REALLY NONDESTRUCTIVE HIGH-RESOLUTION X-RAY COMPUTED TOMOGRAPHY FOR ADVANCED PACKAGING APPLICATIONS

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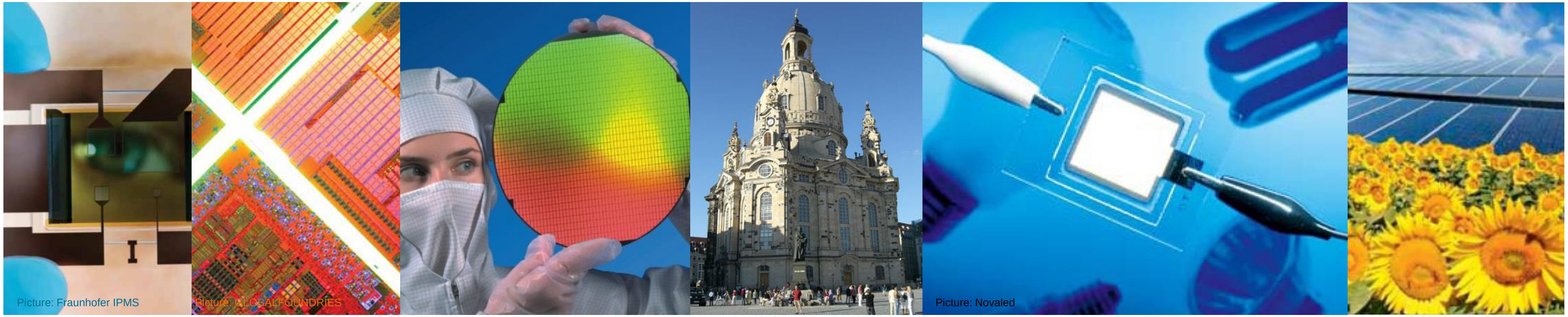

Picture: Fraunhofer IPMS

Picture: GLOBALFOUNDRIES

Picture: Novaled

FCMN Conf., Monterey/CA, 4 April 2019

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Outline

1. High-resolution XCT for 3D metrology and diagnostics
   - Advanced packaging ➔ Micro-bumps
   - Chip-package interaction ➔ BEoL

2. High-energy nano XCT: Needs and possibilities

3. New multi-energy XCT for nondestructive 3D advanced packaging imaging: Fast, high resolution, really nondestructive

4. Future laboratory X-ray microscopy: Full-field vs. scanning X-ray microscopy

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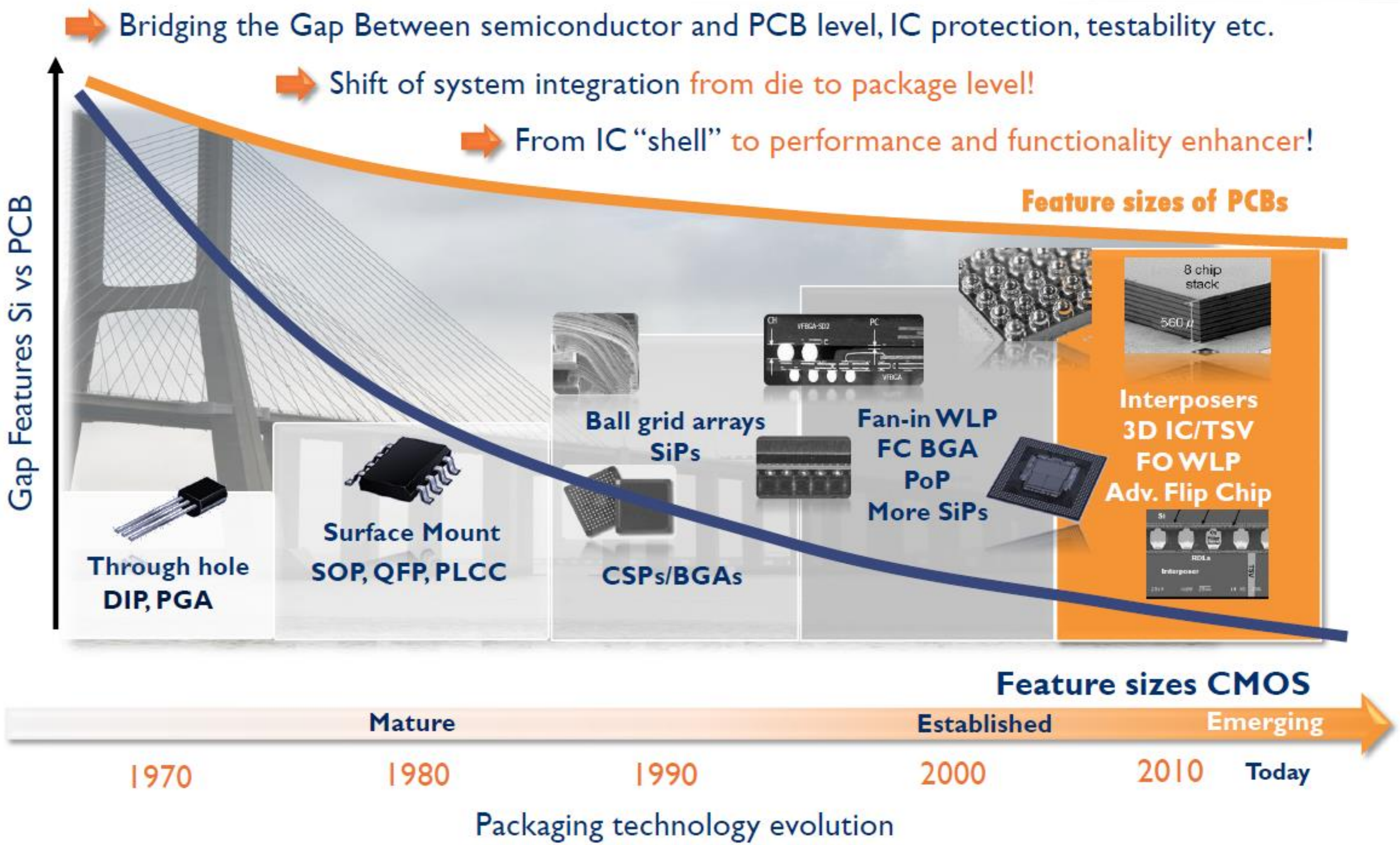
4. Future laboratory X-ray microscopy: Full-field vs. scanning X-ray microscopy

MICROELECTRONIC PACKAGE EVOLUTION

Increase in Packaging Technology Solutions



What is new in advanced packaging / 3D heterogeneous system integration ?

New design / architecture

- Bridging the gap between traditional Si ICs and PCBs
- Enhance system integration to package level
- Package is an (additional) booster for performance and functionality

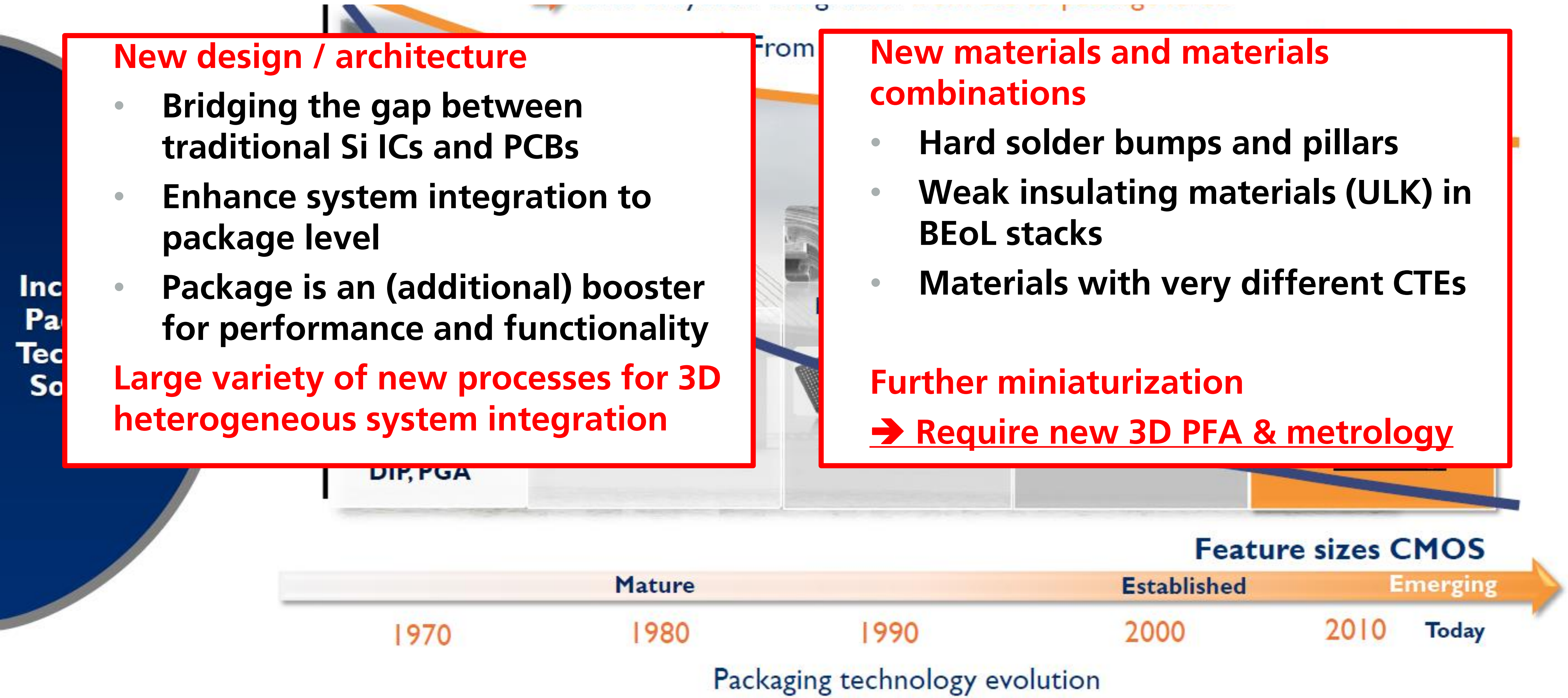
Large variety of new processes for 3D heterogeneous system integration

New materials and materials combinations

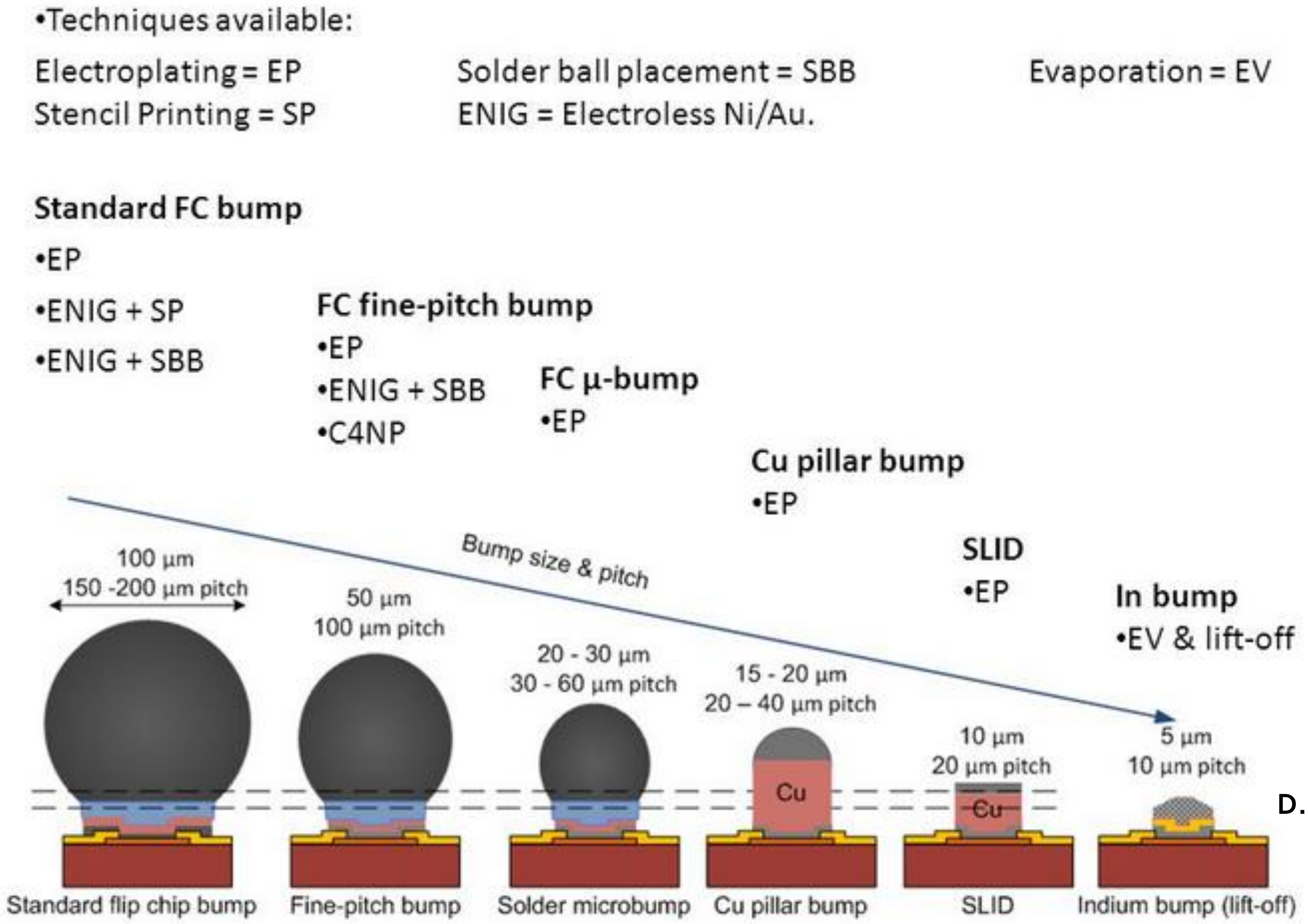
- Hard solder bumps and pillars
- Weak insulating materials (ULK) in BEoL stacks
- Materials with very different CTEs

Further miniaturization

➔ Require new 3D PFA & metrology

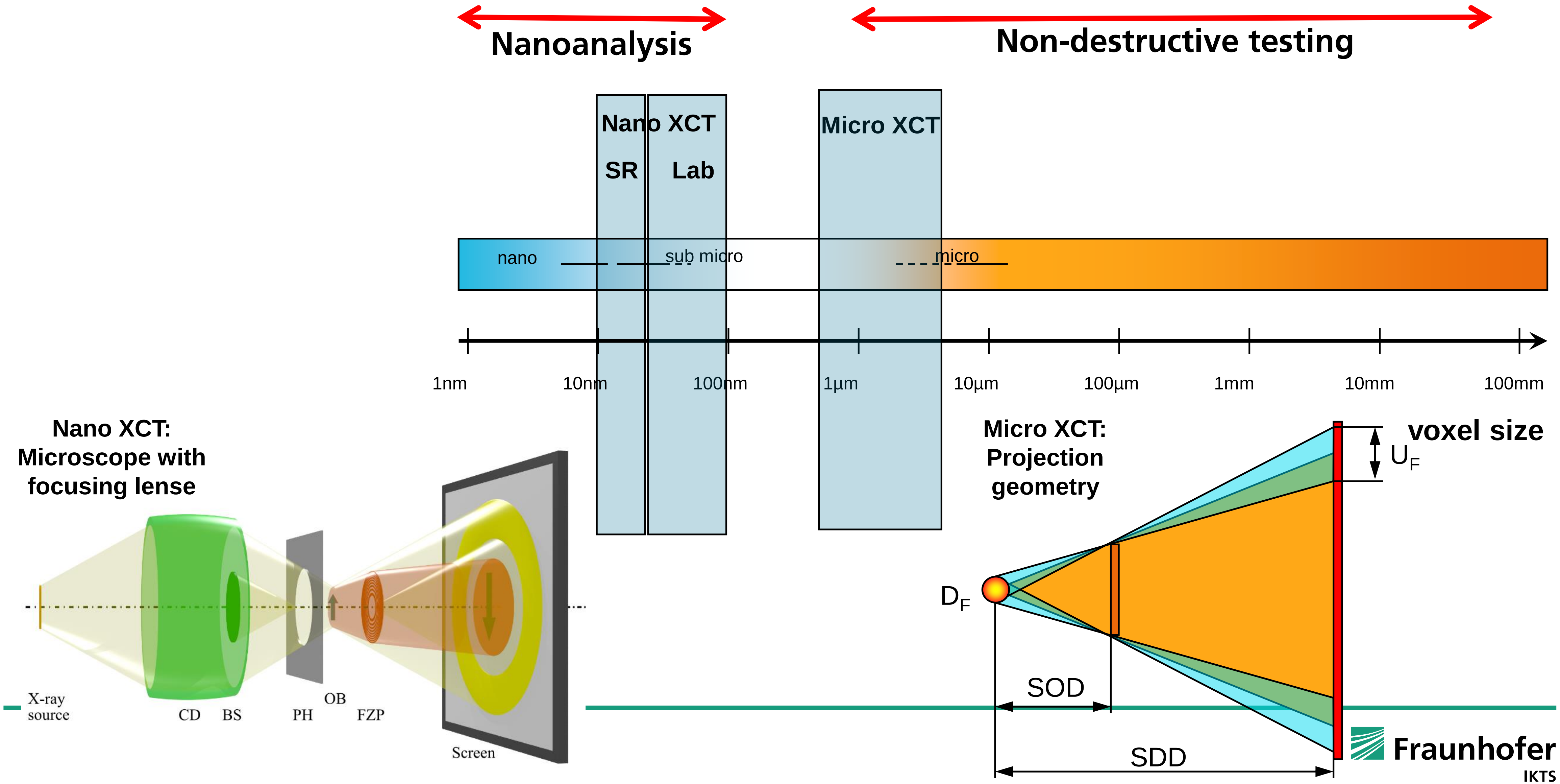


Microbump evolution: Processes, materials stacks and dimensions



D. Dannheim et al., CERN 2018

3D characterization of defects in materials and products using laboratory X-ray computed tomography (XCT)



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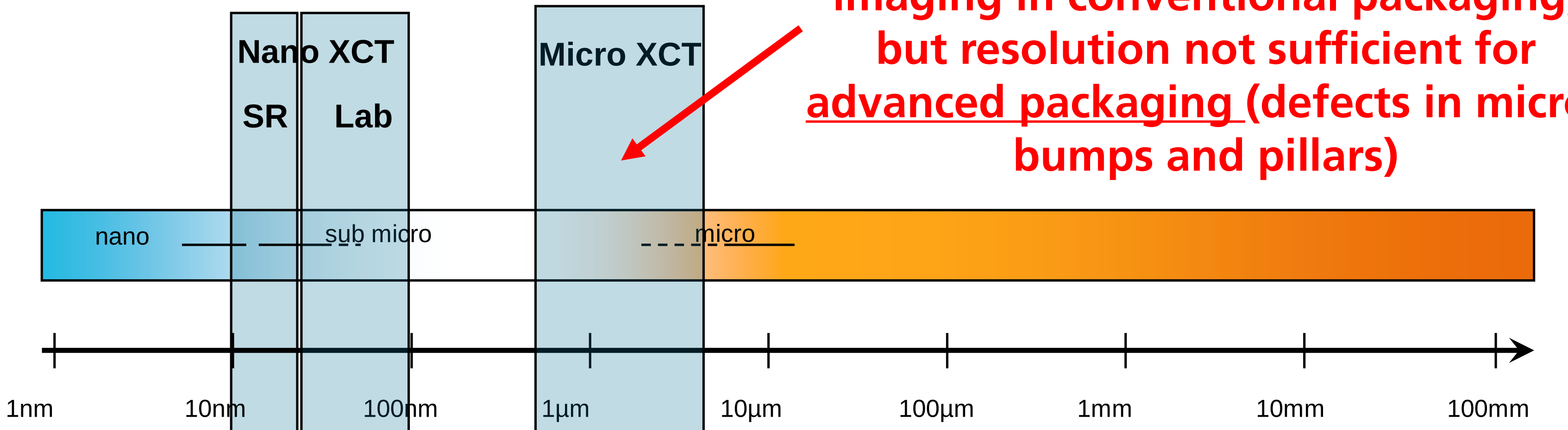
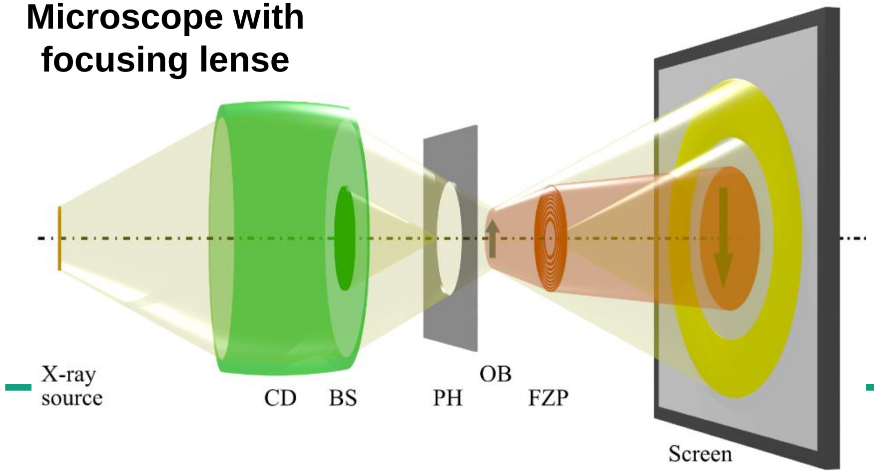
3D characterization of defects in advanced packaging using laboratory X-ray computed tomography (XCT)

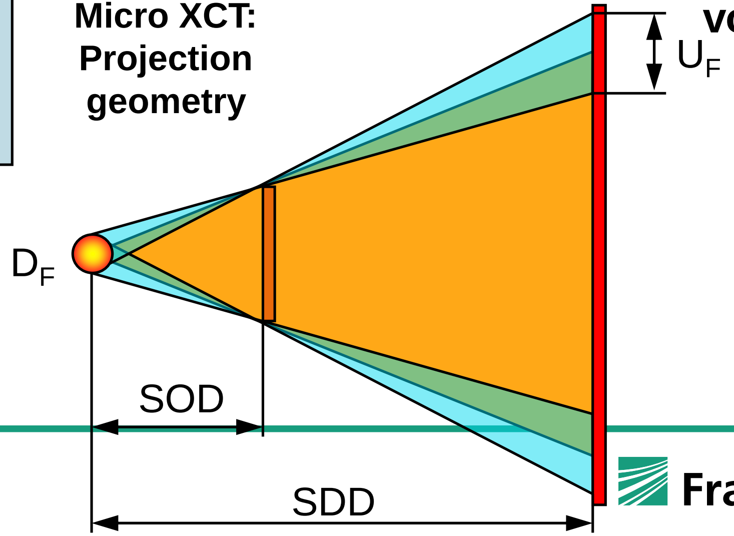
State-of-the-art technique for 3D imaging in conventional packaging, but resolution not sufficient for <u>advanced packaging</u> (defects in micro-bumps and pillars)



Nano XCT: Microscope with focusing lense



Micro XCT: Projection geometry



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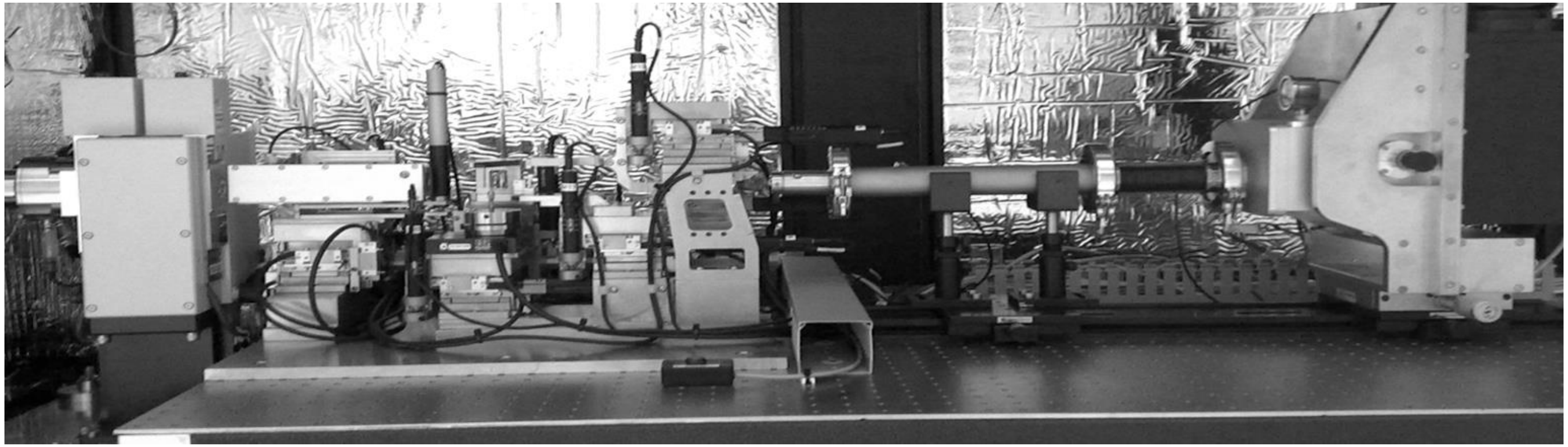
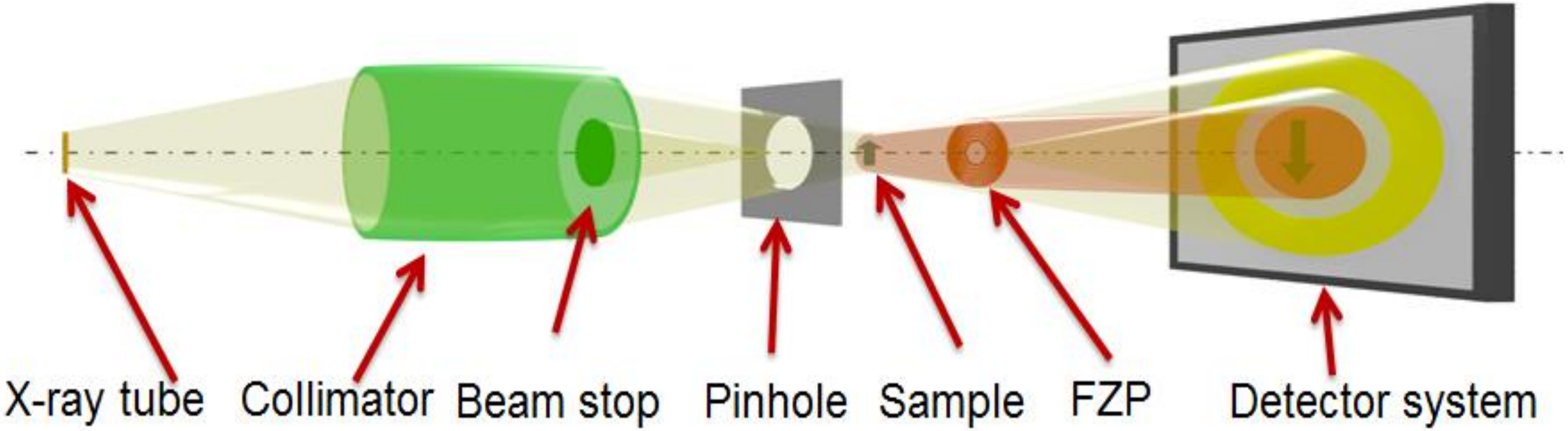
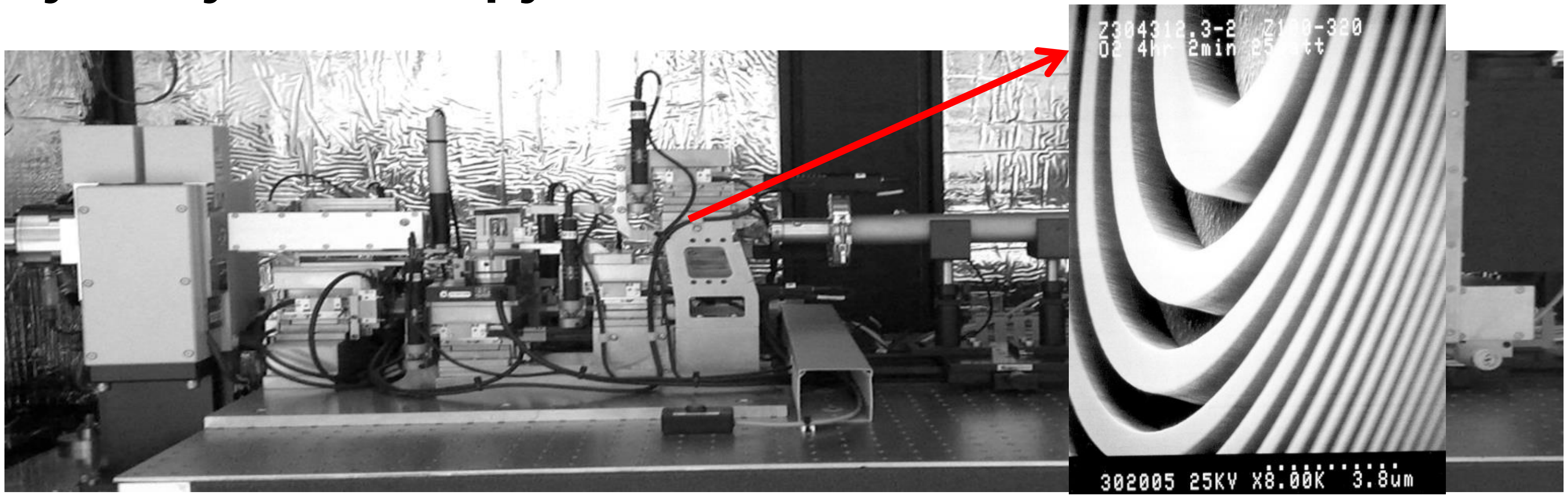
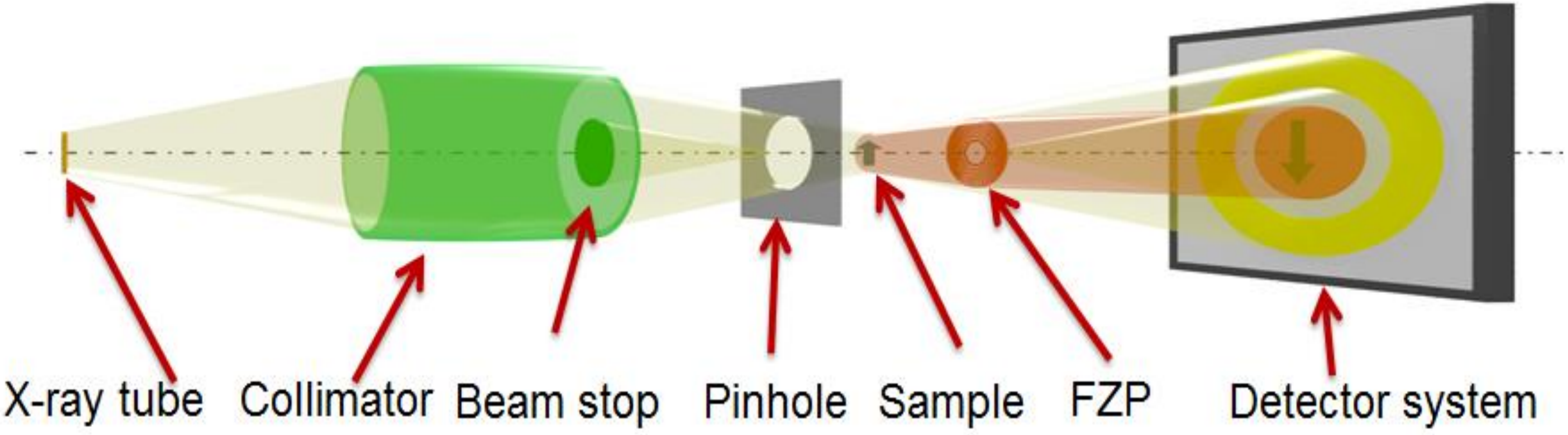
Laboratory X-ray microscopy and nano XCT





Laboratory X-ray microscopy and nano XCT





2D vs. 3D metrology and diagnostics in microelectronics

- Product trends
  - New device architectures: 2D → 3D (FinFET, trigate, FDSOI, NVM, …)
  - 3D chip integration / advanced packaging

- 3D architectures require 3D metrology and diagnostics → "metrology gap"
  - Fast metrology and diagnostics (time-to-data)
  - Nondestructive vs. destructive

  for device (transistor), BEoL, advanced packaging !

- Industrial needs / challenges:
  - Challenges from *new materials / smaller dimensions* on wafer (new gate stacks, new NVM, BEoL stacks, …)
  - Challenges from *advanced packaging* (e.g. micro-bumps, pillars, …)

2D vs. 3D X-ray imaging

2D X-ray imaging is a matured and widely used analytical method for diagnostics/failure analysis in microelectronics

- **Demonstrated capability for defect detection**
- **Real time nature**
- **Availability of automated defect detection routines**

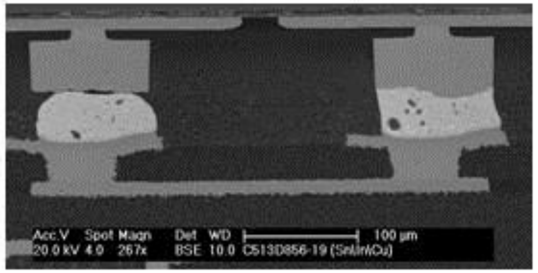
Technical challenges for 2D X-ray imaging are:

- **Development of smaller / more complex packages**
- **Small defects with a lot of interfering features in the FOV**
- **Increasingly difficult and sometimes impossible to image certain defects in non-destructive fashion**
- **Samples often require preparation that may produce artifacts.**

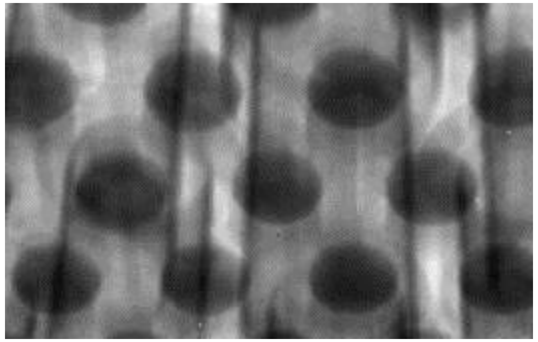
The fundamental limitations of 2D X-ray imaging are a common roadblock driving XCT for failure analysis in semiconductor industry.

➔ conventional packaging: micro XCT

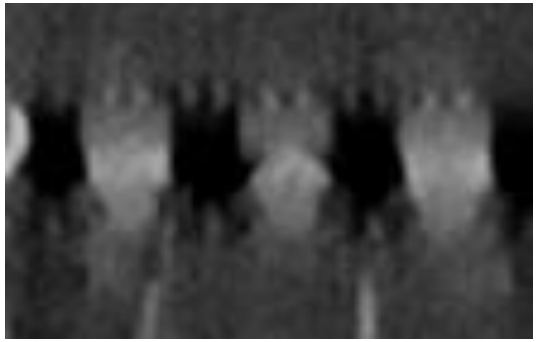
➔ BEoL + advanced packaging: nano XCT



Physical X-section C4 bump



Best 2D radiography ➔ defect not visible!



Virtual X-section based on 3D XCT

High-resolution 3D imaging needs for interconnects: Advanced packaging and BEoL

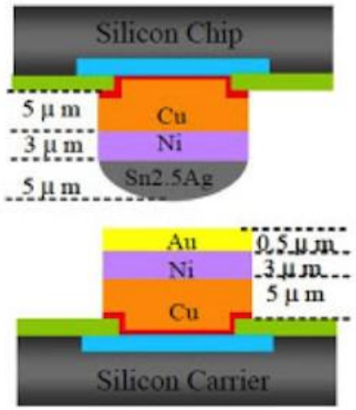
- **Phenomena in advanced package structures**
  - **(Thermo)mechanical failures - Delamination / micro-cracks in interconnect systems**
    - Micro-cracks in thinned silicon
    - ***Failures in microbumps (micro-cracks)***
    - Delamination and cracks in 3D (TSV) / RDL structures

- **Enforcement of (known) phenomena in BEoL structures**
  - **(Thermo)mechanical failures – Cracks in interconnect systems**
    - ***Failures in BEoL structures (micro-cracks)***
  - **Stress-enforced lifetime reduction / electrical effects**
    - Electromigration
    - Stress-induced voiding
    - Time-dependent dielectric breakdown

High-resolution 3D imaging needs for interconnects: Advanced packaging and BEoL

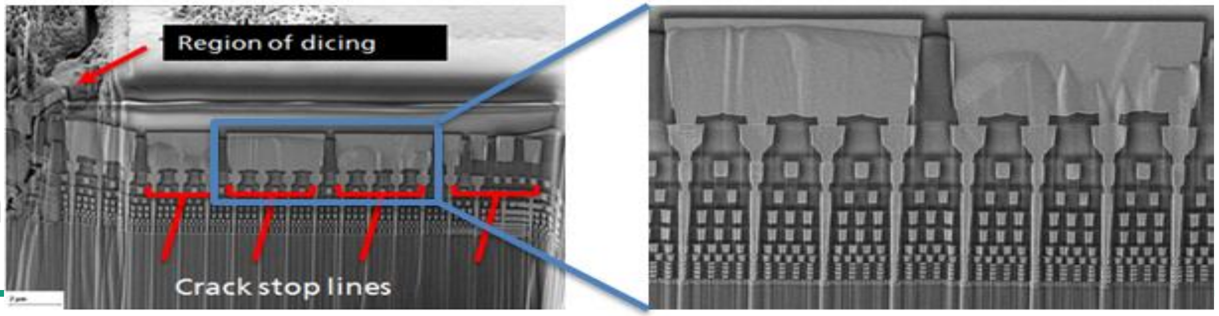
- Phenomena in advanced package structures
  - (Thermo)mechanical failures - Delamination / micro-cracks in interconnect systems
    - Micro-cracks in thinned silicon
    - *Failures in microbumps (micro-cracks)*

      3D imaging of geometry of and defects in micro bumps



- Enforcement of (known) phenomena in BEoL structures
  - (Thermo)mechanical failures – Cracks in interconnect systems
    - *Failures in BEoL structures (micro-cracks)*

      3D imaging of stress-induced crack propagation in BEoL stacks (CPI)
    - Electromigration
    - Stress-induced voiding
    - Time-dependent dielectric breakdown



Demonstration of XCT application for metrology and diagnostics/failure analysis

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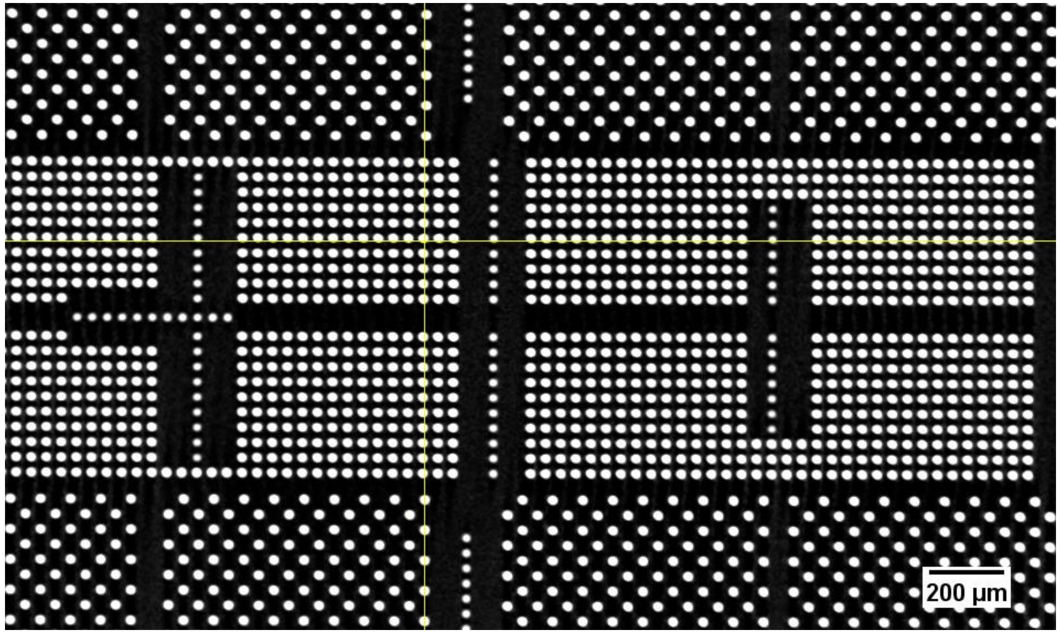
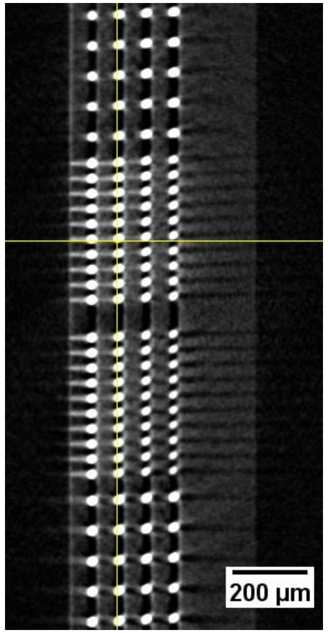
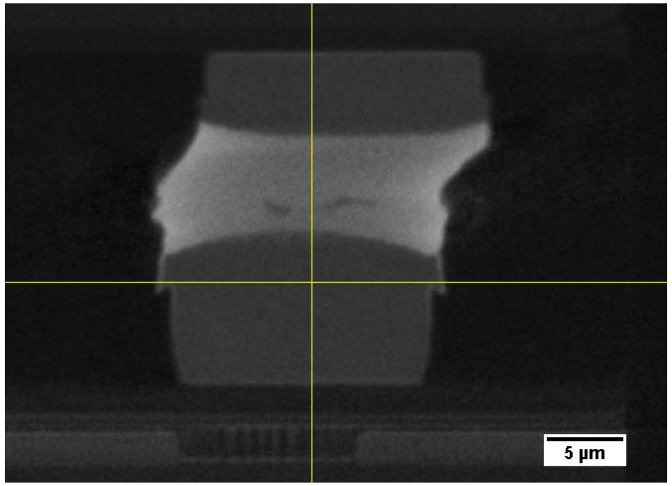
Example: Micro-bumps in 3D IC stacks – HBM

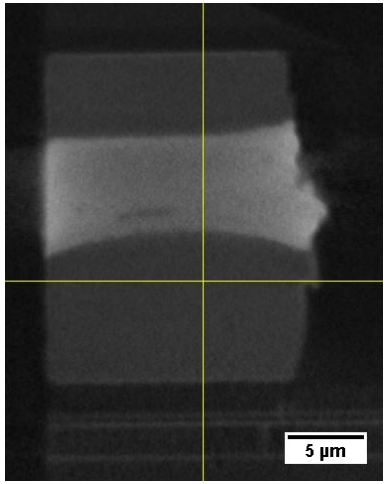
High bandwith memory (HBM) stack:

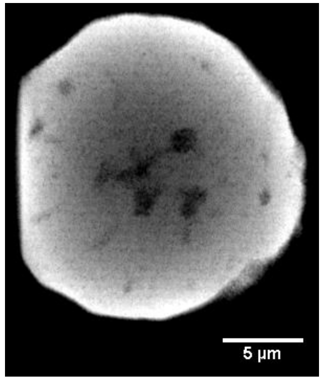




Two virtual 2D images (planar view and cross-section view), based on a 3D data set from *micro XCT*. Nondestructive imaging.



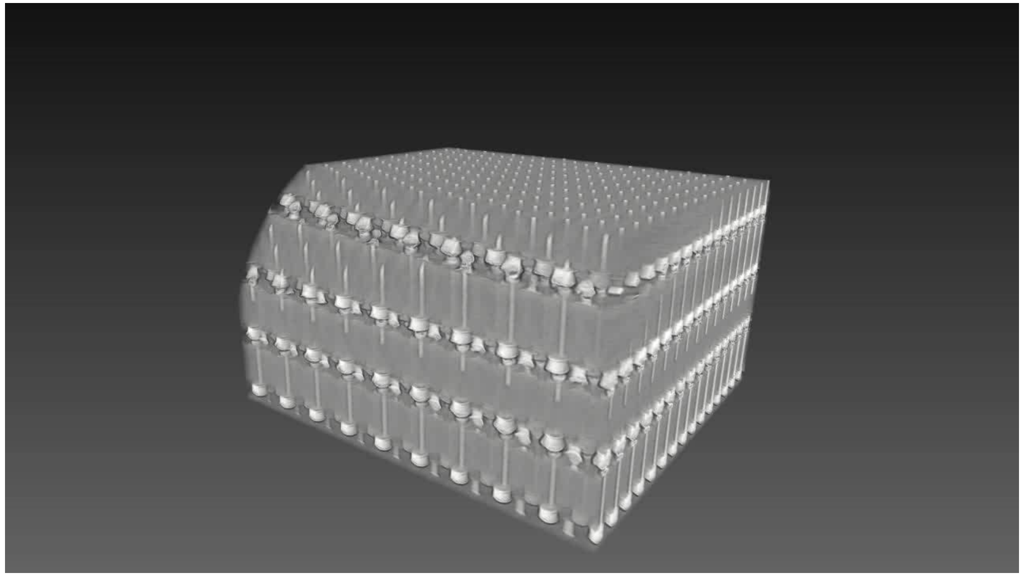


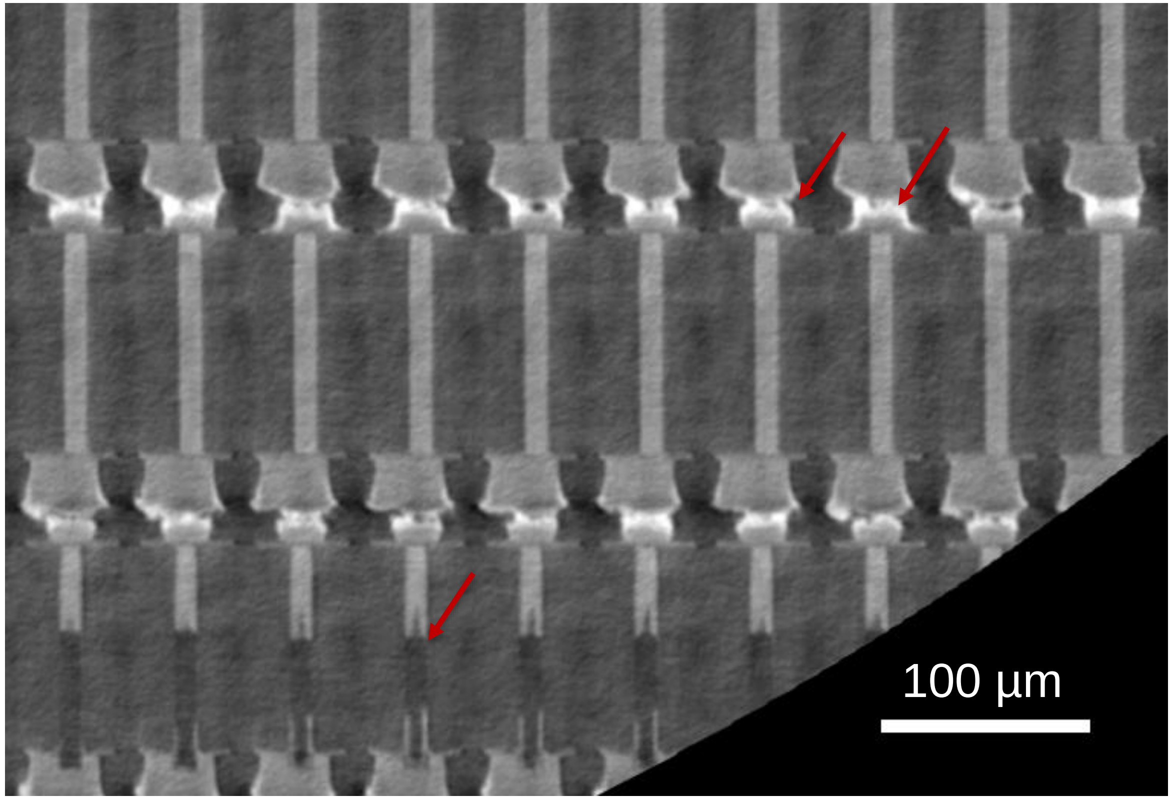


Three virtual 2D images (two perpendicular cross-section views and one planar view), based on a 3D data set from *nano XCT*. Imaging of a small extracted sample.

E. Zschech et al., FCMN 2017
E. Zschech et al., IRSP 2018

Multi-chip 3D TSV stack with micro bumps – *Micro XCT*

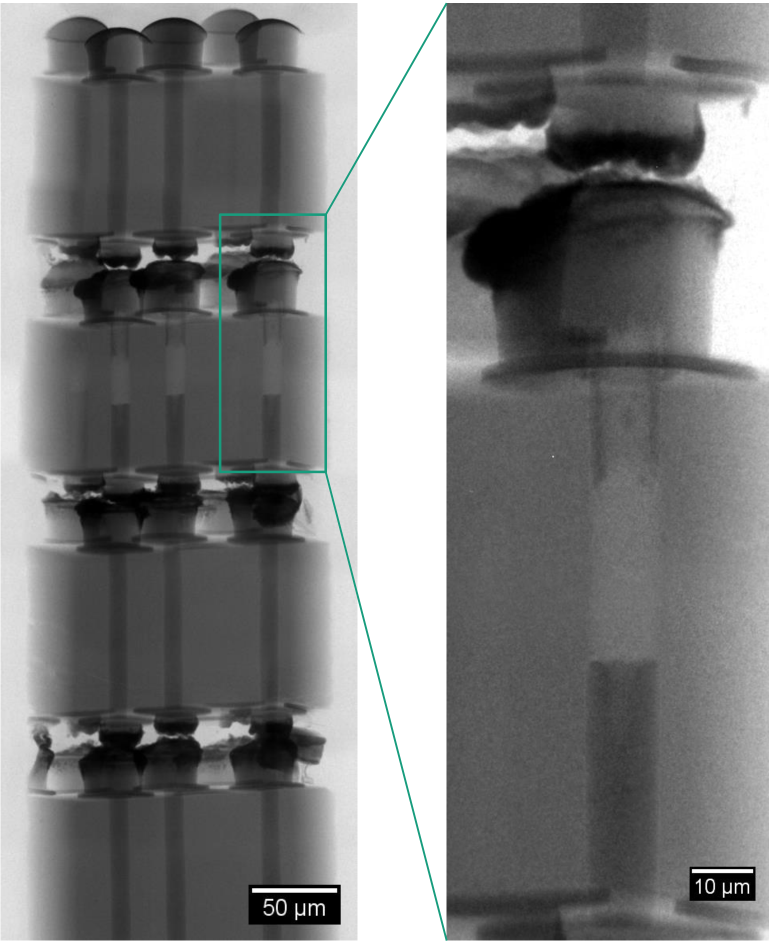


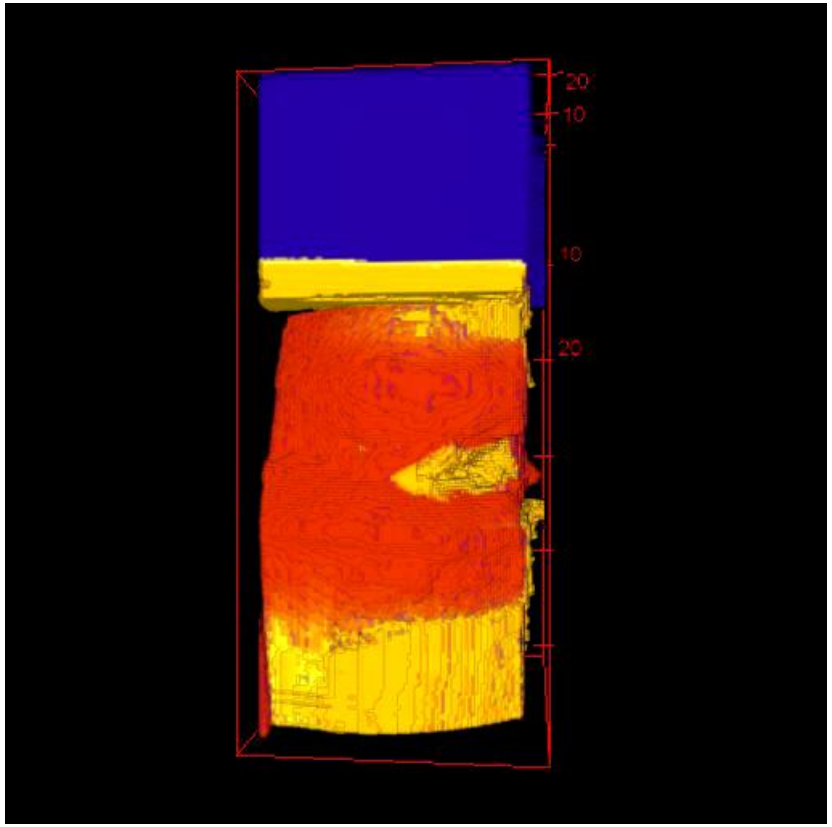


Incomplete Cu TSV filling, variation in solder flow (AgSn)

E. Zschech et al., PanPac 2015

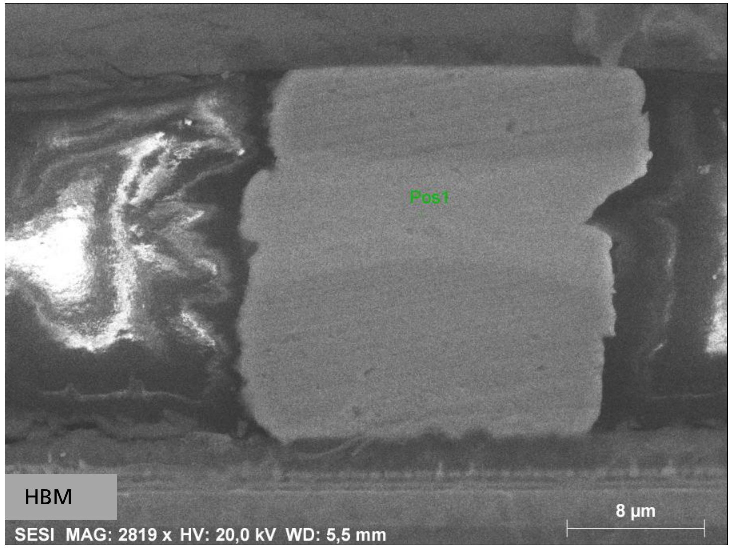
Multi-chip 3D TSV stack: micro bumps – *Nano XCT*

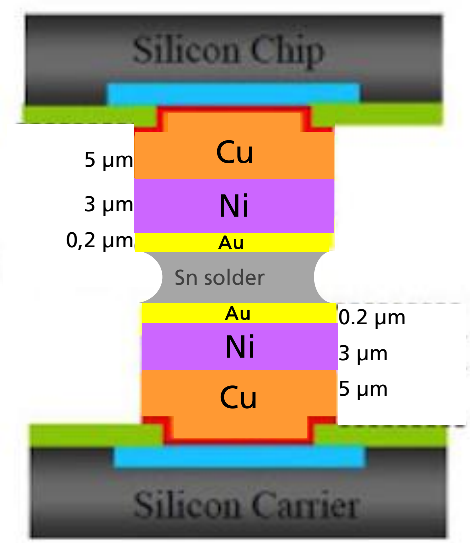




Tomography of a AgSn microbump

XCT parameter determination and monitoring - Microbumps





Exemplary presentation, thicknesses are representing a possibility only

ENIG (Electroless Nickel Immersion Gold)

- **Geometry: Shape of the solder interconnect**
- **Metallurgy: Chemical composition, location of intermetallic phases**
- **Defects: Pores, micro-cracks (also in relation to intermetallic phases)**

Advanced Packaging & Novel Material Combinations
➔ Chip Package Interaction (CPI)

Mechanical properties of (ultra-)low-k materials in the BEoL stack are critical

(POR: CVD porous organosilicate glass (OSG) thin films)

➔ adhesive and cohesive failure

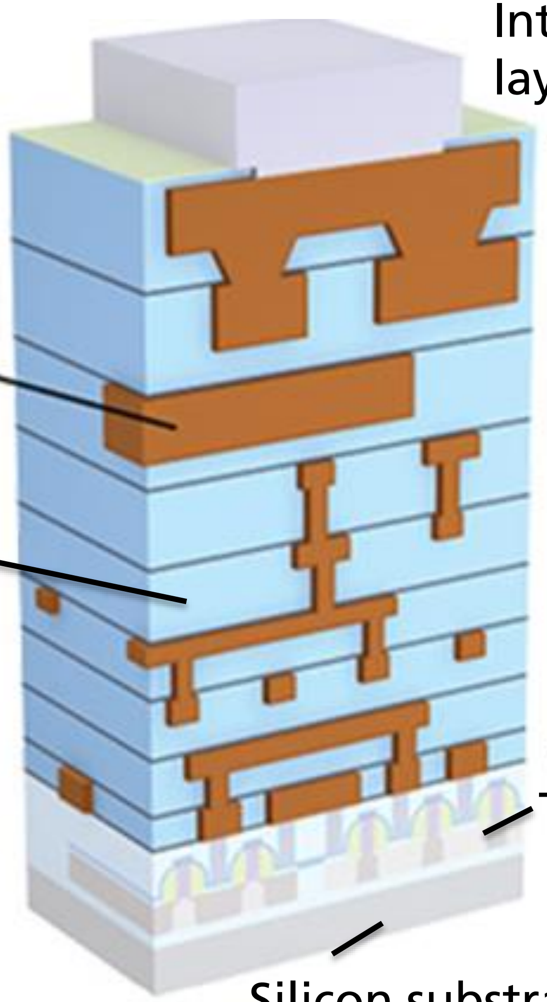
Young's modulus and fracture toughness are needed

Tasks of reliability engineering:

➔ **Understand degradation mechanisms**

Criterion for crack propagation: $\frac{\pi\sigma^2 a}{E} \geq 2\gamma$ → Low E leads to enhanced crack propagation.

σ - stress
a – crack length
ϒ – surface energy
E- elastic modulus

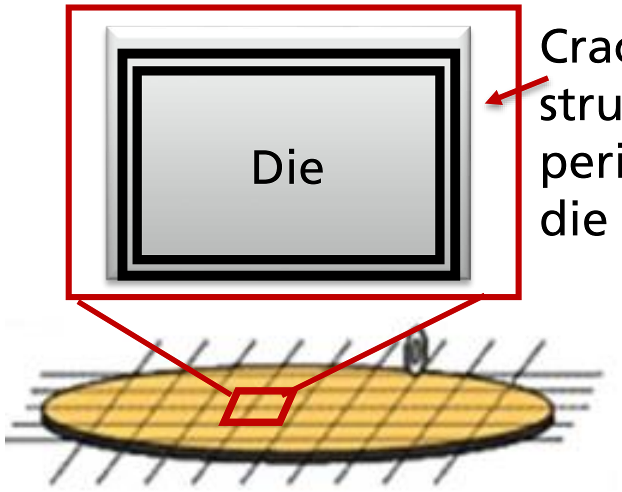


Chip-package interaction (CPI)

is **one of the major reliability concerns** in leading edge chips with **low-k and/or ultra-low-k (ULK) insulating material** in the on-chip interconnect stack, because of the low fracture toughness → **increased risk of crack propagation**

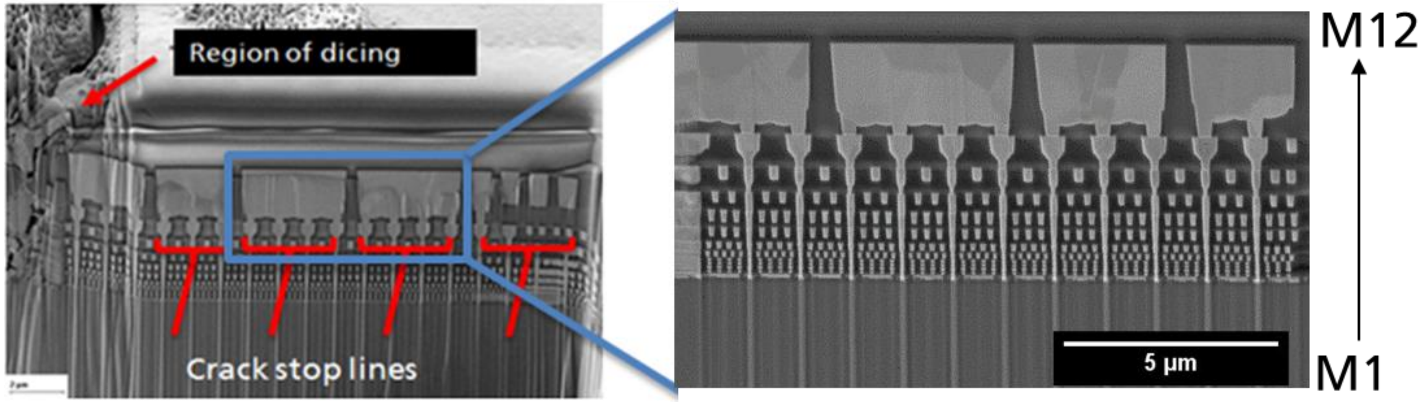
Microchip mechanical properties investigation: Combination of X-ray microscopy and in-situ micro-mechanical testing

- A **crack stop structure** is implemented to prevent chip damage originating from micro crack formation and propagation.



Crack stop structures on the perimeter of the die (guard ring)

Dicing process



SEM images of a cross-section with crack stop structure of a microprocessor chip with 12 copper layers (M1 to M12)

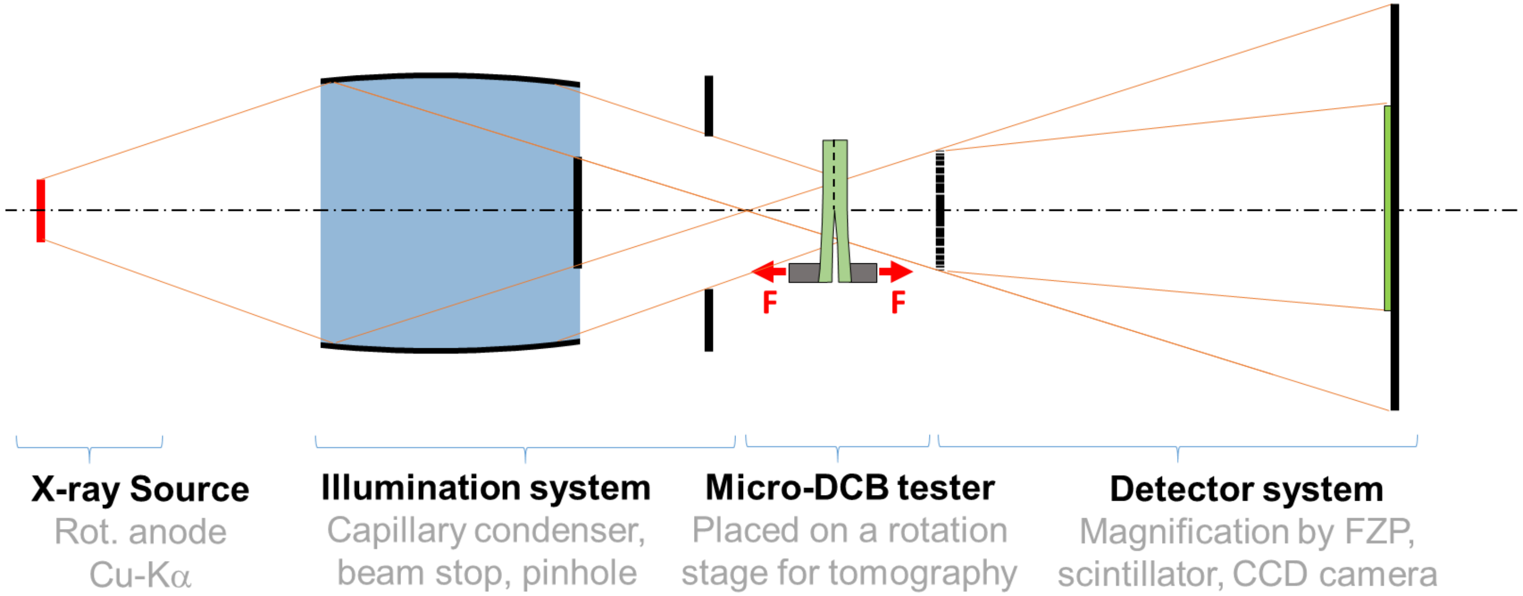
Microchip reliability improvement approach:

- Direct observation of crack propagation and particularly the guard ring efficiency – *in-situ high resolution imaging by X-ray microscopy*
- Material properties evaluation - *micro-mechanical study*

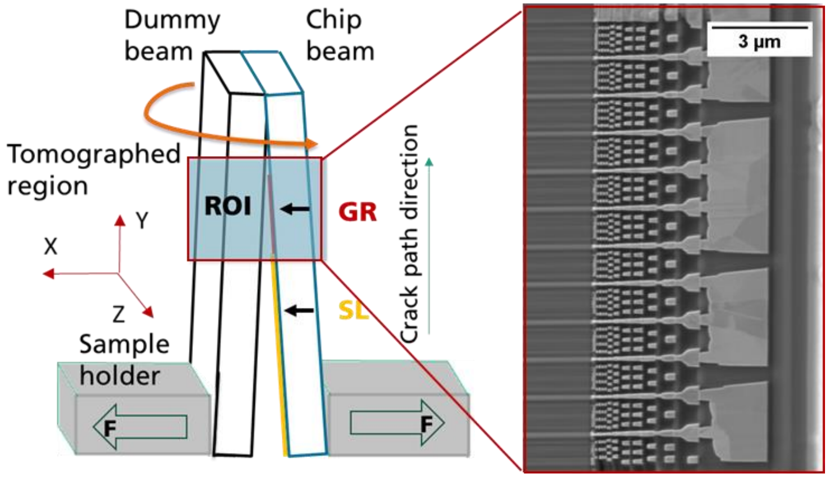
Micro-DCB test

K. Kutukova et al., IRSP 2016, K. Kutukova et al., FCMN 2017, K. Kutukova et al., MRS Spring 2018

Micro Double Cantilever Beam test (micro DCB) in the X-ray microscope



Typical “sandwich” specimen (chip and dummy) dimension: 50 µm × 50 µm × 1000 µm



- X-ray source: Rotating anode, monochromatic radiation: Cu-Kα (8 keV)
- X-ray optics: Capillary condenser and Fresnel zone plate
- Field of view width: 65 µm or 16 µm; Resolution 100 nm or 50 nm, respectively
- In-situ crack evolution study: micro-DCB tester (stuy under load)

ROI GR: guard ring structure M1 – M12

GR - guard ring
ROI - region of interest
SL- scribe line
M12 - metallization layer 12

S. Niese, PhD Thesis, BTU Cottbus 2015

K. Kutukova et al., MRS Advances 2018

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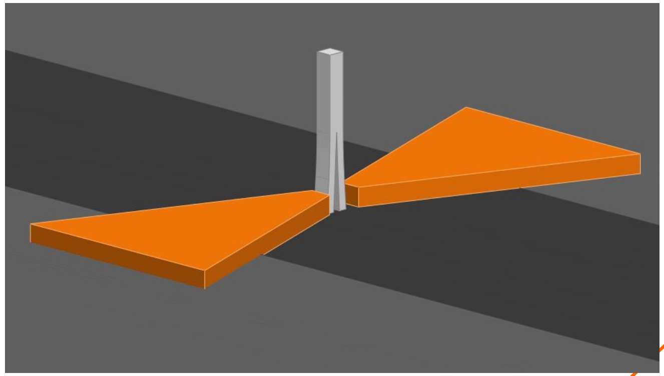
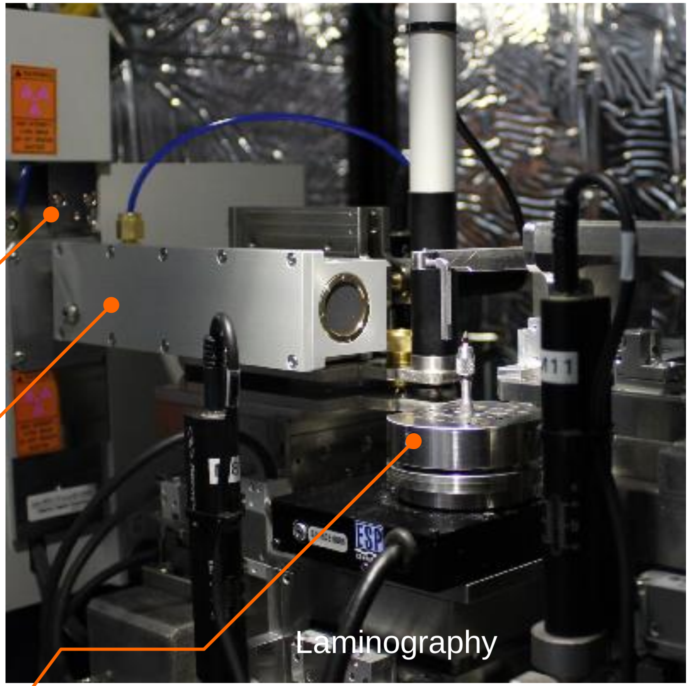
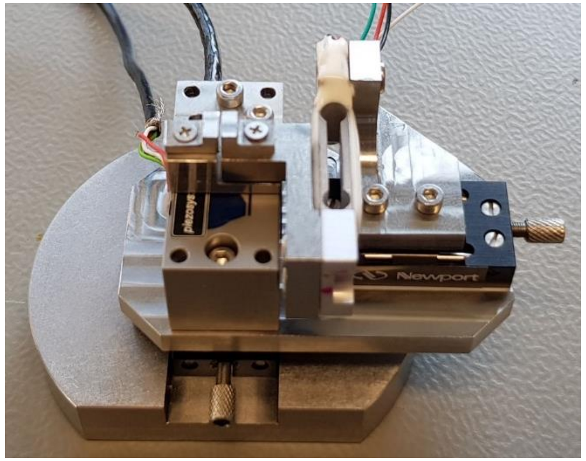
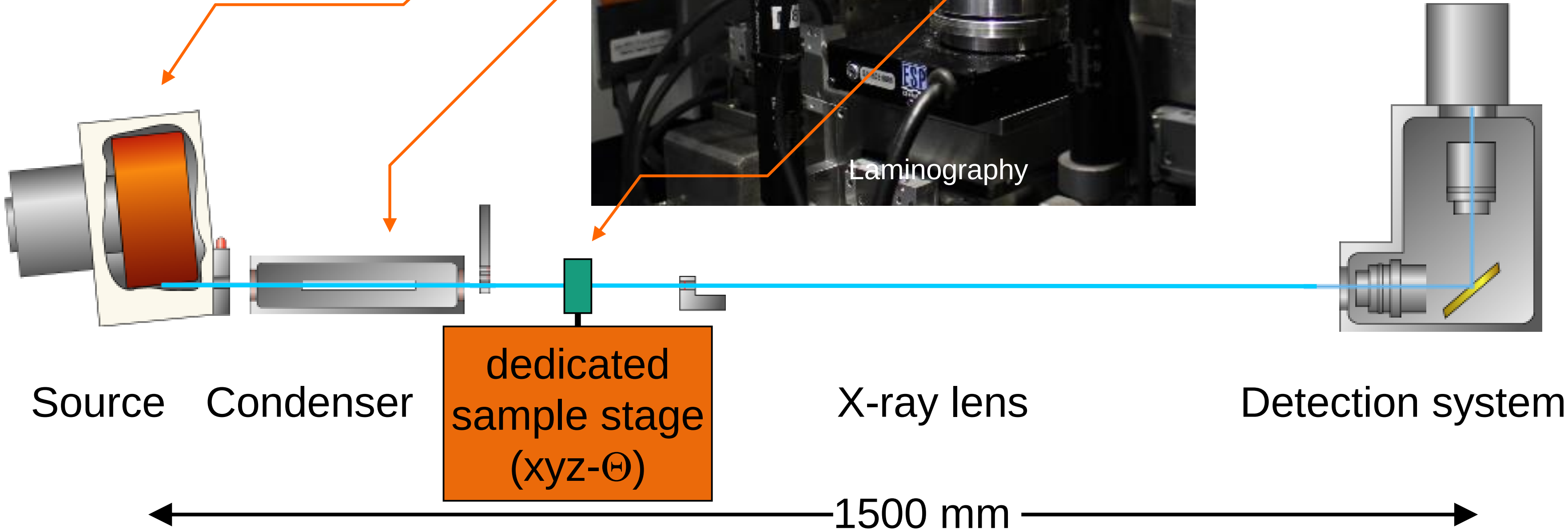






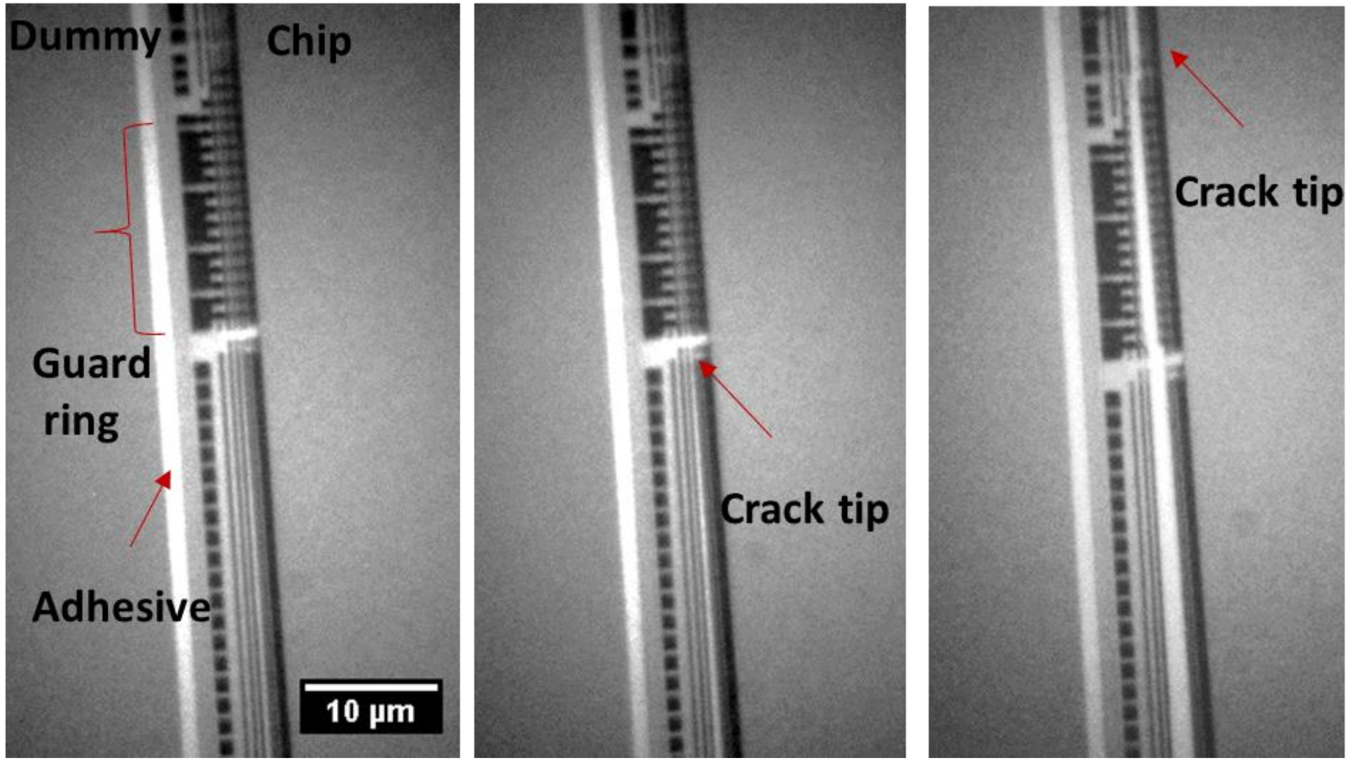
Micro-DCB tester with force sensor



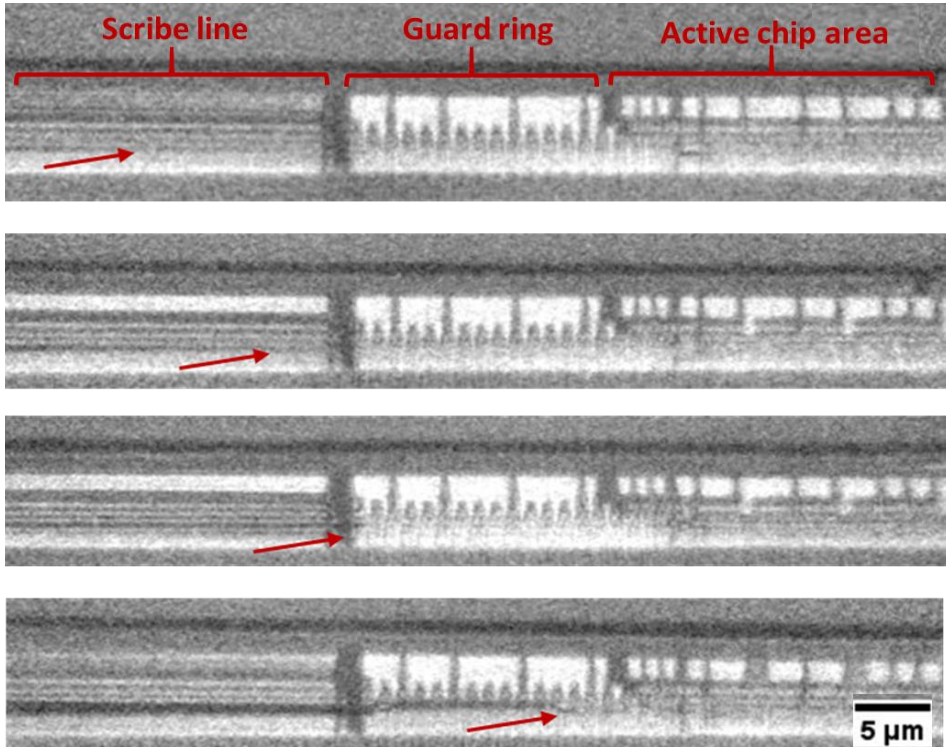
S. Niese, PhD Thesis, BTU Cottbus 2015

K. Kutukova et al., MRS Advances 2018

In-situ micro-DCB test in the nano XCT tool



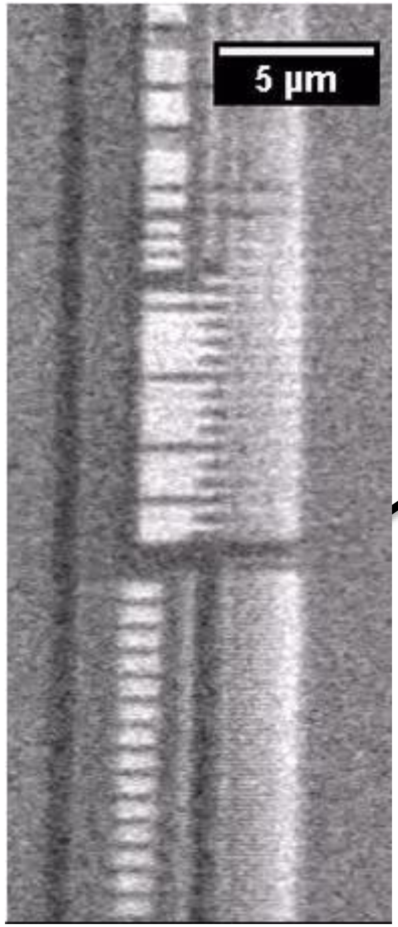
Radiographs series during micro-DCB experiment



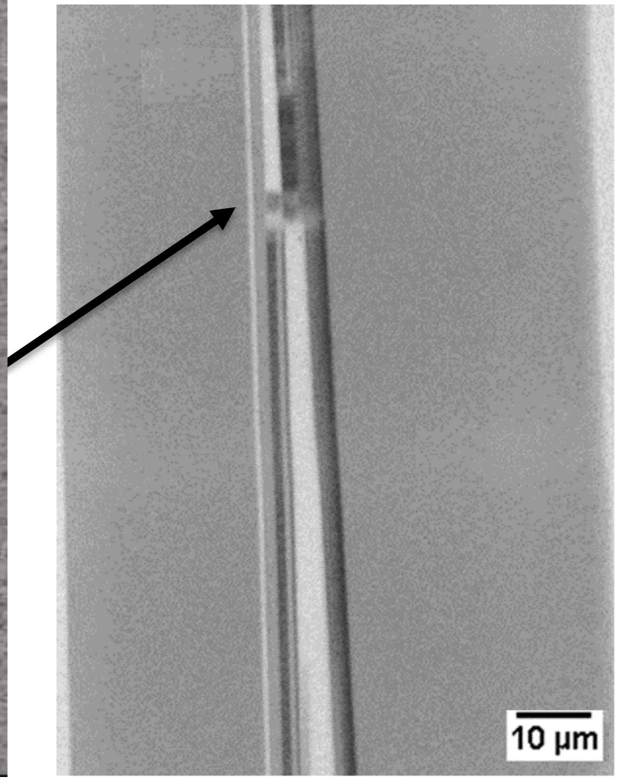
Series of the virtual cross-sections at several loading steps

The crack stops at the guard ring structure, it changes the direction of propagation (energy dissipation), and finally cracking is observed. **Crack evolution depends on design, processes and materials, as well as stress (chip-package interaction).**

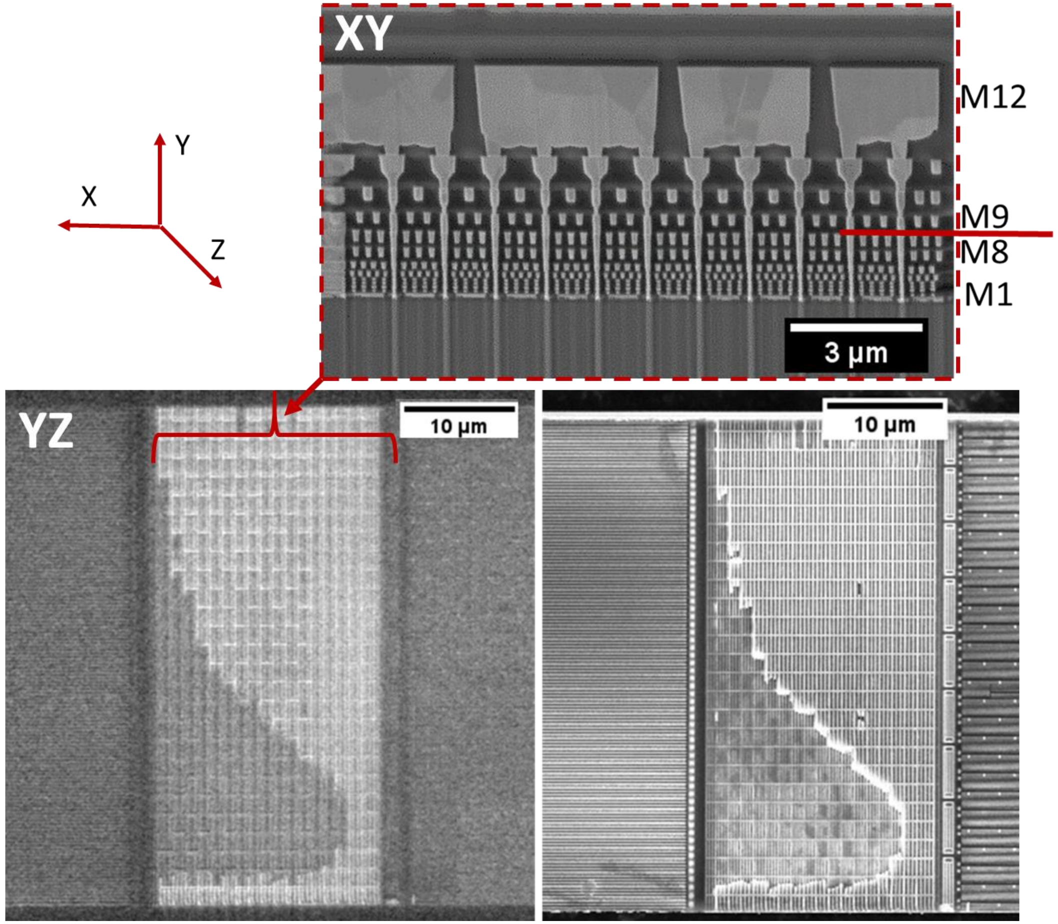
Nano XCT crack path study in BEoL stacks of microchips, Confirmation with SEM @ "post mortem" samples



Movie: Reconstruction data through the sample thickness



Stitched 2D radiograph



Metallization layers (FIB cross-section)

Virtual horizontal cross-section based on 3D data; M8

SEM image

K. Kutukova et al., APL 2018

Determination of the weakest layers/interfaces) in the BEoL stack ➔ Input for the design of guard ring structures

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3. New multi-energy XCT for nondestructive 3D advanced packaging imaging: Fast, high resolution, really nondestructive

4. Future laboratory X-ray microscopy: Full-field vs. scanning X-ray microscopy

State-of-the-art laboratory X-ray microscopy and nano XCT - Solutions

Data acquisition time:

- **X-ray source:** Rotating anode, Cu Kα radiation (8 keV)
- ***Issue:*** Photon flux ➔ Data acquisition time up to 12 hrs

Sample preparation efforts:

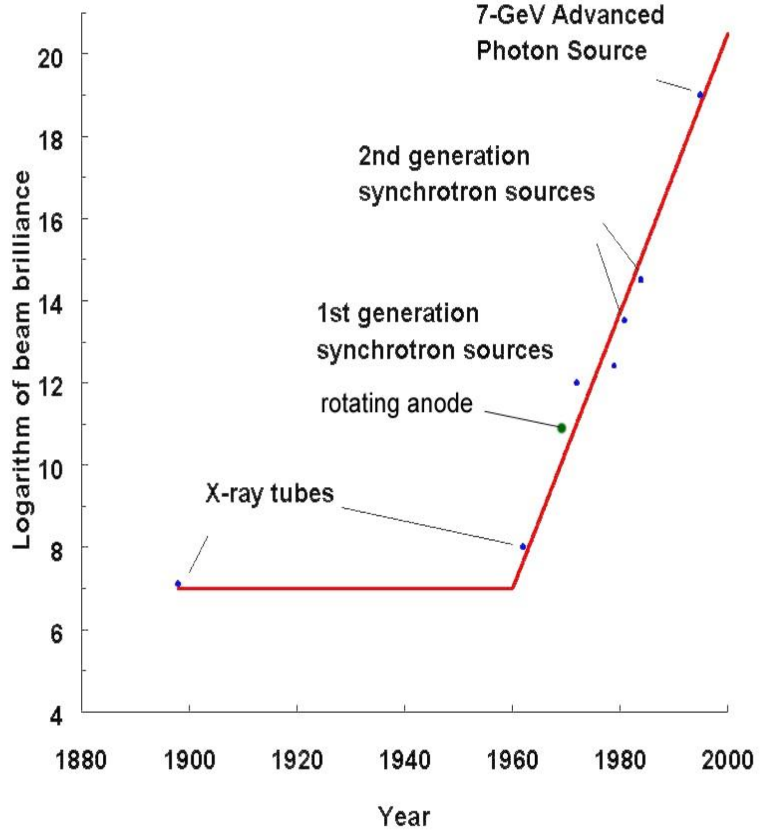
- **X-ray focusing lens:** Fresnel Zone Plate (FZP), manufactured in patterning process
- ***Issue:*** Efficiency > 10 keV (A/R of the FZP rings)

  ➔ Sample thickness ~ 50 µm @ 8 keV (depending on sample composition)

Resolution:

- **X-ray focusing lens:** Fresnel Zone Plate (FZP), manufactured in patterning process
- ***Issue:*** Min. thickness of the FZP rings

  ➔ Resolution ~ 50 nm @ 8 keV



Brightness of rotating anode (30 µm focus): $8*10^9$/s/mm²/mrad²

Brightness of FAAST (1 µm focus, 10 W): $1*10^{12}$/s/mm²/mrad²

FAAST source (~ 2nd gen. SR) vs. rotating anode source

W. Yun, IRSP 2016

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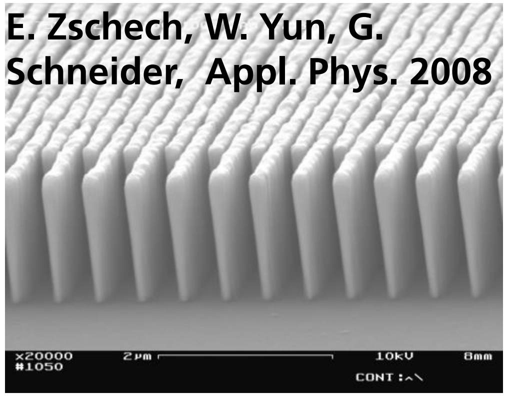
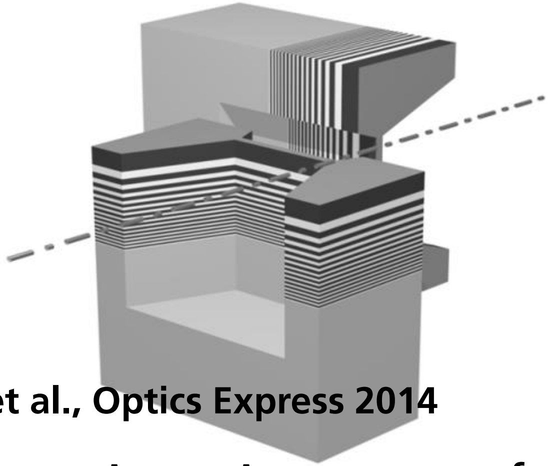


E. Zschech, W. Yun, G. Schneider, Appl. Phys. 2008

Fresnel Zone Plate, manufactured using ebeam lithography + etching



S. Niese et al., Optics Express 2014

Mulitlayer Laue Lens, manufactured using magneton stuttering + assembly

Deposited lens (< 10nm structures, high A/R) vs. patterned lens

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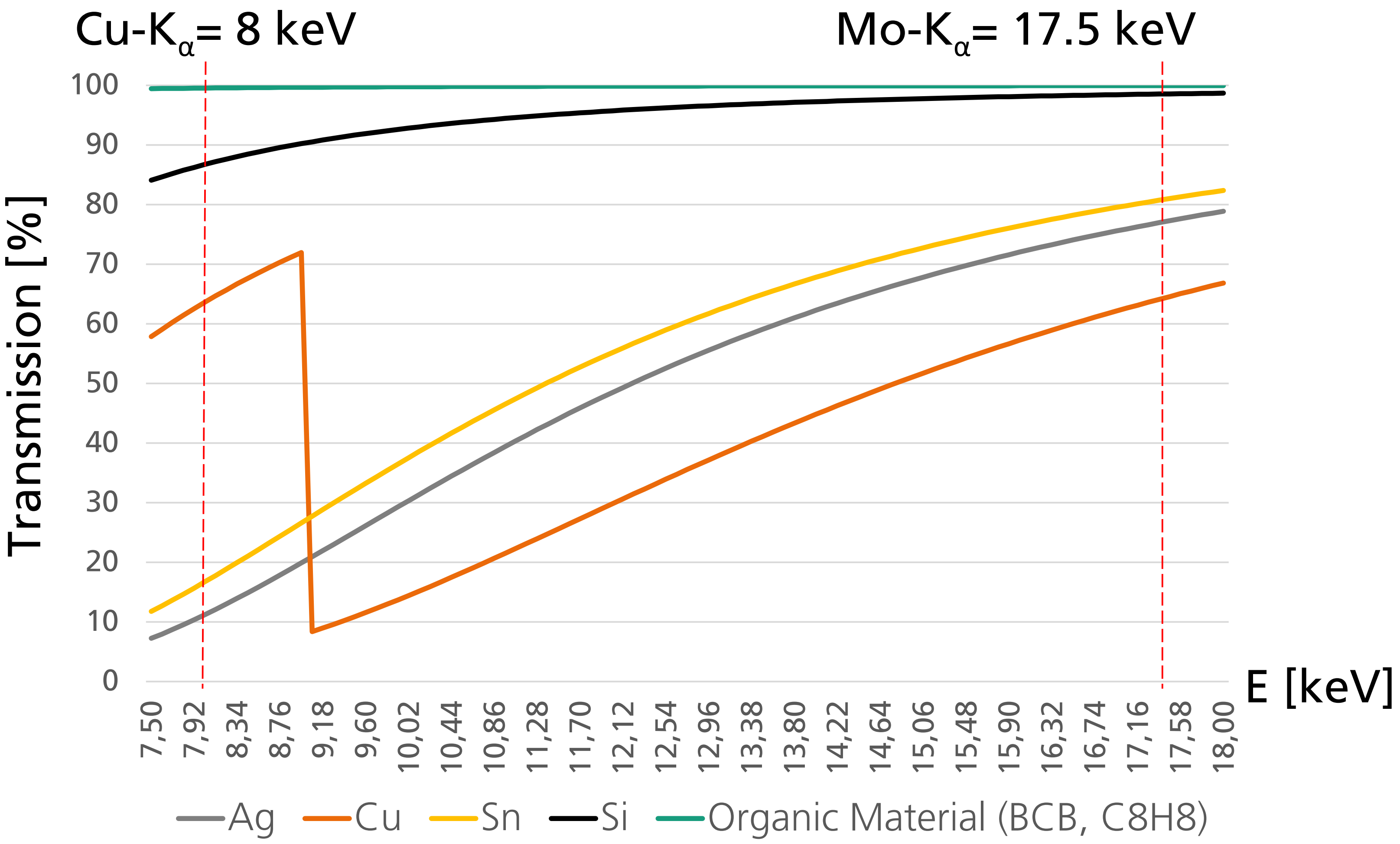
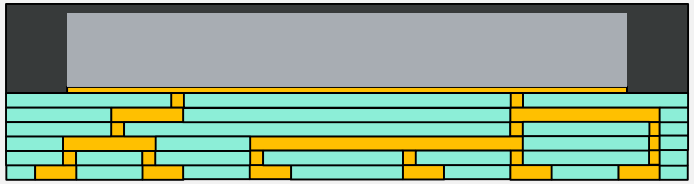
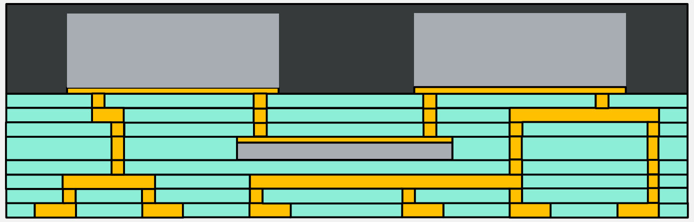
X-ray transmission for several materials, as a function of photon energy

Materials’ thickness 10 µm

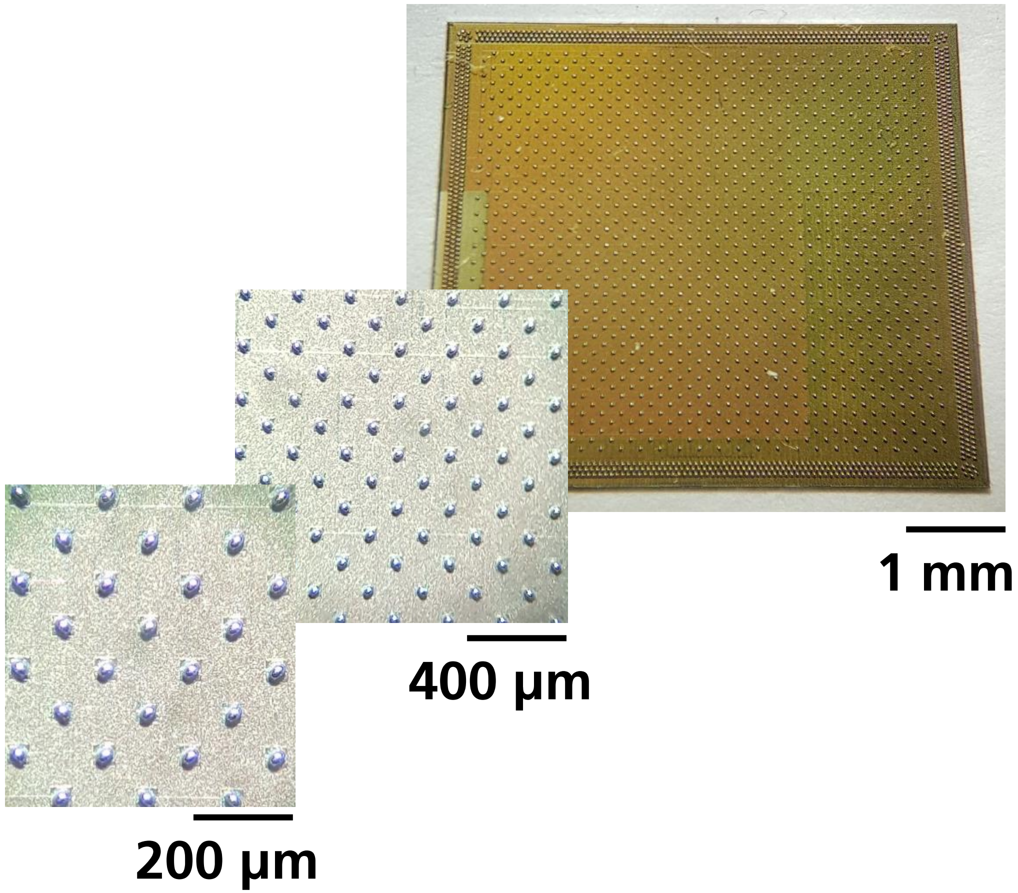


X-ray transmission for specific package samples

Schematic package cross-section	Type and manufacturer	Composition	Cu-K_α Transmission [%]	Mo-K_α Transmission [%]
 eWLB: https://ieeexplore.ieee.org/document/5416412	eWLB/FO-WLP Infineon/Amkor	150 µm Si bulk 4 µm BEoL 1x RDL - 3 µm Cu - 5 µm BCB	9	67
 InFO: https://www.semiwiki.com/forum/content/5070-wafer-level-chip-scale-packaging-technology-challenges-solutions.html	InFO TSMC	150 µm Si bulk 4 µm BEoL 3x RDL - 9 µm Cu - 15 µm BCB	6	46
 EMIB: http://www.3dic.org/EMIB#Heterogeneous_Integration_using_EMIB	EMIB Intel	150 µm Si bulk 4 µm BEoL 50 µm Si bridge 5x RDL - 15 µm Cu - 25 µm BCB	2	32
	22 nm FDX TV GLOBALFOUNDRIES	150 µm Si bulk 4 µm BEoL	11	80.5

Fraunhofer
IKTS

Example: Specific characterization test chip



CPI test chip (GLOBALFOUNDRIES)

Technology	22 FDX
Chiplet size	10 x 10 mm^2
Bump configuration	Cu-Pillar (45 x 75 µm^2)
Die thickness	150 µm

Schematic package cross-section	Type and manufacturer	Composition	Cu-K_α Transmission [%]	Mo-K_α Transmission [%]
	22 nm FDX TV GlobalFoundries	150 µm Si bulk 4 µm BEoL	11	80.5

Courtesy: GLOBALFOUNDRIES

Fraunhofer IKTS

Outline

1. High-resolution XCT for 3D metrology and diagnostics
   - Advanced packaging ➔ Micro-bumps
   - Chip-package interaction ➔ BEoL

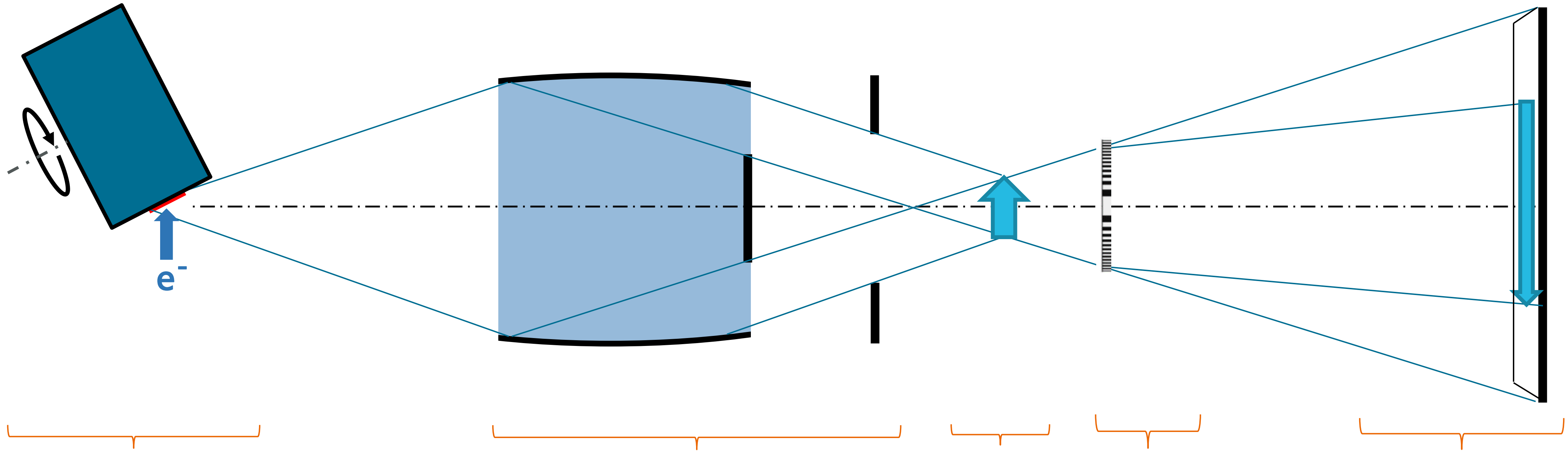
2. High-energy nano XCT: Needs and possibilities

3. New multi-energy XCT for nondestructive 3D advanced packaging imaging: Fast, high resolution, really nondestructive

4. Future laboratory X-ray microscopy: Full-field vs. scanning X-ray microscopy

State-of-the-art X-ray microscope

- Photon energy 8 keV (Cu target)
- Full field imaging using capillary condenser and Fresnel Zone Plate, 50 nm resolution
- Absorption contrast, Zernike phase contrast
- 1024 × 1024 pixel CCD camera



X-ray source: Rotating anode, Cu-Kα

Illumination system: Capillary condenser, beam stop, pinhole

Sample stage: Tomography

Imaging optics: FZP

Detector system: Scintillator, CCD/CMOS camera

Novel X-ray microscope: High flux, high energies, high resolution

Sigray

FAAST source

AXO Dresden

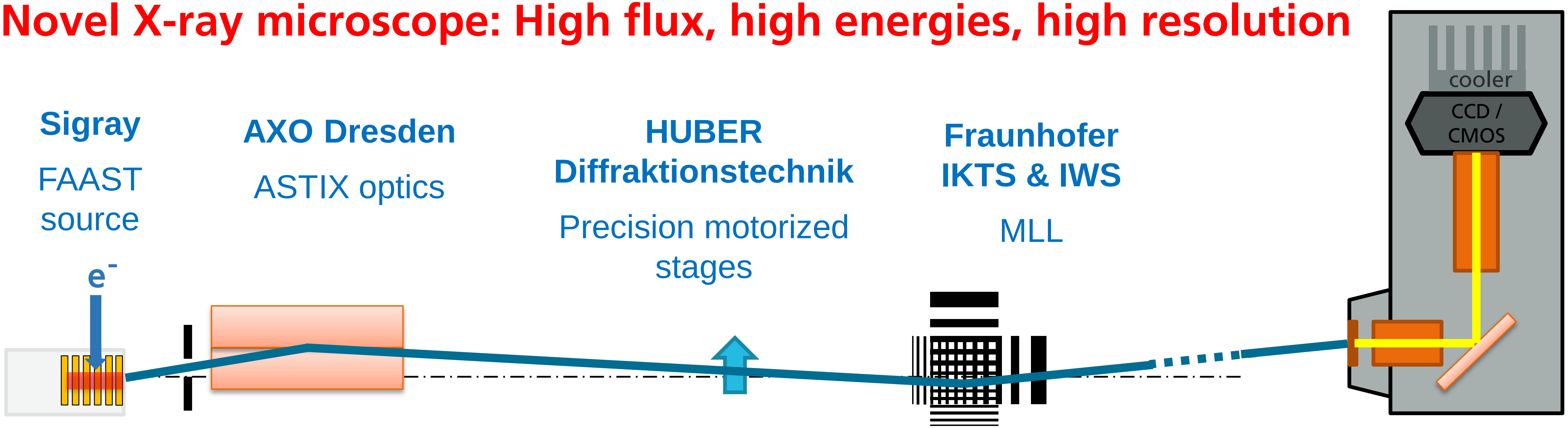
ASTIX optics

HUBER Diffraktionstechnik

Precision motorized stages

Fraunhofer IKTS & IWS

MLL



X-ray source:

High brightness micro-focus source

multi-energies

Illumination optics:

Monochromating focusing mirrors

Sample position:

Tomography, in-situ manipulators and chambers

Imaging optics:

MLL or FZP

Detector system:

Scintillator, CCD/CMOS camera

Crytur

Crycam, Lu

SIGRAY

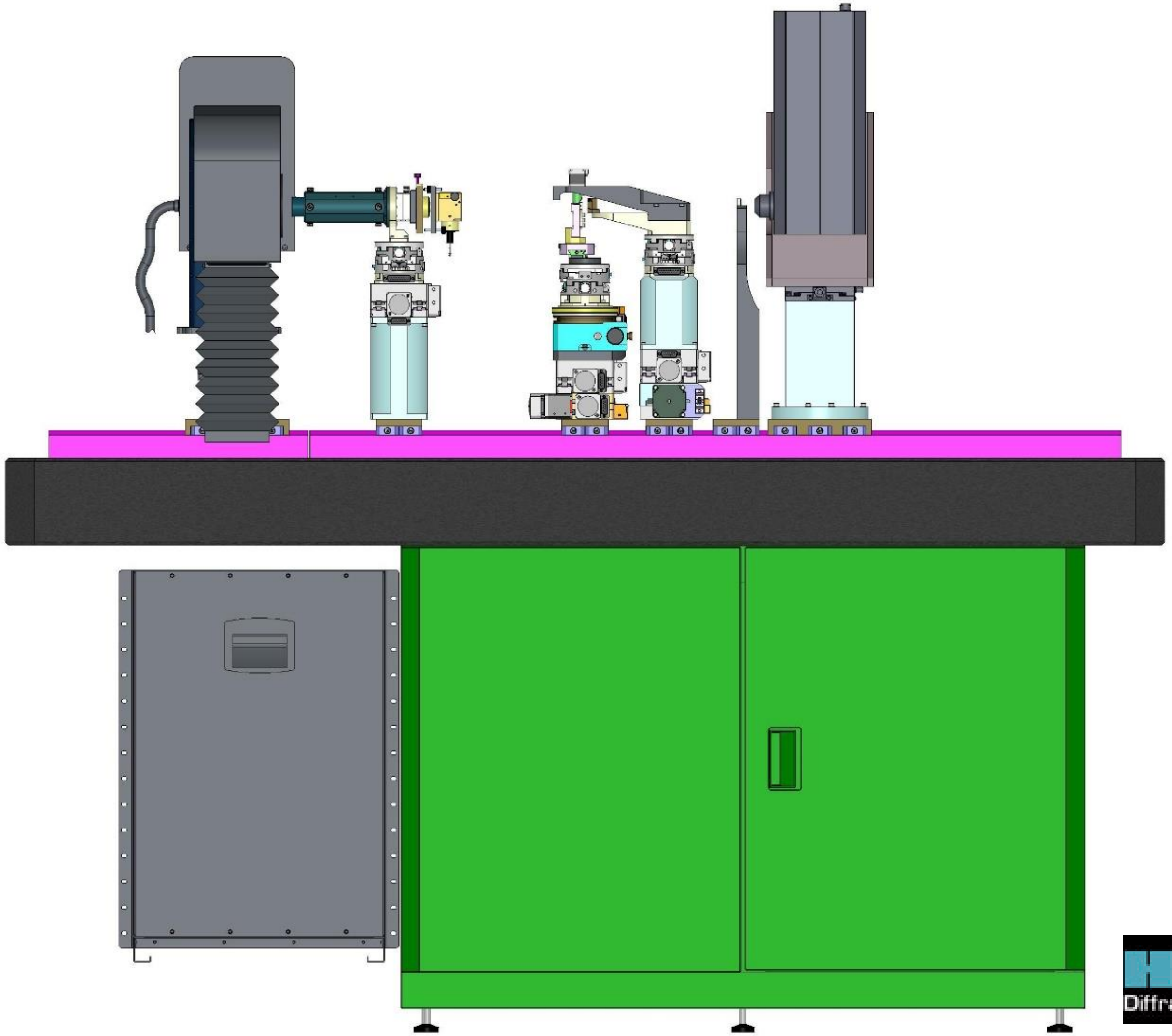
AXO DRESDEN GmbH
APPLIED X-RAY OPTICS
MULTILAYER X-RAY OPTICS
HIGH PRECISION DEPOSITION

HUBER
Diffraction and Positioning Equipment

Fraunhofer IKTS

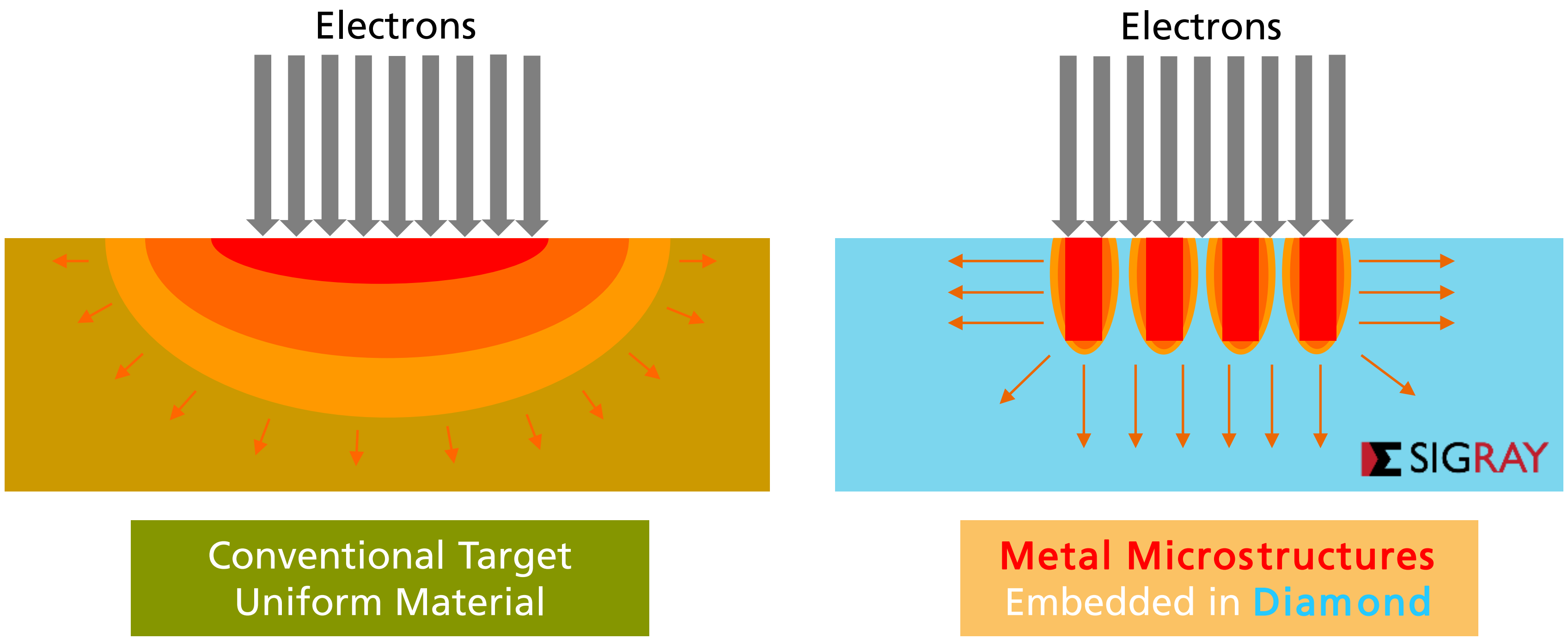
Fraunhofer IWS

Flexible modular base system with precision stages for component adjustment and sample positioning: Huber Diffraktionstechnik



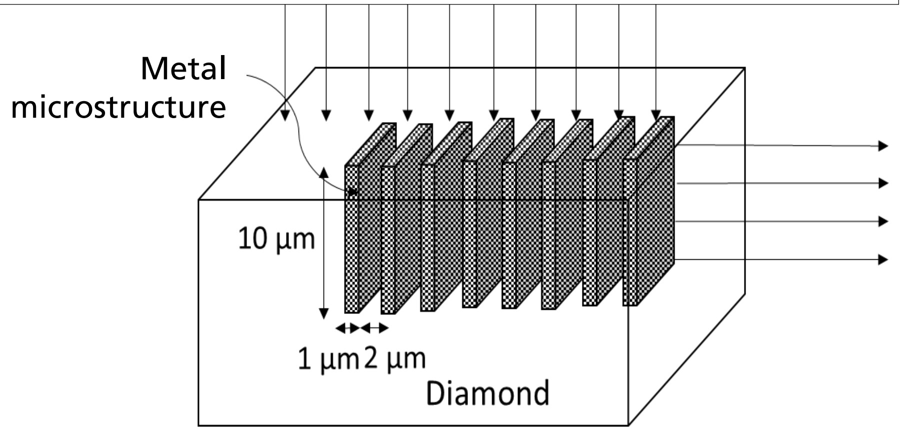
HUBER
Diffraction and Positioning Equipment

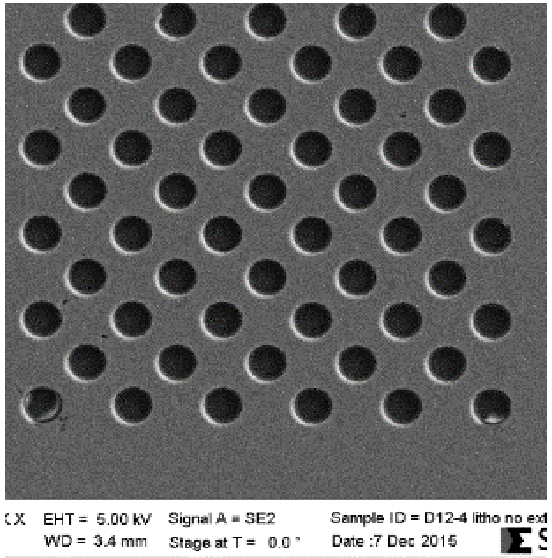
New source concept: Sigray
FAAST (Fine Anode Array Source Technology)
➔ Approach to high-throughput lab-based micro XCT and nano XCT

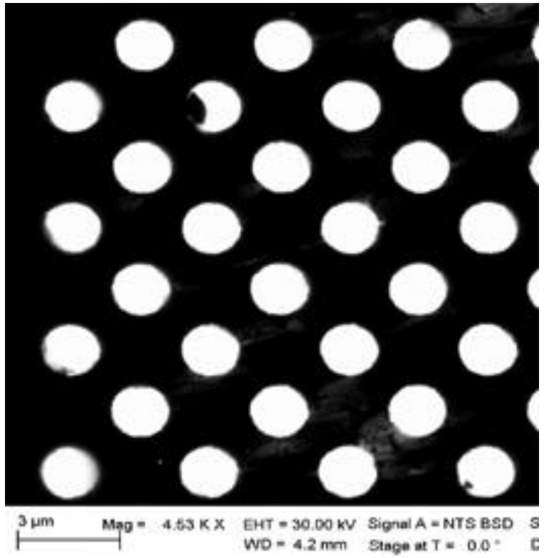


New source concept: Microstructured target
Advantages of FAAST (Fine Anode Array Source Technology)

- Target materials: Cr, Cu, Mo, Rh, W, Pt
- Photon energy 17.5 keV (Mo target)
- max. HV = 50 kV, max. I = 400 µA ➔ max. P = 20 W
- Focus size (Mo) about 12µm (diameter)
- Power density ~ 0.15 W/µm²







Left: Microstructured diamond
Right: Metal-filled microstructures

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

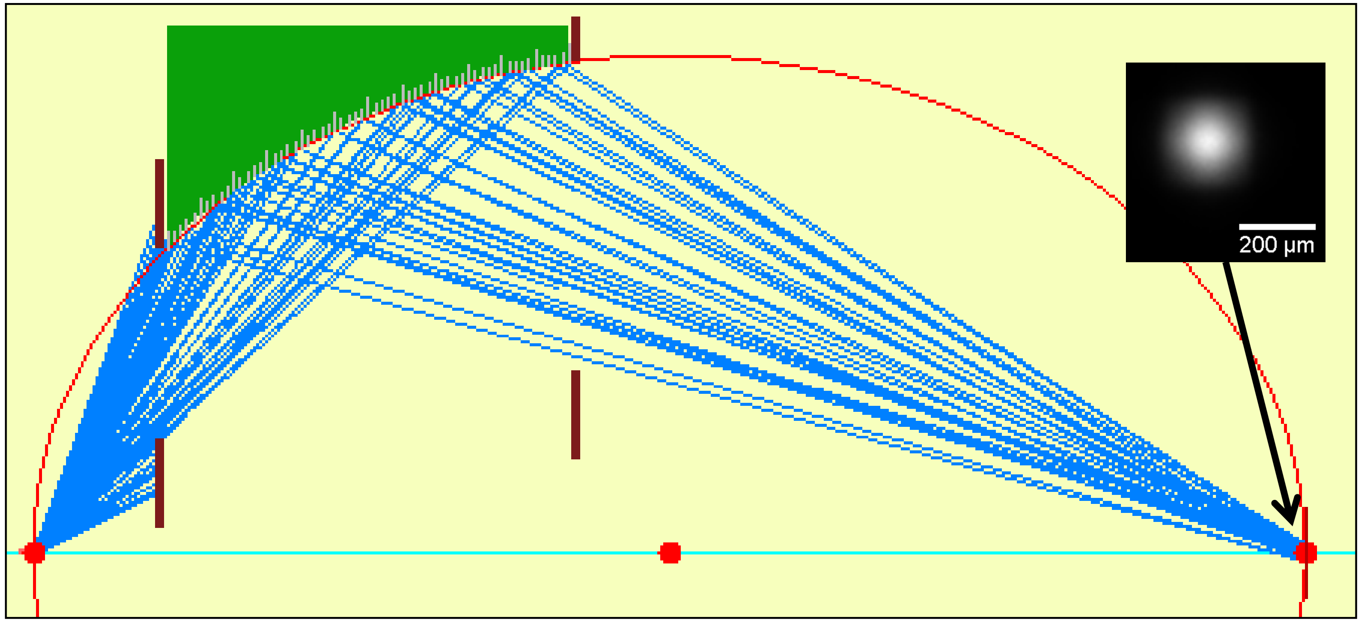
Benefits: Better anode thermal property + optimal linear accumulation of X-rays
Results: Higher source brightness and choice of characteristic lines

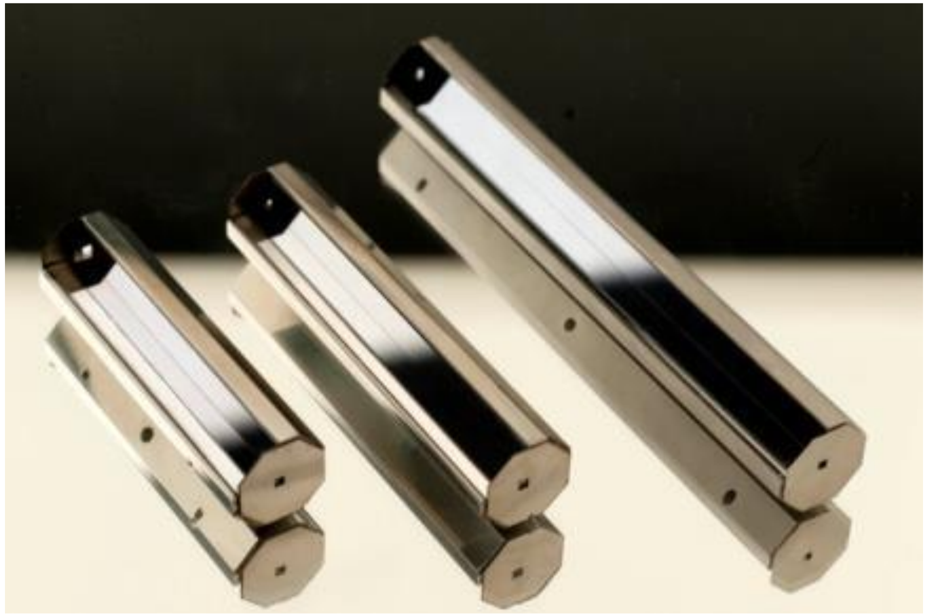
W. Yun, G. Wang, IRSP 2016 & personal information

SIGRAY

Fraunhofer IKTS

Illumination optics - 2D focusing mirror: AXO Dresden





Multilayer simulation & mirror design

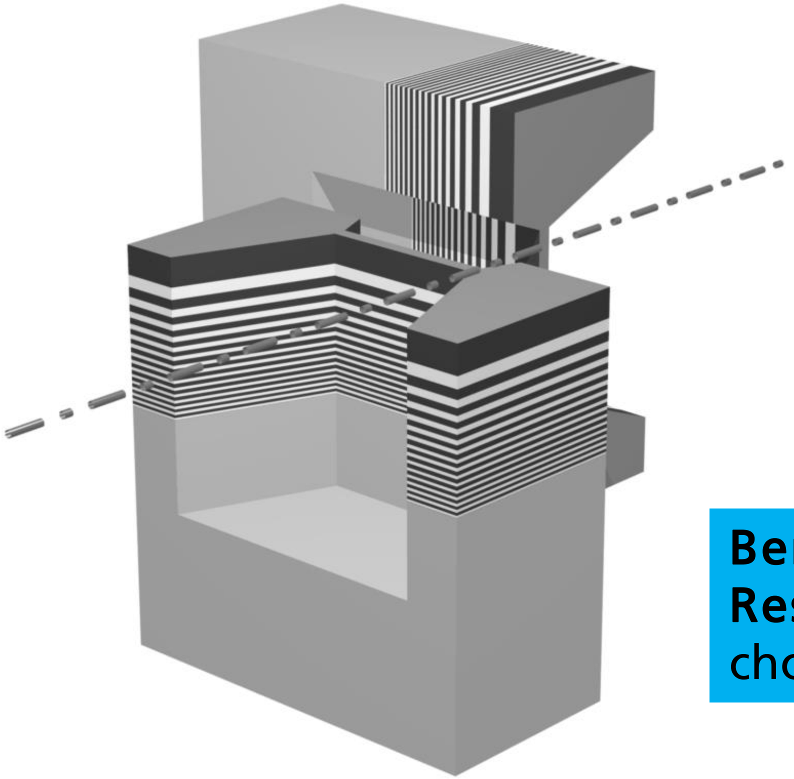
- Comprehensive ray-tracing simulation incl. X-ray source properties, multilayer reflectance and mirror aberrations
- Application-specific optimization of the mirror design

2D focusing mirror "ASTIX-f"

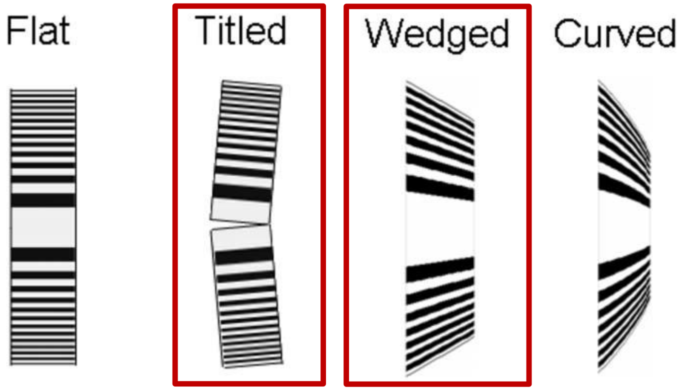
- Flexible optics fabrication
- Side-by-side optics yielding a quasi-monochromatic X-ray beam (e.g. $K\alpha_{1/2}$)

New lense concept: Fraunhofer IKTS + IWS Dresden
Multilayer Laue lense
➔ High resolution (… 10 nm), high photon energies (> 10 keV)

Crossed partial MLLs: two-dimensional focusing and imaging



MLL geometries



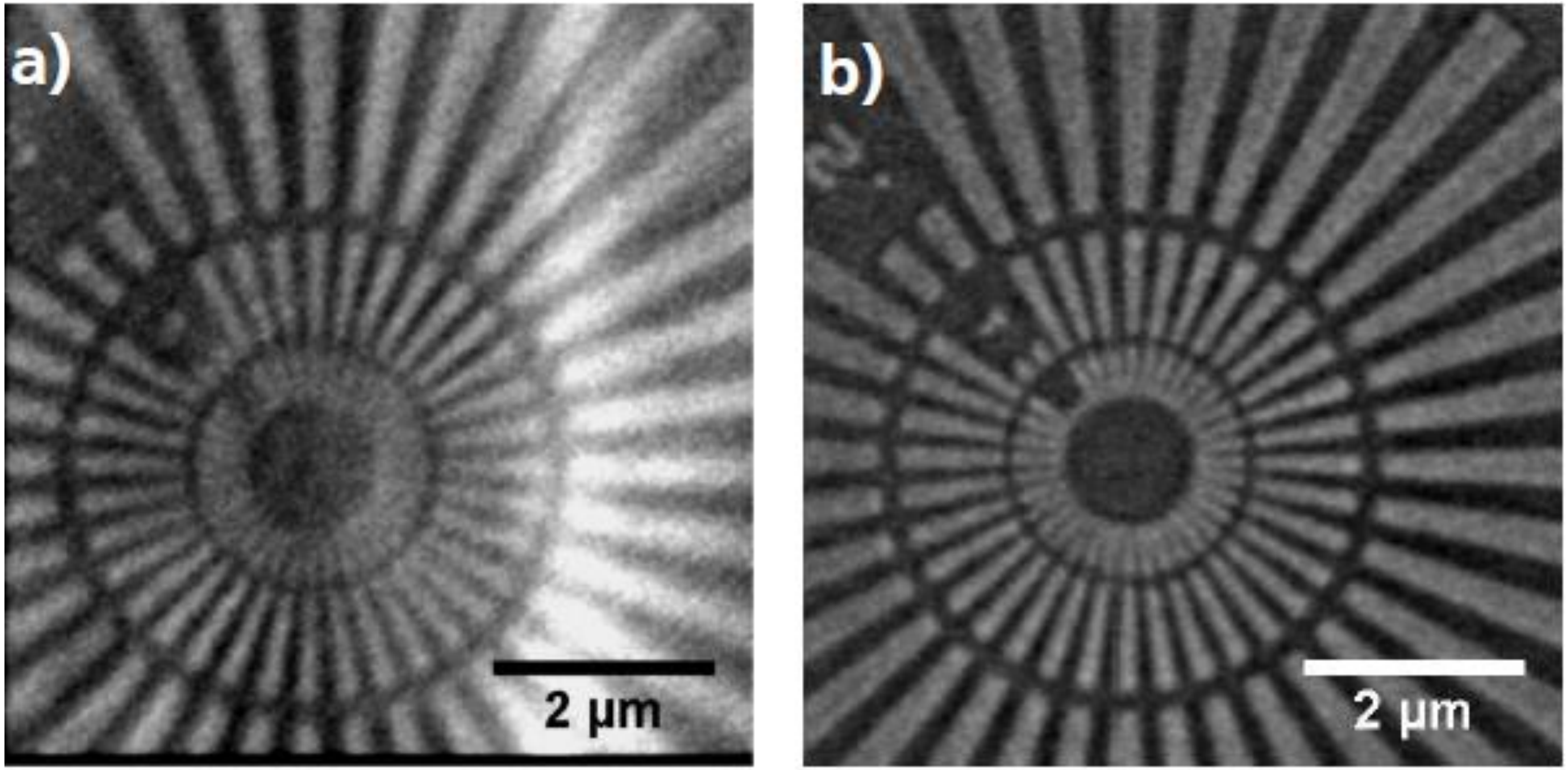
*H. Yan et al. Physical Review B **76**.11, p. 115438 (2007)*

Tuning the optics: Tilting, wedging, curving

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

S. Niese et al., Optics Express 2014

Proof of concept: Multilayer Laue lense (MLL) vs. Fresnel zone plate (FZP)



Multi-Layer Laue lense

Fresnel zone plate

Lab-based X-ray microscopy: 2D image of „Siemens Star“: MLL (left), FZP (right)

S. Niese et al., Optics Express 2014

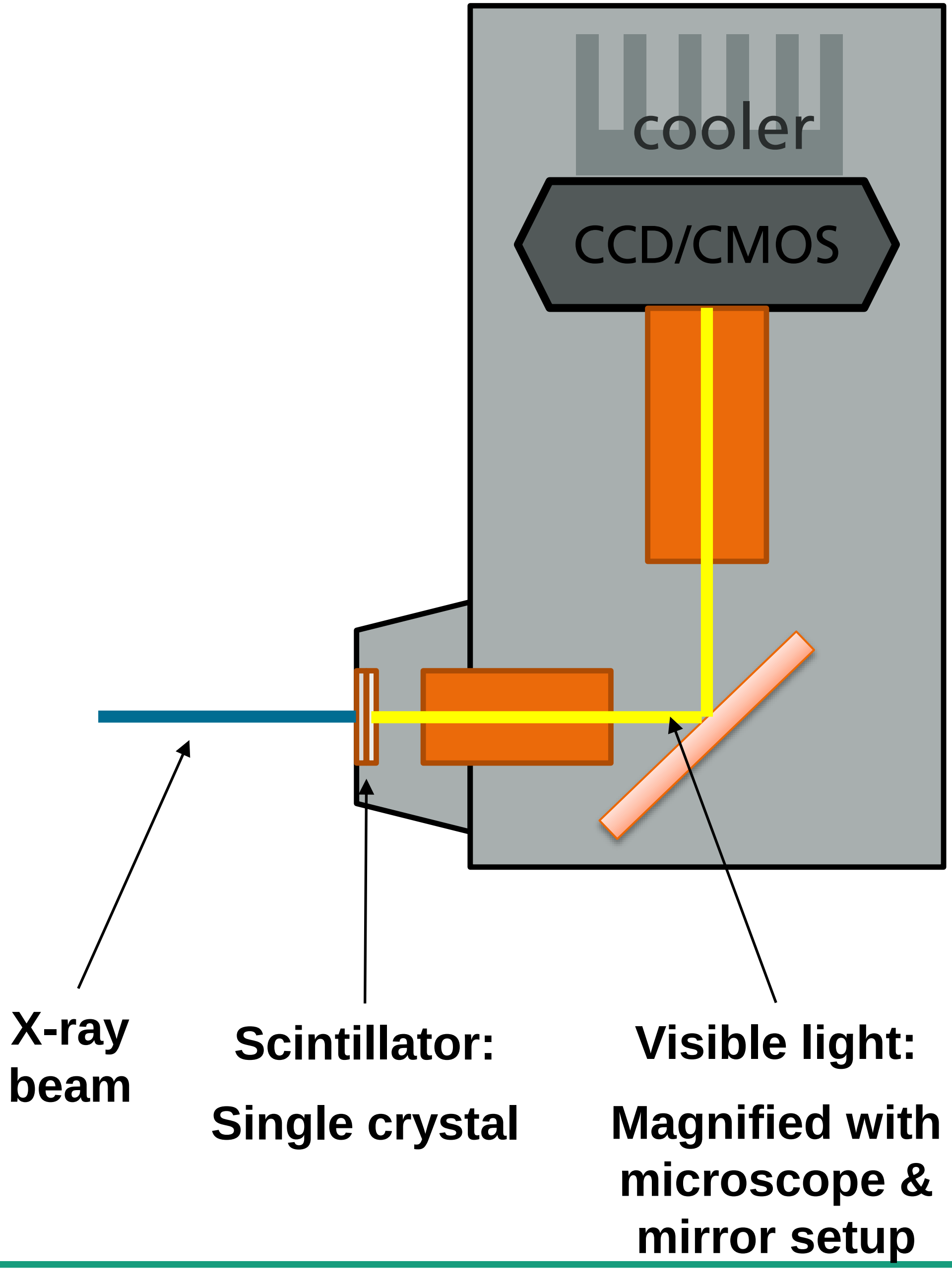
Detection system

<u>Crytur CryCam 3.2, watercooled</u>

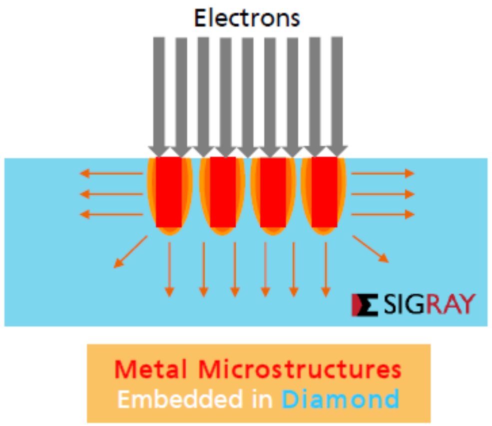
Scintillator:
single crystal LuAG:Ce with frontside silver coating

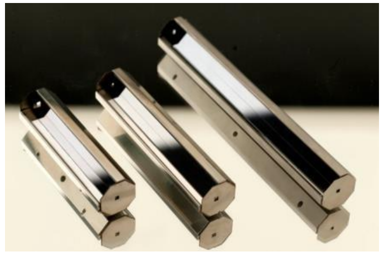
Objectives:
- **2x optical magnification with 100µm thick scintillator**
- **10x optical magnification with 10µm thick scintillator**

CCD matrix:
1024 x 1024 Pixels with $(24µm)^2$ per Pixel (100% filling)

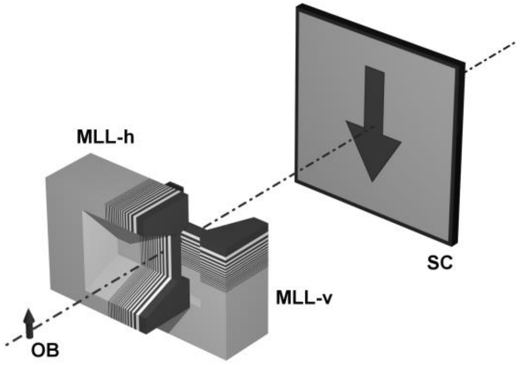


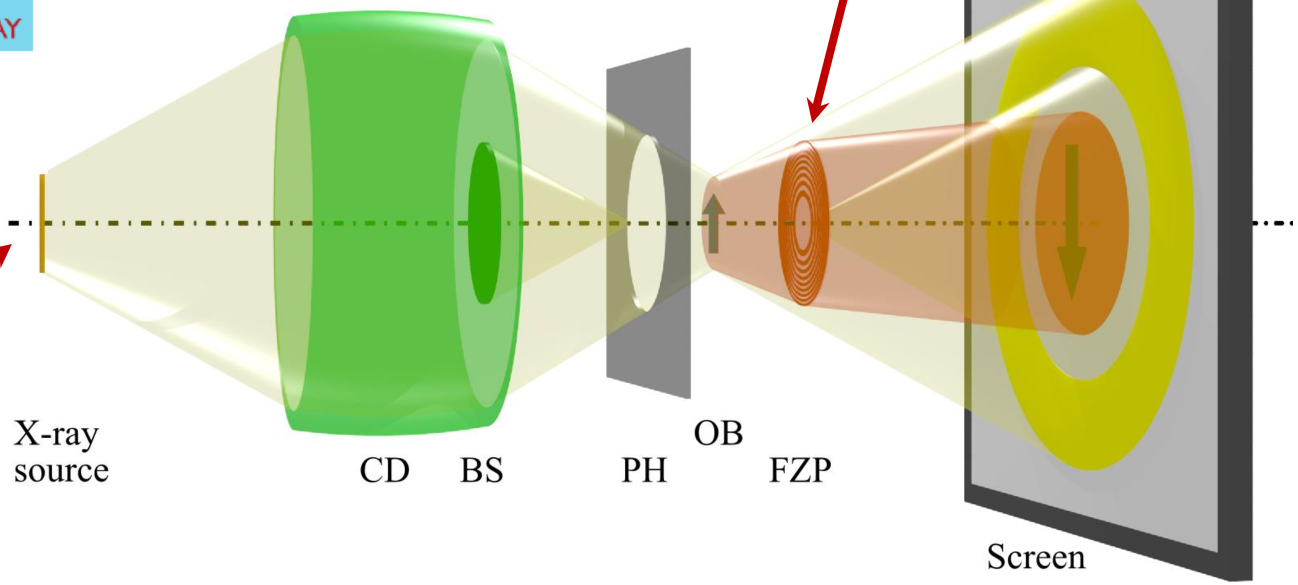
Laboratory X-ray microscopy/nano X-ray tomography @ > 10 keV





Multilayer Laue lense:
enhanced resolution
and high photon energies

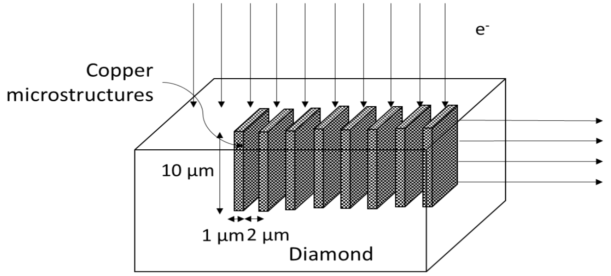




FAAST source:
High flux

Laboratory X-ray microscopy/nano X-ray tomography @ > 10 keV

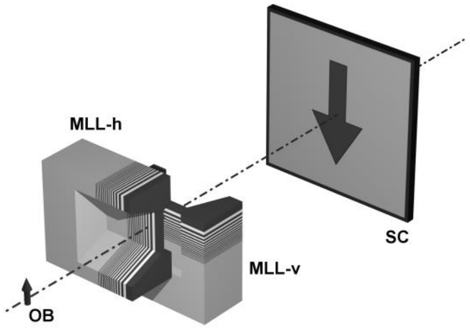
X-ray microscopy with novel sources (High-flux FAAST source)



Increased brightness

➔ *shorter measurement times (physical failure analysis in semiconductor industry, kinetic studies)*

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



Resolution improvement to 10nm (… 1nm)

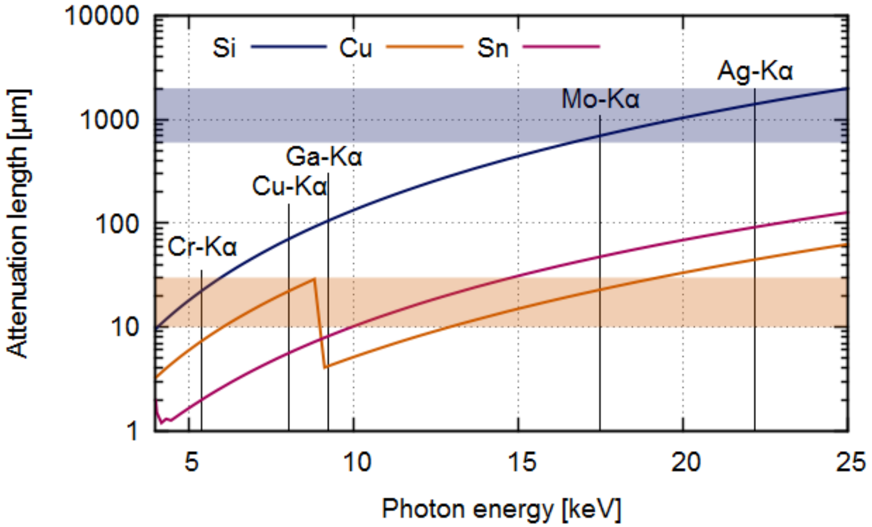
➔ *down-scaled device structures and defects in materials, …*

Larger working distance (~ 5 cm)

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

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

➔ *penetration of whole wafers, wafer stacks*



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IKTS

X-ray microscope for photon energies > 10 keV for microelectronics: Advanced packaging and BEoL physical failure analysis and metrology

Outline

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   - Advanced packaging ➔ Micro-bumps
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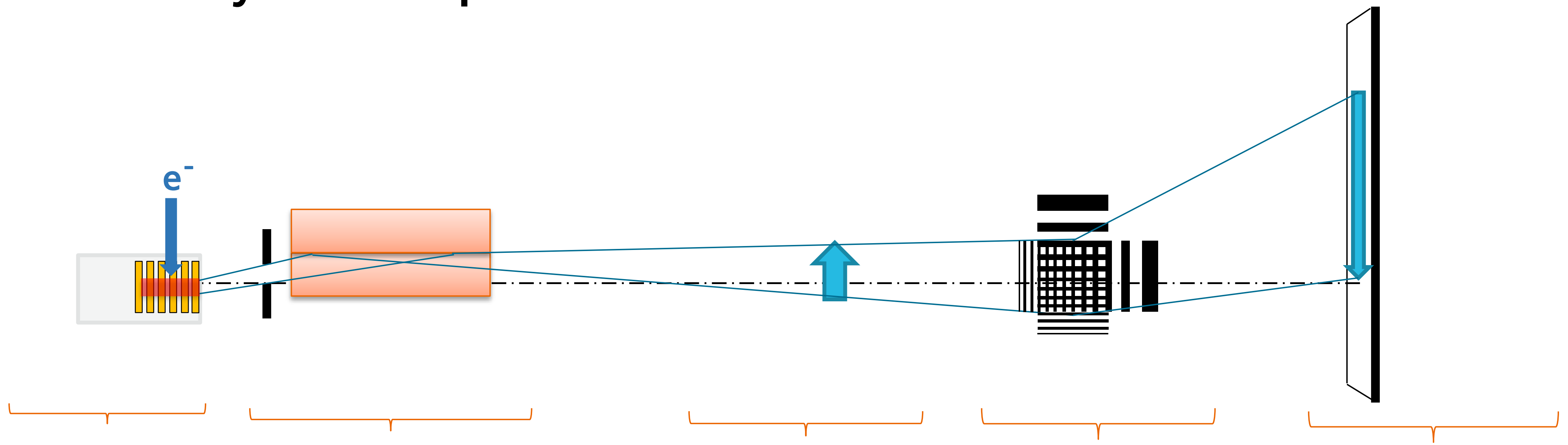
2. High-energy nano XCT: Needs and possibilities
3. New multi-energy XCT for nondestructive 3D advanced packaging imaging: Fast, high resolution, really nondestructive
4. Future laboratory X-ray microscopy: Full-field vs. scanning X-ray microscopy

Full-field X-ray microscope



X-ray source:

High brightness micro-focus source

multi-energies

Illumination optics:

Monochromating focusing mirrors

Sample position:

Tomography, in-situ manipulators and chambers

Imaging optics:

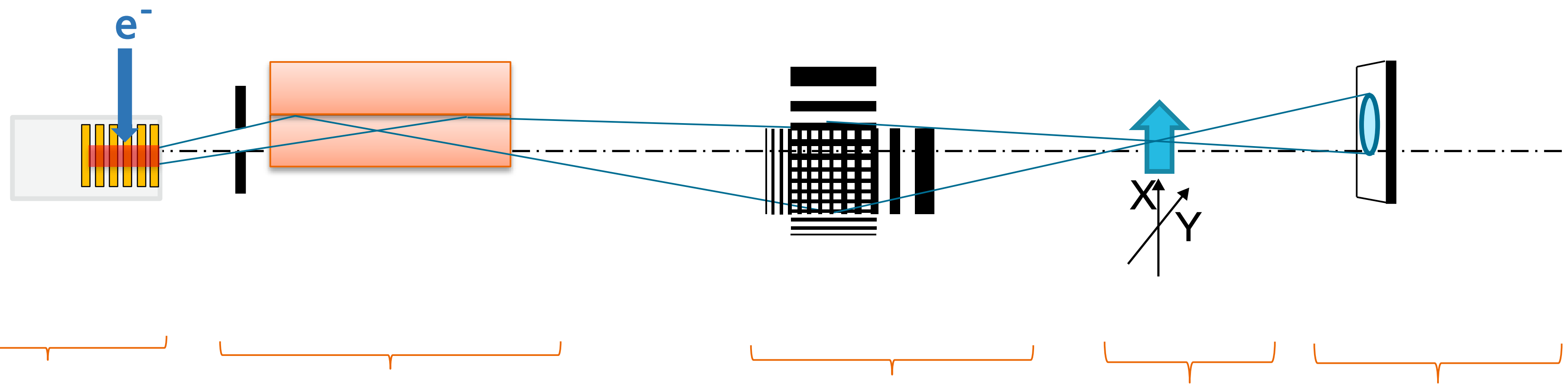
MLL or FZP

Detector system:

Scintillator, CCD/CMOS camera

Scanning X-ray microscope

High flux source, multiple energies + dedicated optics

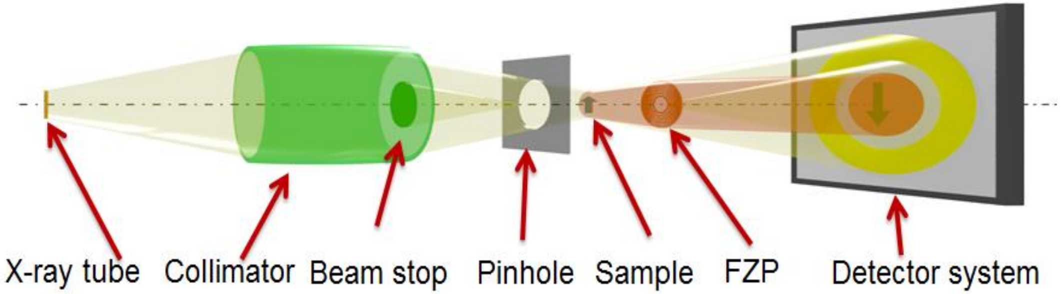


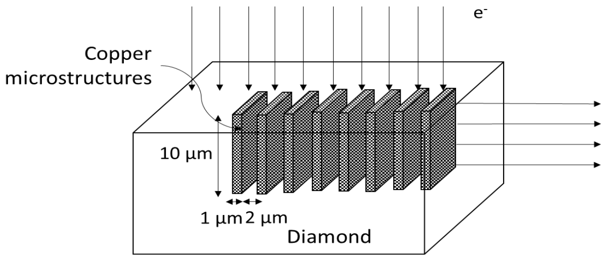
X-ray source:	Illumination optics:	Focusing optics:	Sample position:	Detector system:
High brightness micro-focus source multi-energies	Monochromating focusing mirrors	MLL or FZP	Tomography, in-situ manipulators and chambers	Scintillator, CCD/CMOS camera

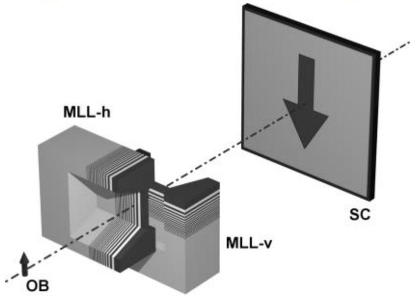
Focusing on sample and scanning ➔ spectroscopy (XRF) and diffraction (XRD) with high resolution

Outlook: Laboratory nano XCT for advanced packaging/interconnect imaging: Nondestructive & 3D, higher resolution, higher throughput

Parameters \ Development	Status	Target
Resolution	50 nm ⇨	**10 nm**
Energy range	< 10 keV ⇨	**> 10 keV**
Acquisition time	2 min – 10 h ⇨	**40x faster**
Sample preparation efforts	high ⇨	**low or no**







Innovations:

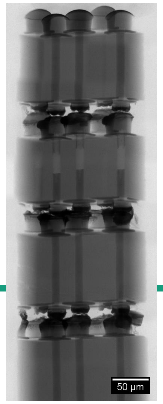
Novel nano X-ray tomography system with

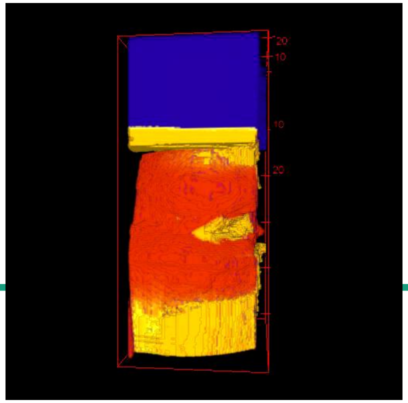
- High-flux X-ray source (Sigray Inc., Concord/CA, USA)
- Novel multilayer Laue lens X-ray optics (Fraunhofer IKTS + IWS Dresden)

Solution/Application:

Novel metrology & PFA solution for advanced packaging and BEoL

- Really non-destructive
- High throughput: 3D data set in minutes
- Resolution down to 10 nm





3D stack w/ Cu TSVs and AgSn microbumps

Thank you !

Norman Huber, Huber Diffraktionstechnik, Rimsting, Germany

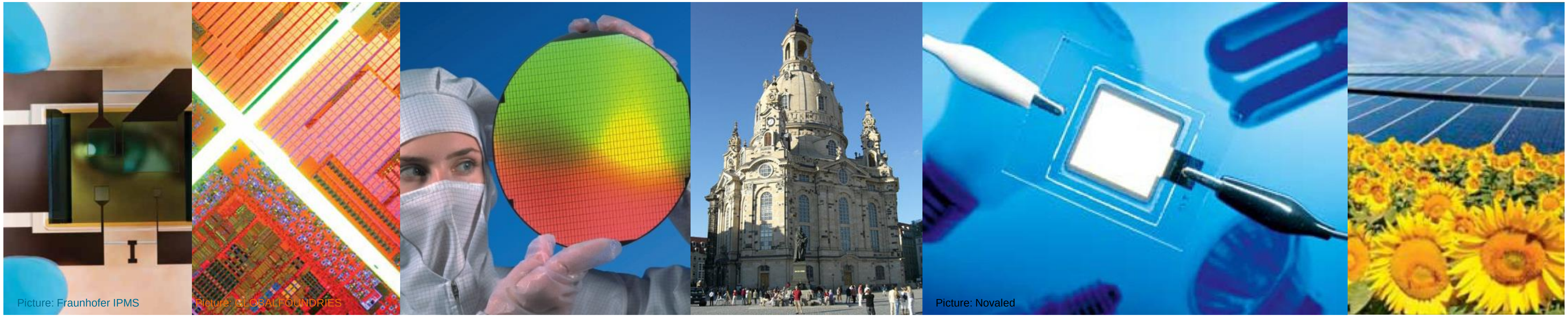
Wenbing Yun, Sigray Concord/CA, USA

Reiner Dietsch, Sven Niese, AXO Dresden, Germany

Jürgen Wolf, Fraunhofer IZM-ASSID Dresden, Germany

Markus Loeffler, TU Dresden, Germany

Han Li, Markus Kuhn, Zhiyong Ma, Intel Hillsboro/OR, USA



Contact: ehrenfried.zschech@ikts.fraunhofer.de

SIGRAY

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

HUBER
Diffraction and Positioning Equipment

Fraunhofer IWS

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