Numerical and Experimental Study of EUV Mask Interface Roughness, Capping Layer Oxide Growth, and Phase Shifting Feasibility

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Introduction

- Stringent requirements are placed on EUV masks reflectivity and uniformity for the multilayer and stack.
- Modeling of multilayer interface roughness / intermixing zones was investigated with the IMD software and verified against experimental data.
- Growth of oxide on Si capping layers was monitored experimentally, and stoichiometric SiO_2 formation models were put forward.
- Simulations were benchmarked via reflectometry and ellipsometry experiments (measurement of oxide thickness).
- Multilayers were more accurately optimized for high reflectance, and reflectivity variations within angle of incidence ranges were calculated, corresponding to exposure tool illumination numerical apertures (NA).
- Phase shift mask feasibility was assessed via modeling for various mask architectures.

Influence of ML Interface Roughness

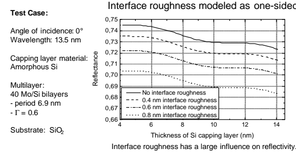
Test Case:

Angle of incidence: 0°
Wavelength: 13.5 nm

Capping layer material: Amorphous Si

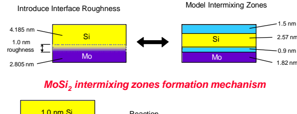
Multilayer:
40 Mo/Si bilayers
- period 6.9 nm
- Γ = 0.6

Substrate: SiO_2



Interface roughness has a large influence on reflectivity.

ML Interface Roughness Modeling Options



Tool-Optimized Masks – No Interface Roughness

(40 bilayers, 11 nm Si)			
Angle of Incidence	6	3.6	6
Centroid Wavelength	13.36 nm	13.45 nm	13.50 nm
Peak Wavelength	13.42 nm	13.52 nm	13.56 nm
Centroid Reflectance	71.55%	71.58%	71.39%
Peak Reflectance	72.07%	72.18%	71.92%
Mo/Si Mo thickness	2.783 nm	2.811 nm	2.838 nm
Mo/Si Si thickness	4.129 nm	4.129 nm	4.155 nm
FWHM	0.637 nm	0.648 nm	0.651 nm

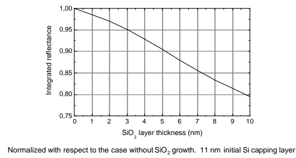
Such simulation results do not agree with experimental data.

Tool-Optimized Masks – with Interface Roughness

(40 bilayers, 11 nm Si)			
Angle of Incidence	6	3.6	6
Centroid Wavelength	13.36 nm	13.45 nm	13.50 nm
Peak Wavelength	13.39 nm	13.48 nm	13.53 nm
Centroid Reflectance	66.00%	66.14%	65.97%
Peak Reflectance	66.27%	66.42%	66.27%
Mo/Si Mo thickness	2.851 nm	2.840 nm	2.855 nm
Mo/Si Si thickness	4.070 nm	4.104 nm	4.143 nm
FWHM	0.537 nm	0.546 nm	0.551 nm

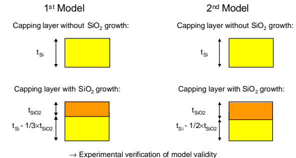
Simulations results agree with experimental data.

Influence of Oxidization of the Si Capping Layer



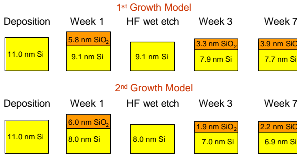
Normalized with respect to the case without SiO_2 growth. 11 nm initial Si capping layer.

Si Oxide Growth Models

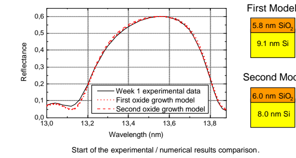


→ Experimental verification of model validity

Predicted Layer Thicknesses vs. Process Step

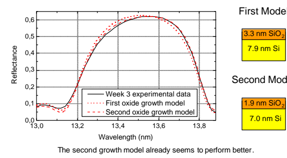


Reflectivity at Week 1



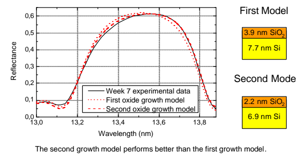
Start of the experimental / numerical results comparison.

Reflectivity at Week 3



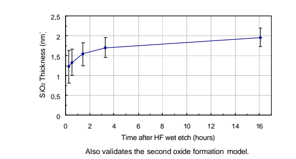
The second growth model already seems to perform better.

Reflectivity at Week 7



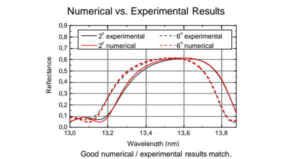
The second growth model performs better than the first growth model.

SiO_2 Thickness Determination via Ellipsometry



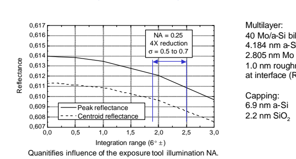
Also validates the second oxide formation model.

Week 7 – Angle of Incidence Variation



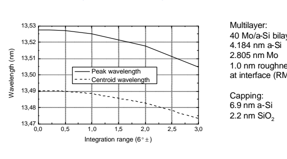
Good numerical / experimental results match.

Integration over Angle of Incidence

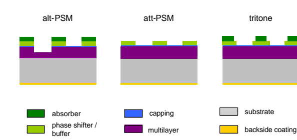


Quanitifies influence of the exposure tool illumination NA.

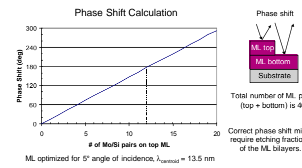
Integration over Angle of Incidence



PSM Architecture

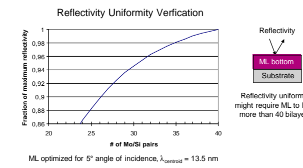


Alternating Phase Shift Mask without Etch Stop Layer



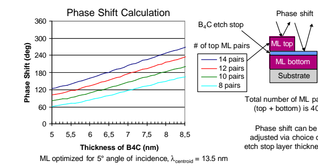
ML optimized for 5° angle of incidence, $\lambda_{centroid}$ = 13.5 nm

Alternating Phase Shift Mask without Etch Stop Layer



ML optimized for 5° angle of incidence, $\lambda_{centroid}$ = 13.5 nm

Alternating Phase Shift Mask with B_4C Etch Stop Layer



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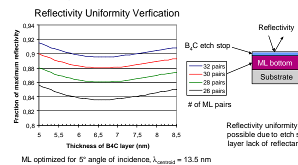

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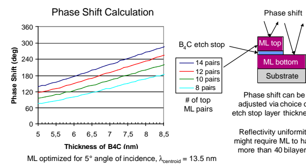

ML optimized for 5° angle of incidence, $\lambda_{centroid}$ = 13.5 nm

Summary and Conclusions

- EUV mask reflectance was modeled using the IMD software, taking into account interface roughness and oxide growth on Si capping layers.
- Excellent agreement with experimental data at various process steps and for different angles of incidence.
- Possible to characterize an EUV mask multilayer and stack from a simple reflectometry measurement.
- Mask multilayer optimal parameters were readily calculated.
- Calculated reflectivity and wavelength integrals over cones of light, corresponding to different exposure tool NA settings.
- Appropriate reflectivity uniformity and phase shift can be obtained with the proper architecture for Alternative PSM.

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