Mask modification for the shadow effect reduction by rigorous coupled-wave analysis in extreme ultraviolet lithography

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Introduction

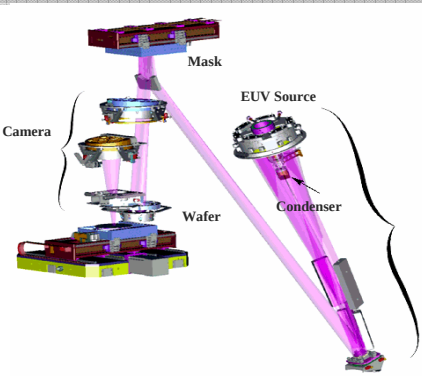


Figure 1. System of extreme ultraviolet lithography

- Extreme ultraviolet lithography (EUVL) is believed to be the next generation lithography and so it is seriously under study globally.
- The absorber layer make a shadow since the light is shining the mask with some degrees from the normal on-axis.
- The shadow effect in EUVL mask is an important factor that decreases the contrast of aerial image and as a result line width variation and pattern shift happen.
- Among the several possible mask structures, we focused on the mask edge slope with a typical incident angle of 5°
- We analyzed electromagnetic wave around the mask by rigorous coupled-wave analysis (RCWA) and reflectivity in the modified mask structure.

Rigorous Coupled-Wave Analysis

1. Derivation of the Coupled-Wave Equations

The periodic modulation is represented by the Fourier expansion

$$n^2(x,z) = \sum_{i=-\infty}^{+\infty} \tilde{n}_i \exp[\, ji(K_x x + K_z z)]$$

Tangential components of the electromagnetic field

$$E_y(x,z) = \sum_{i=-\infty}^{+\infty} E_y^{(i)}(z)\exp(\; jk_x^{(i)} x)$$

$$h_x(x,z) = \sum_{i=-\infty}^{+\infty} h_x^{(i)}(z)\exp(\; jk_x^{(i)} x)$$

From Maxwell's equations

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} = j\omega\mu\vec{H} \;\Rightarrow\; h_x(x,z) = \frac{j}{k_0}\frac{\partial E_y(x,z)}{\partial z} \;\Rightarrow\; \frac{dE_y^{(i)}(z)}{dz} = -jk_0 h_x^{(i)}(z)$$

Coupled-Wave Equations

$$\frac{d\left[h_x^{(i)}(z)\exp(-jiK_z z)\right]}{dz} = -j\left[iK_z h_x^{(i)}(z)\exp(-jiK_z z) + \frac{\left[k_z^{(i)}\right]^2}{k_0} E_y^{(i)}(z)\exp(-jiK_z z) + k_0 \sum_{l\neq i} \tilde{n}_{i-l} E_y^{(l)}(z)\exp(-jlK_z z)\right]$$

$$\frac{d\left[E_y^{(i)}(z)\exp(-jiK_z z)\right]}{dz} = -j\left[iK_z E_y^{(i)}(z)\exp(-jiK_z z) + k_0 h_x^{(i)}(z)\exp(-jiK_z z)\right]$$

- We analyze the propagation of waves inside the grating, using $E_y(x,z)$ and $h_x(x,z)$.
- Coupled-wave equations define an infinite system of first-order differential equations.

2. Computation of Matrices using Matlab

Coupled-Wave Equations written in the matrix form

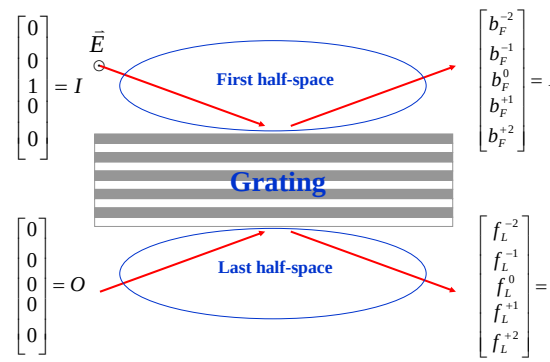
$$\frac{dU(z)}{dz} = [M]U(z)$$

$$\begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} = [C(z_0)]^{-1}\left([P_0(z_0)]\exp\{-(z_1 - z_0)[D]\}[P(z_1)]^{-1}\right)[C(z_1)]\begin{bmatrix} f_L^{-2} \\ f_L^{-1} \\ f_L^{0} \\ f_L^{+1} \\ f_L^{+2} \end{bmatrix}$$

$$\begin{bmatrix} b_F^{-2} \\ b_F^{-1} \\ b_F^{0} \\ b_F^{+1} \\ b_F^{+2} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Characteristic matrix

$$\prod_{l=0}^{m-1}\left([P_l(z_l)]\exp\{-(z_{l+1} - z_l)[D_l]\}[P_l(z_{l+1})]^{-1}\right)$$



- We propose a rigorous and efficient method for calculating the coupled-wave diffraction of periodic gratings of arbitrary thickness.

2 main steps for calculating

(1) Calculation of the eigenvalues and the eigenvectors of a constant coefficient matrix that characterizes the diffracted wave propagation and coupling.

(2) Resolution of a linear system deduced from the boundary matching conditions.

The system coefficients contain exponential functions of the product eigenvalue × thickness.

Simulation

1. Simulation Condition

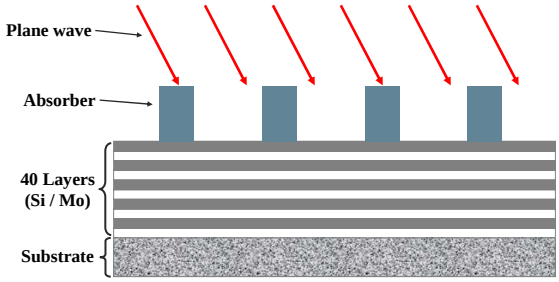


Figure 2. Schematic diagram of an EUVL conventional mask

Wavelength	13.5 nm
Line / Space	30 / 60 nm
Incident angle	5°

	Material	Thickness (nm)	n	k
Absorber	Cr	80	0.932763	0.038639
Mo / Si	Mo	2.8	0.921838	0.006334
	Si	4.1	0.999537	0.001824

- We consider a multilayer grating and an absorber grating with a periodic index profile.

- We assume that the incident light has transverse electric (TE) polarization and the grating has finite conductivity.

- We assume that the incident light is plane wave and coherence light.

2. Multilayer

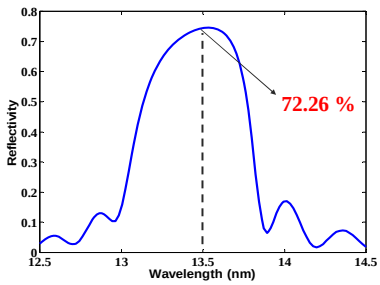
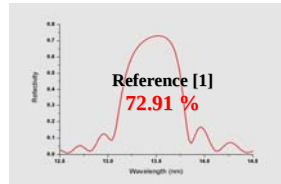


Figure 3. Variation of the reflectivity with the multilayer



Solid-EUV simulation result	
Wavelength	13.5 nm
Reflectivity	72.64 %

3. Multilayer + Absorber

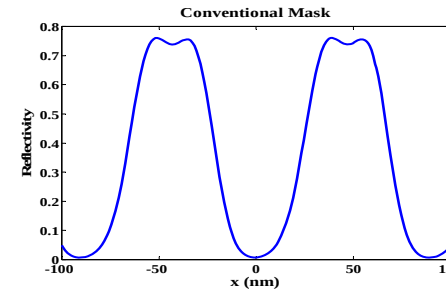
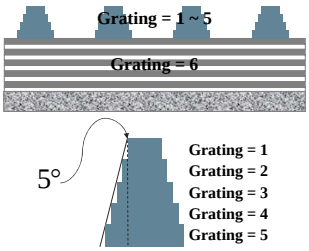


Figure 4. Variation of the reflectivity with the conventional mask

Mask Modification

1. Simulation with Modification Mask



Wavelength	13.5 nm
Material	Cr
Top line / Space	24.3 / 65.7 nm
Bottom line / Space	30 / 60 nm
Height	80 nm
Number of grating	5

Figure 5. Schematic of modified mask and simulation condition

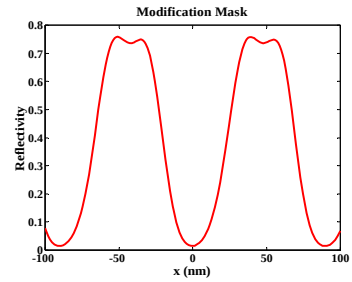


Figure 6. Variation of the reflectivity with the conventional mask

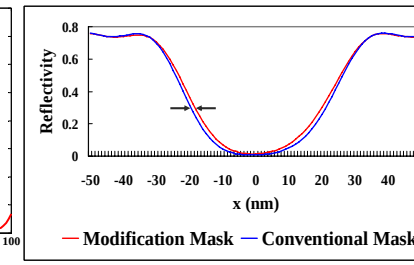


Figure 7. The comparison of conventional mask and modification mask reflectivity

- Modified mask can make desired width for for both line/space dense pattern which is closer to the target CD than conventional mask.
- Modified sidewall angle EUV mask can reduce the shadow effect.

Summary and Conclusion

- The shadow effect is an important factor that decreases the contrast of aerial image and as a result, the line width variation and the image position shift happen.
- The mask modification was performed in order to reduce the absorber shadow effect.
- We analyzed electromagnetic wave around the mask by rigorous coupled-wave analysis (RCWA) and compared with the results based on finite difference time domain (FDTD) method.
- The mask modification could reduce the absorber shadow effect.

1. http://www-cxro.lbl.gov.