Statistical Significance of STEM based Metrology on Advanced 3D Transistor Structures

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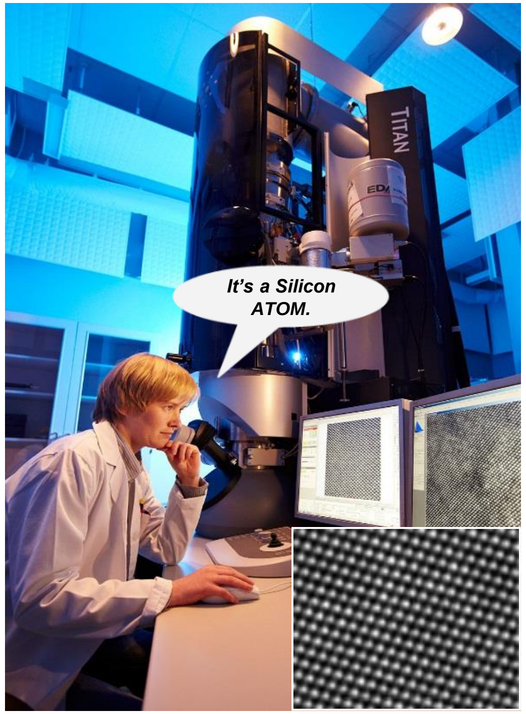
Introduction to STEM-based metrology

Manual TEM microscopy



- Slow, manual, not reproducible
- Operator dependent
- Poor statistics
- ***STEM metrology difficult***

Automated TEM microscopy & metrology

Automated full wafer sample prep

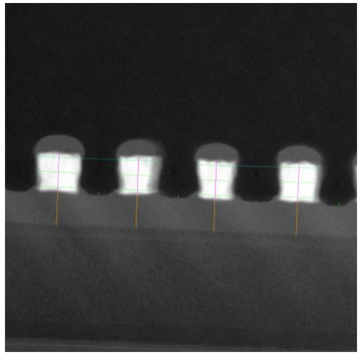
Automated STEM imaging & metrology

- Relatively fast, fully automated & reproducible
- Automated STEM acquisition & automated metrology
- **> 1000 metrology data per hour**
- ***Statistically relevant STEM metrology is possible***

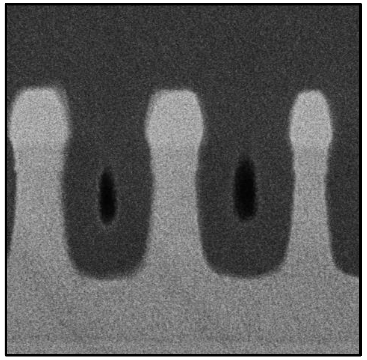
Outline: Why **statistics** do matter in STEM-based metrology

Four examples of statistics and automated STEM acquisition & metrology:

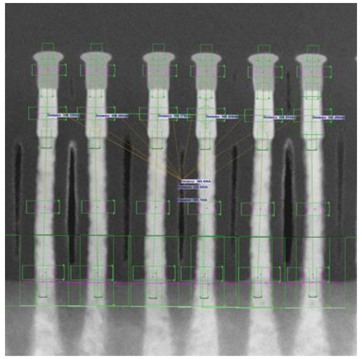
- 1. TEM Microscope’s calibration by pitch measurements



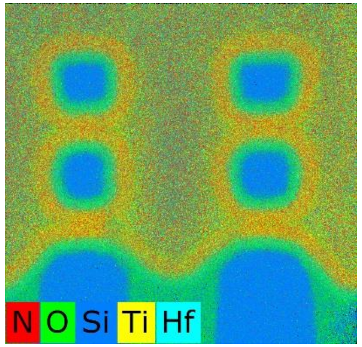
- 2. Low-K dielectric structure metrology

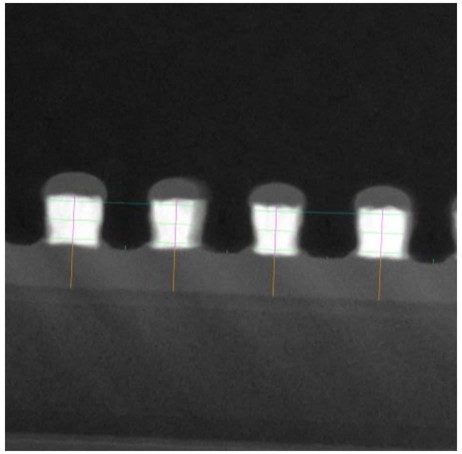


- 3. Pitch walk analysis of complex FinFet transistor structure



- 4. Determination of small process variation in silicon nanowires





STEM METROLOGY EXAMPLE # 1

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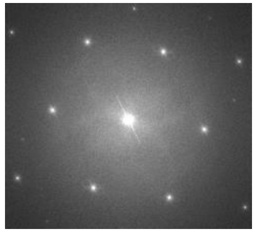
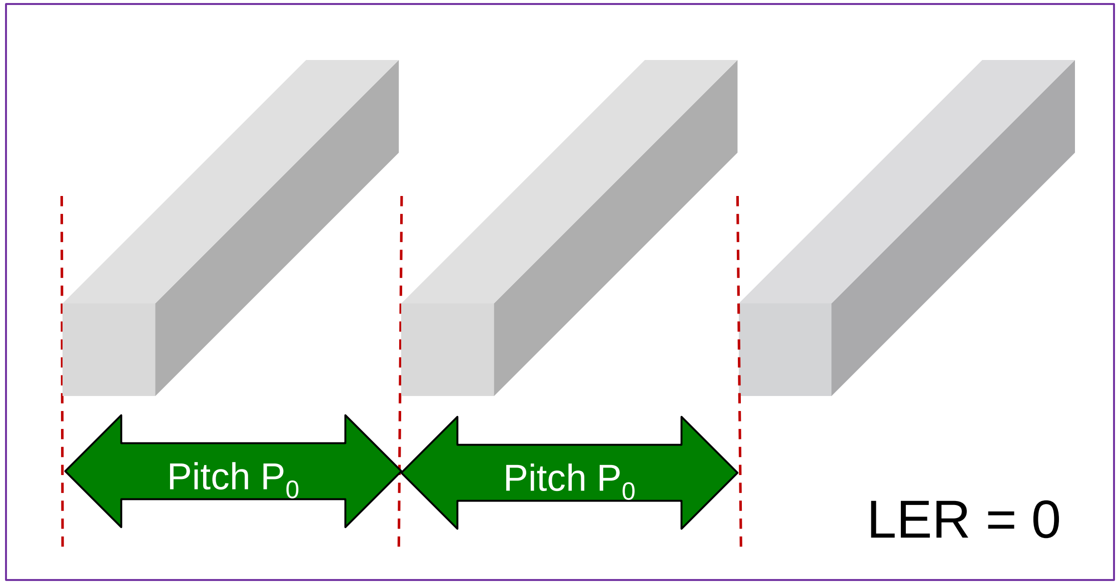
How **precise** can we determine the STEM microscope's **calibration**?

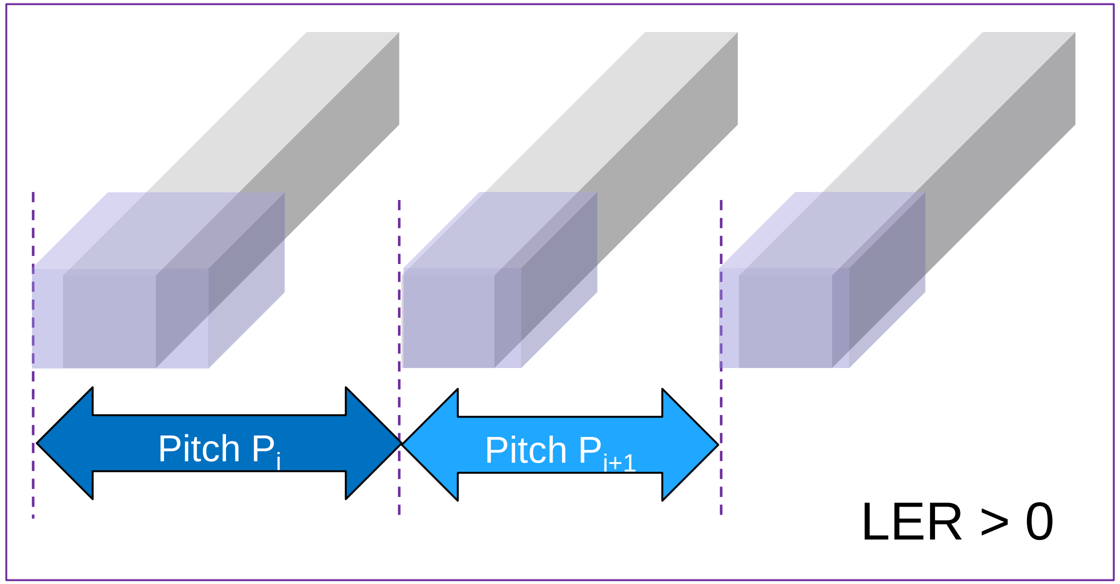
Example # 1

- Typical automated STEM metrology precision is better than ~0.3nm, 3σ --how about accuracy?
- Transmission Microscopes are calibrated using the Silicon lattice as internal standard
  - Calibration and image distortion corrections: proprietary FFT and auto-correlation routines…



- But how can a TEM end-user verify the microscope calibration and its accuracy?
  - All CMOS device dimensions vary and , a priori , are unknown. ***Exception : Lithography patterning pitch***
  - Practical complication with STEM based Pitch measurements: Line Edge Roughness (**LER**):

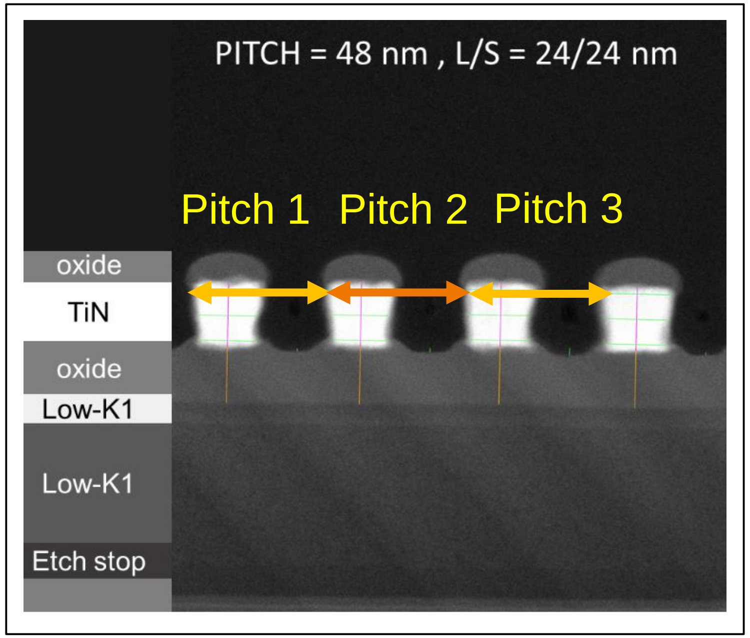




How **precise** can we determine the STEM microscope's **calibration**?

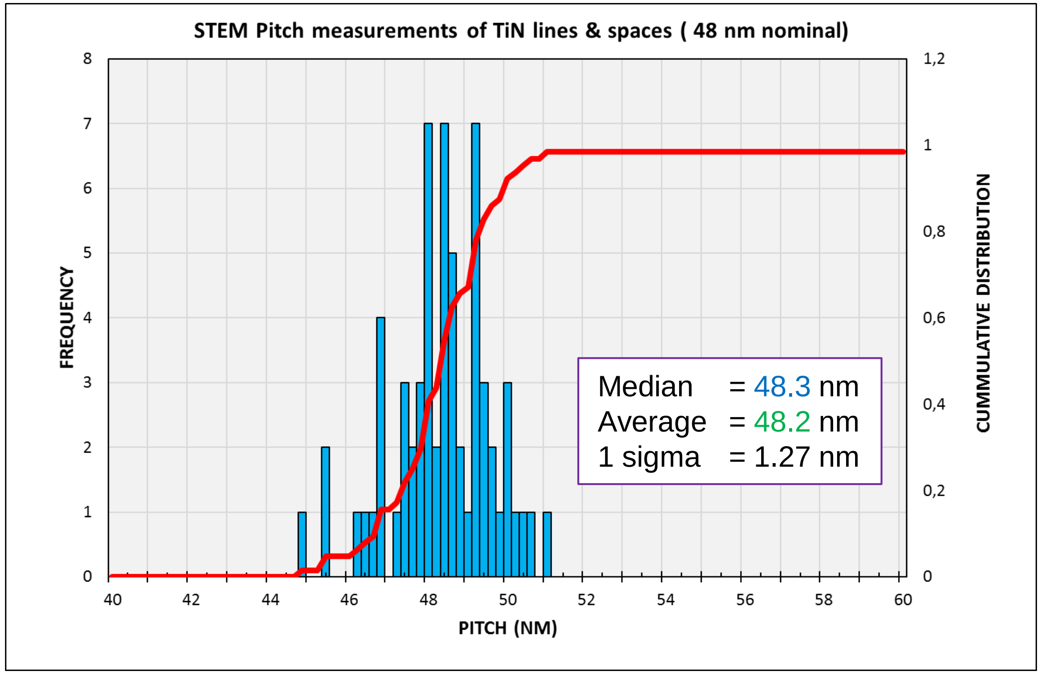
Example # 1

- Pitch measurements on patterned Metal 1 TiN Hard Mask structures (Pitch $_{nominal}$ = 48.0 nm)



55 pitches from one lamella

Variation in pitch due mostly to line edge roughness



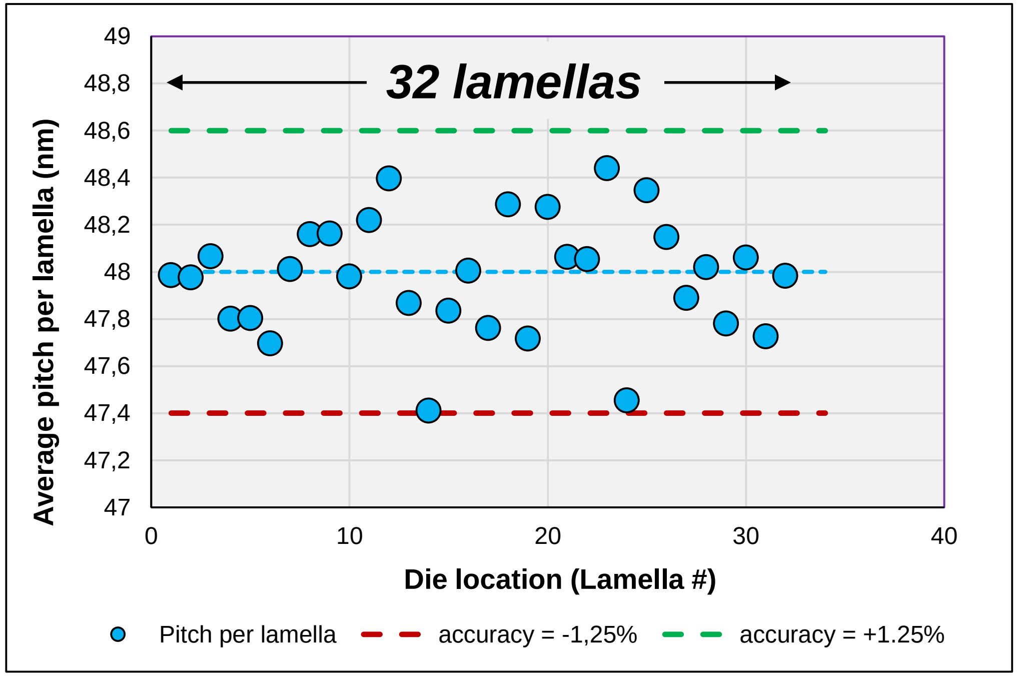
- **N = 55** (features per lamella)
- Average pitch = 48.22 nm, 1σ = 1.27 nm
- Precision of estimated average pitch for one lamella = σ/√N = **0.17** nm (1 standard error)

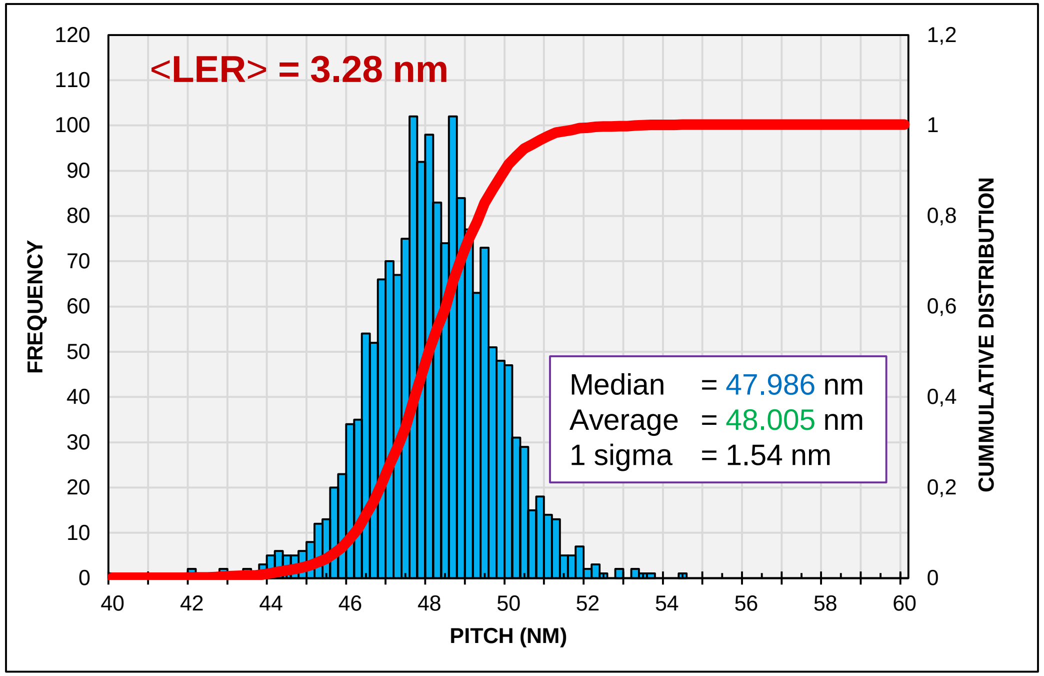
Calibration Accuracy cannot be estimated better than ~ 0.7 % *(95% confidence interval)*

How **precise** can we determine the STEM microscope's **calibration**?

Example # 1

- Pitch measurements on patterned Metal 1 TiN Hard Mask structures (Pitch $_{nominal}$ = 48.0 nm)



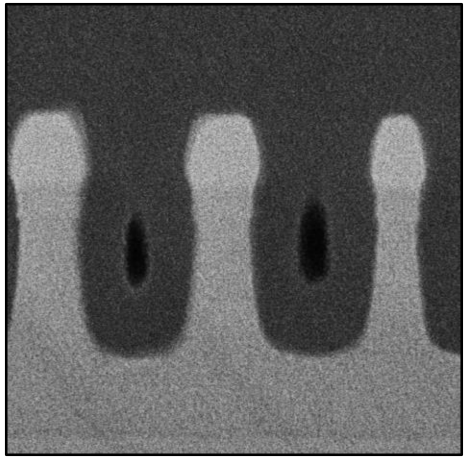


- **N = 55** (features per lamella)
- Precision of estimated pitches = **0.24** nm (1σ)

Accuracy cannot be estimated better than 1%

- **N = 1760** (32 lamellas x 55 features)
- Precision of estimated pitch = **0.036** nm (1σ)

Accuracy can be estimated to within < 0.15%



STEM METROLOGY EXAMPLE # 2

STEM based metrology to evaluate a M1 dielectric etch process

Example # 2

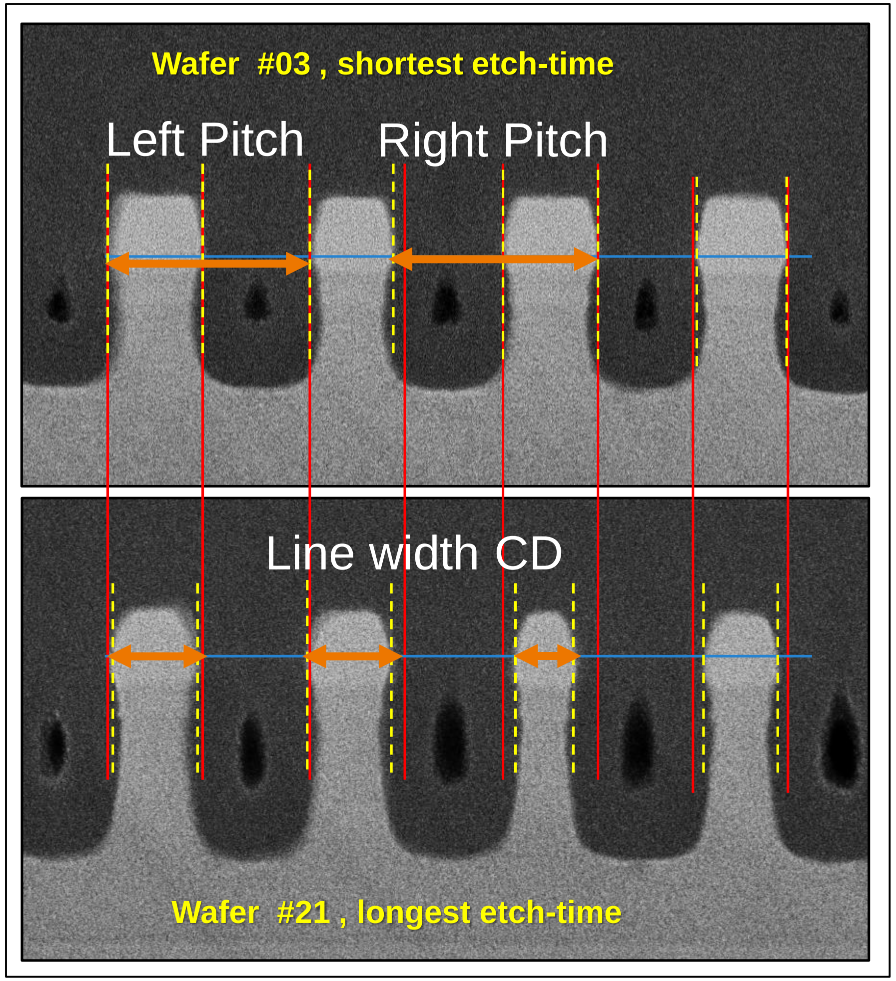
- EUV patterned Low-K Dielectric(Pitch $_{nominal}$ = 48.0 nm)

Left and right pitch measurements to determine Line Edge Roughness and to confirm microscope accuracy

$$LER = 3\sigma \text{ Distribution } (Pitch_{i,i+1}) / \sqrt{2}$$

Oxide CD to determine Line Width Roughness

$$LWR = 3\sigma \text{ Distribution } (CD_i)$$



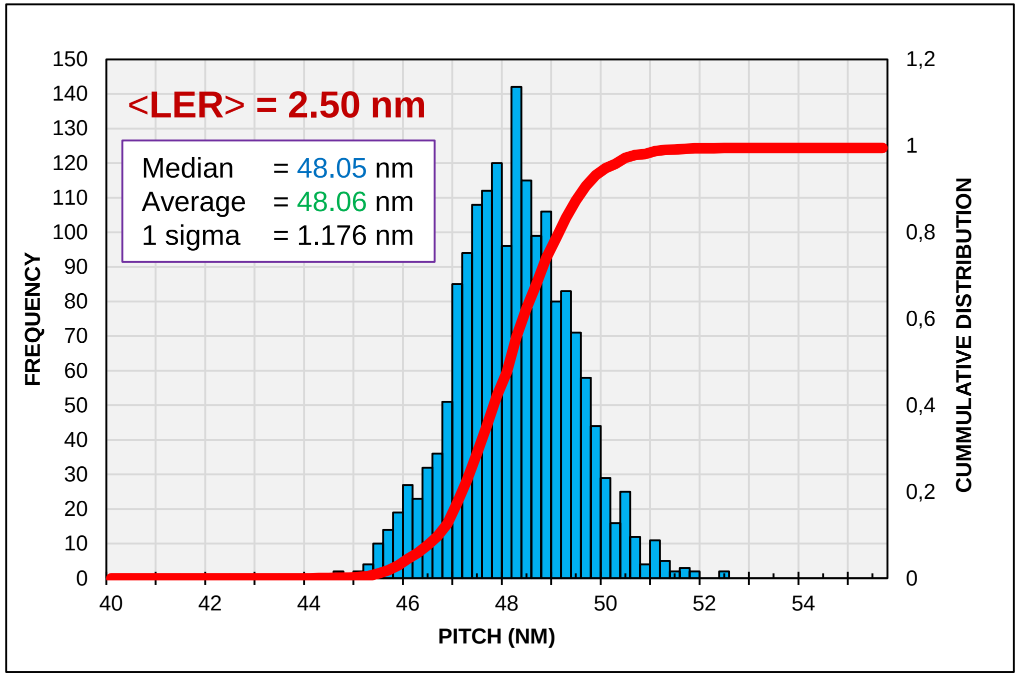
- Study line CD, LER and LWR ***as a function of etch time***
  - STEM sampling: ***5 different wafers***, 5 Die locations per wafer, 60 lines/lamella → ~ 1500 lines analyzed

CD, LER and LWR metrology from STEM pitch and CD distributions

Example # 2

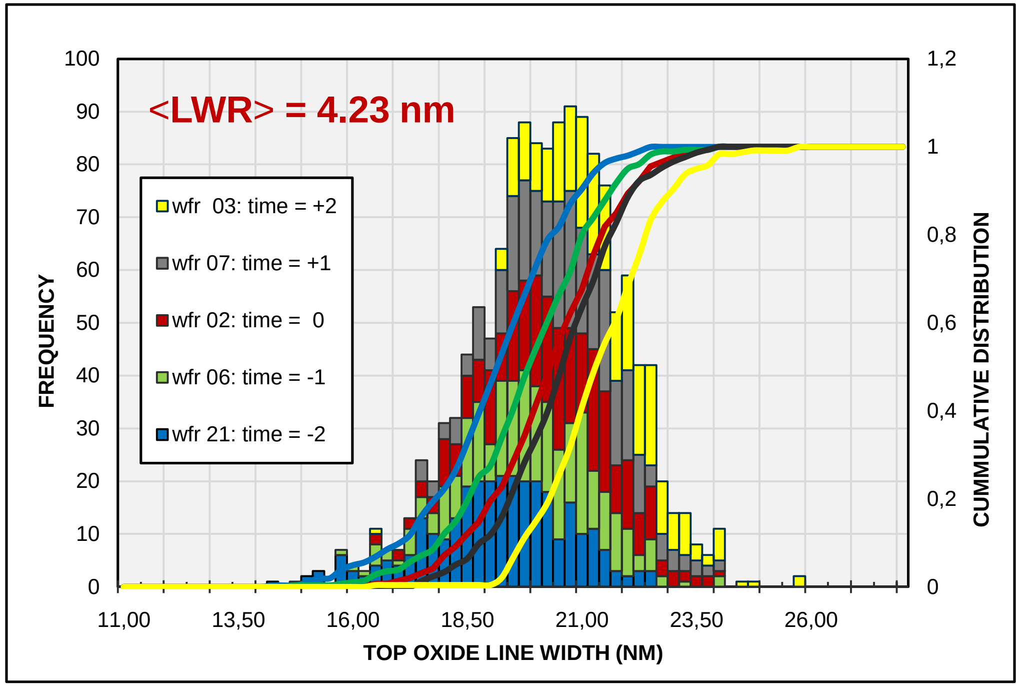
- Pitch and CD measurements on patterned Metal 1 low-K dielectric structures ($Pitch_{nominal}$ = 48.0 nm)

Pitch measurements



- **N = 2824** (left & right pitches of 1412 lines)
- Average Line Edge Roughness = 2.50 nm
- Microscope calibration confirmed

Oxide CD measurements

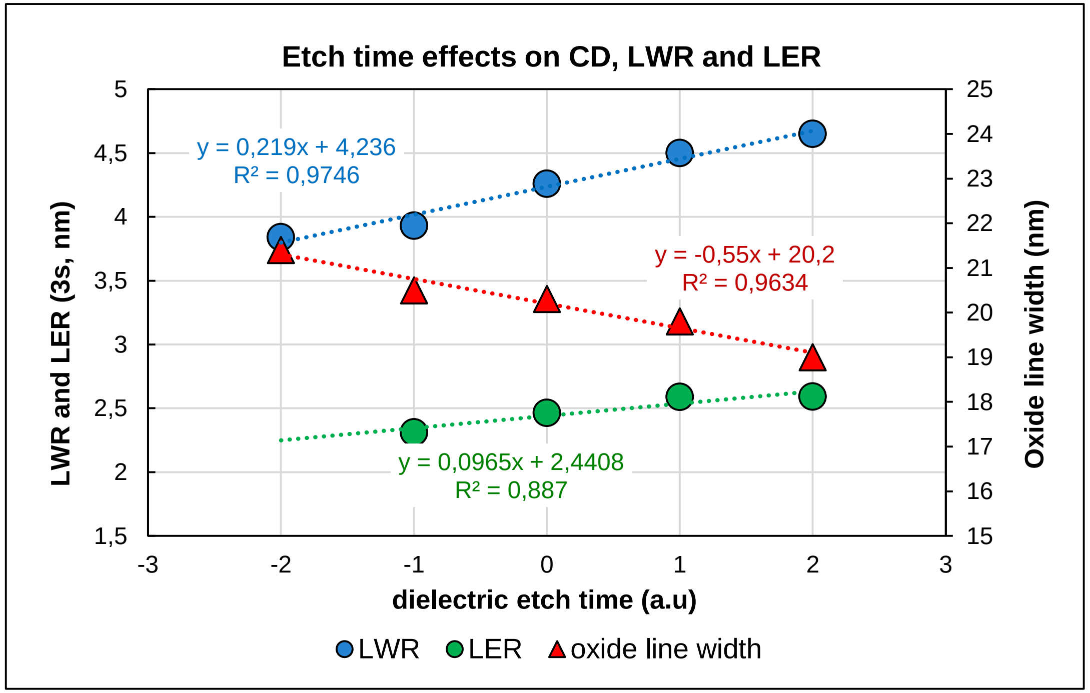


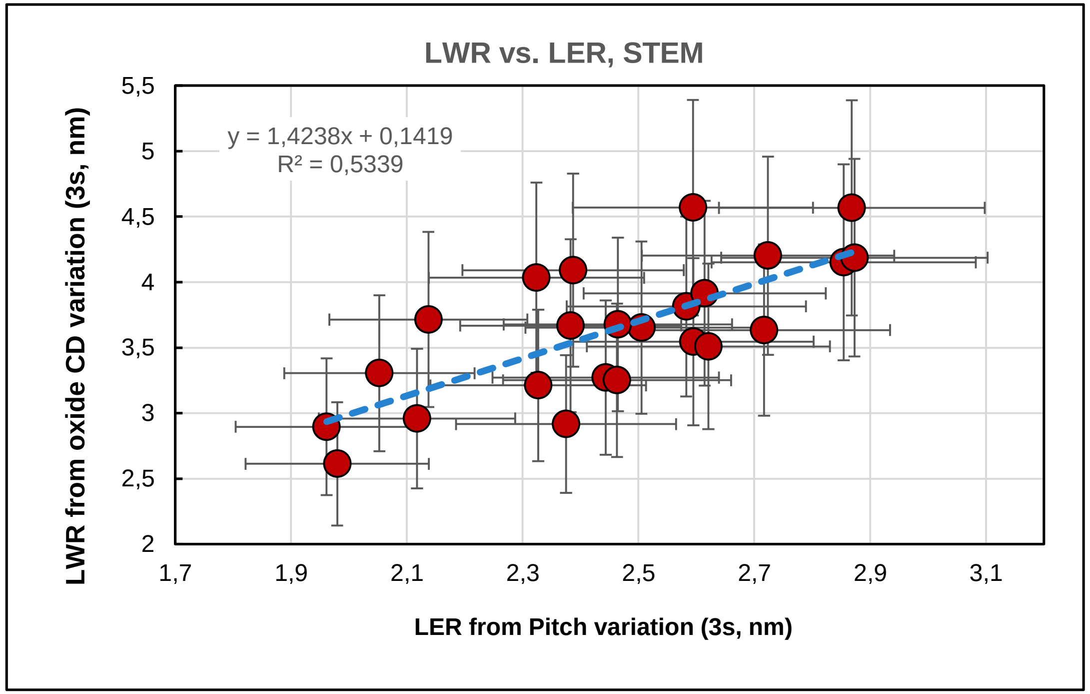
- **N = 1412** (line width CD of 1412 lines)
- CD distributions per wafer (N_w = ~ 300)
- cumulative histogram

Can STEM metrology **quantify** etch time effects on **CD**, **LER** and **LWR**?

Example # 2

- Pitch and CD measurements on patterned Metal 1 low-K dielectric structures ($Pitch_{nominal}$ = 48.0 nm)





- STEM metrology confirms etch trends:
- **Line CD** decreases for longer etch times
- **LER** and **LWR** increase for longer etch times

- LWR and LER values per lamella (**N = 55**):
- Error in LWR / LER estimates: ~ 18 / 8 %
- Ratio LWR / LER ~ 1.42 (LWR = ~ √2 LER)

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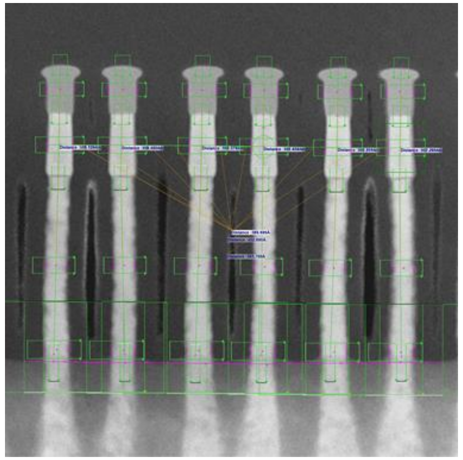
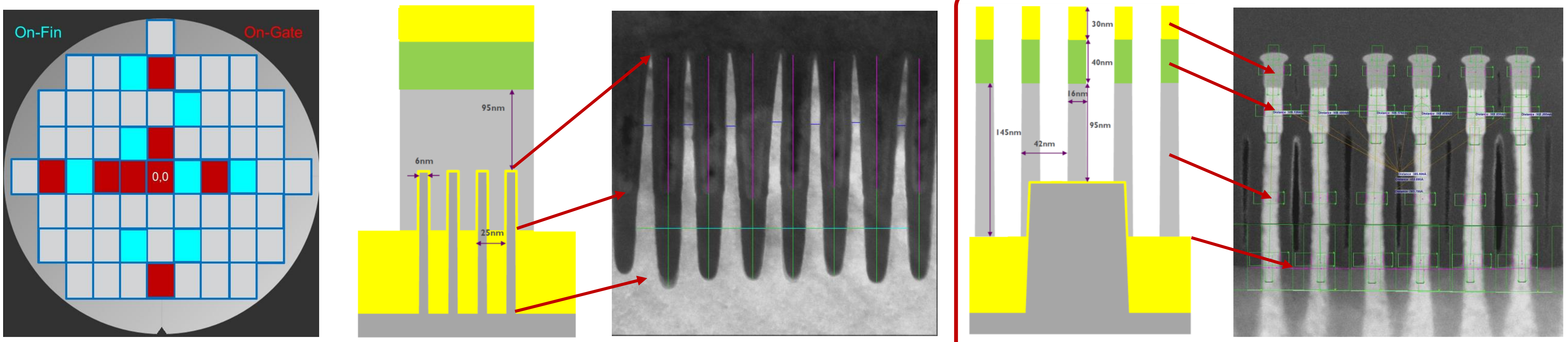


STEM METROLOGY EXAMPLE # 3

STEM based metrology to evaluate a 7 nm-node FinFET device structure

Example # 3

- SADP patterned Silicon dummy Gate lines (Pitch $_{nominal}$ = 42.0 nm, Gate line CD $_{nominal}$ = 16.0 nm)
- SAQP patterned Silicon Fin lines (Pitch $_{nominal}$ = 25.0 nm, Fin line CD $_{nominal}$ = 6.0 nm)



Wafer map of sampled Die locations | "On-Gate" sample orientation | STEM image of Fin structure | "On-Fin" sample orientation | "STEM image of Gate line structure

- Study line CD, (random) LER and LWR, (systematic / random) pitch walk and structural bending
  - STEM metrology sampling: 8+8 Die locations (lamellas), ~ 50 lines/lamella, → ~ 400 Gates/Fins analyzed

Can STEM metrology **detect** & **quantify** systematic & random **Pitch walk**?

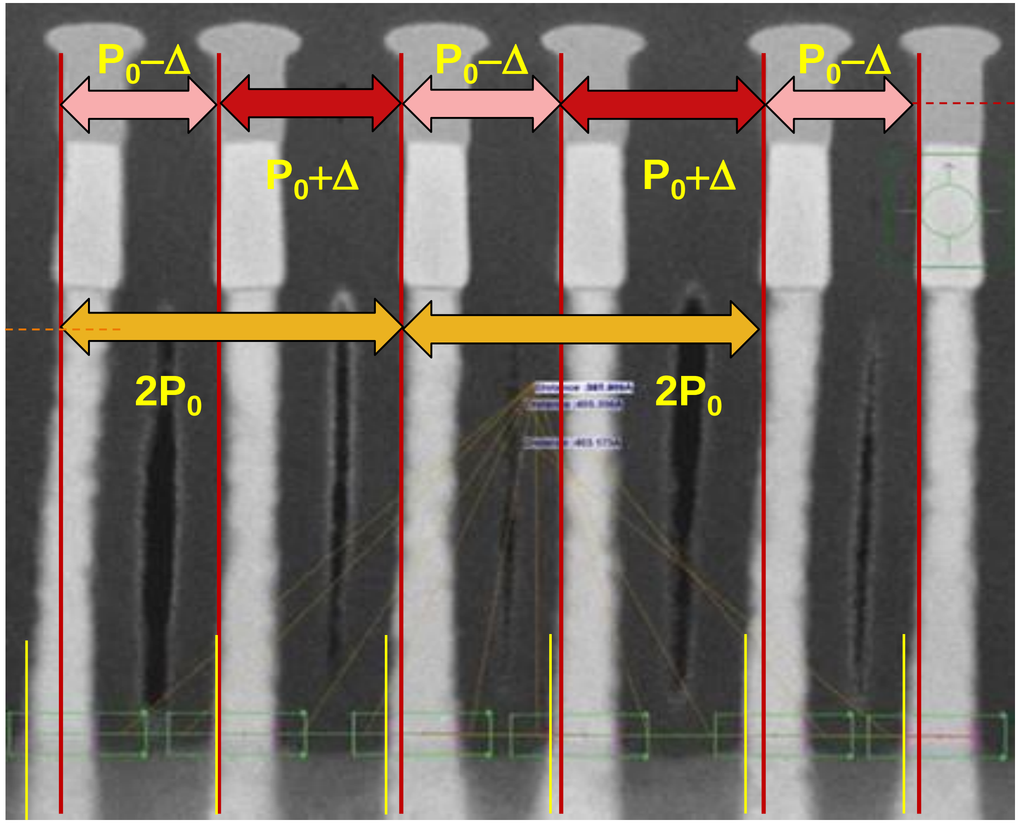
Example # 3

- SADP patterned Silicon dummy Gate lines (Pitch $_{nominal}$ = 42.0 nm, Gate line CD $_{nominal}$ = 16.0 nm)

Core pitch

No pitch walk
Line bending

LER variance
Line bending variance



Core *Pitch &* ***Gate*** *Pitch*

Gate pitch

Pitch walk due to SADP
Line bending

LER variance
Line bending variance

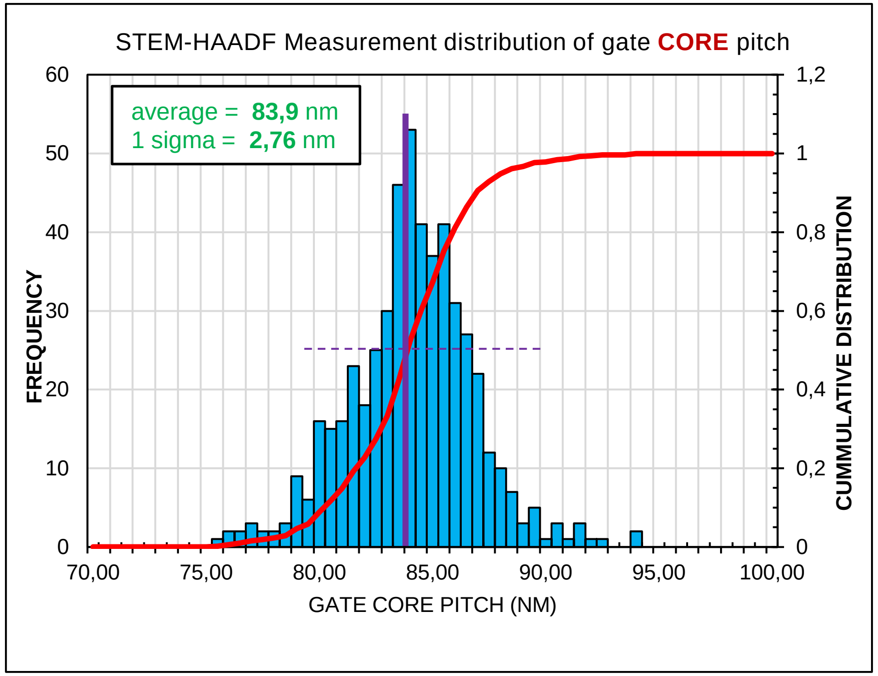
Can STEM metrology **detect** & **quantify** systematic & random **Pitch walk**?

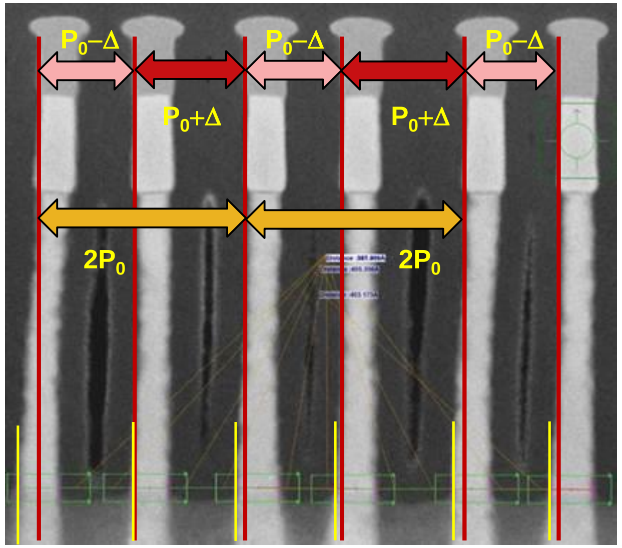
Example # 3

- SADP patterned Silicon dummy Gate lines (Pitch $_{nominal}$ = 42.0 nm, Gate line CD $_{nominal}$ = 16.0 nm)

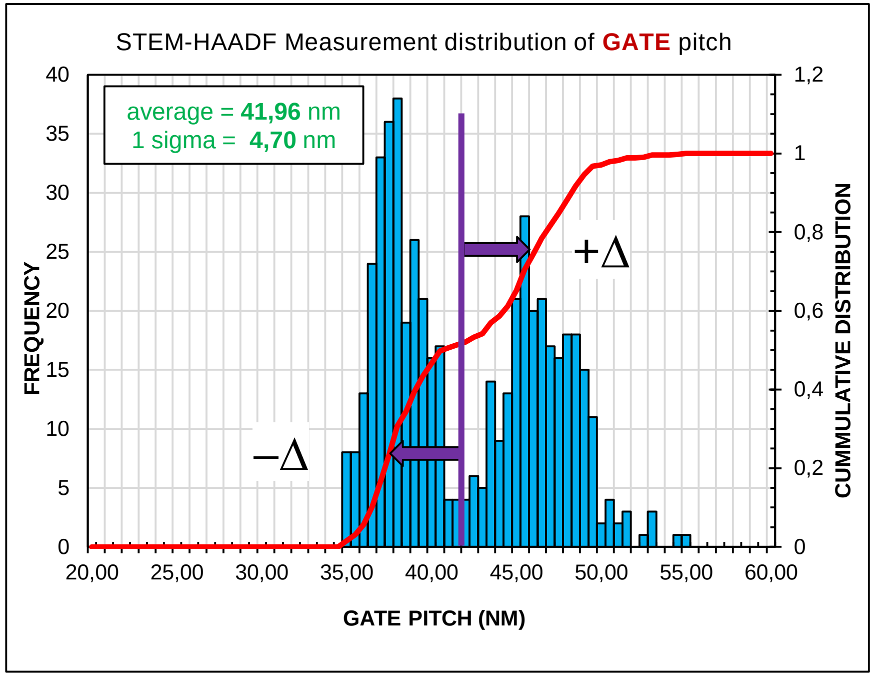
Core pitch

Gate pitch





***Core** Pitch & **Gate** Pitch*



- **N = ~ 400** (Core pitches measured)
- Core Pitch (83.9 nm) : Normal distribution

Variance : ~ random LER and Bending

- **N = ~800** (gate pitches measured)
- Gate Pitch : a *bi-modal* distribution.

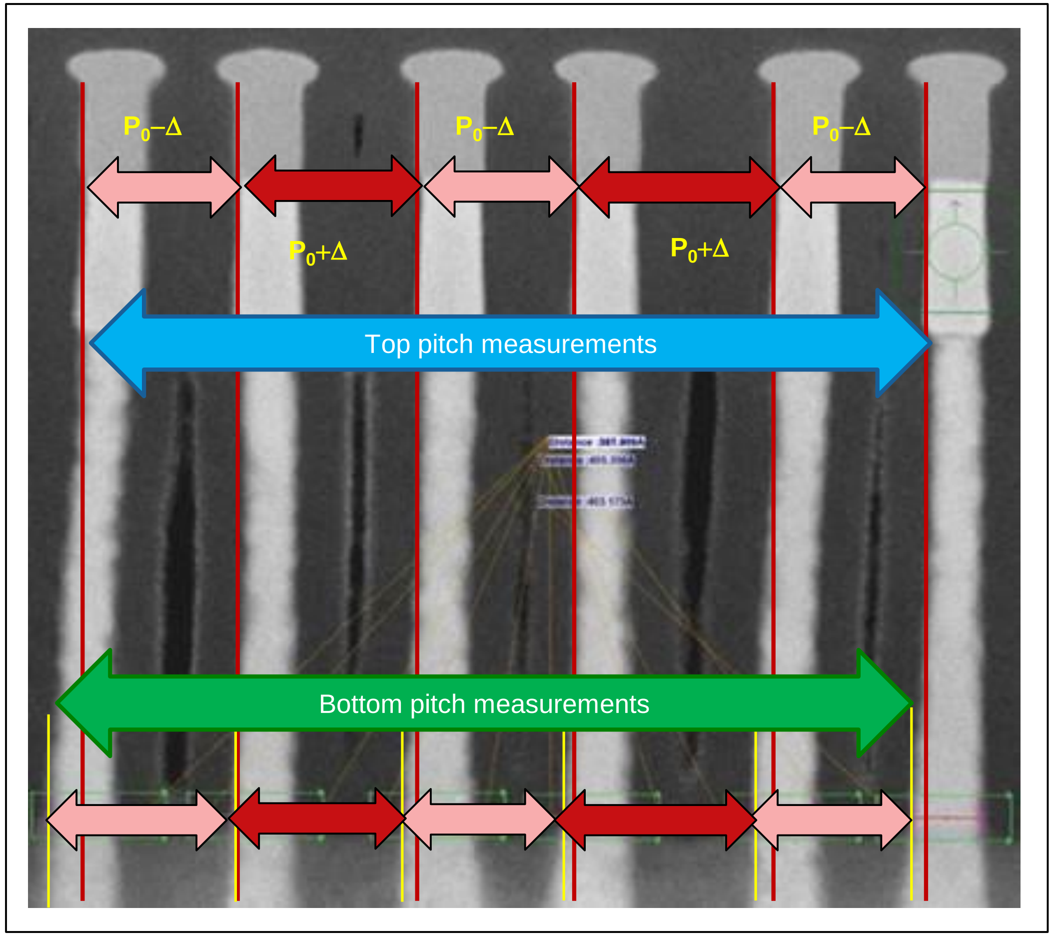
Pitch-walk + Bending is estimated at ~ 8 nm (2Δ)

Can STEM metrology **separate** systematic **Pitch walk** and **Bending**?

Example # 3

- SA**D**P patterned Silicon dummy Gate lines (Pitch $_{nominal}$ = 42.0 nm, Gate line CD $_{nominal}$ = 16.0 nm)

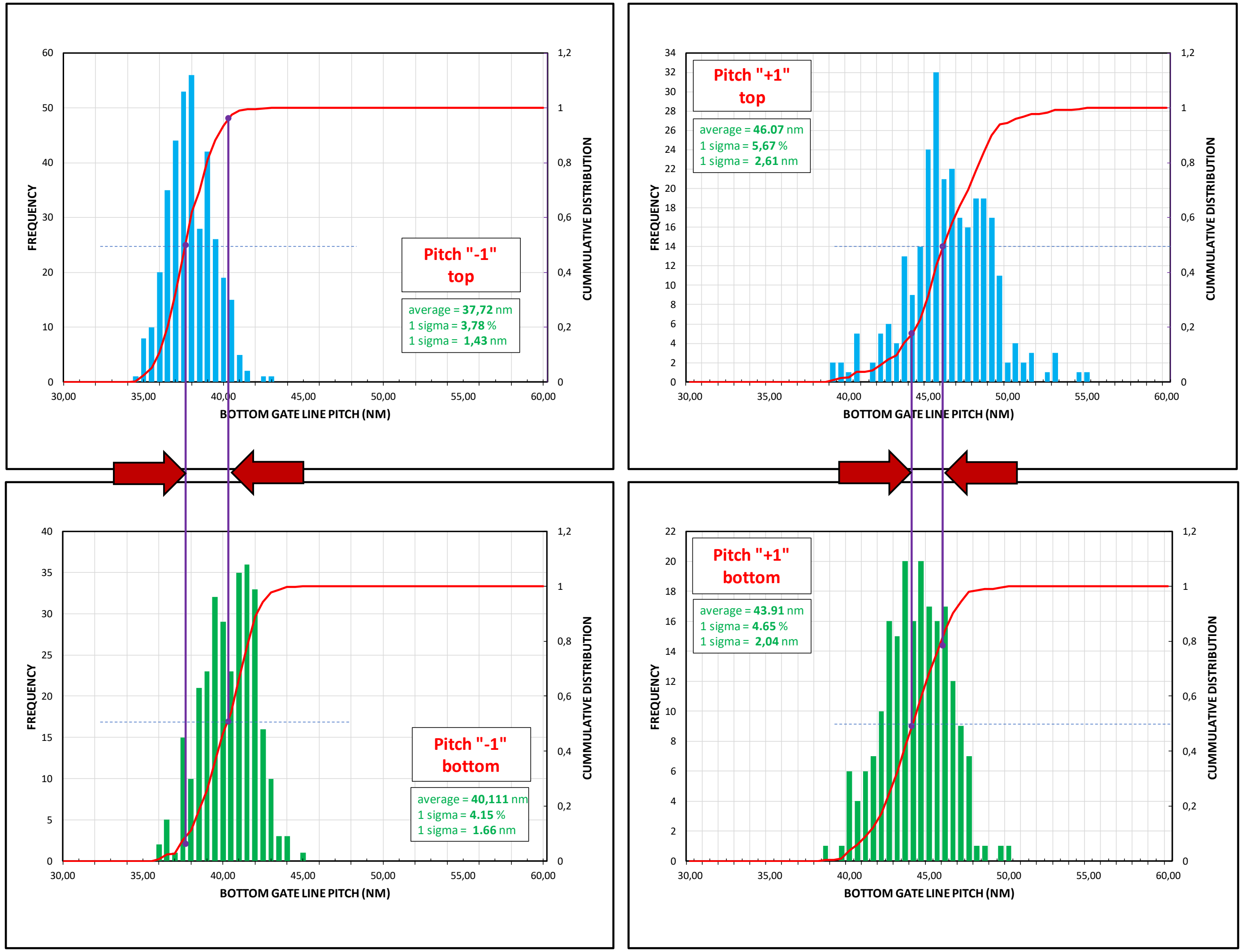
Measure pitch at top of bended Gate lines:
Pitch includes pitch walk **and** bending

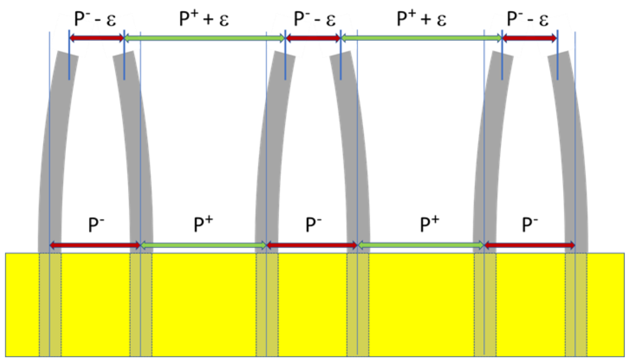


Measure pitch at bottom of bended Gate lines:
Pitch includes pitch walk **but no** bending

Can STEM metrology **separate** systematic **Pitch walk** and **Bending**?

Example # 3

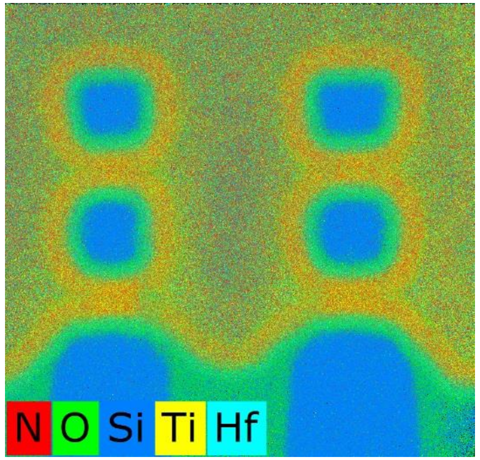




Pitch location	Pitch value (nm)
P^-	40.1
P^+	43.9
$P^- - \varepsilon$	37.7
$P^+ + \varepsilon$	46.0

SADP pitch walk (2Δ)	**3.8 nm**
Line bending (2ε)	**4.5 nm**

- Bottom and Top Gate Pitch measurements allow to separate structural bending from Pitch-walk !

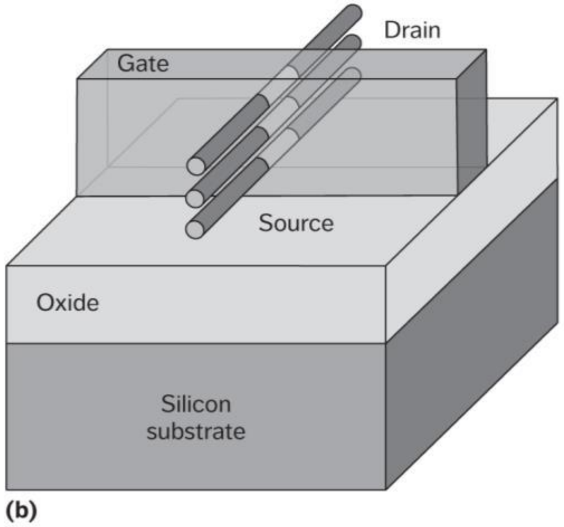


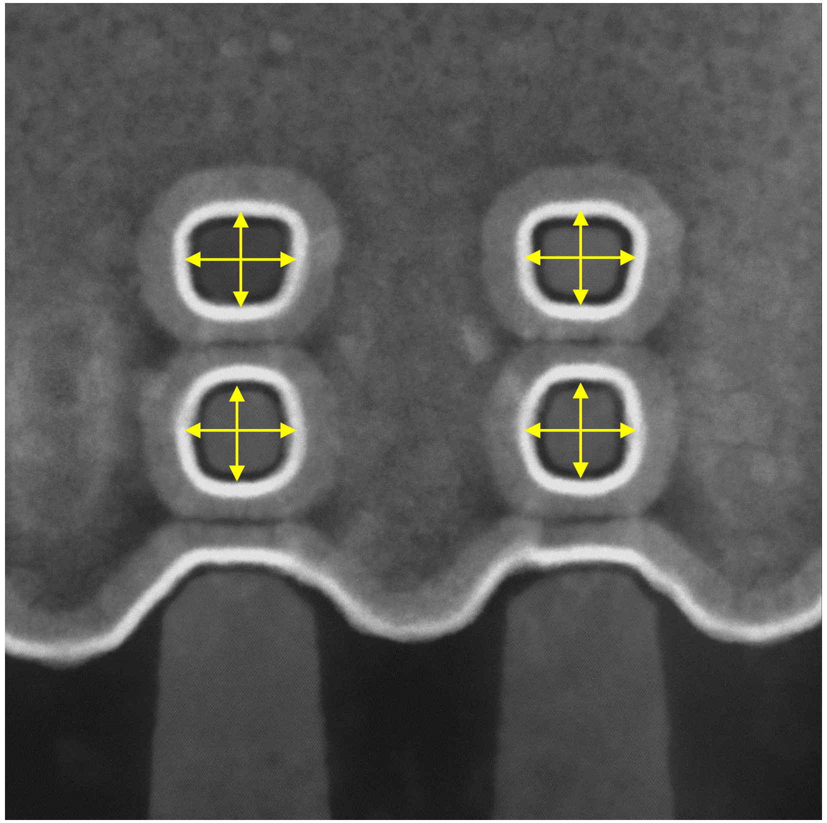
STEM METROLOGY EXAMPLE # 4

How capable is STEM for **process control** and **process development**?

Example # 4

- STEM-EDX metrology on NanoWire devices:
- Horizontal Si nanowires, <7nm node
- Measure height and width of top and bottom nanowires
- 196 nanowires analyzed
- Metrology derived from STEM-EDS elemental maps

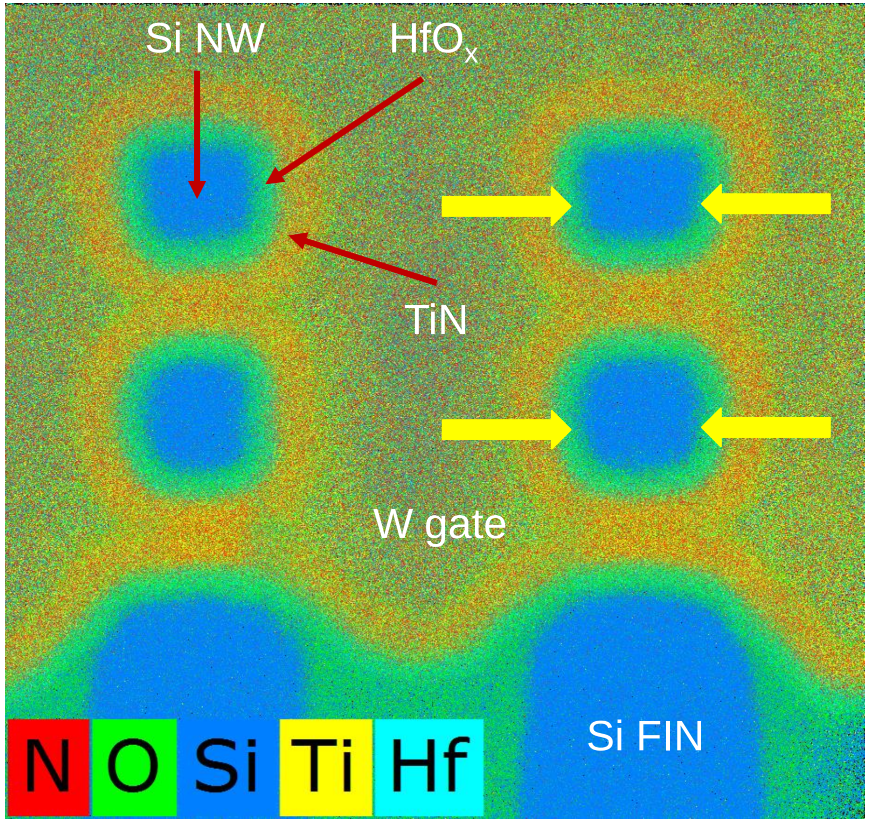


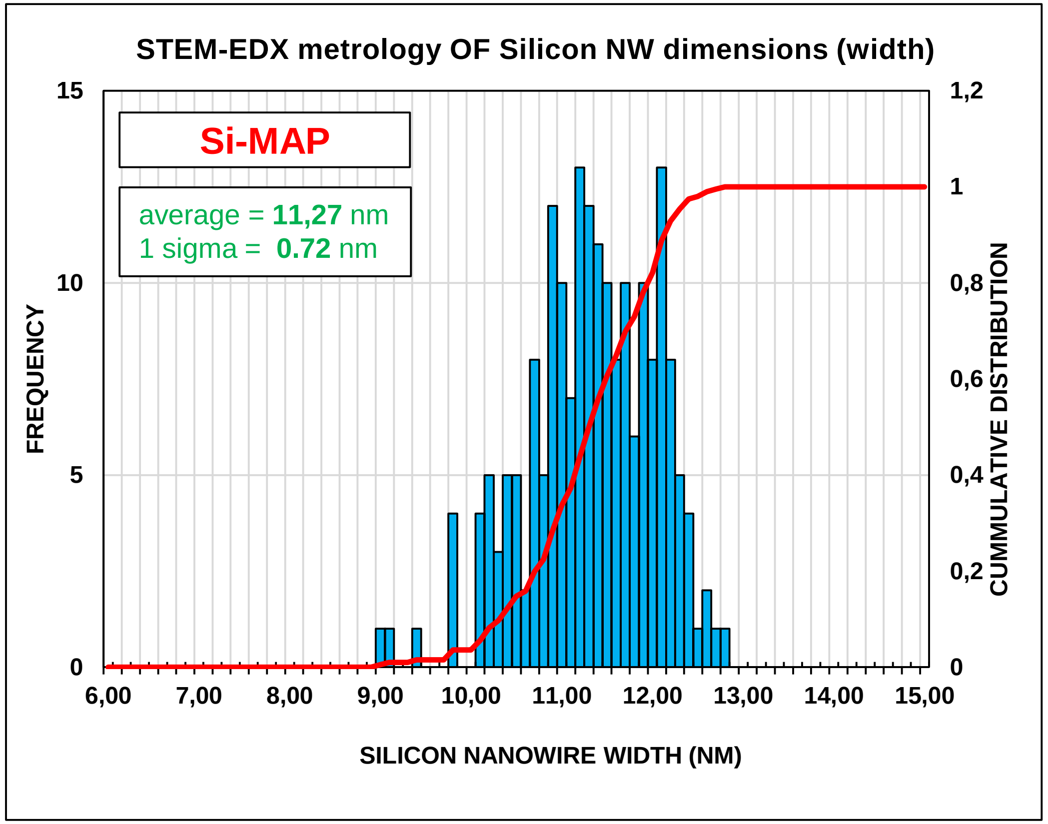


How capable is STEM for **process control** and **process development**?

Example # 4

- STEM-EDX metrology on Silicon NanoWire devices: analysis of NW diameter (height-width)





- Nanowire **width** has a Normal Distribution : NW width = 11.3 nm +/- 0.7 nm (1σ)

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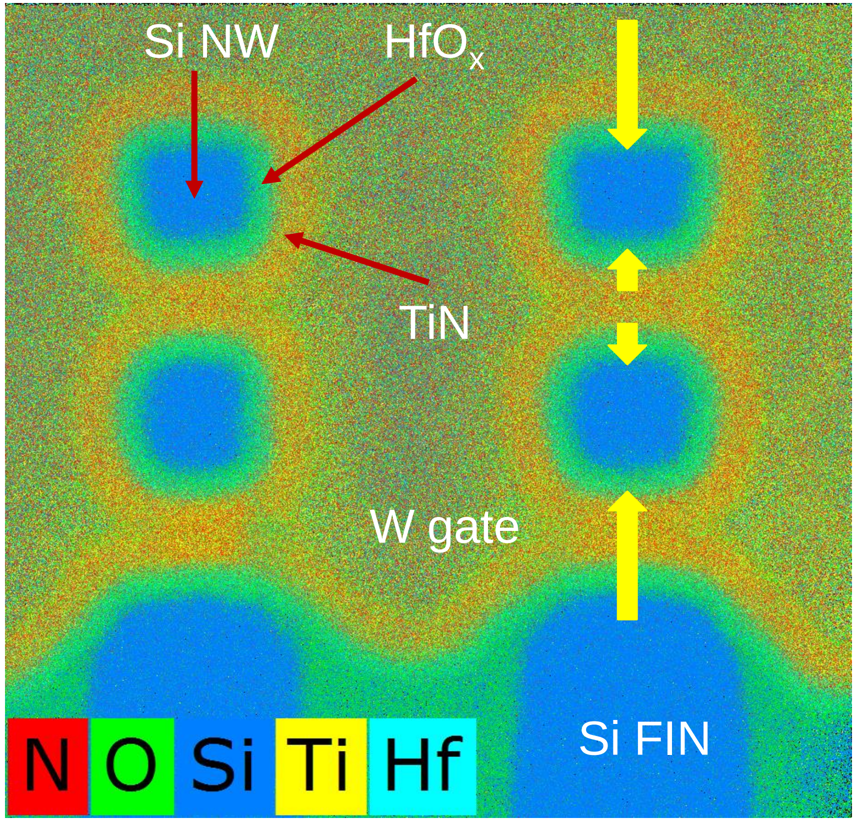
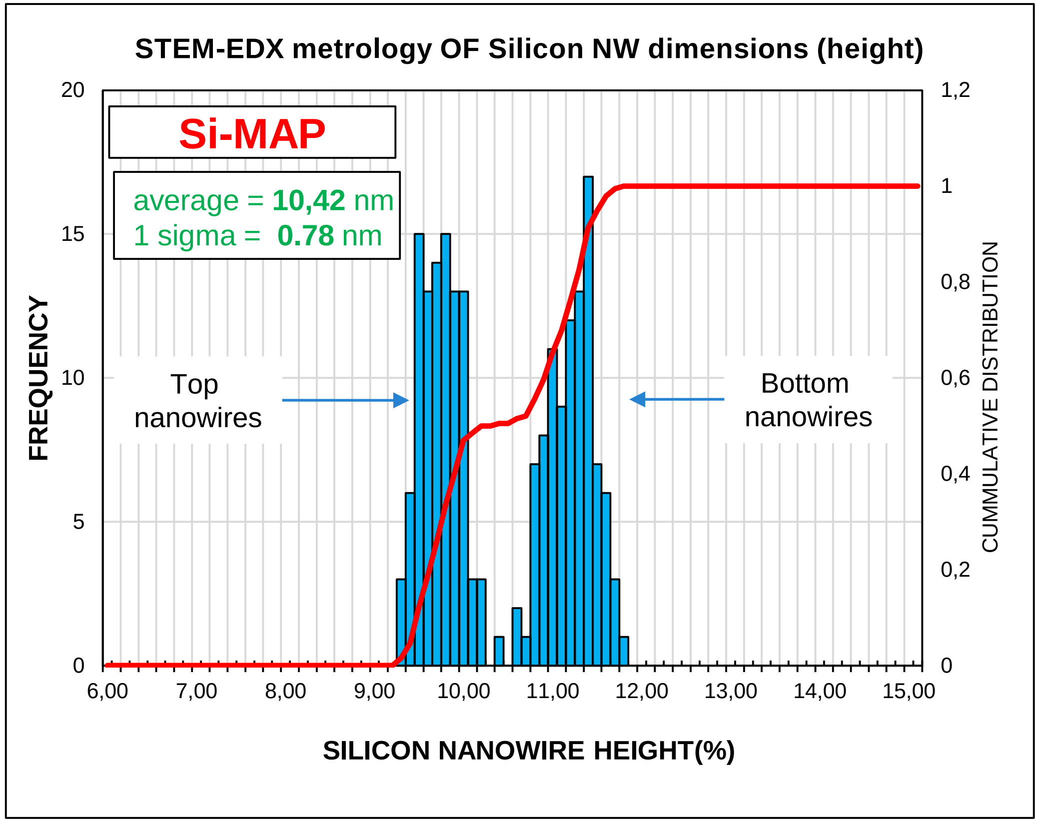
How capable is STEM for **process control** and **process development**?

Example # 4

- STEM-EDX metrology on Silicon NanoWire devices: analysis of NW diameter (height-width)



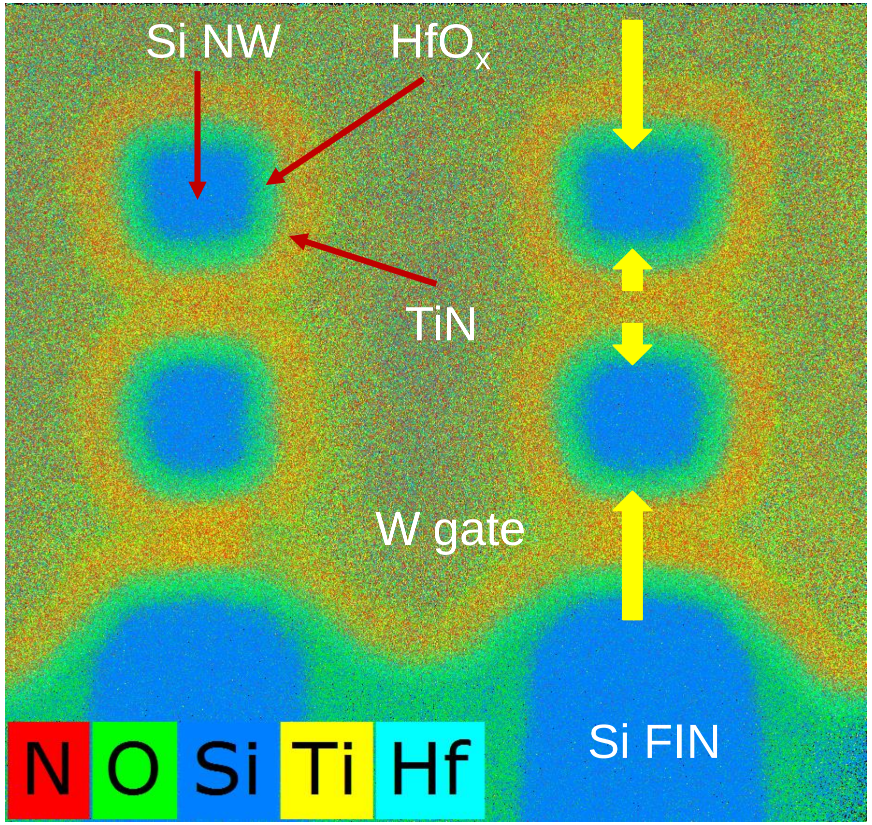


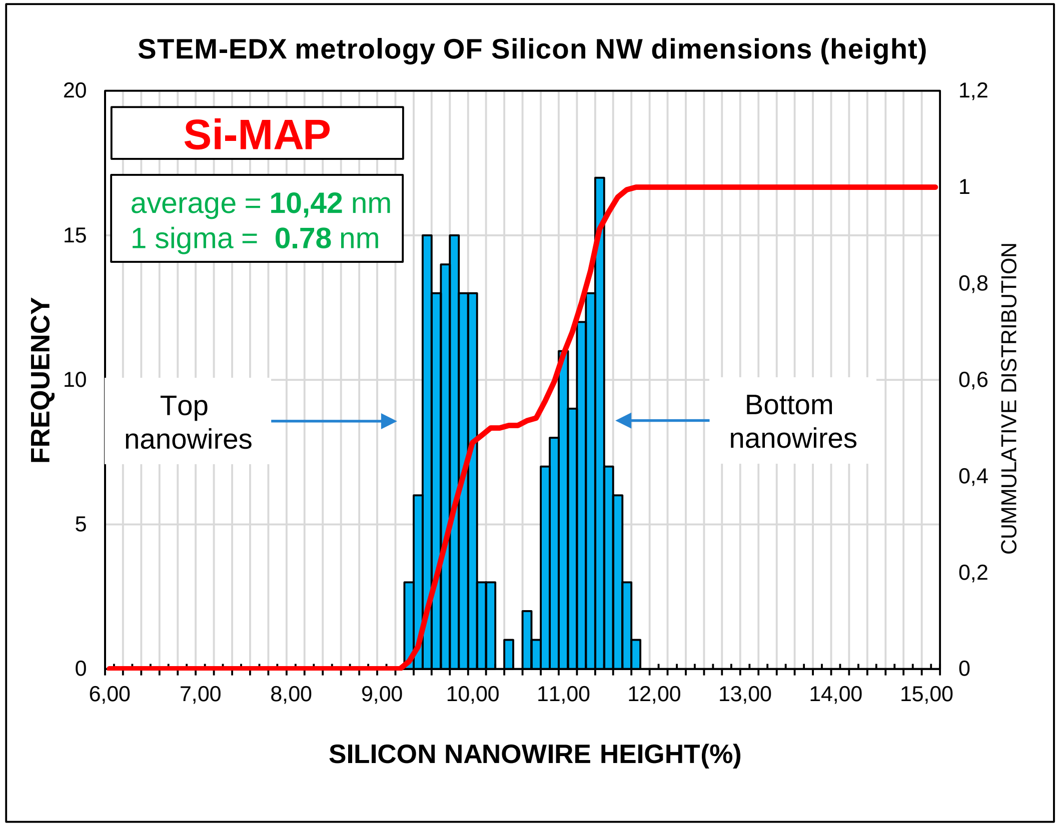
- Nanowire **height** has a Bi-modal Distribution : heights differ (~ 1.4 nm) for top and bottom NW !

How capable is STEM for **process control** and **process development**?

Example # 4

- STEM-EDX metrology on Silicon NanoWire devices: analysis of NW diameter (height-width)

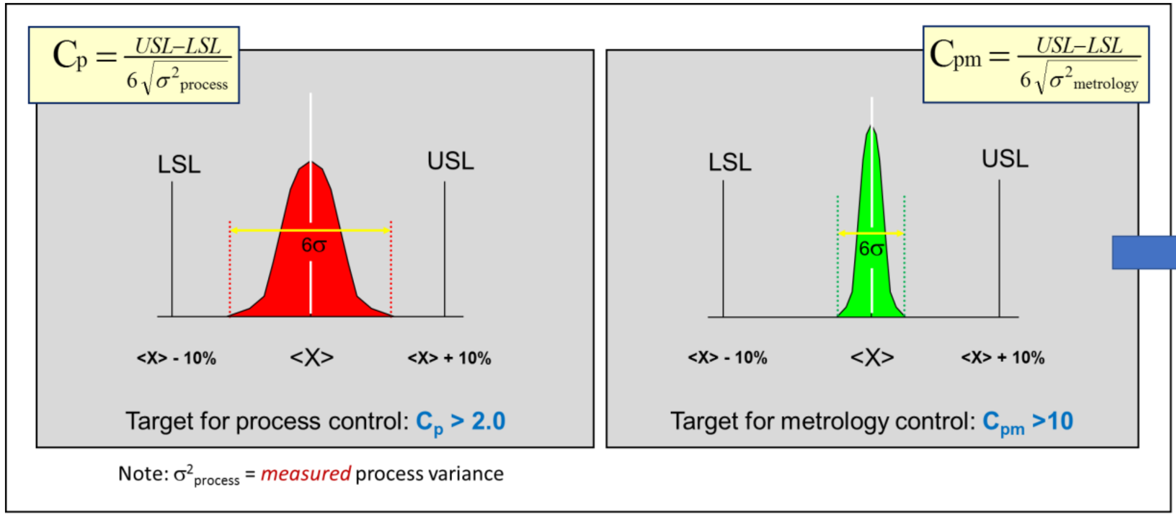


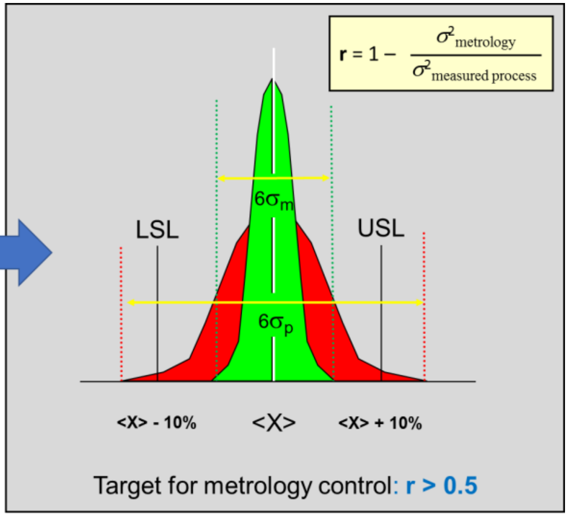


With sufficient sampling, STEM metrology can reveal subtle, systematic 3D dimensional variations !

How capable is STEM for **process control** and **process development**?

- Application of different "Metrology Capability Indicators": P/T ratio and Variability ratio (r)





Measured process (Y) = real process (X) + metrology error (ε)

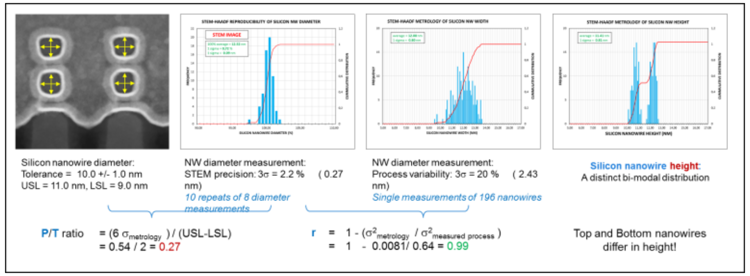
$Y = X + \varepsilon \rightarrow \sigma^2_Y = \sigma^2_X + \sigma^2_\varepsilon$

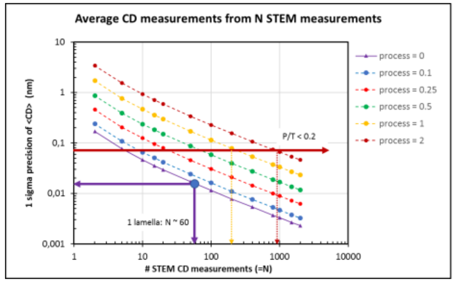
$r = (\sigma^2_{real\ process} / \sigma^2_{measured\ process})$

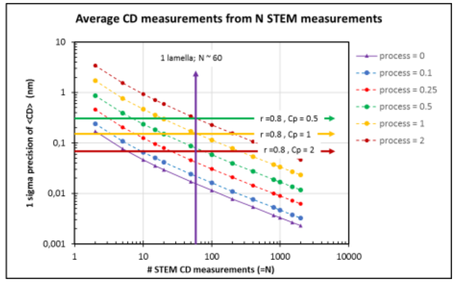
$r = 1 - (\sigma^2_{metrology} / \sigma^2_{measured\ process})$

This variability ratio **r** is a good indicator for the quality of the metrology system to monitor a process:

- First class monitors : **r** > 0.8
- Second class monitors : 0.5 < **r** < 0.8
- Third class monitors: 0.2 < **r** < 0.5
- Fourth class monitors: **r** < 0.2







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In full Paper: more comprehensive analysis of capability indicators and effect of statistics

Conclusions

- Automated TEM workflows allow to efficiently collect statistically significant STEM metrology data that are precise and accurate and can give insights in device characteristics and processes.
- To assess device dimensions that have local fluctuations, many (50-500) individual STEM data have to be averaged to achieve the required precision.
- LER, LWR, but also Pitch Walk and Structural Bending can be deduced from Pitch and CD distributions.
- STEM metrology is shown to be able to pick-up subtle, systematic 3D dimensional variations (~ 1.5 nm) that can not be measured by 2D metrology techniques

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ECSEL Joint Undertaking