The 18th U.S.-Korea Forum on Nanotechnology

Converging AFM Solutions: Pioneering Nanotechnology for Advanced Industries

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The Engine of Korea

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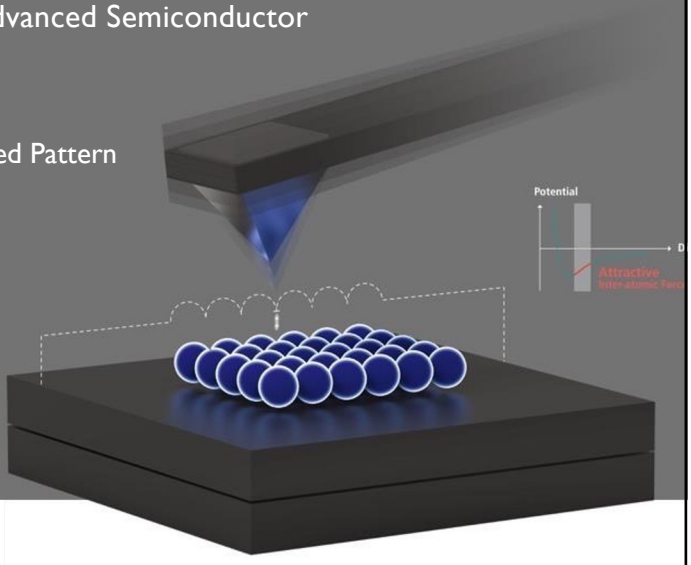
OUTLINE

- Challenges and Opportunities of MI in Advanced Semiconductor
- Fully Automated Industrial AFM
- Characterization Results
  - Automated Measurement on Nanoconfined Pattern
  - Sidewall Roughness
  - Accurate Slope and Pattern Shape
  - Surface Chemical Property
- Summary



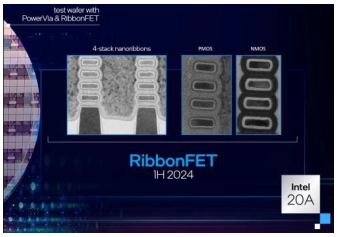
2

We are entering the Nanosheet Era

Samsung

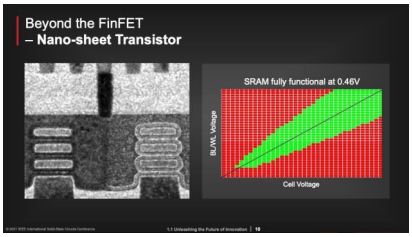
Source: https://www.eetimes.com/wp-content/uploads/Samsung_Alan.jpg

Intel



Source: https://www.eetimes.com/wp-content/uploads/Intel-RibbonFET.jpg

TSMC



Source: https://www.semiconductor-digest.com/gate-all-around-transistors-show-up-at-isscc/

All major Logic foundries/IDMs announced nanosheet mass production

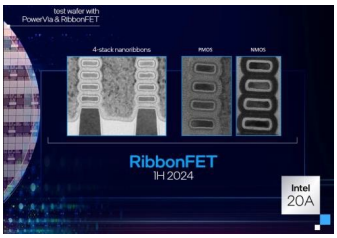
3

We are entering the Nanosheet Era

Samsung

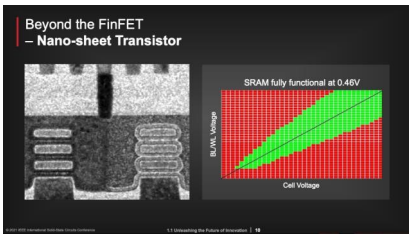
Source: https://www.eetimes.com/wp-content/uploads/Samsung_Alan.jpg

Intel



Source: https://www.eetimes.com/wp-content/uploads/Intel-RibbonFET.jpg

TSMC



Source: https://www.semiconductor-digest.com/gate-all-around-transistors-show-up-at-isscc/

	Samsung	Intel	TSMC
Nanosheet t erminology	Multi-Bridge-Channel FET (MBCFET™)	RibbonFET	Nanosheet / Nano-sheet
Mass production announcements	**1st gen.:2022 (SF3E)** 2nd gen.:2024 (SF3)	1st gen.:2024 (20A)	1st gen.:2025 (2nm/20A)

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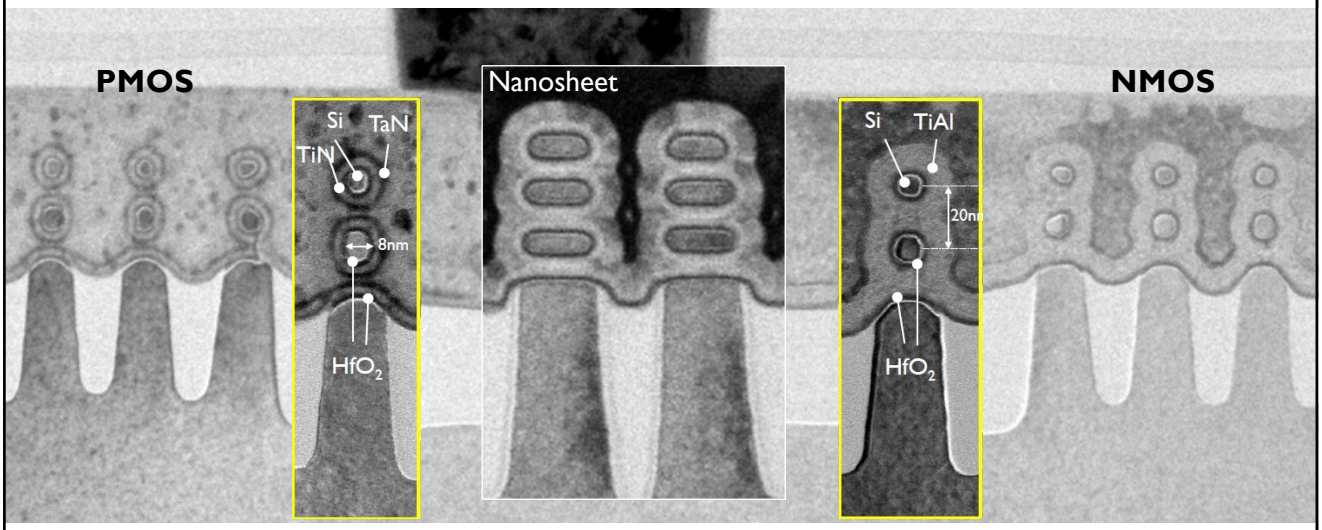
SI GATE-ALL-AROUND(GAA) NANOWIRES/Nanosheet

CMOS INTEGRATION



Source: Imec Technical Forum

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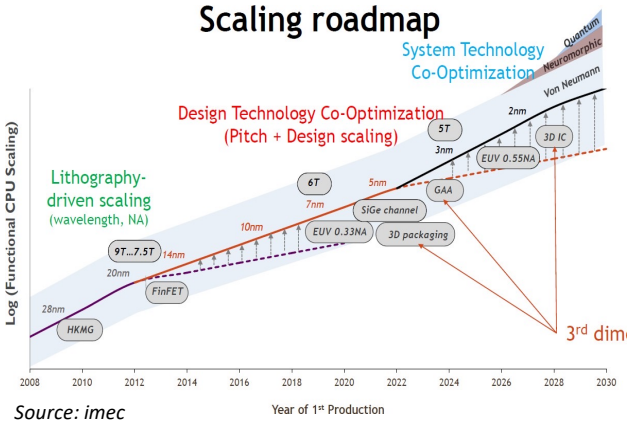
3D Architecture Devices: Logic



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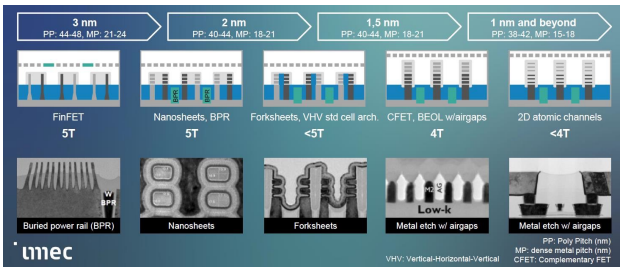
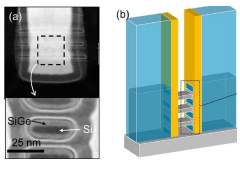
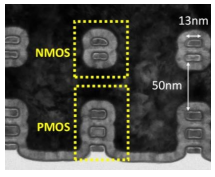




Source: IBM, IEDM 2019



Source: Intel, IEDM 2020

Source: Intel

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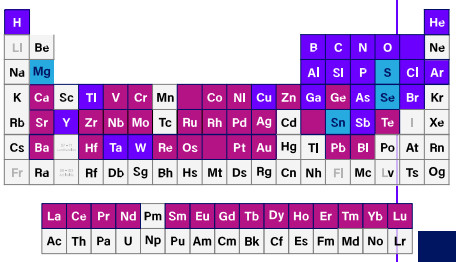
The Materials Era

Past 21 | Present 62 | Future 66

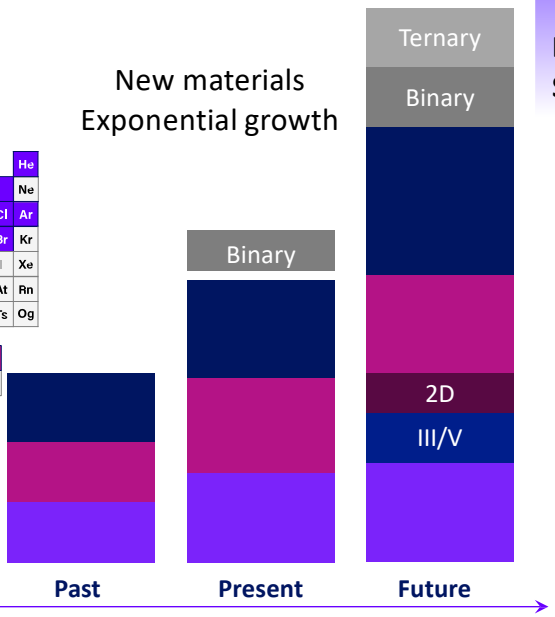


Dielectric

Metal

Semiconductor

New materials
Exponential growth



Broader Metrology Scope

- Composition
- Strain
- Doping
- Crystallinity
- Phase
- Grain size
- Lattice defectivity

Source: R. Koret, IEDM2021

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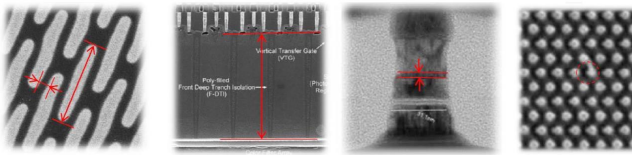
Metrology and Inspection Challenges

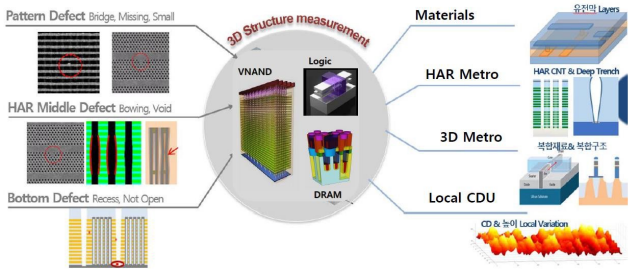
☐ Due to the decreased size and increased aspect ratio (HARC)
※ High Aspect Ratio Contact
→ SNR of target defects and CDs is continuously decreasing
→ Need extremely high resolution with great precision and stability

CDs	Height	Thickness	Defects
Target : 5 ~ 10 nm Precision : 0.1nm	1 nm ~ 10 um 0.1nm	5 ~ 100 A 0.5 A	< 15nm



Source: Samsung, Next gen. Lithography conference 2019

☐ Many things to monitor for the yield improvement



High resolution vs. Massive data

Deep structure vs. Local variation

Physical quality vs. Material quality

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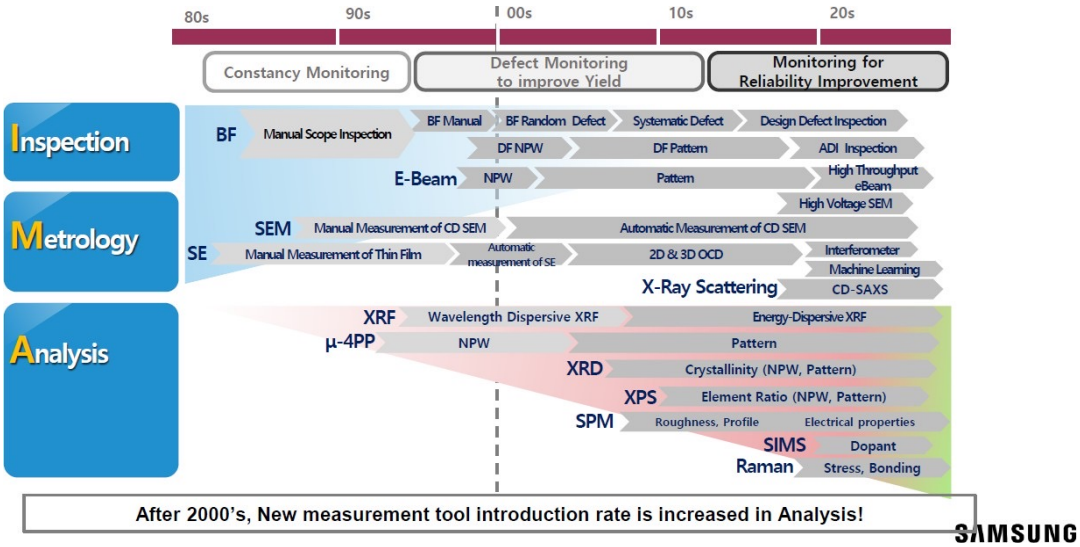
Process Control Solutions at High Volume Manufacturing



SAMSUNG

Source: Samsung, Semicon Korea 2023

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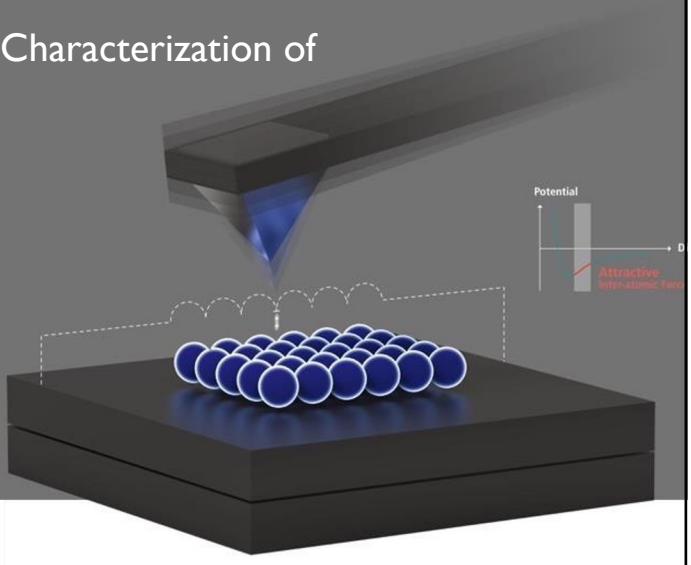
Industrial AFM Activities for Surface Characterization of Complex Nanoconfined Structures



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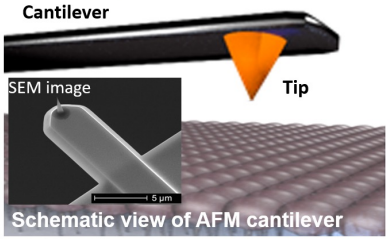
Scanning Probe Microscopy (Atomic Force Microscopy)

AFM Imaging

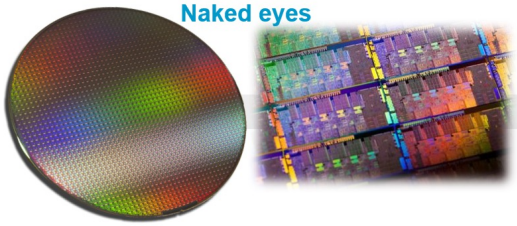


Atomic Force Microscopy (AFM)

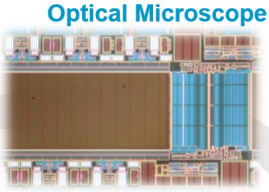
is not like typical optical microscopy,

but it is like a ***probing robot.***

Naked eyes

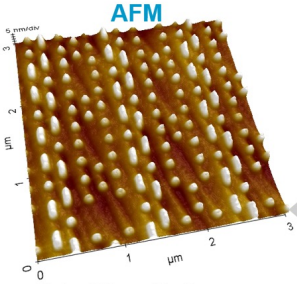


Optical Microscope



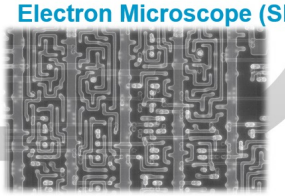
- Up to x10^3 magnification
- Only 2D imaging
- Less analysis method

AFM



- Up to x10^9 magnification
- 3D imaging
- Various analysis method
- Ambient, Vacuum and liquid

Electron Microscope (SEM)



- Up to x10^7 magnification
- Only 2D imaging
- Less analysis method
- Only in Vacuum

SEM image Copyright by Insight Analytical Labs, Inc

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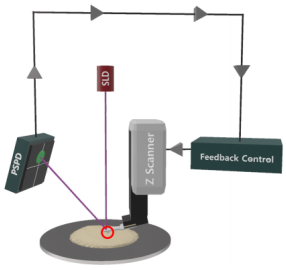
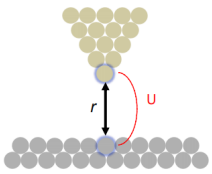
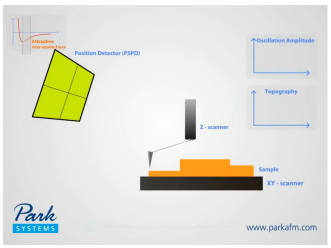
Atomic Force Microscopy (AFM)

Basic principle of AFM



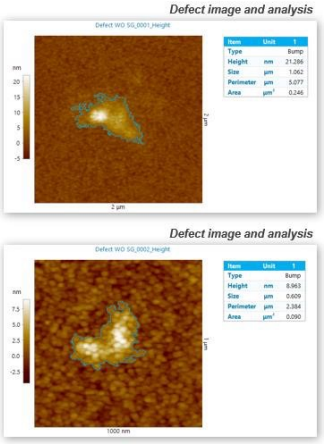


Potential (U) changes depending on the distance between two atoms.



Source : Park Systems Youtube(https://www.youtube.com/watch?v=wiFCYFrXkek)

Topography measurement for Defect Review



- Monitoring the surface topography using interaction(atomic force) between tip and sample surface.
- Using AFM, the electrical mechanical, magnetic and thermal properties as well as topography can be measured

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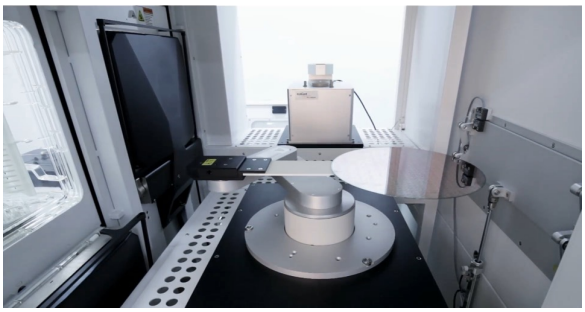
Lab-to-Fab in AFM, 30-year Journey

Research AFM

Industrial AFM



- AFM was born in 1985
- 300mm Industrial AFM, NX-3DM from Park Systems was first introduced in Semiconductor FAB in 2015

- True non-contact measurement
  - No probe-sample damage
  - Long tip lifetime
  - High reliability and repeatability
- XY scan area: 100 x 100 μm^2
- Z scan travel distance: ± 7 μm
- Fab automation compliance

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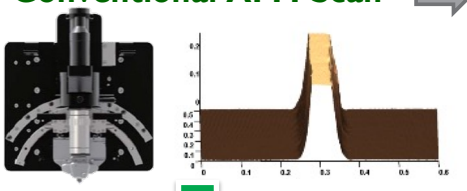
NX3DM, Atomic Force Microscopy for 3D Structure, 3D AFM

Conventional AFM Scan

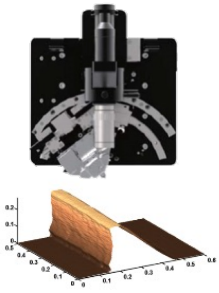


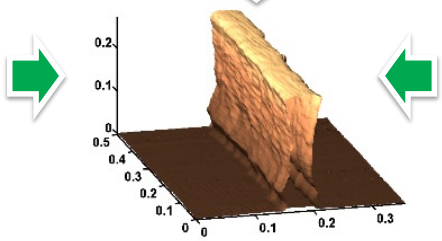
CD at top, Height

+

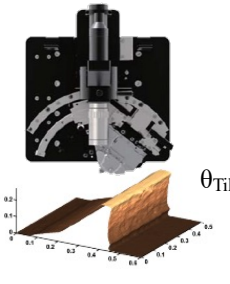
CD, LER, LWR at middle/bottom
Sidewall roughness
Overhang

Left Tilting





Right Tilting



θ_{Tilt} = 19 and 38°

- 3D AFM allows probe to access sidewall by tilted head and after measurement at three positions, 3D shape information of structure can be delivered by stitching of three images

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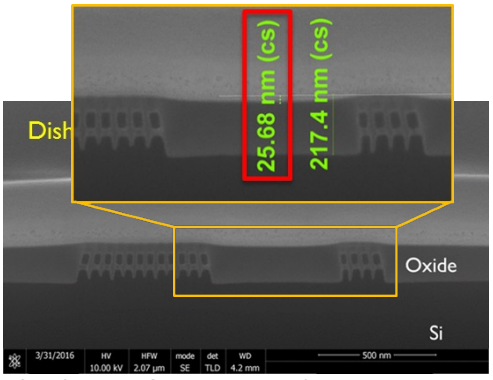
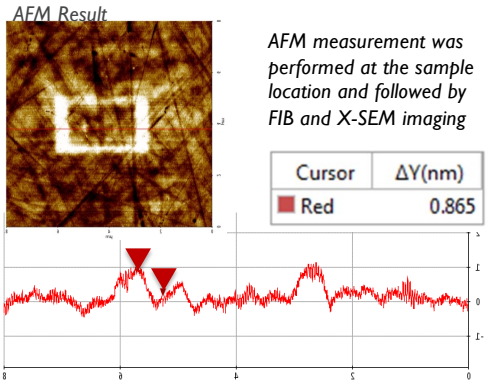
Power of NC-AFM technique for CMP process

2nd Metrology Step



X-SEM of Post-oxide CMP in Fin processes after FIB sample preparation

1st Metrology Step

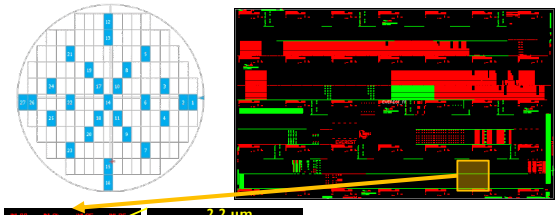


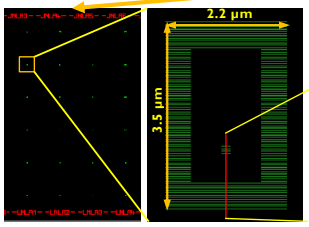
AFM measurement was performed at the sample location and followed by FIB and X-SEM imaging

- AFM metrology solution with non-contact measurement technique
  - Non-destructive atomic resolution height information
  - No requirement of sample preparation step and no sample damage while measuring

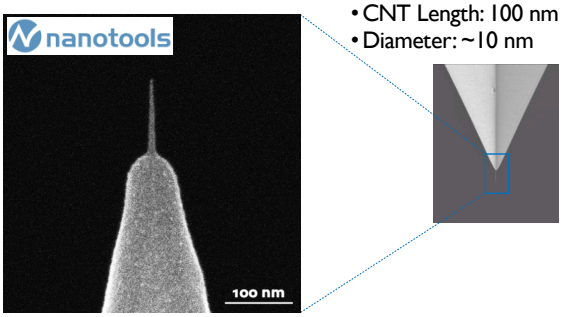
AFM Metrology for FinFET Device Process

REQUIREMENTS FOR RECIPE SETUP

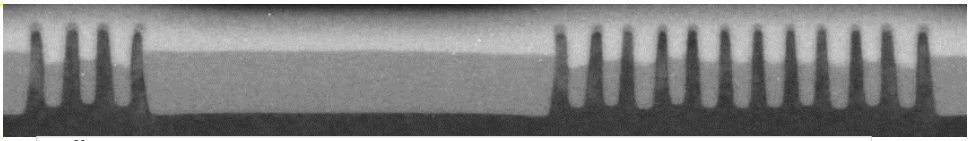


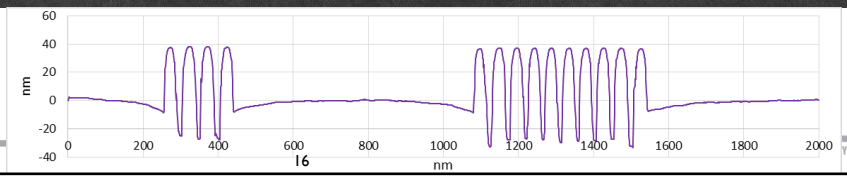


Used Probe: M-CNT-100
- CNT Length: 100 nm
- Diameter: ~10 nm



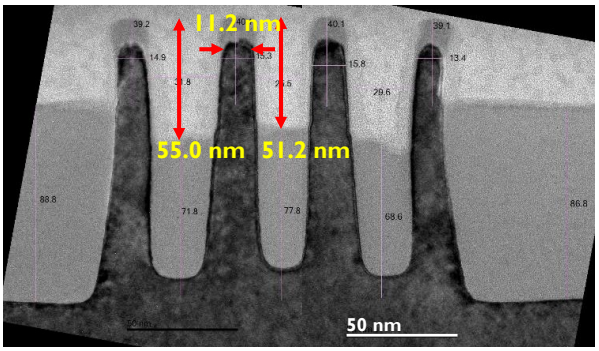
Fin Structure with Pitch 45 nm



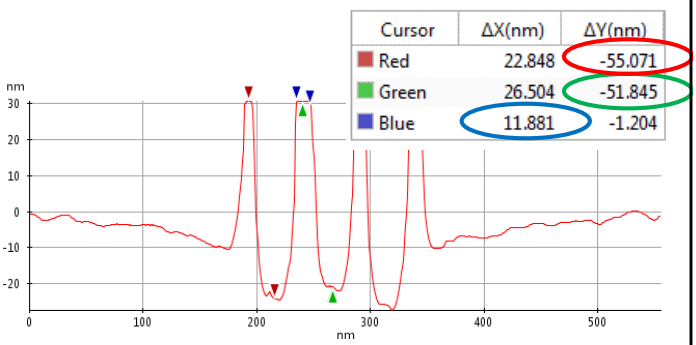


Measurement Accuracy Verification

TEM Results



AFM Profile after Tip Deconvolution



X axis is stretched so x and y scale is not isotropic. Therefore, it shows difference between AFM and TEM images

Height and top CD values were verified by TEM and it shows a good agreement.

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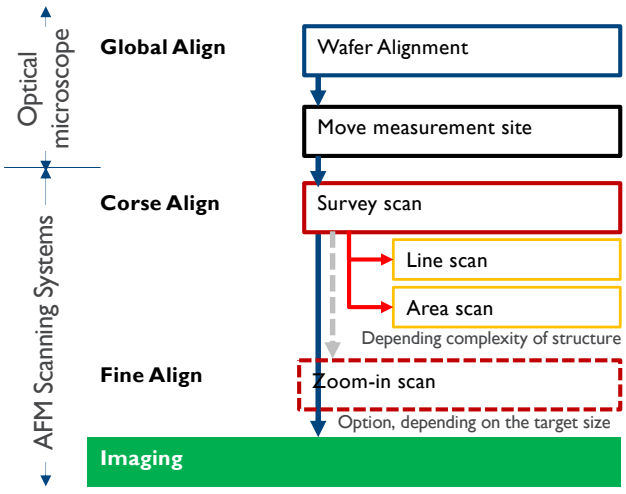
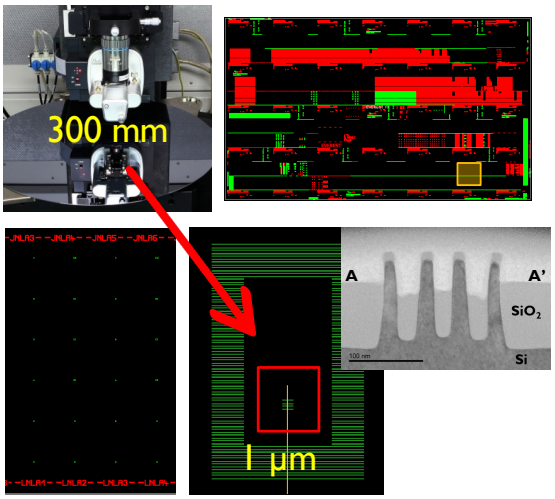
How Measurement Works

- Nanometer position accuracy is key enabler for the measurement using optical microscope and AFM scanning system





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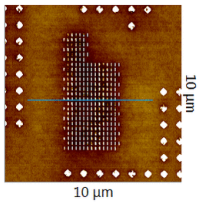
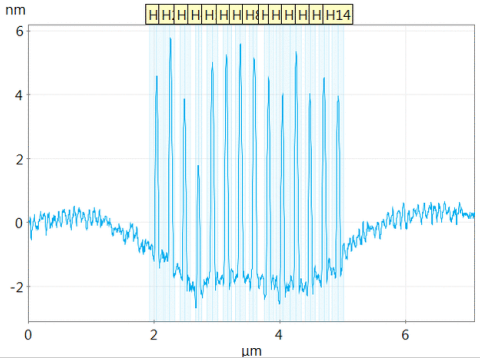
Repeatability in the Positioning and Measurement of Industrial AFM

Animation was made all AFM image on top of each other





V. Item	Unit	H1	H2	H3	H4	H5
Min	nm	-1.498	-1.776	-2.204	-2.556	-2.191
Max	nm	4.528	5.717	3.812	1.719	4.948

V. Item	Unit	H6	H7	H8	H9	H10
Min	nm	-2.155	-1.977	-2.152	-2.405	-2.617
Max	nm	5.191	5.517	5.069	4.452	3.94

V. Item	Unit	H11	H12	H13	H14
Min	nm	-2.23	-2.35	-2.078	-1.802
Max	nm	5.296	3.968	4.473	3.896

- AFM could capture target structures accurately, which has nanometre height variation and provide profile and height information
- Image processing is done automatically by using smart flattening algorithm

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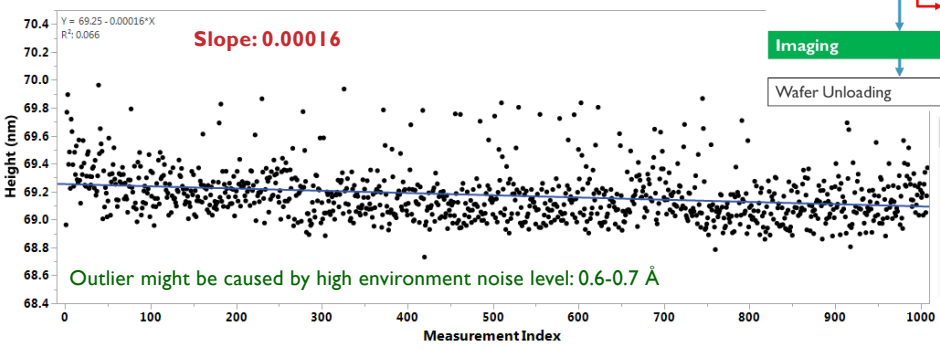
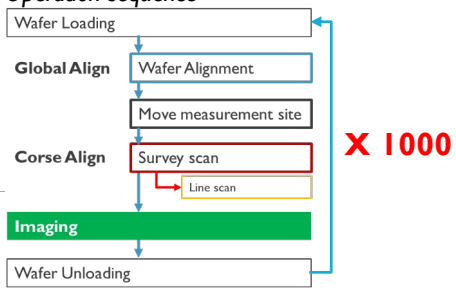
Measurement Long-term Repeatability

- Sample: Fins with 45 nm pitch and 70 nm height
- Operation: Performed several days



Operation sequence



Summary Statistics

Mean	69.173294
Std Dev	0.1813815
Std Err Mean	0.005713
Upper 95% Mean	69.184504
Lower 95% Mean	69.162083
N	1008

- Good measurement reliability, value of non-contact measurement operation
- Long probe lifetime and good cost of ownership

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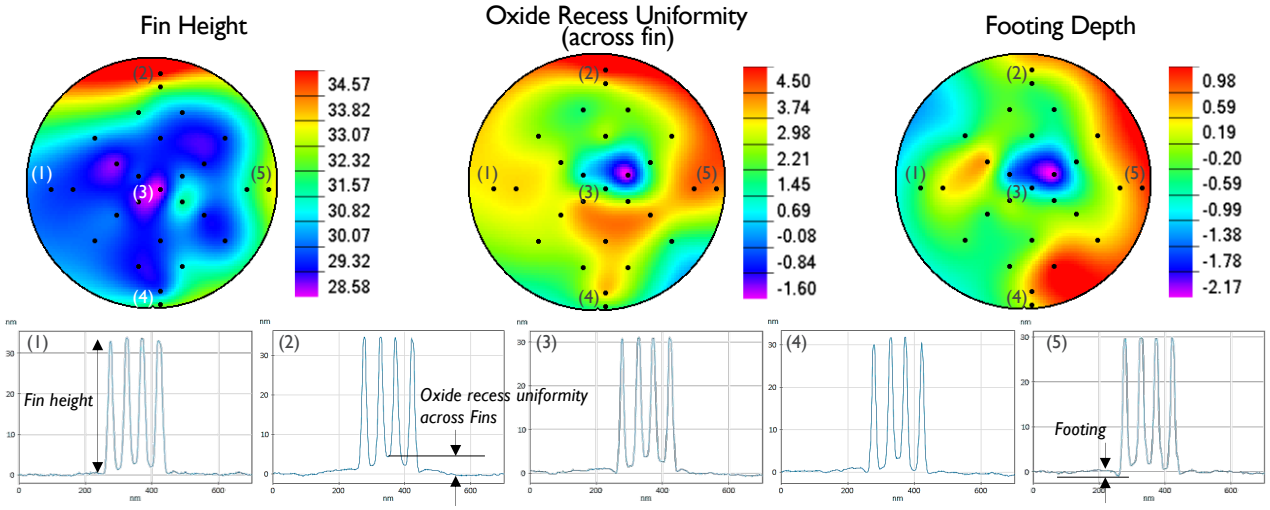
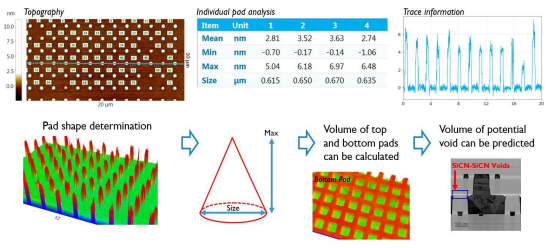
Large Area-High Resolution Measurement Performance



- AFM provides detail topography information of Fin formation at each process step for quick decision making

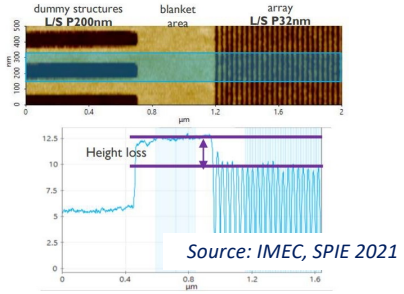
Applications of Current Industrial AFM

Wafer to Wafer Hybrid Bonding



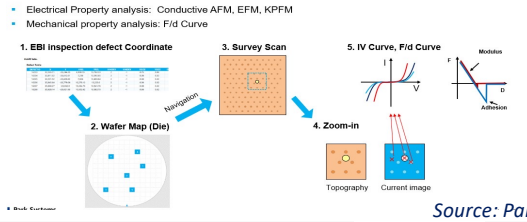
Source: imec

Thin resist (High NA EUV)



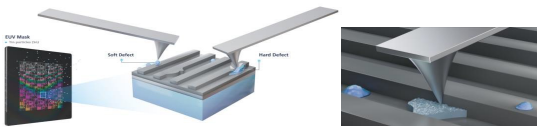
Source: IMEC, SPIE 2021

Electrical Defect Review



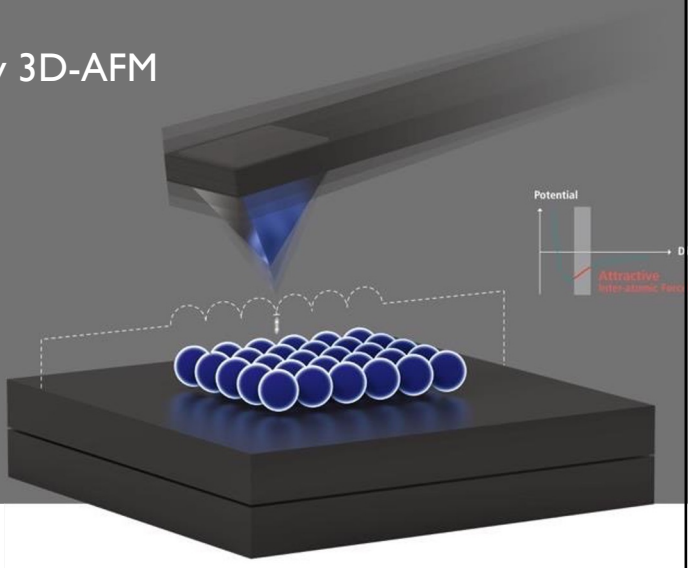
Source: Park Systems

EUV Mask Repair



Source: Park Systems

Pattern Sidewall Characterization by 3D-AFM



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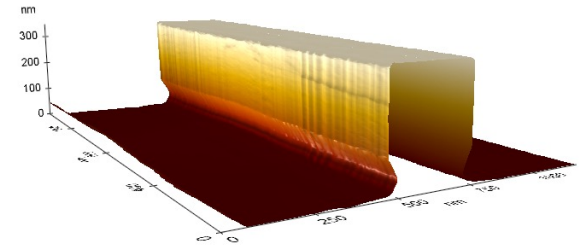
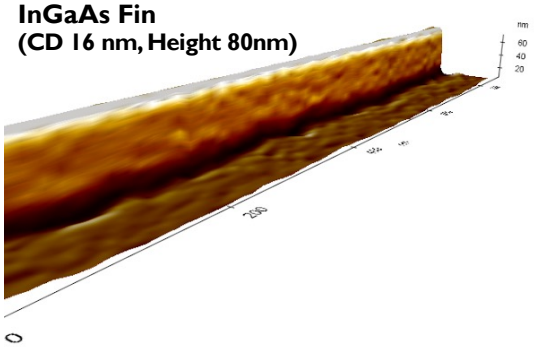
True High Resolution Sidewall Roughness

GaAs Pattern
(CD 100 nm, Height 350nm)



InGaAs Fin
(CD 16 nm, Height 80nm)



- High resolution sidewall roughness could be visualized by 3D AFM with tilted head because of small contact area between tip and sidewall which leads to high spatial resolution

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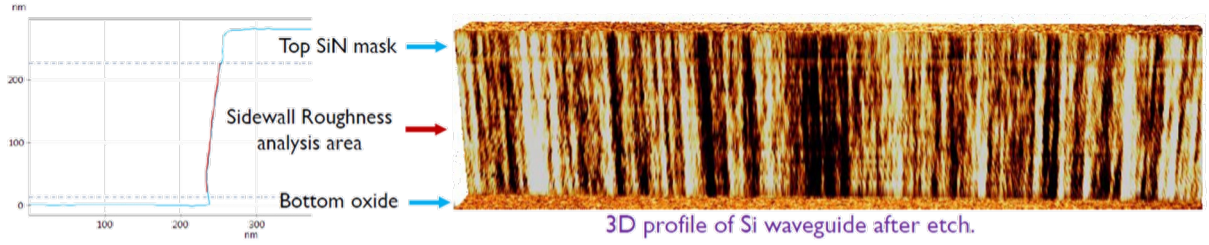
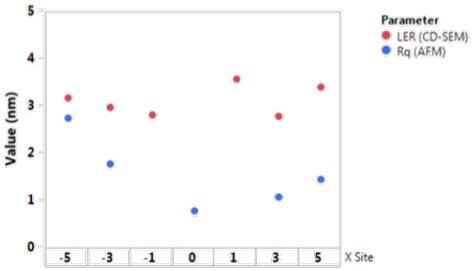
Sidewall Roughness Measurement of Si Waveguide

- 3D-AFM enables direct inspection of surface roughness on the waveguide sidewall.



3D profile of Si waveguide after etch.

- Line edge topography of hard mask layer transfers to Si waveguide pattern
- Similar trend between LER by CD-SEM and sidewall roughness by AFM was observed, but there is an offset.



AFM sidewall roughness vs CDSEM LER

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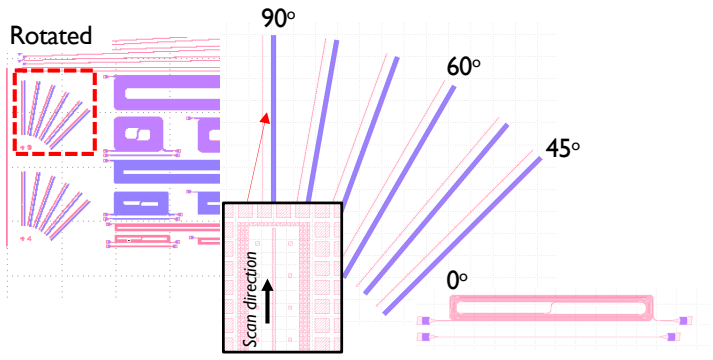
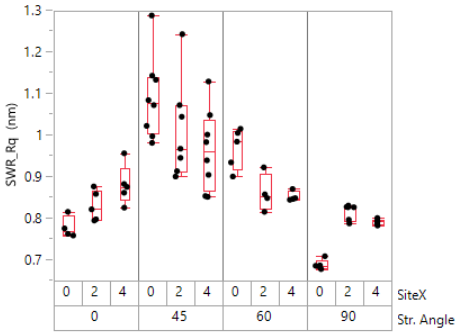
High-Sensitivity Sidewall Roughness Measurement Achievable with 3D-AFM

Sidewall roughness Behavior at Different Patterning Angle





- There might be a structure orientation dependency in sidewall roughness characteristics
- Rsw_q of straight pattern, 0° and 90° show smoother than that of slant patterns, 45° and 60°
- This behavior might be explained by the properties of pattern on mask
  - E-beam writing at slant structure might create more steps due to step scanning than straight structure

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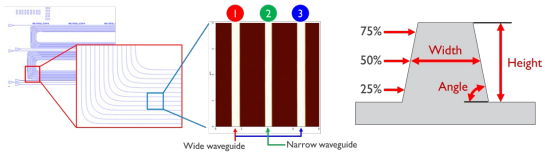
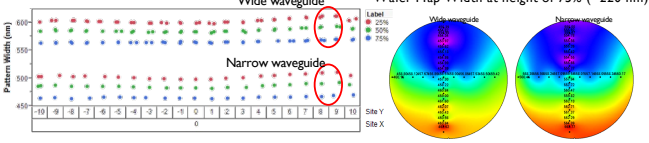
Si Waveguide geometry and sidewall roughness changes

Test structure information

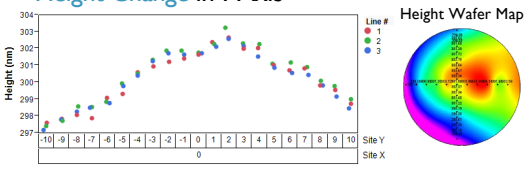


Width Change in Y Axis

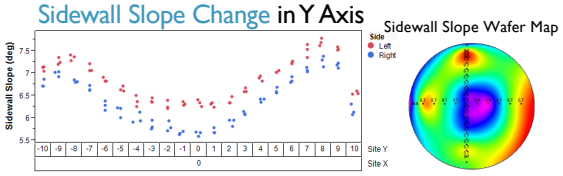


- Width of narrow and wide Si waveguide were captured accurately
- No significant width change in Y axis was observed

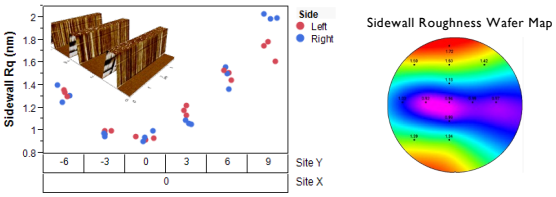
Height Change in Y Axis



Sidewall Slope Change in Y Axis



Sidewall RMS Roughness Change in Y Axis



- Similar sidewall RMS roughnesses were measured no matter of left and right sides except wafer edge

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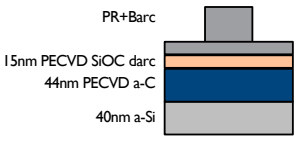
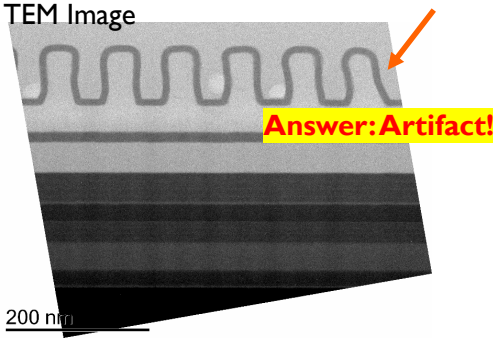
AFM could tell us the true value of the pattern slope

No sample distortion caused by sample preparation occurs

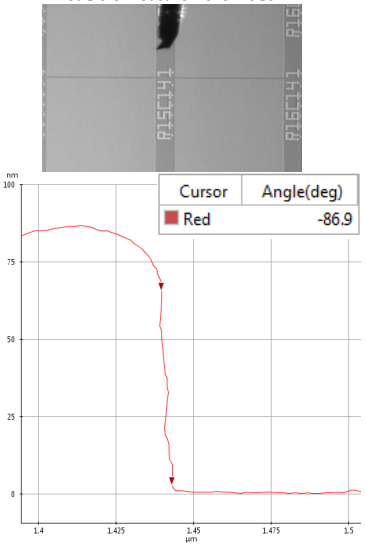
CD ~41nm, pitch 84nm



TEM Image



Head tilt measurement mode



- AFM with the head tilt measurement can give a right answer without sample preparation
- 3D AFM with tilt head is only solution to provide this capability

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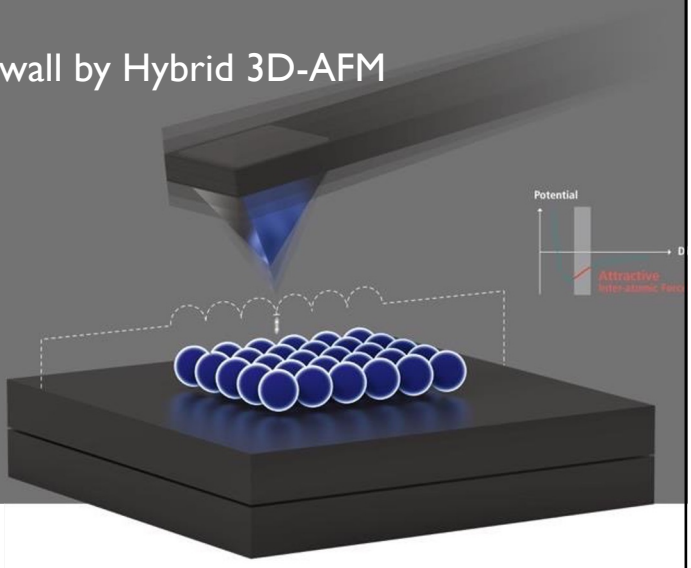
Chemical Properties of Pattern Sidewall by Hybrid 3D-AFM



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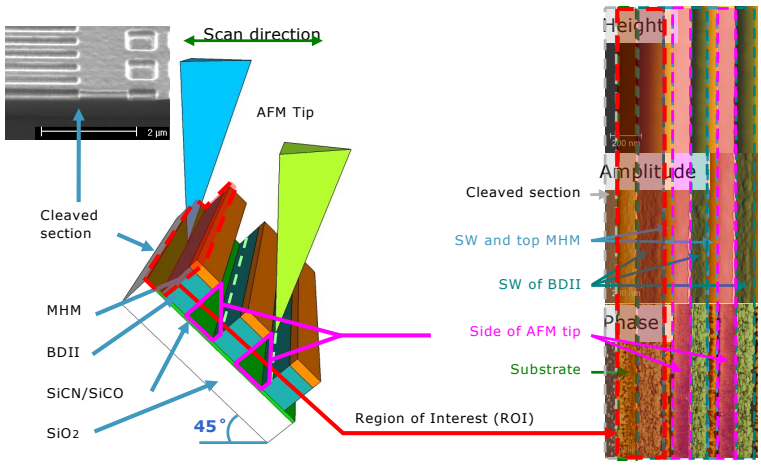
Limitation on Sidewall Measurement

Problem Statement

- Residues remain after the patterning process and should be characterized quantitatively, especially those sticking on the sidewall



Quantitative characterization of the residue sticking on the sidewall needed for better device properties

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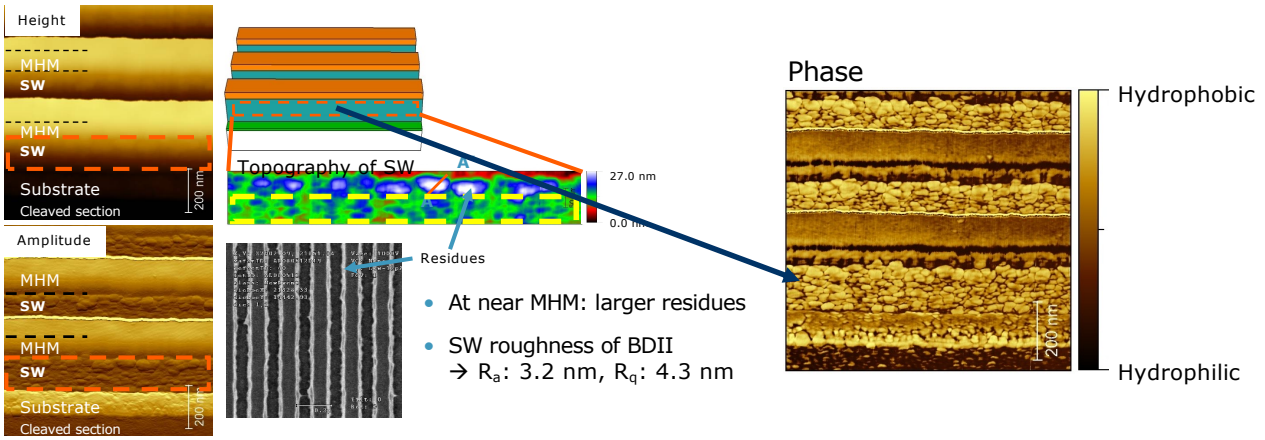
Sidewall Imaging using 3D-AFM with the Functionalized Probe



- At near MHM: larger residues
- SW roughness of BDII
  → R_a: 3.2 nm, R_q: 4.3 nm

- Confirmation of hydrophobic character of sidewall residues

➔ CFx polymers, as seen by AR-XPS, TOF-SIMS and SEM on other samples

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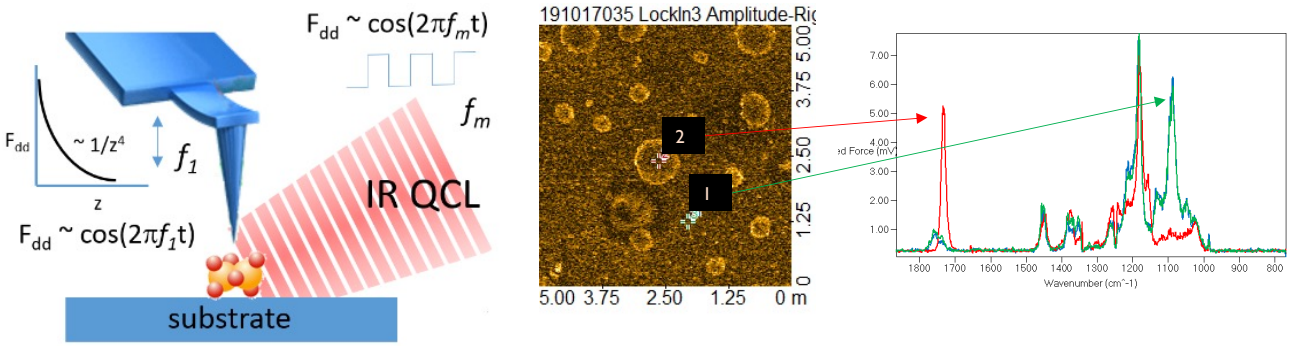
Nano IR technology called Photo-induced Force Microscopy (PiFM) for Chemical Detection



- Combination of AFM and Nano-IR technology
- <10 nm resolution nano-IR imaging
- Higher resolution and sensitivity than conventional FTIR and nano-FTIR

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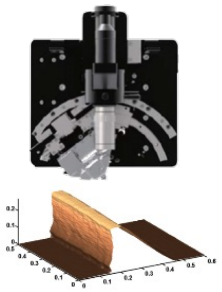
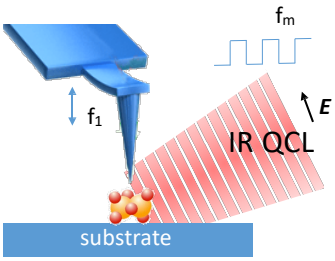
Hybridization of 3D-AFM and PiFM

3D-AFM



PiFM



Broad tunable IR laser
(589 – 4400 cm^{-1})

In-line Defect Review AFM
Topography and Chemical information of the residue sticking on the pattern sidewall

- Hybridization of AFM techniques, 3D-AFM and PiFM could provide a solution providing not only topography but the chemical information of the residues sticking to the pattern sidewall
- The hybridization of different measurement techniques can deliver new value beyond current measurement limits.

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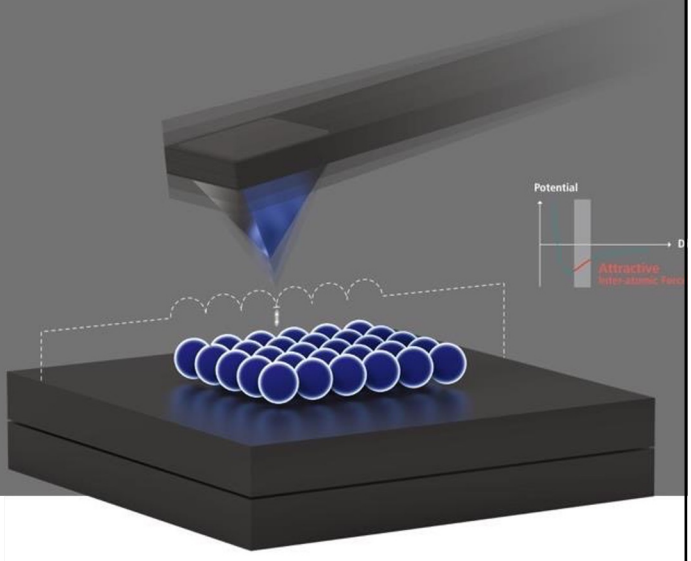
Summary



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Summary

- Industrial AFM has been successfully established for semiconductor surface analysis
  - TEM level atomic resolution full nanotopography information
  - Non-destructive sidewall slope and its roughness
- 3D AFM with the head tilt measurement shows good capabilities in
  - Sidewall roughness
  - Slope and shape of pattern
  - Surface chemistry with chemically functionalized probe
- Journey of Industrial AFM just started and there are many opportunities and business
- The hybridization of measurement technologies to create new value is only possible through technological collaboration, and it will pave the way for various opportunities in the future.

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