NOVEL METROLOGY SOLUTION FOR ADVANCED PACKAGING BASED ON MULTI-ENERGY X-RAY MICROSCOPY AND TOMOGRAPHY

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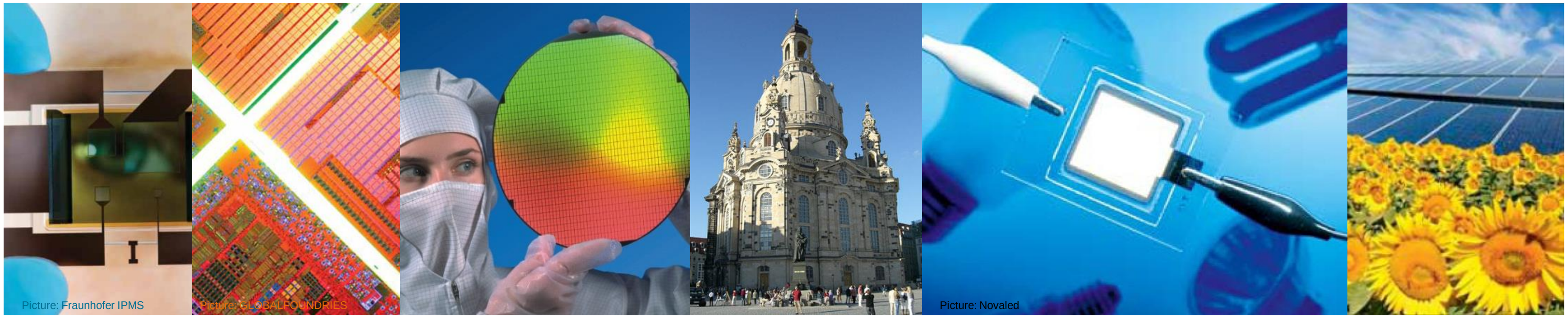
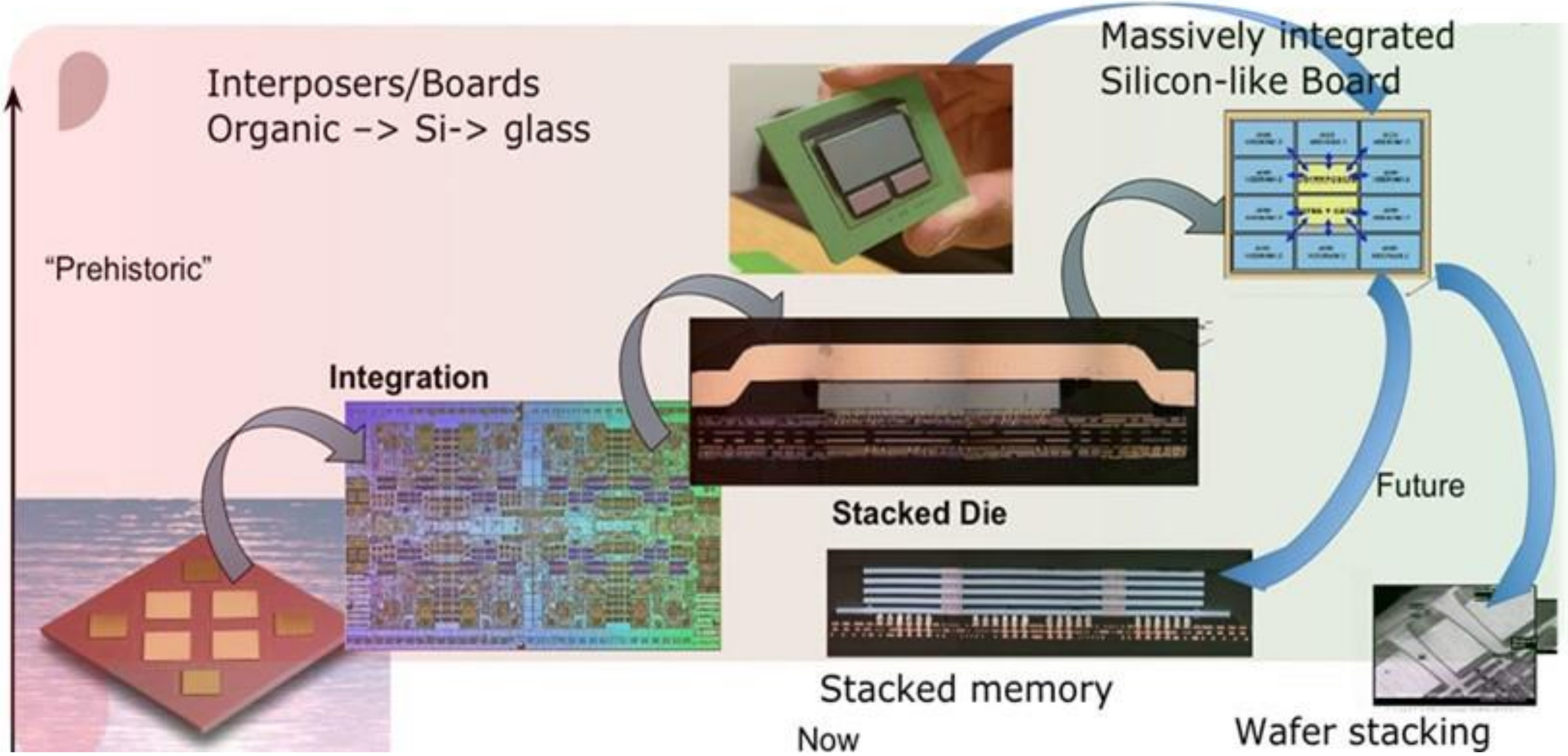

Picture: Fraunhofer IPMS
Picture: GLOBALFOUNDRIES
Picture: Novaled

Monterey/CA | 22 March 2017

Evolution of system level heterogeneous integration



… requires novel solutions for nondestructive 3D characterization of interconnect structures

S. Iyer, UCLA, and B. Bottoms, FCMN 2017

Outline

Characterization of microbumps in HBM stacks: micro and nano XCT

State of the art X-ray microscopy and nano X-ray tomography

Novel solution: Improved experimental setup and components

Detectable parameters for 3D advanced packaging metrology

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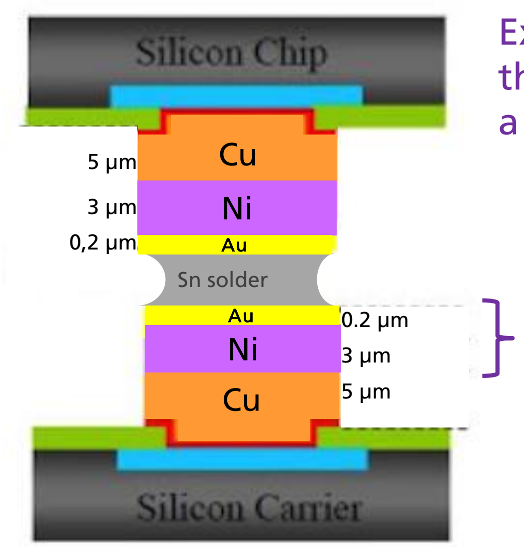
Introduction

Task:

Nondestructive 3D imaging of solder micro bumps in 3D stacks

- **Geometry: Shape of the solder interconnect**
- **Metallurgy: Chemical composition, location of intermetallics**
- **Defects: Pores, micro-cracks**



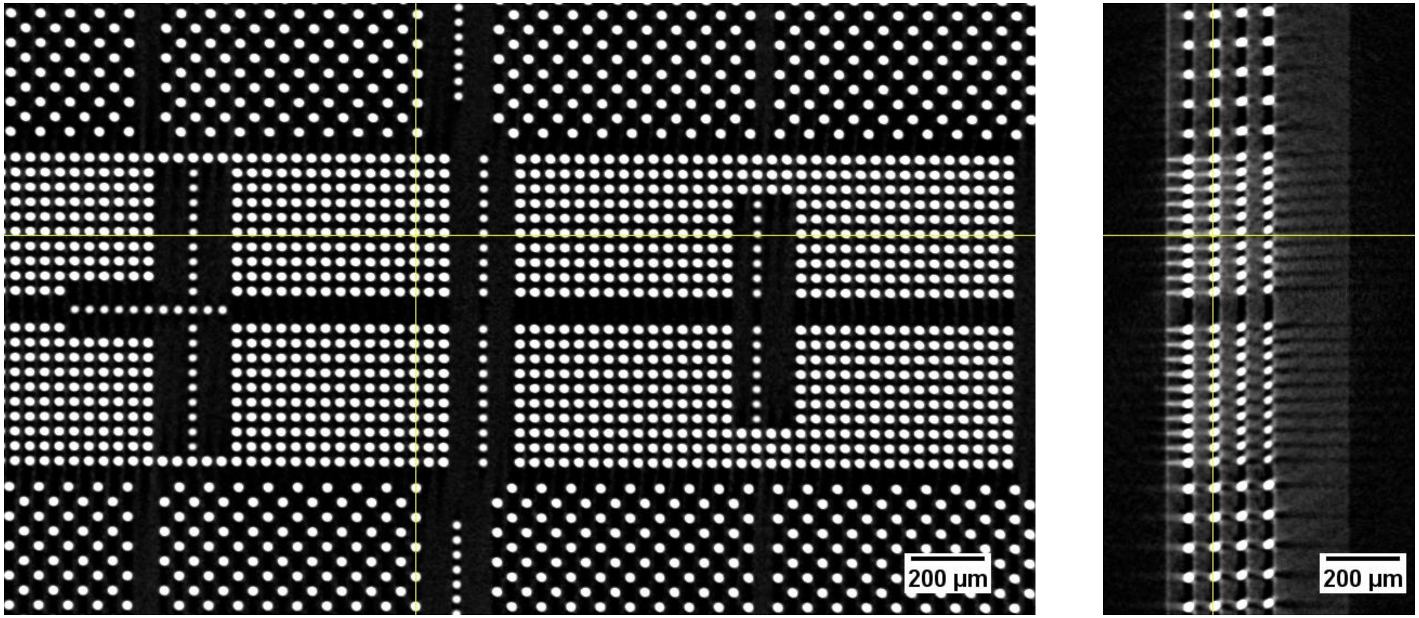
Exemplary presentation, thicknesses are representing a possibility only

ENIG (Electroless Nickel Immersion Gold)

Target of the talk:

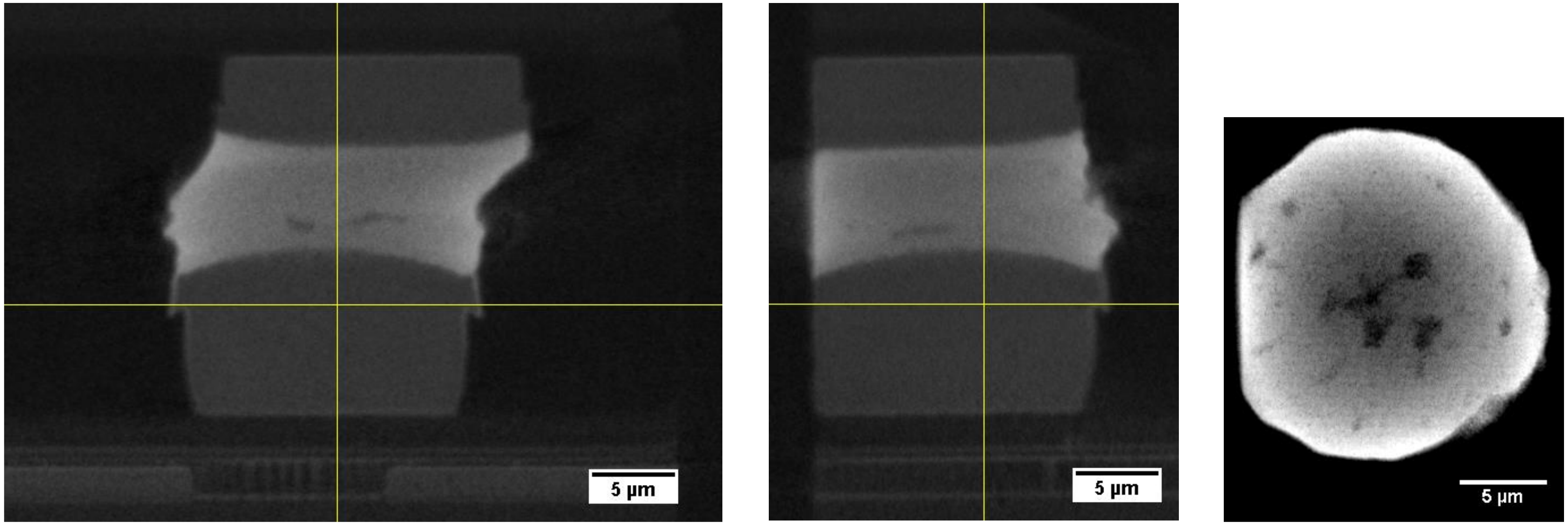
Demonstrate new developments in X-ray tomography for future industrial application in semiconductor industry, particularly advanced packaging

High bandwith memory (HBM) stack:
Virtual cross-sections from 3D micro-XCT data



Two virtual 2D images (plane view and cross-section view) of a HBM stack, based on a 3D data set from micro X-ray tomography. Nondestructive imaging.

High bandwith memory (HBM) stack:
Virtual cross-sections from 3D nano-XCT data



Three virtual 2D images (two perpendicular cross-section views and one planar view) through a solder connection (micro-bump of a HBM stack), based on a 3D data set from nano X-ray tomography. Imaging of a small extracted sample.

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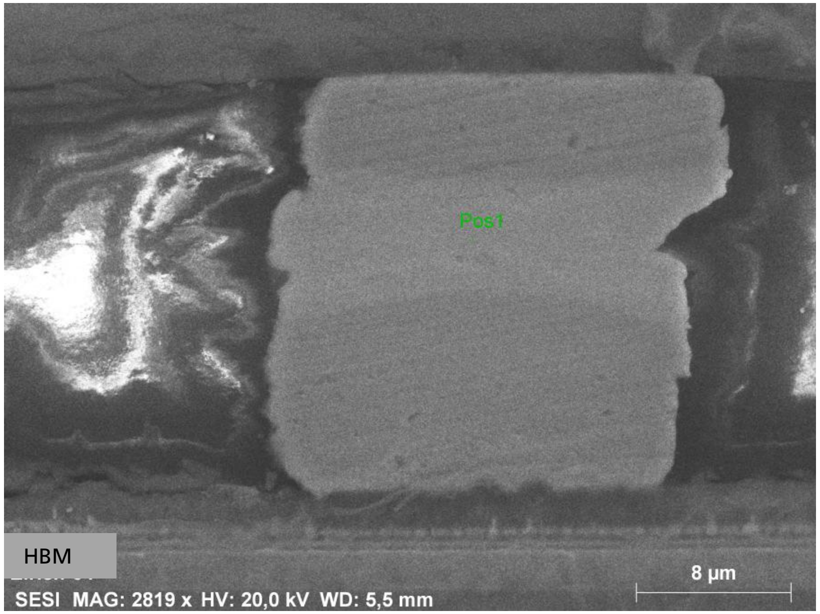
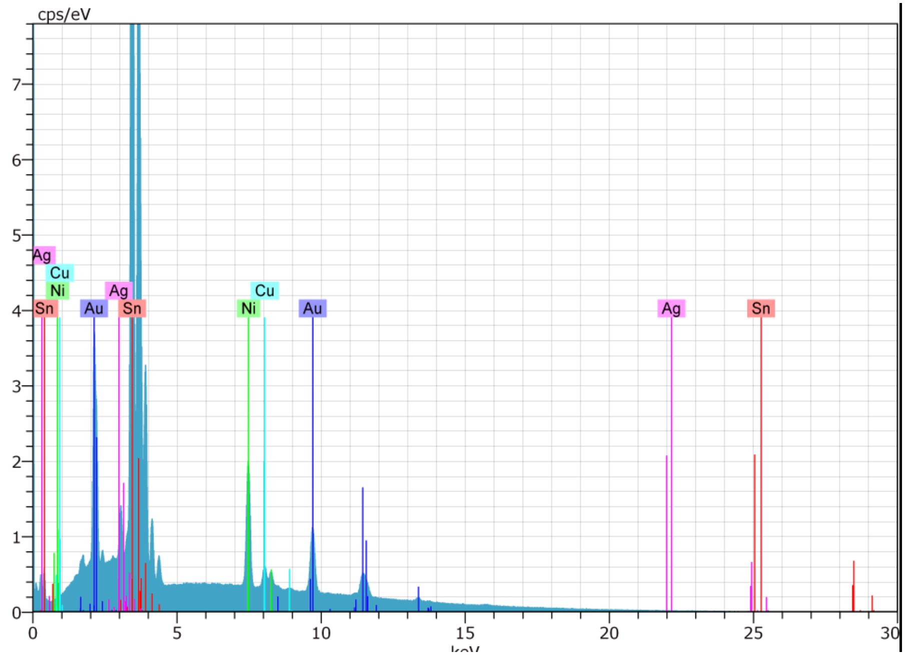
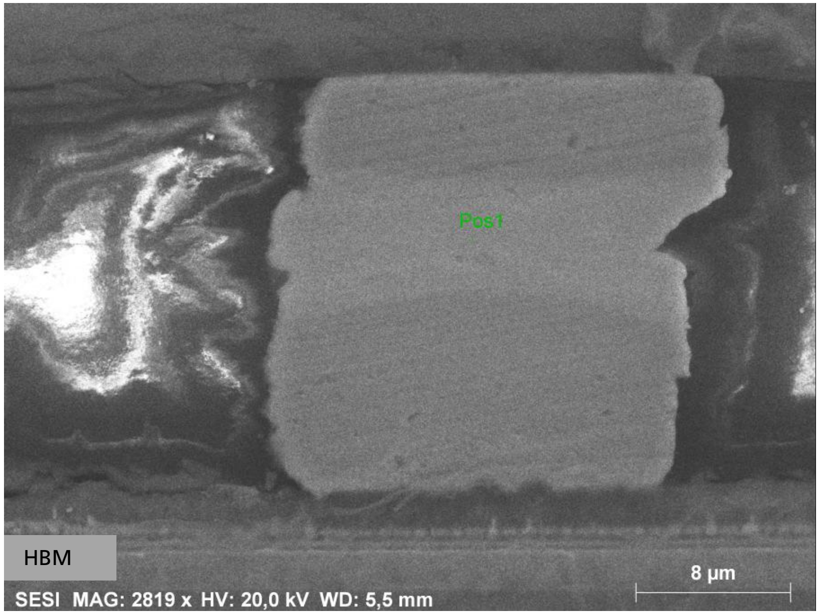
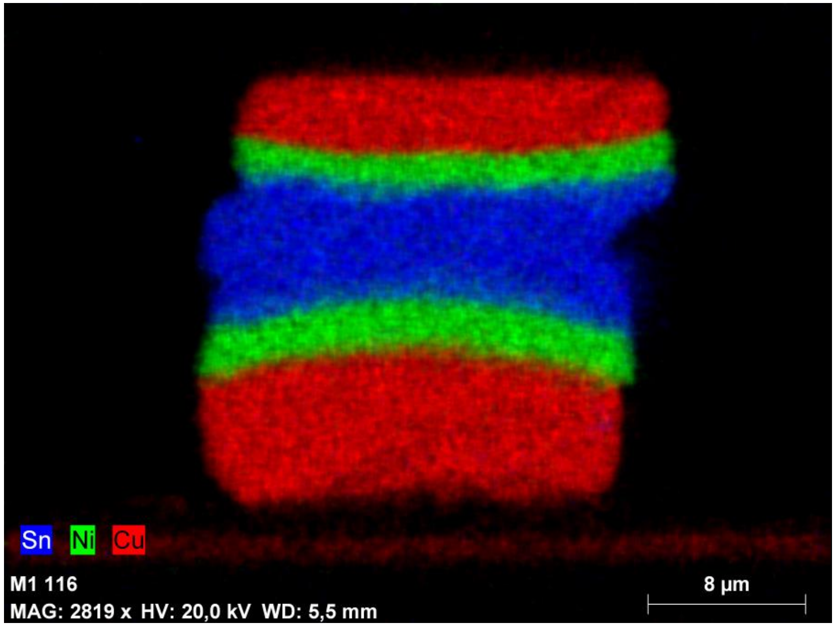
SEM image of cross-section and EDX point analysis (solder)





SEM image of cross-section and EDX element distribution map





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Characterization of microbumps in HBM stacks: micro and nano XCT

State of the art X-ray microscopy and nano X-ray tomography

Novel solution: Improved experimental setup and components

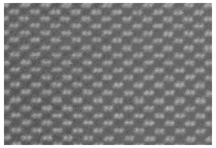
Detectable parameters for 3D advanced packaging metrology

Characterization techniques – from macro to nano

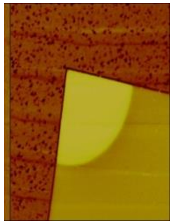
Nanoanalysis

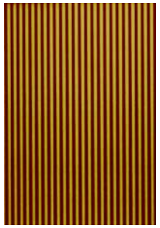
Non-destructive testing

TEM/SEM



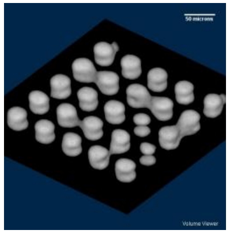
SPM techniques

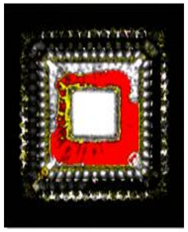




XRD

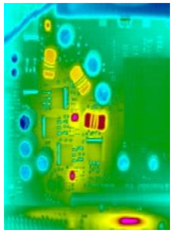
micro XCT

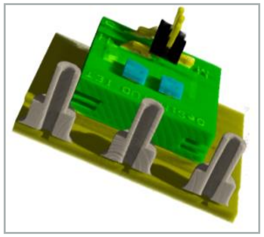




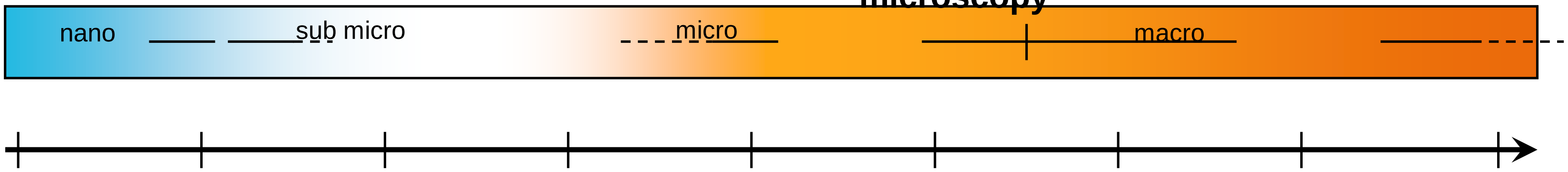
scanning acoustic microscopy

thermography





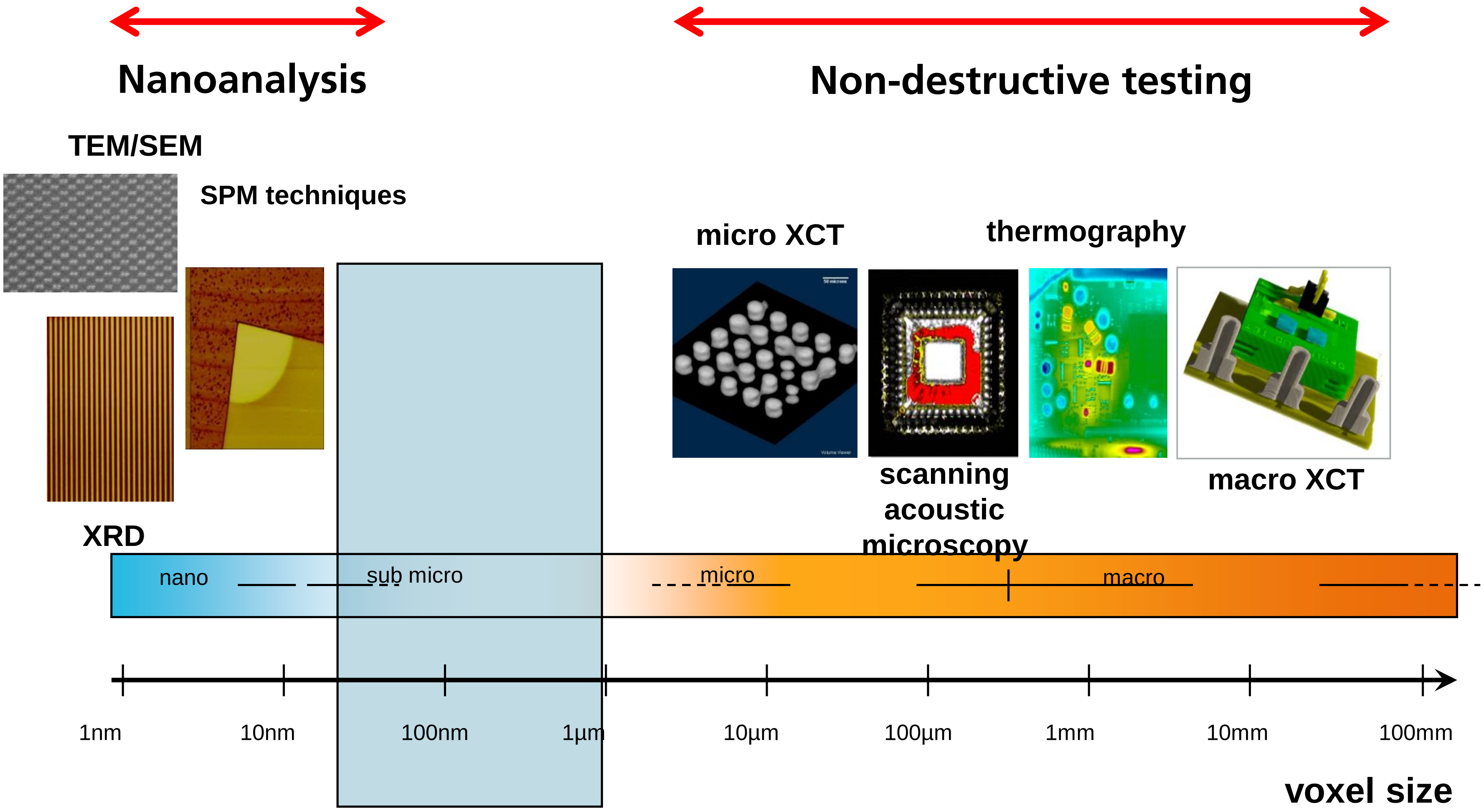
macro XCT



1nm 10nm 100nm 1µm 10µm 100µm 1mm 10mm 100mm

voxel size

Characterization techniques – from macro to nano



Nanoanalysis

Non-destructive testing

TEM/SEM

SPM techniques

micro XCT

thermography

scanning acoustic microscopy

macro XCT

XRD

nano

sub micro

micro

macro

1nm

10nm

100nm

1µm

10µm

100µm

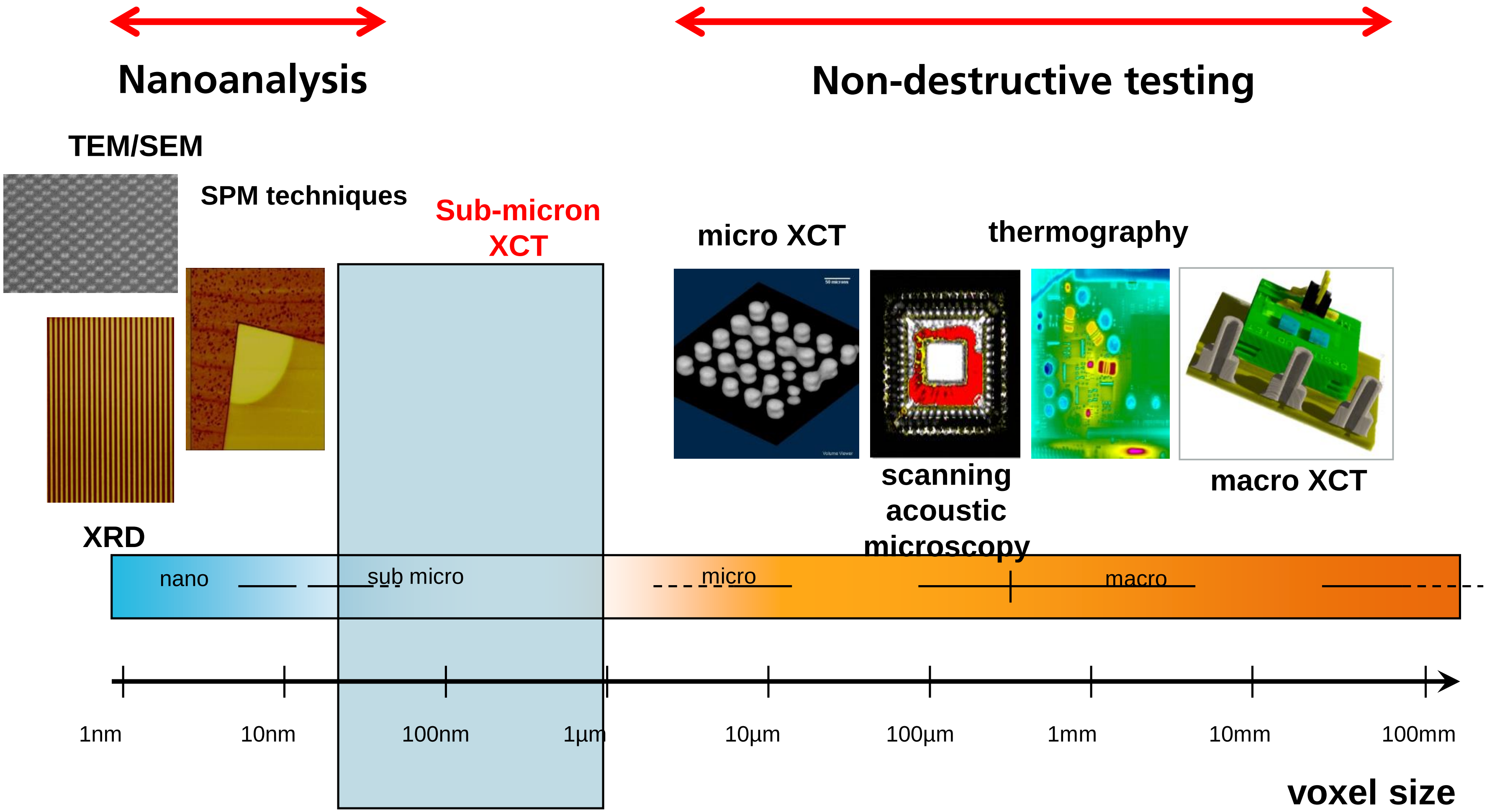
1mm

10mm

100mm

voxel size

Characterization techniques – from macro to nano



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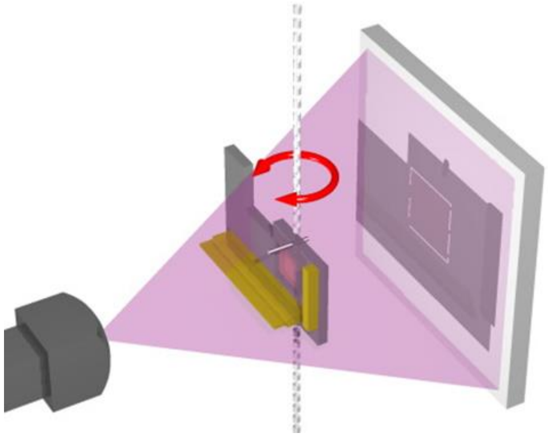
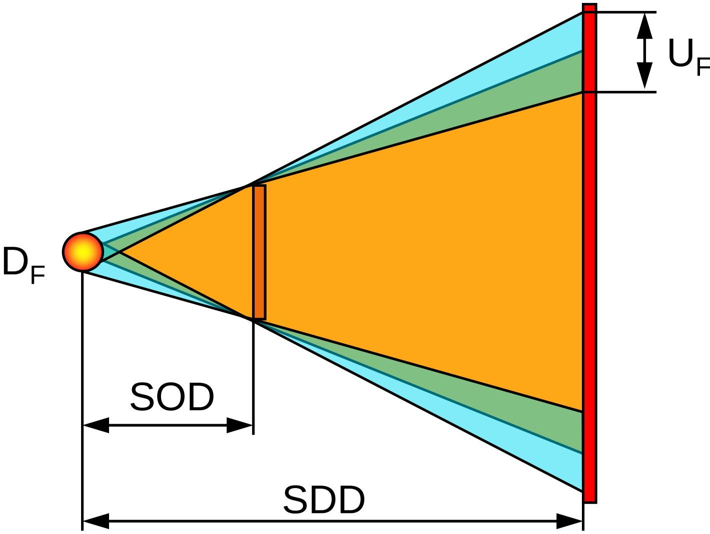
X-ray micro imaging: Principle of conventional radiography

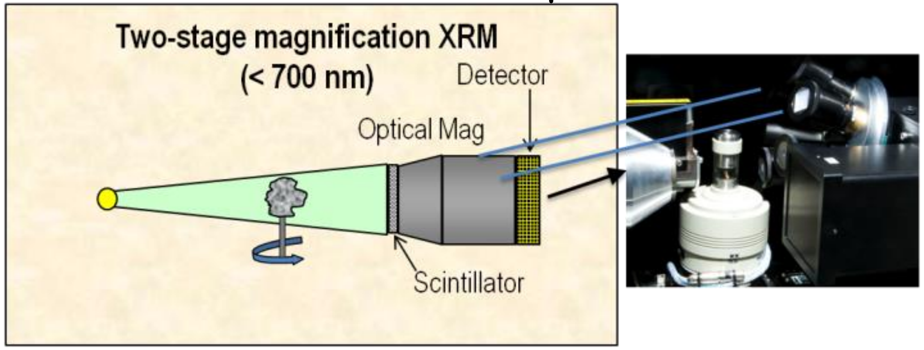
Projection of the (small) specimen on a (large) screen

- $d > D_F$: Resolution is limited by size of the source
- $D_F >$ 0.6 µm (thin target)

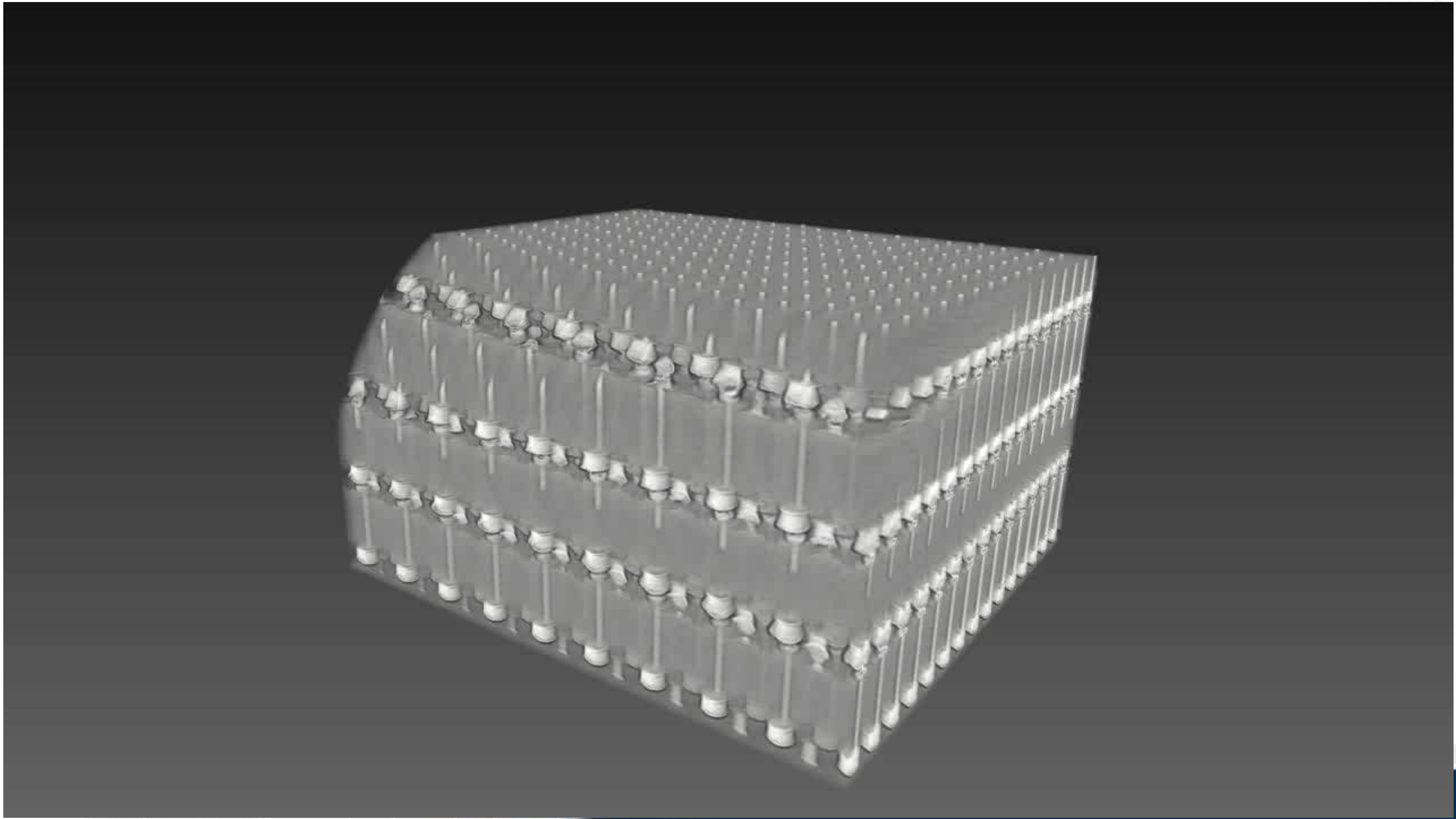




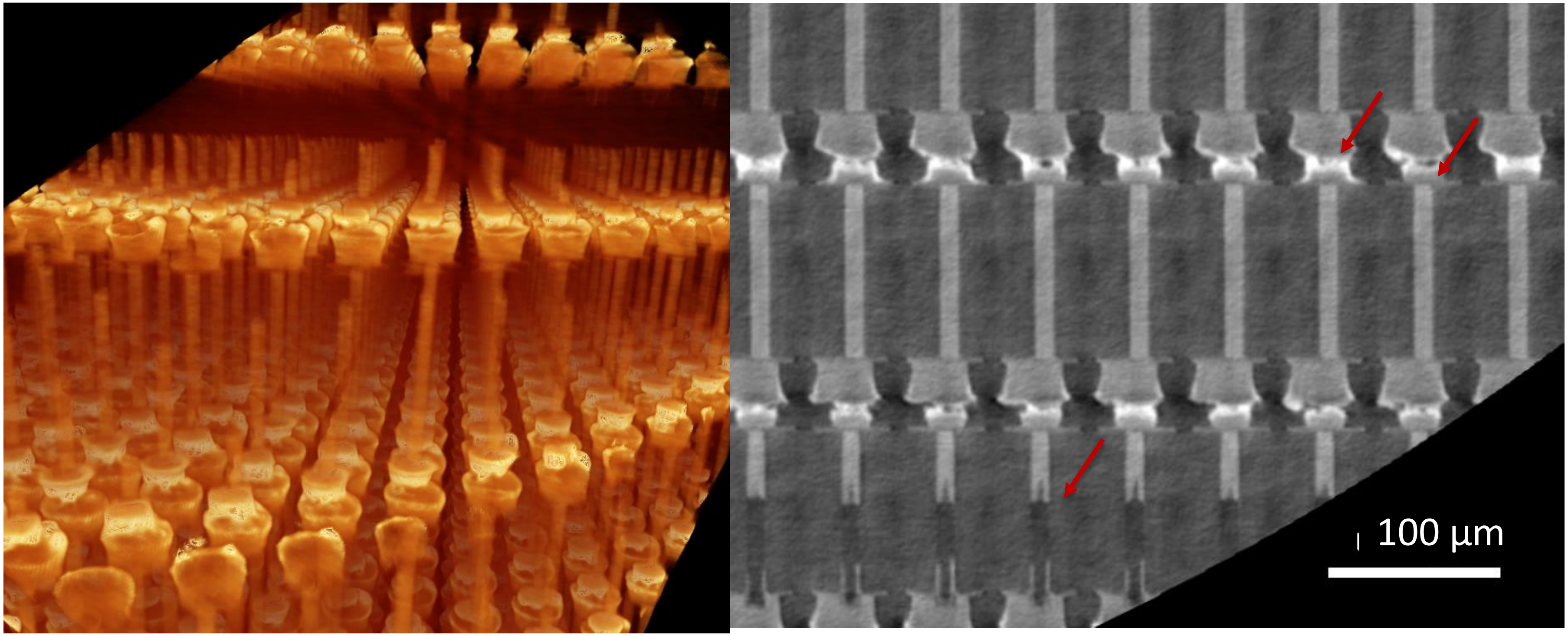
Zeiss Versa XCT 520: 0.7 µm resolution



Multi-chip stack – Micro XCT

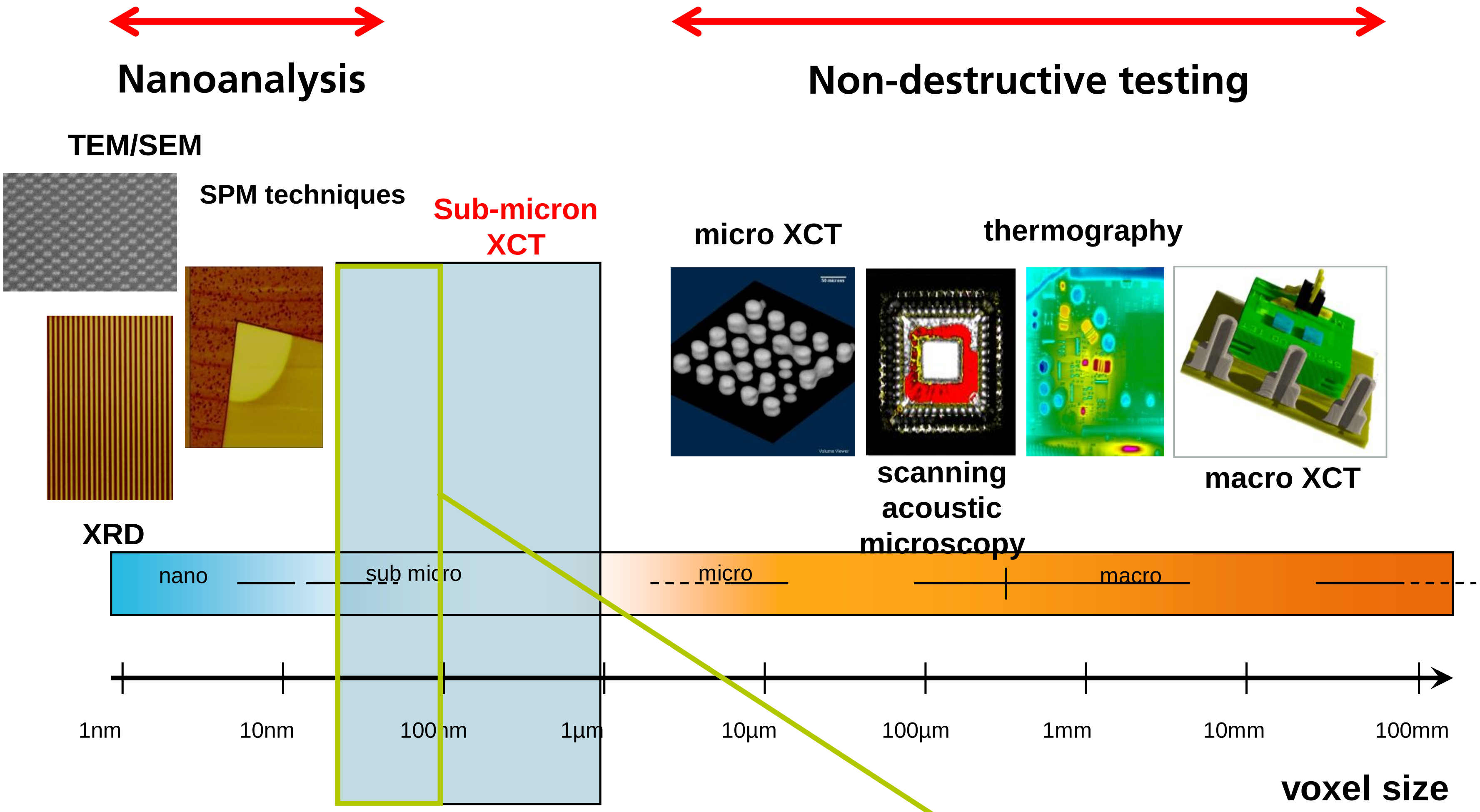


Multi-chip stack – Micro XCT



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

Characterization techniques – from macro to nano



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TEM/SEM

SPM techniques

Sub-micron XCT

micro XCT

thermography

scanning acoustic microscopy

macro XCT

XRD

nano

sub micro

micro

macro

1nm

10nm

100nm

1µm

10µm

100µm

1mm

10mm

100mm

voxel size

Nano Transmission X-ray Microscopy (TXM) / XCT

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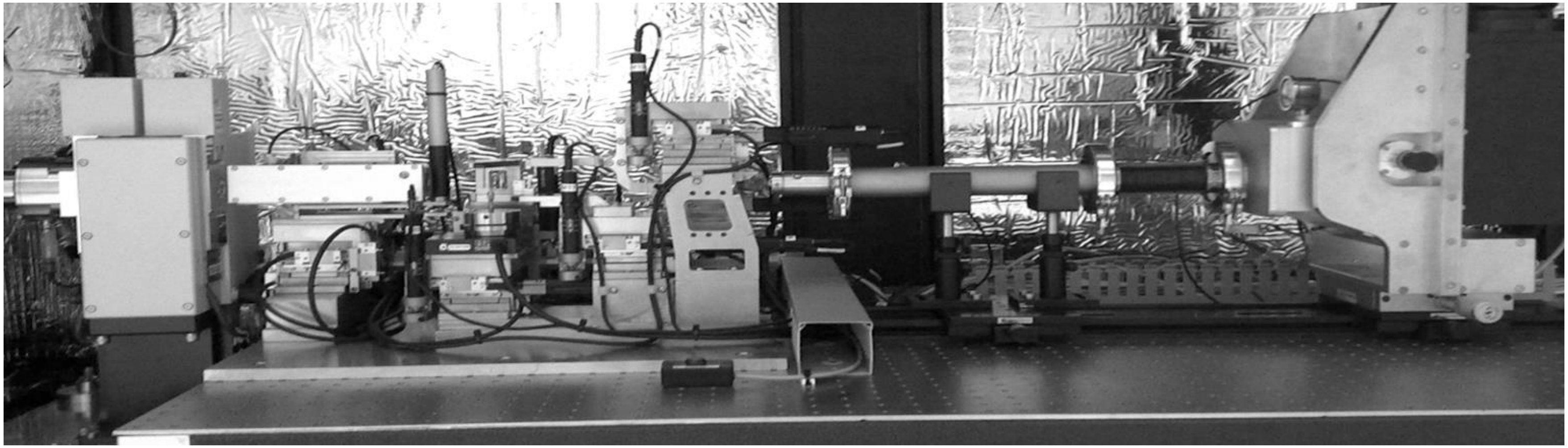
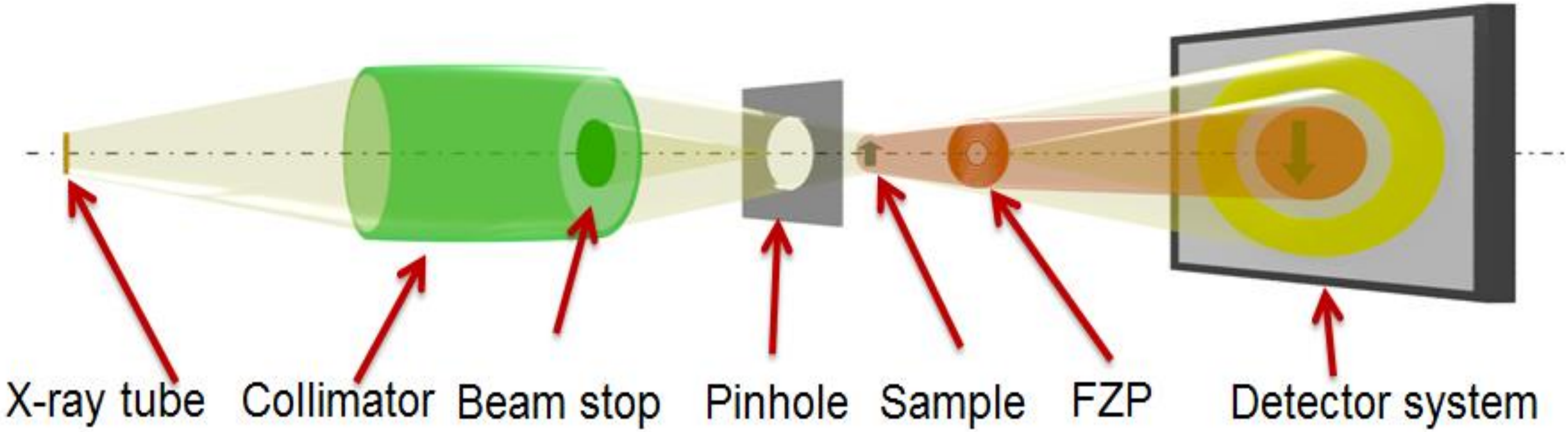
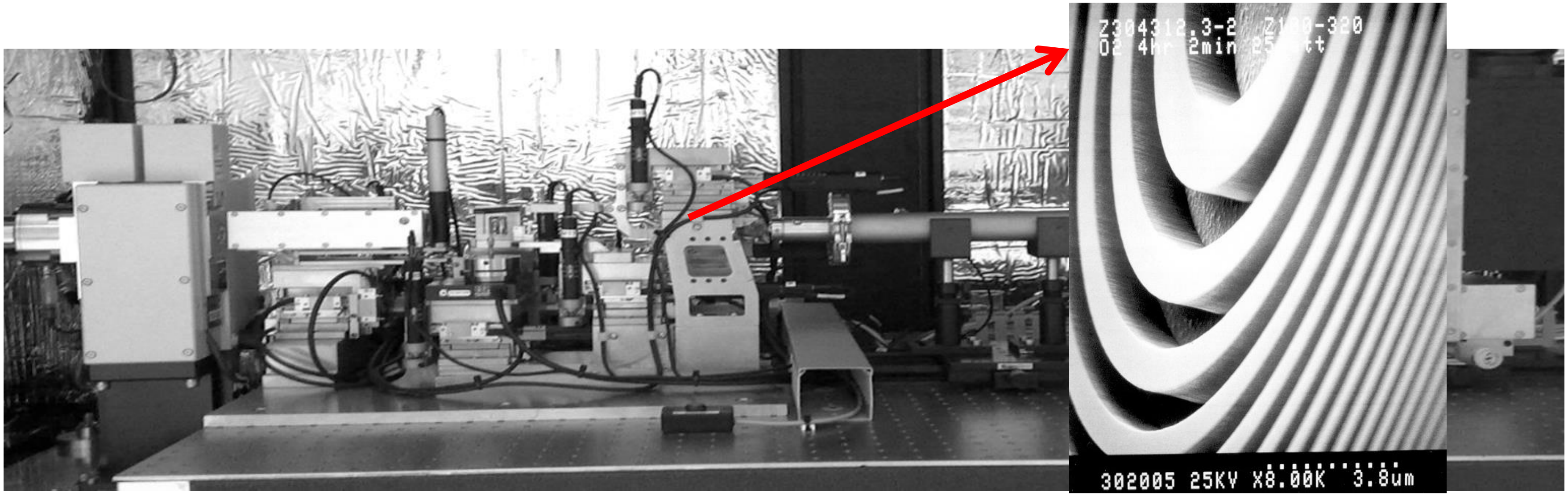
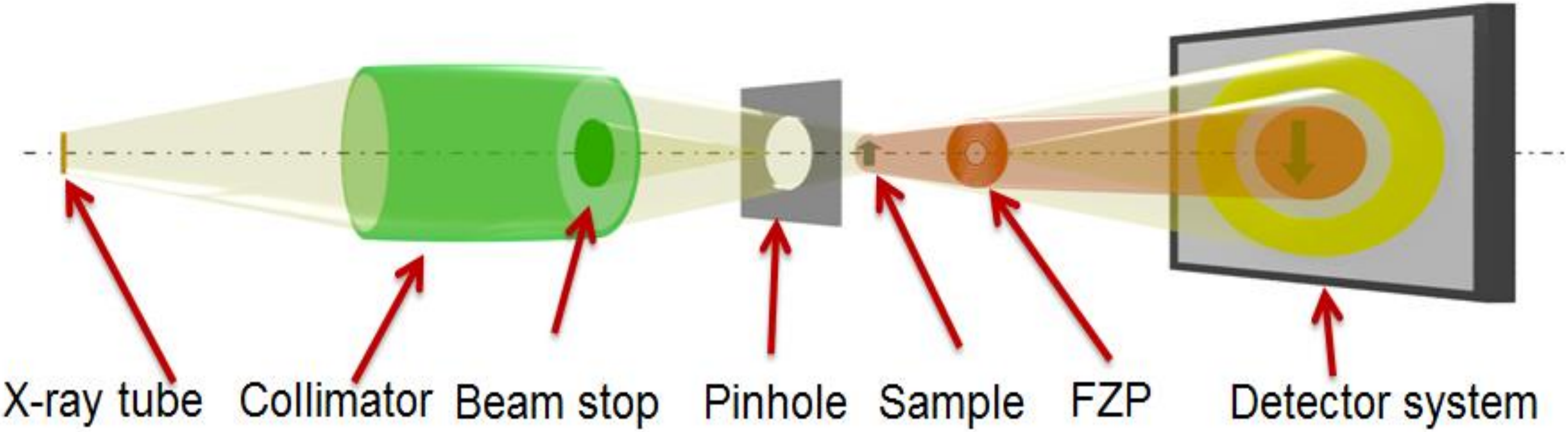
Zeiss/Xradia NanoXCT: Lab based X-ray microscopy





Zeiss/Xradia NanoXCT: Lab based X-ray microscopy





X-ray tube Collimator Beam stop Pinhole Sample FZP Detector system

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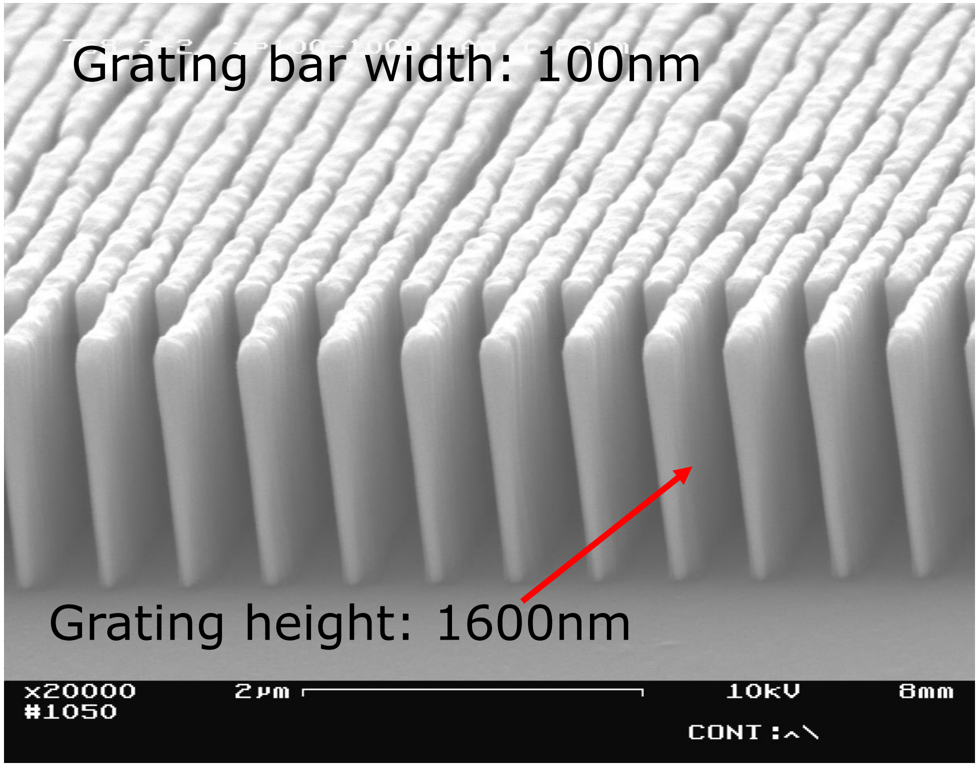
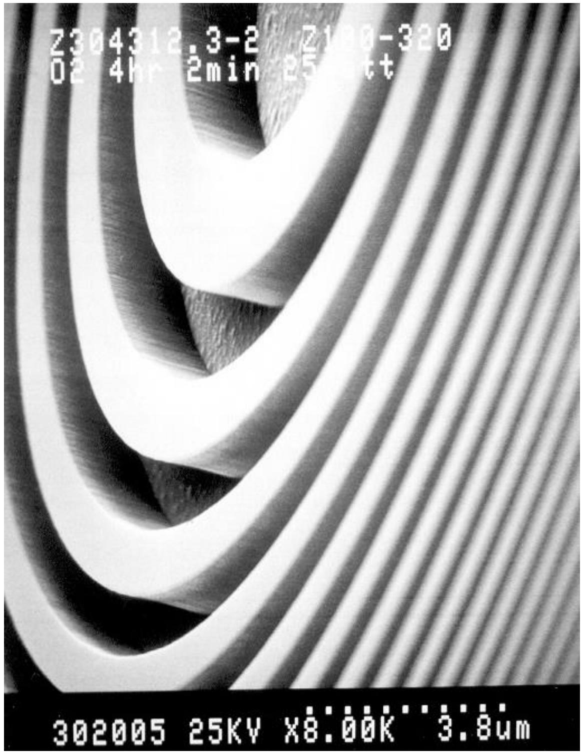
Limits of zone plates: ~ 30 nm structures



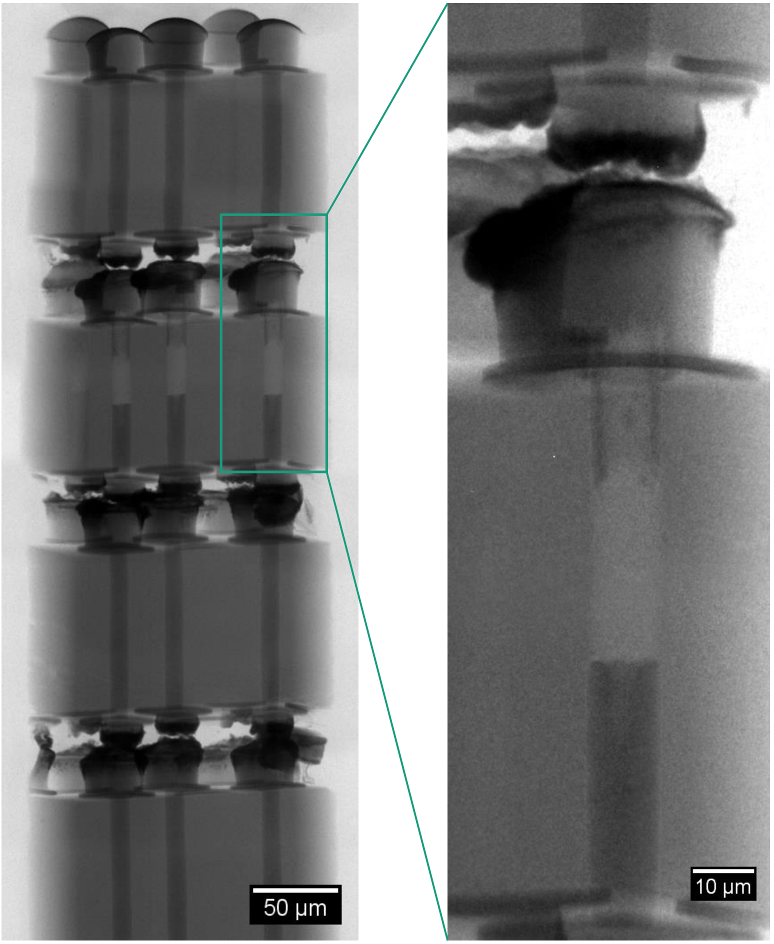


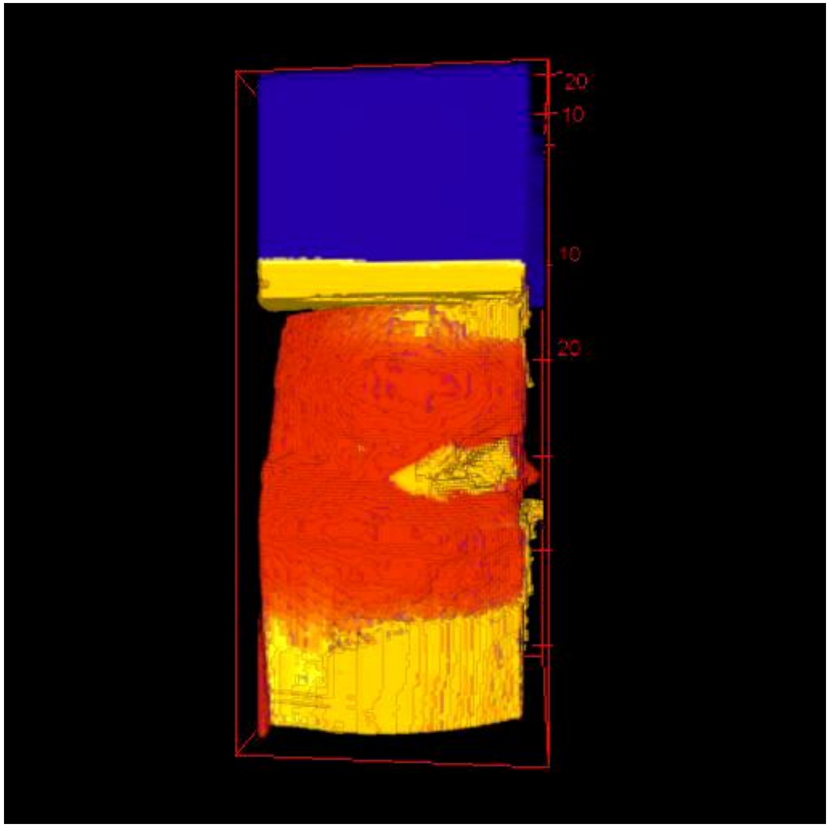
Zone plates are fabricated out of high-Z (typically gold) material using electron beam lithography, reactive ion etching and electroplating.

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

E. Zschech, W. Yun, G. Schneider, Appl. Phys. A 92, 423 – 429 (2008)
Courtesy: Xradia Inc., Concord/CA

Multi-chip stack – High-resolution nano XCT





Tomography of a AgSn solder bump

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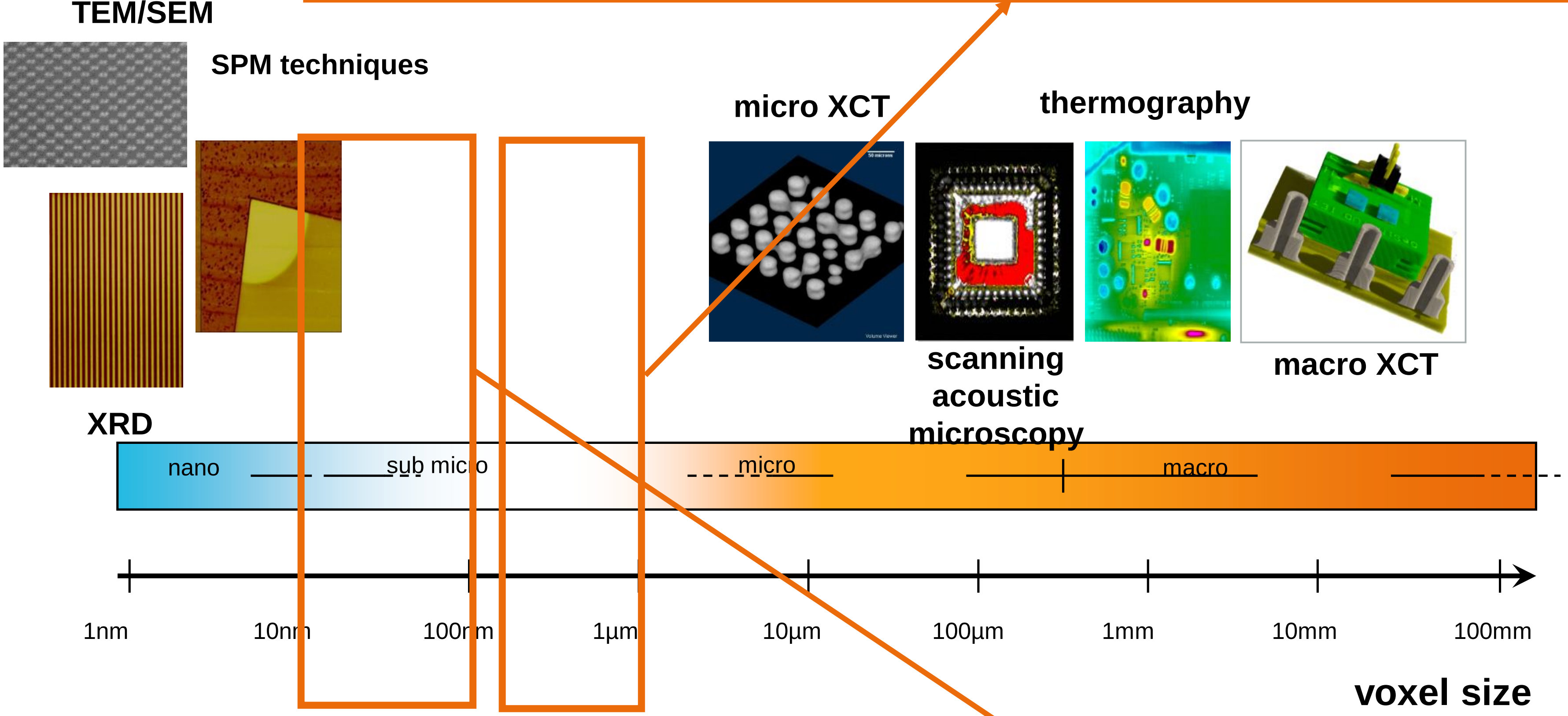
X-ray imaging perspectives (next 3 years)

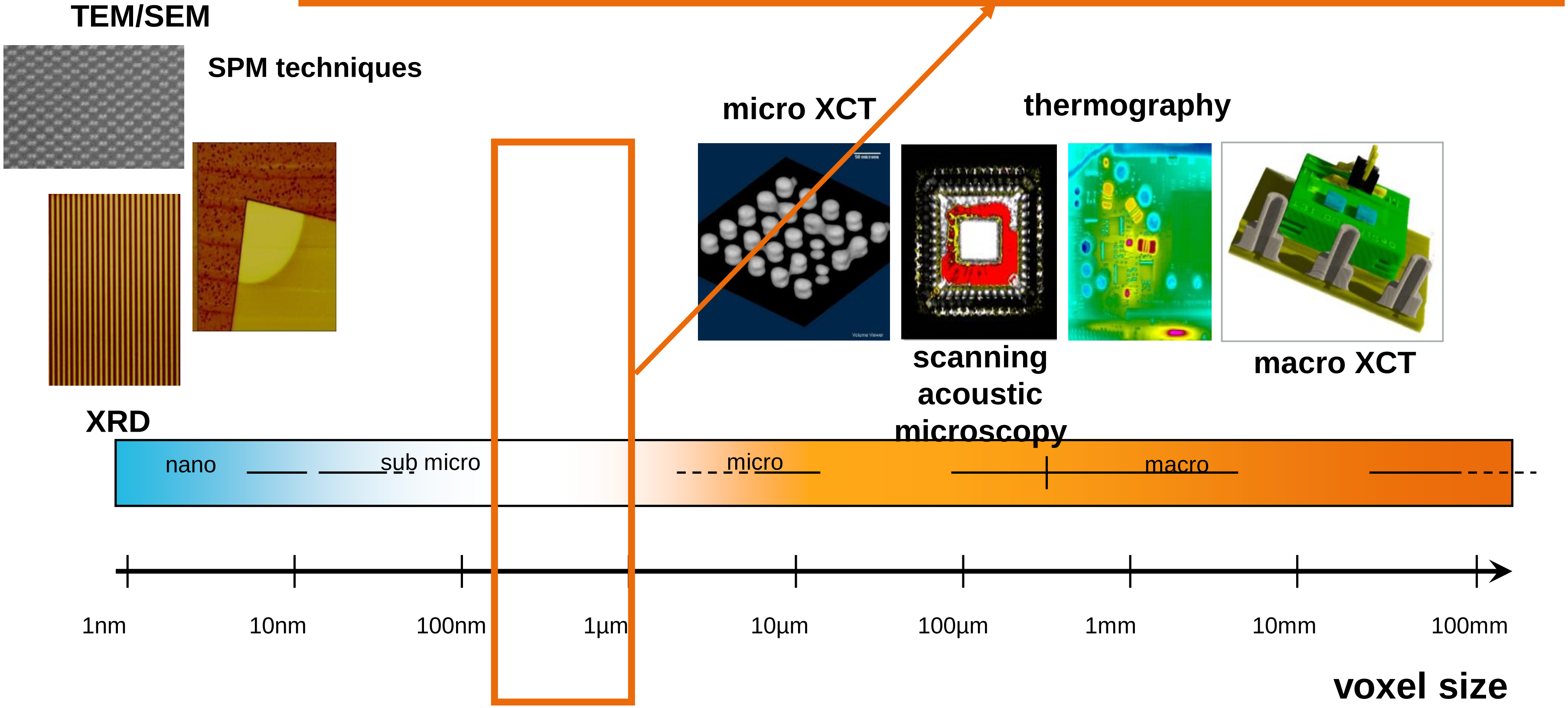
Sub-micron XCT with novel X-ray sources: 0.3 … 1.0 µm resolution



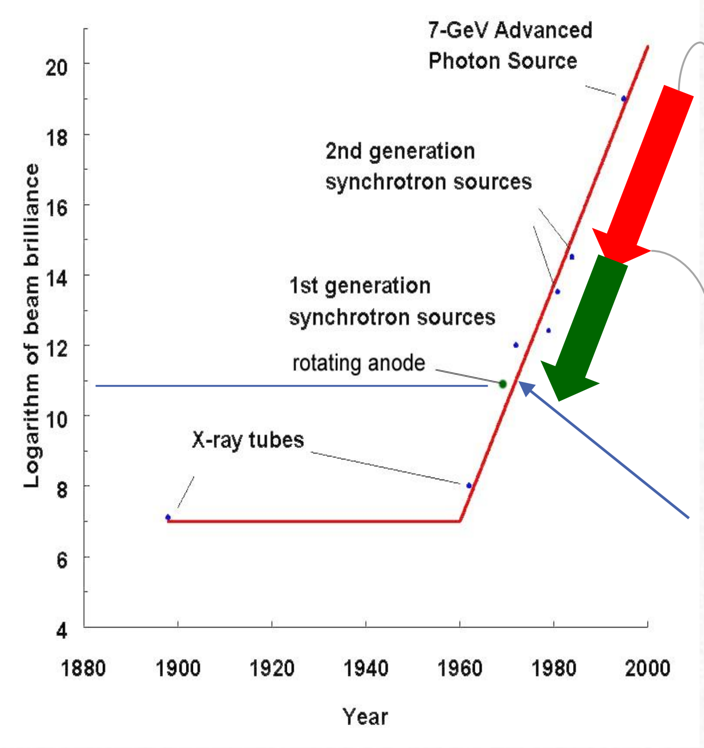
Nano Transmission X-ray Microscopy (TXM) / nano XCT with novel X-ray optics: 10 … 100 nm resolution

X-ray imaging perspectives (next 3 years)

Sub-micron XCT with novel X-ray sources:
0.3 … 1.0 μm resolution



Motivation for novel lab-based X-ray sources:
Higher brightness ➔ 2^{nd} generation synchrotron
Smaller spot size ➔ < 0.6 μm



APS: Highest Brightness. Ideally suited for scanning microprobe.

ALS: Bending magnet source with 10^4 less brightness for hard x-rays but only 20X lower x-ray flux, not too bad for full field imaging

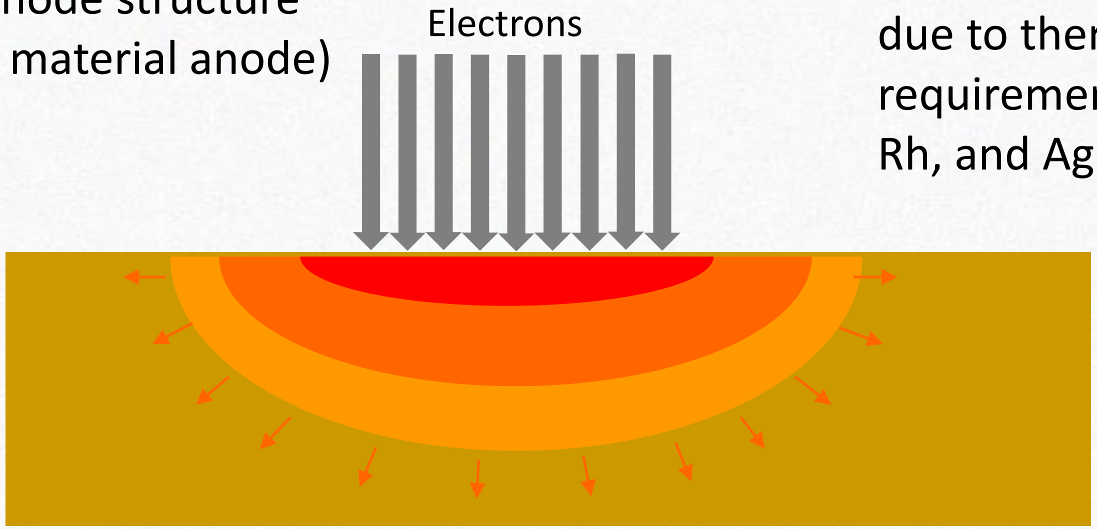
Brightness of rotating anode: 10^{11}/s/mm^2/mrad^2 (data in 1990 ca) actually, $2*10^9$/s/mm^2/mrad^2, 50X WRONG!

$F \sim B * d^2 * NA^2 * N$

F = flux on the sample
B = source brightness
d = resolution
NA = numerical aperture
N = number of coherence modes
(N =1 for microprobe, N ~ 10^5 for imaging microscope)

Limitations of conventional X-ray sources: Target damage

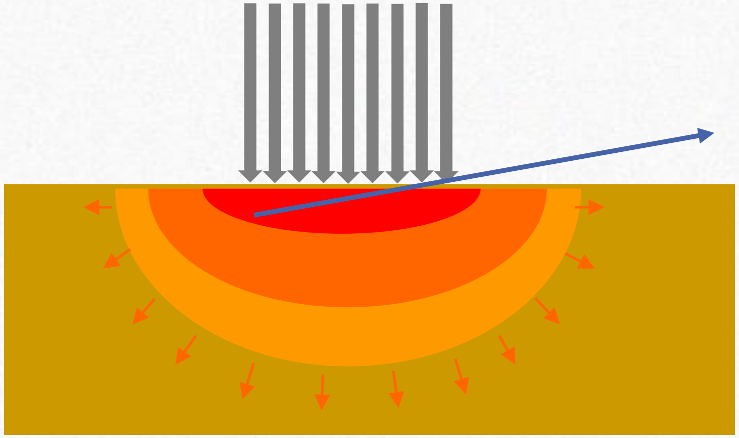
- Limited thermal performance due to simple anode structure (Single uniform material anode)



- Limited choice of characteristic x-ray lines due to thermal property requirement: Cu, Mo, W, Rh, and Ag

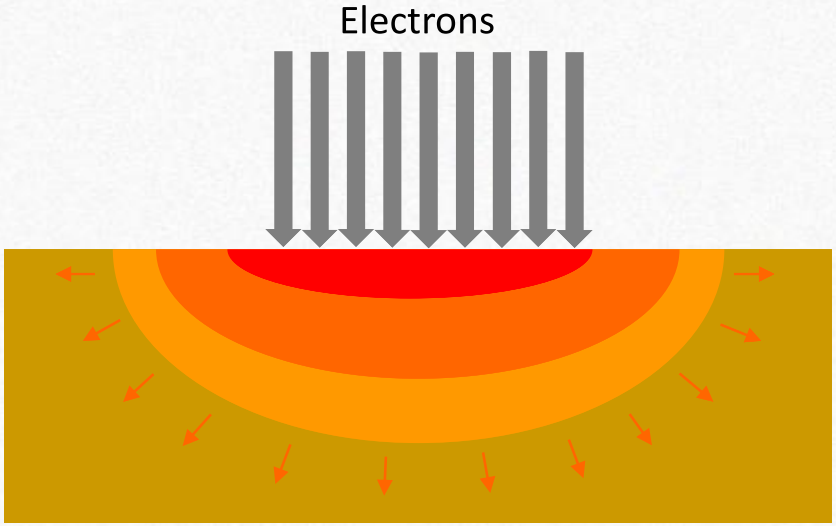
Approaches to increase brightness for laboratory sources

Improve heat from the center of electron beam on the anode

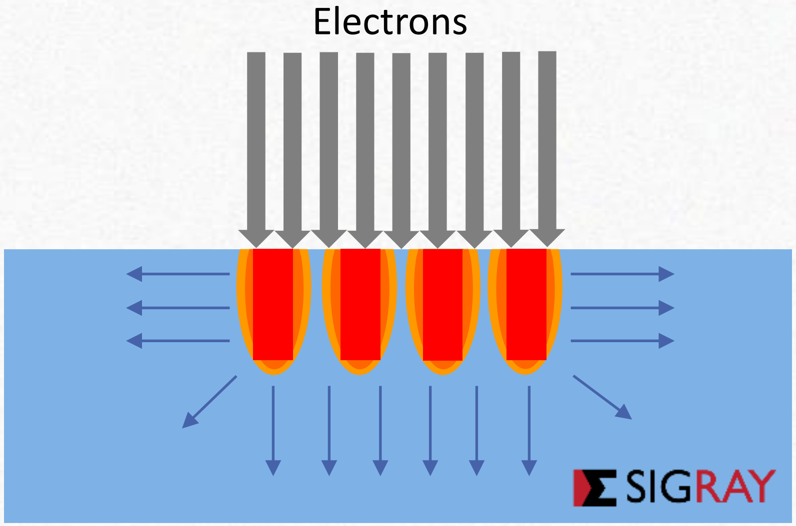


1. Material with high thermal conductivity and melting point: Cu, W, Mo
2. Increasing thermal gradient: Microfocus
3. Low take-off angle: Linear accumulation
4. Increasing electron illumination volume: rotating anode and liquid metal jet

New source concept:
FAAST (Fine Anode Array Source Technology)

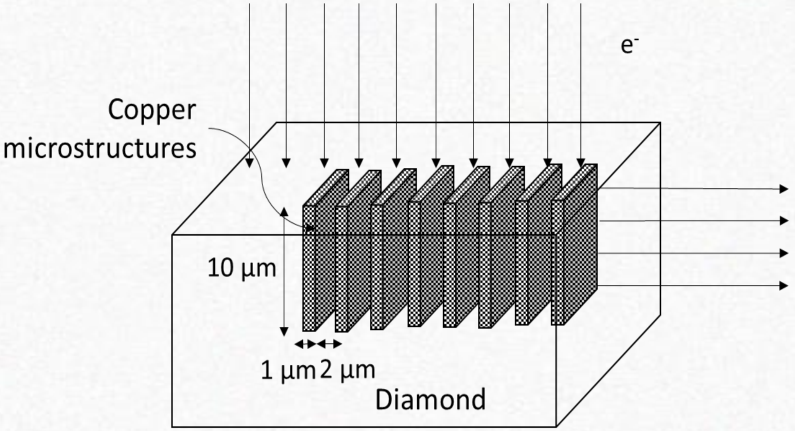


Conventional Target
Uniform Material



Metal Microstructures
Embedded in Diamond

Advantages of FAAST (Fine Anode Array Source Technology)



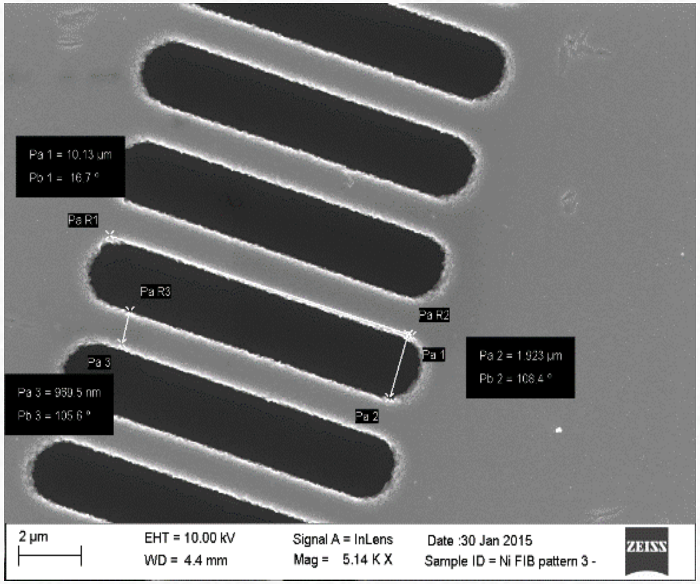
Target (metal microstructures embedded in diamond substrate)

- Outstanding thermal conductivity (5x of Cu)
- Large thermal gradient (due to microstructures)
- Favorable energy deposition in target (low mass density of diamond)
- Optimal linear accumulation of x-rays at low take-off angle (low attenuation of diamond)

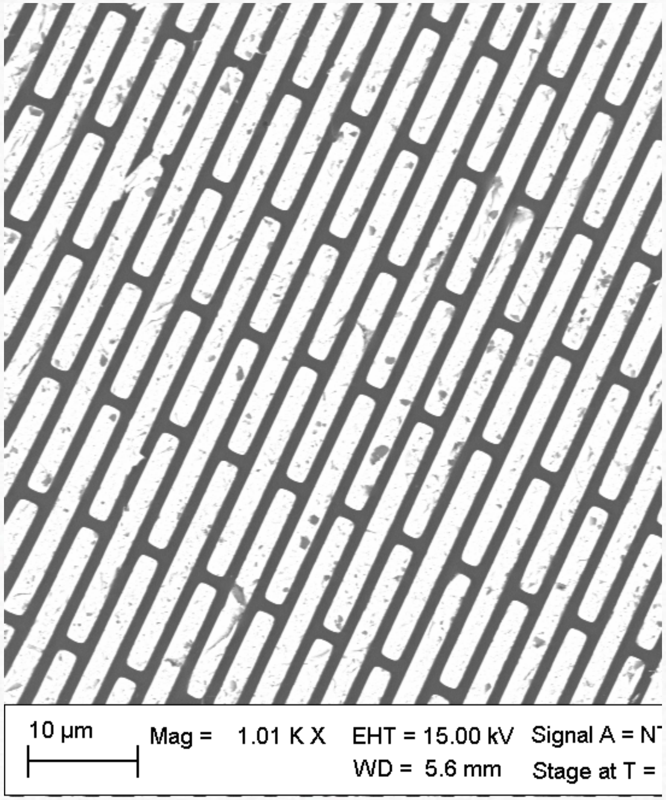
4x higher thermal loading than a solid copper target ➔
up to 50x total brightness gain from optimal linear accumulation and better thermal property

Benefits: Better anode thermal property + optimal linear accumulation of X-rays
Results: Higher source brightness and choice of characteristic lines

Fabrication of microstructured anode array target

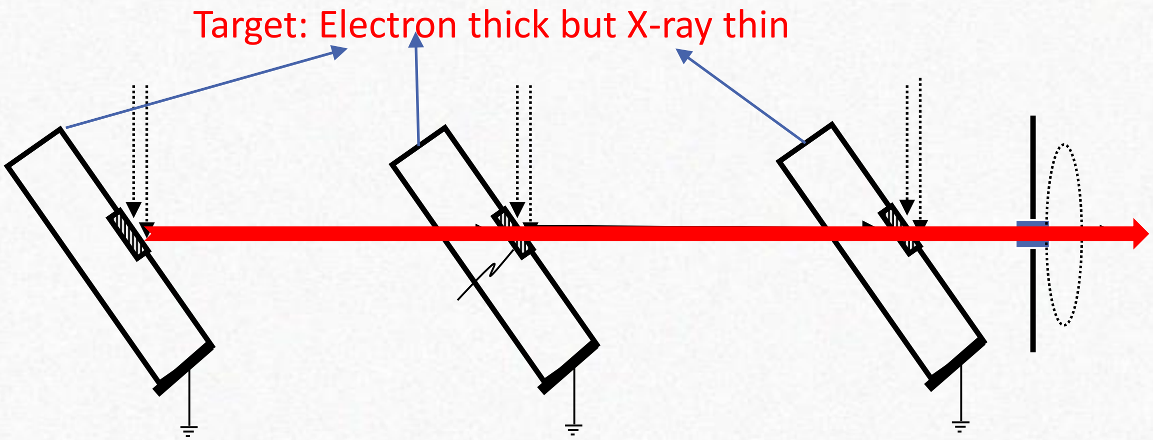


1^{sT} Step: Etch microstructures in diamond substrate



2nd Step: Filling metal in diamond substrate

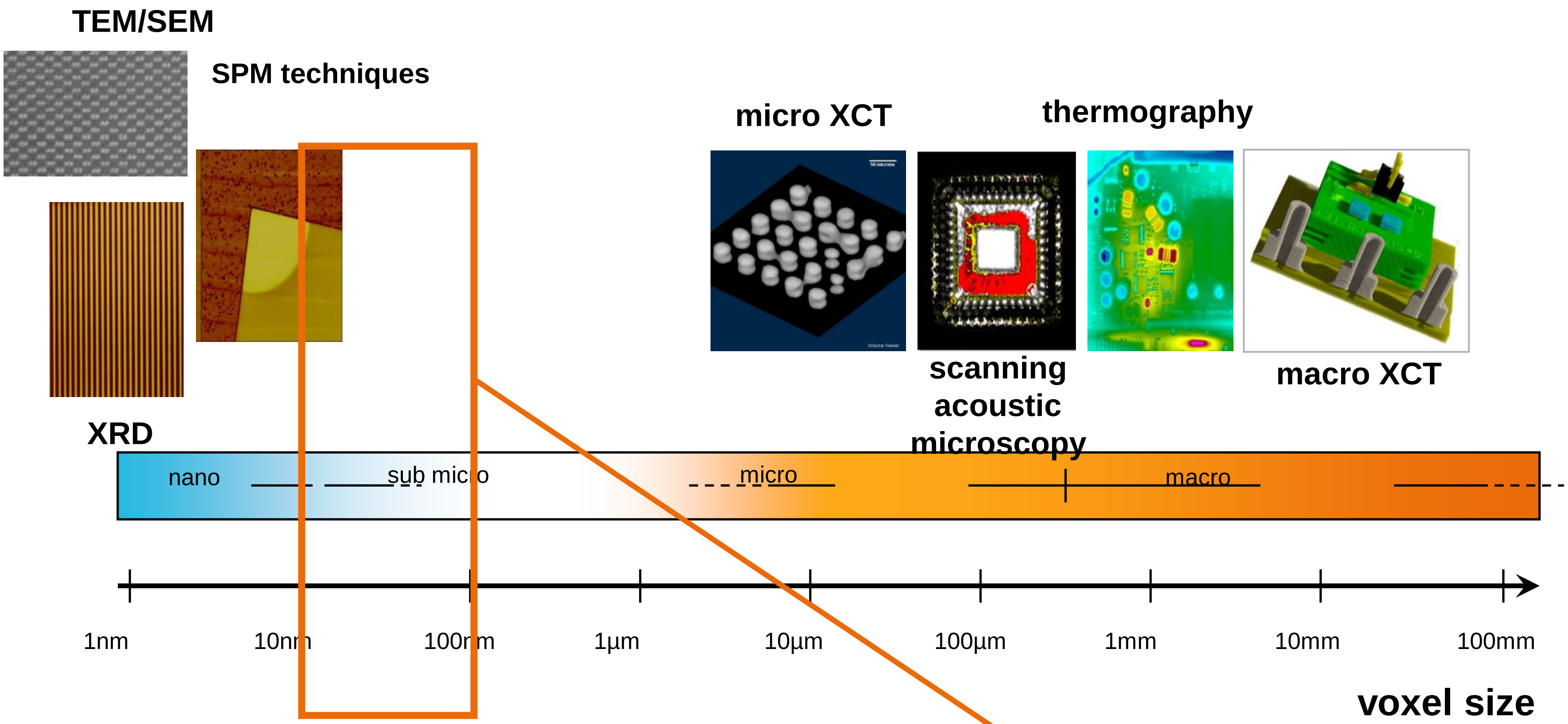
New source concept:
MAAST (Multi Anode Array Source Technology)


Target: Electron thick but X-ray thin

Accumulation of X-rays from multiple anode array sources

Important fact: X-ray penetration is substantially larger than electron penetration, especially for low Z element materials such as diamond.

X-ray imaging perspectives (next 3 years)



TEM/SEM

SPM techniques

micro XCT

thermography

scanning acoustic microscopy

macro XCT

XRD

voxel size

Nano Transmission X-ray Microscopy (TXM) / nano XCT with novel X-ray optics: 10 … 100 nm resolution

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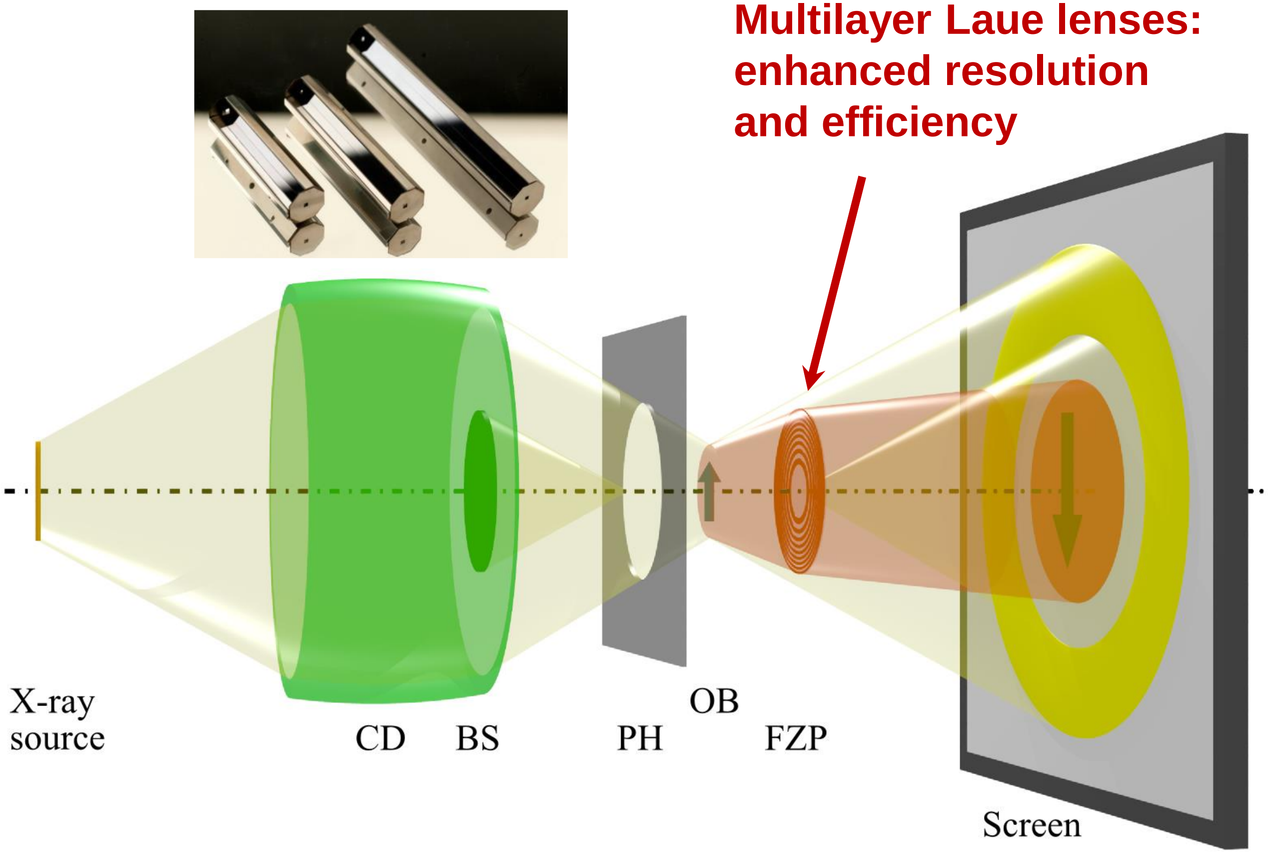
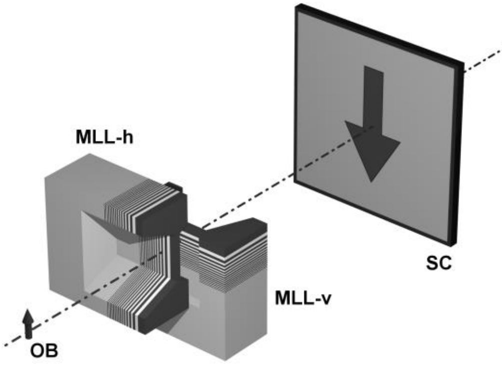
Approach to improve resolution and to extend lab-based X-ray microscopy to higher energies: Focusing condenser optics and Multi-layer Laue lenses

Multilayer Laue lenses: enhanced resolution and efficiency

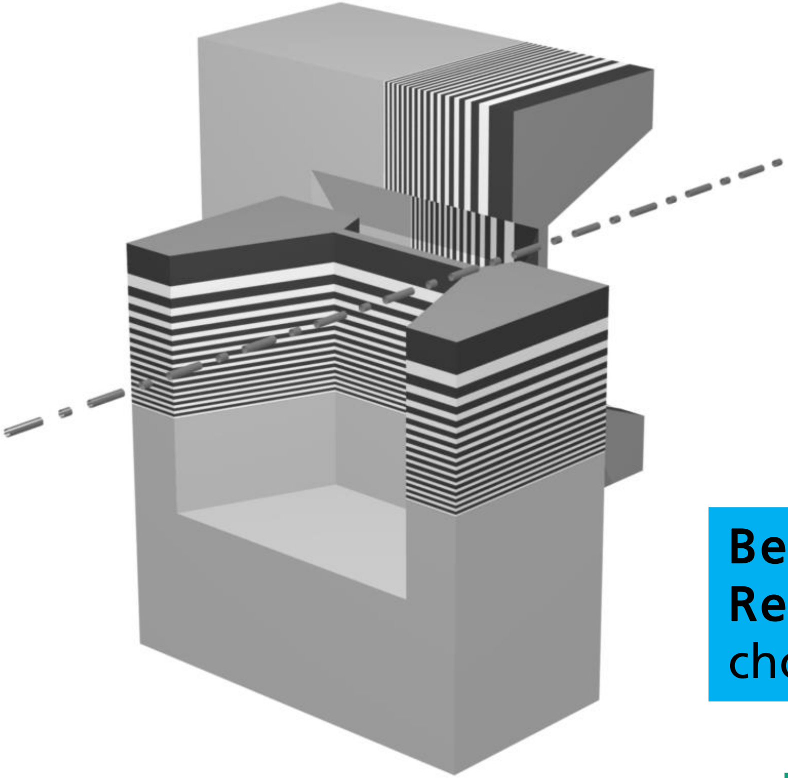




S. Niese et al., 2nd Dresden Nanoanalysis Symposium 2014, XRM 2014

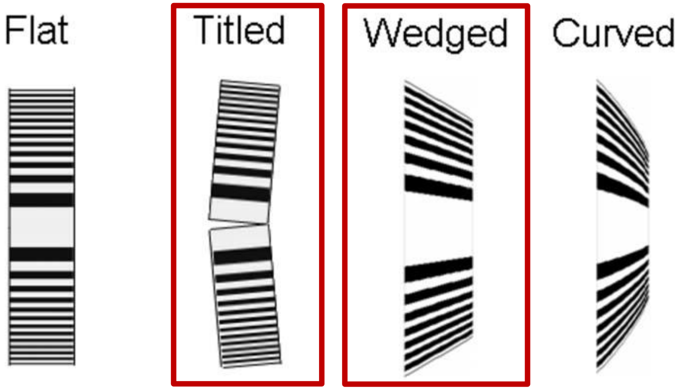
New lense concept: Multilayer Laue lenses ➔ Advantages: High resolution (… 10 nm) high photon energies (> 10 keV)

- Crossed partial MLLs: two-dimensional focusing and imaging



S. Niese, PhD Thesis 2014
S. Niese et al., Optics Express 2014

- MLL geometries

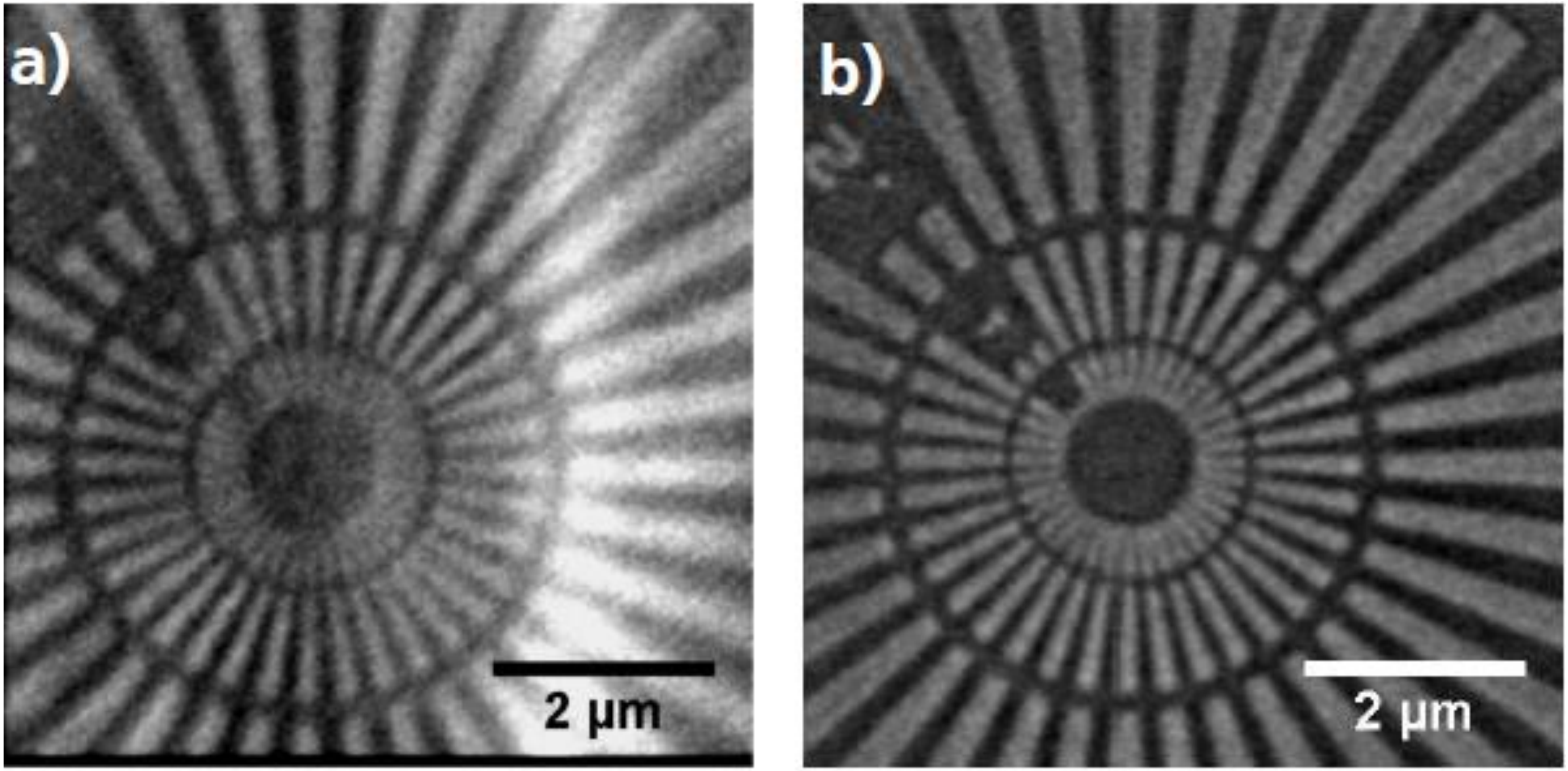


H. Yan et al. Physical Review B ***76****.11, p. 115438 (2007)*

- Tuning the optics: Tilting, wedging, curving

Benefits: Thinner films + higher A/R
Results: Higher resolution and efficiency, choice of X-ray energies > 10 keV

Proof of concept: FZP vs. MLL



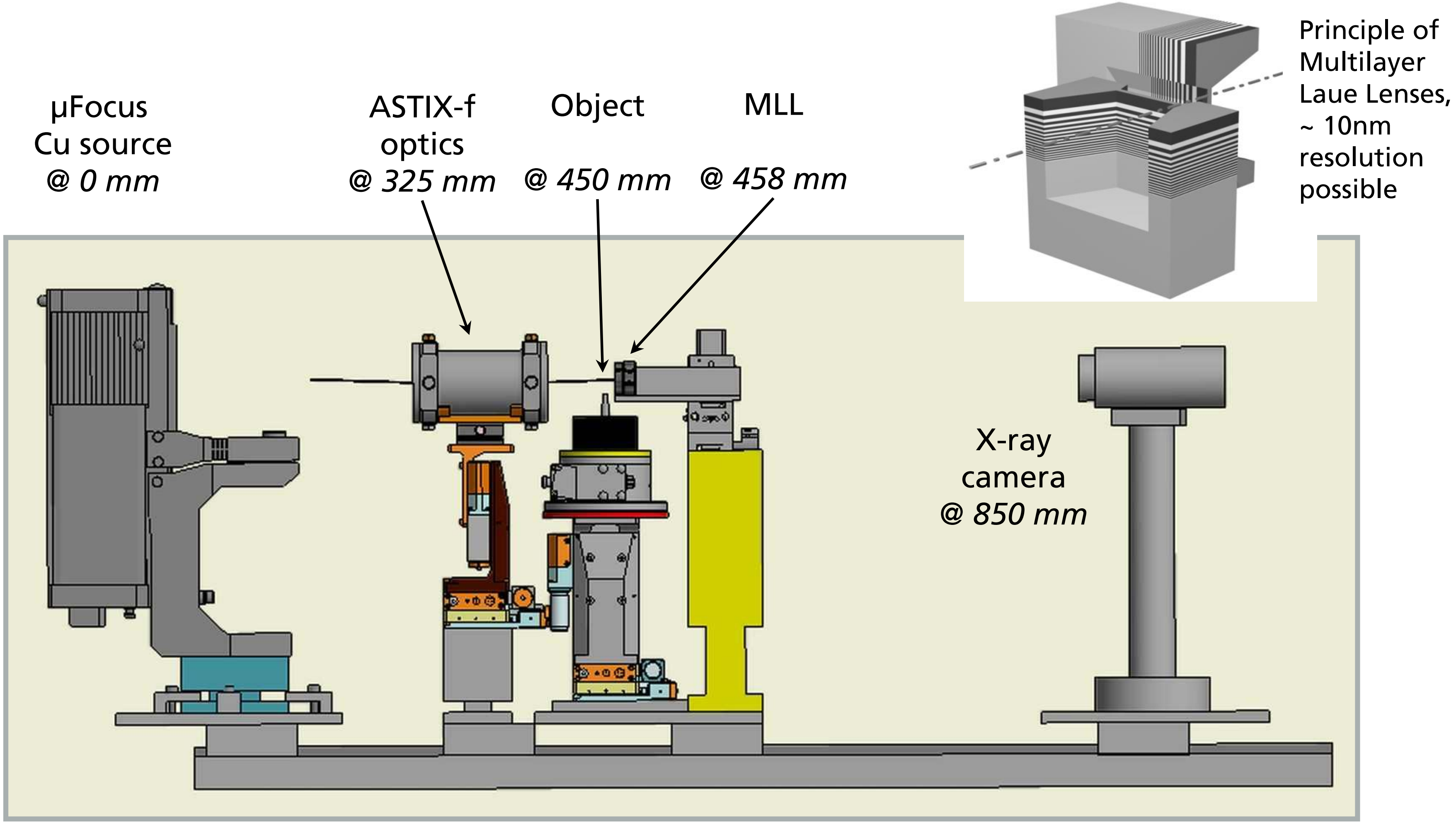
Multi-Layer Laue Lense

Fresnel Zone Plate

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

Advanced X-ray microscopy with MLL optics

Partners: Fraunhofer IKTS, IWS and AXO DRESDEN GmbH

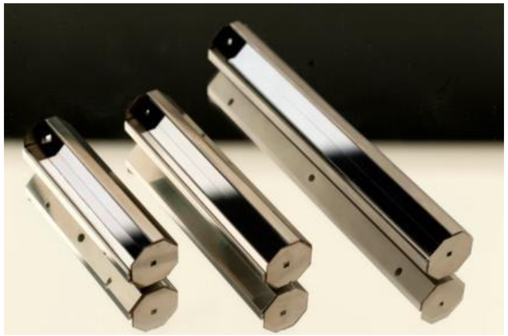


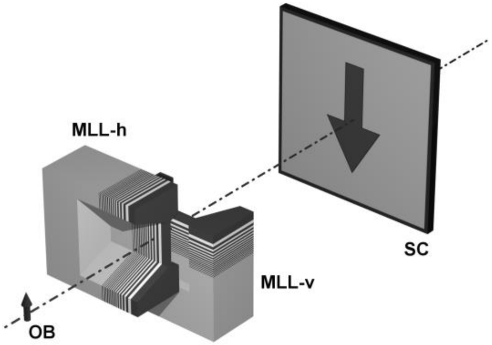
S. Niese, PhD Thesis 2014
S. Niese et al., Optics Express 2014
S. Niese et al., 2nd Dresden Nanoanalysis Symposium
Dresden, July 2014

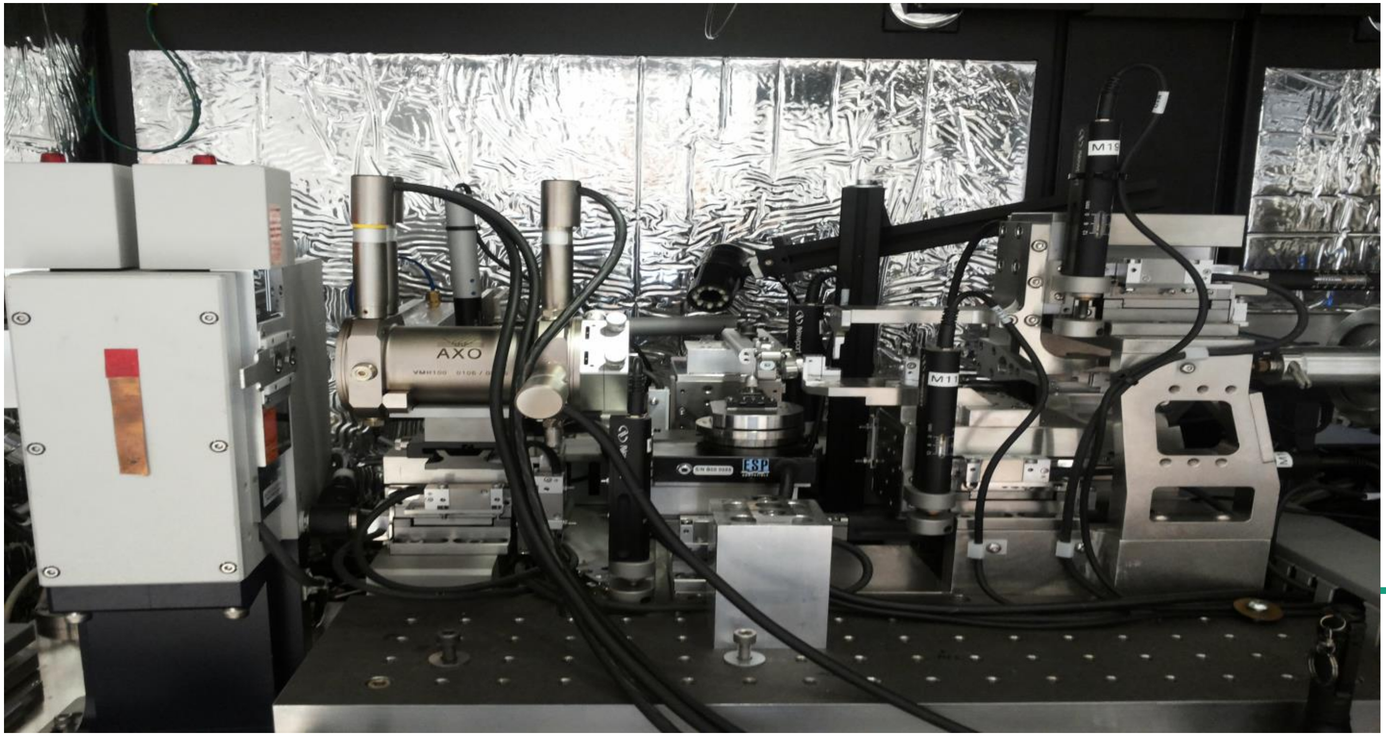
Novel laboratory X-ray microscopy setup at Fraunhofer IKTS for high photon energies

X-ray source: Rotating anode (Mo)
Plan: FAAST source

X-ray optics:
2D focusing mirror “ASTIX-f”
(AXO Dresden)
+ crossed multilayer Laue lense







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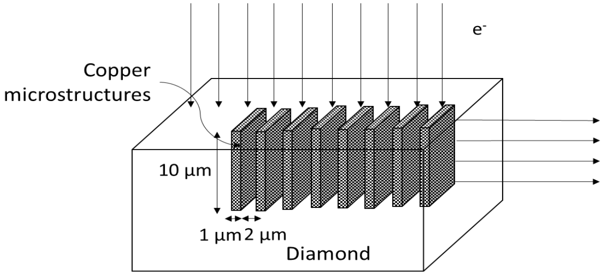
Lab-based X-ray microscopy/tomography – Future

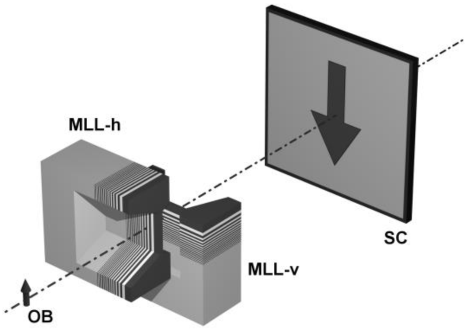
X-ray microscopy with novel sources (High-flux FAAST source)



Increased brightness

➔ *shorter measurement times (industrial applications in semiconductor industry, kinetic studies)*

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



Resolution improvement to 10nm (… 1nm)

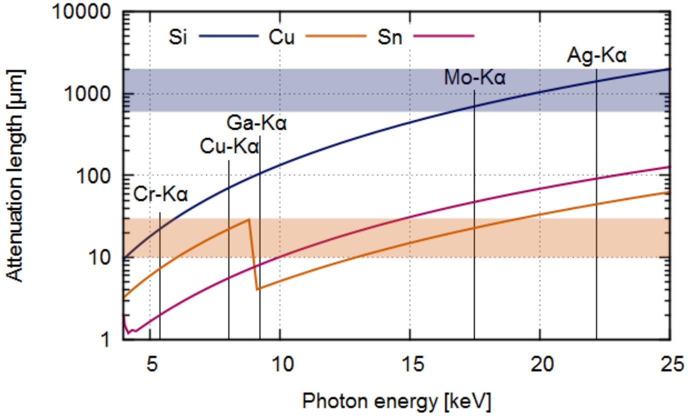
➔ *down-scaled structures and defects in materials, …*

Larger working distance (~ 5 cm)

➔ *chambers (temperature, media, …), mechanical tests (crack propagation)*

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

➔ *penetration of whole wafers, wafer stacks*



Outline

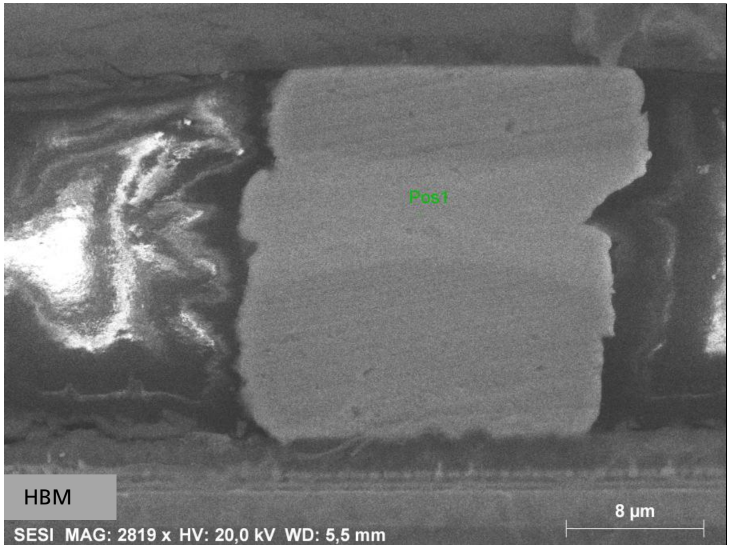
Characterization of microbumps in HBM stacks: micro and nano XCT

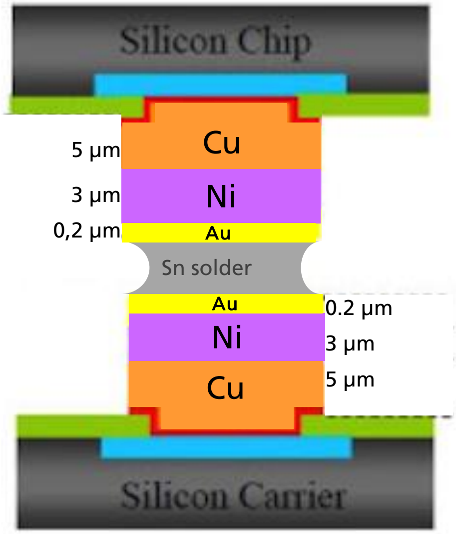
State of the art X-ray microscopy and nano X-ray tomography

Novel solution: Improved experimental setup and components

Detectable parameters for 3D advanced packaging metrology

Solder bump cross-section and detectable parameters





Exemplary presentation, thicknesses are representing a possibility only

ENIG (Electroless Nickel Immersion Gold)

Detectable parameters:

- Monitoring of geometrical shape of microbumps and their chemical composition (including formed intermetallic phases),
- Detection of defects like pores and microcracks (also in relation to formed intermetallic phases) with high resolution.

In addition: nondestructive and high throughput (short time-to-data)

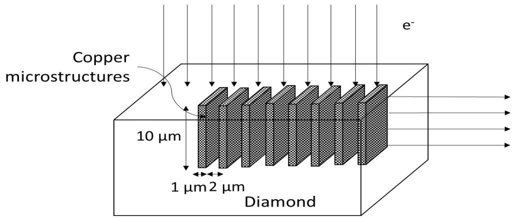
➔ New X-ray sources and optics provide the way for XCT application in advanced packaging!

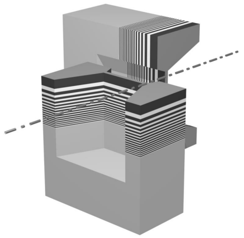
Take-away message

Lab-based sub-micro XCT and nano XCT at multiple photon energies offer intrinsic advantages for 3D imaging and high-throughput metrology for advanced semiconductor packaging, but expected firstly introduced to physical failure analysis:

- Sub-micron XCT in projection geometry (no focusing lenses) down to 0.3 µm resolution (known as “resolution gap”), *based on novel high-flux X-ray sources* ➔ higher throughput, bridging the “resolution gap”

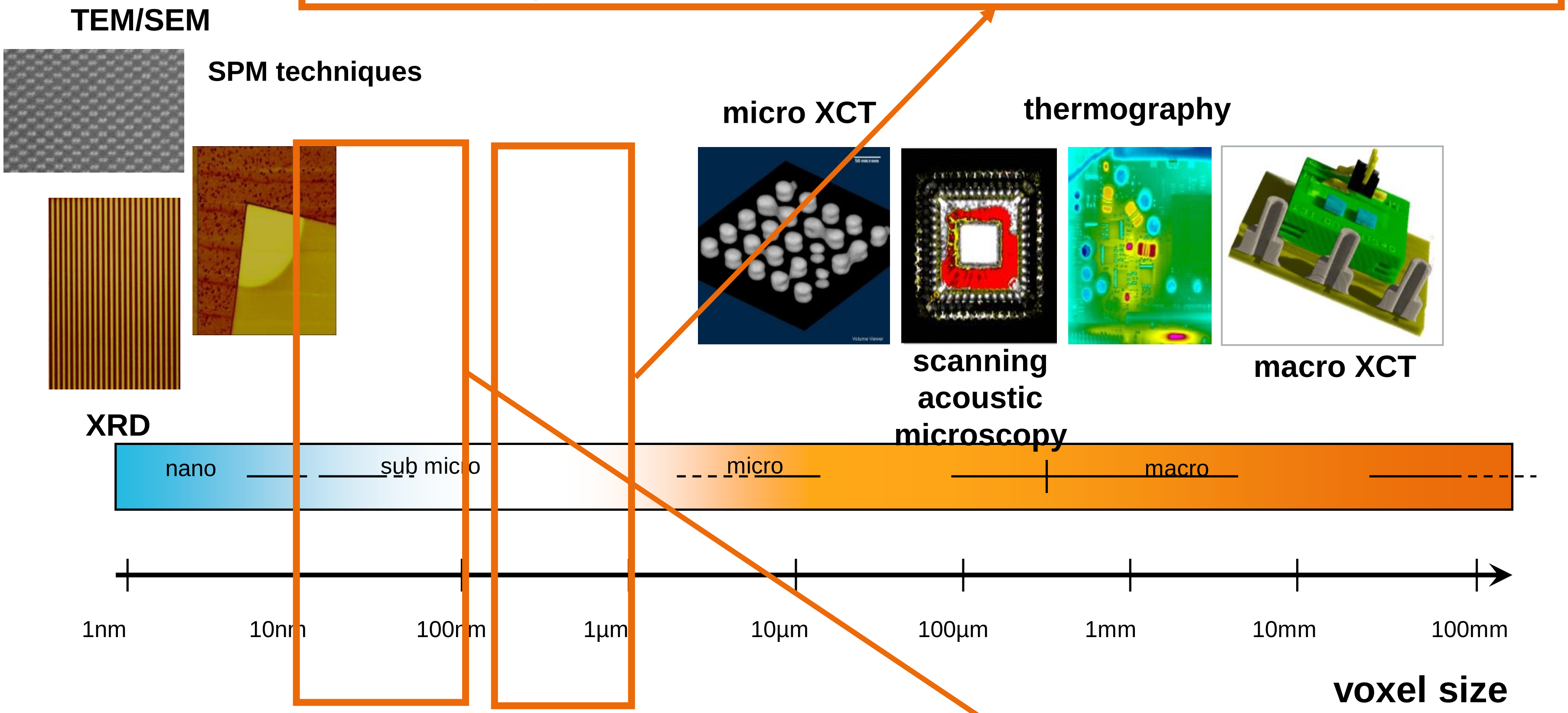
- Nano XCT based on X-ray microscopy (with focusing lenses) at multiple photon energies (incl. > 10 keV) down to 10 nm resolution and *based on novel high-flux X-ray sources and novel high-efficiency X-ray optics* (MLL) ➔ higher throughput (no or less efforts for sample preparation), extending the resolution range to 10nm.





X-ray imaging perspectives (next 3 years)

Sub-micron XCT with novel X-ray sources:
0.3 … 1.0 µm resolution



Nano Transmission X-ray Microscopy (TXM) / nano XCT
with novel X-ray optics: 10 … 100 nm resolution

Thank you !

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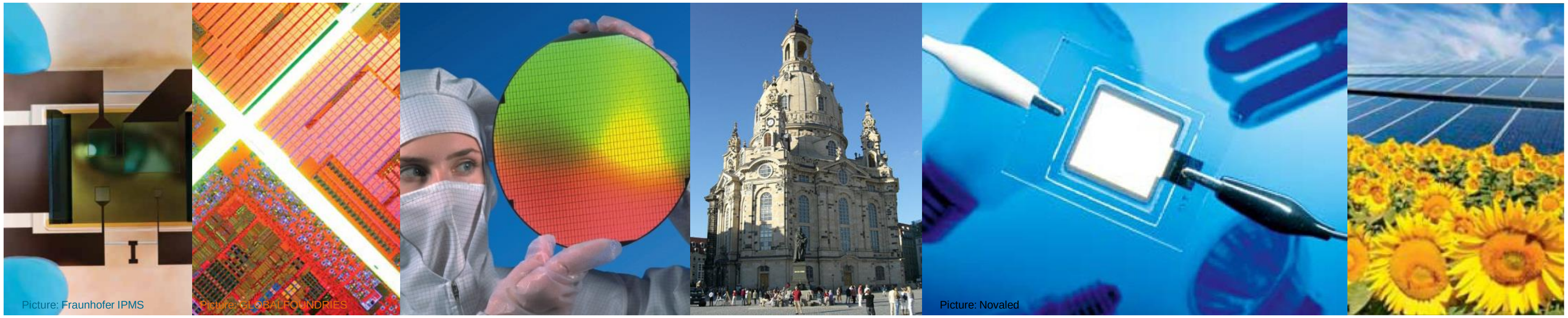

Picture: Fraunhofer IPMS

Picture: GLOBALFOUNDRIES

Picture: Novaled

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