Extrem Ultra-Violet Lithography

„More Moore“ MEDEA+

Christophe Constancias

Extrem Ultra-Violet Lithography

I/ Lithography : State of the Art

II/ EUV Lithography : Why?

III/ EUVL at CEA-LETI

- Mask defect reduction
- Pushing to 22nm node

Limits of optical lithography

- **Rayleigh criteria :**

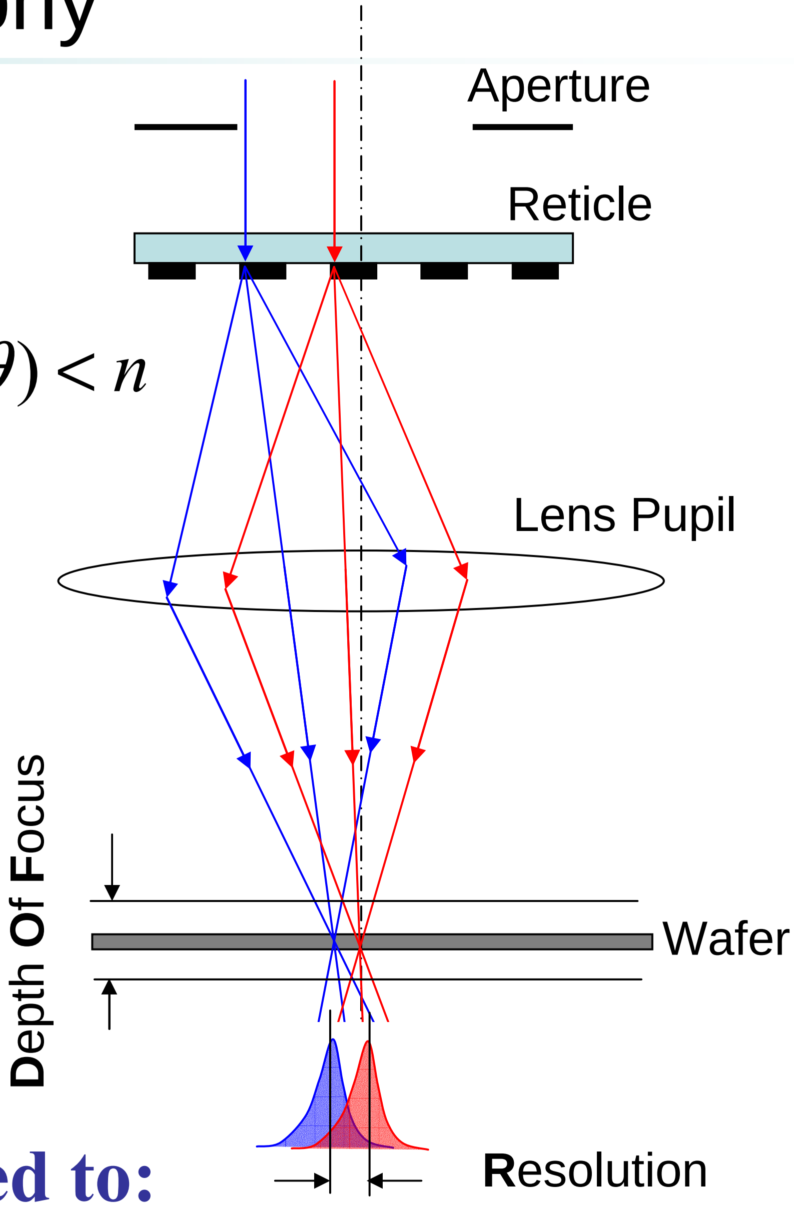
$$R = k_1 \times \frac{\lambda}{NA} \quad with \quad NA = n \times \sin(\theta) < n$$

$$DOF = k_2 \frac{\lambda}{NA^2}$$

k_1 & k_2 *Process factors*

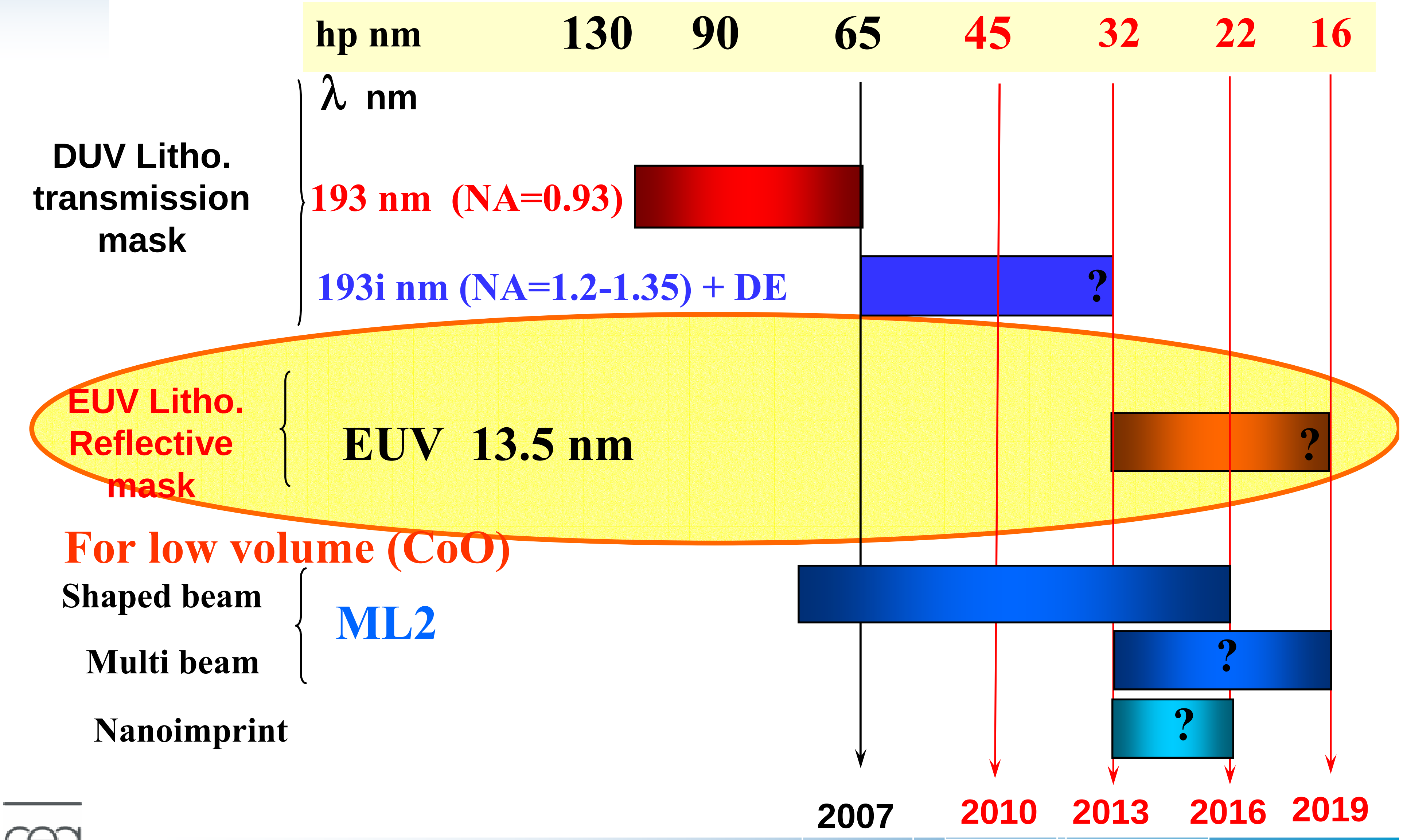
$0.25 < k_1 < 1 + \sigma$

$0.5 < k_2 < 2$



➔To improve resolution we need to:

Leti lithography roadmap (2006)



hp nm 130 90 65 45 32 22 16

λ nm

DUV Litho. transmission mask

193 nm (NA=0.93)

193i nm (NA=1.2-1.35) + DE ?

EUV Litho. Reflective mask

EUV 13.5 nm ?

For low volume (CoO)

Shaped beam

Multi beam

ML2 ?

Nanoimprint ?

2007 2010 2013 2016 2019

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Specificity of EUV wavelength

- Extrem UV : 5 nm → 40 nm (250 eV → 30 eV)
- EUV Lithography : $\lambda=13.5$ nm
- All materials absorb EUV light
  - EUVL ⇒ **Vacuum**
  - **Reflective** optics and mask

EUV Lithography : Why?

R [nm] and DOF	λ= 248 nm	λ= 193 nm	λ= 157 nm	EUV @ λ= 13.5 nm	
	NA= 0.7	NA= 0.75	NA= 0.8	NA= 0.1	NA= 0.25
k_1= 0.6	213 nm 304 nm	154 nm 206 nm	118 nm 147 nm	81 nm 810 nm	32 nm 130 nm
k_1= 0.5	177 nm 253 nm	129 nm 172 nm	98 nm 123 nm		
k_1= 0.5	159 nm 228 nm	116 nm 154 nm	88 nm 110 nm		
k_1= 0.4	142 nm 202 nm	103 nm 137 nm	79 nm 98 nm		

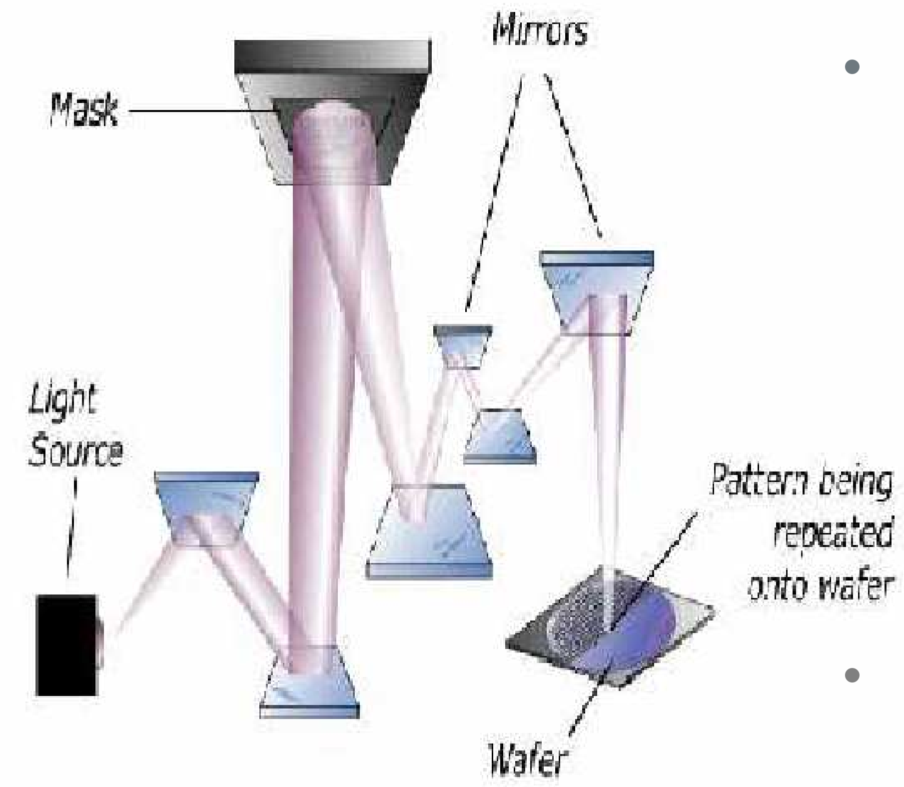
Hyp : $k_1 = k_2$

$R = k_1 \lambda / NA$

$DOF = k_2 \lambda / NA^2$

Note : Production confort with $k_1 \geq 0.6$ **& DOF ≥ 500nm**

EUV Tool : Optic requirements



4X Projection stepper
α tool developed by ASML

- **Mirror Spec for 70nm CD**
  - Aberration
    - Surface figure < 0.2nm RMS
  - Flare (parasitic light)
    - Mid spatial freq. rough. < 0.15nm RMS
  - Reflectivity loss
    - High spatial freq rough < 0.10 nm RMS
  - Highest reflectivity (70% / mirror)
  - At least 6 mirrors for α tool !
- **EUV Source**
  - High wafer throughput : 120Wafer/h ⇒120W EUV light source
  - Life time > 1 year

EUV Mirror : Multilayer interferential reflector

- Bragg mirrors: constructive interference in backward direction
- Periodic stack of heavy and light layers.
- Best couple of materials ⬄
  - **maximum** index gap
  - **minimum** absorption

Mo/Si is the best couple beeing:

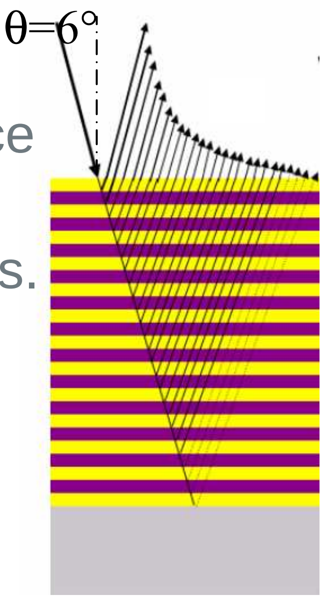
•non toxic

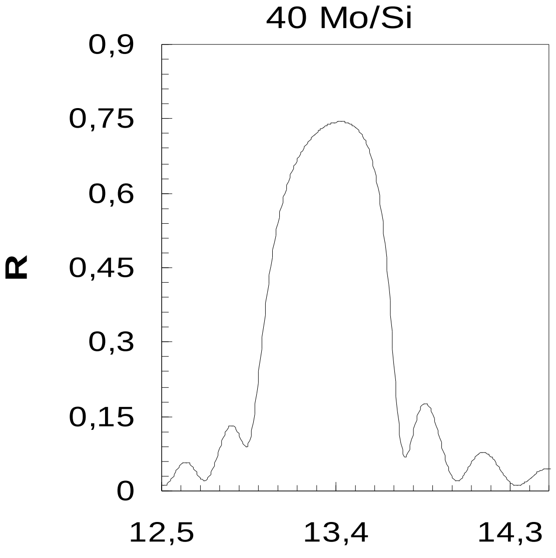
•not too expensive

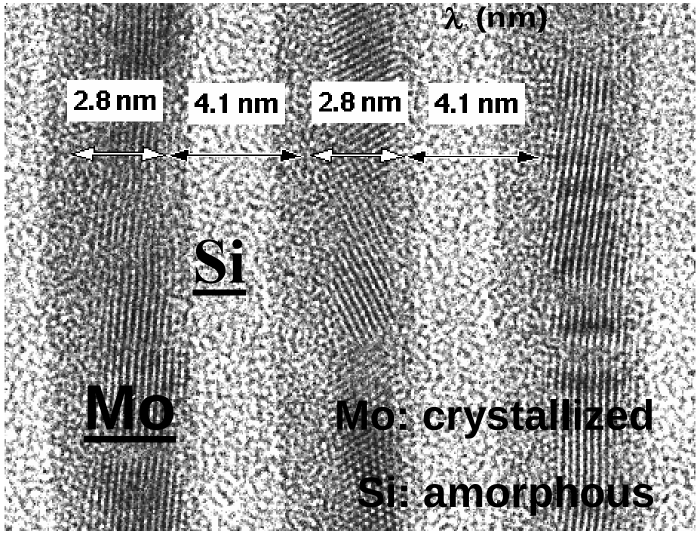
• Typically : 40 x Mo(28Å)/Si(41.5Å)

$R_{\text{theory}} = 74\% \; @13.5\text{nm} \;\&\; \theta = 6°$

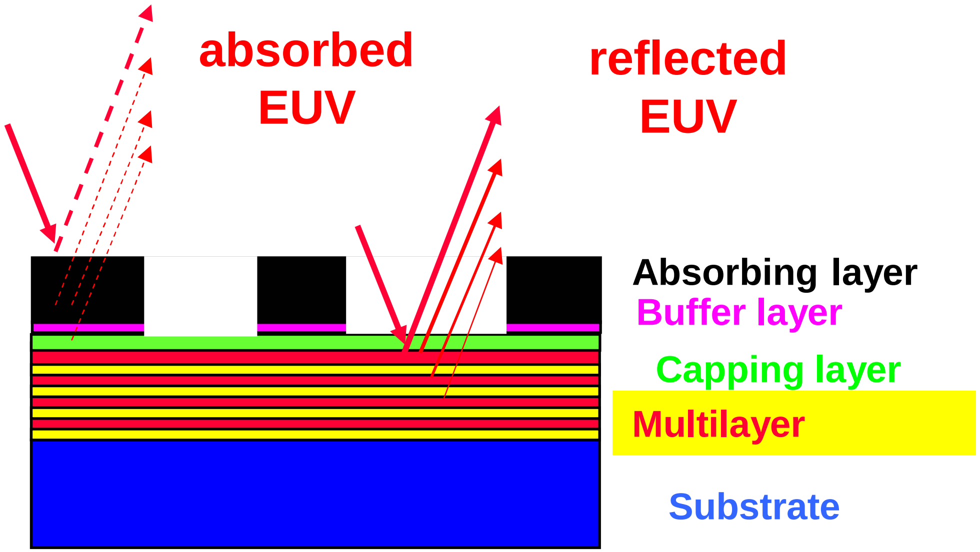
$R_{\text{Best experimental}} \approx 69\%$







EUV reflective mask : Binary type



Binary mask only uses light amplitude modulation

Patterns pitch on 4X mask

Among the different specifications to meet, two are particularly demanding:

- R_{EUV} : high and stable.
- « Defectivity » : **NO** defect, even small ones (25 nm !!)
  Defect density < 10^{-3}/cm² (Ø defect / mask)

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- **Pushing to 22nm node**
- Mask defect reduction

Pushing to 22nm node

- EUV binary masks:
  - ➢ Manufacturing OK
  - ➢ However, they might be limited to the 32 nm node.

$$\text{Res.} = k_1 . \lambda/\text{NA}$$

EUV tool:

NA= 0.25

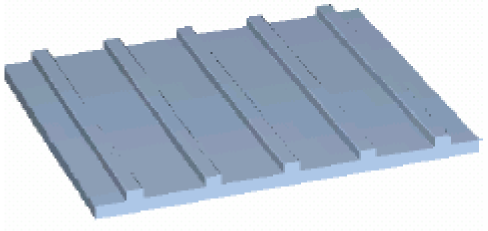
λ=13.5 nm

	Res. (nm)	k_1	Node achievable
Binary mask	27- 54	0.5-1	32
Phase **S**hift **M**ask	14 -27	0.25-0.5	22

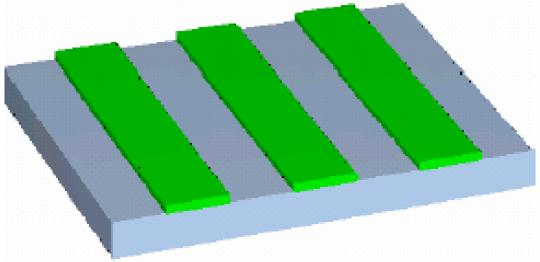
More Moore : evaluation of PSM design and technological issues.

Mask for low k1: Phase Shift Mask (PSM)

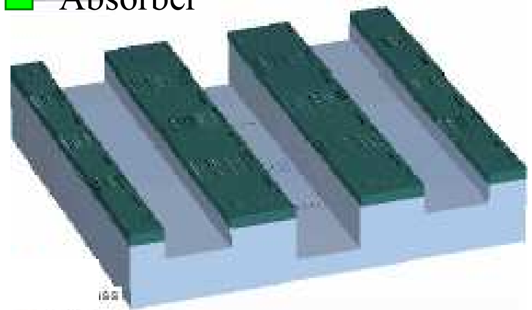
Use phase modulation on the mask allows Resolution improved by a factor x 2



Cr-less Phase Edge Lithography (CPL or Hard PSM)
100% Reflexion, 180° Phase MoSi etching

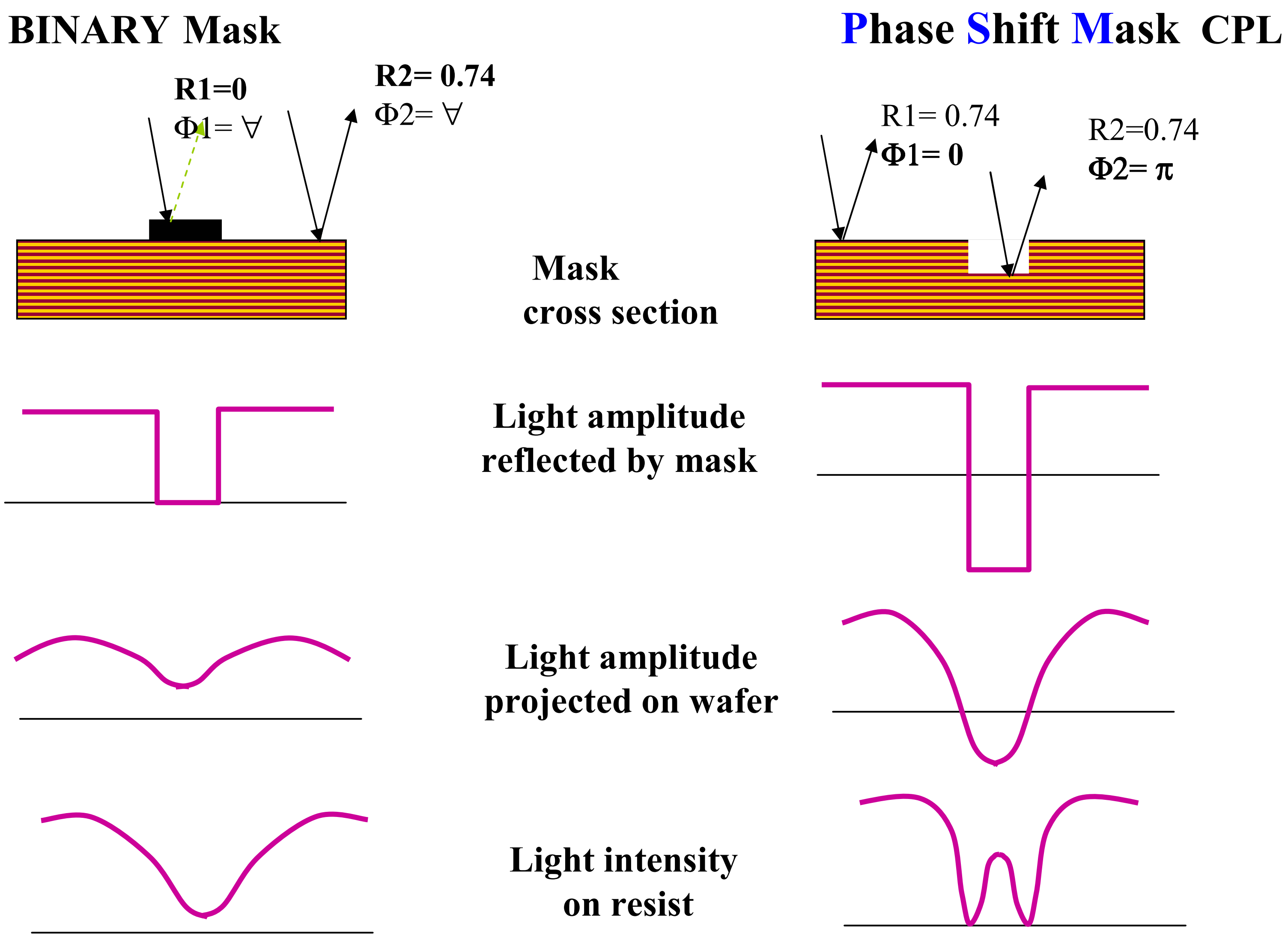


Attenuated PSM (Att-PSM or HTPSM)
6% or 10% Reflexion, 180° Phase MoSi etching



Alternating PSM (Alt-PSM)
0% Reflexion, 180° Phase MoSi etching

EUV reflective mask : reducing k_1



Theoritically: better contrast with PSM

Phase shift tolerance : $\Delta\Phi = 180 \pm 5°$

λ=193nm Transmissive mask

$$\phi = \frac{2\pi}{\lambda} h(n-1) \qquad \delta\phi = \pm 5° \Rightarrow \begin{cases} \Delta h \leq 6nm \\ \Delta\lambda \leq 5.4nm \end{cases}$$

λ=13.5nm Reflective mask

$$\phi = \frac{2\pi}{\lambda}\frac{2h}{\cos\theta_i} \qquad \delta\phi = \pm 5° \quad \Rightarrow \begin{cases} \Delta h \leq 2\mathring{A} \\ \Delta\lambda \leq 4\mathring{A} \end{cases}$$

→ Etch depth control & uniformity

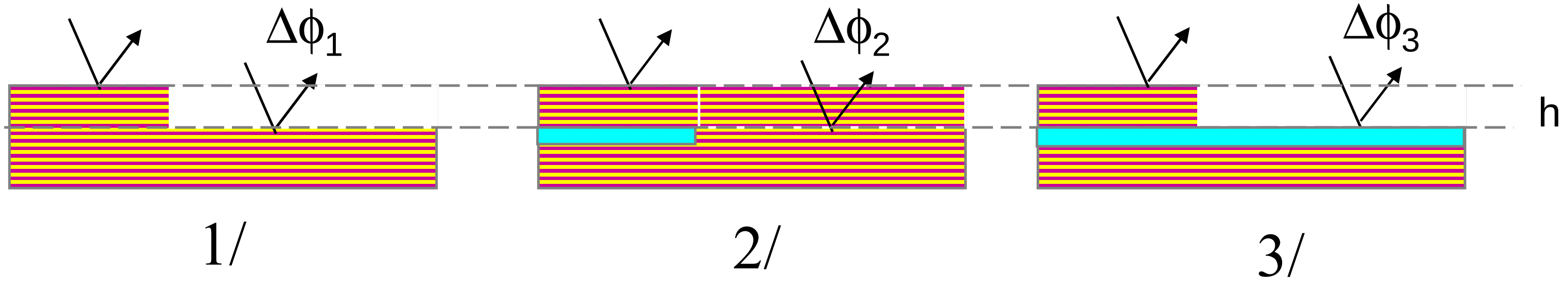
→ Poor tolerance on wavelength

⇒ Technological challenge in terms of etching control and uniformity:

An **Etch Stop Layer is compulsory**.

Phase Shift mechanism understanding

- Phase shift due to
  - step height
  - Embedded materials



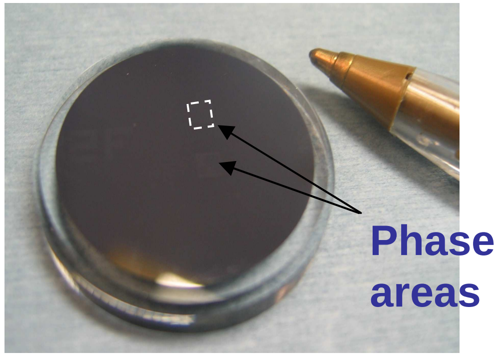
$$\Delta\phi_1 \neq \Delta\phi_2 \neq \Delta\phi_3$$

Samples type 1/ provided and measured

@13.5nm at PSI with partner IOTA-CNRS

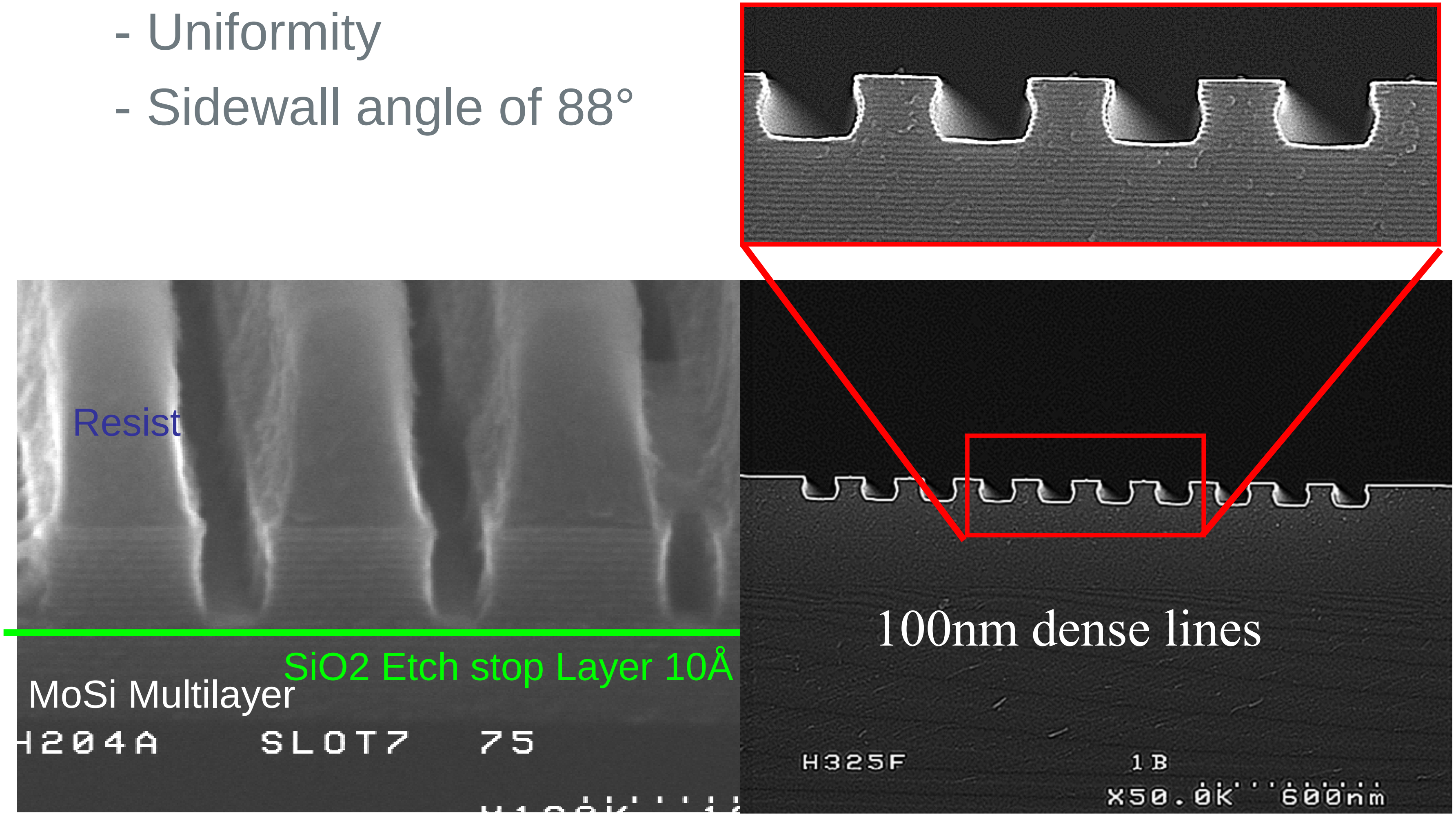
Samples type 2/ 3/

nearly achieved Measurements to be performed

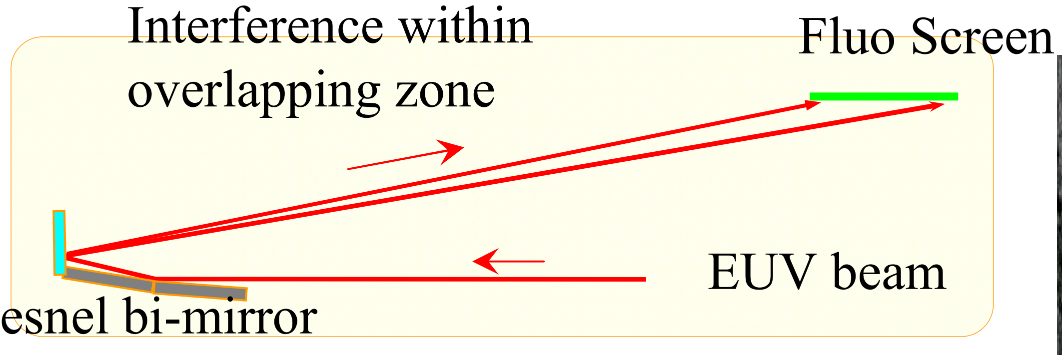

Phase shift areas

Technological development : MoSi etching

- - Precise control of etch depth
- - Uniformity
- - Sidewall angle of 88°



EUV Interferometer



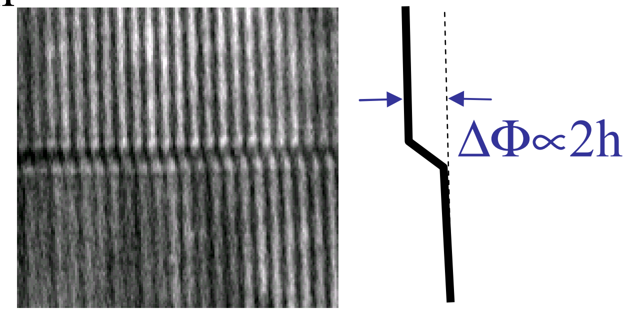
Interference within overlapping zone

Fluo Screen

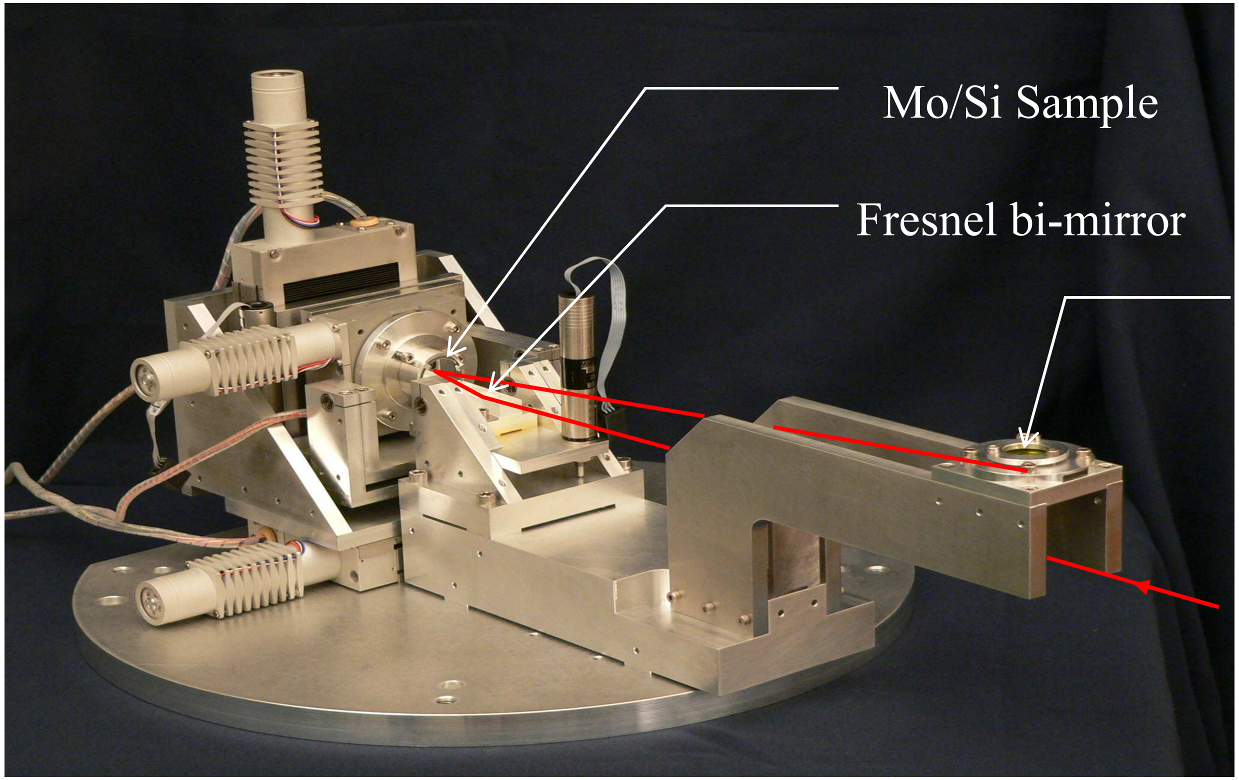
Sample

EUV beam

Fresnel bi-mirror Interferometer



$\Delta\Phi \propto 2h$

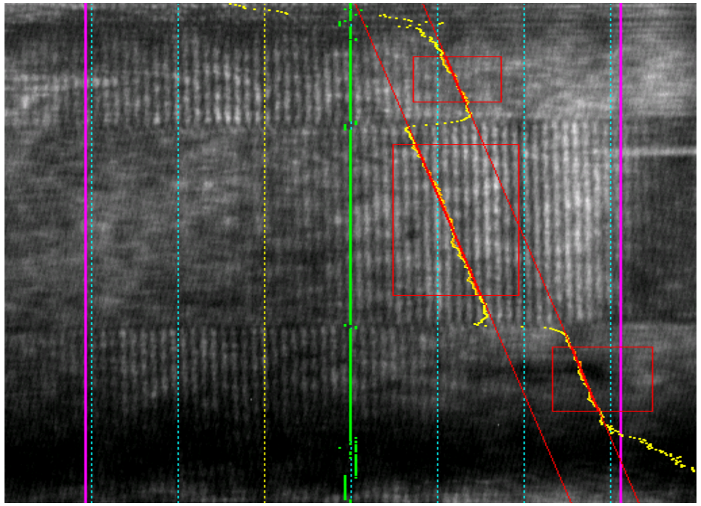


Mo/Si Sample

Fresnel bi-mirror

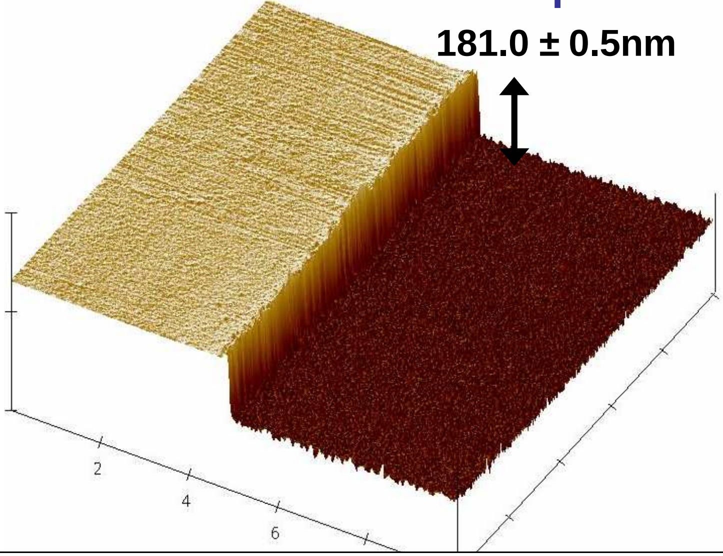
Fluo Screen Fringes

EUV Interferometer measurement

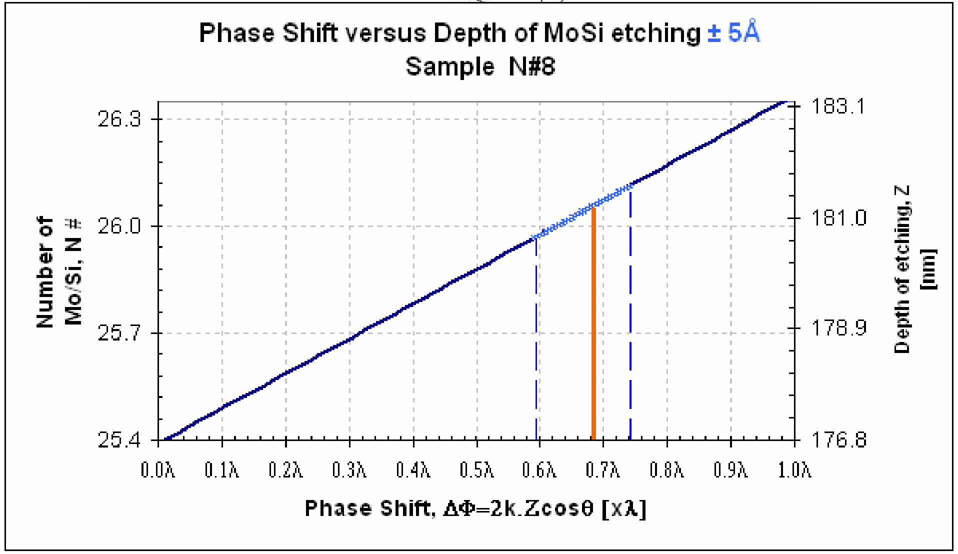


- **Regular fringes:**
  ⇒ Good etching uniformity on a few mm^2
- **Deduced average Phase shift at wavelength (13.5nm):**
  => $\Delta\Phi = 0.685 \pm 0.06\lambda$

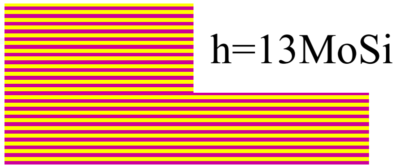
AFM measurement Sample #8



181.0 ± 0.5nm



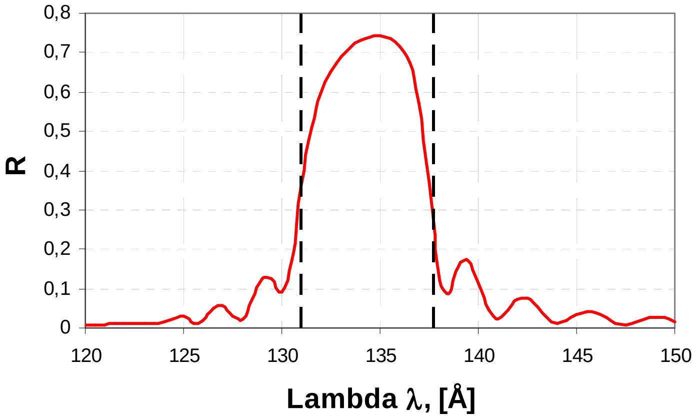
CPL PSM: limitations



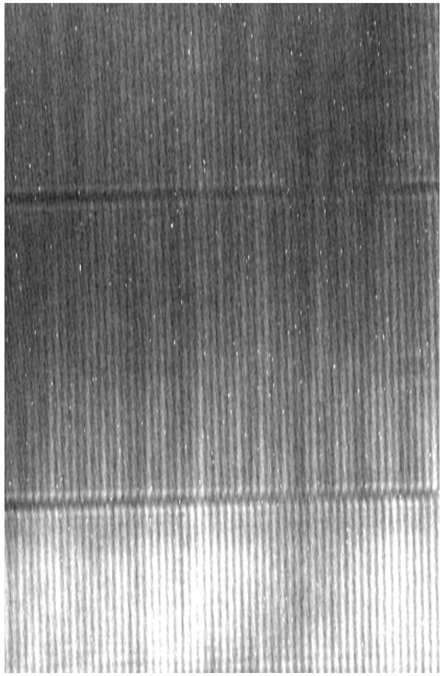
- $\Delta\Phi$ is very sensitive to energy dispersion.
- Example of measurement: $\Delta\lambda = 1.4Å \Rightarrow 58°$!! ($2h \sim 13\lambda$)

« Real life »

- « broadband » EUV light : λ_0 = 135Å ± 2%
- Difficult to control the phase shift on a real EUV tool.

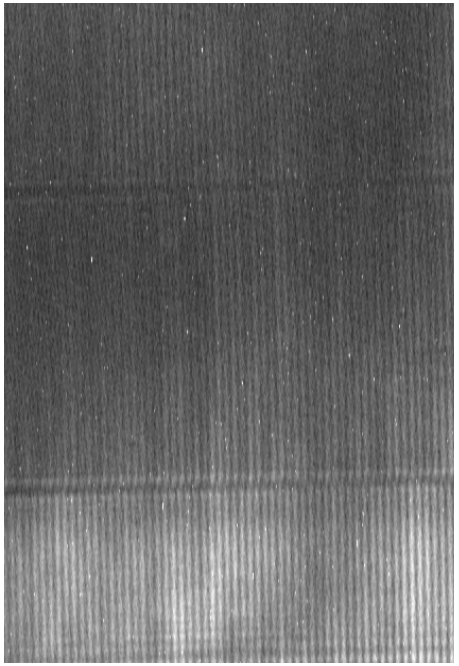


$\Delta\Phi = k + 0.48\lambda \pm 0.01\lambda = 173°$



λ=13.19nm (94eV)

$\Delta\Phi = k + 0.32\lambda \pm 0.02\lambda = 115°$



λ=13.33nm (93eV)

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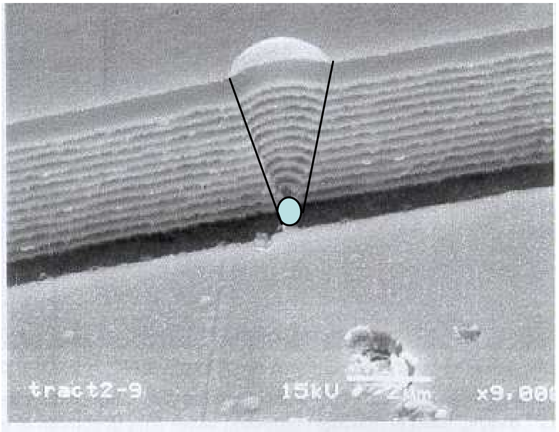
Critical defects for EUV

- **Definition: any perturbation of the multilayer mirror which is printed in the resist.**

- **The critical size of defects for EUV depends on:**
  - **The printability of defect in resist**
  - **The node which is targeted.**

- **Two kinds of defects:**

  - **Nodule defects (also called :decorated)**
    - **Their growth start from the substrate (initial seed) and result from the coating deposition.**



  - **Process added defects:**
    - **Particles, flakes which are transported inside the deposition chamber.**

How to avoid nodule growth ?

Different ways are currently investigated :

- From the beginning by optimizing :
  - the substrate cleaning
  - the deposition geometry

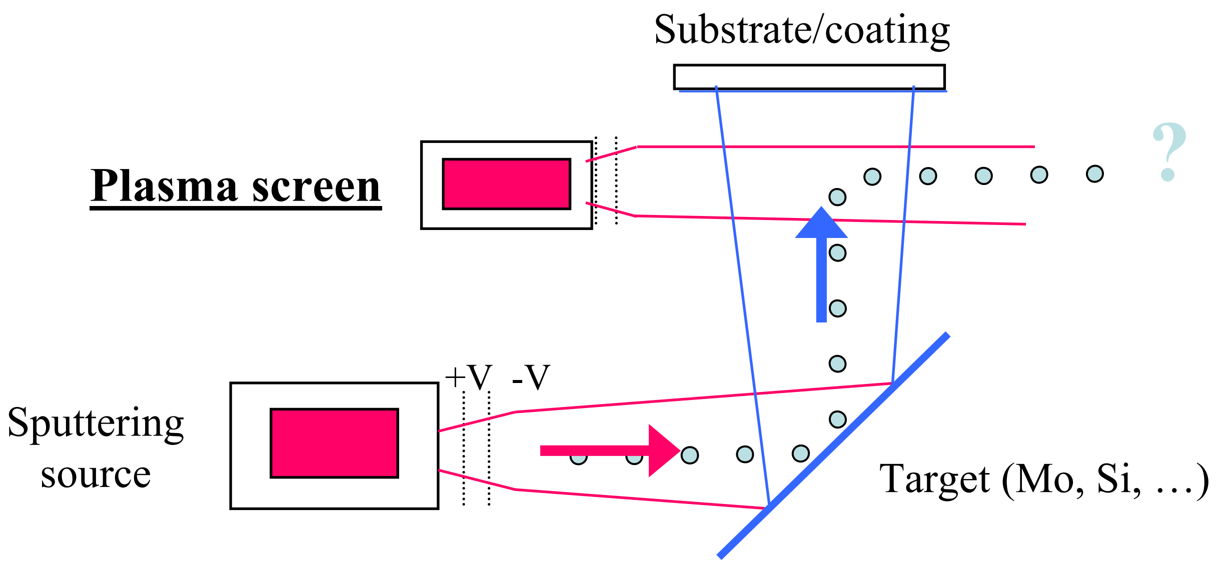
- After or during nodule growth by
  - ion smoothing of nodule defect.
  - **Other innovative mitigation process**

(Addressed in More Moore)

Use of an ion beam to deflect particle

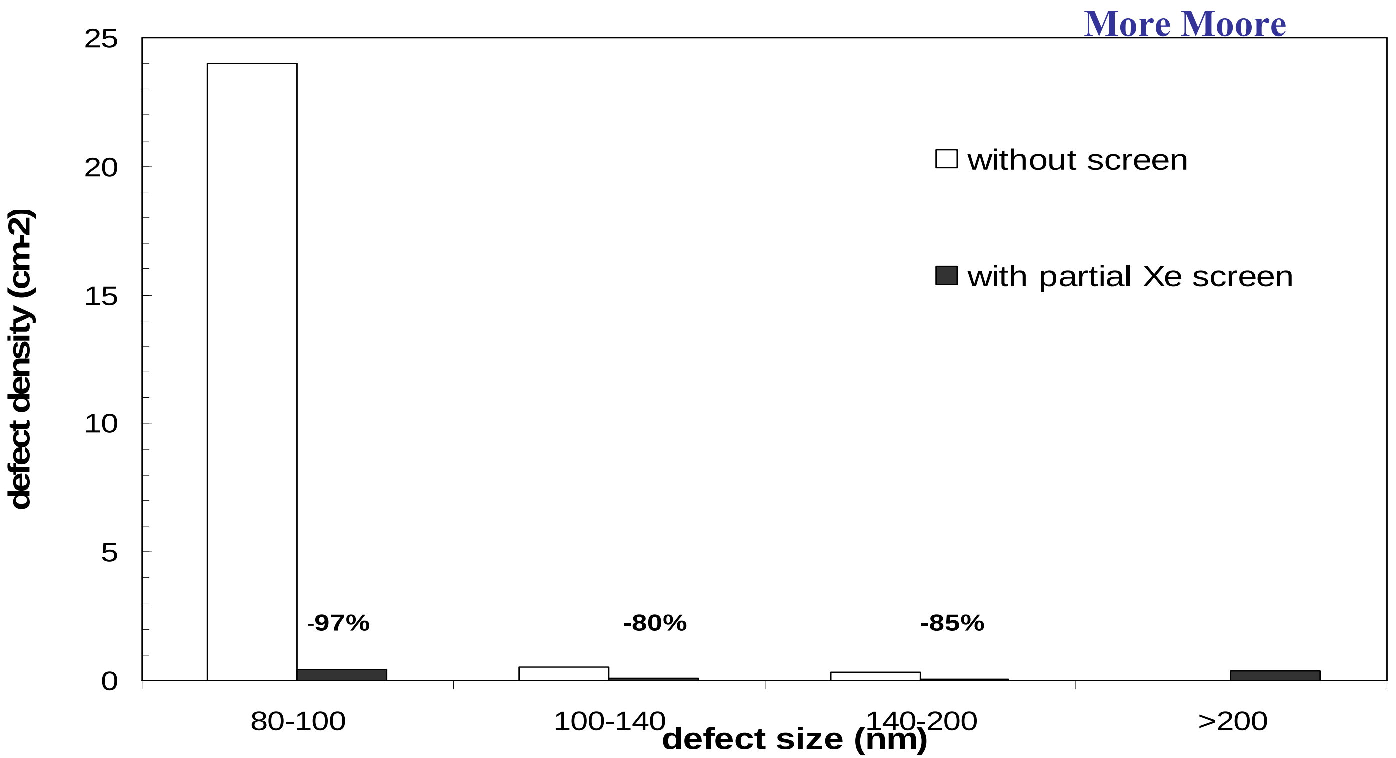
Plasma screen concept*:

Use of an additional ion beam to drag away from coating the particles generated inside the IBS deposition chamber



•CEA patent.

Example of screening results



- 80-100 nm : defectivity divided by **50**
- 100-200 nm : defectivity divided by **5**
- >200: still a few added defects generated by the screen.

Innovative mitigation technique

Principle: to reverse the Mo/Si stack to leave the largest part of nodule far from mask surface

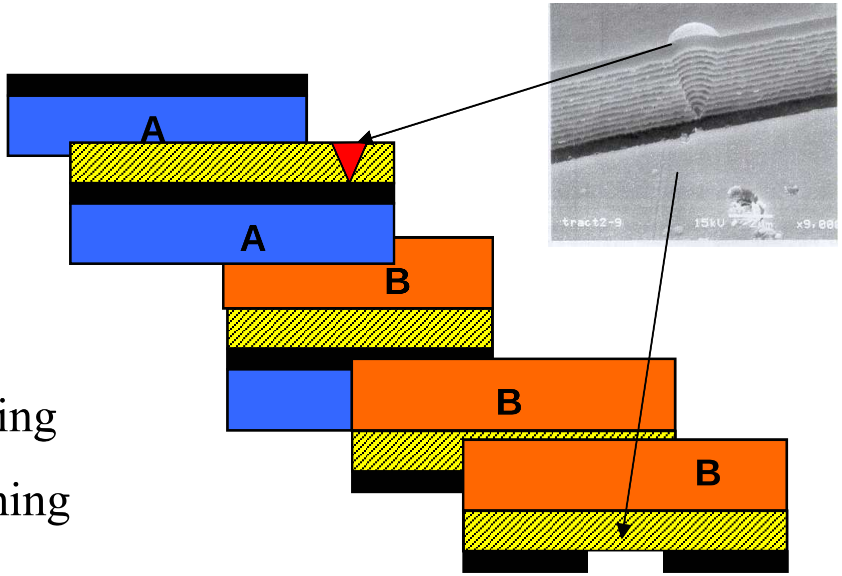
Step 1 : Absorb. coating

Step 2 : 40 x Mo/Si

Step 3 : sticking B on A

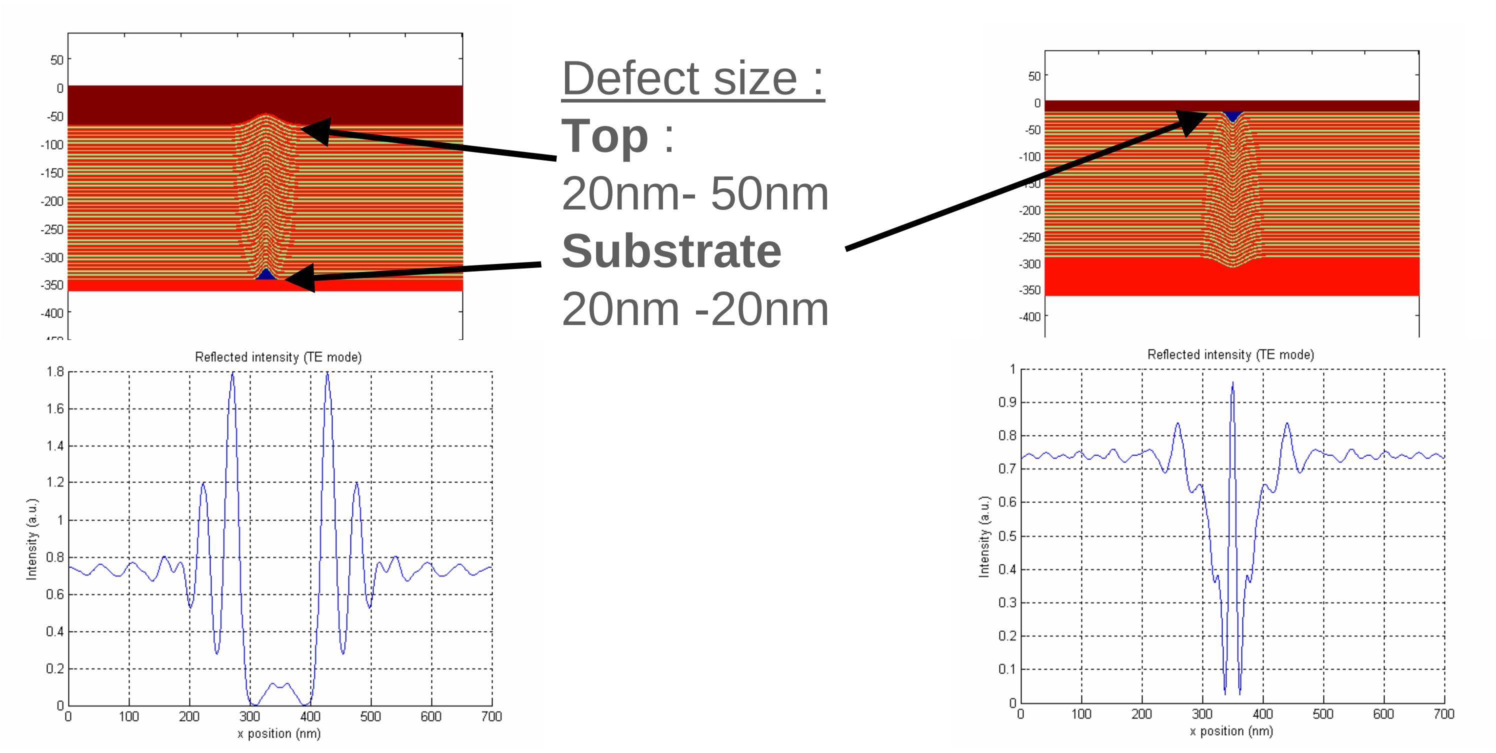
Step 4 : substrate A polishing

Step 5 : Absorber patterning



Simulation:Reverse Technology defect impact

Reflected intensity standard incidence *Reflected intensity reverse incidence*



Defect size :

Top :

20nm- 50nm

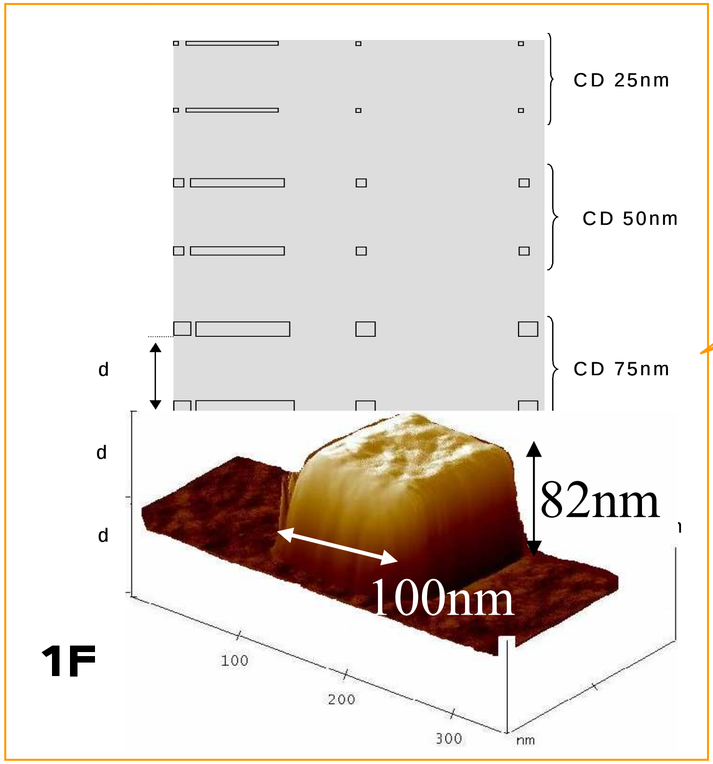
Substrate

20nm -20nm

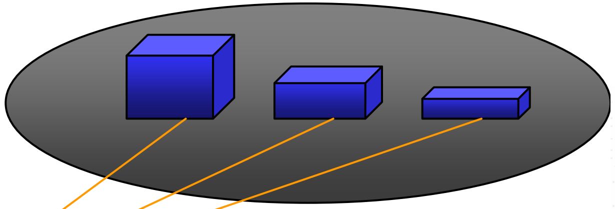
These simulations show that apparent size of the defect is smaller in reverse incidence compared to the standard incidence.

Reverse technology : feasability

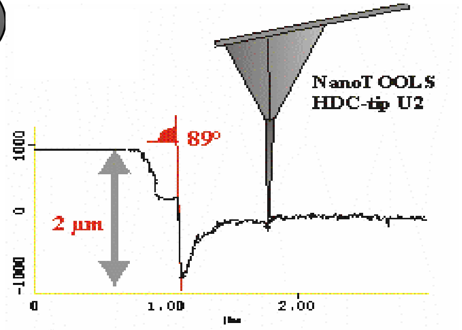
Programmed defect layout : <u>various</u> defect sizes (width&height)

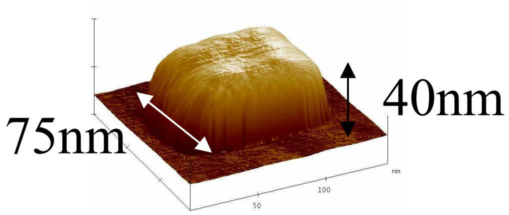


h = 80nm, 40nm, 20nm

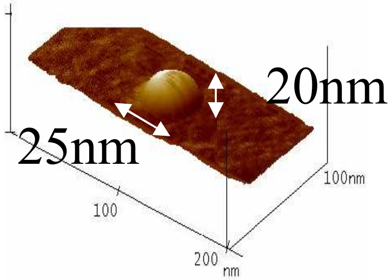


AFM 2D VEECO tool

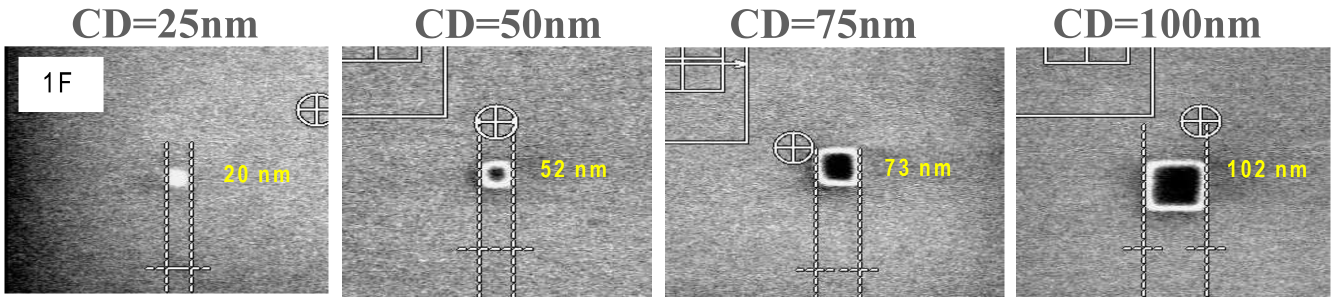




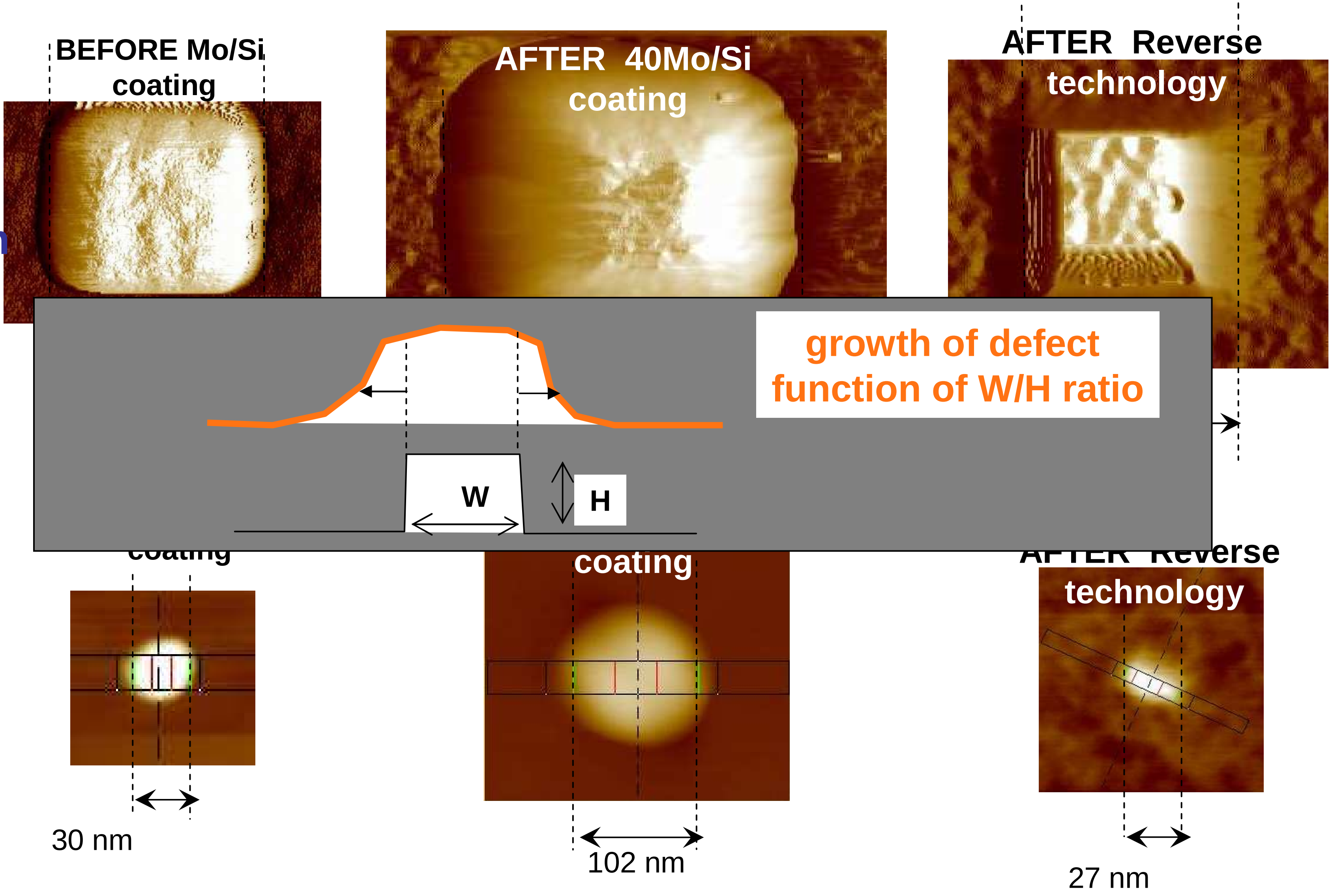
Before Mo/Si coating



h=80nm


CD=25nm CD=50nm CD=75nm CD=100nm

Reverse technology : AFM Characterisations



CD 100 nm

BEFORE Mo/Si coating

AFTER 40Mo/Si coating

AFTER Reverse technology

growth of defect function of W/H ratio

CD 25 nm

coating

coating

AFTER Reverse technology

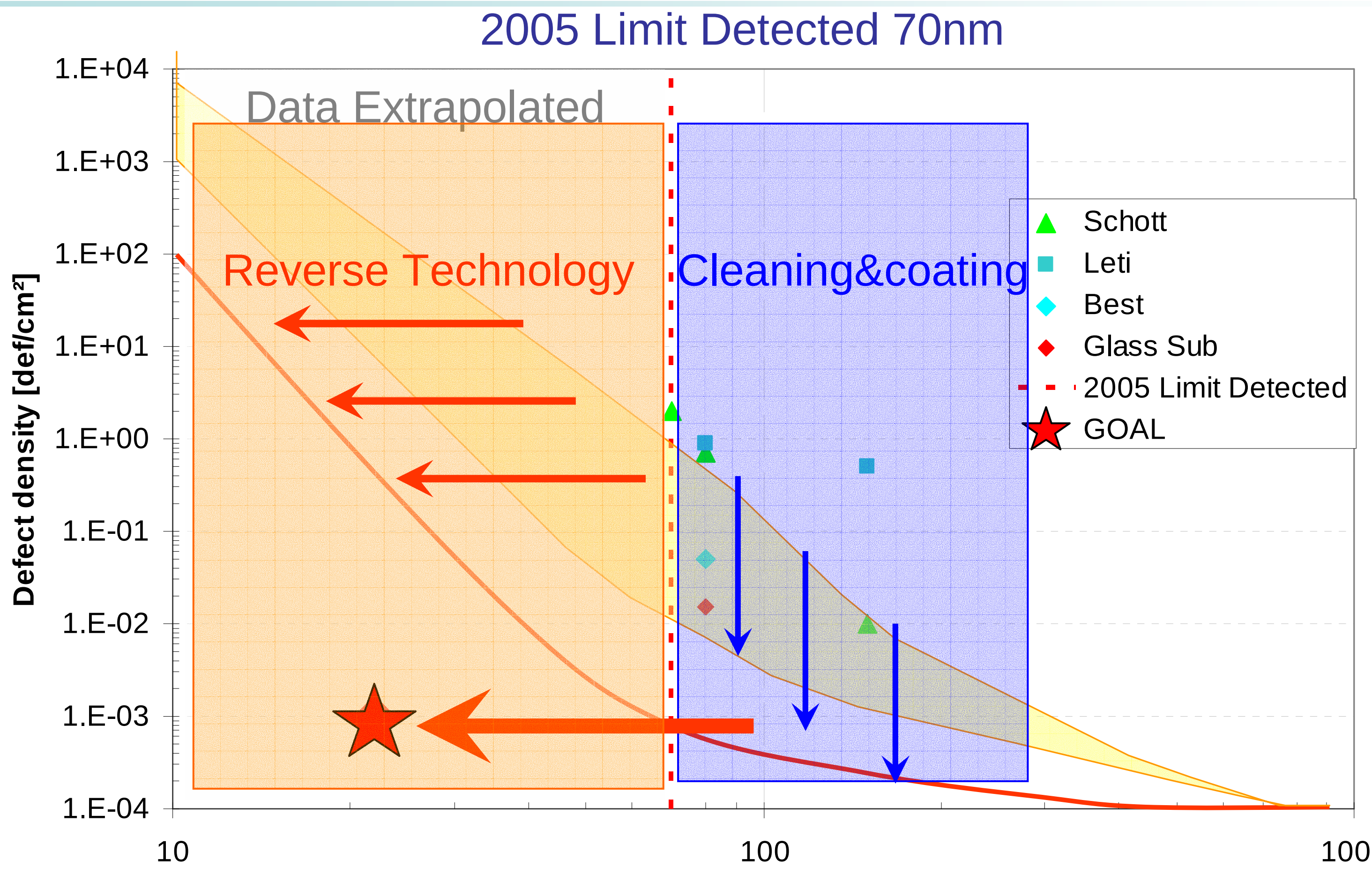
30 nm

102 nm

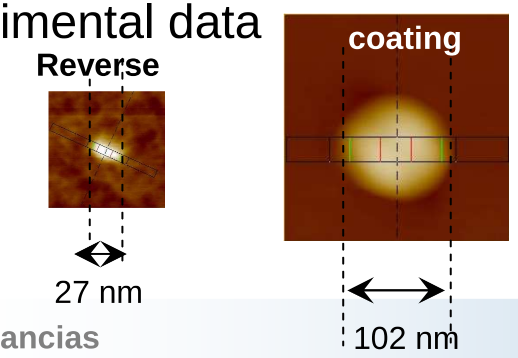
27 nm

Leti 2005

Defect reduction innovation action



Experimental data



EUVL News / Summary

- EUV Lithography competes to the 32nm node and below
  - α–Tool (0.25 NA) developped by **ASML** available Q2 2006
  - 32nm dense line demonstrated **ASML** (resist limitation)

- 40-50 W Source power achieved @IF

- 22nm node might need PSM mask
  - 70nm dense line printed with CPL EUV mask by **AMD** 2005

- Defect printability due to very small substrate defects could be a serious concern.
  - Best 2005 0.025def/cm²@80nm 0.9def/cm²@70nm
  - 2008 Goal : 0.01def/cm²@40nm

- Cleaning and coating techniques are not suitable: more innovation is required.
  - These topics are addressed in More Moore

Critical Technical Issues for EUVL

According 2005 EUVL Symposium

Top 3 Critical Issues 2005	2004 Rank
1. Resist resolution, sensitivity	3
Line Edge Roughness	2
2. Source/ Collector liftime	1
3. Availabiity of defect free mask	
4. Source Power	

Thank you for your Attention

EUV Team at CEA-Leti

S. Tedesco; J.Y Robic; M. Richard; R. Tiron; C. de Nadaï; E. Quesnel; V. Muffato; J. Hue; C. Vannufel; J. Simon; P. Michallon; B. Dal'zotto; J. Foucher; C. Sourd; J. Chiaroni; R. Blanc; J. Vallejo

CNRS – IOTA EUV Interferometer

D.Joyeux; P. Pichon; D.Phalippou; N. de Oliveira

SPIE 2006 : Phase Shift Mask for EUV Lithography, 6151-69 V. 2 (p.1 of 12)