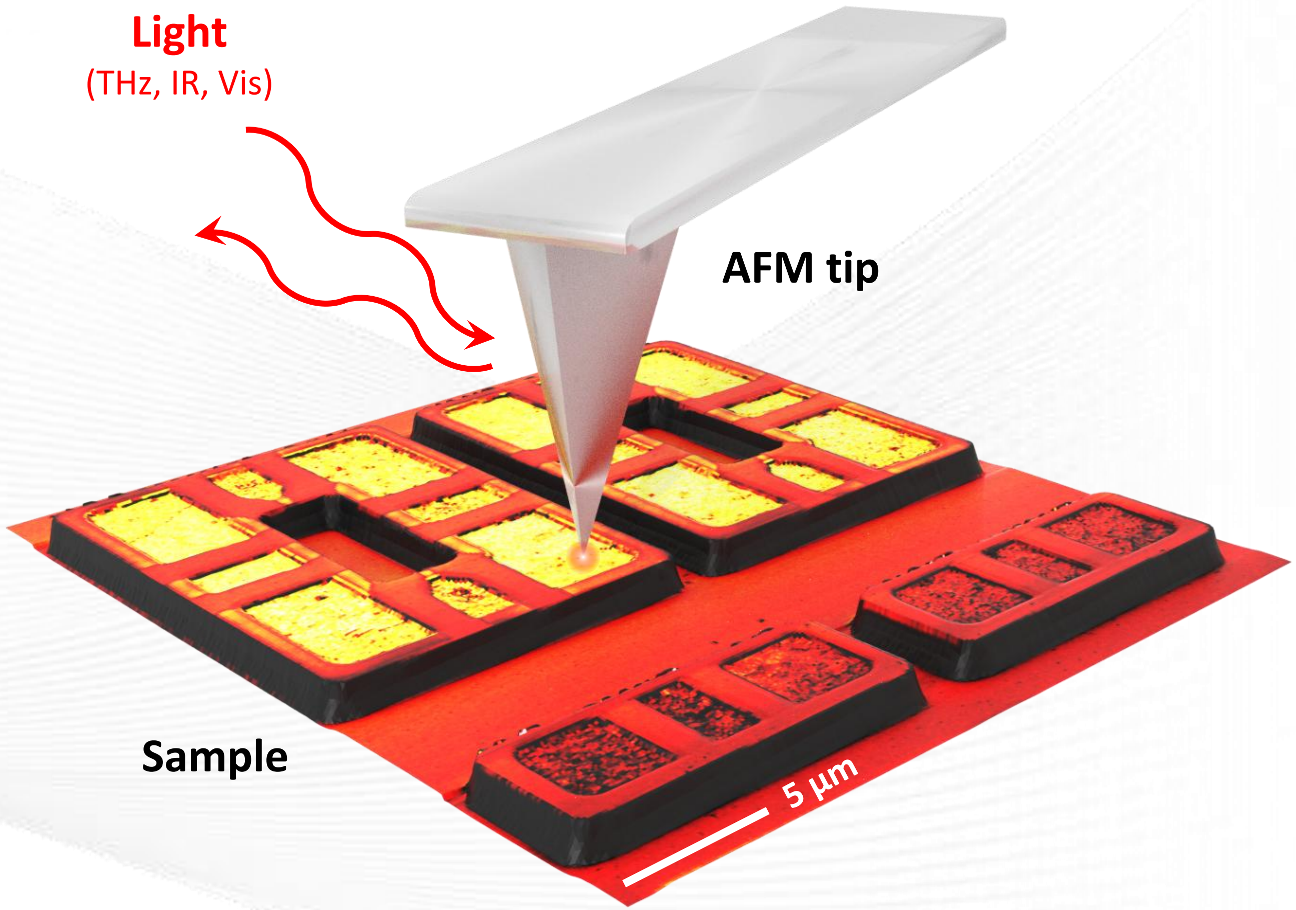
Nano-optical imaging and spectroscopy – An overview

attocube
WITTENSTEIN Group



1 **Nano-IR probing principle(s)**
AFM-IR / nano-FTIR

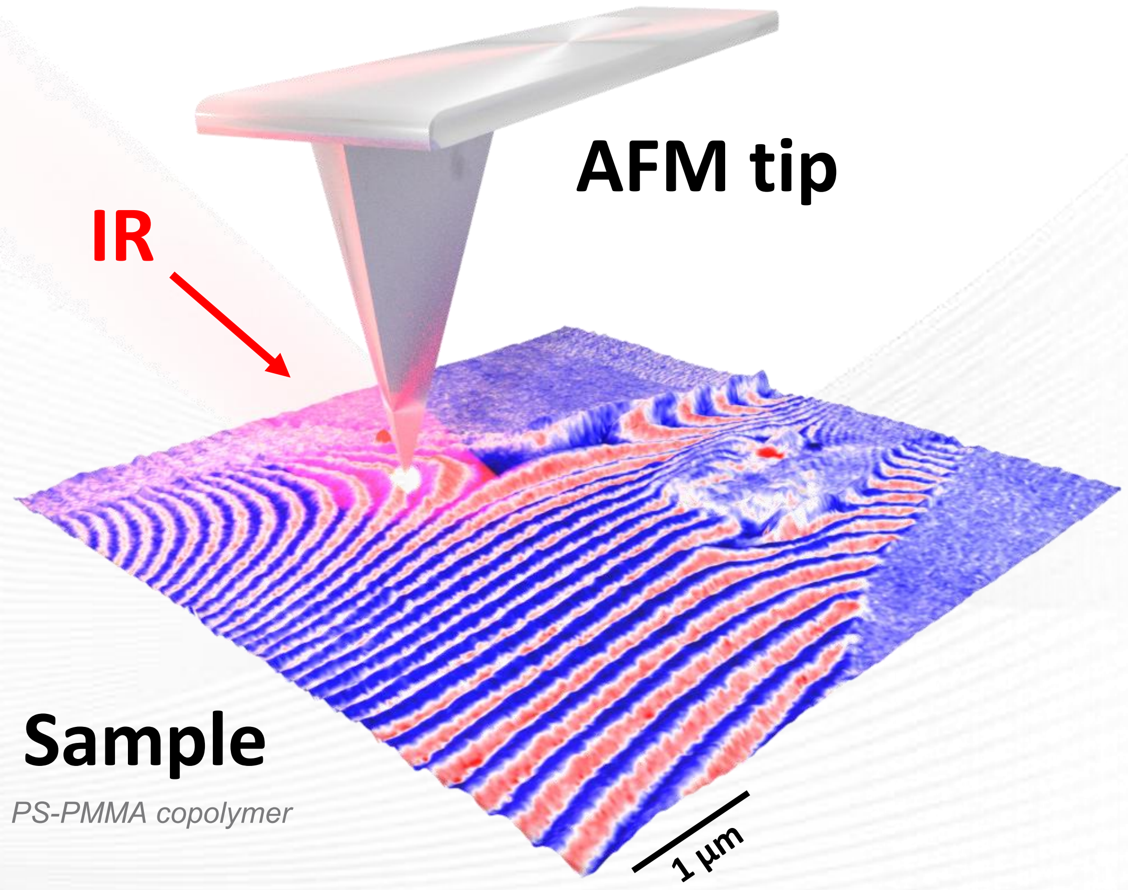
2 **Application to Semicon Materials**
Organic / Inorganic / Charge carriers

3 **Not covered today**
2D materials / photonics

neaspec see the nanoworld

NANOSCALE ANALYTICS
advanced imaging & spectroscopy

nano-IR – infrared imaging & spectroscopy beyond the diffraction-limit



IR spectroscopy + **Atomic Force Microscopy**

- Based on atomic force microscopy (AFM) technology
- Focused laser-beam illuminates metal AFM tip
- Concentrated optical hot spot below the tip apex
- **nano-IR absorption** is measured via
  - Photo-thermal force detection (**AFM-IR, PiFM**)
  - All-optical light detection (**nano-FTIR, s-SNOM**)
- Imaging & spectroscopy by sample scanning

Infrared imaging and spectroscopy at ca. 10 nm spatial resolution

- B. Knoll, F. Keilmann, *Nature* **399**, 134 (1999)
- **R. Hillenbrand et al., Nat. Rev. Mat. 10, 285 (2025)**

neaspec – world-leading nanoscopy solutions

attocube
WITTENSTEIN group

neaSNOM
platform for near-field microscopy
2009

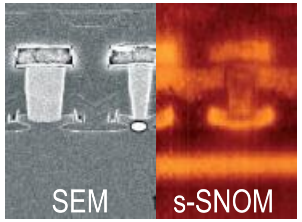
attocube systems AG
acquires neaspec GmbH
2014

neaSCOPE
microscopes for nanoscale analytics
2022

IRa-SCOPE
new era in vibrational spectroscopy
2025

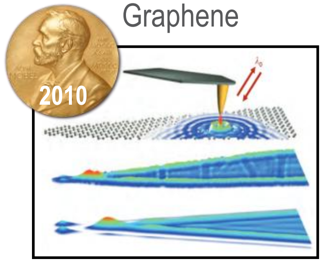
- 2005 – **s-SNOM**
- '07
- '11 – Transmission
- '12 – **nano-FTIR**
- '13 – nano-THz
- '16 – Cryogenic
- '18 – Pump-probe nano-FTIR
- '19-21 – **AFM-IR, Raman/PL**
- '23 – Liquid cell, nano-photocurrent
- '24 – nano-PL, TERS

Transistor



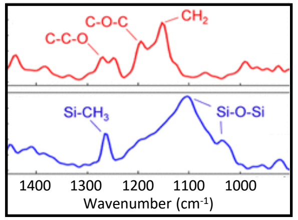
Huber (2007)

Graphene



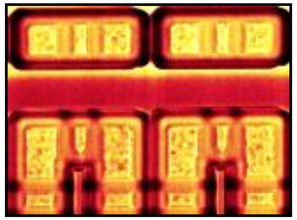
Chen (2012)

nano-FTIR



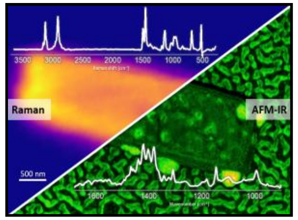
Huth (2012)

nano-THz

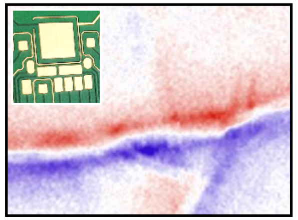


Aghamiri (2019)

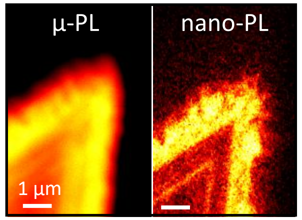
AFM-IR / Raman



nano-photocurrent



nano-PL



Product Line
neaspec

NANOSCALE ANALYTICS
advanced imaging & spectroscopy

nano-IR as characterisation tool for semiconductor materials

List of publications for semiconducting materials

Silicon

Quantification of carrier density gradients along axially doped silicon nanowires using infrared nanoscopy, Jung et al, *ACS Photonics* **6**, 7, 1744-1754 (2019)

Hyperspectral time-domain terahertz nanoimaging, Aghamiri et al, *Optics Expr.* **27**, 24231 (2019)

All-electronic terahertz nanoscopy, Liewald et al, *Optica* **5**, 2, 159-163 (2018)

Mapping Free-Carriers in Multijunction Silicon Nanowires Using Infrared Near-Field Optical Microscopy, Ritchie et al, *Nano Lett.* **17**, 11, 6591-6597 (2017)

Terahertz Near-Field Nanoscopy of Mobile Carriers in Single Semiconductor Nanodevices, Huber et al, *Nano Lett.* **8**, 11, 3766-3770 (2008)

SiN

Simultaneous IR Material Recognition and Conductivity Mapping by Nanoscale Near-Field Microscopy, Huber et al., *Adv. Mater.* **19**, 2209 (2007)

SiO_x

Near-field infrared spectroscopy of SiOx nanowires, Milekhin et al, *Appl Surf Sci* **584**, 152583 (2022)

Model for quantitative tip-enhanced spectroscopy and the extraction of nanoscale-resolved optical constants, McLeod et al, *Physical Review B*, **90**, 085136 (2014)

SiC, GaN

Nanoscale Infrared Spectroscopic Characterization of Extended Defects in 4H-Silicon Carbide, Criswell et al, *Nano Lett.* **24**, 1, 114-121 (2024)

Near-field imaging and spectroscopy of locally strained GaN using an IR broadband laser, Bensmann et al., *Opt. Expr.* **22**, 19, 22369 (2014)

Nanoscale residual stress-field mapping around nanoindents in SiC by IR s-SNOM and confocal Raman microscopy, Huber et al, *Nature Nanotech* **4**, 153 (2009)

Nanoscale Resolved Infrared Probing of Crystal Structure and of Plasmon–Phonon Coupling, Huber et al, *Nano Lett.* **6**, 774 (2006)

Subwavelength-scale tailoring of surface phonon polaritons by focused ion-beam implantation, Ocelic et al, *Nature Materials* **3**, 606 (2004)

InP

Nanoscale Free-Carrier Profiling of Individual Semiconductor Nanowires by Infrared Near-Field Nanoscopy, Stiegler et al, *Nano Lett.* **10**, 1387 (2010)

InAs

Ultrafast multi-terahertz nano-spectroscopy with sub-cycle temporal resolution, Eisele et al, *Nature Phot.* **8**, 841-845 (2014)

Ultrafast Dynamics of Surface Plasmons in InAs by Time-Resolved Infrared Nanospectroscopy, Wagner et al, *Nano Lett.* **14**, 8, 4529-4534 (2014)

Tunable Low Loss 1D Surface Plasmons in InAs Nanowires, Zhou et al, *Adv. Mat.* **30**, 35, 1802551 (2018)

Unveiling the detection dynamics of semiconductor nanowire photodetectors by terahertz near-field nanoscopy, Pogna et al, *Light Sci Appl* **9**, 189 (2020)

2DEG

Phonon-Enhanced Near-Field Spectroscopy to Extract the Local Electronic Properties of Buried 2D Electron Systems in Oxide Heterostructures, Barnett et al, *Adv Mat* **30**, 46, 2004767 (2020)

High sensitivity variable-temperature infrared nanoscopy of conducting oxide interfaces, Luo et al, *Nature Comm* **10**, 2774 (2019)

Organic semicon.

Two-dimensional polyaniline crystal with metallic out-of-plane conductivity, Zhang et al, *Nature* **638**, 411-417 (2025)

Solvent-structured PEDOT:PSS surfaces: fabrication strategies and nanoscale properties, Sanviti et al, *Polymer* **246**, 124723 (2022)

Photo-resist

Near-field infrared nanoscopic study of EUV- and e-beam-exposed hydrogen silsesquioxane photoresist, Kim et al, *Nano Convergence* **9**, 53 (2022)

Microdomain homogeneity evaluation of perpendicular lamellar structures in block copolymer films: X-ray scattering and IR nanospectroscopy analyses, Lee et al, *Polymer Testing* **104**, 107409 (2021)

Contam. ID

Nano-FTIR Absorption Spectroscopy of Molecular Fingerprints at 20 nm Spatial Resolution, Huth et al, *Nano Lett.* **12**, 8, 3973-3978 (2012)

On-surface photopolymerization of two-dimensional polymers ordered on the mesoscale, Grossmann et al, *Nature Chemistry* **13**, 730-736 (2021)

Correlating gas permeability and morphology of bio-based polyether-block-amide copolymer membranes by IR nanospectroscopy, David et al, *J of Membrane Science* **708**, 123001 (2024)

Others, inorganic

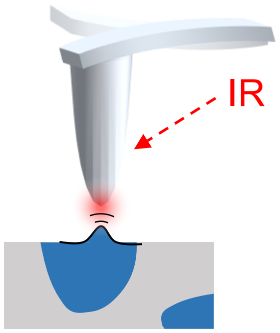
Characteristic length scales of the electrically induced insulator-to-metal transition, Luibrand et al, *Phys. Rev. Research* **5**, 013108 (2023)

Characterization of semiconductor materials using synchrotron radiation-based near-field infrared microscopy and nano-FTIR spectroscopy, Hermann et al, *Optics Express*, **22**, 17948 (2014)

Mott Transition in VO2 Revealed by Infrared Spectroscopy and Nano-Imaging, Qazilbash et al, *Science* **318**, 5857 (2007)

nano-IR spectroscopy in a nutshell

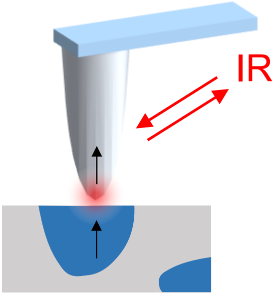
AFM-IR
Force detection



Probing absorption κ ~ Im ε
(via photo-thermal expansion)

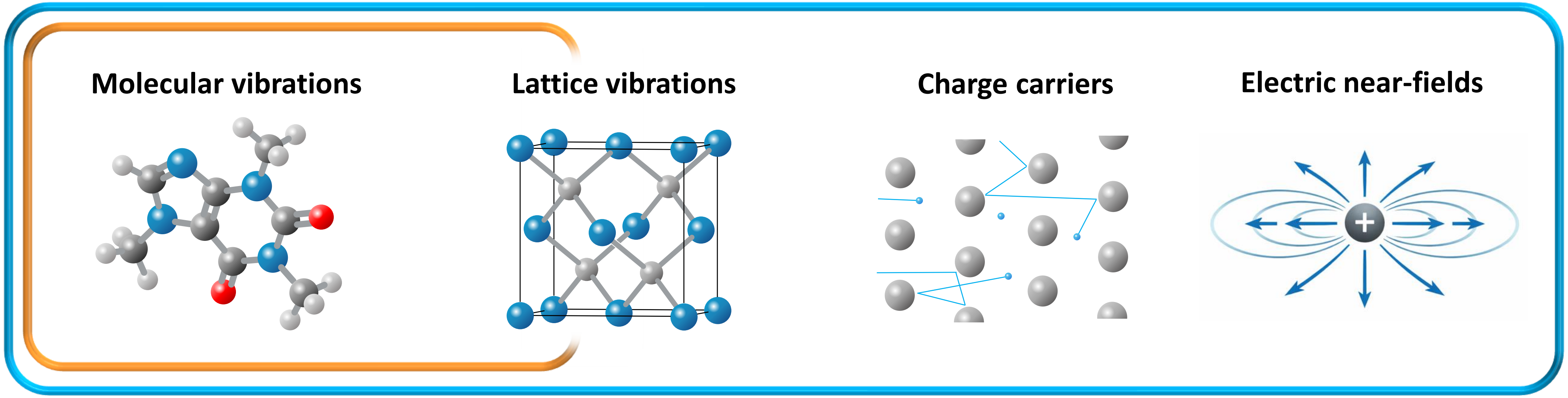
- Absorption
- Excels on organic materials
- Cheaper (less optics)
- Quantitative, relative

nano-FTIR
Light detection



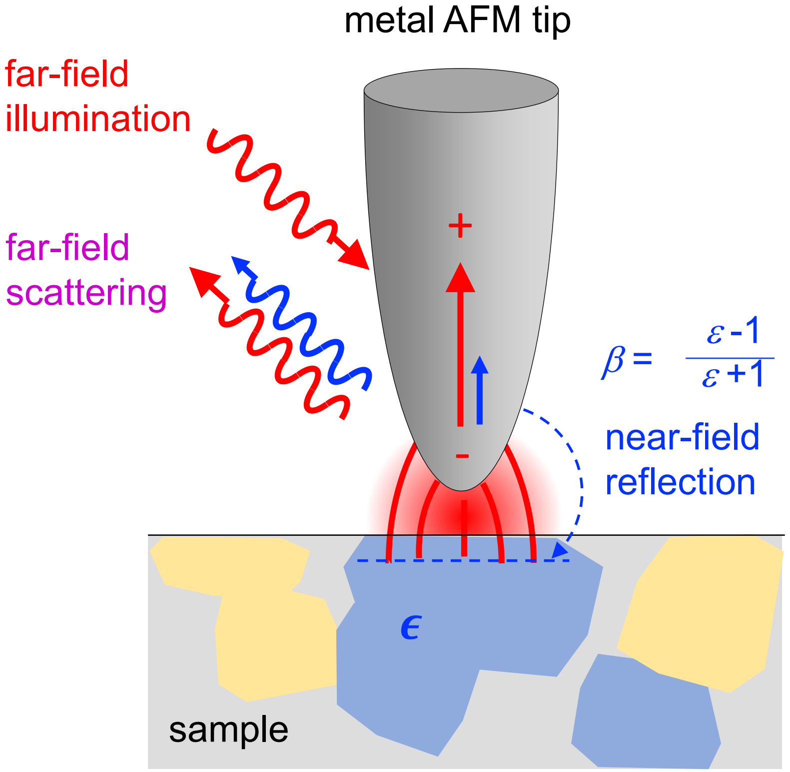
Probing permittivity ε
(via dipole-dipole interaction)

- Reflection & absorption
- Most Versatile (all materials)
- THz, Infrared, Visible light
- Quantitative, absolute



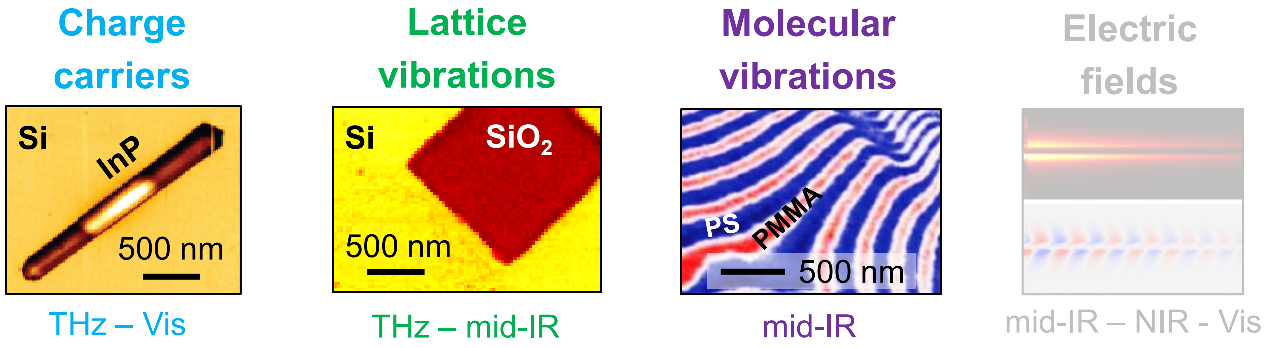
Probing mechanism in nano-IR

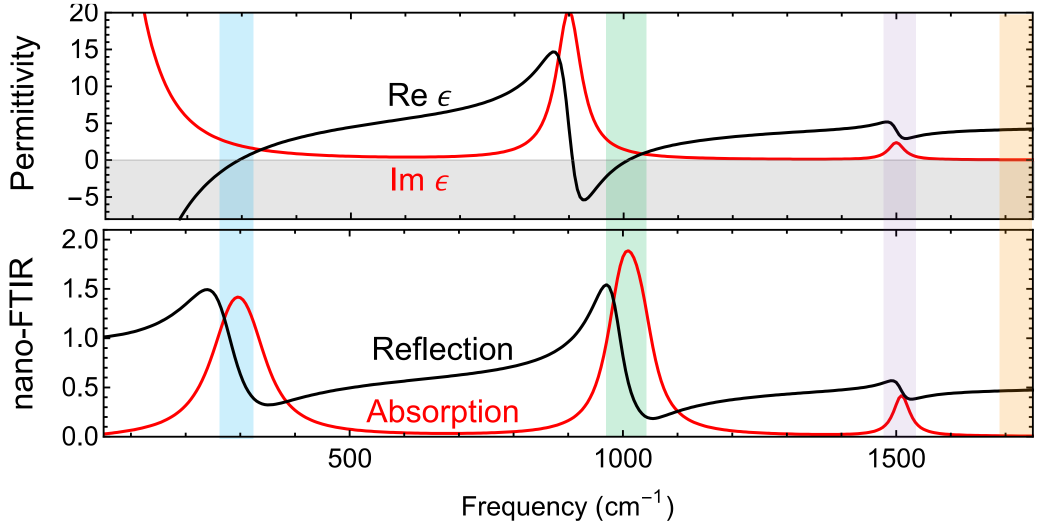
Spectroscopic information explains image contrasts



nano-FTIR essentially probes sample permittivity ε, via $\beta(\varepsilon)$

AFM-IR probes Im(ε)





Recent review
Hillenbrand et al, *Nature Rev. Mat.* **10**, 285-310 (2025)

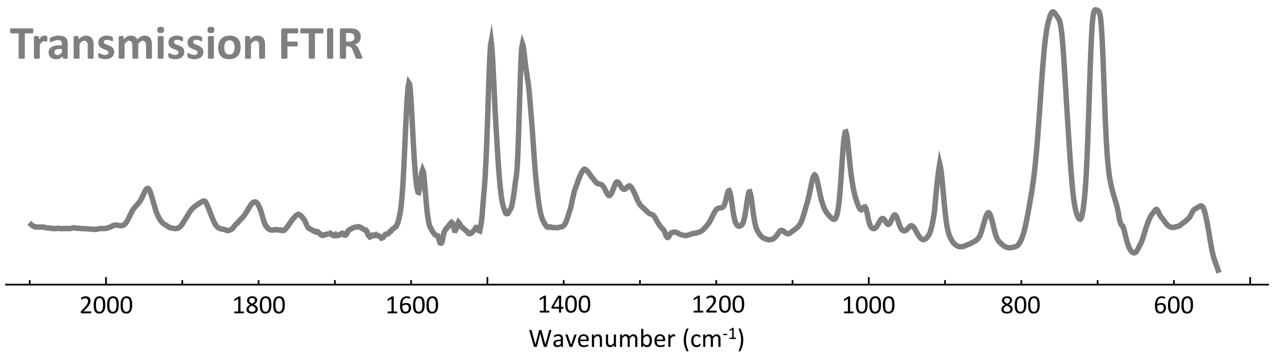
$$\varepsilon = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 - i\omega\gamma_p}\right) + \frac{A_{ph}^2}{\omega_{ph}^2 - \omega^2 + i\omega\gamma_{ph}} + \frac{A_m^2}{\omega_m^2 - \omega^2 + i\omega\gamma_m}$$

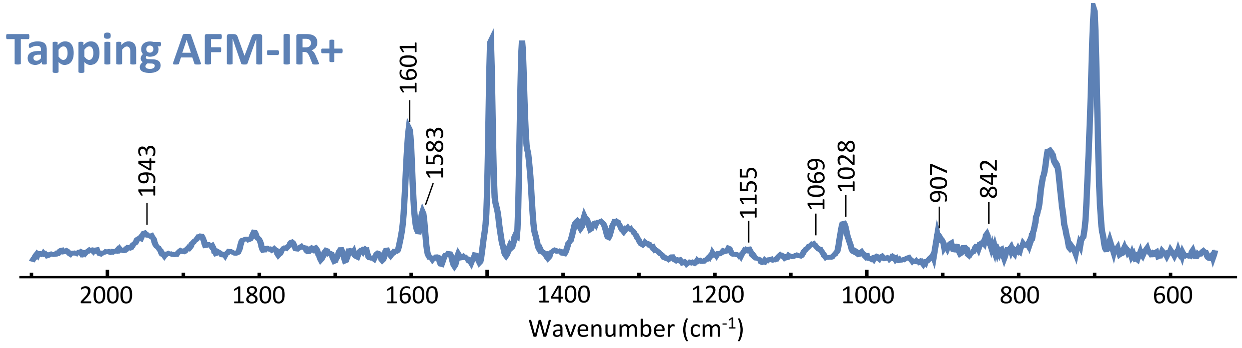
Dielectric constant | Drude model | Strong oscillator | Weak oscillator

NANOSCALE ANALYTICS
advanced imaging & spectroscopy

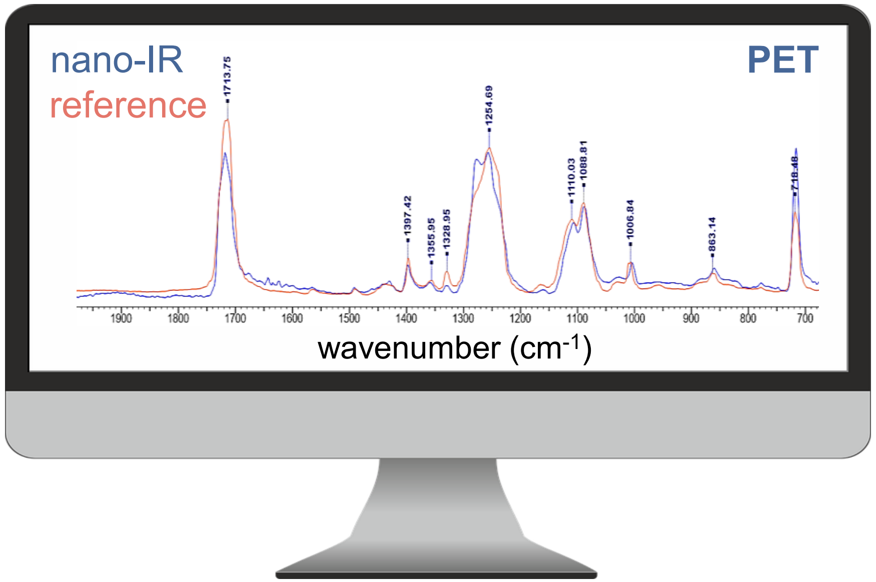
Chemical identification of nanoscale contaminants

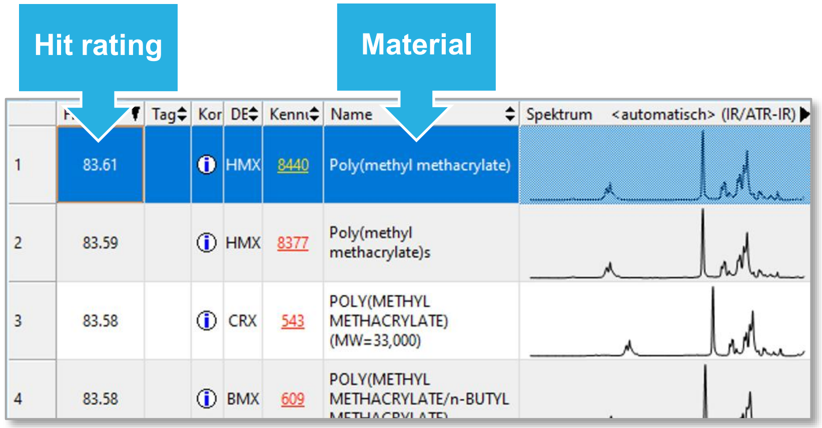
Enabled by spectral match of FTIR and nano-IR data





Chemical nano-identification based on established FTIR libraries

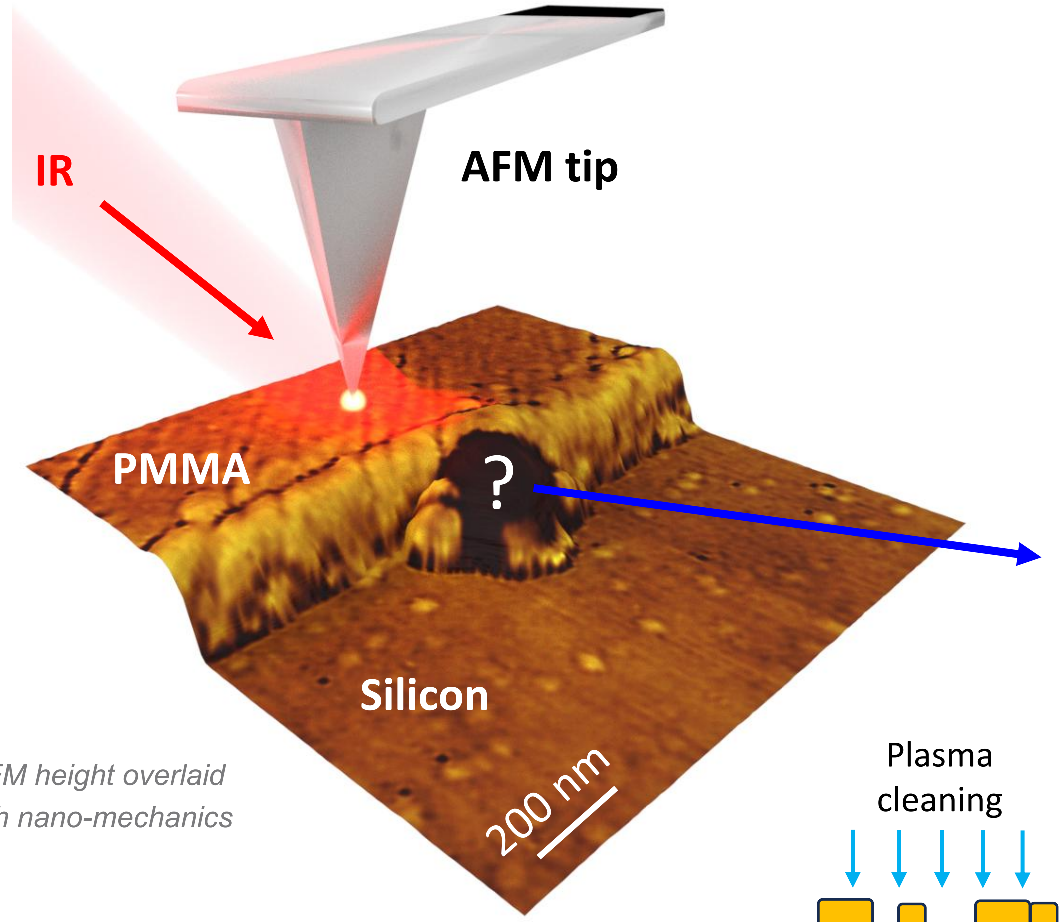




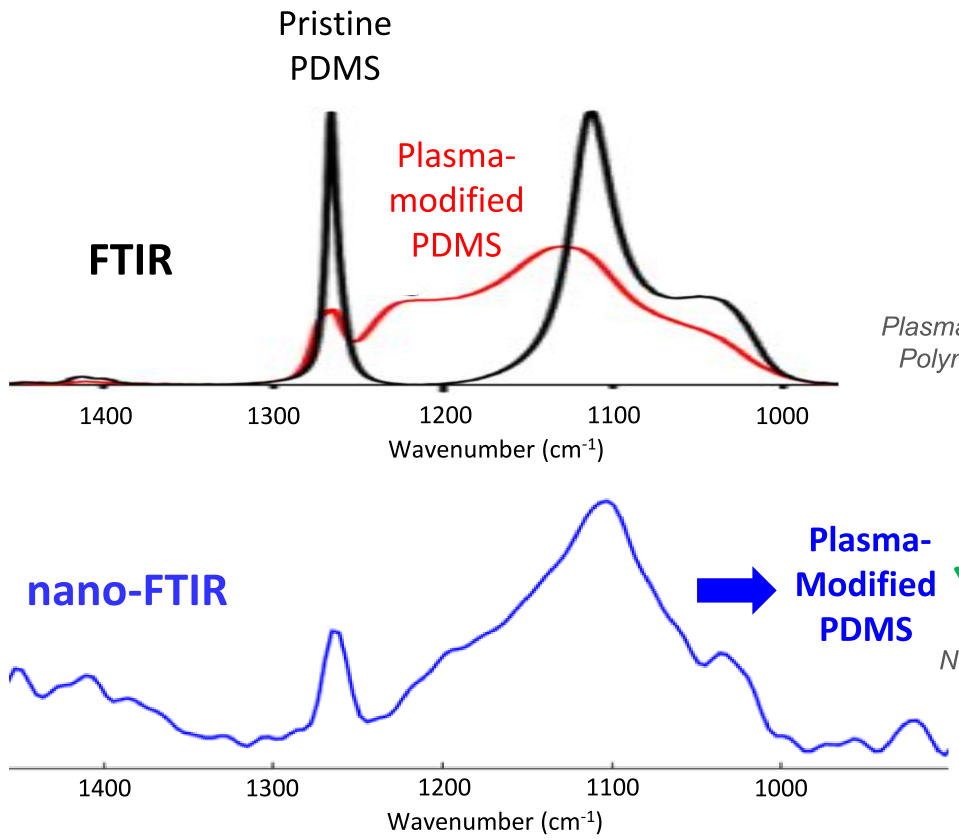
Polystyrene calibration standard, measured with neaSCOPE and wOPO laser

Beyond identification: Tracing the origin of nanoscale contaminants

Enabled by spectral match of FTIR and nano-IR data

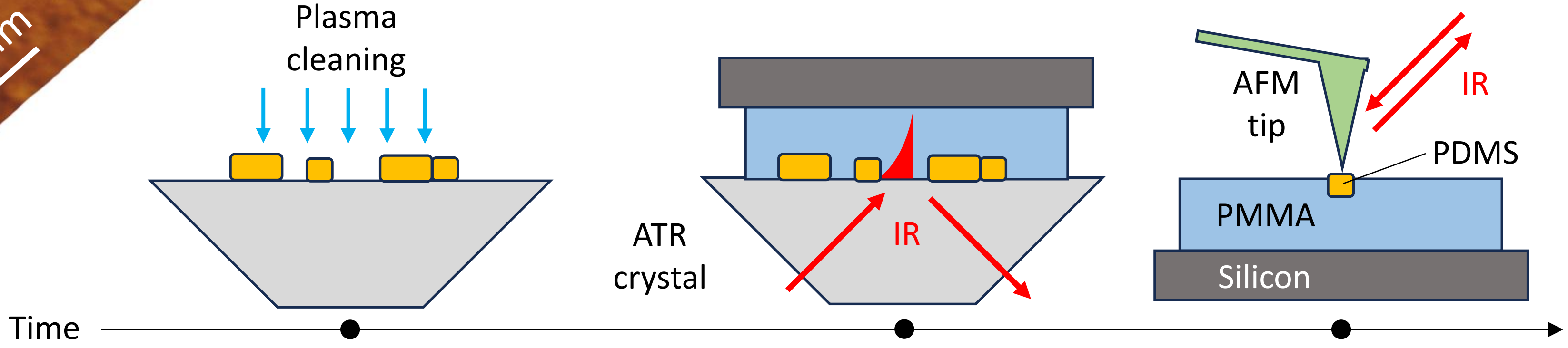


AFM height overlaid with nano-mechanics



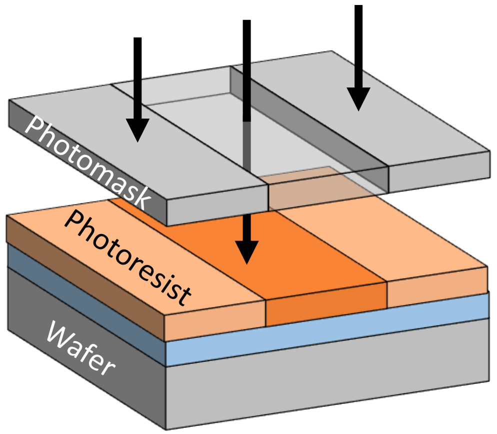
V. Danilov et al., *Plasma Proceesses and Polymers*, **8**, 11 (2011)

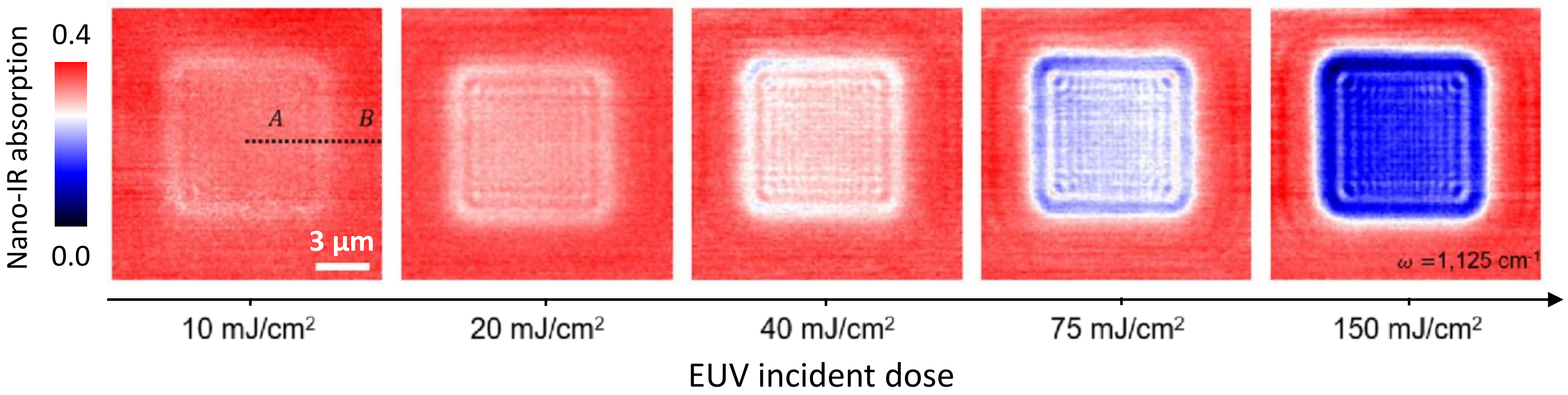
F. Huth et al., *Nano Letters*, **12**, 8, 3973-3978 (2012)

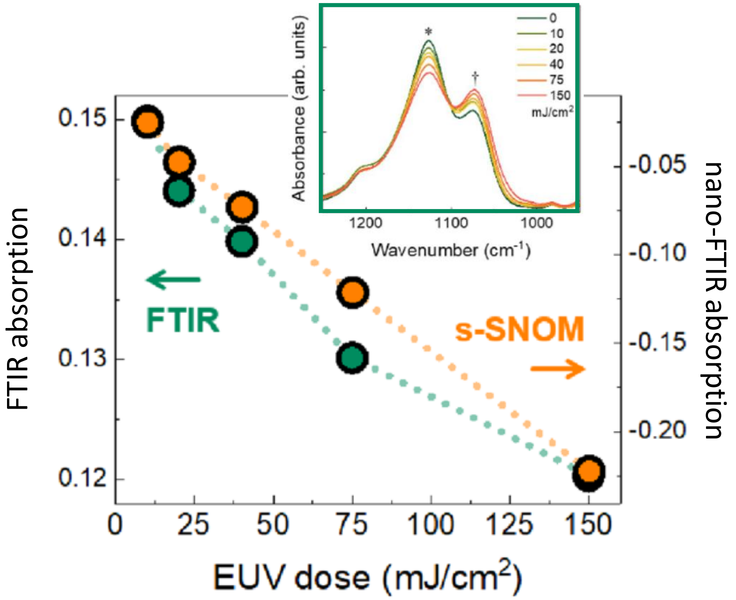


Lithography – probing local resist chemistry using nano-IR

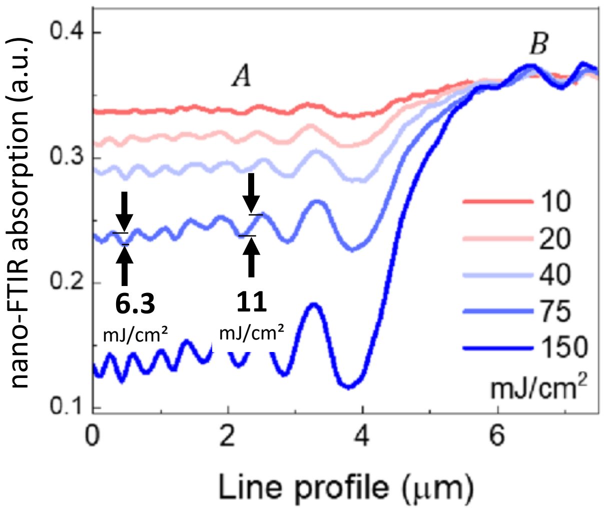
Photoresist HSQ (hydrogen silsesquoxane)







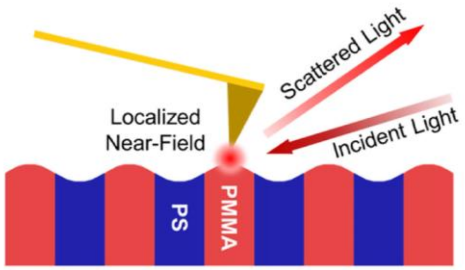
- **Change in cross-linking density** leads to nano-IR image contrast
- Local absorption contrast **scales linearly with EUV exposure** dose (analogous to FTIR in HSQ resist)
- Thus, image contrast can be interpreted and quantified as **local variations in EUV incident dose**



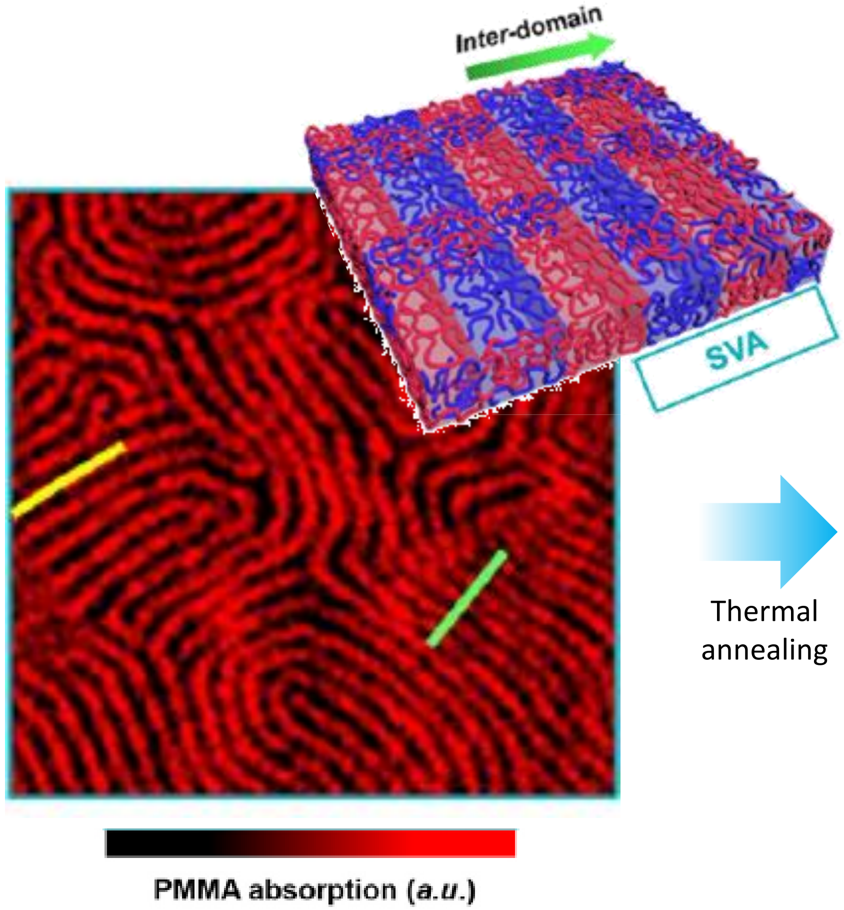
J. Kim et al. *Nano Convergence* **9**, 53 (2022)

Optimizing photoresist & process steps with the help of nano-IR

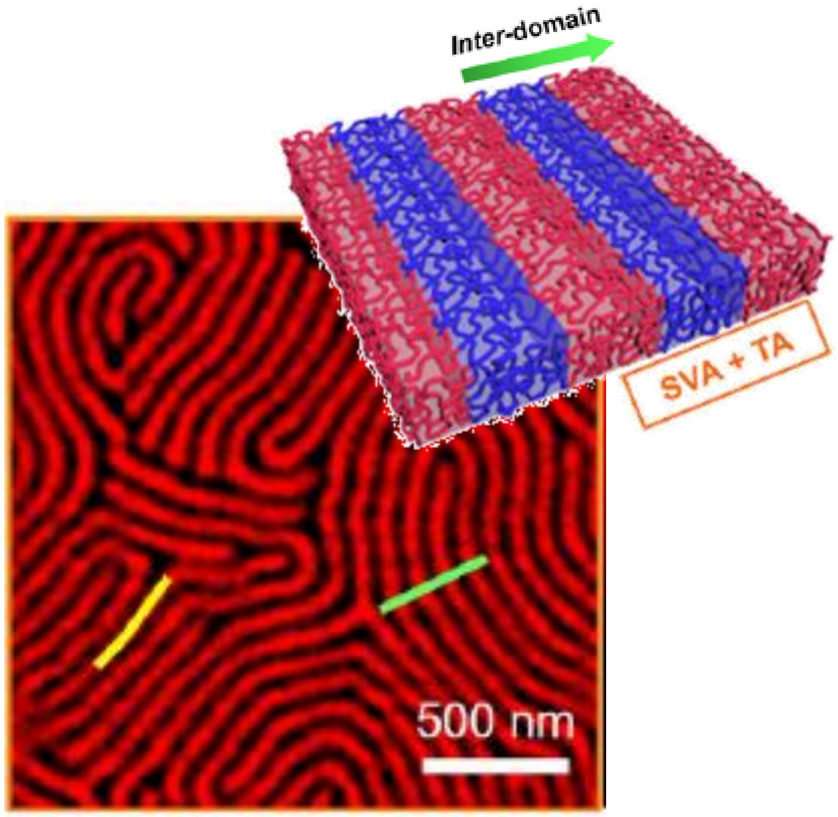
Co-polymer PS-*b*-PMMA for directed self-assembly



- Significant **enhancement of Inter-domain chemical contrast** upon SVA + TA treatment (nano-FTIR 3.3x, GISAXS 4x)
- **Intra-domain uniformity increased** as confirmed by nano-FTIR absorption mapping



Thermal annealing



W. Lee, et al., *Polymer Testing* **104**, 104409 (2021)
J. Kim et al. *Spect. Act. A* ***274***, 121095 (2022)

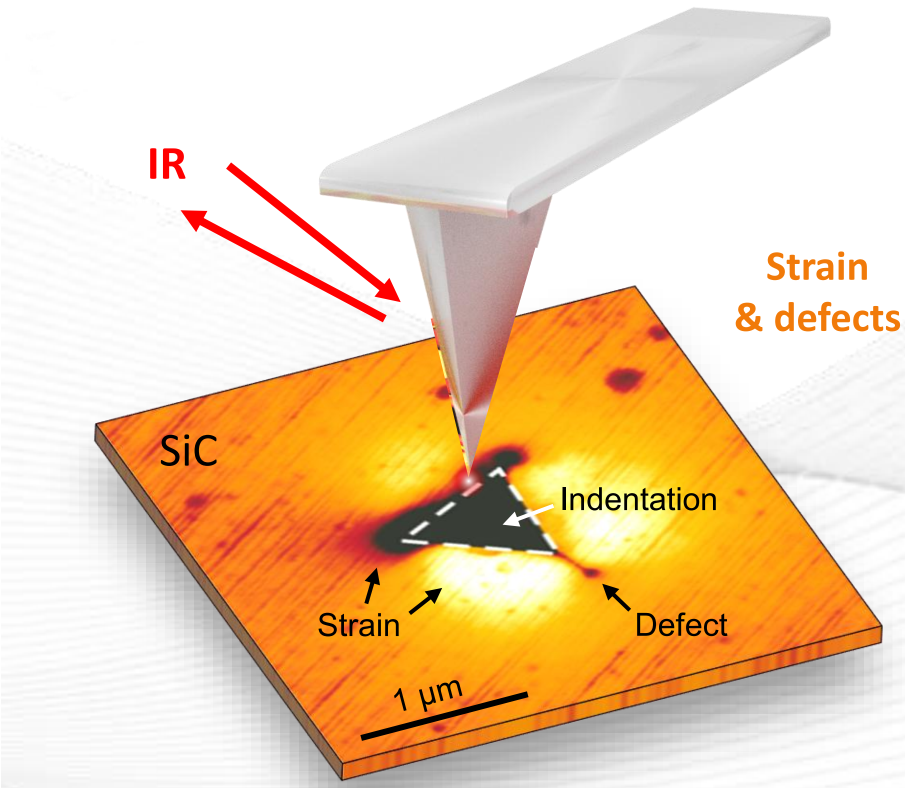
Chemical noise
Mapped by nano-FTIR

Increased chemical contrast
After thermal annealing

Crystal lattice vibrations

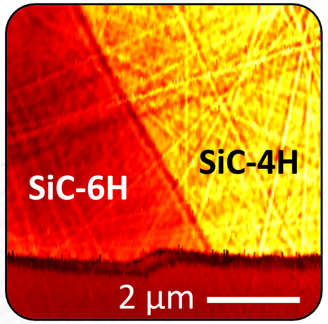
nano-IR beyond molecular absorption

Strain & defects



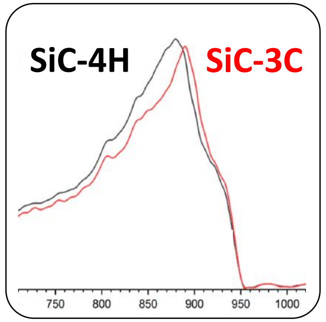
A Huber (2009)

Polytypes



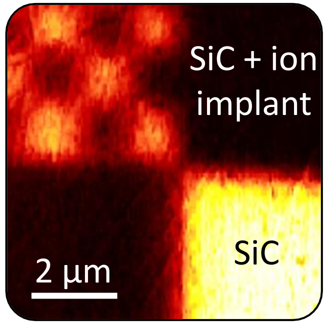
Huber (2006)

Stacking faults



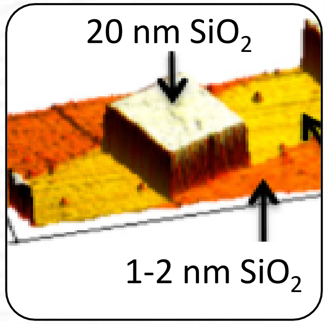
Criswell (2024)

Lattice damage



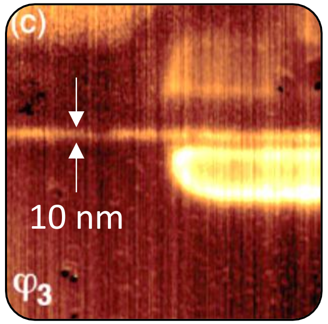
Ocelic (2004)

Oxides



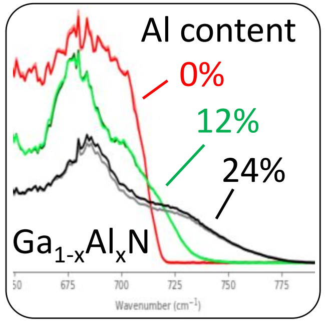
L M Zhang (2012)

Nitrides



A Huber (2007)

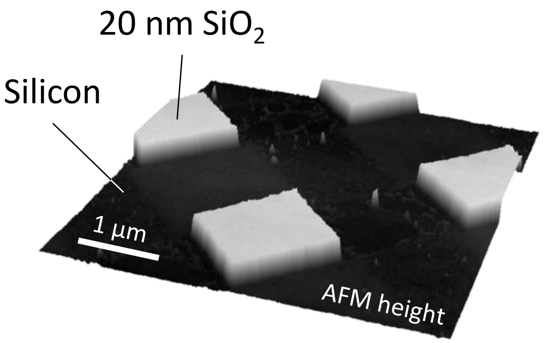
Composition



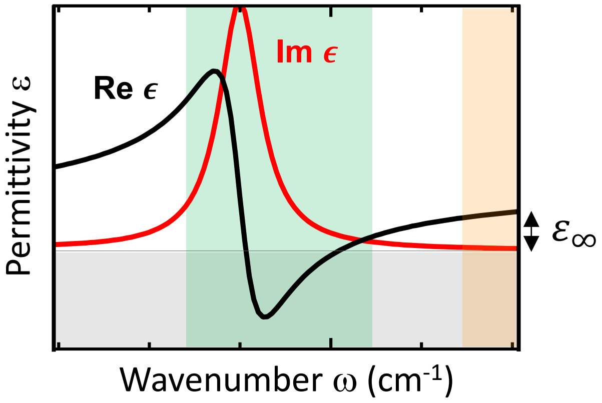
NANOSCALE ANALYTICS
advanced imaging & spectroscopy

Probing mechanism in nano-IR – Lattice vibrations

Spectroscopic information explains image contrasts



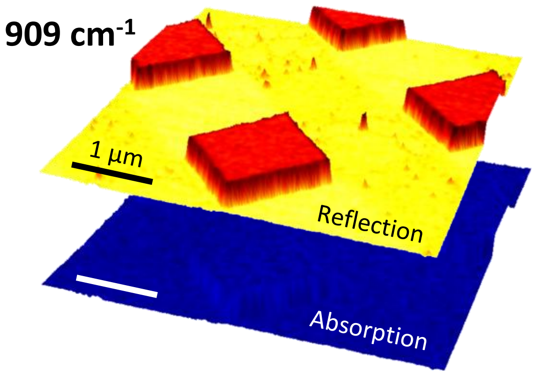
Optical properties
of lattice vibrations



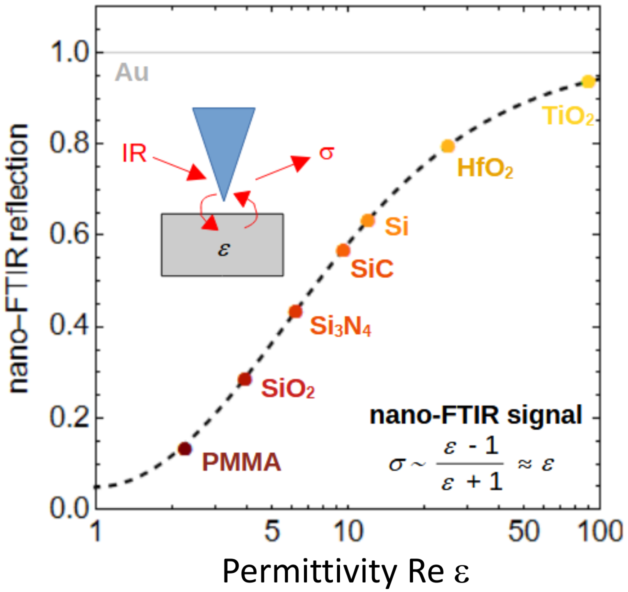
$$\varepsilon = \frac{A_{\mathrm{ph}}^2}{\omega_{\mathrm{ph}}^2 - \omega^2 + i\omega\gamma_{\mathrm{ph}}} + \varepsilon_\infty$$

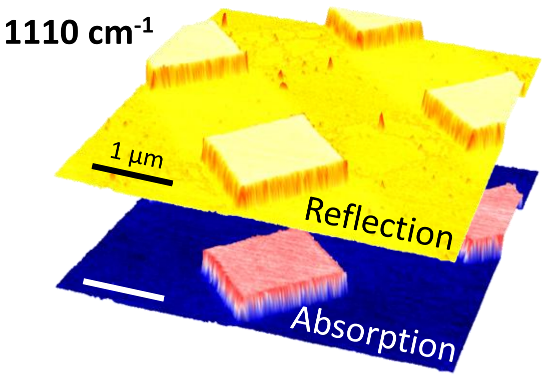
Strong oscillator

Dielectric constant

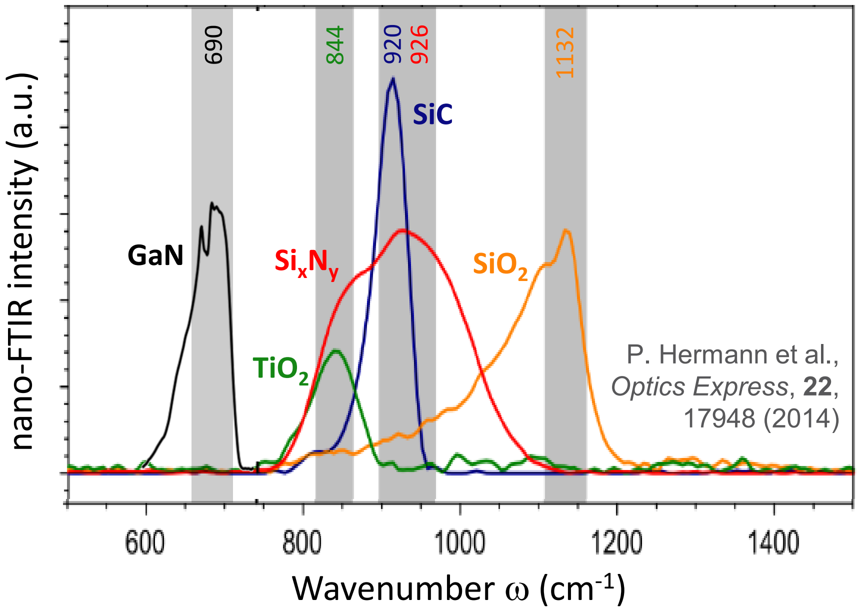


Off-resonant
(non-absorbing)





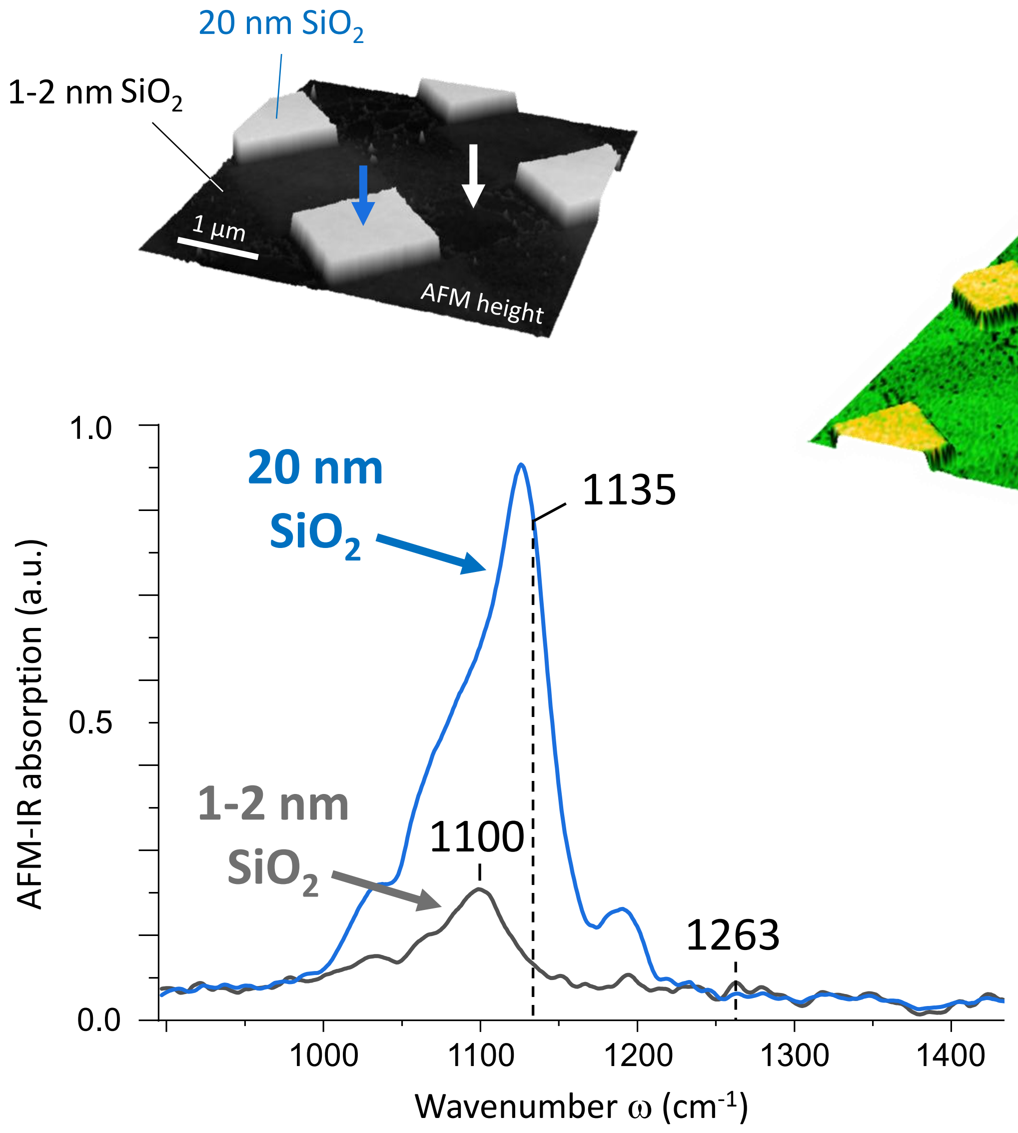
Resonant
(absorbing)

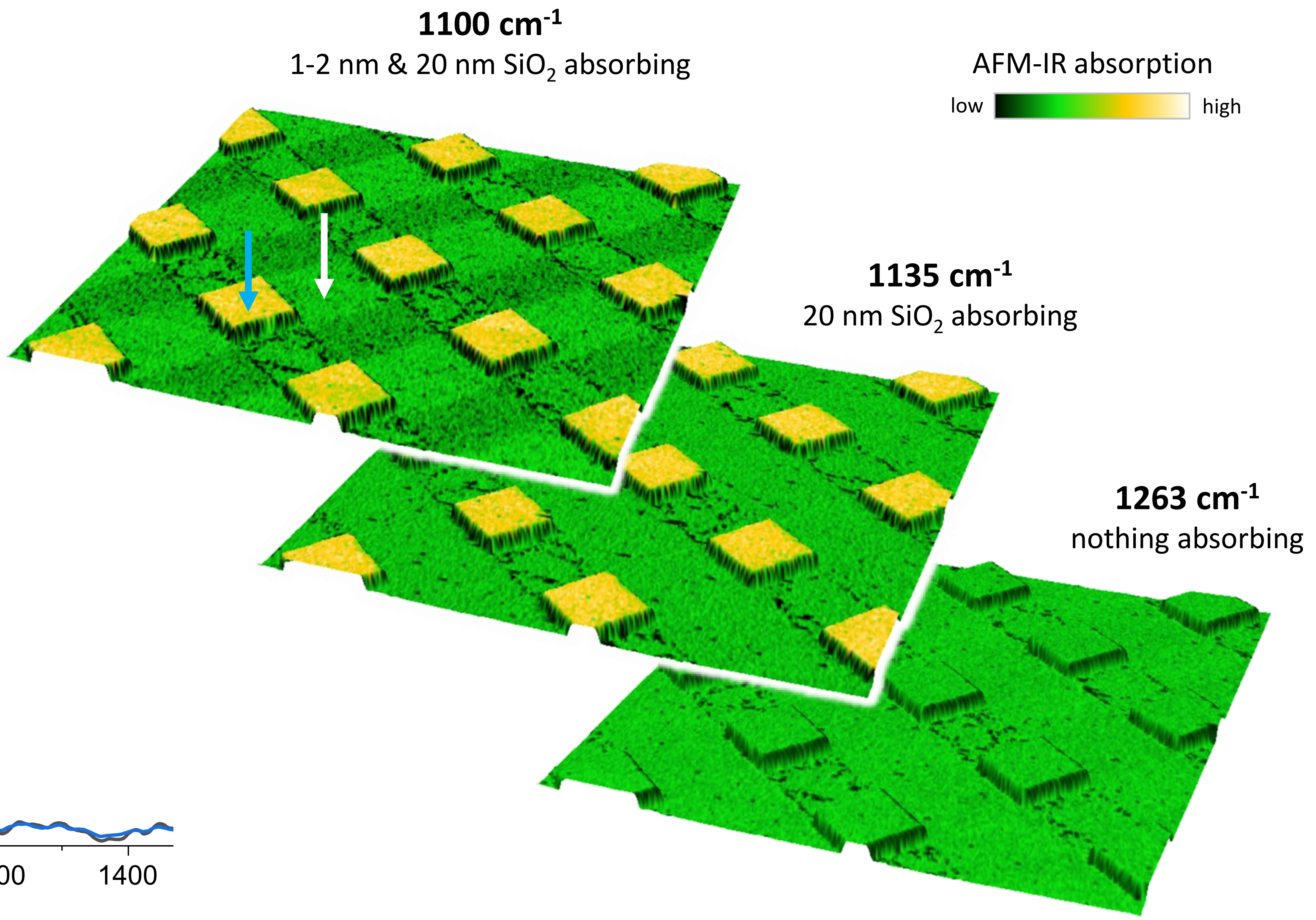


NANOSCALE ANALYTICS
advanced imaging & spectroscopy

Characterization of thin films (oxides, nitrides, …)

Attocube Tapping AFM-IR+ on calibration sample TGQ1

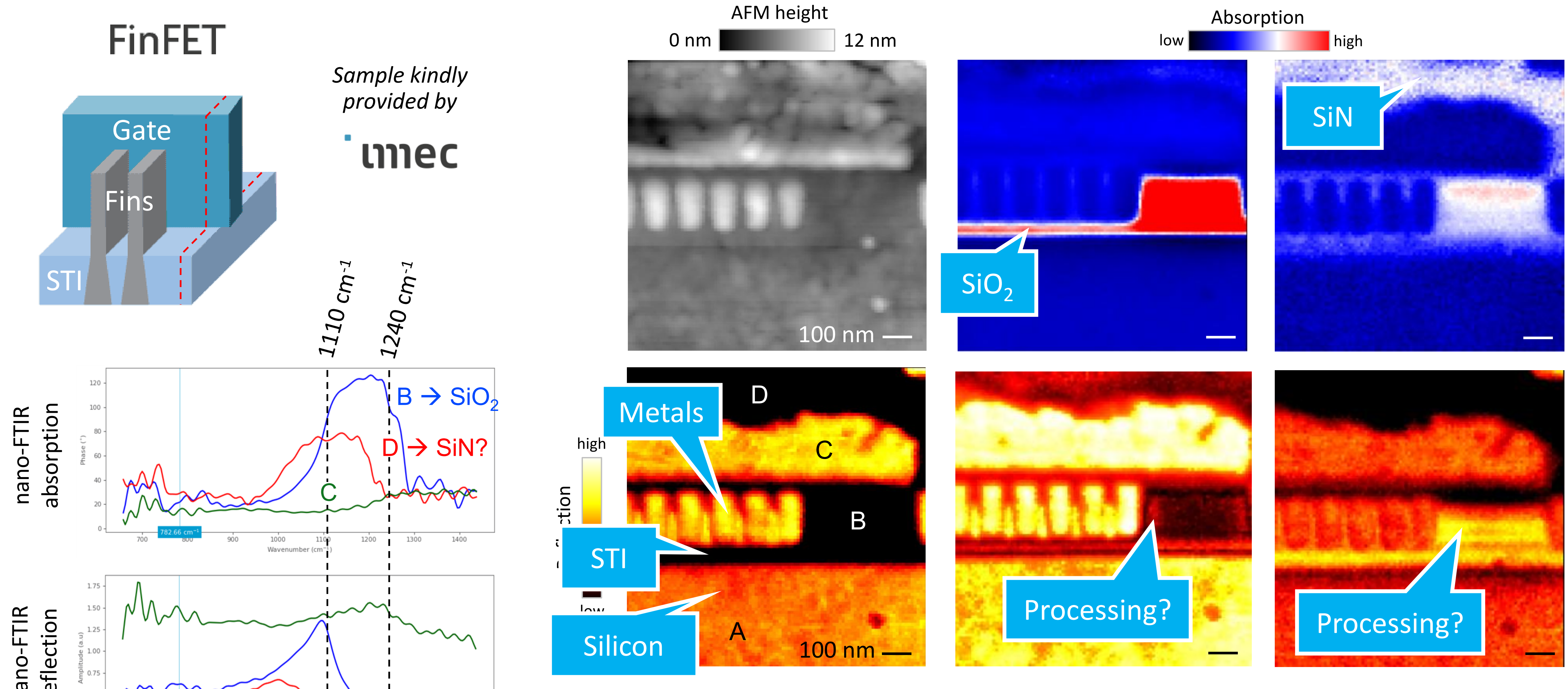




NANOSCALE ANALYTICS
advanced imaging & spectroscopy

Preliminary nano-IR results on FinFET test structure

Cross-sectionned parallel to fin plane



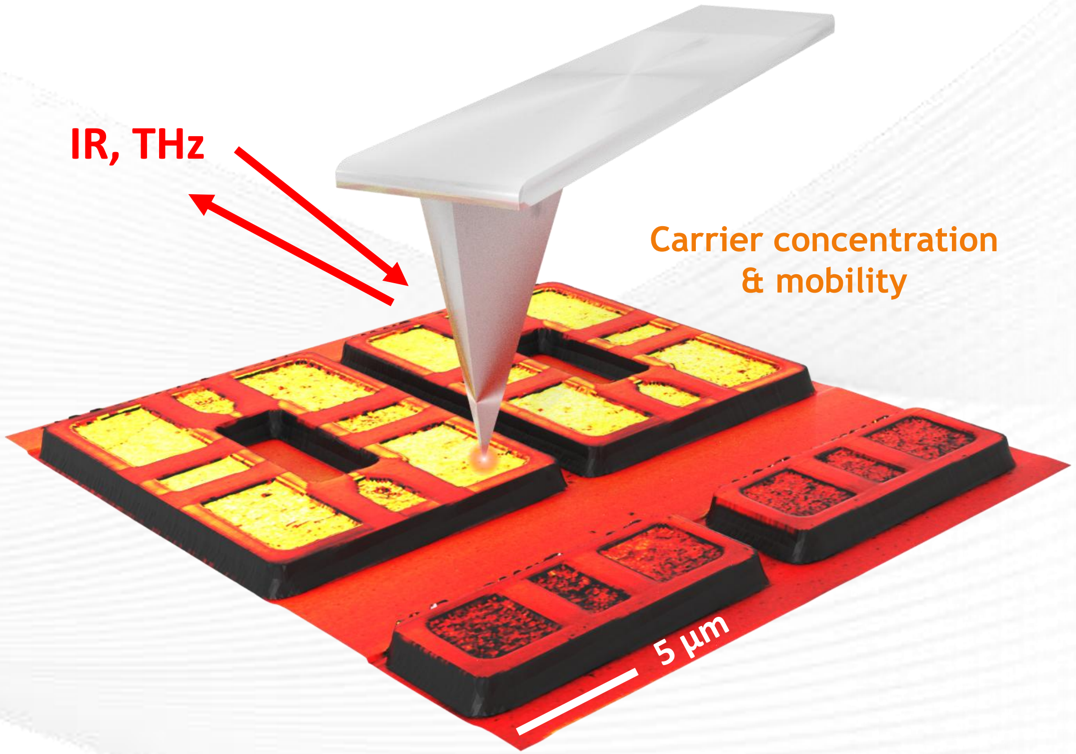
1600 cm^{-1}
Reflection ≈ dielectric constant

1240 cm^{-1}
SiO_2 absorbing
SiO_2 low reflection

1110 cm^{-1}
SiN + SiO_2 both absorbing
SiO_2 high reflection

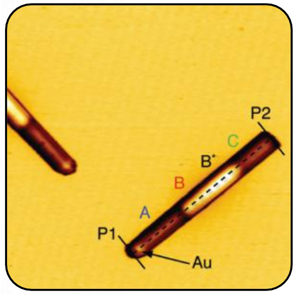
Optical probing of electrical properties

At infrared and terahertz frequencies



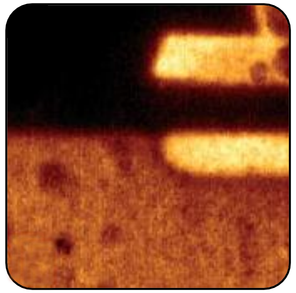
Carrier concentration & mobility

Nanowires



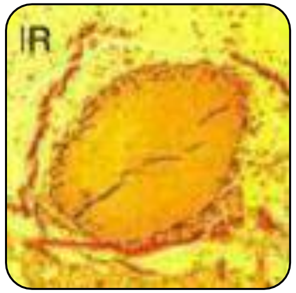
J Stiegler (2010)

Devices



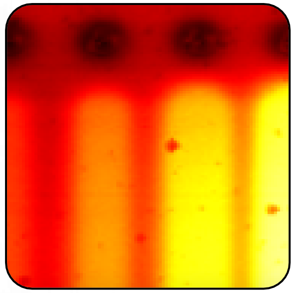
A Huber (2007)

2D organic conductors



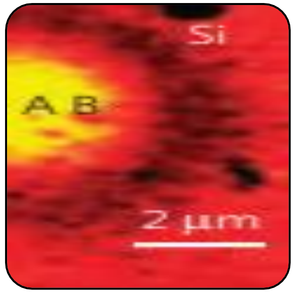
T Zhang (2025)

Dopant profiling



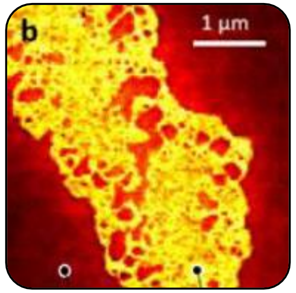
C Liewald (2018)

Carrier diffusion



F Huth (2011)

Sub-surface conductivity

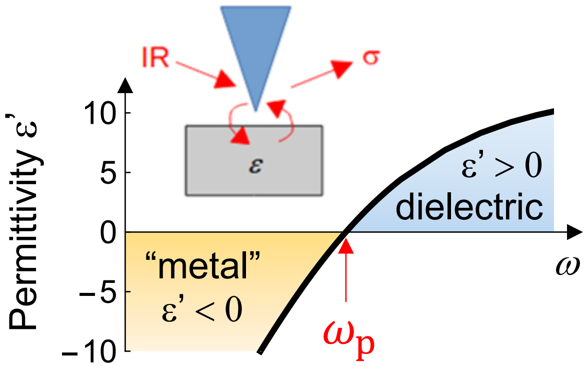


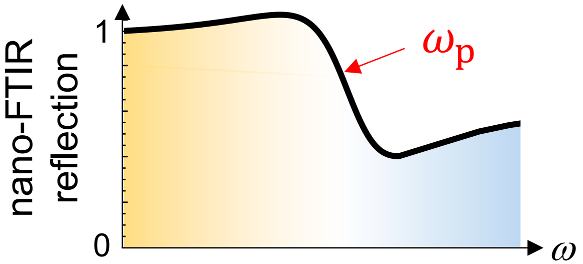
M Sanviti (2022)

Probing mechanism in nano-FTIR – Charge carriers

Optical response (Drude model)

$$\epsilon(\omega) = \epsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}\right)$$

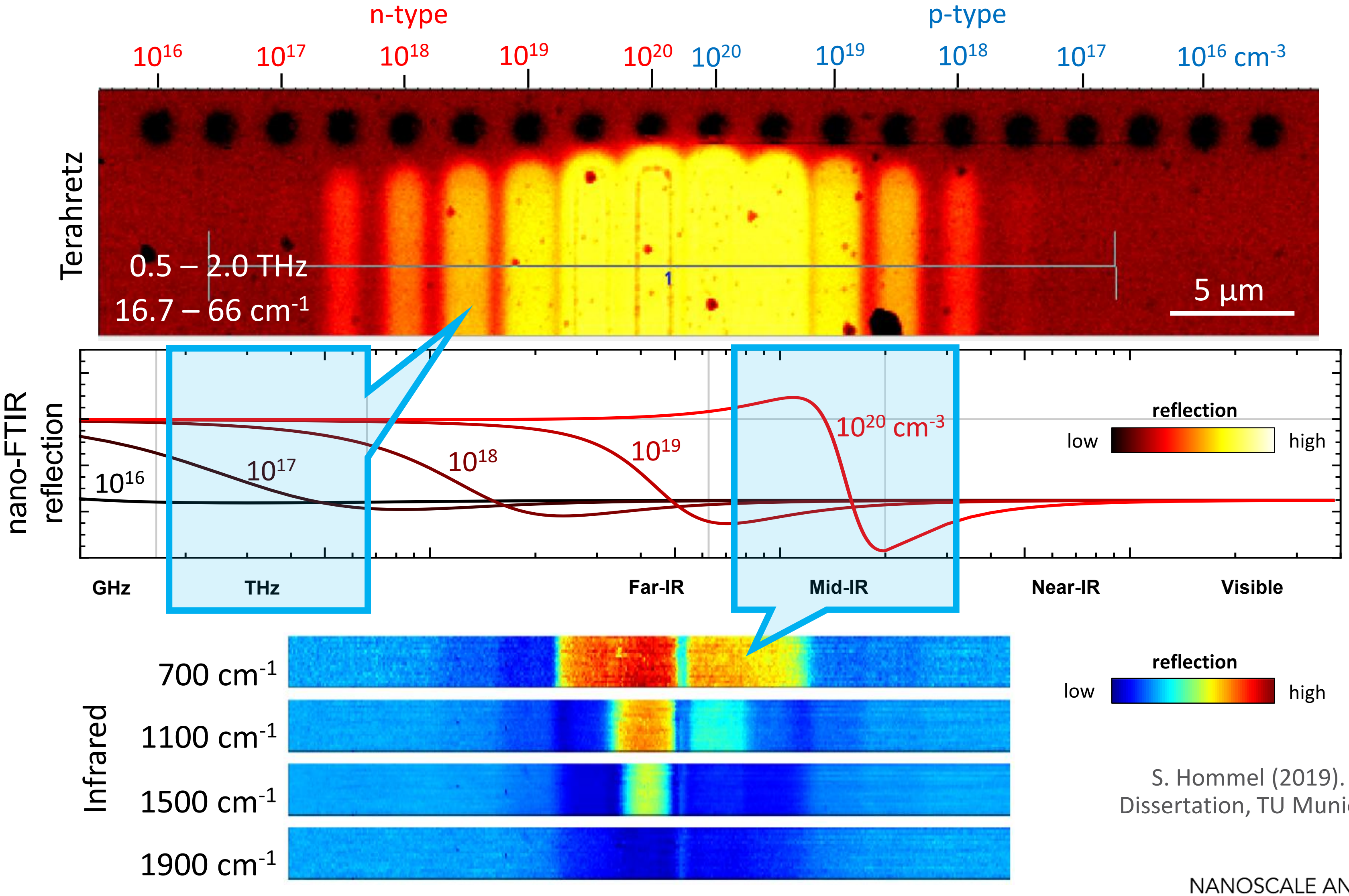




Plasma frequency: $\omega_p = \sqrt{\frac{ne^2}{\epsilon_\infty \epsilon_0 m^*}}$

=> n: Carrier concentration

Doped silicon calibration sample



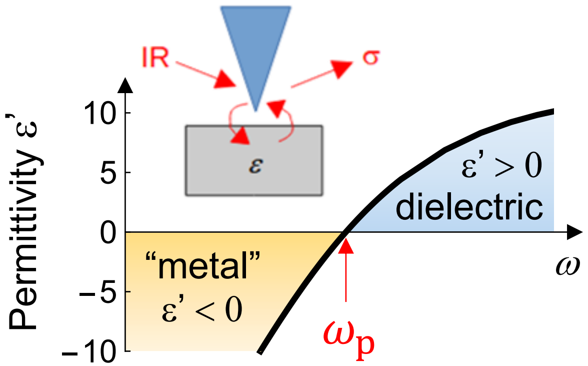
S. Hommel (2019). Dissertation, TU Munich.

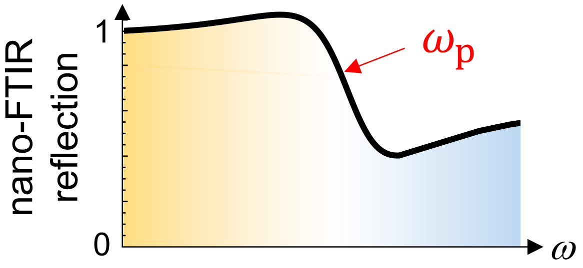
NANOSCALE ANALYTICS
advanced imaging & spectroscopy

Probing mechanism in nano-FTIR – Charge carriers

Optical response (Drude model)

$$\epsilon(\omega) = \epsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}\right)$$

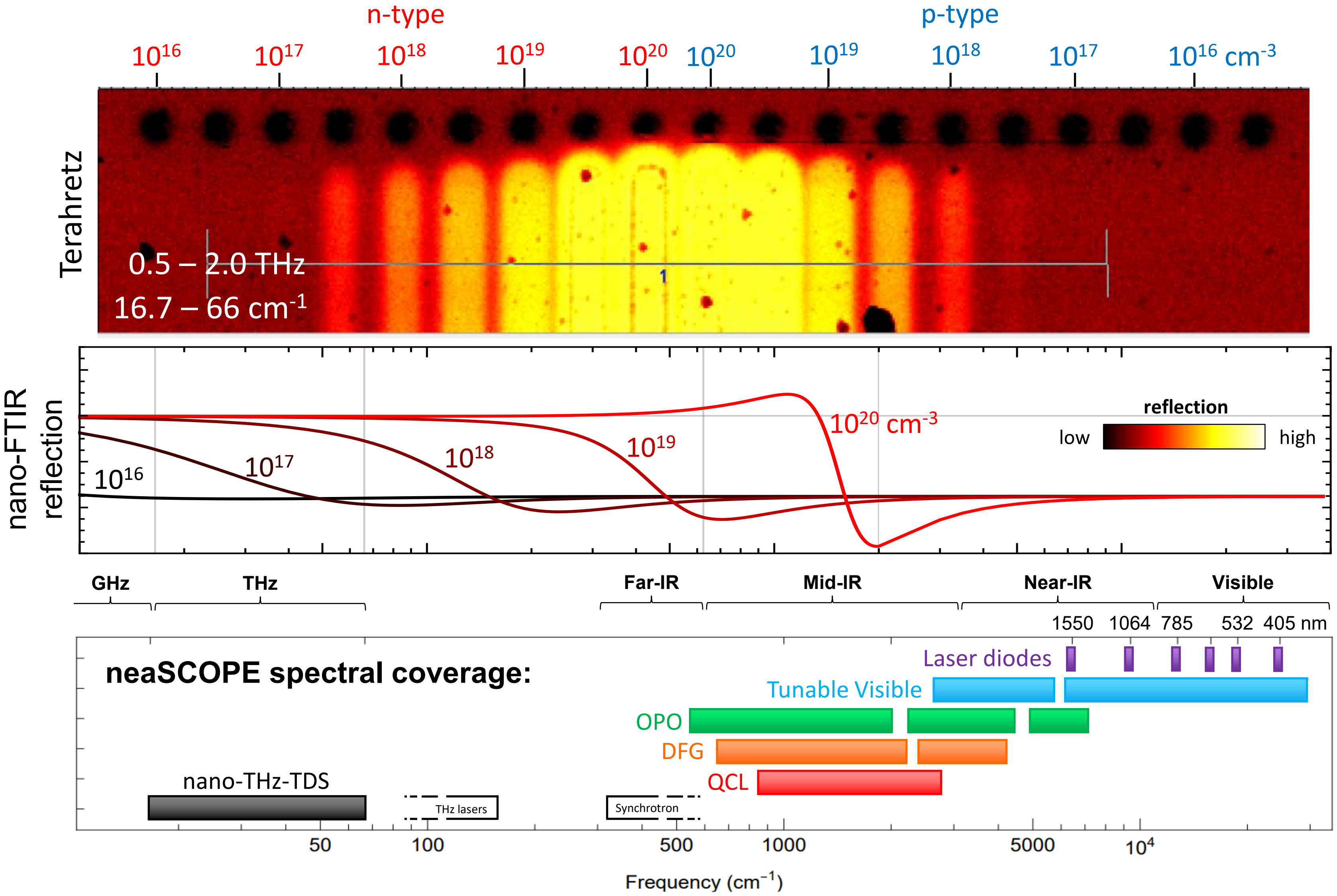




Plasma frequency: $\omega_p = \sqrt{\frac{ne^2}{\epsilon_\infty \epsilon_0 m^*}}$

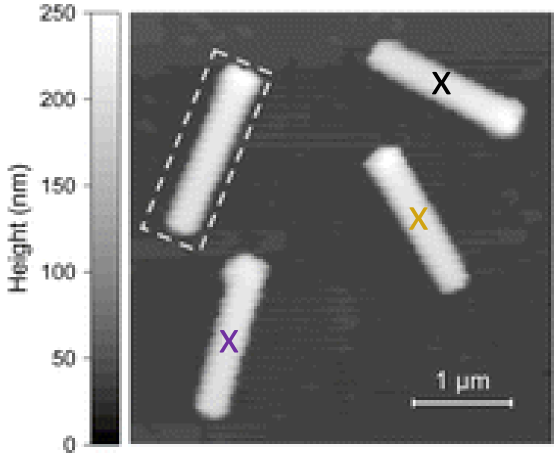
=> n: Carrier concentration

Doped silicon calibration sample

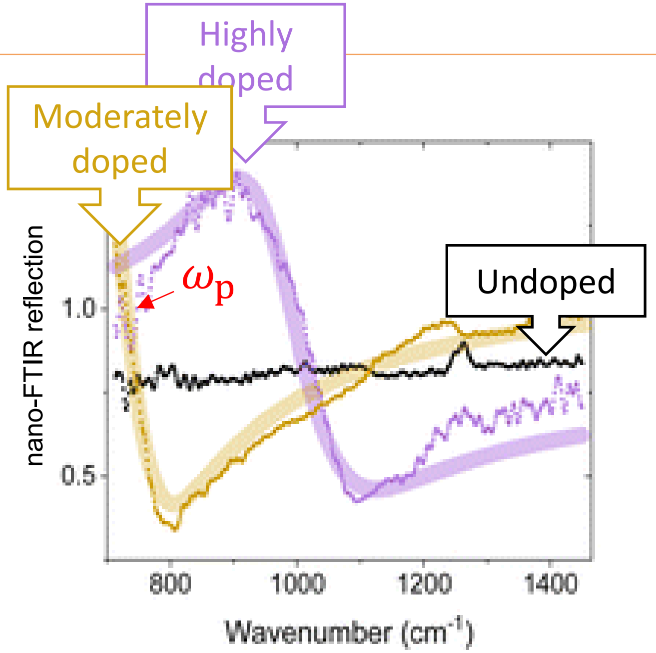


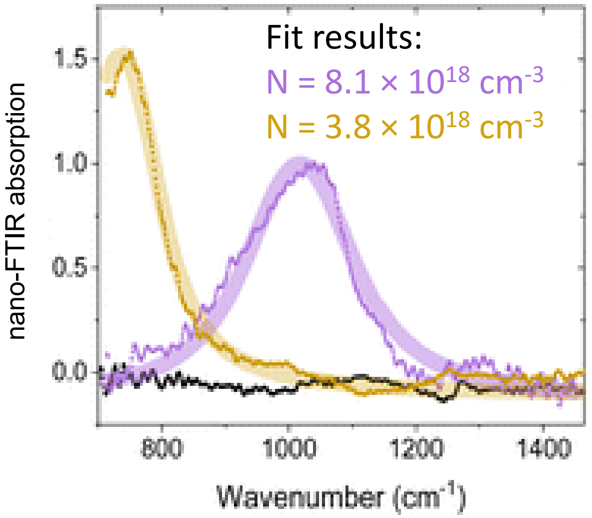
Nanoscale quantification of carrier concentration in individual nanowires

InGaAs nanowires

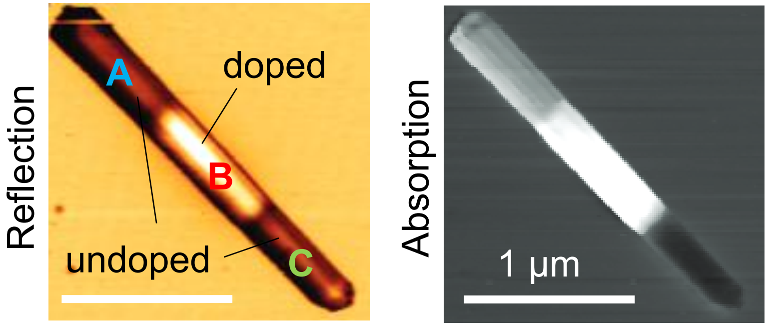


Luferau, *Nanoscale Adv.* ***7***, 3692-3700 (2025)

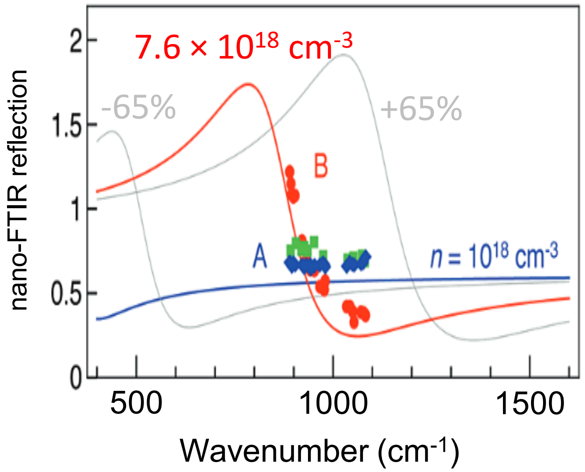


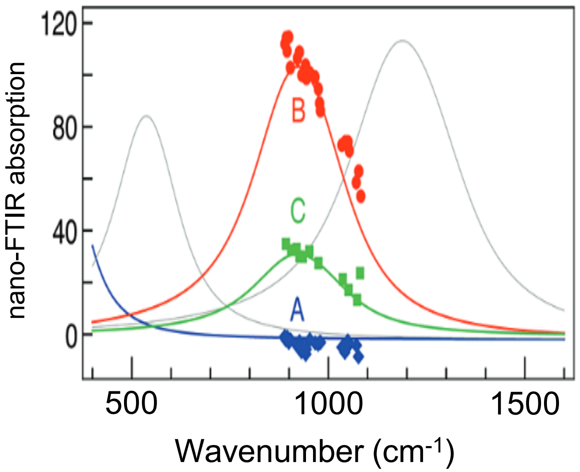


Modulation-doped InP nanowire

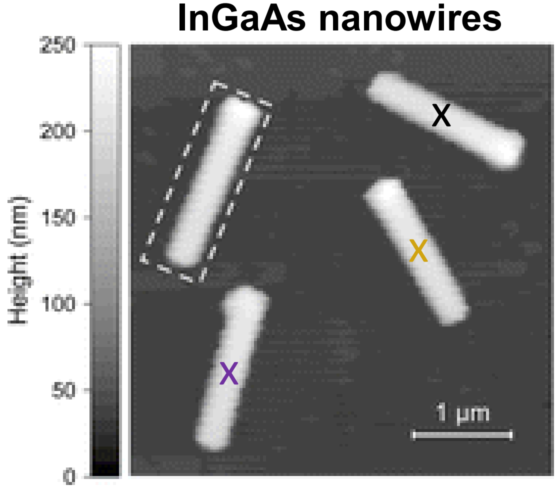


Stiegler, *Nano Lett.* ***10***, 1387-1392 (2010)

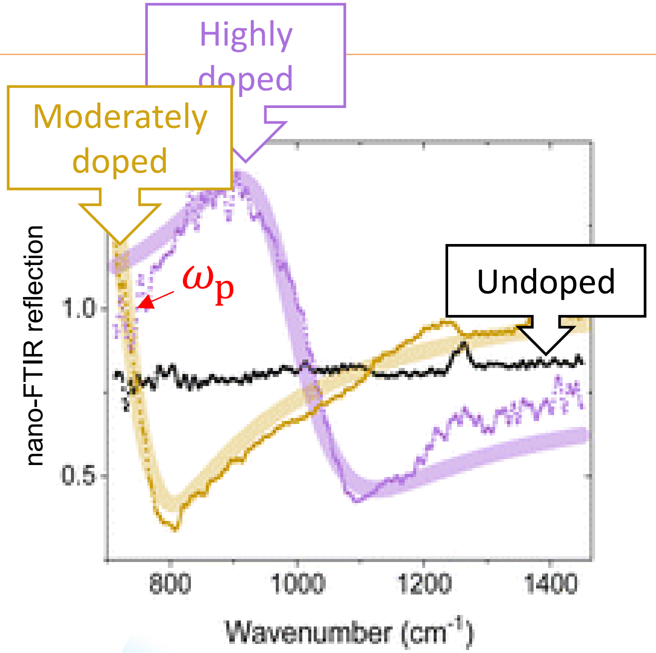


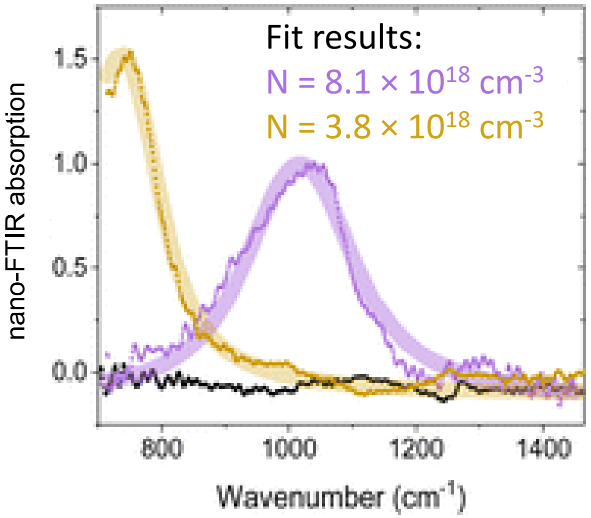


Nanoscale quantification of carrier concentration in individual nanowires



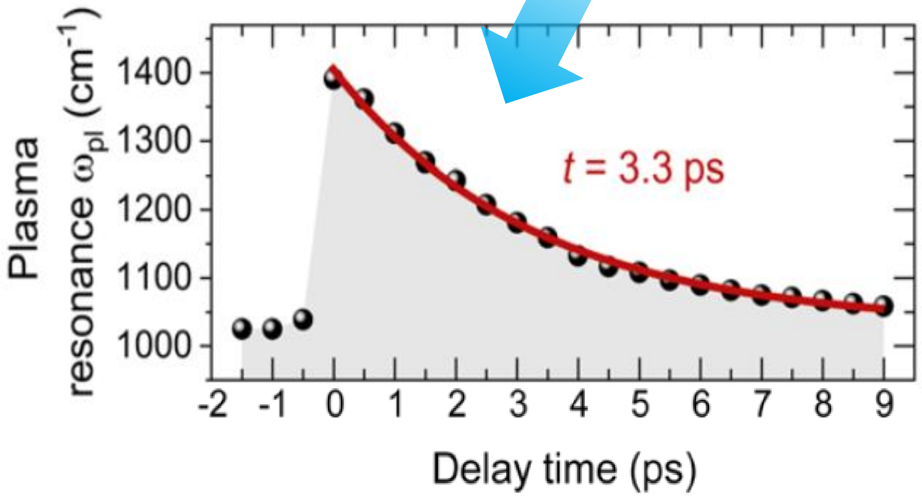
Luferau, *Nanoscale Adv.* ***7***, 3692-3700 (2025)

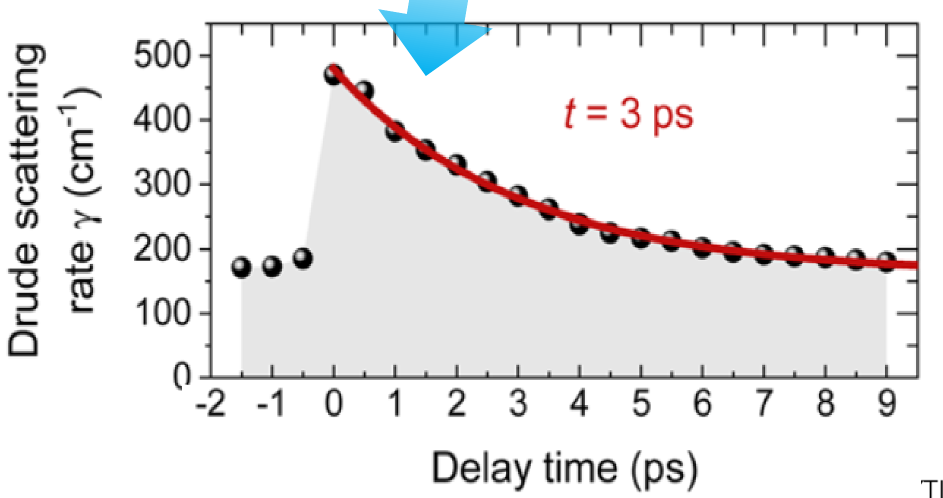




Pump-probe nano-FTIR

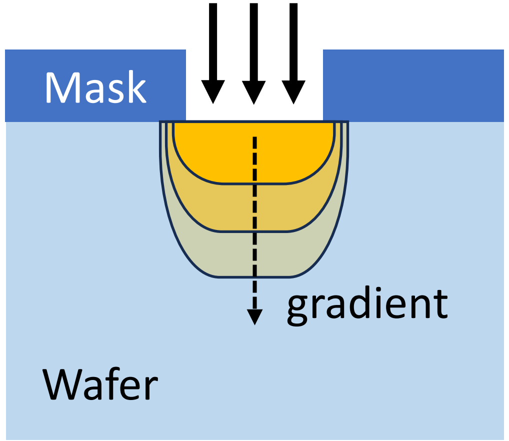
also at cryogenic temperatures, also in vacuum





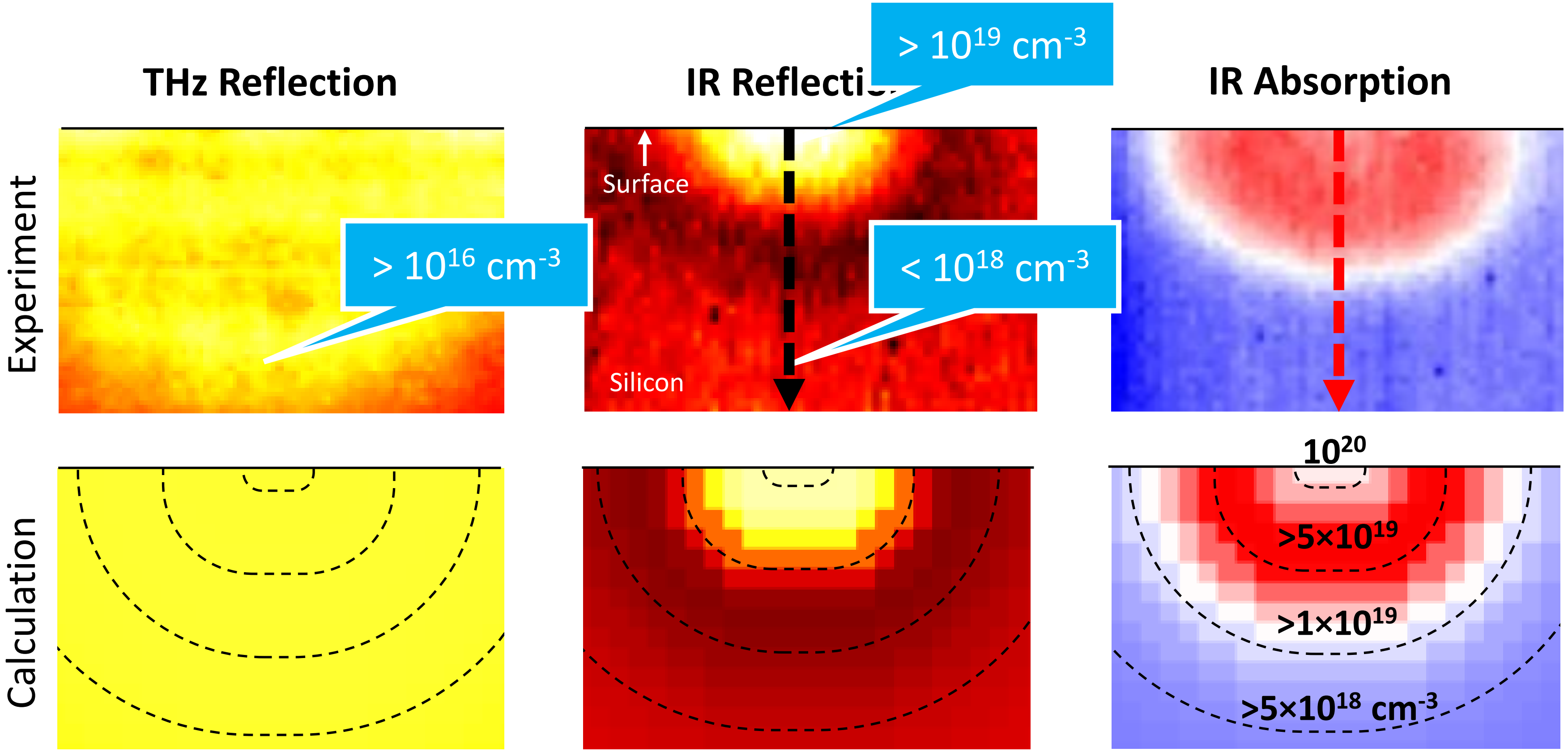
Dopant profiling of radial **carrier concentration gradient** using nano-FTIR

Ion implantation



Sample cross-section

See also:
Huth et al, *Nature Mat.* **10**, 352-356 (2011)



Order-of-magnitude-estimates of the carrier concentration:

✓ (Electrical) Contact-free

✓ Calibration-free

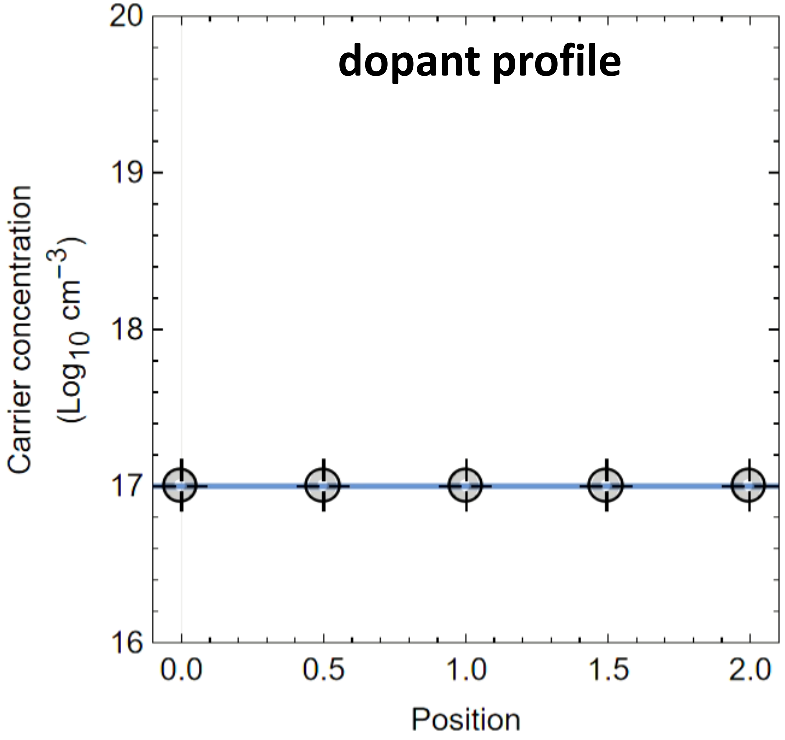
✓ (Mathematical) Model-free

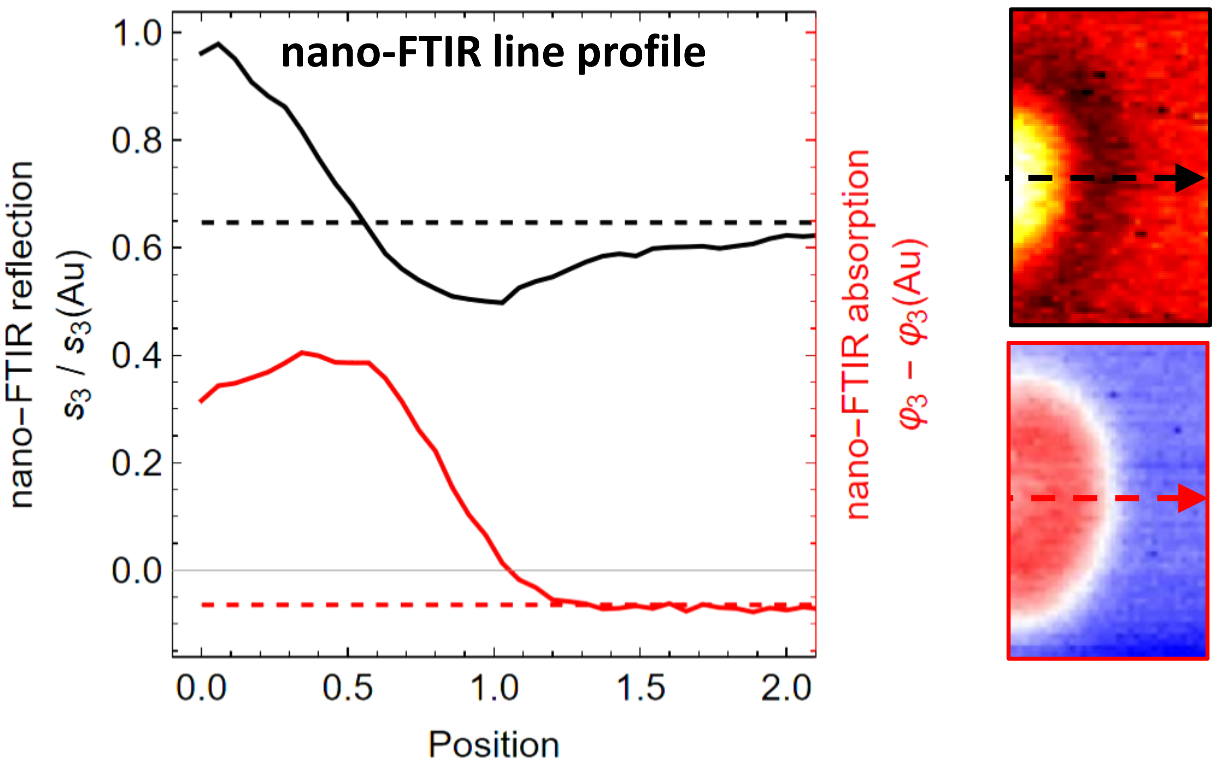
✓ Non-destructive

…but we have models ☺

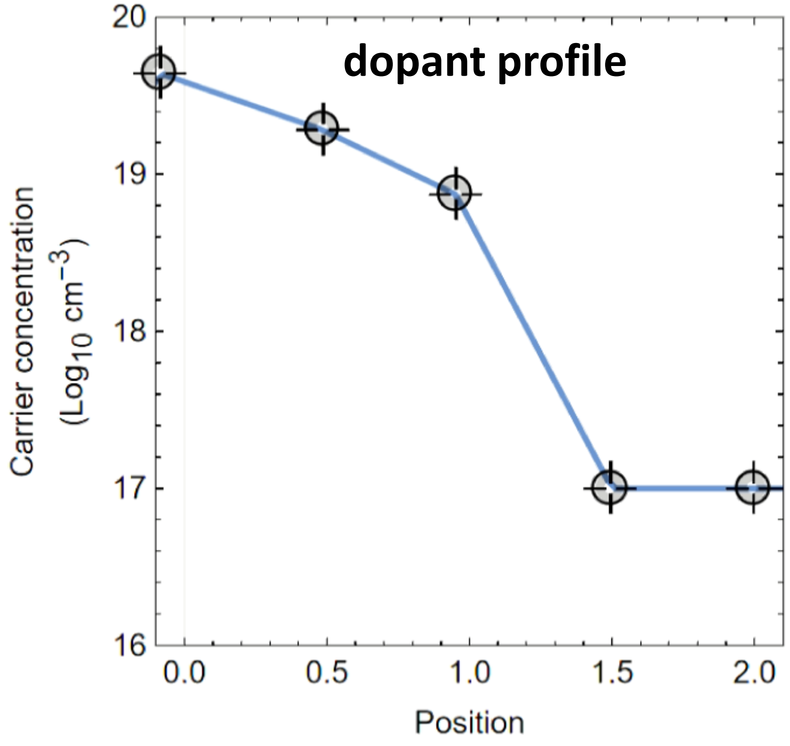
NANOSCALE ANALYTICS
advanced imaging & spectroscopy

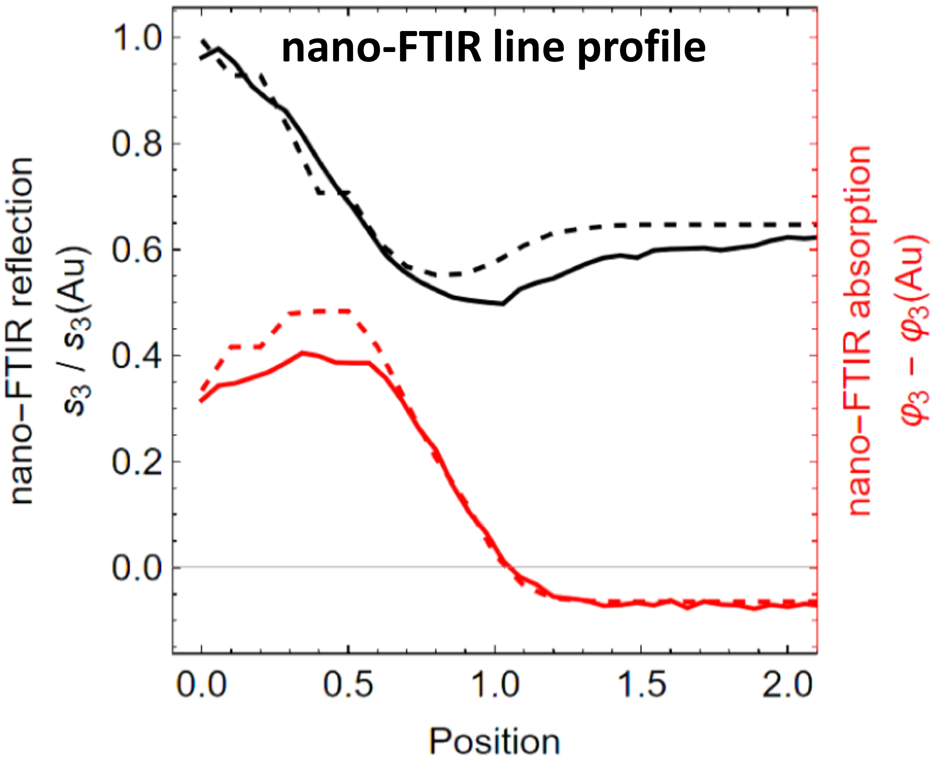
Model-based quantification of carrier concentration gradients

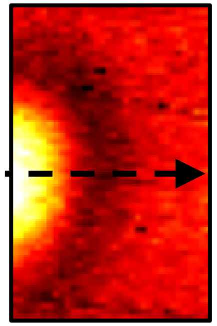


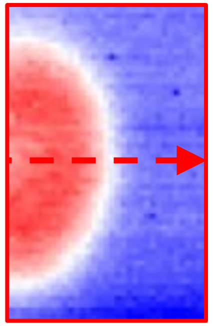


Model-based quantification of carrier concentration gradients









✓ High precision

✓ Subsurface-carrier profiling

✓ Simultaneous electrical AFM

(✓) Detailed study on calibration sample missing

(✓) Lateral size-effects unexplored

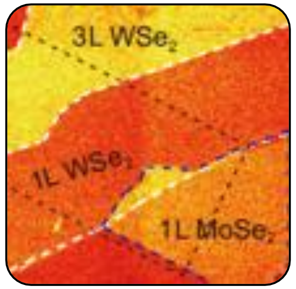
Applications for 2D materials in near-field microscopy

neaspec see the nanoworld | attocube WITTENSTEIN Group

2D Materials Conference

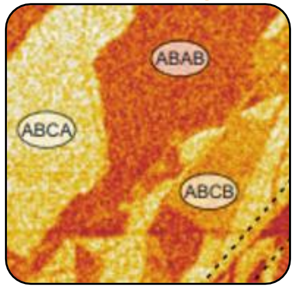
June 8 - 13, 2026 Munich

Monolayers



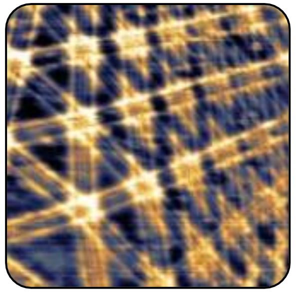
S Zhang (2022)

Stacking



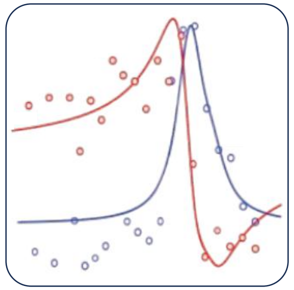
K Wirth (2022)

Moiré



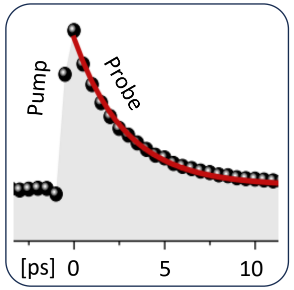
Y Luo (2020)

Excitons



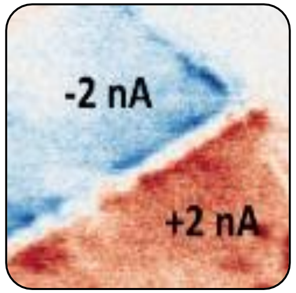
S Zhang (2022)

Dynamics



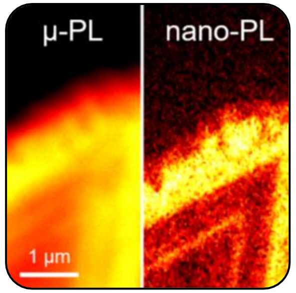
A Luferau (2025)

Photocurrent



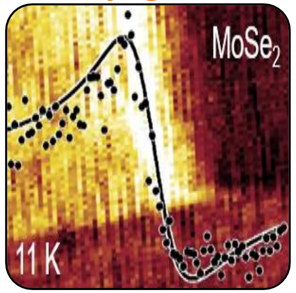
attocube (2023)

Nano-PL



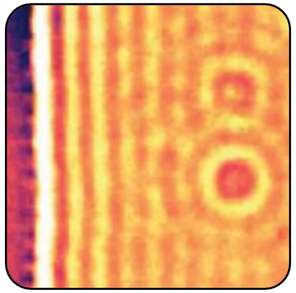
attocube (2025)

Cryogenic



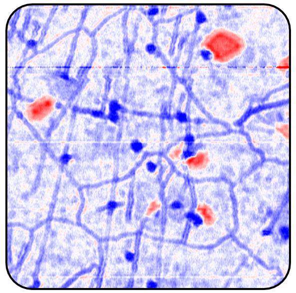
A Roche (2025)

Defects



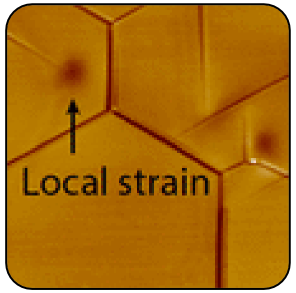
D Rizzo (2020)

Grain boundaries



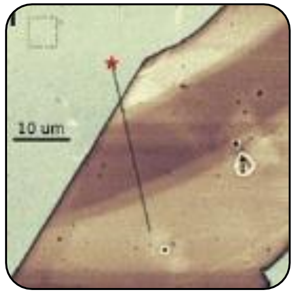
M Schnell (2020)

Strain



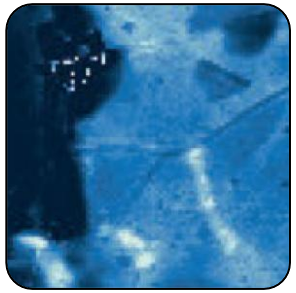
B Lyu (2019)

Conductivity



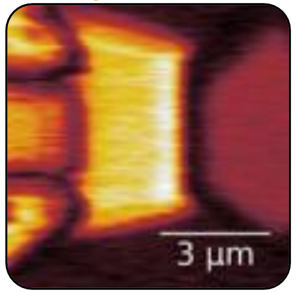
H Lassen (2023)

Intercalation



J Pereira (2022)

Graphene FET

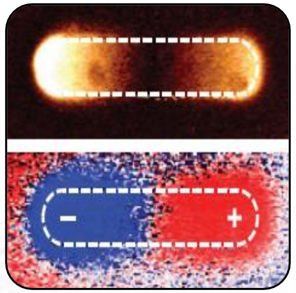


A Soltani (2020)

Applications in photonics using near-field microscopy

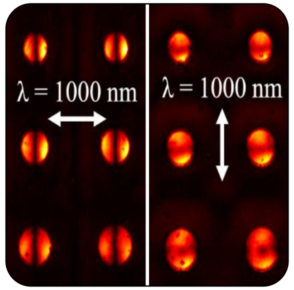
see the nanoworld nea spec attocube WITTENSTEIN Group

Plasmonics



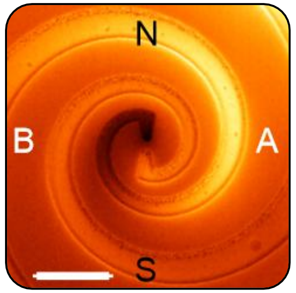
M Schnell (2010)

Polarization



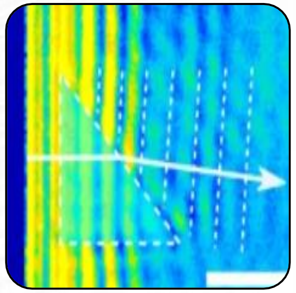
V Zenin (2017)

Resonators



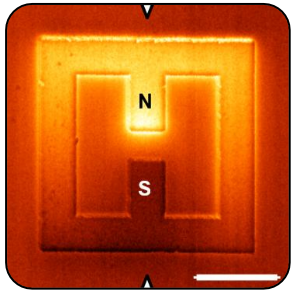
L Thomas (2022)

Wavefronts



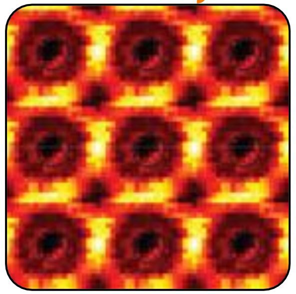
K Chaudhary (2019)

Metamaterials



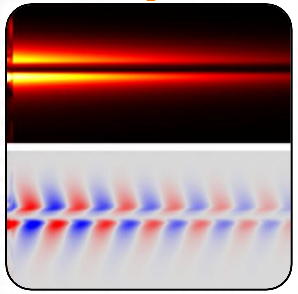
L Thomas (2022)

Photonic Crystals



F Alfaro-Mozaz (2021)

Waveguides

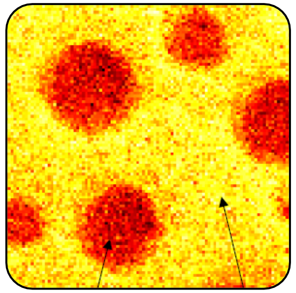


A Andryieuski (2014)

Densification

N Shchedrina (2024)

Refractive index

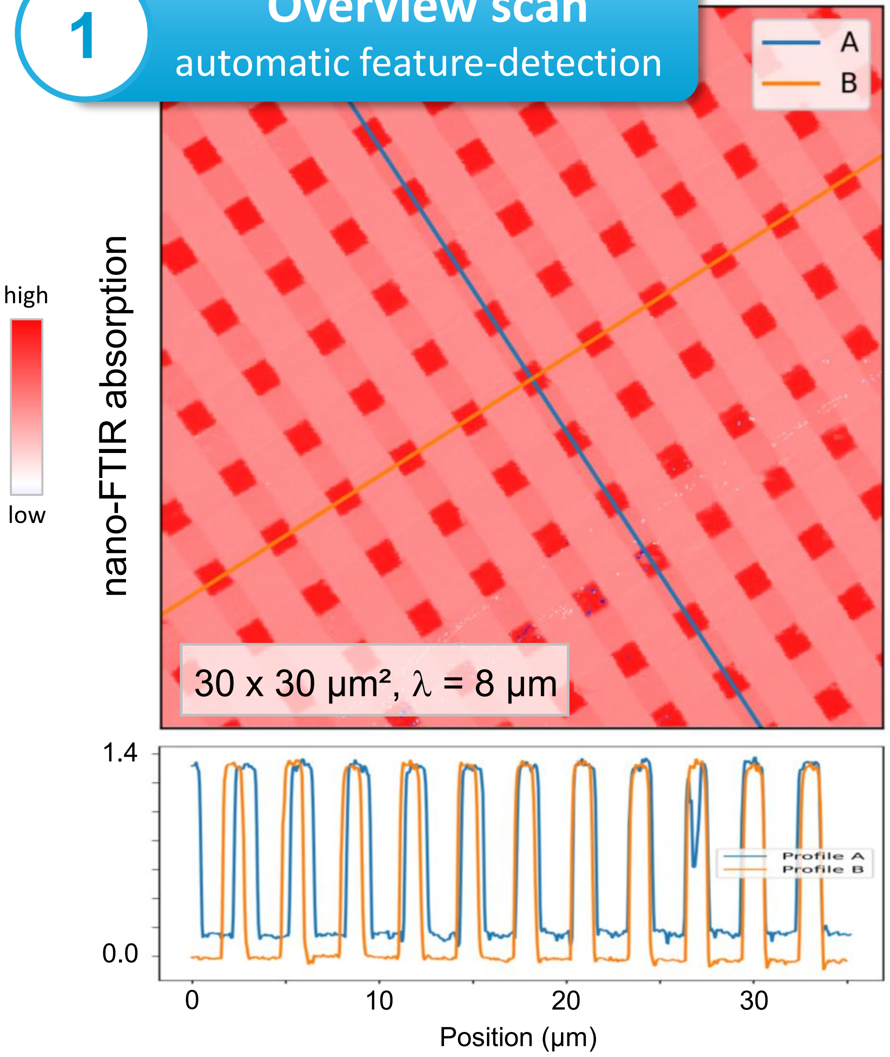


attocube (2025)

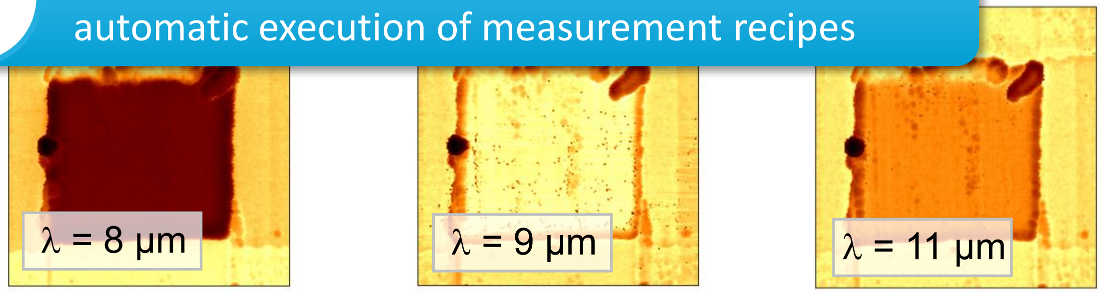
Full system automation is possible

Define measurement recipes “Storyboards” via expert mode “neaOSCI”, to run 1-click automated measurements & report

1 Overview scan
automatic feature-detection



2 Zoom-in & spectroscopic imaging
automatic execution of measurement recipes



3 Generate report
automatic data analysis and print to PDF

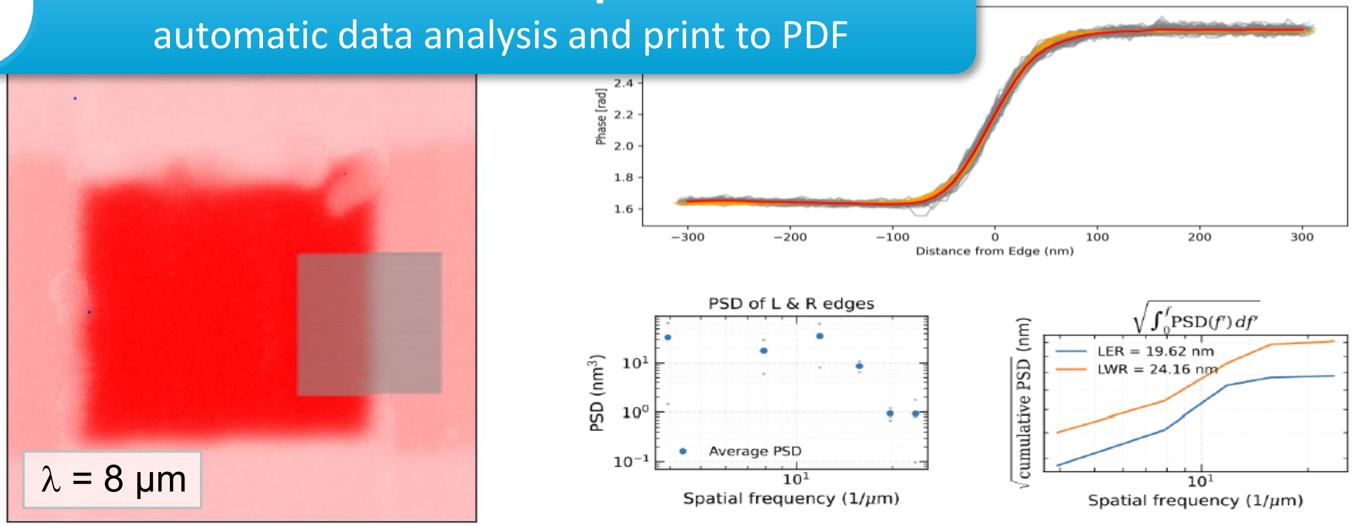


Figure 3. Power spectral density (PSD) analysis of line edges.

→ **Talk to our automation experts!**

NANOSCALE ANALYTICS
advanced imaging & spectroscopy

Microscopes for nanoscale analytics

Nanoscale Imaging & Spectroscopy

neaSCOPE

pioneering nanospectroscopy solutions for all spectral ranges

IRa-SCOPE

routine infrared vibrational analysis at micro- & nano-scales

All Tip-enhanced Optical Techniques

AFM-IR, nano-FTIR, s-SNOM, nano-Raman, nano-PL, nano-photocurrent at ambient & cryogenic conditions

Unmatched Spectral Coverage

From Visible to infrared to THz frequencies

Market-Leading Technology

Tailored for pioneering research & cutting-edge performance

Correlative Nano-IR Capabilities

Combines nano-FTIR and AFM-IR imaging & spectroscopy for best performance on all sample types

Multidimensional Vibrational Spectroscopy

Integrates µ-IR, nano-IR and Raman with top-quality AFM

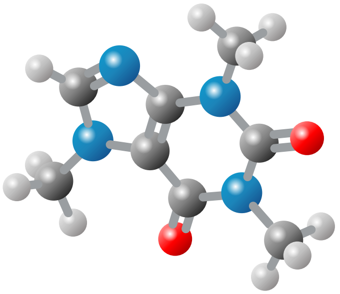
Reliability & Ease of Use

Sample-centric workflow, global coordinate system, instrument automation

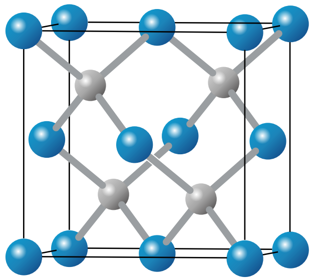
Summary – Attocube nano-IR for semiconducting materials

neaspec see the nanoworld | attocube WITTENSTEIN Group

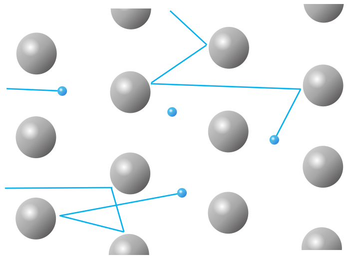
Molecular vibrations



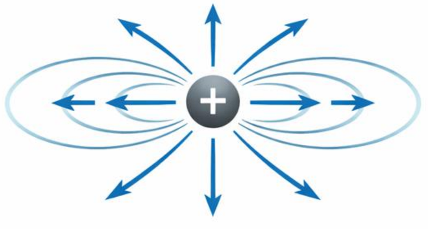
Lattice vibrations



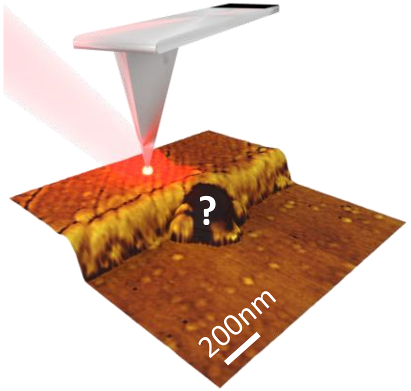
Charge carriers



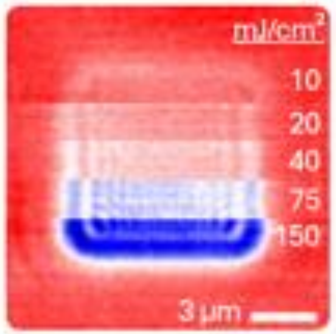
Electric fields



Contamination ID



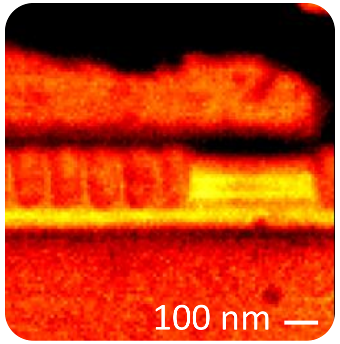
Lithography / Resists



AFM-IR

Infrared

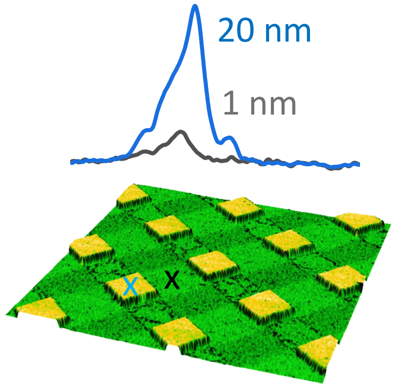
Dielectrics



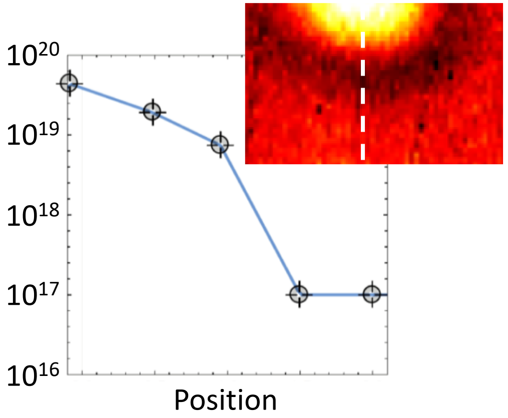
nano-FTIR

Infrared, THz, Visible

Thin films



Dopant profiling



NANOSCALE ANALYTICS
advanced imaging & spectroscopy