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High Speed AFM as an Enabling Technology for Next Generation Semiconductor Devices

Professor Andrew Humphris
Founder and CTO

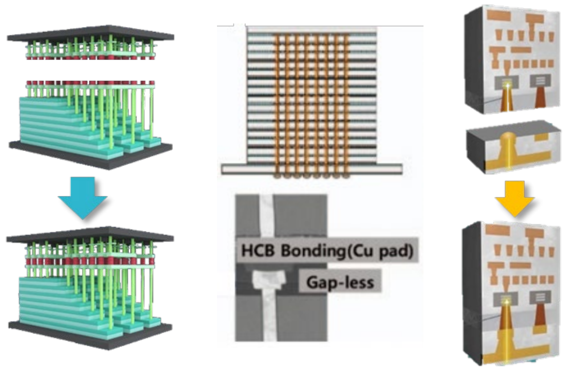
Overview

- Increasing Pressure on Dimensional Metrology
- RPM Hybrid Optical AFM Enables Speed and Accuracy
- Key Application Areas for High-speed AFM
  - Advanced Packaging
  - EUV Lithography
  - High Aspect Ratio Etch
  - Tomography
- Next Steps for High-speed AFM
- Summary

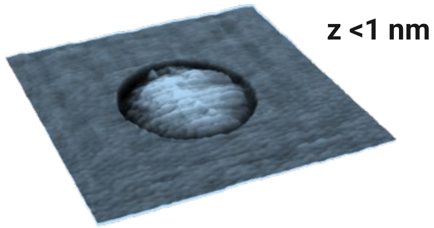
Increasing Pressure on Dimensional Metrology

Heterogeneous Integration

Memory on Logic | HBM & 3D DRAM | Logic BPDN

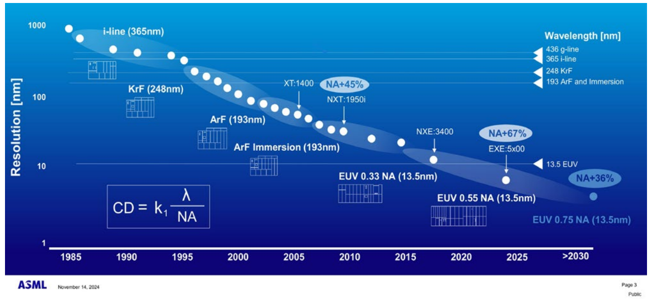


Cu pad recess for Hybrid Wafer Bonding

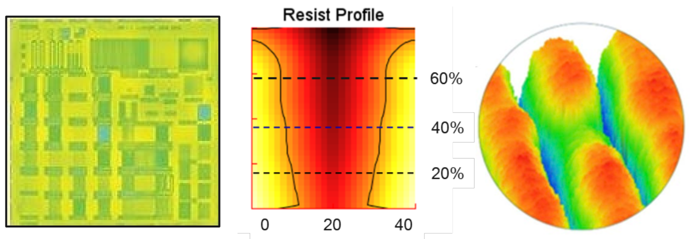


Dimensional Scaling with EUV Lithography

EUV NA: 0.33 → 0.55 → 0.75

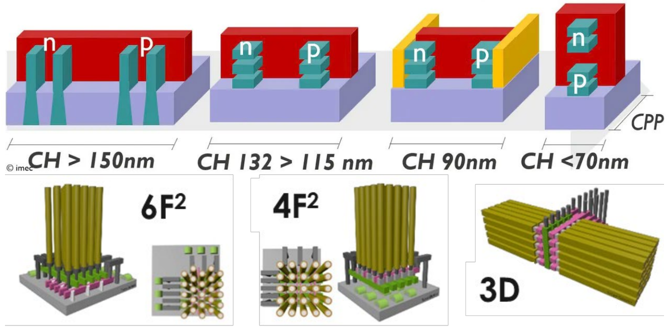


CMP hot spots reduced DoF | 3D resist metrology & stochastic defects

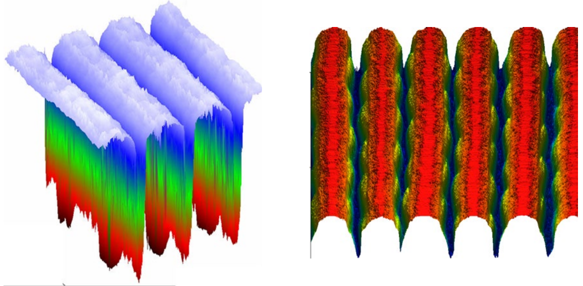


3D Device Scaling

Logic Transistor Scaling
DRAM Cell Scaling & 3D



High Aspect Ratio 3D metrology



Sources include: IMEC, Applied Materials, TEL Investor Relations, ASML, SKHynix

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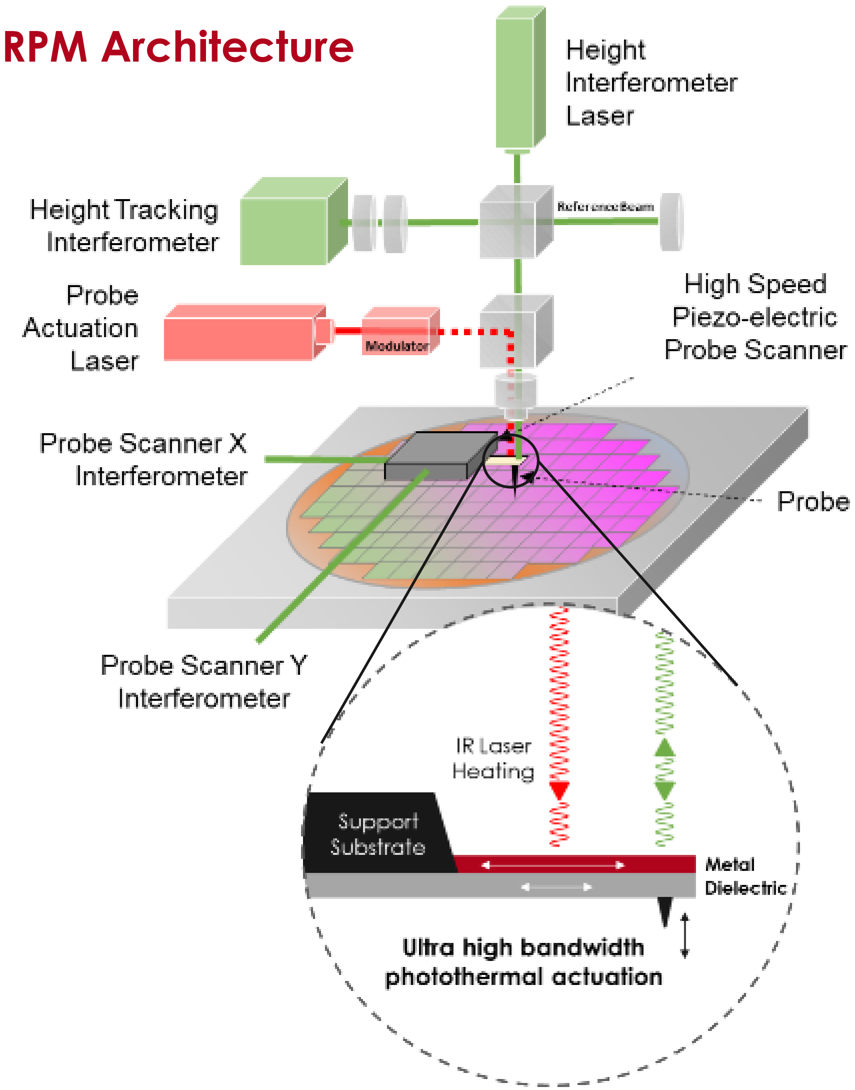
RPM Hybrid Optical AFM Enables Speed *and* Accuracy

Conventional AFM *RPM*

RPM Architecture



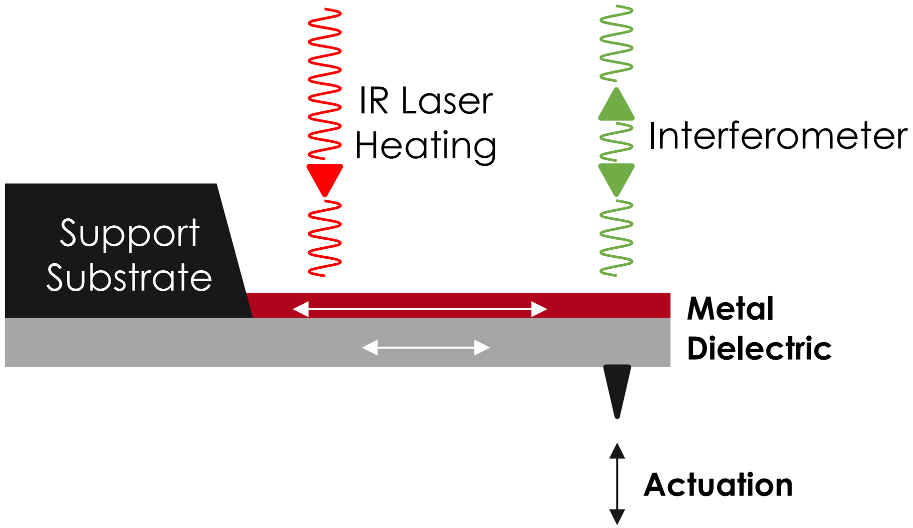
High speed imaging enabled using **photothermal actuation** of cantilever with greater than **>10x higher mechanical resonant frequency** than conventional piezo based AFM.

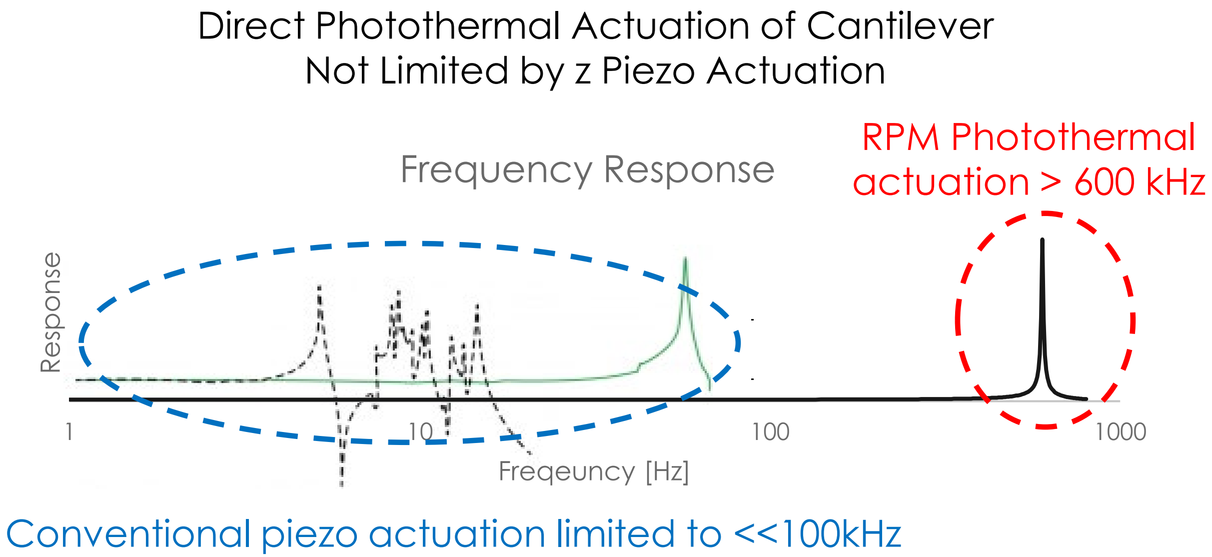
Fast surface detection enabled using **direct interferometer feedback**, 10x faster than conventional AFM systems for 10x longer probe tip lifetime.

Enhanced probe control enabled using photothermal actuation of cantilever to capture each individual pixel with minimum lateral force on topographical structures.

RPM Direct Height Measurement and Photothermal Actuation

Conventional AFM is limited by mechanical response of the piezo actuator
RPM enables higher bandwidth using photo-thermal actuation





- A Photothermal (PT) Drive controls the intensity of the IR laser, which impinges on the cantilever beam
- The thermal expansion of aluminium is greater than silicon oxide which create stress and controlled flexing of the cantilever
- Modulating the intensity of the drive laser enables complex tip motion profiles

Operating Modes

Die by Die Metrology

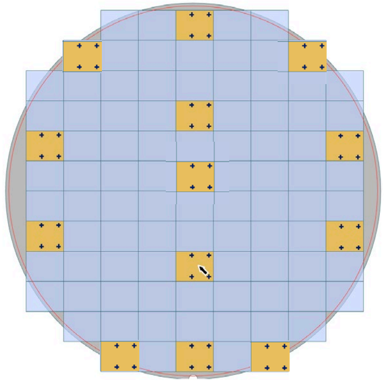
- High speed MAM enables
- In-line SPC capability
- Typical throughput for CHB, 13 sites per wafer, 60 to 100 WPH, < 3 sec MAM

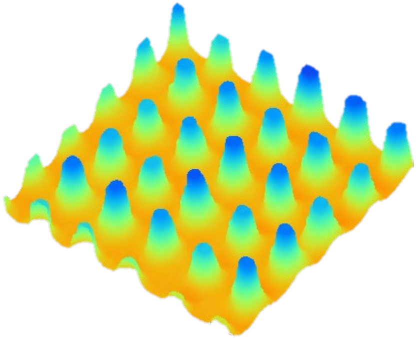
Linear Profiling

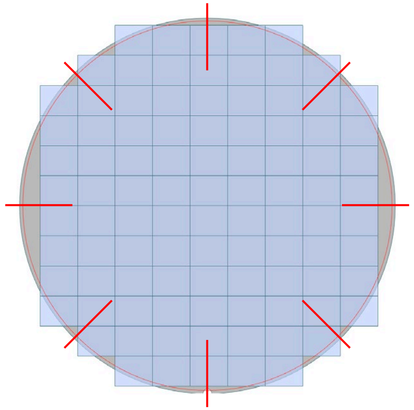
- Wafer edge profile measurement
- Within wafer profiling of scribe lines & keys
- Long range multi-axial line scans

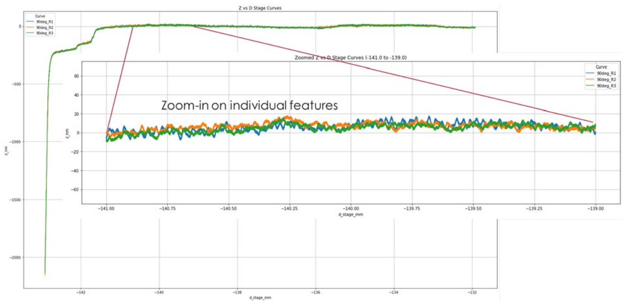
Large Area Metro-Inspect

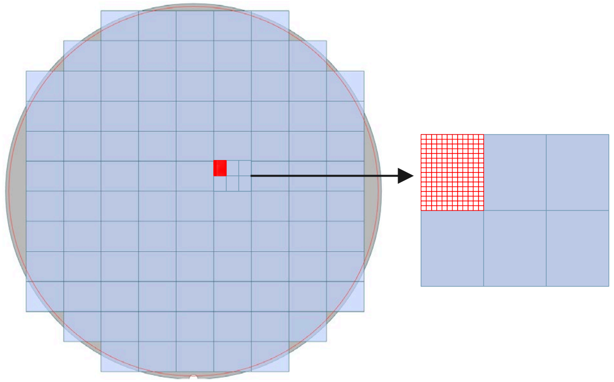
- Full die raster scanning & stitching
- CMP hot spot detection and long-range dishing
- EUV stochastic defectivity

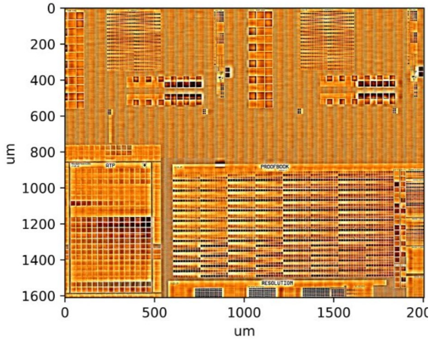








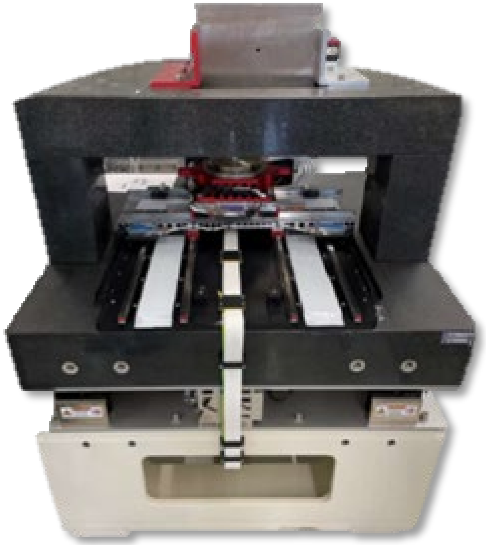




High Speed System Components

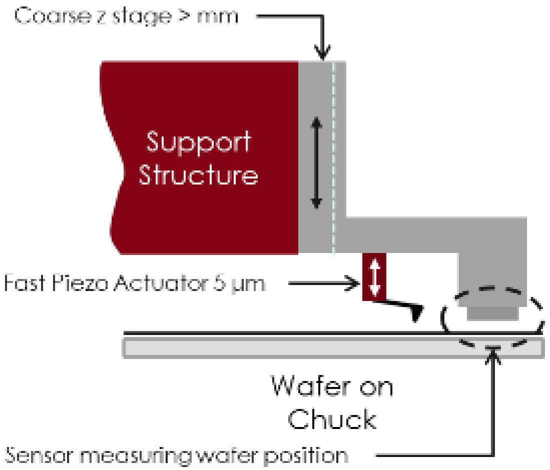
Ultra Low Noise Active Stage

- Ultra-low noise linear motor stage with high accuracy encoders
- Stage motors remain active enabling high dynamic stability either static or in motion



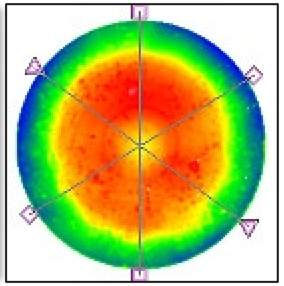
Wafer Surface Position Detection

- Multipoint sub nm accuracy detection system monitor position of wafer
- Enables rapid probe engage
- Long range measurement accuracy and correct for any positioning errors

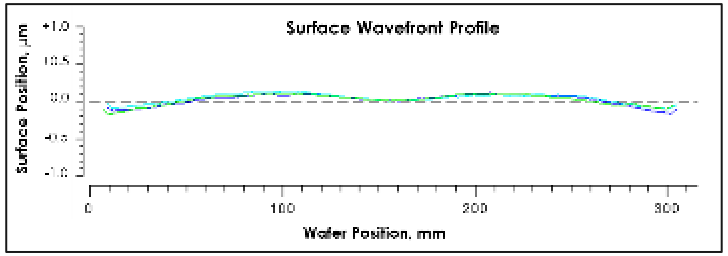


Ultra Flat Ceramic Chuck

- Ultra-flat and stiff chuck for low noise and large area measurement application



343nm pk-pk



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Opportunity Space for High-Speed AFM : CMP (FEOL / HWB)

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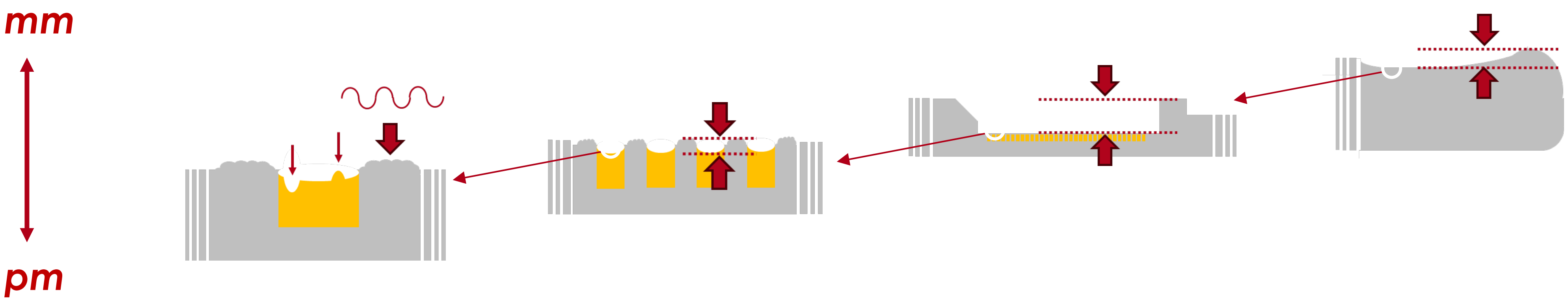
High speed AFM offers a solution for CMP process control at all length scales

- Address need for multiple tool types to control all key parameters
- Avoids need for metal coating (WLI) hence wafer rework or scrap.
- Avoids the need for ground truth model calibration (OCD)
- Flexibility to measure all features irrespective of pattern (OCD)

Requirement	OCD	WLI	High Speed AFM
Cu recess depth	Yes	Yes	Yes, Å resolution
Local pad variation	No	No	Yes
Surface roughness	Yes	Yes, um level	Yes, pm level
Wafer Edge Roll Off	In development?	No	Yes, multi-axial
Long range flatness	No	Yes	Yes
Recipe Set-up	~ 1 week	?	~ 1 hour
Speed, MAM	< 1sec	<10 sec	2~3 sec
Cost / Measurement	Low	Medium	Single tool solution
Challenge	Needs model calibration with AFM or TEM. Regular pad layouts only.	Film Interference. Low resolution/contrast	Charge mitigation Probe lifetime

Hybrid Bonding - CMP Flatness is Critical at *All* Scales

	Hyper Local	Local	Long Range	Very Long Range
Measurements	**Dielectric Roughness LCDU**	**Pad profile (dishing)**	**Long range flatness e.g. erosion**	**Wafer edge flatness**
Lateral Scale	50 nm - 0.5 um	5 – 50 um	1 - 30 mm	10 mm - 50 mm
Height Scale	50 pm – 2 nm	0.5 – 15 nm	1 – 5 nm	100 nm - 5 um

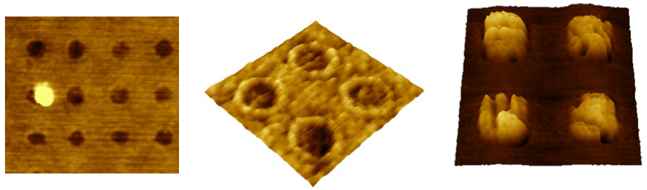


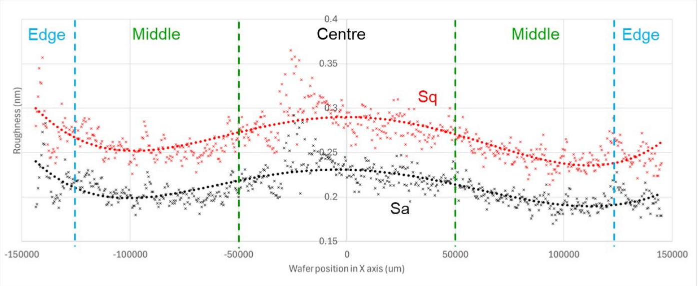
High Speed AFM - Single Tool from pm to mm Scale

Hyper Local

Example:

- Hyper local information in each image
- Individual pad features
- Dielectric roughness



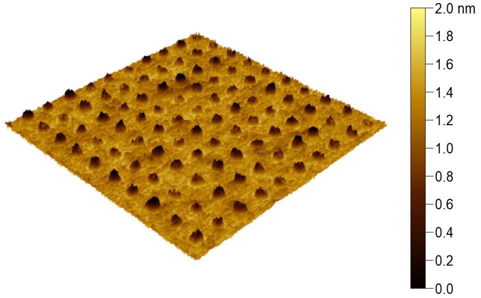


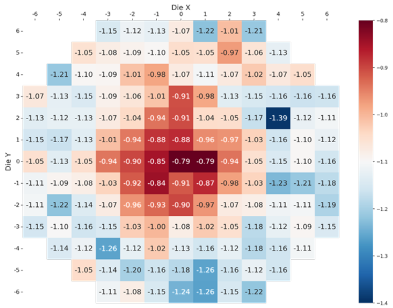
Roughness Wafer Profile
Measurement noise floor < 100 pm

Local

Example:

- ~40 nm pads, ~1 nm depth FEOL
- 13 sites
- In-line throughput at **60 WPH**

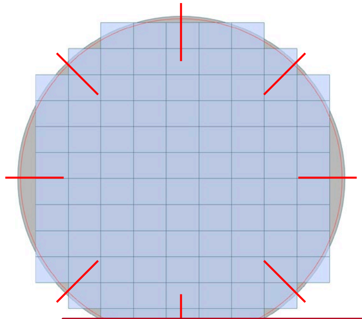


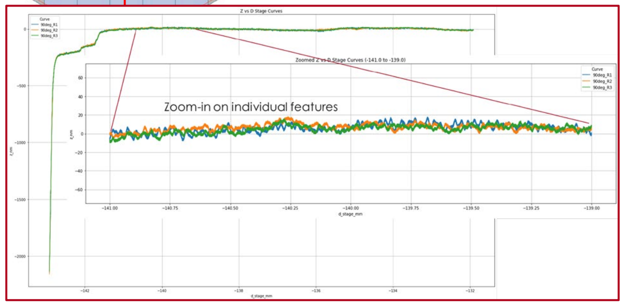


Long Range

Example:

- Wafer edge roll off
- 20mm profile, 12 angles (30º)
- In-line throughput at **30 WPH**





Sources include: imec, partners

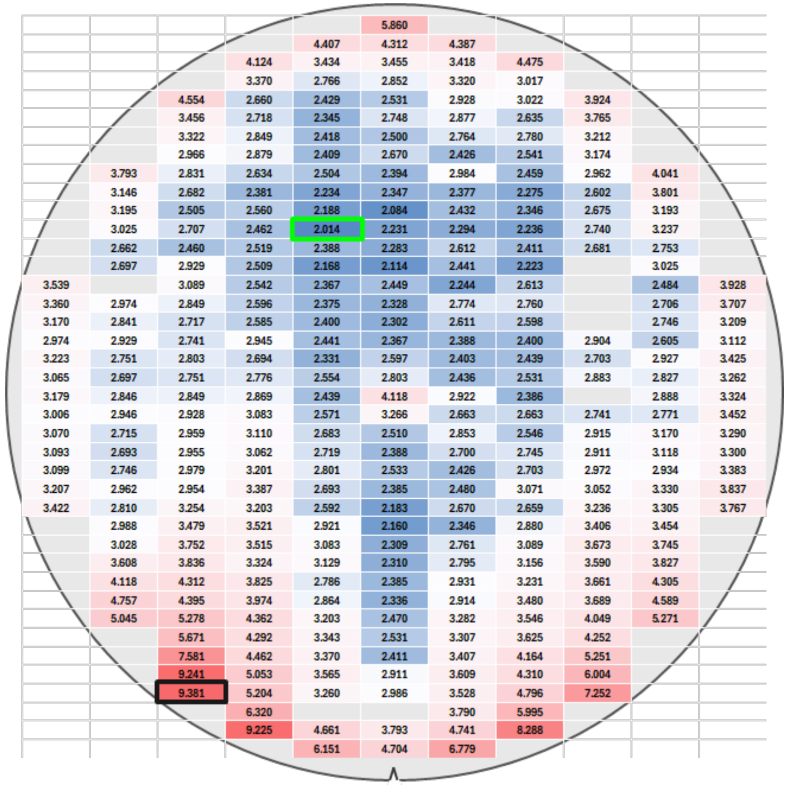
Full Wafer Cu Pad Recess Metrology

Measurement Summary

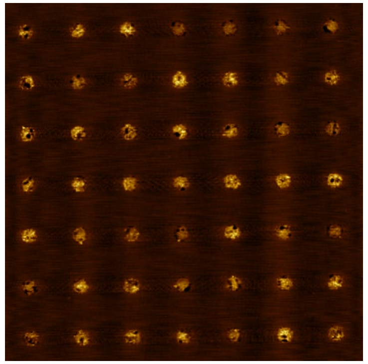
Acquisition time per image	3 seconds (*current capability <1.6s*)
MAM time	**4.9 seconds**
Total wafer map time	**1 hour, 21 minutes 36 seconds**
Total dies	334
Images per die	3
Total images per wafer	1,002
Field of View used per image:	7 x 7 µm
Pixels per image	512 x 512
Total pixels per wafer	2.6 billion
Probe distance travelled	3.6 meters

*Note: **Single probe used for all measurements***

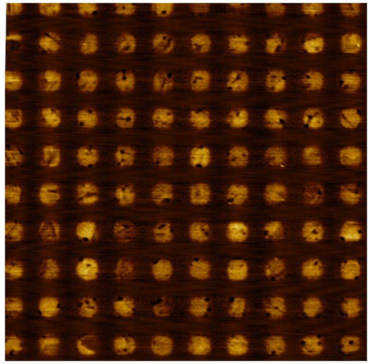
Imec 3DSOC KD4
(W2W hybrid bonding project)



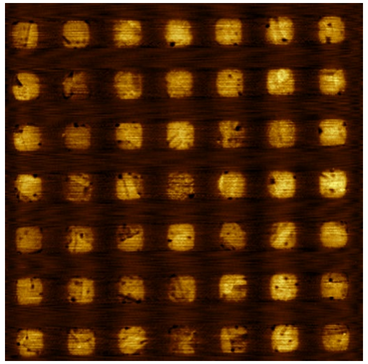
Example Measurements



250 nm pad, 1000 nm pitch



350 nm pad, 700 nm pitch



500 nm pad, 1000 nm pitch

Data Courtesy: imec

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Opportunity Space for High-Speed AFM : EUV Resist DI Metrology

High speed AFM offers a solution for High NA system set-up and in-line process monitoring

- Only solution for optimisation of dose, focus, and systematic stochastic defects in 3D.
- Enables full 3D in-line performance monitoring without damage to resist (CD SEM)

Requirement	OCD	CD SEM	High Speed AFM
CD	Target only	Yes	Yes
LCDU	No	Yes	Yes
Stochastic effects	No	Partial	Full
LER / LWR	No	Yes	Yes, in 3D
Profile / Feature depth	Global / Model	No	Yes
Surface roughness	No	No	Yes
Resist Thickness (blanket)	Yes	No	Yes
Resist loss (pattern)	Yes	No	Yes
Recipe set-up	~ 1 week	~ 1 hour	~ 1 hour
Speed, MAM	< 1sec	Few seconds	Few seconds CD only 15 – 30 sec full 3D
Cost / Measurement	Low	Low	Medium
Challenge	No local data Requires model calibration	Resist shrinkage No 3D information	Probe contamination

High Speed AFM – Full 3D resist characterisation

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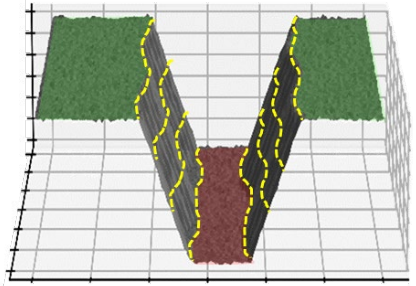
Surface Characterisation

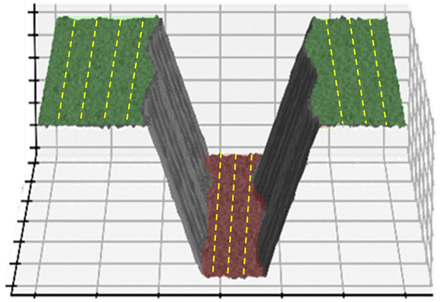
Example:

- LER / LWR at any x-section
- Resist surface and feature bottom surface roughness

Line Edge Roughness & Line Width Roughness



Top Surface & Bottom Surface Roughness

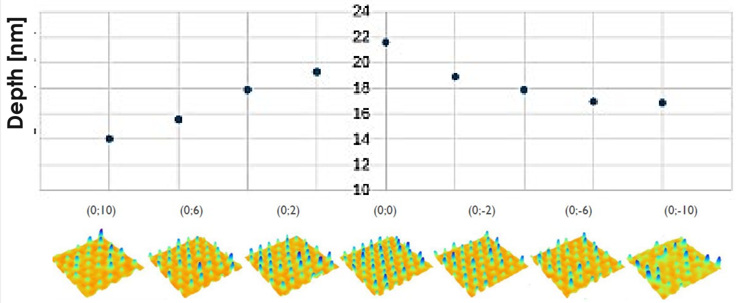


3D Metrology

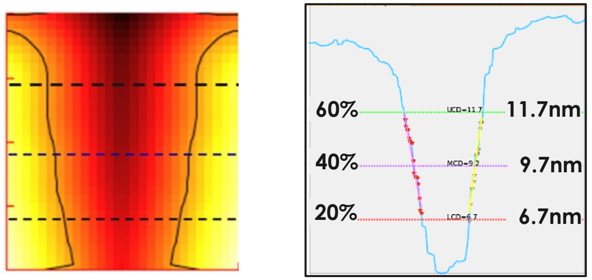
Example:

- Quantify 3D feature dimensions & determine if fully resolved
- Quantify local variance

Global & Local Feature Depth Variance



Resist Sidewall Angle & CDs at any threshold

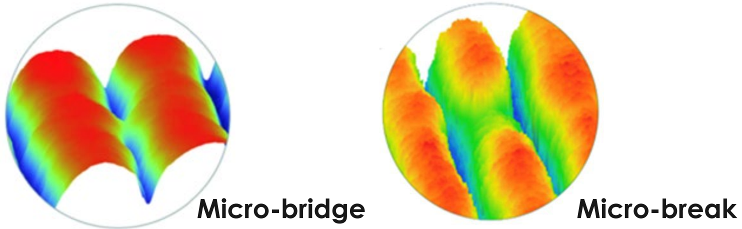


Pattern and Process Variability

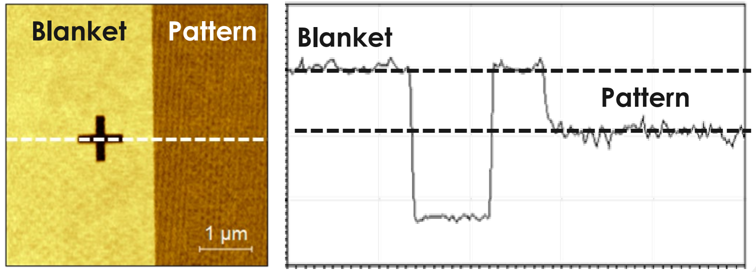
Example:

- Identify & quantify stochastic resist defects
- Quantify pattern dependent resist loss

Stochastic Defects

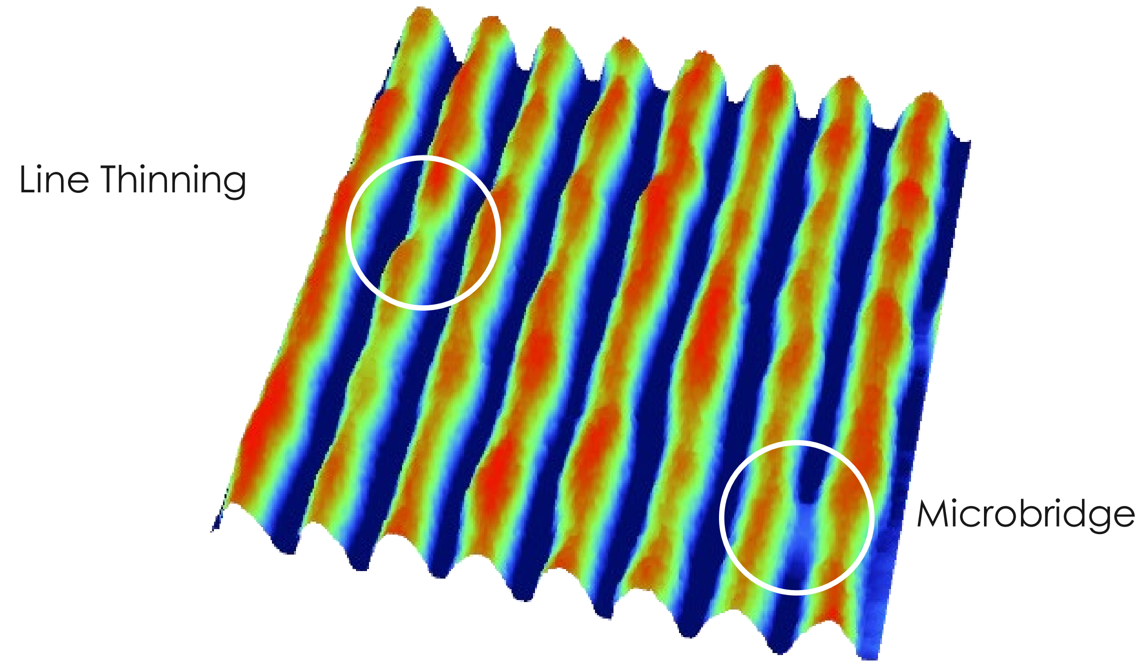


Pattern dependent resist loss



Sources include: IMEC, Applied Materials, TEL Investor Relations, ASML, SKHynix

Lithography - Extraction of 3D Resist Parameters – 14nm L/S



- Probe deconvolution algorithms for true (lateral) CD extraction
- Measurement of CD, LER, & LWR at arbitrary depths

Metrology	Value
Trench Depth	15.70 nm
Critical Dimension @ 2 nm Depth	14.3 nm
Critical Dimension @ 5 nm Depth	10.5 nm
Critical Dimension @ 10 nm Depth	6.2 nm
Line Edge Roughness @ 5 nm	2.1 nm
Line Width Roughness @ 5 nm	4.6 nm
Line Top Roughness (Ra)	0.62 nm
Trench Bottom Roughness (Ra)	0.46 nm
Side Wall Angle	62.5°

Data Courtesy: ASML

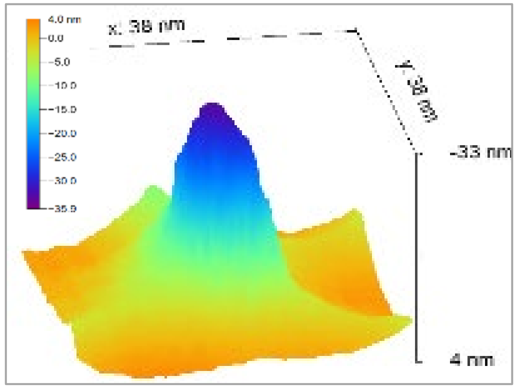
Contact Hole FEM Analysis – 16 nm Nominal Dia.

- Probe deconvolution algorithms for true profile extraction
- Data Analysis algorithms extract CD, circularity, resist top surface roughness and other parameters
- Litho tool and process setup, in – line process monitoring as part of SPC

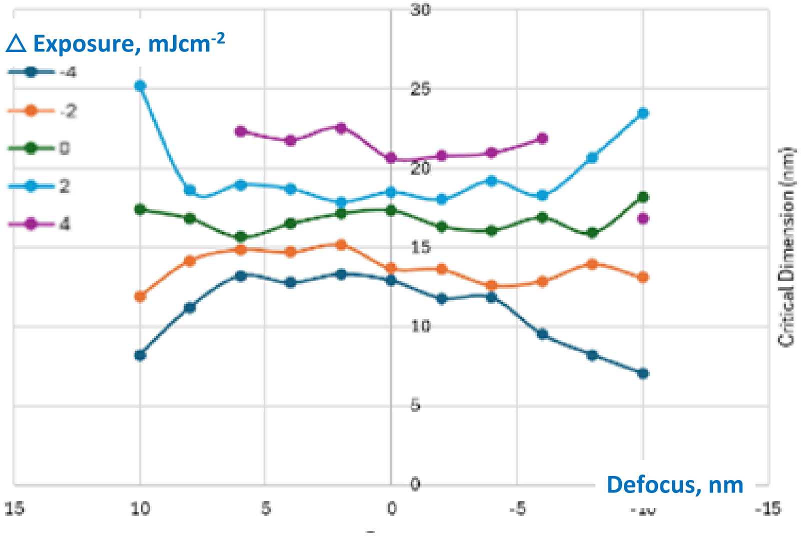
CD @ 5nm depth

	-4	-2	0	2	4
-10		13.1	18.2	23.5	
-8		13.9	15.9	20.7	
-6	9.5	12.9	16.9	18.3	21.9
-4	11.8	12.6	16.1	19.2	21.0
-2	11.8	13.6	16.3	18.0	20.8
0	12.9	13.7	17.3	18.5	20.6
2	13.3	15.2	17.1	17.9	22.5
4	12.8	14.7	16.5	18.7	21.8
6	13.2	14.9	15.7	19.0	22.4
8	11.2	14.2	16.8	18.6	
10		11.9	17.4	25.2	

Inverted CH Profile



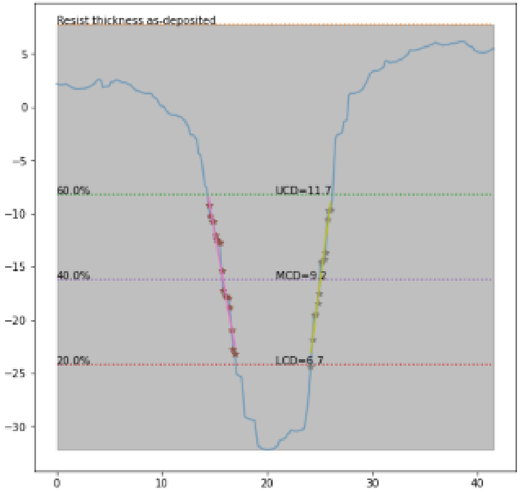
Bossung Plots – CD at 5 nm resist depth



LCDU @ 5nm depth

	-4	-2	0	2	4
-10		2.6	6.1	11.2	
-8		2.3	2.6	5.7	
-6	0.6	2.5	2.8	3.7	5.8
-4	2.2	2.7	2.0	2.9	4.7
-2	1.9	1.7	2.4	2.7	4.3
0	2.1	2.4	2.0	2.8	3.4
2	1.5	2.5	2.3	2.4	11.3
4	3.5	2.2	2.2	2.7	8.4
6	2.2	2.4	2.6	3.2	7.5
8	2.7	2.5	2.8	2.6	
10		2.3	5.9	8.3	

CH Profile Analysis



32 nm pitch contact holes, 40 nm CAR

Data Courtesy: imec

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Opportunity Space for High-Speed AFM : HAR structures

High speed AFM offers a solution for process monitoring and fast ground truth calibration of OCD

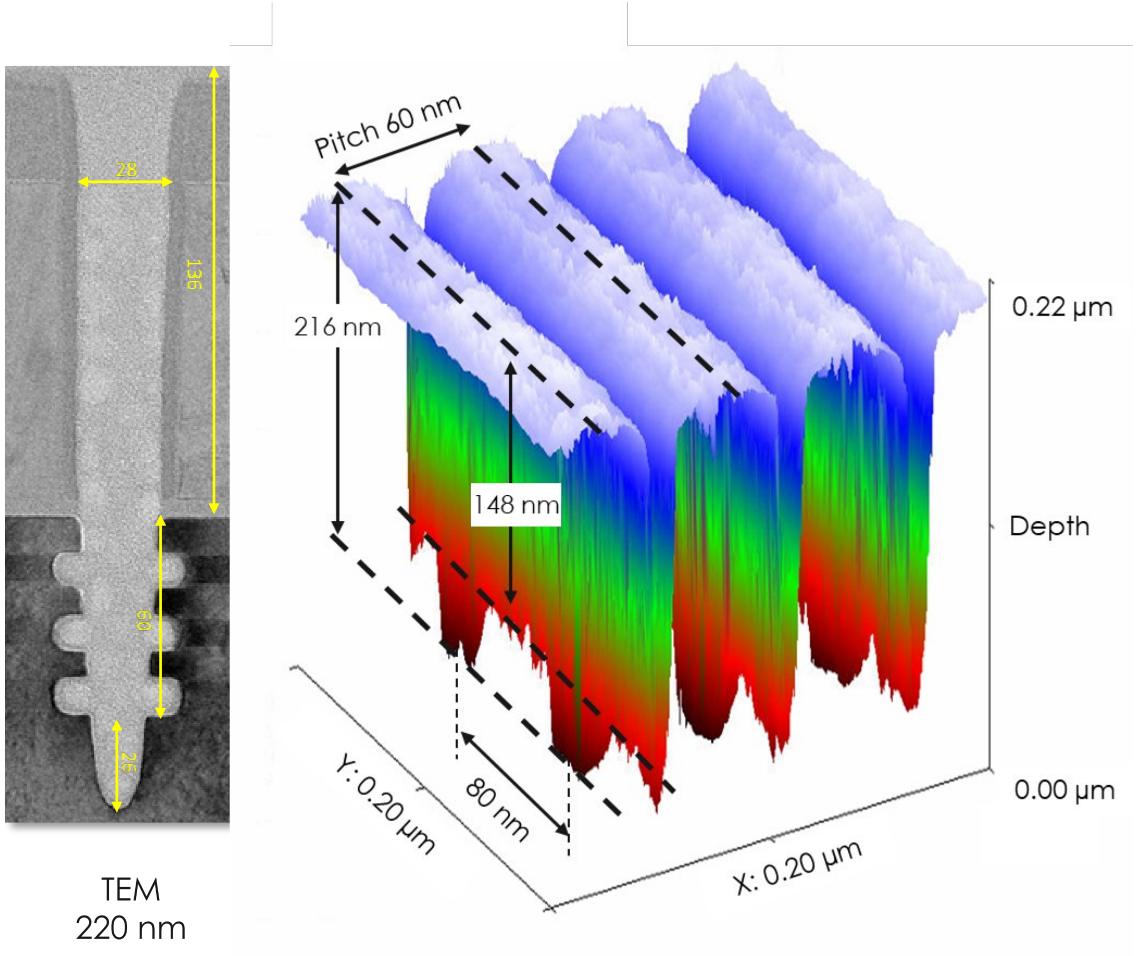
- Enables fast non-destructive (compared to TEM) calibration of OCD
- Potential to measure some complex sidewall structures e.g. GAA
- In-line process monitoring without need for complex model build and monitoring (OCD)

Requirement	OCD	TEM	High Speed AFM
CD	Target only	Yes	Yes
LCDU	No	No	Yes
Feature depth	Global (Model)	Yes	Yes
Profile <90 deg	Global (Model)	Yes	Yes
Profile >90 deg, recesses	No	Yes	Model or 3D tomography*
Recipe set-up	~ 1 week	Sample prep??	~ 1hour
Speed, MAM	Seconds	Hours	1~2 mins
Cost / Measurement	Low	High	Medium
Challenge	Very complex model complexity. Model sensitive to small changes in process.	Destructive	Accurate tip / force correction. Aspect Ratio limited 3:1 ~10:1

** Using on axis automated probe switching*

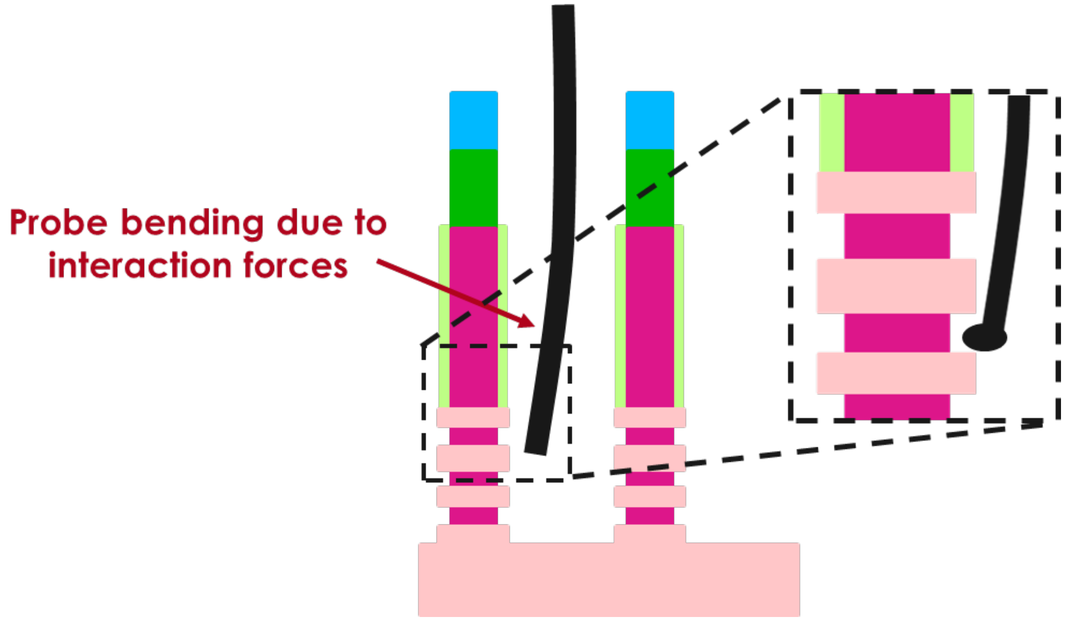
High Aspect Ratio 3D Metrology

GAA – 1:8 aspect ratio



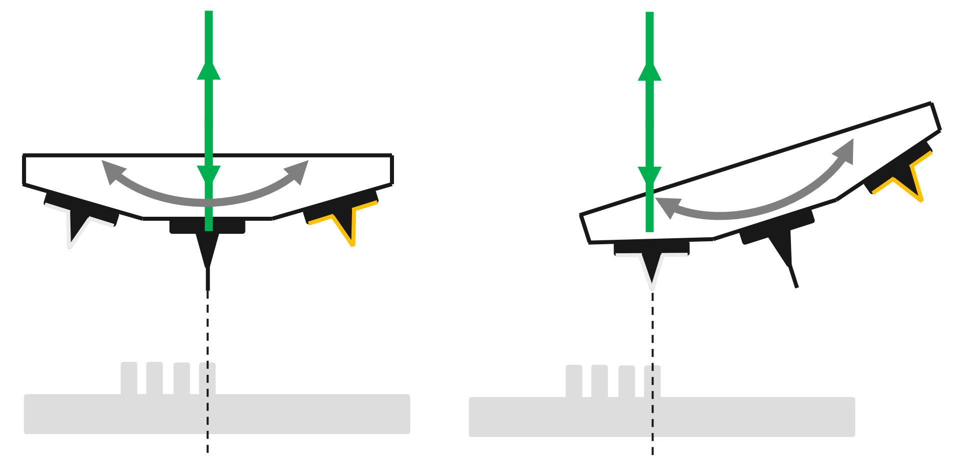
TEM
220 nm

Probe bending enables access to re-entrant structures

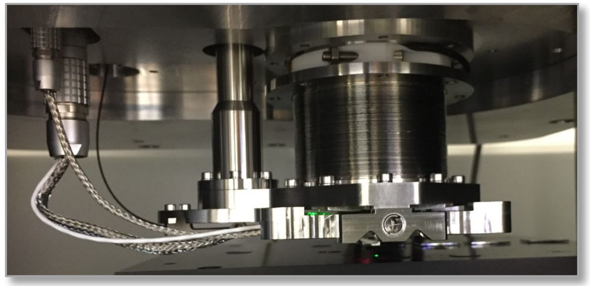


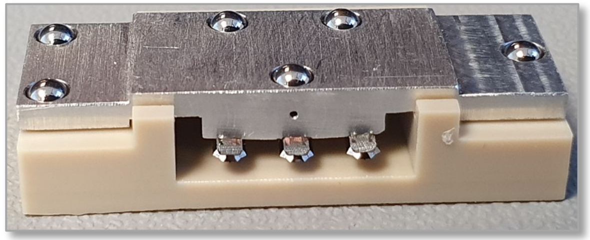
High-speed On Axis Probe Switching

- High speed alternative to TEM for sub-surface structures that do not have surface probe access
- Electrical characterisation with simultaneous CAFM and SSRM
- Automated probe switching and positioning
- Optimum probe for selection for material removal and electrical measurements

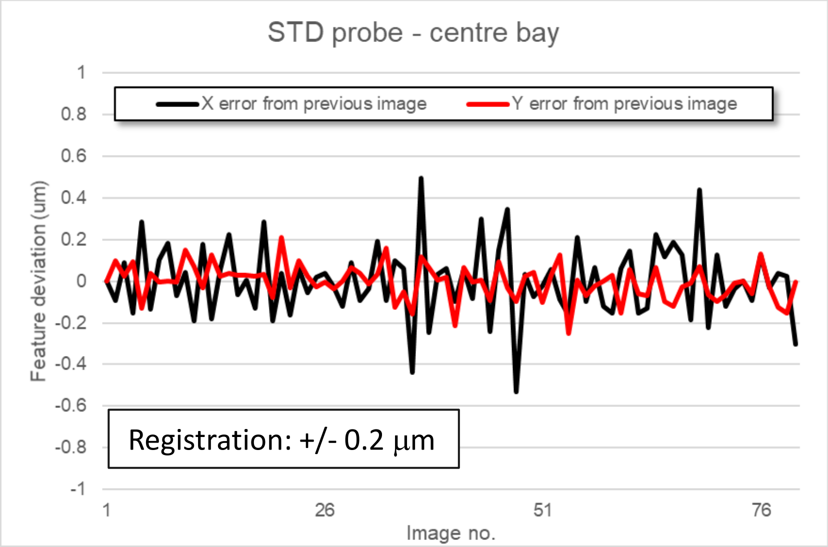


Sample registration maintained during switching of probe





Probe Switching Performance

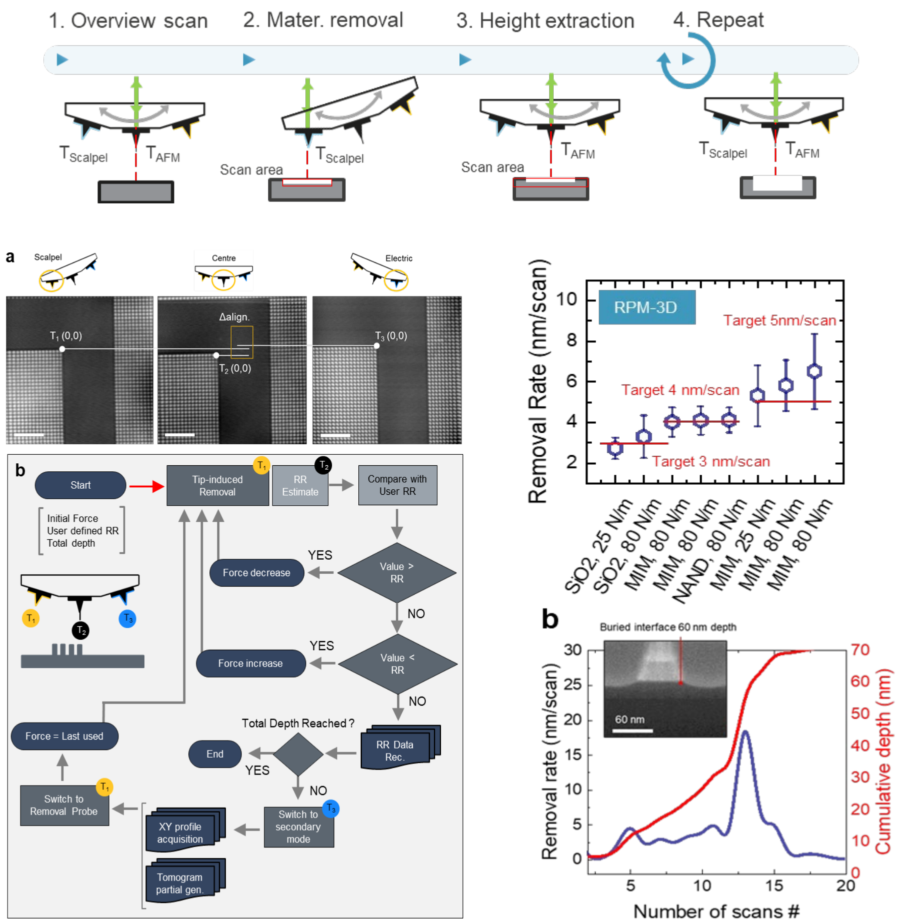


Example Probe Types and Applications

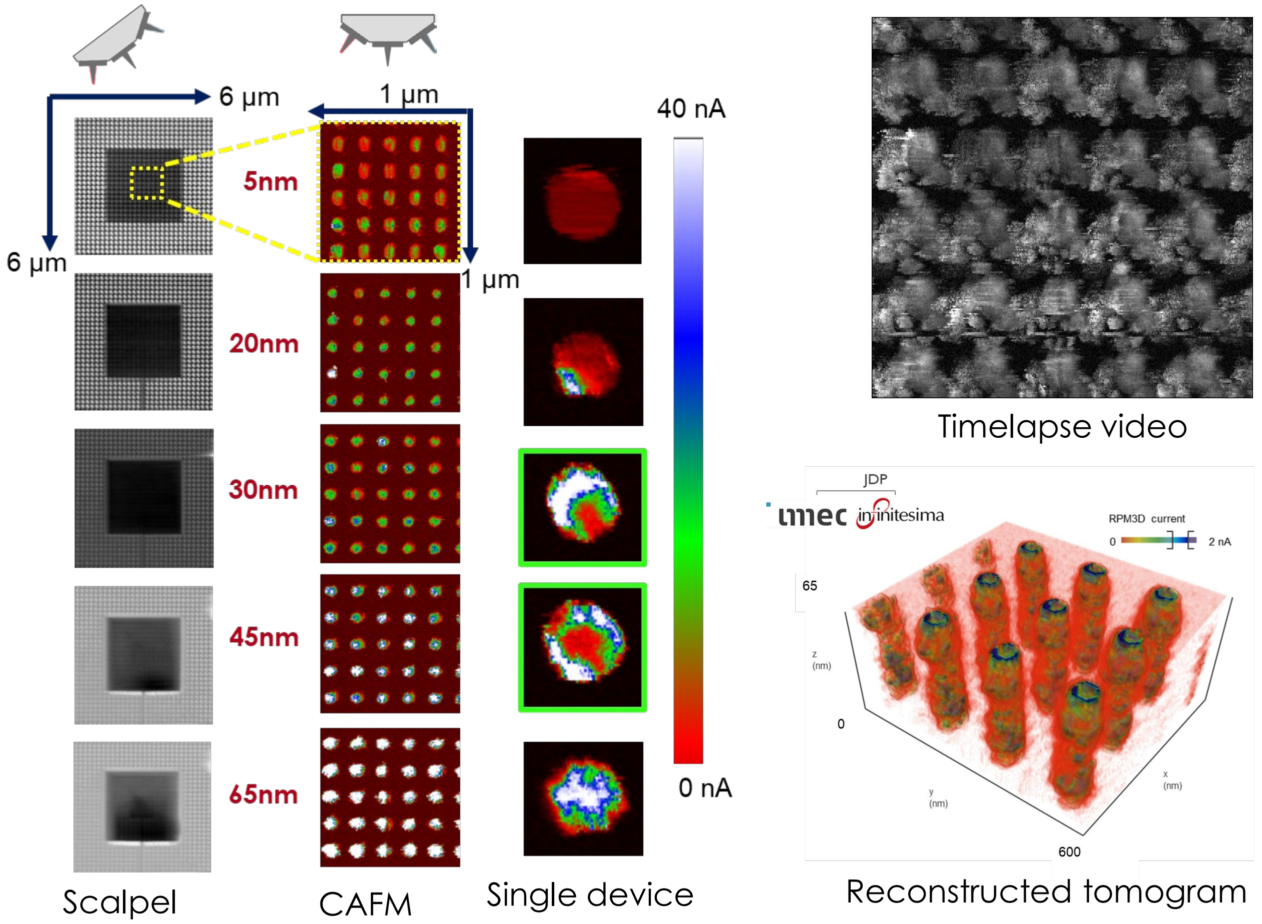
- High aspect ratio tip for 3D profiling e.g. 15 x 200 nm or 7 x 40 nm
- Conventional tip or other for material characteristics e.g. conductive, magnetic
- Further alternative tip for sample modification e.g., hardwearing diamond

High-speed AFM for Tomography

Removal Rate Control



Extended tomographic capability



Data Courtesy: imec

[Celano, U., et al., IPFA Tech. Dig. 2023]
[Sharma, D., et al., Electronic Device Failure Analysis, Nov. 2023)]

Overview

- Increasing Pressure on Dimensional Metrology
- RPM Hybrid Optical AFM Enables Speed and Accuracy
- Key Application Areas for High-speed AFM
  - Advanced Packaging
  - EUV Lithography
  - High Aspect Ratio Etch
  - Tomography
- **Next Steps for High-speed AFM**
- Summary

Summary

- High speed AFM enables ground truth metrology to transition to in-line production
- Three key areas where high speed AFM supports industry challenges:

  1. Hybrid wafer bonding ► Flatness at all scales

  2. EUV ► 3D metrology

  3. HAR ► Etch depth, side wall & re-entrant structures

  ► Tomography

- The technology is further scalable

imec ASML

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Metron^{3D}

Thank you!