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Electromagnetic simulation of EUV masks

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Abstract

The Fourier modal Method (also known as Rigorous Coupled Wave Analysis, RCWA) is one of the simplest method to deal with diffraction by gratings. It is used to model the case of reflective EUV masks. We present the computation of the electromagnetic fields within and in the near vicinity of the multilayer EUV mask for periodic features in both TE and TM polarization.
The very time efficient method allows studying easily the influence of the different mask parameters. Several simulation results are shown, illustrating the influence of the absorber properties. Interfacing the rigorous simulation at the mask with a commercial lithography simulator enables to compute aerial image at the wafer level (with a number a simplifications that are discussed)
Current status of the tool only considers 2D structures.

The Fourier Modal Method (~RCWA)

The solution of Maxwell's equations is reduced to the solution of an algebraic eigenvalue problem in discrete Fourier space.
In such a configuration, the diffraction problem is reduced to the study of the two fundamental cases of polarization, and the unknown function $\psi(x,y)$ is the z component of the electric or magnetic field for TE and TM polarizations respectively.

The field can be represented by a superposition of eigenmodes:

$$\psi(x,y)=[a_q \exp(-ikr_q y) + b_q \exp(ikr_q y)]\ \varphi_q(x)$$

where a_q and b_q are constant modal-field amplitudes and r_q and $\varphi_q(x)$ are modal eigenvalues and eigenfunctions, which are determined by the periodic boundary-value problem:

$$L(x)*\varphi_q(x) = r_q^2\ \varphi_q(x) \qquad (1) \qquad\qquad \varphi_q(x+d) = \exp(-ik\alpha_0 d)\ \varphi_q(x)$$

with

$$L(x) = \frac{\partial^2}{\partial x^2} + k^2 n^2(x) \qquad \text{for TE polarisation}$$

$$L(x) = \left(\frac{\partial}{\partial x}\ (1/n^2(x)\ \frac{\partial}{\partial x}) + k^2\right) n^2(x) \qquad \text{for TM polarisation}$$

The derivation of the matrix operator involves two steps:

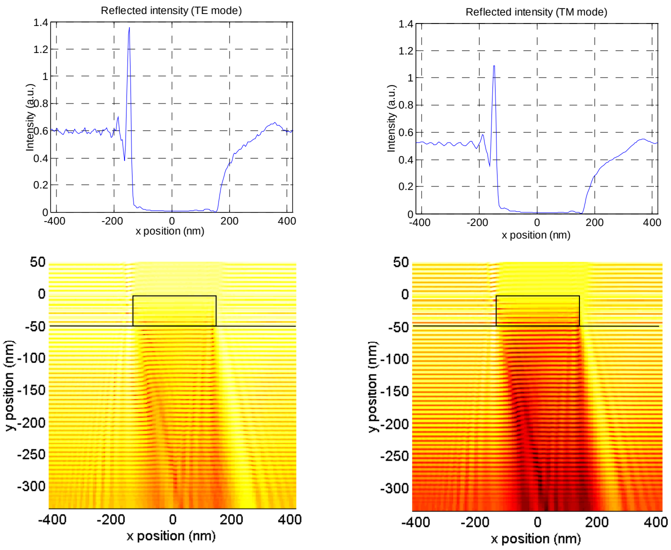
(1) the electromagnetic field is expanded into Floquet-Fourier series

$$\varphi_q(x)= \phi_{mq} \exp(-ik\alpha_m x) = \phi_{mq} \exp[-ik(\alpha_0+ m\ \lambda/d)x]$$

(2) the periodic coefficient (the permitivity function) of Maxwell's equations is expanded into Fourier series.
and then we project Eq.1 onto the Fourier basis $\exp(-i2\pi x/d)$ and find the eigenmodes and eigenvalues of the matrix
The a_q and b_q amplitudes are found by solving the boundary conditions at the layer interfaces using a Scattering matrix formalism. Large layer thickness can be handled without numerical instabilities.
The number of terms used in the Fourier series can be chosen in order to compromise between computing time and accuracy.

Examples of fields computations

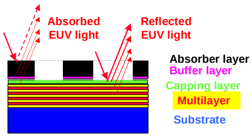
Light intensity reflected (top) and within the EUV mask (bottom) for TE (left) and TM (right) polarisations. (Convergence rate is similar)
incidence angle 10°, 40 Molybdenum/Silicon bilayers (reflectivity not optimised in these conditions); absorber 50nm thick Chrome 280nm line/560nm space (70nm/140nm at wafer level)



The tilted shadow of the Cr absorber is clearly seen on the intensity map.
Asymmetry in the reflected light and a pattern shift are due to the tilted illumination and distributed mirror.

Conclusion

We have presented a method able to model the periodic problem of EUV masks in a fast way in 2 dimensions. Extension of the domain of application of the method to 3D features is ongoing. Hopkins approach is not relevant for EUV mask, aerial image simulation can be performed using a double Fourier transform computation.

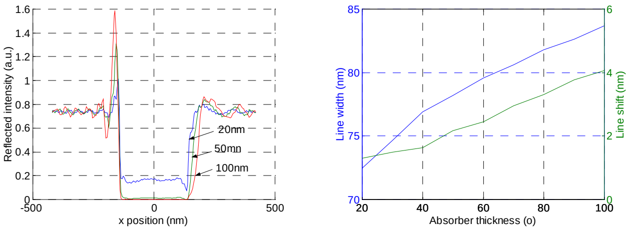


EUV reflective mask

Examples of simulation results

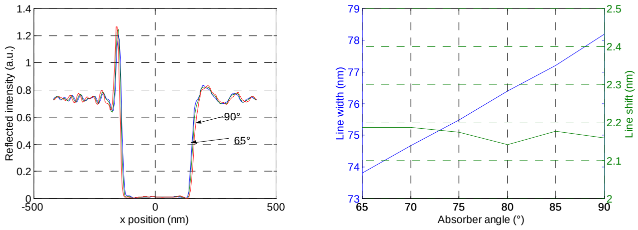
Illumination is considered fully coherent (plane wave) incident at an angle. Line width are evaluated at a threshold of 0.2 of the reflected intensity, they are given at wafer scale (4x reduction). Intensity plot are at mask scale.
λ=13.3nm; absorber Cr 50nm thick; incidence 5°; line width 280nm (70nm at wafer); space 560nm, TE polarisation

Influence of the absorber thickness



Absorber thickness strongly influences the line shift due a shadowing increasing with pattern height. A compromise is to be found between sufficient absorption and minimum line shift.

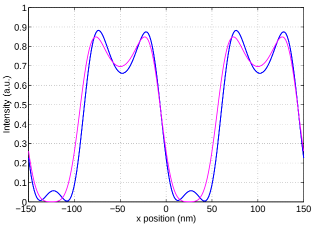
Influence of the absorber slope



Absorber slope only affects the position of the line edges. The line shift is not changed

Aerial image simulation

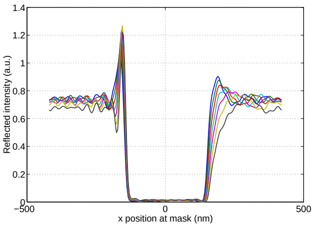
The reflected near field computed using FMM can be used as an input mask for SOLID-C (from Sigma-C Gmbh) . Hopkins approach is used to compute the aerial image at the wafer (including effect of Numerical aperture NA and partial coherence σ)



Comparison between rigorous near field computation (blue line)and an EUV mask considered as planar (magenta line).

(line=50nm,space=100nm, NA=0.3, σ=0.6, 4x)

Line shift due to the finite thickness of the absorber can only be accounted for if a rigorous approach is used



Limitation of Hopkins approach for EUV masks:

Complex reflectance of the EUV mask is strongly affected by the incidence angle (in the figure: 2° to 8° i.e. NA=0.3, σ=0.52 @ 4x magnification) and polarization state

-> the full diffraction integral has to be used instead of effective source convolution of Hopkins approach

FM Method : + and -

++ very fast (< 1 mn in 2D under Pentium III + Matlab, not optimized)
+ reasonable memory consumption
- basically adapted for periodic features (isolated treated as large space to line ratio)
Other methods can be more general but very heavy:
FDTD very unpractical for EUV (short λ + numerous layers => huge number of grid points => memory, time)
Diffraction integral method : also time consuming