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# MICRO AND NANO X-RAY TOMOGRAPHY OF 3D IC STACKS

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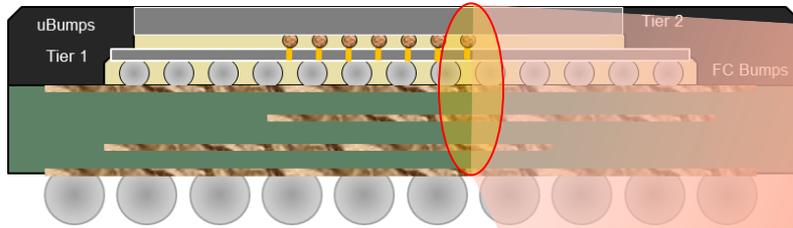
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# 3D stacking of chips: Through Silicon Via (TSV) technology



## Die Integration Technology

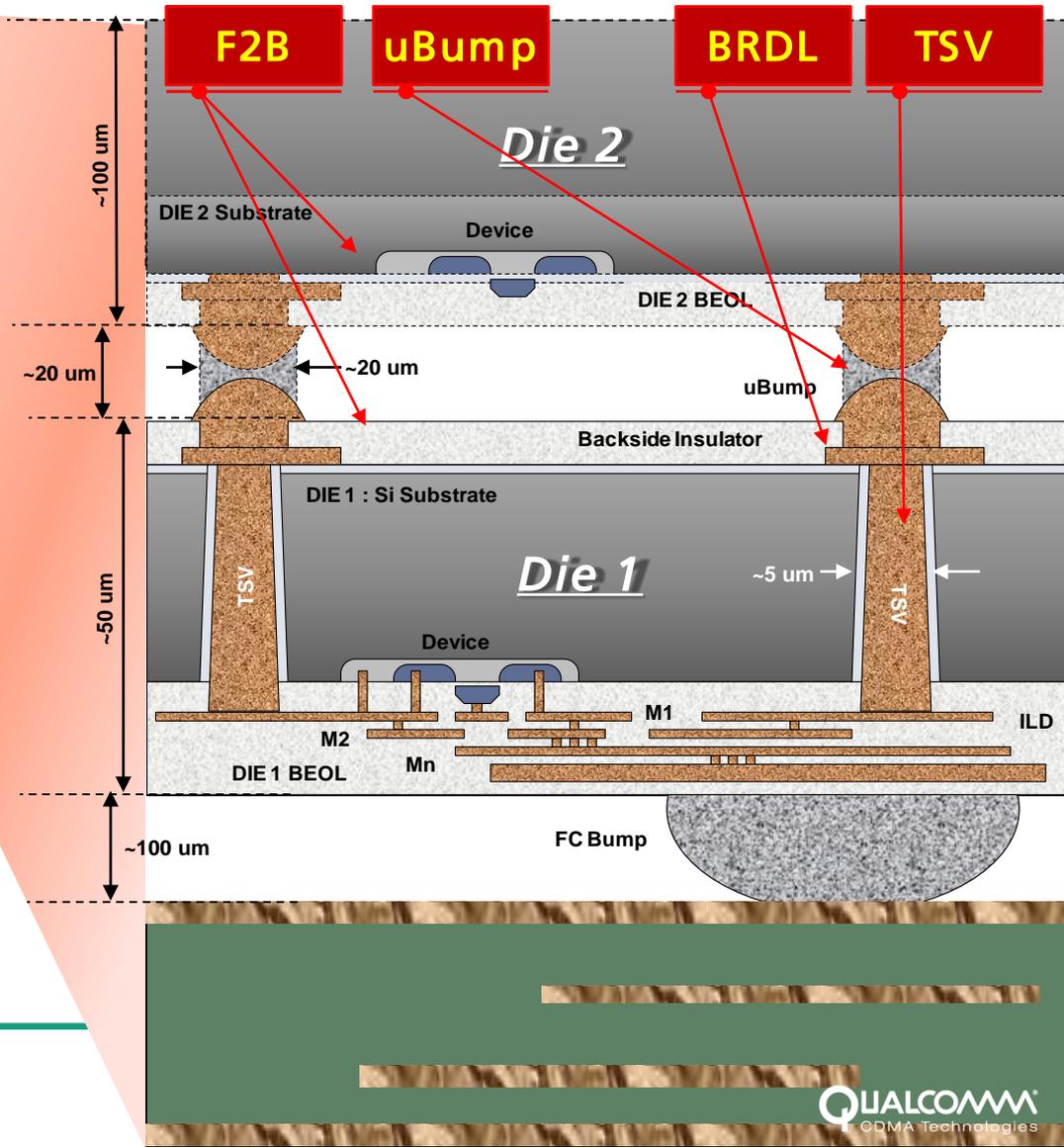
- using Through Si Vias
- electrical connection from front to back (on die or interposer)

## Value Proposition

- Small form factor (in X-Y & Z)
- Improved Performance
- Heterogeneous Integration

## Typical Implementation

- Memory-on-Logic
- Die on (Active) Interposer



Courtesy: R. Radojcic, Qualcomm

# Characterization techniques – from macro to nano

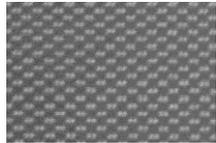


**Nanoanalysis**

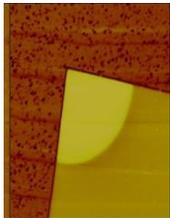


**Non-destructive testing**

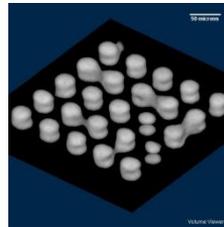
**TEM/SEM**



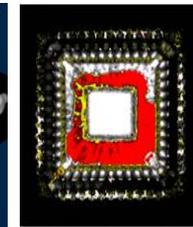
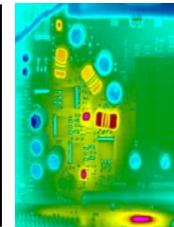
**SPM techniques**



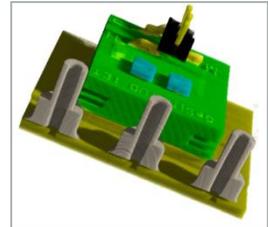
**micro XCT**



**thermography**

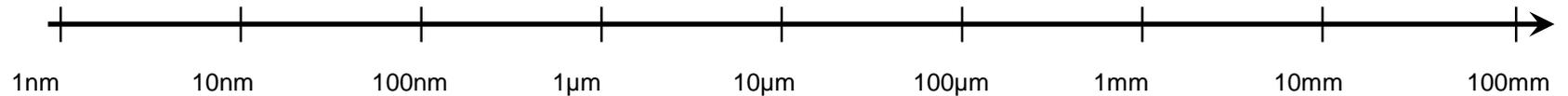


**scanning  
acoustic  
microscopy**



**macro XCT**

**XRD**



**voxel size**

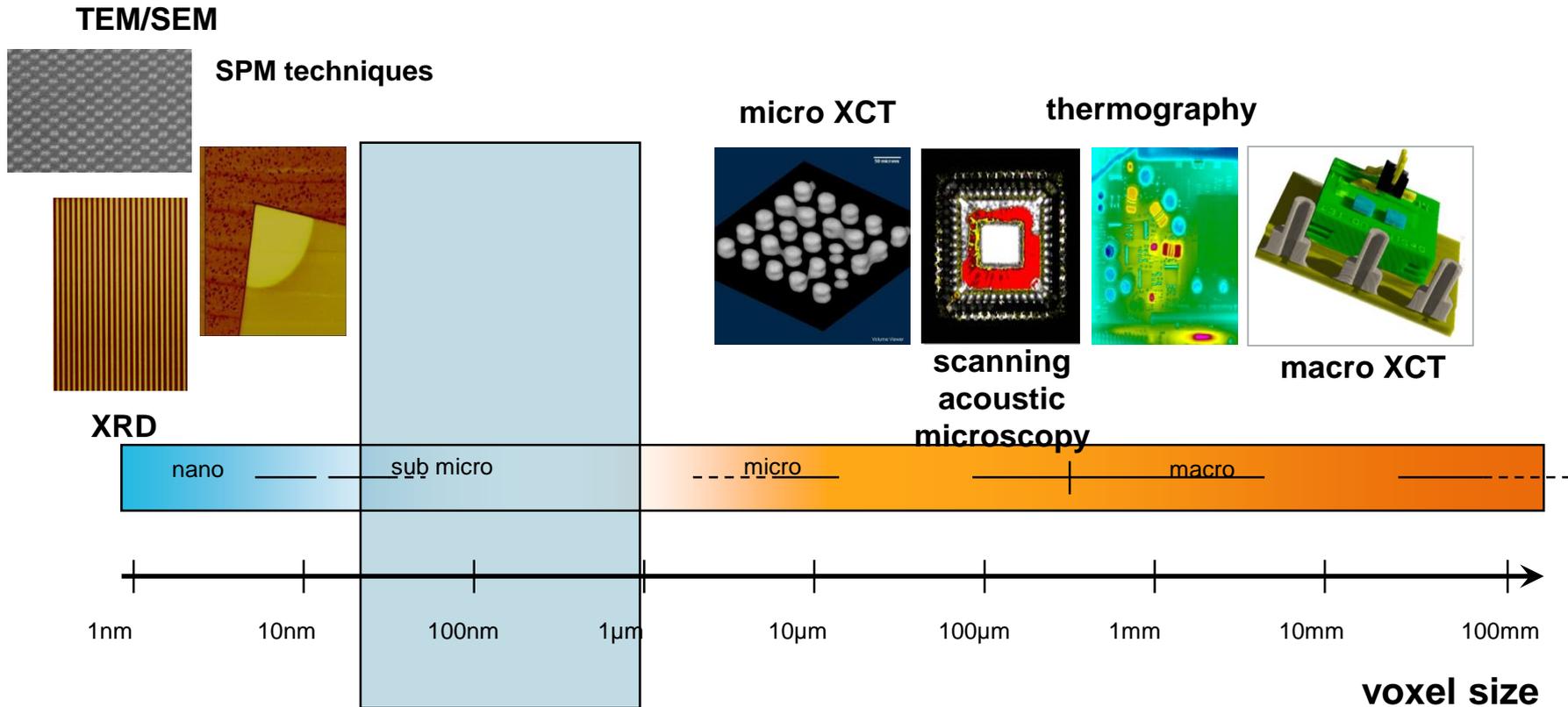
# Characterization techniques – from macro to nano



Nanoanalysis



Non-destructive testing



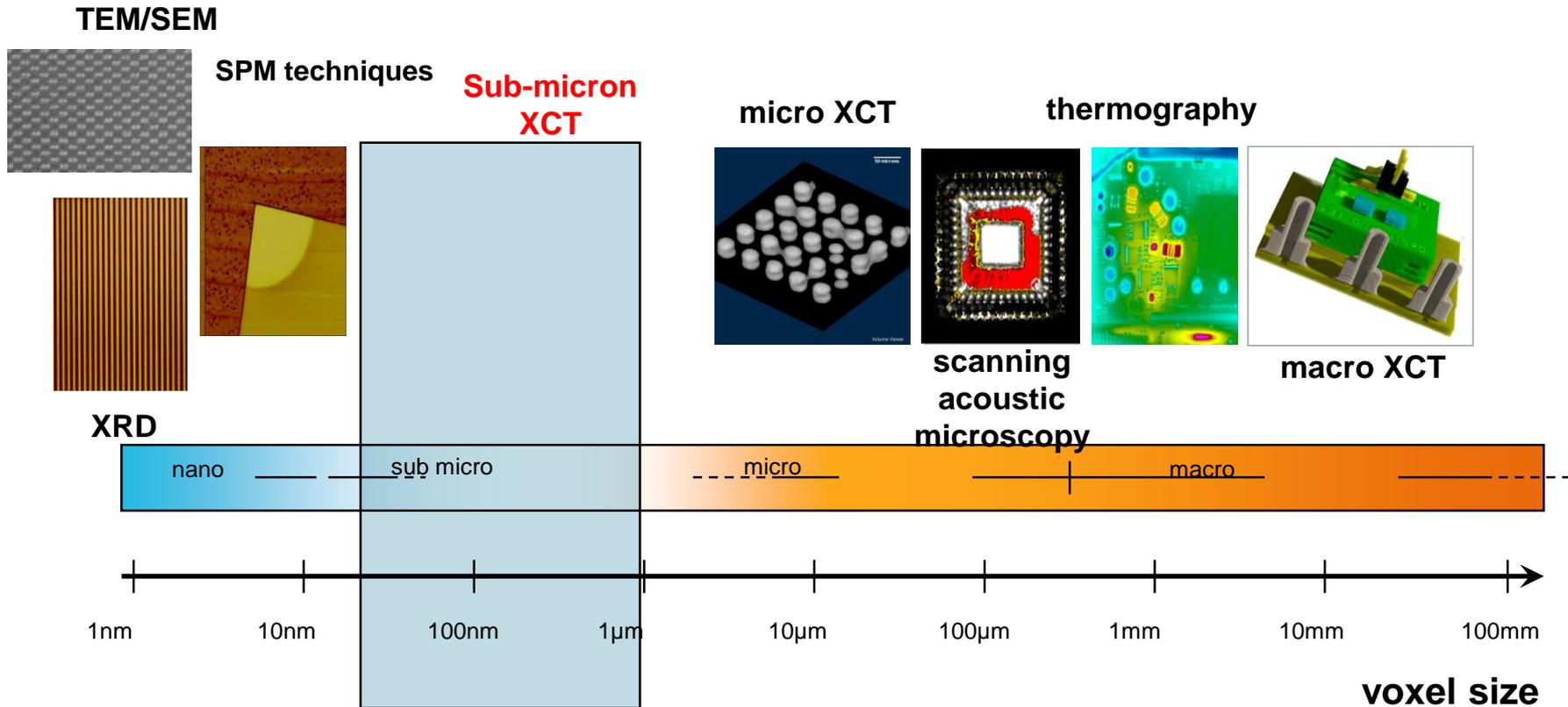
# Characterization techniques – from macro to nano



Nanoanalysis



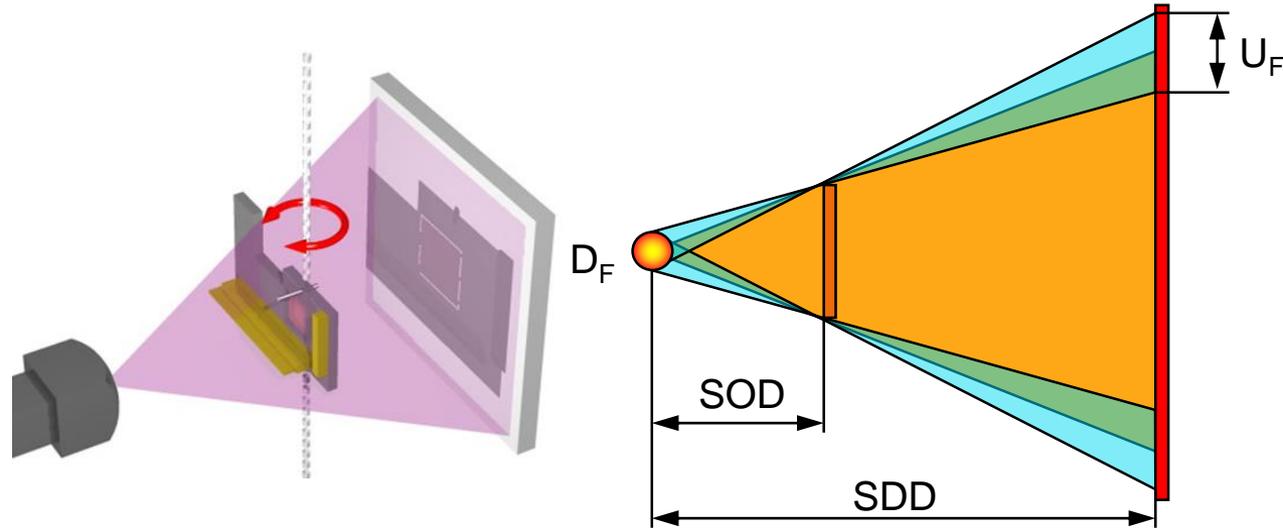
Non-destructive testing



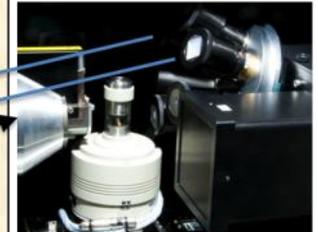
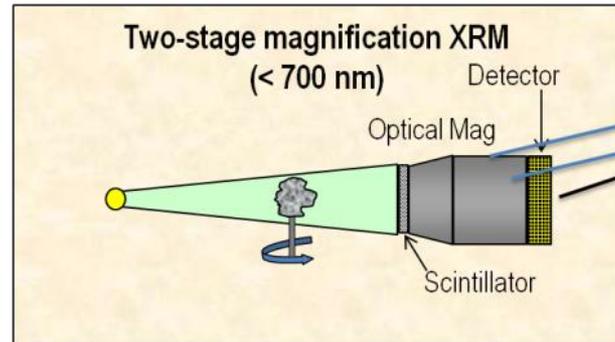
# X-ray micro imaging: Principle of conventional radiography

Projection of the (small) specimen on a (large) screen

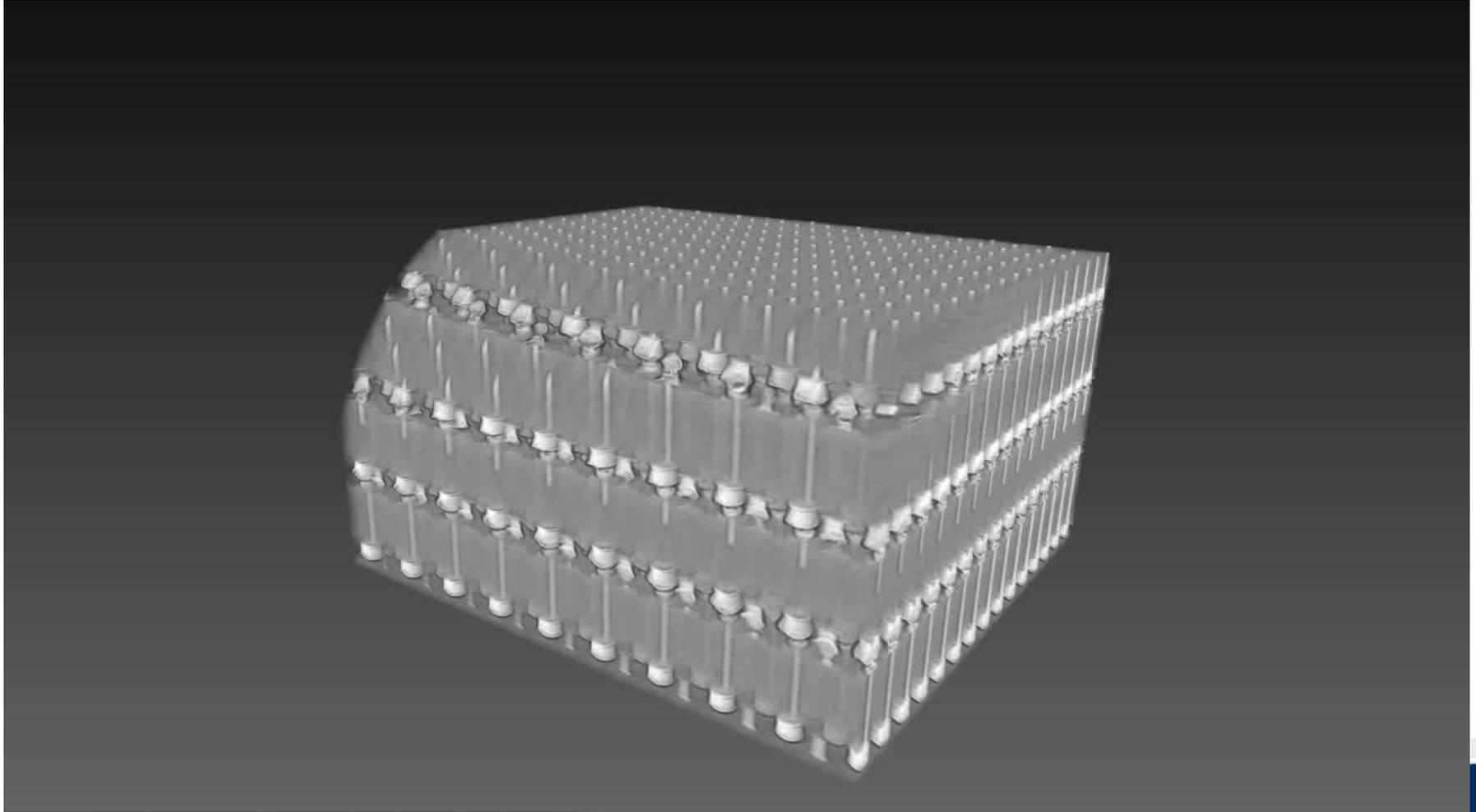
- $d > D_F$ : Resolution is limited by size of the source
- $D_F > 0.6 \mu\text{m}$  (thin target)



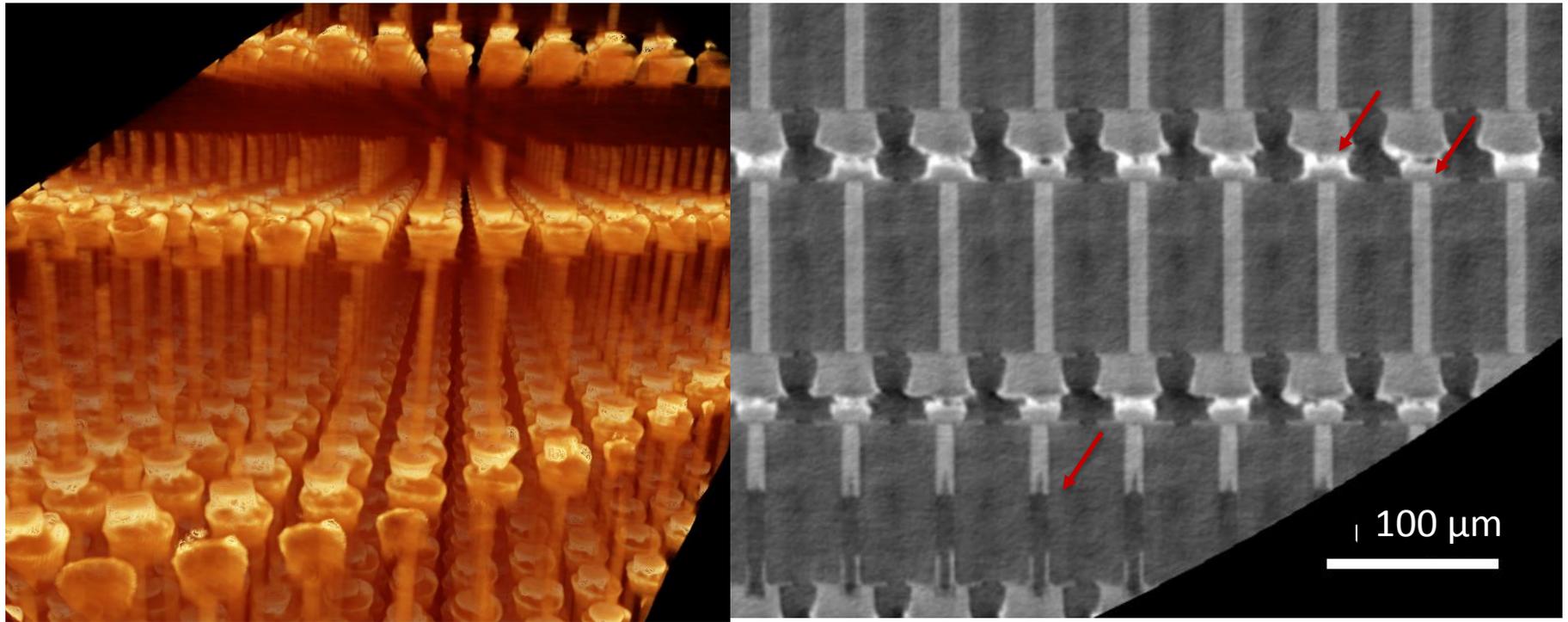
Zeiss/Xradia Versa XCT 520:  $0.7 \mu\text{m}$  resolution



# Sub-micron X-ray tomography for advanced packaging: 3D TSV stacking



# Physical failure analysis for advanced packaging: Combination of multi-scale nondestructive evaluation and destructive techniques: $\mu$ XCT, nXCT + SEM/FIB/TEM



X-ray computed tomography (XCT): Incomplete Cu TSV filling, variation in solder flow (AgSn) around the Cu bumps

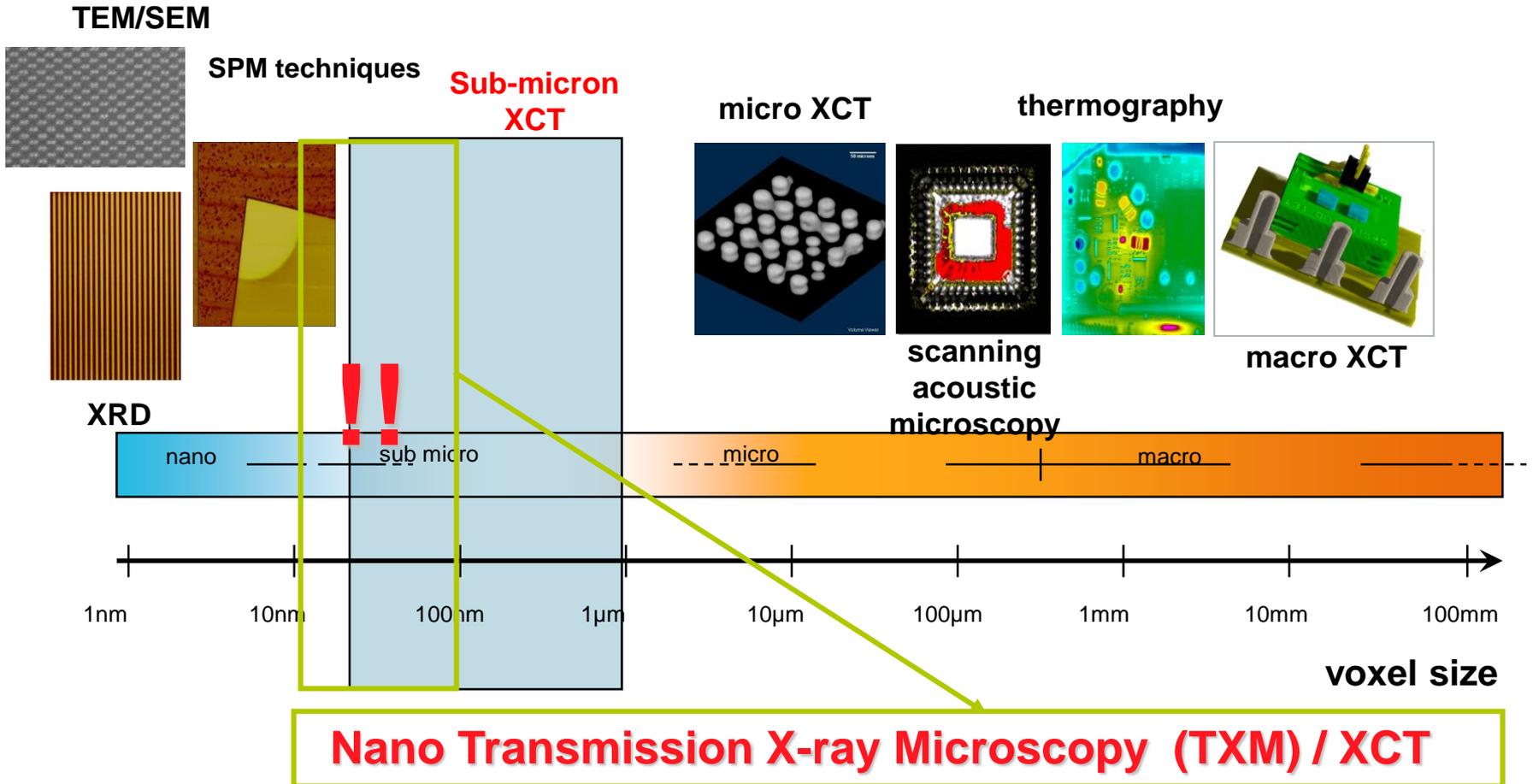
# Characterization techniques – from macro to nano



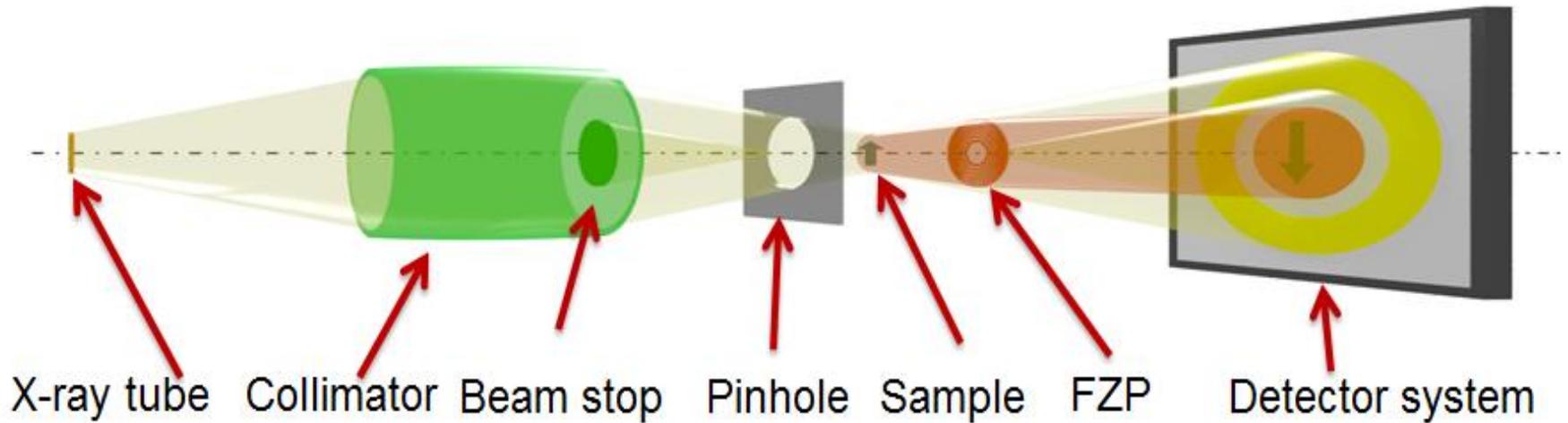
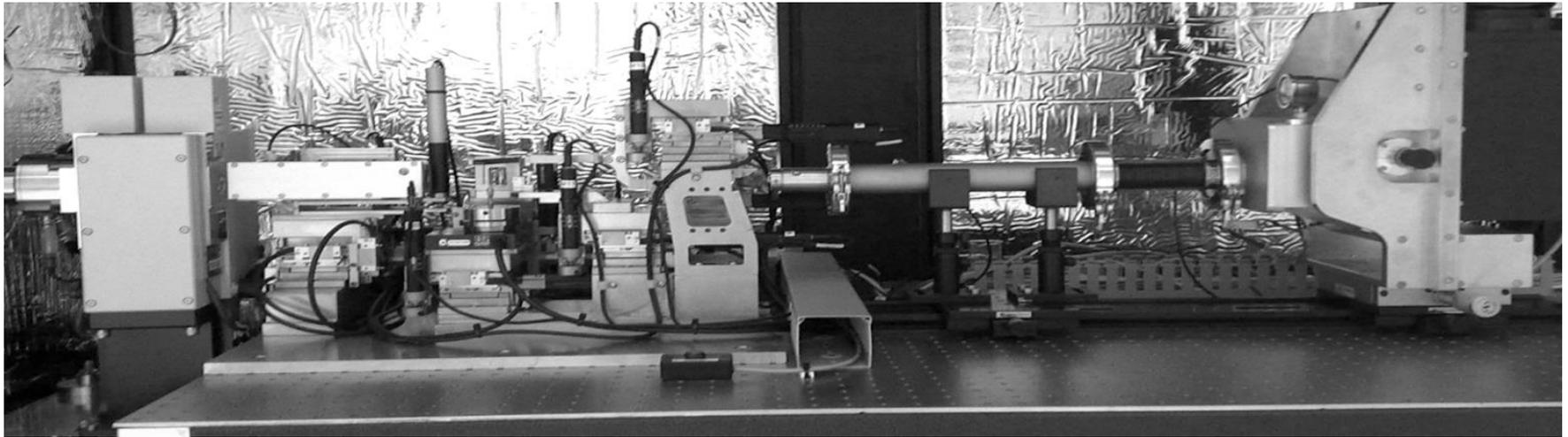
Nanoanalysis



Non-destructive testing

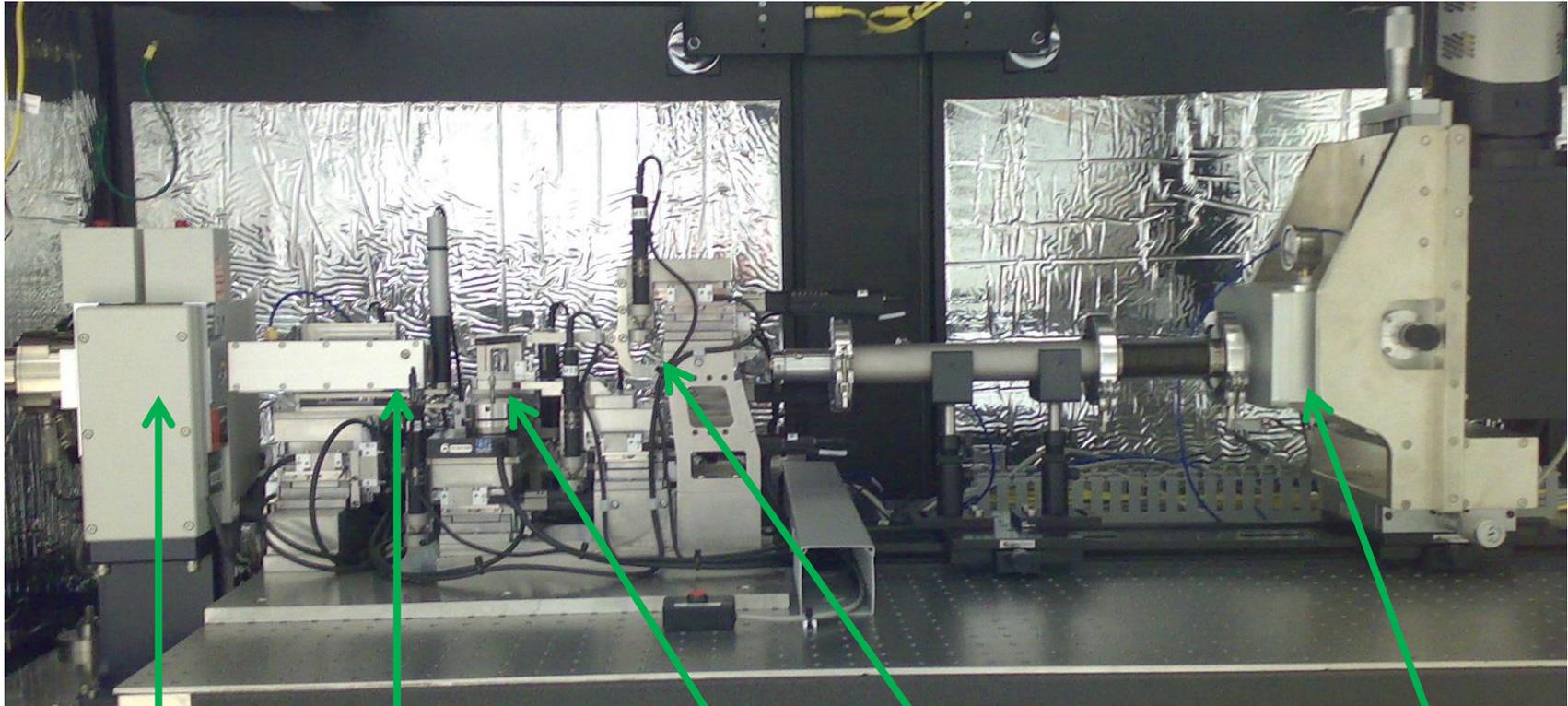


# Zeiss/Xradia NanoXCT: Lab based X-ray microscopy



# High-resolution characterization of materials and structures with nano XCT

- Photon energy 8 keV (Cu target) or 5.4 keV (Cr target)
- Full field imaging using Fresnel zone plates
- 65  $\mu\text{m}$  and 16  $\mu\text{m}$  field of view, respectively absorption contrast, Zernike phase contrast
- 1024  $\times$  1024 pixel CCD camera



Rotating Anode  
Micro Focus High  
Power X-ray Tube

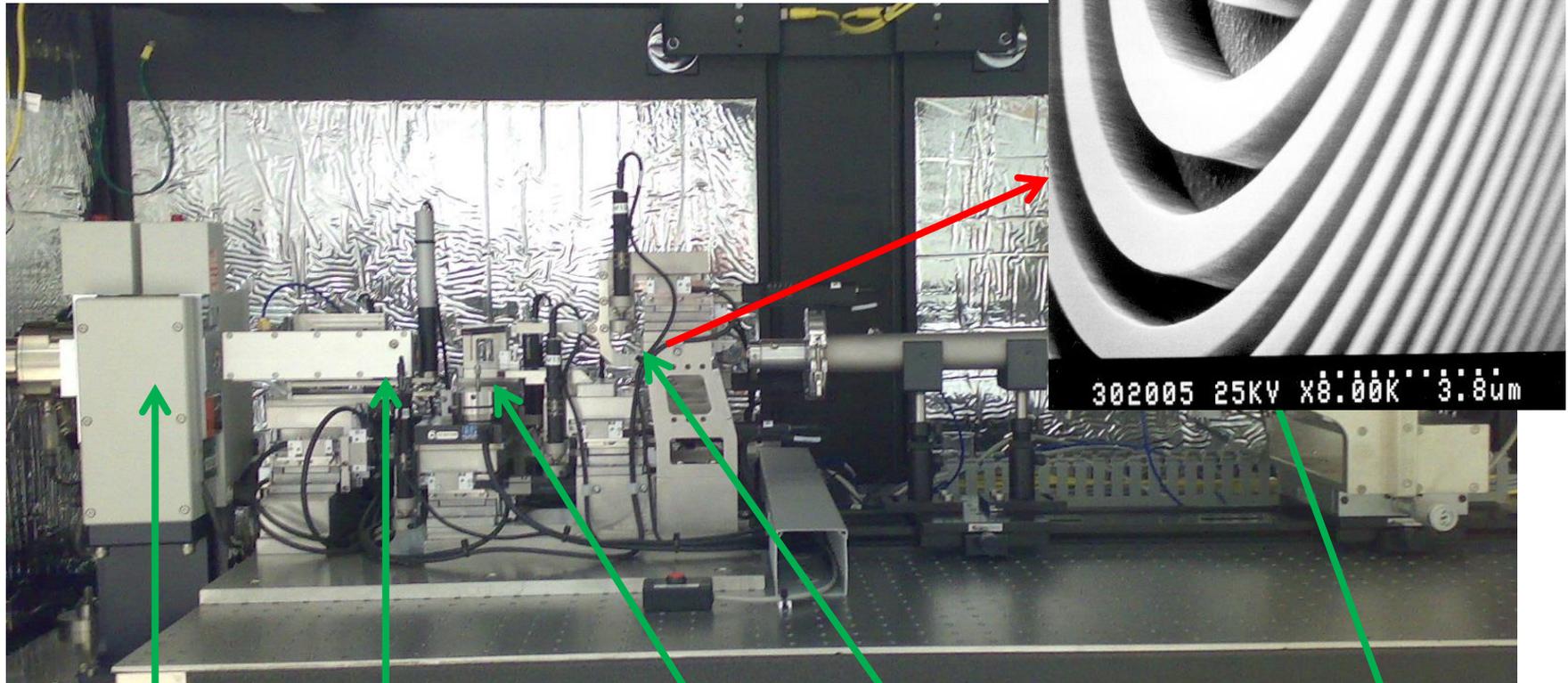
Condensing  
Mirror

Object

Fresnel  
Zone Plate

X-ray  
Camera

# 50nm resolution with Fresnel zone plate



Rotating Anode  
Micro Focus High  
Power X-ray Tube

Condensing  
Mirror

Object

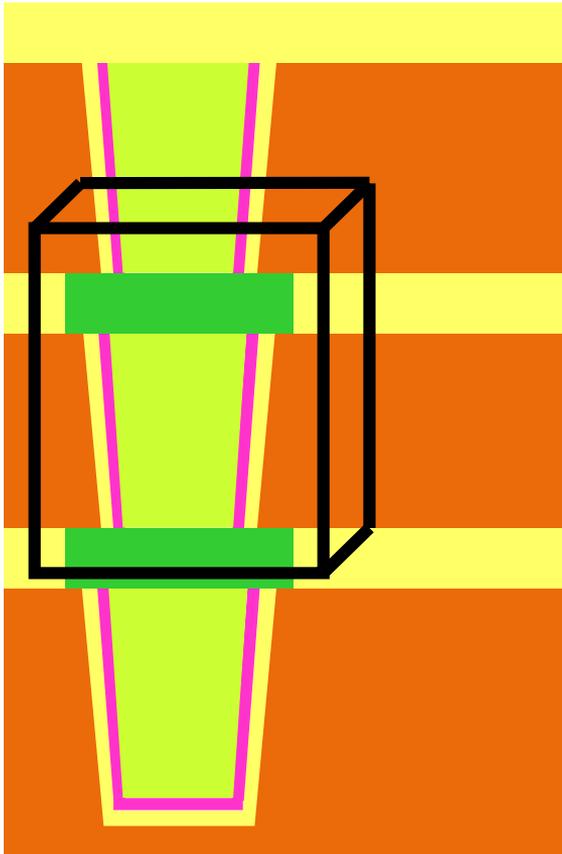
Fresnel  
Zone Plate

X-ray  
Camera

E. Zschech, W. Yun, G. Schneider,  
Appl. Phys. A 92, 423 – 429 (2008)

# FIB preparation of a not affected sample (including ROI) for a nano XCT study

## 3D ROI



Nano XCT requires a preparation that is non-destructive for the ROI

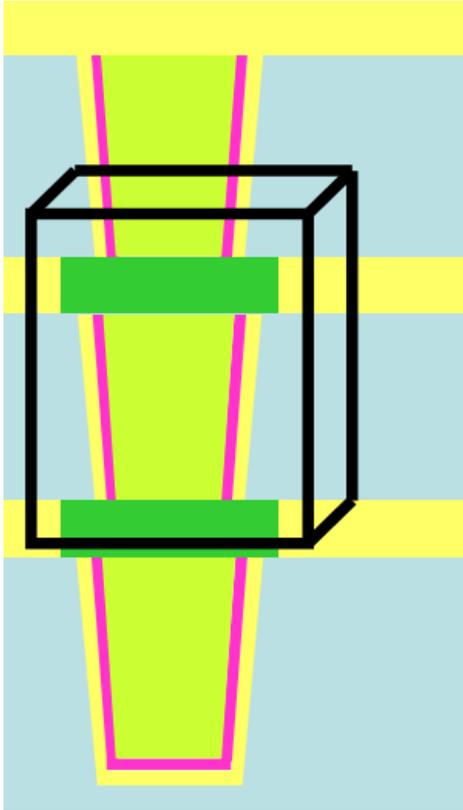
Most of the sample preparations require the removal of an extraordinary large amount of material in front of the ROI

## Solutions

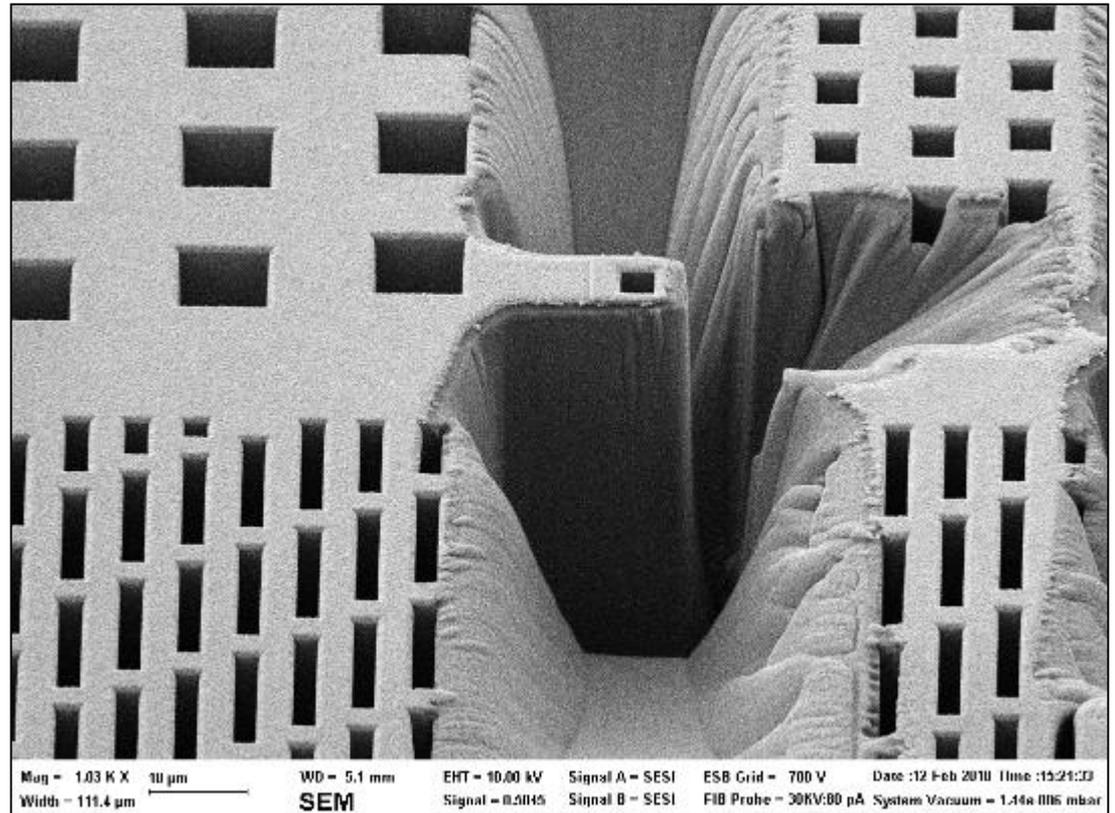
- Laser ablation + FIB
- High beam current FIB or Plasma FIB
- Efficient combination of the two approaches
- .....
- **(→ Laser ablation) → FIB → NanoXCT**

# Sample preparation of an array of TSVs

... for X-ray tomography



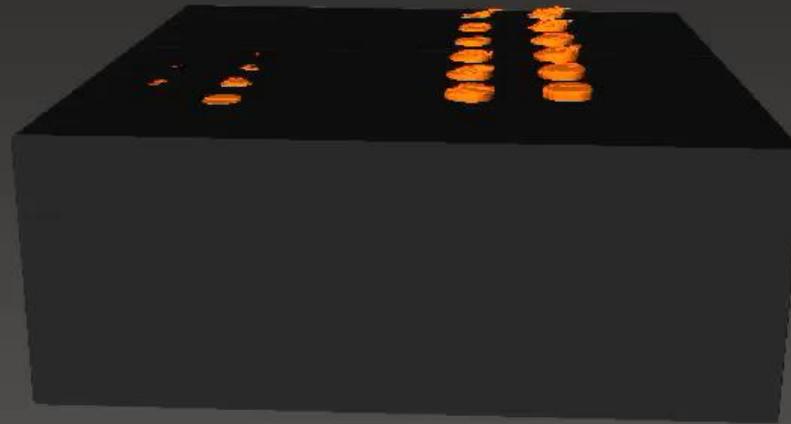
$50 \times 50 \times 150 \mu\text{m}^3$



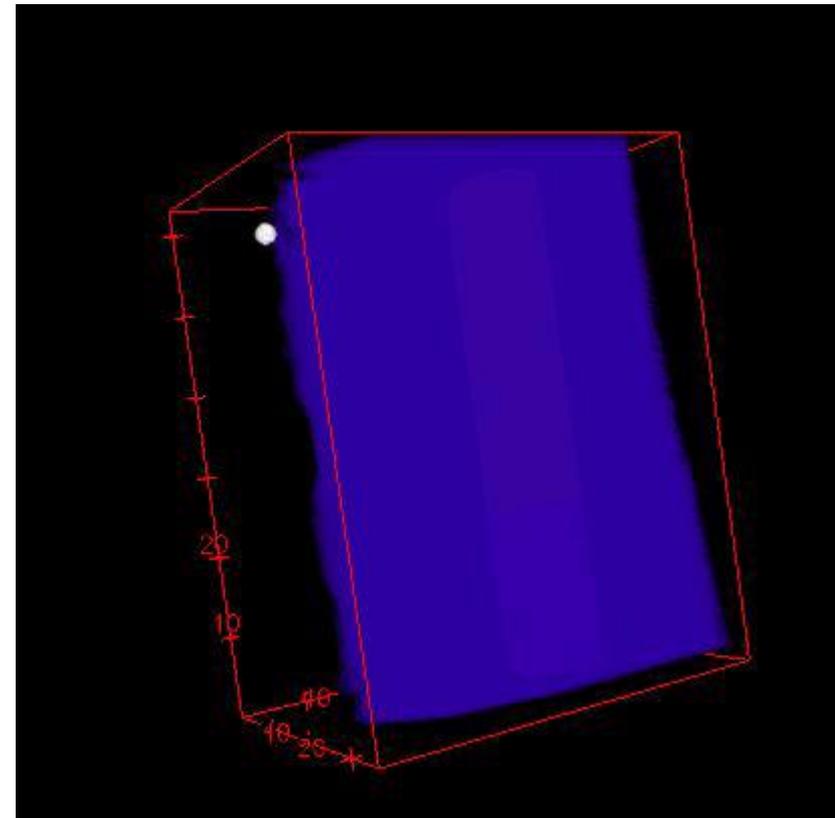
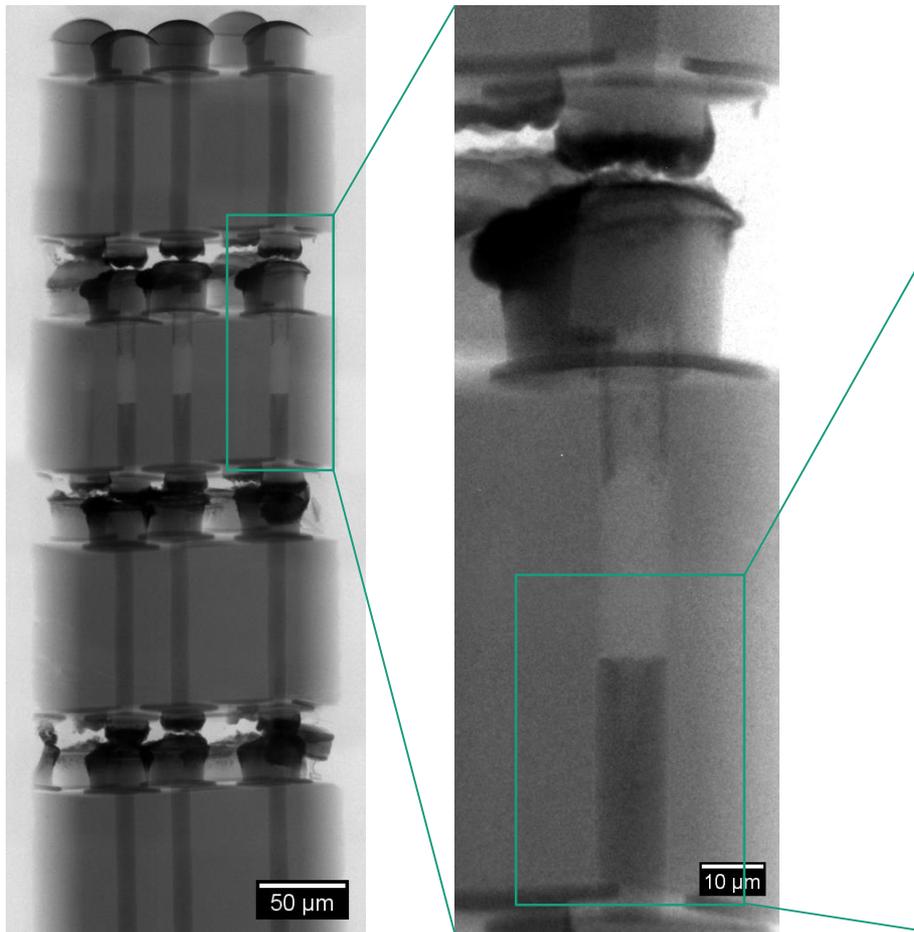
Nano XCT sample preparation using laser ablation

# X-ray tomography @ TSVs

Through-silicon vias: 150 nm resolution

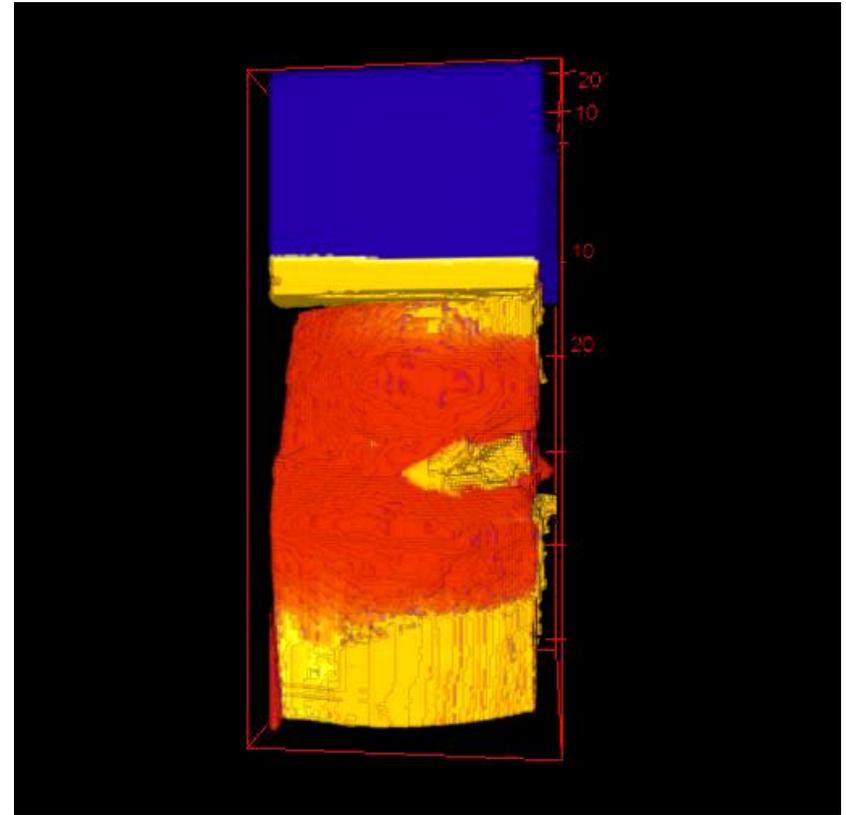
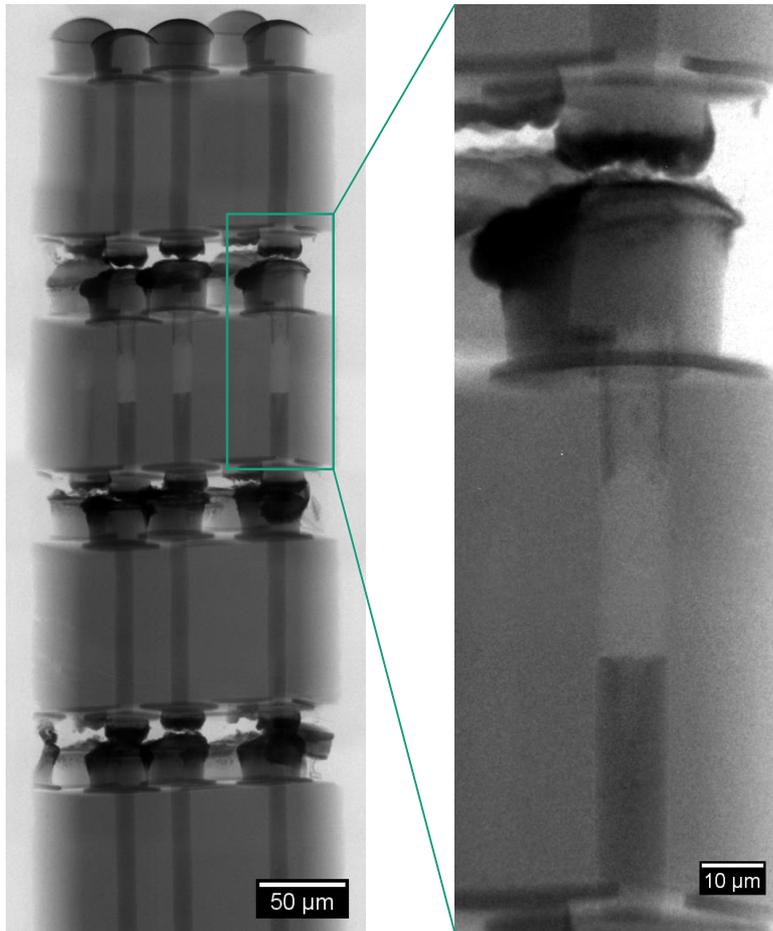


# Multi-chip stack – High-resolution nano-XCT



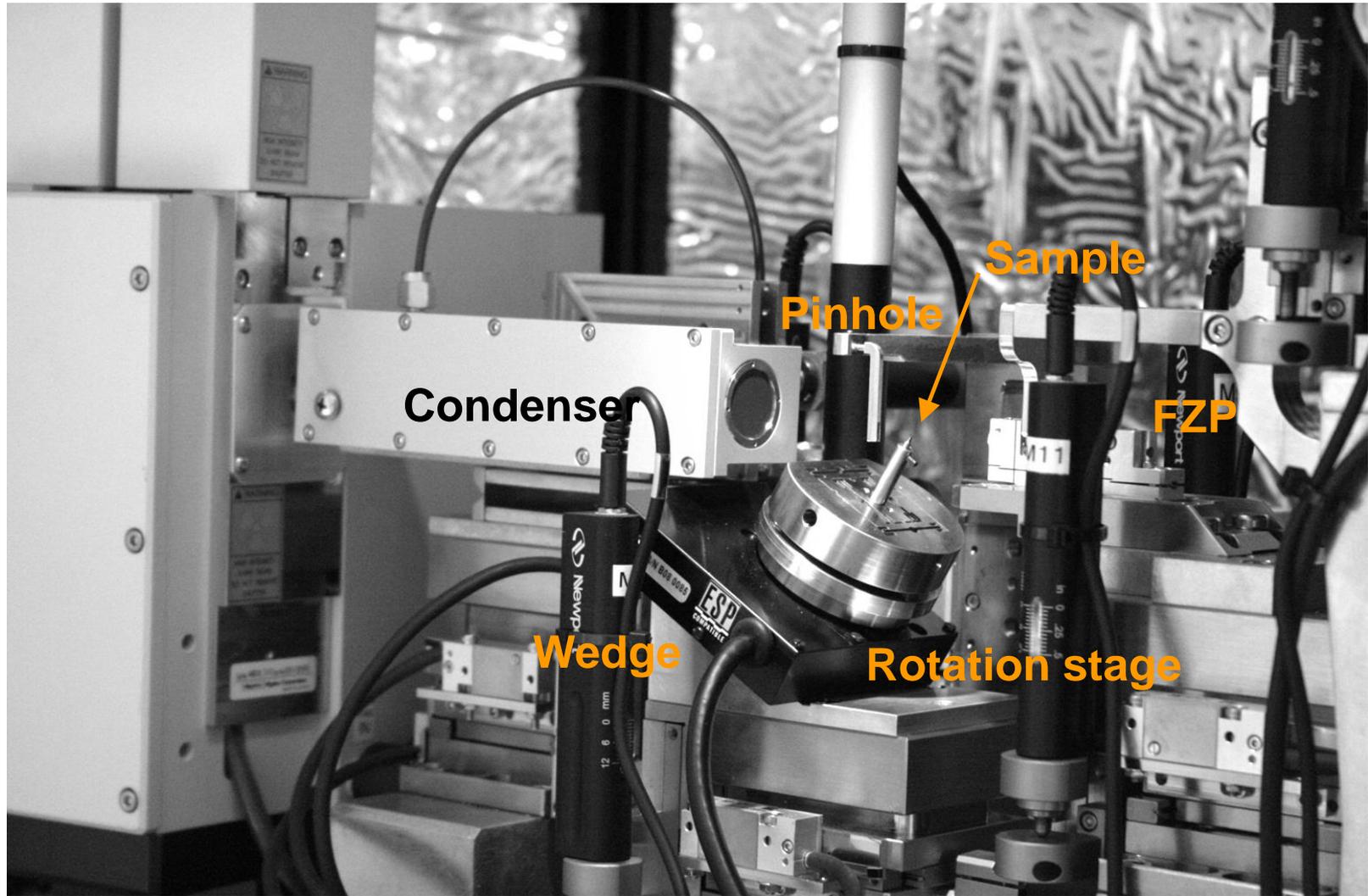
Tomography of a partially filled Cu TSV

# Multi-chip stack – High-resolution nano XCT



Tomography of a AgSn solder bump

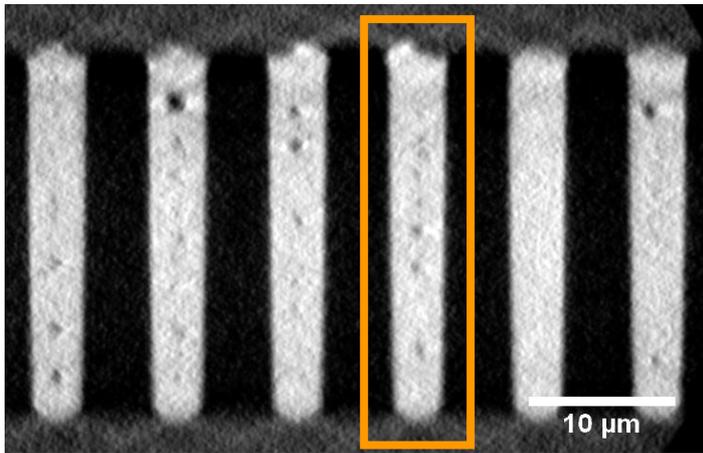
# Nano XCT, sample stage for CT with tilted rotational axis



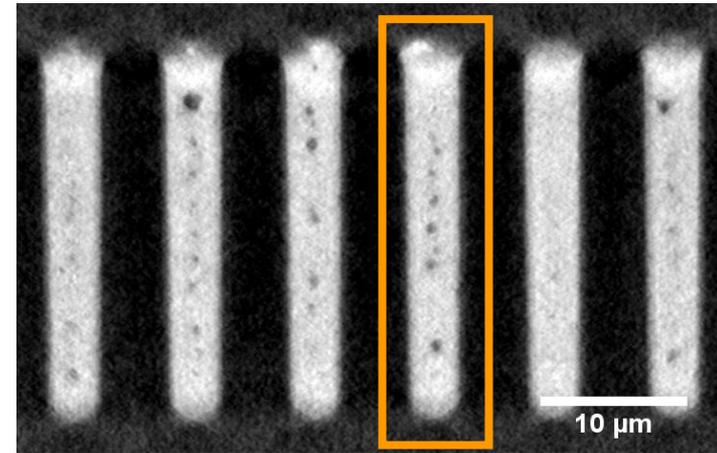
# X-ray computed laminography study of TSVs

Comparison for equal measurement time

## ■ Limited Angle CT

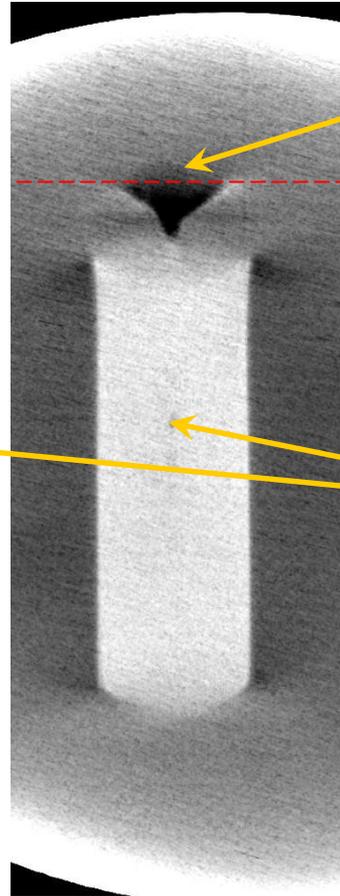
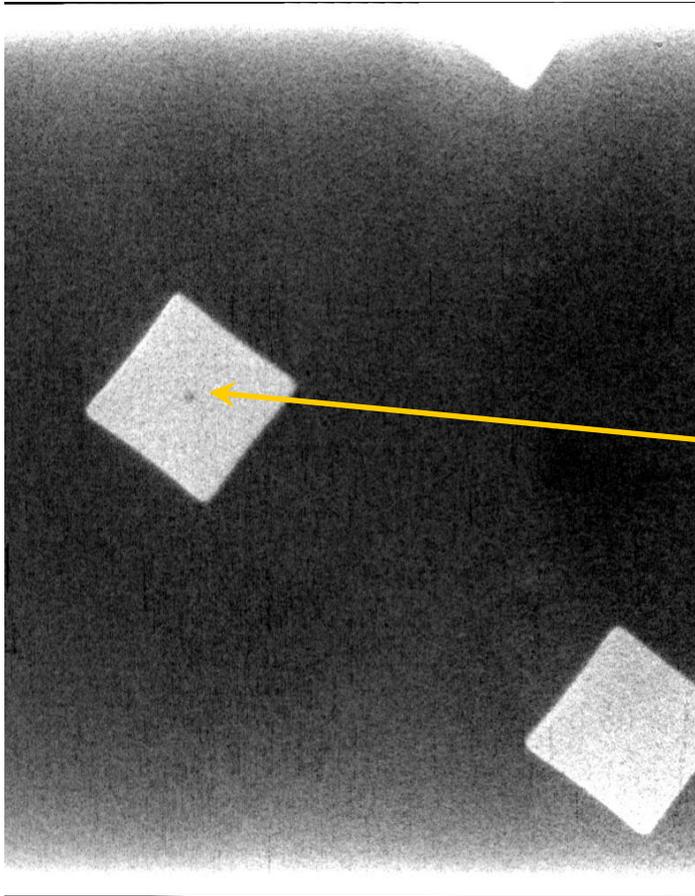


## ■ CT with tilted rotational axis



- ➔ Better image quality (contrast)
- ➔ Less artifacts at the bottom of the TSV

# Nano XCT at TSV sample: < 100nm voids visible



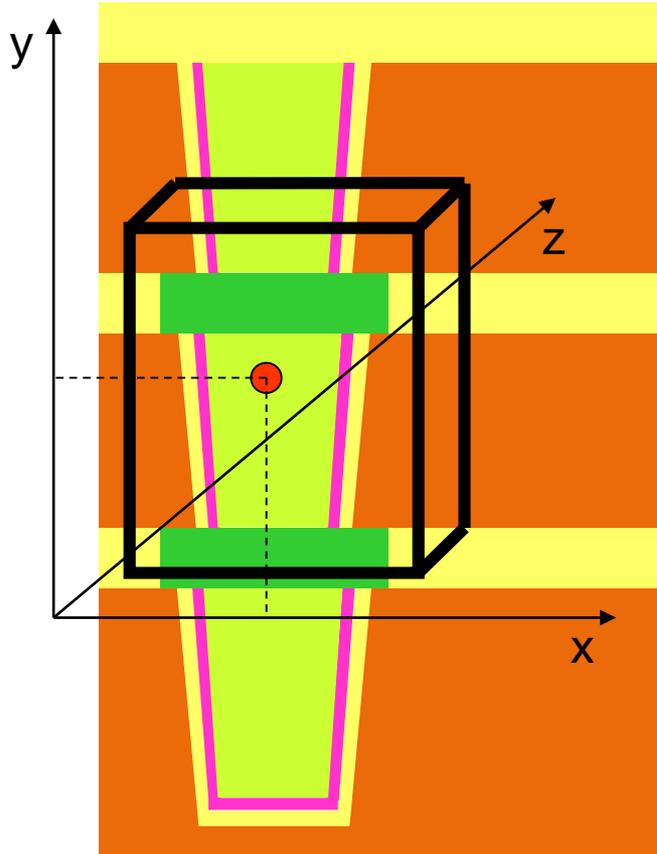
**Cavity**

**Position of the surface**

**single void**

**Average over  
10 Slices**

# FIB preparation of a ROI for SEM/TEM study based on navigation data from nano XCT

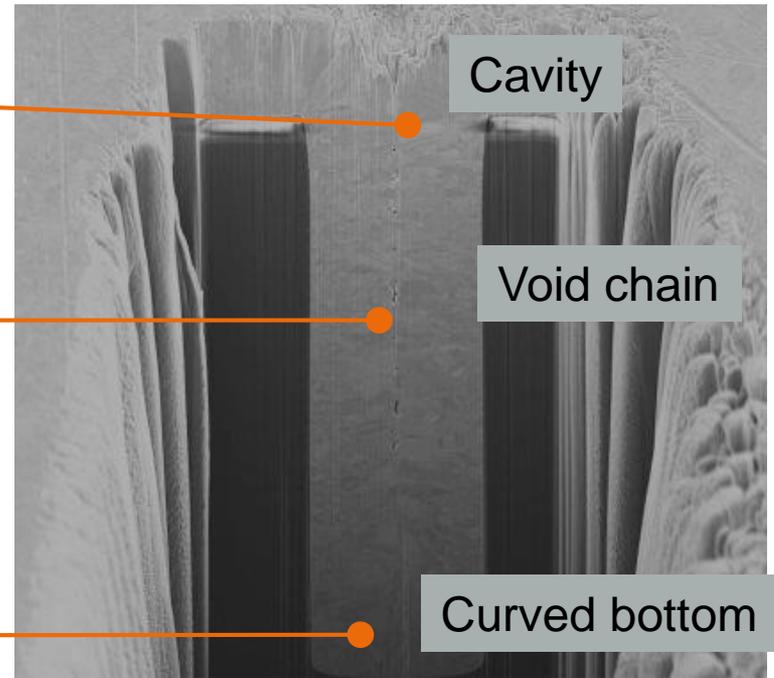
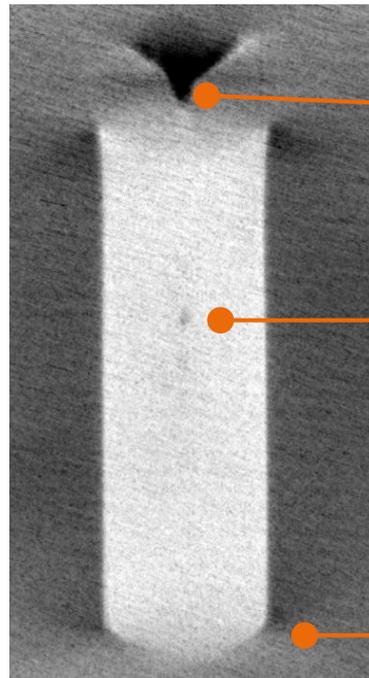
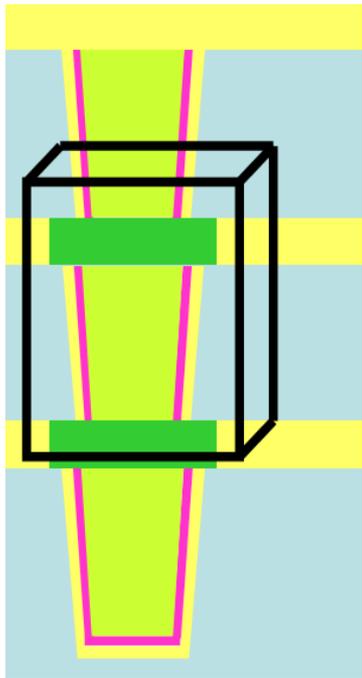


## Navigation

- 3D characterization methods deliver 3D coordinates of the ROI
- For further FIB preparation and ROI imaging with TEM/SEM a precise, reliable and effective coordinate and specimen transfer is necessary
- **NanoXCT (→ Laser ablation) → FIB → SEM/TEM**

# SEM image of FIB X-section of Copper TSV after nano XCT study

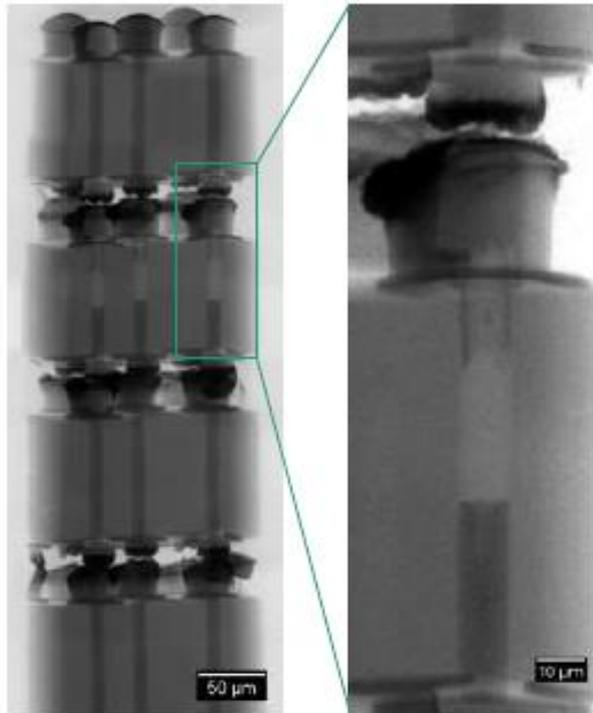
1. Nondestructive failure localization: Voids ~ 100 nm size can be localized
2. Destructive physical failure analysis: Validation of nano XCT results



M. Baklanov, P. S. Ho, E. Zschech, "Advanced Interconnects for ULSI Technology" (Eds.), John Wiley & Sons Chichester, pp. 437 - 502 (2012)

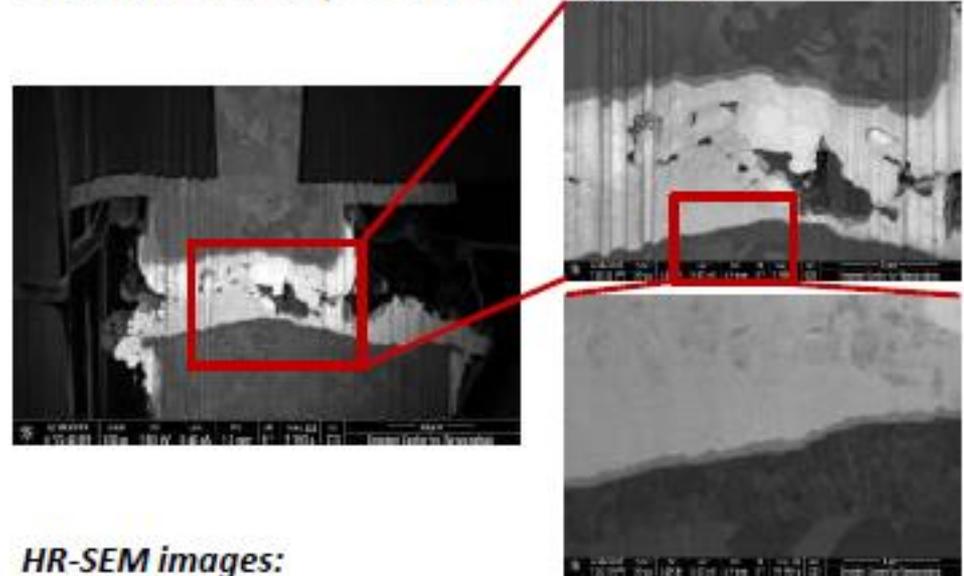
L. W. Kong, E. Zschech, et al., J. Appl. Phys. 110, 053502 (2011) DOI:10.1063/1.3629988

# SEM image of FIB X-section of AgSn solder micro-bump after nano XCT study



4x10 Mosaic

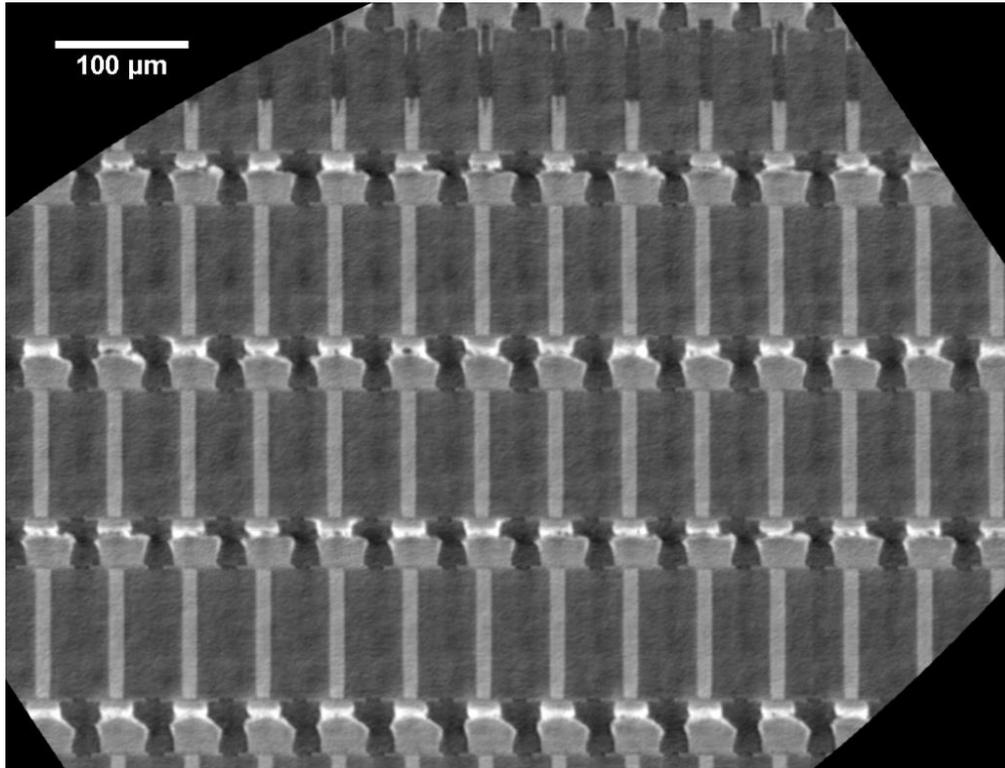
## Further inspection by SEM



### *HR-SEM images:*

- material contrast also in the solder and grain structures as well as intermetallic phases on both sides of the solder/Cu bump interface
- The lower bump also shows recrystallization close to the solder with much smaller grains

# Requests to hard X-ray microscopy/tomography @ high resolution (→ 10 nm) and @ high photon energies !



Micro XCT - 3D TSV stack with Cu TSVs and AgSn solder bumps

## Example:

Solder quality study requires

... ~ 10 nm resolution → quantification of shape of solder joints, size of voids, kind and size of intermetallic phases)

... high photon energies → no or less efforts for sample preparation (deprocessing/thinning) → high sample throughput

# X-ray microscopy to 10 nm ... 1 nm ???

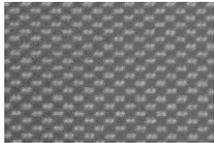


Nanoanalysis

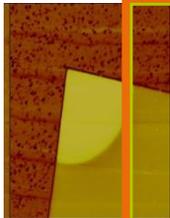


Non-destructive testing

TEM/SEM

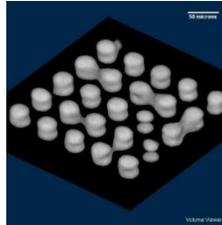


SPM techniques

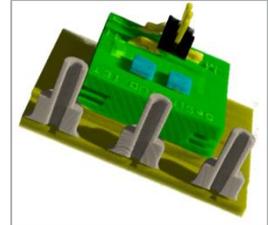
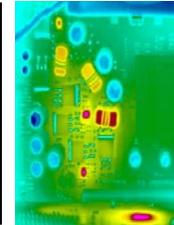
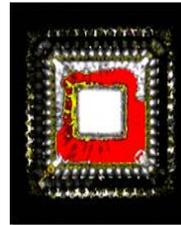


Sub-micron  
XCT

micro XCT



thermography



macro XCT

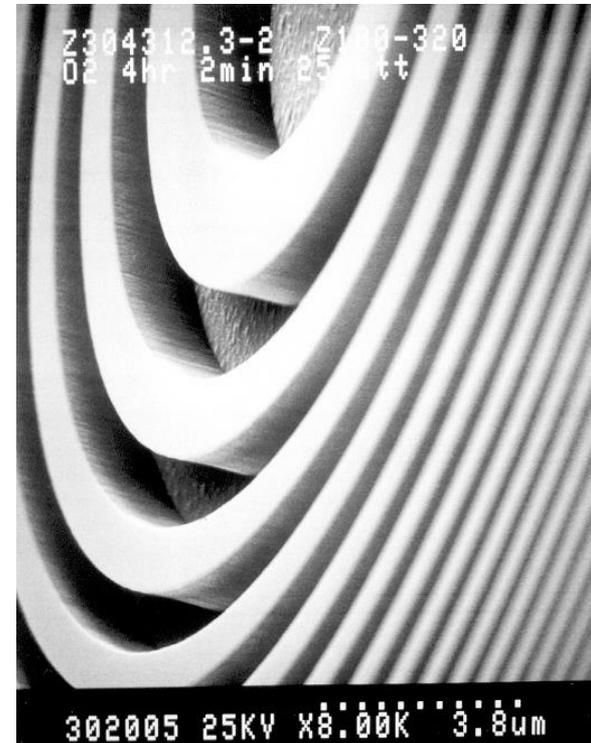
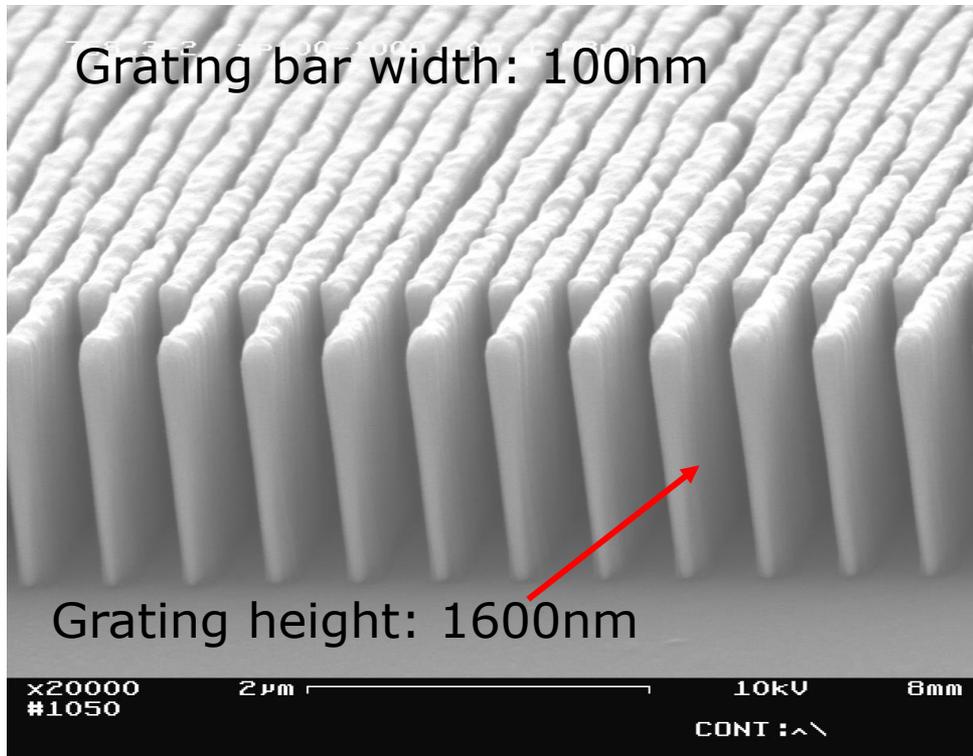
XRD



voxel size

**Nano Transmission X-ray Microscopy (TXM) / XCT  
with novel X-ray optics**

# Limits of zone plates: ~ 30 nm structures

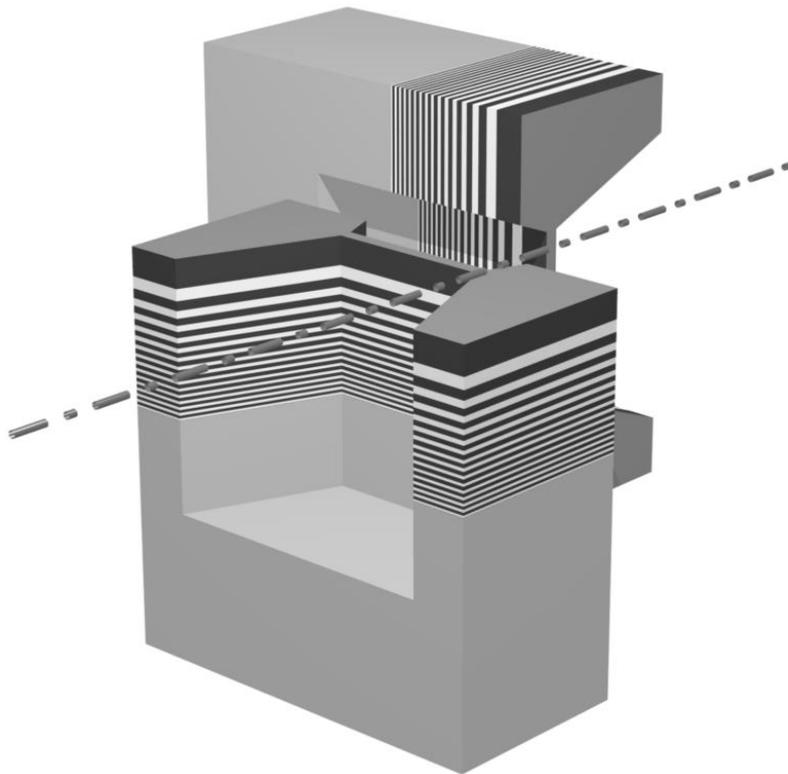


Zone plates are fabricated out of high-Z (typically gold) material using electron beam lithography, reactive ion etching and electroplating.

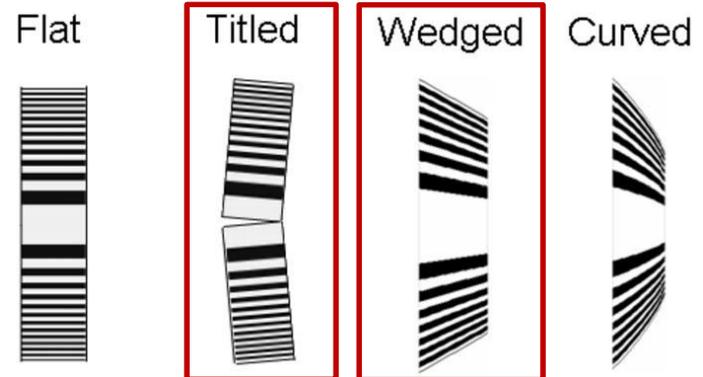
Focusing efficiencies 10-30% currently achievable (depends on A/R).

# Multilayer Laue lenses – Tuning of optics: *High resolution, high photon energies*

- Crossed partial MLLs: two-dimensional focusing and imaging

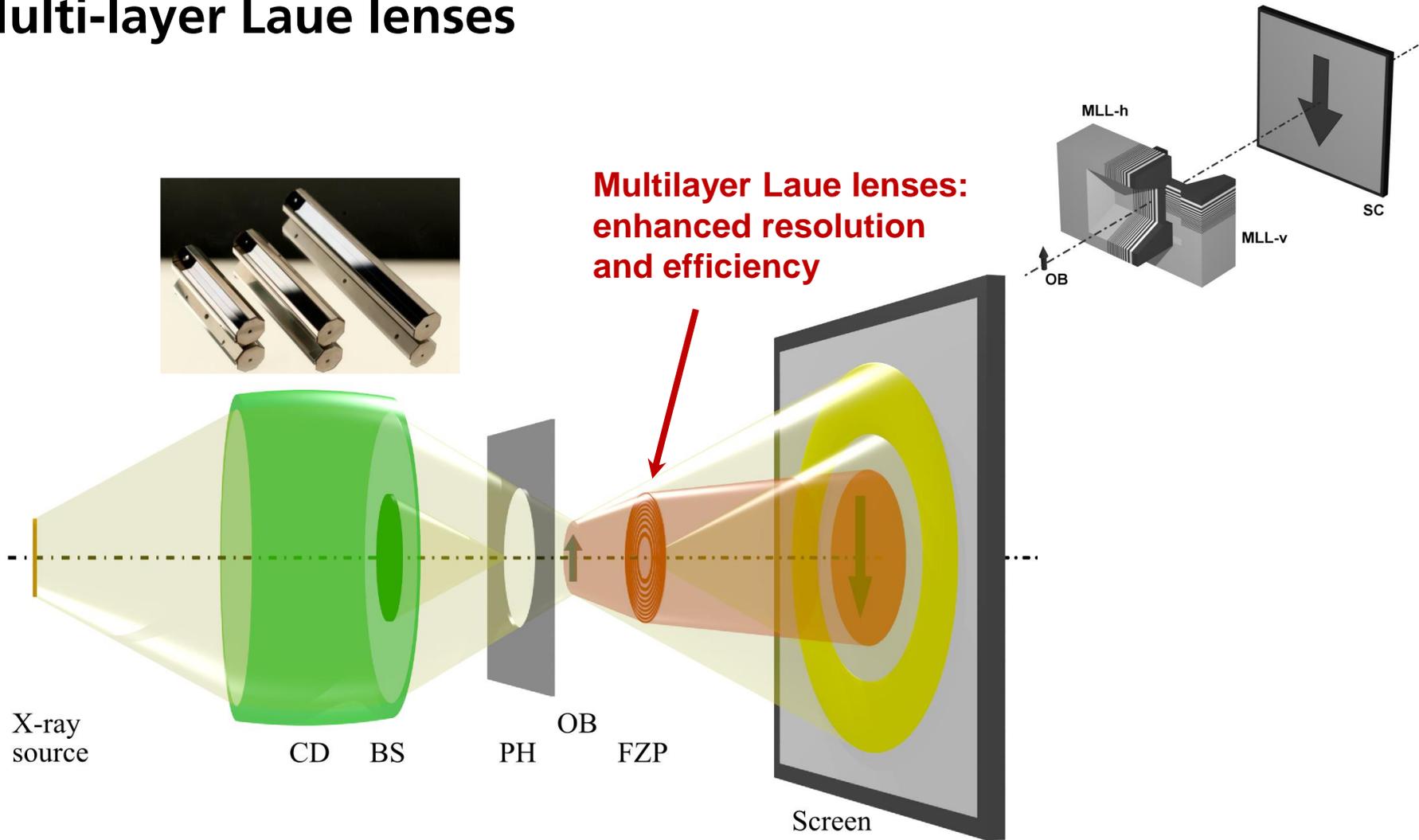


- MLL geometries

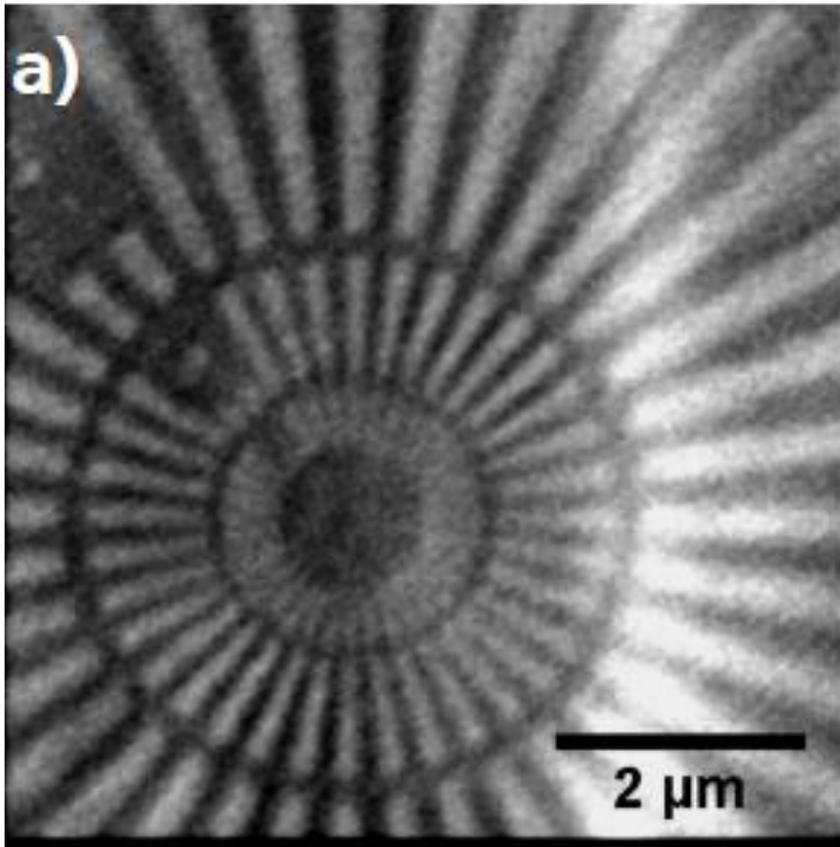


*H. Yan et al. Physical Review B 76.11, p. 115438 (2007)*

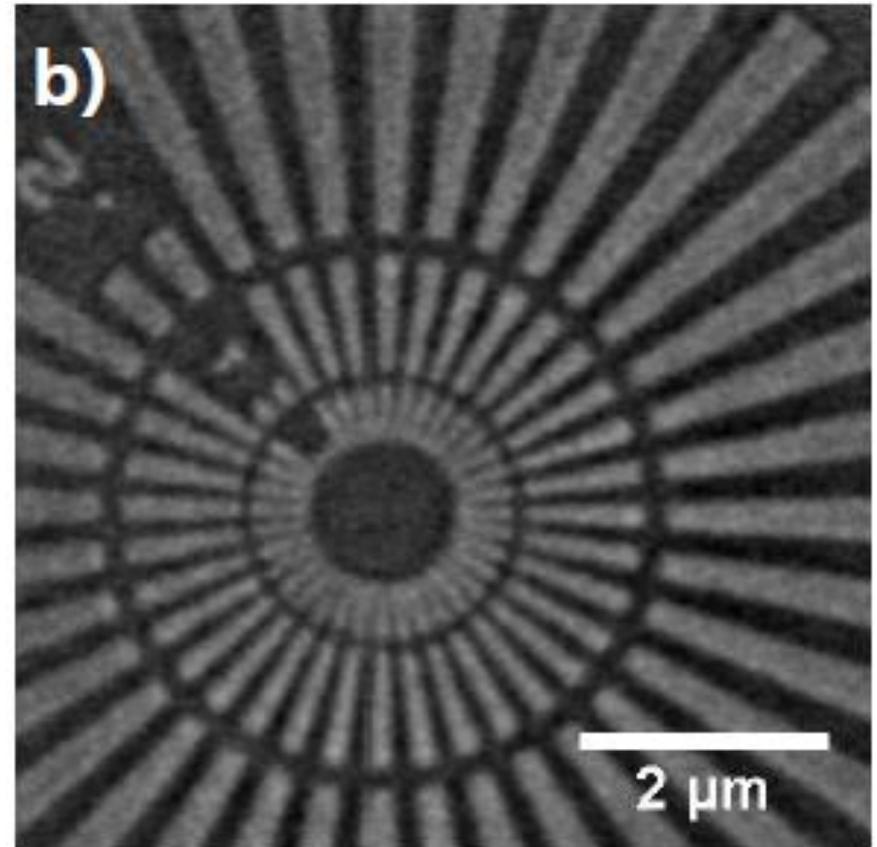
# X-ray microscopy with focusing condenser optics and Multi-layer Laue lenses



# Proof of concept – X-ray microscopy with MLL



Multi-Layer Laue Lense



Fresnel Zone Plate

## Lab-Based X-ray Microscopy: 2D Image of „Siemens Star“: FZP vs. MLL

S. Niese, PhD Thesis 2014

S. Niese et al., Optics Express 2014

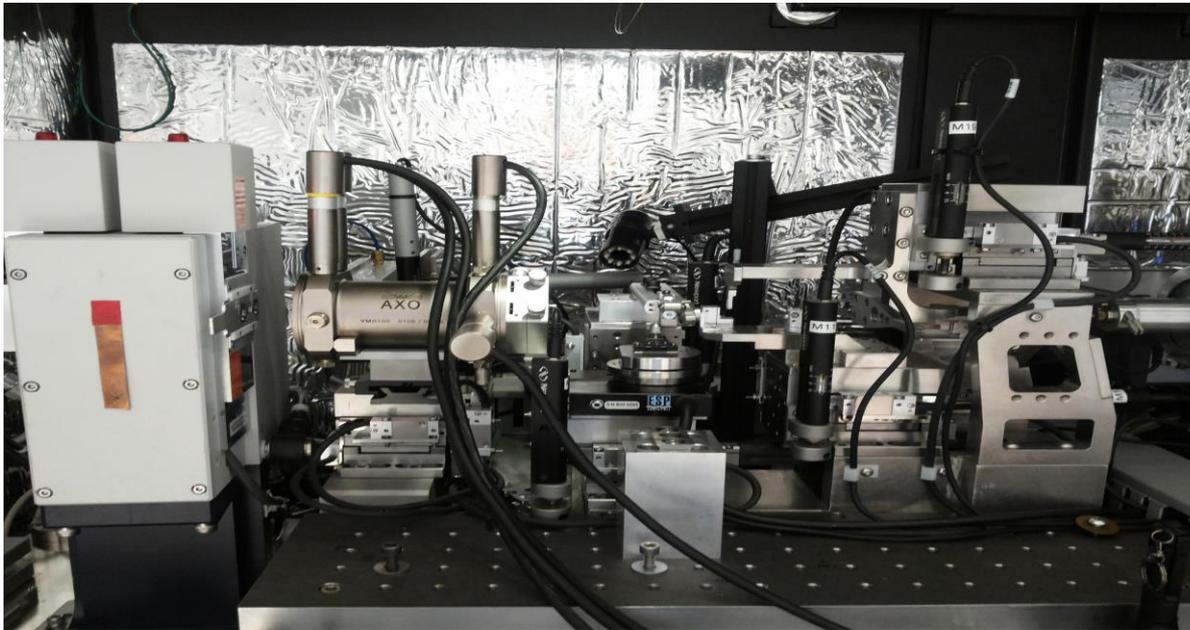
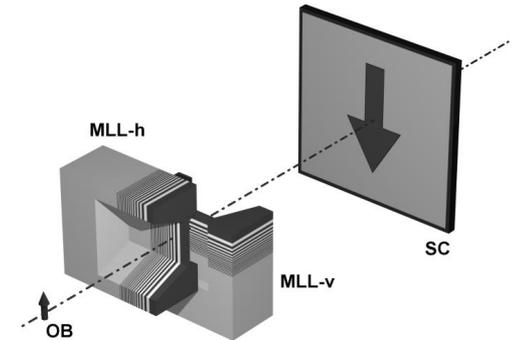
# Novel laboratory X-ray microscopy setup at Fraunhofer IKTS for high photon energies

X-ray source: Rotating anode (Mo)

X-ray optics:

2D focusing mirror “ASTIX-f”  
(AXO Dresden)

+ crossed Multilayer Laue lens



S. Niese, PhD Thesis 2014

S. Niese et al., 2nd Dresden Nanoanalysis Symposium,  
Dresden, July 2014



**AXO DRESDEN GmbH**  
APPLIED X-RAY OPTICS  
MULTILAYER X-RAY OPTICS  
HIGH PRECISION DEPOSITION



# Extension of laboratory-based X-ray microscopy/nano XCT

## Today

X-ray microscopy bridges the “resolution gap” between light microscopy and electron microscopy (3D information)

→ 30...50nm resolution (Cu  $K\alpha$ , Cr  $K\alpha$ )

## Novel approach:

**X-ray microscopy with novel optics  
(Multilayer Laue lenses)**

**Resolution improvement to 10nm (... 1nm)**

→ *down-scaled structures and defects in microelectronic products, ...*

## Increased efficiency

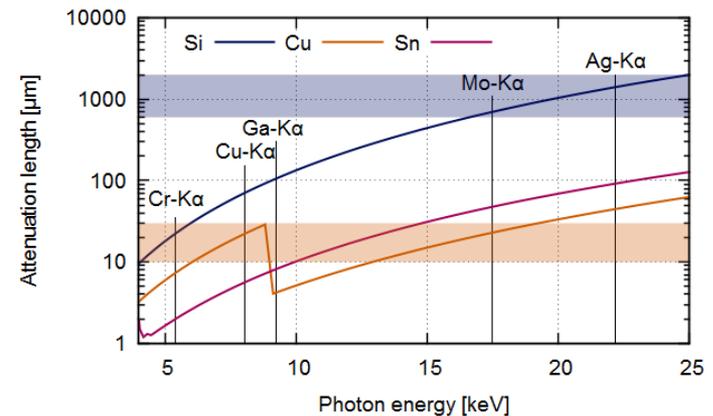
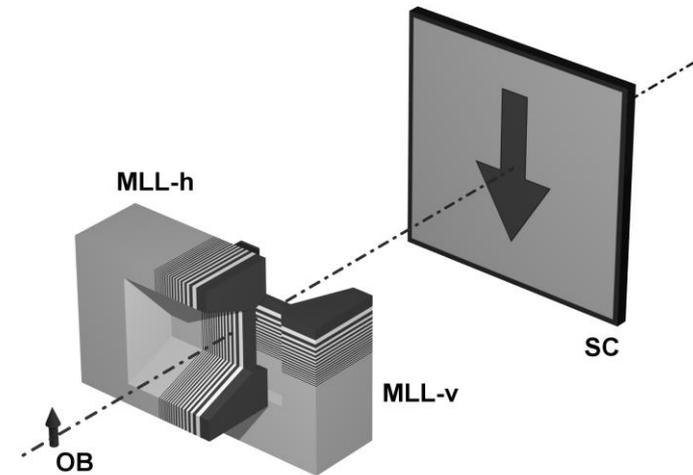
→ *shorter measurement times (industrial applications, kinetic studies)*

**Larger working distance (~ 5 cm)**

→ *chambers (temperature, chemical reactions, ...), mechanical tests (crack propagation)*

**Higher X-ray energies (e. g. Mo source)**

→ *penetration of devices (wafers), ...*



# Thank you !

Martin Gall, FhG IKTS Dresden

Adam Kubec, FhG IWS Dresden

Reiner Dietsch, Sven Niese, AXO Dresden GmbH

Project No. 16ES0070, within the frame of the projects EC „Master 3D“ and BMBF „3D-Innopro“.



Contact: [ehrenfried.zschech@ikts.fraunhofer.de](mailto:ehrenfried.zschech@ikts.fraunhofer.de)