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Refilled mask structure for Minimizing Shadowing Effect on EUV Lithography

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ABSTRACT

Extreme ultraviolet (EUV) lithography using 13.5 nm wavelengths is expected to be adopted as a mass production technology for 32 nm half pitch and below. One of the new issues introduced by EUV lithography is the shadowing effect. Mask shadowing is a unique phenomenon caused by using mirror-based mask with an oblique incident angle of light. This results in a horizontal-vertical (H-V) biasing effect and ellipticity in the contact hole pattern. To minimize the shadowing effect, a refilled mask is an available option. The concept of refilled mask structure can be implemented by partial etching into the multilayer and then refilling the trench with an absorber material. The simulations were carried out to confirm the possibility of application of refilled mask in 32 nm line-and-space pattern under the condition of pre-production tool. The effect of sidewall angle in refilled mask is evaluated on image contrast and critical dimension (CD) on the wafer. We also simulated the effect of refilled absorber thickness on aerial image, H-V CD bias, and overlapping process window. Finally, we concluded that the refilled absorber thickness for minimizing shadowing effect should be thinner than etched depth.

Key Words : EUV, Mask shadowing, refilled mask structure, H-V CD bias

1. Introduction

Extreme ultraviolet (EUV) lithography using 13.5 nm wavelengths has become a leading lithography technology expected to provide a commercial solution for manufacturing semiconductor devices with a half pitch of 32 nm and below [1-2]. One of the new issues introduced by EUV lithography is shadowing effect due to the non-telecentric off-axis illumination on the mask and the three dimensional mask topography [3-5]. When the incident ray is parallel to the mask pattern (horizontal), there is no difference between designed pattern and printed pattern. However, if the incident ray is perpendicular to the mask pattern (vertical), the printed pattern is biased. This results in a horizontal-vertical (H-V) critical dimension (CD) biasing effect and ellipticity in contact hole pattern. Since the impacts of shadowing normally depend on the height of the absorber stack, application of thinner absorber is needed to minimize the shadowing problems. However, the thinner absorber is not a good solution because of the image contrast degradation.

In this study, the refilled mask structure is evaluated as an available option to minimize the shadowing effect. The concept of refilled mask structure can be implemented by partial etching into the multilayer and then refilling the trench with an absorber material [6-7]. The effects of etched depth and sidewall angle on image properties were studied using aerial image simulation. To evaluate the shadowing effect, we simulated data for H-V CD bias, aerial image, and process window with absorber thickness.

2. Experiment

All the simulations were carried out with the EM-Suite simulation tool [8]. The simulation to obtain data for image contrast, process window, and H-V CD bias was conducted using 32 nm line-and-space

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(L/S) patterns. Basically, exposure conditions of pre-production tool, a numerical aperture (NA) of 0.25, a degree of coherence of 0.8, and incident angle of 6° with 4x system, were applied [9]. The material parameters used in this simulation were taken from the CXRO database [10]. Refractive indexes of the mask stack are n = 0.9260 and k = 0.0436 for TaN, n = 0.9237 and k = 0.0064 for Mo, and n = 0.9990 and k = 0.0018 for Si at a wavelength of 13.5 nm. All simulations have a fixed grid node size dz = 0.35 nm. EUV mask stacks used in this simulation consist of a TaN absorber and 40 pairs of Mo/Si multilayer. Mo layer is 2.8 nm thick and Si layer is 4.2 nm thick. The effects of the projection optics aberration and the resist model were not considered in this simulation.

3. Results and Discussion

Fig. 1(a) shows a schematic diagram of a typical refilled mask structure. The designed refilled mask structure consists of absorber for EUV absorption and Mo/Si multilayer for EUV reflectivity. This is a geometric approach to minimize shadowing effect by flattening the mask surface. Since the shadowing effect and image contrast have conflicting dependences on the height of the absorber stack, application of refilled mask structure can be a solution to correct shadowing problems with conserving high image contrast. The simulation results in Fig. 1(b) show the image contrast vs. refilled depth using 32 nm L/S horizontal and vertical pattern. The image contrast is defined as $(I_{max} - I_{min}) / (I_{max} + I_{min})$, where I_{max} and I_{min} are maximum and minimum intensities in the aerial image curves, respectively. The refilled depth is varied from 0 nm to 98 nm at intervals of 7 nm. As the refilled depth increases, the image contrast initially increases from 0 nm to 56 nm and then remains constant, as shown in Fig. 1(b). The image contrast difference between the horizontal and vertical pattern was negligible.

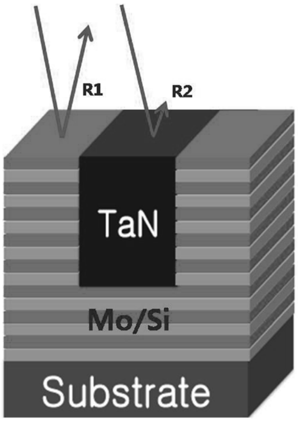


Fig. 1(a). Schematic diagram of refilled mask structure.

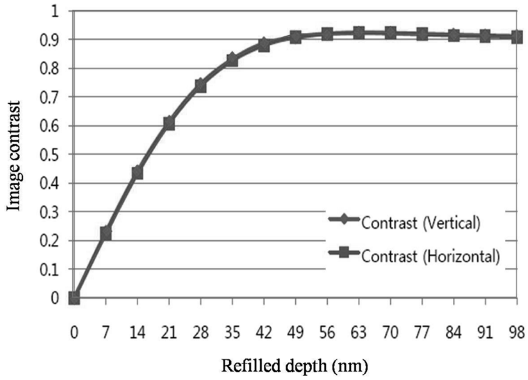


Fig. 1(b). Image contrast vs. refilled depth.

We chose an etch depth of 77 nm with different refilled depth to evaluate the imaging properties. Etching process during mask patterning can cause sidewall profiles in the multilayer. Therefore, we calculated the influence of sidewall angle of Mo/Si multilayer to imaging performance. Fig. 2(a) shows the near field intensity of refilled mask with sidewall angle of -10° and 10° at the 32nm L/S vertical pattern.

It should be noted that the mask pattern size is

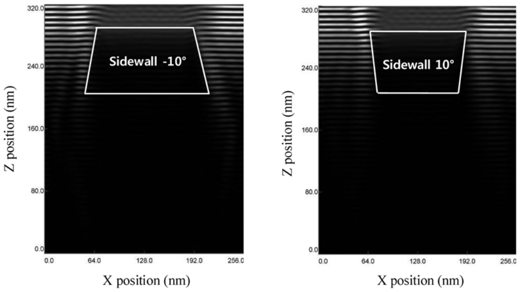


Fig. 2(a). Near field intensities with refilled mask with sidewall angle.

defined as the dimension at the top surface. The negative sidewall generally allows lighter absorbed by absorber and thus less light reflected. This could result in a high image contrast and a wider line printed, while the positive sidewall generally allows less light absorbed by absorber and thus more light reflected. This could result in a low image contrast and a narrower line printed [11]. The image contrast and CD change with sidewall angle was also calculated. The sidewall angle of Mo/Si multilayer was varied from -10^o to 10^o at intervals of 1^o at the 32 nm L/S vertical pattern. Fig. 2(b) shows the calculated image contrast vs. sidewall angle. As sidewall angle increases, the image contrast decreases slightly, but not seriously. Fig. 2(c) shows the calculated vertical pattern CD vs. sidewall angle.

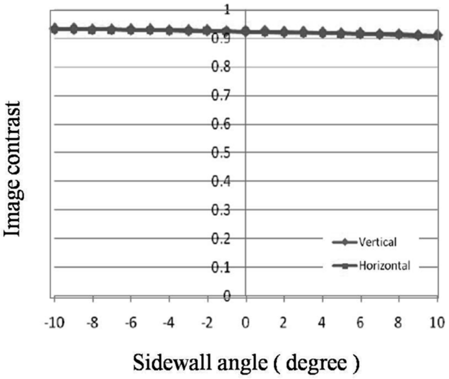


Fig. 2(b). Image contrast vs. sidewall angle.

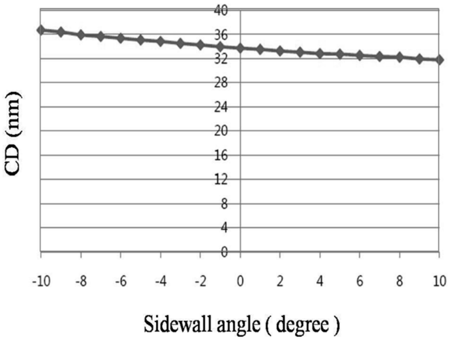
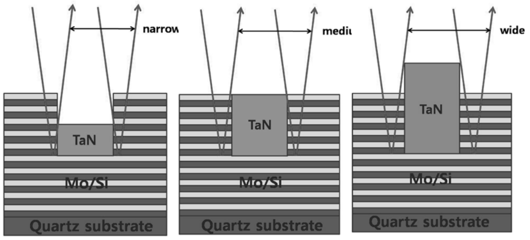


Fig. 2(c). CD vs. sidewall angle.

For vertical pattern, the light is illuminated perpendicular to the pattern so that there is shadowing. As sidewall angle varied from -10^o to 10^o, the vertical pattern CD increased slightly. Fig. 3 shows the schematic design to explain the effect of refilled absorber thickness vs. etched depth. The etched depth was fixed at 77 nm and refilled absorber thickness was varied from 57 nm to 97 nm.



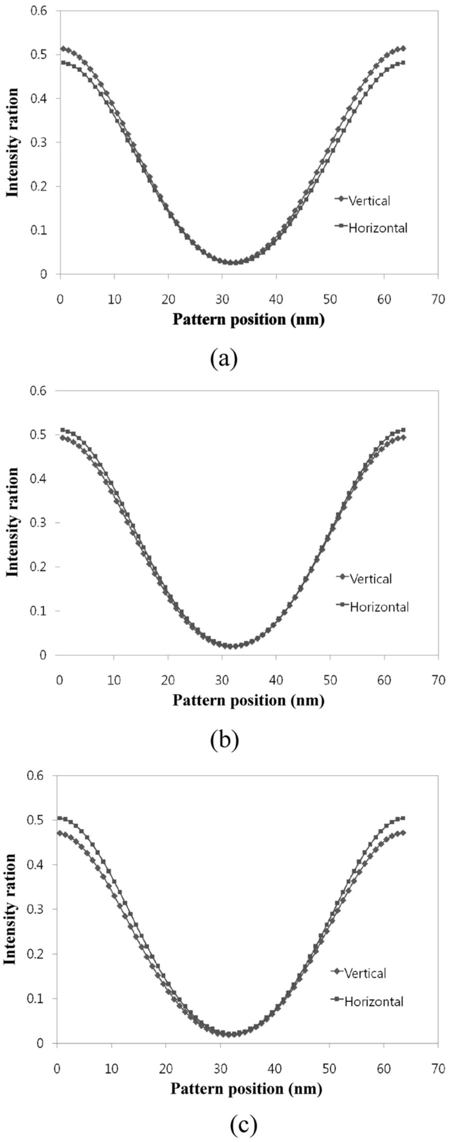
(a) (b) (c)

Fig. 3. Schematic design to explain the effect of refilled absorber thickness vs. etched depth (a) refilled absorber thickness < etched depth and (b) refilled absorber thickness = etched depth and (c) refilled absorber thickness > etched depth.

When the refilled depth is smaller than etched depth, the reflection area of multilayer is increased. This results in a narrower vertical pattern CD than horizontal pattern CD. However, when the refilled depth is larger than etched depth, the reflection area of multilayer is decreased due to the shadowing effect. This results in a wider vertical pattern CD than horizontal pattern CD. We can conclude that the H-V CD bias could be controlled changing the refilled absorber thickness at the above refilled mask structure. Fig. 4 shows the aerial image with refilled absorber thickness.

As the refilled absorber thickness increases, the width of aerial image in vertical pattern increases. When the refilled absorber thickness is smaller than etched depth, the vertical pattern CD is smaller than the horizontal pattern CD due to the reflection from wider range of multilayer as shown in Fig. 3(a) and Fig. 4(a). However, when the refilled absorber thickness is larger than etched depth, the vertical pattern CD is larger than the horizontal pattern CD due to the shadowing effect, which is shown in Fig. 3(c) and Fig. 4(c). Fig. 5 shows the calculated H-V CD bias vs. refilled absorber thickness.

The H-V CD bias is defined as (CD_h – CD_v), where CD_h and CD_v are the horizontal pattern CD and the



(a)

(b)

(c)

Fig. 4. Aerial image with refilled absorber thickness (a) 57 nm, (b) 77 nm, and (c) 97 nm with fixed trench depth of 77 nm.

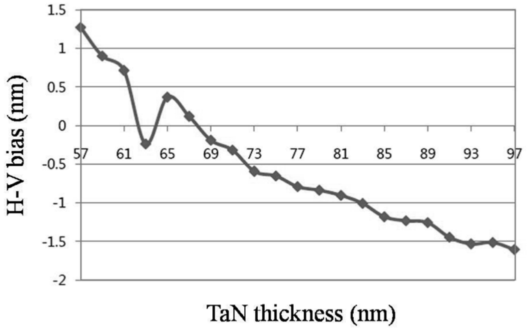


Fig. 5. H-V CD bias vs. refilled absorber thickness.

vertical pattern CD in same level of aerial image. When the refilled absorber thickness is smaller than etched depth, the value of vertical pattern CD is decreased. Therefore, the H-V CD bias has the positive values. However, when the refilled absorber thickness is larger than etched depth, the value of vertical pattern CD is increased, and the H-V CD bias has negative values. However, it is not a refilled absorber thickness of 77 nm where the H-V CD bias is zero. This is related to the reflection area of multilayer and CD oscillation with TaN thickness. Fig. 6 shows the calculated CD variation of 32 nm L/S vertical and horizontal pattern with TaN refilled absorber thickness.

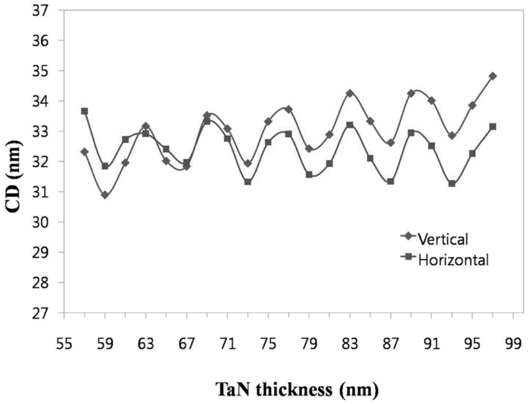


Fig. 6. CD variation of 32 nm L/S vertical and horizontal pattern with TaN refilled absorber thickness.

As the TaN refilled absorber thickness decreases, the vertical pattern CD decreases with oscillation. However, the horizontal pattern CD remains constant. The oscillation, the period of which is about half of the wavelength, is due to the multiple constructive interferences of reflected light [12]. As the TaN refilled absorber thickness decreases, CD difference between horizontal and vertical pattern decreases and CD value crosses each other at about 67 nm TaN refilled absorber thickness. Therefore, we can find out the thickness where the H-V CD bias becomes zero through controlling proper refilled absorber thickness. The results of overlapping process windows at horizontal and vertical patterns were simulated with a 32 nm 1:1 L/S pattern, as shown in Fig. 7. On the basis of the Bossung plot results, process window analysis was carried out with a ±10% tolerance on the target CD. The elliptical process windows were obtained from the aerial image at the refilled depth of 57 nm, 67 nm 77 nm and 97 nm. The best overlapping process window was obtained at refilled depth of 67 nm as shown in Fig 7(b). Thus, the optimization of refilled depth could be a possible solution to minimize the shadowing effect while conserving high image contrast.

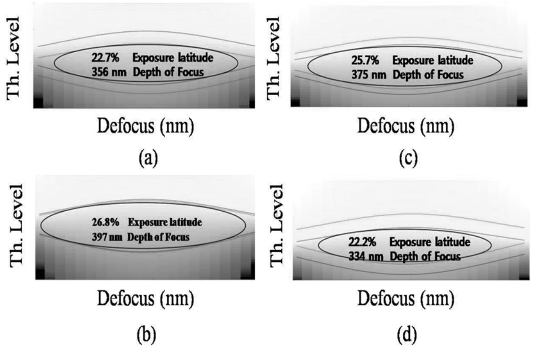


Fig. 7. Overlapping process windows with refilled absorber thickness (a) 57 nm, (b) 67 nm (c) 77 nm, and (d) 97 nm.

4. Conclusions

This paper has demonstrated that the refilled mask is a viable option to minimize shadowing effect. The concept of refilled mask structure can be implemented by partial etching of the multilayer and refilling the trench with TaN absorber. When the refilled absorber thickness is smaller than etched depth, the vertical pattern CD is smaller than the horizontal pattern CD due to the reflection at sidewall edge of multilayer. When the refilled absorber thickness is larger than etched depth, the vertical pattern CD is larger than the horizontal pattern CD due to the shadowing effect. Therefore, we can find out the thickness when the H-V CD bias becomes zero through controlling proper refilled absorber thickness. In this simulation condition, the H-V CD bias was zero at a refilled depth of 67 nm into 77nm trench. Thus, the shadowing effect could be minimized through the optimization of the refilled mask structure.

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