Multi-layer Resist Process Using Top-layer Resist as Phase Shifters

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A new resolution enhancement method named SPLIT (Superimposition of Phase-shifting Layer for Image Transformation) is proposed. In the new method, top-layer resist patterns act as clear phase shifters for bottom-layer exposure. Since the phase shifters are closely contacted on the bottom-layer resist, very fine patterns are printed just under edges of top-layer shifter patterns. Theoretical resolution limit is infinitely small if the bottom-layer resist is infinitely thin. Using THMR iP3300 and KRF-M60G as the top- and the bottom-layer resists, feasibility of the new method is investigated. The top-layer shifter patterns are printed by projection exposure using blue light with a wavelength of 480 nm. The bottom layer is exposed to flood UV light with a wavelength of and 254 nm. As a result, 130-nm line pairs with a pitch of 240 nm are successfully printed.

Keywords: top-layer resist, phase shifter, SPLIT, resolution enhancement

1. Introduction

Fabrication technology of LSI devices has been greatly improved, and various powerful system LSI devices are developed. Such progress greatly depends on minimization of pattern sizes and pitches in lithography process.

Research targets in lithography have been guided by International Technology Roadmap for Semiconductor (ITRS), and pattern rules with a half pitch of 65 nm and 45 nm are required in 2007 and 2010, respectively. [1]

Projection optical exposure systems using KrF and ArF excimer laser sources are used as main tools in mass production. However, it is too difficult to print such tiny patterns by only utilizing conventional exposure systems.

For this reason, various new next generation lithography (NGL) systems are researched very eagerly. Recently, water immersion lithography using ArF excimer laser source has recognized as the most favorable candidate. Resist process has

been widely researched from various fields, and exposure tools will be available in the near future. Mirror projection lithography system using extreme ultra violet (EUV) light with a wavelength of 13 nm is also researched vigorously. It is thought that EUV lithography is one of the most promising candidates for the post immersion lithography. Electron beam lithography is also a candidate for NGL.

However, it is not easy to print such fine patterns less than 65 nm accurately, even using any NGL systems mentioned above. Therefore, other innovative ideas for printing finer patterns such as super resolution techniques and optical proximity effect correction (OPC) should be applied presumably.

In this paper, a new method is investigated for obtaining higher resolution in various lithography systems without depending on wavelengths and light sources. Using top-layer resist patterns as clear phase shifters, high resolution is expected.

2. Principle of Resolution Enhancement

Figure 1 shows the principle of the new exposure method that was named SPLIT (Superimposition of Phase-shifting Layer for Image Transformation). [2-4] Basic configuration of SPLIT is a double-layer resist structure shown in the figure. Top-layer resist can be patterned at first by any conventional exposure methods, and the printed top-layer resist patterns after development are used as clear phase shifters for the second exposure. In the second exposure, bottom-layer resist is exposed simply to parallel light rays without using any imaging optics. The top-layer resist patterns act as clear phase shifters, and light waves passing through the resist shifters and air interfere each other at the shifter boundaries. Therefore, fine line patterns are formed just under the edges of the top-layer resist patterns after developing the bottom-layer resist. To prevent the bottom-layer resist is sensitized to the first exposure light, different wavelengths

should be selected for the double exposures.

It is well known that resolution for optical projection lithography is limited by numerical aperture of the projection lens. This is the reason why immersion lithography is noted remarkably worthy. If patterns were printed in liquid, superficial numerical aperture becomes large in proportion to the refraction index of the liquid. However, if the phase shifters are formed directly on the resist instead of using phase-shifting masks, and if the phase shifters are illuminated directly without using projection optics, the resolution is not almost restricted by the numerical aperture. In other words, numerical aperture for ultimate contact printing is infinitely large, because any diffraction lights coming from patterns are not restricted at all.

Optical path-length difference Δd between the paths through resist and air is calculated by following eq. 1.

$$\Delta d = (n_t - 1)t. \quad (1)$$

Here, n_t is the refractive index of the top-layer resist, and t is the thickness of the resist shifter. To minimize interfered light intensity at shifter edges, Δd should be a half wavelength of the light for exposing bottom-layer resist. Therefore,

$$\Delta d = \frac{\lambda_b}{2}. \quad (2)$$

Here, λ_b is the wavelength.

From eqs. 1 and 2, best shifter thickness t is shown as follows.

$$t = \frac{\lambda_b}{2(n_t - 1)}. \quad (3)$$

3. Patterning Experiments

Double-layer resist structures were investigated for substantiating the new idea using possessing experimental tools.

Considering accessible exposure tools for each resist layer, wavelengths of around 480 nm and 254 nm were selected. Hand-made projection exposure system with a numerical aperture of 0.85 shown in Fig. 2 was used for printing the top-layer shifter patterns. [5]

Fig. 1 Principle of new exposure method SPLIT.

Fig. 2 Projection exposure system

Exposure light source of the system is a halogen lamp, and wavelengths of the lights are filtered using a blue color plate. Second exposure is a flood one and it needs no image optics. For this reason, 254-nm bright-line spectrum of a low-pressure mercury lamp was used.

THMR iP3300 (Tokyo Ohka Kogyo Ltd.) and KRF-M60G (JSR) were applied for top-layer and bottom-layer resist, respectively. At first, it was verified that double-layer resists were coated without mixing, and only the top-layer resist was exposed without losing sensitivity and resolution performance of the bottom-layer resist. They were coated in separate, and the top layer patterns were printed successfully as shown in Fig. 3.

Fig. 3 Top-layer resist patterns on bottom-layer resist.

Since the refractive index of THMR iP 3300 is $n_f=1.75$, appropriate top-layer resist thickness t

is calculated to be 171 nm by eq. 3. Thin resist was coated successfully by diluting the resist solution with a special thinner. Side-walls of top-layer resist patterns were made almost vertical in this thickness as shown in Fig. 3, though the photograph is somewhat vague. On the other hand, bottom-layer resist thickness was controlled to about 220 nm. Figure 4 shows an example of printed fine bottom-layer resist patterns with a line width of about 200 nm.

Fig. 4 Printed bottom-layer patterns

Top-layer patterns with smoother edges were required for printing finer bottom-layer patterns. For this reason, a chromeless phase-shifting mask was adapted. [6-8] Line and space patterns were used with a width of $1\ \mu\text{m}$, and line pattern widths of the top-layer resist printed at the shifter edges were slimmed by changing development time as shown in Fig. 5. Obtained minimum top-layer pattern width was 240 nm.

Fig. 5 Relationship between top-layer resist pattern width and development time.

Figure 6 shows the dependency of bottom-layer pattern width on exposure time. Minimum pattern widths were reduced to 130 nm

as shown in the figure. Figure 7 shows the printed bottom-layer resist patterns with a width of 130 nm and a pitch of 240 nm. It was verified that dense line pattern pairs with a width of at least about half the wavelength was printable.

Fig. 6 Bottom-layer pattern width dependency on exposure time

Fig. 7 Printed minimum bottom-layer patterns.

4. Analysis of Patterning Performance

Light intensity distribution in the bottom-layer resist was calculated for estimating process margin of SPLIT. The calculation assumed Fresnel diffraction. [9] Strictly speaking, the distance from the patterns is too short to apply Fresnel diffraction since the bottom-layer resist is closely contacted to the top-layer shifter patterns. However, Light intensity distribution calculated assuming Fresnel diffraction corresponds well to experimental results for conventional contact printing from experience. It is also noted in a reference that Fresnel diffraction is applicable for positions just close behind the objects. [10]

Diffraction distance z was assumed representatively to be half the bottom-layer resist thickness, that is to say, z was assumed to be 110 nm, since the bottom-layer resist thickness was 220 nm. Absorption of the exposure light energy through the top-layer resist was investigated actually. Energy transmittance T is measured by

$$T = \frac{I_t}{I_i} \quad (4)$$

Here, I_i and I_t are the incident light energy and transmitted light energy, respectively.

Amplitude absorption coefficient α was calculated by

$$\sqrt{T} = e^{-\alpha t} \quad (5)$$

$$\therefore \alpha = \frac{\ln \sqrt{T}}{-t} \quad (6)$$

Since T was 0.548 for 770-nm thick top-layer resist, α becomes

$$\alpha = 7.82 \times 10^{-4} \text{ nm}^{-1}.$$

T for 171-nm thick resist is calculated to be 0.875. Light intensity was calculated using a model shown in Fig. 8. When the top-layer resist thickness is just 171 nm, light intensity was calculated as shown in the figure. Valley width of the intensity curve is proportional to $\sqrt{\lambda_b z}$.

Fig. 8 Calculated light intensity.

In the case of conventional contact printing, gaps between a photo mask and a wafer are not

uniform and it is quite difficult to contact the mask and wafer ultimately close. On the other hand, double layer resists are completely contacted uniformly in the case of SPLIT. Therefore, diffraction distance z is kept constant and the intensity distribution is kept stable.

Setting some slice levels for the calculated light intensity curves, printed pattern widths were calculated. When the top-layer resist has phase-shifting errors, bottom-layer pattern widths change as shown in Fig. 9. Plus phase-shifting errors correspond to the case of too thick top-layer resist. It was clarified that the phase-shifting error margin was about ± 15 deg, if the pattern width tolerance was $\pm 10\%$. This phase-shifting error corresponds to the top-layer resist thickness error of ± 14 nm.

Fig. 9 Pattern width dependency on phase-shifting error.

Light intensity contrast C was also calculated by eq. 7, when the bottom intensity I_b of the dark part and minimum intensity I_a of the bright part are defined as shown in Fig. 8.

$$C = \frac{I_a - I_b}{I_a + I_b} \quad (7)$$

Figure 10 shows the relationship between phase-shifting error and the contrast value C . It is known from the figure that the contrast degrades only a little depending on the phase-shifting error or the thickness error. If the phase error is within ± 25 deg, contrast value C is kept more than 0.8.

This phase-shifting error of ± 25 deg corresponds to the thickness error of ± 24 nm.

Fig. 10 Contrast degradation caused by phase-shifting error.

5. Variations of Resist Structure

It is necessary to print top-layer resist patterns with vertical and sharp edges in order to get fine patterns using SPLIT. It is also favorable that the pattern edges are smooth. Moreover, since short-wavelength exposure lights are absorbed in the top-layer resist shifter, highly transparent shifters are preferable. Accordingly, multi-layer resist structure shown in Fig. 11 will be favorable. A highly transparent material is put between top and bottom-layer resists as an intermediate layer. The top-layer resist patterns is used as masks for etching the intermediate transparent layer, and the patterned intermediate transparent material works as the phase shifter.

Fig. 11 Multi-layer resist structure for SPLIT using a transparent intermediate layer.

On the other hand, multi-layer process for the bottom-layer resist will be effective to reduce the bottom-layer resist thickness and to enhance the

resolution. Figure 12 shows an example of resist structure. It will be also effective to combine SPLIT with other various multi-layer resist process such as a surface imaging process. [11-13]

Fig. 12 Multi-layer resist structure for SPLIT to improve the resolution in bottom-layer patterning.

7. Conclusion

A new resolution enhancement method SPLIT was proposed. Top-layer resist patterns on bottom-layer resist worked very well as phase-shifters, and feasibility of printing fine and dense patterns was clarified.

Double layer resists of THMR iP 3300 and KRF-M60G were successfully coated without being mixed each other. Top-layer resist patterns of THMR iP 3300 were printed by blue light with wavelengths of around 480 nm, using a hand-made projection exposure system. Bottom-layer resist KRF-M60G was exposed to flood UV light with a wavelength of 254 nm without using any reticles or imaging optics. When the bottom-layer resist was 220-nm thick, line patterns were formed at both edges of 240-nm wide top-layer shifters separately. Minimum bottom-layer pattern width was 130nm.

Phase-shifting error margin for the top-layer resist was investigated by calculating light intensity distribution. Phase-shifting error tolerance for suppressing the pattern width change within $\pm 10\%$ was ± 15 deg, and the tolerance for keeping the contrast more than 0.8 was ± 25 deg. Phase angles of ± 15 deg and ± 25 deg correspond to top-layer resist thickness of ± 14 nm and ± 24 nm, respectively.

SPLIT is applicable without depending on exposure wavelength, and theoretical resolution limit is infinite if the bottom-layer resist is thin enough. SPLIT will be a useful resolution enhancement technique to cleave a path for next generation lithography.

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