

IWAPS2020



Electron Beam Metrology for Advanced Patterning

11/5/2020

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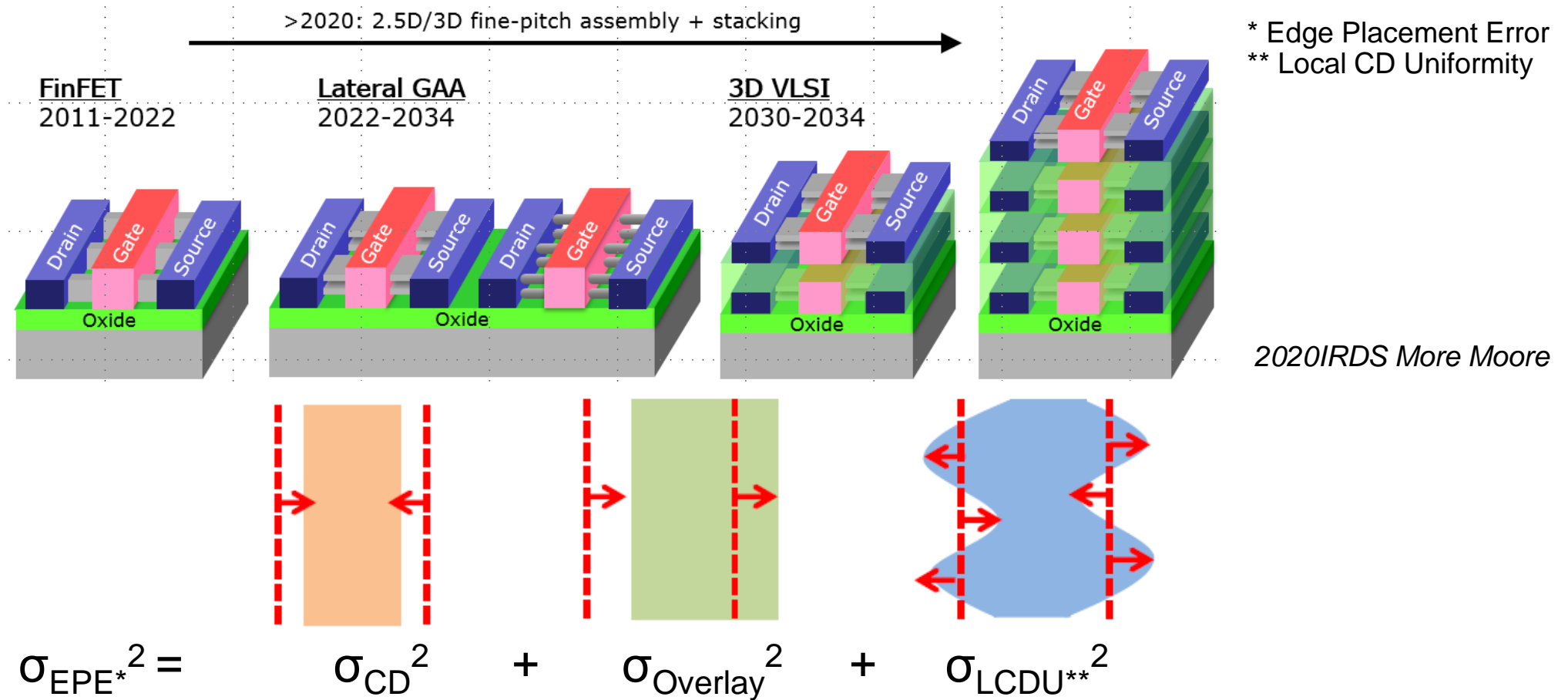
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- 1. Device Trend and Requirement for Metrology Tools**
- 2. High Precision Measurement by CD-SEM**
 - 2.1 Tool to Tool Matching**
 - 2.2 LCDU (Roughness) Measurement**
- 3. New Metrology**
 - 3.1 Overlay Measurement with Buried Patterns by HV-SEM**
 - 3.2 3D NAND BCD Monitor with Auto Beam Tilt Function**
 - 3.3 EUV Issues and Solutions**
- 4. Summary**

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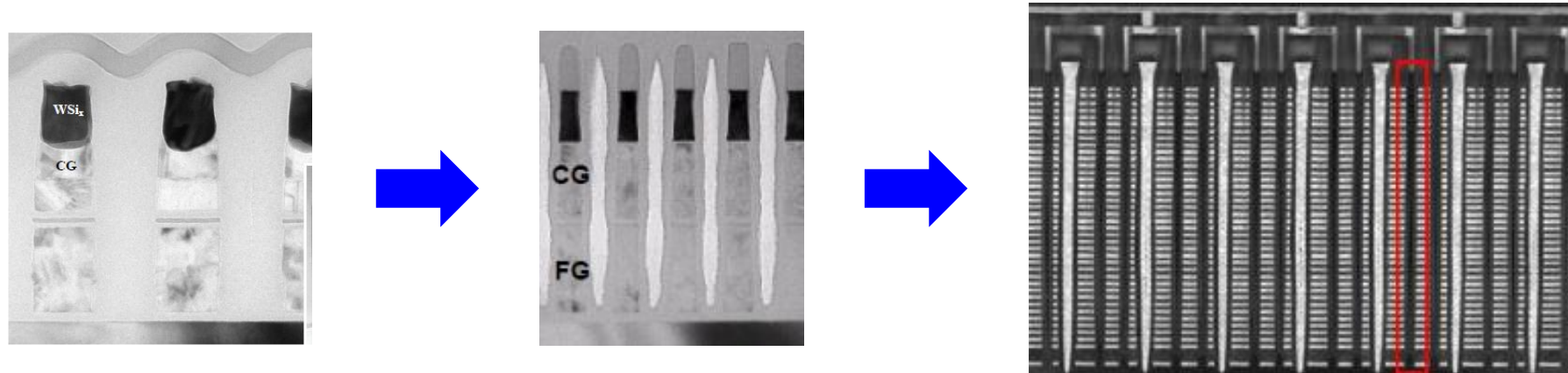
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1.1 Device Trend and Metrology Needs (Logic)



For logic, 1D/2D pattern shrink and 3D technology proceed concurrently. For 1D/2D pattern shrink EPE is becoming critical. For further shrink, EUV light source is being implemented and overlay with buried patterns need to be monitored.

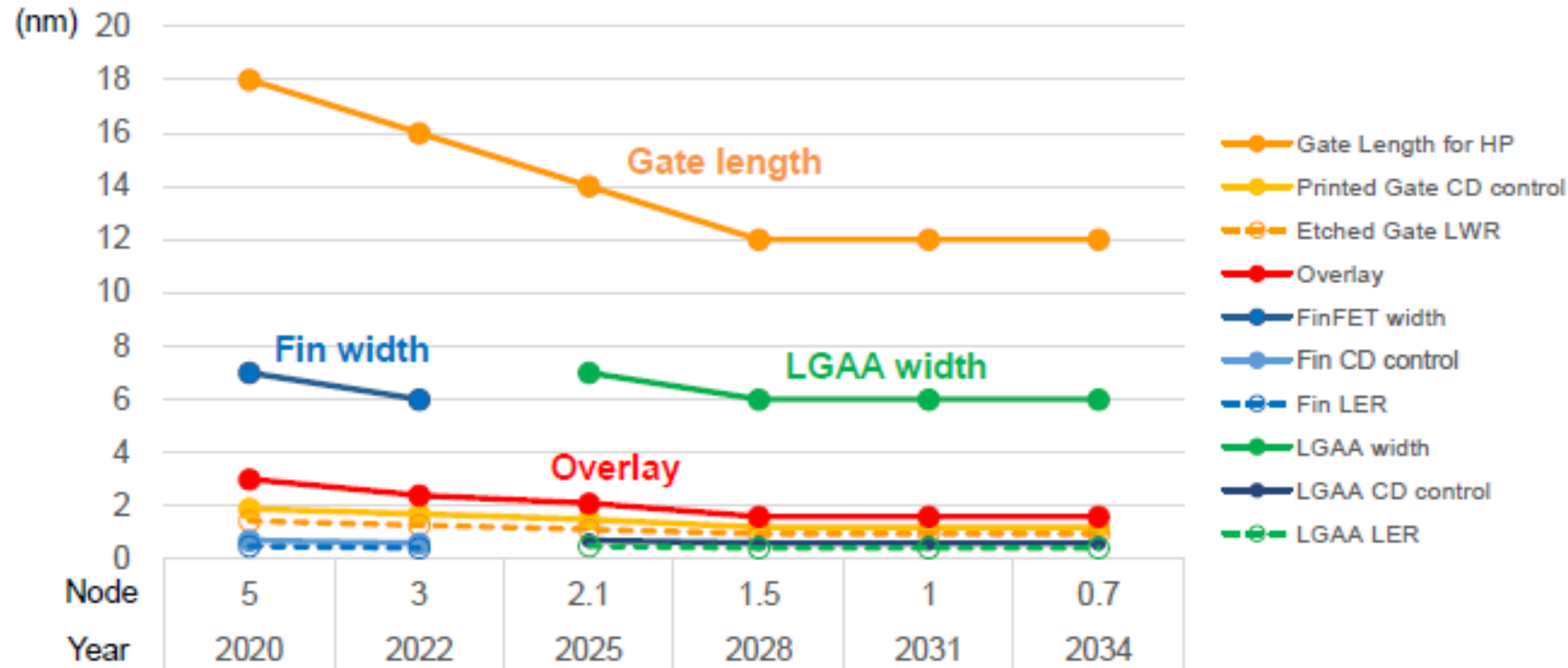
1.2 Device Trend and Metrology Needs (Memory)



**For NAND memory, 1D/2D pattern shrink is reaching its limit and structure is switching to 3D.
New process issues related to high aspect ratio pattern are arising.**

1.3 Required EPE Based on IRDS

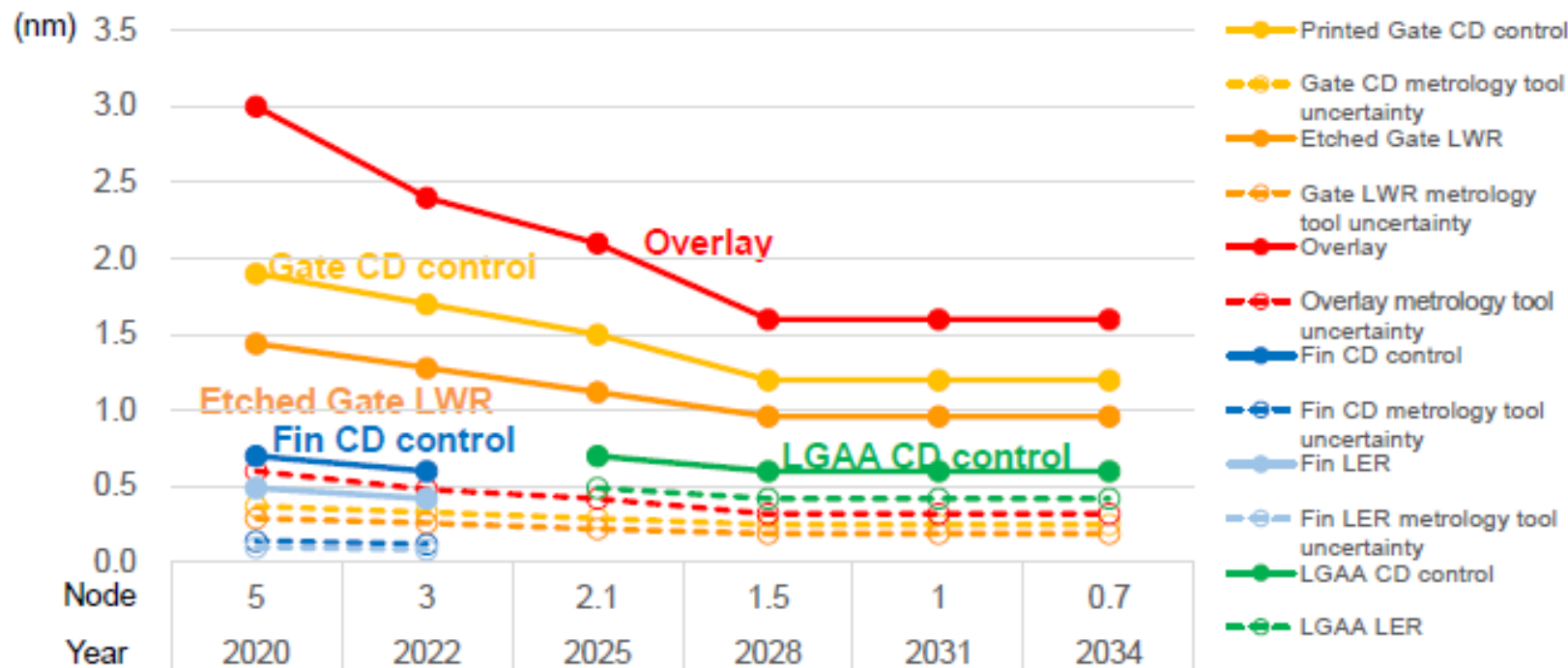
$$\sigma_{EPE}^2 = \sigma_{CD}^2 + \sigma_{Overlay}^2 + \sigma_{LCDU}^2$$



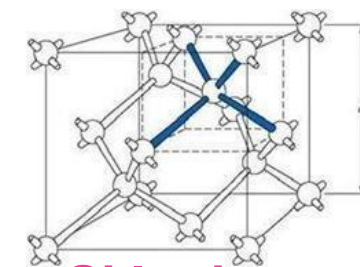
For Fin/LGAA patterns, sub-nanometer level of CD/LCDU control is required and its target is tighter than Overlay.

1.4 Required Precision for Metrology Tools

$$\sigma_{EPE}^2 = \sigma_{CD}^2 + \sigma_{Overlay}^2 + \sigma_{LCDU}^2$$



Generally, required metrology tool uncertainty is less than 20% of tolerance.
For Fin/LGAA patterns, less than 0.15nm of precision is necessary for metrology tools.



**Si lattice constant
~0.543 nm**

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2.1.1 Metrology Budget Analysis


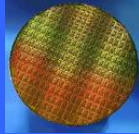
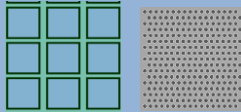
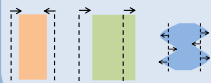
Process variation =

$$\sqrt{\sigma(\text{Process})^2 + \sigma(\text{metrology})^2}$$

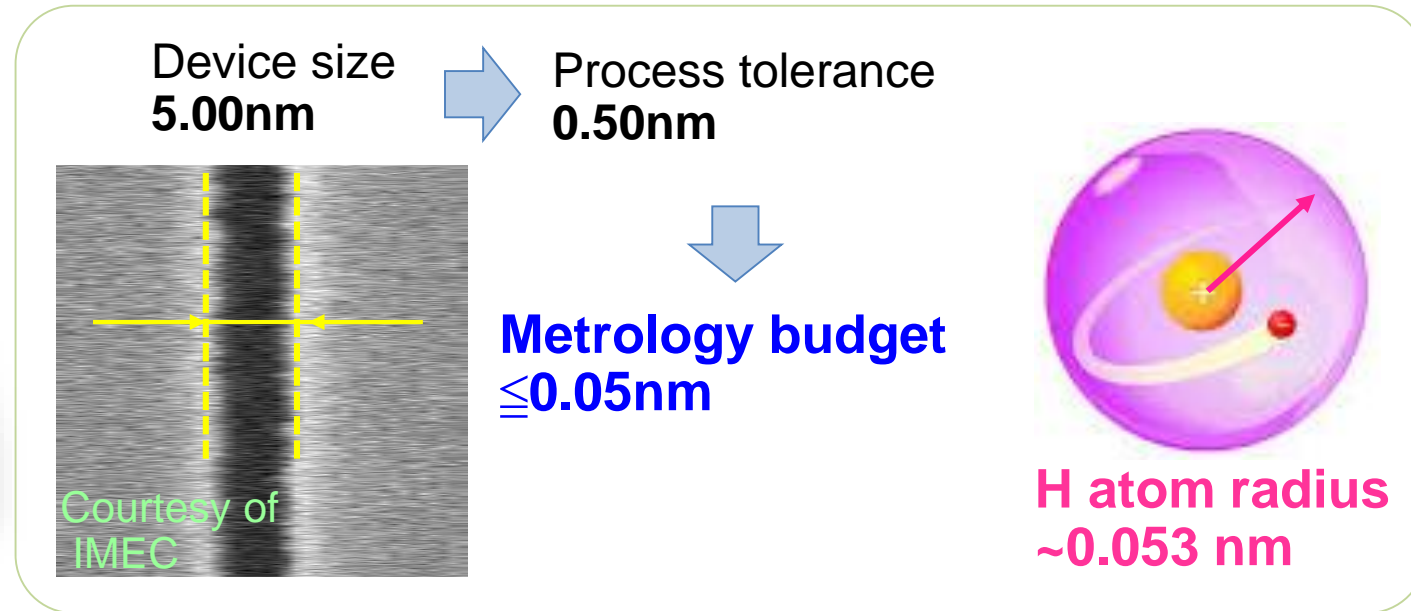
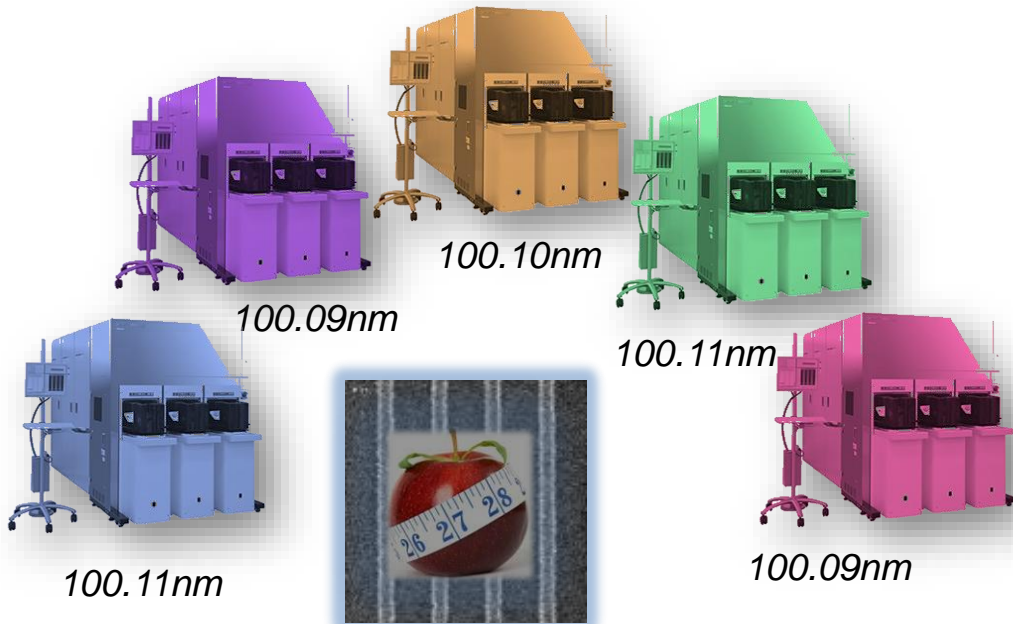
$\sigma(\text{metrology}) =$

$$\sqrt{\sigma(\text{mat.})^2 + \sigma(\text{uni.})^2 + \sigma(\text{rep.})^2}$$

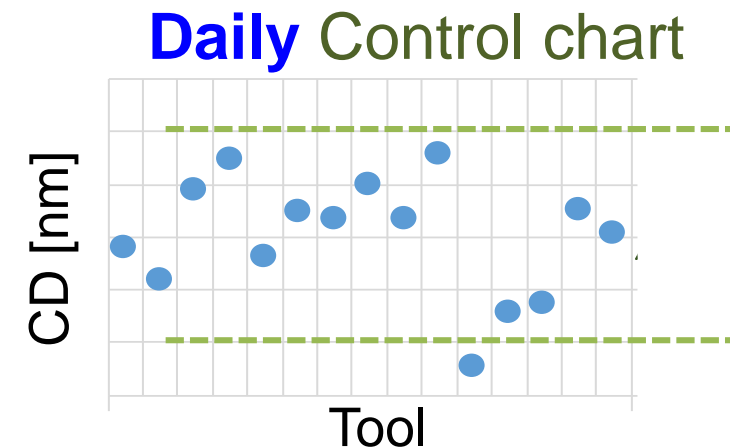
***Tool matching tops
metrology topic***

Process	Metrology factors
<p><i>Inter wafer</i></p> 	<p><i>Tool matching: 0.10 ~ 0.20nm</i></p>
<p><i>Intra wafer</i></p> 	<p><i>CD uniformity (global & local) : ~0.10 nm</i></p>
<p><i>Intra chip</i></p> 	<p><i>Repeatability <0.10 nm</i></p>
<p><i>Intra pattern</i></p> 	

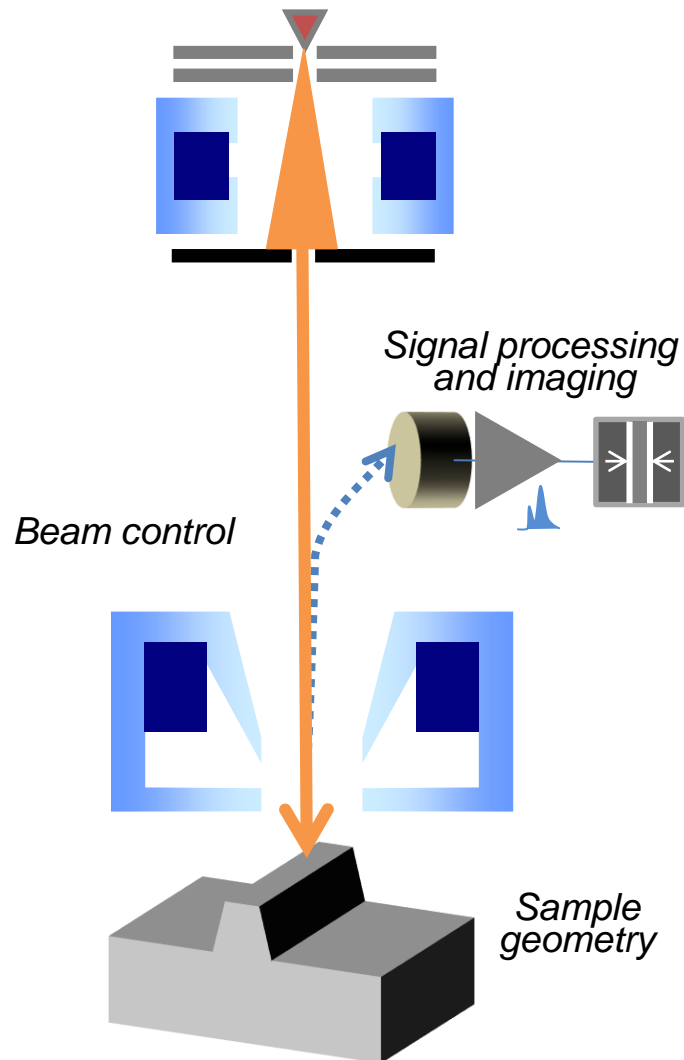
2.1.2 What is Atomic Tool Matching?



Productivity ($\sim 100\text{kWPM}$) for tool fleet consisting 10-100 prevalent CD-SEMs

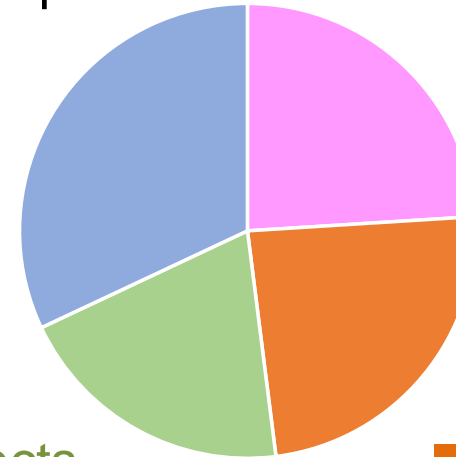


2.1.3 Budget Analysis of CD-SEM Matching



■ **QC monitor errors**
Measurement repeatability, Sample variation, etc.

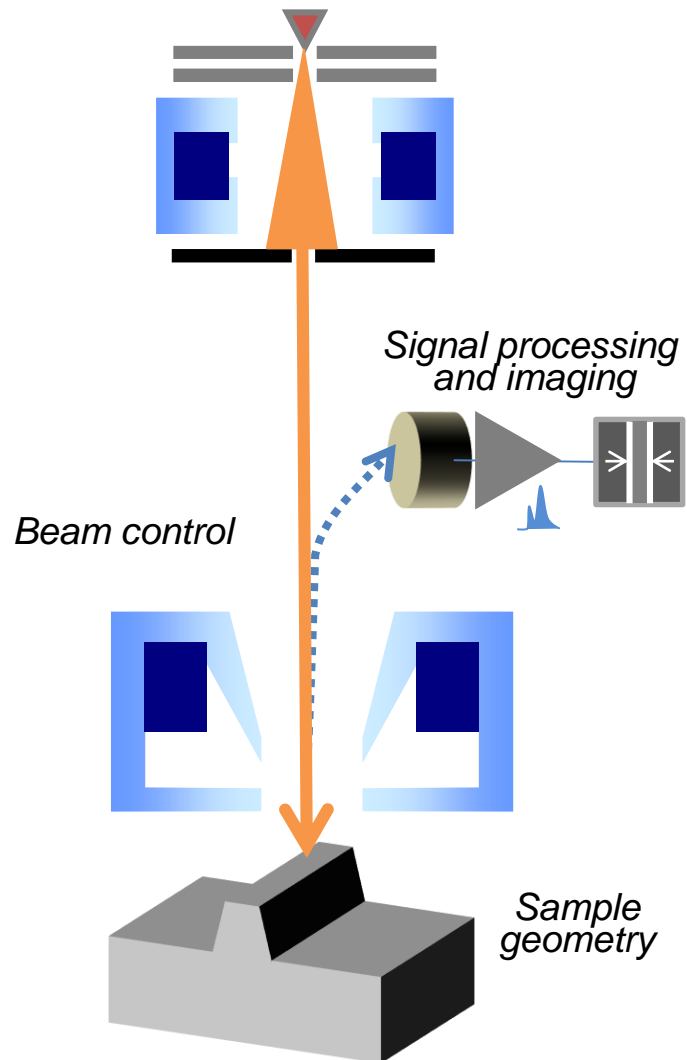
■ **Hardware variation**
Optics, Contamination, etc.



■ **Environment effects**
Electro-magnetic noise, Mechanical vibration, etc.

■ **Tool calibration errors**
Column/Beam alignment, Focus offset, etc.

2.1.4 Efforts for Matching Improvement



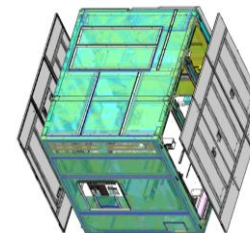
■ **QC monitor errors**
Measurement repeatability, Sample variation, etc.

■ **Detection / image level matching**

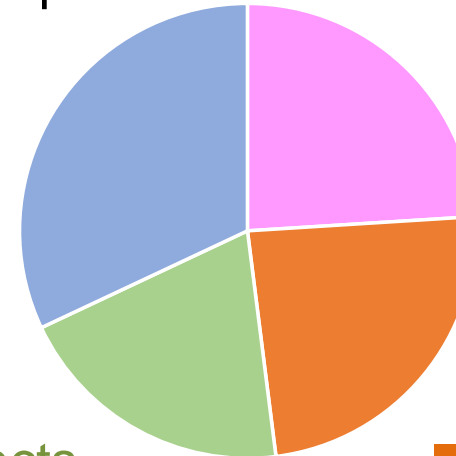
Detector Adjustment
Image level tuning

■ **Environment effects**
Electro-magnetic noise, Mechanical vibration, etc.

Noise Robustness with shield equipped



■ **Hardware variation**
Optics, Contamination, etc.

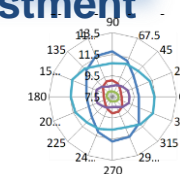
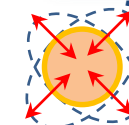


H/W uniformity

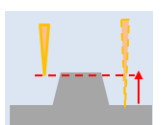
Precise column manufacturing

■ **Tool calibration errors**
Column/Beam alignment, Focus offset, etc.

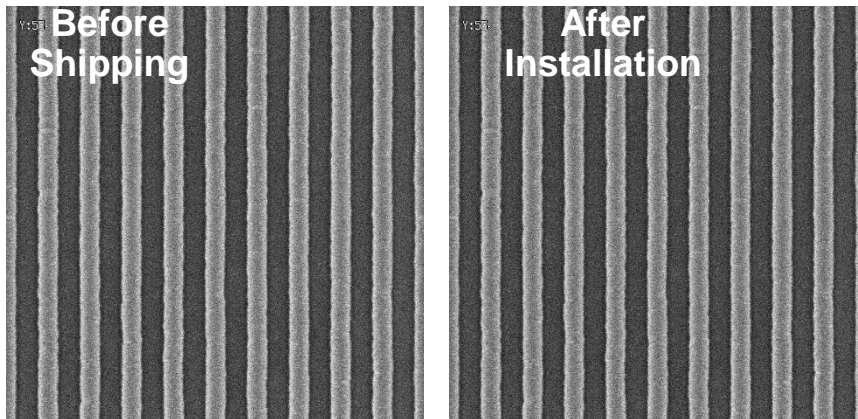
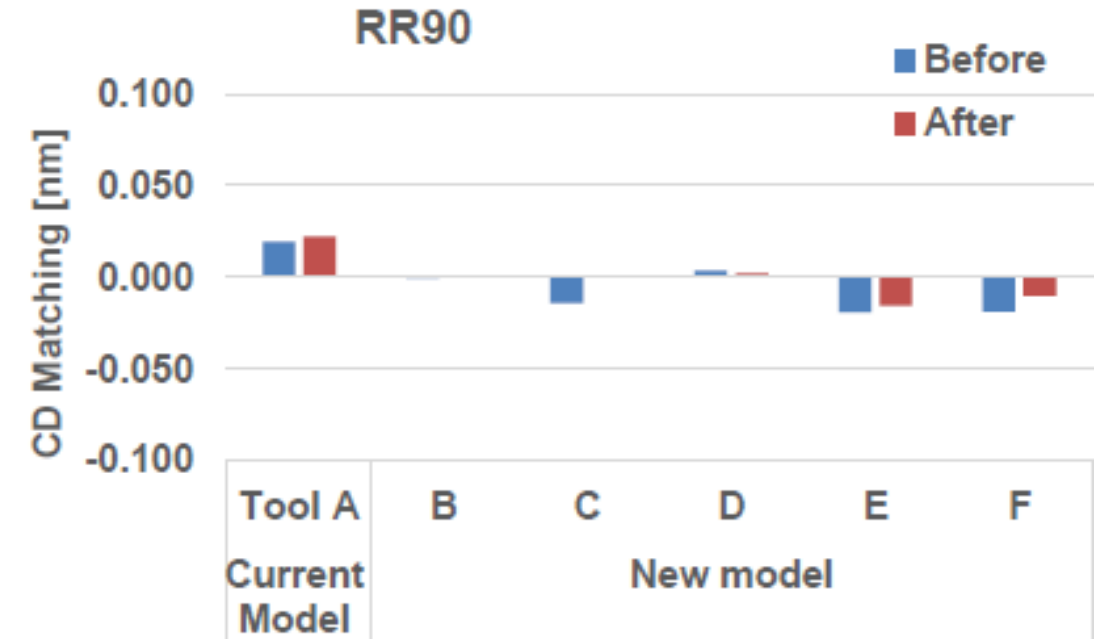
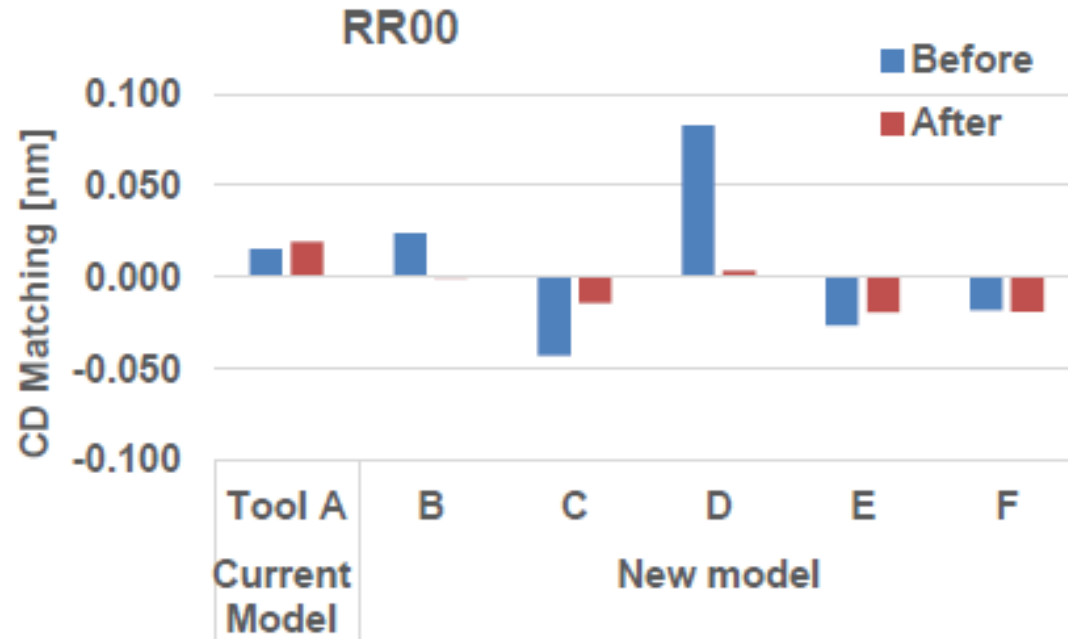
Beam Adjustment



Focus height adj.



2.1.5 Evaluation Data of Atomic Tool Matching



Hitachi standard wafer, HR mode, 800 V and 8pA

Atomic level of tool matching can be achieved.

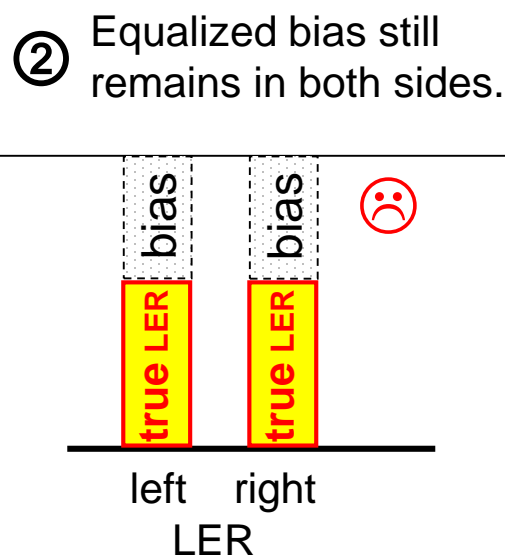
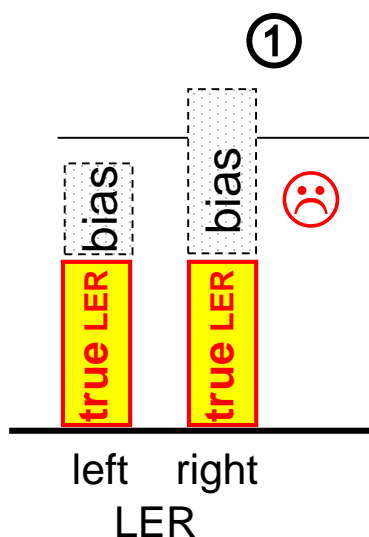
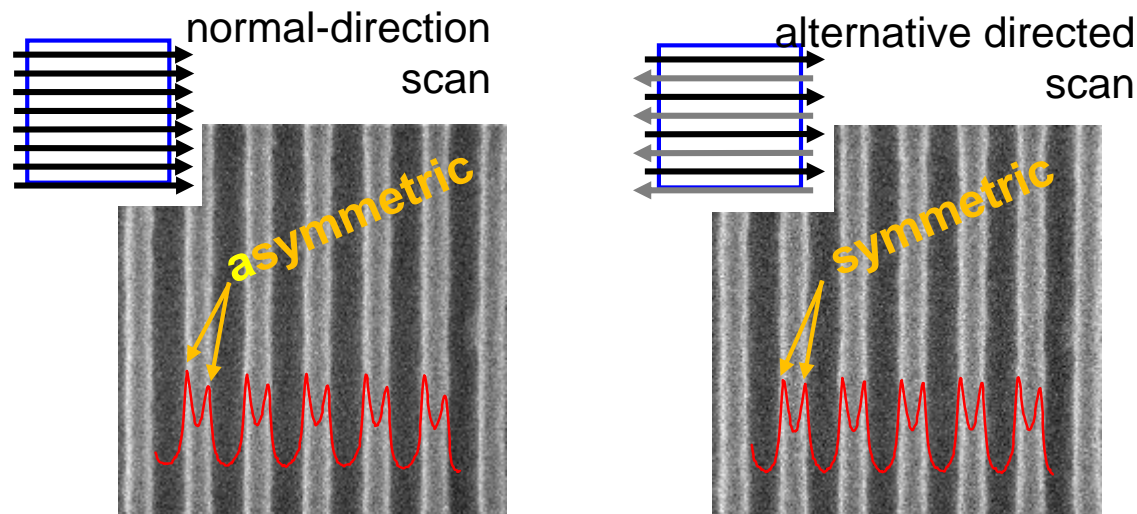


**H atom radius
~0.053 nm**

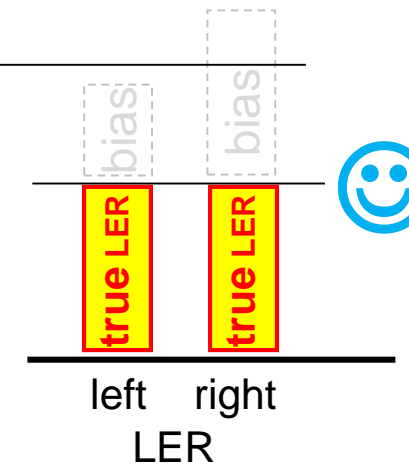
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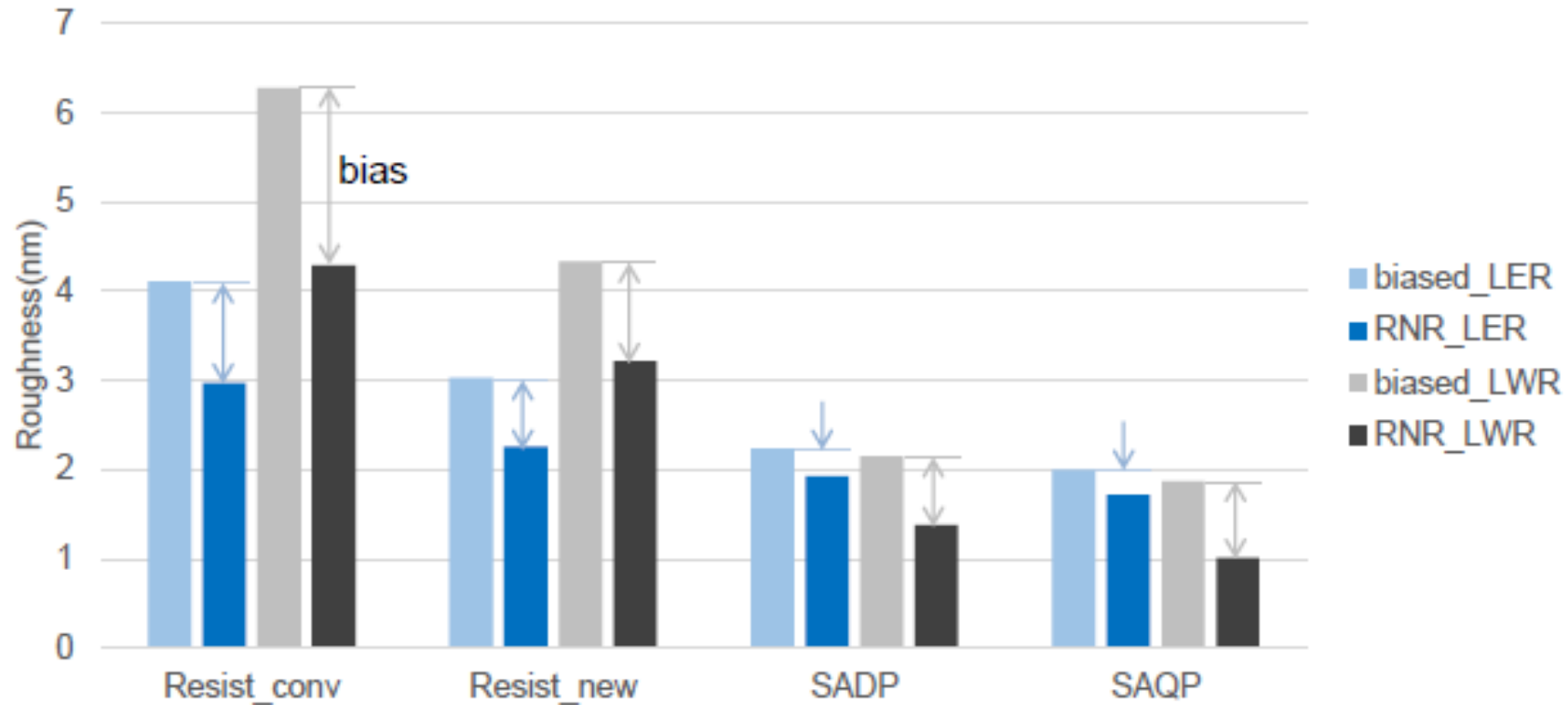
2.2.1 LCDU(Roughness) Measurement Issue



- ① Due to **asymmetric** SEM-signal, bias in right-LER is larger than left-LER.
- ② By the alternative scan, bias **remains equally** in right- and left-LERs.
- ③ To remove the bias, we calculate it **individually** in right- and left- LERs.

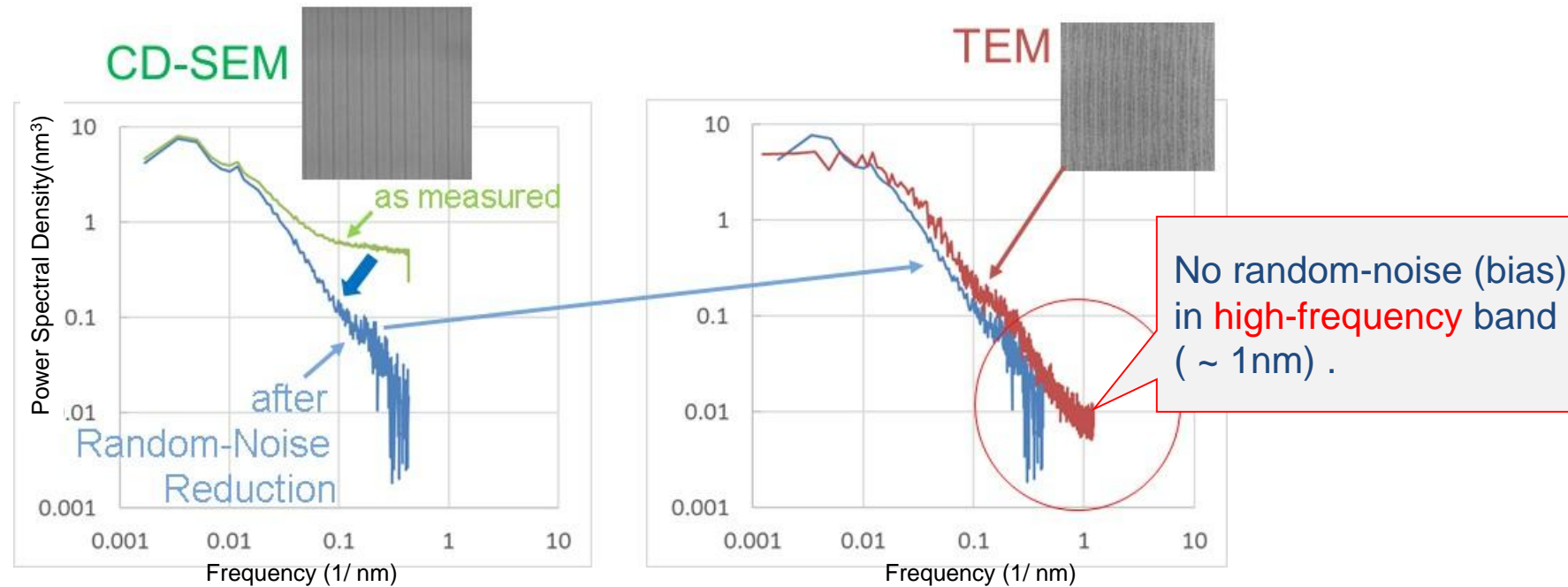


2.2.2 Bias Removal by Random Noise Reduction (RNR)



**Random noise contribution is large especially for resist patterns and it cannot be negligible.
Even after RNR, roughness is far beyond the target and eats up EPE budget.
Accurate roughness monitoring is important.**

2.2.3 Accuracy Verification of Roughness with RNR

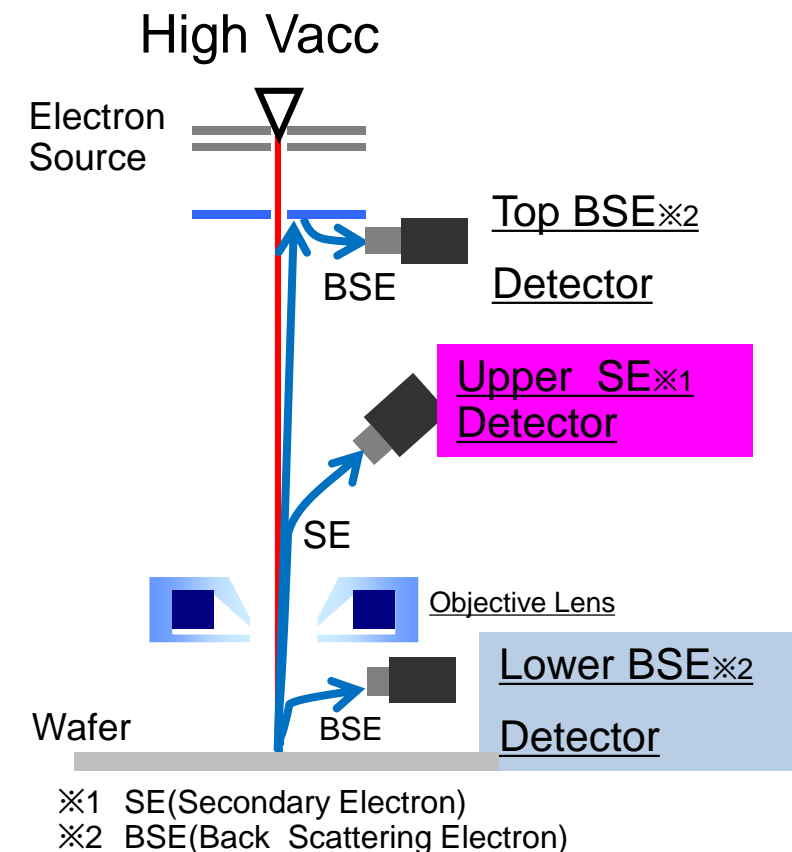
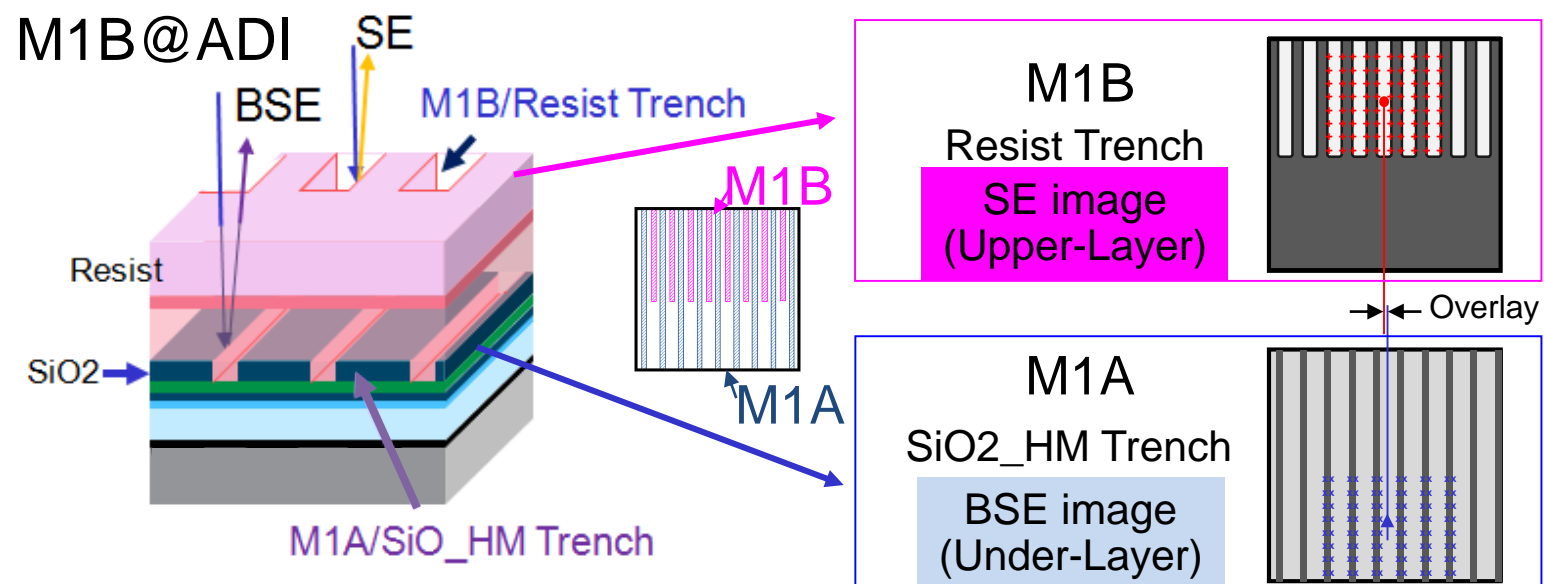


Accuracy of RNR function of CD-SEM was verified by Planar-TEM. The reference PSD of Planar-TEM has no random noise and has good agreement with PSD of CD-SEM after RNR.

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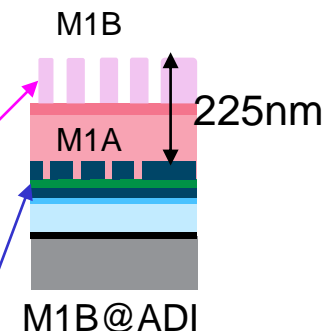
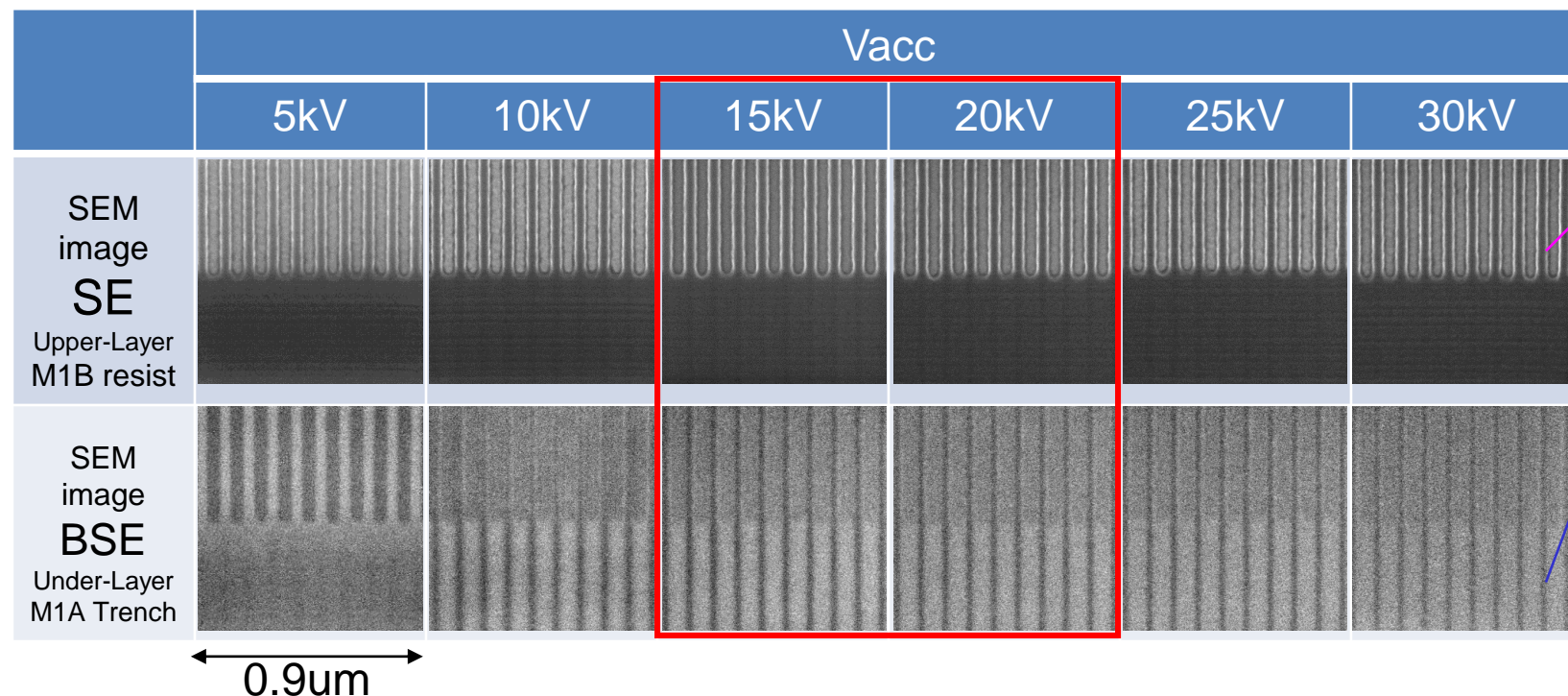
3.1.1 Overlay Measurement by HV-SEM



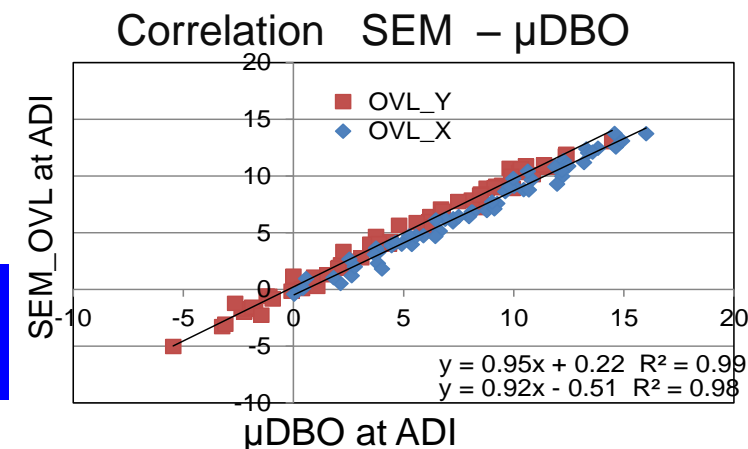
**SE is used to observe the surface while BSE is used to observe material contrast of the lower layer.
Thus, overlay between upper and under layer can be measured.**

3.1.2 Overlay by HV-SEM (M1B-M1A)

Pitch 96nm, Upper/M1B_Resist 48nmTrench, Lower/M1A_HM 24nmTrench

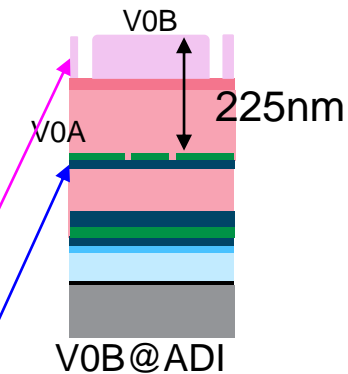
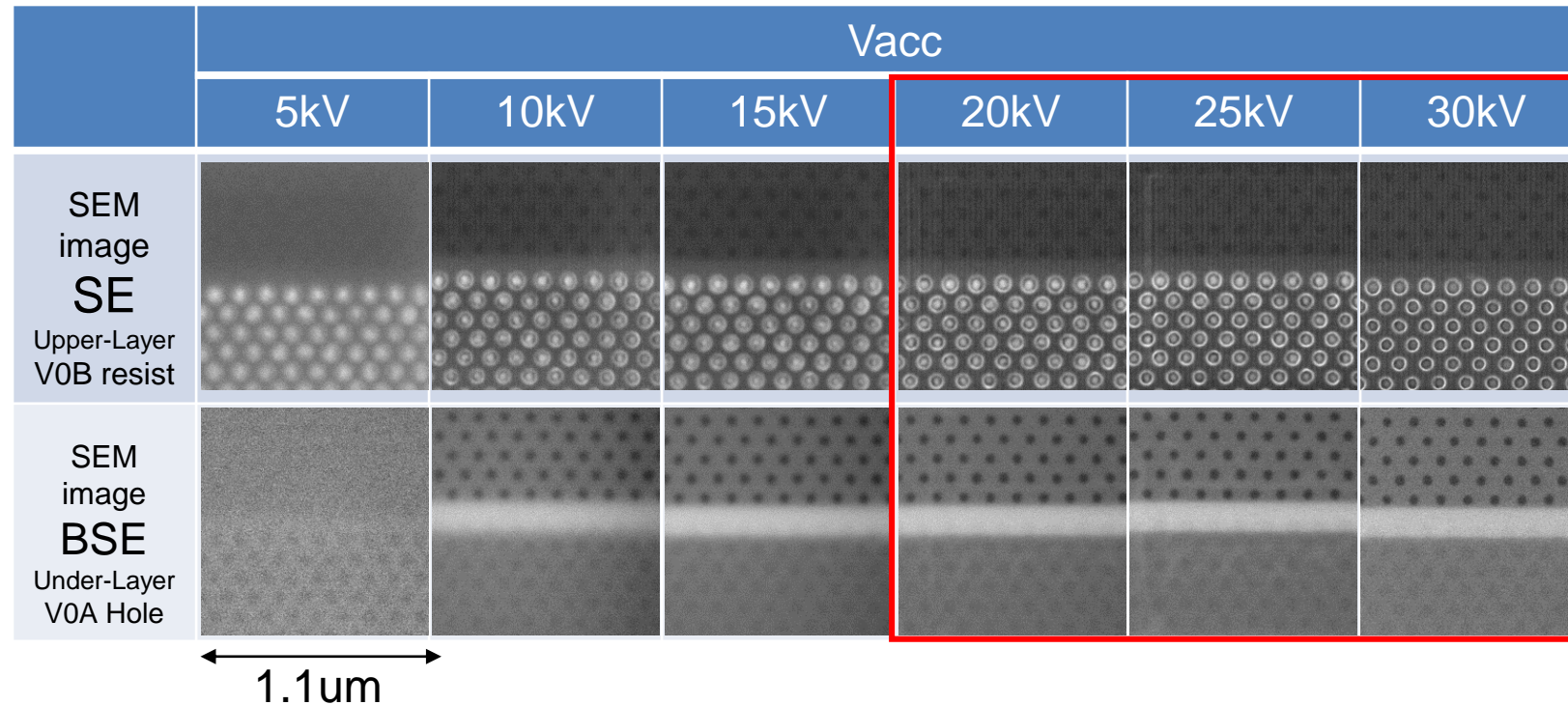


**Accelerated Voltage 15kV was chosen based on image contrast.
SEM OVL results at ADI show good correlation to Optical OVL.**

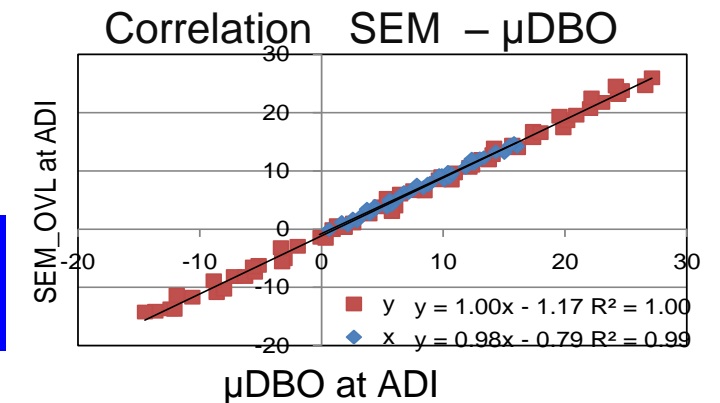


3.1.3 Overlay by HV-SEM (V0B-V0A)

Pitch 64nm, Upper/V0B_Resist 40nm Hole, Lower/V0A_HM 40nm Hole

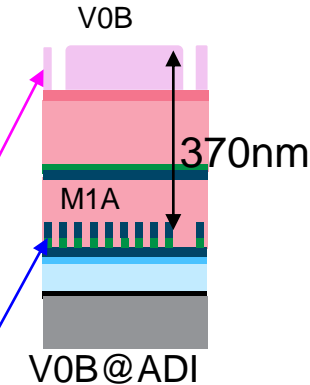
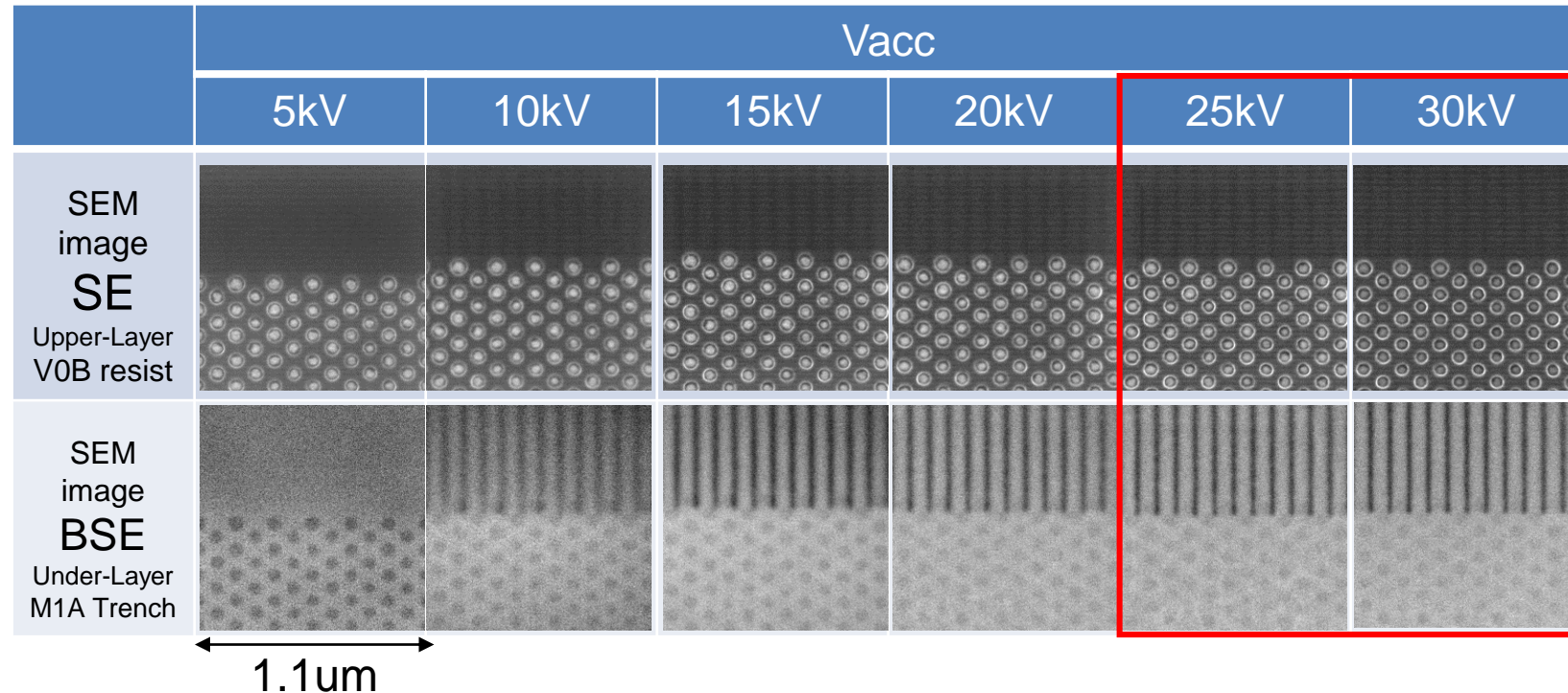


**Accelerated Voltage 25kV was chosen based on image contrast.
SEM OVL results at ADI show good correlation to Optical OVL.**

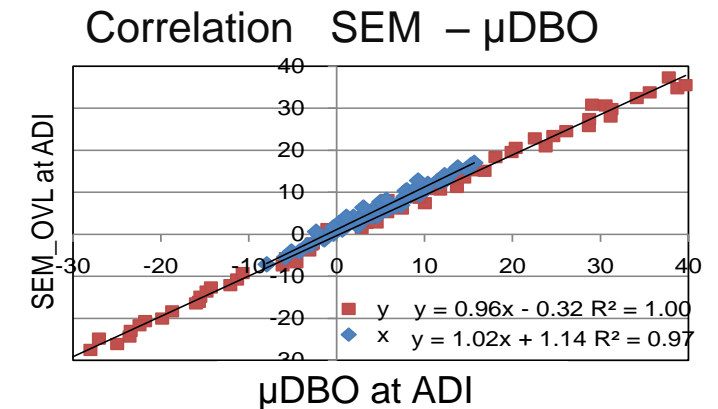


3.1.4 Overlay by HV-SEM (V0B-M1A)

Pitch 96nm, Upper/V0B_Resist 40nm Hole, Lower/M1A_HM 24nm Trench



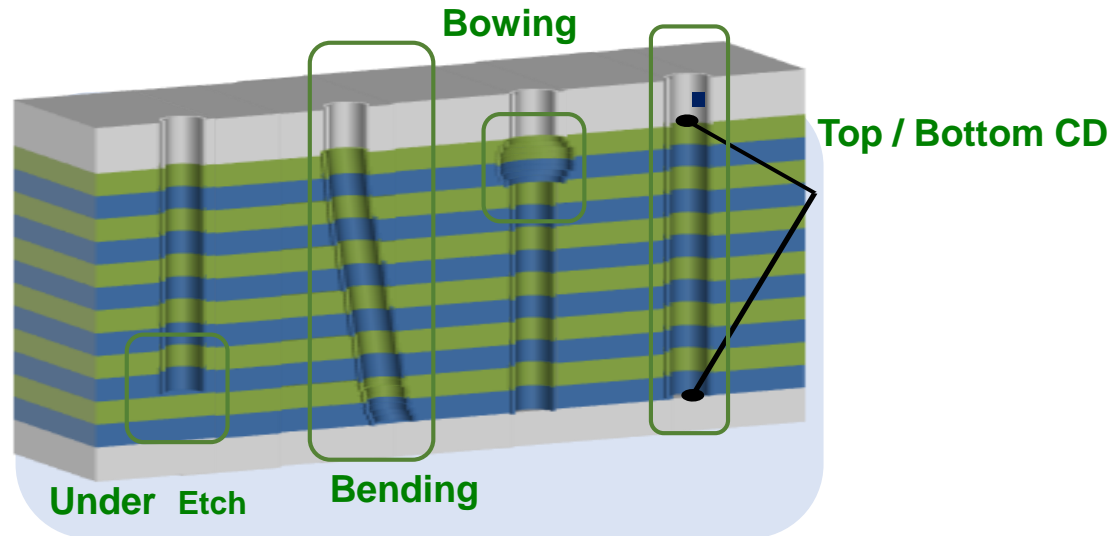
**Accelerated Voltage 30kV was chosen based on image contrast.
SEM OVL results at ADI show good correlation to Optical OVL.**



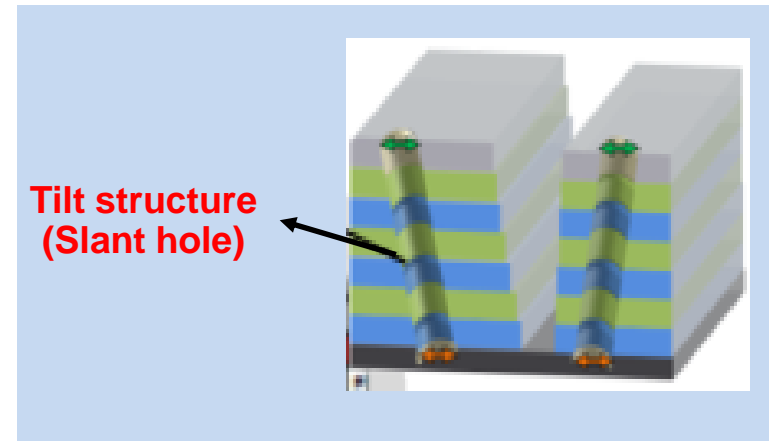
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3.2.1 3D NAND Process Issues



Today's topic



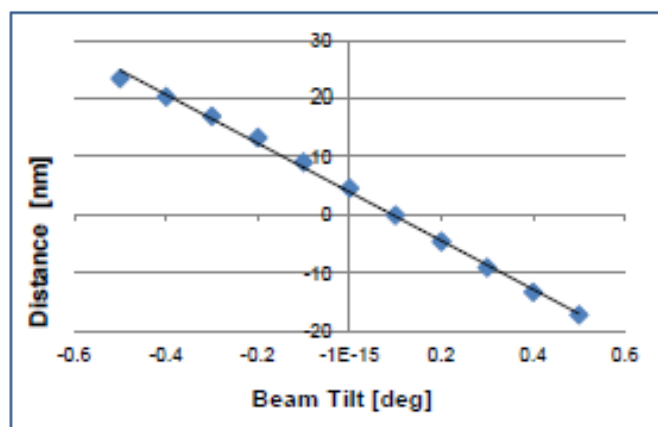
3D NAND suffered from several process issues such as

- ✓ Under Etch
- ✓ Bending
- ✓ Bowing
- ✓ Top/Bottom CD difference
- ✓ Slant

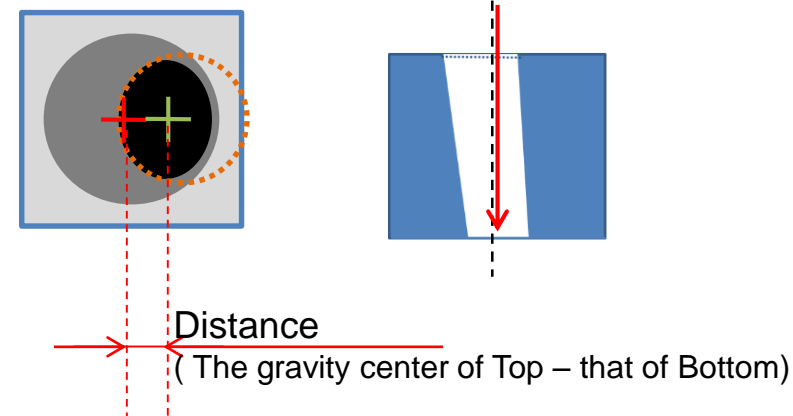
3.2.2 Auto Electron Beam Tilt Function

[Step-0]

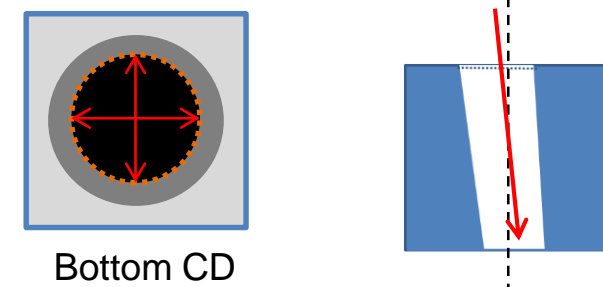
Calculate the correlation between beam tilt and overlay.



[Step-1] Measure overlay with no tilt.



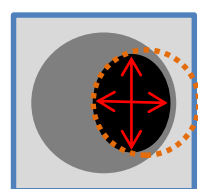
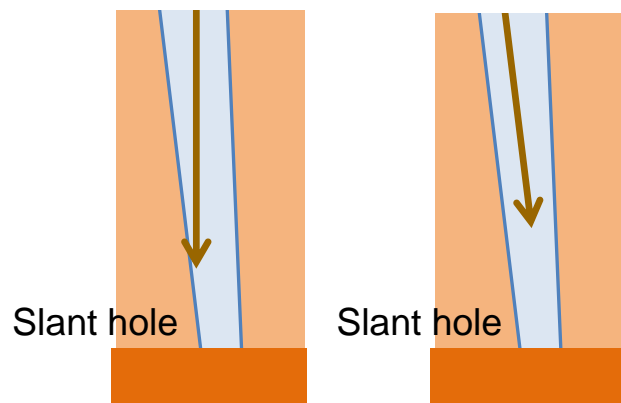
[Step-2] Measure Bottom CD with beam tilt matched with the hole (trench) slope.



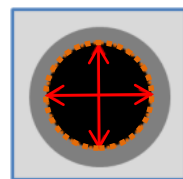
Auto beam tilt function is for accurate bottom CD measurement when hole slant exists.

3.2.3 BCD Monitor with Auto Electron Beam Tilt Function

【Before beam tilt】 【After beam tilt】



Not real BCD

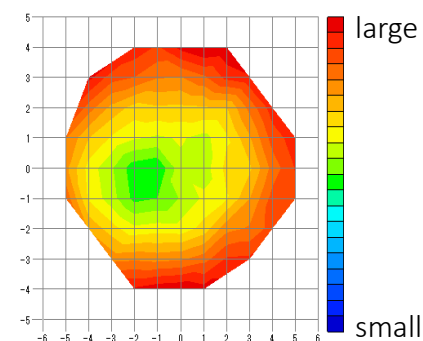


Real BCD

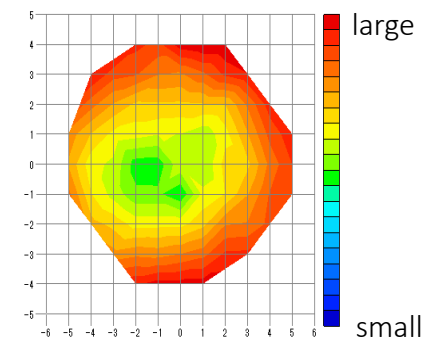
For slant hole

Real BCD is available after beam tilt

【Before beam tilt】

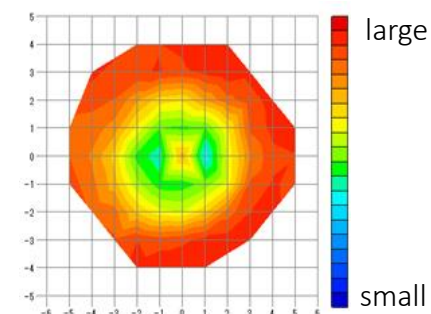


【After beam tilt】

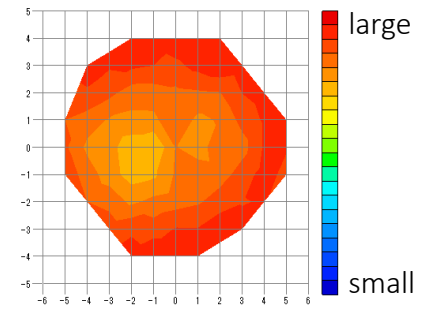


Top CD does not change

【Before beam tilt】



【After beam tilt】



Real BCD measurement are demonstrated

After Beam tilt measurement, CDU of Top CD does not change while BCD becomes larger . This means Real Bottom CD can be measured.

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3.3.1 EUV Lithography Challenges

Materials requirements

- Today's microprocessors have >1B transistors
- If every VIA has to work for a die to yield, for a 99% probability of the die to yield (Y), the probability of a VIA failure (f) is

$$f \sim (1-Y)/Z$$

If number of VIAs $Z = 10^{10}$

$$f \sim E^{-12}$$

The Failure rate per VIA must be on the order of 1 part per Trillion!!!

We must control variability and stochastics
Resolution is not sufficient

Slide by Anna Lio

Britt Turkot/ Intel

2017 International Workshop on EUV Lithography, 10 June, Berkeley, California

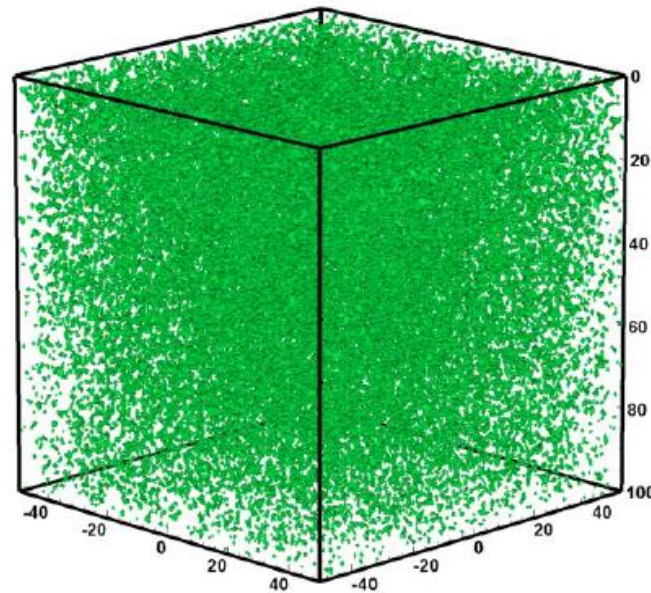


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It is necessary to monitor 1E12 vias!!

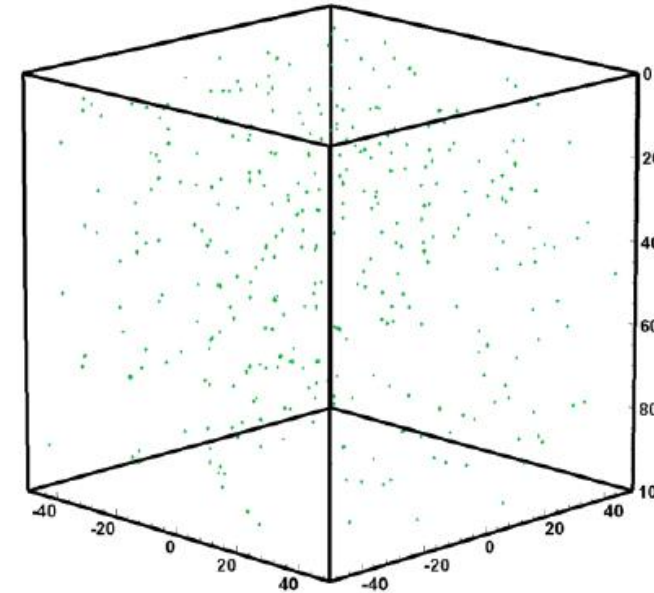
3.3.2 EUV Lithography Challenges (Cont.)

Fig. 1 - A comparison of photon counting at ArF and EUV in a volume when absorbance coefficient and dose are constant across wavelength. About 14X fewer photons are absorbed at EUV vs. ArF.



ArF, $10 \text{ mJ} / \text{cm}^2$, $\alpha = 4 / \mu\text{m}$

$n_{\text{absorbed}} = 366528$, $E_{\text{absorbed}} = 2354 \text{ keV}$



EUV, $10 \text{ mJ} / \text{cm}^2$, $\alpha = 4 / \mu\text{m}$

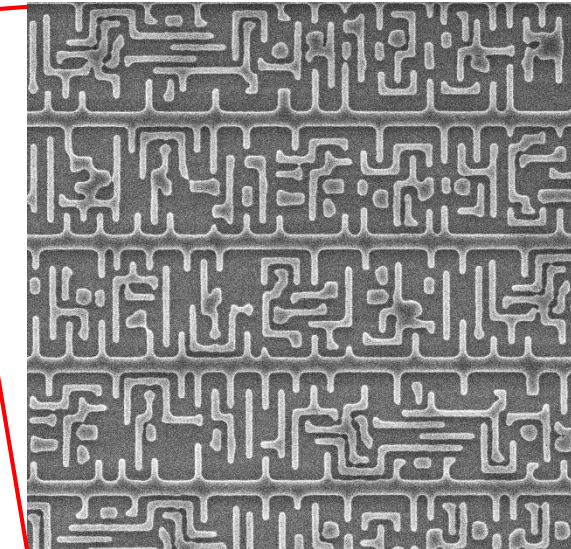
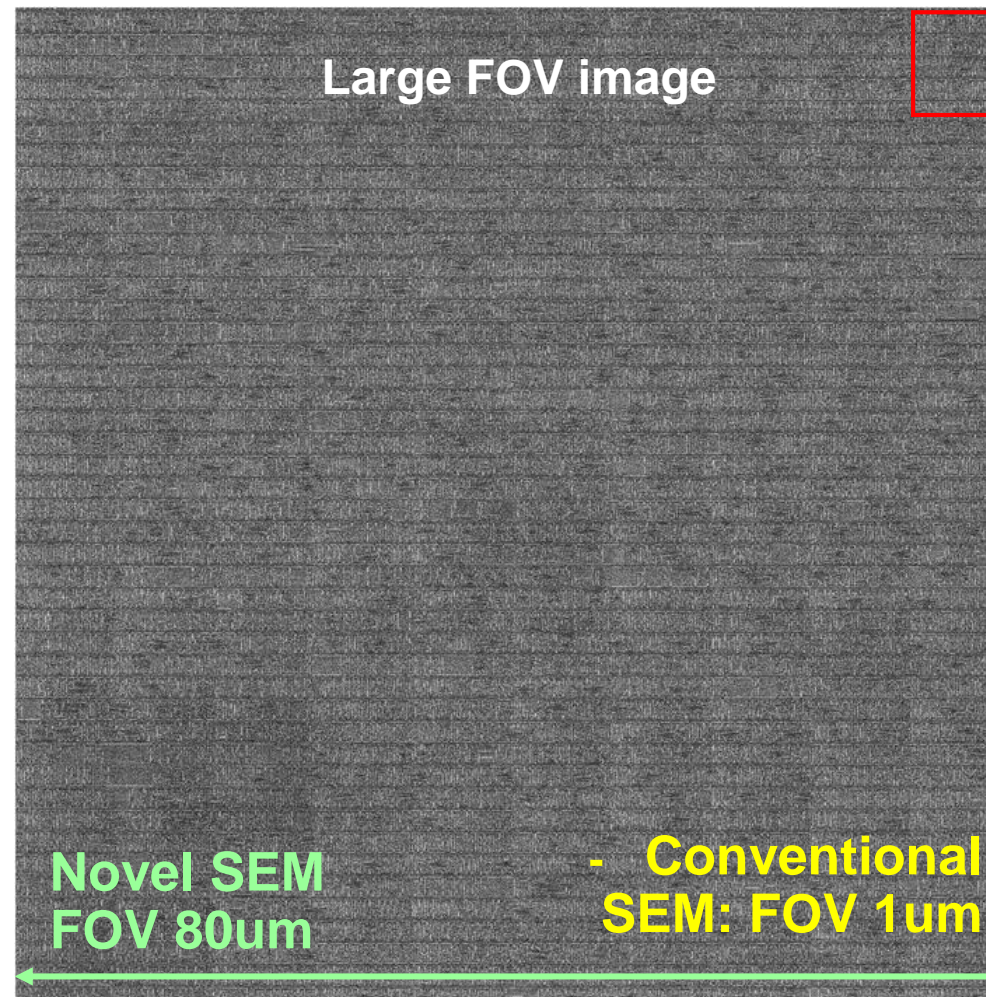
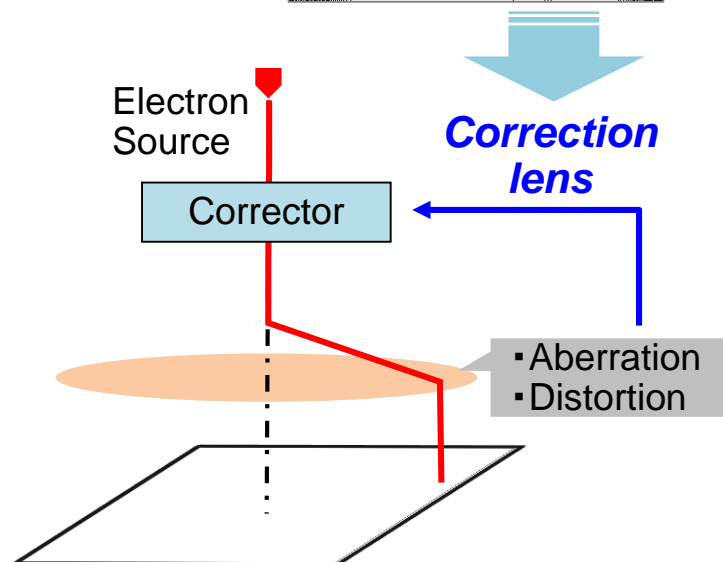
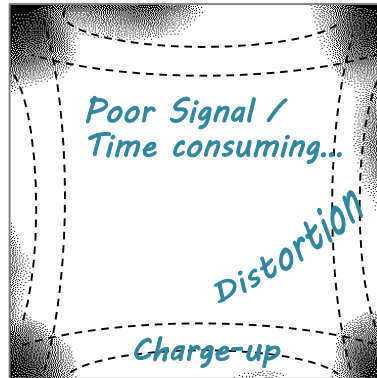
$n_{\text{absorbed}} = 25328$, $E_{\text{absorbed}} = 2326 \text{ keV}$

Problematic variations—also known as stochastic effects

--- by Mark Lapedus (Semiconductor Engineering)

3.3.3 Mass Measurement System with AI-SEM

Schematic of
Large FOV
imaging issues



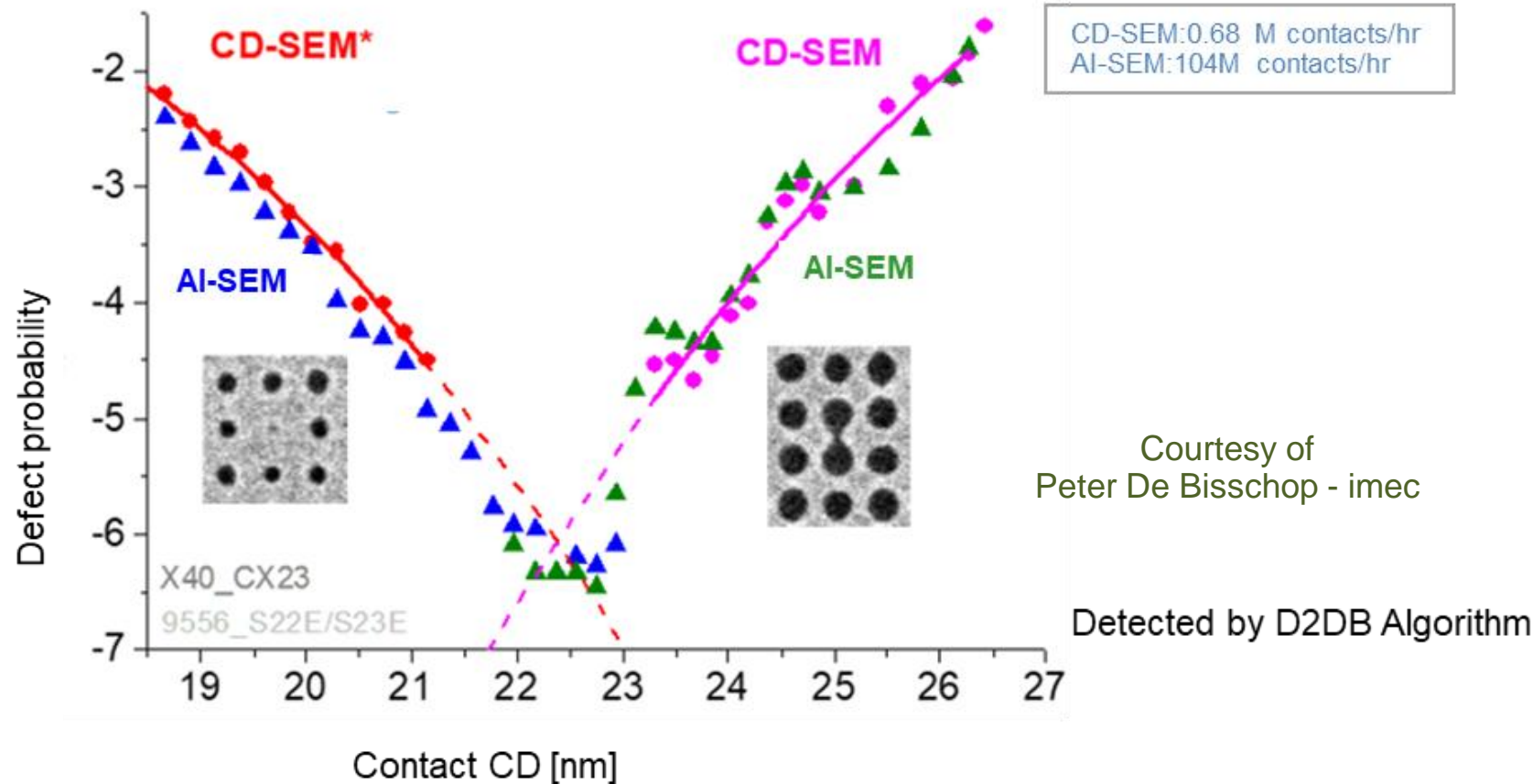
<LFOV Uniformity>

- Resolution < 0.2nm
- Distortion < 0.02%

Imaging time: 15sec
@ 2nm/pixel

Extremely uniform large FOV imaging by aberration/distortion correction technology

3.3.4 Mass Measurement System with AI-SEM



Courtesy of
Peter De Bisschop - imec

Proc. SPIE Vol 10957, 10957-10 (2019)

Area Inspection SEM results compatible to conventional SEM, with higher sensitivity and throughput , applicable to stochastic defect evaluation

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- ❑ EPE is the critical parameter and it consists of 3 components, CD error, overlay error and LCDU such as line edge roughness. For Fin/LGAA patterns, less than 0.15nm of precision is necessary for metrology tools.
- ❑ High precision measurement with atomic level of tool to tool matching can be realized by HW/ Calibration/ Environment /QC monitor improvement.
- ❑ Accurate LCDU can be measured by RNR function.
- ❑ Overlay with buried patterns can be measured by HV-SEM and correlation with optical overlay tool was verified.
- ❑ Auto electron beam tilt function is effective for channel hole slant monitor for 3D NAND.
- ❑ Stochastic defect monitor is critical for EUV process and mass measurement with AI-SEM can be a solution.

END



Electron Beam Metrology for Advanced Patterning

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