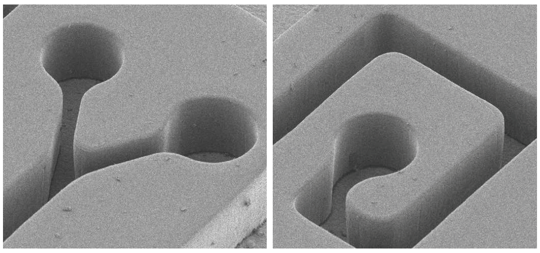


Figure 7: Width variances of micro-reactor patterns.



(a) Entrance holes (b)Exit hole

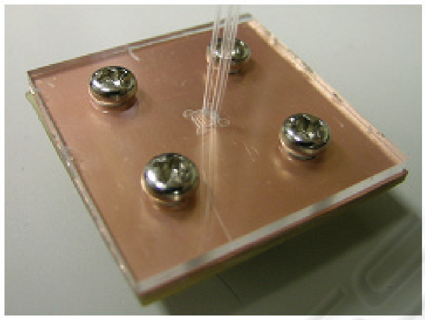
100 µm

Figure 8: Entrance and exit patterns of a micro-reactor. The minimum groove width was 73 µm.

4 ASSEMBLY OF A MICRO-FLUIDIC MIXER

Using the snail-shape grooves shown in Fig. 6 and 8 as fluid paths, a micro-reactor was fabricated. The resist grooves were tightly covered by an acrylic lid plate to make the paths sealed. The lid plate had a concave with a size a little larger than the outer edge of the resist block, two entrance holes, and one exit hole. The plate was machined using a simple automatic 3-dimensional milling machine (Roland, PNC-300 CAMM-3). Micro-tubes with an outer and inner diameters of 500 and 300 µm were inserted into the three holes and adhered, as shown in Fig. 9. The tubes were made of poly-fluoro-acrylate (PFA).

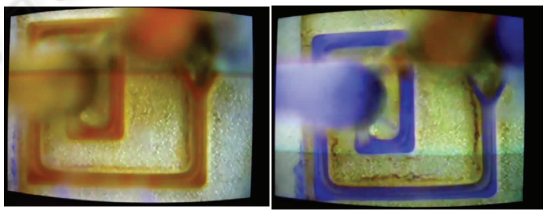
Flowing and mixing capability was checked by injecting colored waters from the two entrances using syringes. The injected waters were colored red and blue using watercolors. The colored waters were successfully mixed while they passed through the snail-shape paths, as shown in Fig. 10, and the ejected water had an even dark purple color, that means the red and blue waters were mixed well. The waters did not leaked, and the flow paths made of resist SU-8 were not damaged at all, and it was verified that the simply and easily fabricated microfluidic mixer was useful.



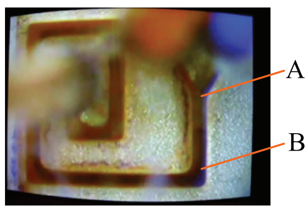
(a) Total outlook. 10mm

(b) Main part. 1mm

Figure 9: Outlook of the fabricated microfluidic mixer.



(a) Red water injection. (b) Blue water injection.



100µm

(c) Injection of Red and blue waters.

Figure 10: Successful mixing of two colored waters.

5 CONSIDERATION

First, advantages and disadvantages of the proposed microfluidic mixer were considered. Because the SU-8 patterns are easily printed and they are used as the flow paths as they are, the fabrication process was very simple and easy. Although reticles were needed for projection lithography, very low-cost film-reticles were applicable without any problems. In addition, microfluidic mixers are generally used by themselves, and accurate reticle alignment is not needed. For this reason, projection exposure systems may be very simple and plain. Even handmade exposure systems or photo printers used for printing off photographs from the negative films are useful.

The proposed microfluidic mixers are applicable to some micro total analysis systems (μ-TAS). The tolerances for various body fluids, juices and chemical reagents have to be investigated hereafter. The tolerances may not be universal comparing with those of quartz and glass. However, probably, the proposed microfluidic mixer will also have good tolerances for most of the fluids including blood.

Next, fluidic parameters were studied. Although the colored waters were manually injected using syringes at the room temperature this time, and the flow rate was not severely controlled, Reynold's number $Re=Vd/(\mu/\rho)$ was roughly estimated. It took less than or equal to 0.1 s to flow the waters through the device, and the flow path length between the entrance and the exit was approximately 5.6 mm. Therefore, the average flow rate V is roughly calculated to be V=60 mm/s. On the other hand, the path width d, fluid viscosity μ and the density ρ are 135 μm, ≈1 mPa·s and ≈1 g/cm^3, respectively. Therefore, Re is calculated to be ≈8. Accordingly, the flow is supposed to be a laminar flow. In fact, the red and blue waters divide the path into halves between points A and B in Fig. 10(c).

It is not always necessary to make the groove so deep. However, device sizes can be reduced by using the deep grooves to secure the same cross sectional area sizes and allocate the groove closely each other.

6 CONCLUSIONS

A new method to fabricate microfluidic reactors or mixers very simply and easily was demonstrated. Negative SU-8 resist being composed of epoxy resin with a thickness of 380 μm was used as flow paths. Because even the 1:1 L&S patterns were printed with very high aspect ratios of more than 5, deep flow grooves were easily fabricated. A snail-shape micro-reactor with a minimum flow-path width of 73 μm was actually fabricated. The resist flow paths were sealed covering the resist block by an acrylic lid plate with a concave a little larger than the resist block and combining the substrate and the lid plate by screws. Micro tubes were attached to the entrance and exit holes, and red and blue colored waters were injected through the micro-tubes using syringes. As a result, the colored waters were successfully mixed in a dark purple color, and ejected from the exit tube without any leaks. The new method and structure for the microfluidic devices are practical and effective.

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