Improvement of Patterning Homogeneity in a Field of Projection Exposure System Using a Gradient-Index Lens Array

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Pattern width homogeneity in an exposure field of gradient-index (GRIN) lens array was greatly improved by changing the sub-scan method for averaging the pattern widths. By investigating the pattern width distribution in the exposure field, it was clarified that the parts, where the printed patterns were degraded and pattern widths were notably changed, appeared as striped lines. It was supposed that the striped abnormal pattern-width change was caused by the extra exposures for the times when the sub-scan stage was stopped at both the sub-scan ends for turning the scan direction. For this reason, sub-scan length was vastly extended, and the sub-scan stage was turned at the both ends after all the patterns on a reticle passed over the actually used parts of a GRIN lens array. By this method, no patterns were exposed and projected on a wafer while the sub-scan stage was stopped for turning at the both ends. As a result, 15-µm L&S patterns were almost homogeneously printed in the exposure field within a variation range of ±6%.

Keywords: Gradient-index lens array, Pattern width homogeneity, Projection exposure, Sub-scan

1. Introduction

Photolithography has been applied many years to mass productions of integrated circuits, and it has become one of the most trustworthy technology for realizing new electronic devices. It is amazing that even at the present era when the minimum pattern rules are reaching at 10 nm, almost all the electronic products are fabricated using photolithography [1-3].

However, it should be strongly notified that the photolithography is also applied to printing of far large patterns with sizes of µm ranges. Major applications are flat panel displays, image sensors composed of charge coupled devices (CCDs) [4] and complementary metal oxide semiconductor (CMOS) devices [5,6], various micro electro mechanical systems (MEMS) such as sensors for measuring pressures, accelerations, forces, temperatures, and others [7-10].

In recent years, in addition to these conventional applications, photolithography has been used for printing further large patterns with 10-100 µm sizes. They are required for developing micro-fluidic devices such as reactors, mixers, ejectors, cell selectors, and others [11-14]. The patterning is also required for developing optical micro-components such as lens and prism arrays, and others [15-19]. However, fabrications of things with complicated shapes of these sizes are considerably difficult by mechanical cutting or electro discharge machining.

From the view point of pattern sizes or resolution limit of photolithography, it seems easy to print such large patterns. However, required volumes and frequencies of patterning are far smaller and lower than those of mass-produced semiconductor products. In addition, total costs have to be lower than those of conventional mechanical cutting and electro discharge machining. When the conventional methods are applied, metals are directly cut. On the other hand, because photolithography is a method for printing patterns using a photosensitive resin (resist), etching or metal deposition should be accompanied afterward. In addition, it is difficult to fabricate three dimensional shapes. Therefore, the costs should be sufficiently low to disclaim the disadvantages mentioned above.

For these reasons, the authors have been
developing novel lithography systems using gradient index (GRIN) lens arrays as projection lenses [20-23]. Because the GRIN lens arrays are generally used for scanners and copying machines, they are inexpensively obtainable.

In the past researches, the first prototype system was developed, and the feasibility of projection lithography using a GRIN lens array was demonstrated [20,21]. In this system, the reticle and the wafer are fixed, and the illumination optics and the GRIN lens array were scanned together. However, it was considered inappropriate that the projection lens was moved because the vibration and inclination of lens axes during the scan was worried. For this reason, in the second prototype system, the scan method was improved, and the reticle and the wafer were scanned together by combining the reticle and wafer stages together [22, 23]. In addition, the reticle and the wafer were reciprocally scanned in the lens array direction during the main scan to the direction perpendicular to the lens array. By this method, patterning homogeneity in the exposure field was considerably improved. However, the homogeneity was not satisfactory still.

For this reason, the reticle and wafer stages were reconstructed, and the scanning strokes were increased by removing the mechanical interferences of stage components. In this paper, a new sub-scan method is contrived, and how the patterning homogeneity is improved is shown.

2. Improved exposure system used for the research

In this research, the second prototype exposure system was used after reforming it. As the reforms, rods connecting the reticle and wafer stages were moved to the outside for preventing the rods interfered with the fixed structure of the system during the scans. By grace of the reforms, the main and sub-scan strokes were improved from 80 and 120 mm to 130 and 150 mm, respectively. The reformed exposure system is shown in Fig. 1. The exposure source is an ultra-violet lamp with a major wavelength of 365 nm (Inflidge, UVB-300, 330W). The illumination light rays were mixed using a square rod lens in the illumination optics, and the intensity distribution of the light on the reticle was homogenized in flat. A 30-mm long area, where the light intensity was almost homogeneous, was used for the exposure. The variation of the light intensity in the area used for the exposure was within ±2.5%. As a GRIN lens array, 2-line type was used, as shown in Fig. 2.

The diameter of the element lens was 1.085 mm, and the lens length was 16.28 mm. The distances between the reticle and lens, and the lens and wafer were kept to 7.84 mm, respectively. As a result, 1:1 erect images of reticle patterns were projected on a wafer, as shown in Fig. 3.

![Fig. 1. Improved exposure system used for this research.](image)

(a) General view of the GRIN lens array. The sizes are 195.4×4.82×16.28 mm.

(b) Partially magnified view of the GRIN lens array. The element lens diameter is 1.085 mm.
3. Improvement of patterning homogeneity in an exposure field

In the past research, it was clarified that degradations of image intensity and image contrast distributions were caused by the individuality of the element lenses composing the lens array and correlativity of neighbored element lenses [23]. For this reason, patterning characteristics were mainly distributed in the array direction, and the homogeneity of pattern widths in the exposure field was not sufficiently improved even if the reciprocal sub-scan was applied. Therefore, the exposure dose margin for printing patterns with almost same widths within an allowance in a wide exposure area became extremely small, and in some cases, the distribution of resist pattern height or remained thickness had to be allowed to some extent for obtaining the pattern width homogeneity. However, such compromises are unfavorable, and it is necessary to print patterns with same width and same cross section profiles homogeneously in a large exposure field.

For this reason, discontinuity of patterns projected by neighbored element lenses were investigated again in detail to clarify the causes of pattern width distribution in the array direction [23]. When patterns were printed without scanning the stages, they were variously shifted at the positions corresponding to the boundaries of element lenses. Examples of pattern shifts or discontinuity are shown in Fig. 4. The patterns are 30 µm lines and spaces printed using a positive resist THMR iP-3300 (Tokyo Ohka Kogyo) with a thickness of approximately 1 µm. Pattern shifts were measured at each contact point of upper and lower column lenses contacted in 30 degree inclined directions, considering the plus or minus of shifted directions, as shown in Fig. 5. Distributions of pattern shifts in the lens array direction (sub-scan direction), and in the direction perpendicular to the lens array direction (main scan direction) are shown in Figs. 6 and 7. It was clarified that the patterns printed by neighbored lenses were variously shifted, and the maximum shifts reached approximately ±40 µm. It was known that a lot of largely shifted positions existed.

Fig. 4. An example of 30-µm L&S patterns simply printed without any scans.

(a) Horizontal L&S patterns.

(b) Vertical L&S patterns.
In the conventional method, a reticle and a wafer were scanned back and forth within a short length so that the patterning fields are always included in a usable area of GRIN lens array where is not covered by blind sheets. Figure 8 shows 15-µm line and space (L&S) patterns printed in an exposure field with a width of 30 mm in the sub-scan direction and a length of 15 mm in the main scan direction under the scan conditions of 36 µm/s main scan speed, 15 mm/s sub-scan speed, and 7.7 mm sub-scan length. It is known that the color of the patterns slightly changes at the position approximately 5 mm from the left end, and a vague stripe is observed, as shown in Fig. 9. The striped color change means that the resist pattern widths and the resist pattern thicknesses are different at the parts from other places. In fact, when the patterns were observed by an optical microscope, pattern shapes at point A were different from the shapes at point B and C, as shown in Fig. 10.

Fig. 8. Conventional sub-scan method. Sub-scan stroke was short, and reticle patterns were always exposed.

Pattern widths were measured along these lines.

Fig. 9. General view of 15-µm L&S patterns printed using the conventional sub-scan method.

(a) Patterns at A (b) C 100 µm

Fig. 10. Magnified views of 15-µm L&S patterns printed using the conventional sub-scan method.
Measured pattern widths were also different in the striped region from other places, as shown in Fig. 11. The widths distributed between 14.6-19.7 μm for the mean width of 16.4 μm. However, even if discontinuities of patterns existed, it was strange that the effects were not sufficiently averaged, and discontinuities of patterns did not influence equally to all the places in the field. For this reason, why the homogenization by the sub-scan became insufficient only in a few striped areas was deliberated.

It was guessed that the reticle and wafer stages were stopped at the sub-scan ends many times for changing the scan direction, and at the turning points of both the ends, times exposed through particular lenses became longer than the times exposed through the other lenses. Accordingly, it was thought that at particular places exposed through discontinuous lenses for long times when the reticle and wafer stages were turned, printed patterns were degraded. For this reason, the stopping time of the reticle and wafer stages was actually measured using a stop watch at both sub-scan ends. As a result, the mean stopping time was approximately 0.11 s. When the sub-scan length was 7.7 mm and the sub-scan speed was 15 mm/s, it took \((7.7 \times 2) / 15 = 1.027\) s for back and forth scans. On the other hand, it took \((1.085 \text{ mm}) / (0.036 \text{ mm/s}) = 30.14\) s for scanning the length corresponding to the element lens diameter. For this reason, the frequency of sub-scan during the main scan of 1.085 mm was 30.14/1.027 = 29.3 times, and the total stopping time at both sub-scan ends was calculated to be \(0.11 \times 29.3 \times 2 = 6.45\) s. Therefore, the total stopping time reached more than 21% of the exposure time, and it seemed reasonable that the patterns were degraded at a few particular places.

To verify the above mentioned supposition, the sub-scan length was vastly lengthened, and the sub-scan stages were turned after the reticle patterns completely passed the used lens array area, as shown in Fig. 12. It was expected that all the places in the patterning area are equally exposed through all the same element lenses and their stitched areas by applying this countermeasure. For this reason, the same 15 μm L&S patterns were printed under the conditions of 10 μm/s main scan speed, 15mm/s sub-scan speed, and 55 mm sub-scan length for evaluating the effects of the new sub-scan method.

Figure 13 shows 15 μm L&S patterns printed in a 30 mm×15 mm area. The patterns were almost uniform at a glance, and no longitudinal stripes in the main scan direction appeared. When the patterns were observed by an optical microscope, pattern
shapes at point A, B and C were almost same, as shown in Fig. 14. Measured pattern width distribution is shown in Fig. 15. It was demonstrated that pattern width variation in the sub-scan direction became very small. Pattern widths were within a range of 14.7-16.6 μm for the mean width of 15.6 μm, and the width variation was within ±6% of the mean pattern width.

![Patterns at A, B, and C](image)

Fig. 14. Magnified views of 15-μm L&S patterns printed using the new sub-scan method.

![Width distribution of 15-μm L&S patterns](image)

Fig. 15. Width distribution of 15-μm L&S patterns printed using the new sub-scan method.

4. Conclusion
To improve the homogeneity of patterning performance in the field of projection exposure using a GRIN lens array, a new sub-scan method was contrived. It has been strange why pattern widths are abnormally changed at particular positions in the exposure fields despite of adding reciprocal sub-scans. In the conventional sub-scan, the scan lengths were as short as less than 7.7 mm, and the exposure was constantly continued for all the exposure time including the time when the sub-scan stages stopped and changed the scan direction. For this reason, it was worried that the exposure time was lengthened at both sub-scan ends, and stitching errors of patterns printed by neighbored lenses would be emphasized during the stops of the sub-scan stages. Therefore, the sub-scan length was vastly extended to more than the effective length of the GRIN lens array. By this countermeasure, it was aimed that reticle patterns were not exposed at all at both sub-scan ends where the sub-scan stages was stopped for changing the scan direction. As a result, all the parts in the exposure field were uniformly exposed, and pattern width uniformity of 15.6±1.0 μm was obtained. The pattern width homogeneity in the lens array direction was greatly improved, and the feasibility of homogeneous printing in a wide exposure field was demonstrated.

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