2019 EUVL workshop

Fabrication and Evaluation of SiN-based EUV Pellicle

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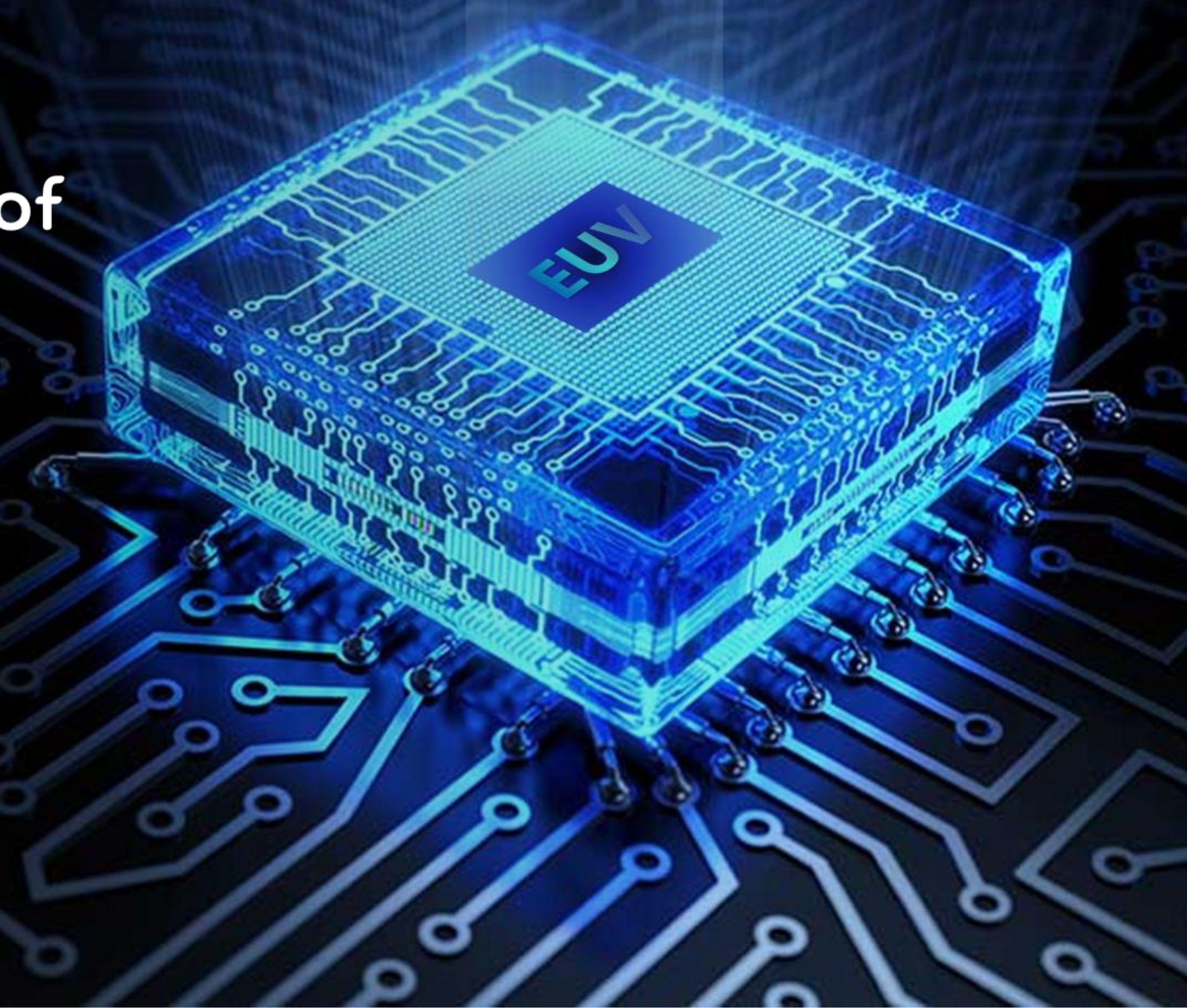

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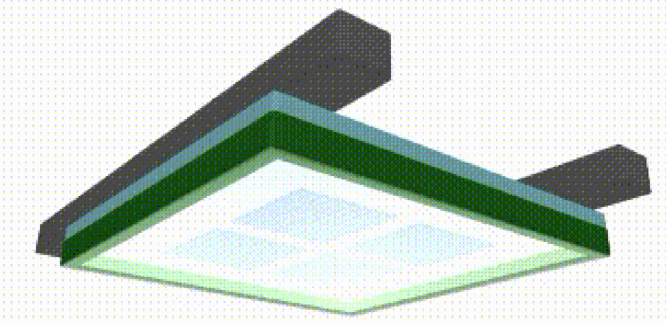
Requirements on EUV pellicle



Problems of nano-scale membrane EUV Pellicle
- mechanical stability (handling, mask stage movement, evacuation)
- thermal stability (heating/cooling by EUV scanning)

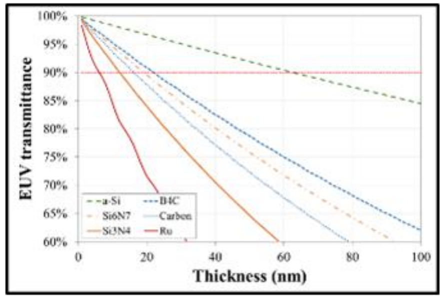
EUV pellicle requires very special specifications
- Extremely thin (<50nm) for EUV transmittance (> 88%)
- Mechanically strong
- Chemical stable for H^+ radical environment
- Highly emissive for effective cooling
- Low EUV reflectivity for imaging quality

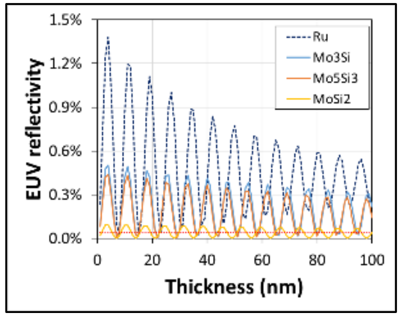
	Item	Requirement
Pellicle material requirements	EUV transmittance	≥ 88% single pass
	EUV transmittance non-uniformity	≤ 0.4% half-range
	EUV reflectance	≤ 0.04%
	EUV power capability	≥ 300W @IF
	# of exposed wafers	10,000 wafers
	Particle printability lower limit	> 15 μm
Pellicle + frame requirements	Stand-off distance during expower	2.5 mm
	Max lateral acceleration	250 m/s^2
	Max vertical acceleration	400 m/s^2
	Max film deflection @2 Pa	0.7 mm
	Max added weight to reticle	15 gram

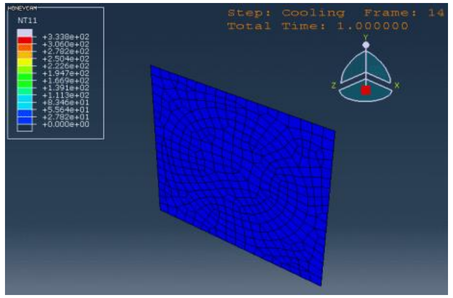
Ref. 2018 EUVL symposium. 10810-34

Infrastructure for EUV pellicle research

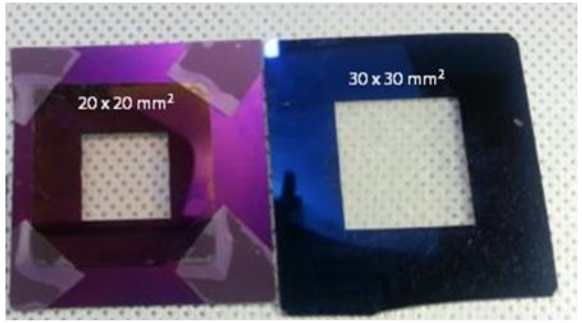
Optical/thermal /mechanical simulation

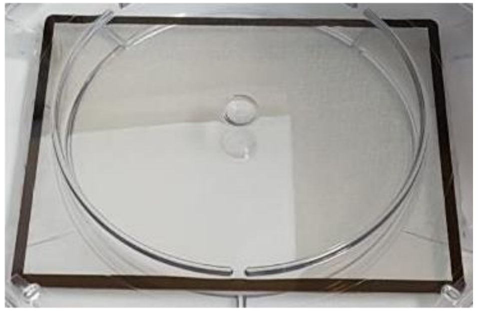




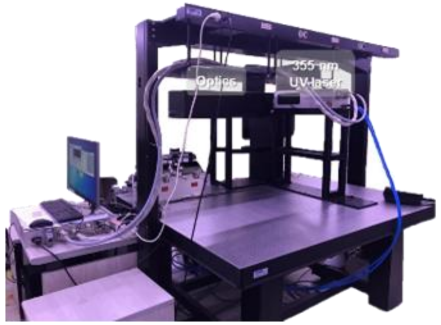


EUV pellicle fabrication





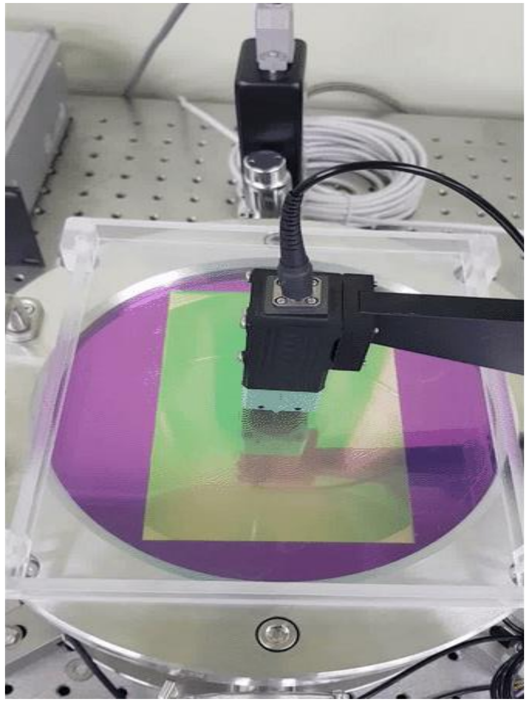
Optical/thermal /mechanical evaluation



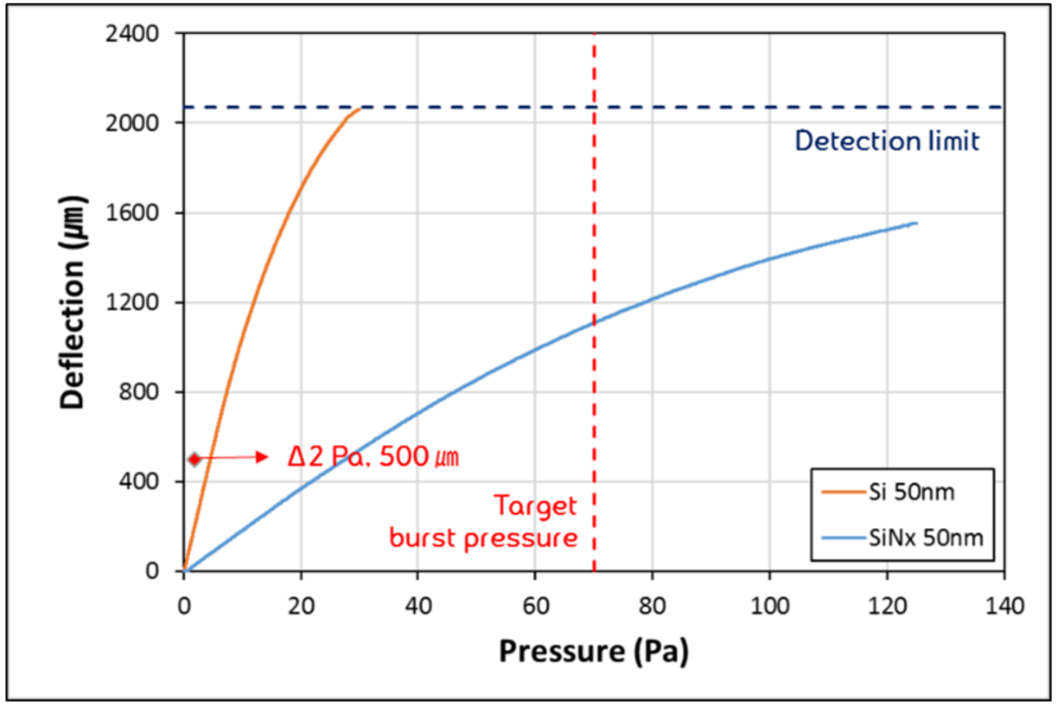
Mechanical properties of full-size EUV pellicle (SiN vs. Si)

❖ Bulge test results of full size pellicle (110 mm X 144 mm)

Image of bulge test for full-size pellicle



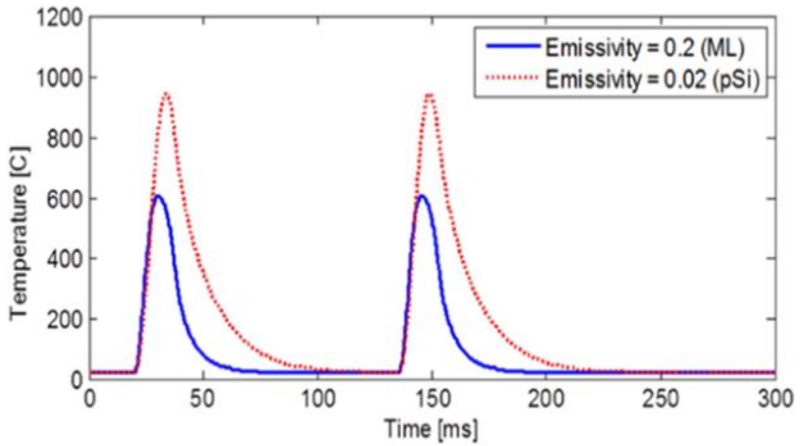
Bulge test results

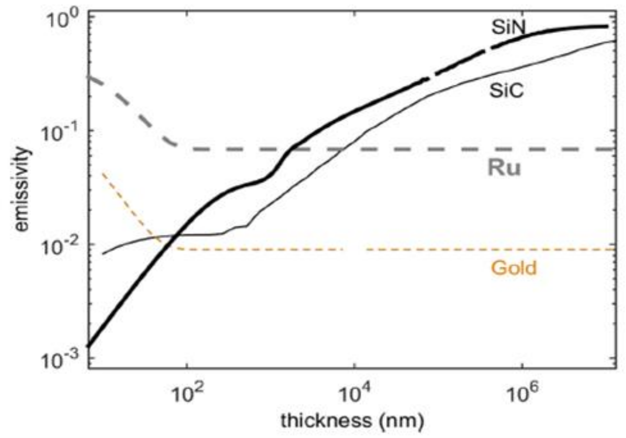


- Mechanical property requirements :
  - deflection < 700 um at ΔP = 2 Pa
  - burst pressure > 70 Pa

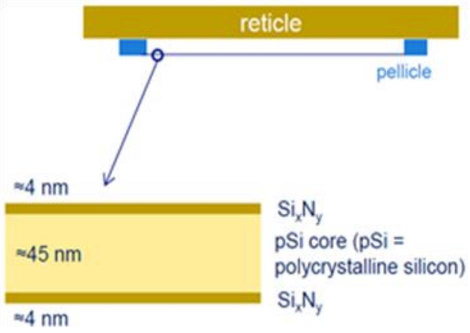
*Collaboration with S&S Tech

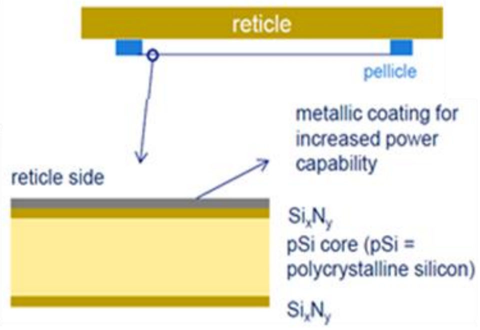
Emissivity is an issue !

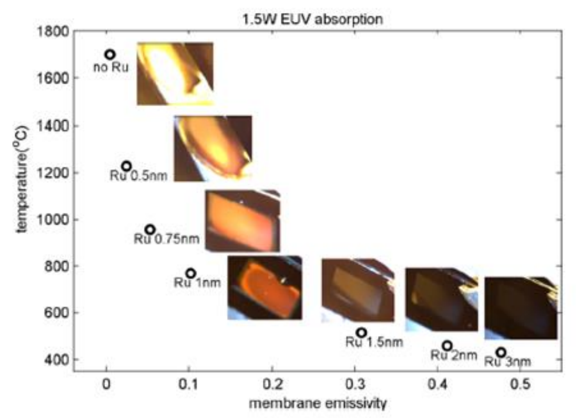




Thinner membrane is required for higher transmittance
– but (Si, SiN, SiC) emissivity decreases with the thickness





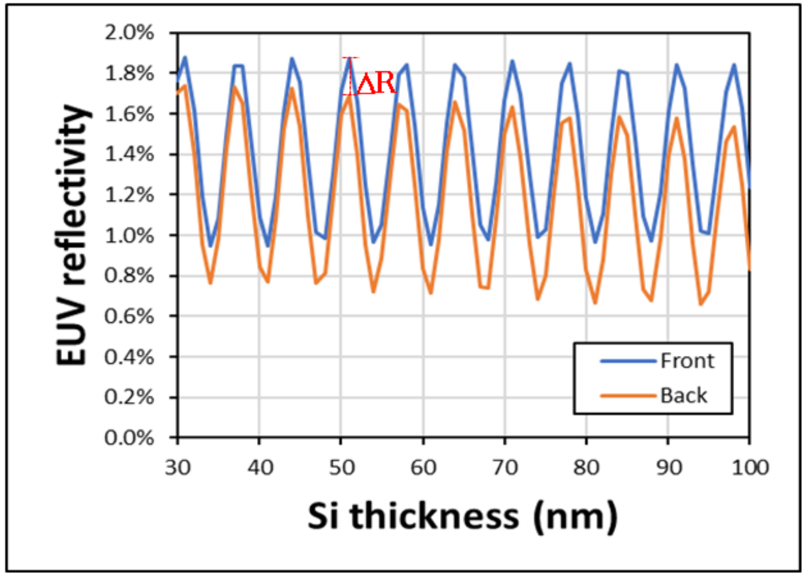


Thin metallic coating (Ru) improves cooling efficiency

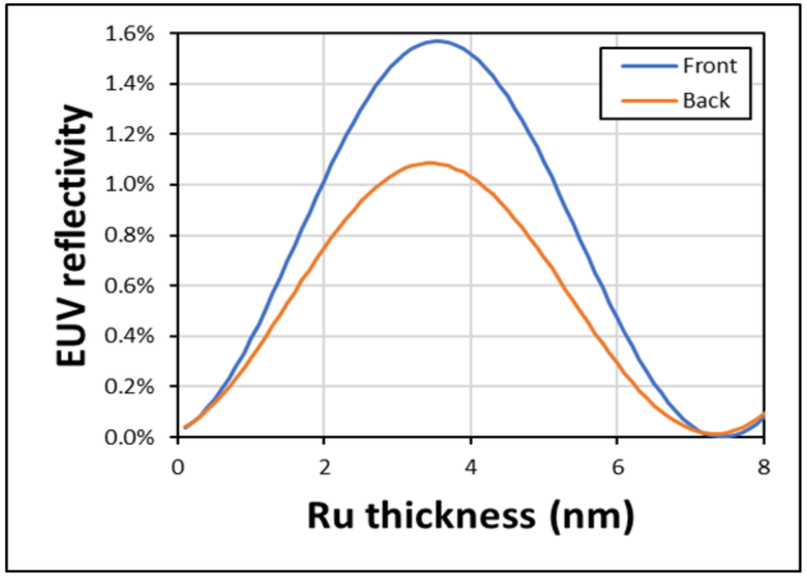
*ASML

Limitation of Ru thermal emission layer (simulation)

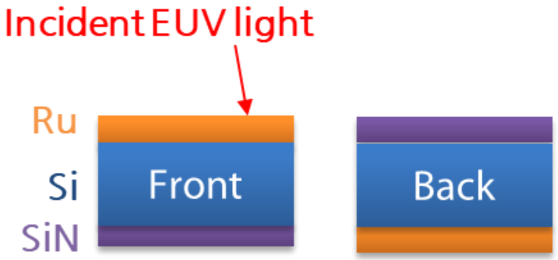
❖ EUV reflection from pellicle invalidates the effect of black border
→ very low reflectivity (〈 0.04%) is required



* 3 nm Ru, 3 nm SiN



* 3 nm SiN, 60 nm Si



t_{Si} : 30 ~ 100 nm
t_{Ru} : 1 ~ 8 nm

Materials	n	k
Ru	0.8864	0.0171
Si	0.9991	0.0018
SiN	0.9832	0.0059

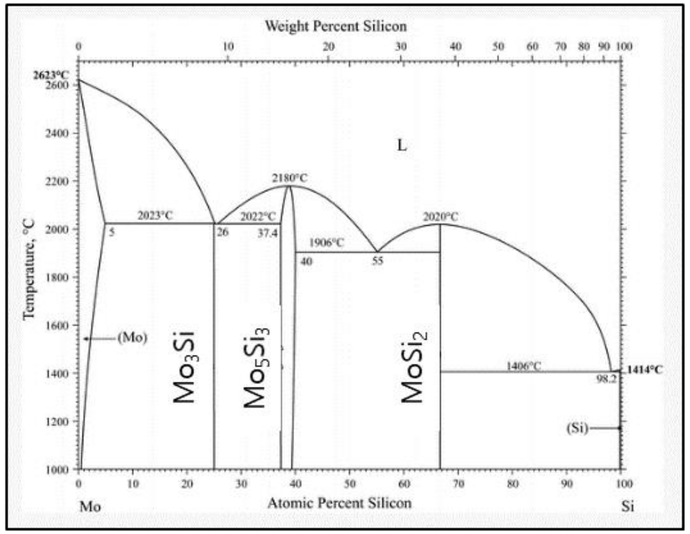
- It is difficult to achieve target EUVR (〈 0.04%) for the pellicle composite w/ Ru layer

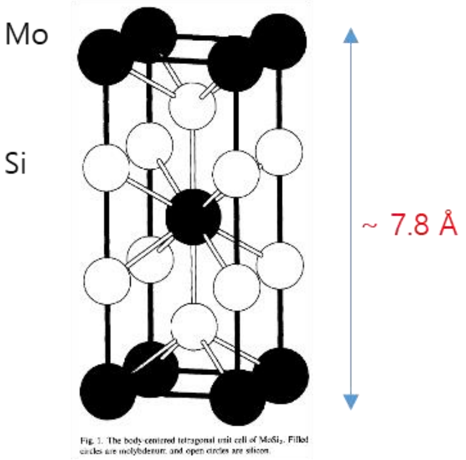
Another option for low-reflectivity thermal emission layer (Mo-silicide)

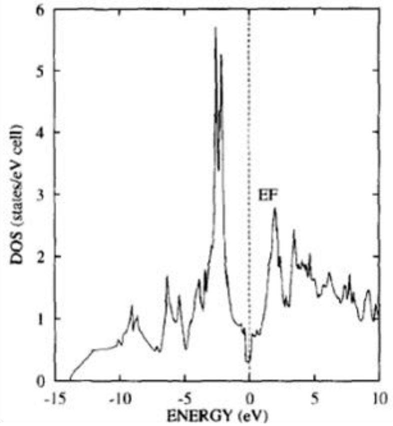
- Refractory materials (heat-resistant)
  - Melting point ~2000 ° C
- High temperature oxidation resistance
- Mixed covalent and metallic bond → "Intermetallic"
- Low electrical conductivity

- Hard & brittle at low T (strong covalent bond)
  - Substitutional doping to improve ductility
- Two polymorphs (**tetragonal** and hexagonal)

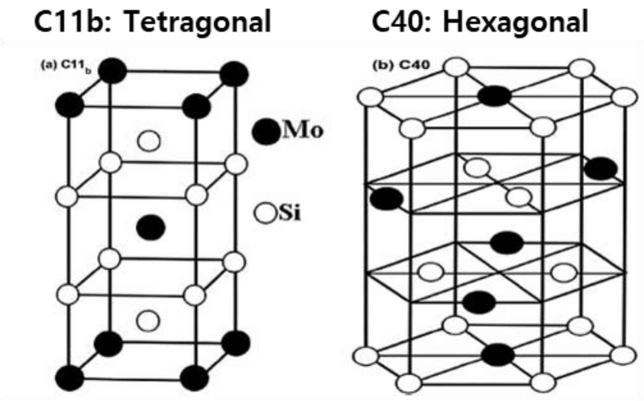
Mo-Si phase diagram







O.K. Anderson. Physica B **204**, 65 (1995)

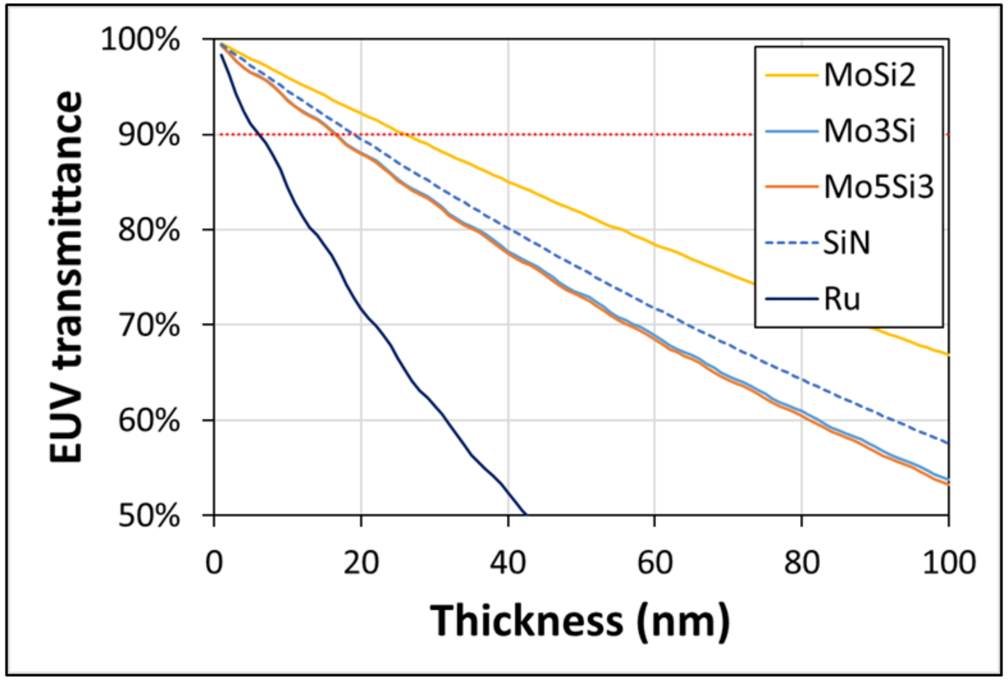


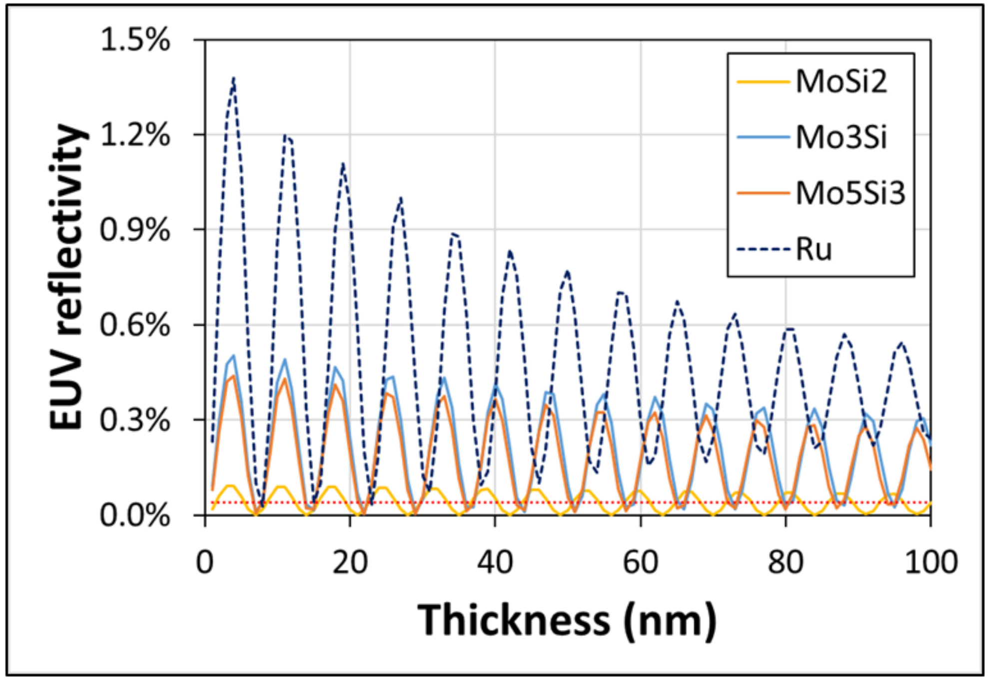
*Intermetallics **67**, 26 (2015)*

Optical properties of molybdenum silicides (simulation)

❖ Optical simulation results

Simulation results for EUV transmittance (left) and reflectivity (right)



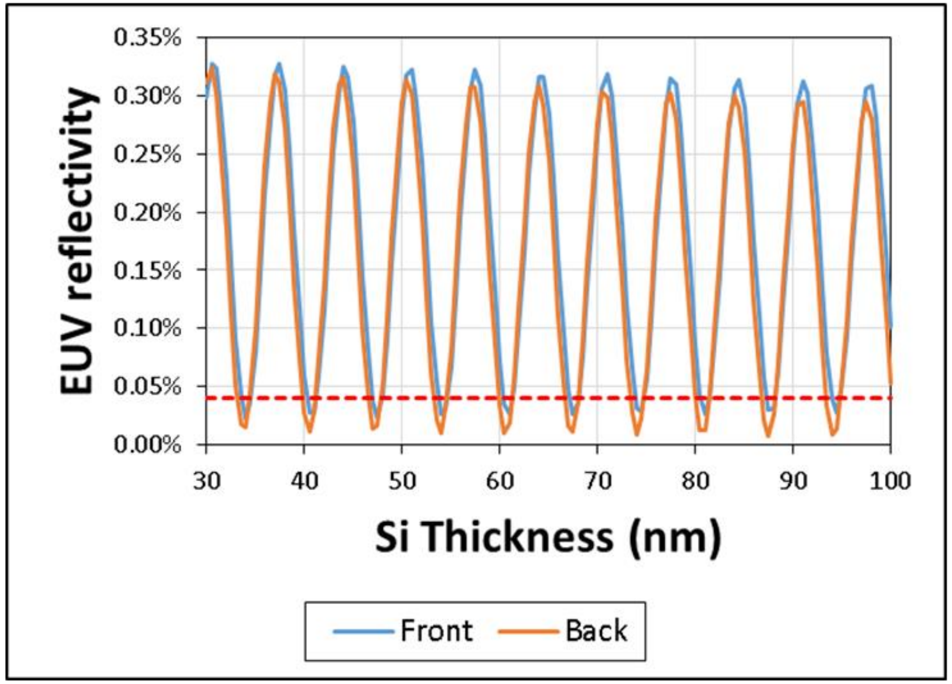


Materials	n	k
$MoSi_2$	0.9693	0.0043
Mo_5Si_3	0.9345	0.0067
Mo_3Si	0.9302	0.0066
SiN	0.9832	0.0059
Ru	0.8864	0.0171

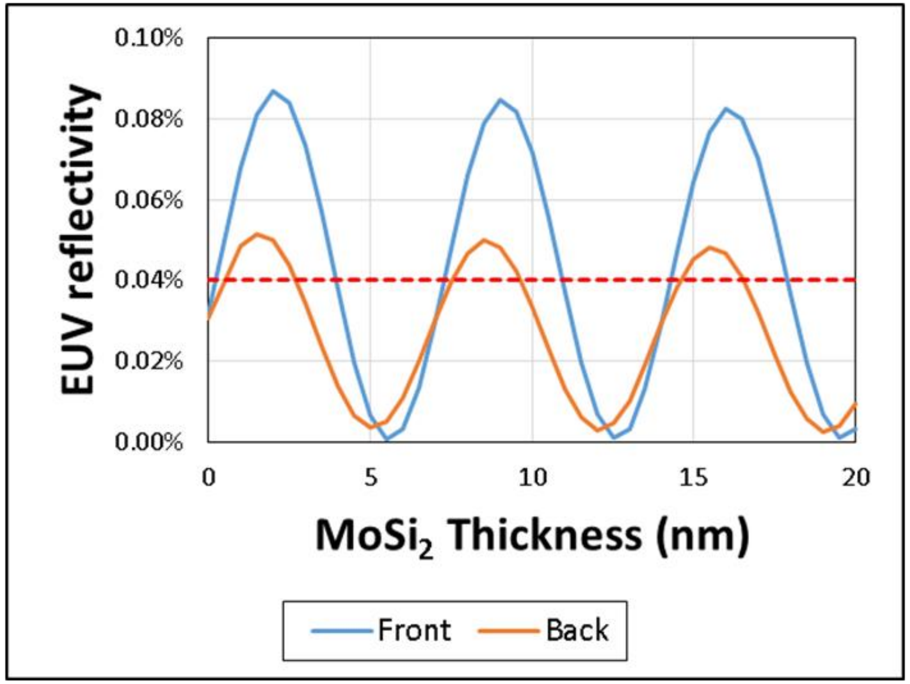
C11b (Tetragonal)

- $MoSi_2$ shows high EUVT (90% @26 nm) and Low EUVR
- Feasibility to replace Ru in terms of optical property

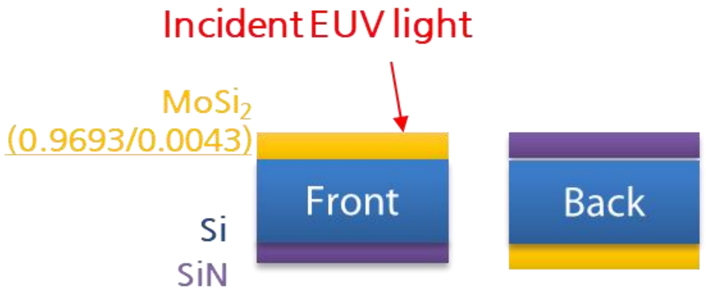
Thickness of $MoSi_2$ for minimum reflectivity (simulation) – Si core



* 3 nm $MoSi_2$, 3 nm SiN



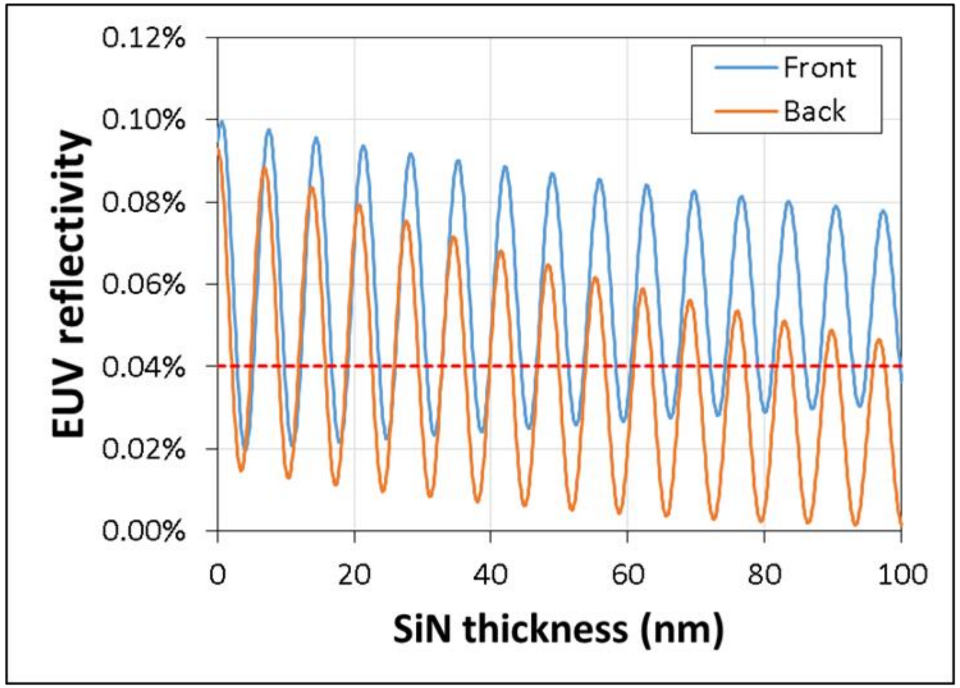
* 3 nm SiN, 60 nm Si



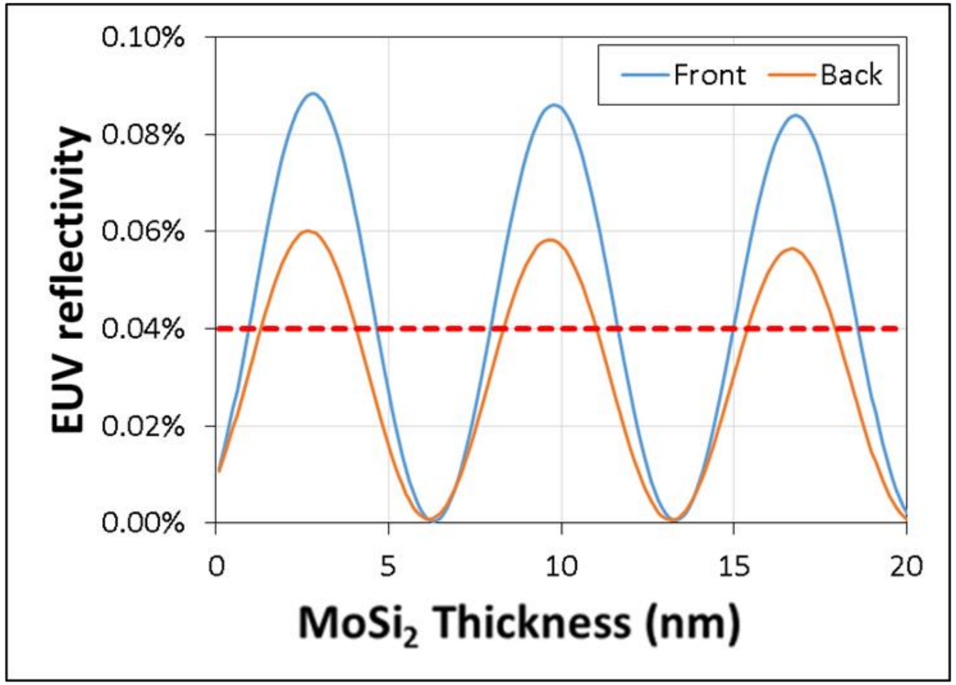
t_{Si} : 30 ~ 100 nm
t_{MoSi2} : 1 ~ 20 nm

- With optimized thickness combination, MoSi2 can easily provide very low EUVR (〈0.04%)

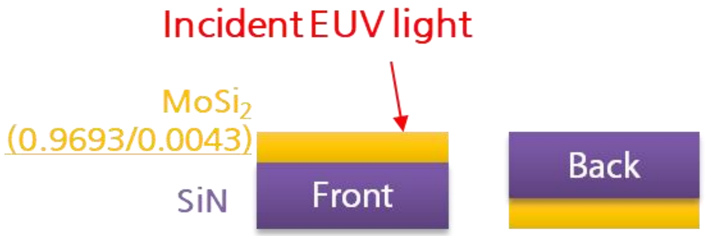
Minimization of EUVR with $MoSi_2$ (simulation) – SiN core



* 3 nm $MoSi_2$



* 22 nm SiN



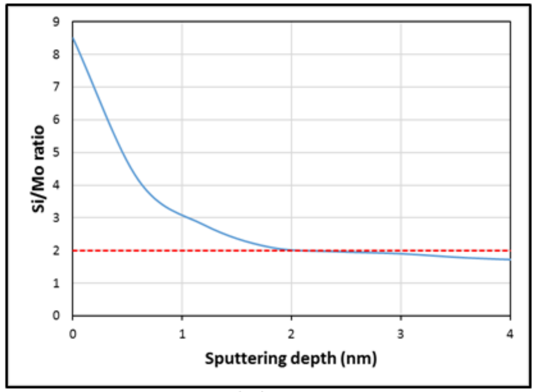
t_{SiN} : 0.1 ~ 100 nm
t_{MoSi2} : 1 ~ 20 nm

- The total thickness of the pellicle composite was thinner considering EUVT, but we can obtain even lower reflectivity

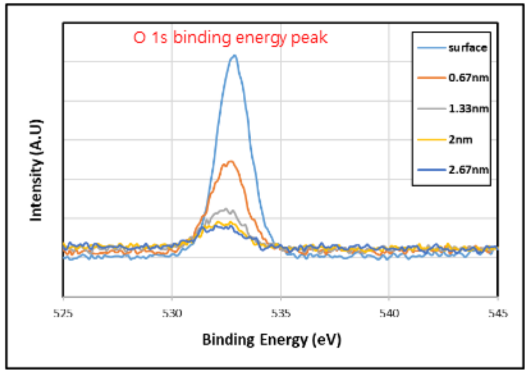
Analysis of $MoSi_2$ thin film (experimental)

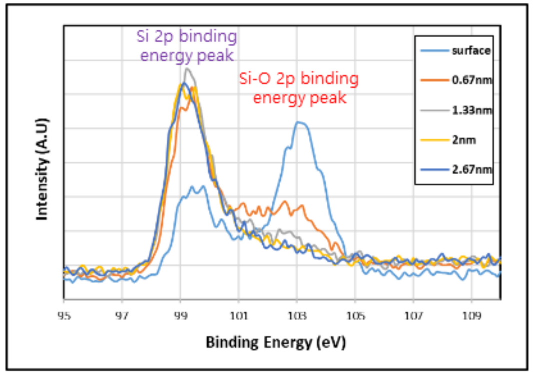
❖ Sputter deposited $MoSi_2$ and post-annealing effect

Depth profiling by XPS



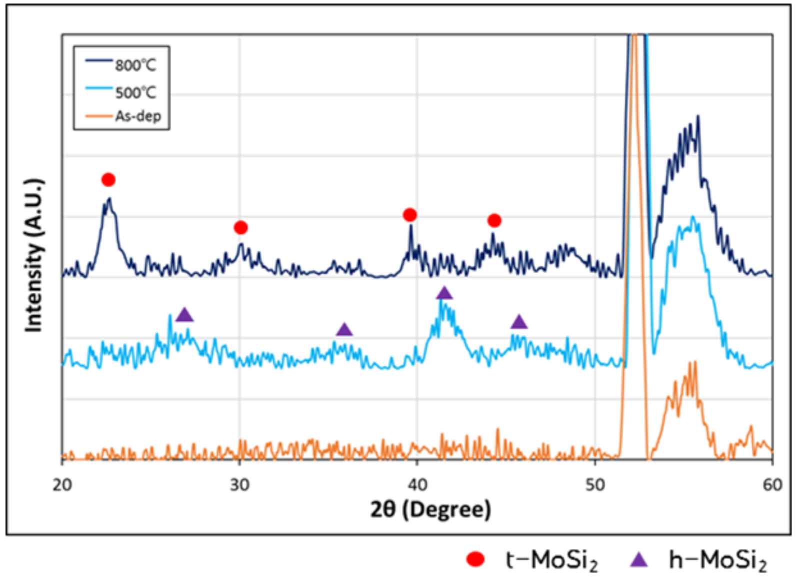
* 150W RF power (Si), 800℃ annealing condition





- Stoichiometric $MoSi_2$ thin film was obtained, but about 1 nm thick SiO_2 existed on the surface

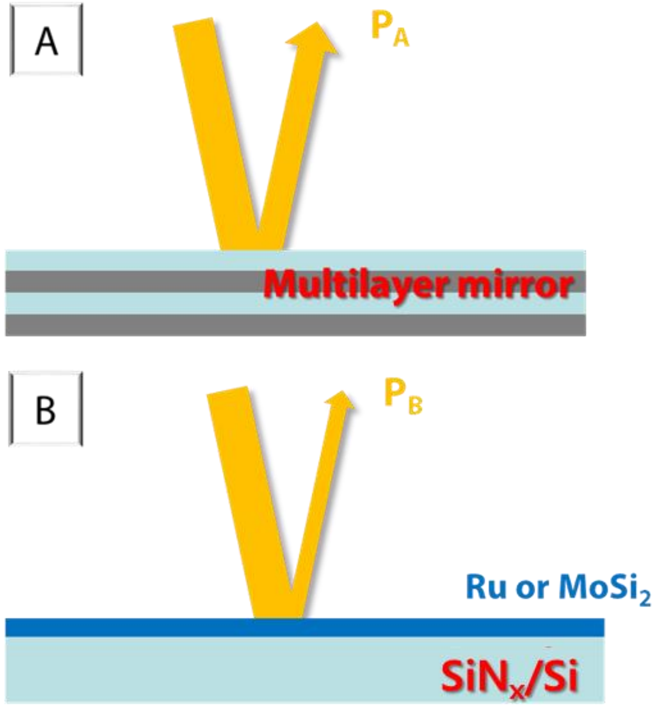
XRD – Crystal structure



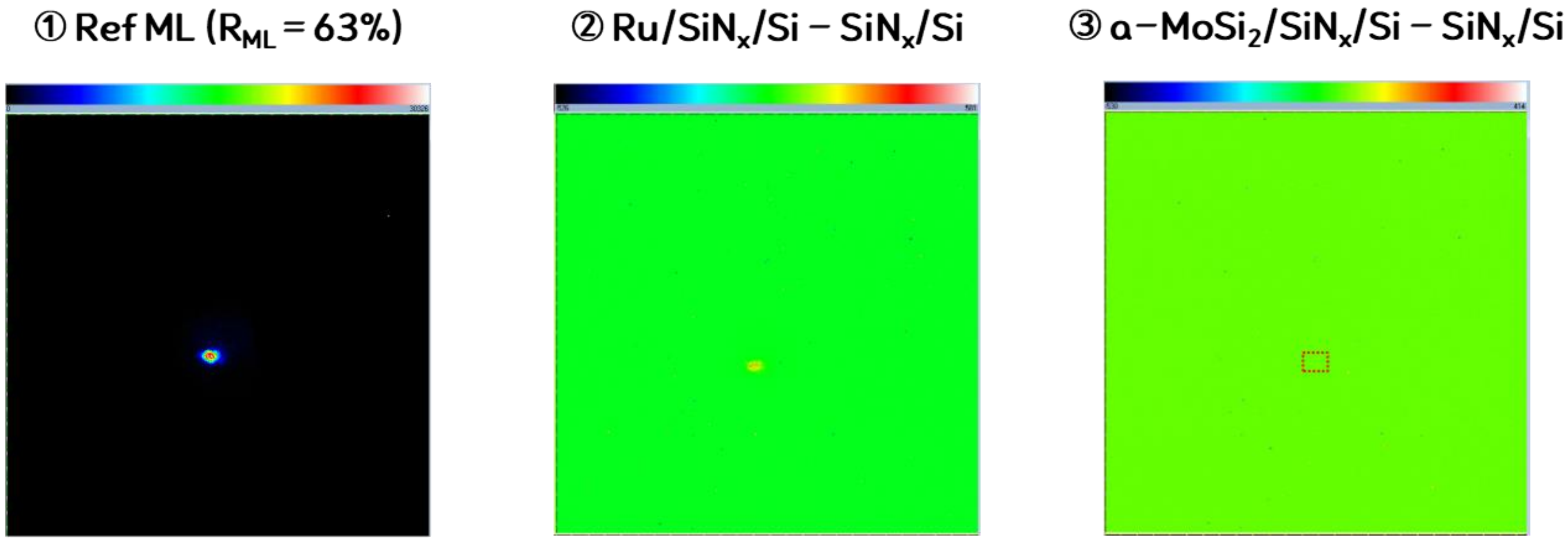
- As-deposited $MoSi_2$ thin film is amorphous
- It is transformed into hexagonal and tetragonal structure at 500℃ and 800 ℃, respectively

*Applied Surface Science, Volumes 70-71, part1, 2 (1993), 222-225
J. Mater. Res., Vol. 5, No. 12, (1990)

EUVR measurement for thermal emission layers



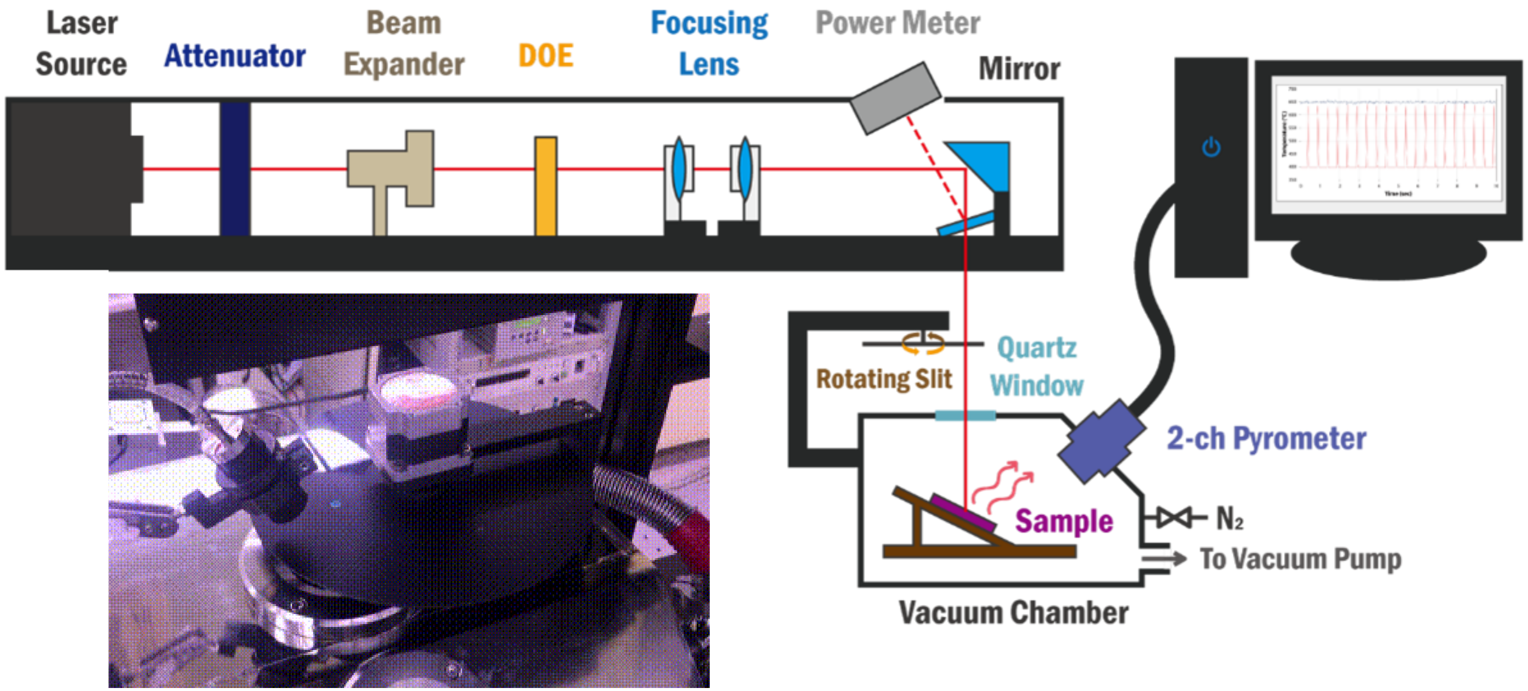
Reflectivity of Ru or $MoSi_2$ layer = $P_B/P_A * R_{ML}$



Sample	Avg	EUVR
① Ref ML	30326	63%
② Ru	420	0.524%
③ $a-MoSi_2$	35	0.019%

- EUVR of ~0.02% was measured for amorphous $MoSi_2$ sample
- EURV of tetragonal $MoSi_2$ was below detection limit

Thermal property measurement



① $\frac{P_{UV}}{D_{UV}} * A_{UV} = I_{abs}$

Variable — Adjustable

② $\phi_{EUV} * A_{EUV} = \phi_{UV} * A_{UV}$

Absorbed heat intensity by EUV source — Absorbed heat intensity by UV laser

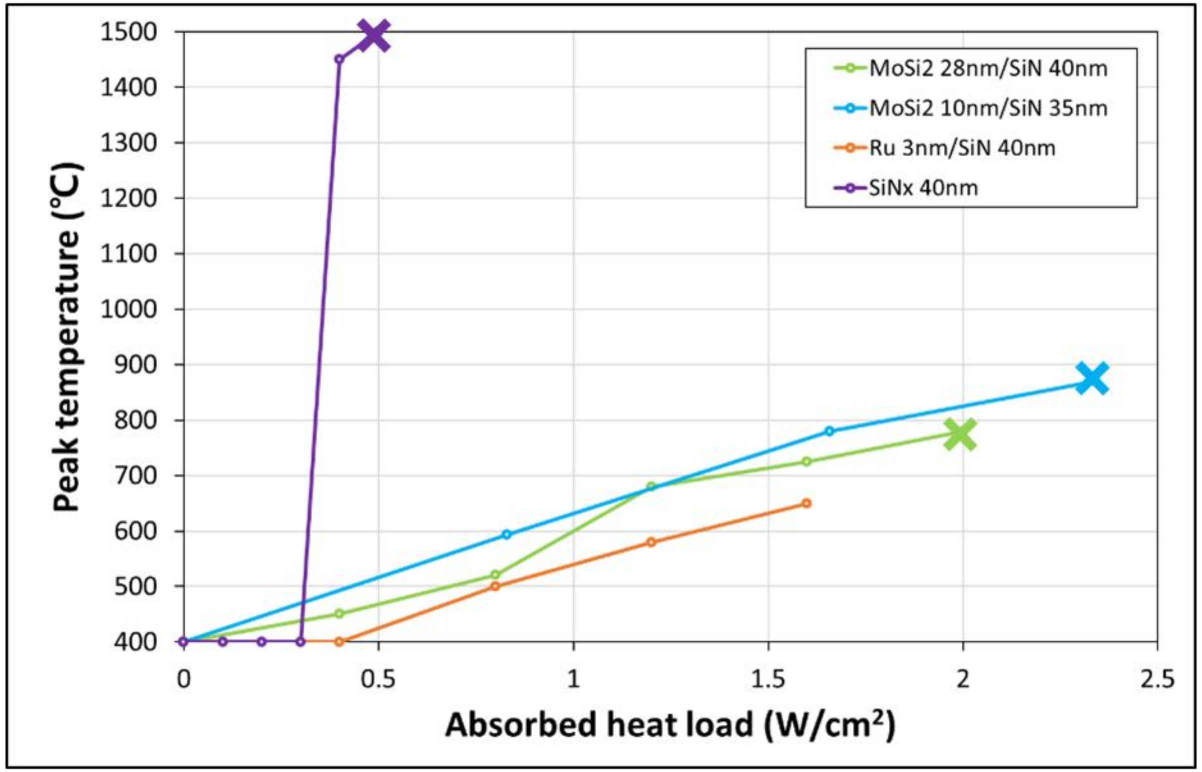
I : absorbed heat intensity @ pellicle [W/cm^2]
Φ : Incident heat intensity ($^P/_D$)
P : source power [W], *D* : beam size [cm^2]
A : absorbance of pellicle membrane

Parameter	Value
Beam diameter	0.6 cm
Heating/cooling time	0.1 / 0.9 sec
Vacuum	〈 6×10^{-6} torr

- EUV source power can be emulated by UV laser considering absorbance of membrane
- High vacuum and rotating slit provides heat load condition in EUV scanner

Effect of thermal emission layer (experimental)

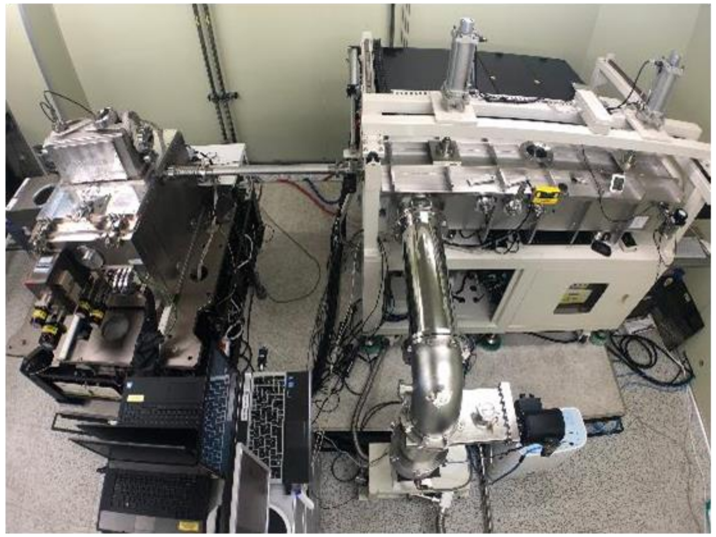
❖ **Heat load test results depending on thermal emission layer**



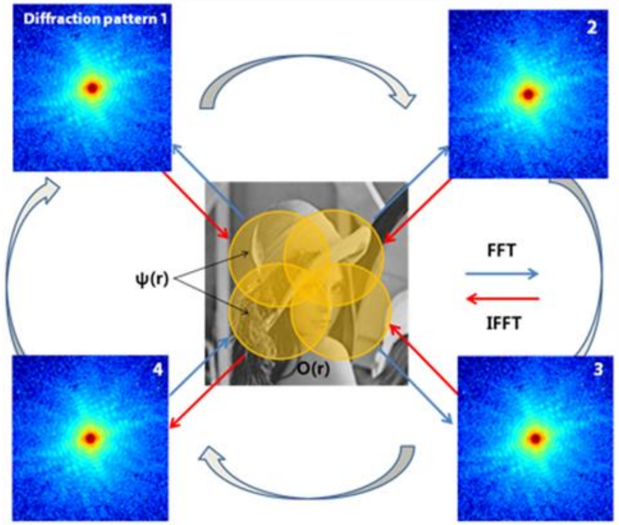
- EUV transmittance : Ru 3 nm / SiN_x 40 nm – 75.6% (measured),
- $MoSi_2$ 28 nm / SiN_x 40 nm – 71%(calculated)

- $MoSi_2$ is a good thermal emission layer for SiN_x based pellicle structure (not optimized yet)

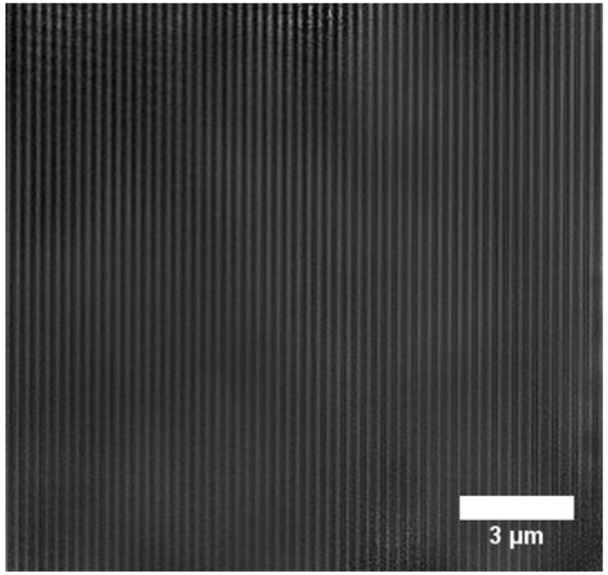
EUV-ptychography microscope imaging



① Capture the diffraction patterns using EUV-ptychography microscope



② Image reconstruction using ptychography algorithm



③ Analyzation of reconstructed image

Hardware noise issue

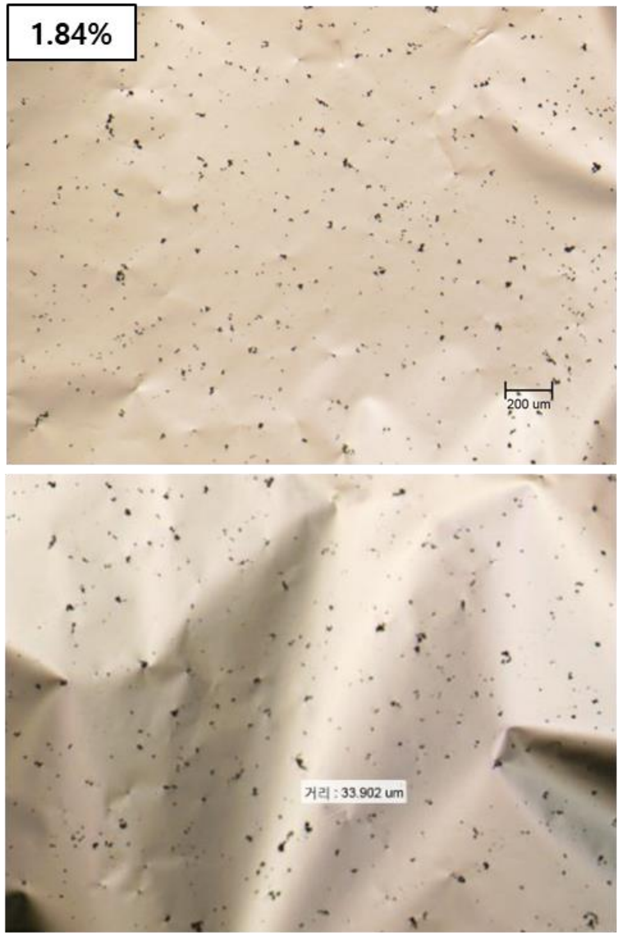
- ✓ Inspection beam shape
- ✓ Intensity fluctuation
- ✓ Position inaccuracy (beam drift or stage drift)
- ✓ Background noise (CCD, stage)

Software solution

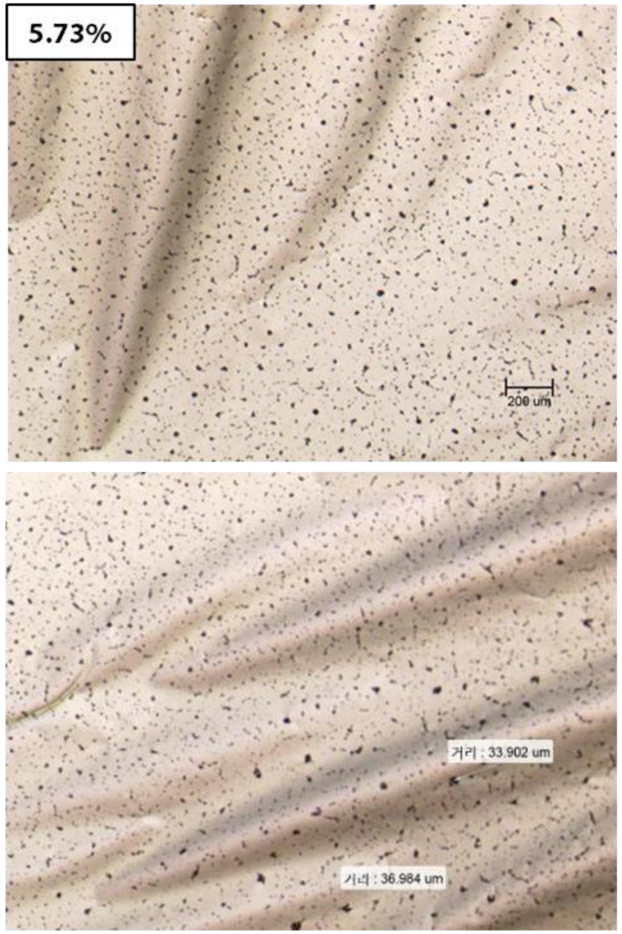
- ✓ Probe updating algorithm
- ✓ Probe constraint method
- ✓ Position correcting algorithm

Results of pellicle contamination by spin coating

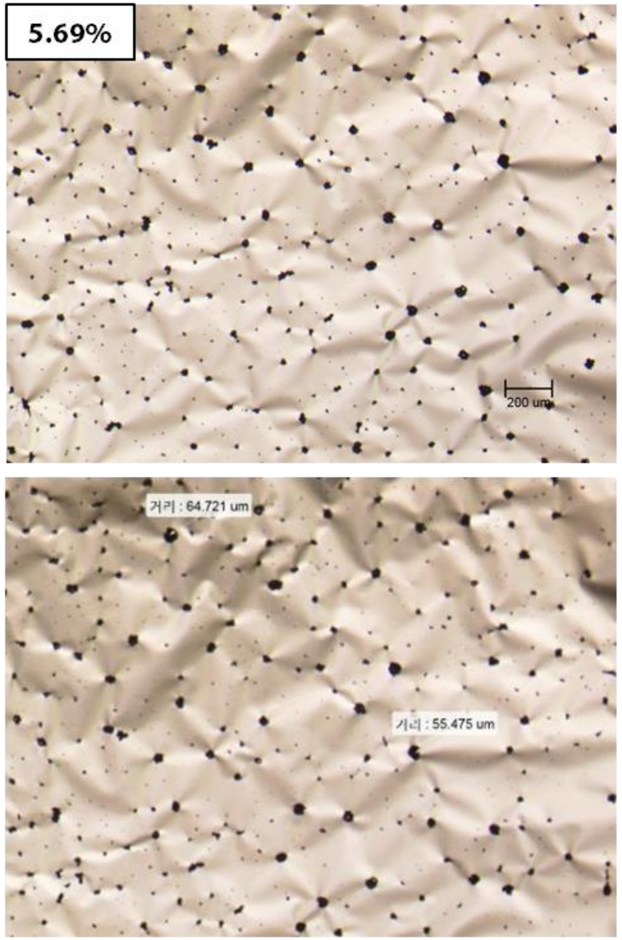
〈Carbon〉



〈Fe〉



〈Ti〉

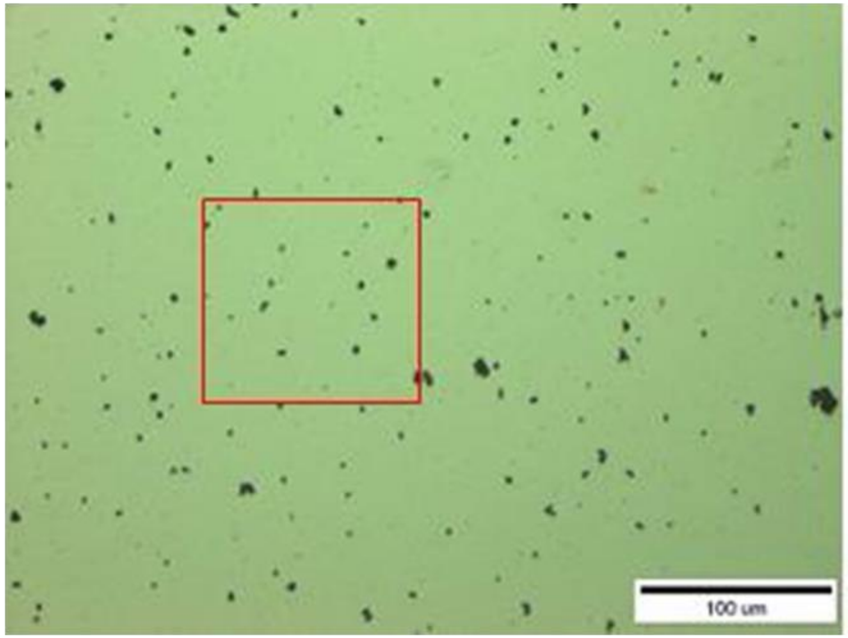


- Density and size of the particles can be controlled.
- The maximum size of carbon and Fe particles is about 35 ㎛ and Ti particles is about 65㎛

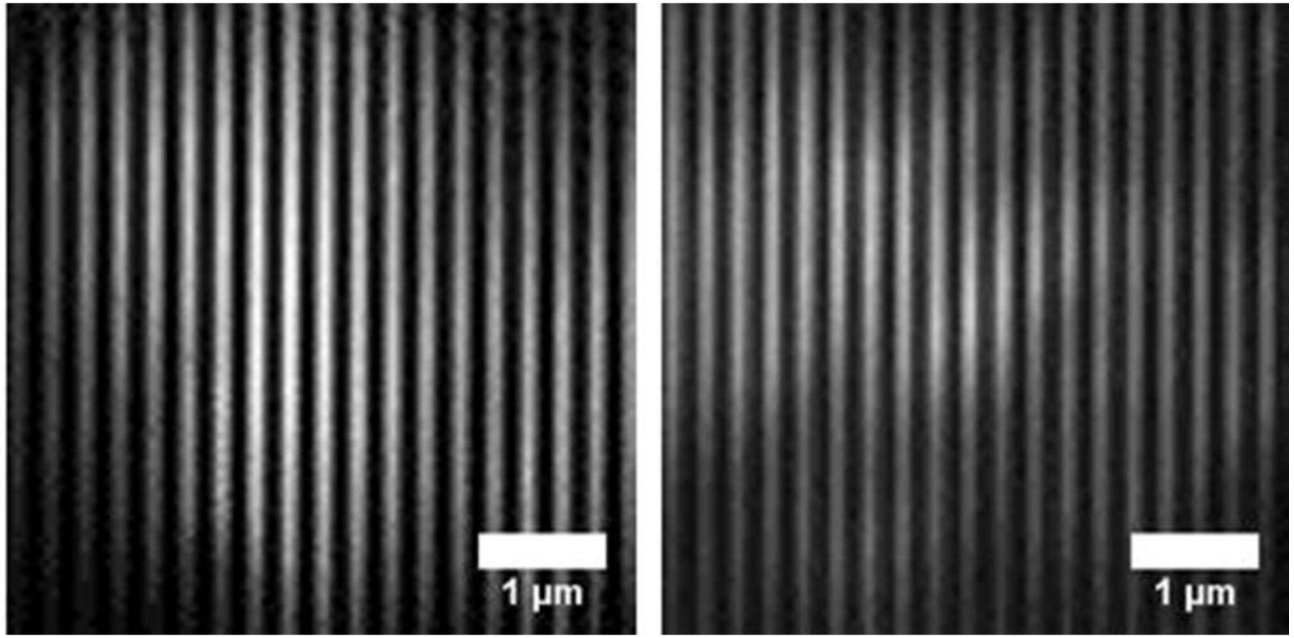
Printability of small particles

❖ Through-pellicle imaging with contaminated membrane (Particle size 〈 10 μm)

Spin-coated particle (OM)



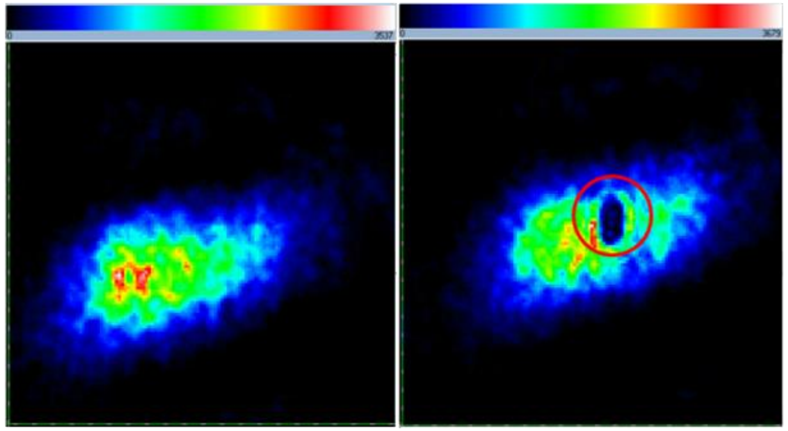
Mask image (left) w/o, (right) w/ pellicle

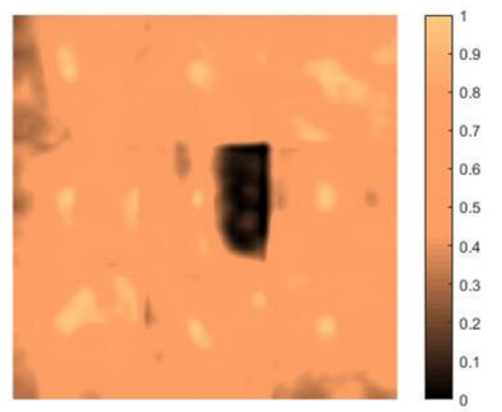


- Particle smaller than 10 ㎛ on the pellicle hardly degrades imaging properties

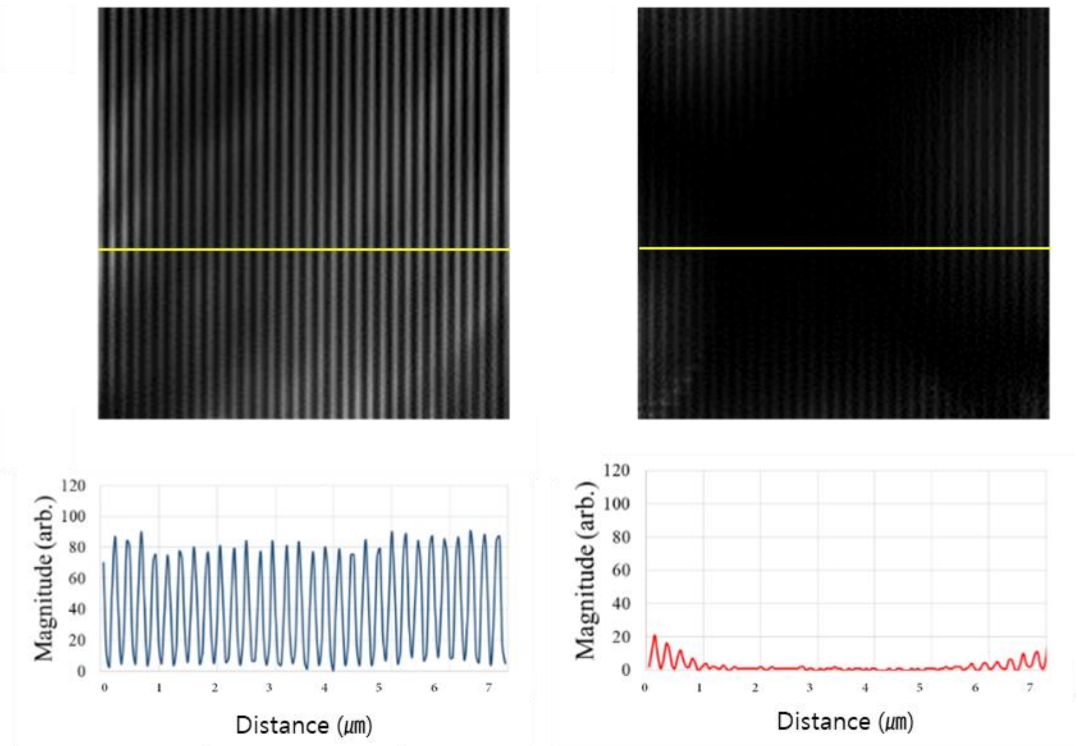
Printability of large particle

❖ Through-pellicle imaging with contaminated membrane <u>(Particle size > 10 μm)</u>





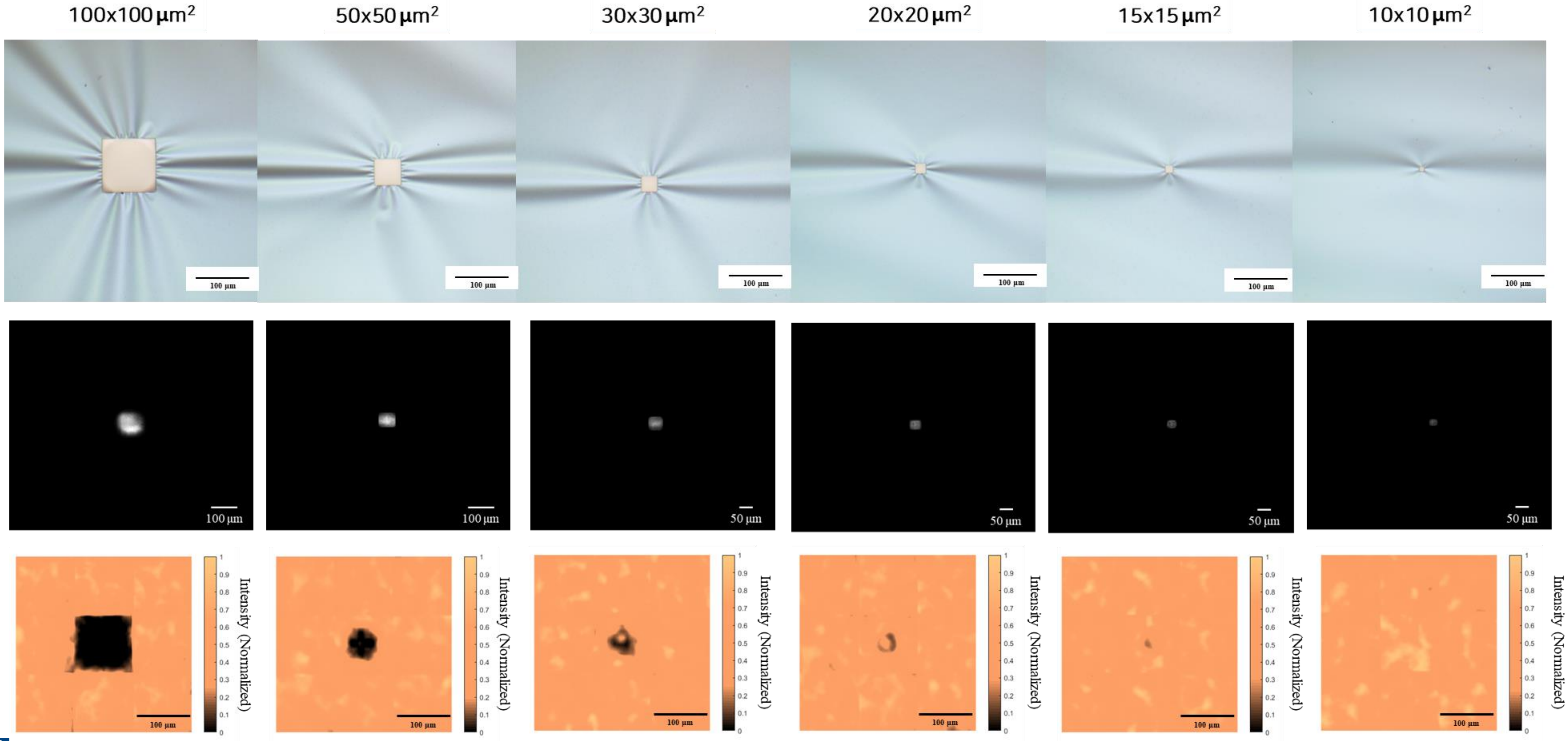
Mask image (left) w/o. (right) w/ pellicle



* 128 nm half-pitch nm L/S pattern

- Particle larger than 10 ㎛ on the pellicle induced severe degradation of imaging properties

Programmed pellicle defect (Ti) mapping – UV line scan & EUV correlation

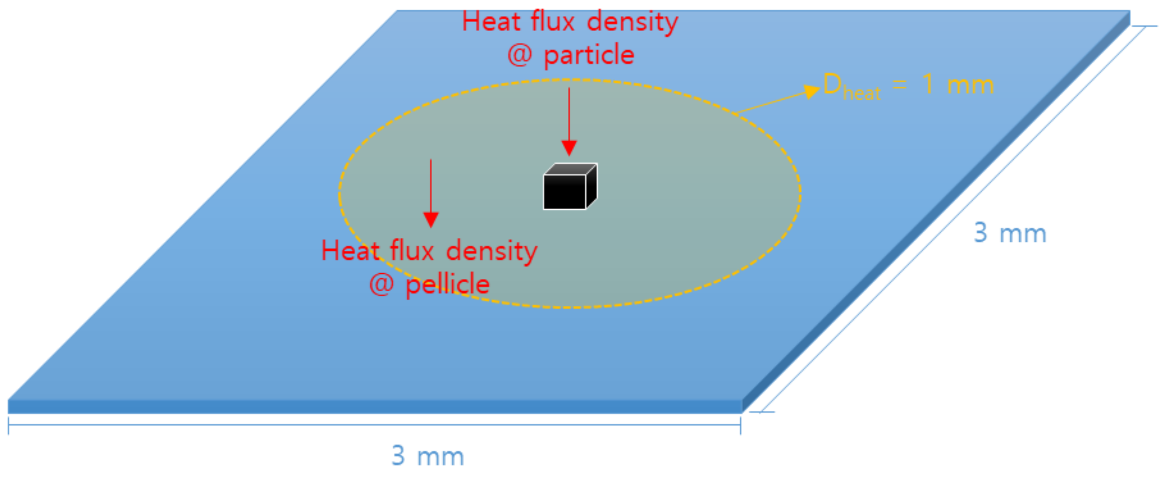


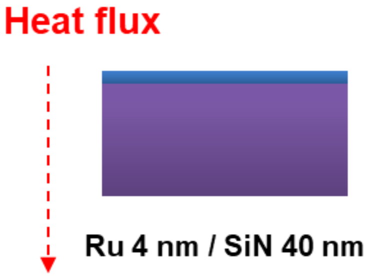
Simulation of thermal behavior with particle contamination

❖ ABAQUS standard & explicit model

Parameter	Density (kg/m^3)	Specific heat ($J/kg \cdot K$)	Thermal conductivity ($W/m \cdot K$)	Emissivity
SiN_x	3170	673	2.5	0.0035
Ru	12500	238	11.7	0.4
Ti	4510	544	21.9	0.70
Fe	7874	450	80.4	0.70
C	2267	734	96.0	0.95

Parameter	Value	
Incident EUV intensity @ pellicle (ϕ_{EUV})	250W	5.0 W/cm^2
	375W	7.5 W/cm^2
	⋮	⋮

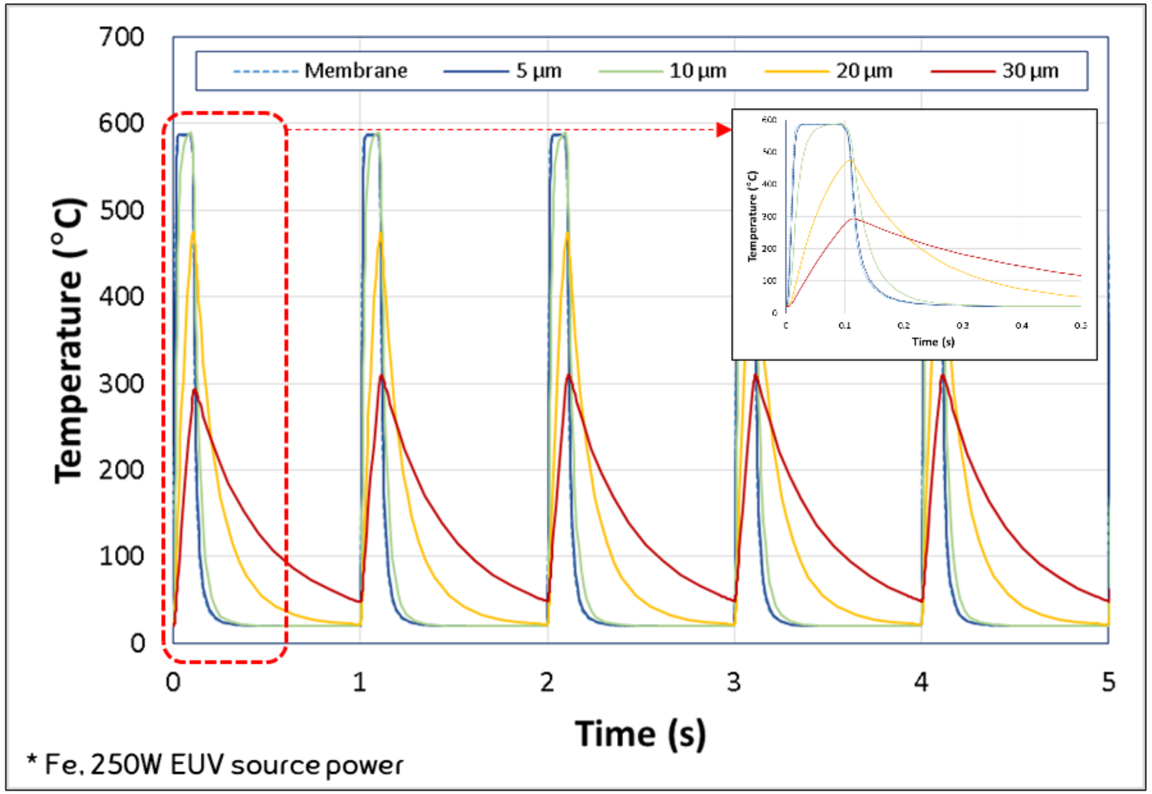


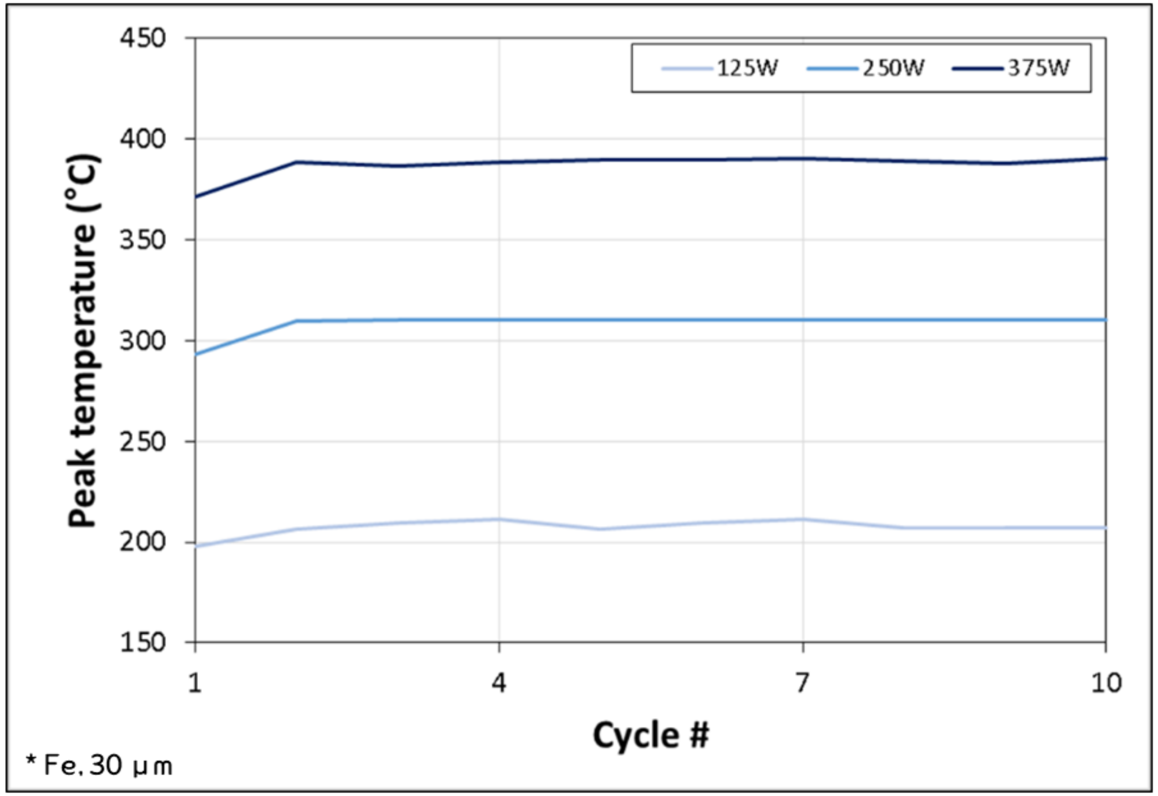


- ✓ Heating/cooling time = 0.1 / 0.9 sec
- ✓ $A_{particle} = 1$
- ✓ $A_{pellicle} = 0.26$
- ✓ Particle size = 5^3, 10^3, 20^3, 30^3 μm^3

- Finite element simulation was performed – 4 nm Ru / 40 nm SiN_x composite pellicle
- Cubic particle was employed to calculate temperature difference between the pellicle and particle

Temporal temperature distribution depending on particle size and cycle





$$\frac{dT}{dt} = \frac{Q}{c_p \cdot m}$$

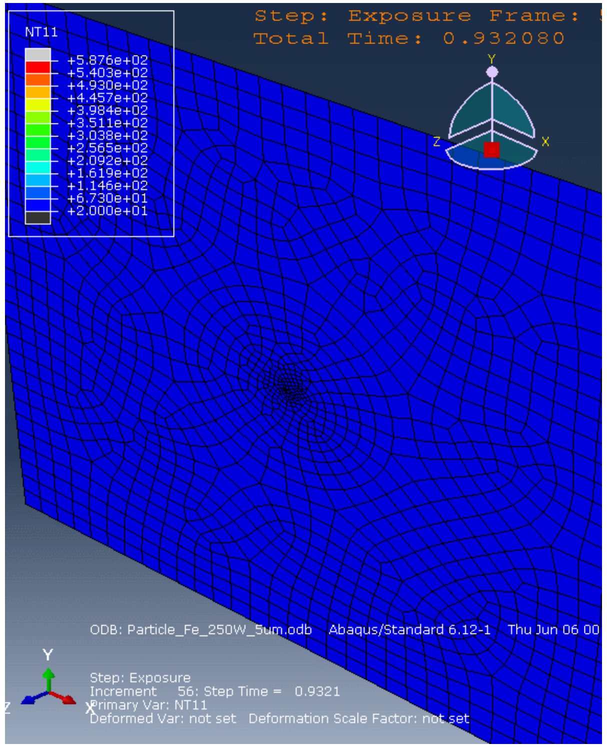
Heat flow (J)

Heat capacity (J/K)

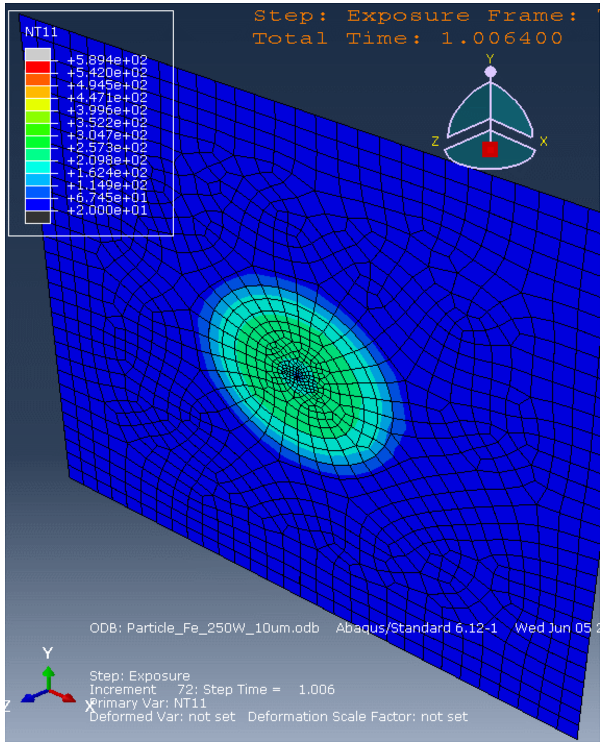
- Increased heat capacity with larger particle size induced lower peak temperature of the particle
- Constant peak temperature depending on cycle # was observed

Spatial temperature distribution – particle size

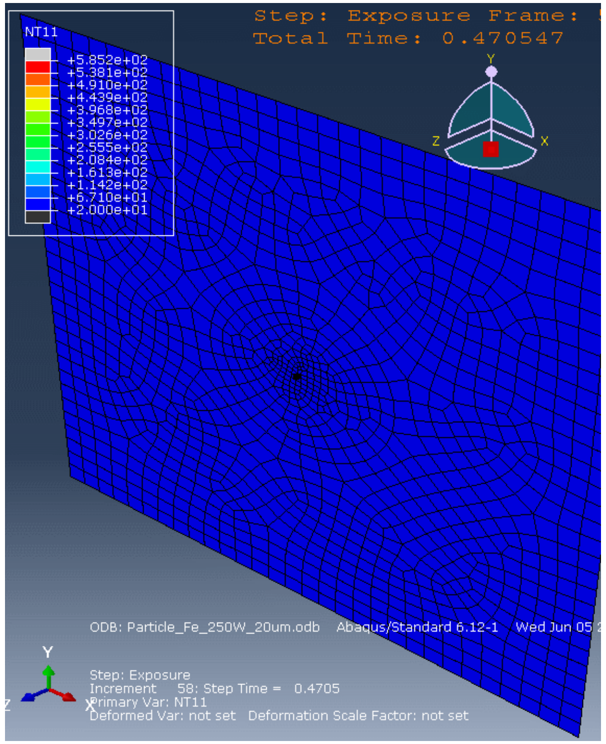
5 ㎛



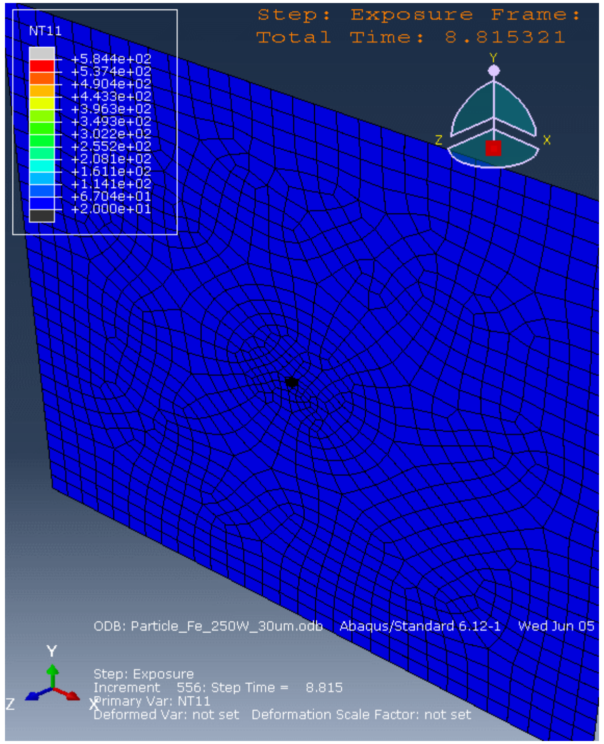
10 ㎛



20 ㎛



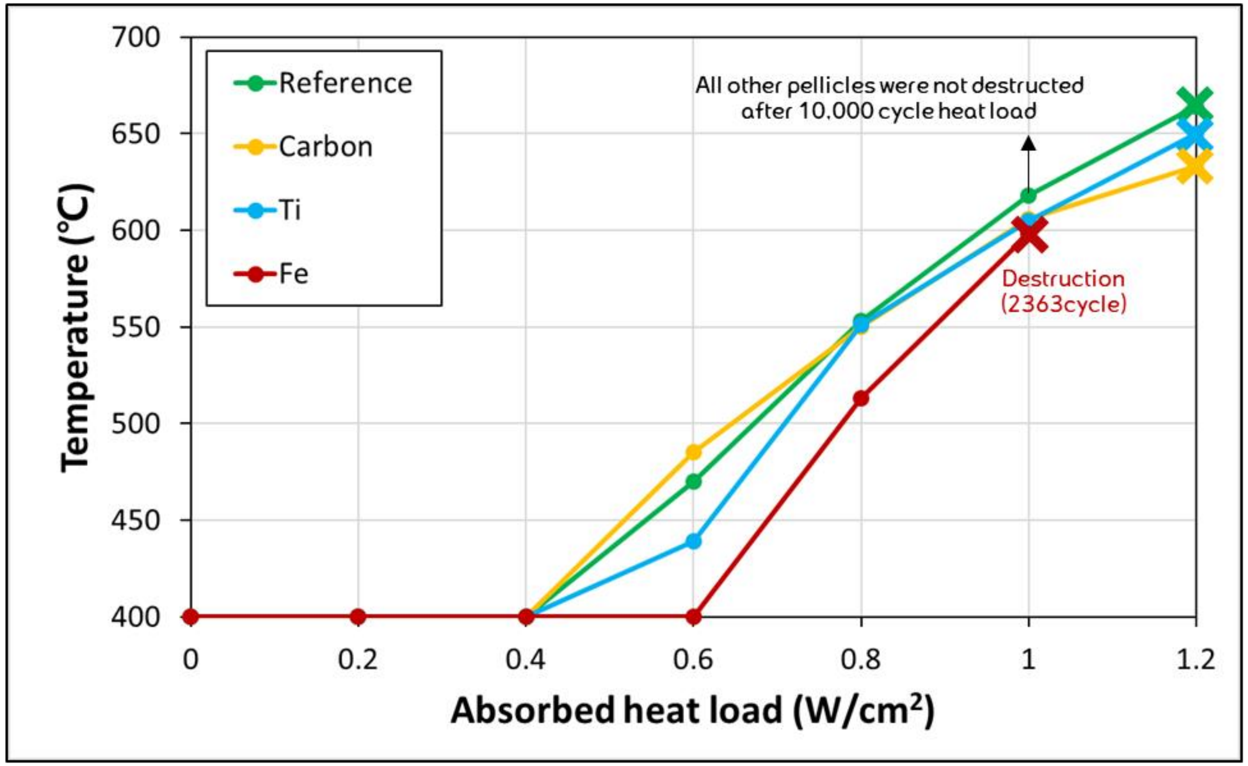
30 ㎛



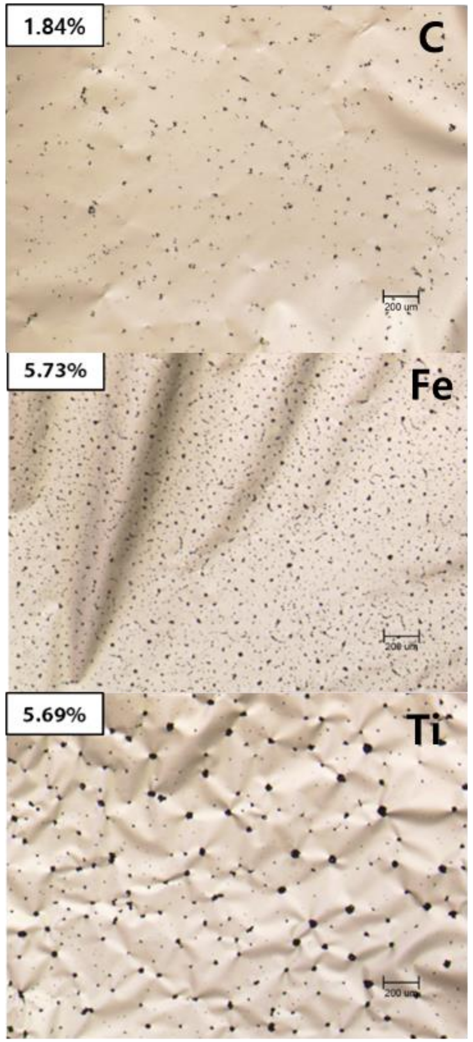
- Comparison of spatial temperature distribution of pellicle w/ Fe particle at the condition of 250W EUV source power

Experimental heat load test of pellicle with particles

❖ Heat load test results depending on type of particle



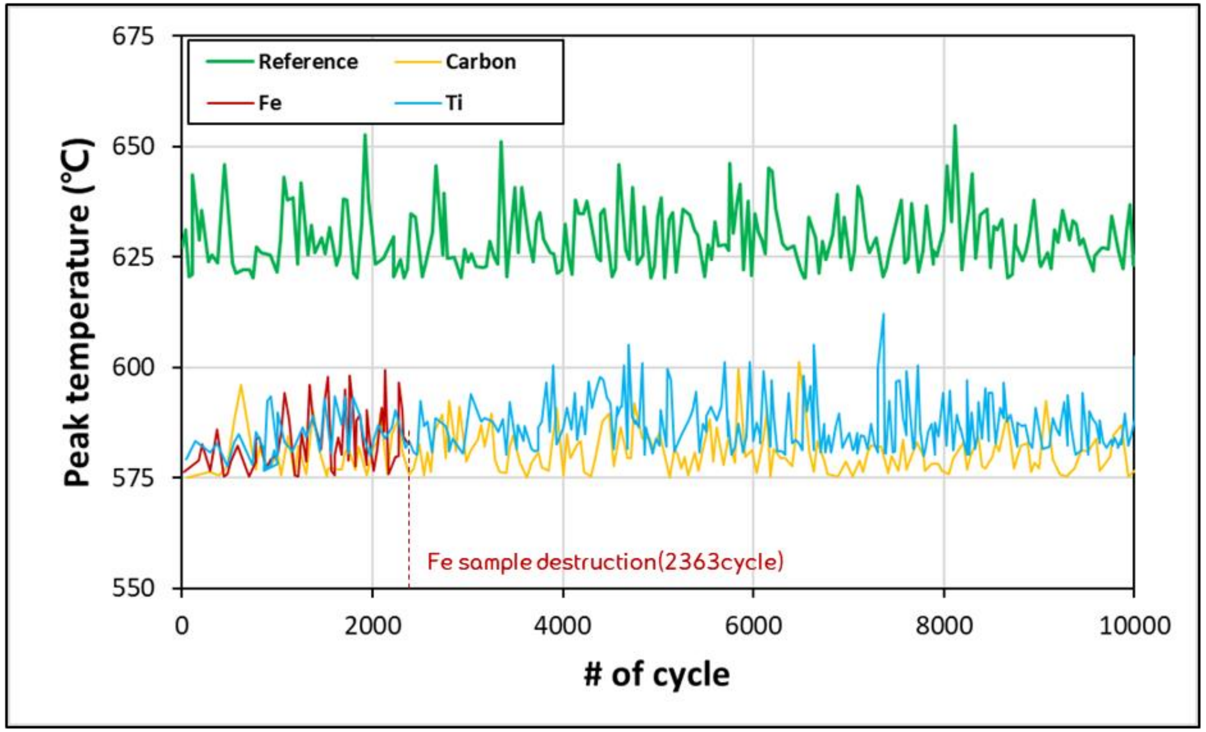
* 10,000 cycle heat load test



- Particle contaminated pellicles exhibit less heating compared to clean pellicle
- For 10,000 cycle heat load test, all the pellicles (except Fe-contaminated) survived beyond absorbed heat load of 1 W/cm^2

Cyclic heat load test (experimental)

❖ Heat load test results depending on type of particle

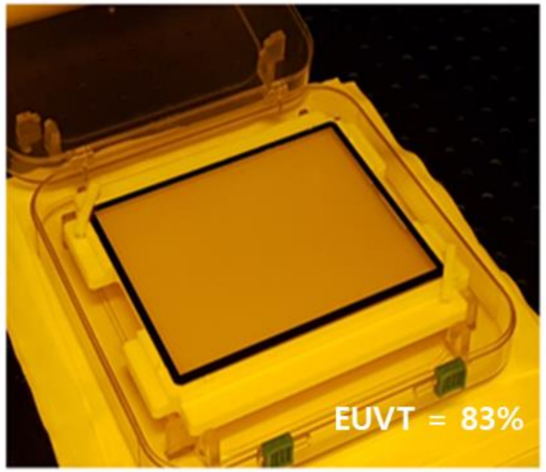


* 1 W/cm^2 absorbed heat load condition

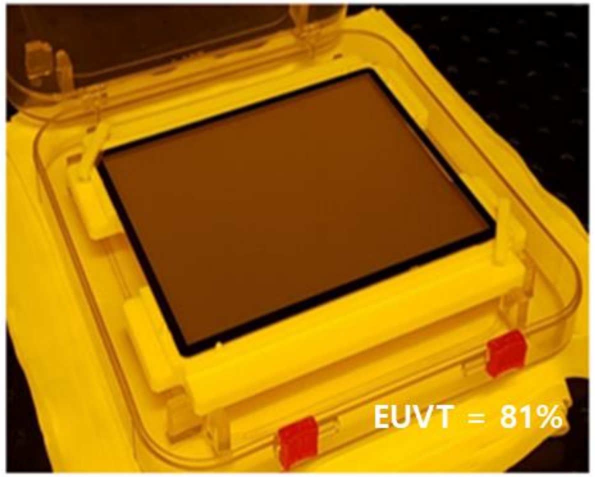
- Due to the high heat capacity of particles, temperature of the contaminated pellicle was measured to be lower.
- Most of the pellicles were alive beyond 10,000 cycles at absorbed heat load of 1 W/cm^2

Summary

- Silicon nitride-based pellicles were successfully fabricated (83%, 81%)
- $MoSi_2$ is a good candidate for the emission layer (high EUVT and very low EUVR)
- Particles smaller than 10um does not affect mask imaging
- Particle contaminated pellicle shows less and slow heating during exposure
- Particles on the pellicle surface may not affect pellicle lifetime.



⟨SiN pellicle⟩



⟨Ru-capped SiN pellicle⟩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