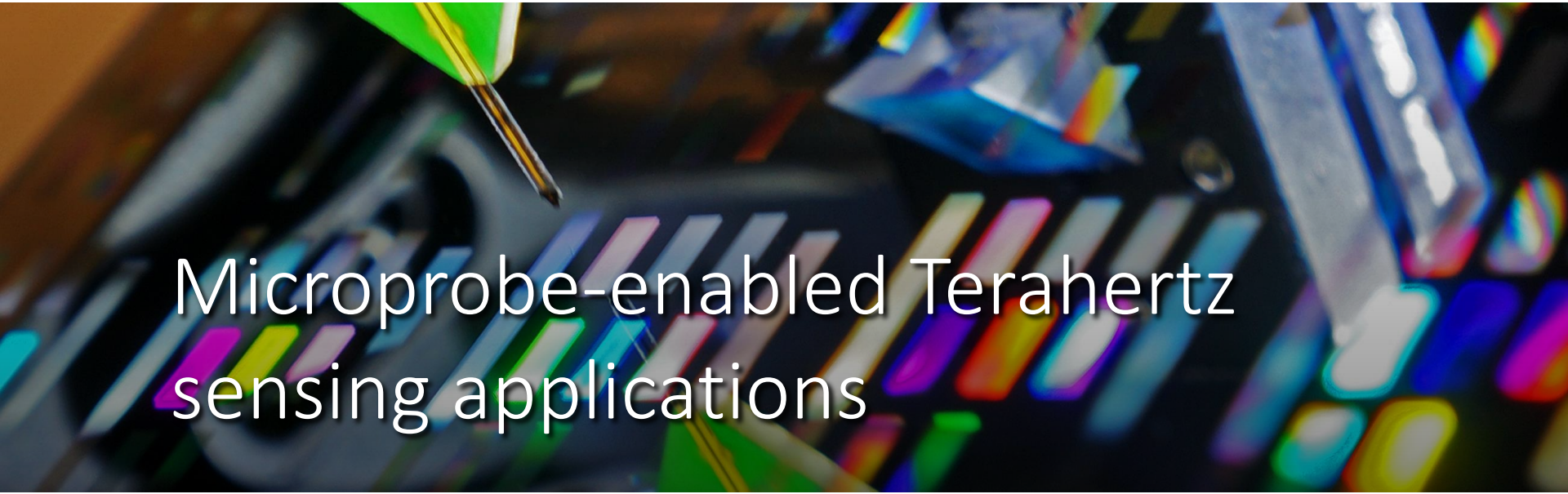
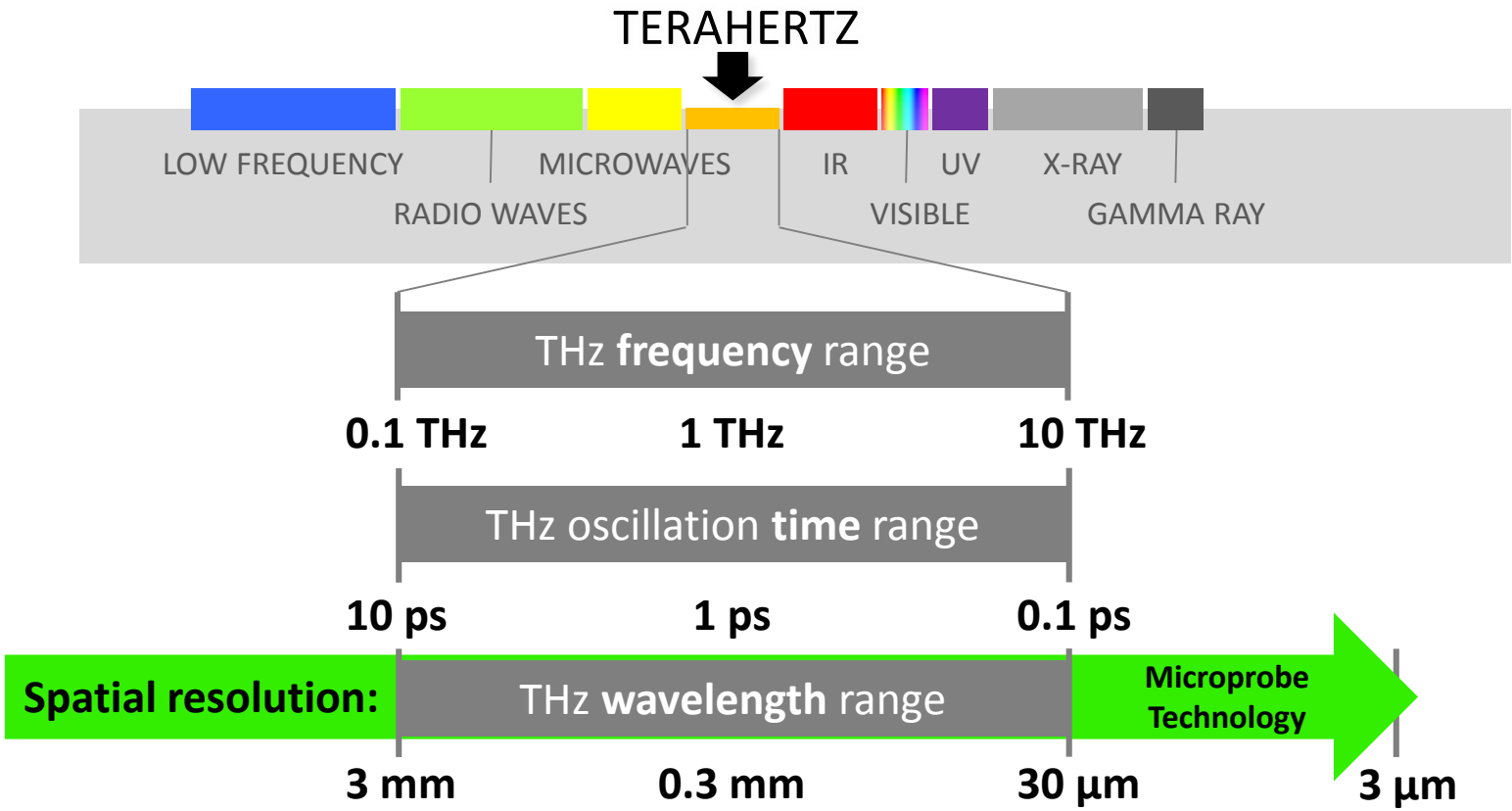


Microprobe-enabled Terahertz sensing applications

M. Nagel
Protemics GmbH, Aachen, Germany

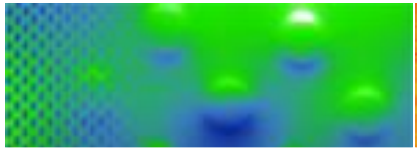
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Terahertz microprobing applications:

Taking advantage of Terahertz frequency range benefits without being compromised by wavelength-based resolution limitations.



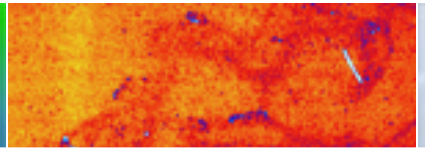
Terahertz Research

Application areas:

- Metamaterials
- Plasmonics
- Devices
- Waveguides
- Sensor surfaces
- Graphene

Benefits:

- Near-field access
- High-sensitivity
- Low-invasiveness
- Polarisation sensitive
- Broadband



Thin-film Analysis

Application areas:

- Solar cells
- Displays
- Flexible electronics
- Doping layers
- Graphene
- Transparent conductors

Benefits:

- Sheet resistance imaging
- Contactless
- Micron-scale resolution
- Large-area scanning
- High-speed scanning



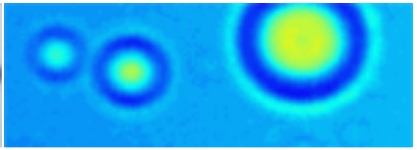
Chip-Testing

Application areas:

- Time-domain reflectometry
- Fault isolation
- Packaging level inspection
- 3D integration
- Through silicon via (TSV)

Benefits:

- Market leading TDR resolution
- Contactless
- Non-destructive
- Cost advantage



Volume Screening

Application areas:

- Plastic weld inspection
- Fiber inforced polymers
- Chip underfill inspection
- Organic layer screening

Benefits:

- Non-destructive
- Fast inspection
- Screening of opaque plastics
- Detection of microdefects

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Outline

- **Introduction**
  - Mismatch between THz radiation wavelengths and micro/nanostructure size
- **THz microprobes**
  - Working principle
- **Thin-film analysis with sub-wavelength resolution on large areas**
  - Thin-film conductors (Metals, Graphene, Semiconductors, ITO and ITO-replacement materials)
- **THz Metamaterials**
  - THz-Metamaterials, Metamaterial-based sensing
- **Plastic laser weld inspection**
  - Near-field detection of micro-defects
- **THz device analysis**
  - THz on-chip device characterization
  - Failure localization in chip packages

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When focusing is not enough…

Large THz wavelengths are problematic:

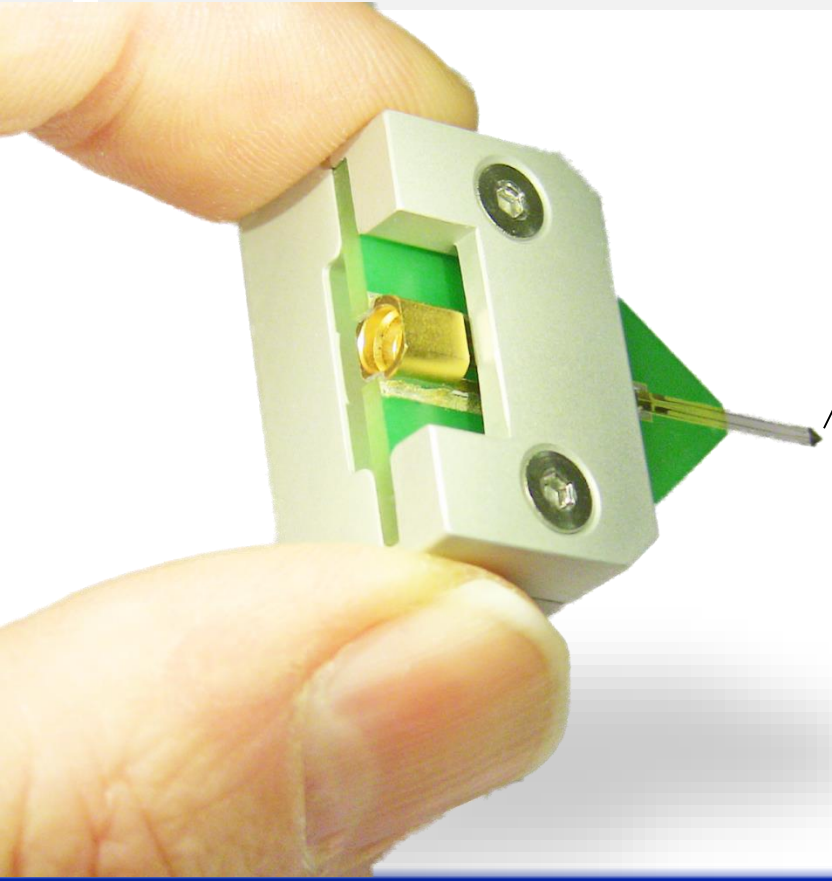
- When structures under test are too small (similar to λ or even smaller)
  - Lateral Micro/Nanostructures (Solar cells, electronic structures, micro defects, …)
  - Only minute (pl) sample volumes available (-> biosensing)
- On signal transfer to or from THz field confining structures
  - Waveguides
  - Integrated devices

Solution:

- Make THz emitter and/or detector smaller than the wavelength
- Bring the miniaturized emitter/detector in sub-wavelength distance to structure under test

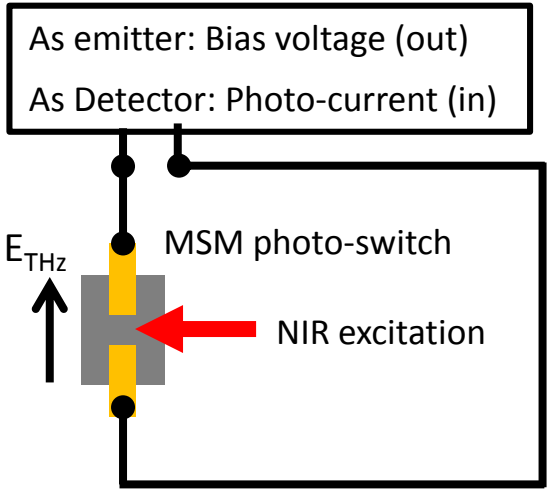
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THz micro-emitters/detectors



Active microstructure

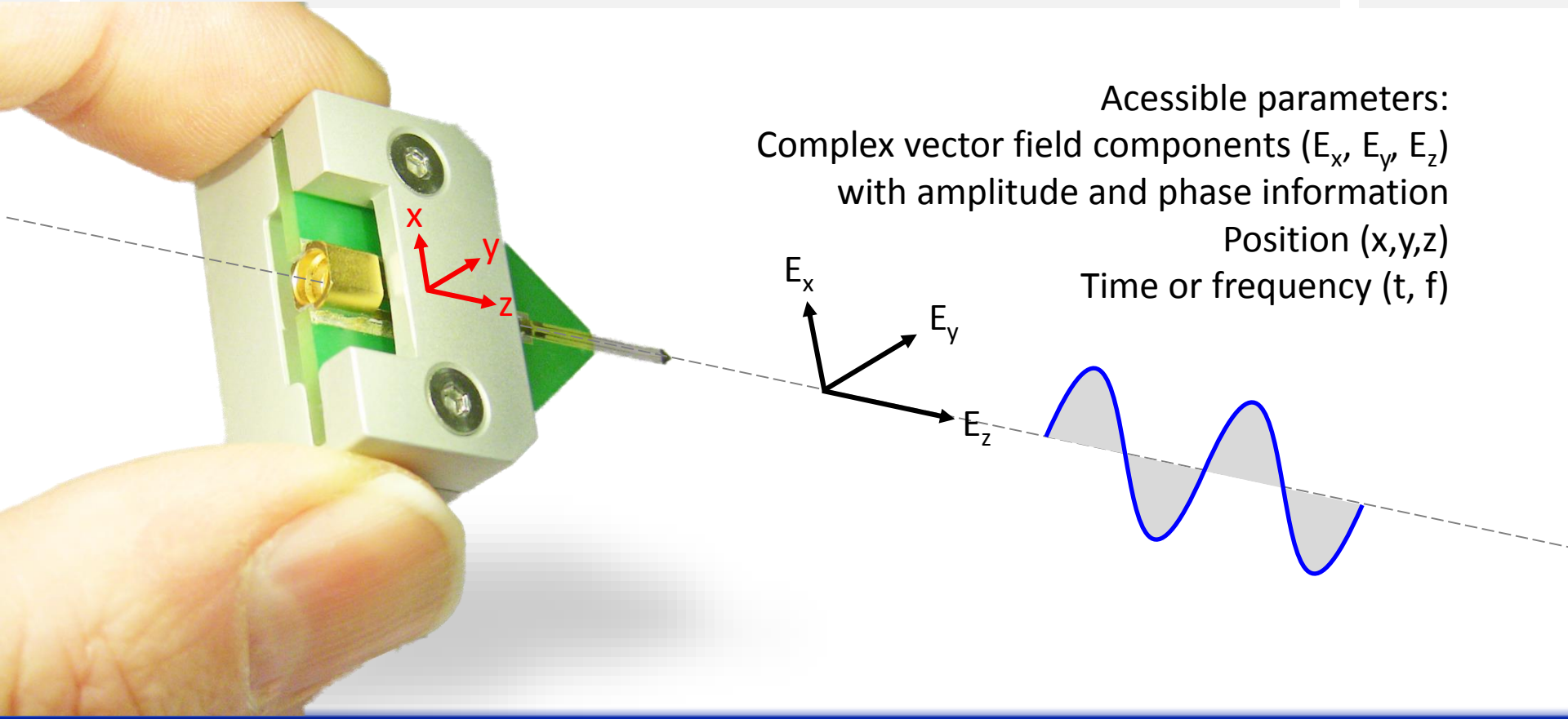
Cantilever thickness = 1 µm



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Ultra-fast photoconductive

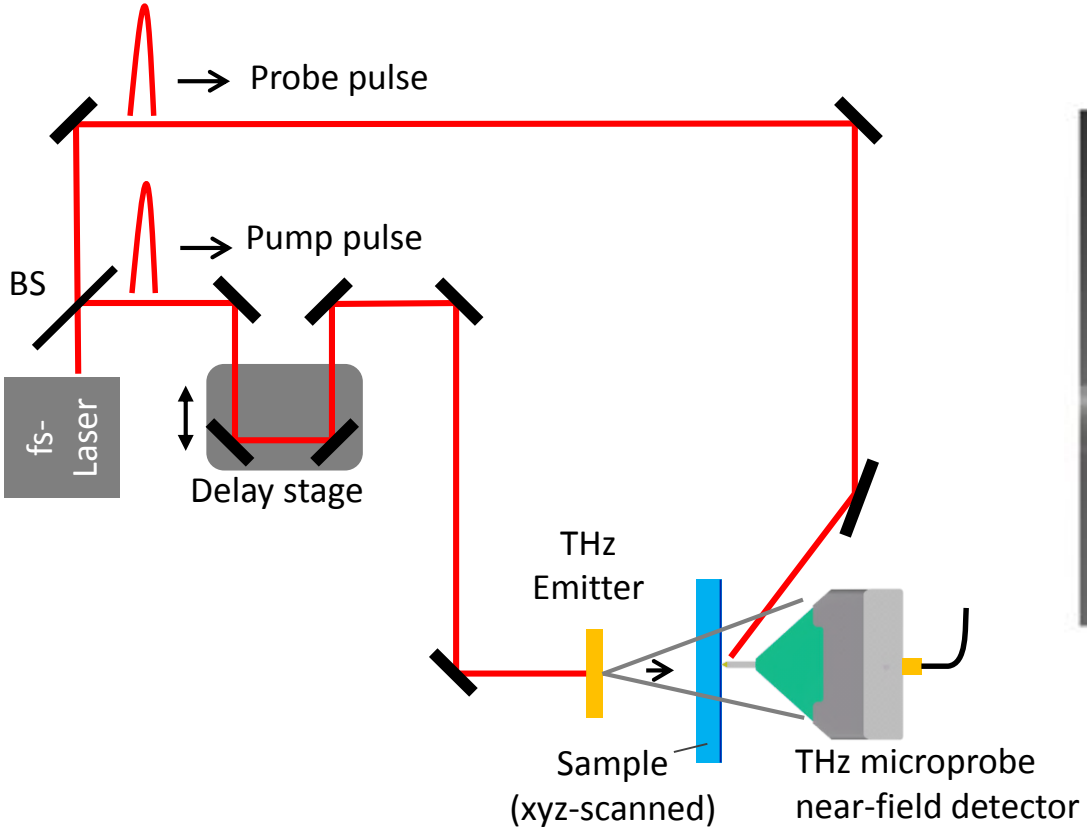
THz micro-emitters/detectors

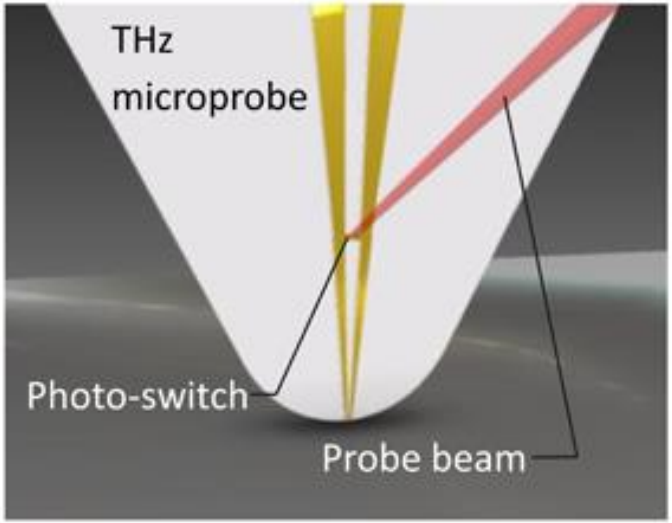


Acessible parameters:
Complex vector field components (E_x, E_y, E_z)
with amplitude and phase information
Position (x,y,z)
Time or frequency (t, f)

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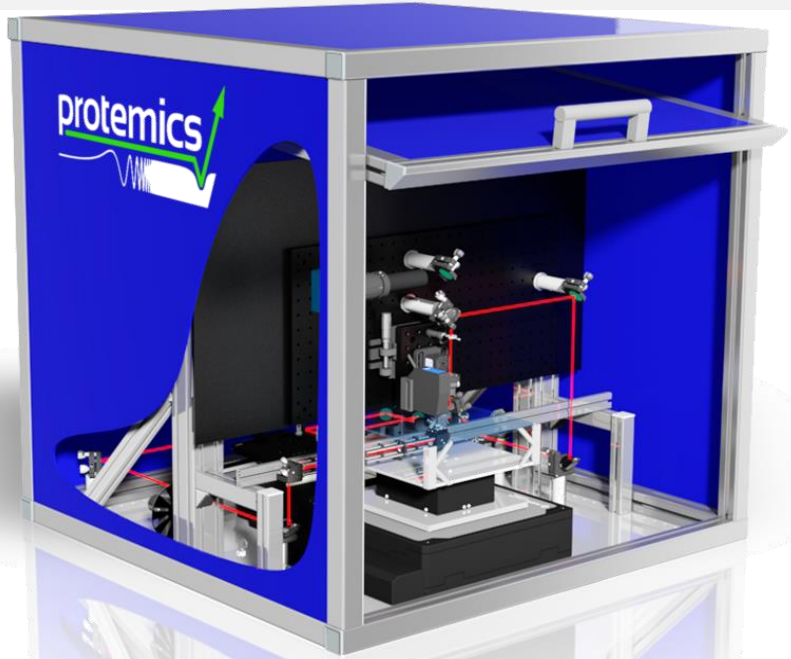
TD near-field sampling





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TD near-field scanning system



TeraCube Scientific

- **Automated table-top system**
  - 90x90x90 cm box including:
    - Laser
    - Scanning components
    - Opto-mechanics
    - Optics
    - Electronics
  - External components
    - PC
    - Supply unit

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Terahertz microprobing applications:

Taking advantage of Terahertz frequency range benefits without being compromised by wavelength-based resolution limitations.

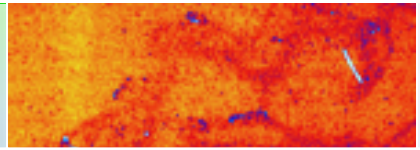
Terahertz Research

Application areas:

- Metamaterials
- Plasmonics
- Devices
- Waveguides
- Sensor surfaces
- Graphene

Benefits:

- Near-field access
- High-sensitivity
- Low-invasiveness
- Polarisation sensitive
- Broadband



Thin-film Analysis

Application areas:

- Solar cells
- Displays
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- Doping layers
- Graphene
- Transparent conductors

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- Non-destructive
- Fast inspection
- Screening of opaque plastics
- Detection of microdefects

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Thin-film conductors

Disadvantages of contact-based approaches (e.g. 4-point-probe):

- Inaccurate on **large-bandgap** semiconductors (e.g. GaN or SiC) because of nonlinear contacts.
- Inapplicable on **passivated** samples (e.g. Solar cells).
- Not directly applicable on **nanostructures** (e.g. metal mesh nanostructures). Formation of additional contact pads required.
- **Very slow!** Typically 5s/measurement point.
- Generation of **contact marks** from needles

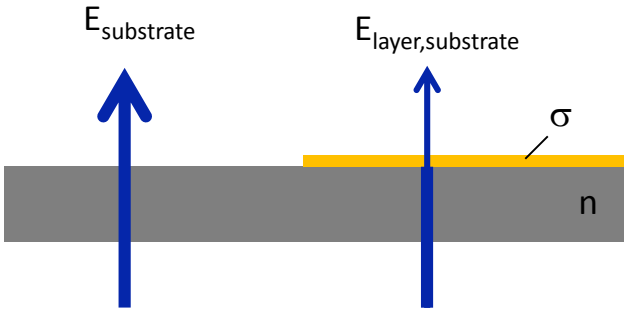
Disadvantages of contact-free approaches (e.g. Eddy current probe):

- Spatial resolution is limited to **1 cm** or 2 mm for **quantitative** or qualitative measurements, respectively.

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Thin-film conductors

- **Surface analysis with sub-wavelength resolution on large areas**
  - Sheet resistance imaging of thin-film conductors such as
    - Metals
    - Graphene
    - Doped semiconductors
    - Optically transparent conductors: ITO and ITO-replacement materials



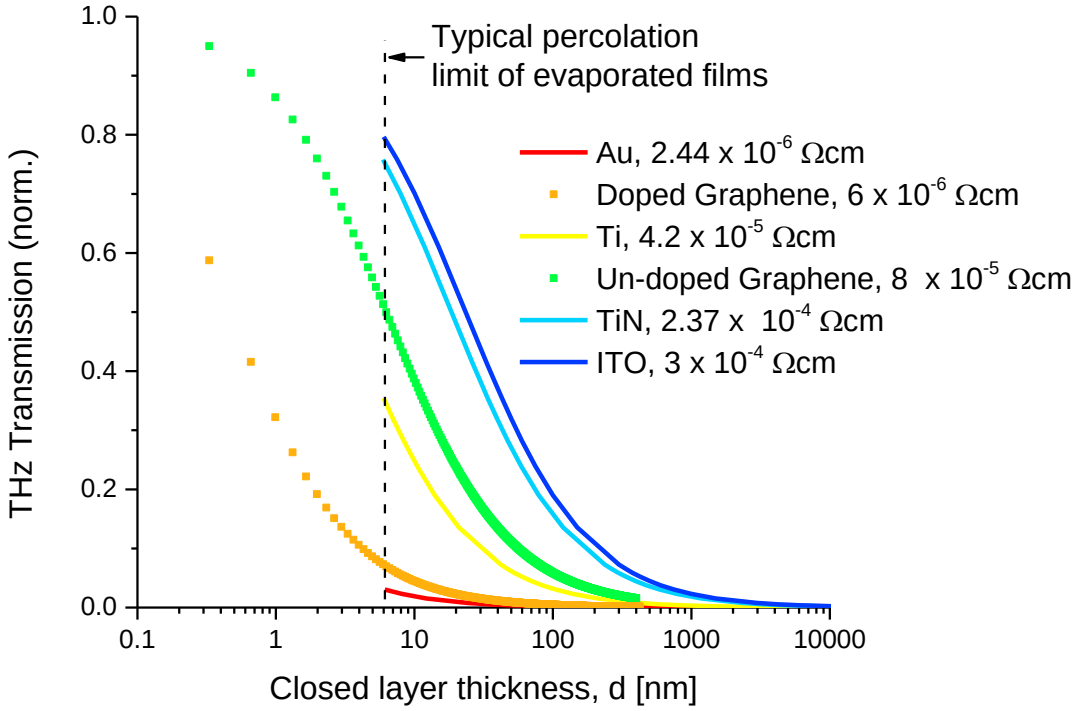
Tinkham Formula:

$$\frac{E_{layer,substrate}(\omega)}{E_{substrate}(\omega)} = \frac{1+n}{1+n+Z_0\sigma(\omega)d}$$

Accessible sheet resistance range: 0.1 – 10000 Ohm

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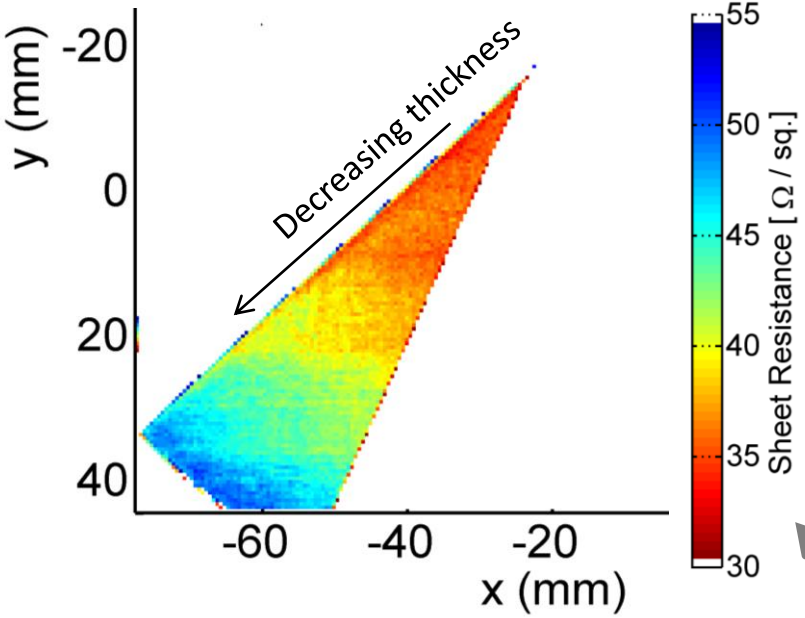
Thin-film conductors



Substrate:
Silicon

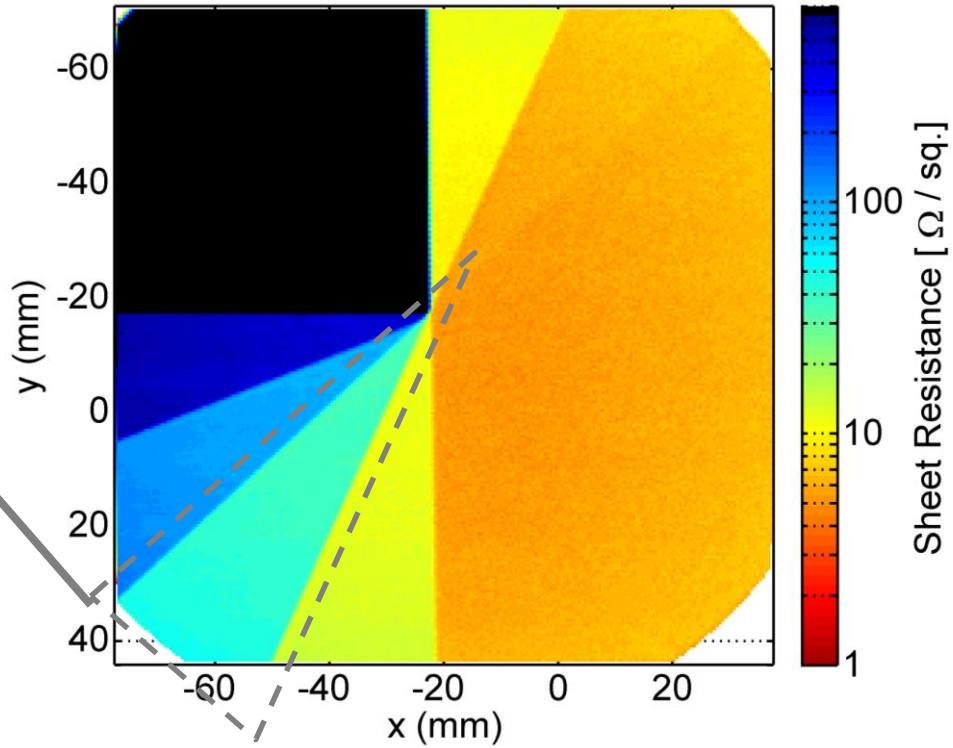
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Thin-film conductors



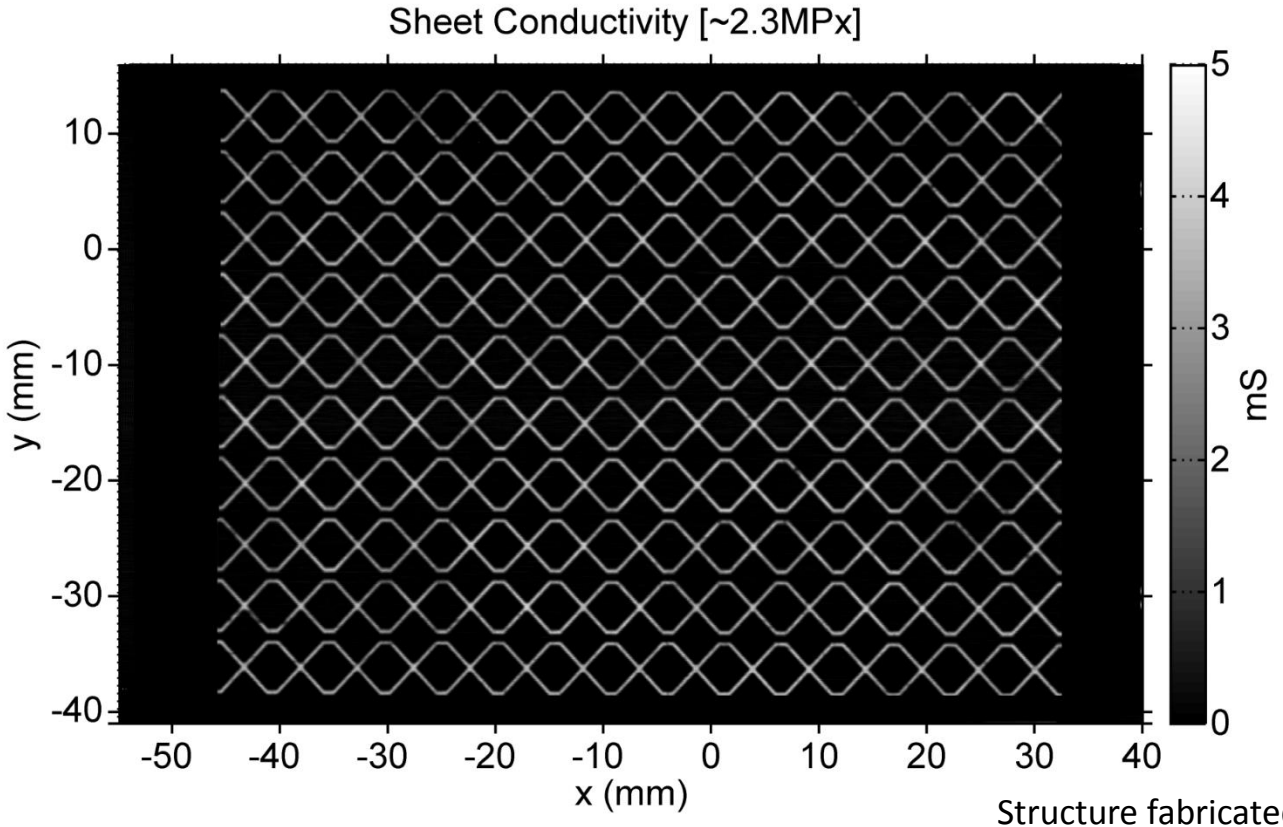
Example: Sputtered metal layers with varying thickness on glass.

Measured with THz microprobe



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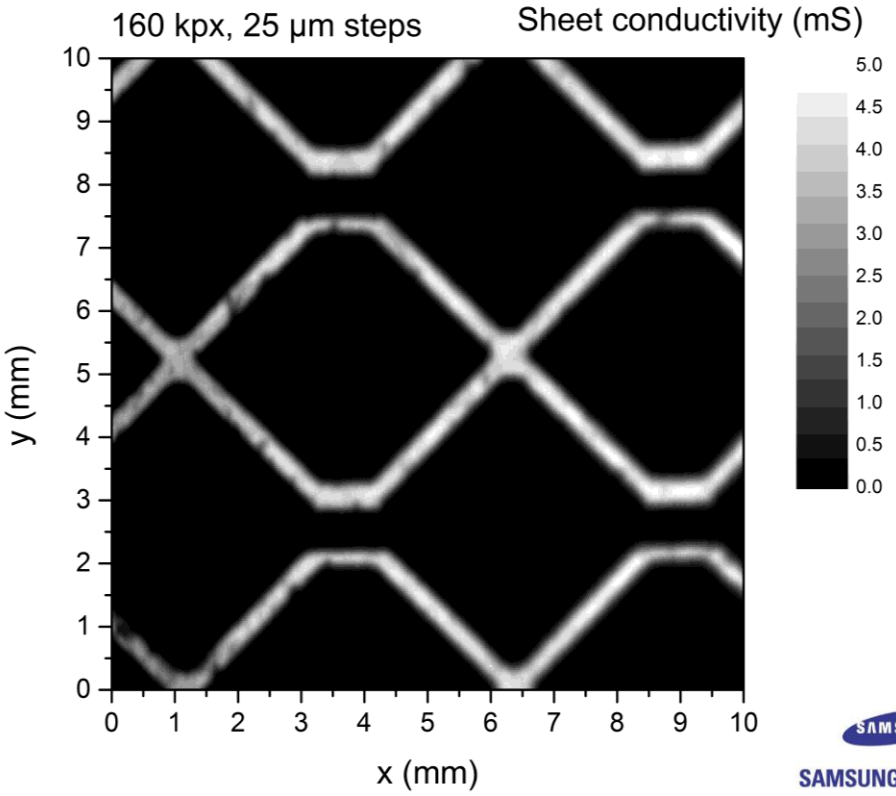
Thin-film conductors: Graphene



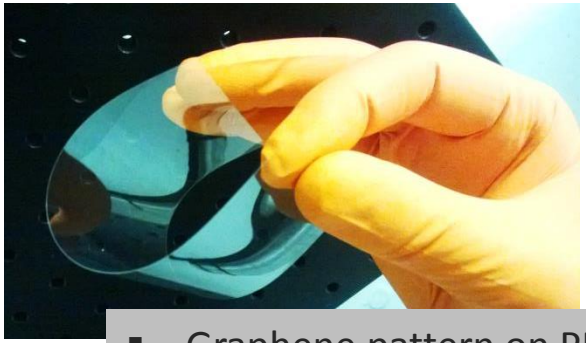
Structure fabricated by: SAMSUNG TECHWIN

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Thin-film conductors: Graphene



SAMSUNG TECHWIN



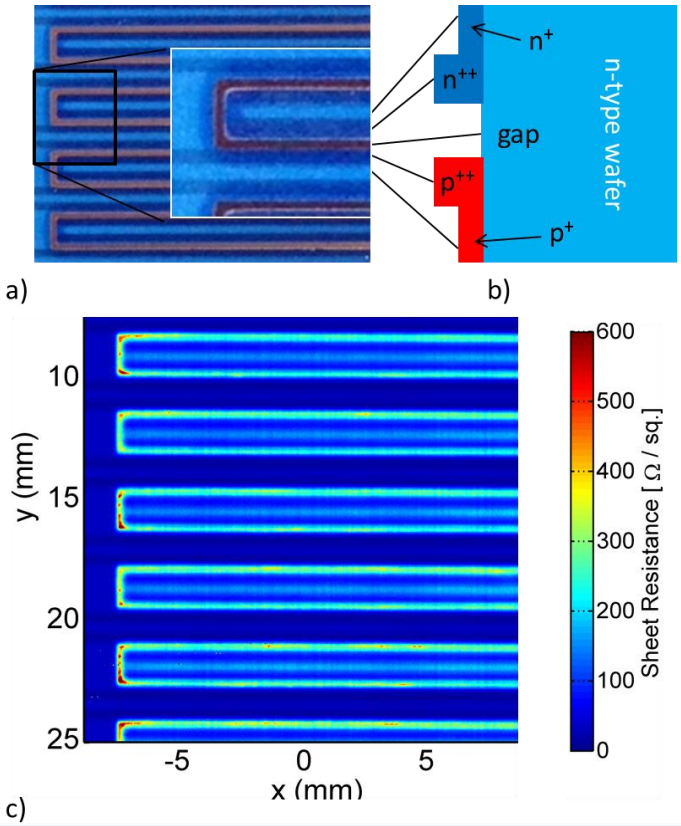
- Graphene pattern on PET foil
- Flexible display application

High-speed contactless raster scanning on **bended** surfaces.

Measured using the interband excitation range of 0.1–1 THz.

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Thin-film conductors: Doped mc-Si



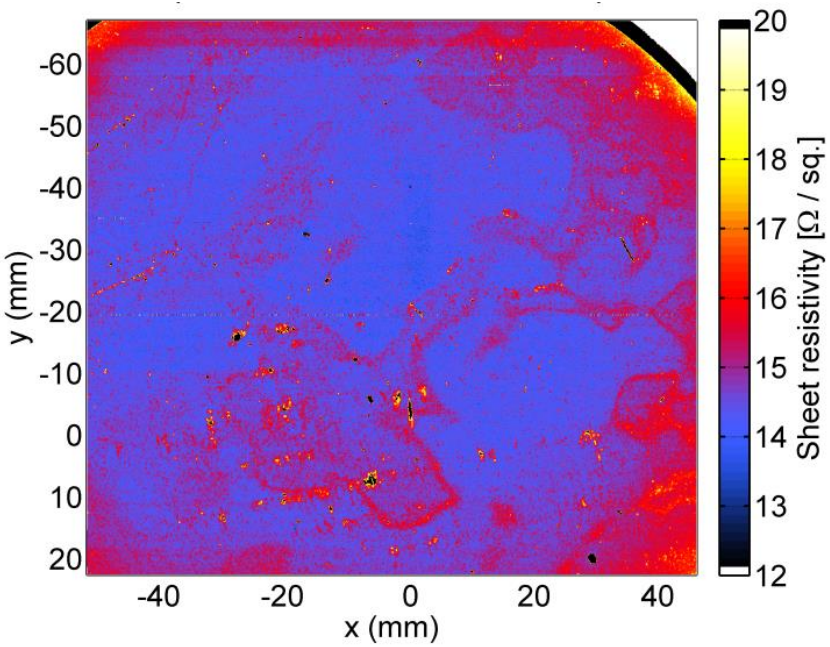
- IBC solar cell structure
- Laser-based material ablation process

- Sheet resistance image reveals areas of process induced inhomogenuity
- Applicable on full cell area and textured surfaces

In collaboration with: ECN

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Thin-film conductors: ITO-replacements

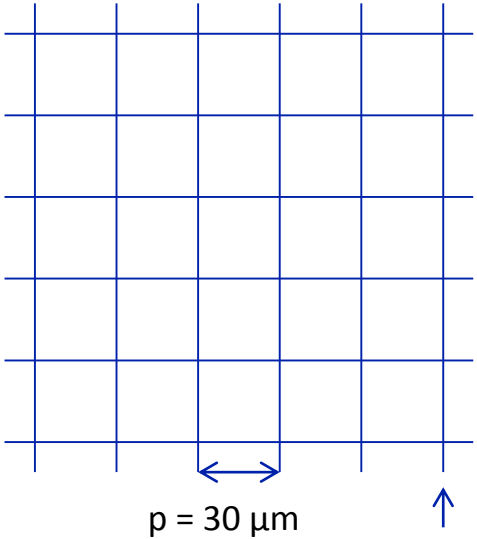


Sample:



Al nanowire mesh on glass

Optical (VIS-IR) Transparency > 94%

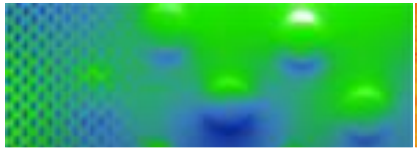


Implication of metal mesh structure vs. continuous layer:
Sheet resistance value retrieval from THz transmission data requires careful spectral analysis.

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Terahertz microprobing applications:

Taking advantage of Terahertz frequency range benefits without being compromised by wavelength-based resolution limitations.





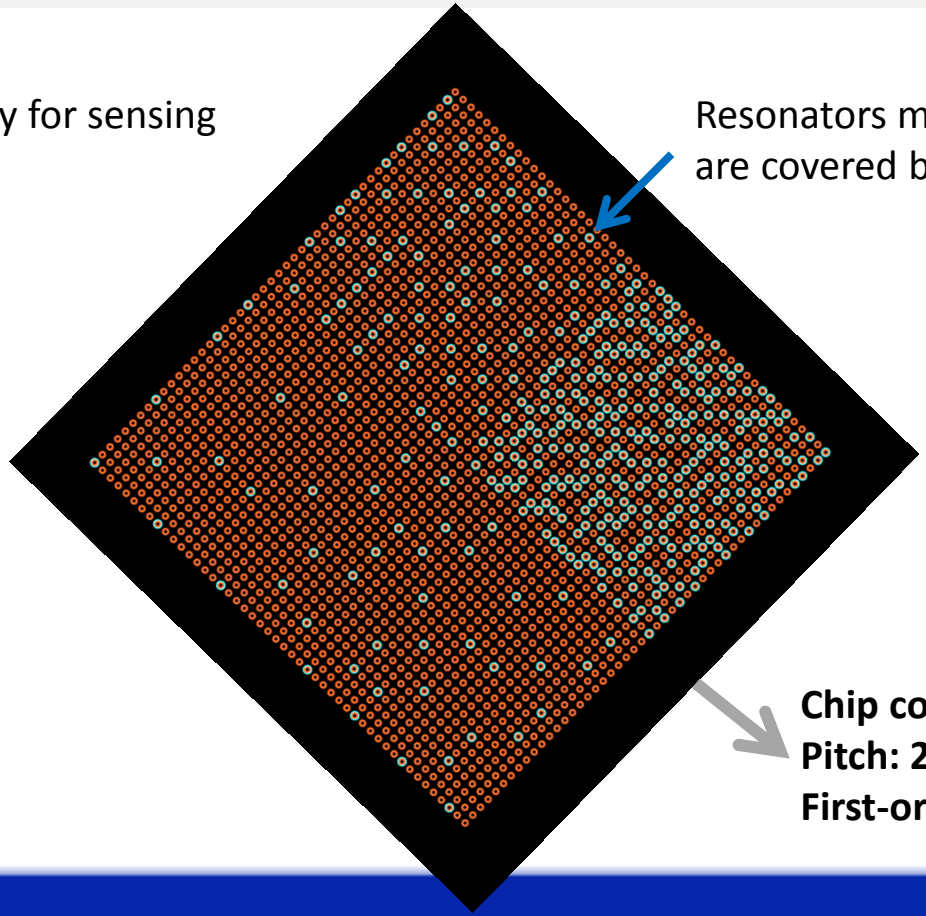


Terahertz Research	Thin-film Analysis	Chip-Testing	Volume Screening
Application areas: • Metamaterials • Plasmonics • Devices • Waveguides • Sensor surfaces • Graphene	**Application areas:** • Solar cells • Displays • Flexible electronics • Doping layers • Graphene • Transparent conductors	**Application areas:** • Time-domain reflectometry • Fault isolation • Packaging level inspection • 3D integration • Through silicon via (TSV)	**Application areas:** • Plastic weld inspection • Fiber inforced polymers • Chip underfill inspection • Organic layer screening
Benefits: • Near-field access • High-sensitivity • Low-invasiveness • Polarisation sensitive • Broadband	**Benefits:** • Sheet resistance imaging • Contactless • Micron-scale resolution • Large-area scanning • High-speed scanning	**Benefits:** • Market leading TDR resolution • Contactless • Non-destructive • Cost advantage	**Benefits:** • Non-destructive • Fast inspection • Screening of opaque plastics • Detection of microdefects

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Metamaterials for sensing

Ringresonator array for sensing applications:

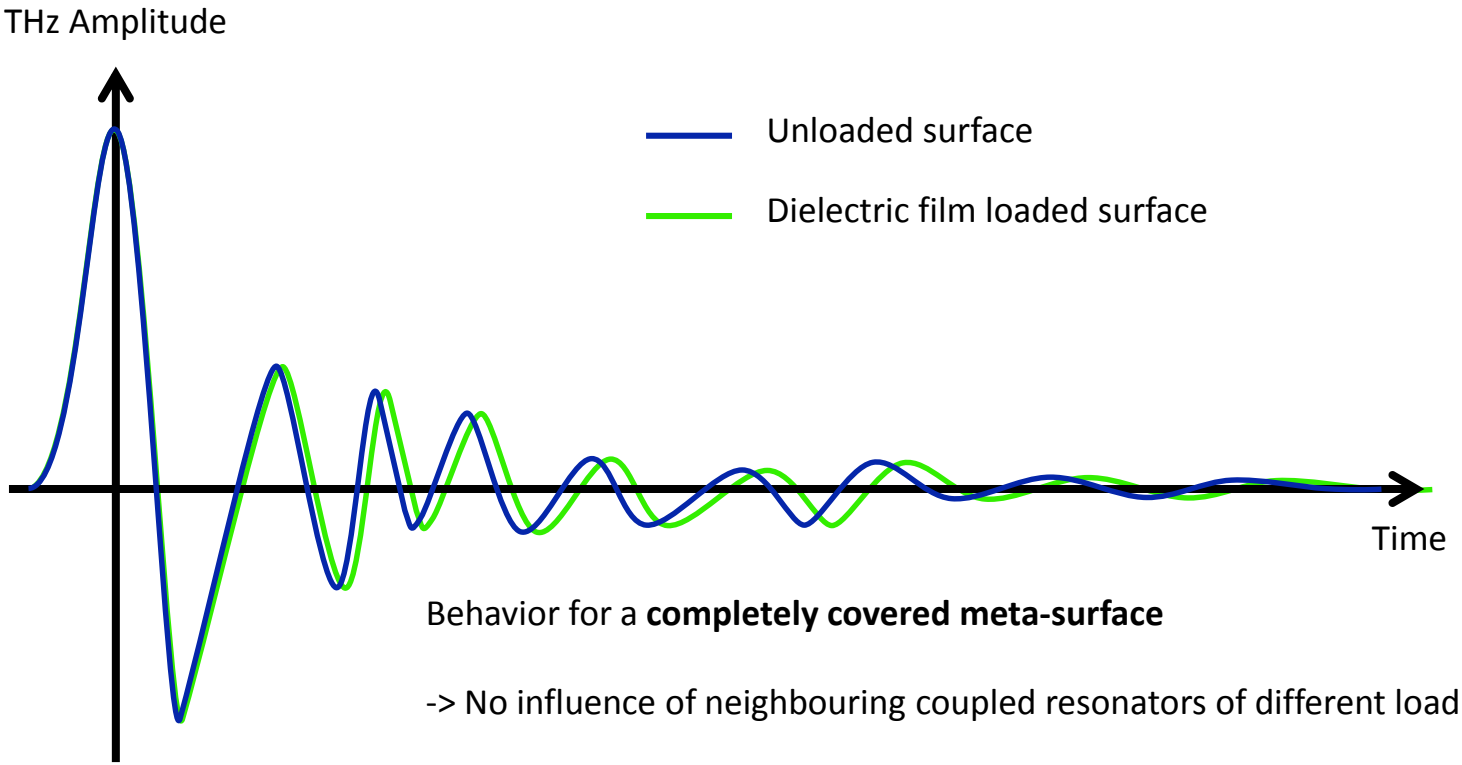


Resonators marked by bright spots are covered by thin low-k dielectric layer

Chip contains 2304 sensor spots
Pitch: 260 µm
First-order resonance at f_r = 0.5 THz

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Metamaterials for sensing



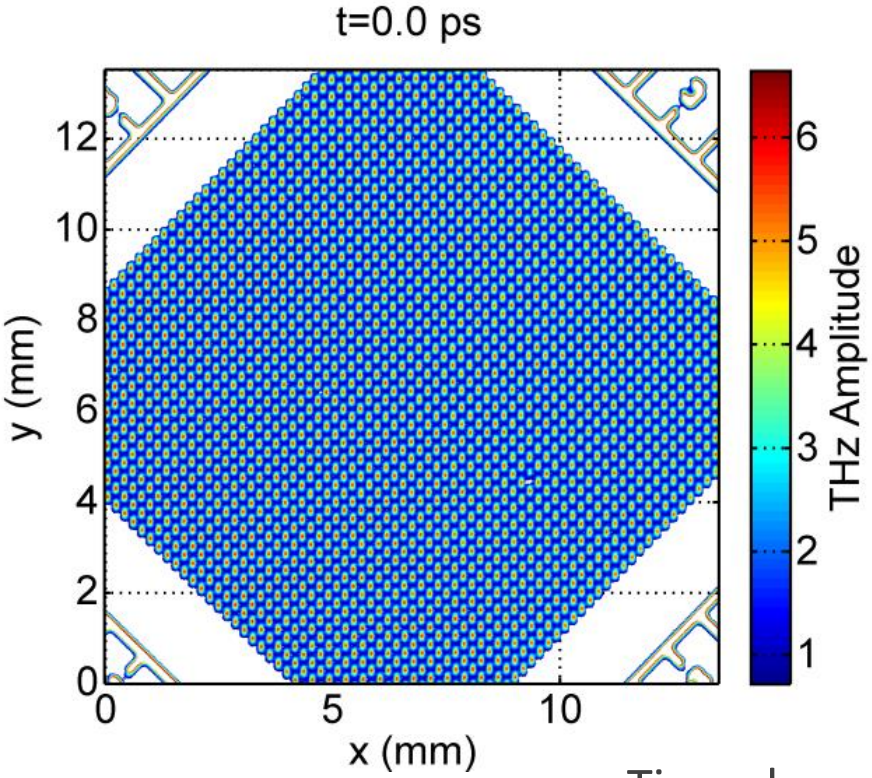
Behavior for a **completely covered meta-surface**

-> No influence of neighbouring coupled resonators of different loading state.

What about single element loading?

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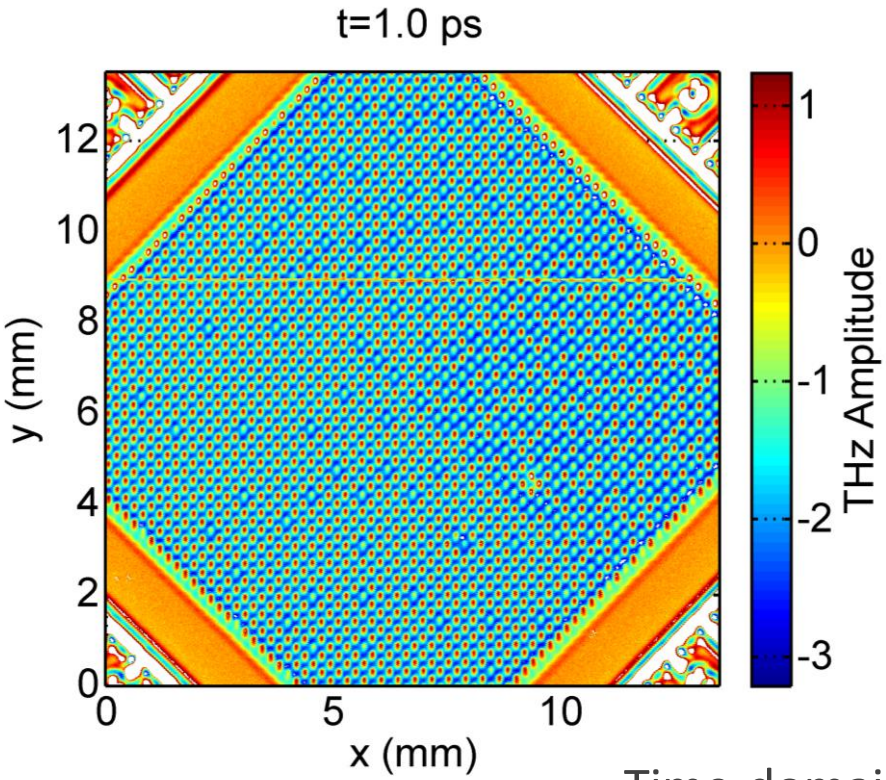
Metamaterials for sensing

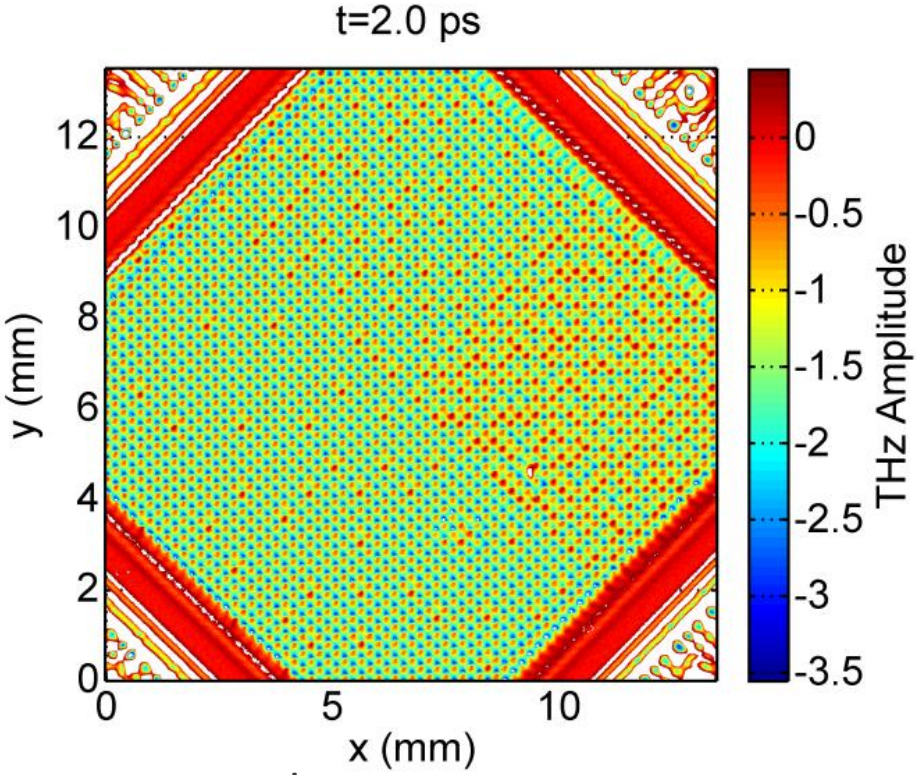


Time-domain measurements

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Metamaterials for sensing

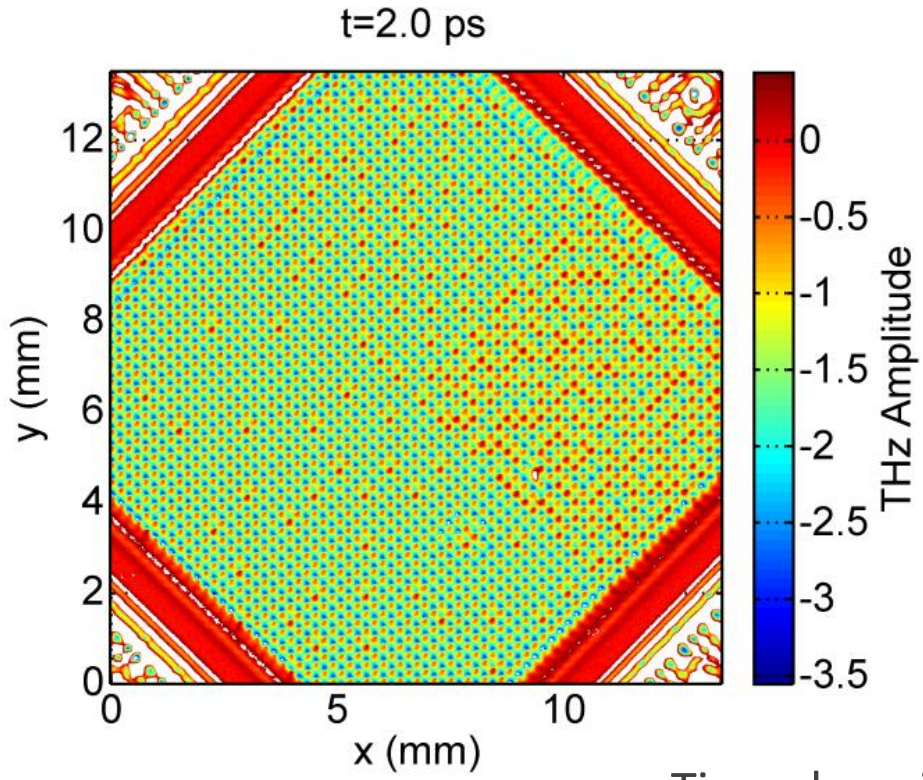


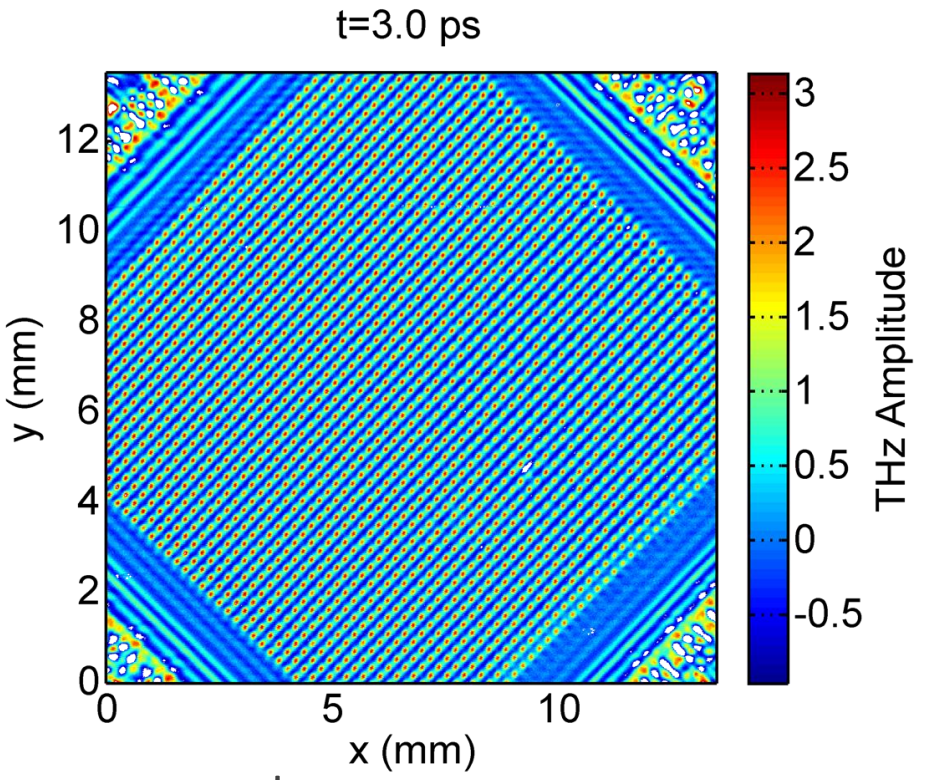


Time-domain measurements

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Metamaterials for sensing

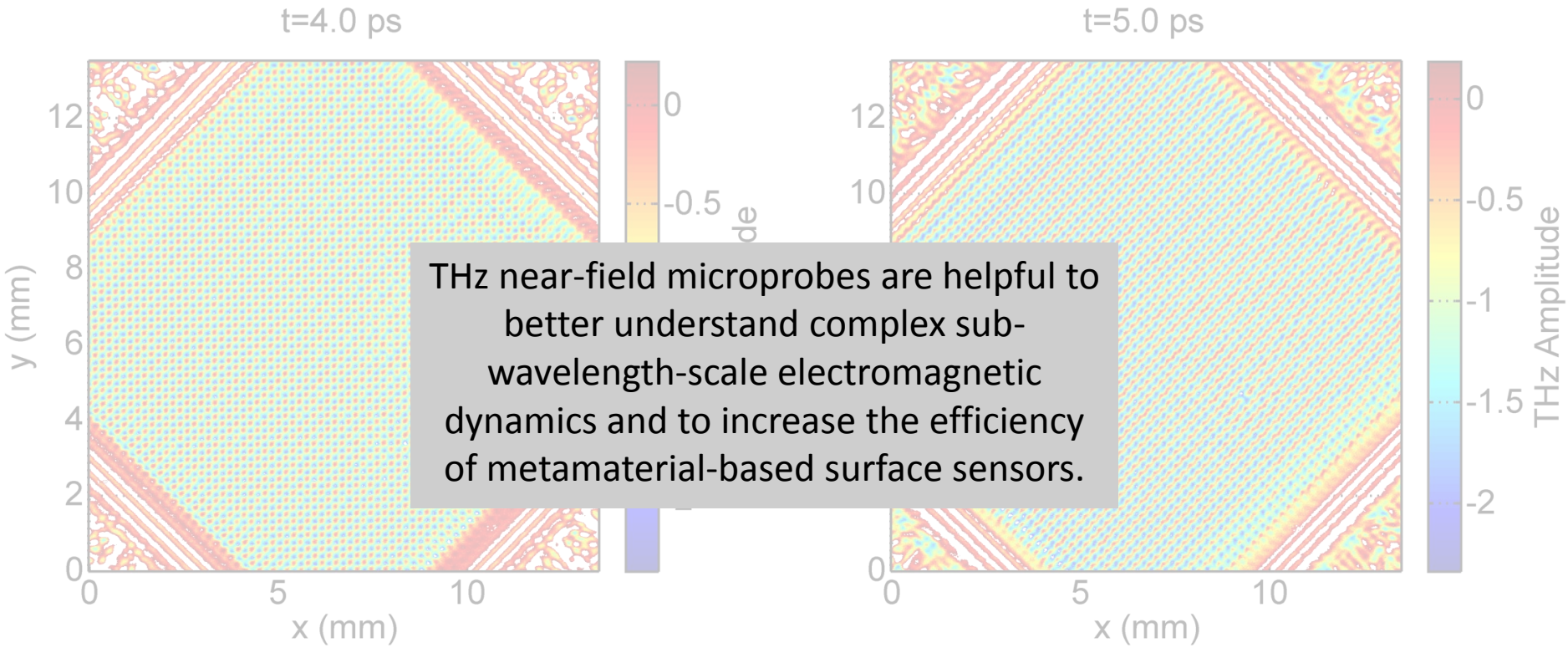




Time-domain measurements

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Metamaterials for sensing



THz near-field microprobes are helpful to better understand complex sub-wavelength-scale electromagnetic dynamics and to increase the efficiency of metamaterial-based surface sensors.

Time-domain measurements

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Terahertz microprobing applications:

Taking advantage of Terahertz frequency range benefits without being compromised by wavelength-based resolution limitations.

Terahertz Research

Application areas:

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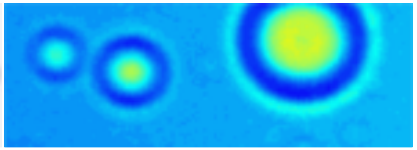
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Volume Screening

Application areas:

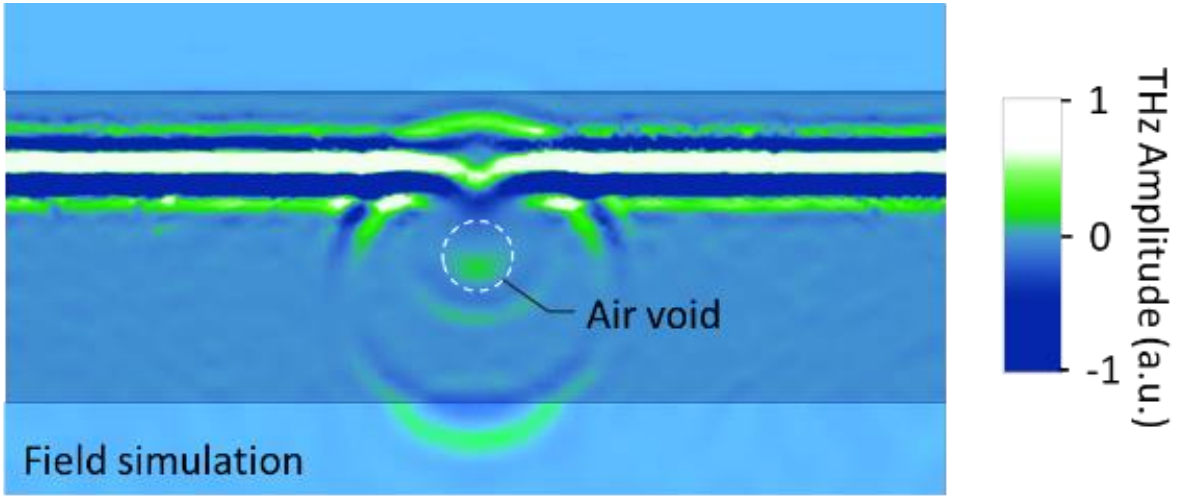
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Laser plastic weld inspection

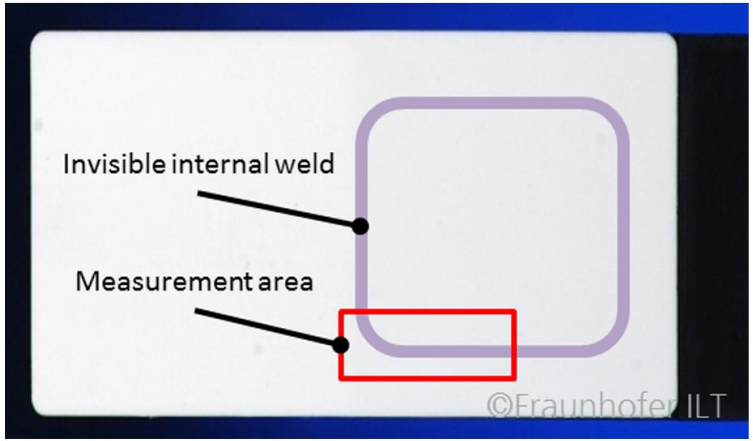


Small sub-wavelength objects can´t be seen by diffraction-limited free-space transmission, but they generate scattering light.

The scattering light can be detected in sufficiently close distance to the scatterer.

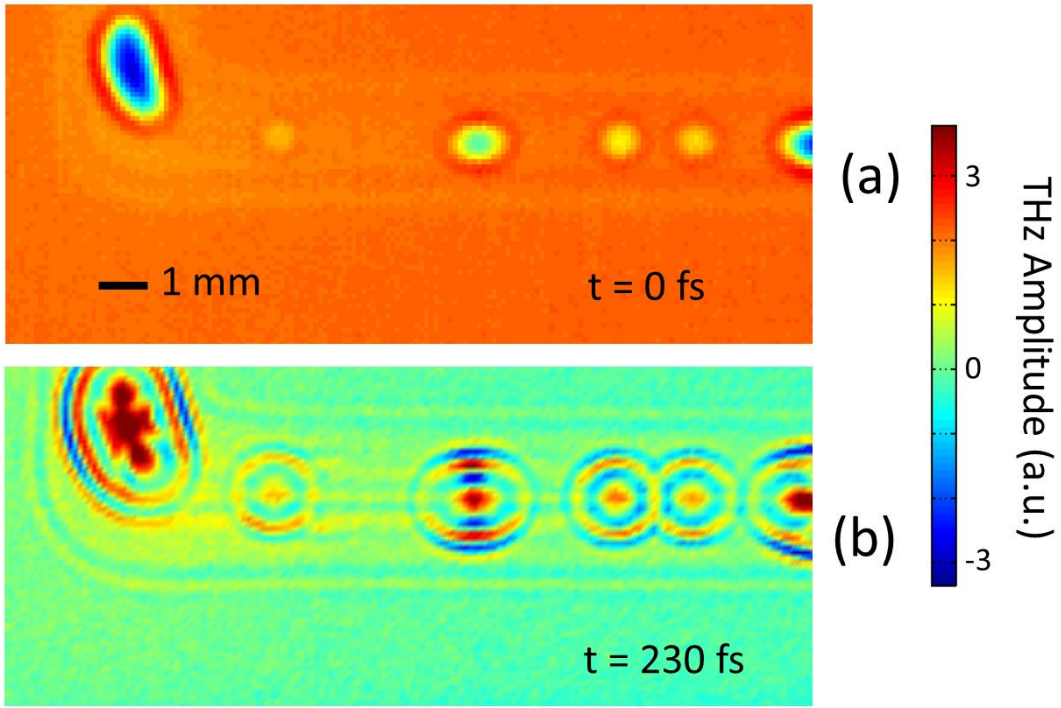
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Laser plastic weld inspection



THz microprobing is important, because there are certain plastics which cannot be inspected through light from other spectral ranges.

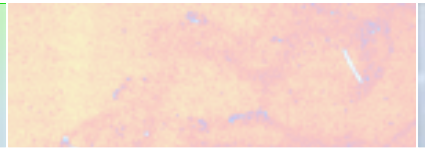
THz microprobe measurement data



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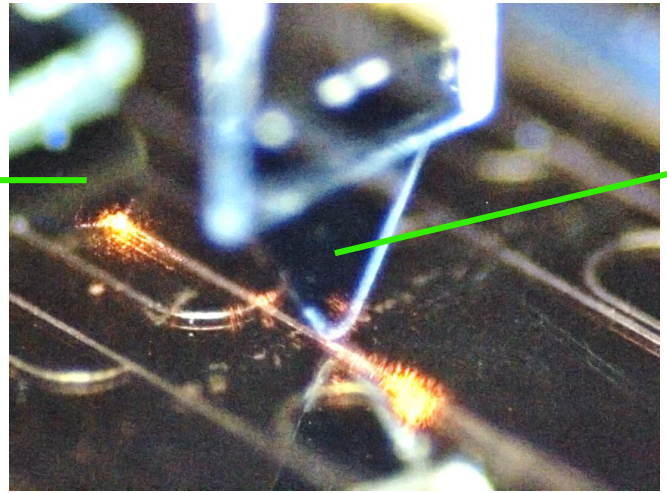
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THz on-chip analysis



On-chip pulse emitter tip

Near-field detector tip

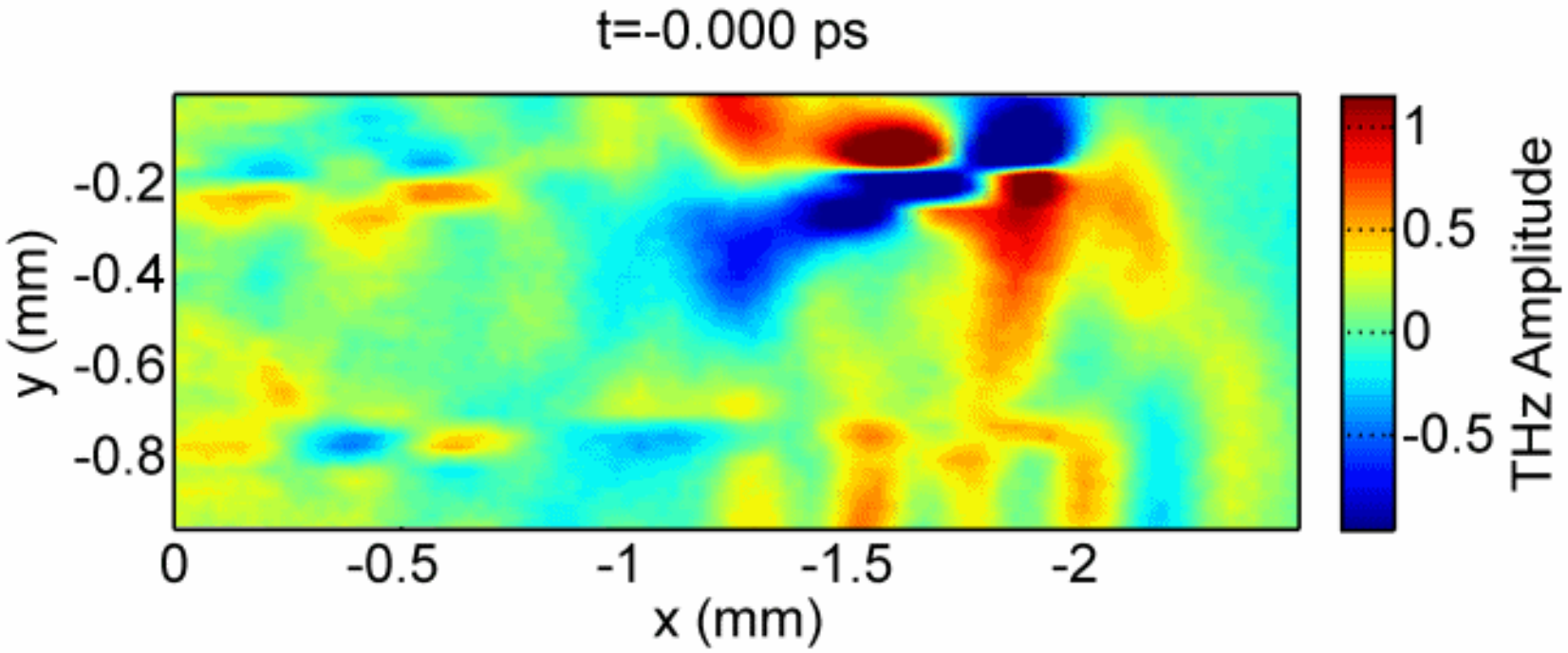
Scanning area

30 µm

Thin-film microstripline

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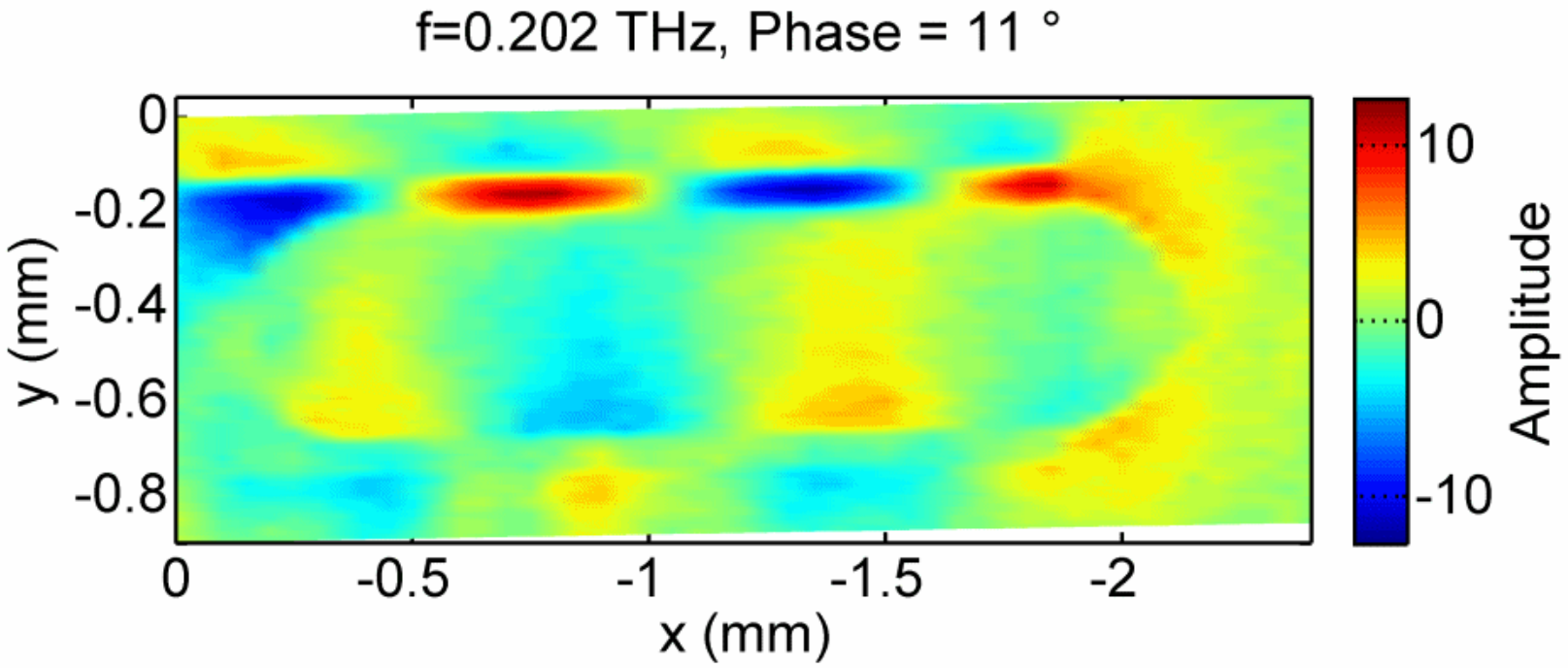
THz on-chip analysis



Time-domain measurement

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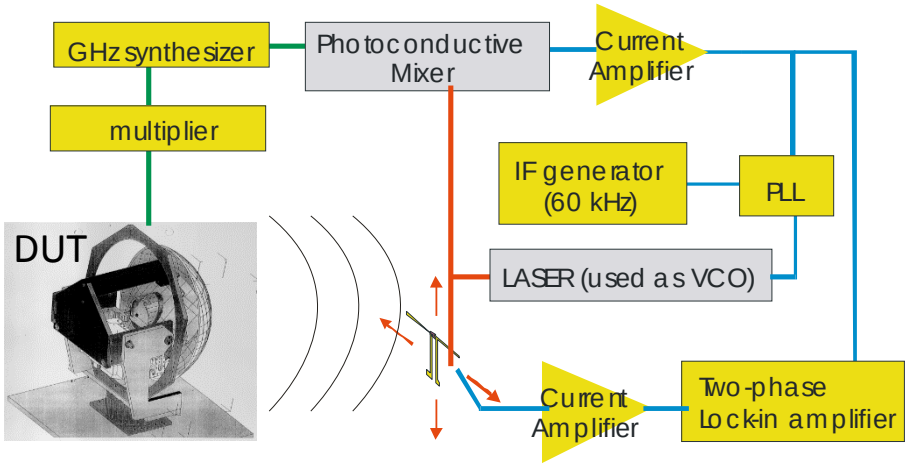
THz on-chip analysis



Frequency-domain measurement data extraction

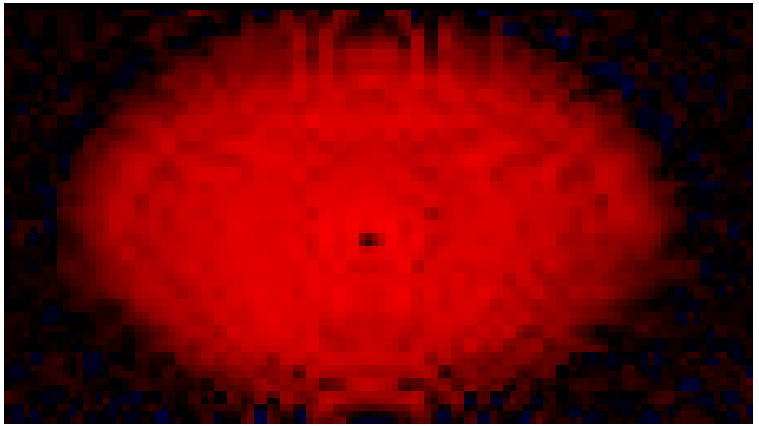
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94 GHz photo-conductive near-field sampling



Subharmonic synchronization to synthesizer

Measurement data



94 GHz Antenna near-field pattern (DUT: DASA)

Citation
M. Nagel, H. P. M. Pellemans, M. Brucherseifer, P. H. Bolívar, H. Kurz, and G. Schindler, "94 GHz radar antenna characterization with synchronized near-field photoconductive sampling," in Ultrafast Electronics and Optoelectronics, A. Sawchuk, ed., Vol. 49 of OSA Trends in Optics and Photonics (Optical Society of America, 2001), paper UThA1.

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Failure localization



Failure localization → Target preparation → Failure analysis → Material characterization

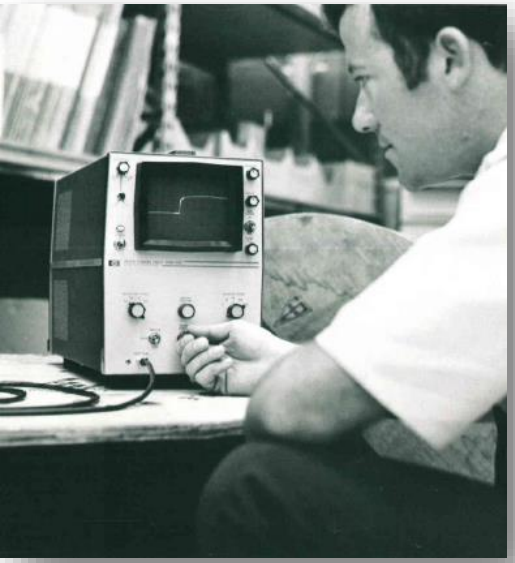
Failure localization	Target preparation	Failure analysis	Material characterization
(non-destructive) LIT, **TDR**, X-ray, …	**(destructive)** Laser, FIB, RIE, wet chemistry, milling, abrasive blasting, ...	**(image defect & physical analysis)** SEM / EBSD, EDX, TEM, ToF-SIMS...	Image correlation, ESPI, …

Limited accuracy/information but fast

Expensive & time consuming

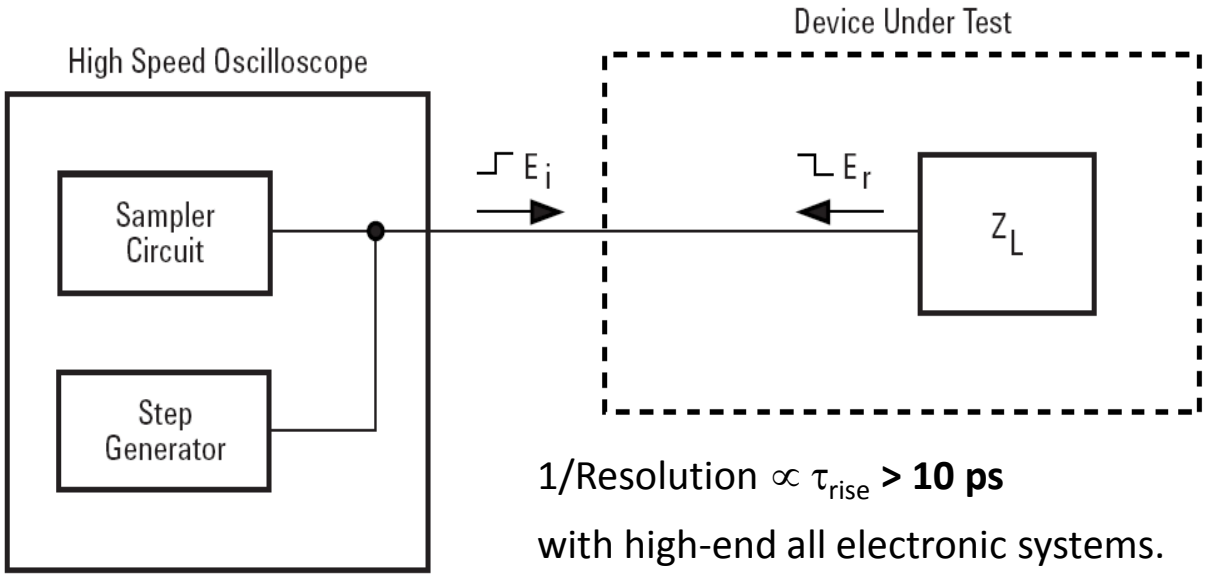
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Failure localization



Hewlett-Packard Journal,
“Time domain reflectometry“
June 1969, Vol. 20, No. 10

TDR principle scheme:

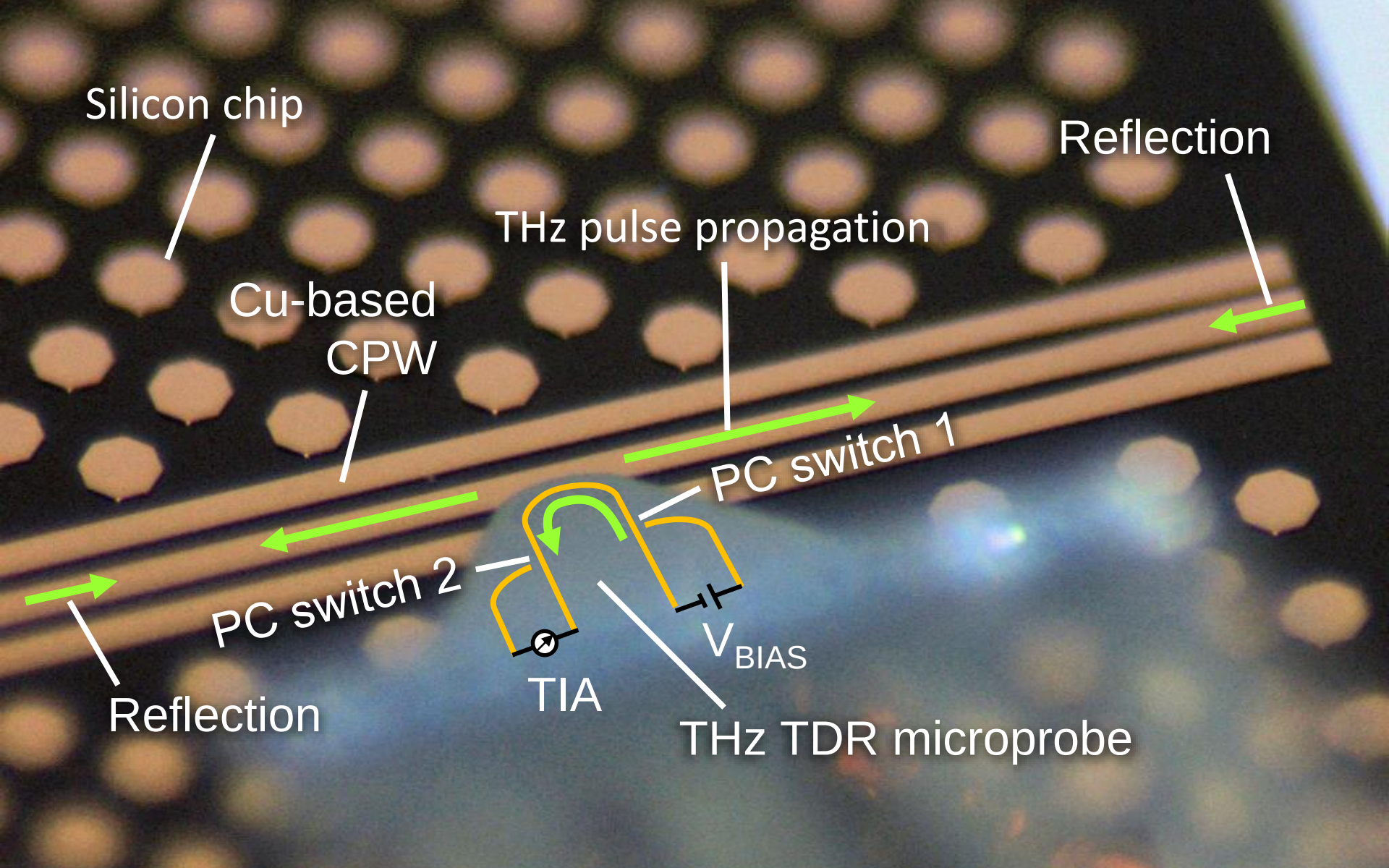


1/Resolution $\propto \tau_{rise}$ **> 10 ps**

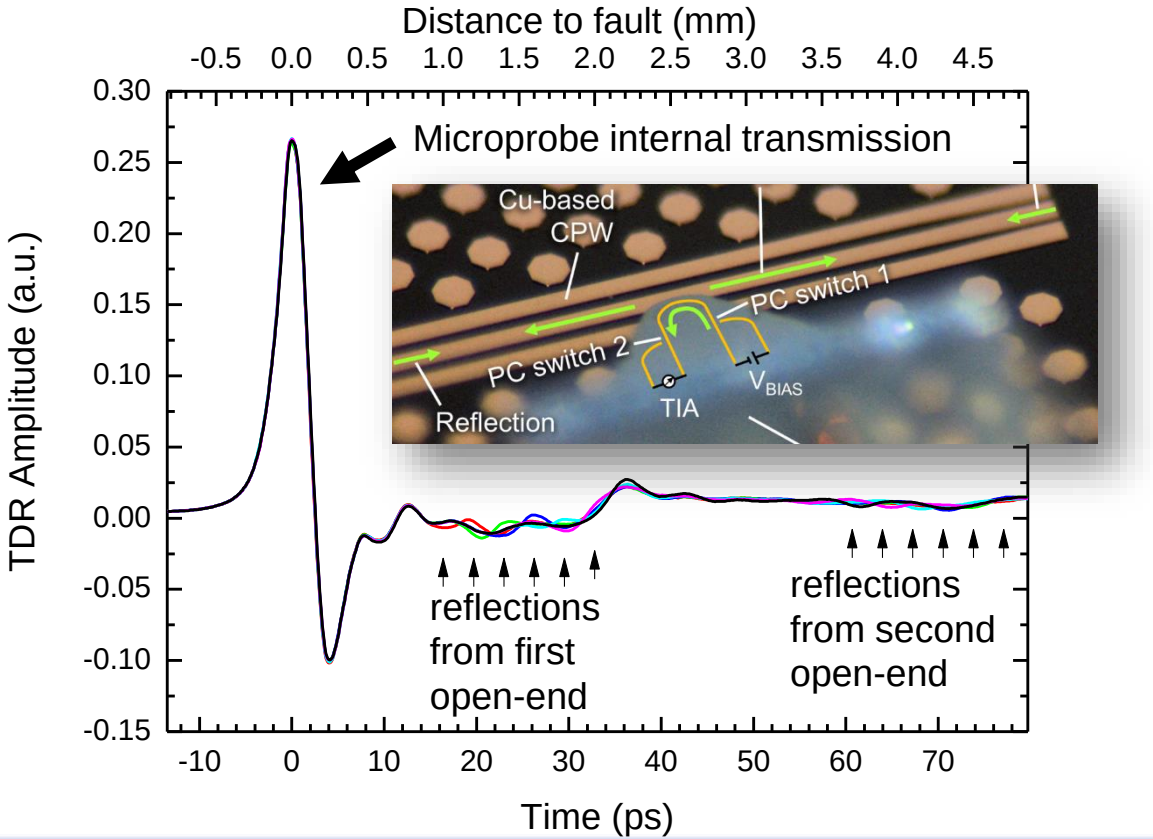
with high-end all electronic systems.

Our Terahertz microprobes achieve up to sub-1 ps rise-times!

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Silicon chip
Reflection
THz pulse propagation
Cu-based
CPW
PC switch 1
PC switch 2
V_{BIAS}
TIA
Reflection
THz TDR microprobe

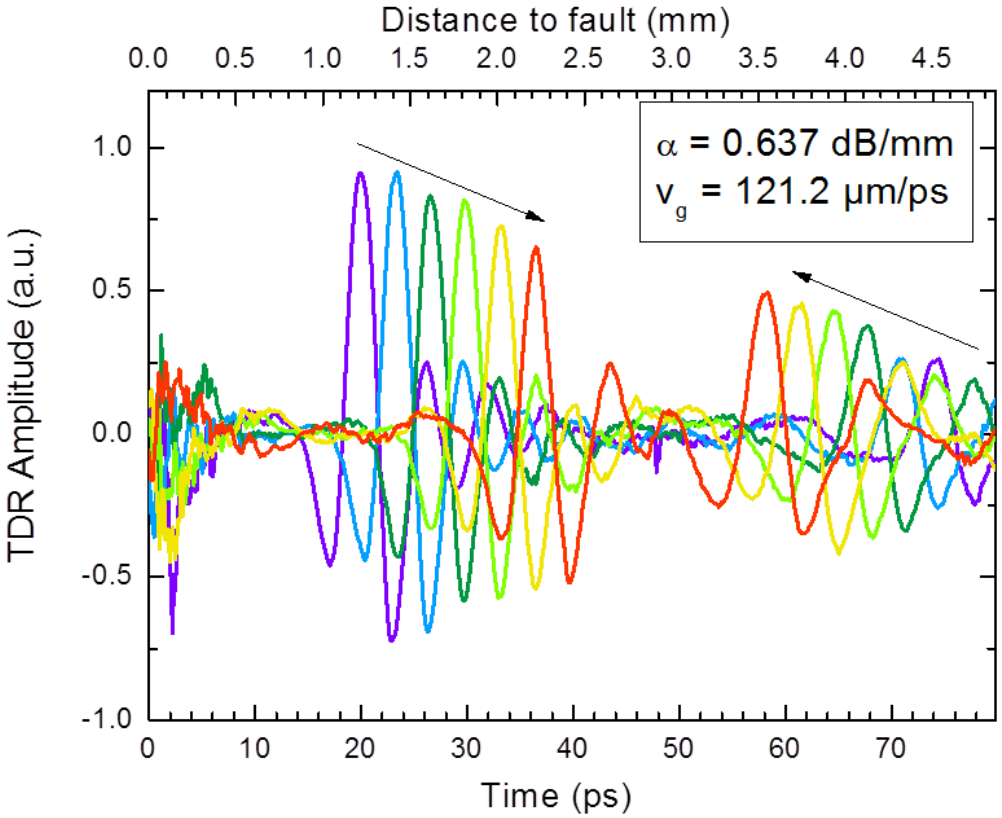
Failure localization



- Internal transmission as reference signal
- Multiple transient scans at different distances to fault
- Reflection signals from short and far distance opens

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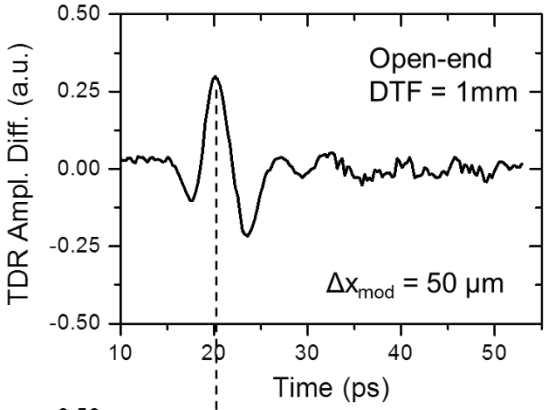
Failure localization

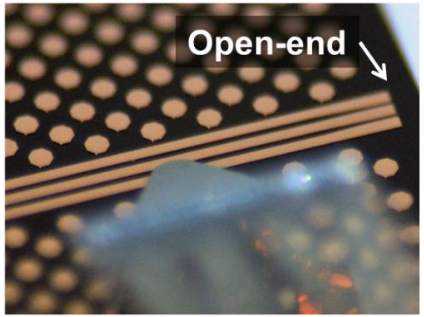


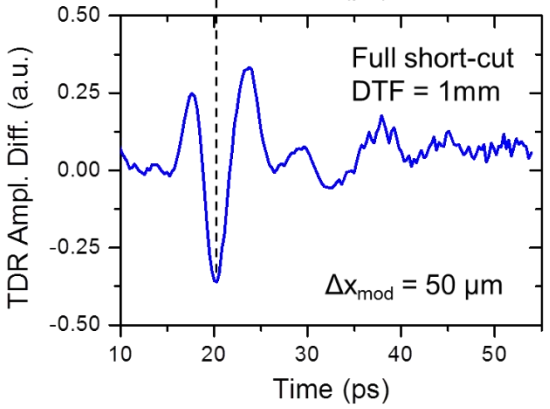
- Suppression of internal transmission signal through distance-to-fault modulation
- Determination of propagation dynamics:
  - Attenuation
  - Group/phase velocities

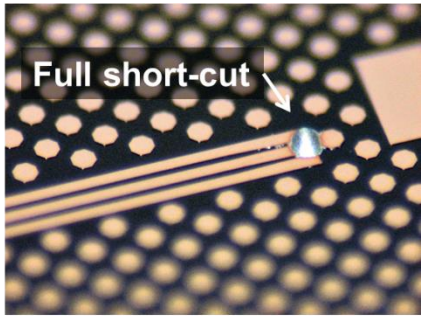
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Failure localization





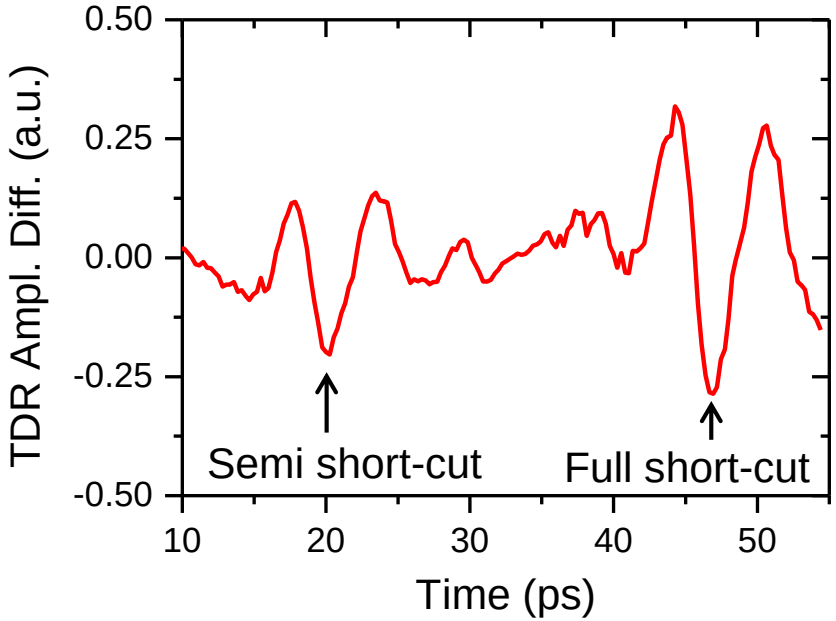


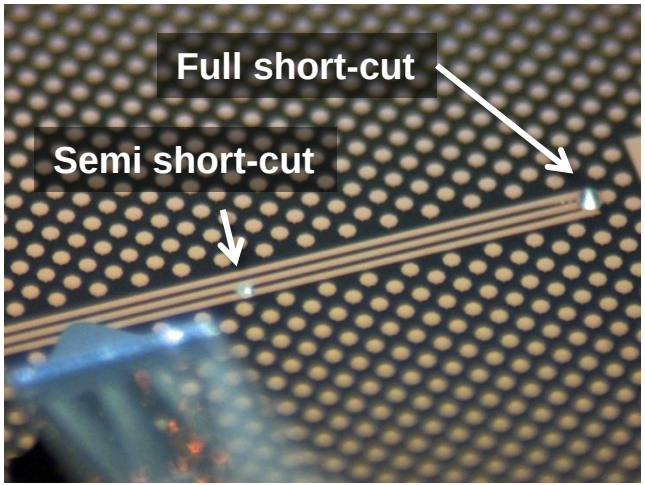


- Type of fault discremination
- Open vs. Short-cut
- Resistive faults
- Resonant faults

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Failure localization





- Detection of consecutive faults

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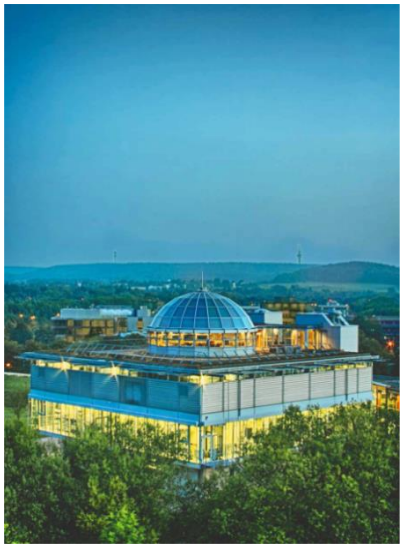
Conclusion

- **THz microprobes**
  - Efficient and versatile tools to avoid inefficient coupling of free-space THz radiation to micro/nanostructures
- **Examples: Surface analysis**
  - **Sheet resistance imaging**
    - Non-destructive (contactless), Fast (< 5ms/Pixel)
    - Quantitative (R_{sh} range: 0.1 – 10000 Ohm)
    - High resolution (ca. 10 µm)
  - **Metamaterial-based sensing**
    - Increased sensitivity through near-field single element read-out
- **Examples: THz device analysis**
  - **THz on-chip testing:** Access to field vector components, amplitude, phase, time- & frequency domain information
  - **Failure localization in chip packages:** > 10-times increased fault location resolution through sub-ps rise-time THz signals

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