New Maskless Lithography System for Fabricating Biodevices using Light-Emitting Diodes and Squared Optical Fibers

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Abstract: A new low-cost lithography system convenient for fabricating biodevices was developed. Using the new system, various patterns of cell arrays, chamber arrays, flow paths of micro-fluidic devices, and others were easily printed without preparing any reticles or masks. In the system, light-emitting diodes (LEDs) were used as exposure sources and squared optical fibers arrayed in a 10×10 matrix were used as the combination of a secondary light source and a reticle. Light rays emitted from each LED were individually led to each fiber, and bright or dark of each LED was assigned by a personal computer. As a result, it became possible to print arbitrary patterns without preparing any reticles or masks. In addition to the ordinary patterning using various lightening maps of LEDs and their stitching, scan exposure was also tried. When bright images of optical fiber ends were scanned on a resist film by moving the wafer stage, long patterns appropriate for micro fluidic paths were very smoothly formed.

1 INTRODUCTION

Various researches are vigorously practiced for supporting medical treatments and diagnosises, and clarifying causes of diseases. As techniques or procedures of such researches, chemical or medical analysises using cell arrays and micro-fluidic devices are frequently used. For example, functions of cells and DNAs are often investigated. To speak about researches on cells, for example, when and in what state, what cells work and how to work are the subjects (Arnandis et al., 2012; Choi et al., 2010; Kim et al., 2013). It is often investigated what proteins are made from particular DNAs also (Gach et al., 2014; Schmidt et al., 2013). In such cases, it is important to evaluate a lot of cell and DNA samples efficiently. For this reason, in many cases, it is required to develop special devices for analyzing them using minute volume samples. Micro-chamber array chips or micro-cell array chips are the most simple devices for such usage (Bianchi et al., 2013; Lei et al., 2014). That is, the micro-chambers or micro-cells work as a lot of test tubes. Accordingly, by minimizing the sizes of micro-chambers or micro-cells, it becomes possible to reduce costs and analyzing time, and save reagents. Micro-fluidic devices are also used for analyzing various mixing and separation of small quantity liquids (Wang and Hu, 2010).

As a fabrication method of such devices, optical lithography is usually used (Boero et al., 2014; Ilyas et al., 2014; Li et al., 2005; Malainou et al., 2012; Moraes et al., 2010; Negrete and Cerrina, 2008; Tanii et al., 2004). However, exposure systems for lithography are very expensive even for printing very large patterns with sizes of several tens or hundreds microns. In addition, conventionally available mask aligners and projection exposure systems with large numerical apertures are not suitable for printing thick resist patterns required for fabricating above mentioned biodevice patterns. Because depth of focus is generally small in such systems, it is difficult to print thick resist patterns with almost vertical side walls. In addition, because masks and reticles are also expensive, it is not easy to change or improve pattern shapes after once they are decided.

In this paper, a new exposure system is developed using light-emitting diodes (LEDs) as exposure sources. It has great advantages from the viewpoints of cost and simplicity. Maintenance times are also much reduced. In addition, optical fibers with squared ends are developed, and the squared optical fibers were bound in a matrix for printing smoothly stitched patterns. Because bright or dark are directly assigned by simply lighting and extinguishing LEDs, this

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combination of LEDs and a fiber matrix is very effective for easily printing arbitrary patterns as if they are pixel arts without using any reticles. On the other hand, it is also possible to print oblique and curved patterns if the wafer stages are programmatically scanned. It is demonstrated that various patterns of biodevices are fabricated using the exposure system.

2 NEW EXPOSURE SYSTEM

2.1 LED Exposure Optics

The newly developed exposure system is shown in Figure 1. The sizes of the system were 600 mm wide, 400 mm deep, and 2,000 mm high. Bullet-type LEDs with a central wavelength of 405 nm (OptoSupply, OSSV5111A) were used as exposure sources, and 100 pieces of LED were attached to a universal board in a 10×10 matrix. Assignments of ON or OFF were given to all the LEDs using a personal computer. Accordingly, arbitrarily designed patterns were obtained without using reticles. The projected field size was approximately 1×1 mm^2, and the element pattern size was 100×100 μm^2 because the projection ratio was 1/10, and the squared fiber matrix size of 10×10 mm^2 was reduced by a factor of 10 through the projection lens. The numerical aperture of the lens was 0.4. Two-axis automatic stage (SIGMAKOKI, SHOT202) was used as the wafer stage. The stage was used for both step-and-repeat and scan exposures. Ultra-high pressure mercury lamps are often used as exposure sources in usual optical projection exposure system. However, there is fear of lamp burst. In addition, an expensive elliptical collector mirror is required. Without using these optical components, the cost of exposure-source was much reduced.

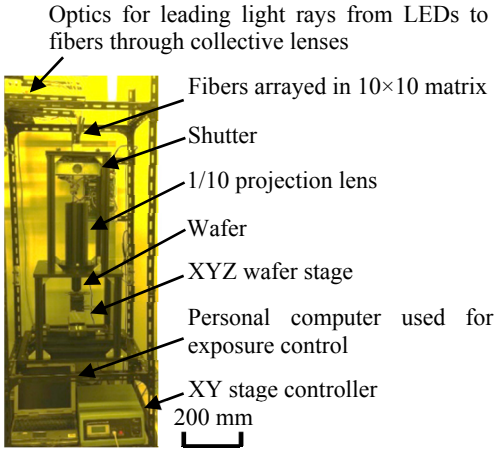

Figure 1: Exposure system used for the research.

2.2 Squared Optical Fiber

At the early stage of the past research, patterns were printed directly using LEDs arrayed in a matrix. However, because each LED had a strong intensity distribution of emitted light, it was difficult to print element patterns with a uniform shape. For this reason, to obtain a uniform surface emission, optical fibers were used. Collective-lens optics were designed and inserted between each couple of an LED and a fiber. In addition, to collect light rays emitted from LEDs efficiently, plastic optical fibers (Mitsubishi Rayon, Eska CK-40E1) with a diameter of 1 mm and clad thickness of 10 μm were used. The end of each fiber was transformed to a square shape in approximately 20 mm length from the fiber end. The sequence used to deform circular optical fibers to square ones is shown in Figure 2. First of all, an optical fiber was inserted into a square clearance of a deforming instrument and clamped using screws (a). The square clearance was controlled to a size of 1×1 mm^2. Next, the instrument was heated at 150 °C on a hot plate for 5 min (b). Though the end part of the fiber heated in the square space was expanded to fill the space, it became shorter in the longitudinal direction. After heating and deforming the fiber to a square cross section, the fiber was cooled down in the instrument (c), and taken out (d). Finally, the squared fiber end was polished with emery papers. As a result, the cross section of the optical fiber was deformed to a square, as shown in Figure 3.

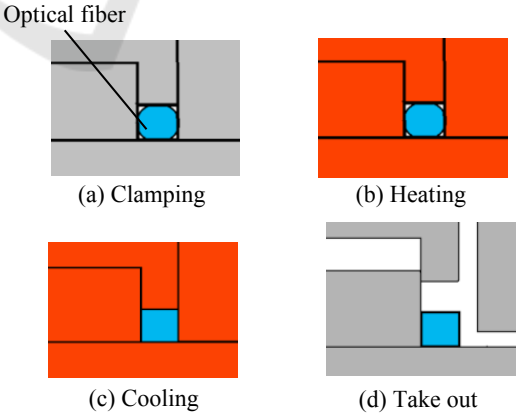

Figure 2: Method used for deforming optical fiber ends to square shapes.

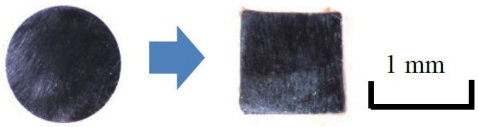

Figure 3: Fiber ends before and after squared.

2.3 Fiber Matrix

Sizes of all the squared fibers were measured using a micrometer, and fibers with regular shapes and sizes in a permissible range of within 1 ± 0.01 mm in both vertical and horizontal directions were selected. Next, the selected 5 optical fibers were simultaneously inserted in a bundling instrument with a 5-mm opening space, as shown in Figure 4, after coating adhesive (Loctite LPP-005), and aligned in a line. Such 5-fiber alignment and bonding were repeated 4times more. As a result, 5×5 fiber matrix was obtained after the adhesive was hardened. 10×10 matrix was fabricated by bonding such 4 pieces of 5×5 matrices using the same adhesive, as shown in Figure 5. The matrix end was polished again with emery papers. Measured maximum gap between fibers was 49 μm, and it was approximately 5% of the square size. Accordingly, the maximum gap was sufficiently small to use the fiber matrix as an exposure tool.

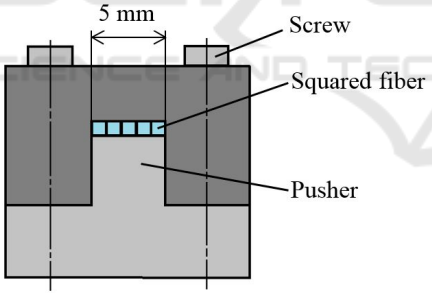

Figure 4: Bundling instrument used for aligning and bonding squared 5 fibers, and piling them.

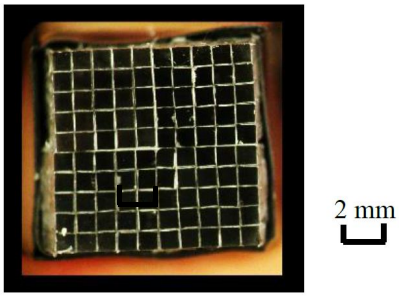

Figure 5: Fibers arrayed in a 10×10 matrix and fixed to the exposure system.

3 EXPERIMENTS

3.1 Patterning by using Exposure Maps

Resist patterns formed by lithography are variously applicable to biodevices. If thick patterns are obtained, they are directly available to cell or chamber arrays, and micro-fluidic paths. They are also applicable to molds of soft lithography used for replicating them to poly dimethyl siloxane (PDMS) (Lyu et al., 2014). On the other hand, if the resist patterns are used as etching masks, thin resist patterns are also applicable. Here, considering the wide varieties of application, thick resist patterning was investigated. To print thick resist patterns, negative-type PMER N-CA3000PM (Tokyo Ohka Kogyo) was spin-coated on Si wafers in a thickness of approximately 30 μm.

At first, checker patterns were printed by giving assignments of lighting LEDs alternately. It was anticipated that all the square resist patterns were slightly separated from neighbored patterns at every corner caused by the gaps between fibers explained in section 2.3 if fiber-matrix elements were faithfully printed in square shapes. For this reason, sufficient exposure dose was given, and the gaps between elements were eliminated by excessively sensitizing the resist. As a result, the checker patterns were connected at corners, as shown in Figure 6. It is thought that the patterns are usable as a micro-cell array. Though the ordinary exposure time was 30-40 s, it took 80 s to print sufficiently connected checker patterns. The patterning characteristics that the projected element-pattern sizes were controllable by changing the light intensity of LED and the exposure time were almost similar to the conventional lithography using lamps or lasers as the exposure sources. Pattern width controllability by exposure time is shown in Figure 7.

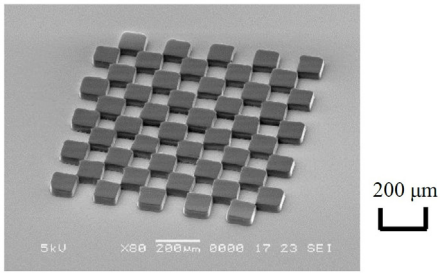

Figure 6: Printed checker patterns usable as a cell array.

Other kinds of chamber patterns were also fabricated by variously assigning the lighting LEDs, as shown in Figures 8-10. The exposure time was set for 70 s in these experiments. Figure 8 shows a pattern

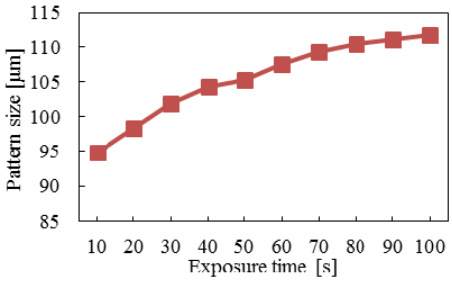

Figure 7: Pattern size controllability by adjusting the exposure time.

fabricated by lighting only the fiber elements at outer periphery. It has a 800-μm square hollow chamber surrounded by a 100-μm wide outline fence. Figure 9 shows a cell array fabricated by lighting LEDs corresponding to 3×3 fiber elements except the center, and repeating exposures and step movements. Repeated 300-μm square cell patterns with 100-μm square hollows were regularly printed.

In Figure 8 and 9, concave chamber and cells were directly fabricated. However, it is also possible to print convex resist patterns at first, and replicate the patterns to PDMS using soft lithography (Wang et al., 2008). Figure 10 shows an example of convex resist pattern array. Square dot patterns with a size and a pitch of 100 and 200 μm were regularly printed in a wide area. Cell arrays would be fabricated by replicating them to PDMS using soft lithography.

Thus, it was demonstrated that various chamber and cell array patterns were easily fabricated by the new exposure system without using reticles.

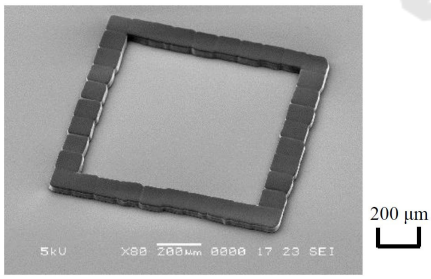

Figure 8: Chamber pattern with 800-μm square chamber and 100-μm wide fence.

3.2 Scan Exposure

It was demonstrated that arbitrary patterns were printable by assigning LED lighting maps. However, curved or oblique patterns were not printable by the direct exposure using the squared fiber matrix. For this reason, scan exposure using automatic stage control was investigated next. Exposure light spots with a 100-μm square shape were relatively moved in X and Y directions by scanning the wafer stage. Scan speeds were changed between 5 μm/s and 20 μm/s. Figure 11 shows the relationship between the scan speed and measured pattern width. Pattern width was controllable between 93 and 115 μm by changing the scan speed.

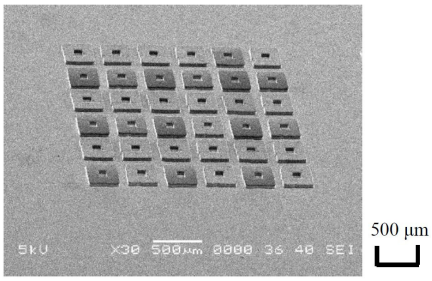

Figure 9: Dispersively arrayed 300-μm square patterns with 100-μm square hollow cells.

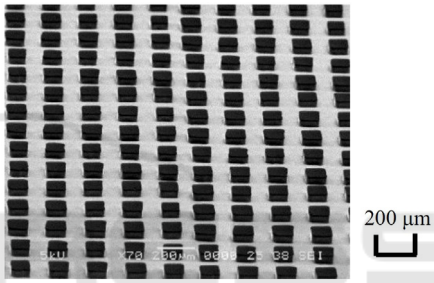

Figure 10: Arrayed 100-μm square pillars. If patterns were replicated to PDMS using soft lithography, a cell array would be obtained.

Next, a flow-path mold of a micro-mixer with a width of 100 μm was fabricated by scanning a light spot from one LED at a scan speed of 10 μm/s. However, at the inlets and outlet of the mixer, all the LEDs were lit, and 1-mm square patterns were printed without scanning the stages. Fabricated flow path pattern is shown in Figure 12. Patterns were successfully delineated in 6×12 mm^2 area.

Pattern widths were measured at 15 points, as shown in Figure 13. Figure 14 shows the results.

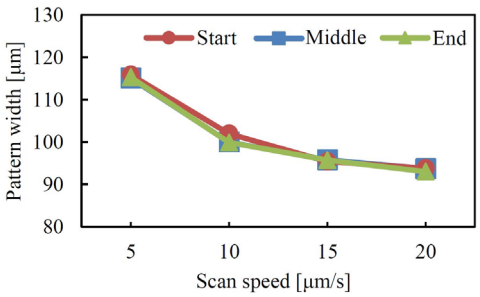

Figure 11: Pattern width control by adjusting the scan speed.

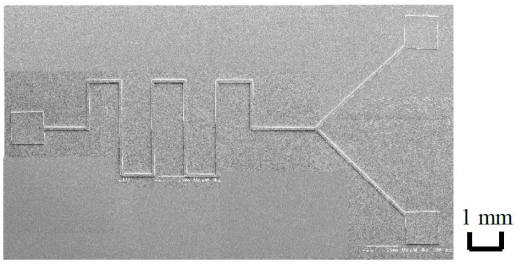

Figure 12: Micro-fluidic device pattern.

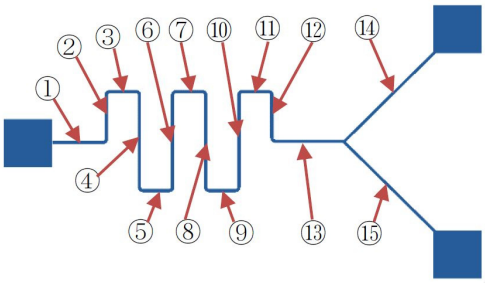

Figure 13: Points selected for measuring pattern widths.

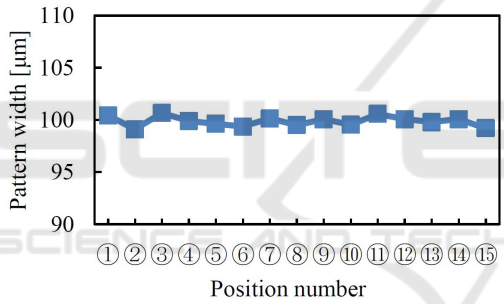

Figure 14: Width homogeneity of fabricated micro-fluidic device patterns.

Pattern widths of vertical parts and horizontal parts were almost uniform. In addition, widths of 45° oblique patterns became almost the same as those of the vertical and horizontal patterns. Deviation of line widths for all the measurement points was as small as less than 1μm.

4 EXTENDABILITY

It was demonstrated that various biodevice patterns were easily fabricated using the new system. However, the minimum pattern size was decided by the fiber size, and it was approximately 100 μm. In some cases, patterns with smaller sizes are required. For this reason, it was investigated whether finer squared fibers were obtained or not. Figure 15 shows a cross section of 500-μm square fiber. The fiber was fabricated by deforming the end of a circular fiber with a diameter of 500 μm. It was verified that the profile and corner roundness were almost the same as those of 1-mm fiber. Accordingly, it is probably possible to reduce the minimum pattern size at least to 50 μm. If the element fiber size is reduced in a half, and LED light rays are efficiently collected in the fiber, the intensity of light spot on a wafer is increased by a factor of 4, and the exposure time is reduced to 1/4.

On the other hand, if the new system is applied to fabrication processes of biodevices using etching, and resist patterns are used as etching masks, highly sensitive thin positive resist is applicable. In such cases, exposure time becomes considerably short. For example, even using 1-mm square fiber-matrix, patterns were printable within 4 s using 1-μm thick THMR iP-3300PM (Tokyo Ohka Kogyo). The new exposure system is very flexible and has a wide extendability.

(a) 1-mm fiber (b) 500-μm fiber

Figure 15: Half-size squared optical fiber with a cross section profile similar to that of current size fiber.

5 CONCLUSIONS

Applicability of the newly developed low-cost maskless exposure system to the fabrication of biodevices was investigated. In the new system, LEDs were used as original exposure sources, and a squared optical fiber matrix was used as a component combining a secondary light source and a reticle with bright and dark parts. It was demonstrated that various chamber or cell arrays were directly fabricated using 30-μm thick negative resist and LED lighting control. In addition, combining with the scanning exposure, a flow path pattern applicable to a replica mold for soft lithography using PDMS was fabricated. It was verified that the new exposure system was prospective for the use of biodevice fabrication. If optical fibers with a smaller diameter are used, and the matrix size is enlarged in future, convenience and applicability will be extended further. The minimum element pattern size, pattern size accuracy and repeatability, and other performances of the exposure system should be investigated further more hereafter.

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