Modeling Image Formation In EUV Lithography

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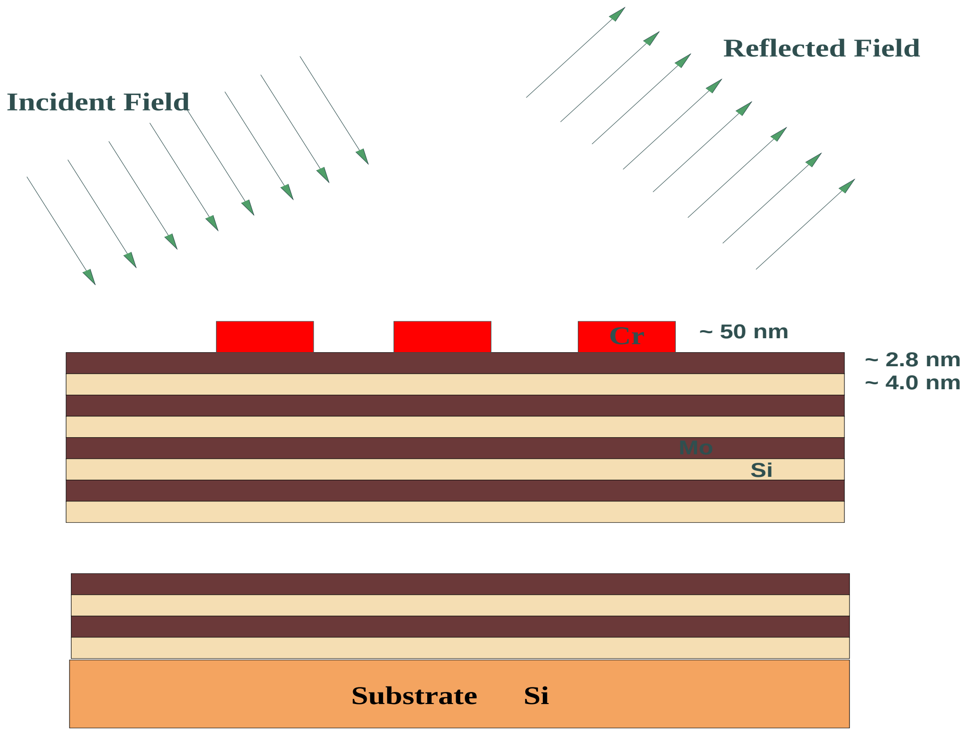
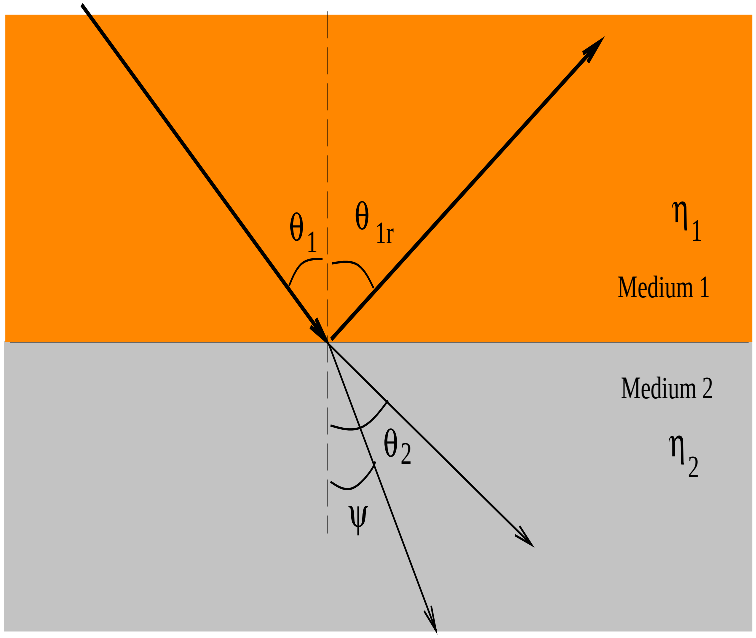
Schematic of a multilayer mask



- What is the role of the multilayer stack in the image reflected by the mask?
- Is the masking layer a simple “mask” or do we need to consider diffraction?
- Study image formation in mask alone (Condenser and optical system excluded).

Reflection and Refraction at a conductor-conductor interface



ψ = real angle of refraction (different from complex angle)

- The reflection coefficient ρ and transmission coefficient τ are dependent on polarization (p or s) and incidence angle.
- At EUV wavelengths both *Mo* and *Si* have finite conductivity. As a result, inhomogeneous plane waves are generated at the interface due to refraction.

Propagation Method in each layer

Modulate incident field by transmission

$$E_t(x,y) = E_i(x,y)T(x,y)$$

Transfer field to Fourier domain

$$FE_t(x,y) = \int\int_{-\infty}^{\infty} E_t(x,y)e^{-i(\frac{2\pi}{\lambda})(xf_x+yf_y)}dxdy$$

Propagate the field in Fourier space

$$FE_o(x,y) = FE_t(f_x,f_y)K(f_x,f_y)$$

Transfer the field to real domain

$$E_o(x,y) = \int\int_{-\infty}^{\infty} FE_o(x,y)e^{i(\frac{2\pi}{\lambda})(xf_x+yf_y)}df_x df_y$$

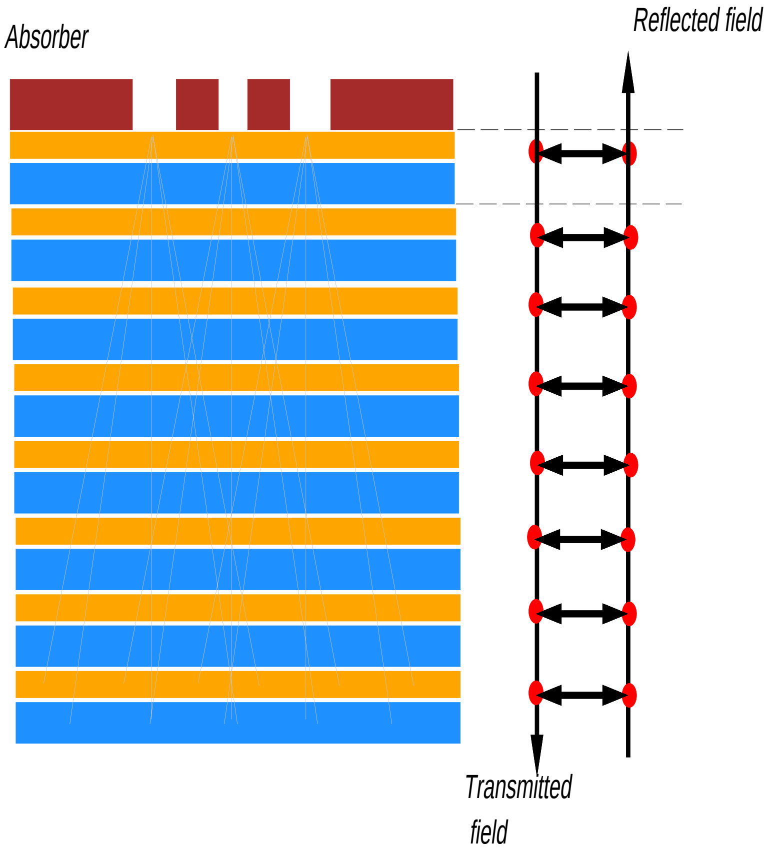
Multilayer d-spacing*

Mirror	β_{opt}	d_{opt}(nm)	λ(nm)
Mo-Si	0.4118	6.8	13.3
Mo-Be	0.4	5.81	11.35

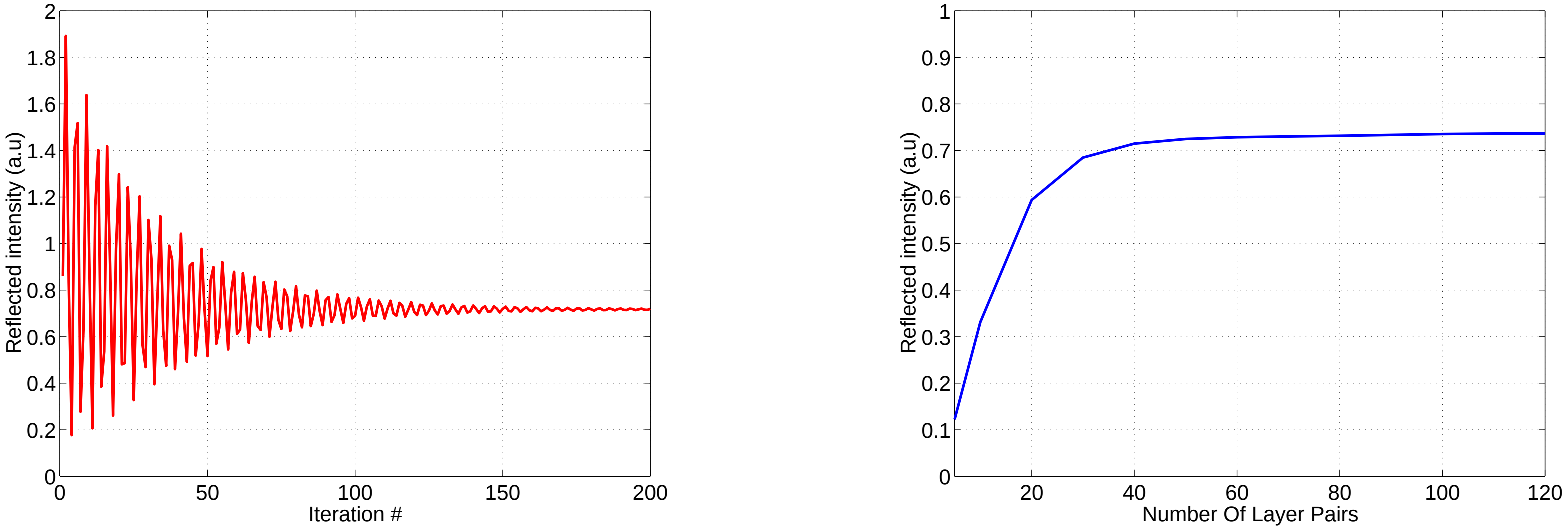
- Let $\widetilde{n_H} = n_H - ik_H$ and $\widetilde{n_L} = n_L - ik_L$
- The optimal ratio β_{opt} is given by $\boxed{\tan(\pi\beta_{opt}) = \pi(\beta_{opt} + \frac{n_L k_L}{n_L k_L - n_H k_H})}$
- The optimal multilayer period is given by $\boxed{d_{opt} = \frac{\lambda}{2}(1 - \delta(\widetilde{n_H}, \widetilde{n_L}))}$
- * Vinogradov A. V., Zeldovich B. Ya. *X-ray and far uv multilayer mirrors: principles and possibilities*, Applied Optics, Vol. 16, No. 1, pp 89-93, 1977.

Diffraction in Layered Media

- Input field is filtered by absorber
- Multiple reflections take place
- Image is progressively distorted as it propagates in the stack
- The final emerged image has a characteristic diffraction pattern

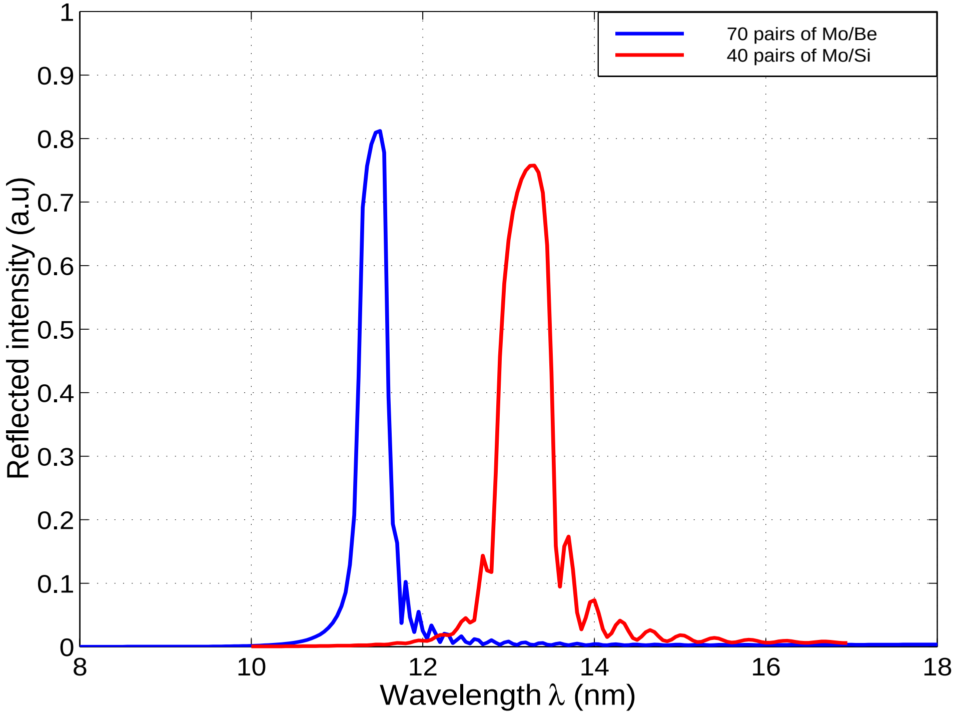


Convergence of reflectance : Iterative nature of the algorithm



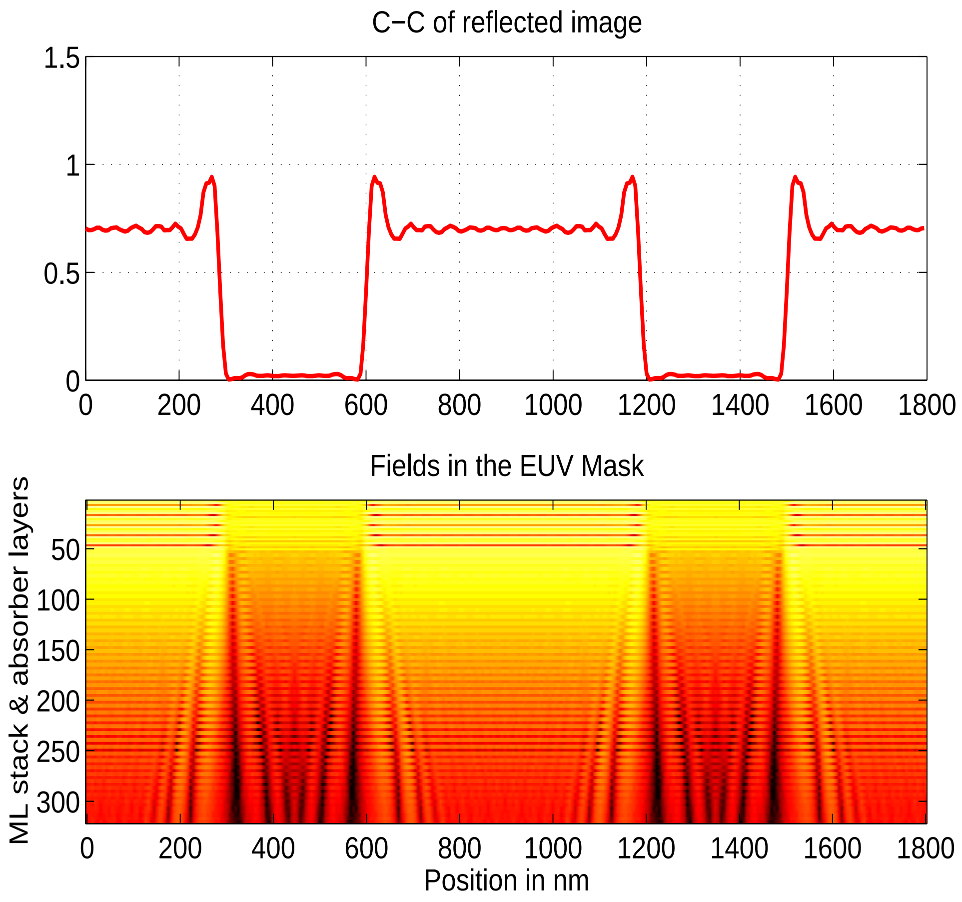
- Reflectance of 50 pairs of *Mo/Si* with iteration number for normal incidence.
- The higher the number of layer-pairs the higher is the number of iterations to achieve convergence.
- The reflectance value saturates with number of layer pairs. At 40 layer pairs, the reflectance is about 72% at $\lambda = 13.3$ nm.

Reflectance vs. wavelength



- Multilayer mirrors are extremely wavelength selective.
- The theoretical reflectivity may be reduced due to interlayer roughness.

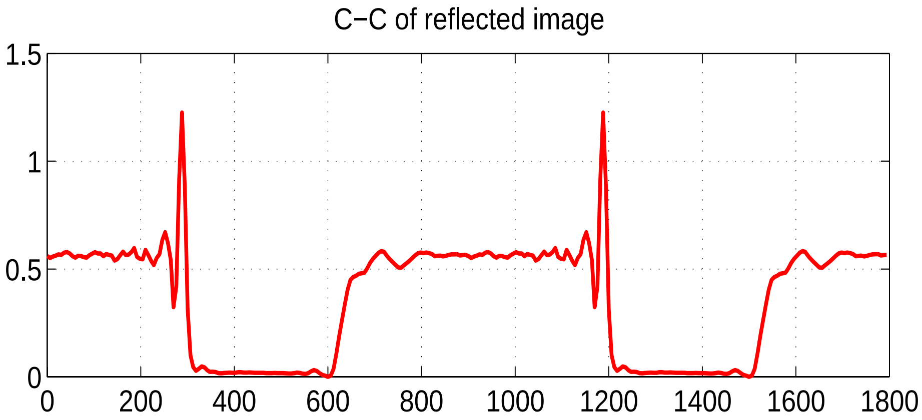
Propagation within the multilayer

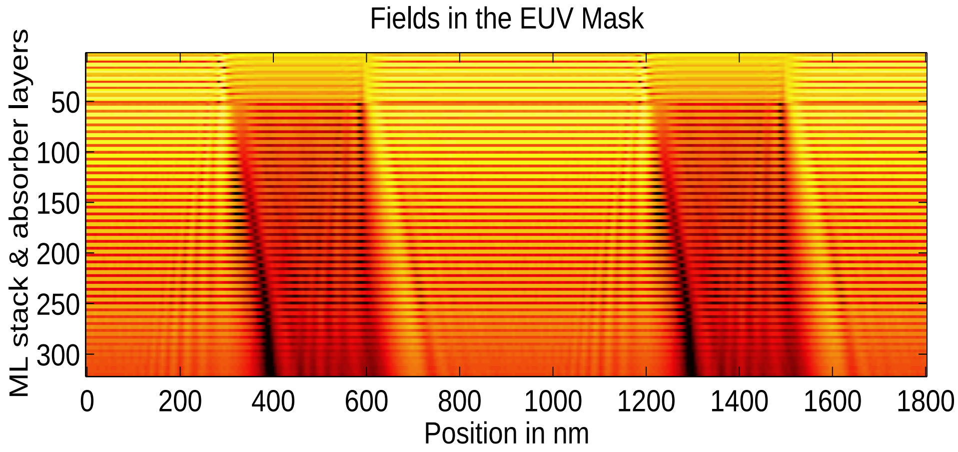


Absorber Region
↑
Multilayer Stack
↓

- Notice the broadening of the image intensity with depth in the multilayer stack due to diffraction. (logarithm of intensity)

Propagation within the multilayer : Oblique incidence





Absorber Region

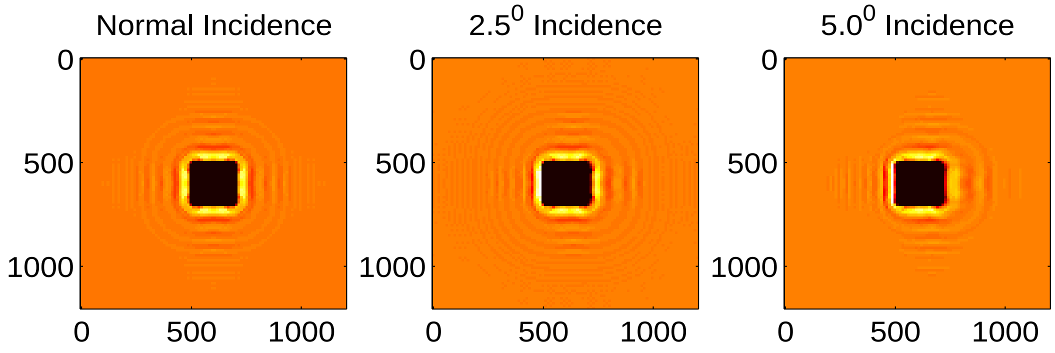
↑

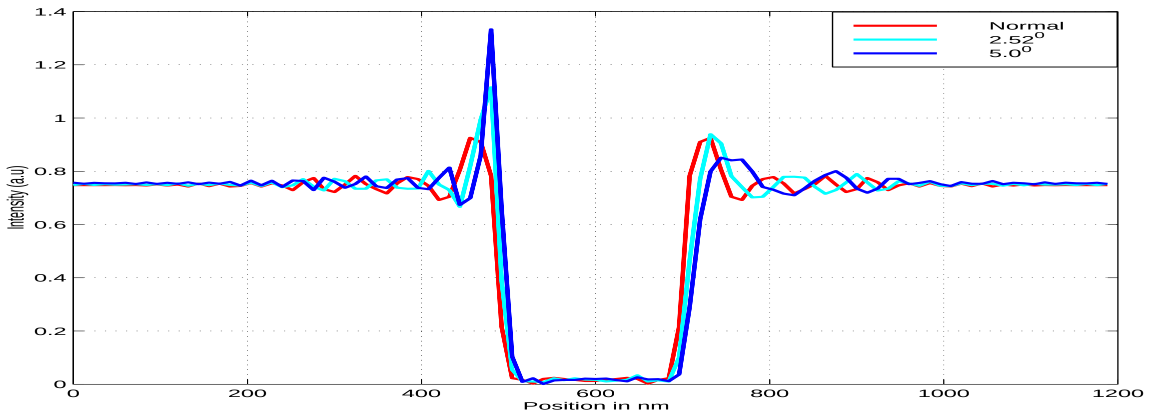
Multilayer Stack

↓

- Notice the shift in the propagated image due to oblique incidence and broadening due to diffraction. (logarithm of intensity)

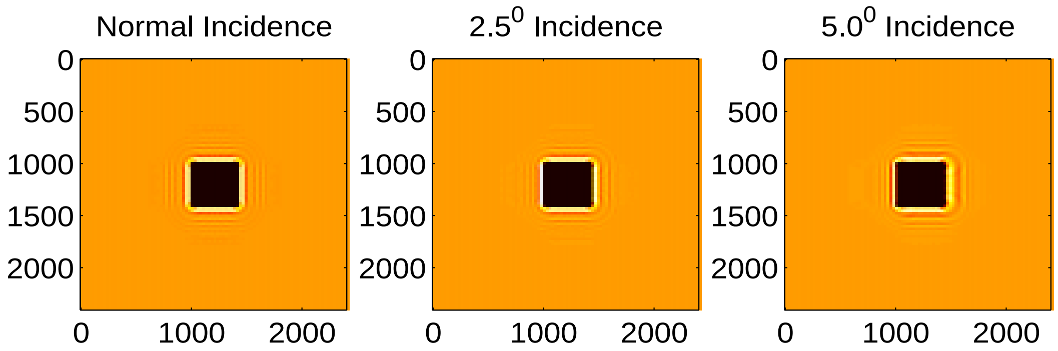
Illustrative Example 1

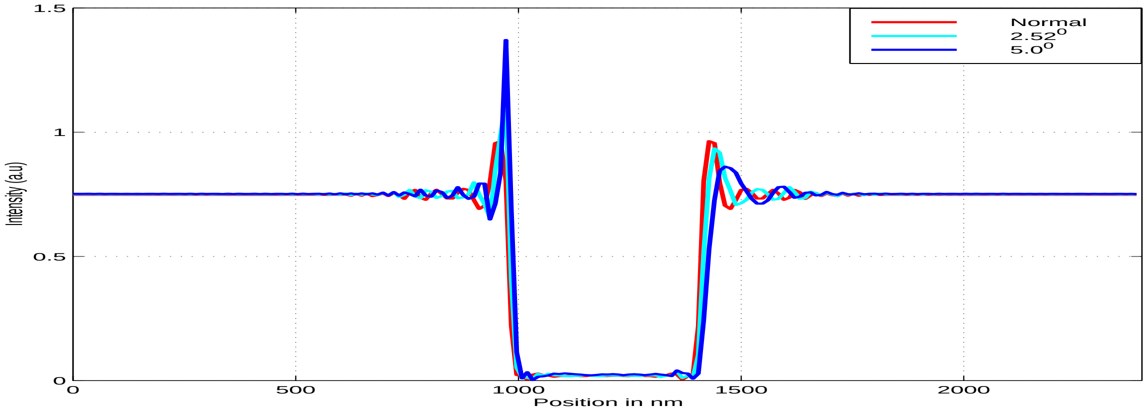




- Reflected images for a square pattern with CD $= 200$nm.
- The ML stack consisted of 40 layer pairs of Mo/Si and $\lambda = 13.3$nm.
- Computation time 8 hours each on HP-9000 J Class work station.

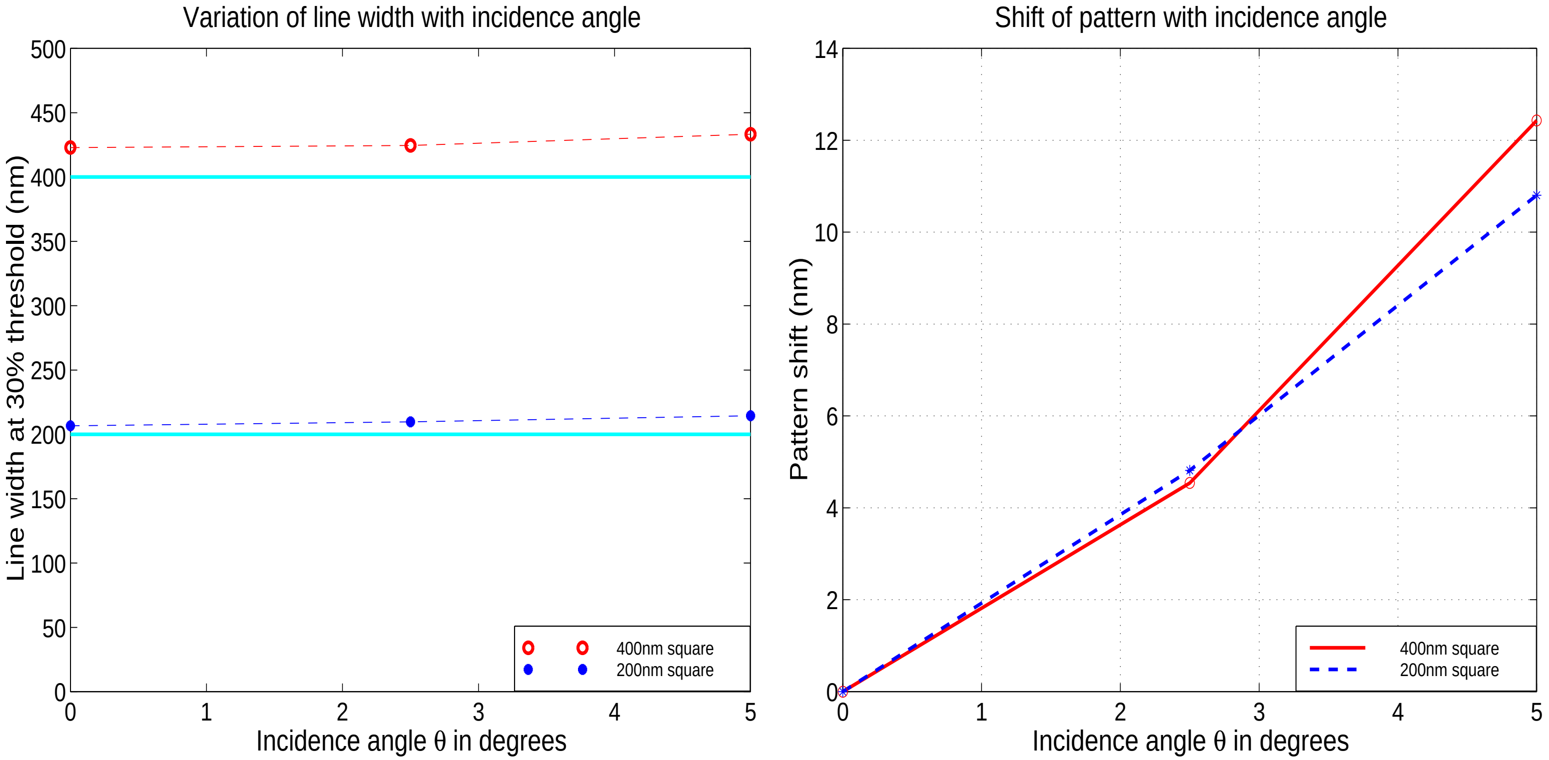
Illustrative Example 2





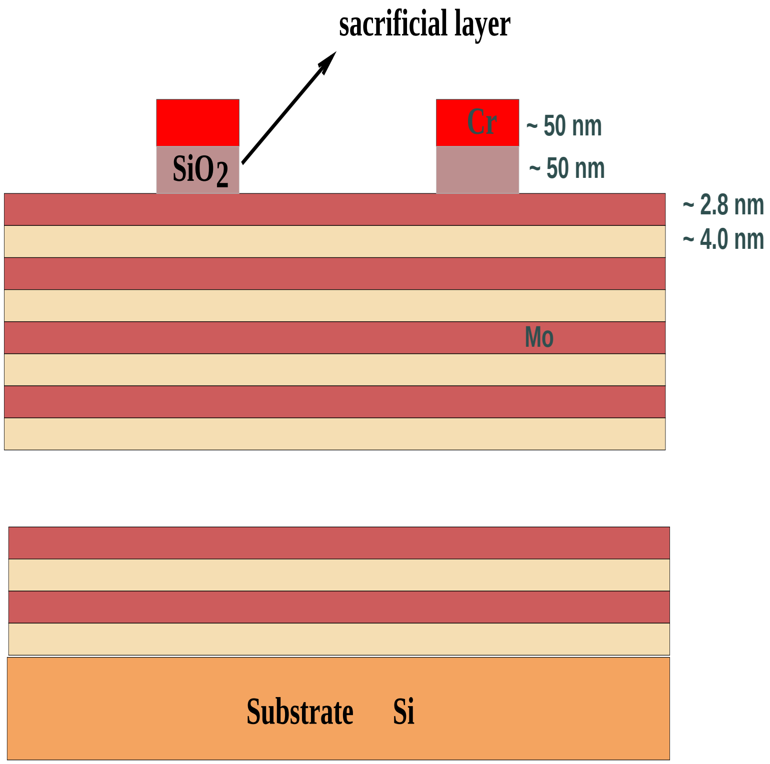
- Reflected images for a square pattern with CD $= 400$nm.
- Grid size $= 200$X200 ; λ = 13.3nm.
- Computation time 12 hours each on HP-9000 J Class work station.

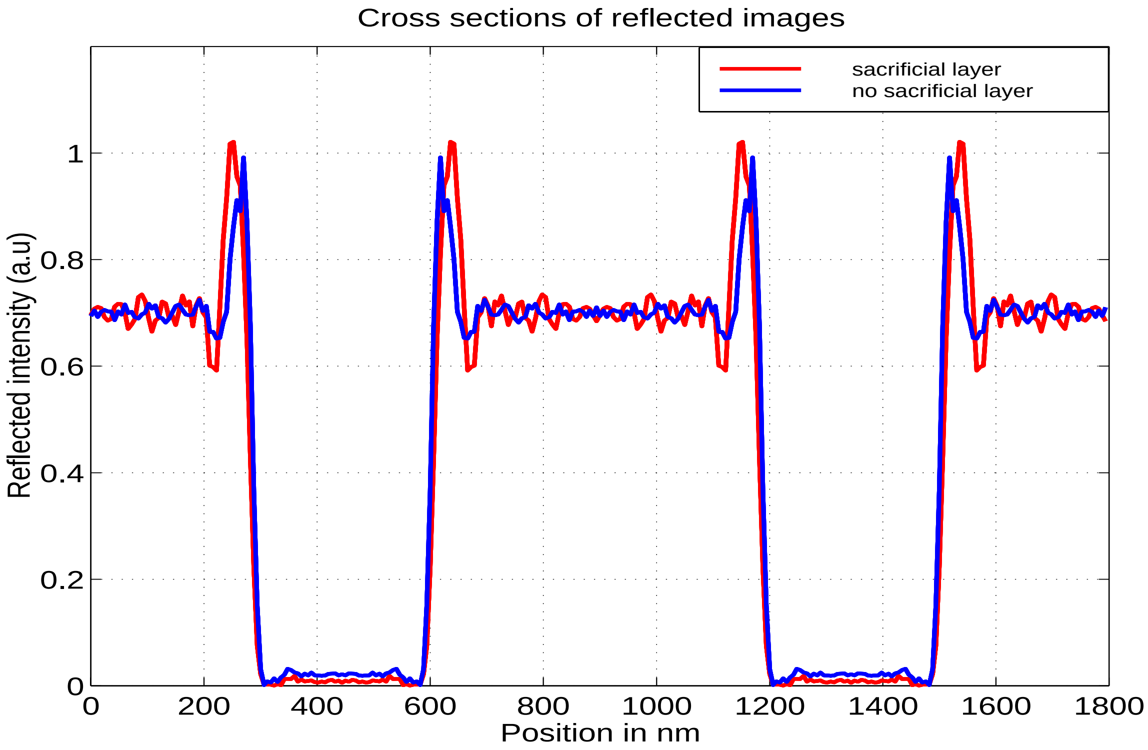
Effects of Oblique Incidence



- LEFT : Line Width Variation RIGHT : Shift of Pattern
- The threshold was chosen to be at 30%.

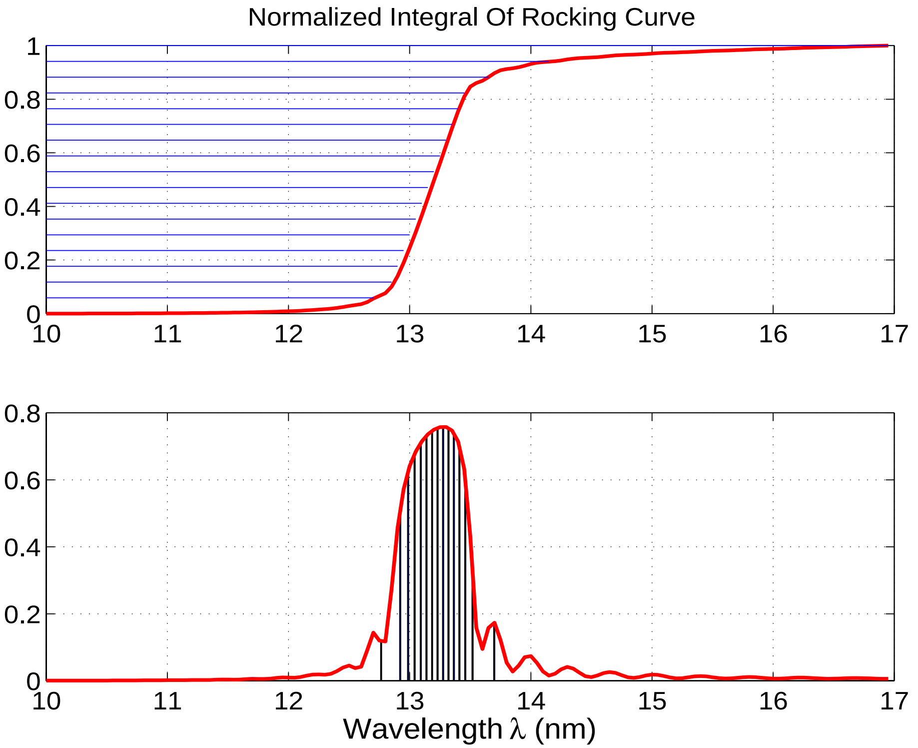
Effect Of A Sacrificial Layer

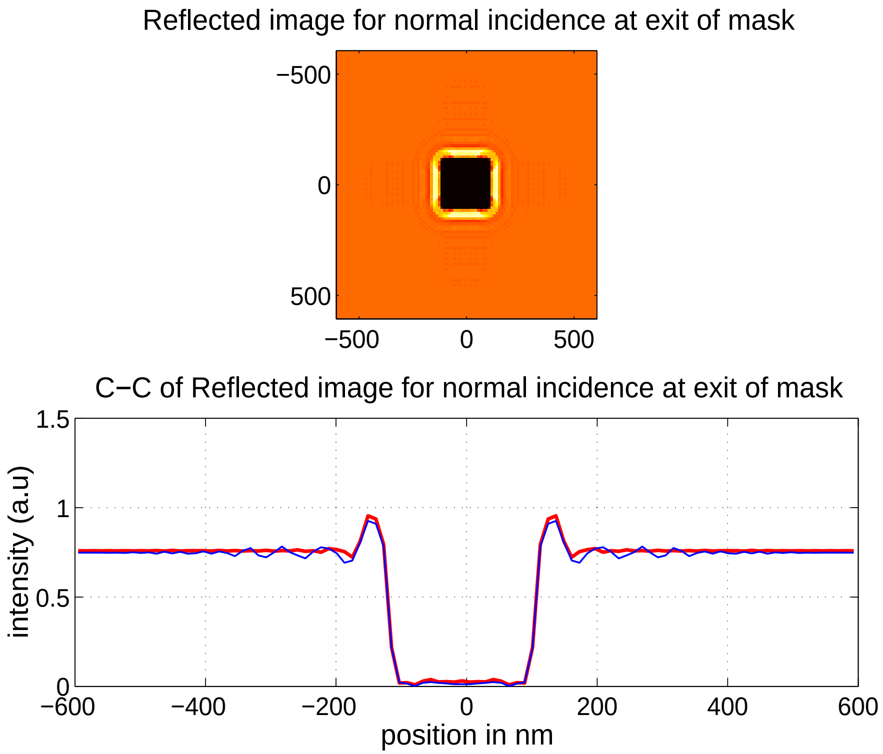




- The presence of a sacrificial layer causes a slight change in contrast and widening of feature widths due to slightly increased diffraction. The effect on final image, if any, needs to be assessed.

Reflection due to a polychromatic spectrum


Normalized Integral Of Rocking Curve


Reflected image for normal incidence at exit of mask

C−C of Reflected image for normal incidence at exit of mask

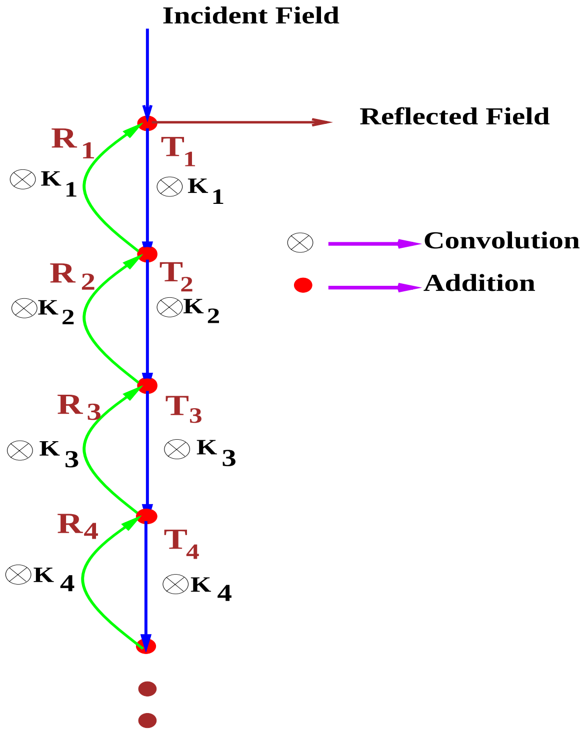
- LEFT : The spectrum used was a stochastic sampling of the Mo/Si rocking curve with 17 wavelengths.
- RIGHT : The reflected image of a square pattern (CD = 200 nm) due to the polychromatic spectrum.
- Notice the smoothing caused by polychromatic spectrum.

EUV Mask As An LSI System

- Linearity
  - *T_i & R_i indicate product in real space and they contain the transmission and reflection coefficients.*
  - *Let $\mathcal{I}$ be the incident field and $\mathcal{R}$ be the reflected field.*
  - *It can be shown with a bit of algebra that*

$$\boxed{\mathcal{R} = \mathcal{I}\sum_{i=1}^{N}\prod_{j=1}^{N}[[T_j \otimes K_j]R_j]\otimes K_j + \mathcal{I}\rho}$$

  - *$\Rightarrow$ it is a sum of several linear sub-systems.*



- Shift Invariance
  - *Follows from the convolution terms in the above equation.*

Summary

- We have done some preliminary modeling studies on reflection from multilayer masks.

- We observed some interesting phenomena, such as increased brightness under the absorber.

- The models have been implemented in software using CXrL toolset.

- Some basic properties such as *wavelength selectivity* and variation of reflectance with number of layer pairs have been verified with previously well known results and with other groups (Sweeney, LLL).

Conclusions

- The contrast of the reflected images is very high, suggesting good printability.
- The EUV mask is optically thick and diffraction into the multilayer must be explicitly taken into account.
- Angle of incidence has strong effect on imaging conditions.
- The EUV mask has been shown to be an LSI system. As a result, the case of partial coherence of incident illumination, can be computed as a convolution with the source. This will be implemented in future.