Investigations of Matrix-Exposure Lithography Using Stacked Linear Arrays of Squared Optical Fibers

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Plastic optical fiber matrices with squared ends were investigated. Such fiber matrices are particularly required for printing two dimensional code marks by using them as new lithography tools combining with light emitting diodes. A large number of fibers with a diameter of 500 µm were packed in an oblong slit of a jig, and fiber ends were simultaneously transformed into square shapes by heating the jig on a hotplate. Next, three linear arrays, each composed of 10 fibers, were simply stacked and bound without coating any adhesives and/or opaque films. It was anticipated that light leaks from neighbored bright fibers degraded the printed pattern qualities. However, checker patterns were normally printed without influenced by neighbored bright fibers when the fiber ends were projected on a wafer through a 1/10 projection lens. Considering the advantages, a regularly arranged 10×10 fiber matrix was fabricated on trial for demonstrating the availability of the matrix required for developing a matrix-exposure lithography system.

Keywords: Squared optical fiber, Optical fiber matrix, LED exposure, Projection lithography, Code mark printing

1. Introduction

Matrix-exposure lithography using a plastic optical fiber matrix with squared ends was proposed in our past research earlier than 2010 [1-4]. Each fiber in the matrix was led individually to a light emitting diode (LED) for supplying exposure light. Bright and dark conditions of the fiber ends were assigned by lighting the LEDs arbitrarily using a personal computer, and patterns corresponding to a brightness map of the fiber matrix were projected on a wafer by reducing the sizes in 1/10 through a projection lens.

It is thought that such a method is simple and low-cost, and effective for printing two dimensional (2D) code marks. In particular, lithographic printing of 2D code marks is practically used in actual production lines of display panels. That is, code marks including serial numbers, lot numbers and others are frequently printed at an early process step, and they are used for quality controls. However, commercially available exposure systems for the exclusive use of code mark printing [5,6] are rare and expensive.

It has been demonstrated that 2D code marks were successfully printed using a 10×10 fiber matrix fabricated by binding plastic optical fibers with a diameter of 1 mm and squared ends. The marks are readable using a commercial code mark reader without failures [7-11]. However, it is worried that printed code mark patterns with a unit size of 1 mm×10=100 µm were too large to increase the matrix scale to 22×22, 44×44, and others [12,13]. It is required to control the 2D code mark sizes less than approximately 2 mm square.

For this reason, in this research, fibers with a diameter of 500 µm are used instead for reducing printable element pattern sizes in a half. In addition, to fabricate precise fiber matrices efficiently using such fine fibers, a new method is developed for fabricating linear arrays of optical fibers with squared ends. Fibers are contacted and arrayed in an oblong slit of a jig, and fiber ends are simultaneously transformed into square shapes by heating the jig on a hotplate [14]. Next, linear arrays of squared fibers obtained by the new method are simply stacked and bound together.
without coating any adhesives and/or opaque films. Then, using the 3×4 fibers in a 3×10 fiber-matrix, patterning characteristics are investigated. Besides, fabrication feasibility of a precise 10×10 fiber matrix is also investigated.

The system will also be applicable to maskless lithography for fabricating various microstructures such as bio-devices [15,16], micro-fluidic devices [17-19], micro-lenses [20,21] and others in the future. On the other hand, lithography using LEDs is also watched with keen interest depending on the recent developments of ultra-violet and short visible light LEDs with strong intensities [22,23].

2. Lithography using squared fibers

A basic structure of the exposure system to be developed is shown in Fig. 1. A matrix of fine optical fibers is used in place of a reticle, and the brightness distribution of fiber ends assigned by a bright LED map is projected on various substrates such as panel boards, glass sheets and wafers coated with resist films. As a result, arbitrary patterns are printed on the substrates.

Printing of 2D code mark patterns is the primary application of this exposure method. To improve the quality and readability of code marks, the optical fiber ends should be square, and printed square unit patterns of dots or holes should be stitched precisely. Sizes and pitches of unit patterns should be kept uniform, and neighbored unit patterns should be printed closely each other.

In the past research, two methods for transforming circular fiber ends to square ones were developed. In the method developed at first, each optical fiber end was transformed by heating the fiber end one by one using a jig with the structure shown in Fig. 2. The heated fiber end expanded in the jig to be transformed into a square shape and shrank in the axial direction instead. As a result, the fiber end was successfully transformed. However, it took a long time to get a lot of squared fibers required for fabricating a matrix. In addition, it was very difficult to assemble a lot of separated fibers in a regularly and precisely arranged matrix.

For this reason, a new method was developed next. In the new method, circular optical fibers were inserted in an oblong slit, and tightly arrayed in a line using a jig with the structure shown in Fig. 3. Fibers inserted in the jig slit were pushed from both sides not to make any gaps between neighbored fibers. Therefore, when the jig was heated on a hot plate, all of the heated fiber ends were simultaneously transformed into squared shapes. Heights of the squared fibers became almost uniform though the widths slightly fluctuated at random.

In this research, the new method was adopted. As a 0.5-mm plastic optical fiber, a commercial general-purpose fiber (Mitsubishi Chemical, Eska, CK20) was used. It was demonstrated in the past research that at most 40 fibers were simultaneously transformed into square shapes within width and height errors of ±7.2 and ±6.5 nm, respectively, using the same fiber [14].

Moreover, in addition to the convenience for fabricating the fiber arrays, another advantage of the new method was found. That was the decrease of the fiber damages during the heat treatment.

[Diagram of exposure system]

Fig. 1 Basic structure of aimed exposure system.

[Diagram of jig structure]

Fig. 2 Structure of the jig for transforming an optical fiber end to a square shape one by one.

[Diagram of jig structure for large number of fibers]

Fig. 3 Structure of the jig for transforming a large number of optical fiber ends into square shapes simultaneously.
When fibers were transformed into squares one by one, heated fiber clads were separated from cores, and light from LEDs leaked much from the damaged fibers. In comparison, in the new method, damages between neighbored fibers were almost prevented, and average light leak of 10 fibers was decreased from 34.4% to 20.4% [14].

For this reason, patterning characteristics of a fiber array and a matrix fabricated by the new method were investigated. The heating temperature was kept at 120°C.

### 3. Patterning Characteristics

Lithography performances of a linear fiber array composed of 10 fibers was investigated at first. Actually, the 8 fibers except 2 fibers with irregular shapes at both sides were used, as shown in Fig. 4. Exposure light rays from blue LEDs with a central wavelength of 405 nm were supplied to fibers through condenser lenses. Each fiber was paired with a LED (OptoSupply, OSSV5111A). The squared fiber array was placed at the reticle position of a test exposure system equipped with a 1/10 projection lens [7-11]. The numerical aperture of the lens was 0.4. As a resist, positive THMR iP-3300 (Tokyo Ohka Kogyo) with a thickness of approximately 1 µm was used.

Thus, when square patterns were printed using each fiber one by one solely, the sizes varied depending on the exposure time, as shown in Fig. 5. The sizes were the widths and heights measured crossing the pattern centers. The trends of size changes were normal and regular. Pattern widths and heights of 8 fibers at the appropriate exposure time of 2.2 s were 49.7±1.0 µm, and 51.0±1.0 µm, respectively. Width and height fluctuations were almost similar.

Typical shapes of printed squared hole patterns are shown in Fig. 6. Although the side edges of squared fibers were almost straight, pattern shapes were rather round. It was considered that the light intensity was strong at the center and weak at the corners, because the length of the squared parts of fibers were as short as 30 mm.

Next, patterning characteristics were investigated using a small-scale fiber matrix fabricated by stacking and binding the fiber arrays. Because fibers were tightly assembled without gaps in the array (row) direction, it was expected that fiber arrays were stacked without gaps also in

![Fig. 4 The fiber array used for investigating patterning characteristics. Fibers except irregular ones at both sides were practically used.](image)

![Fig. 5 Size dependence of printed square hole patterns on the exposure time. Pattern width dependence (a) and pattern height dependence (b) are compared.](image)

![Fig. 6 Typical shapes of printed square hole patterns.](image)
the column direction.

For this reason, a small-scale matrix was fabricated on trial by simply stacking and binding 3 linear fiber arrays composed of 10 fibers without coating any opaque films and/or adhesive materials. The fabricated fiber matrix is shown in Fig. 7. The matrix was assembled by sandwiching the linear arrays using a pair of parallel aluminum plates bound by 2 pairs of a screw and a nut.

All the squared fibers obtained simultaneously were weakly adhered each other, and they are easily separated by pulling the fibers to be removed. Therefore, wrongly deformed fibers at both sides were peeled off from regularly transformed inner fibers.

Although the fiber damage during the heating process was fairly reduced by the adoption of the new method, it was anticipated if patterns were faithfully printed as assigned by an on-off map of the LEDs. That is, it was worried that exposure light might leak through the slightly damaged fiber clads, and patterns different from the assigned ones might be printed. Therefore, it was investigated whether the light leaks badly influenced on the patterning or not. Using the 3×4 fibers shown in Fig. 7, checker patterns assigned in bright and dark alternately were printed under various exposure time conditions.

The results are shown in Fig. 8. Before the experiments, it was thought that the dark square parts surrounded by the bright square parts might be sensitized by the light leaked from the bright parts. However, the resist was correctly sensitized under appropriate exposure-time conditions as assigned by the bright fiber map, as shown in Fig. 8(a). Even if a very large exposure dose of 10 times larger than the appropriate one was given, parts corresponding to the dark fibers were not sensitized, as shown in Fig. 8(b).

Next, linear continuous patterns in the row direction were printed using the 3×4 fiber matrix. The results are shown in Fig. 9. It was confirmed that straight linear patterns with almost uniform widths of approximately 50 µm were printed though fine notches were observed periodically corresponding to the corner roundness of each element fiber.

4. Fabrication of 10×10 Fiber Matrix

It was demonstrated in the previous chapter that a fiber matrix fabricated by simply stacking and binding without using any opaque films and/or adhesive materials was applicable to matrix-exposure lithography. For this reason, availability of a quite large-scale fiber matrix was investigated by fabricating a 10×10 fiber matrix.

As the first step, 10 linear arrays, each of which was composed of 10 fibers with squared regular shapes, were fabricated. Next, the 10 linear fiber arrays were stacked by sandwiching them by 2 flat aluminum plates, and binding by 2 pairs of a screw and a nut at both sides. As a result, a well-assembled fiber matrix was obtained, as
shown in Fig. 10.

Fiber sizes were evaluated next. Because all the fibers were tightly contacted with the neighbored ones, the fiber sizes were equal to the fiber pitches. Measured fiber sizes in horizontal and vertical directions, or the fiber widths and heights are shown in Figs. 11 and 12. The widths and heights are plotted only for No. 1, 4, 7, 10 raw from the top, because it became difficult to detect size fluctuations in each raw, if all the size data were plotted together. Distribution or fluctuations of fiber widths and heights for all the 10×10=100 fibers were 489±20 μm and 500±5 μm, respectively. Uniformity of the widths was inferior to that of the heights. It was considered that this result was caused by the simultaneous deformation process of a large number of fibers from circular cross sections to square ones.

![Image](image1)

Fig. 10 10×10 fiber matrix assembled by stacking and bounding 10-fiber linear arrays.

![Image](image2)

Fig. 11 Measured fiber width uniformity.

![Image](image3)

Fig. 12 Measured fiber height uniformity.

On the other hand, square ratio \( S \) defined by Eq. (1) was also evaluated [4]. Here, \( d_1 \) and \( d_2 \) are the diagonal lengths, \( w \) is the width, and \( h \) is the height of a fiber cross section. \( S \) becomes 0 for a circular shape, and \( S \) becomes 1 for a square shape. Calculated \( S \) values were distributed between 0.49-0.75, and differed from row to row, as shown in Fig. 13. The average value was 0.64. The ratio should be improved up to 0.70 by making some more progresses in the array fabrication processes or preparing spare fiber arrays and selecting superior ones.

\[
S = \frac{1}{\sqrt{2} - 1} \frac{(d_1 + d_2) - (w + h)}{w + h}
\]

(1)

In the past research, a 10×10 fiber matrix composed of individually squared 1-mm fibers was
fabricated, as shown in Fig. 14 [8, 10]. The fiber matrix was used for printing 2D code marks on Si wafers using the same 1/10 projection exposure system and resist processes, and the 2D code marks were certainly read without fails by a commercial code mark reader [8-11]. The size uniformity and regulation of the fiber matrix obtained in this research and shown in Fig. 10 is obviously superior to the fiber matrix obtained in the past research and shown in Fig. 14. It is considered that the size errors and fluctuations shown in Figs. 10-12 are within allowable ranges.

5. Discussion

In the new method, fibers were deformed almost symmetrically in both width and height directions of fiber cross sections, because all the fibers were tightly packed, and all fiber sides became straight. In addition, squared fiber corners became almost circular. Considering these facts, relationship between the square ratio and the corner roundness was investigated assuming all the fiber corners were geometrically circular.

In the past research, the square ratio $S$ was defined by Eq. (1) in the past research at first as a parameter expressing the normalized difference between the average diagonal length and side length of a fiber cross section. However, this time, it was clarified that $S$ related directly and

\[
S = \frac{1}{\sqrt{2} - 1} \frac{2\sqrt{2}(a - 2r) + 4r - 2a}{2a}
\]

\[
= \frac{1}{\sqrt{2} - 1} \frac{(\sqrt{2} - 1)a - 2(\sqrt{2} - 1)r}{a}
\]

\[
= 1 - \frac{2r}{a}
\]  (3)

This relationship between $S$ and $r$ is shown in Fig. 16. It is known from Eq. (3) and Fig. 16 that $S$ decreases linearly in proportion to $r$. The square ratio $S$ was defined by Eq. (1) in the past research at first as a parameter expressing the normalized difference between the average diagonal length and side length of a fiber cross section. However, this time, it was clarified that $S$ related directly and

\[
d_1 = d_2 = d = \sqrt{2}(a - 2r) + 2r
\]  (2)

If Eq. (2) is substituted in Eq. (1) assuming both the fiber width $w$ and the height $h$ are equal to $a$, $S$ is calculated by Eq. (3).

![Silver lacquer and adhesive coated on fibers](image)

Fig. 14 Fiber matrix composed of 1-mm square fibers fabricated in the past research [8, 10].
linearly to the corner radius $r$. It was found that $S$ was a more qualified, reasonable and eligible parameter than it had been recognized.

5. Conclusion

A new method for transforming end parts of plastic optical fibers with a diameter of 500 μm into square ones simultaneously in a line was applied to the fabrication of fiber matrices. In addition, applicability of the matrices to the matrix-exposure lithography was investigated.

It had been anticipated if arbitrary patterns were regularly printable using a fiber matrix fabricated by simply stacking and binding linear arrays of squared fibers without coating any opaque films and/or adhesives. However, it was verified that checker patterns were exactly printed without influenced by neighored bright fibers.

In addition, availability of a regularly and precisely arranged 10×10 fiber matrix was demonstrated. Moreover, it was clarified that the square ratio $S$ proposed in the past research was simply expressed by $S=1-r/2a$, when corners of squared fibers with a side length of $a$ were circularly rounded to a radius of $r$. It was found that $S$ is a qualified parameter expressing the corner roundness relevantly.

Prospects for the reduction of pattern size unit to a half are promising if the new method is adopted. Further research efforts should be made.

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