Investigation of Mask Defect Density in Full-Field EUV Lithography

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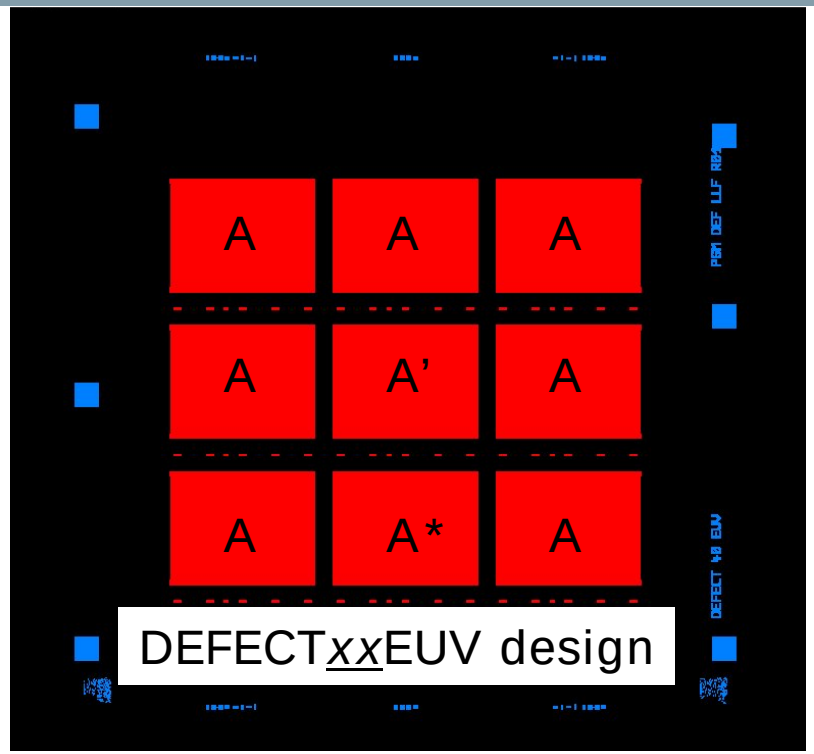
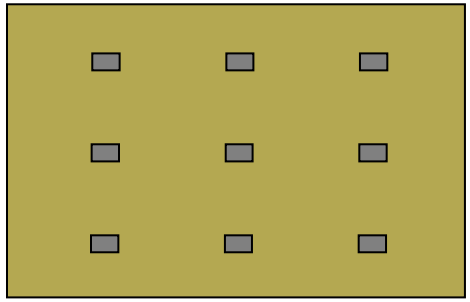
(Toppan assignee)*

Outline

- Introduction: methodology and goal
- Reminder from EUVS08:
  First evidence of ML-defect printability ? … !!
- Experimental results with programmed ML-defects
- Benchmarking of reticles for mask defectivity
- First study of options for ML-defect repair
- Conclusions

Methodology:
Detection of mask defects via wafer inspection





Detail of A'

9 blocks of programmed defects

- Subdie (A) consists of vertical *xx* nm L/S, with 3 variations:
  - A: without programmed defects
  - A': with opaque absorber defects
  - A*: intended for substrate defects
- Wafer inspection on KLA2800
  - Broadband DUV (260-380nm)
  - 0.28µm pixel size
  - Detection by cell-to-cell comparison
  - Very sensitive setting possible
  - Analysis is confined to **repeating defects** among #dies printed (= **reticle** defects)

(EUVS2008)

IMEC's EUV mask defectivity work **in 1 slide**

- Use **inspection of printed wafers** + repeater analysis
  - Try to capture multiple wafer inspection tools available
- Evaluate masks from multiple sources
- Focus on **natural defects**,
  but learn through programmed defects.
- Correlate to **blank inspection**
  - Try to capture multiple blank inspection tools available
- Correlate to what **mask inspection**
  - Try to capture multiple mask inspection tools available
- **2 goals:**
  - **Evaluate defectivity level of state-of-the-art EUV reticle supply *(THIS presentation)***
  - Visualize tool capability gaps (if any)
    + learn why tools missed printing defects
    (presentation tomorrow)

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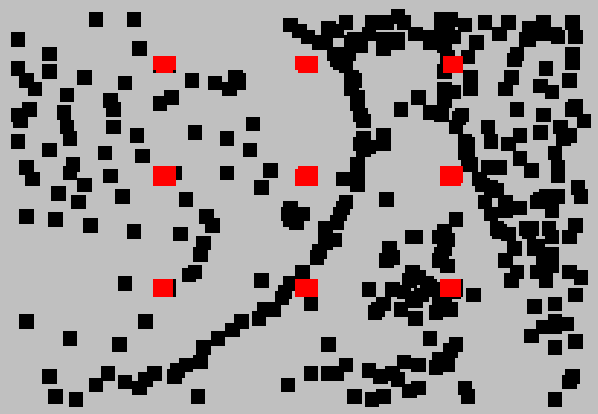
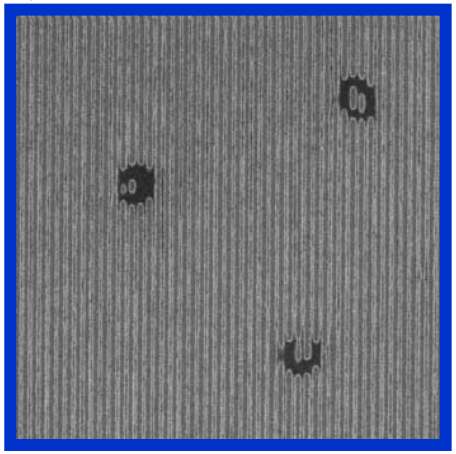
1st Defect40EUV reticle: ML-defects found ??



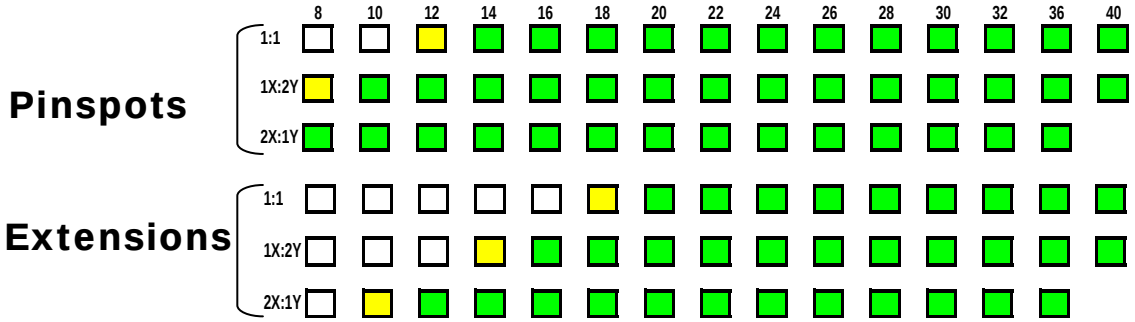
Central module only

- **Programmed** absorber defects detected
- Detection of **other** repeaters, considered as natural defects, consisting of
  - Particles
  - **ML defects**

?



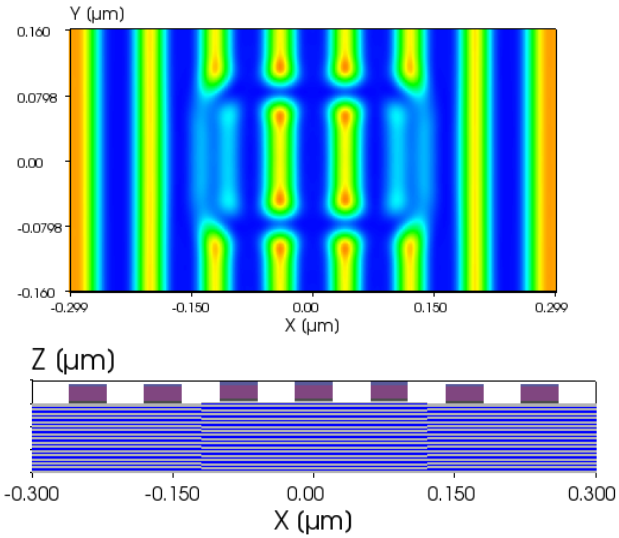
Detected defect on wafer
(sizes at wafer level, nm)



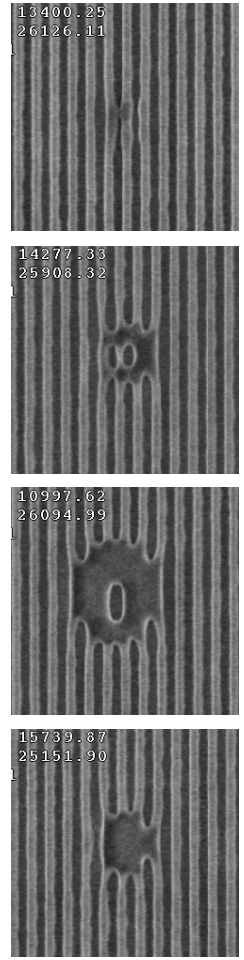
(EUVS2008)

SEM-review of wafer (1st Defect40EUV)

Simulation ***could*** explain defects found as ML-defects



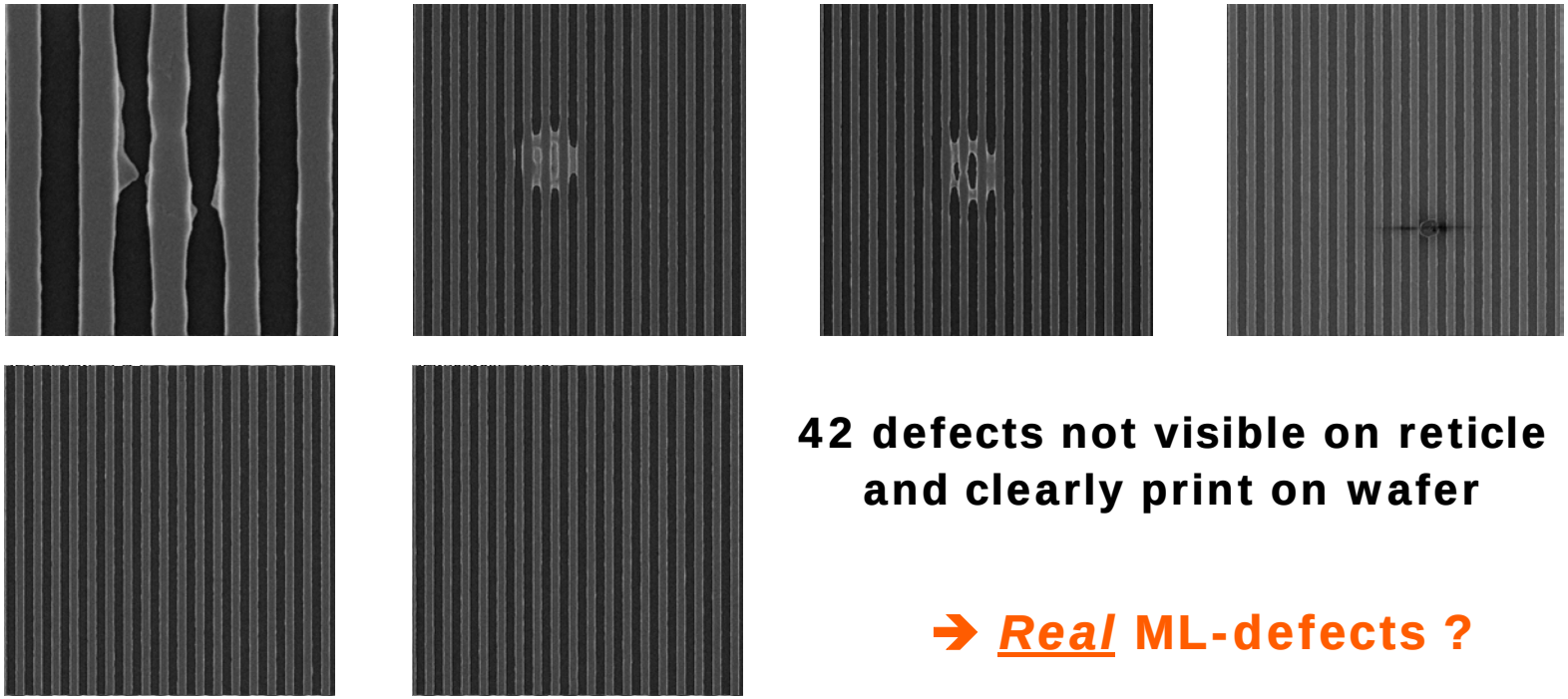
Rectangular cross-section substrate bump defect underneath the ML with height ~λ/4



(PMJ2009)

SEM-review of the reticle (1st Defect40EUV)

~~Candidate ML-defects~~



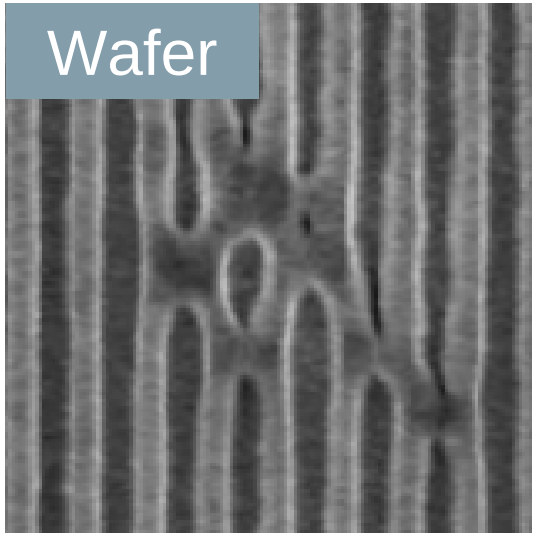
??

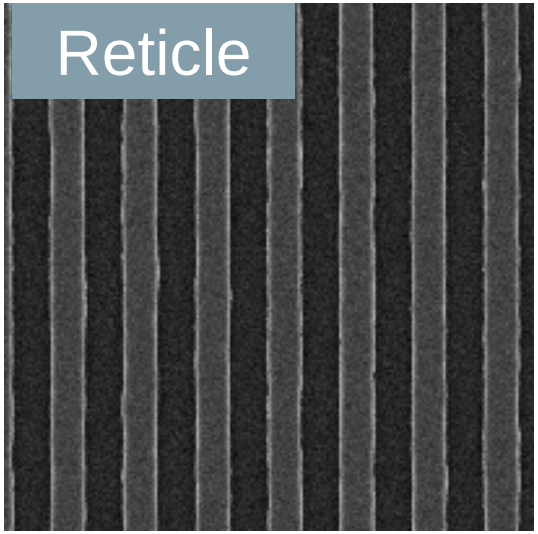
42 defects not visible on reticle and clearly print on wafer

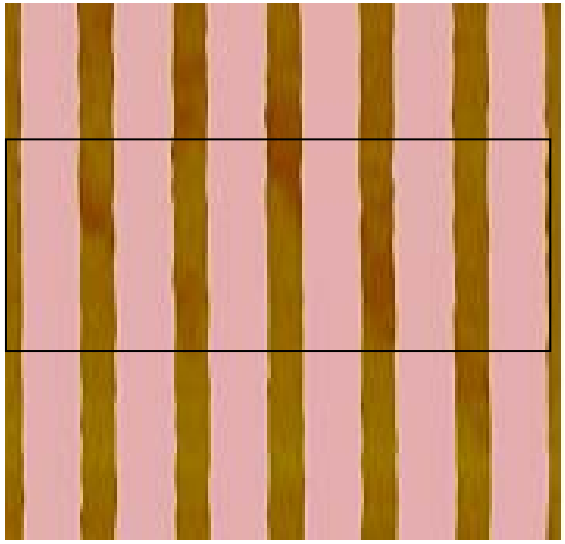
➔ ***Real*** **ML-defects ?**

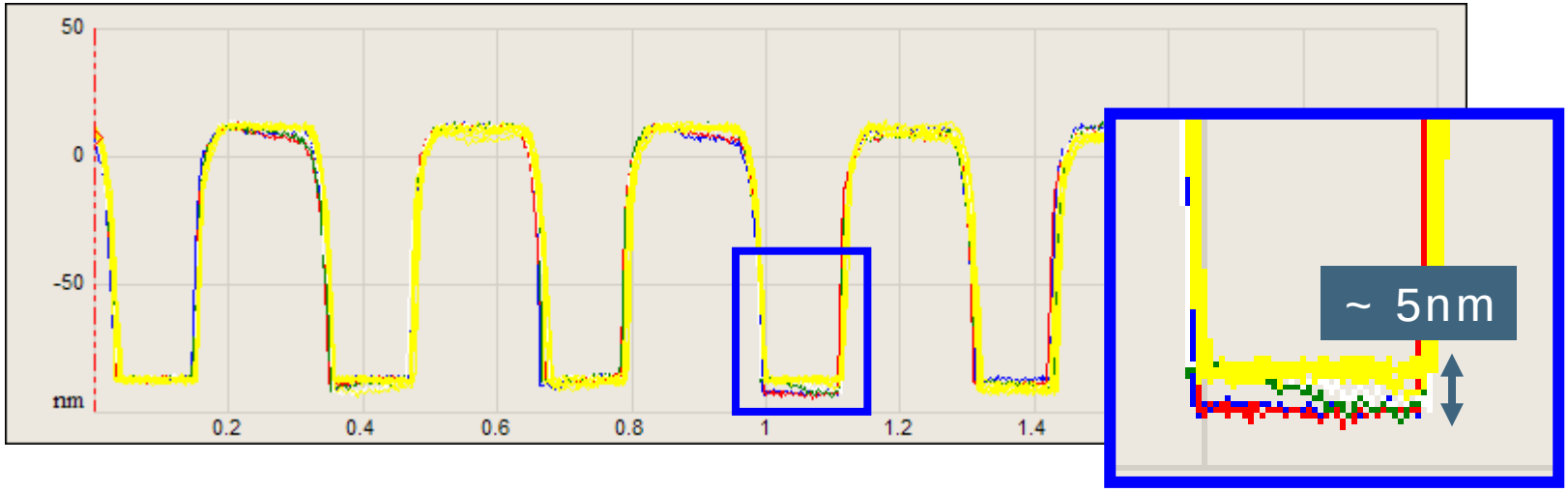
Estimated density ~6 def/cm^2

AFM analysis of a “SEM non-visible” on reticle









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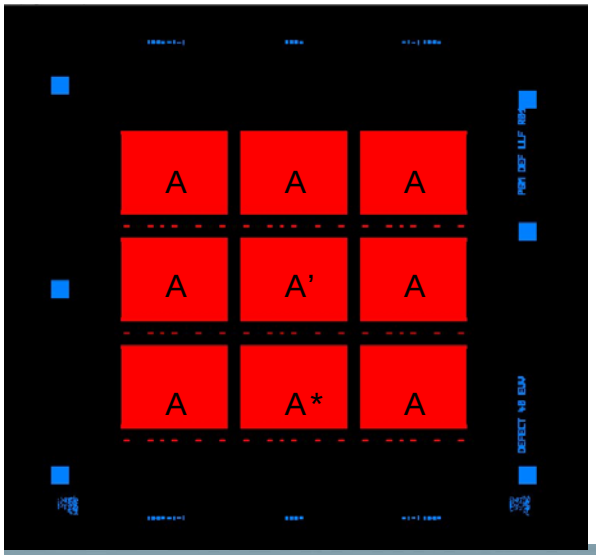
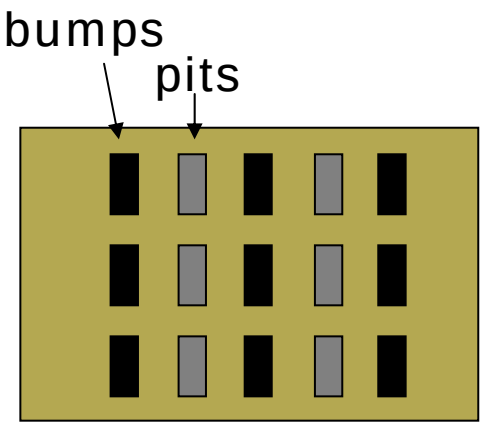
Programmed ML defects - Methodology

- Pattern the substrate with defects before ML-coating
  - Ref. Y. Tezuka, SPIE 6517 (patterned CrN layer underneath the ML)
  - Bumps and pits together
- Defect sizes:
  - 12nm to 40nm per 4nm, + 50, 60, 80, 100nm (at 1X)
  - Dot - and line defect (400nm long)
- pitch ML-defect = n * pitch absorber pattern + δ
- 2 reticles with 2 different targets for ML-defect height: $\lambda/4$ (~3.5nm) and $\lambda/2$ (~7nm)
- Expectation according to simulation: $\lambda/4$ prints more than $\lambda/2$





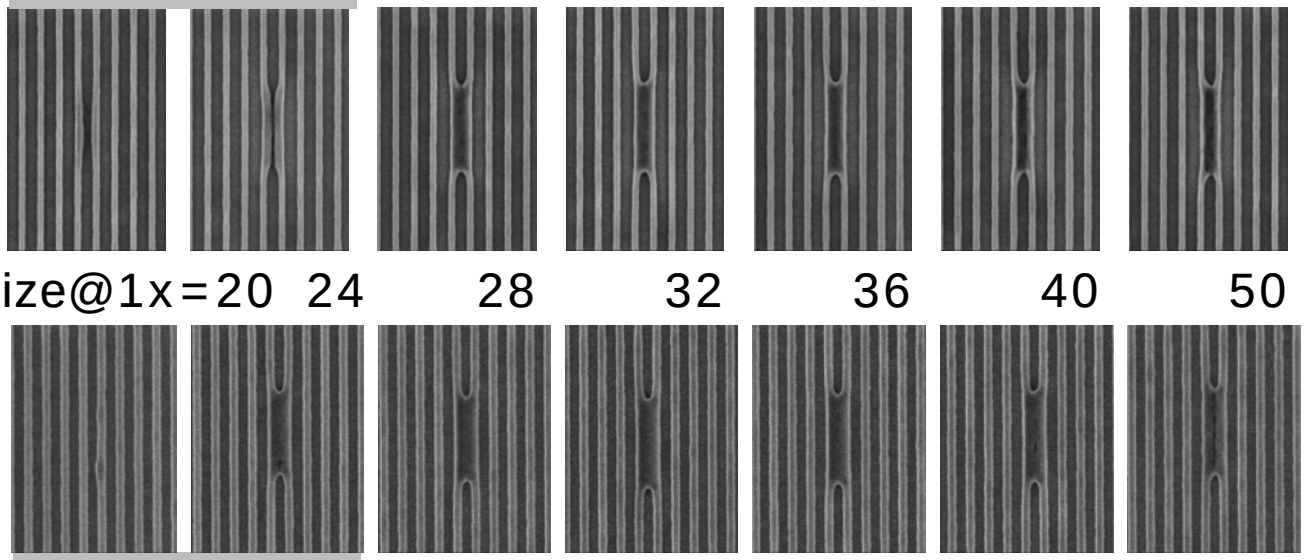
Detail of A*

Nonius principle

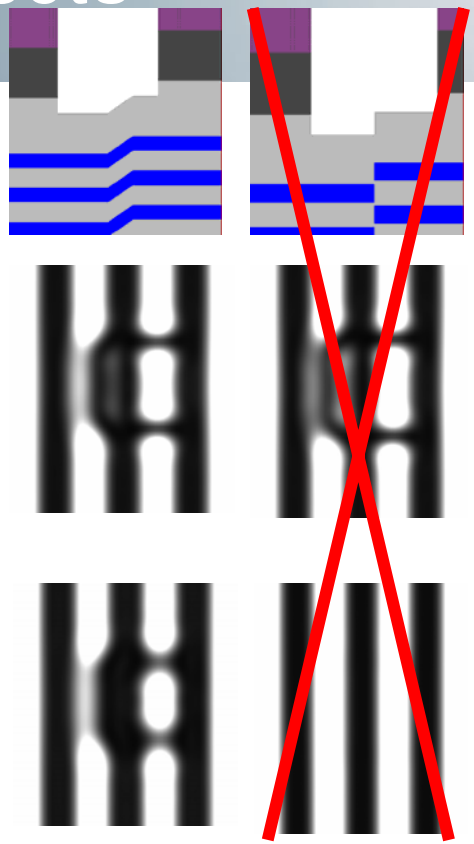
Printability of programmed ML-defects

Example: Bumps – line defects – central position

Height = λ/4



Height = λ/2



- Small difference between λ/4 and λ /2 proves dominating impact of defect slope (= light scatter) rather than phase difference.
- **Conclusion**: Gaussian cross-section likely more representative as cross-section.

Outline

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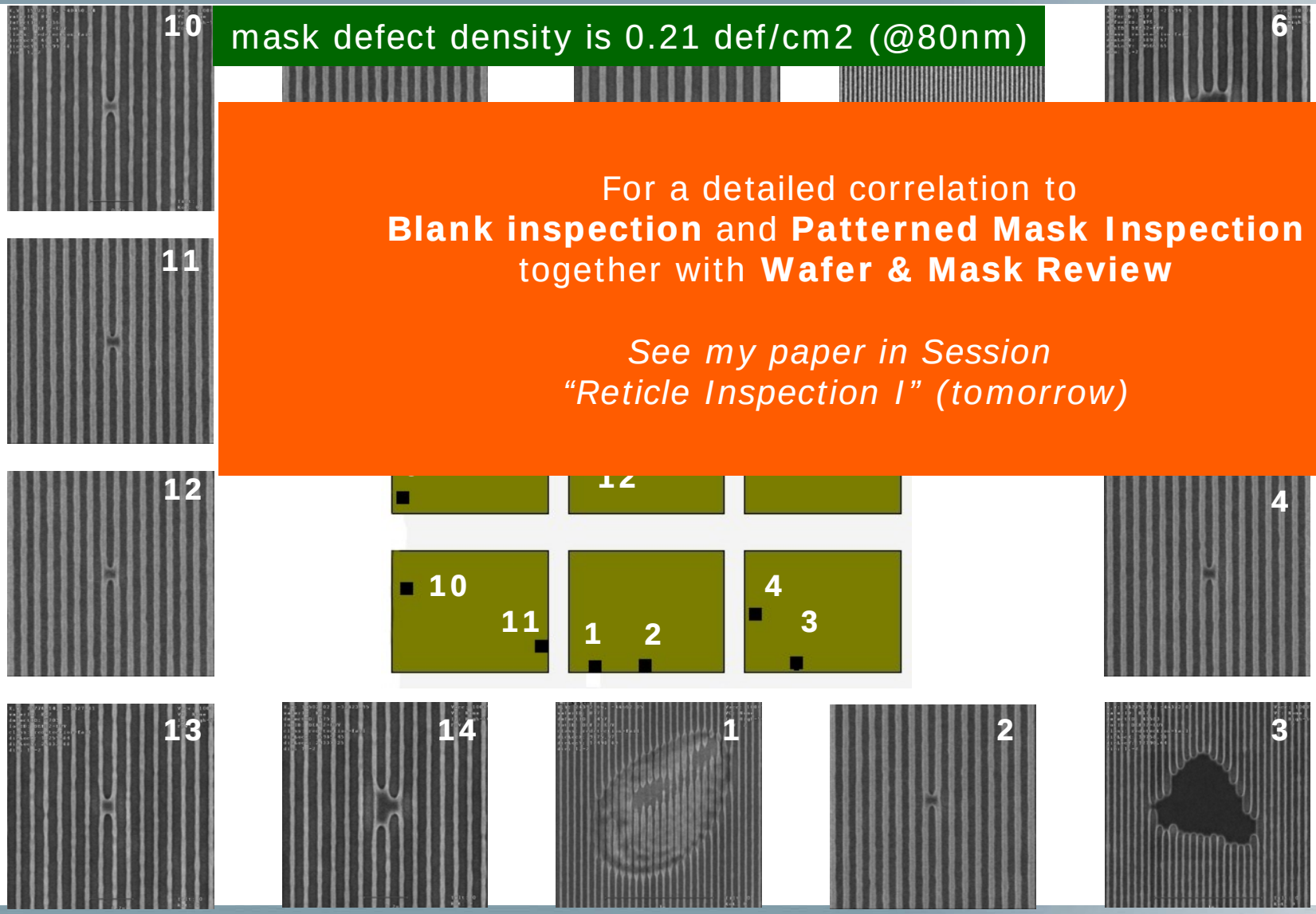
Defect32EUV

wafer inspection found **only 14 defects** (area ~ 50% of ADT field)

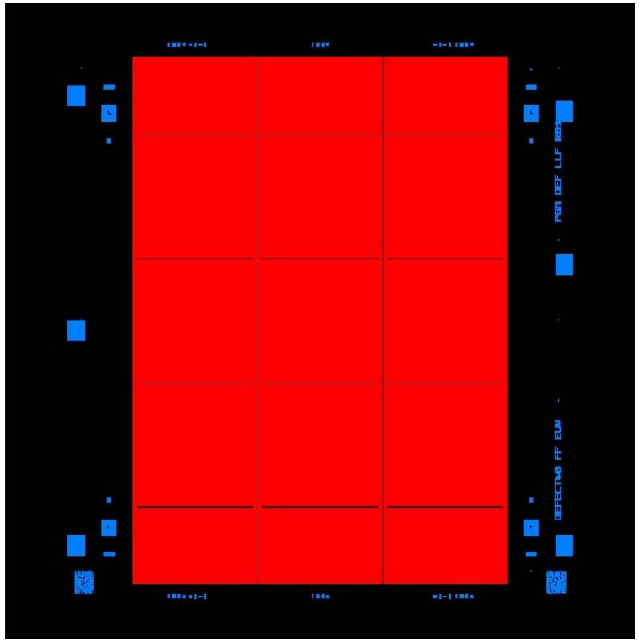
mask defect density is 0.21 def/cm2 (@80nm)



For a detailed correlation to
Blank inspection and **Patterned Mask Inspection**
together with **Wafer & Mask Review**

See my paper in Session
"Reticle Inspection I" (tomorrow)

DEFECT40**FF** comparison

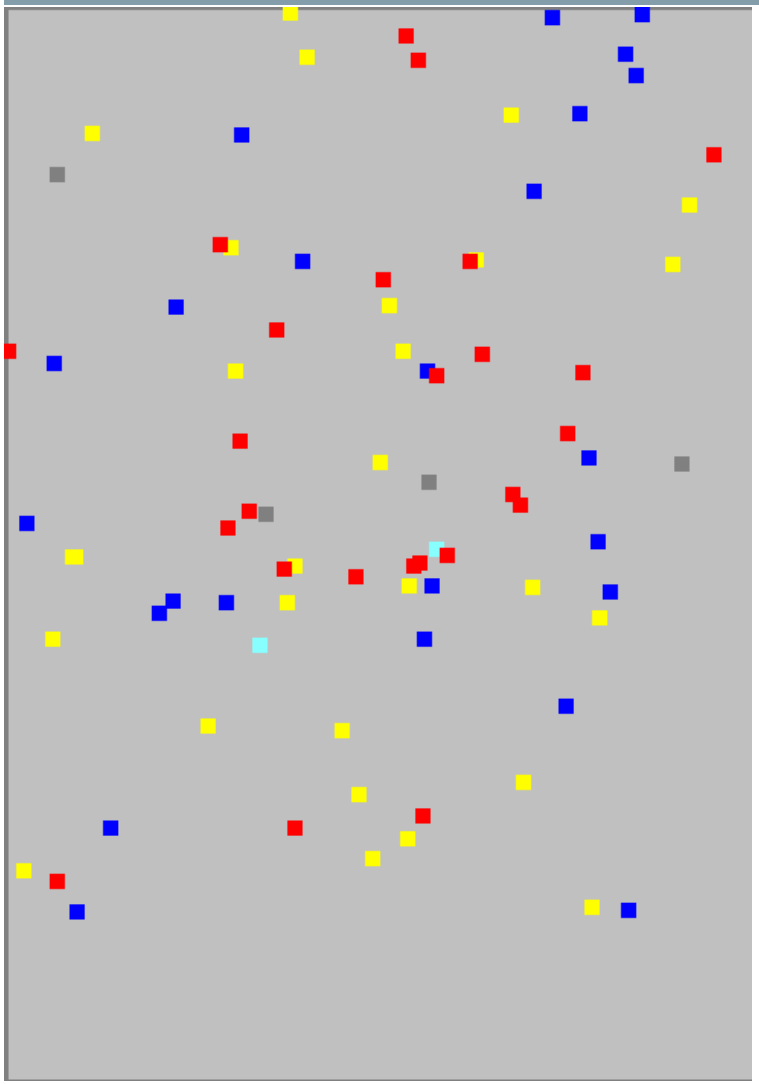


- **3 new reticles** obtained from different vendors were compared to DEFECT32-reticle.

- Change in **Layout**
  - **maximum coverage** of the ADT exposure field
  - **40nm L/S**

- For each reticle the following **inspections** were performed, intending **correlation** between detections :
  - blank inspection after **ML** deposition
  - blank inspection after **absorber** deposition
  - **Patterned Mask** inspection after absorber patterning
  - **Wafer** inspection

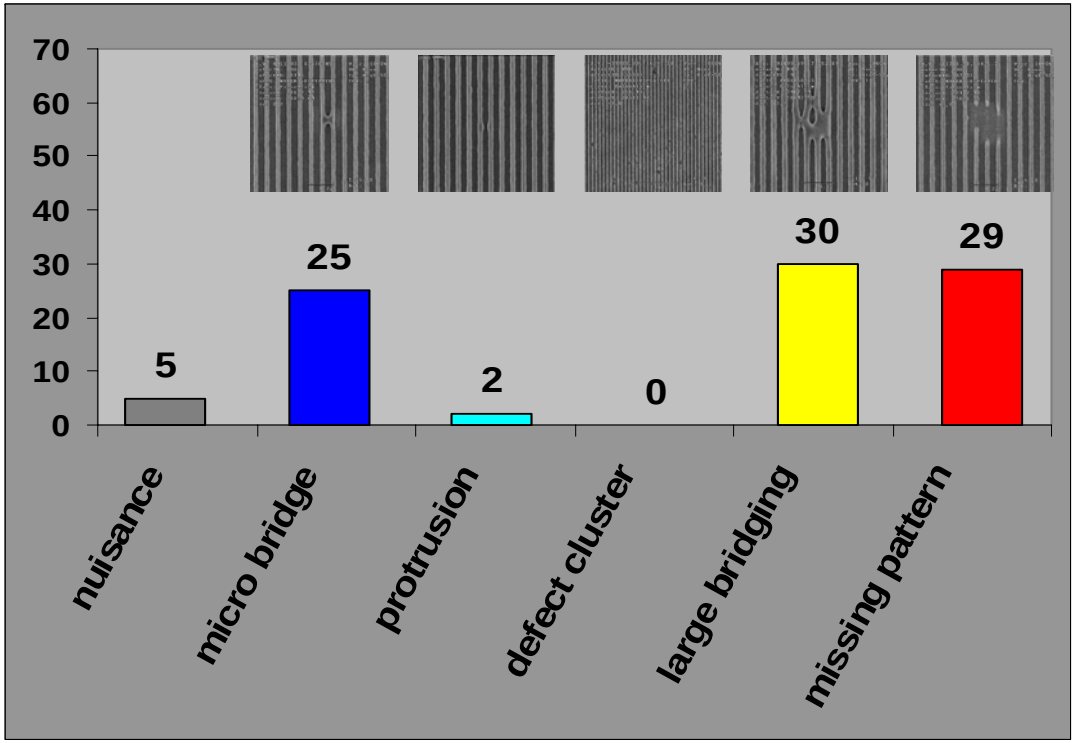
Reticle A
Detections by KLA2800



Total random repeaters = 91 defects:

- no defect in SEM (noise)
- micro bridges
- line protrusions
- defect cluster
- large bridging defects
- missing pattern

Classification by wafer review



Comparison DEFECT40FF reticles Summary

- Defect density based on defects detected by KLA2800
  - RET A: area = 132 cm^2, nr. of defects= 91 → **density= 0.68 defects/cm^2**
  - RET B: area = 132 cm^2, nr. of defects= 110 → **density= 0.83 defects/cm^2**
  - RET C: area = 132 cm^2, nr. of defects= 37 → **density= 0.27 defects/cm^2**
  - ***DEFECT32:*** *area = 66 cm^2, nr. of defects= 14* → ***density= 0.21 defects/cm^2***

Still best result

  - **Including wafer review of blank and patterned mask detections**
    (See my paper in Session "Reticle Inspection I" (tomorrow))
    the updated result found is ***0.48 defects/cm^2***
  - **TARGET: ~0.036 defects/cm^2**
    (= 5 defects for the whole ADT exposure field)
  - **Still ~ 13x improvement required in defect density**
    + @~30nm defect size (instead of ~80nm now)

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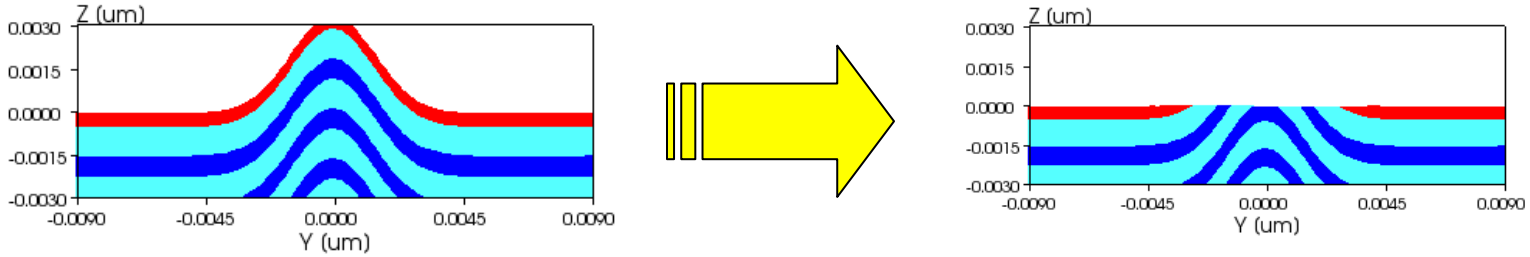
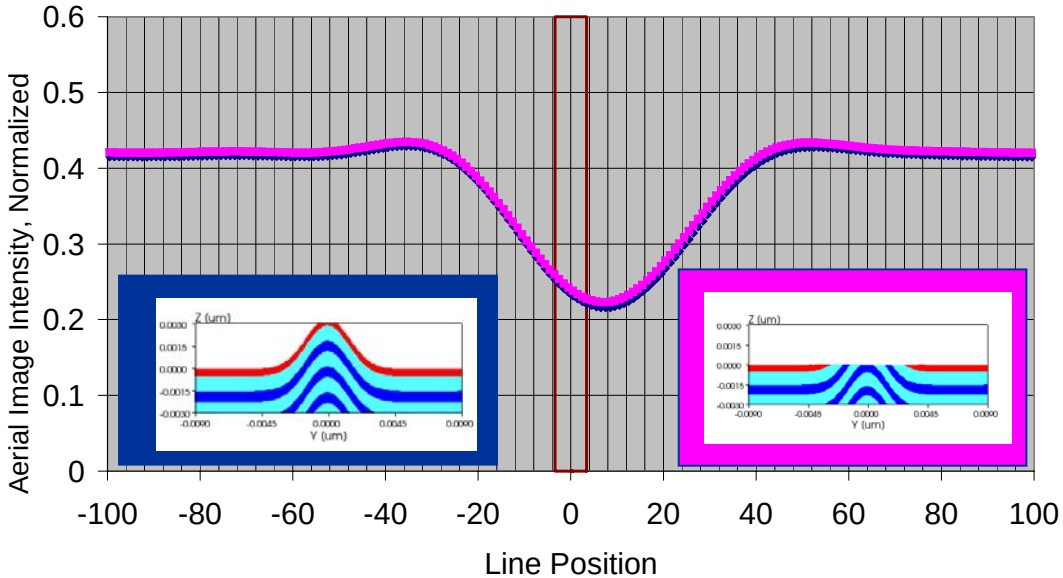
ML-defect Planarization

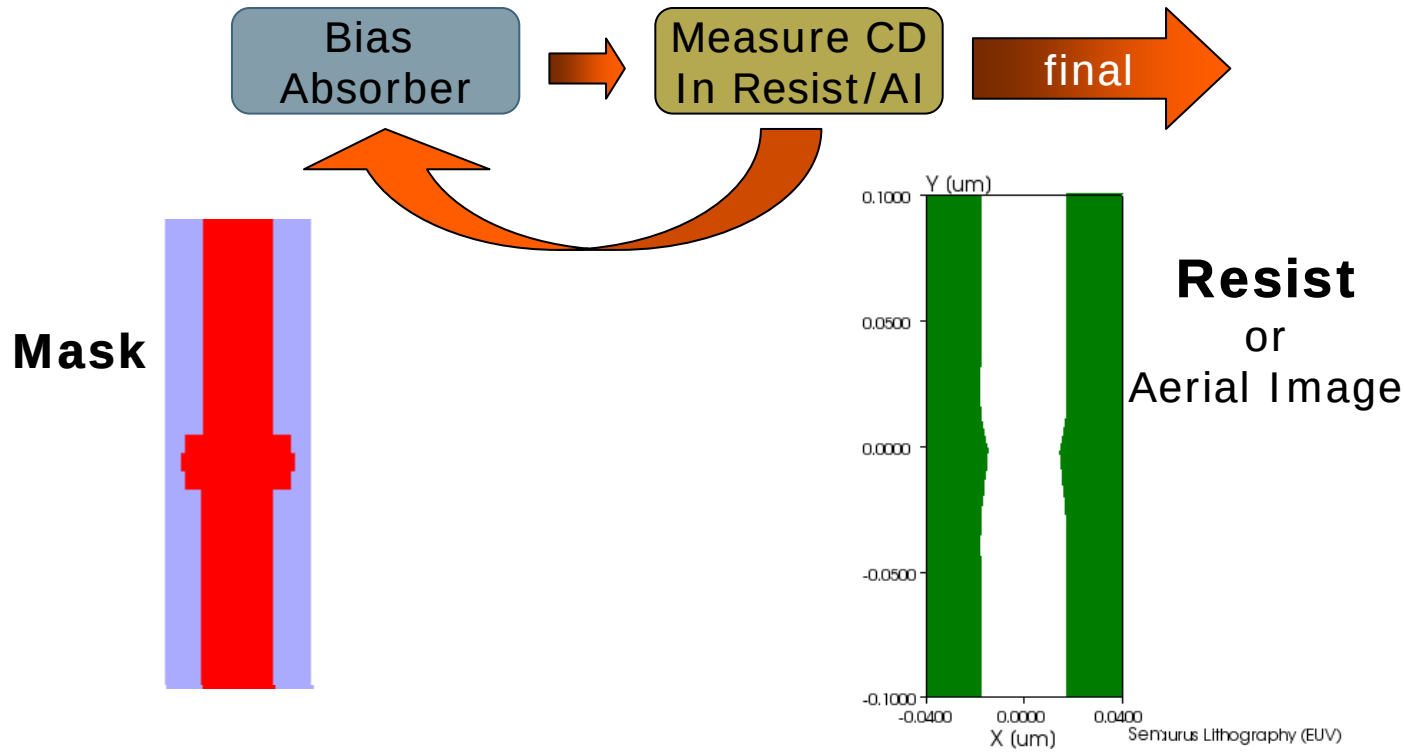


- "Planarize" the ML-defect ?
- Minimal Impact to Aerial Image
  - **No improvement**



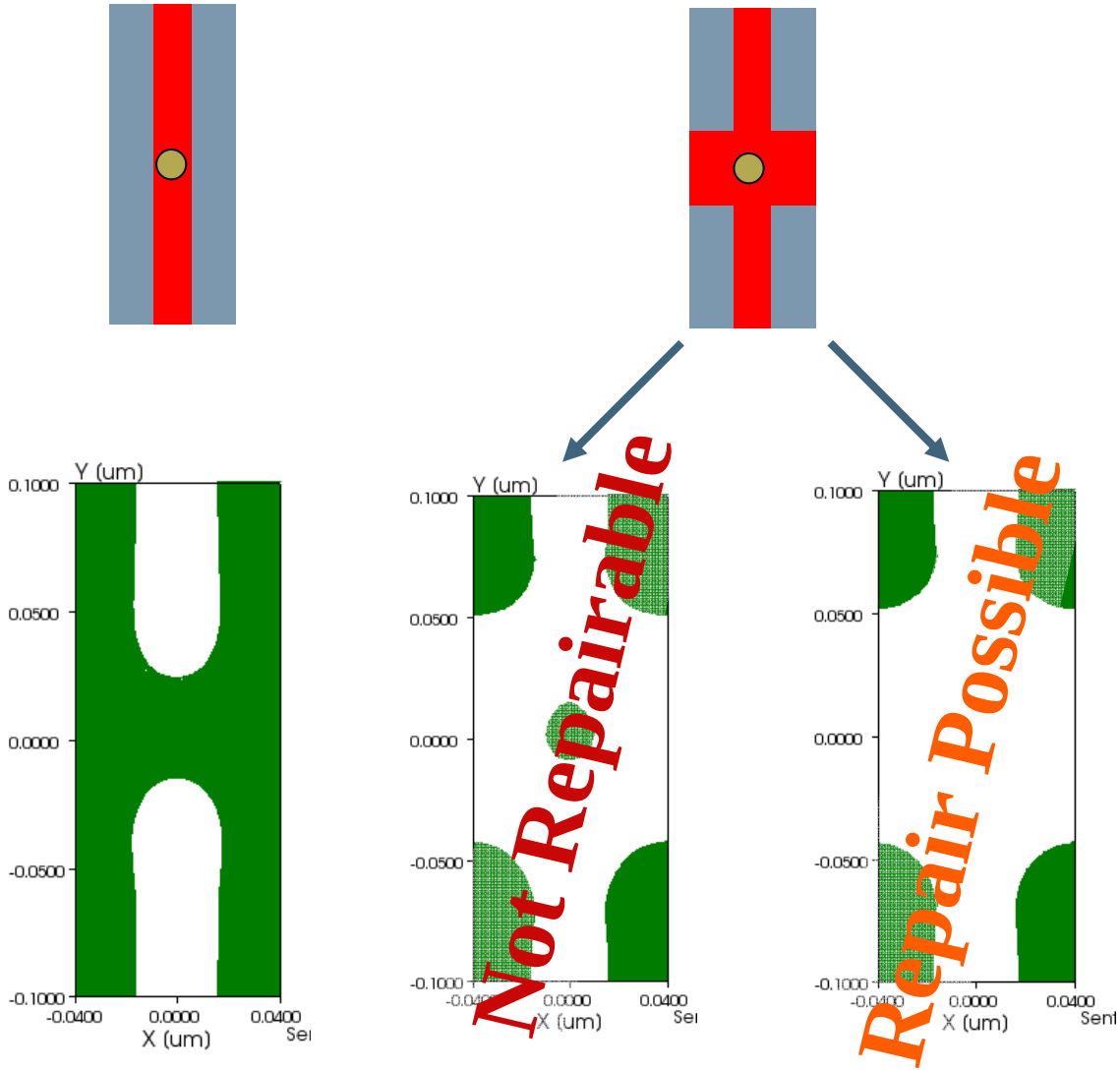
ML-defect "repair" by absorber pattern compensation

- Etch away Absorber to Compensate for ML-defect.
  - Iterative Process



Absorber Compensation: *feasibility screening method*

- Approach
  - Cut absorber line completely (most extreme "repair" possible, i.e. line break).
- Result
  - Defect is not repairable if line breaks before defect resist clears.



Repairable Space: ML Point Defects

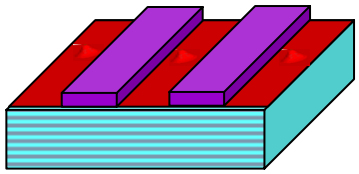
Vertical 40nm L/S

Height

λ	4X	1x	FWHM = Aspect Ratio x Height 0.5	1	1.5	2	4
1/8	1.70	0.425	0.85@4X 0.2125 @1X	1.7@4X 0.425 @1X	2.55@4X 0.6375 @1X	3.4@4X 0.85 @1X	6.8@4X 1.7 @1X
1/4	3.40	0.850	1.7@4X 0.425 @1X	3.4@4X 0.85 @1X	5.1@4X 1.275 @1X	6.8@4X 1.7 @1X	13.6@4X 3.4 @1X
1/2	6.80	1.700	3.4@4X 0.85 @1X	6.8@4X 1.7 @1X	10.2@4X 2.55 @1X	13.6@4X 3.4 @1X	27.2@4X 6.8 @1X
3/4	10.20	2.550	5.1@4X 1.275 @1X	10.2@4X 2.55 @1X	15.3@4X 3.825 @1X	20.4@4X 5.1 @1X	40.8@4X 10.2 @1X
1	13.60	3.400	6.8@4X 1.7 @1X	13.6@4X 3.4 @1X	20.4@4X 5.1 @1X	27.2@4X 6.8 @1X	54.4@4X 13.6 @1X
1 1/4	17.00	4.250	8.5@4X 2.125 @1X	17@4X 4.25 @1X	25.5@4X 6.375 @1X	34@4X 8.5 @1X	68@4X 17 @1X
1 1/2	20.40	5.100	10.2@4X 2.55 @1X	20.4@4X 5.1 @1X	30.6@4X 7.65 @1X	40.8@4X 10.2 @1X	81.6@4X 20.4 @1X
1 3/4	23.80	5.950	11.9@4X 2.975 @1X	23.8@4X 5.95 @1X	35.7@4X 8.925 @1X	47.6@4X 11.9 @1X	95.2@4X 23.8 @1X
2	27.20	6.800	13.6@4X 3.4 @1X	27.2@4X 6.8 @1X	40.8@4X 10.2 @1X	54.4@4X 13.6 @1X	108.8@4X 27.2 @1X

- **Required Detection Limits**
  - **Height ~ 3.4nm (4x)**
  - **FWHM ~ 10nm (4x)**
- **Repair window**
  - Heights up to 27nm (4x)
  - FWHM up to 40nm (4x)

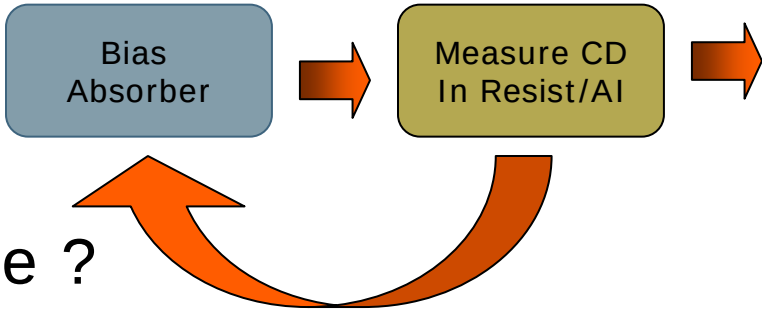
<10% Deviation
>10% Deviation Repair Likely
>10% Deviation Repair Unlikely



Observations about repair

- Repair by absorber pattern compensation possible
  - for point defects up to height 2λ (27nm-4x) and with aspect ratio 1:1.5 (H:FWHM) (40nm-4x FWHM)

- How compensate the absorber pattern?
  - Each defect requires a unique repair.
  - Iterative Repair based on printing information shown feasible.



- How to know how to compensate ?
  - **Surface Topography** is **insufficient**
  - ***Either*** knowledge of defect **within** ML stack is required to predict printability.
    - Defect height, base (FWHM), slope, depth within ML, and propagation through ML (constant, increasing, diminishing) impact printability.
    - Not realistic
  - ***Or*** Actual **Printing Behavior** (**AIMS** or wafer print)

Conclusions / final thoughts

- **Combination** of the **3 inspection techniques + wafer review** of prior detections is our **current best technique** to qualify defect density.
  - **Defect density of our champion reticle is still (>)13x higher than the "target" of ~0.04 defects/cm²**
  - And **detecting defects by printing is too late**

- **ML-defect repair**
  - Is **possible by absorber pattern compensation**, but has a limited capability window.
  - **Its need must be avoided.**
  - Most likely will need to be iterative.
  - **Need for AIMS review.**

Outlook

- Continue to **benchmark defect density** on state-of-the-art EUV reticles
- Refine **wafer inspection** sensitivity
- Round robin of patterned **mask inspection** tools
- Assess **blank inspection** capability
- Experimental work on **ML defect repair**

Acknowledgements

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- Contributions from:
  - AGC
  - AMAT
  - ASML
  - DNP
  - Hoya
  - Intel
  - KLA-Tencor
  - NuFlare
  - Toppan
  - …
- All partners in IMEC's Advanced Lithography Program

25
imec
Years of Making
Technology Fly

intel
Micron
Panasonic
ideas for life
SAMSUNG
tsmc
ELPIDA
hynix
Semiconductor
PSC
NXP
infineon
SONY
QUALCOMM