Research on a New Lithography Method Utilizing Laser Speckles for Printing Random Patterns

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A new simple and low-cost optical lithography method utilizing speckles was developed for printing random patterns on surfaces of three-dimensional objects with various shapes, and patterning characteristics were investigated by assembling a handmade exposure system. In the system, a laser beam was irradiated on a transparent diffuser plate, and generated speckles were projected onto a wafer coated with a resist. As a result, resist patterns with random shapes were successfully formed after the development. The size and number of patterns were controllable by adjusting the exposure time. Pattern sizes were between several tens microns and a few hundred microns. It was demonstrated also that the pattern sizes were controlled by changing the wafer position from the diffuser plate. However, the sizes and numbers of patterns were varied together when the exposure time or the distance between the diffuser and the wafer was changed.

Keywords: Random pattern, Lithography, Speckle

1. Introduction
Lotus leaves and rose petals have minute surface structures barely observable without using a microscope, and it causes their hydrophobic properties [1-7]. Similar hydrophobic performances have been discovered in various plants and insects though modified surface structures and the performances are different [8-17].

If water-repellent surfaces are obtained by giving some surface modifications on various things used outdoors daily or casually, utilities and values of the things will be much improved. The purpose of this research is to print random patterns with sizes of between tens microns and a few hundred microns on silicon wafers, stainless steel plates or other material objects with arbitrary shapes easily and inexpensively using an original lithography method utilizing laser speckles. If the patterned objects are etched, the surfaces are modified, and changes of hydrophobic properties are expected.

Generally speaking, in various optical systems, speckles are disliked because they cause fine uneven brightness distribution, and efforts for decreasing speckles are made vigorously [18-21]. In contrast, in this research, patterns are printed by positively utilizing high-contrast speckles. As a related research, speckle lithography is applied to creation of non-reflective silicon structure [22]. However, applications to improvements of hydrophobic properties have hardly been reported.

By using the speckle lithography, it is possible to provide simple and inexpensive exposure systems with large exposure fields for printing random patterns. In addition, though patterns are printed only on flat surfaces in most of the conventional lithography systems, it is considered that patterns can be formed on curved or stepped surfaces of objects with three-dimensional shapes.

It is expected that fine structures formed by etching substrates or objects using the random resist patterns as etching masks improve the hydrophobic properties. The idea of forming hydrophobic structures on non-planar objects utilizing speckles is novel and looks promising.

2. Properties of speckles
Speckles are light spots with irregular light intensity distributions generated by interference of
reflected or transmitted light from a rough material surface irradiated by a laser beam. Light scattered at the rough surface is radiated in various directions. When coherent light is used, the scattered light is complicatedly interfered each other, and high-contrast spot-like patterns with random shapes are generated in space. Because the speckle patterns are not formed by the imaging such as the projection using a lens or a mirror, they are clearly projected even if the distance between the rough surface and the object is changed. Therefore, they are thought applicable to the lithography onto arbitrary objects including three-dimensional ones, as shown in Fig. 1.

It was considered that if the bright and dark light distributions of speckles were projected on an object coated with a photosensitive resist film, patterns with random shapes were formed on the object after developing the exposed resist. Just to make sure, speckle patterns are projected on a flat white board, and taken by a camera before investigating the lithography. The photograph shown in Fig. 2 is a binarized image. White parts are places irradiated strongly, and black parts are places irradiated weakly. It was confirmed that patterns with various sizes between 10 and 100 μm and random shapes were observed.

3. Principle of exposure utilizing speckles

To confirm the principle, a simple experimental exposure system was assembled, and basic exposure characteristics of speckle lithography were investigated. An appearance of the system is shown in Fig. 3. The system consists of a laser diode with a wavelength of 405 nm and a power of 7 mW, a diffuser (#1000 SIGMAKOKI Co., Ltd.), and a wafer stage. The wafer was held by a vacuum chuck. They are fixed on a guide rail in a line.

To efficiently and systematically grasp the patterning characteristics, it was decided to execute many experiments on one wafer under various exposure conditions. Therefore, a light-shading plate was placed in front of the wafer stage for limiting the exposure area to a 10 mm square. The space between the laser and the diffuser is prepared for mounting additional optical lenses, if necessary.

4. Patterning results and discussion

4.1. Influence of exposure time

In this research, all the wafers were coated with a positive resist THMR-iP3300 (Tokyo Ohka Kogyo Co., Ltd.) in approximately 1 μm thick using a spin coater. The wafer diameter was 4 inches.

At first, influences of the exposure time on patterning characteristics were investigated. The exposure time was adjusted by turning the laser on and off. The distance between the diffuser plate and the wafer was set to 45 mm, and the exposure time was changed between 4 and 12 s. Printed patterns under each exposure time conditions are shown in Fig. 4.

Because the positive resist was used, the resist at the place where the speckle light intensity was strong disappeared in the development process, and patterns with irregular shapes were formed randomly. To evaluate the patterns quantitatively, the pattern size and the number of patterns were measured.
Measurement methods of the size and the number of patterns are shown in Fig. 5. As the pattern size, the maximum size of the largest pattern in the microscope image field of approximately $75 \times 10^{-3}$ mm$^2$ was measured. And, the number of independent patterns in which the resist was completely removed was counted in the microscope image field of 1 mm square.

Fig. 6 shows the relationship between the pattern size and the exposure time, and Fig. 7 shows the relationship between the number of patterns and the exposure time.

The pattern size increased as the exposure time was extended. Similarly, the number of patterns increased as the exposure time was lengthened.

It was found possible to adjust the pattern size and the number of patterns to some extent by controlling the exposure time. However, it was difficult to control both the pattern size and the number of patterns independently.
4.2. Influence of diffuser-wafer distance

Patterns were printed changing the distance $L$ between the diffuser and the wafer. $L$ was changed between 45 and 200 mm. Because the exposure system was required to have a large exposure field, an optical element such as a reduction projection lens was not inserted between the diffuser and the wafer. Therefore, the scattered light spread and the intensity of speckle light decreased as the wafer was moved away from the diffuser. For this reason, the light intensity $I$ on the wafer surface was measured. And the exposure time $t$ was adjusted as the exposure dose $D$ was almost constant using the following equation.

$$D = It$$  

(1)

Patterns printed at various distances are shown in Fig. 8. It seemed that the pattern size increased and the number of patterns decreased as the distance was lengthened. To clarify the relationship between the diffuser-wafer distance and the size, or the number of patterns, pattern sizes and numbers of patterns were evaluated quantitatively. The change of pattern sizes depending on the distance is shown in Fig. 9.

It was clarified that the pattern size could be controlled also by changing the distance between diffuser and wafer.

Next, the numbers of printed speckle patterns for various distances between diffuser and wafer were counted. Because the pattern density depended on the exposure time, the numbers were counted for various exposure times. Patterns used for the evaluation are shown in Figs. 10-12.

Figures show the results of exposures under different exposure-time conditions when the distance between diffuser and wafer is 45 mm, 100 mm, and 200 mm.
Fig. 8. Speckle patterns printed under various exposure time conditions when the distance between diffuser and wafer was 100 mm.

Fig. 11. Speckle patterns printed under various exposure time conditions when the distance between diffuser and wafer was 100 mm.

Fig. 12. Speckle patterns printed under various exposure time conditions when the distance between diffuser and wafer was 200 mm.

Fig. 13. Relationship between the exposure time and the number of patterns for each distance.

Counted pattern numbers for each distance and exposure time are shown in Fig. 13. It was clarified quantitatively that the number of patterns decreased as the distance between diffuser and wafer was lengthened. It was verified also that the number of patterns increased as the exposure time was extended regardless of the distance between diffuser and wafer.

5. Conclusion
It was demonstrated that random patterns were printed on the resist by using the light intensity distribution of laser speckles. Both the pattern sizes and the number of patterns increased as the exposure time was extended.

On the other hand, by lengthening the distance between diffuser and wafer, the pattern sizes increased and the numbers of patterns decreased.

It is expected that the new lithography method utilizing speckles is applicable to printing of random minute patterns on curved surfaces of three-dimensional structures with various unique shapes. It is prospected that hydrophobic properties and/or other surface characteristics may be improved, if the surfaces are etched or modified by using the resist patterns as masking materials.

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