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Novel Applications of Nanoscale IR Spectroscopy Coupled with AFM for Semiconductor Metrology

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3/17/2026

Outline

01 Introduction to AFM and AFM-IR

Case Studies

02 Surface Nanocontamination

03 Selective Thin-film Deposition

04 Dielectric Composition

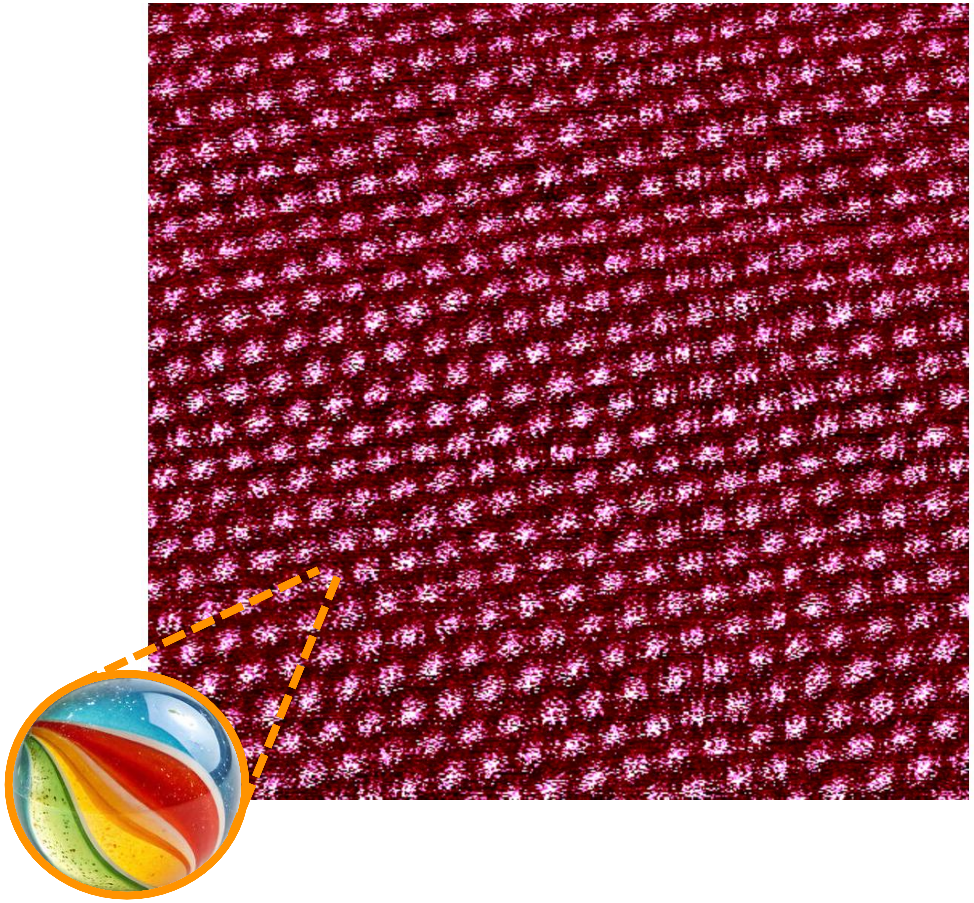
05 Surface Activation for Advanced Packaging

06 Characterizing EUV Photoresists

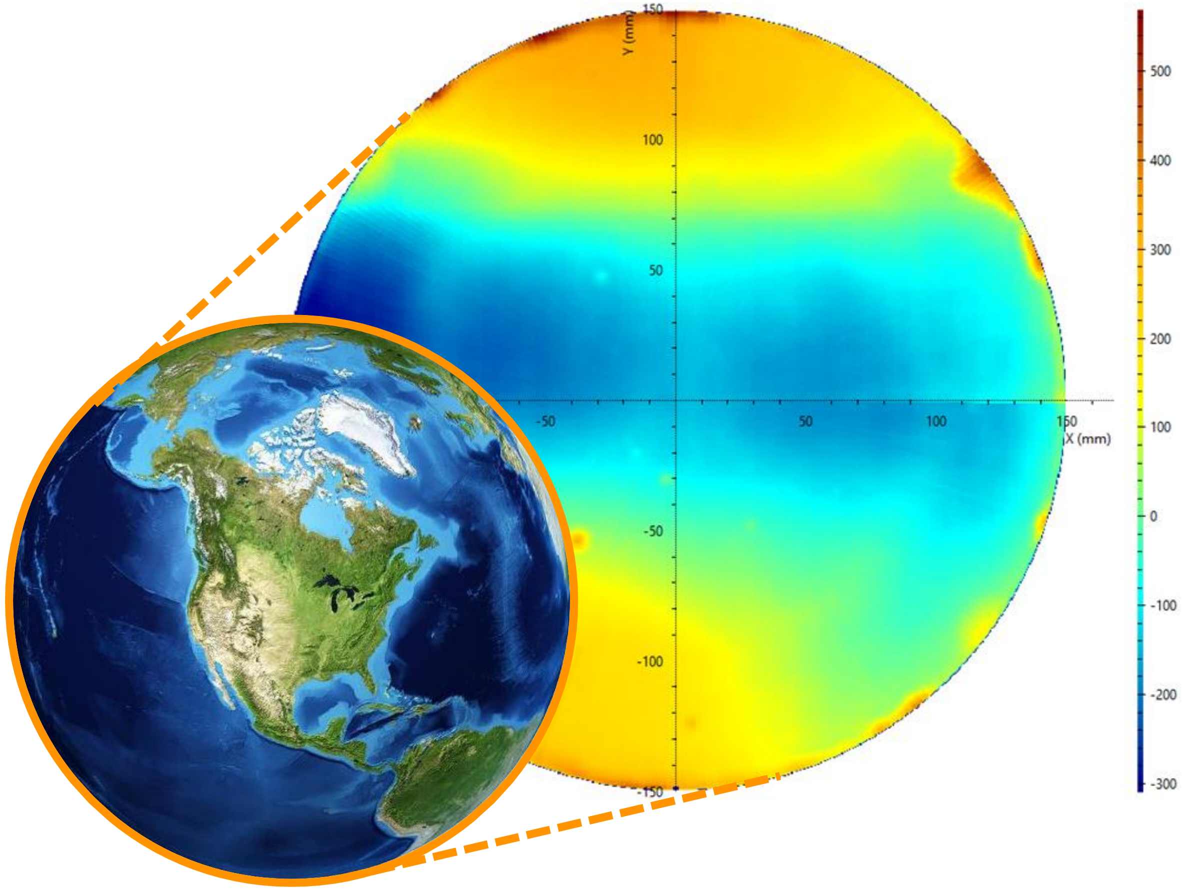
07 Future Materials Correlative 2D characterization

From Atoms to 300 mm Wafers..

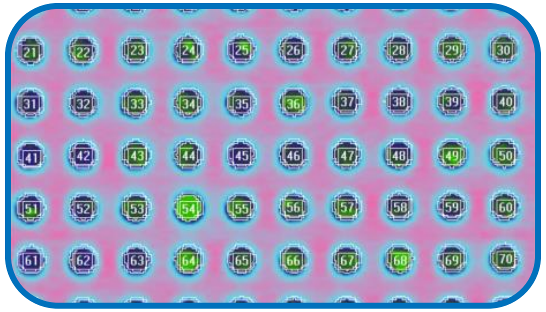
6.x6 nm



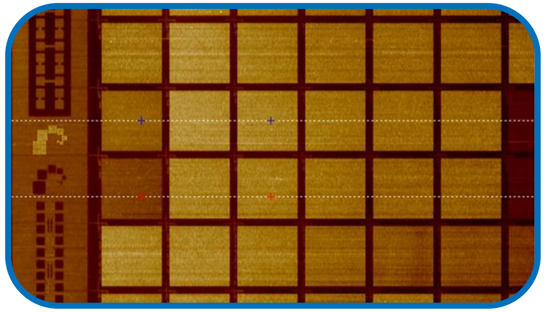
300x300 mm



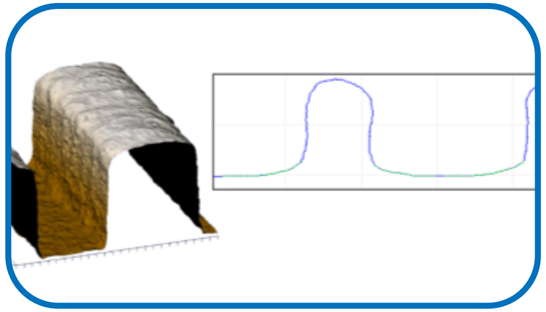
AFM for Semiconductor Material & Device Characterization



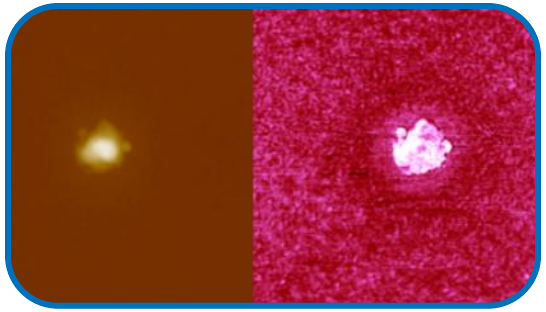
Roughness Metrology



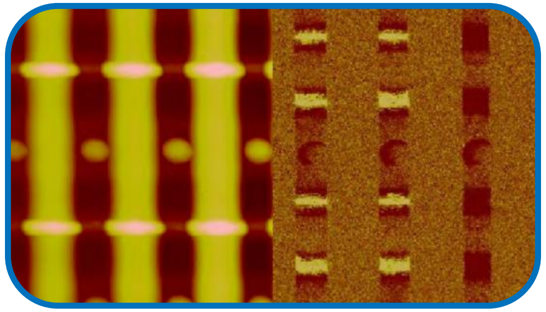
Large Area Metrology & Profiling



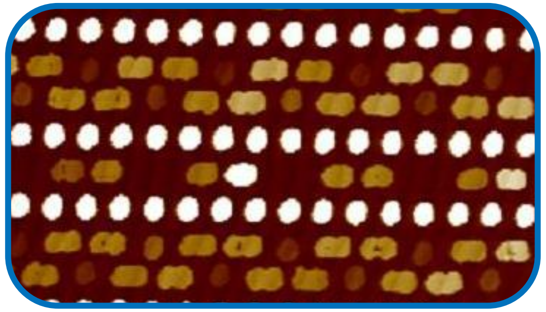
Depth & Critical Dimension Metrology



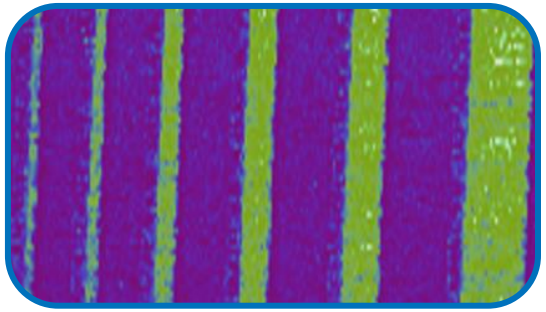
Defect Review



Carrier / Dopant Profiling



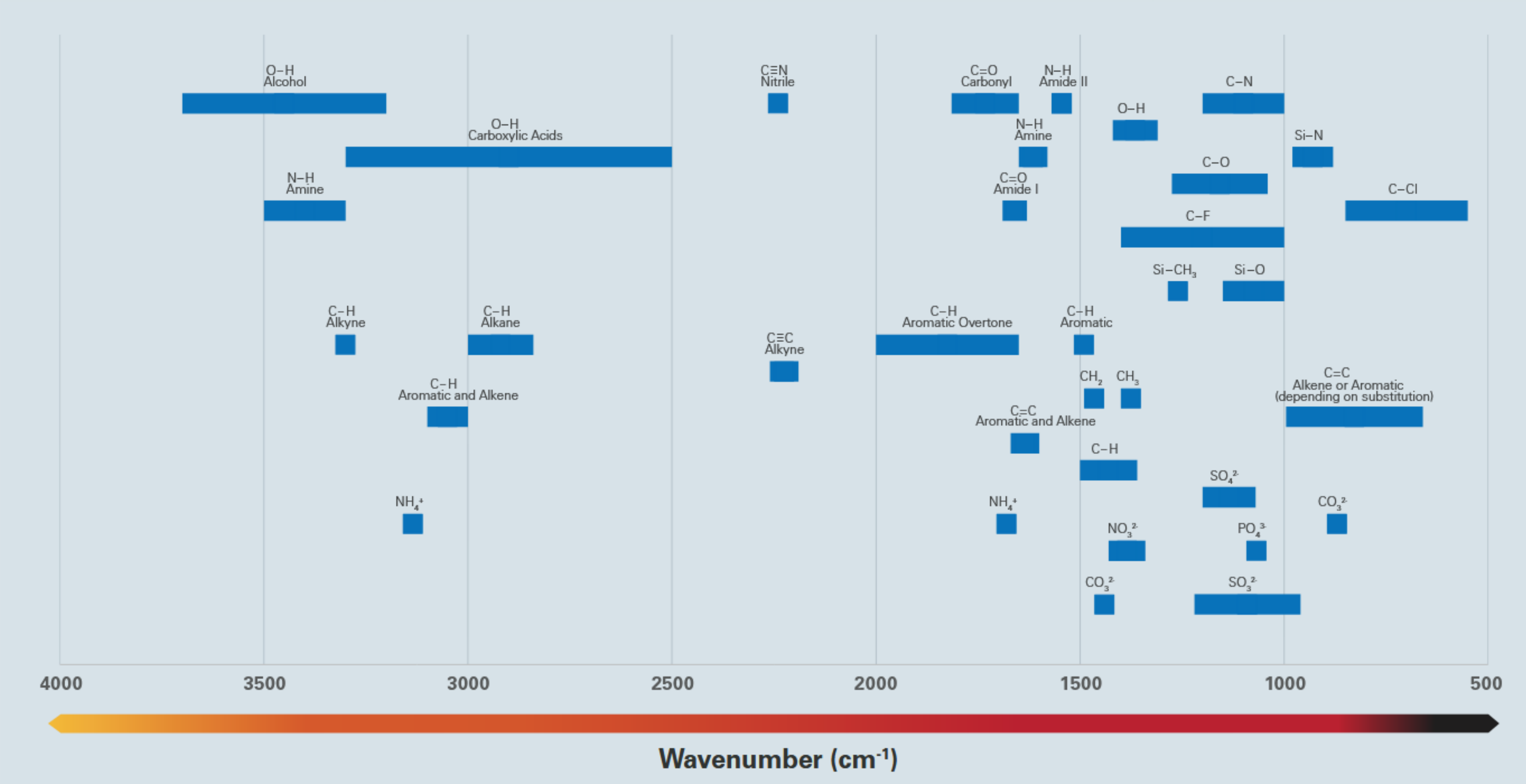
Failure Analysis



Nanoscale IR Imaging & Spectroscopy

Mid-infrared Spectroscopy Identifies Molecular Bonds

- Mid IR absorptions stem from bond vibrations and phonon modes.
- Bonds can be used to identify material's species, serving as a fingerprint.
- Bonds are sensitive to its local environment, molecular structure and crystallinity.

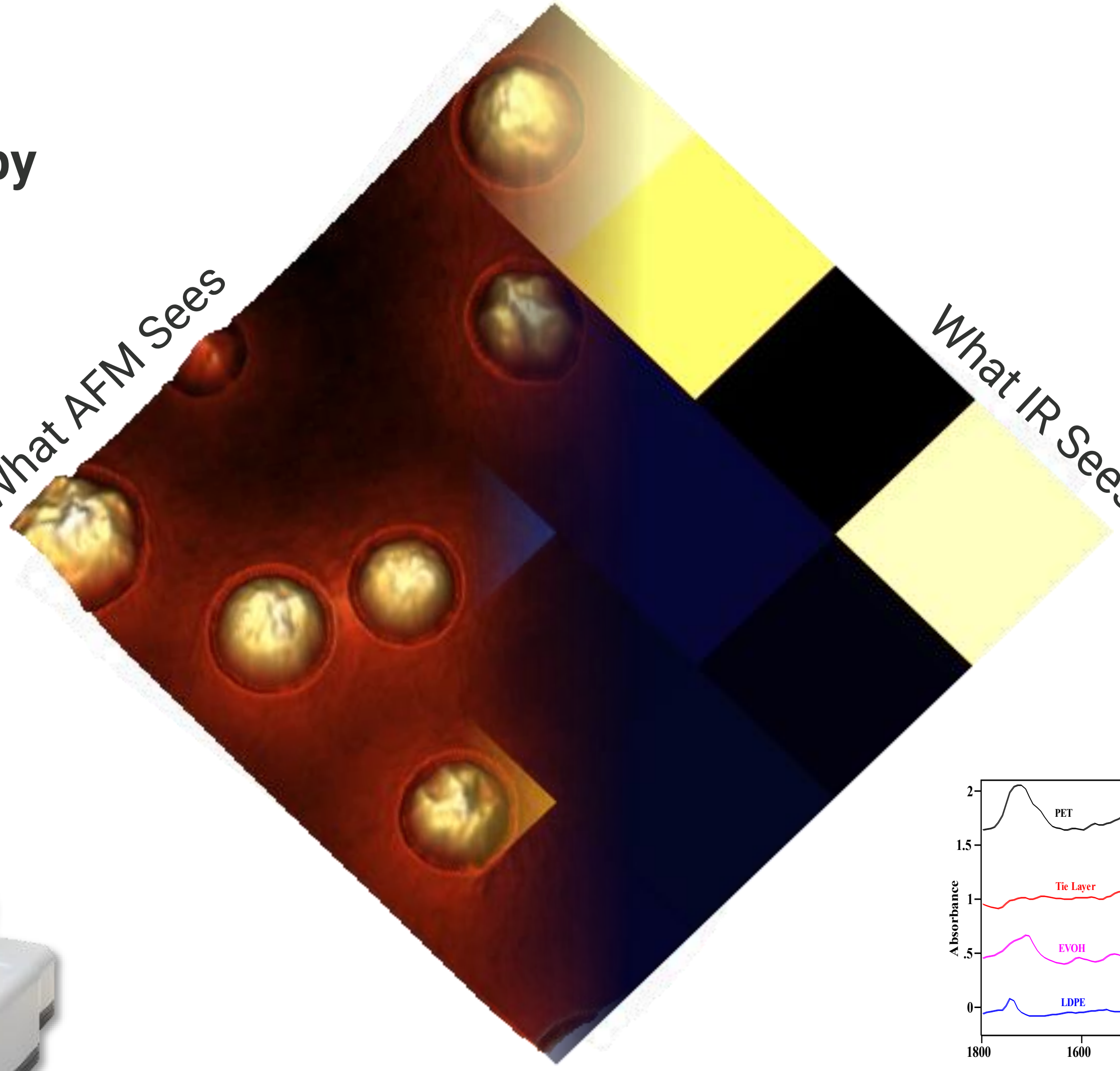


Why Nanoscale IR?

Atomic Force Microscopy

- Provides nanoscale topography, mechanical, electrical properties
- No direct chemical determination.

What AFM Sees



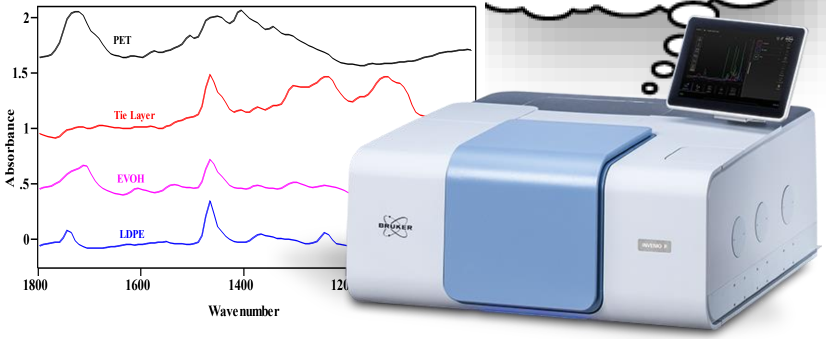
What IR Sees

IR Spectroscopy

- Provides chemical bonding information.
- Restricted by the diffraction limit to several µm pixel size.

What the heck is that?

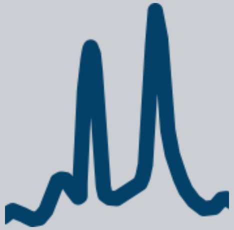
It's too small!



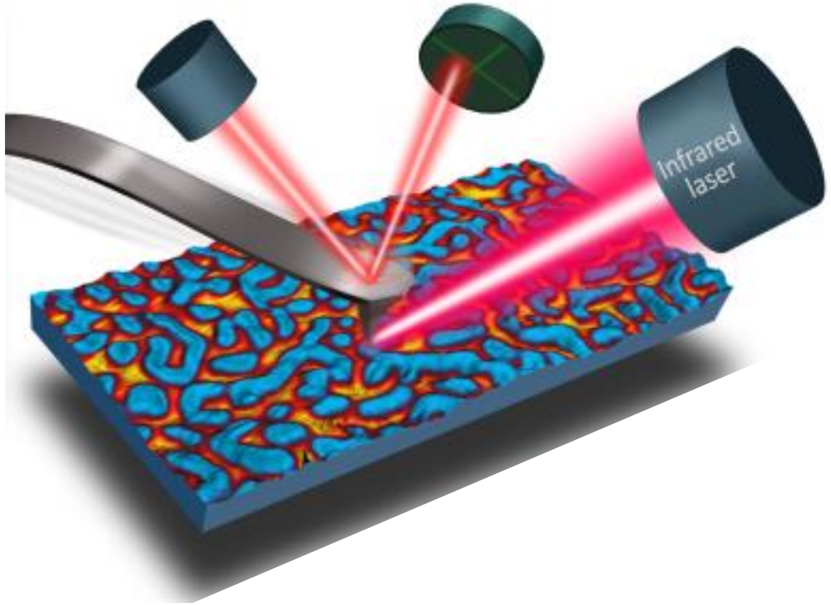
Intro to AFM-IR - nm resolution and attogram sensitivity IR spectroscopy by using the AFM probe as the IR detector

❶ An IR pulse arrives on the sample surface

❷ The sample absorbs the IR pulse, heats up and expands, applying a mechanical force on the AFM probe

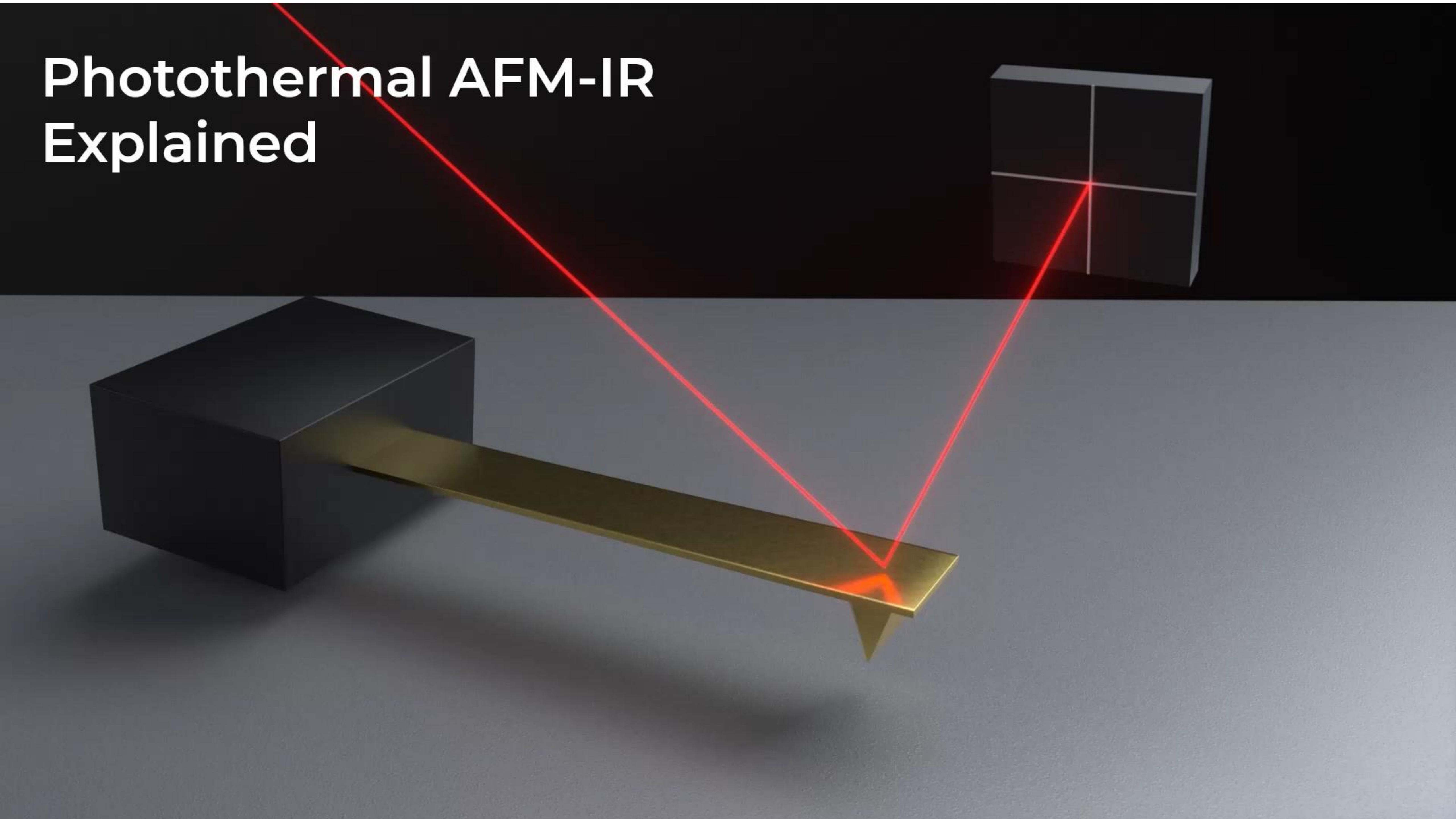


❸ The magnitude of this force is proportional to the absorption coefficient and so the FTIR response



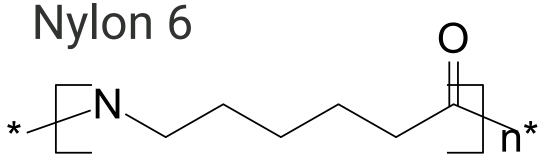
- Detects force
- Absolute measurement
- No dispersion artifacts

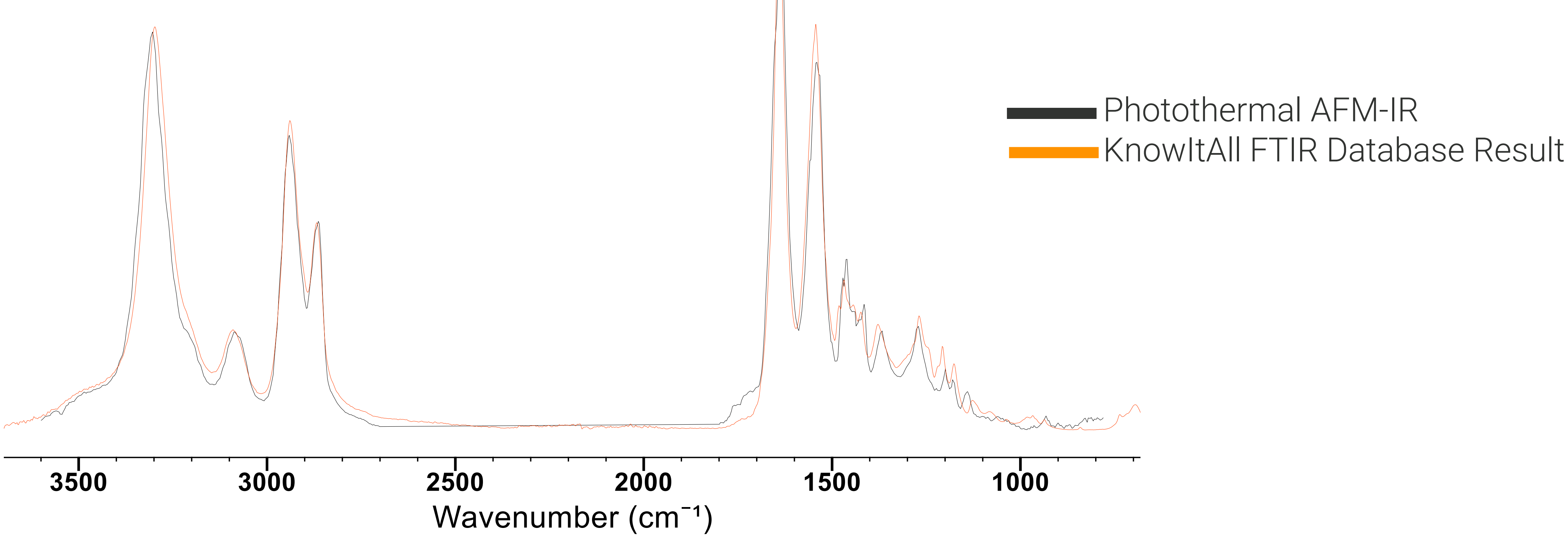
Photothermal AFM-IR Explained



Results in Direct Excitation Scheme Maintain Peak Positions and Ratios Between AFM-IR and FTIR

Nylon 6





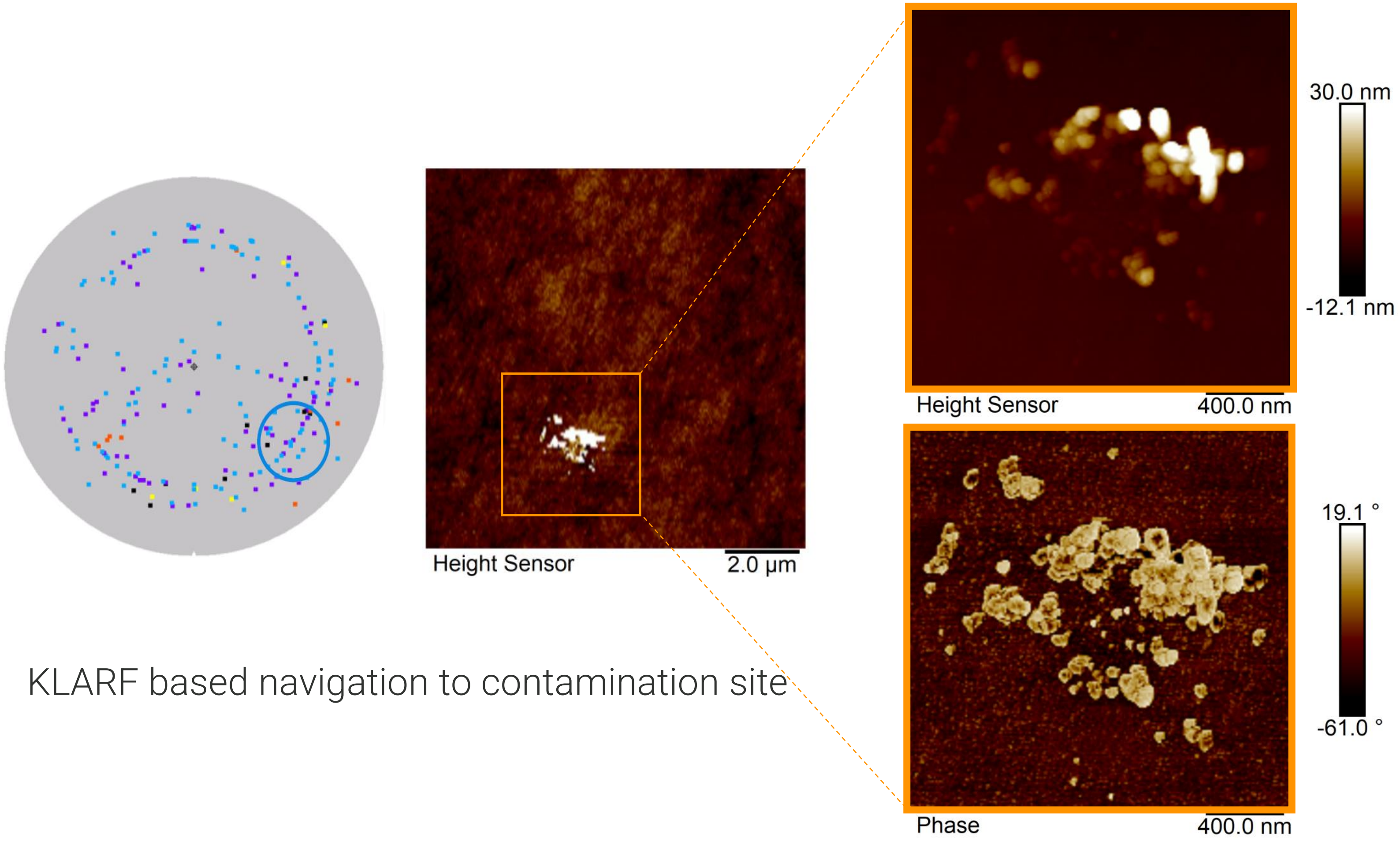
Comparison to Other Surface Analysis Techniques
What makes AFM-IR special?

- Photothermal AFM-IR key advantages:
  - <5 nm lateral resolution
  - Tunable <20 nm to bulk vertical resolution
  - Ambient operation
  - Best for light elements (Cl and below)
  - Chemical bonding and crystallinity information
  - Non-destructive, no e-beam, ion beam or carbon stamping
  - Directly interpretable as FTIR data

Method	Chemical Bond Information	Nanometer Scale Localized	Non-Destructive	Correlated electrical or mechanical properties
AFM-IR	🟢	🟢	🟢	🟢
AFM	🔴	🟢	🟢	🔴
FTIR	🟢	🔴	🟢	🔴
EM/EDS	🔴	🟡	🟡	🔴
XPS	🟢	🔴	🟢	🔴
Tof-SIMS	🟢	🟡	🔴	🔴

Nanocontamination of Wafers and Photomasks

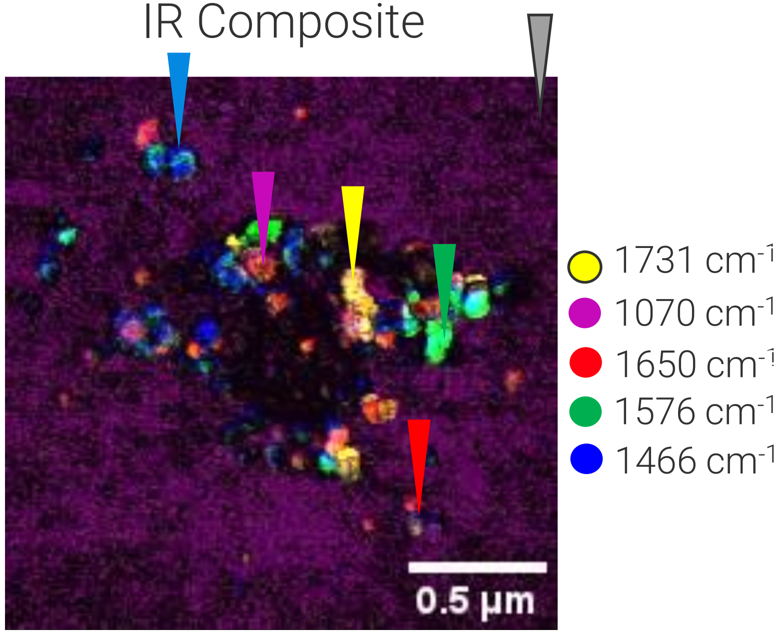
Traditional AFM Approach to Nanocontaminants



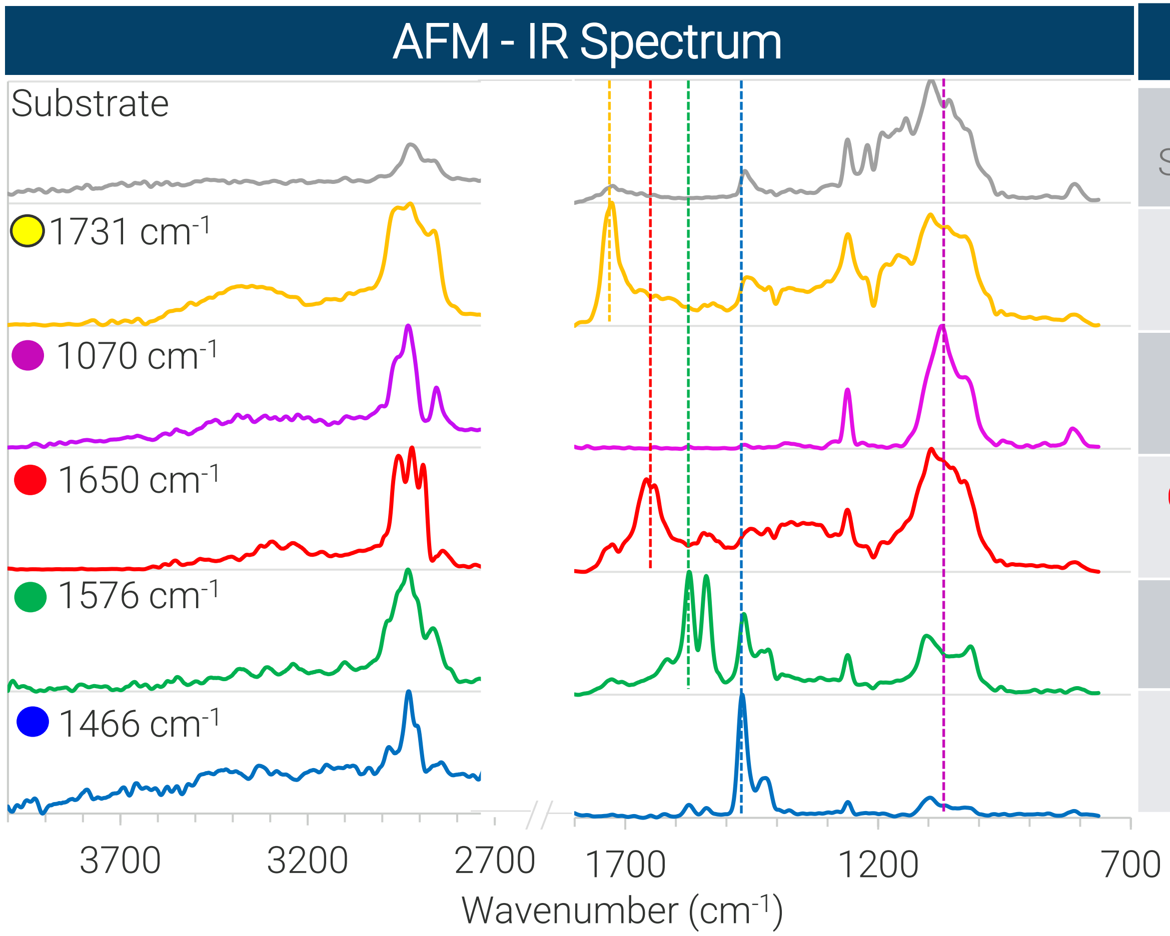
KLARF based navigation to contamination site

- Key Problems:
- We know where the contamination is, not what it is.
- Nanoscale products of unknown origin are found with KLARF navigation.
- Phase channel shows uniform stiffness among the particles – no distinction of material composition.

AFM-IR Reveals Unique Molecular ID in a Single Contamination Site



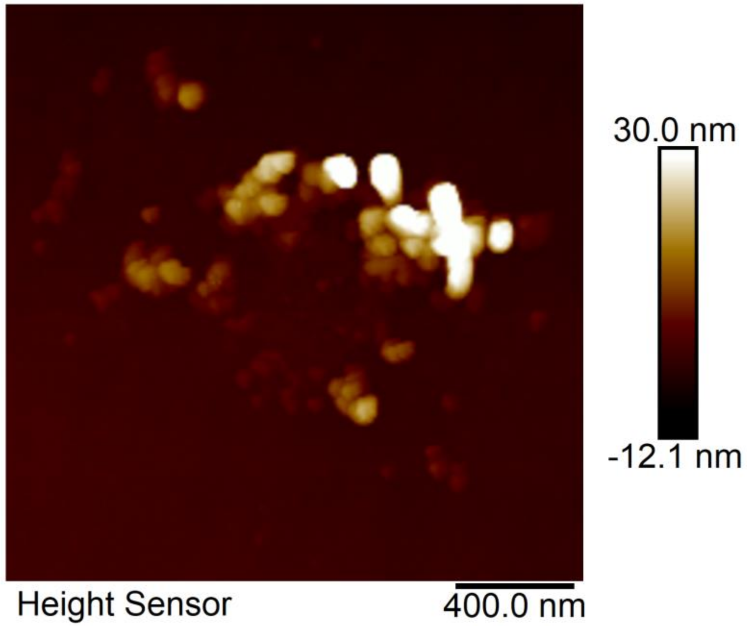
- IR spectrum collected at designated spots (∇)



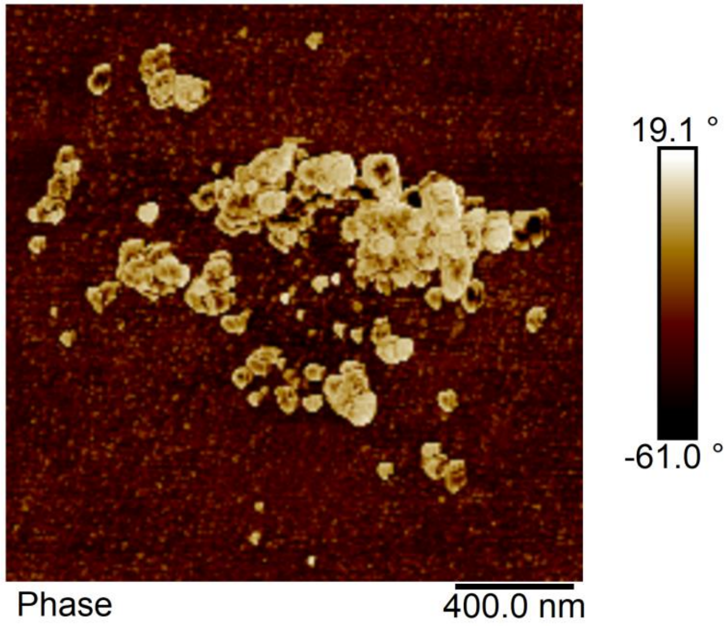
Assignments
Broad Si-O: Silicon and Silicone
Carbonyl, CH, OH: Acrylate
Narrow Si-O: Silicon
Carbonyl and N-H: Amides
CH and COO-: Stearates
Carbon rich : Lubricants, Wax, Polyethylene

AFM-IR Adds Critical Insight - Evidence of Multiple Contamination Origins

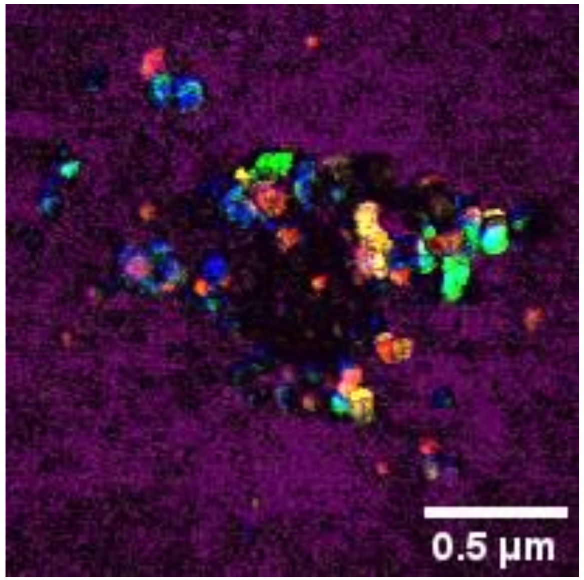
Height



Phase



IR Composite



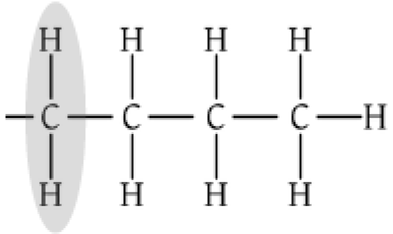
- 1731 cm^{-1}
- 1070 cm^{-1}
- 1650 cm^{-1}
- 1576 cm^{-1}
- 1466 cm^{-1}

- IR map reveals distribution of 5 unique chemical functionalities.
- Compare to <1 pixel in a standard FTIR microscope

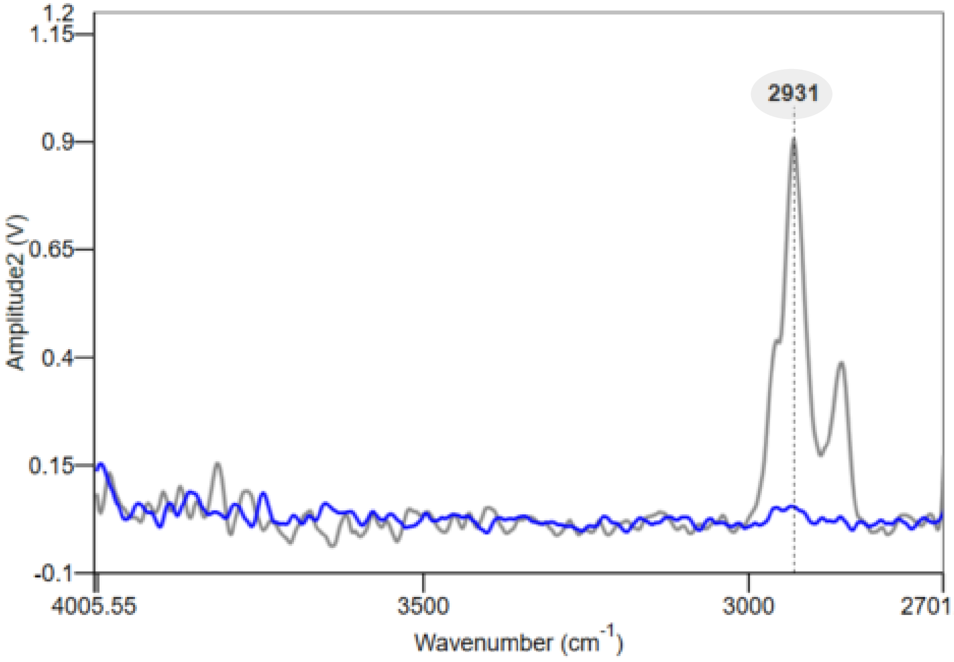
Selective Deposition of Thin Films

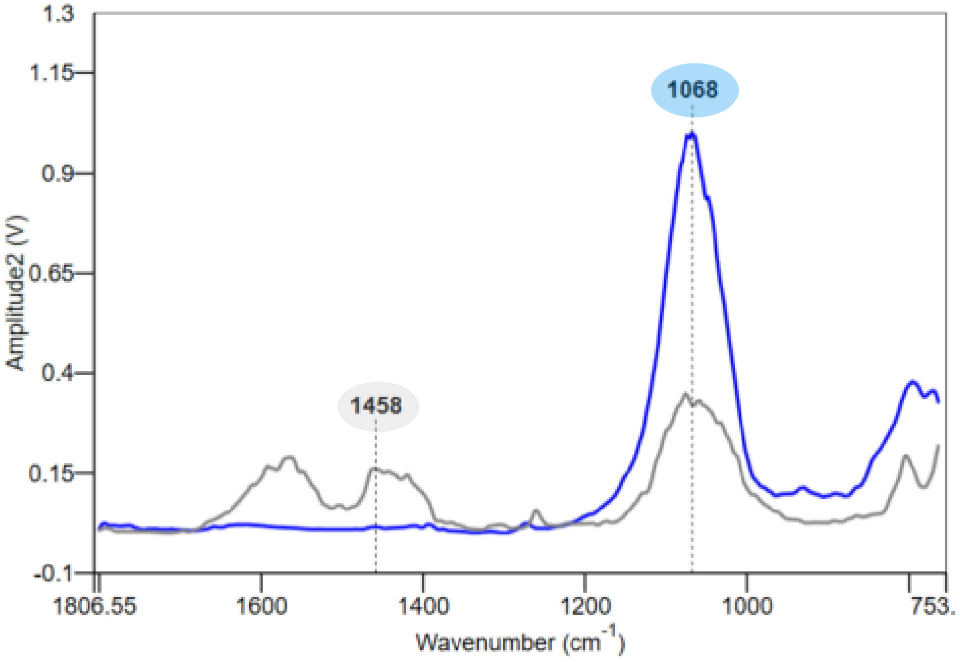
SAM on Dielectrics Nanochemical ID of principal components

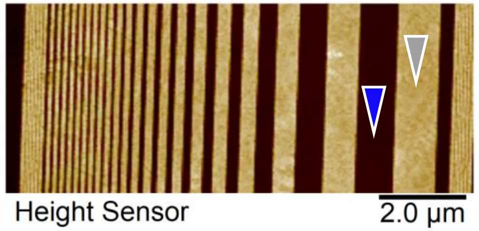
- Alkyl based SAM
  - C-H bending ~1458 cm^{-1}
  - C-H stretch ~2930 cm^{-1}



- Dielectric
  - Si-O ~1068 cm^{-1}

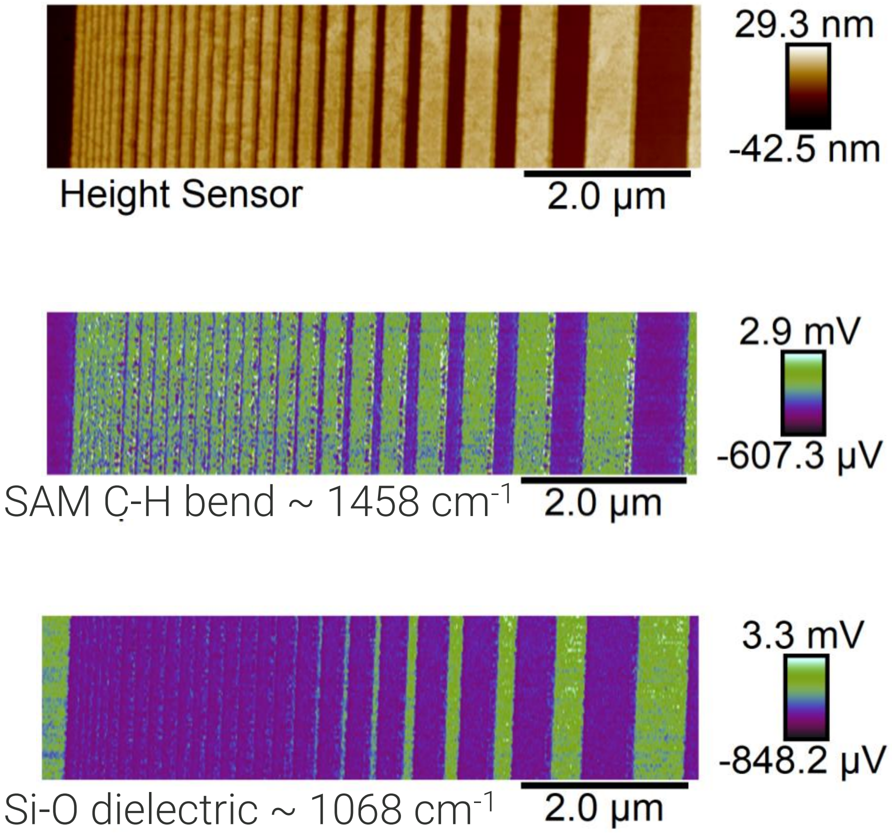






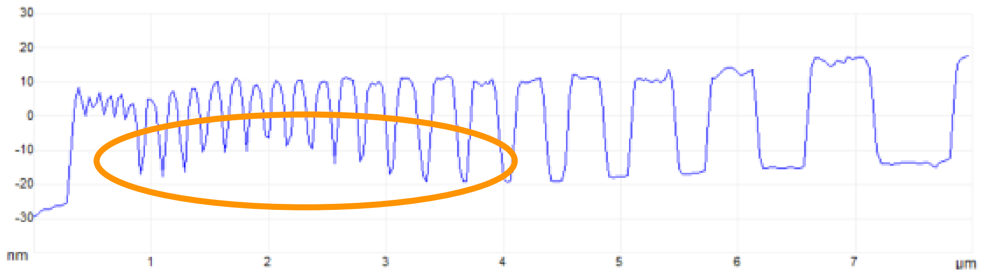
SAM on Dielectrics Nanochemical mapping of each component

- Tapping AFM-IR maps

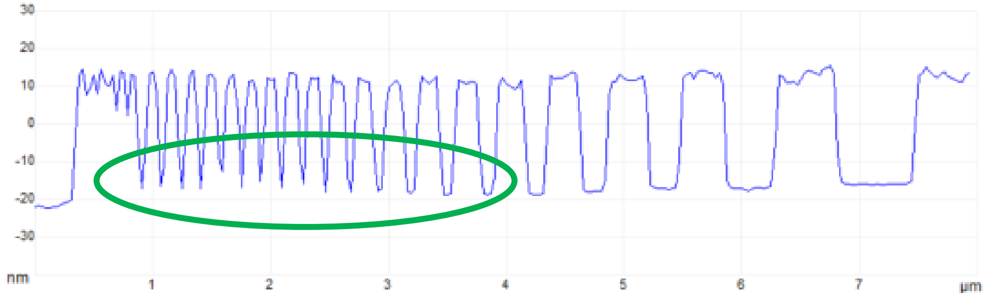


- Correlated high quality metrology + chemical analysis

Height profile during Tapping AFM-IR with a ~30 nm tip

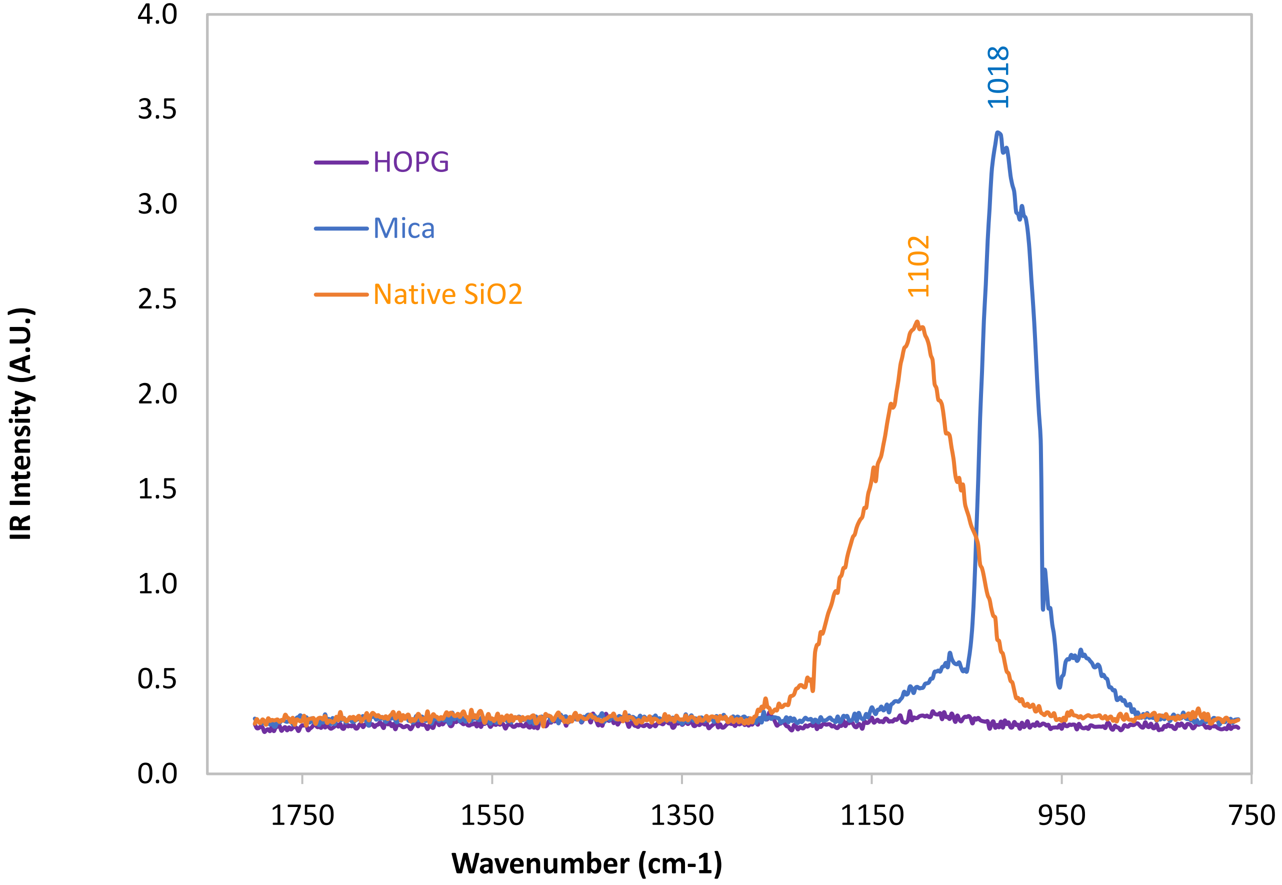


Height profile with Peakforce Tapping using a ~1 nm



Dielectric Composition

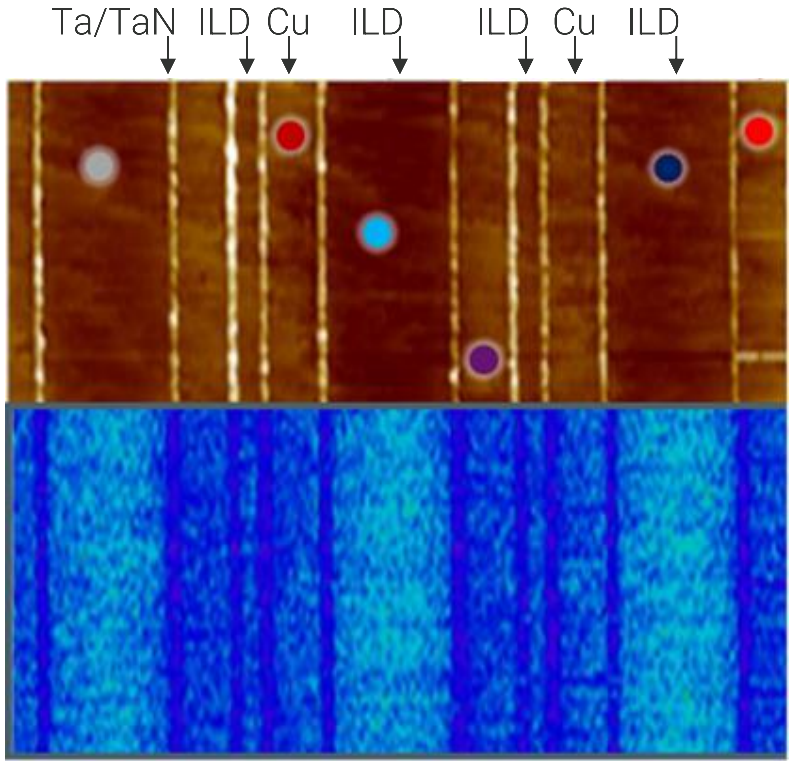
High Sensitivity (< 2nm) Native SiO_2



- Native SiO_2 peak is clearly resolved, demonstrating <2 nm sensitivity on non-IR-enhancing substrate.
- Mica shows a different primary peak corresponding to a different SiO structure

Interconnects affect surface chemistry of adjacent l

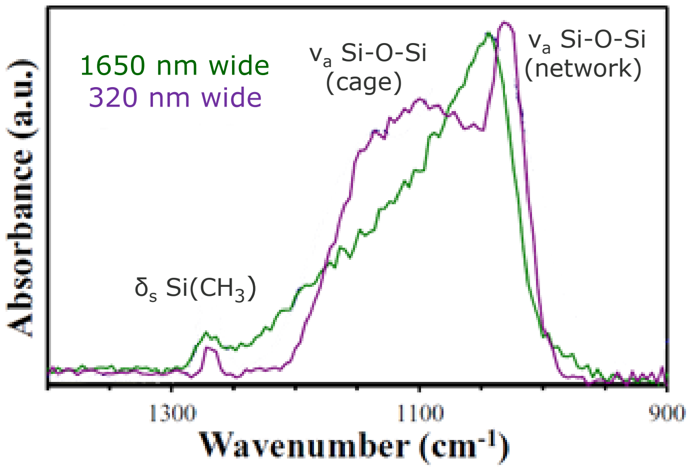
- AFM-IR spectroscopy: Differences in C-H stretching intensity are obs
  (blue and light blue) vs thick (green and gray) channels of low-k diele
- **Collaboration Bruker / Intel.** ECS J. Solid State Sci. Technol. **2016**, 5



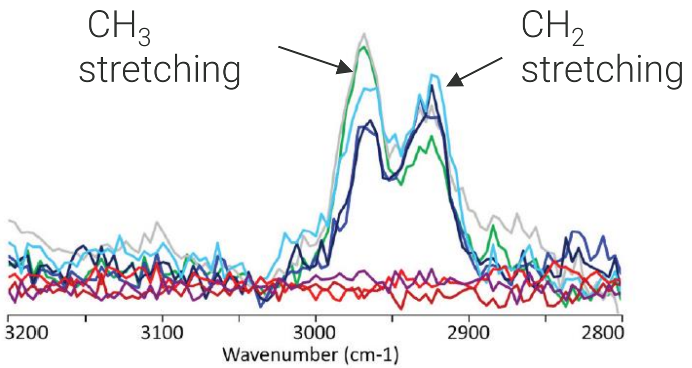
Height Image

(10 µm x 5 µm)

IR image at 2960 cm^{-1}

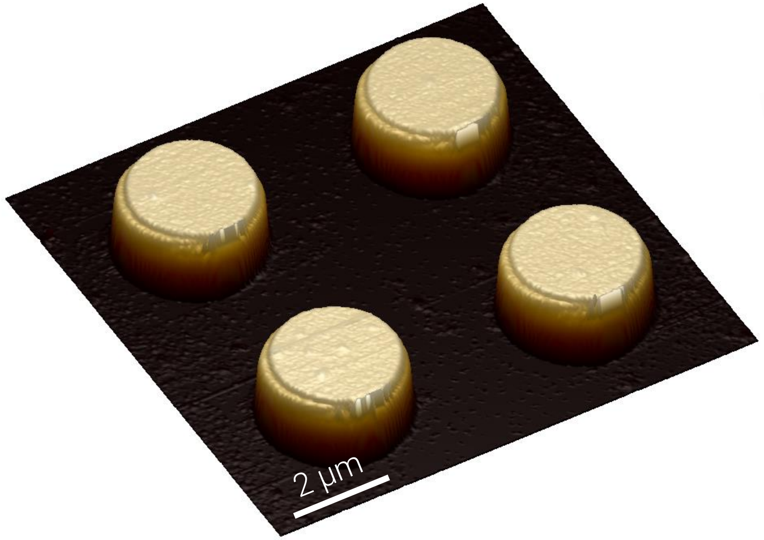


AFM-IR spectra

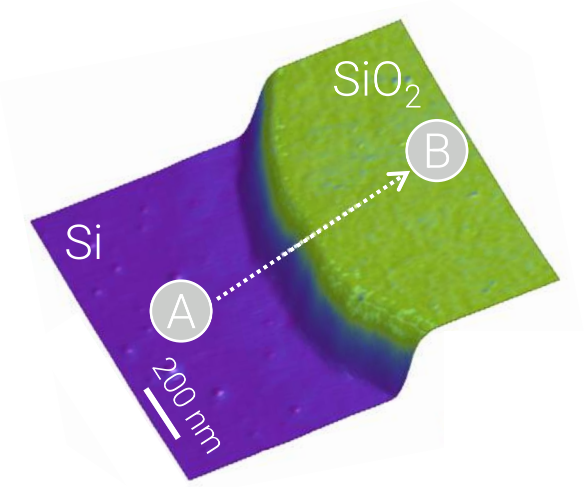


AFM-IR for Crystallinity of Dielectric Structure

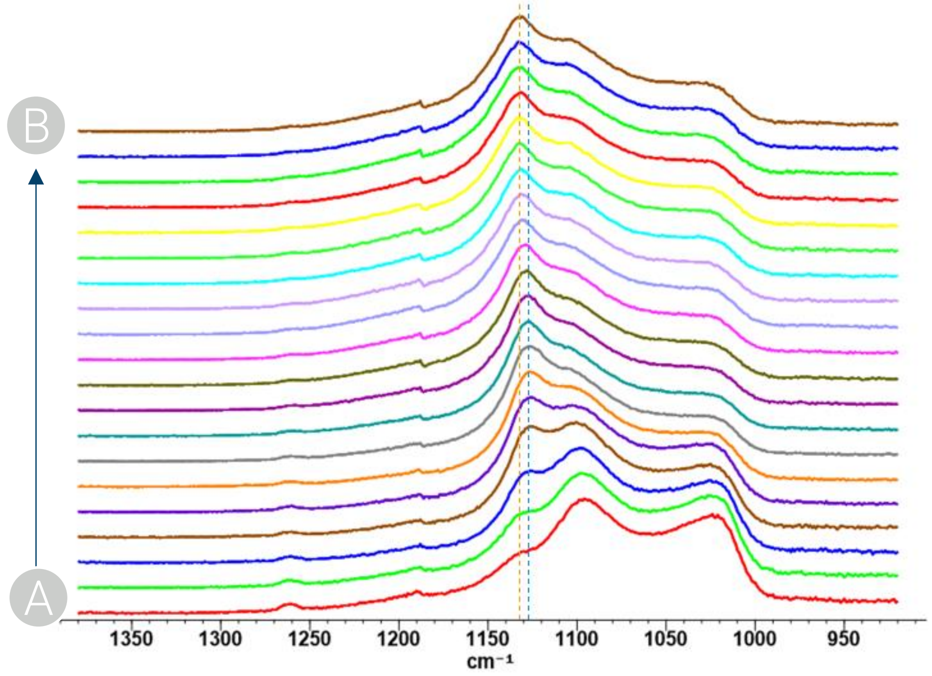
- 100 nm SiO_2 pillars on Si
- SiO_2 peak wavenumber shifts at pillar edges between 1125 ~ 1134 cm^{-1} indicating Si-O-Si crystallinity / structural changes near the edge.



Topography

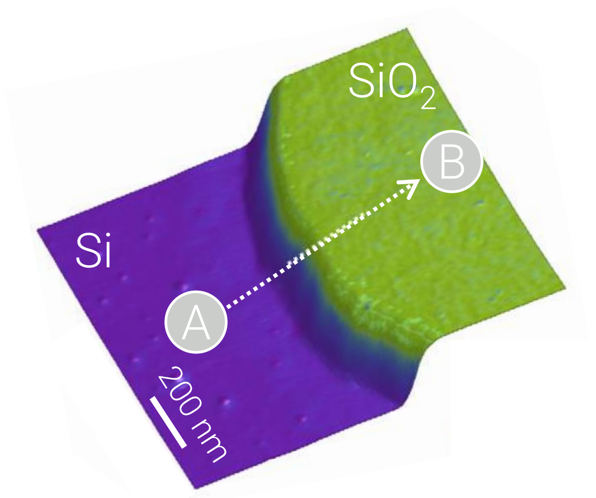


IR absorption @ 1132 cm^{-1}

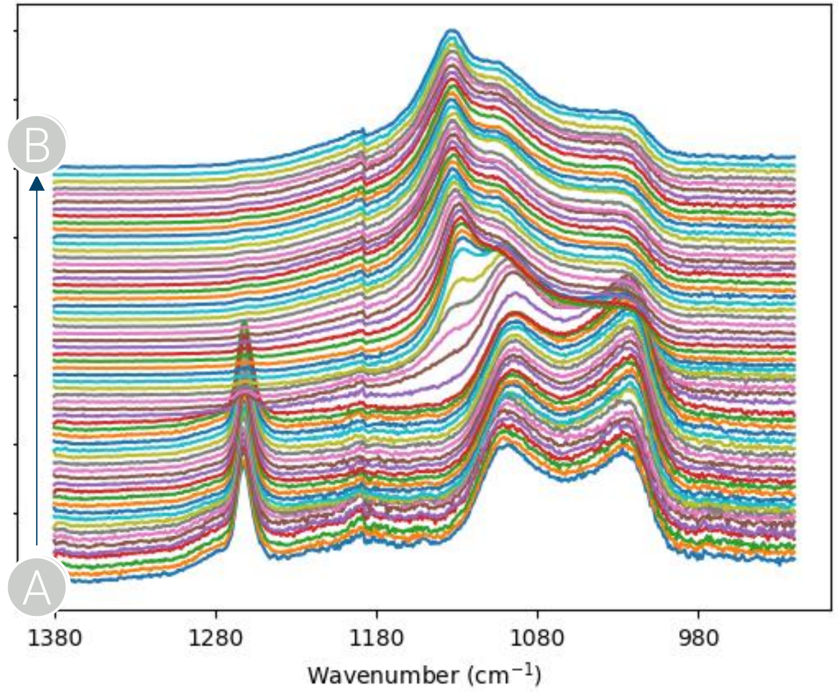


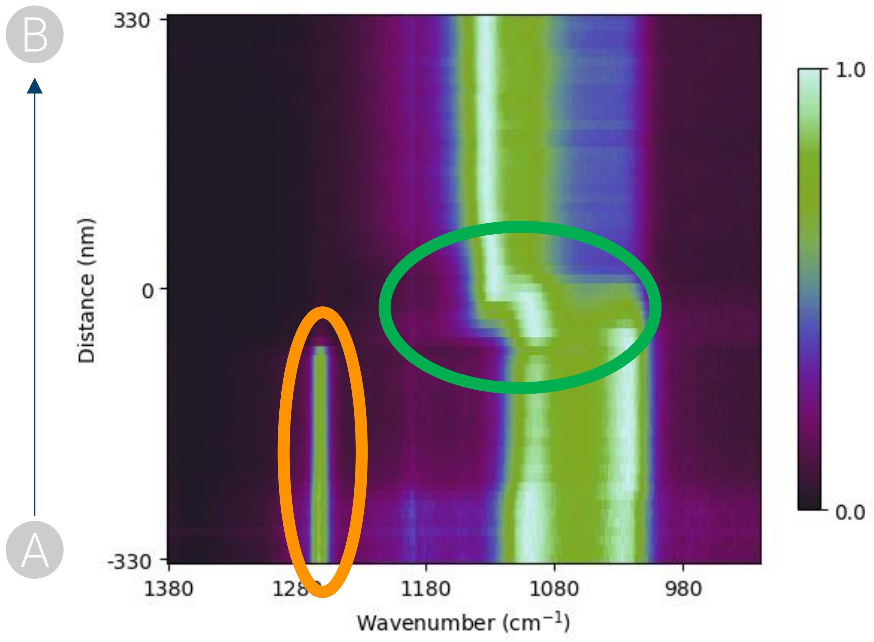
AFM-IR Reveals Crystaline to Amorphous Transition at the Interface

- 100 nm SiO_2 pillars on Si
- SiO_2 peak wavenumber shifts at pillar edges between 1125 ~ 1134 cm^{-1} indicating Si-O-Si crystallinity / structural changes near the edge.



IR absorption @ 1132 cm^{-1}

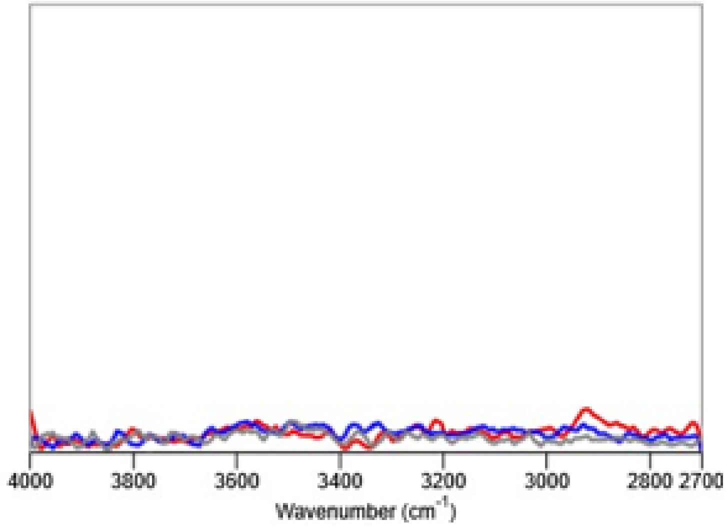




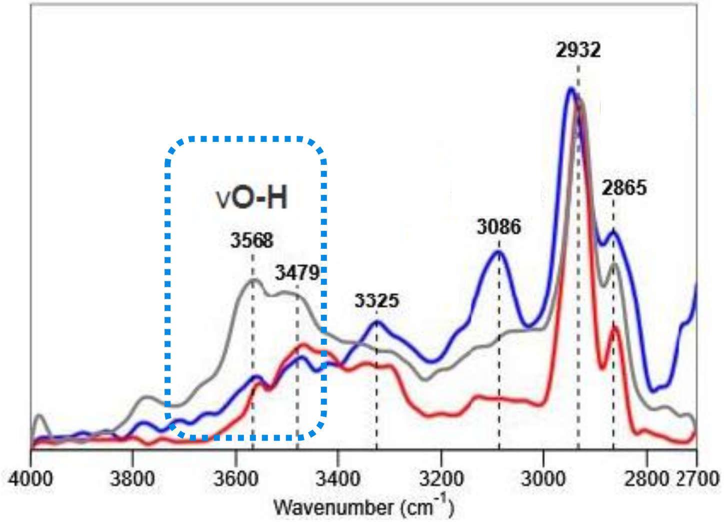
Advanced Packaging

Copper Pad Surface Chemistry
Surface Activation for Improved Bonding

Control



Surface Activation

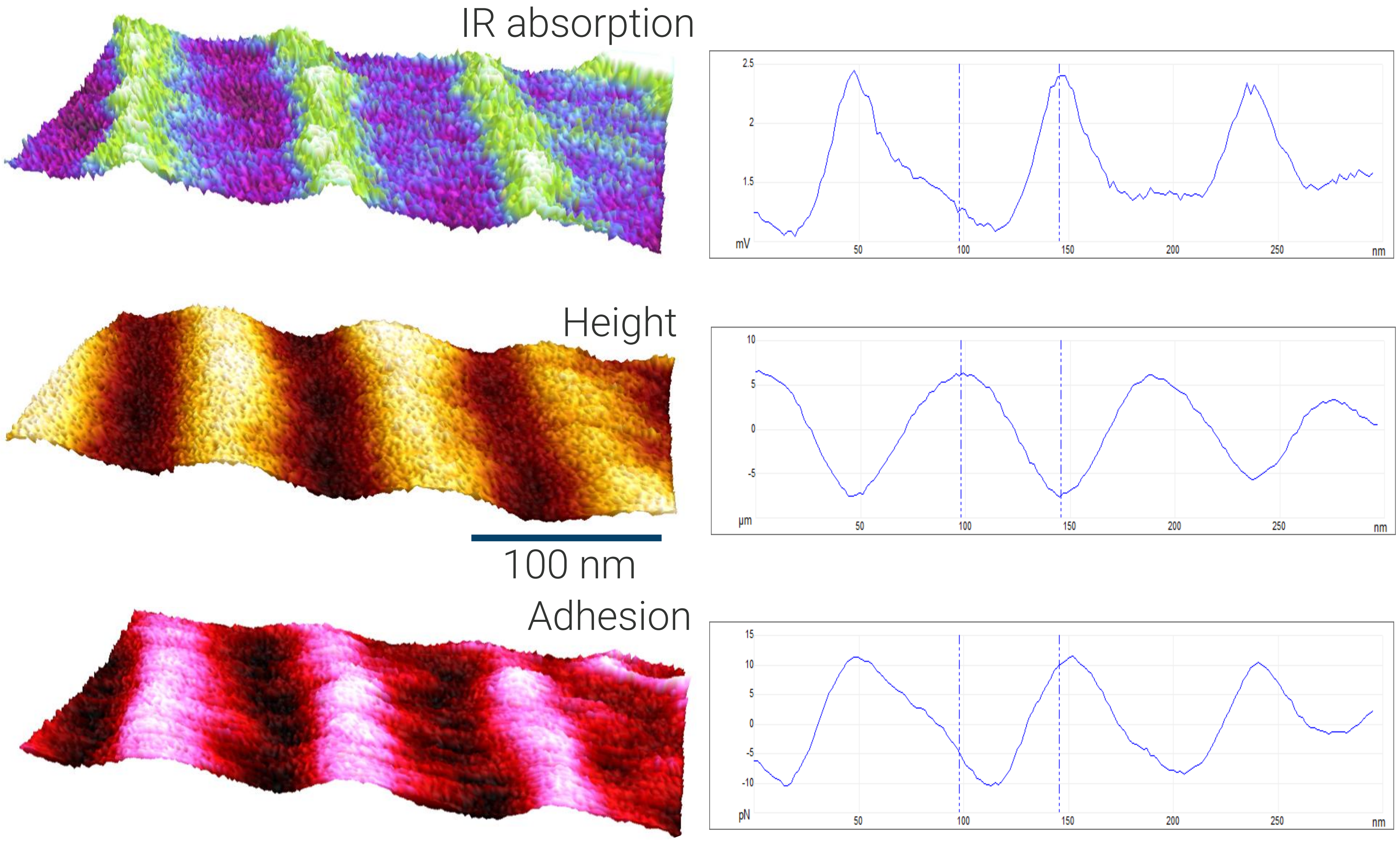


- AFM-IR reveals chemistry changes between control and surface activated Cu pads
- Exposes differences from different surface treatments
- AFM-IR is the only technique which can measure surface activation of wafers and copper pads on this length scale

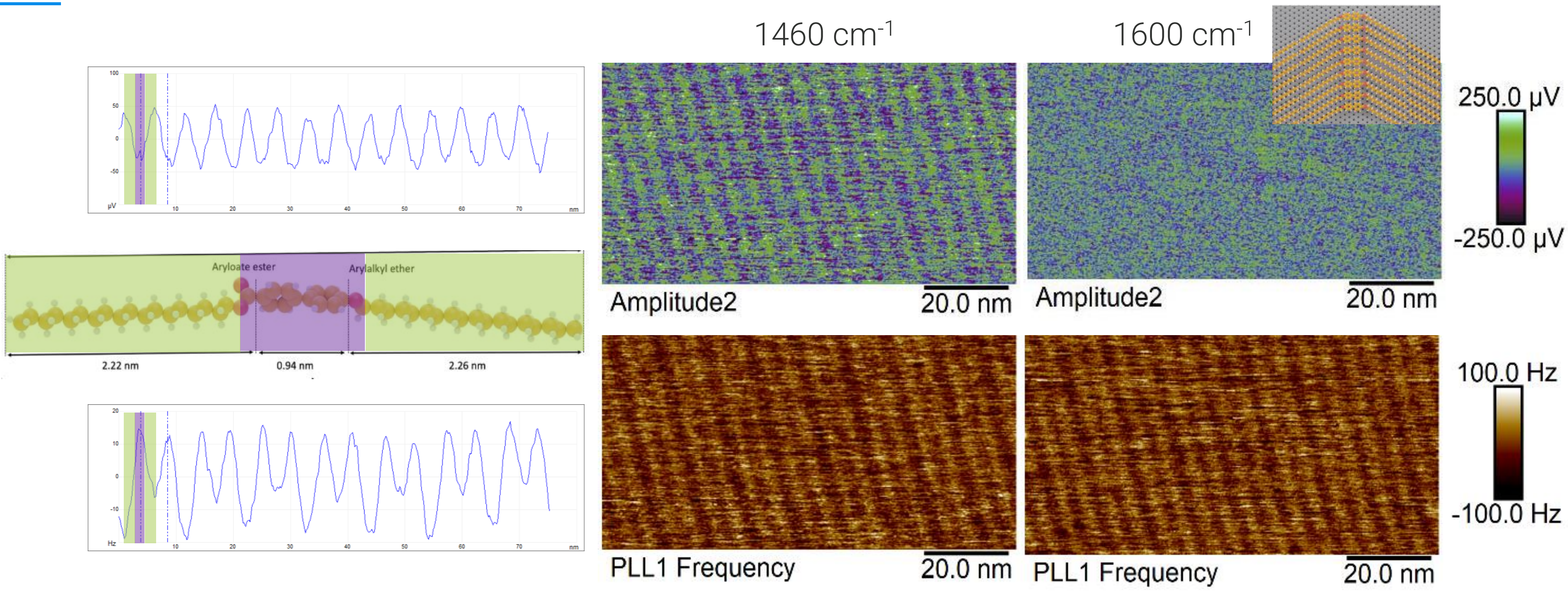
EUV Photoresist Characterization

Photoresist Lithography Characterization

- 100 nm pitch
- Higher IR absorbance in valley vs. ridge, as expected
- Patterning recipe can be tweaked (EUV dose, underlayer chemistry, PAG molecules, etc.) and tracked.
- Low-force mechanical modes (e.g. Force Volume) are ideal for working on soft, delicate samples
- Sample courtesy: TNO, Netherlands



Ultrahigh Resolution Test Sample Framework for Further EUV Exploration

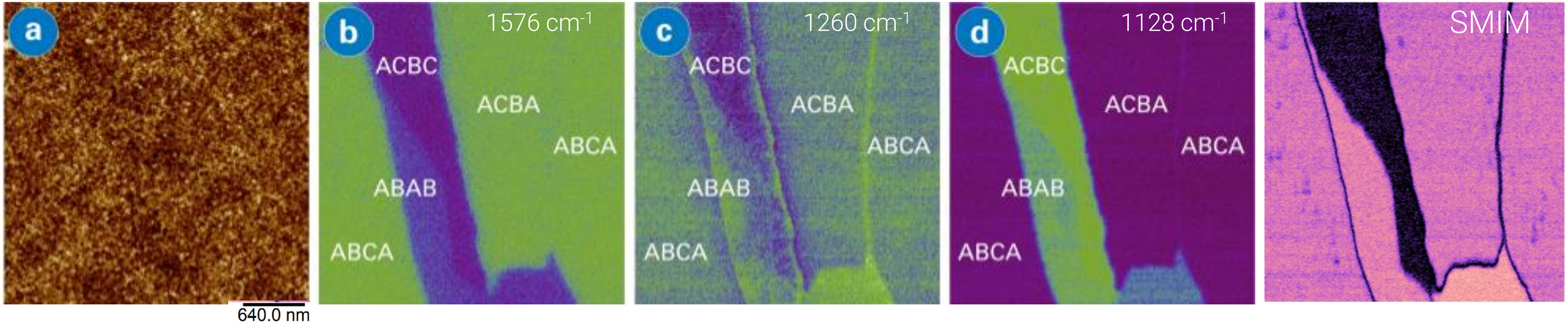


- Resolution: **1-2 nm** (10-90% 'level')
- Monolayer (0.8 nm) sensitivity on HOPG
- Low drift: < 0.2 nm/min

J. Phys Chem Lett. 2025 Apr 10;16(14):3433:3437

Future Materials
Graphene Characterization

4-Layer Graphene Correlation Between Electronic Properties and Chemical Structure



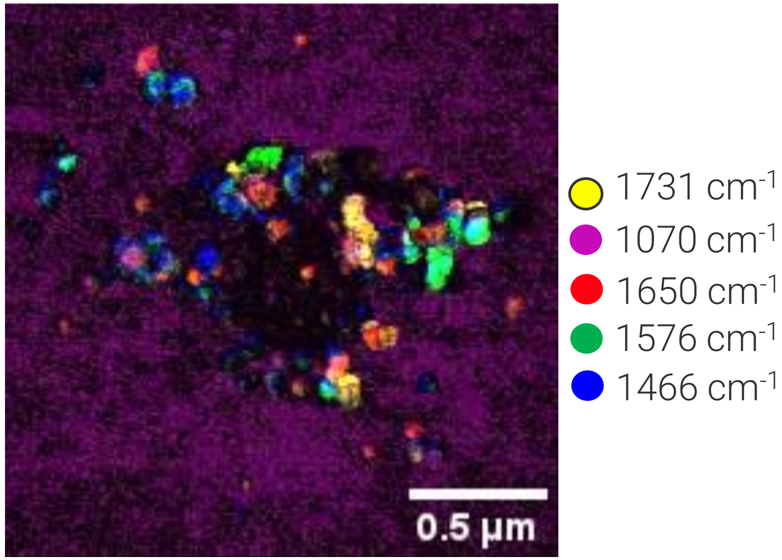
- AFM-IR and SMIM (scanning microwave impedance microscopy) provide complimentary data on an otherwise flat surface
- SMIM reveals carrier density and type
- AFM-IR reveals layer ordering

Nano Lett. 2025, 25, 33, 12487–12494

Summary

Summary

- Photothermal AFM-IR adds additional characterization capabilities to existing metrology workflows
- AFM-IR is used wherever chemical information is needed below 500 nm feature sizes
- AFM-IR provides novel insights on:
  - Nanocontamination
  - Surface selective deposition
  - Dielectric variation
  - Advanced Packaging
  - EUV Photoresists
  - 2D Materials



Learn more:

APPLICATION NOTE | NANOSCALE INFRARED SPECTROMETERS

Application Note: Photothermal AFM-IR for Semiconductor Materials and Devices

Discover how AFM-IR offers insights into contamination, interfaces, and material performance

Acknowledgements

- We thank our academic & industrial partners, active in collaborations to further develop AFM-IR technology for Semiconductor & 2D material applications:

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Prof. Alex Dazzi & team (AFM-IR Inventor)

Stanford University

Stanford Nano Shared Facilities

UC SANTA BARBARA

Prof. Andrea Young & team

EAG LABORATORIES

intel

imec

Ongoing JDP

Innovation with Integrity