

Mask Fabrication Challenges

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Outline

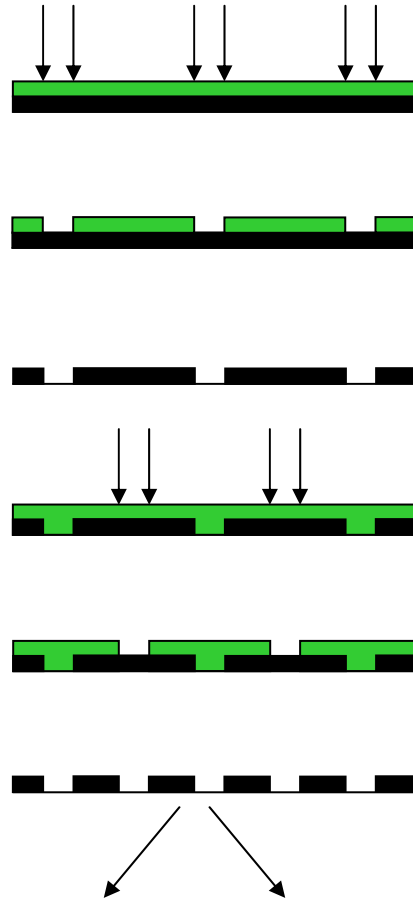
Mask specifications for double exposure

High NA impact on mask performance

Mask fabrication challenges

Double Exposure Options – Mask Implications

Exposures are uncorrelated → Independent defect printability



Assumes double resist coating, exposure, develop, and etch steps

Assumes positive tone wafer resist → negative tone wafer resist only changes mask polarity

CD = Line

Edge of CD printed on different exposure
Correlation between CD control and overlay

CD = Space

Edge of CD printed on same exposure
CD and overlay uncorrelated

If double resist processing + one etch step → defect printability is correlated

ITRS 2005 – Single Exposure

Year of production	2013
DRAM 1/2 pitch (nm)	32
Mask nominal image size (nm)	85
Mask minimum primary feature size (nm)	59
Mask sub-resolution feature size (nm) opaque	42
CD uniformity (nm, 3 sigma) isolated line MPU	1
CD uniformity (nm, 3 sigma) dense lines DRAM	2,4
CD uniformity (nm, 3 sigma) contact/via	1,3
Linearity (nm)	5,1
CD mean to target (nm)	2,6
Image placement (nm)	3,4
Defect size (nm)	26

CD control

Registration

Defects

- All key numbers **RED** for 32nm node single exposure
- ITRS numbers used for reference and for comparison between single and double exposure
- What specification should we use for double exposure ?

Double exposure – Impact on ITRS Scaling Relations

Current ITRS scaling relations for single exposure

CD mean-to-target = $2\% \times \text{DRAM } \frac{1}{2} \text{ pitch} \times \text{MAG}$
Mask CD control = $40\% \times \text{CD} \times \text{MAG} / \text{MEEF}$
Placement = $\text{Overlay} \times \text{MAG} \times 15\%$
Linearity = $3.8\% \times \text{DRAM } \frac{1}{2} \text{ pitch} \times \text{MAG}$
Defect size = $\text{DRAM } \frac{1}{2} \text{ pitch} \times \text{MAG} / 5$

Possible changes for double exposure

- Additional mask to mask specifications needed for
 - overlay specification
 - linearity difference
 - CD mean-to-target difference
- Assuming that the two masks are independent → mask to mask errors will tend to be larger → tighter specification for each mask individually
- Defect specification → printability test needed for one mask, exposures independent
- CD uniformity, registration, overlay scaling relations need to be reviewed
- Assume that error budget for mask is the same for single vs. double exp.

CD, Overlay and Registration Transfer Functions (LINE)

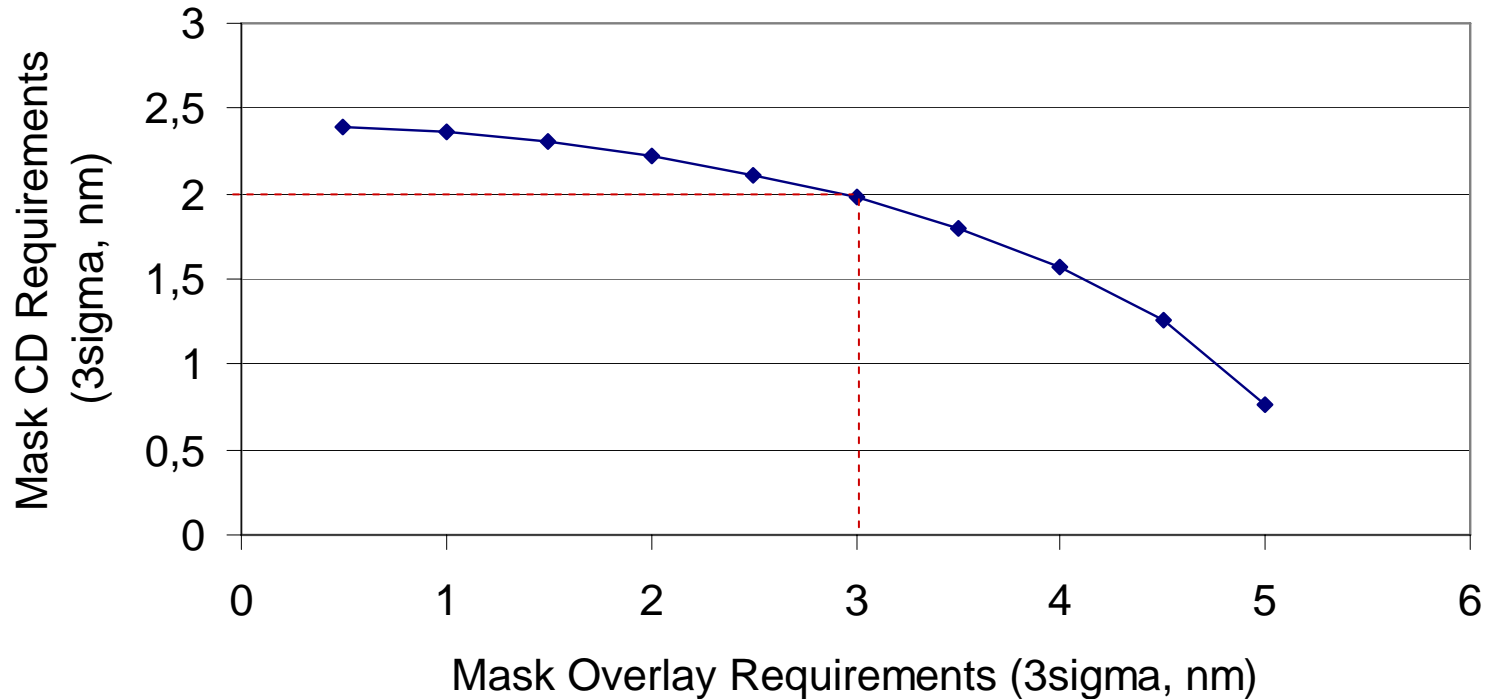
Single Exposure

	Mask CD Error	Mask Registration Error
Wafer CD Error	MEEF / MAG	0
Wafer Overlay Error	0	1 / MAG

Double Exposure (CD = line)

	Mask CD Error	Mask Overlay Error	Mask Registration Error
Wafer CD Error	MEEF / MAG	1 / MAG	0
Wafer Overlay Error	0.5 MEEF / MAG	0.5 / MAG	1 / MAG

CD and Overlay Requirements DRAM Lines and Spaces Level (LINE)



Mask registration requirements: 2.2 (3sigma, nm)

Specification Comparison – Single vs. Double Exposure LINE

MPU (Line)	Single Exposure	Double Exposure
CD (3 sigma, nm)	1	0.6
Overlay (3 sigma, nm)	NA	1.5
Registration (3 sigma, nm)	3.4	3.3

DRAM (Line)	Single Exposure	Double Exposure
CD (3 sigma, nm)	2.4	2.0
Overlay (3 sigma, nm)	NA	3
Registration (3 sigma, nm)	3.4	2.2

CD, Overlay and Registration Transfer Functions (SPACE)

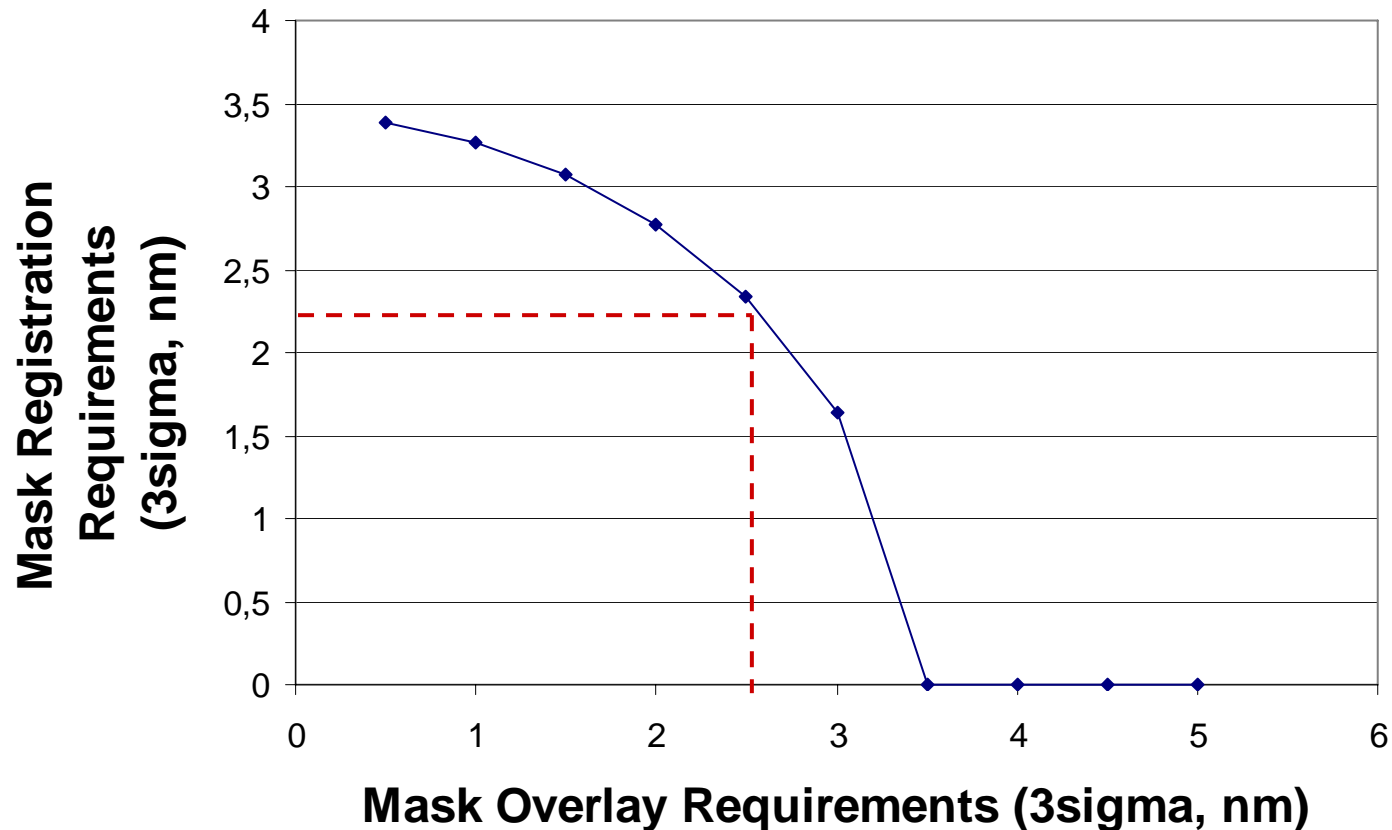
Single Exposure

	Mask CD Error	Mask Registration Error
Wafer CD Error	MEEF / MAG	0
Wafer Overlay Error	0	1 / MAG

Double Exposure (CD = space)

	Mask CD Error	Mask Overlay Error	Mask Registration Error
Wafer CD Error	MEEF / MAG	0	0
Wafer Overlay Error	0	1 / MAG	1 / MAG

Overlay and Registration Requirements DRAM Space and Contact Level (SPACE)



→ Mask registration requirements = 2.4 (3sigma, nm)

→ Mask overlay requirements = 2.4 (3sigma, nm)

Specification Comparison – Single vs. Double Exposure - SPACE

Contact	Single Exposure	Double Exposure
CD (3 sigma, nm)	1.3	1.3
Overlay (3 sigma, nm)	NA	2.4
Registration (3 sigma, nm)	3.4	2.4

DRAM (Space)	Single Exposure	Double Exposure
CD (3 sigma, nm)	2.4	2.4
Overlay (3 sigma, nm)	NA	2.4
Registration (3 sigma, nm)	3.4	2.4

How to address tight specifications

- Revisit validity of single exposure 32nm specifications
- Change error budget given to the mask
- Improve MEEF → choose low MEEF RET option
→ use highest NA tool for double exposure

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Impact of High NA Lithography on Mask Performance

Large angle of incidence at the mask

NA=1.35 → max. angle ~ 20 degrees

NA= 1.65 → max. angle ~ 25 degrees



Effective Source and Pupil Uniformity

Blank transmission → effective source

Pellicle apodization → effective pupil

Subwavelength mask features

ITRS 2005 for 32nm hp node:

Minimum main feature size = 59nm

Minimum sub-resolution = 42nm

Increased aspect ratio of mask features

Material thickness = 70nm

Min main feature aspect ratio ~ 1.2

Sub-res. feature aspect ratio ~ 1.7



Polarization effects

Transmission function of mask type and mask material

Mask topography effect

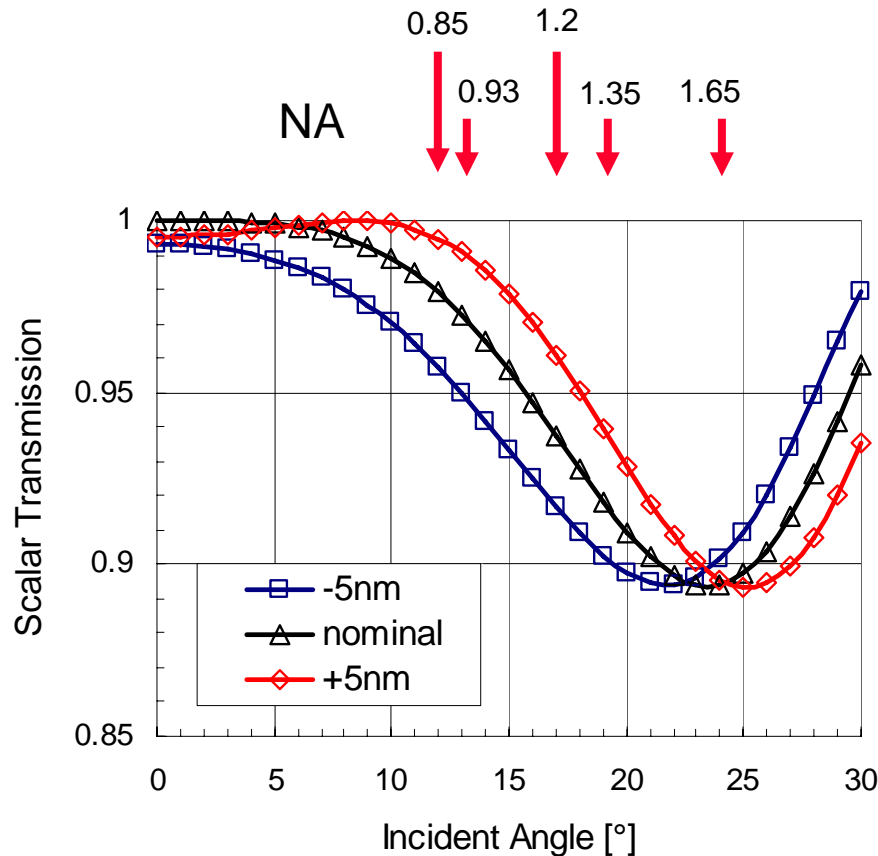
Increased effects with higher aspect ratio

Polarization effects and topography effects are convoluted

No show stopper identified but two concerns for 32nm hp:

- **Overall mask transmission: ~50% drop in TE from 40nm to 30nm**
- **Pellicle apodization**

Pellicle Apodization



- Significant apodization for angles larger than 10°
- Transmission loss $\sim 10\%$ at outer rim of pupil for NA=1.35
- Refractive index: $n=1.4$, $k=0$
- Thickness: 828nm
- Optimized for 100% transmission on axis

- Pellicle impact on wafer images: OPC correction difference 1nm @ 1X with-without pellicle
- Sensitivity of pellicle thickness on wafer images: 5nm error \rightarrow 3% CD error for 45nm CD
- Antireflective coating necessary to limit apodization

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Mask Fabrication – Key Challenges for 32nm Node

Pattern generation

CD and registration specifications lower than current tool residual errors

Compromise between tool parameters, resist process, performance, and cost (write time)

Data volume increase → increase current density → resist heating and charging

Tighter specifications → lower resist sensitivity and diffusion length, reduced beam blur

Mask OPC signature stability

Pattern transfer

Material choice: polarization effect, patterning, defectivity

Metrology

Inadequate precision for CD and registration measurements

LER

Mask Inspection

Capability, no actinic inspection, prediction of mask effects (polarization, topography)

Mask Repair

Edge placement error, damage

Mask Cleaning

Compromise between efficiency, pattern damage, residues

Research and Development Paths

- Error budget analysis → use technology gaps to drive improvement programs
- Equipment and material availability → reduce tool noise levels, resist, material easier to etch and with low defectivity
- Correction of systematic signatures at the tool level or at the layout level → CD and registration specifications
- Utilize wafer equipment and processes where possible → inspection for example
- Develop mask infrastructure for double exposure
- No additional mask type anticipated, old one might be dropped

Example: Mask Registration Error Budget Analysis Possible Solutions to Improve Image Placement

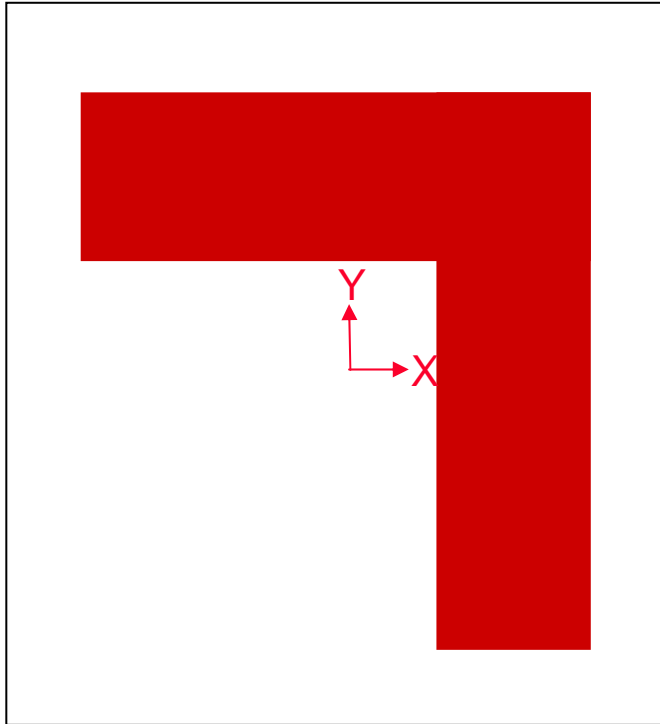
Sources of Placement Error	Systematic / Noise	Availability of Models	Possible Solutions
Writer positioning	Noise	No	Tool tuning and tool improvements
Absorber etching	Systematic	Yes	Model-based correction or use new material
Writer heating	Systematic	Yes	Small due to low dose and multipass writing
Measurement	Noise	No	Tool tuning and tool improvements
Blank tolerances	Systematic	Yes	Monitoring properties or tighten tolerances
Charging effects	Systematic	No	Introduce new material or develop model

→ **Error budget analysis used to drive improvement projects**

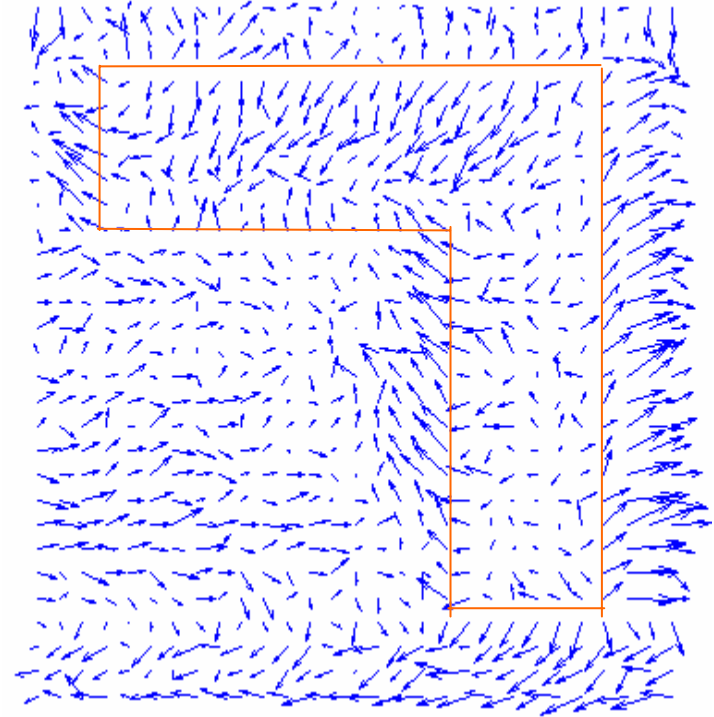
→ **Basis for correction of systematic errors**

Charging Effects on Mask Registration

Layout



Results



Data Analysis					
[nm]	x	y			
Mean	0.00	-0.00	Min	-8.46	-6.79
3 Sigma	9.87	6.99	Max	11.61	8.04

→ Charging represents a large portion of the overall registration budget

Summary

- **Double Exposure:** tighter specifications for double exposure derived using simple error budget analysis
 - **CD, overlay, and registration specifications are correlated and on the same order of magnitude**
 - **tighter CD, registration, and overlay when CD = Line**
 - **tighter registration and overlay when CD = Space**
- **High NA Single Exposure:** No show stopper on mask performance but concern about **transmission loss** and **pellicle apodization effects** → pellicle impacts wafer image and **pellicle thickness uniformity becomes critical**
- **Mask Fabrication:**
 - **Specification requirements are below projected noise levels or capability of tools.** Best specifications will be achieved by using error budget analysis to drive further improvements and by correction of systematic errors
 - **Mask fabrication potential show stoppers in all areas** but more particularly:
 - Blank material, mask patterning, inspection, metrology, cleaning

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