Scanning Probe Microscopy: Pushing the Boundaries with Multi-Probes and Reverse Tip Sample Scanning

Umberto Celano & Thomas Hantschel

On behalf of

H.S. Kim, P. Lagrain, A. Minj, N. Peric, J. Serron, L. Wouters, D. Sharma, M. Tedaldi, A.D.L. Humphris

Outline

Pushing the Boundaries with Multi-Probes and Reverse Tip Sample Scanning

- Introduction
- Multi-probes sensing
- Reverse tip-sample scanning

On the impact of **SPM** in Nanoelectronics

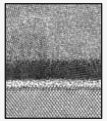
Applications

Transistors: 134,000
Min. feature size: 1.5 µm

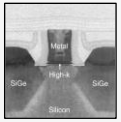
Transistors: 1,200,000
Min. feature size: 0.8 µm

180 nm

High-k + MG



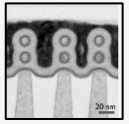
45 nm



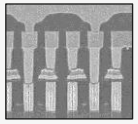
FinFET

Spintronics

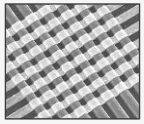
GAA/Nanosheet



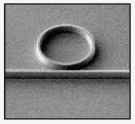
FeRAM



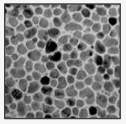
Emerging memory



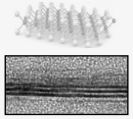
Photonics



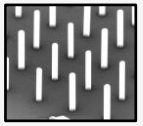
HAMR



2D Materials

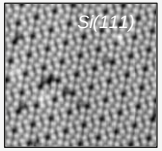


V-GAA



1980 | 1990s | 2000s | 2010s | Today

Techniques



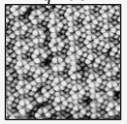
STM

AFM

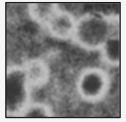
MFM

C-AFM

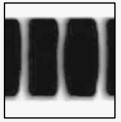
qPlus



AFM IR



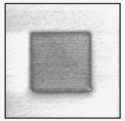
Sidewall AFM



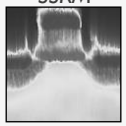
TERS

SCM

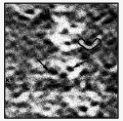
PFM



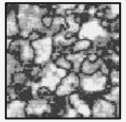
SSRM



PSTM

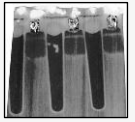


BE-PFM



Scalpel SPM

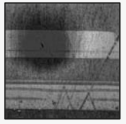
sMIM



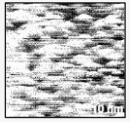
SNOM

KPFM

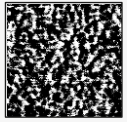
SThM



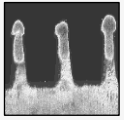
s-SNOM



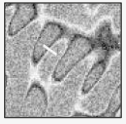
Force mapping



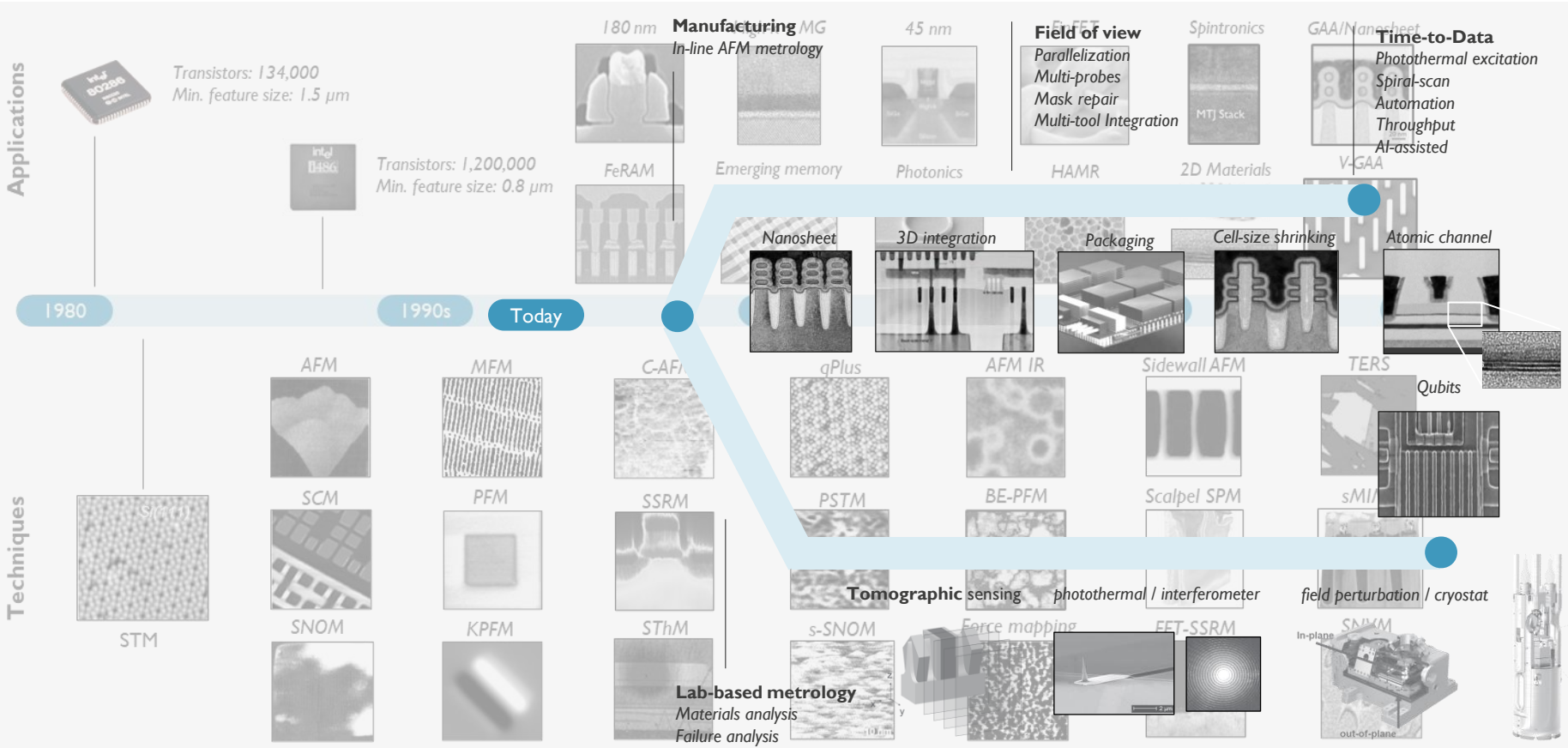
FFT-SSRM



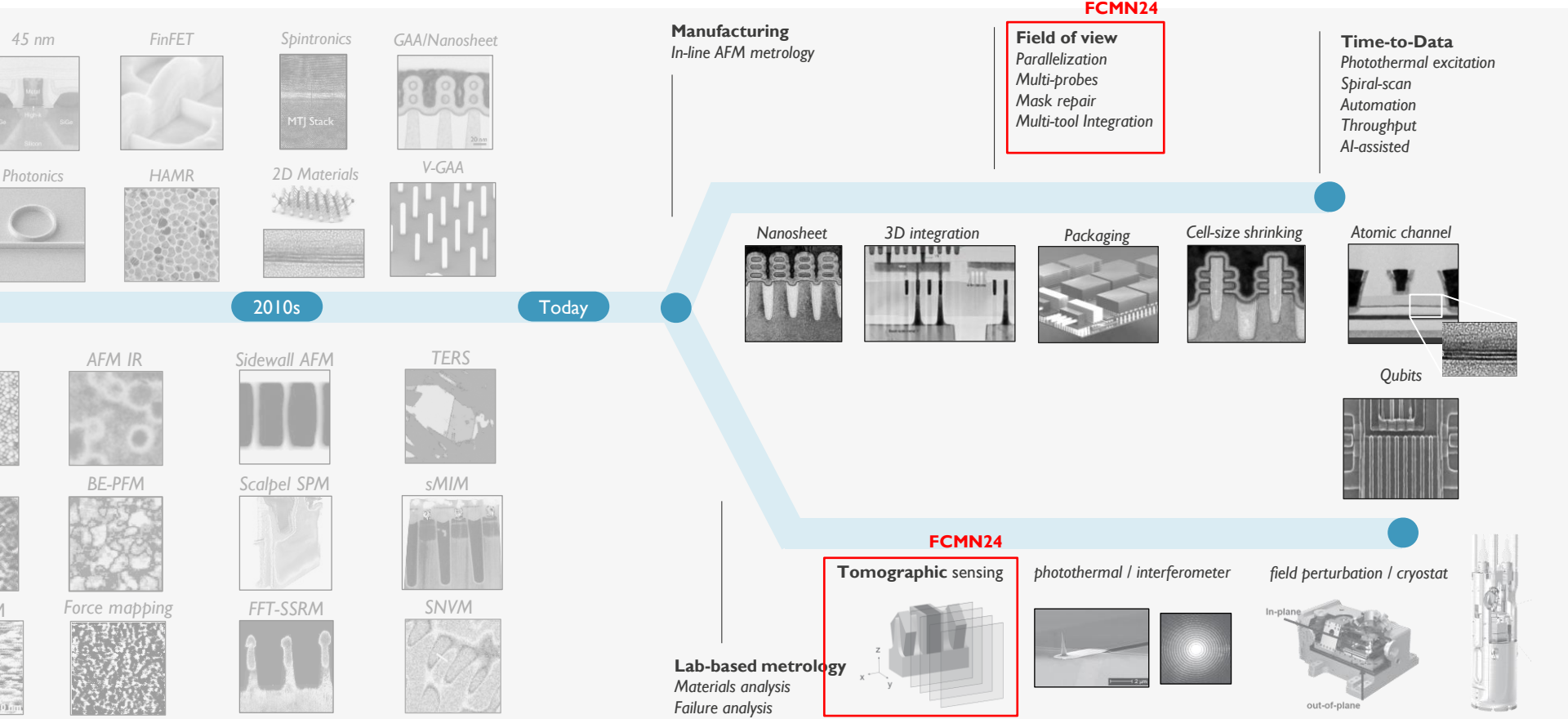
SNVM



On the impact of **SPM** in Nanoelectronics

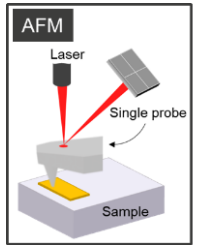


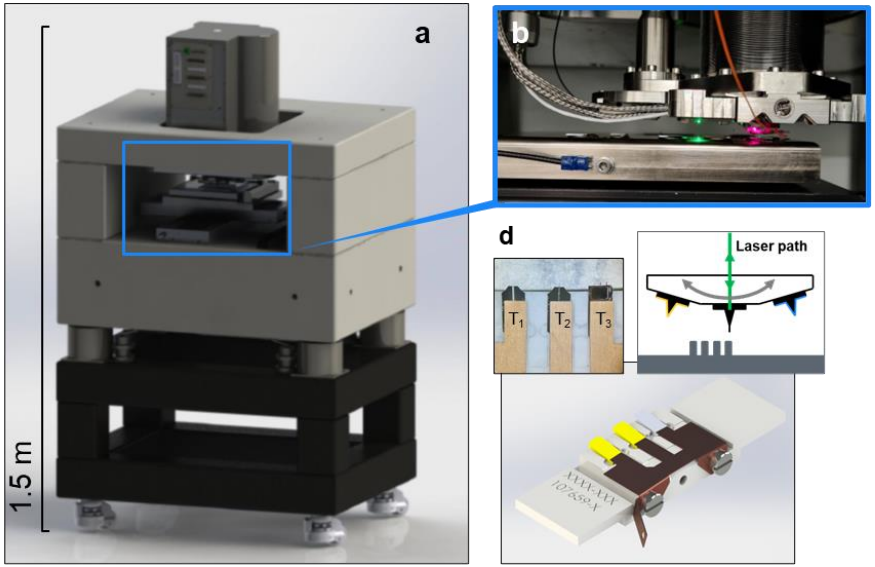
On the impact of **SPM** in Nanoelectronics

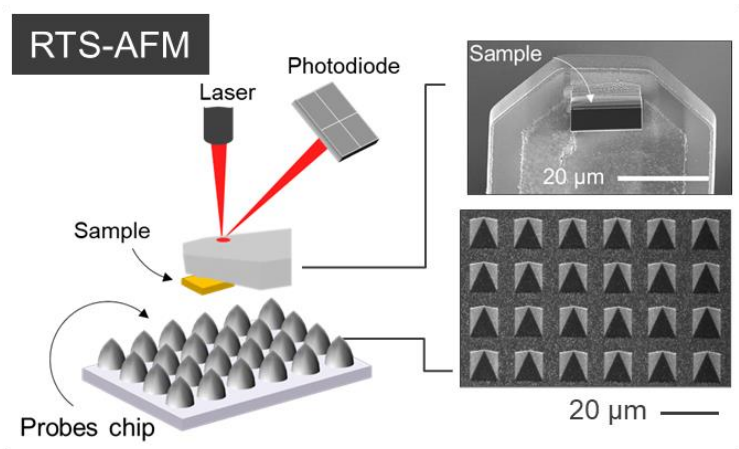


Multi-probes sensing & Reverse tip-sample scanning

Fueling innovation in Atomic Force Microscopy (AFM)







[Sharma, D., et al., Electronic Device Failure Analysis, 4, 20-26, **2023**]

[Celano, U., et al., IEDM Tech. Dig., 10, **2019**]

Active Joint-development projects (JDPs)

Outline

Pushing the Boundaries with Multi-Probes and Reverse Tip Sample Scanning

Introduction

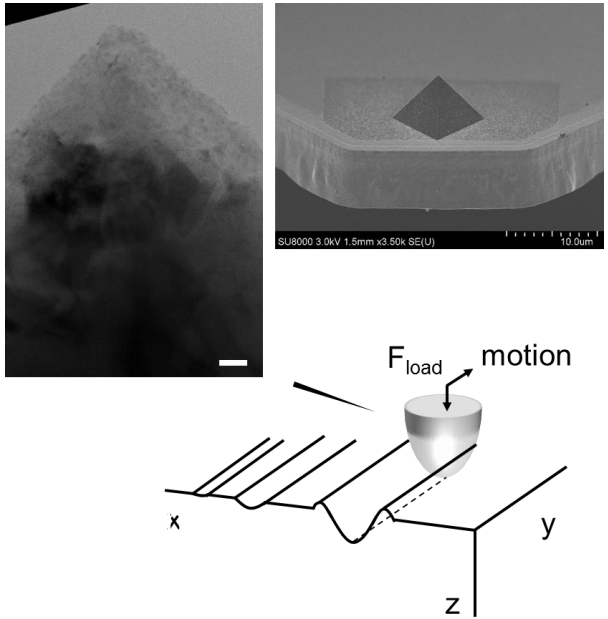
Multi-probes sensing

Reverse tip-sample scanning

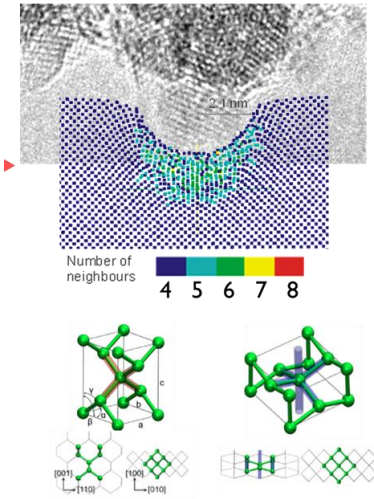
Tip-induced material removal for 3D tomography

harnessing nm-precise material tip-induced erosion

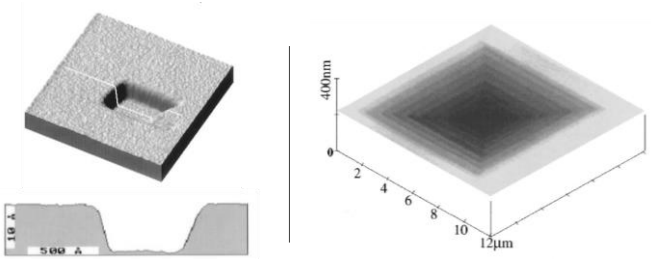
- Pressure-assisted material removal



[Celano, U. et al., *Scientific Report*, 8, 2994, **2018**]
[Hantschel, T. et al., *Physica Status Solidi (a)*, *206*(9), **2006**]

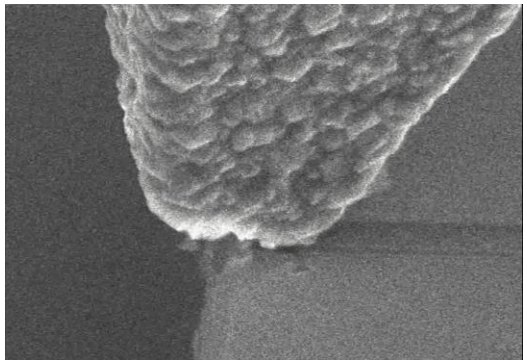


- nm-controller
- Air/Oil environment
- Stress-assisted removal



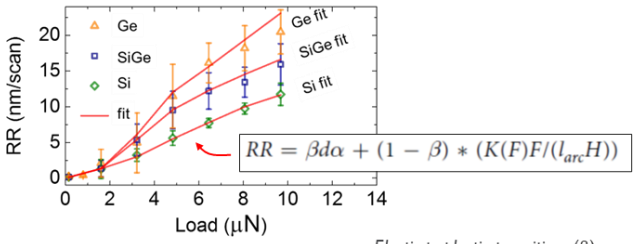
[Hu, J. et al., Surf. Sci., 237, (**1995**)]
[Xu., M.,W. et al., Appl. Phys. Lett., 81, (**2002**)]

In-situ SEM observation

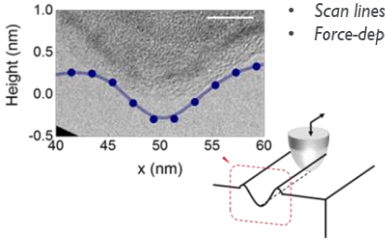


Controlling the tip-induced material removal from air to oil

Removal of material, with precision down to single digit nm



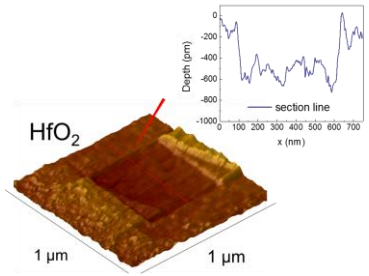
- *Elastic-to-plastic transition* (β)
- *Indentation-depth (d)*
- *Scan lines overlap coefficient (α)*
- *Force-dependent wear-coefficient K(F)*

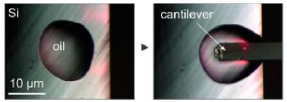


[Celano, U. et al., *IIRW*, 81, **2014**]
[Celano, U. et al., *Scientific Reports*, 8, 2994, **2018**]
[Tseng, A. A., J. Vac. Sci. Tech. B, 23 (3), 877, **2005**]

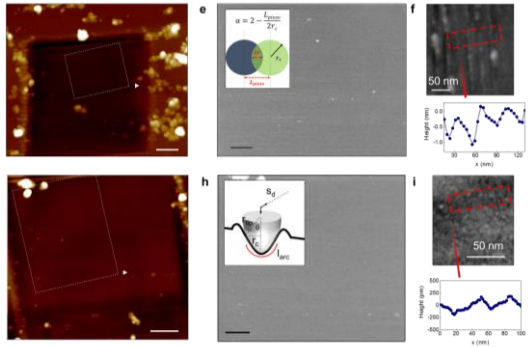
Mineral oil (3M)
Castor bean oil

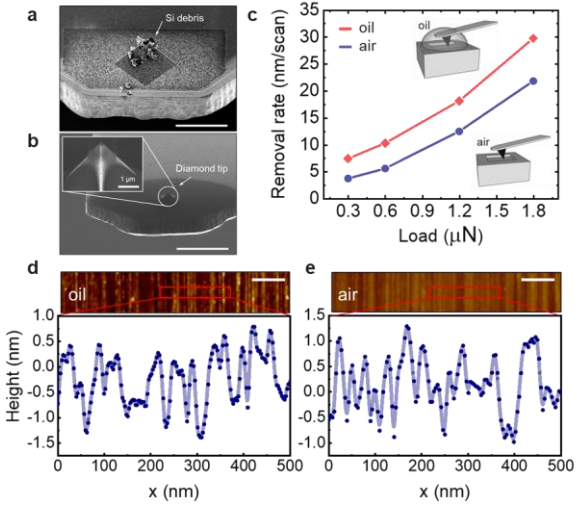
Sub-nm control





[Noël C, et al., Front. Mech. Eng. 7, 797962, **2021**]



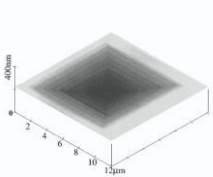


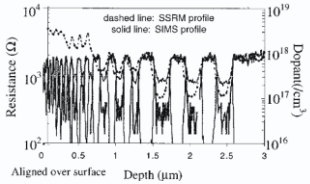
Applicability demonstrated for: Si, SiGe, Ge, InGaAs, InP, TiN, Cu, Ti, Ru, HfO_2, SiO_2, Al_2O_3,TiO_2

Applications in nanoelectronics

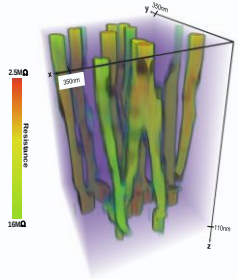
[Xu, M., et al., APL, 81, (1), 177, 2002]

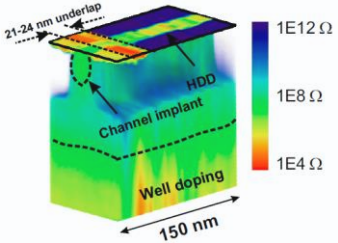
in-dept sensing





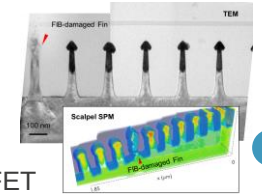
Tomographic sensing





[J. Mody, et al., IEDM tech Dig., 6.1.1-6.1.4, 2011]
[Schulze, A., et al., Nanotechnology, 23, (30), 305707, 2013]

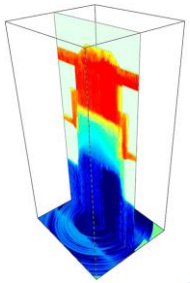
[Schulze, A., APL, 102, (5), 052108, **2013**]



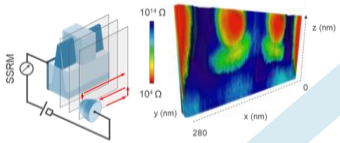
[Celano, U., et al., FCMN Tech. Dig., 8. 2017]

Logic

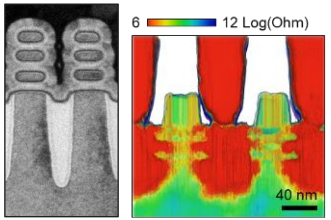
TFET



FinFET

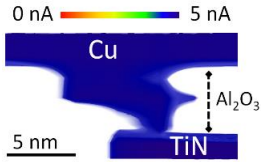


NS-FET



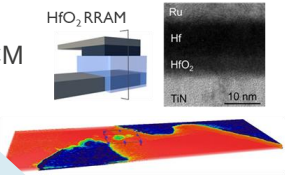
[Eyben, P. et al., IEDM Tech, Dig., 3, **2019**]

CBRAM

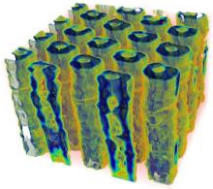


[Celano, U. et al., IEDM Tech, Dig., 3, **2014**]
[Celano, U. et al., Nanoletters, 2401, 14, 5, **2014**]

VCM



3D NAND

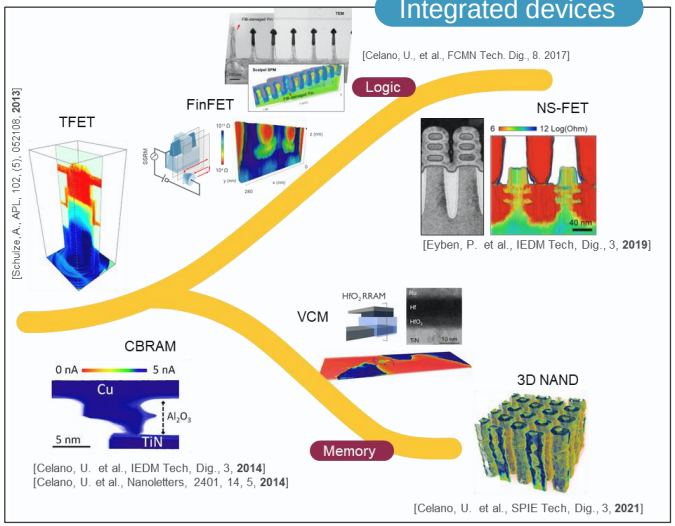


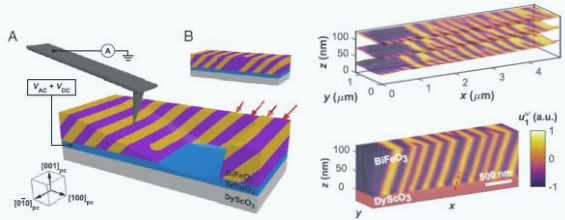
Memory

[Celano, U. et al., SPIE Tech, Dig., 3, **2021**]

Applications range: from nanoelectronics and material science

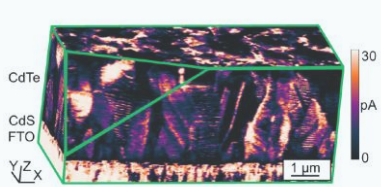
Integrated devices



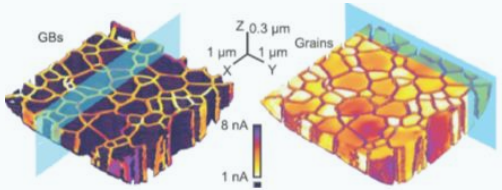


[Steffes et al. PNAS, 116 (7) 2413, **2019**]

Functional photovoltaic materials

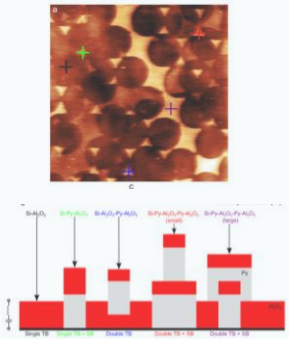


[Atamanuk et al., Beilstein J. Nanotechnol. 9, 1802, **2018**]
[Luria, J., Nat. Energy, 1, 11, **2016**]

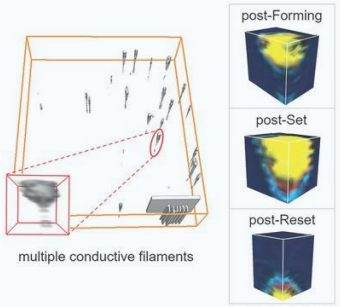


[Song. J., et al., Appl. Phys. Lett. 118, 080501, **2021**]
[Sharma, D., Nature Energy, 9, pages163–171, **2024**]

Bulk materials properties



[Kang-Jun Toh, A., et al. Materials Characterization, 111783, 186, **2022**]

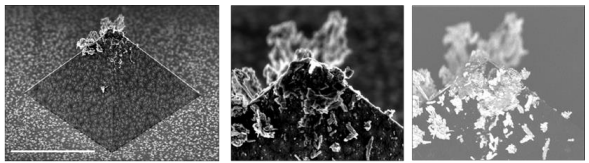


[T. Wei, et al., Adv. Mater., 35, 2209925, **2023**]

A **multi-probes** approach to scalpel SPM

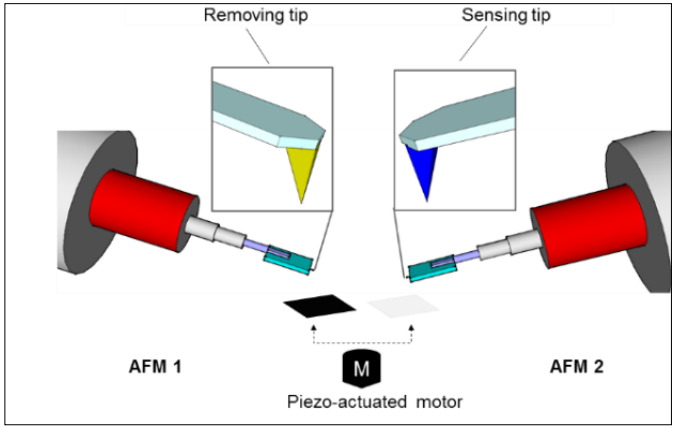
Open issues with current Scalpel SPM

- Limited to one-probe contact modes
- Tip wear/blunting/degradation
- No functional probes (only-diamond)
- Limited lateral resolution/slow



[Chen, S. et al., Adv. Funct. Mater., *28 (52),* **2018**]
[Celano, U. et al., *Scientific Reports*, 8, 2994, **2018**]

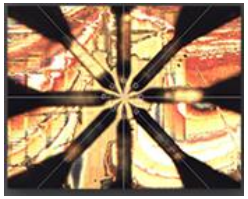
Multi-probes Scalpel SPM approach

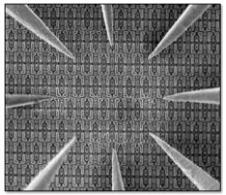


- non-contact AFM ▸ MFM, KPFM, IR-SPM, PFM,...
- Magnetic domain imaging ▸ 5 nm resolution MFM
- Controlled depth increment ▸ < 1nm depth resolution
- Biased device operation ▸ external magnetic fields, voltage,
- Speed through Automation and dedicated diamond tip design (and fabrication)

Achieving multi-probes (heads) capabilities

Hyperion II

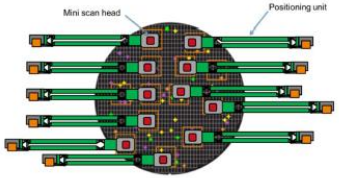


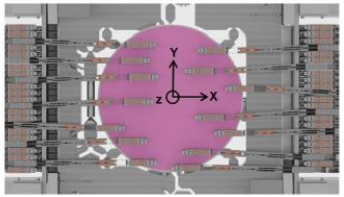


Up to 8 probes / MEMS mirror cantilever

TNO - NFI

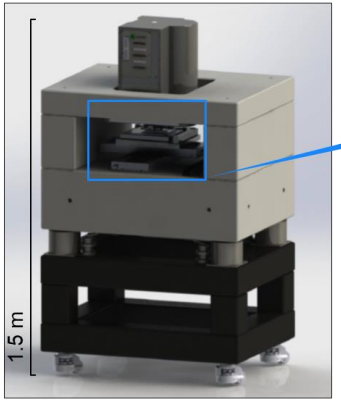
NEARFIELD INSTRUMENTS

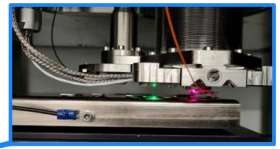


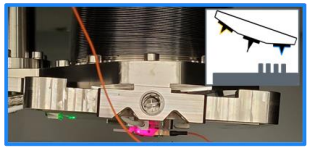


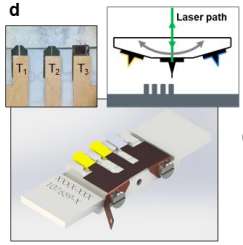
10+ parallel AFM head / Large area sensing

Imec – Infinitesima approach









Installation
Tool delivery and installation in MCA

Q2 2021

Rapid Probe Microscope (RPM) 3D

System overview

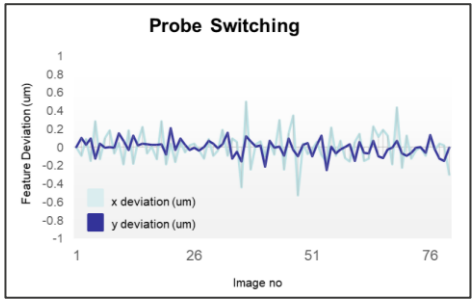
- Air operation
- Stage motion 200 x 200 mm
- Field of view 8 x 8 µm
- Z linearity < +/- 2nm

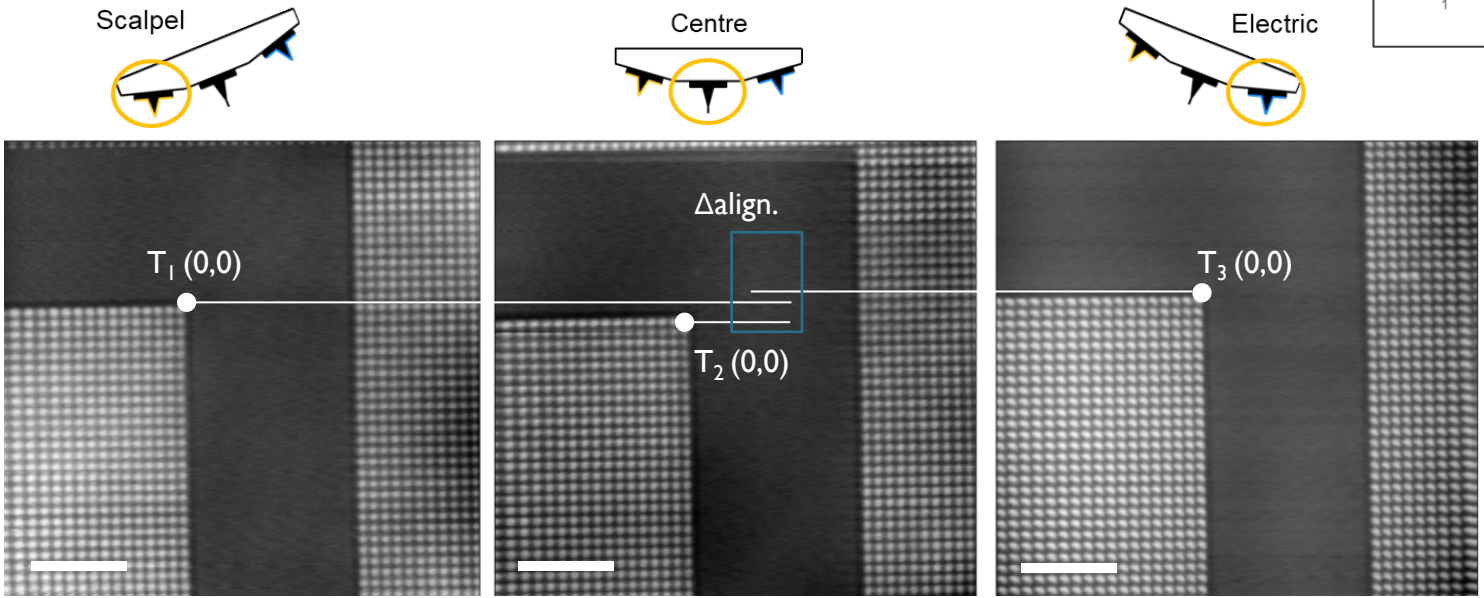
infinitesima imec

[Sharma, D., et al., Electronic Device Failure Analysis, 4, 20-26, **2023**]

A **multi-probes** sensing

Probes alternation





scalebar 800 nm

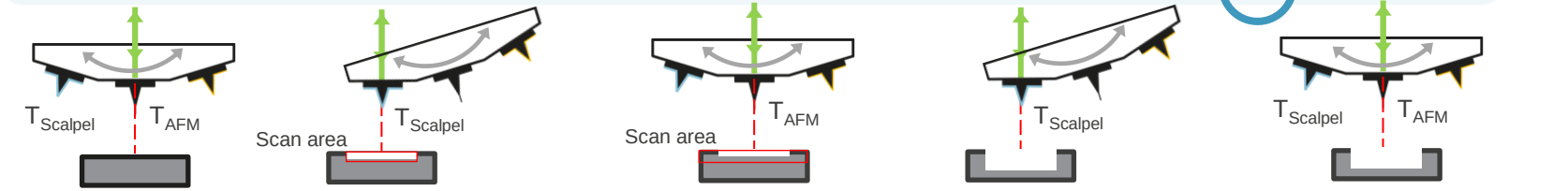
[Celano, U. et al., *SPIE Tech. Dig.*, **2021**]
[Celano, U. et al., *IPFA Tech. Dig.*, **2021**]

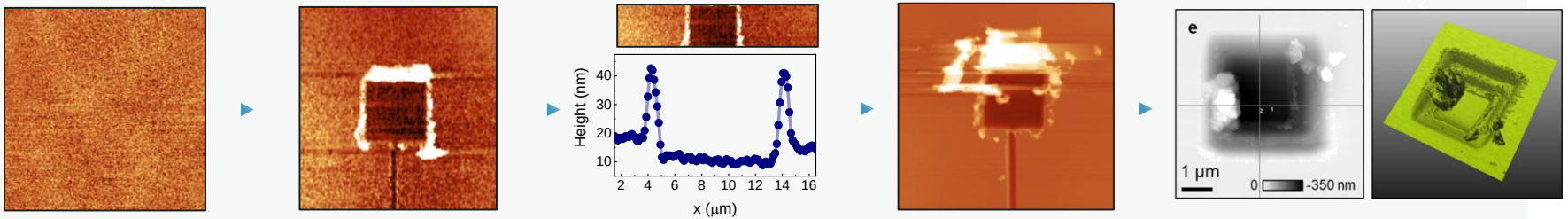
A **multi-probes** material removal flow

Decoupling digging and sensing

1. Overview scan
2. Mater. removal
3. Height extraction
4. Mater. removal
5. Iteration

Repeat





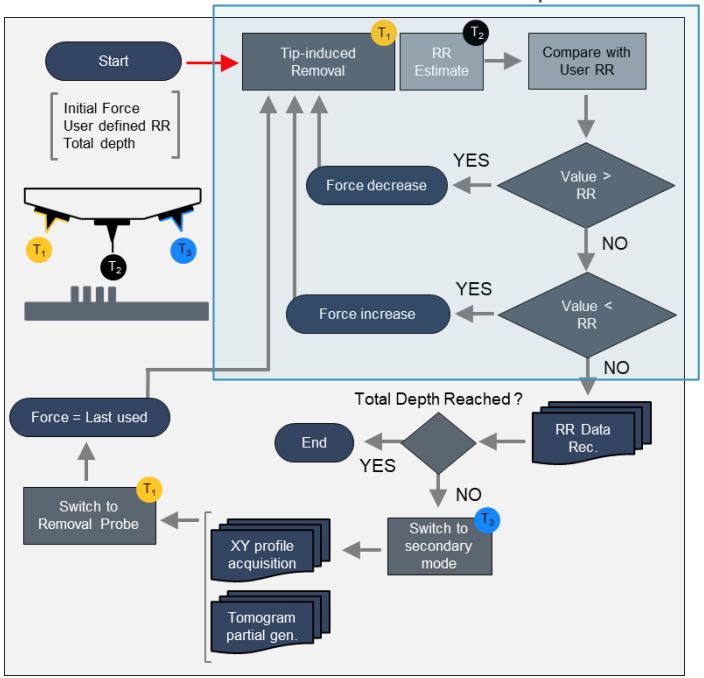
Locating area of interest | Start a slow-rate removal | Removal-rate estimate | Adjust and Repeat

[Celano, U. et al., *Proc. SPIE, 11611,* **2021**]
[Celano, U. et al., *IPFA Tech dig.*, **2021**]

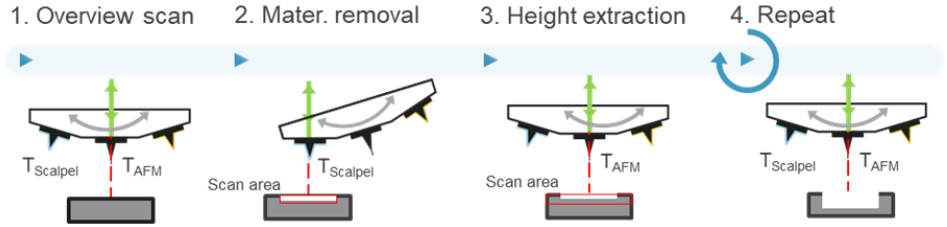
Improving control in the material removal and removal-rate

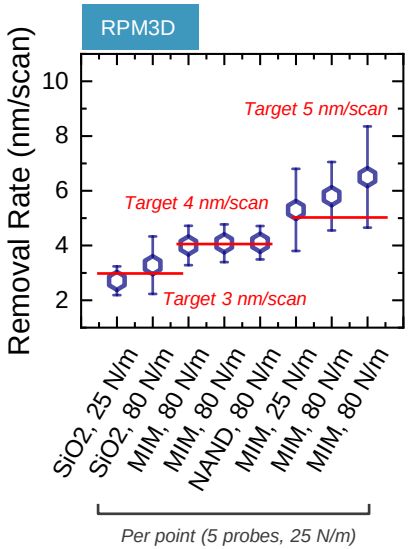
Tunability of the removal-rate

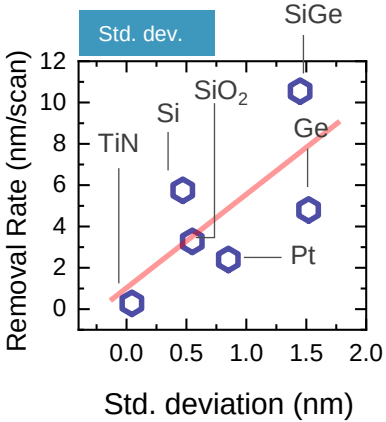
User-defined scriptable blocks



[Sharma, D., et al., Electronic Device Failure Analysis, 4, 20-26, **2023**]

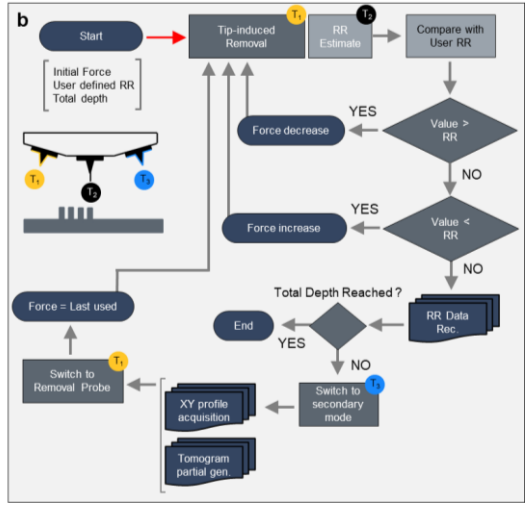


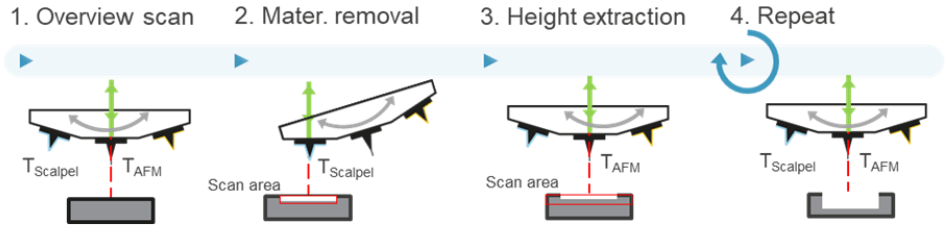


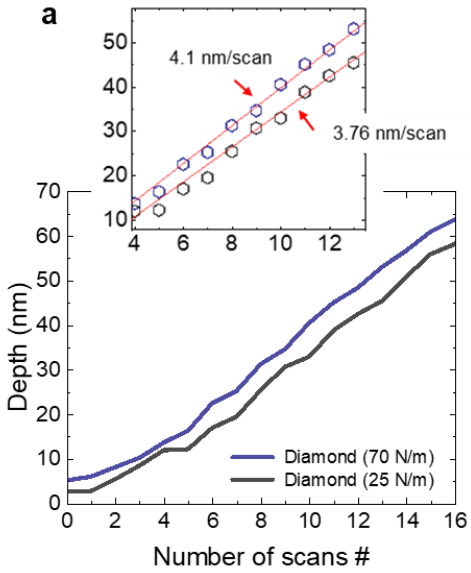


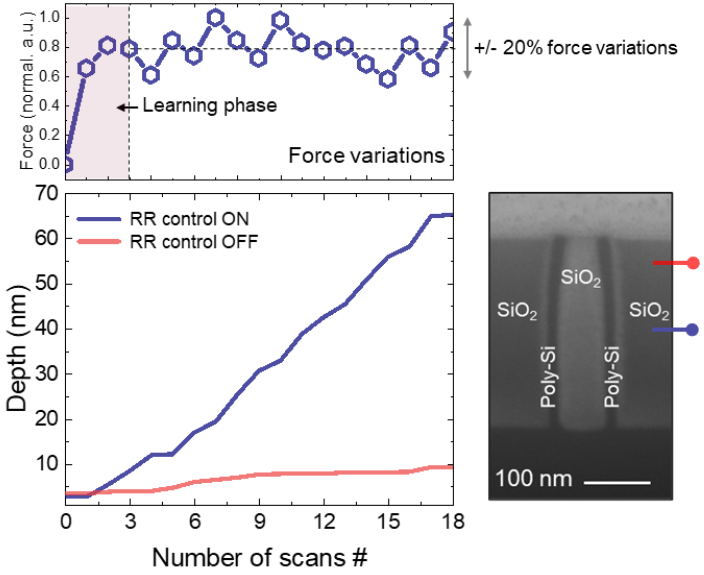
Automated removal-rate control

Scriptable removal-rate control 4 nm/scan



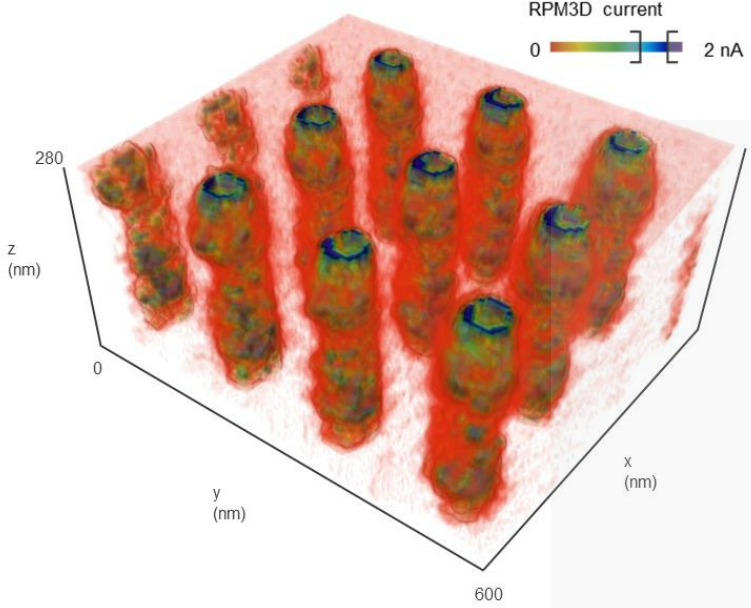


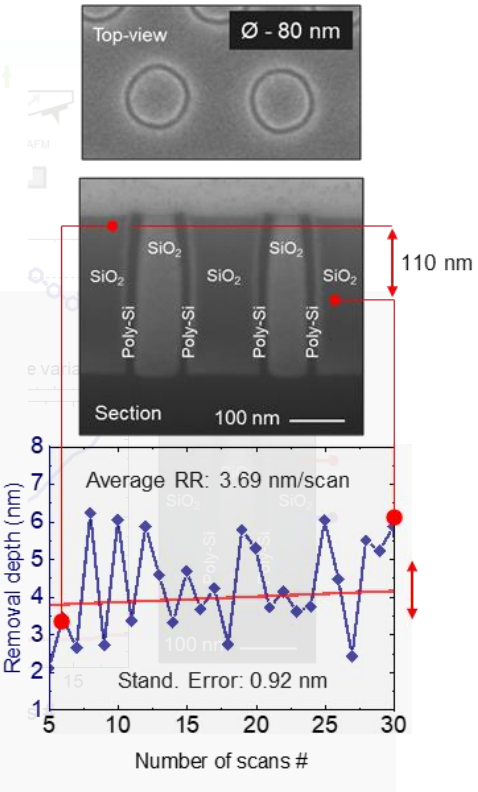




Removal-rate control & **tomographic reconstruction**

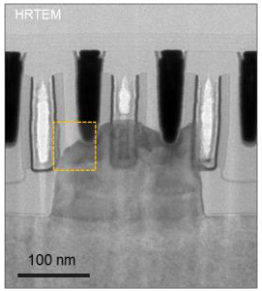
imec infinitesima

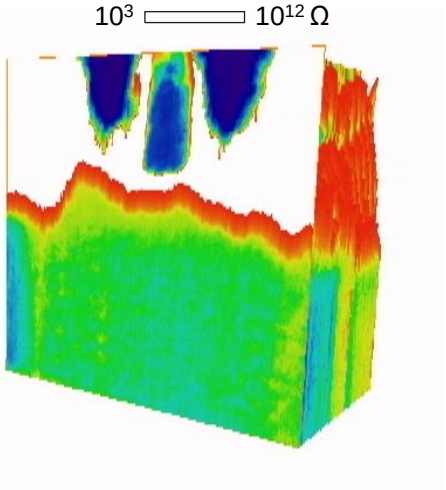




[Sharma, D., et al., Electronic Device Failure Analysis, 4, 20-26, **2023**]
[Sharma, D., IPFA Tech. Dig., **2023**]

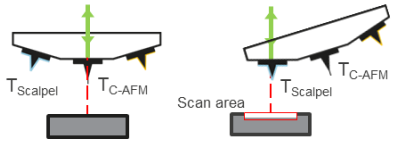
On-going SSRM demo in RPM3D





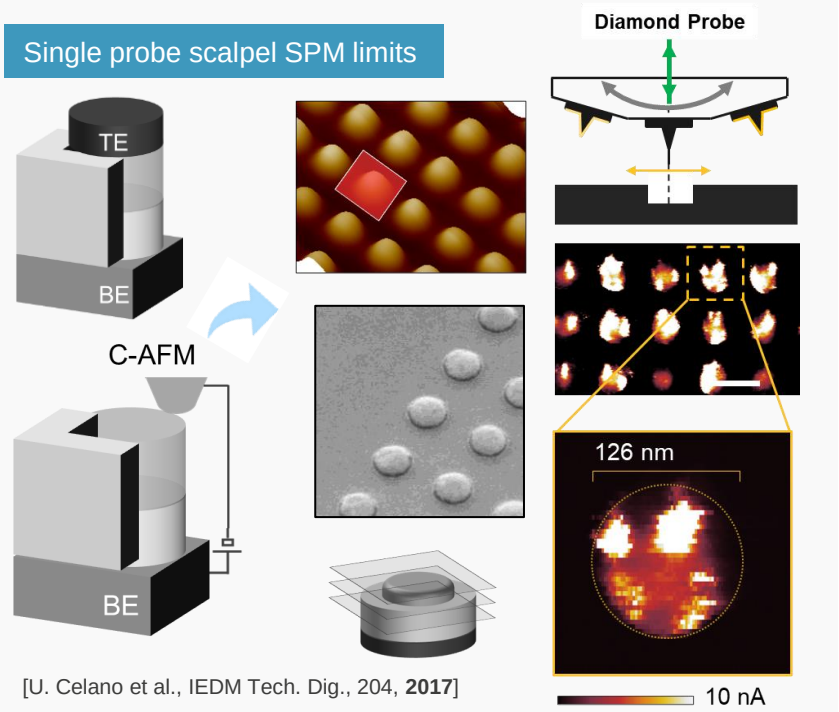
[Eyben, P., IEDM Tech. dig., 11.3, **2019**]

Improving tip-sample convolutional artefacts



Enabling artifacts-free high resolution in electrical modes

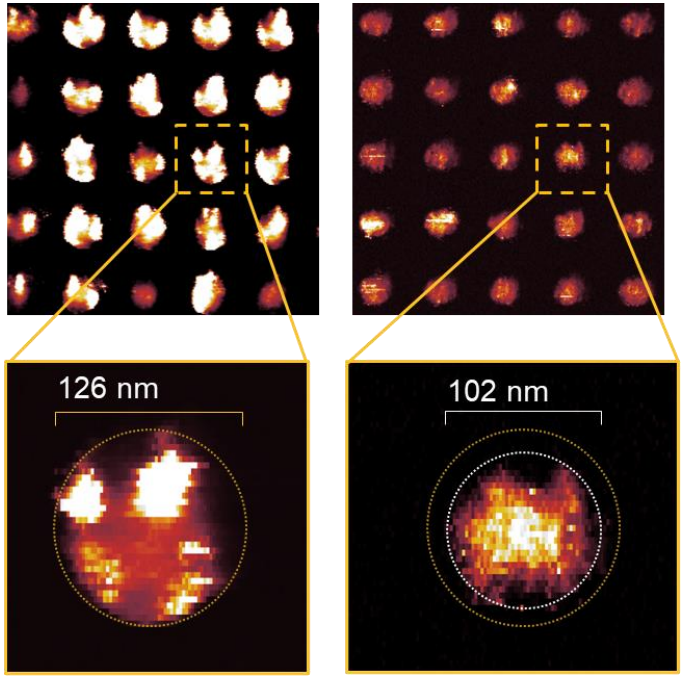
Single probe scalpel SPM limits



[U. Celano et al., IEDM Tech. Dig., 204, **2017**]

Single probe

Multi probe



[Sharma, D. et al. IPFA Tech Dig. 2023]

Outline

Pushing the Boundaries with Multi-Probes and Reverse Tip Sample Scanning

Introduction

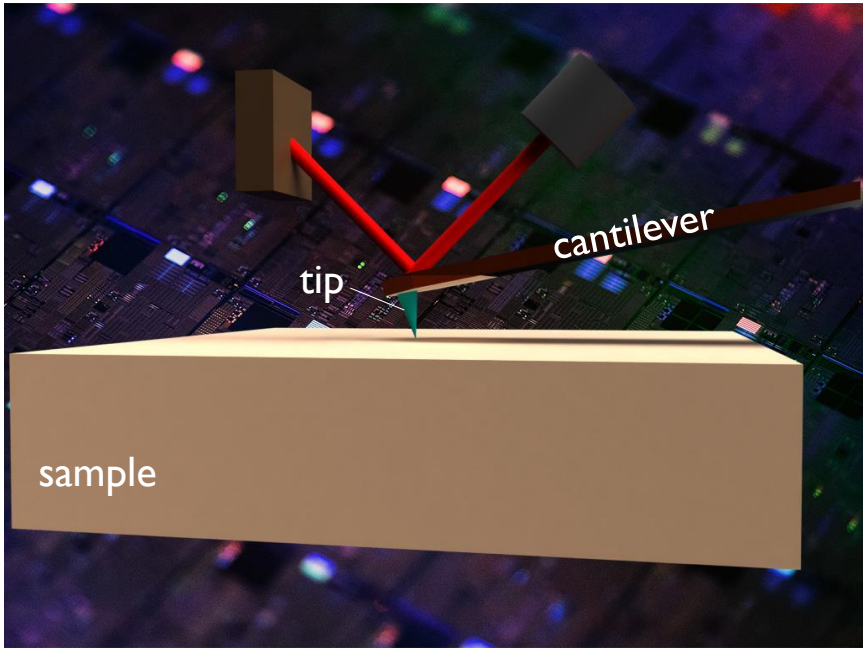
Multi-probes sensing

Reverse tip-sample scanning

From single-probe SPM to RTS SPM

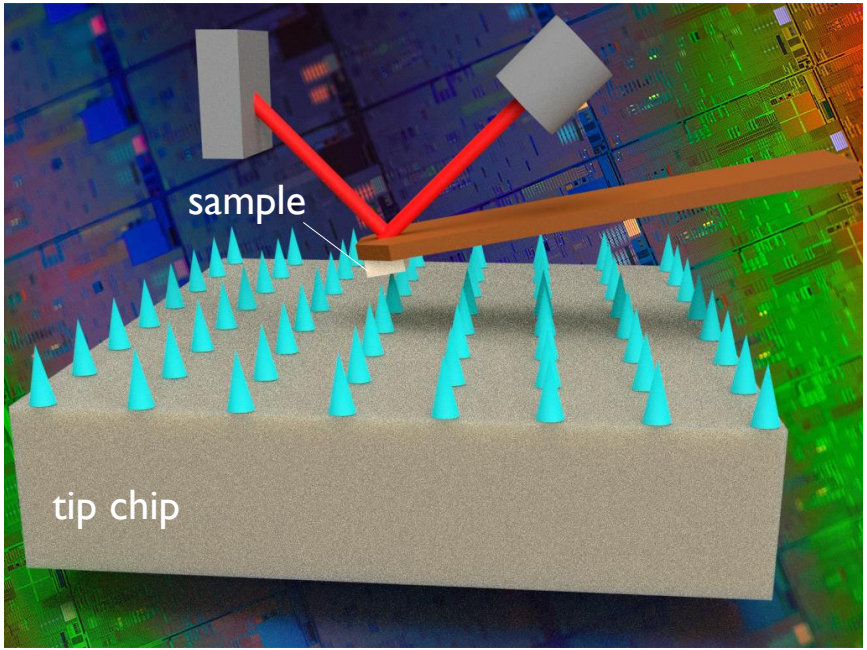
(RTS: Reverse Tip Sample)

SPM:



- Standard configuration with tip on cantilever
- Tip blunting = probe exchange (≥10 min)
- Limited to single-tip scanning

RTS SPM:

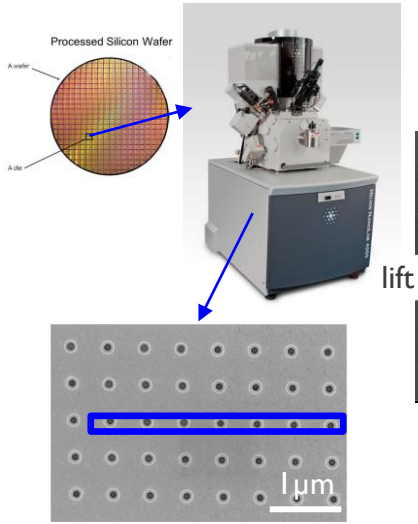


- Sample fixed to cantilever ⇨ FIB prep procedures
- Seamless tip change (~1 s) ⇨ Tip chip development
- Multiple-tip scanning possible

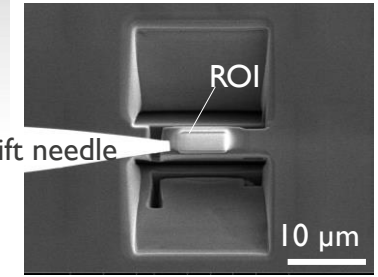
FIB for RTS-SPM sample preparation – basic steps overview

Aim: Development of reliable, reproducible & time-efficient FIB prep procedures

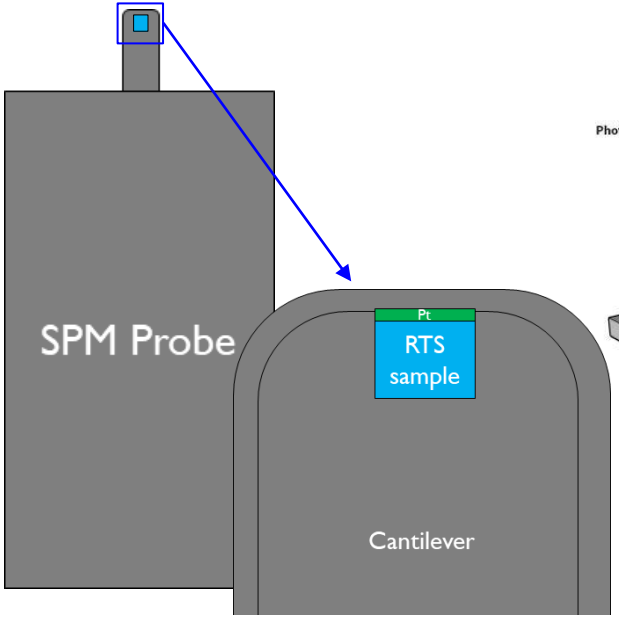
Loading wafer die/sample into FIB



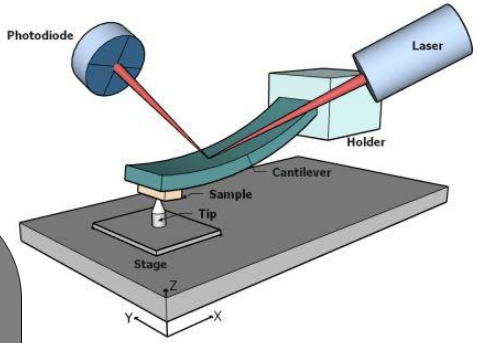
Extracting ROI sample from die



Mounting ROI sample on cantilever

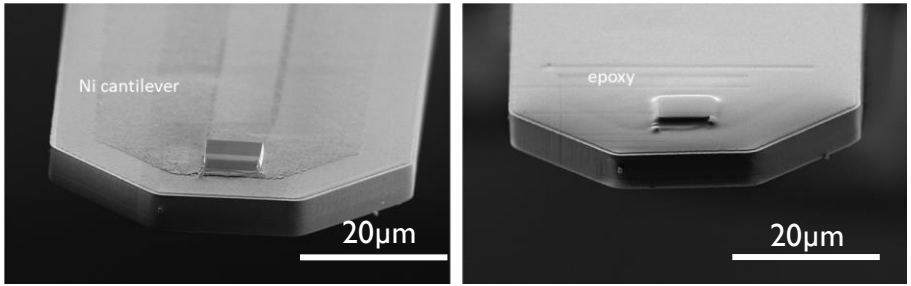


Measuring sample in RTS SPM mode



FIB for RTS-SPM sample preparation – improved fixation step

After FIB mounting → After epoxy cementation



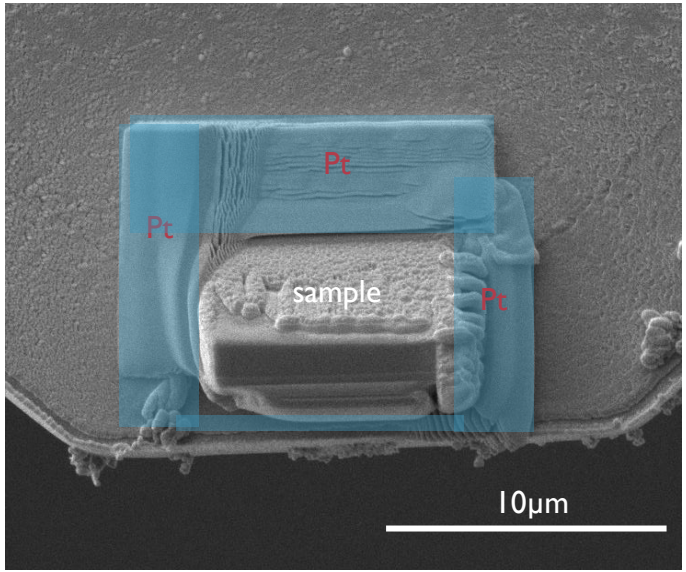
Previous FIB prototype preparation

After FIB, extra manual gluing step ('cementation') required to ensure strong enough sample-to-cantilever fixation

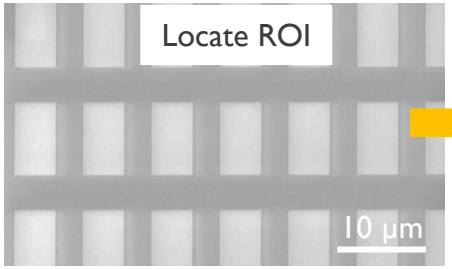
[Lagrain, P., et al., Micro and Nano Engineering, 23,10024735, **2024**]

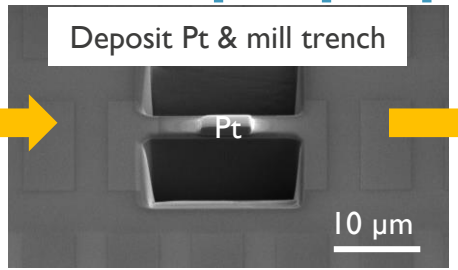
New FIB-only preparation approach

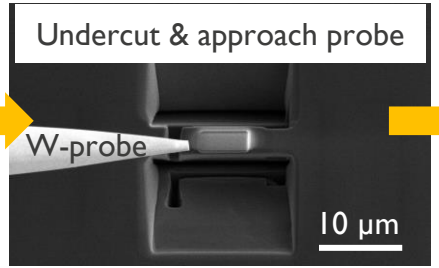
Pt-all-around sample encapsulation step yields high mechanical bond strength & ensures good electrical contact to cantilever

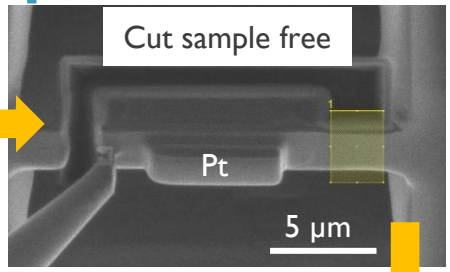


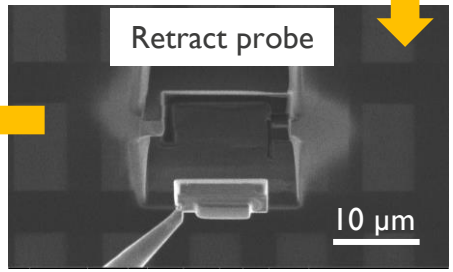
FIB for RTS-SPM sample prep – Cross-section procedure

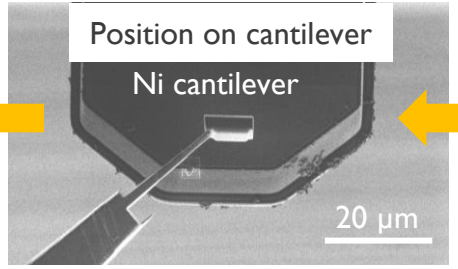


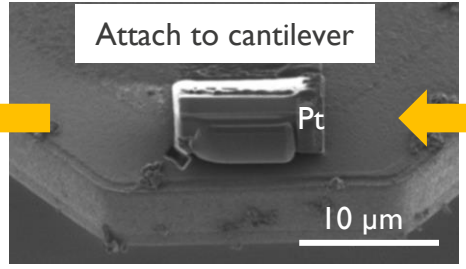


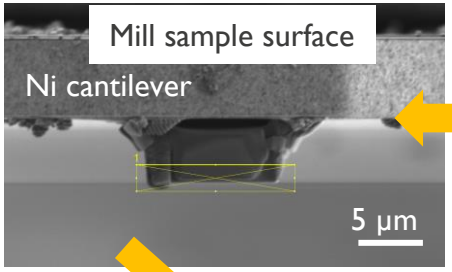


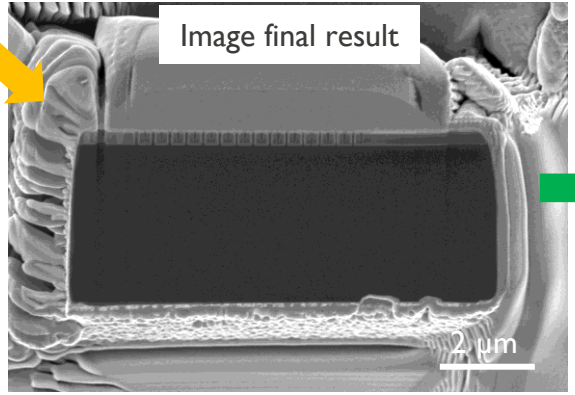


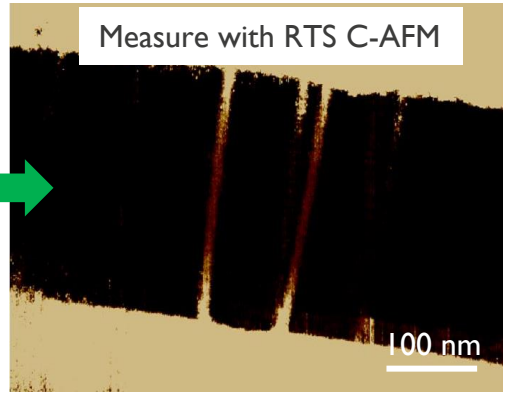










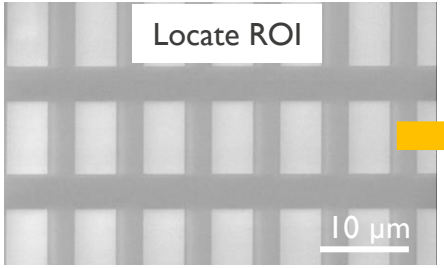


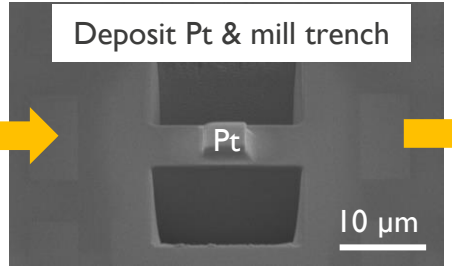
Cross-section of 3D NAND memory structure probed with diamond tip by RTS C-AFM

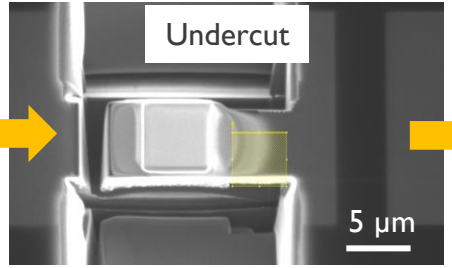
imec

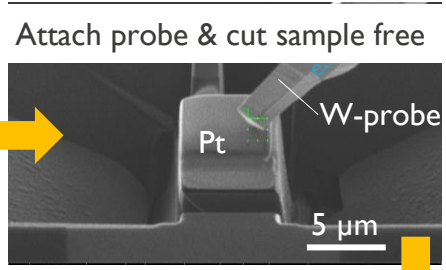
[Lagrain, P., et al., Micro and Nano Engineering, 23,10024735, **2024**]

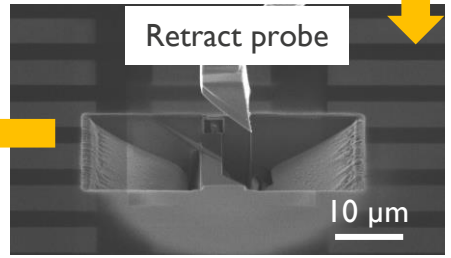
FIB for RTS-SPM sample prep – Top view procedure

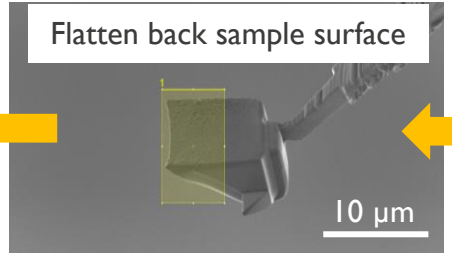


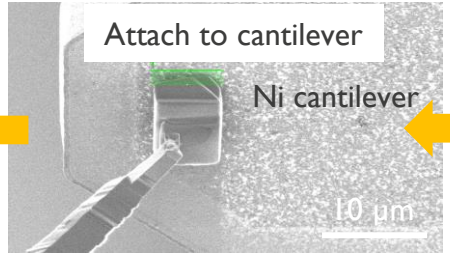


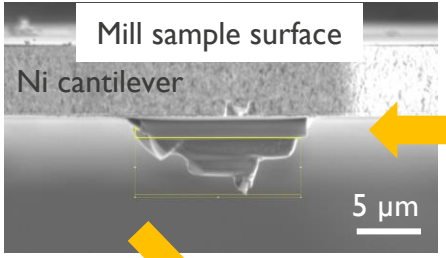


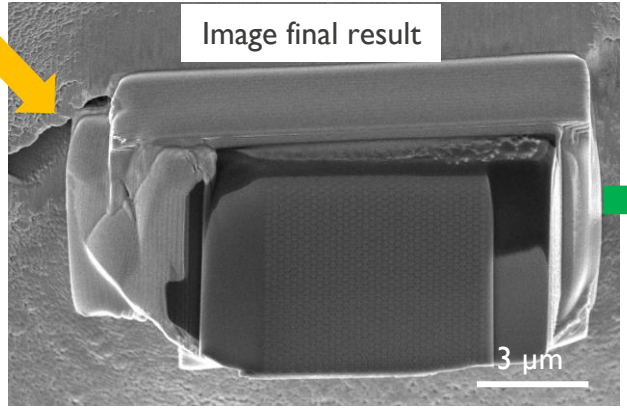


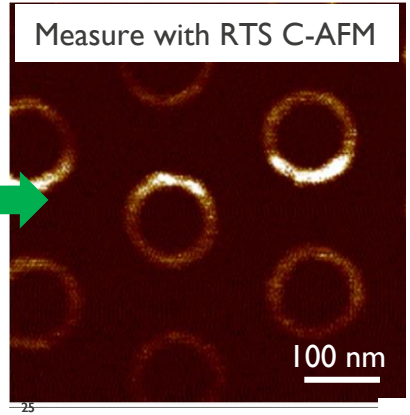










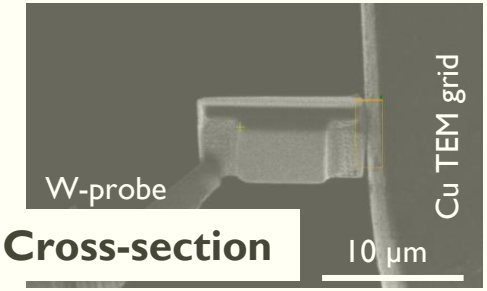


Top view of 3D NAND memory structure probed with diamond tip by RTS C-AFM

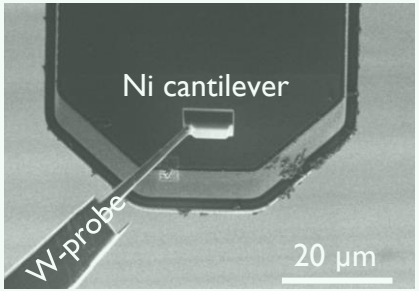
imec

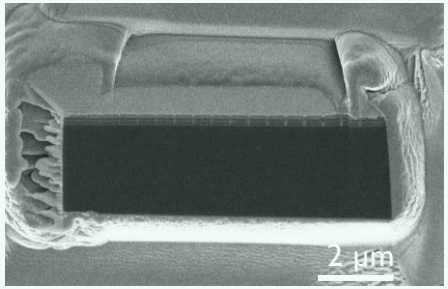
FIB for RTS-SPM sample prep – demo of inline process

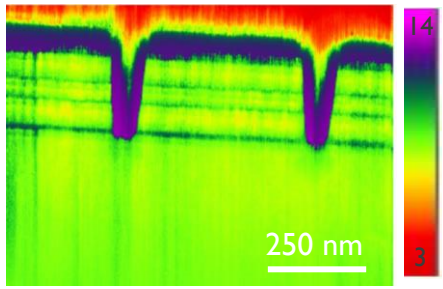
Attach to Cu TEM grid → **Transfer to cantilever** → **Image final result** → **Measure with RTS SSRM**

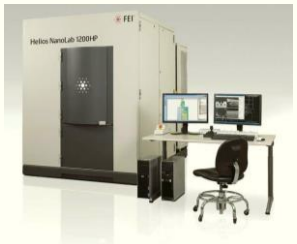


Cross-section





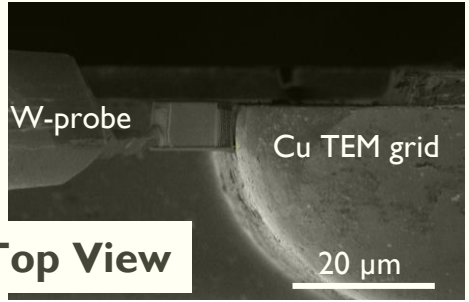




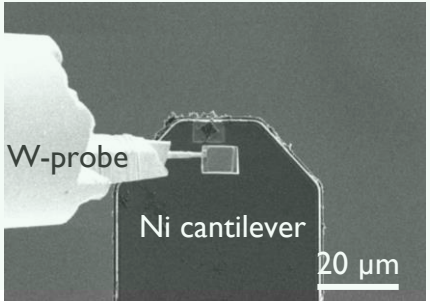
Inline

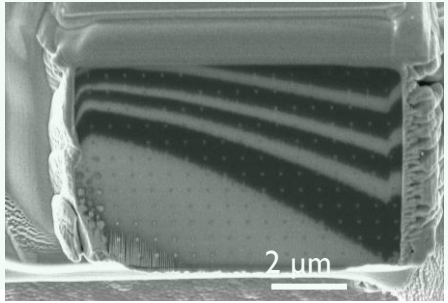
Out of line

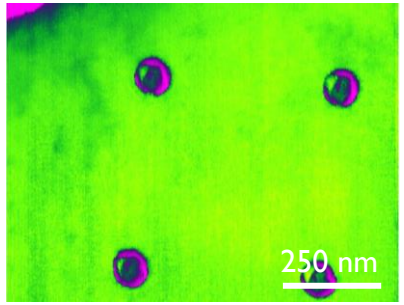
Cross-section & top view of stack memhole structures probed with diamond tip by RTS SSRM



Top View







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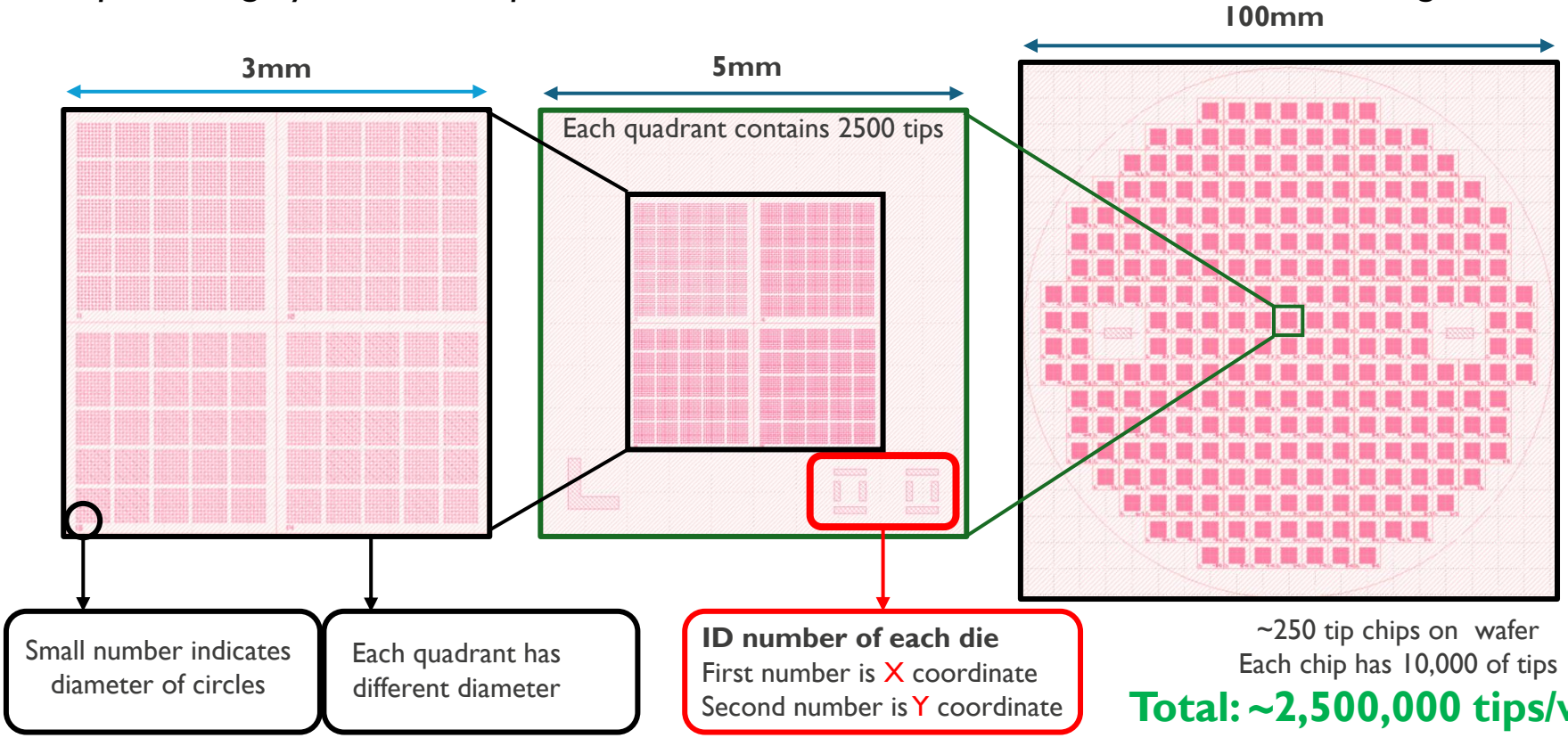
[Lagrain, P., et al., Micro and Nano Engineering, 23,10024735, **2024**]

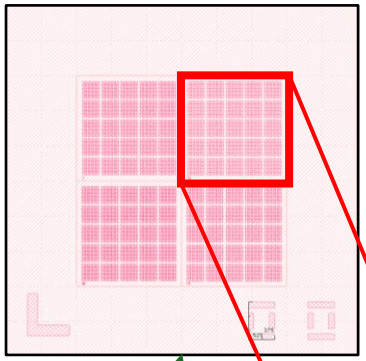
All-Si tip chips for RTS SPM – design

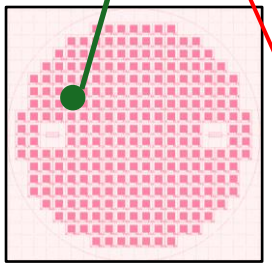
Compact design yields 2.5M tips on 4-inch wafer & ensures cost-efficient manufacturing

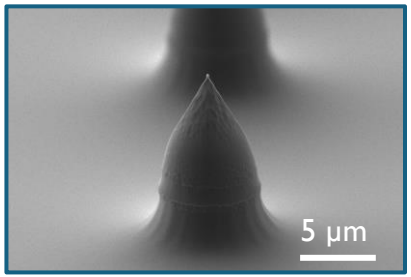


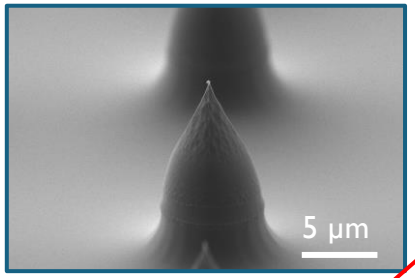
All-Si tip chips for RTS SPM – fabrication results

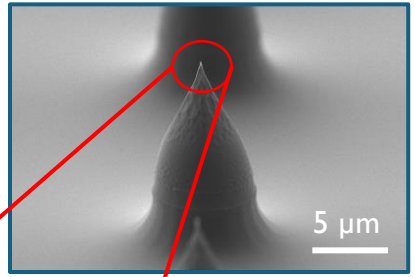
Novel single-run multiple-step dry-etching approach developed for wafer scale fabrication



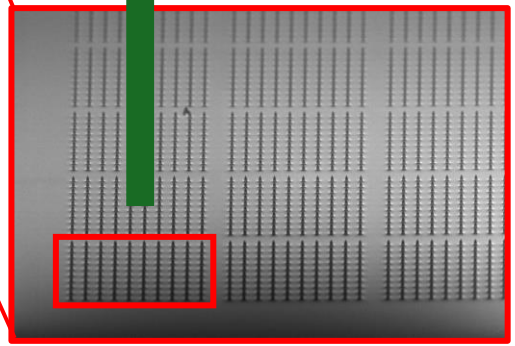








Three locations



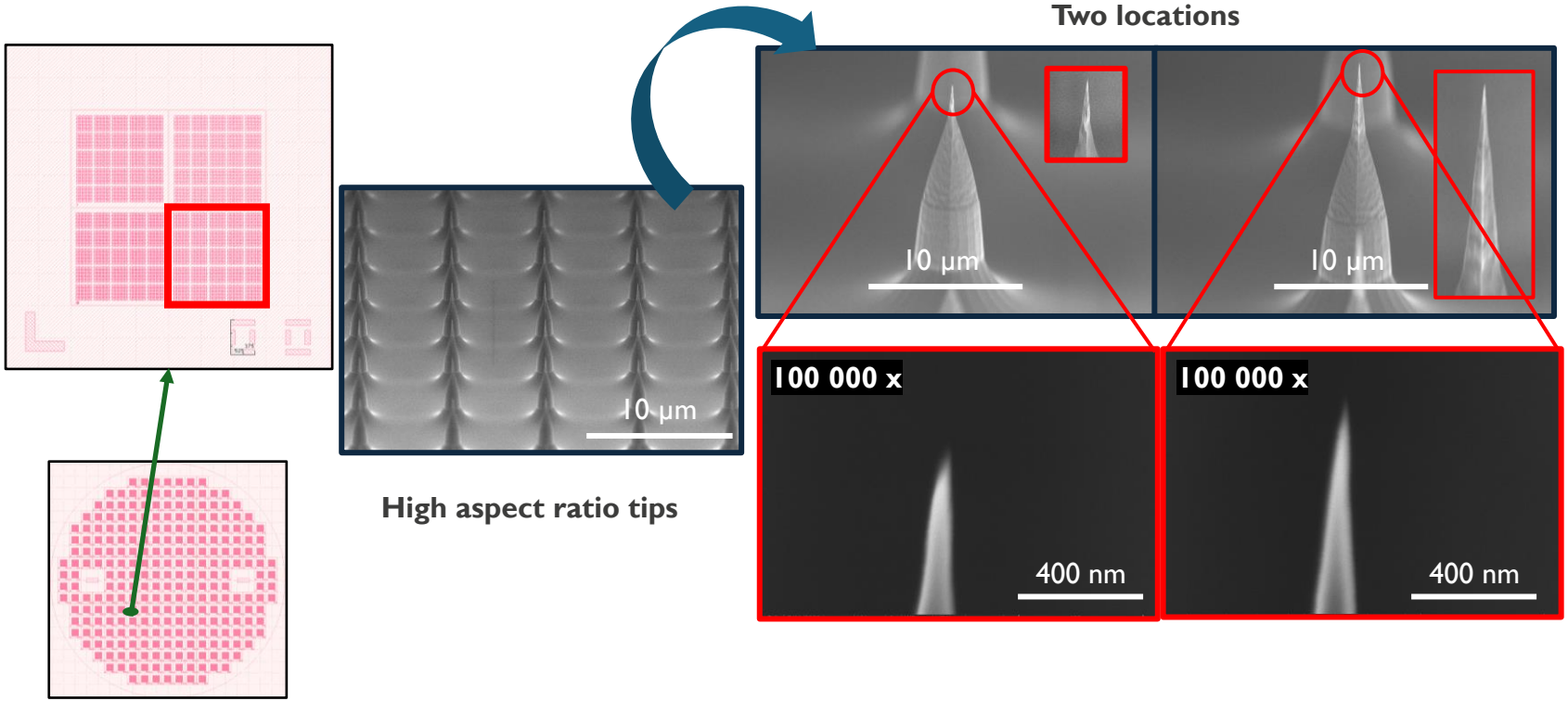
Diameter : < 10nm

Sharp tip apex

[Kim, H.S., et al., Nanotechnology, 35 2657034, **2024**]

All-Si tip chips for RTS SPM – fabrication results

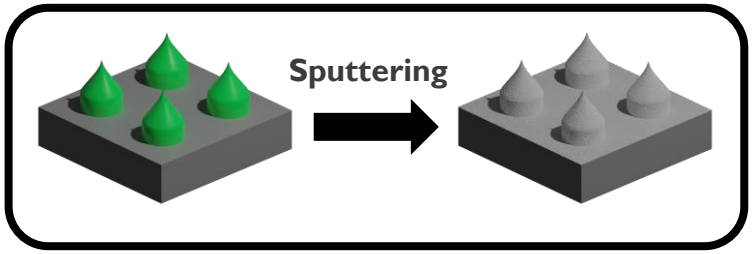
Process fine-tuning allows also for high-aspect-ratio Si tip wafers



[Kim, H.S., et al., Nanotechnology, 35 2657034, **2024**]

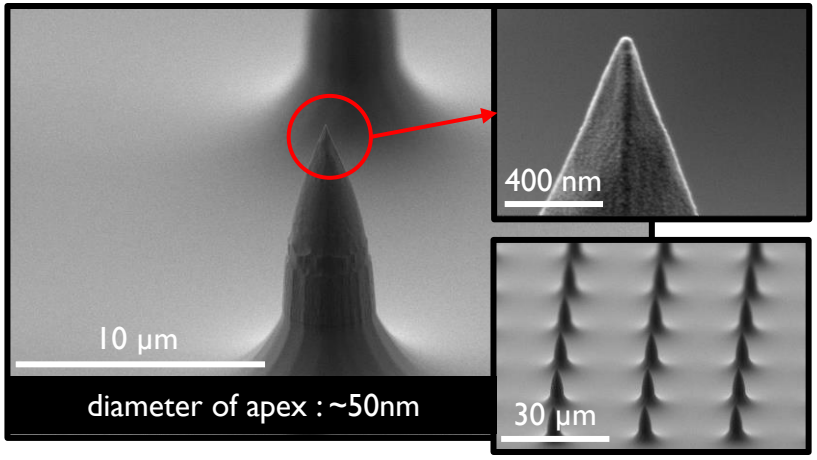
All-Si tip chips for RTS SPM – metal coated tips

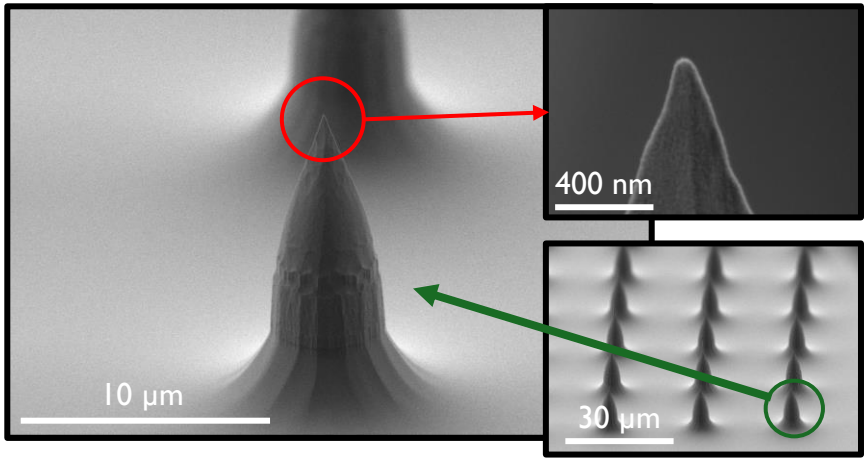
Tip chips can be adapted for special methods by application of thin-layer coatings (e.g. metal)



10nm of Cr (adhesion layer) + 30nm of Pt

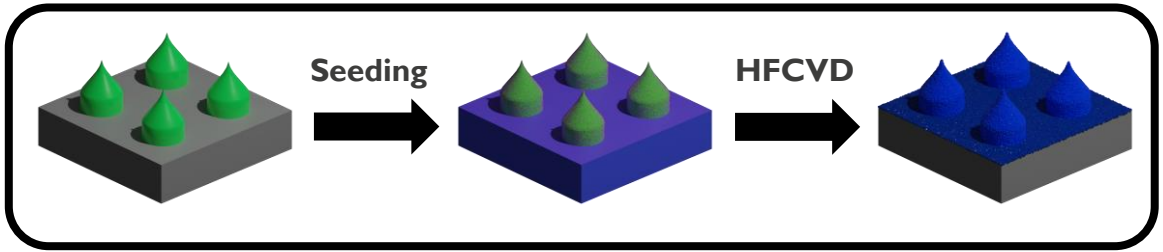
[Kim, H.S., et al., Nanotechnology, 35 2657034, **2024**]





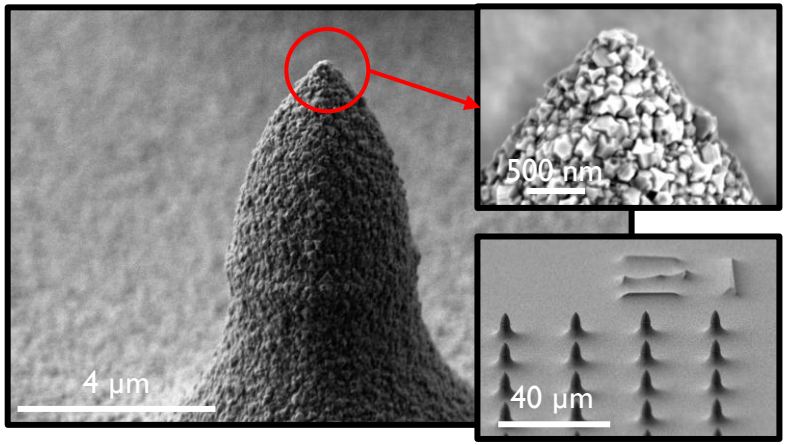
All-Si tip chips for RTS SPM – diamond coated tips

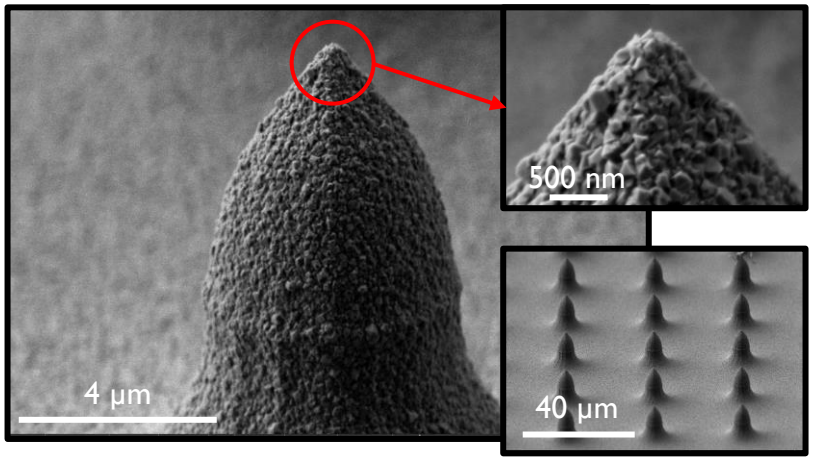
First diamond coated tip chip wafers were made and validated for electrical SPM measurements



200nm of Boron doped polycrystalline diamond layer

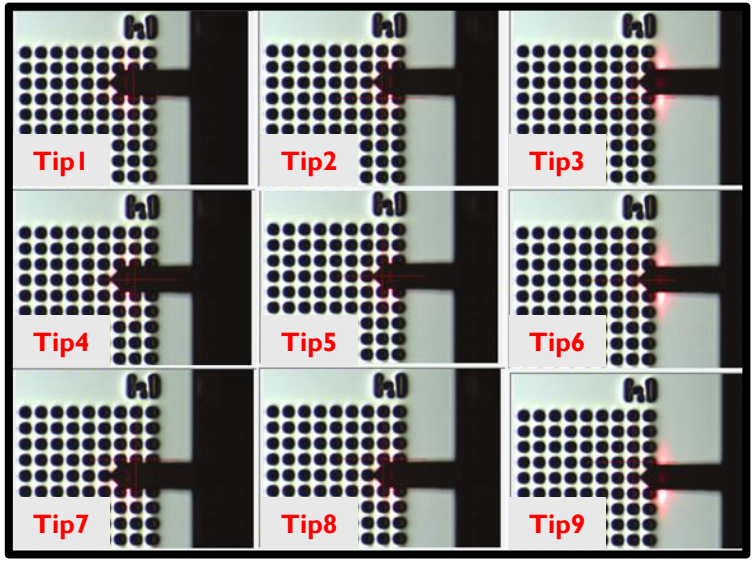
[Kim, H.S., et al., Nanotechnology, 35 2657034, **2024**]





RTS AFM measurement in tapping mode using Si tip

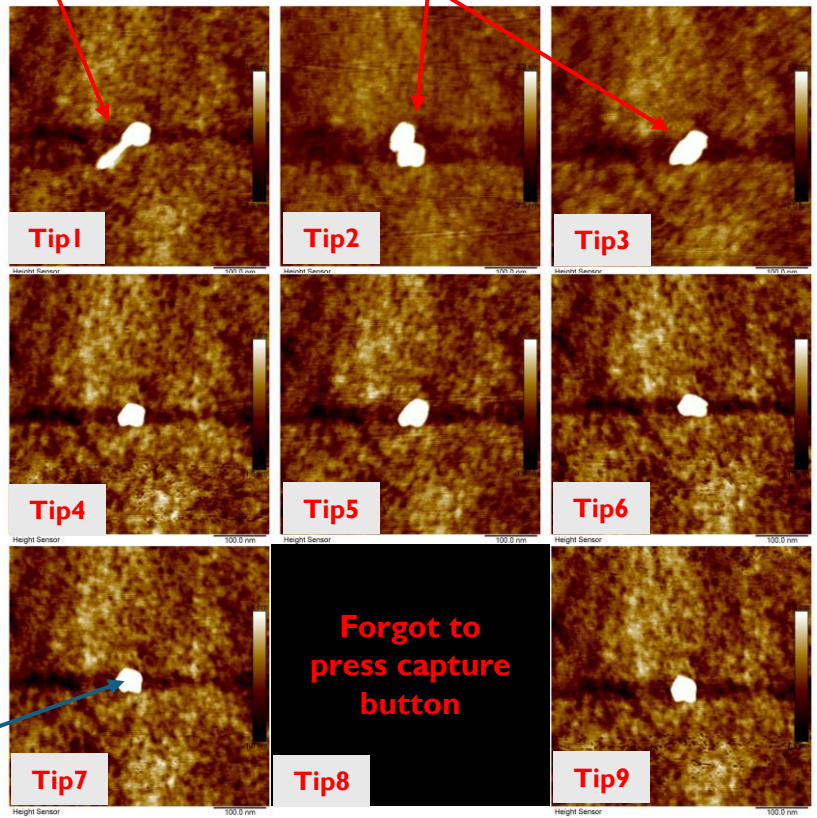
Multiple tip scans identify tip related artifacts & improve quality of measurement data



[Kim, H.S., et al., Nanotechnology, 35 2657034, **2024**]

Double tip with different tip diameter

Double tip



Height of this particle : 9nm
Diameter : 55nm

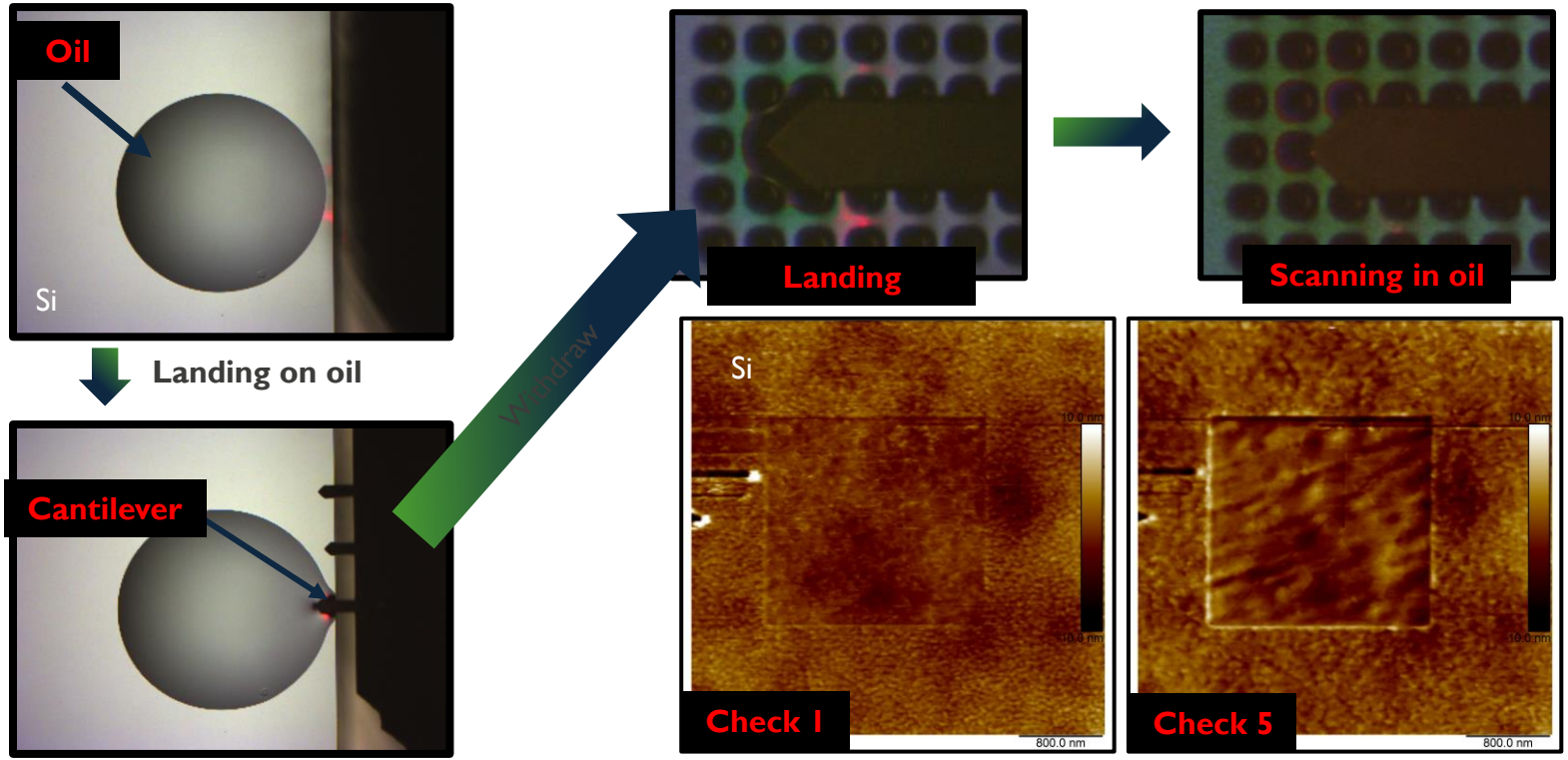
Scan area : 500nm, Z-height

Scalpel RTS SPM in oil using diamond coated Si tip

Use of oil in 3D SPM results in tip lubrication & efficiently removes scalpel debris from ROI & tip

1. Dip Si cantilever sample into high-viscosity oil

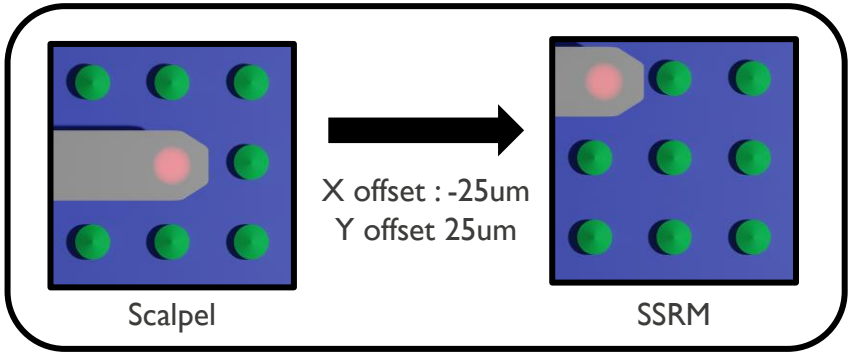
2. Engage Si sample onto diamond tip & scalpel

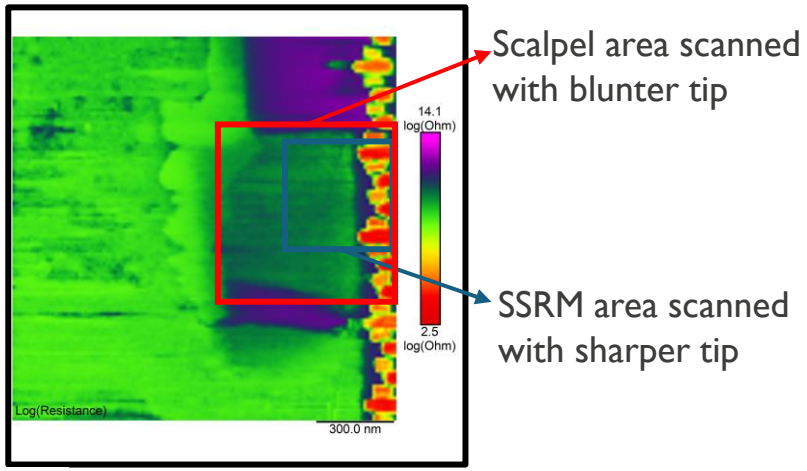


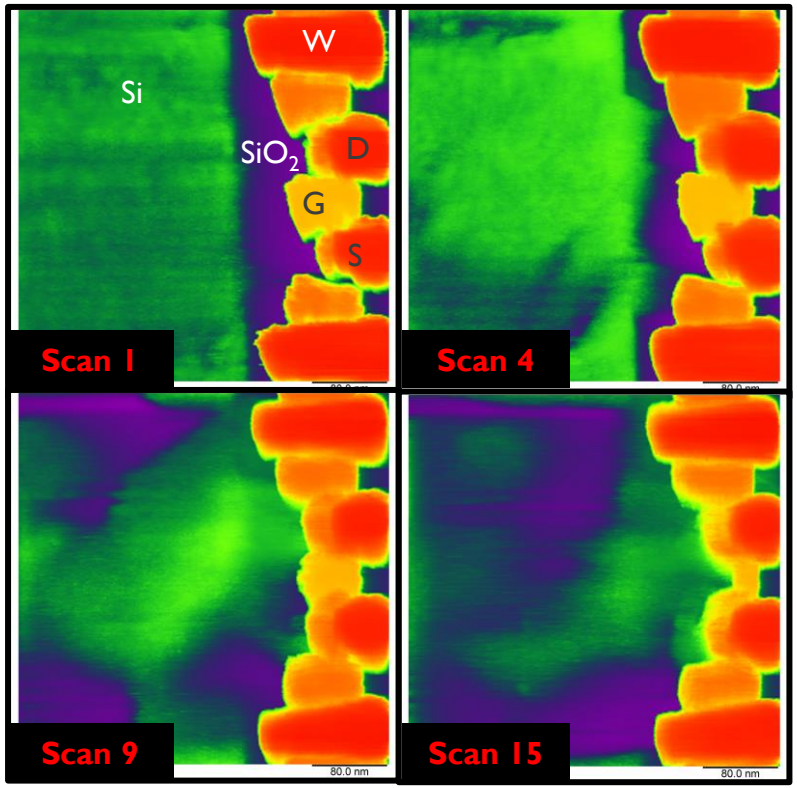
[Noël, C., et al., Front. Mech. Eng. 7:797962, **2021**]

Seamless tip switching in scalpel RTS SSRM measurement

Alternating tips in between materials removal & electrical measurement scans

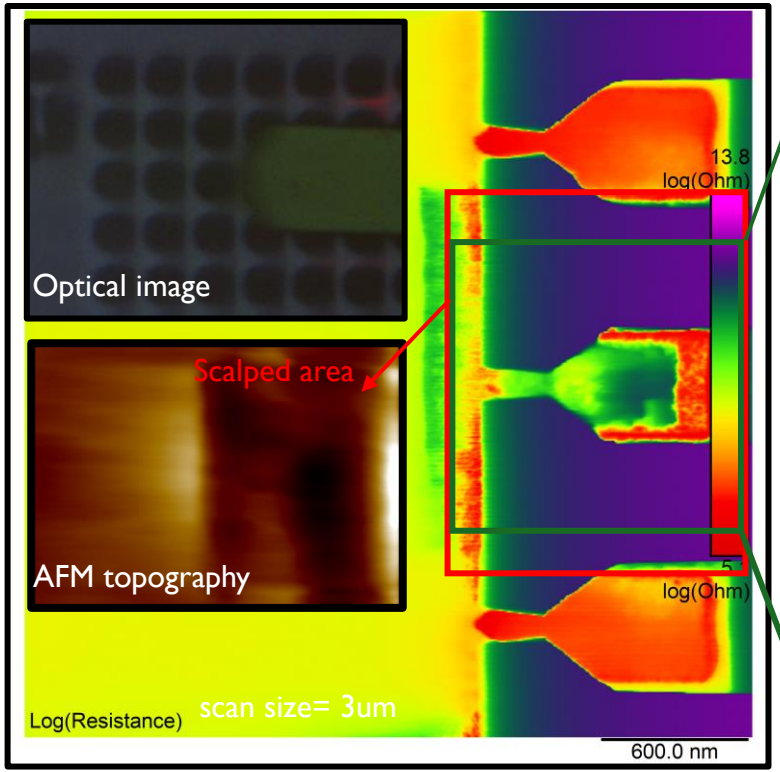


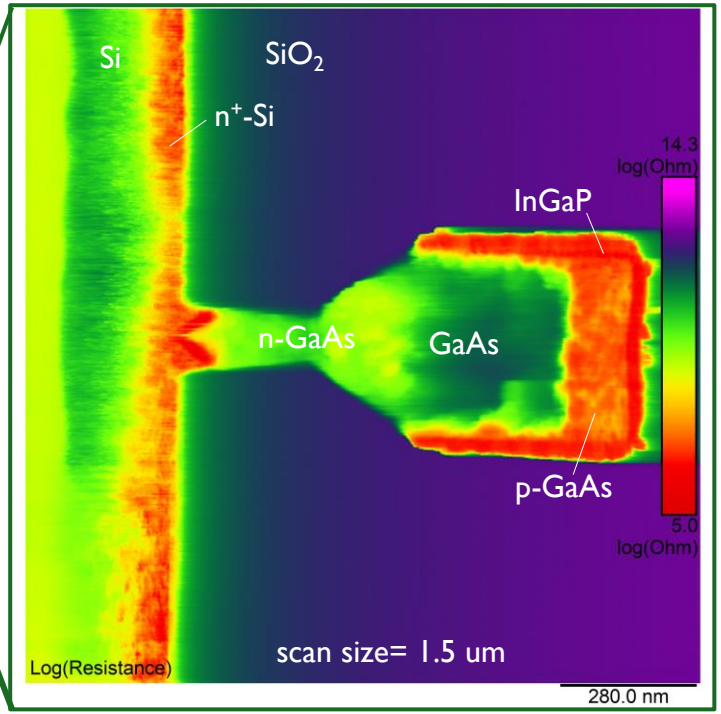


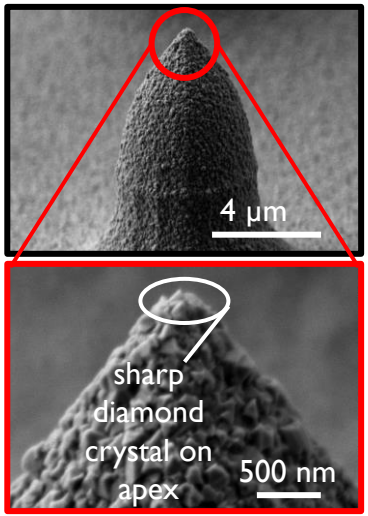


RTS SSRM measurement of III-V nanoridge structure

Diamond tip removes first amorphized layer from FIB & probes then ROI of device structure







Outline

Pushing the Boundaries with Multi-Probes and Reverse Tip Sample Scanning

Introduction

Multi-probes sensing

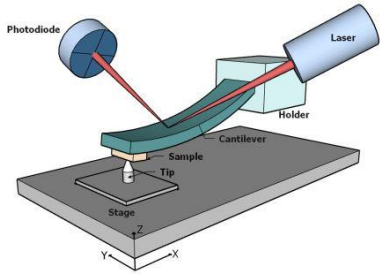
Reverse tip-sample scanning

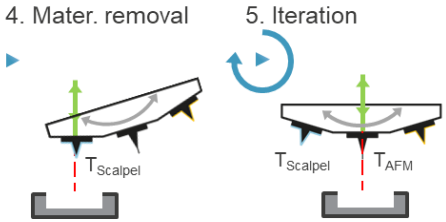
Conclusions

Conclusions

- Continued and renewed impact of SPM in Nanoelectronics
- Multi-probe sensing RPM3D & RTS SPM
  - Innovative approaches for data collection
- RTS offers multiple tips & techniques; overcomes single-tip barrier of existing SPM
- Both strategies have high potential for 3D tomography of confined nanoelectronics devices (de-layering)
- Enabler for use of novel high-performance tip platforms
- Outlook

Increase level of integration into commercial tools
Remove barriers for usability
Expand sensing modes for routine application





Acknowledgements:
H.S. Kim, P. Lagrain, A. Minj, N. Peric, J. Serron, L. Wouters, D. Sharma, M. Tedaldi, A.D.L. Humphris