2007 International EUVL Symposium

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Image Placement Error due to non-Flatness of EUV Photomask: realistic approach and correction technique

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Photomask Team, Samsung Electronics

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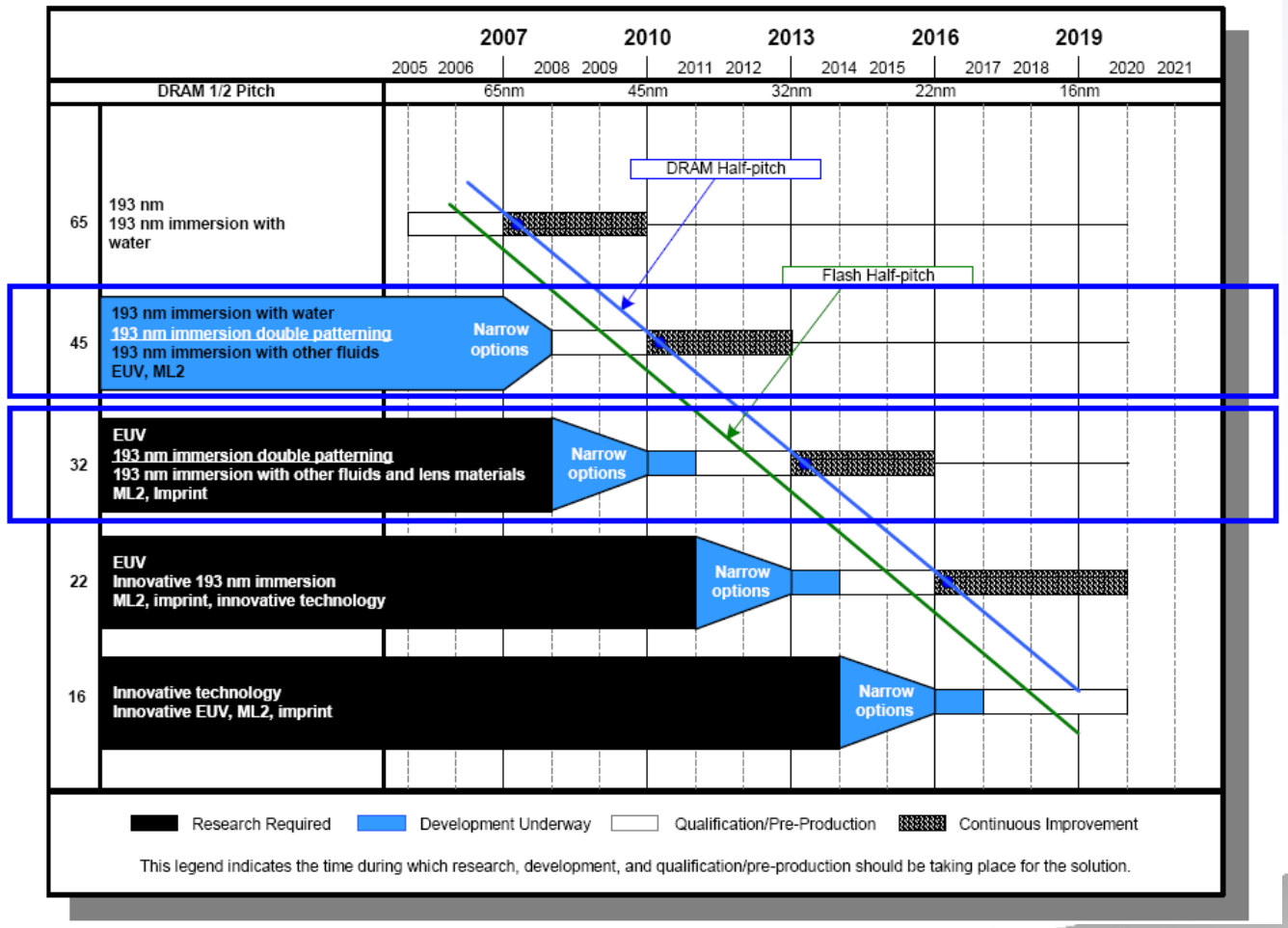
EUV Lithography

What is next generation of lithography ?



(Ref: ITRS 2006 update, "Lithography Exposure Tool Potential Solutions")

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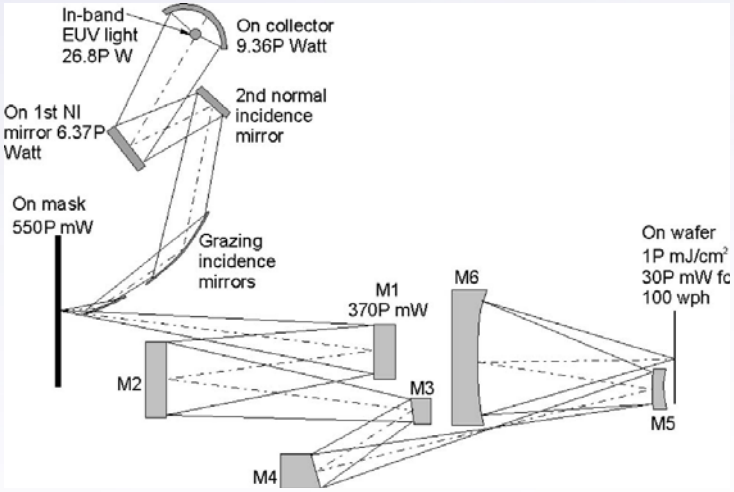
Special Features of EUV Lithography

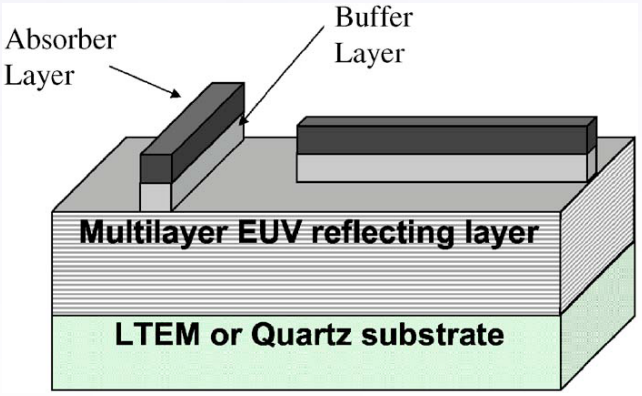
At EUV wavelength, there is no transmitting material, so that optical imaging must depend on reflection.

1) Non-telecentricity of object side



Ref: JMMM, Vol. 5(3), 033005 (2006)

2) Reflective photomask



Ref: JMMM, Vol. 5(2), 023003 (2006)

- The reflection of conventional material is low at EUV wavelegnth.
- Reflectivity is built up with a multilayer stack consisting of 40 to 50 layer pairs of Mo and Si, to achieve 65 to 70% reflectivity.
- This enables an all-reflective optical system that must include the illumination optics, the mask, and the imaging optics.

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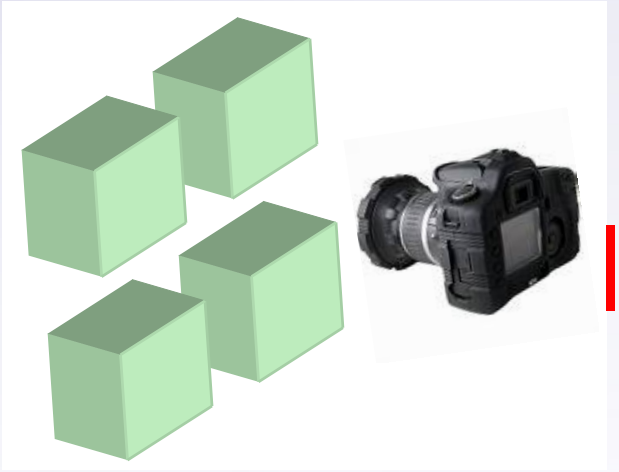
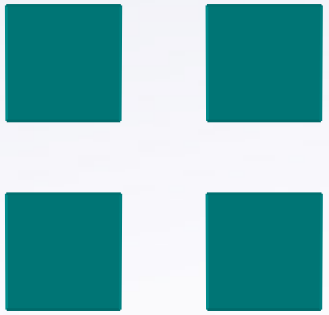
Special Features of EUV Lithography

(Non-telecentricity)

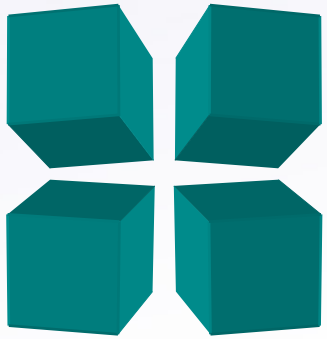


Image

1) Telecentricity

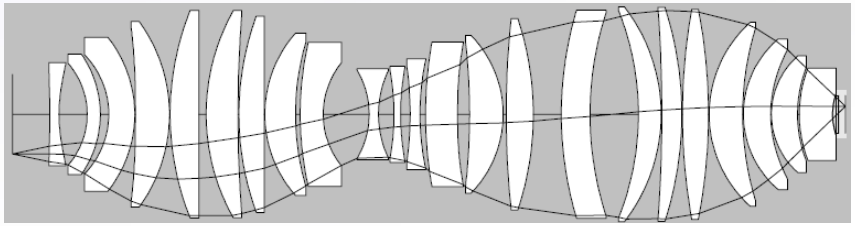


2) Non-telecentricity



Ref. http://www.edmundoptics.com/

ArF lithography

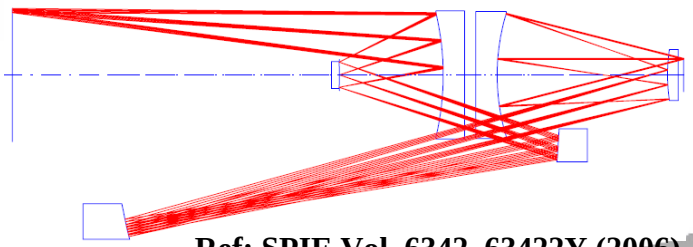


Ref: SPIE Vol. 6342, 63421T (2006)

90º Incident angle of chief ray

=> Objective & image sides telecentricity

EUV lithography



Ref: SPIE Vol. 6342, 63422Y (2006)

Tilted chief ray at image side

(however, objective side has telecentricity)

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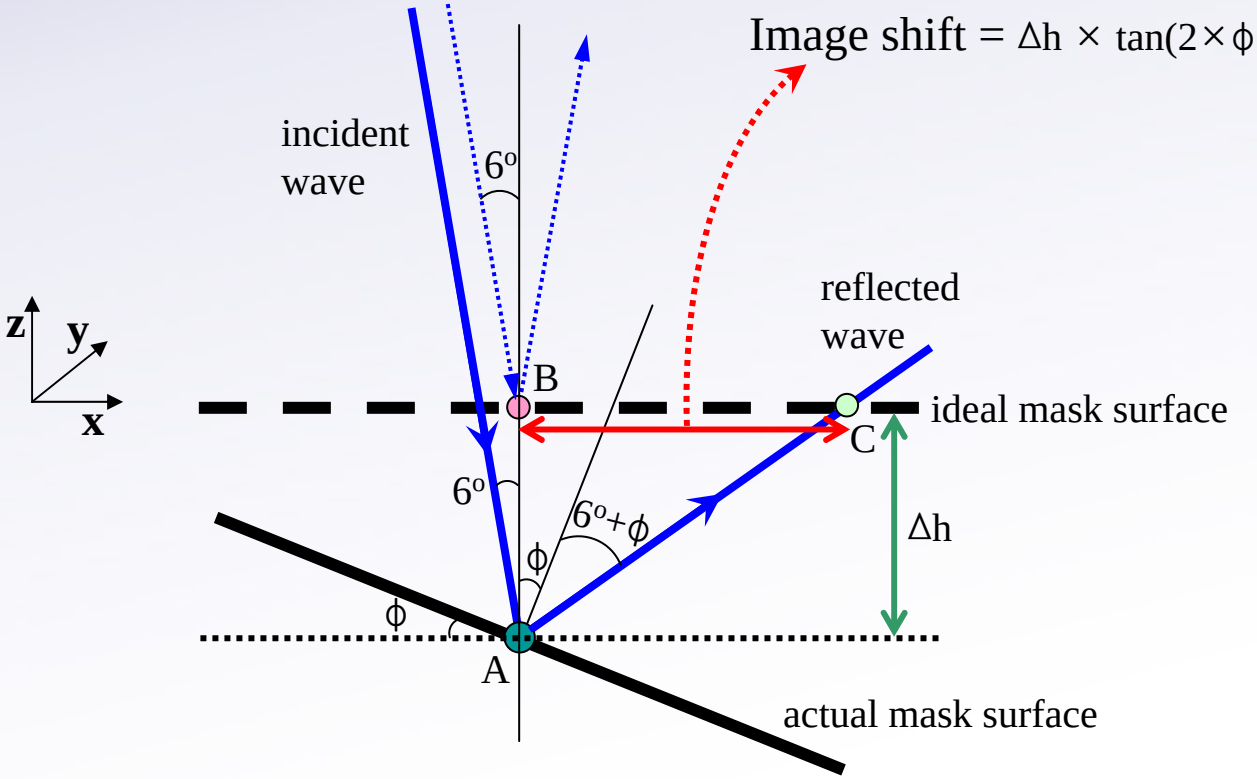
Roughness of EUV Photomask

(Low Spatial Frequency Range)

Image shift = $\Delta h \times \tan(2\times\phi + 6^{o}) \times$ Magnification

(where, Magnification=0.25)



: position A (Real position of pattern)

: position B (Pattern position when Δh is zero)

: position C (Object position corresponding to pattern position at wafer)

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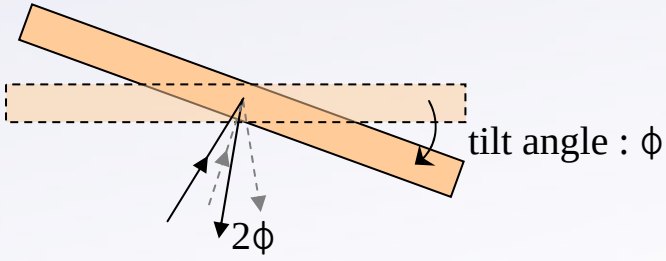
Roughness of EUV Photomask

(Low Spatial Frequency Range)

Mask Slope Errors Coupled with Defocus

At Photomask



At Wafer

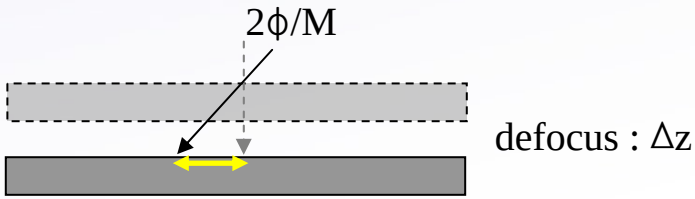
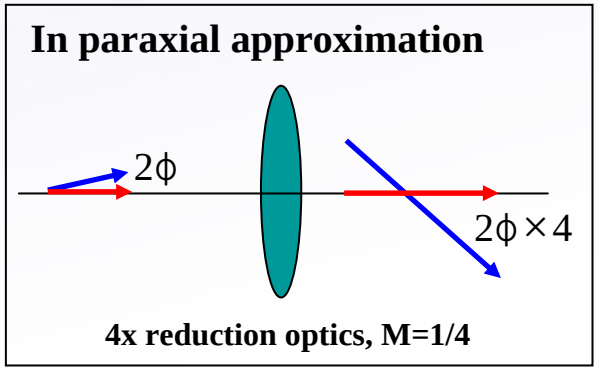


image shift =Δz×tan(2ϕ/Magnification)
≈Δz×2ϕ/Magnification



when $\Delta z = 0.5\lambda/NA^2$, NA=0.25, and Magnification=0.25

image shift: 1 nm ↔ photomask tilt ϕ: 1.2 mrad
(at Δz=110nm)

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Roughness of EUV Photomask

pre-correctable
during e-beam writing

scattering angle of about 15 degrees

M x NA / λ

1/(1 mm)
= 10^{-6}/nm

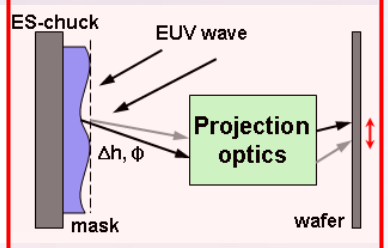
1/(10 μm)
= 0.0001/nm

1/(250 nm)
= 0.004/nm

1/(50 nm)
= 0.02/nm

spatial frequency

LSFR | **MSFR** | **HSFR**



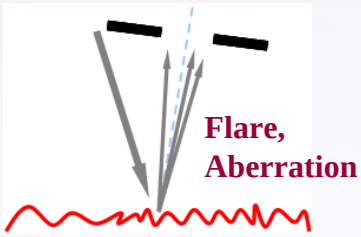
pattern shift

due to flatness
$\Delta = \sigma \times \tan(2\sigma_s + 6^o) \times M$

due to local slope
$\Delta = 2\sigma_s z/M$

Δ <1.0 nm
→ σ_s < 1.5 mrad
→ σ < 38 nm

Light is scattered within the aperture of the optics



Random phase variation & pattern shift

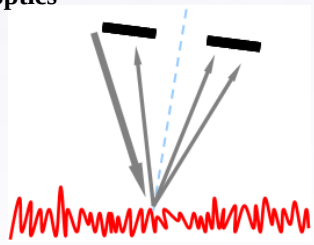
① Line width roughness
LWR = $\sqrt{2}(2\sigma_s)z/M$

② Image placement error
$\Delta = 2\sigma_s z/M$

③ Speckle ④ Aberration

LWR <1.8 nm
→ σ_s < 1.8 mrad
σ < 0.15 nm

Light is scattered outside the angular acceptance of the optics



Loss in reflectivity

$R/R_0 = \exp[-(4\pi\sigma/\lambda)^2]$

2 % reflectivity loss
→ σ < 0.15 nm

Light scattered from the individual interfaces of the multilayer coating no loager adds in phase and the effect of the roughness is diminished

σ : roughness (Δh),
σ_s : local slope (ϕ),
z : defocus distance at the wafer (±90nm),
M : magnification ratio of the optics (0.25),
NA: numerical aperture of the optics

Reference: E. Gullikson, "Proposed specification of EUVL mask substrate roughness," 2nd International EUVL Symposium (2003).
SEMI P37-1102, SEMI Standard Specification for Extreme Ultraviolet Lithography Mask Substrates (2002).
S. Yoshitake, et. al, EUV Mask Flatness & Carrier/Loadport Workshop (2006)

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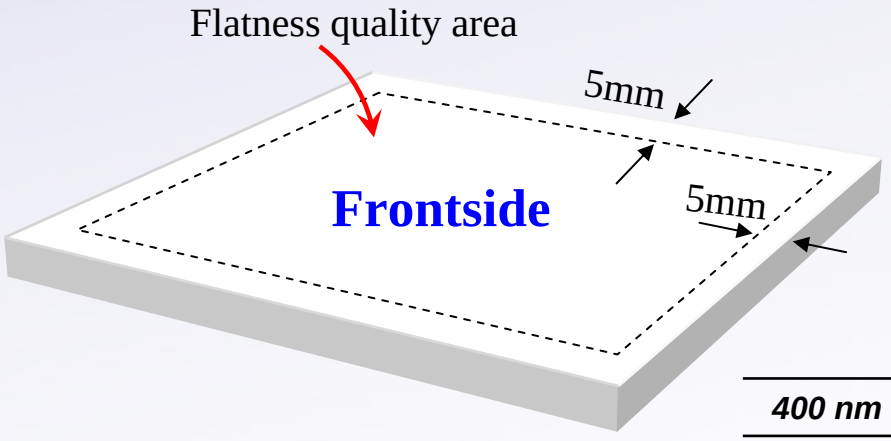
Required Roughness Spec. of EUV Photomask

SEMI standard P37-1102



Class	Frontside flatness	Backside flatness
A	100 nm (P-V)	100 nm (P-V)
B	75 nm (P-V)	75 nm (P-V)
C	50 nm (P-V)	50 nm (P-V)
D	30 nm (P-V)	30 nm (P-V)

400 nm ≤ Frontside $\lambda_{spatial}$ ≤ 100 mm	*slope ≤ 1.0 mrad*
Frontside $\lambda_{spatial}$ ≤ 10 μm	roughness ≤ 0.15 nm (rms)
50 nm ≤ Backside $\lambda_{spatial}$ ≤ 10 μm	roughness ≤ 0.5 nm (rms)

Still challenging goal !!

ITRS roadmap (2006 update ed.)

Year of Production	2008	2009	2010	2011	2012	2013
DRAM 1/2 pitch (contacted)	57 nm	50 nm	45 nm	40 nm	36 nm	32 nm
Flash 1/2 pitch (un-contacted poly)	51 nm	45 nm	40 nm	36 nm	32 nm	28 nm
Mask substrate flatness (nm, P-V)	75 nm	60 nm	50 nm	41 nm	36 nm	32 nm

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Registration Error due to Roughness of EUV Photomask

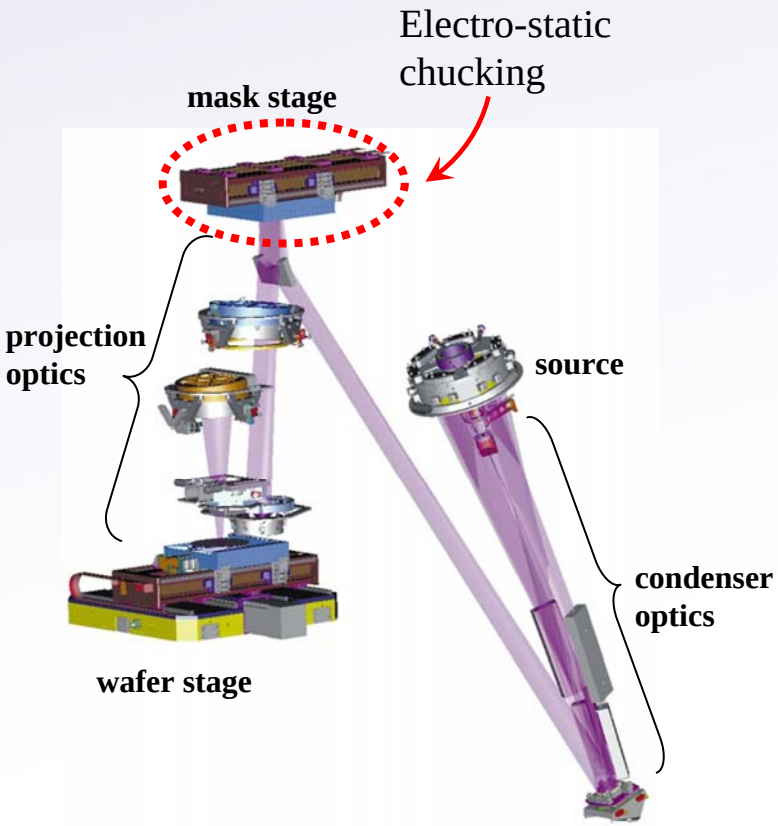
Total Registration Error

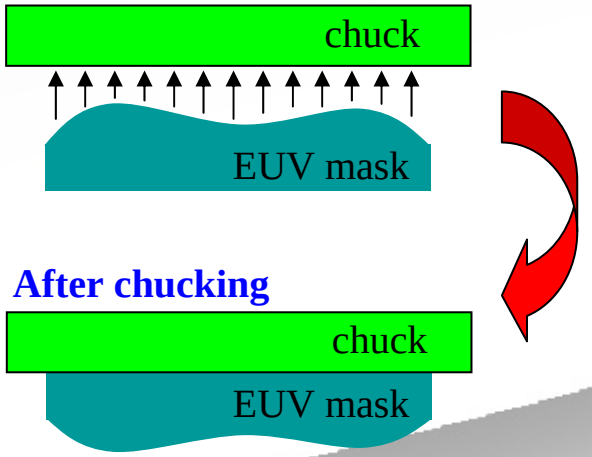
Registration error due to mask flatness

$\Delta h \times \tan(2\phi + 6^{o}) \times M + \Delta z \times 2\phi / M$

Δh : flatness
ϕ: local slope
Δz : defocus distance at the wafer
M : magnification ratio of the optics (0.25)

Registration error due to mask clamping





Lawrence Livermore National Laboratory, EUVL progress report (1999)
http://www.llnl.gov/str/pdfs/11_99.1.pdf

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Mask Distortion due to Electro-static Chucking

Flatness before chucking

$Z_{frontside}$, $Z_{backside}$

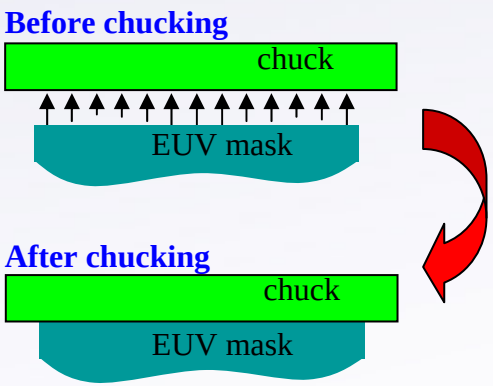
Finite Element Modeling

Flatness after chucking

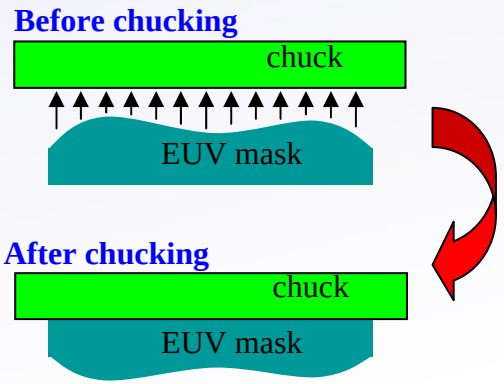
$Z'_{frontside}$, $Z'_{backside}$

used to calculate registration

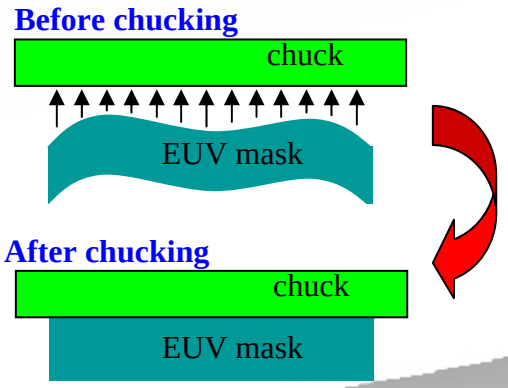
Type 1



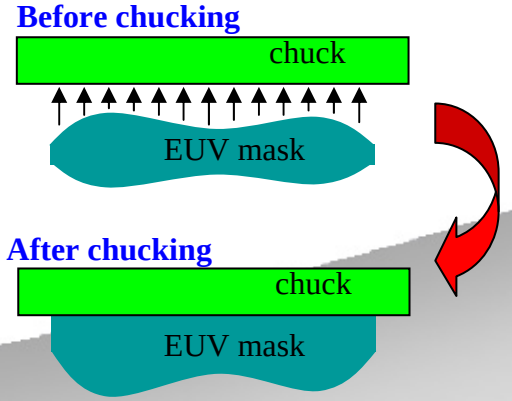
Type 2



Type 3



Type 4



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Mask Distortion due to Electro-static Chucking

Finite Element Modeling Input File Generation

$f_i(x_i, y_i)$: Measure flatness profile

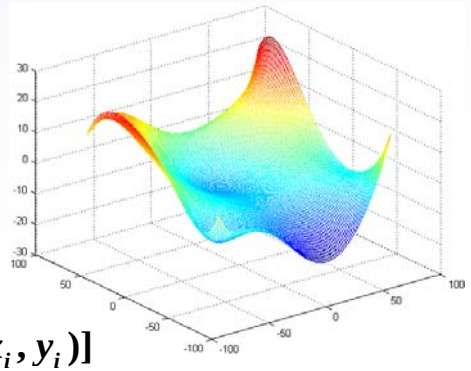
$z^1(x_i, y_i),\ z^2(x_i, y_i),\ z^3(x_i, y_i),\ \cdots$: Legendre polynomial components

$$Z_i(x_i, y_i) = c^1 z^1(x_i, y_i) + c^2 z^2(x_i, y_i) + c^3 z^3(x_i, y_i) + \cdots$$: Legendre polynomial function

$$R_i(x_i, y_i) = [f_i(x_i, y_i) - Z_i(x_i, y_i)]^2$$: Error function between surface profile and Legendre expansion

$$\sum_i R_i(x_i, y_i) = \sum_i [f_i(x_i, y_i)]^2 + \sum_i [Z_i(x_i, y_i)]^2 - 2\sum_i [f_i(x_i, y_i) Z_i(x_i, y_i)]$$

$$\nabla \sum_i R_i(x_i, y_i) = 0$$: Condition of least square

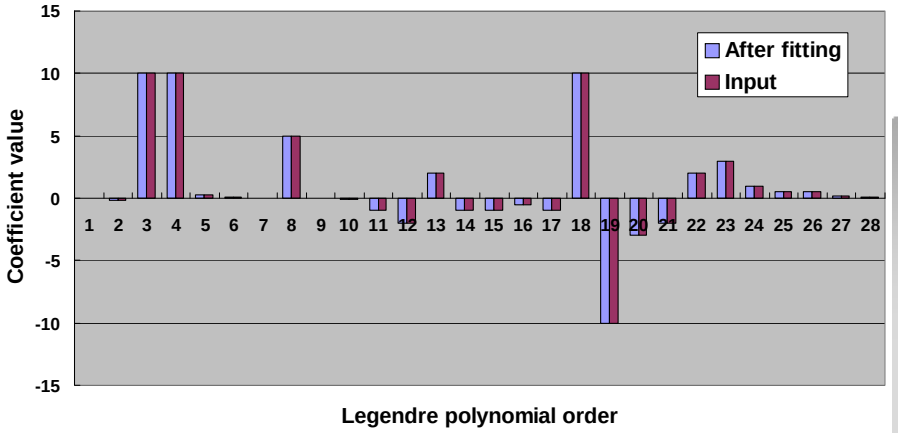


$$\sum_i [Z_i(x_i, y_i) z^n(x_i, y_i)] = \sum_i [f_i(x_i, y_i) z^n(x_i, y_i)]$$

$$\sum_i \{c^1 z^1(x_i, y_i) + c^2 z^2(x_i, y_i) + c^3 z^3(x_i, y_i) + \ldots\} z^n(x_i, y_i) = \sum_i [f_i(x_i, y_i) z^n(x_i, y_i)]$$

$$\begin{pmatrix} \sum_i z_1^2 & \sum_i z_1 z_2 & \sum_i z_1 z_3 & \cdots \\ \sum_i z_2 z_1 & \sum_i z_2^2 & \sum_i z_2 z_3 & \cdots \\ \sum_i z_3 z_1 & \sum_i z_3 z_2 & \sum_i z_3^2 & \cdots \\ \vdots & \vdots & \vdots & \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ \vdots \end{pmatrix} = \begin{pmatrix} \sum_i f_i z_1 \\ \sum_i f_i z_2 \\ \sum_i f_i z_3 \\ \vdots \end{pmatrix}$$

c_n = Legendre polynomial coefficient

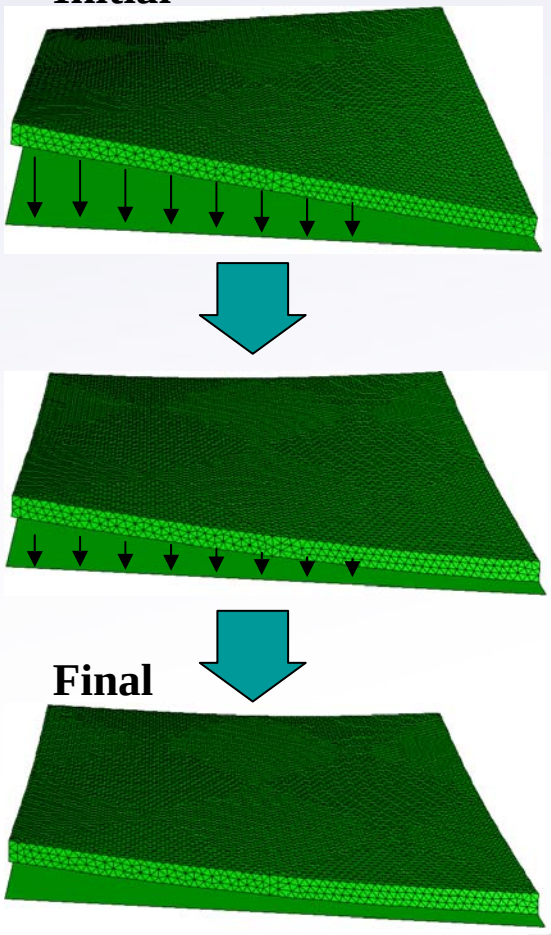


Mask Distortion due to Electro-static Chucking

Finite element modeling

(using ABAQUS)

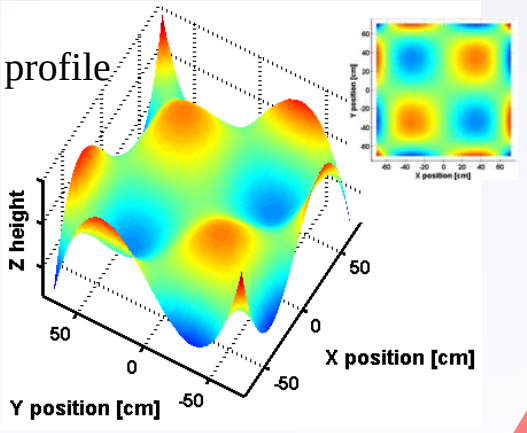
Initial



Final

Comparison with previous study

L33 profile



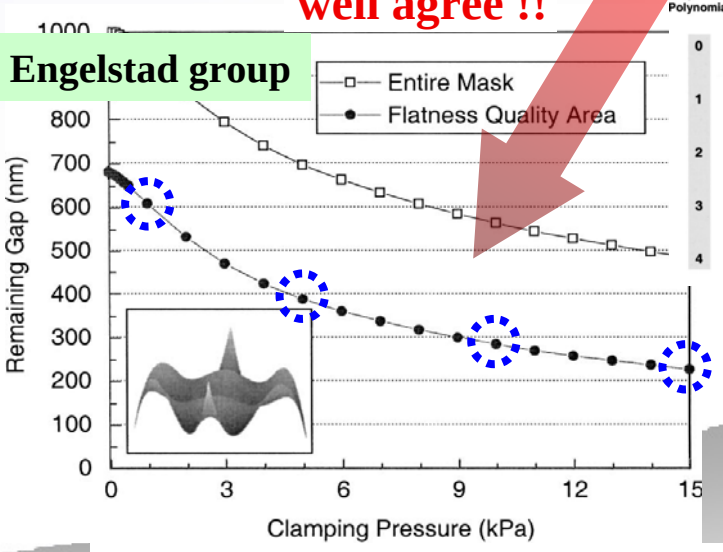
Our result

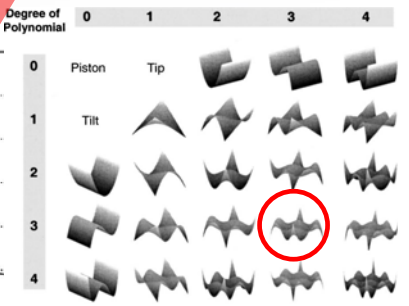
Remaining Gap

1kPa = 593.17 nm
5kPa = 401.04 nm
10kPa = 296.12 nm
15kPa = 240.04 nm

well agree !!

Engelstad group





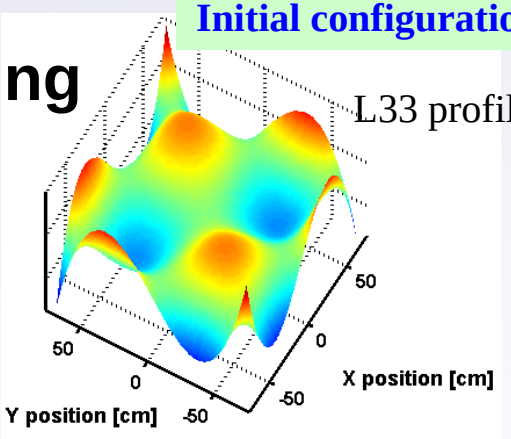
L33 profile

Ref: A. Mikkelson, et. al., J. Vac. Sci. Technol. B 21, 3091 (2003)

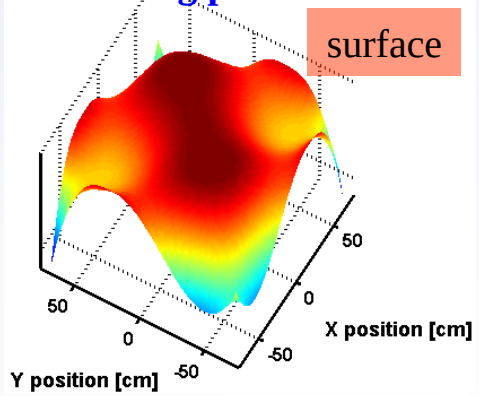
Registration Error due to Mask Clamping

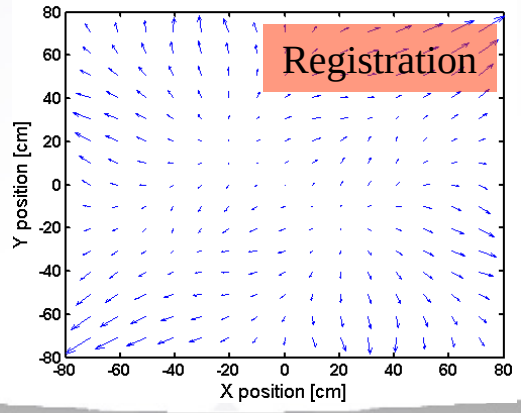
Registration due to Mask Clamping
= (final position of mesh) - (initial position of mesh)

Initial configuration

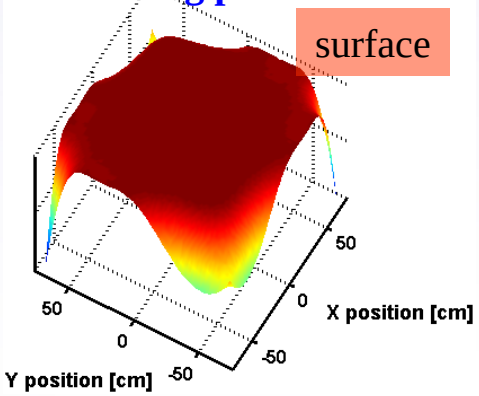


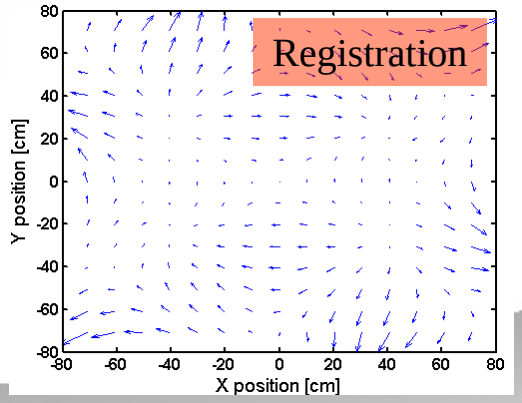
When chucking pressure is 1kPa



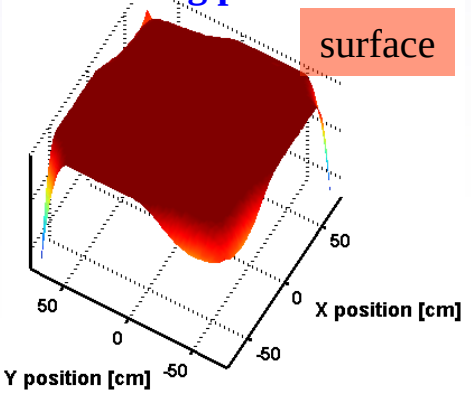


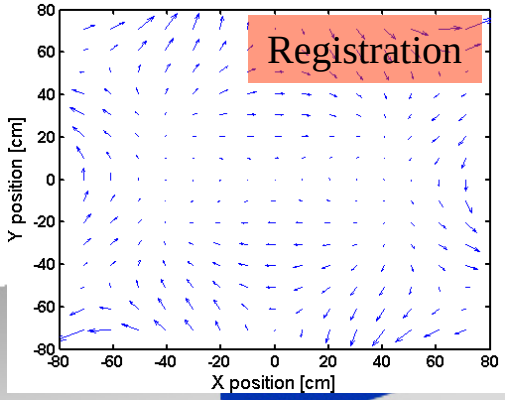
When chucking pressure is 5kPa





When chucking pressure is 15kPa



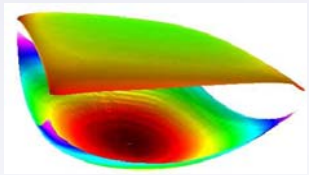


ELECTRONICS

Registration error due to mask flatness

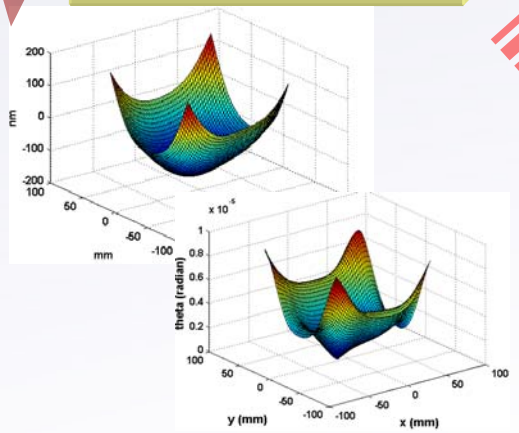
(Simulation Code Development)

Flatness measurement



Ref: SPIE Vol. 5752, 621 (2005)

Height, Local slop

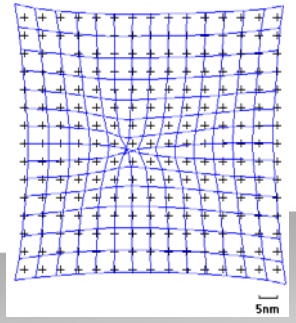


Pattern shift calculation

Registration due to flatness
= Δh×tan(2ϕ + 6°)×M + Δz×2ϕ/M

Δh : flatness
ϕ: local slope
Δz : defocus distance at the wafer
M : magnification ratio of the optics (0.25)

Registration map



Grid control parameter to correct registration map

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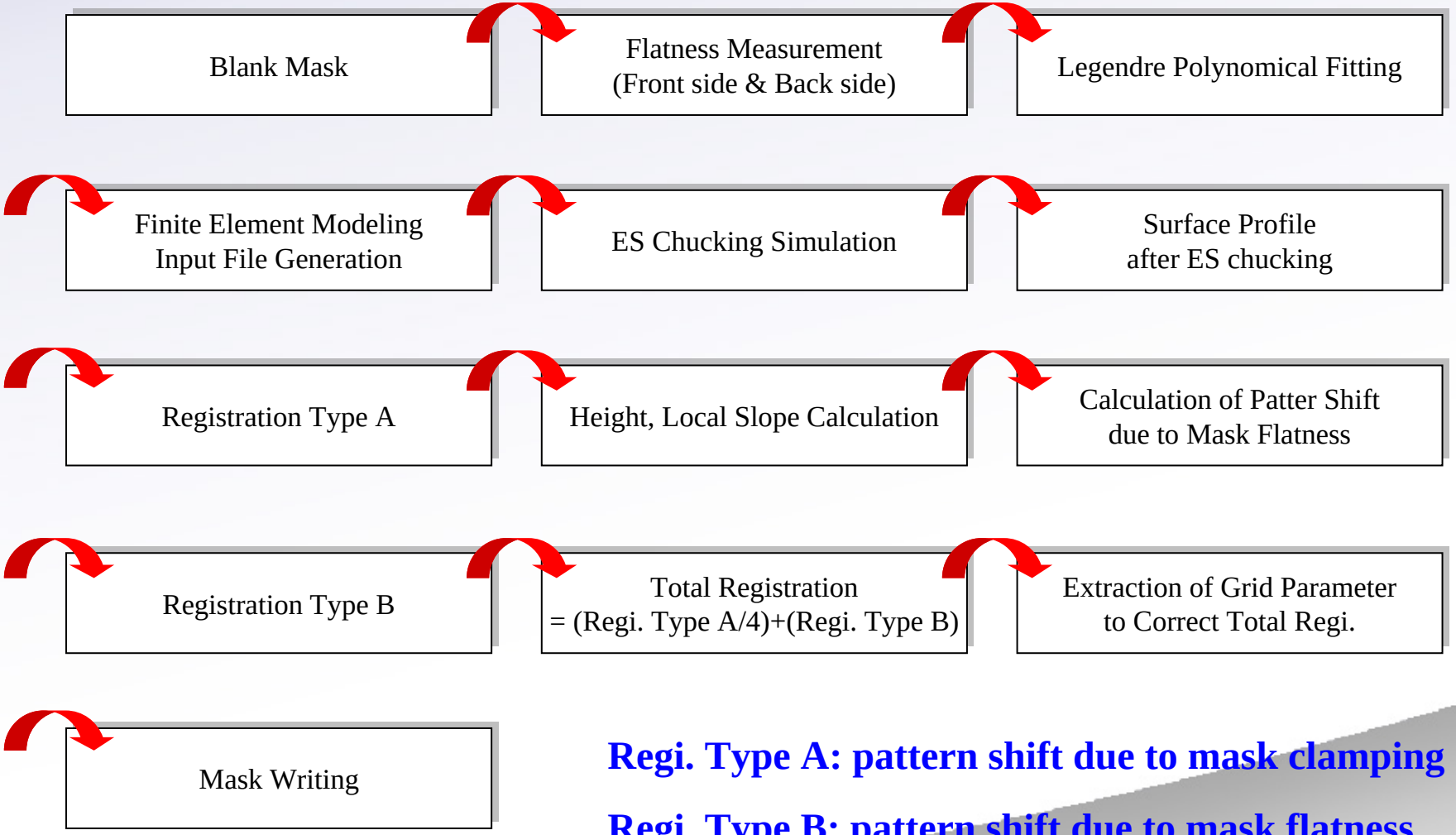
Registration Error: Realistic Approach and Correction Technique



Regi. Type A: pattern shift due to mask clamping

Regi. Type B: pattern shift due to mask flatness

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Conclusions

- **Special Features of EUV Lithography**

  Reflective photomask & Non-telecentricity of object side

- **Registration Error due to Roughness of EUV Photomask**

  1) Registration error due to mask clamping - Regi. Type A

  simulated by finite element modeling

  depend on ES chuck spec. and chucking pressure

  2) Registration error due to mask flatness - Regi. Type B

  calculated using height and local slope

  $\Delta h \times \tan(2\phi + 6o) \times M + \Delta z \times 2\phi/M$, where Δh : flatness, ϕ: local slope

- **Registration Error: Realistic Approach and Correction Technique**

  Total Registration Error = (Regi. Type A) + (Regi. Type B)

  Registration correction by grid control of mask writer

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