A practical approach for modeling EUVL mask defects

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Abstract

An approximate method is proposed to calculate the EUV scattering from a defect within a multilayer coating. In this single surface approximation (SSA) the defective multilayer structure is replaced by a single reflecting surface with the shape of the top surface of the multilayer. The range of validity of this approximation has been investigated for Gaussian line defects using 2D finite-difference-time-domain simulations. The SSA is found to be valid for sufficiently low aspect ratio defects such as those expected for the critical defects nucleated by particles on the mask substrate. The critical EUVL defect size is calculated by combining the SSA with a multilayer growth model and aerial image simulations. Another approximate method for calculating the aerial image of an unresolved defect is also discussed. Although the critical substrate defects may be larger than the resolution of higher NA cameras, the point defect approximation provides a useful framework for understanding the printability of a wide range of defects.

I. Introduction

The reflective masks used in extreme ultraviolet lithography (EUVL) consist of a low thermal expansion glass substrate coated with a Mo/Si multilayer and a patterned absorber layer. Defects within the multilayer coating are of particular concern since they are difficult to repair. Defects consisting of a local bump within the multilayer, need only have a height of $\lambda/4$ (λ= 13.4 nm) to effectively scatter EUV light. Simulations[1] of $\lambda/4$ phase defects with a top-hat profile indicate that rather small defects can be printable in an EUV imaging system.

The physical structure of a defect produced by a particle within the multilayer coating of an EUVL mask can be complex. Particularly important are defects nucleated by particles or pits on the mask substrate. Recent experiments on the growth of Mo/Si multilayers over gold nanoparticles have lead to an improved understanding of the physical structure[2] of such defects. In order to determine the smallest particle capable of producing a printable defect, it is crucial to be able to model such defects. Modeling is also essential in guiding strategies to enhance the smoothing of substrate defects either by controlling the multilayer deposition or by using an additional buffer layer. The interaction of EUV light with such a defect can be rigorously calculated using finite difference time domain (FDTD) simulations[3]. However, such simulations are computationally intensive and their use is thus limited. In this work we show that it is possible to make approximations for both the scattering and imaging of a defect greatly simplifying the calculation of printability for an important class of defects.

As outlined in Fig. 1, the problem of calculating defect printability can be divided into four independent parts. The first part is to determine the physical structure of the defect in the multilayer. The recent experiments[2] on defects nucleated by gold nanoparticles have lead to the development of an analytical model describing the growth of a defect within a multilayer.

The second part of the problem is to calculate the scattering of EUV light from the defect. An approximate method is introduced where the complex multilayer structure is replaced by a single reflecting surface with the shape of the top surface of the multilayer. We refer to this as the single surface approximation (SSA). The range of validity of the SSA has been investigated using FDTD simulations of EUV light scattering from 2D Gaussian defects.

The third part is to calculate the imaging of the reflected and scattered EUV light by the optical system. The image of a critical defect unresolved by the lithographic camera can be estimated using a point defect approximation. In this approach the aerial image is given by the point spread function of the camera and is proportional to the total scattering cross section of the defect.

Finally, a criterion must be applied to the aerial image to determine whether the given defect is printable. For example, this may involve looking at the increase in the width of a nearby pattern.

Both the SSA and the point defect approximation provide a practical approach to estimating the printability of critical defects. These simple approximations allow for the investigation of a wide range of defect sizes, camera numerical aperture NA, and smoothing and buffer layer strategies that would be impractical with the more rigorous approaches.

II. Multilayer Defect Structure

Significant progress has been made[2] in understanding the nature of defects within multilayers. Experiments have been performed using gold nano-particles with diameters ranging from 30 nm to 100 nm deposited on the substrate. The shape of the bump at the top surface of the multilayer was found to depend on the angle of incidence of the deposition flux. The surface bump size was minimized with near-normal incidence for ion beam deposited Mo/Si multilayers, where a Gaussian bump was observed with a full width at half maximum (FWHM) of about 65 nm. The height of a Gaussian bump with volume, V, and FWHM = 2.355ω is given by

$$h(r) = \frac{V}{2\pi\omega^2} e^{-r^2/(2\omega^2)} .$$

Cross-sectional TEM results indicate that the layers of the multilayer are intact and vertically displaced by the particle, see Fig. 2. It was also observed that the volume of the Gaussian bump was reduced from that of the seed particle. A non-linear growth model was developed to describe these observations.

III. Scattering

Incident EUV light will be scattered by a multilayer defect. A rigorous calculation of the scattering is possible using, for example, FDTD simulations but such calculations are computationally expensive. For the related problem of scattering from a multilayer deposited on a rough surface[4], it is found that for roughness with sufficiently long periods and small amplitudes the rough multilayer can be approximated by a single surface with the same topography. The scattering may then be calculated from simple scalar diffraction theory. We refer to this as the single surface approximation (SSA).

In the SSA the perturbation in the reflected field produced by a defect with height *h(x)* and with EUV light at normal incidence, is given by

$$F(\vec{x}) = \exp(i4\pi h(\vec{x})/\lambda) - 1\,.$$

Here the amplitude of the reflected field is unaffected and the phase is shifted in proportion to the local surface height. The SSA is expected to be valid if *h(x)* varies slowly enough. In order to determine the limits of applicability of the SSA we have performed 2D FDTD simulations and compared the results with the predictions of the SSA. A comparison is shown in Fig. 3 for a Gaussian line defect with a FWHM of 60 nm and a peak height of 1.5 nm. In the FDTD calculation, a plane wave with a wavelength of 13.4 nm was normally incident on the surface of a Mo/Si multilayer with 40 periods. Each bilayer consisted of 3 nm of Mo and 4 nm of Si and the FDTD cell size was 0.5 nm. The FDTD simulations were performed with a Gaussian defect that was perfectly replicated in all 40 bilayer pairs. The light was polarized with the electric field along the direction of the linear defect. The reflected "near-field" intensity was sampled in a plane 315 nm above the multilayer top surface. The oscillations in the near field intensity are a result of the propagation of the scattered light and depend on the distance to the sampling plane. To match the FDTD results with the SSA, it was necessary to assume that the defect surface was located approximately 5 layers below the multilayer surface. That is to say that a pure phase perturbation would occur at approximately 35 nm below the top multilayer surface. This seems reasonable since it is about the depth where the electric field intensity drops to half of its value at the surface.

Since the electric field above the mask surface depends on the location of the sampling plane and since it is the far-field diffracted light that determines the aerial image, it was decided to perform the comparisons in the far-field using the differential scattering cross section. The differential scattering cross section is calculated from Fourier transform of the reflected field by

$$\frac{d\sigma}{d\Omega} = \frac{\lambda^2}{4\pi^2}|S|^2 \text{ where } S(\vec{f}) = -\frac{2\pi}{\lambda^2}\int_A F(\vec{x})e^{-i2\pi\vec{f}\cdot\vec{x}}da .$$

The amplitude of the diffracted field is S and $\vec{f} = \vec{\xi}/\lambda d$ where $\vec{\xi}$ is the location of a point in the pupil plane and d is the distance to the pupil plane. For a line defect the problem reduces to one dimension and the scattering cross section per unit length, which depends only on one angle, is

$$\frac{1}{L}\frac{d\sigma}{d\theta}=\frac{1}{\lambda}\left|\int F(x)e^{-i2\pi fx}dx\right|^2.$$

where $f = \sin\theta/\lambda$.

A series of FDTD simulations were performed for Gaussian line defects with various heights and widths. Calculations of the differential scattering cross section are shown in Fig. 4 for a set of Gaussian line profiles with FWHM=60 nm. When the peak height is less than $\lambda/4$ the phase change is smaller than 180 degrees and the differential scattering cross section is approximately Gaussian in shape. When the peak height exceeds $\lambda/4$, a more complicated angular distribution is observed.

The results of these cases and also those for wider and narrower Gaussian profiles are summarized in Fig. 5. In general the SSA works well for low aspect ratio profiles but breaks down if the peak height is greater than about FWHM/6. Also shown in Fig. 5 are the expected sizes of defects nucleated by a particle at the substrate beneath the multilayer. The defect size at the top surface was calculated using the multilayer growth model described in Ref. 1. It can be concluded that the SSA should provide an accurate description of the EUV scattering from the defects nucleated by particles approximately 50 nm in diameter and smaller. The curve for the critical defect size is derived from aerial image simulations that use the SSA and are discussed in the last section of this paper.

An important assumption in the SSA is that the perturbation caused by the defect doesn't vary much in the top layers of the multilayer. While this is reasonable if the defect is nucleated near the substrate it is not expected to hold for a particle that is embedded in the top layers. Another approximate model recently introduced by Ito[5] may be better suited for these cases.

The above mentioned simulations were performed with EUV light normally incident on the mask. In actuality the light will be incident off normal, with an average angle of a few degrees and with a range of angles dictated by the partial coherence of the illumination. FDTD simulations were also run with the light incident at 4 degrees off normal. As expected, there was essentially no difference in the differential scattering cross section for these isolated defects.

Pits or scratches in the mask substrate can also produce defects. In the SSA, the scattering is the same for either a bump or pit of the same size. This assumption was tested with the FDTD simulations for a set of replicated Gaussian scratches with a FWHM of 60 nm and depths ranging from 1.5 nm to 20 nm. Again, good agreement was found with the SSA for depths shallower than about 10 nm.

IV. Imaging

The calculation of the aerial image for an optical system with partially coherent illumination is well understood. There are commercially available programs which, given the field at the mask, will calculate the aerial image with reasonable computing resources. Nevertheless, a simple approximate method is often useful for estimations and in providing physical insight.

Consider an isolated defect in an open field. For coherent illumination, the perturbation to the field in the image plane is

$$u(\vec{x}) = -\frac{\lambda^2}{2\pi}\int_P S(\vec{f})e^{ikW(\vec{f})}e^{-i2\pi\vec{f}\cdot\vec{x}}\,d\vec{f}\ ,$$

where the integral is performed over the pupil of the imaging system, $k=2\pi/\lambda$, and $W(f)$ describes the phase errors of the optical system.

The light scattered by an *unresolved* defect will be a spherical wave with approximately constant amplitude and phase across the entrance pupil of the optical system and

$$u(\vec{x}) \approx -\frac{\lambda^2}{2\pi}S(0)\int_P e^{ikW(\vec{f})}e^{-i2\pi\vec{f}\cdot\vec{x}}\,d\vec{f}$$

where the integral is the amplitude point spread function (PSF) of the optics. In the focal plane of a diffraction-limited optical system, the phase errors of the optical system are zero and

$$\int_P e^{-i2\pi\vec{f}\cdot\vec{x}} d\vec{f} = \mathrm{PSF}(r) = \frac{\alpha^2}{4\pi}(2\frac{J_1(\alpha r)}{\alpha r}) \quad \text{where} \quad \alpha = k\mathrm{NA},$$

where NA is the numerical aperture of the imaging optic. In this case the aerial image intensity is

$$I(r) = |1 + u(r)|^2 \approx 1 + 2u_1(r) \approx 1 - \frac{\lambda^2}{\pi} S_1(0)\mathrm{PSF(r)},$$

where u_1 refers to the real part of u. Finally we can make use of the optical theorem to relate the real part of the forward scattering amplitude to the total extinction cross section

$$\sigma = \frac{\lambda^2}{\pi} S_1(0)$$

So we have the image intensity of an unresolved object

$$I(r) \approx 1 - \sigma\mathrm{PSF}(r) \qquad (2)$$

This is just what would be expected from the conservation of energy. The light missing from the integrated image intensity is equal to the total cross section, since we have assumed that nearly all of the light is scattered out of the entrance pupil of the camera. This approximation is valid for either amplitude or phase defects. The central dip in the aerial image intensity is

$$1 - I(0) = \frac{\sigma}{\pi r_0^2} \quad \text{where} \quad r_0 = \frac{\lambda}{\pi MNA}$$

The magnification M is typically 1/4. The main effect of partially coherent illumination is to reduce the oscillations in the wings of the aerial image. The central dip is unaffected for a typical value of the partial coherence (~0.7).

For an unresolved defect, the image in the focal plane is completely described by just one number, the scattering cross section of the defect. If the phase errors, described by W(*f*), are not zero then the PSF can be complex and the aerial image can depend on both the real and imaginary parts of S.

It is interesting to plot the total cross section of defects nucleated by particles at the substrate. This is shown in Fig. 6 where the profile of the bump at the top surface of the multilayer was calculated using the multilayer growth model[2] with the typical parameters (ν = 1.2 nm, $\delta\Lambda$ = 0.8 nm) for an ion beam deposited multilayer. The scattering was calculated using the SSA. The potential improvement with a buffer layer to enhance the smoothing, is illustrated with the curve labeled optimized buffer in Fig. 6. The scattering cross section was calculated with growth parameters (ν = 0.3 nm, $\delta\Lambda$ = 1.5 nm) chosen for increased volume contraction. Recently, significant improvements in smoothing have been obtained using a secondary ion beam directed at the mask substrate[6].

A rough estimate for the range of validity of this point defect approximation can be made by assuming that less than 30% of the scattered light must be collected by the optics. For a Gaussian bump with peak height smaller than $\lambda/4$, this gives

$$\text{FWHM} < 0.2\pi r_0 .$$

For a camera with NA=0.1 and M=0.25 the condition FWHM < 107 nm is satisfied by the typical defects which occur in ion beam deposited multilayers (FWHM ≈ 65 nm). However, for higher NA cameras even the smallest defects will be partially resolved. In this case the printability will be overestimated by the point defect approximation.

V. Printability

By definition, a defect is "printable" only if it causes the resulting printed image to be out of specification. One of the more critical applications is the gate in a microprocessor chip. Tight control is required for the width of the gate since it can influence the chip speed. To determine the printability of a defect in proximity to a gate, the aerial image was calculated for a defect in a 1:3 pitch line to space pattern. A diffraction-limited imaging system (NA=0.25) was assumed with partially coherent illumination (0.7). Simulations were performed for 25, 35, and 45 nm wide lines. A simple threshold model was used for the resist.

An interesting property of these phase defects is that the disturbance in the aerial image can become worse away from the focal plane. In order to determine whether a defect is printable, it is therefore important to simulate its effect throughout the range of focus. There are a variety of criteria that have been applied to determine defect printability. In Fig. 7, the results are shown for a set of Gaussian defects with a FWHM of 60 nm located 35 nm (on the mask) from a 35 nm line (in the image). The maximum increase in linewidth is plotted versus peak height of the Gaussian. The increase in linewidth is largest with 100 nm of defocus. Using a 20% criterion, defects higher than 2 nm would be printable. If the allowable linewidth increase is 10% then defects higher than 1.1-nm would be printable. In the second half of Fig. 7 the aerial image of an isolated 2-nm high Gaussian defect is shown. Similar simulations for Gaussian defects with widths between 35 nm and 150 nm were performed and the results were used to generate the curve shown in Fig. 5.

VI. Conclusion

Rigorous FDTD simulations of the EUV scattering from Gaussian line defects have been used to determine the range of applicability of the single surface approximation (SSA). The SSA is found to provide a good approach to modeling the critical defects for EUVL which are nucleated by particles on the mask substrate. A simple point defect approximation to the imaging of a defect is described and provides an intuitive view of the imaging of unresolved defects. Each of these provide a simple and practical approach to determining the printability of small defects within an EUVL mask.

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Figure Captions

Figure 1. The defect printability problem can be divided into four parts: 1) determining the physical structure of the defect, 2) calculating the electro-magnetic scattering, 3) calculating the aerial image, 4) applying a criterion to determine the printability. The calculation of EUV scattering from the defect, using for example finite difference time domain (FDTD) simulations, is particularly difficult and an approximate method (SSA) is described here.

Figure 2. The structure of a defect nucleated by a gold particle on the mulilayer substrate. AFM measurements of the top surface of the multilayer are well described by a growth model described in Ref. 2.

Figure 3. Comparison of the single surface approximation (SSA) to rigorous FDTD calculations of the electromagnetic field scattered from a Gaussian line defect with FWHM=60 nm and peak height = 1.5 nm. Good agreement is obtained for the reflected intensity in a plane 315 nm above the mask surface.

Figure 4. The differential scattering cross section of a set of line defects with FWHM=60 nm. The results calculated by FDTD simulations are compared with the SSA.

Figure 5. The single surface approximation (SSA) is found to be valid for Gaussian defects with a sufficiently large width and small height. The points show the expected size of defects nucleated by a particle at the substrate beneath the multilayer coating, as calculated using a multilayer growth model. The size of a critical defect was determined from the calculated aerial image (NA = 0.25, coherence = 0.7, and

perfect optics) of a defect near a 35 nm line (140 nm on the mask). A defect is considered printable if it causes a 20% CD change anywhere within a ±100 nm depth of focus.

Figure 6. The total cross section versus particle diameter for defects nucleated by substrate particles. The scattering was calculated using the multilayer growth model and the SSA. The solid curve was calculated for a standard Mo/Si multilayer deposited by ion beam sputtering and having 40 bilayers. The dotted curve is for an ion beam deposited multilayer with 80 bilayers. The dashed curve is calculated by optimizing the parameters of the growth model and is indicative of what might be obtained if the multilayer deposition process could be further optimized to enhance smoothing and volume contraction. If the defect is unresolved by the imaging optics the printability can be described by a critical value of the cross section. The horizontal line is the critical cross section where a defect would become printable as determined by simulations for a 35 nm line with a 0.25 NA camera.

Figure 7. The increase in width of a 35 nm line with a Gaussian defect located 35 nm from the line edge (on the mask) is plotted versus peak height for Gaussian defects with FWHM=60 nm. The linewidth increase is greater with 100 nm of defocus. A defect was considered printable if the linewidth increase was greater than 20%. The aerial image of an isolated critical defect is also shown.

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