Optical and Physical Characteristics of EUV Phase Shift Masks

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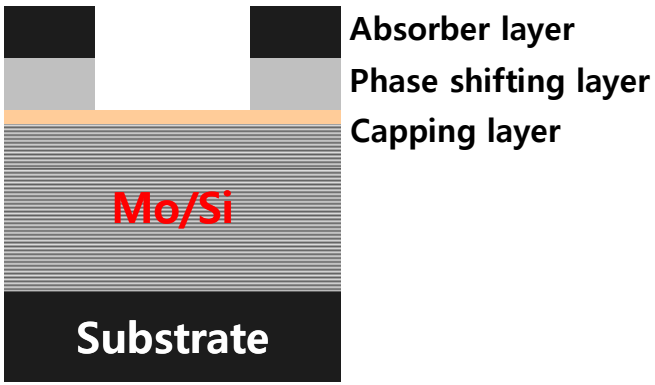
Abstract

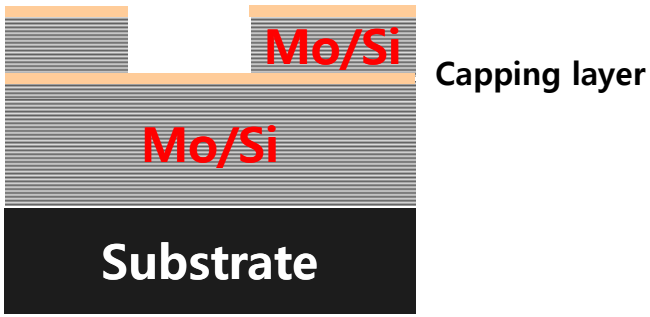
Phase shift mask (PSM) is an important issue to improve the resolution limit in the conventional optical lithography. Since 1997, many works have been tried to apply phase shift concept to the EUV lithography mask. Strong concerns remain with PSM structure design owing to difficulty of manufacture and need of different PSM types as application demands.

Two types of PSM were investigated in this work. One is an embeded attenuated PSM as an additive type, which has high reflectance (~10%) with $TaN/Al_2O_3/Mo$ absorber stack thinner than 50 nm. This PSM shows good normalized image log slope, contrast, and inspection characteristics compared to our previous thinnest Al_2O_3/TaN absorber mask through simulation study. The other is an etched multilayer alternating PSM as a subtractive type, which shows line and space resolution as small as 15 nm half-pitch in this study. Also sidewall passivation as another important issue was studied to keep an etched sidewall of multilayer from degradation. It is required to optimize the passivation layer affecting the aerial image intensity of the adjacent peaks.

Types of EUV phase shift mask

Att- and alt- phase shift mask





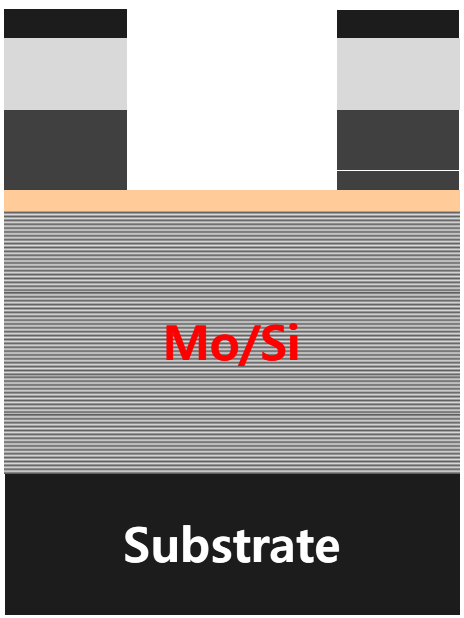
<Attenuated phase shift mask>

- Phase control : $|\varphi 2 - \varphi 1| = 180 \pm 6°$
- Attenuation: ~5% - ~12%
- High contrast strategy for mask inspection
- Low height difference against shadow effect

<Alternating phase shift mask>

- Phase control : $|\varphi 2 - \varphi 1| = 180 \pm 6°$
- EUV reflectivity : high reflectivity (~70%)
- Equilibrium of aerial image intensity

Schematic of att-PSM



TaN attenuator

Al_2O_3 spacer

Mo phase shifting layer

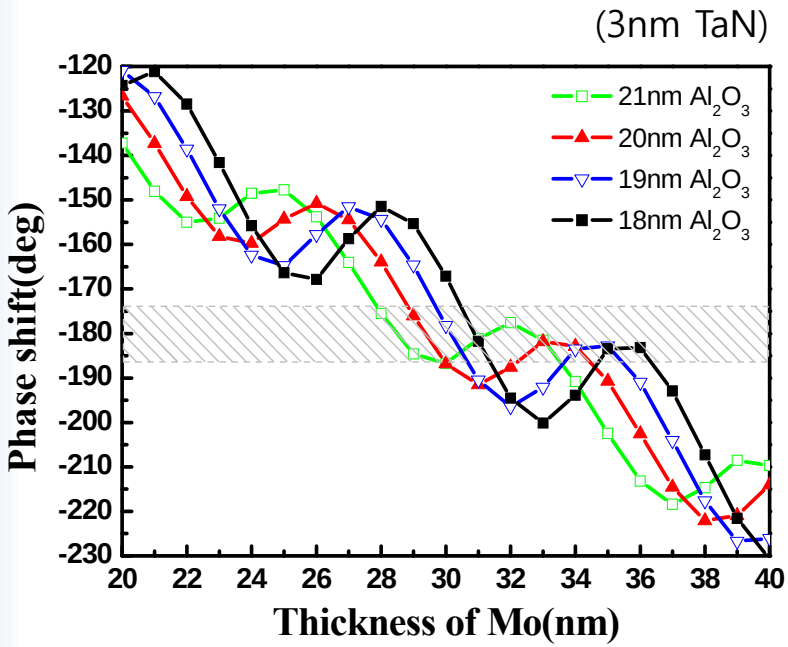
Ru capping layer

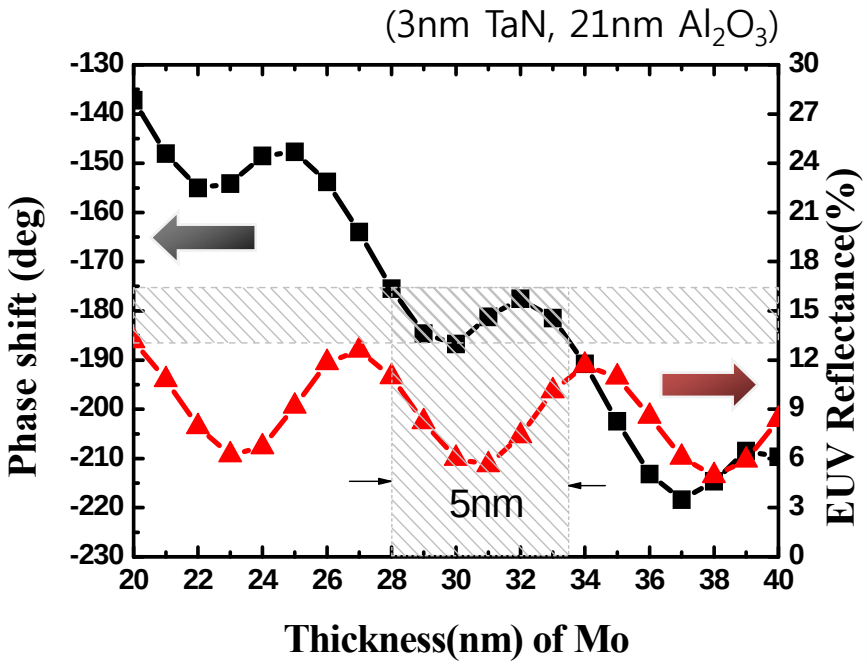
Febry-Perot structure

- 180° phase difference: ±6° tolerance
- Good destructive interference due to EUV reflectance of >5%
- High inspection efficiency (high DUV contrast)
- Conventional etch process : Common materials
- Minimum shadow effect due to small height difference

Phase shift and EUV reflectivity of att-PSM

To optimize att-PSM stack regarding phase shift and EUV reflectivity, each layer's thickness were changed in TaN/Al_2O_3/Mo/Ru-capped-ML/Substrate.

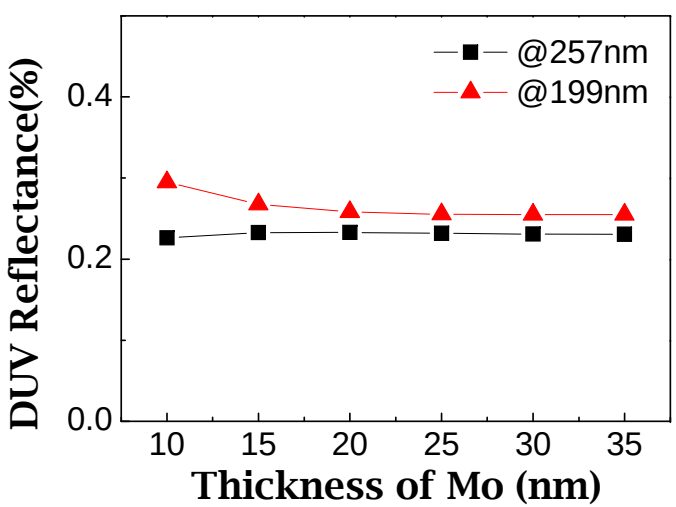




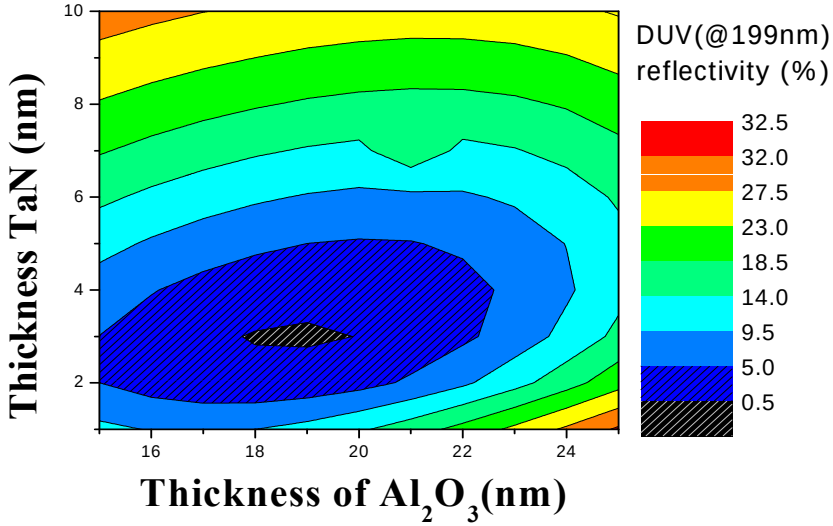
- 3-nm-TaN/21-nm-Al_2O_3/31-nm-Mo stack is desirable both phase shift (~180˚) and EUV reflectivity (~6%) through the simulation of thickness control.

DUV Reflectivity simulation for mask inspection

Effect on DUV reflectivity to Mo thickness variation



Effect on DUV reflectivity to TaN & Al_2O_3 thickness variation



DUV reflectivity @199nm

Al_2O_3 / TaN	18nm	19nm	20nm	21nm	22nm
2nm	1.58	2.09	3.47	5.7a1	8.73
3nm	0.26	0.03	0.57	1.93	4.11
4nm	2.28	1.60	1.56	2.23	3.65

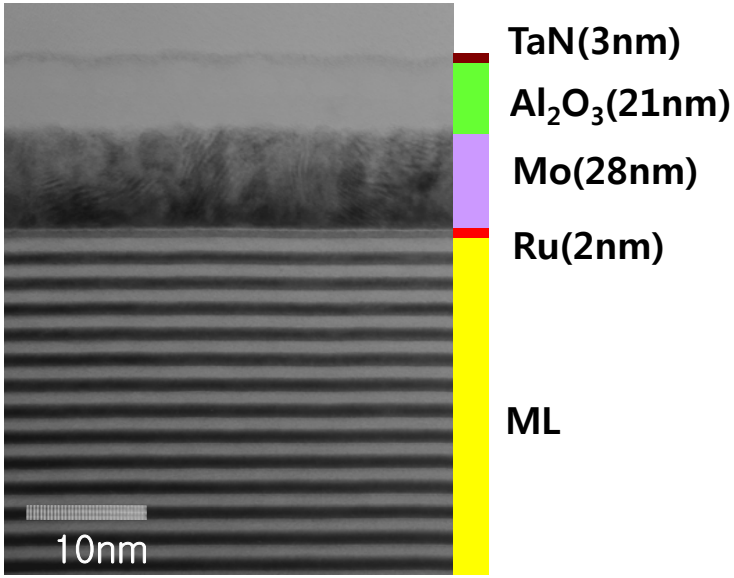
DUV reflectivity @257nm

Al_2O_3 / TaN	18nm	19nm	20nm	21nm	22nm
2nm	7.17	5.12	3.42	2.12	1.22
3nm	4.65	3.09	1.86	0.97	0.42
4nm	5.10	3.98	3.14	2.58	2.30

DUV measurement for mask inspection

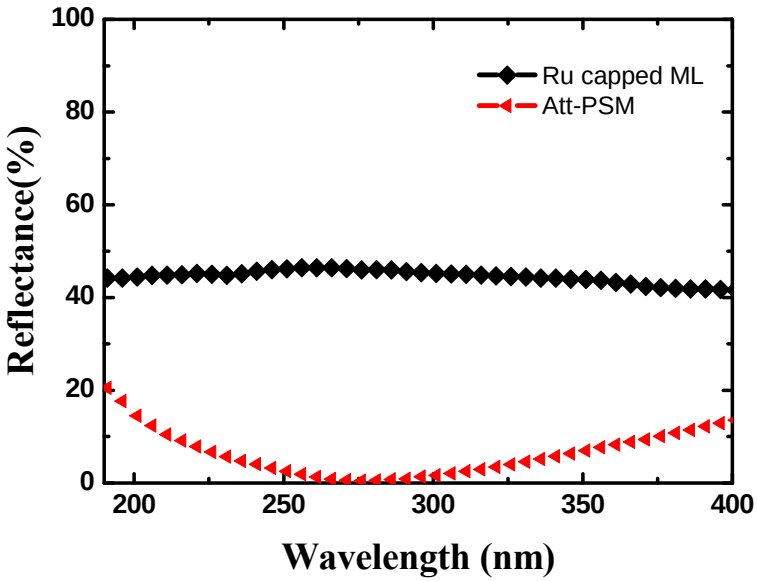
To confirm contrast for mask inspection, DUV reflectivity on att-PSM structure of 3-nm-TaN/21-nm-Al_2O_3/28-nm-Mo/2-nm-Ru/ML was measured by spectrophotometer.

X-sectional TEM image



Att-PSM structure:
TaN/Al_2O_3/Mo/Ru/ML

DUV measurement

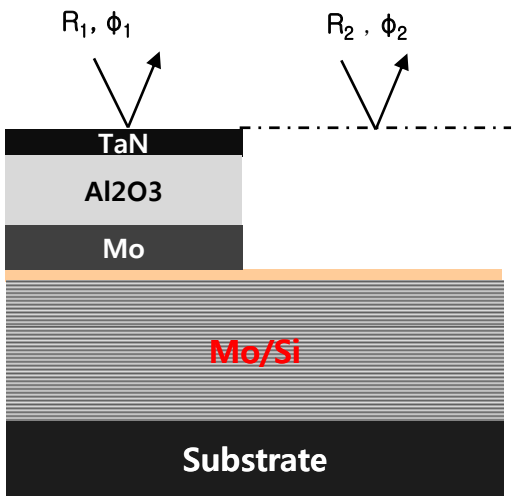


	$R_{1\ DUV}$ (%)	$R_{2\ DUV}$ (%)	Contrast(%)
@199nm	44.6%	15.6%	48.2%
@257nm	46.4%	1.7%	92.8%

Imaging quality with EUV reflectivity on absorber stack

❖ *Simulation condition*

Parameter	Value
Median wavelength	13.5nm
Temporal bandwidth	2% FWHM
NA	0.25
Magnification factor	4
Spatial coherence factor, sigma	0.5
Incident angle	6°
Isolated line	14nm
Dense line	22nm/32nm



Att-PSM

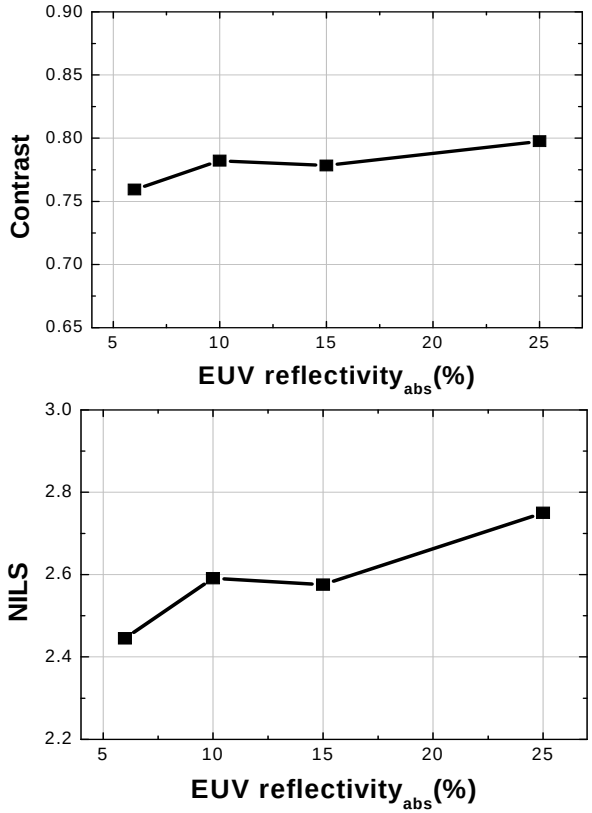
❖ *List of mask structures*

Type	Structure	Absorber thickness (nm)	$R_{EUV(abs)}$ (%)
Att-PSM-1	TaN(3nm)/Al_2O_3(21nm)/Mo(31nm)/Ru(2nm)/ML	55nm	5.6 %
Att-PSM-2	TaN(3nm)/Al_2O_3 (21nm)/Mo(28nm)/Ru(2nm)/ML	52nm	9.5 %
Att-PSM-3	TaN(3nm)/Al_2O_3 (18nm)/Mo(31nm)/Ru(2nm)/ML	52nm	14.4%
Att-PSM-4	TaN(3nm)/Al_2O_3 (7nm)/Mo(35nm)/Ru(2nm)/ML	45nm	25%

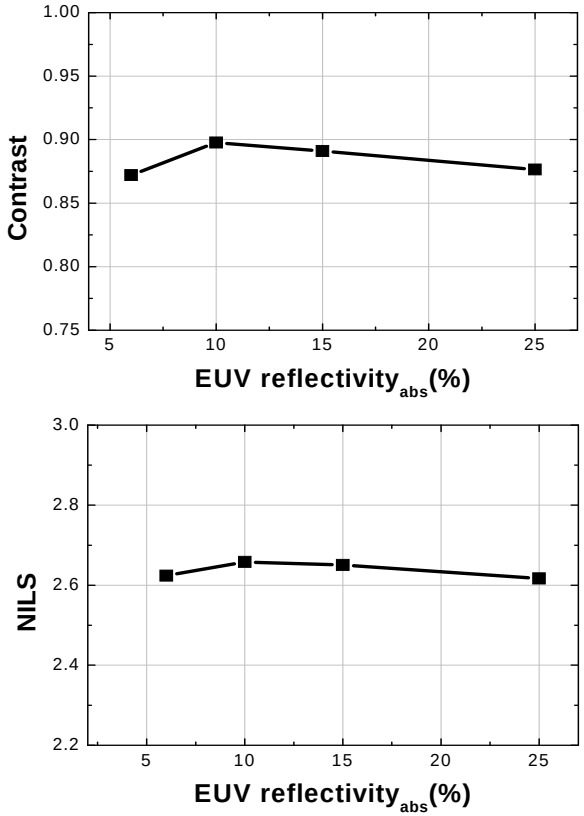
Image contrast & NILS

- Image contrast and NILS of att-PSMs were compared at the threshold of 20% through the aerial image simulation.

14nm Isolated line

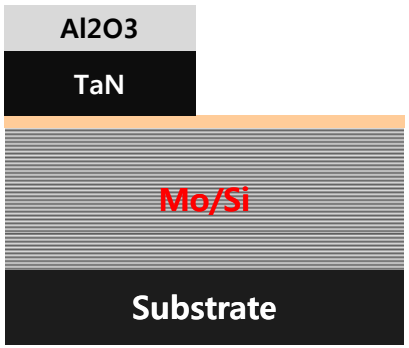


22nm line with 54nm pitch

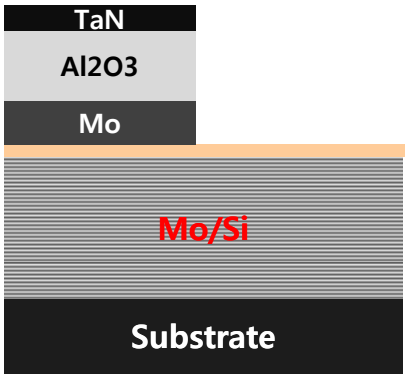


Comparison between BIM & att-PSM

BIM

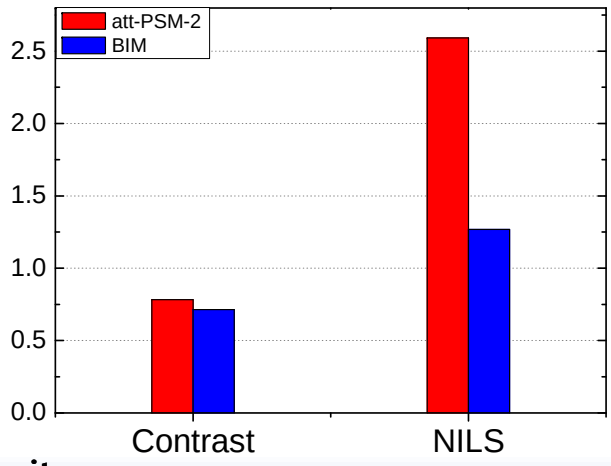


Att-PSM

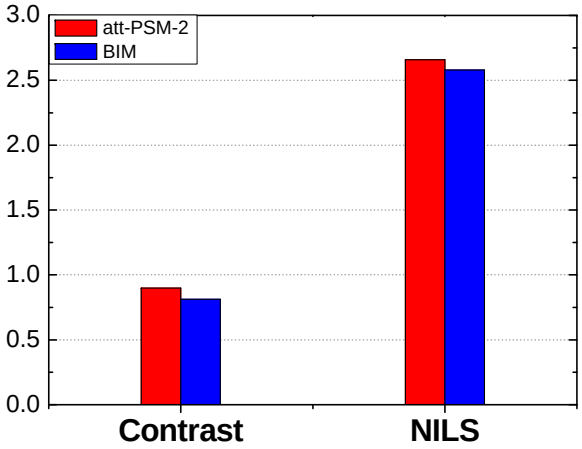


Type	Structure	Absorber thickness (nm)	R_{EUV} @ absorber (%)
Att-PSM-2	3-nm-TaN/21-nm-Al_2O_3/28-nm-Mo/ 2-nm-Ru/ML	52 nm	9.5 %
BIM	20-nm-Al_2O_3/27-nm-TaN/2-nm-Ru/ML	47 nm	0.9 %

14nm Isolated line

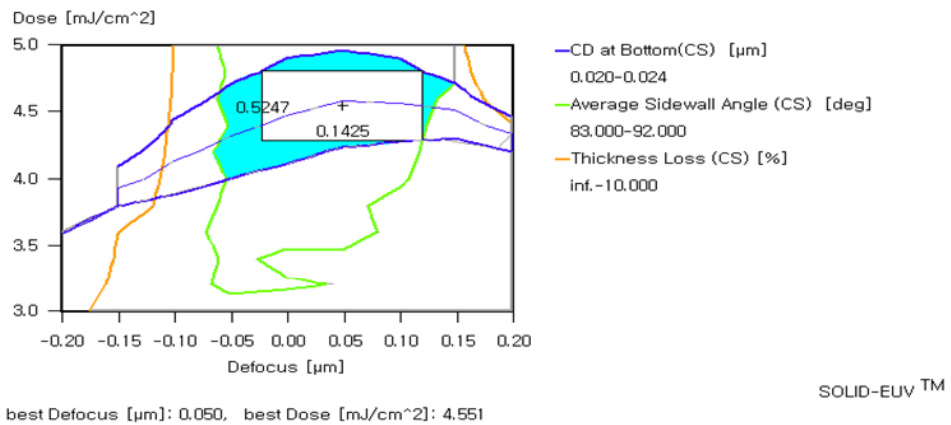


22nm line with 54nm pitch

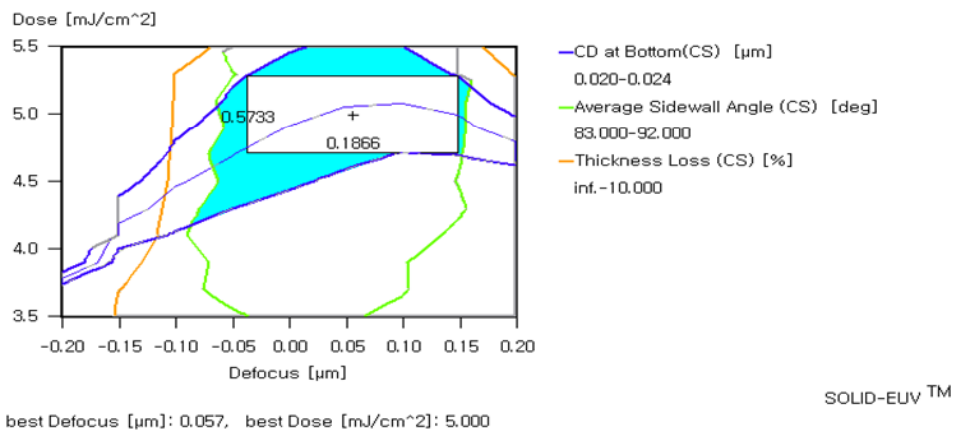


Process window

Binary mask



Attenuated PSM



➢ **Condition**

-CD error at bottom:

10% (20~24nm)

-Sidewall angle(deg): over 83°

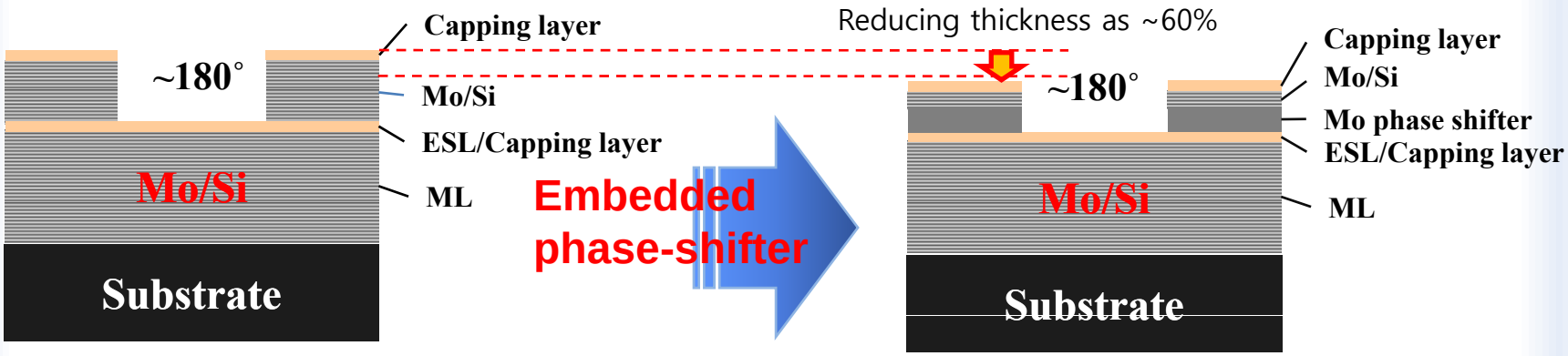
-Thickness loss: -10%

-Threshold: 20%

-Target CD: 22nm

➢ **The att-PSM provides a larger process window than binary mask**

Alt-PSM using a concept of multilayer-etching



periodic-ML-etched Alt-PSM

Thinner stack ~140nm ➔ ~60nm

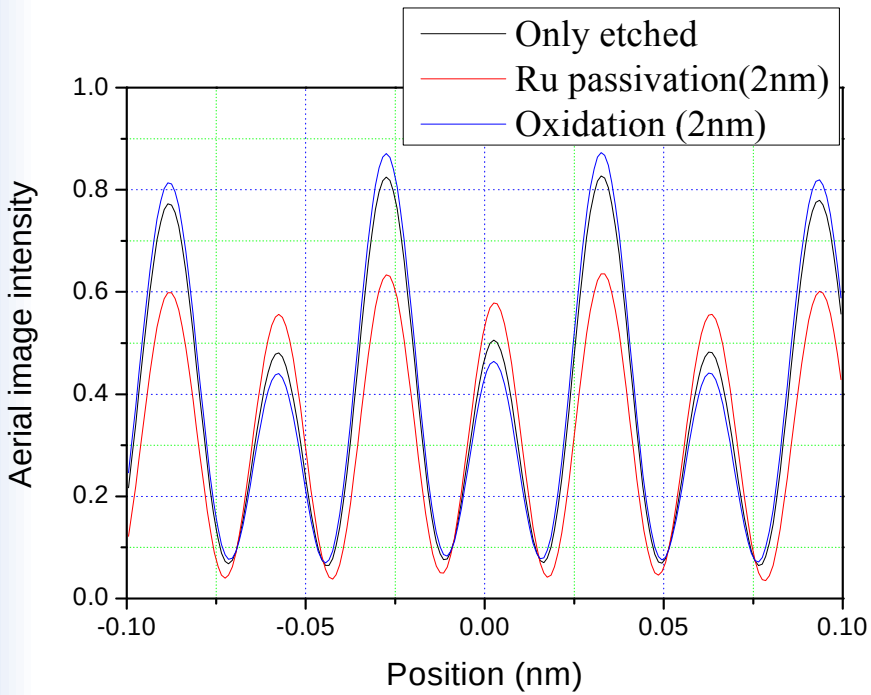
Etched multilayer alt-PSM with embedded phase-shifter

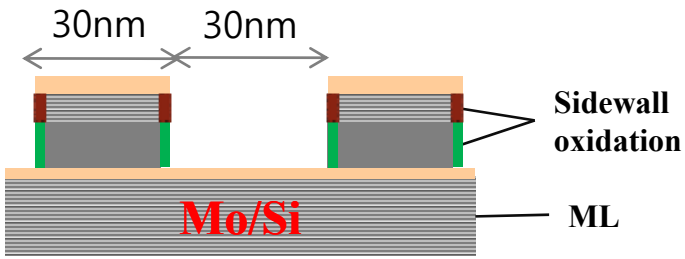
Phase shifter	# of Ml pairs	Reflectivity(%)	Depth (nm)	Phase shift (°)
31-nm Mo	3	62.7	57.8	186.6
	4	64.2	64.8	165.6
	⋮	⋮	⋮	⋮
	19	74.1	169	
	⋮	⋮	⋮	⋮

Concern with the unevenness of aerial image intensity!
No idea about DUV mask inspection!

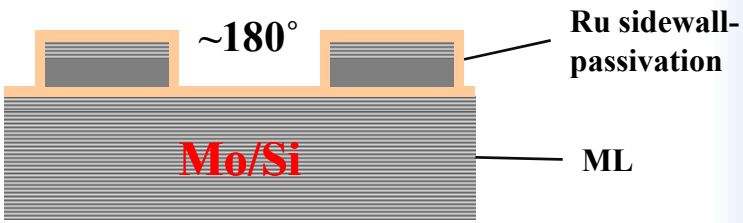
Effect of sidewall-passivation

- **15 nm L/S pattern (DI image)**





- **Sidewall oxidation can increase the unevenness of aerial image intensity.**

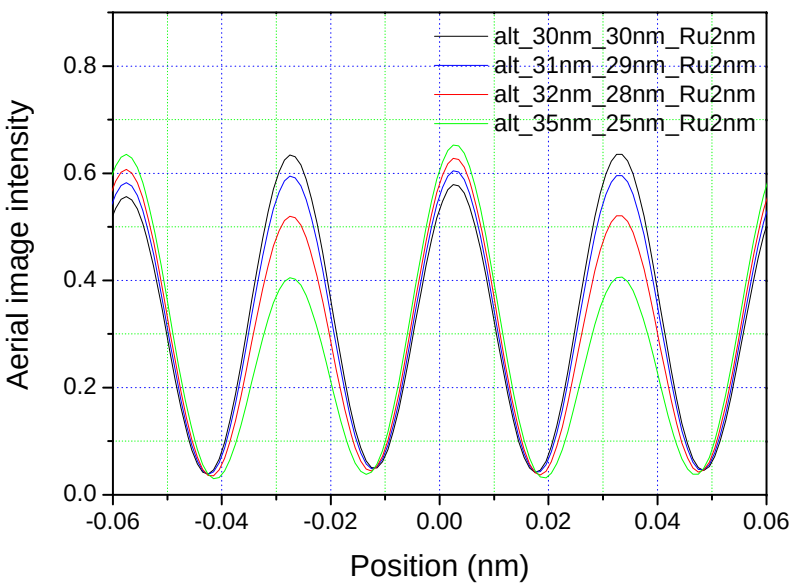


- **Ru sidewall-passivation can reduce the unevenness.**

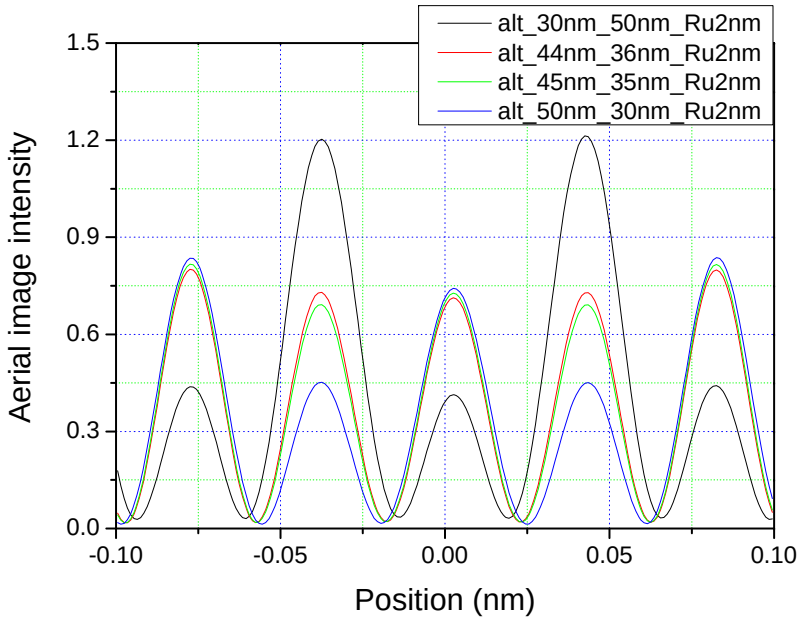
Effect of mask bias in alt-PSM with Ru passivation

- **Aerial image intensity of alt-PSM with 2nm-Ru passivation; 15nm L/S and 20nm L/S (DI image)**

15 nm L/S



20 nm L/S



- **Method of mask-bias-control can even the aerial image intensity off.**

Summary

- **Att-PSM with TaN-attenuator/Al_2O_3-spacer/Mo-phase-shifter**
  - **High inspection contrast (> ~90%)**
  - **Good thickness margin of Mo phase shifter (~5nm) with tolerance of phase shift (180±6°)**
  - **Good NILS and greater image contrast compared to the binary mask**
  - **Larger exposure and focus latitude compared to the binary mask.**

- **Alt-PSM with Ru passivation**
  - **High resolution of 15nm L/S pattern (DI image)**
  - **Oxidation can increase the unevenness of aerial image intensity.**
  - **Ru passivation and mask bias can reduce the unevenness.**