3D METROLOGY AND DIAGNOSTICS AT MULTIPLE LENGTH SCALES – STATUS AND OUTLOOK

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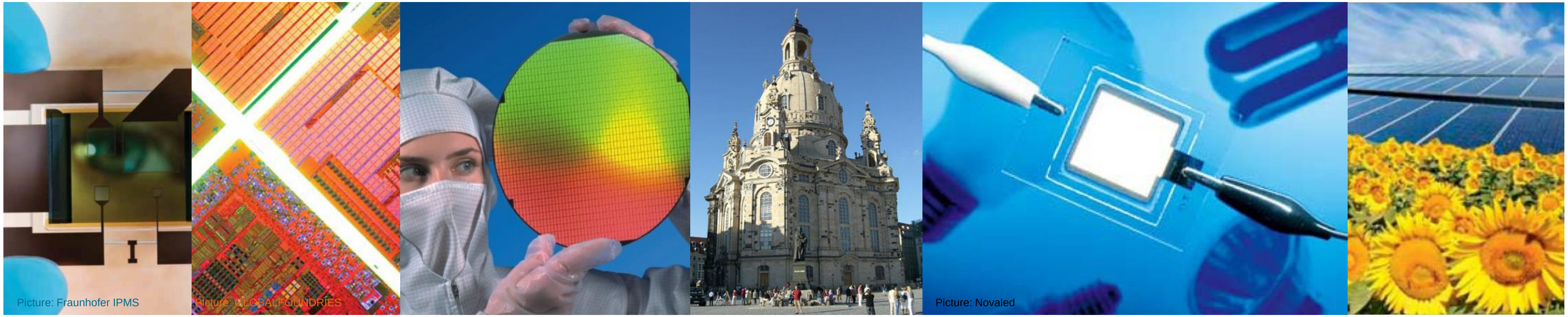
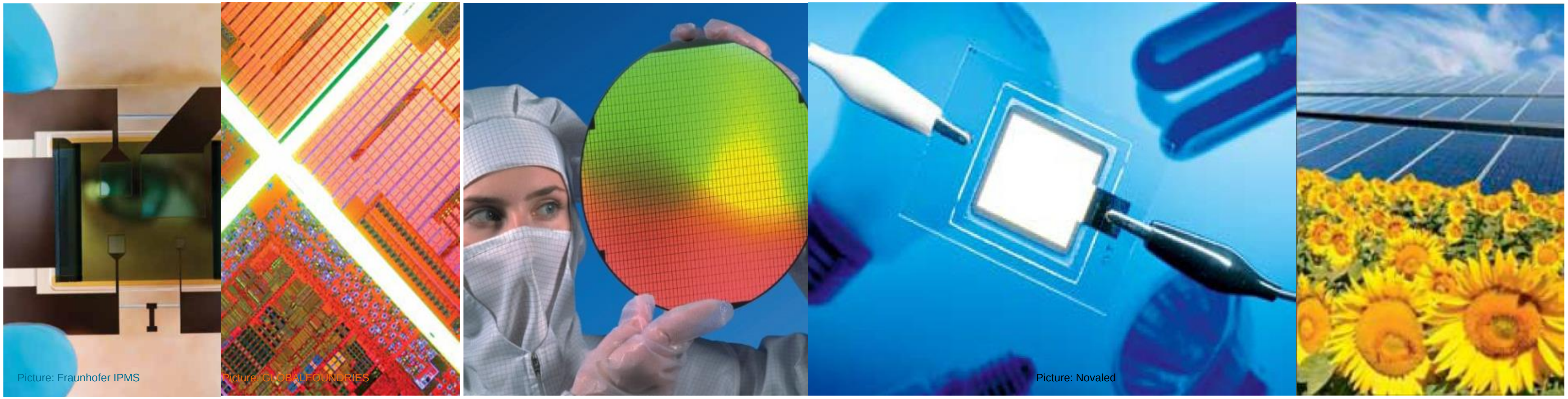


Picture: Fraunhofer IPMS
Picture: GLOBALFOUNDRIES
Picture: Novaled

3DAM Workshop, Grenoble, 15 March 2019

DRESDEN –
A CULTURAL TOWN

DRESDEN –
A TOWN OF SCIENCE AND INNOVATION



Picture: Fraunhofer IPMS

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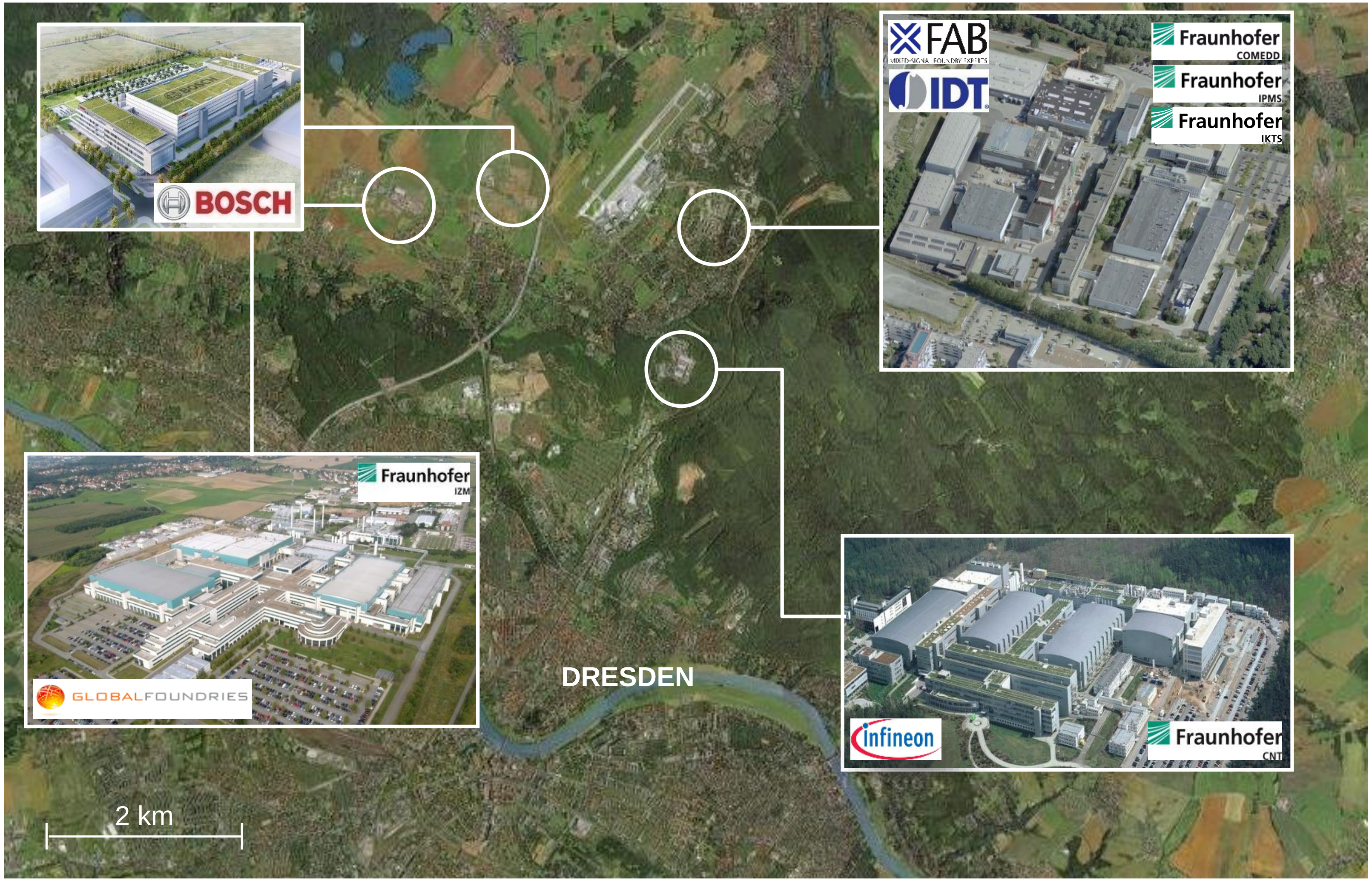
particularly in ICT/Microelectronics and advanced materials

MICROELECTRONICS/ ICT IN SAXONY

Production sites of chip manufacturers in Dresden and selected Fraunhofer Institutes



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Outline

1. 3D metrology and diagnostics challenges in microelectronics
    - Role of X-ray techniques

2. X-ray imaging of 3D structures: From micro to nano
    - Example 1 - Advanced packaging: Failures in TSVs and micro-bumps
    - Example 2 – BEoL stack: Crack propagation

3. Outlook:
    - X-ray microscopy: Fast, high resolution, really nondestructive

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2D vs. 3D metrology and diagnostics in microelectronics

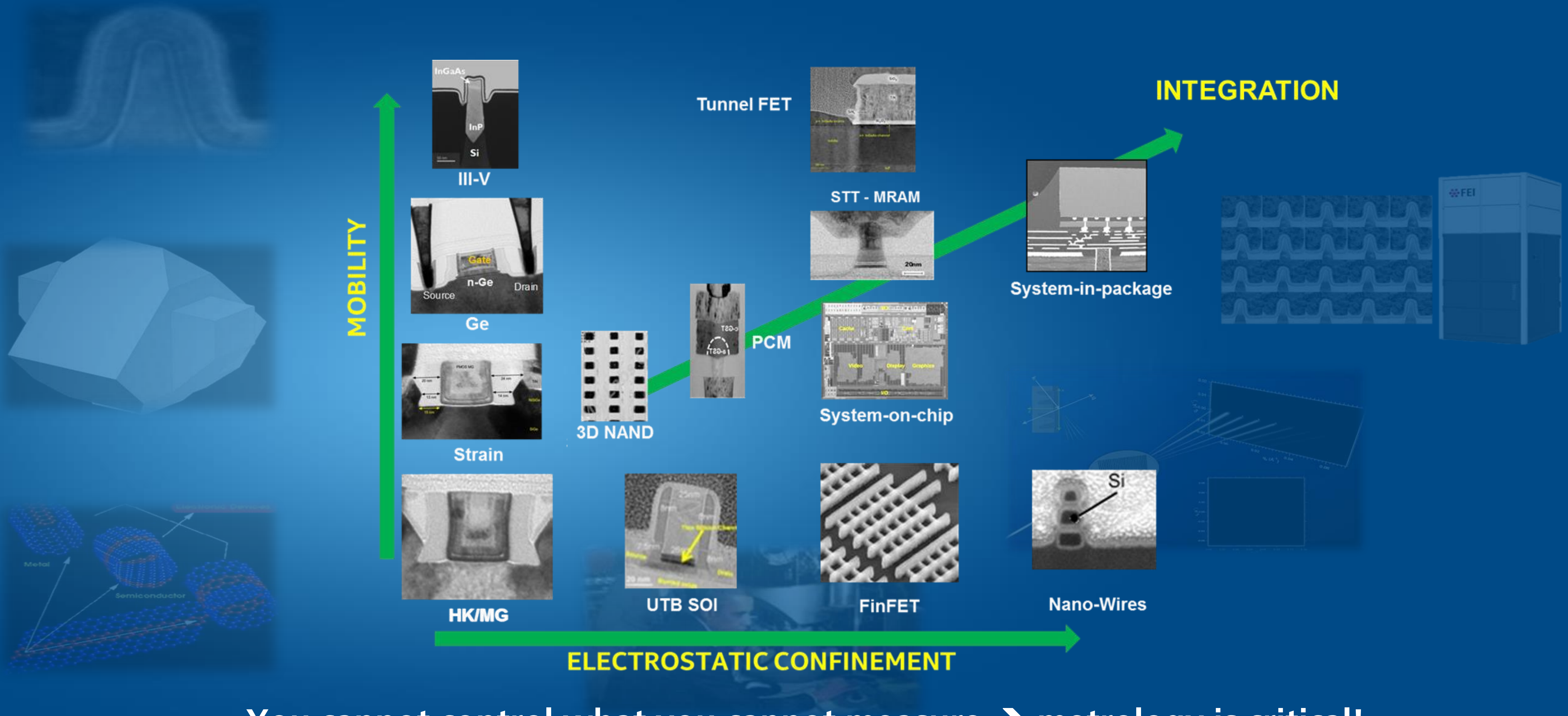
- Product trends
  - New device architectures: 2D ➔ 3D (FinFET, trigate, FDSOI, NVM, …)
  - 3D chip integration / advanced packaging

- 3D architectures require 3D metrology and diagnostics ➔ "metrology gap"
  - <u>Fast</u> metrology and diagnostics (time-to-data)
  - <u>Nondestructive</u> 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, RDLs)

Future Products will be Increasingly More Complex



MOBILITY

III-V

Ge

Strain

HK/MG

3D NAND

UTB SOI

PCM

Tunnel FET

STT - MRAM

System-on-chip

FinFET

System-in-package

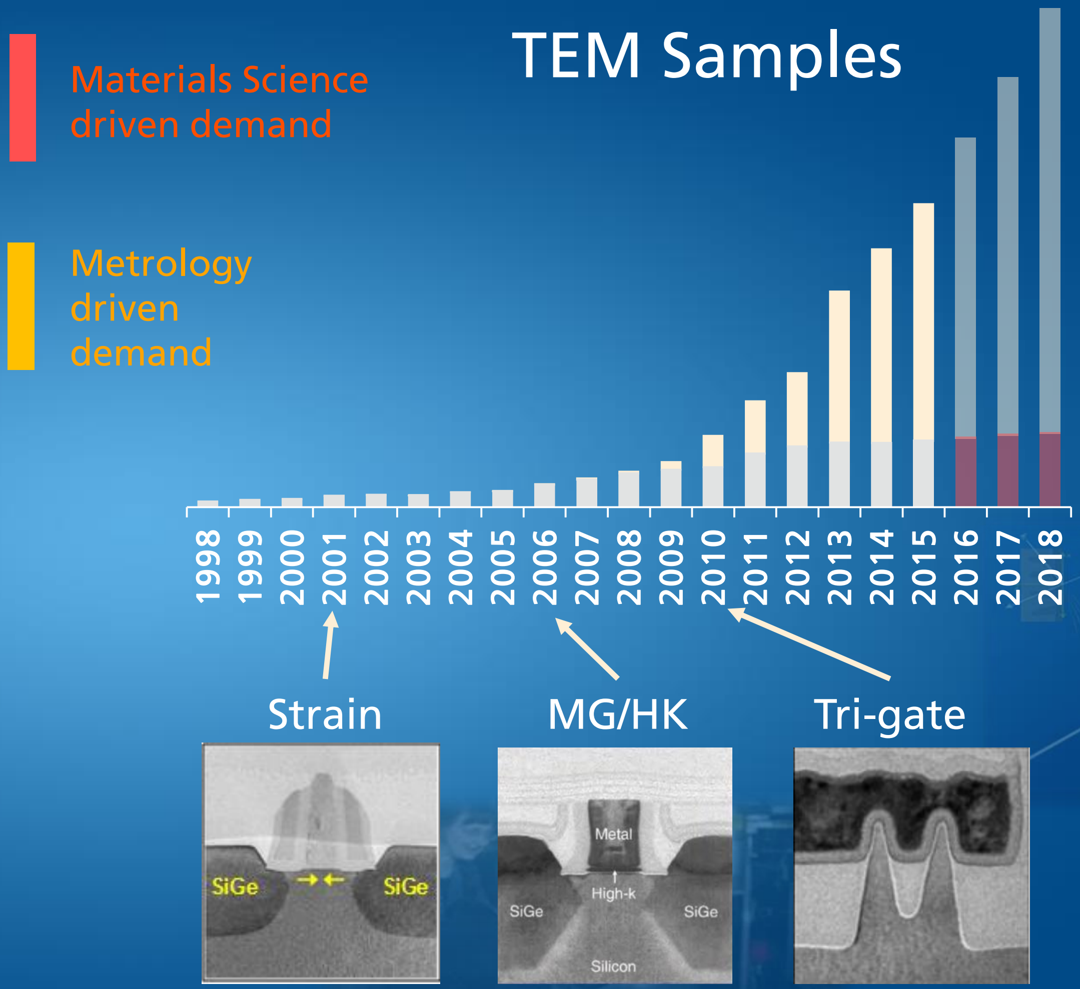
INTEGRATION

Nano-Wires

ELECTROSTATIC CONFINEMENT

You cannot control what you cannot measure ➔ metrology is critical!

Dimensional Metrology Lab Demand (driven by 3D transistor)



Automated TEM flow as near-fab metrology solution

X-ray techniques for metrology and diagnostics

Integral technique covering large areas / many devices ➔ metrology

- X-ray diffraction XRD and small angle X-ray scattering SAXS (local technique at individual structures: TEM (CBED, ENBD, Holography, … + brightfield imaging)
- X-ray reflectometry XRR (local technique at individual structures: TEM)
- X-ray spectroscopy XRF, XAS (local technique at individual structures: TEM/EDX+EELS)

High resolution imaging techniques ➔ diagnostics/failure analysis

- (micro) X-ray computed tomography micro-XCT
- Transmission X-ray microscopy TXM / nano X-ray computed tomography nano-XCT

Combination of techniques ➔ hybrid metrology and diagnostics

- high-resolution (3D) imaging (nano-XCT) & high-resolution XRF and XRD

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

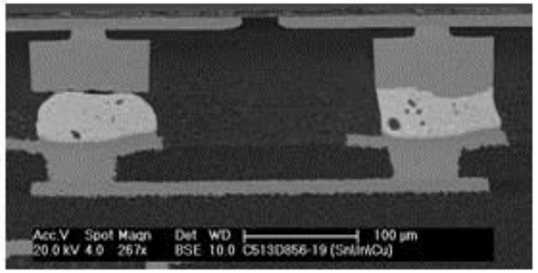
Technical challenges for 2D X-ray imaging are:

- 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.

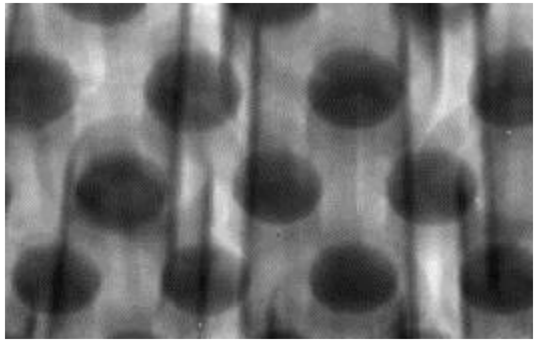
The fundamental limitations of 2D X-ray imaging technology are a common roadblock driving X-ray computed tomography (XCT) for failure analysis in semiconductor industry.

➔ conventional packaging: micro-XCT,

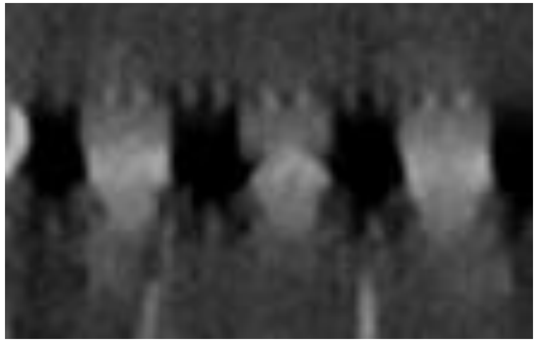
➔ BEoL + advanced packaging: nano-XCT



Physical X-section C4 bump



Best 2D radiography ➔ defect not visible!



Virtual X-section based on 3D XCT

Z. Ma, E. Zschech, IRSP 2016

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3. Outlook:
    - X-ray microscopy: Fast, high resolution, really nondestructive

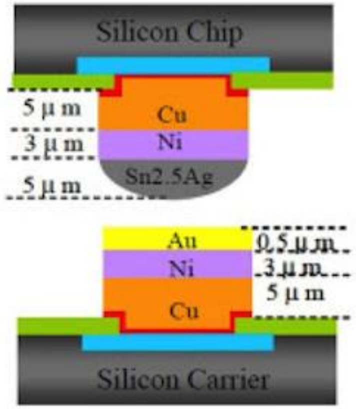
Reliability of advanced and 3D integrated ICs – *It's all about stress*

- **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

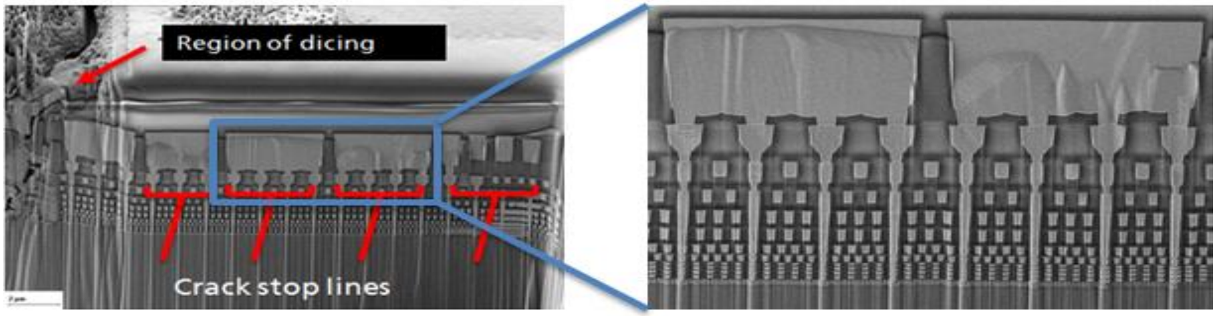
- **Enforcement of (known) phenomena in BEoL structures**
  - **(Thermo)mechanical failures – Cracks in interconnect systems**
    - ***Failures in BEoL structures (micro-cracks)***
  - **Stress-enforced lifetime reduction / electrical effects**
    - Electromigration
    - Stress-induced voiding
  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

Reliability of advanced and 3D integrated ICs – *It’s all about stress*

- 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



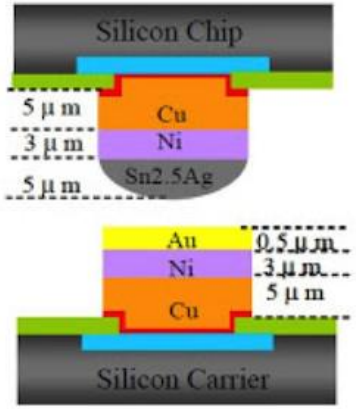
- Enforcement of (known) phenomena in BEoL structures
  - (Thermo)mechanical failures – Cracks in interconnect systems
    - *Failures in BEoL structures (micro-cracks)*
      3D imaging of stress-induced crack propagation in BEoL stacks (CPI)
    - Electromigration
    - Stress-induced voiding
    - Time-dependent dielectric breakdown



Effects of stress on reliability in Si-based electronics

- 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



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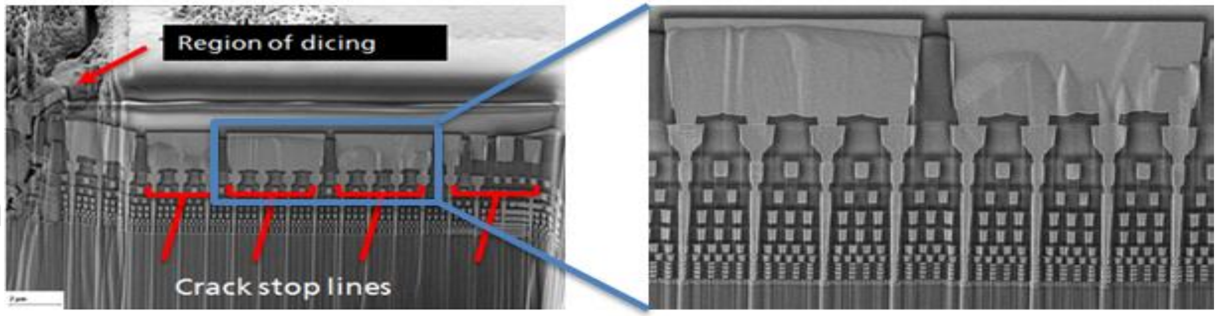
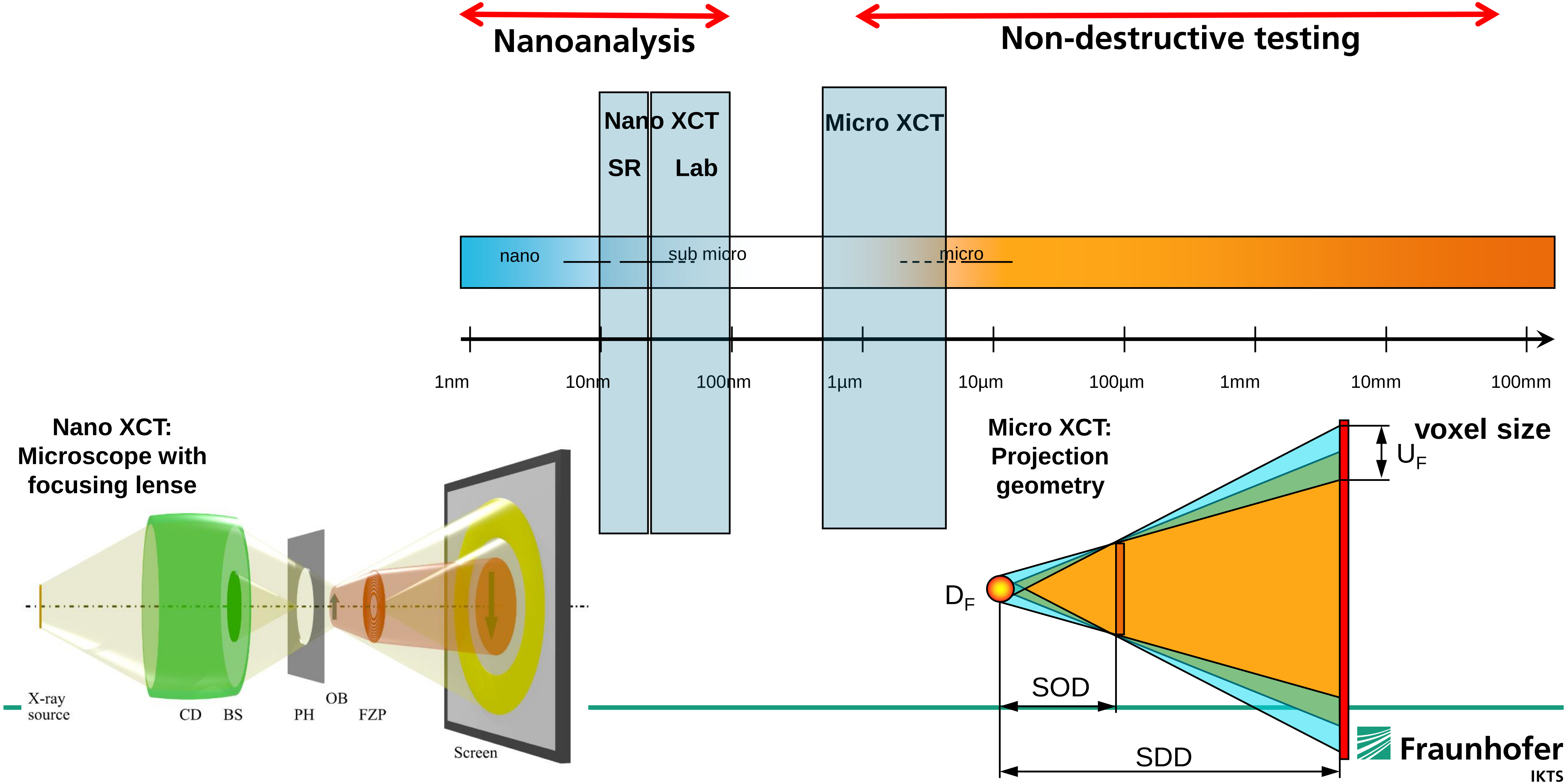


Demonstration of new developments in X-ray tomography for future industrial application: Metrology and diagnostics/failure analysis in semiconductor industry

3D characterization of micro-cracks in advanced materials and microchips using laboratory X-ray computed tomography (XCT)

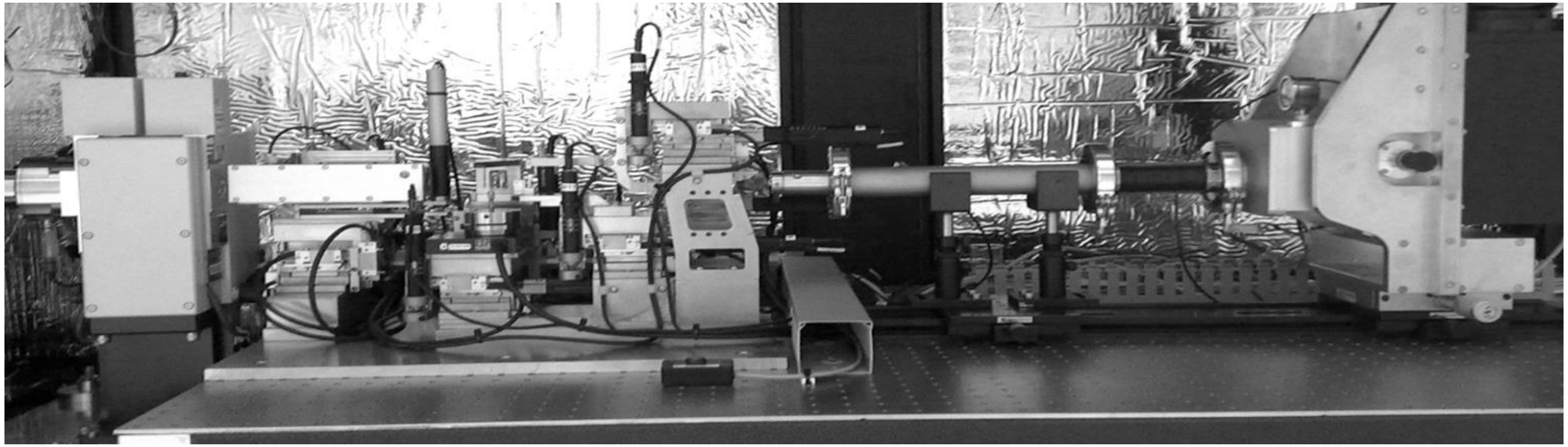


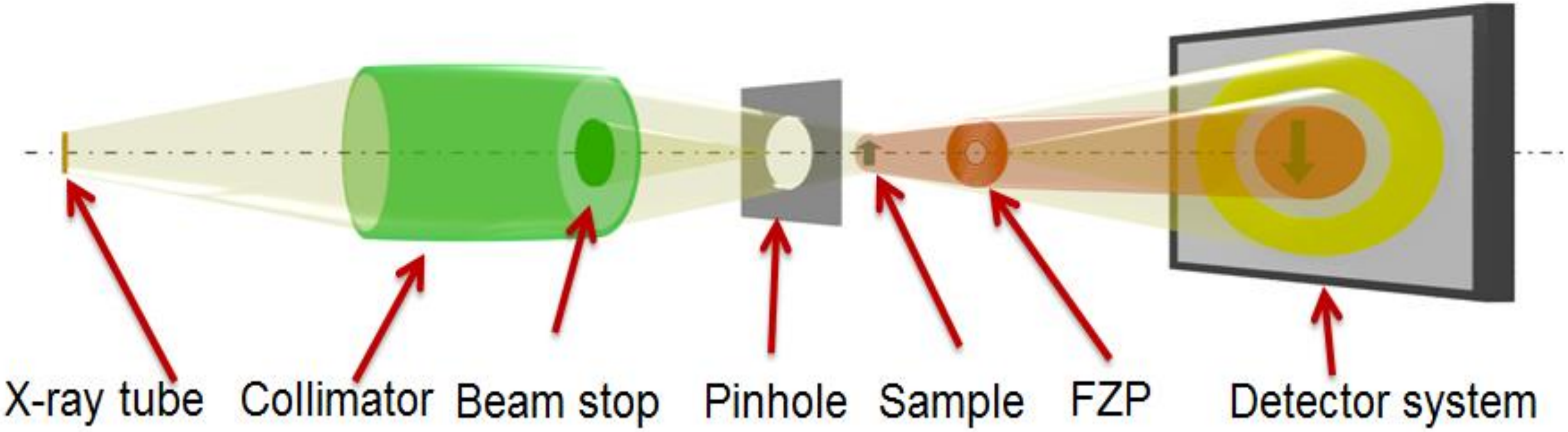
Nano XCT: Microscope with focusing lense

Micro XCT: Projection geometry

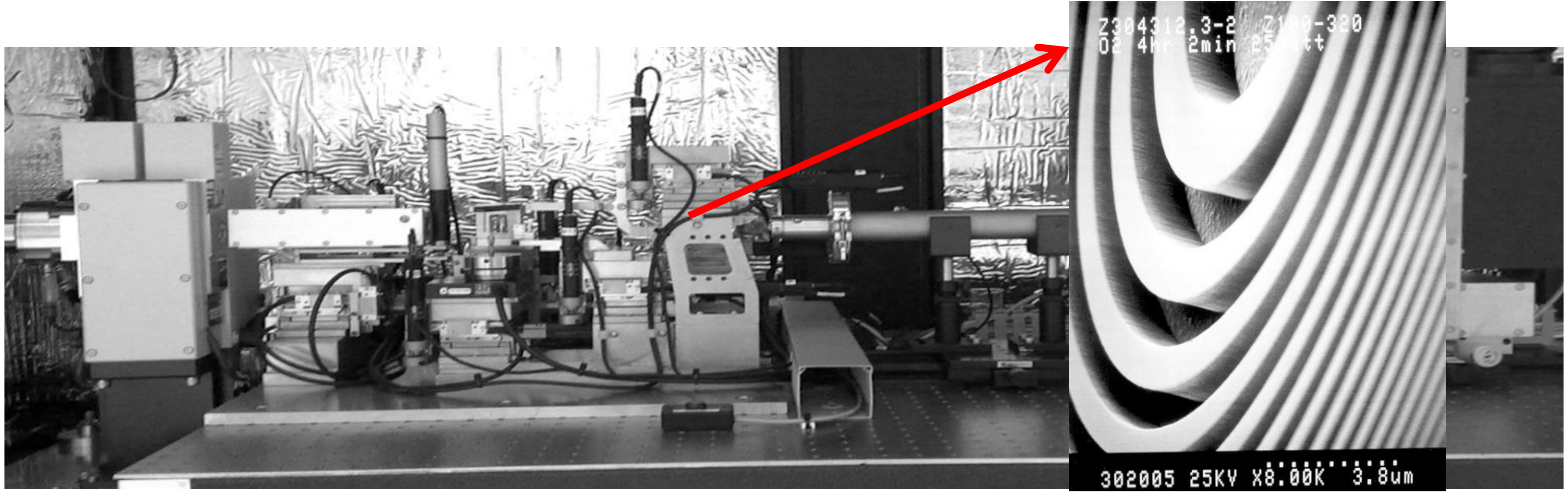
Fraunhofer
IKTS

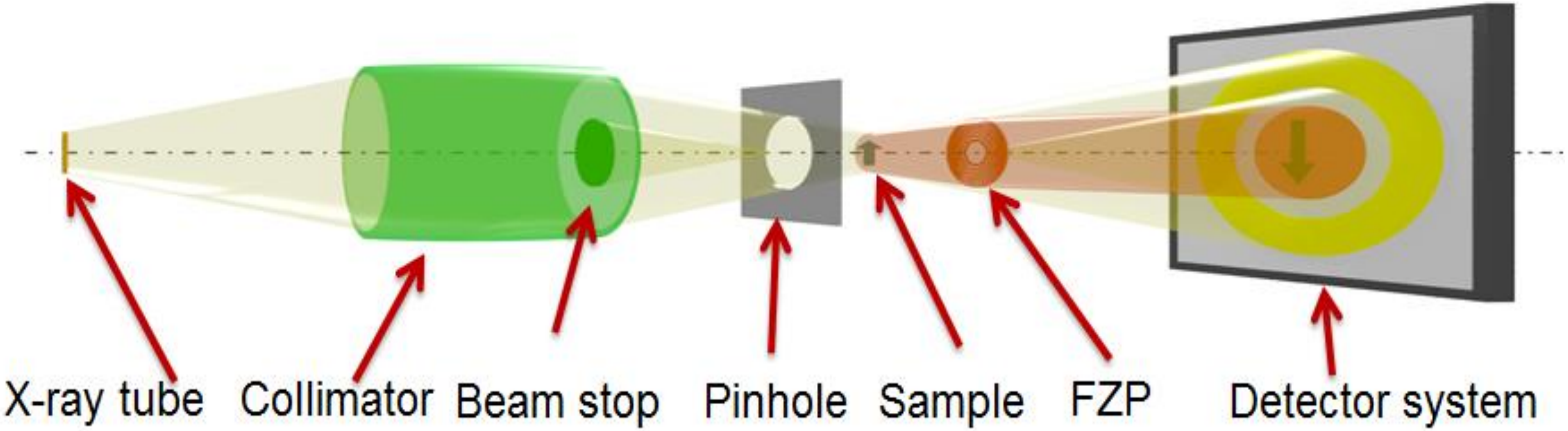
Laboratory X-ray microscopy and nano XCT





Laboratory X-ray microscopy and nano XCT





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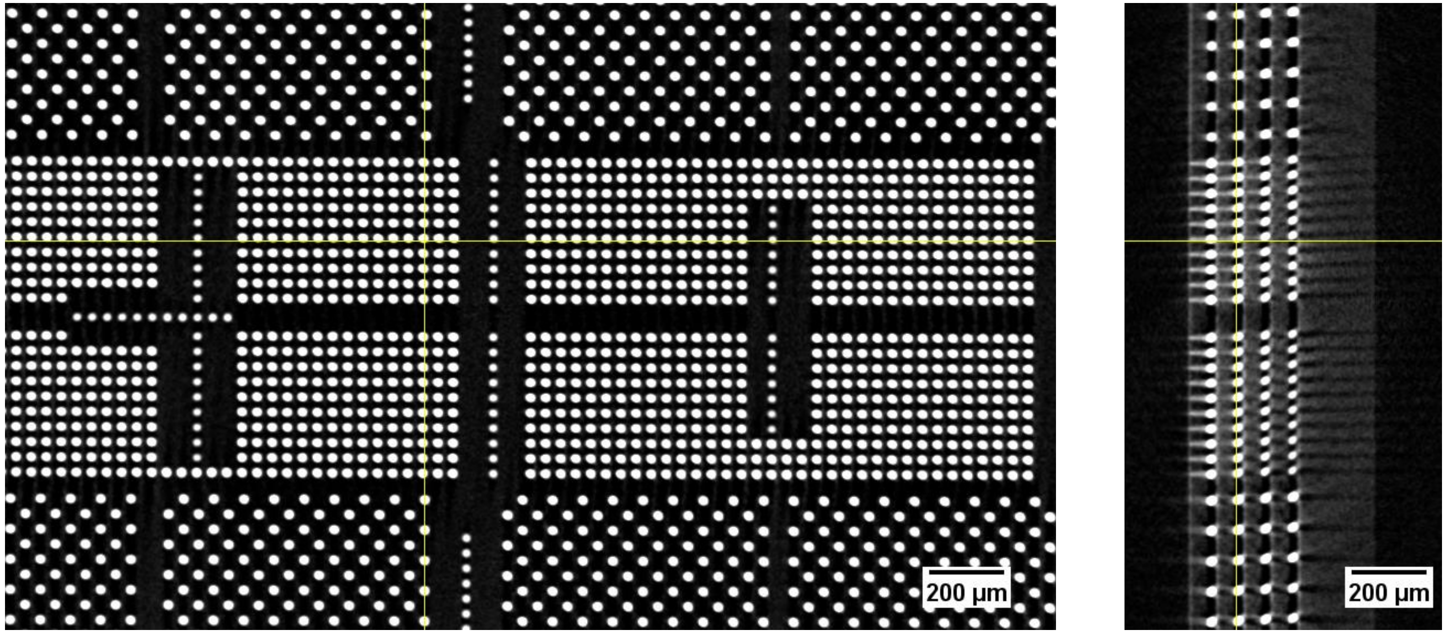
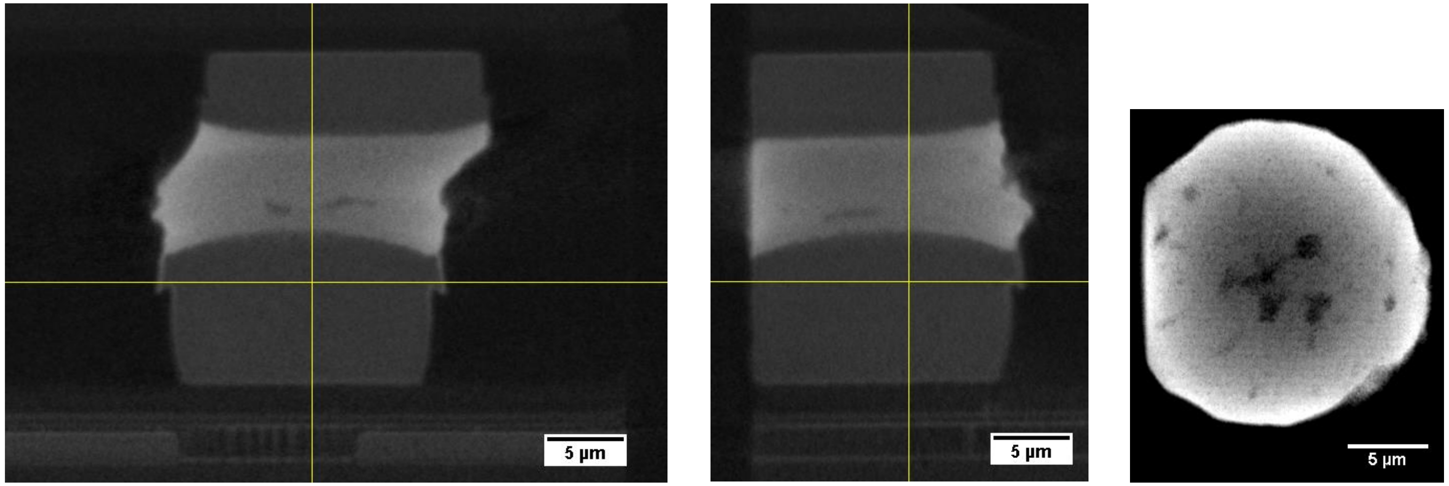
Example: Micro-bumps in 3D IC stacks – HBM



High bandwith memory (HBM) stack:

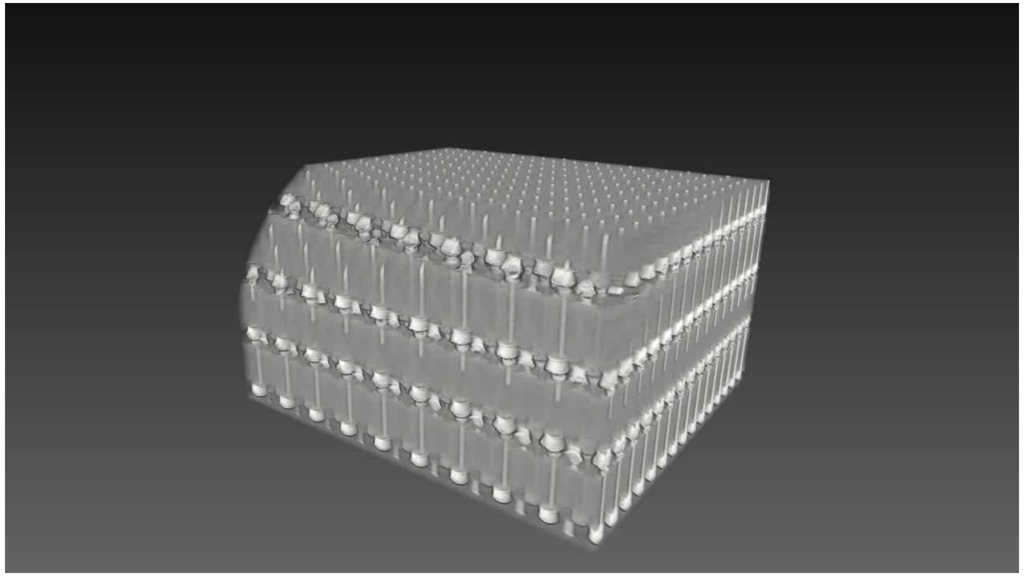
Two virtual 2D images (planar view and cross-section view), based on a 3D data set from *micro XCT*. Nondestructive imaging.

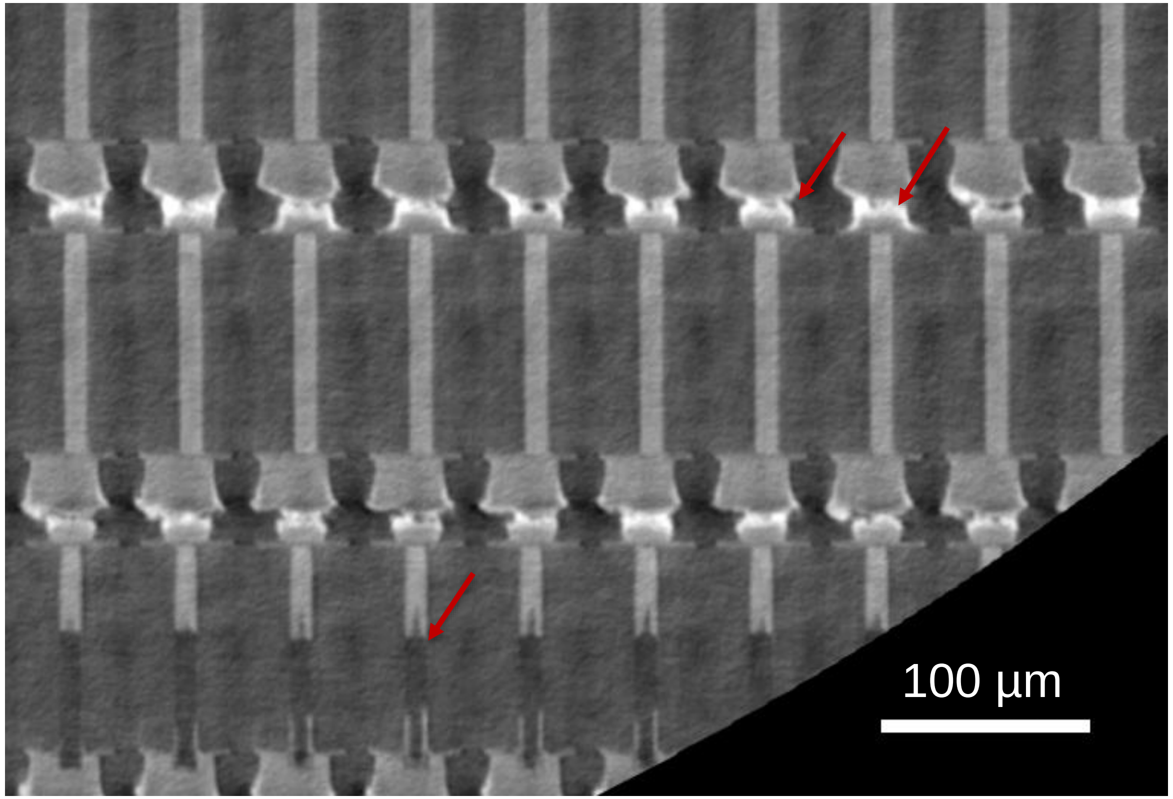


Three virtual 2D images (two perpendicular cross-section views and one planar view), based on a 3D data set from *nano XCT*. Imaging of a small extracted sample.

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

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

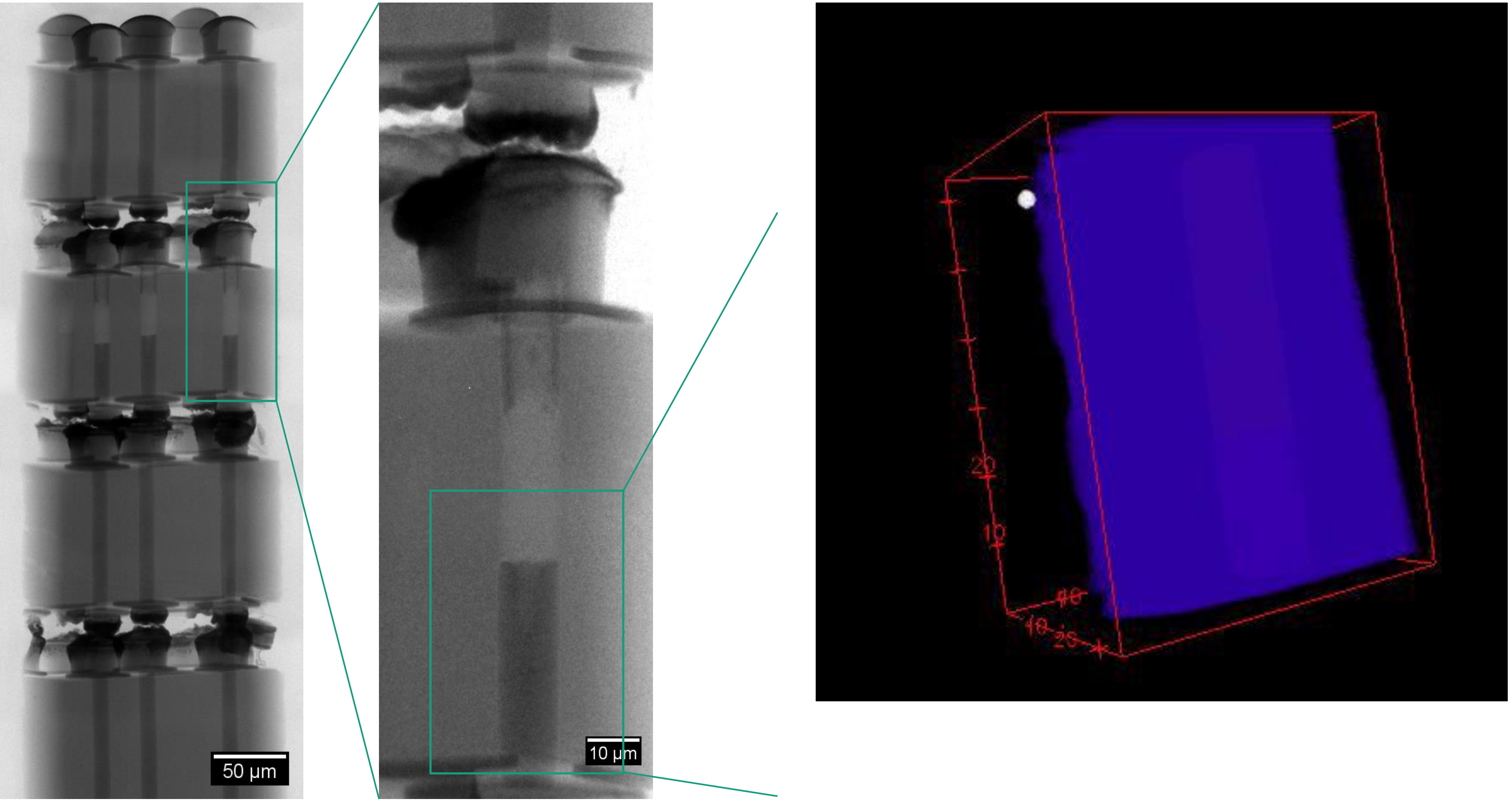




Incomplete Cu TSV filling, variation in solder flow (AgSn)

E. Zschech et al., PanPac 2015

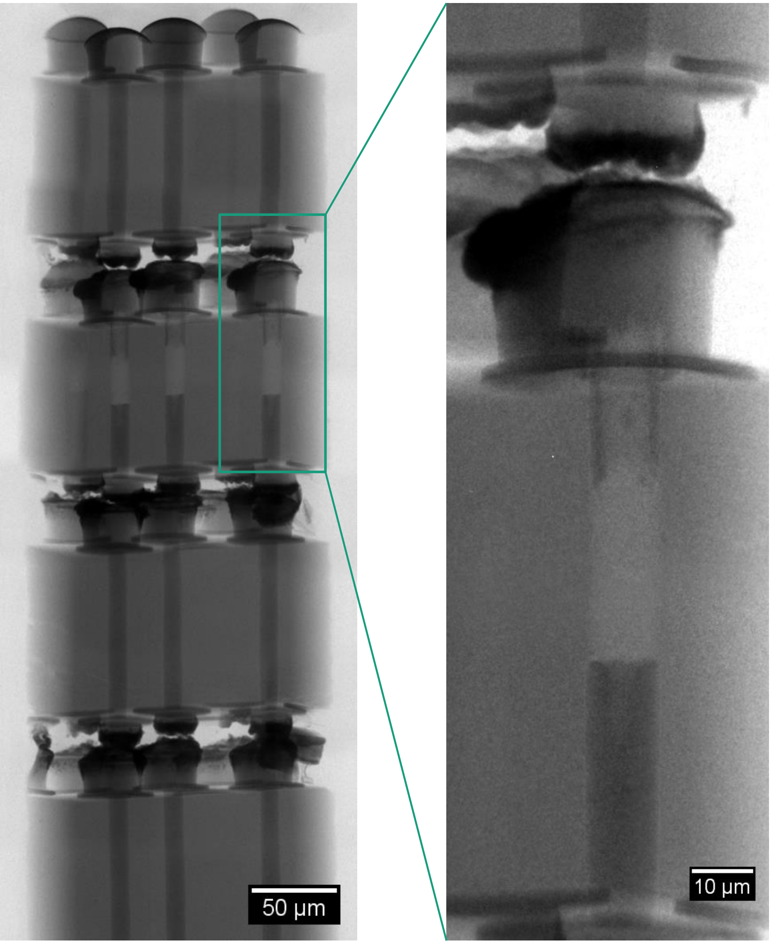
Multi-chip 3D TSV stack: TSV – *Nano XCT*

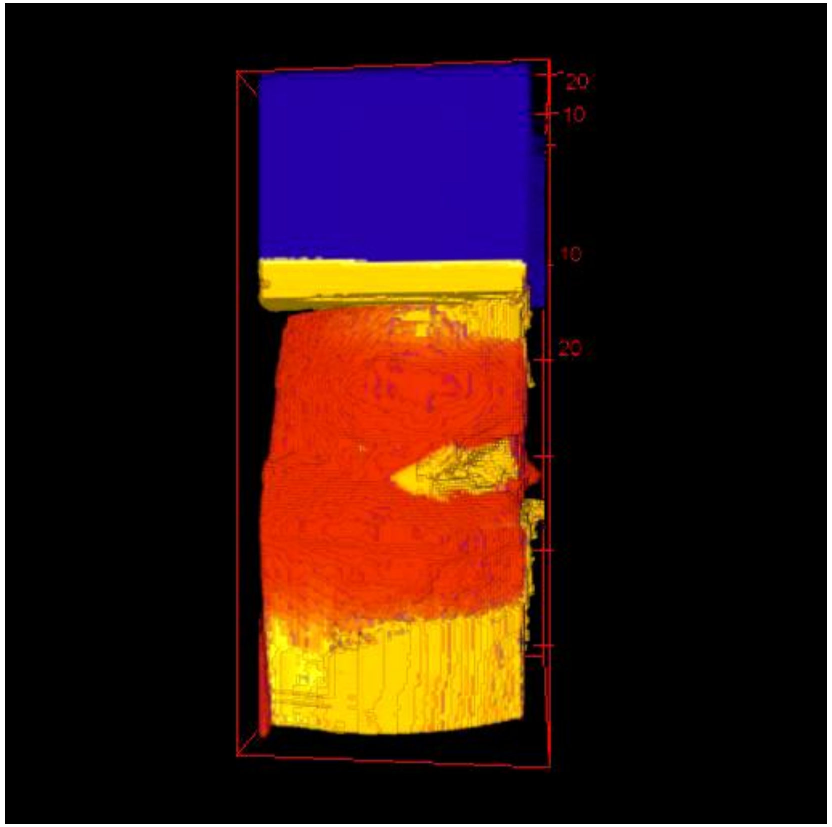


Tomography of a partially filled Cu TSV

E. Zschech et al., PanPac 2015

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

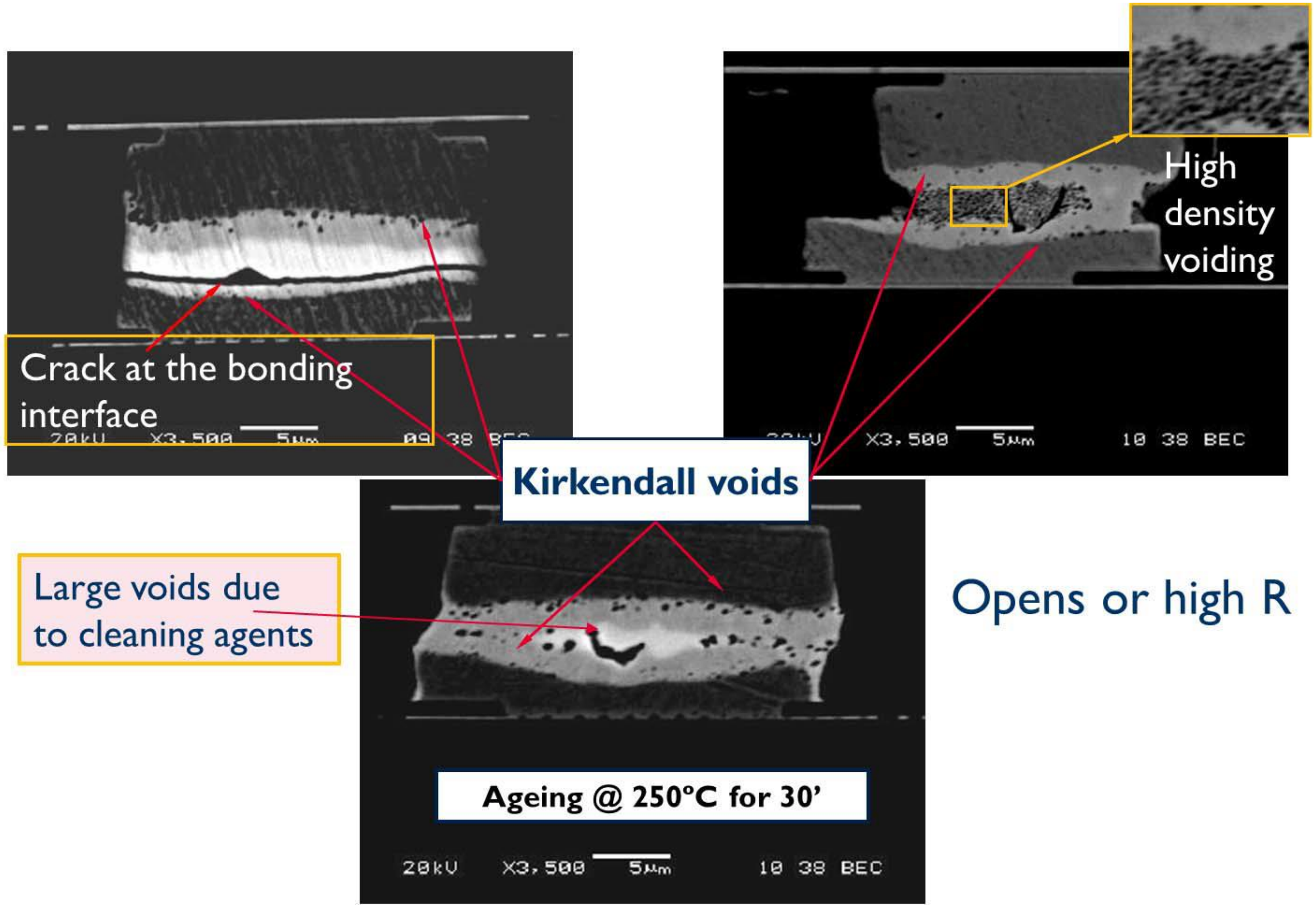




Tomography of a AgSn microbump

E. Zschech et al., PanPac 2015

Typical failures in microbumps



Crack at the bonding interface

High density voiding

Kirkendall voids

Large voids due to cleaning agents

Ageing @ 250°C for 30’

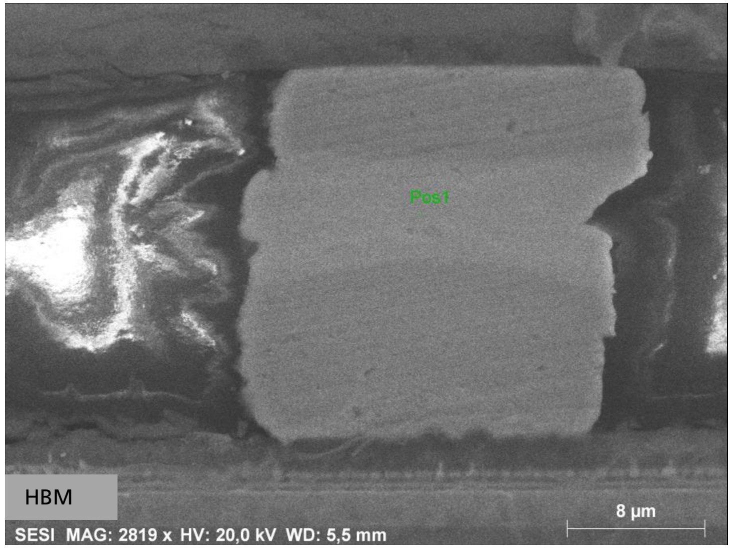
Opens or high R

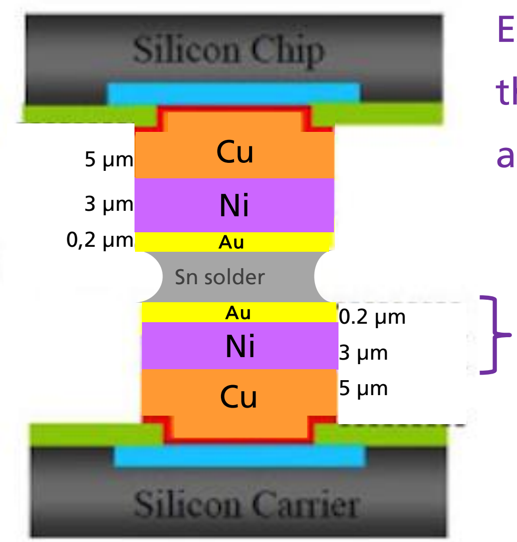
… but that’s not all !!!

Geometry AND materials (phases, microstructure) AND defects are playing a role !!!

I. De Wolf et al., IEEE TCPMT 2018

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)**

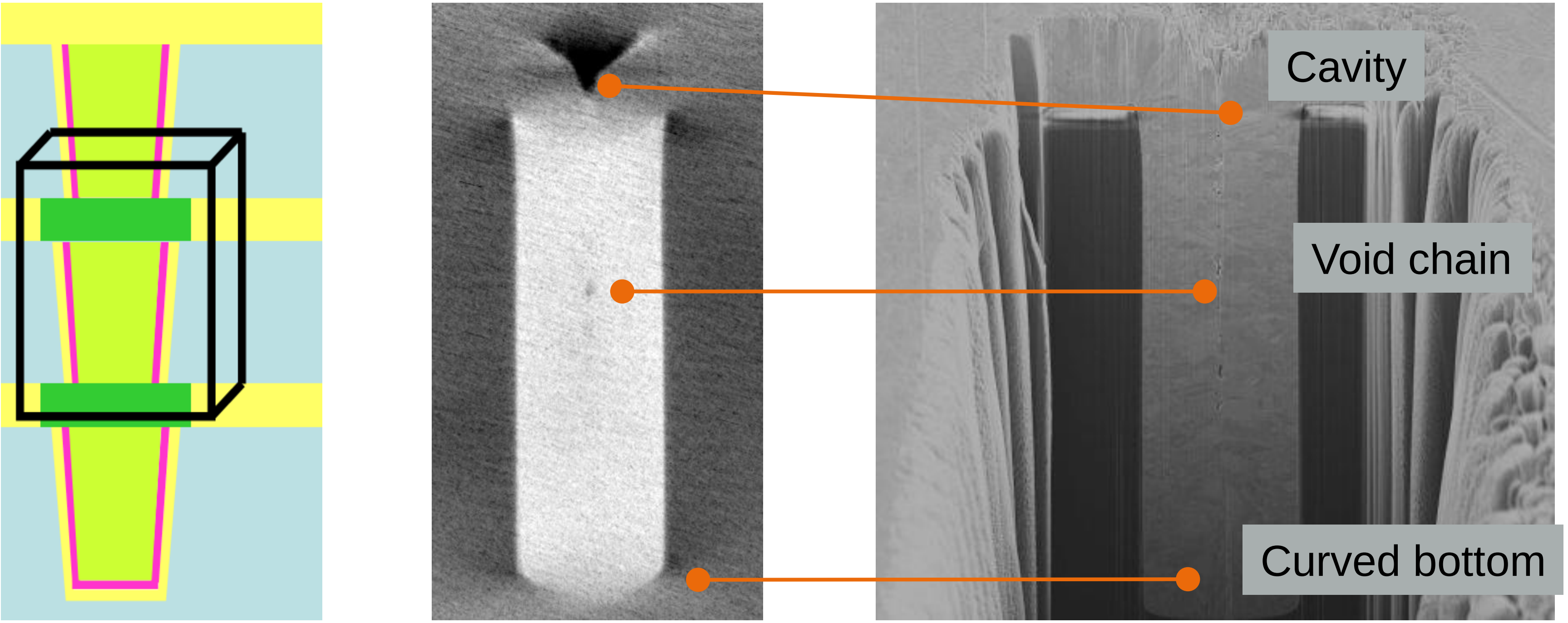
E. Zschech et al., IRSP 2018

Determination of shape variations and defects in solder interconnects ➔ Conclusions regarding reliability risks

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

Nondestructive failure localization: Voids ~ 100 nm size can be localized

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

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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

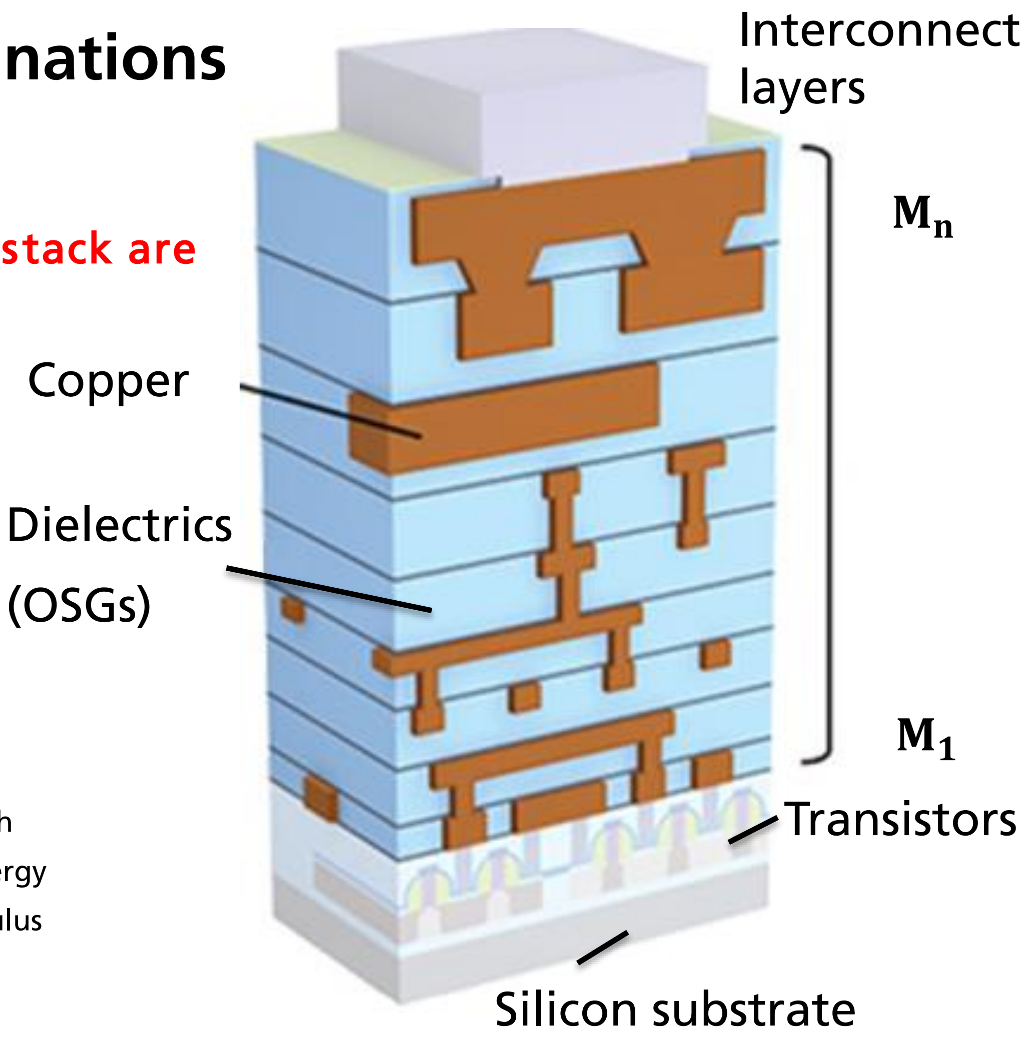
Young's modulus and fracture toughness are needed

Tasks of reliability engineering:

➔ Understand degradation mechanisms

Criterion for crack propagation: $\frac{\pi\sigma^2 a}{\textcircled{E}} \geq 2\gamma \longrightarrow$ 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**

Mechanical test set-ups for in-situ study of degradation kinetics of materials and 3D systems in the X-ray microscope

- Objective
  - Ensure required in-service mechanical performance and reliability of advanced products and systems.

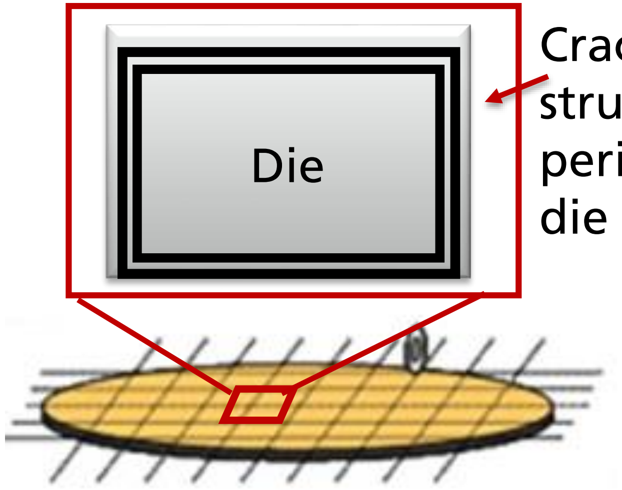
- Challenges
  - Fracture mechanics explains mechanical properties.
  - Metallographic preparation destroys the samples and is not representative for a product.
  - Understanding of degradation kinetics and failure in materials and microelectronic products requires nondestructive in-situ visualization of crack propagation.

- Solution
  - **In-situ study of the fracture behavior of multi-component 3D systems:** High-resolution imaging of crack opening and propagation in 3D structures – generation of 4D data sets.

➔ Integration of (thermo)mechanical test set-ups into an X-ray microscope / nano-XCT tool.

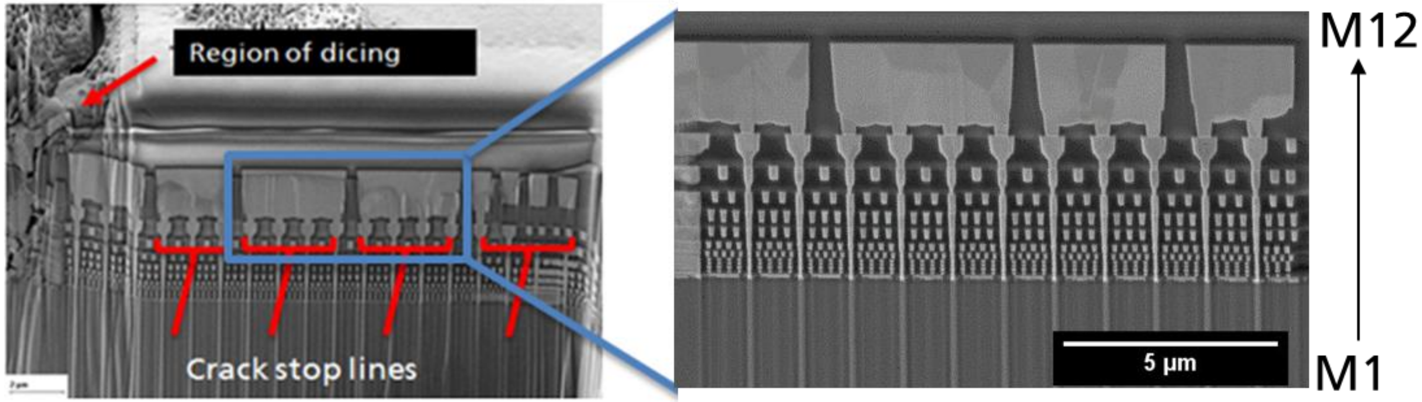
Microchip mechanical properties investigation: Combination of X-ray microscopy and in-situ micro-mechanical testing

- 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)

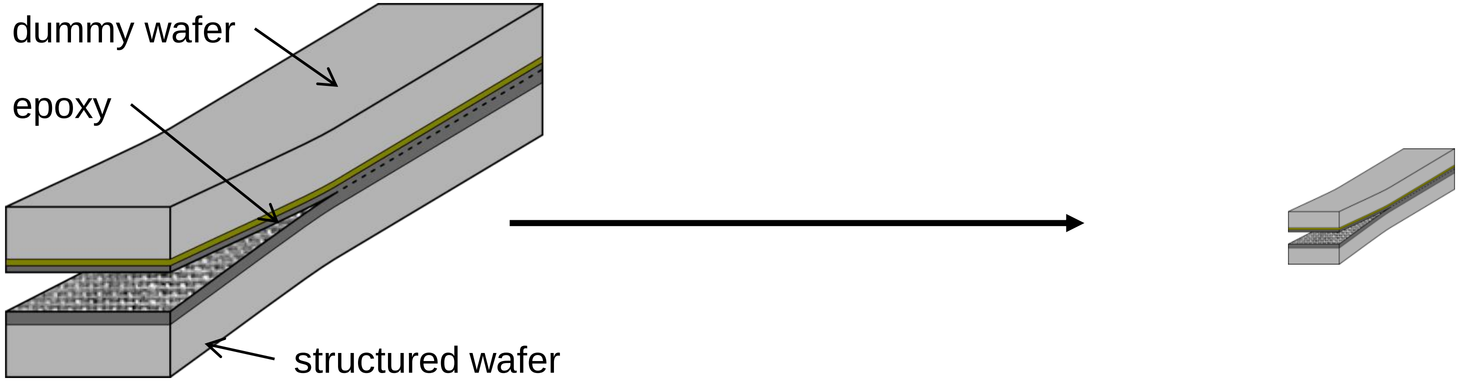
Microchip reliability improvement approach:

- 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

Double Cantilever Beam (DCB) test: Macro vs. Micro



- **Macro DCB test**
  - Standard test in fracture mechanics, e.g. for determination of adhesion properties:

    stable crack growth due to fast release of stored elastic energy during crack propagation (ERR), mode I node
  - sample dimension: 1.7×5×50 mm³

Preparation

  - Epoxy bonding with dummy wafer
  - Two side lapping and precision sawing
  - Notching, if needed

Micro DCB test

- 2D and 3D visualization of crack propagation through patterned systems (Cu/ULK BEoL stack) at several load steps
- sample dimension: ~ 50×50×1000 µm³

Preparation

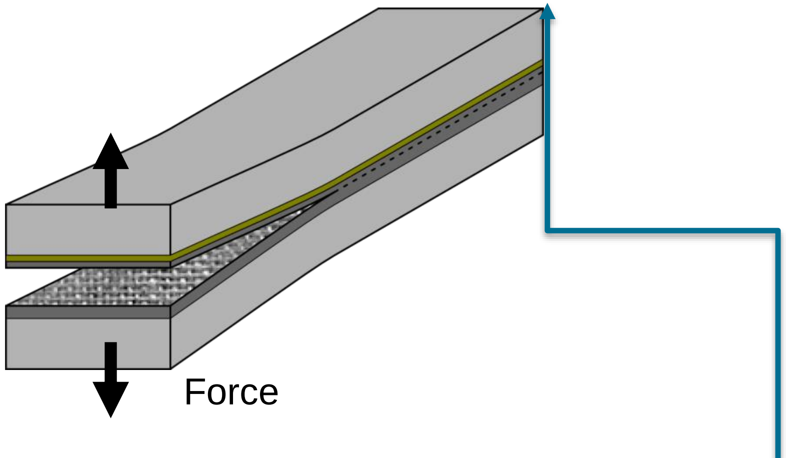
- Razer blade or FIB notching
- In addition: epoxy UV curing, bonding to MicroDCB fixture, ROI alignment to X-ray beam

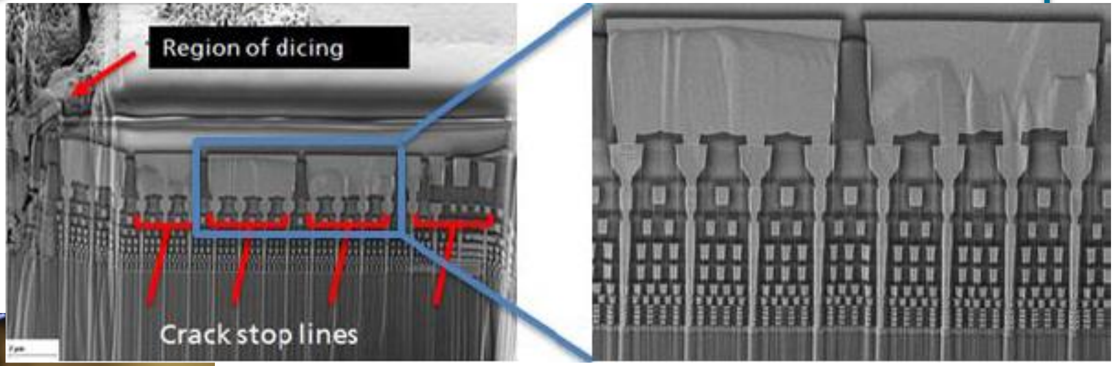
S. Niese, PhD thesis, BTU Cottbus 2015

In-situ mechanical testing of multilayer systems in the X-ray microscope

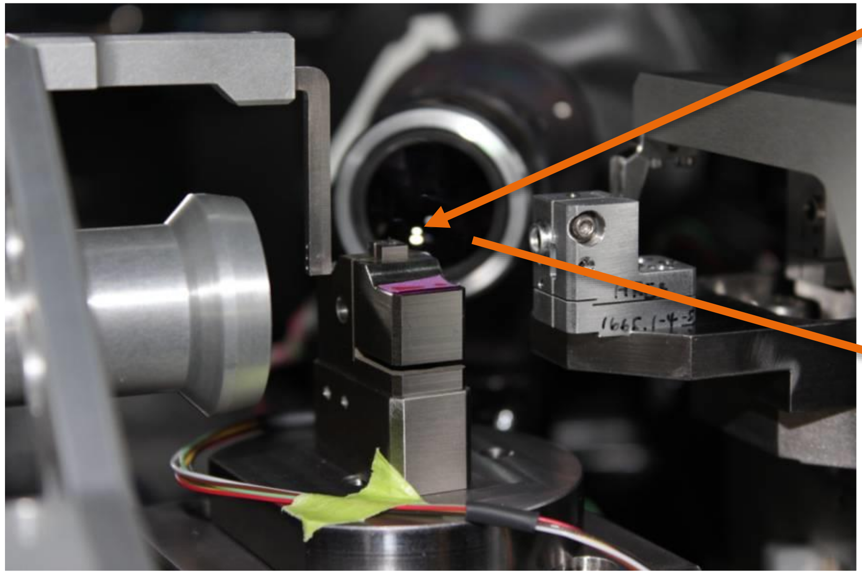
- **Micro Double Cantilever Beam test (MicroDCB)**
- **Scope: Crack initiation and propagation, particularly in guard ring structure**
- **X-ray microscopy / nano-XCT study under load**

Typical specimen, “sandwich”, dimension: 50 × 50 × 1000 µm³

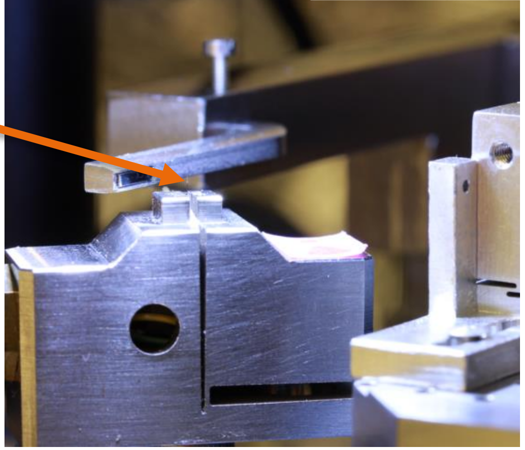




SEM image of the guard ring structure, representing 4 crack stop lines and 12 copper metallization layers



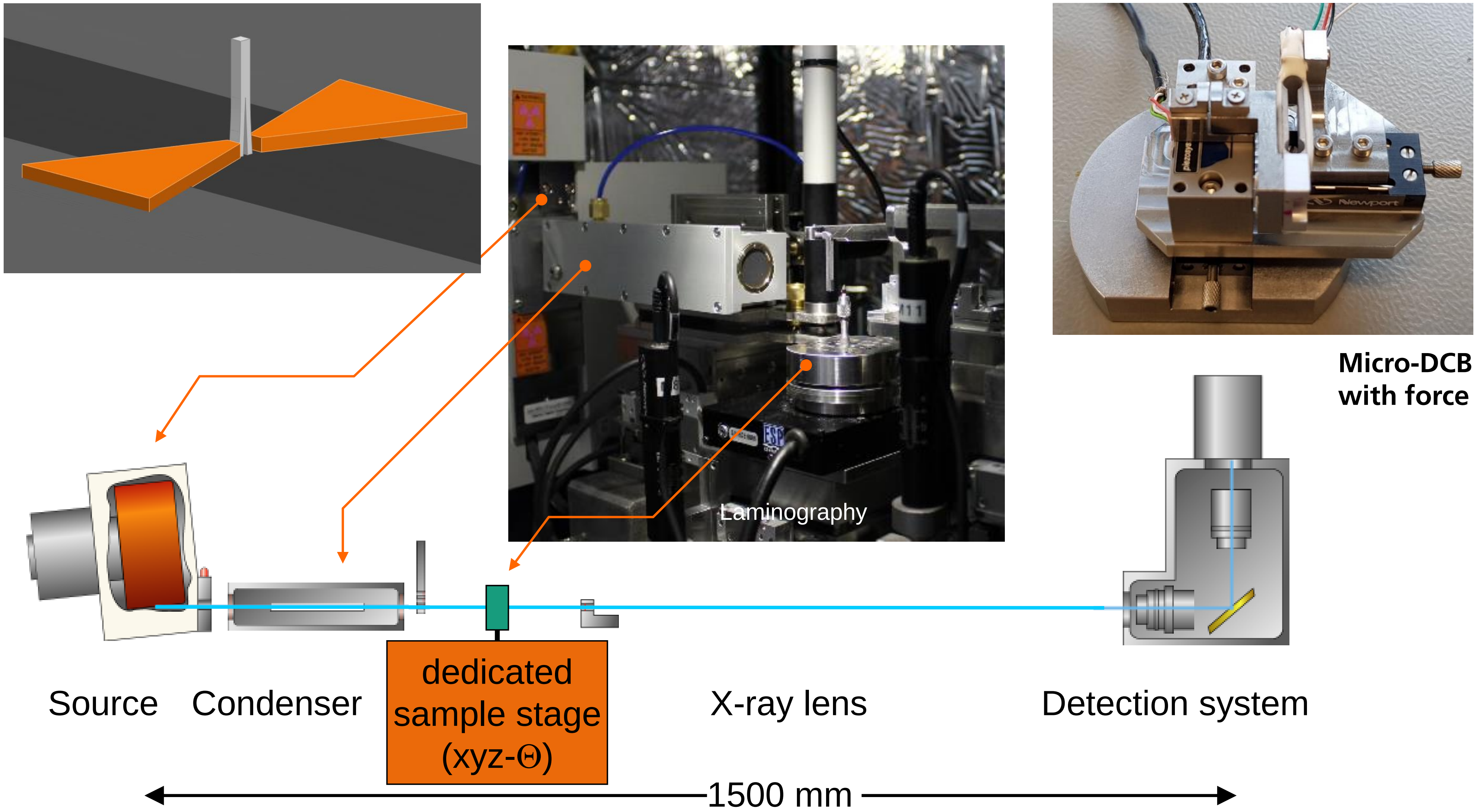
MicroDCB tester inside the nano-XCT



S. Niese, PhD Thesis, BTU Cottbus 2015

K. Kutukova et al., MRS Advances 2018

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



Micro-DCB tester with force sensor

Source

Condenser

dedicated sample stage (xyz-Θ)

X-ray lens

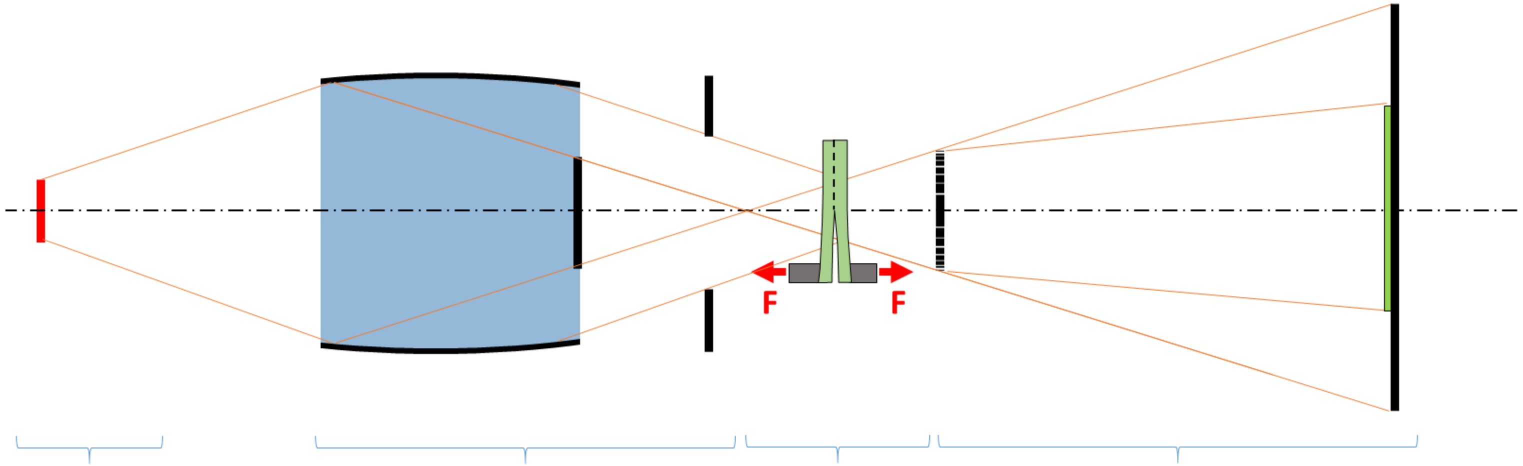
Detection system

1500 mm

S. Niese, PhD Thesis, BTU Cottbus 2015

K. Kutukova et al., MRS Advances 2018

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



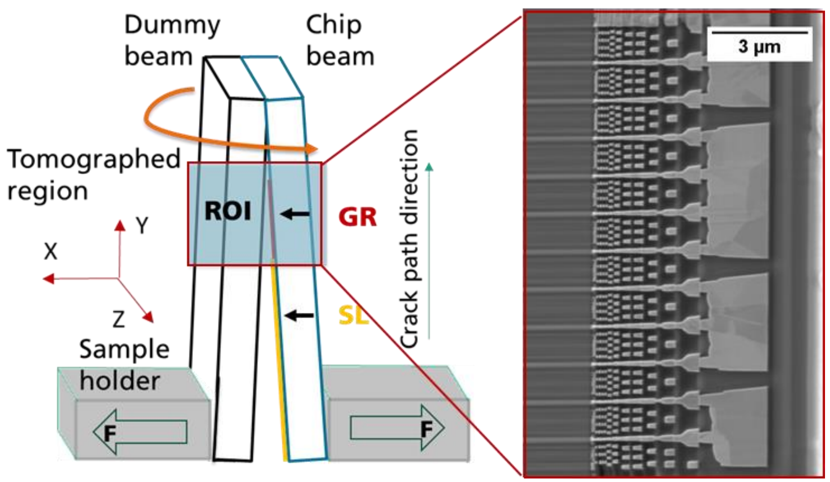
X-ray Source
Rot. anode
Cu-Kα

Illumination system
Capillary condenser,
beam stop, pinhole

Micro-DCB tester
Placed on a rotation
stage for tomography

Detector system
Magnification by FZP,
scintillator, CCD camera

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 path study: micro-DCB tester

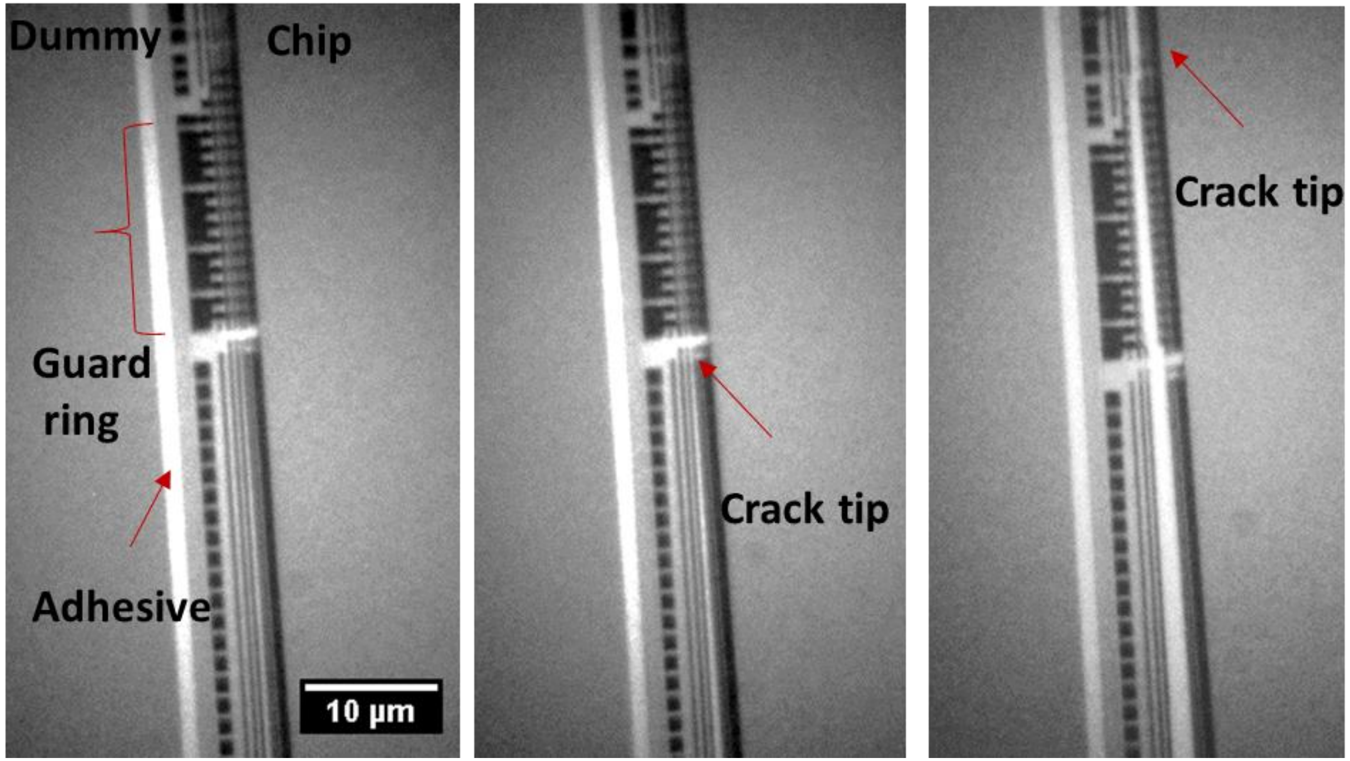
ROI GR: guard ring structure M1 – M12

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

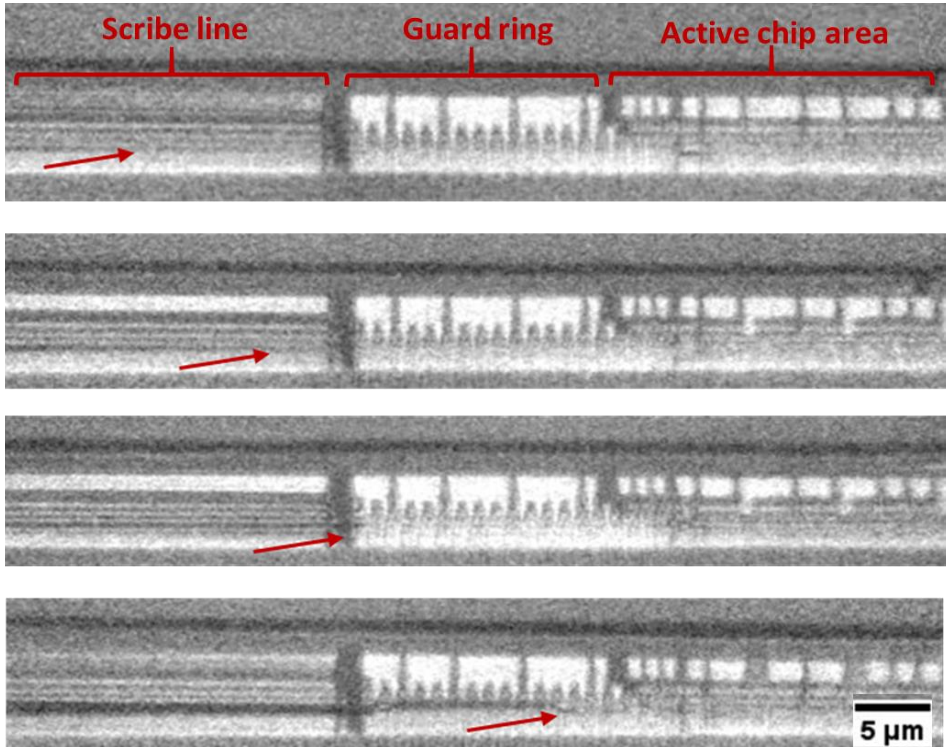
S. Niese, PhD Thesis, BTU Cottbus 2015

K. Kutukova et al., MRS Advances 2018

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



Radiographs series during micro-DCB experiment

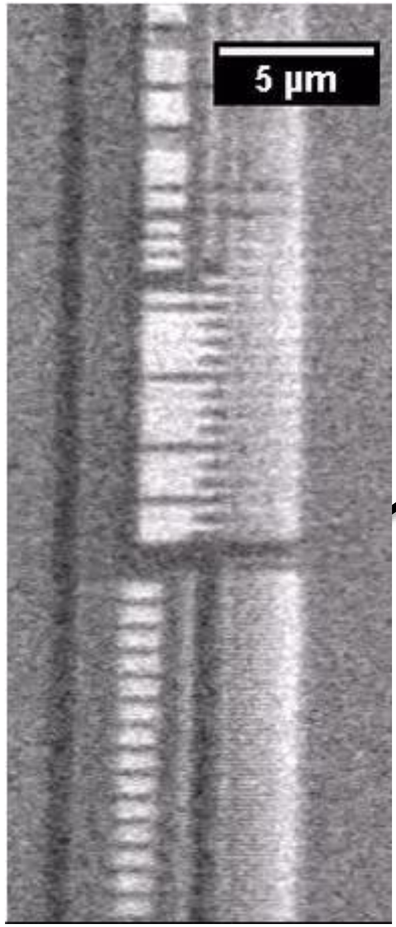


Series of the virtual cross-sections at several loading steps

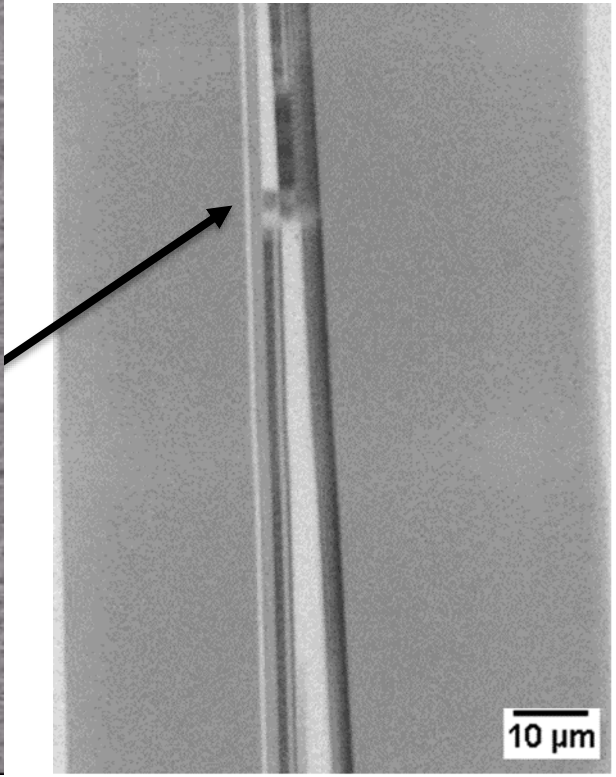
The crack stops at the guard ring structure, it changes the direction of propagation (energy dissipation), and finally cracking is observed. **Crack evolution depends on design, processes and materials, as well as stress (chip-package interaction).**

K. Kutukova et al., APL 2018

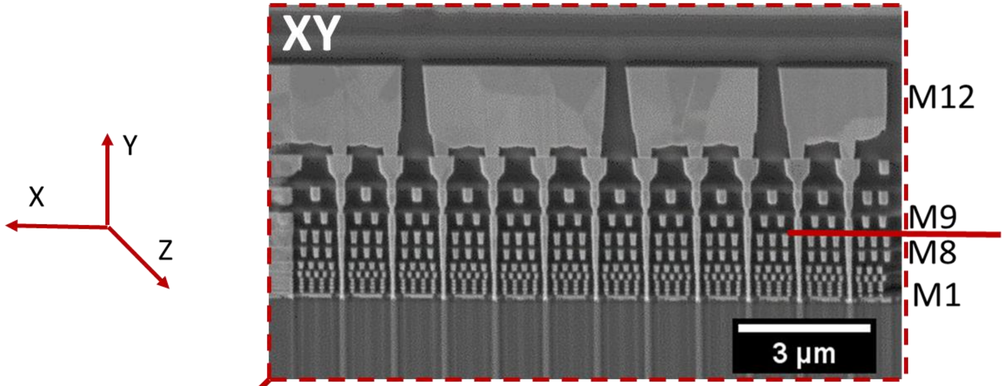
Nano-XCT crack path study in BEoL stacks of microchips, Confirmation with SEM @ “post mortem” samples



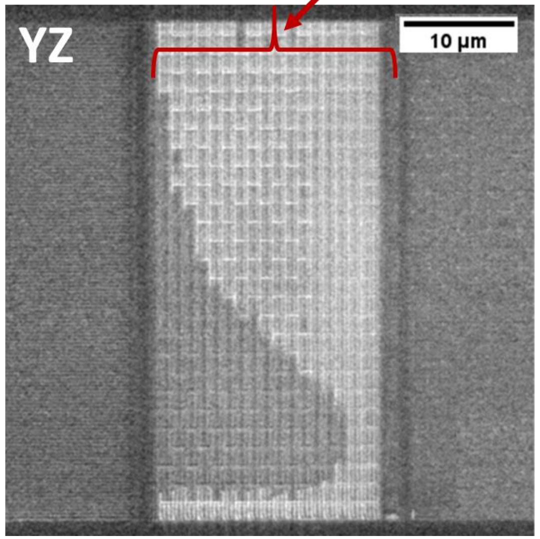
Movie: Reconstruction data through the sample thickness



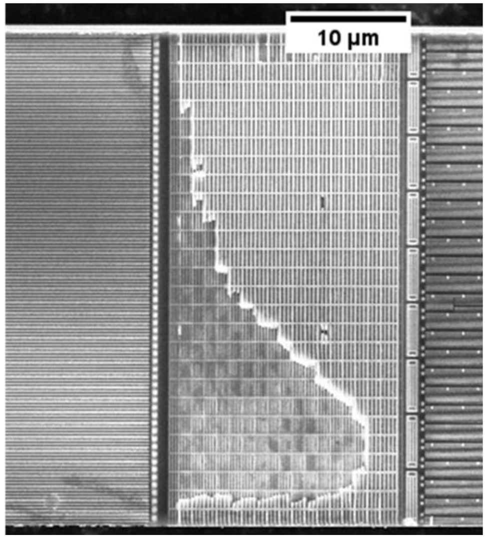
Stitched 2D radiograph



Metallization layers (FIB cross-section)



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



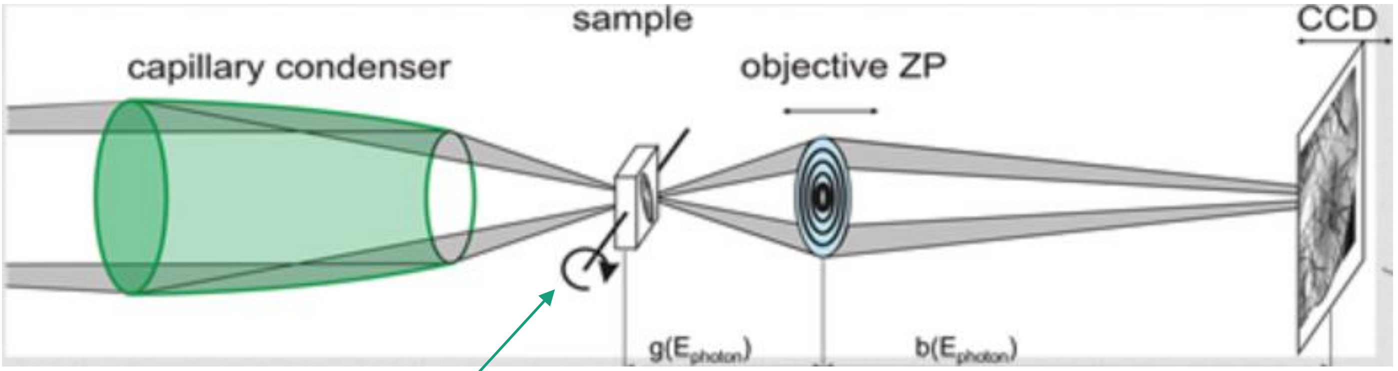
SEM image

K. Kutukova et al., APL 2018

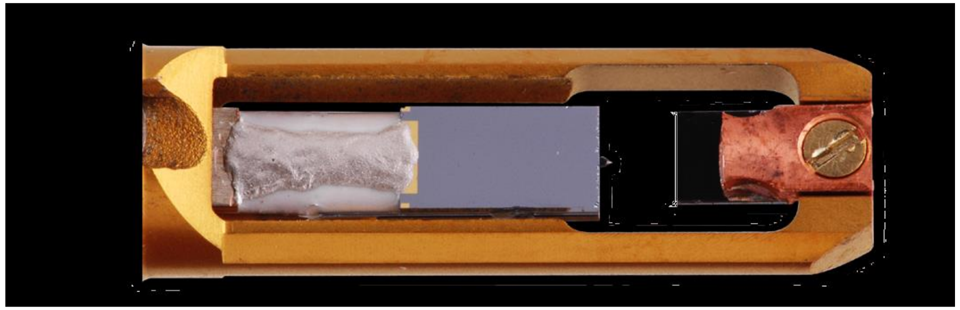
Determination of the weakest layers/interfaces) in the BEoL stack ➔ Input for the design of guard ring structures

High resolution synchrotron radiation for in-situ micro-mechanical experiments

- Beamline U41 – TXM specifications
- (BESSY II, Berlin)
  - Range of energies: 0.27 - 1.5 keV
  - Spatial resolution for 2D: 25 nm - 11 nm
- Possible to integrate special mechanical setup:
  - Modified PI 95 Hysitron/Bruker TEM PicoIndenter with indenter

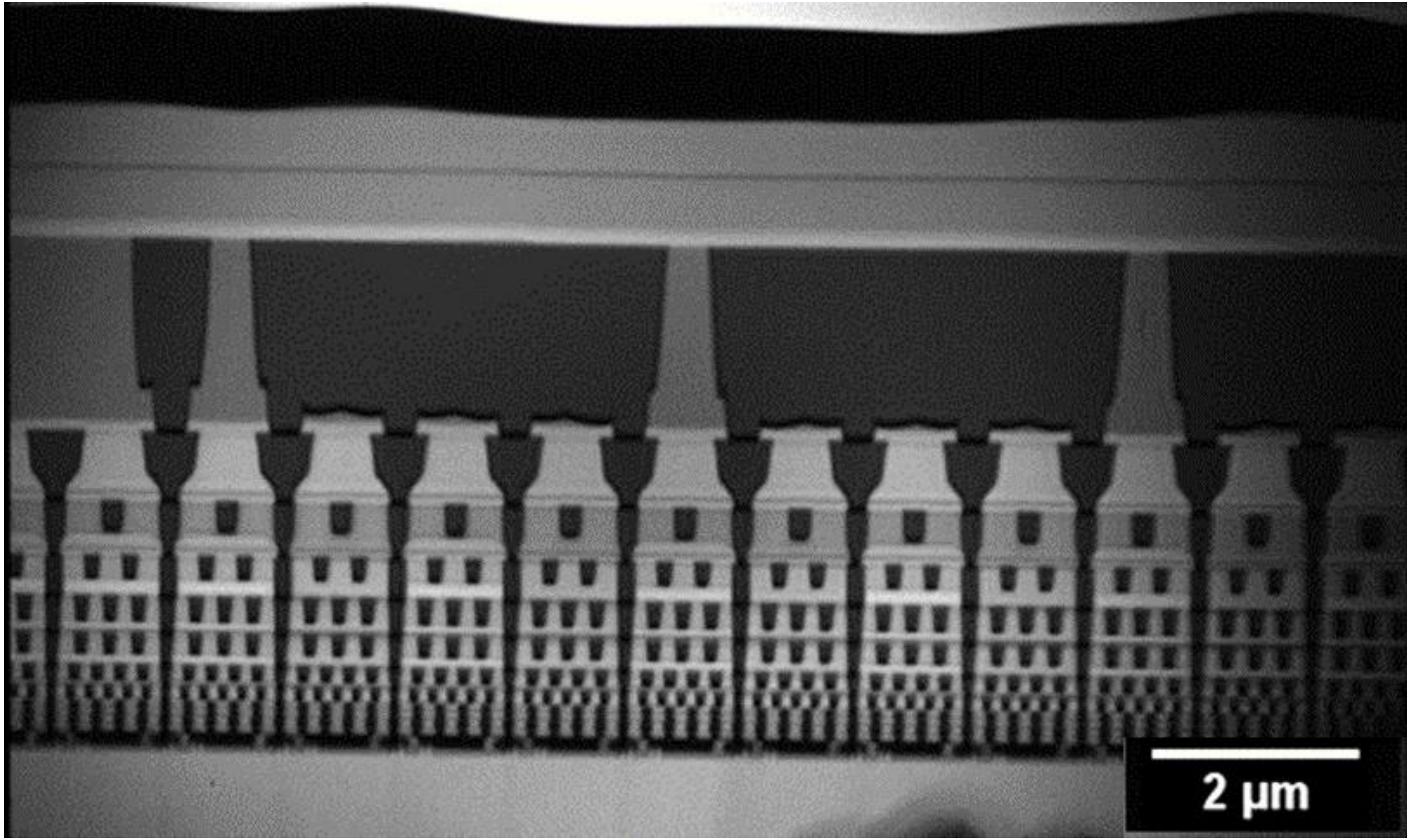


PI 95 TEM PicoIndenter (Bruker/Hysitron)



Sample holder with wedge indenter (tungsten tip)

High-resolution X-ray imaging of the guard ring structure at BESSY II



2D radiograph:
925 eV photon energy,
at 1st order -

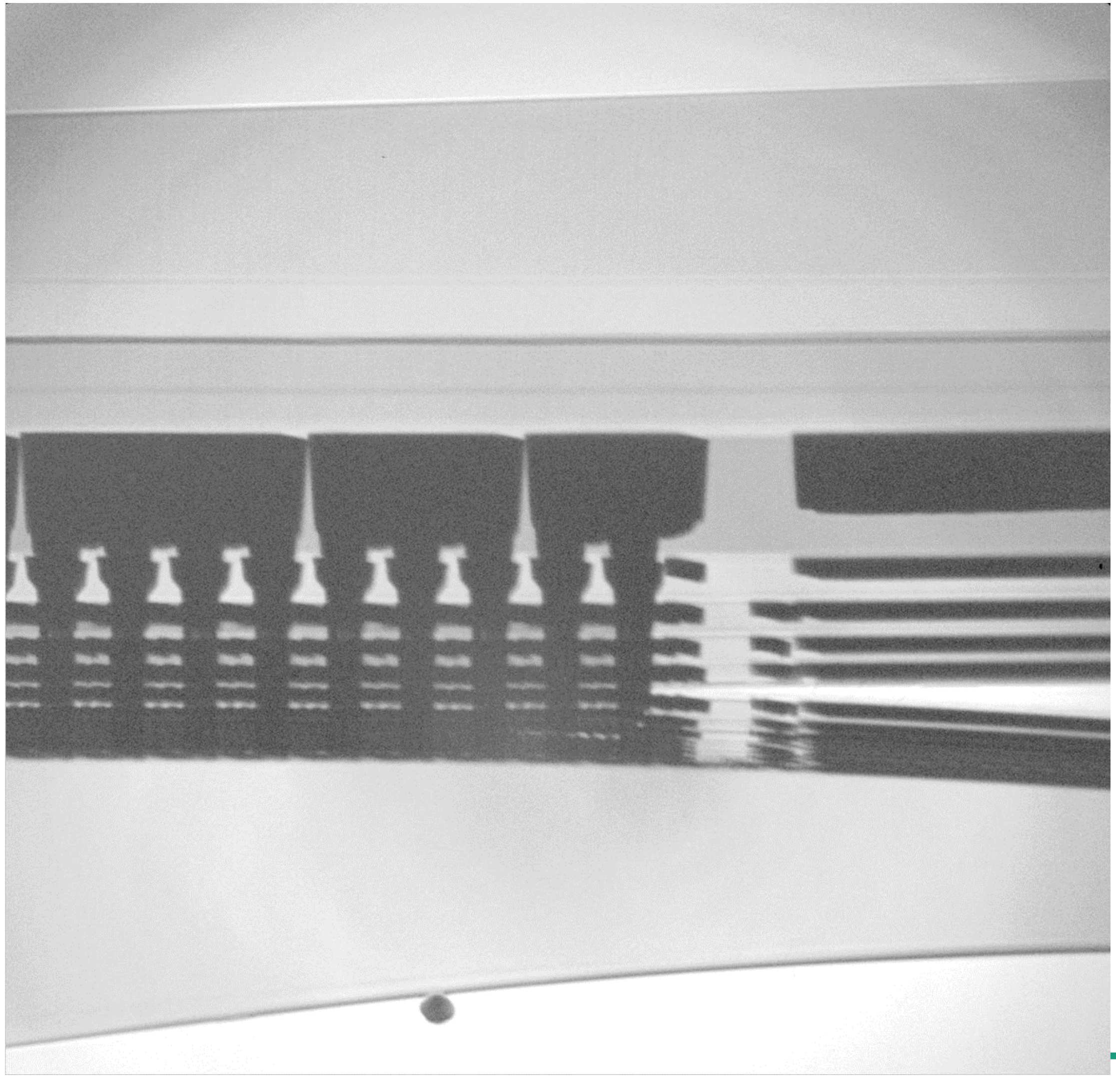
1.5 µm thick lamella:

11 nm resolution

K. Kutukova et al., MRS Advances 2018

G. Schneider & P. Guttmann, Helmholtz Zentrum Berlin

Preliminary BESSY II experimental results: Crack propagation in BEoL stacks (2.5 µm thick sample, 1200 eV, 1st zone plate order)



Movie: Crack evaluation in a mechanical in-situ X-ray microscopy experiment using synchrotron radiation, step size 25 nm

K. Kutukova et al., MRS Spring 2018

G. Schneider & P. Guttmann, Helmholtz Zentrum Berlin

Outline

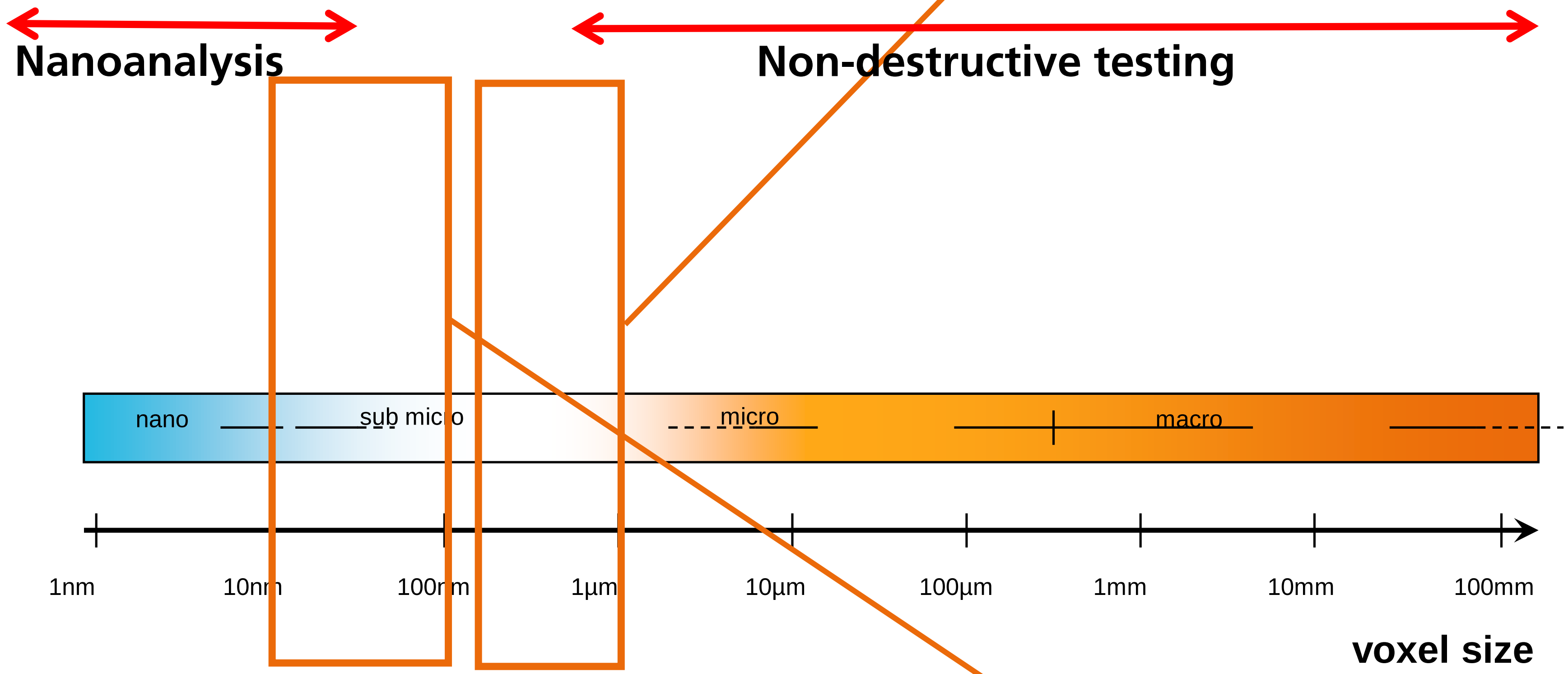
1. 3D metrology and diagnostics challenges in microelectronics
    - Role of X-ray techniques

2. X-ray imaging of 3D structures: From micro to nano
    - Example 1 - Advanced packaging: Failures in TSVs and micro-bumps
    - Example 2 – BEoL stack: Crack propagation

3. Outlook:
    - X-ray microscopy: Fast, high resolution, really nondestructive

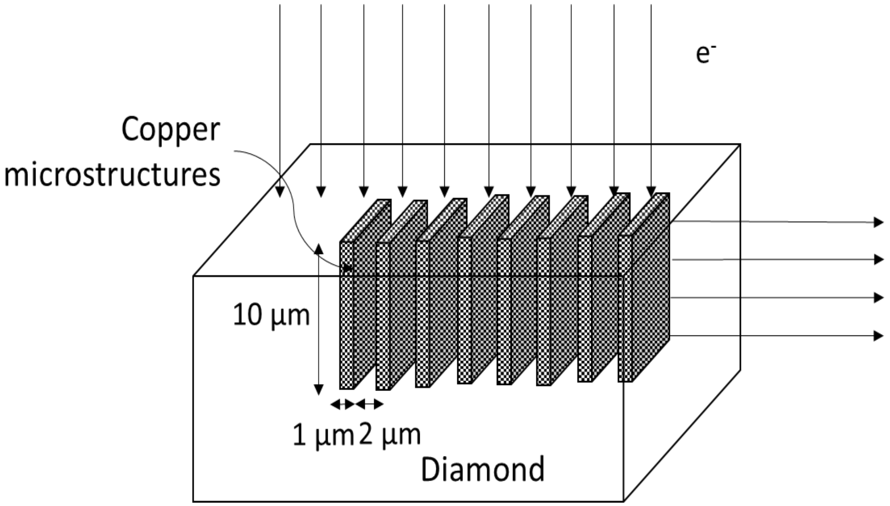
X-ray imaging perspectives (next 3 years)

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

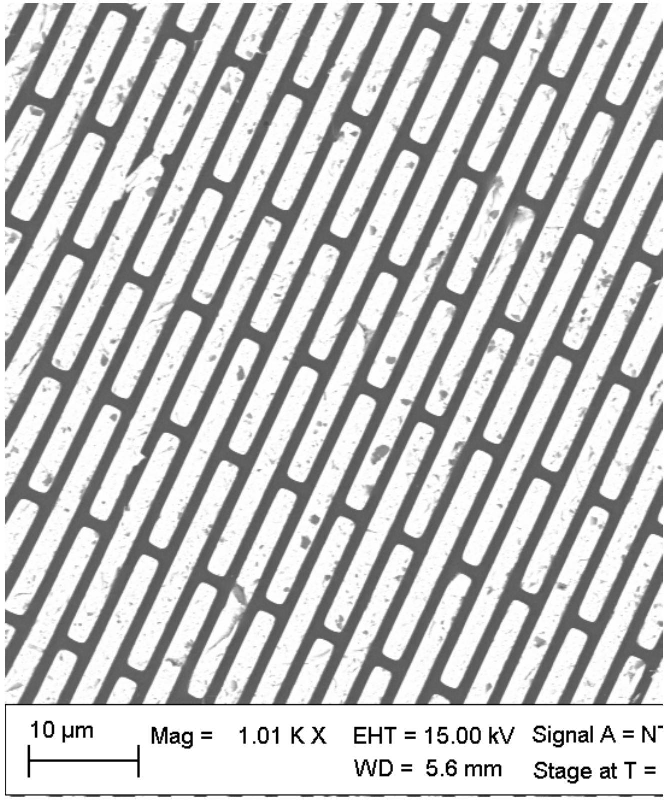


Nano Transmission X-ray Microscopy (TXM) / nano XCT with novel X-ray optics: 10 … 100 nm resolution

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



Diamond / metal microstructures after diamond etch and metal fill



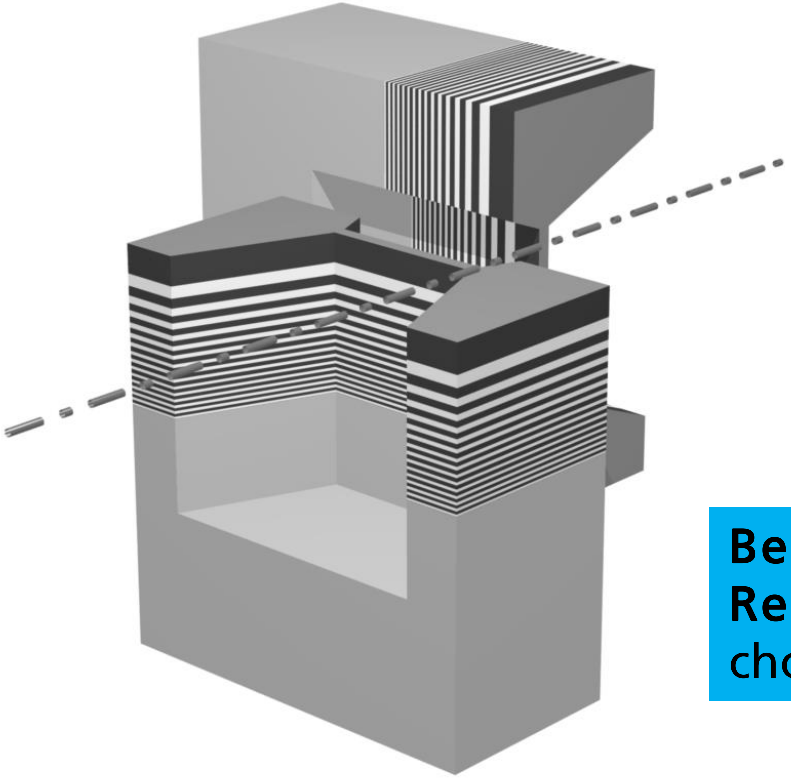
4x higher thermal loading than a solid copper target ➔
up to 50x total brightness gain from optimal linear accumulation and better thermal property

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

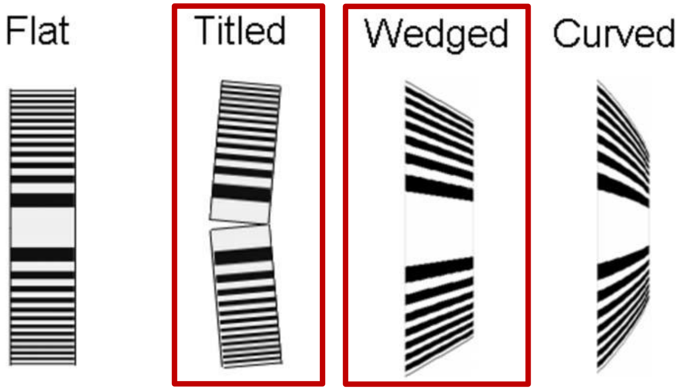
E. Zschech, W. Yun, FCMN 2017

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

Crossed partial MLLs: two-dimensional focusing and imaging



MLL geometries



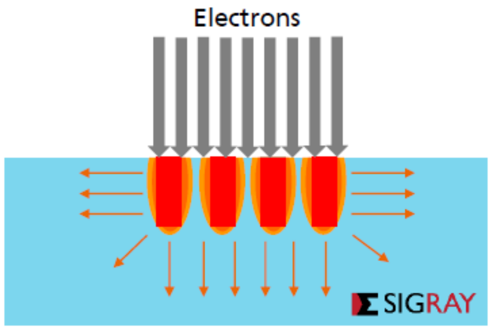
H. Yan et al. Physical Review B ***76****.11, p. 115438 (2007)*

Tuning the optics: Tilting, wedging, curving

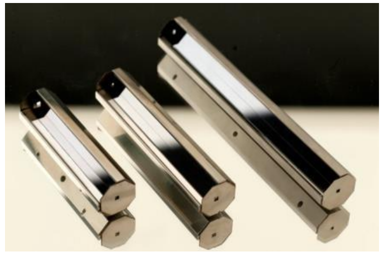
Benefits: Thinner films + higher A/R
Results: Higher resolution and efficiency, choice of X-ray energies > 10 keV

S. Niese et al., Optics Express 2014

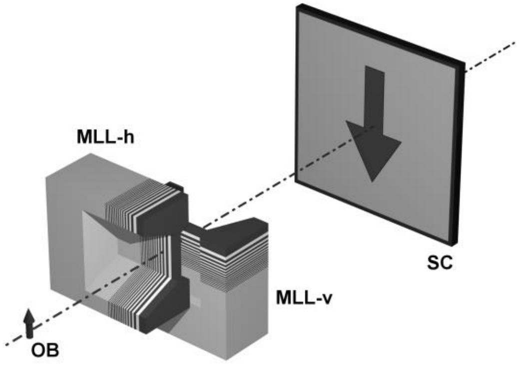
Focusing condenser optics and Multi-layer Laue lenses
➔ Approach to improve resolution and to extend lab-based X-ray microscopy to higher energies

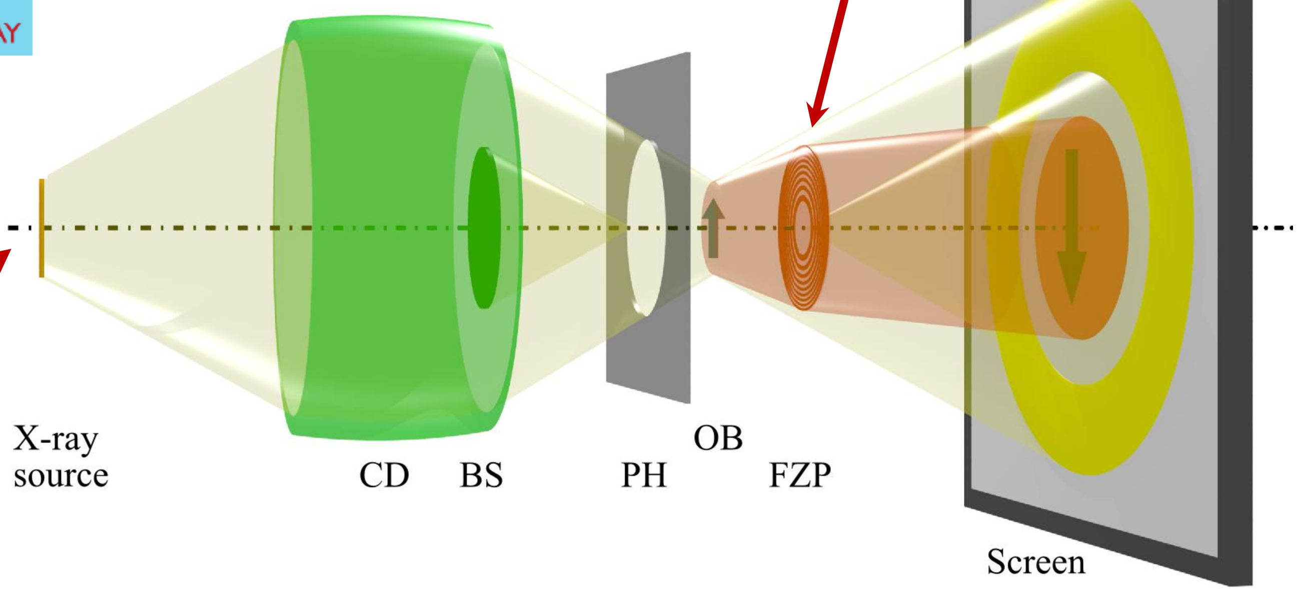


Metal Microstructures
Embedded in Diamond



Multilayer Laue lenses:
enhanced resolution
and high photon energies

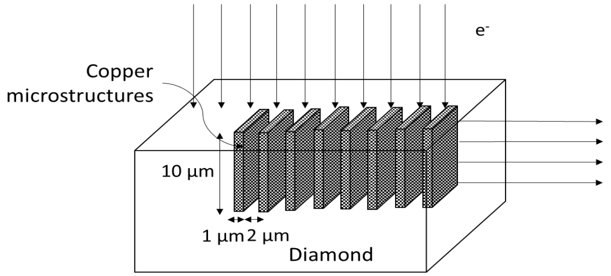




FAAST source:
High flux

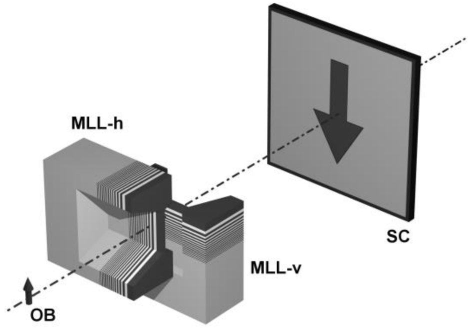
S. Niese et al., 2nd Dresden Nanoanalysis Symposium 2014, XRM 2014

Lab-based 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)*

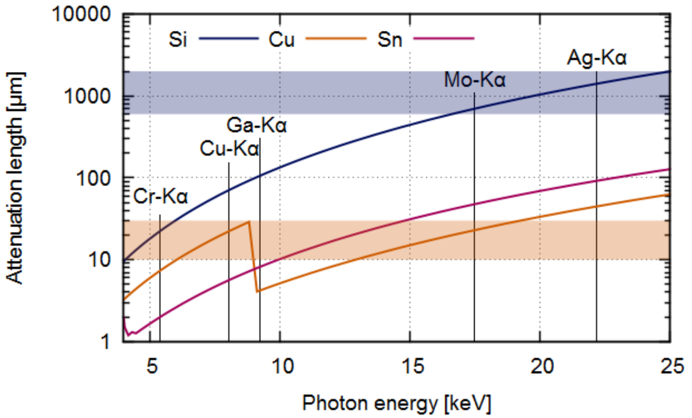


X-ray microscopy with novel optics (Multilayer Laue lenses)

Resolution improvement to 10nm (… 1nm)
➔ *down-scaled device structures and defects in materials, …*

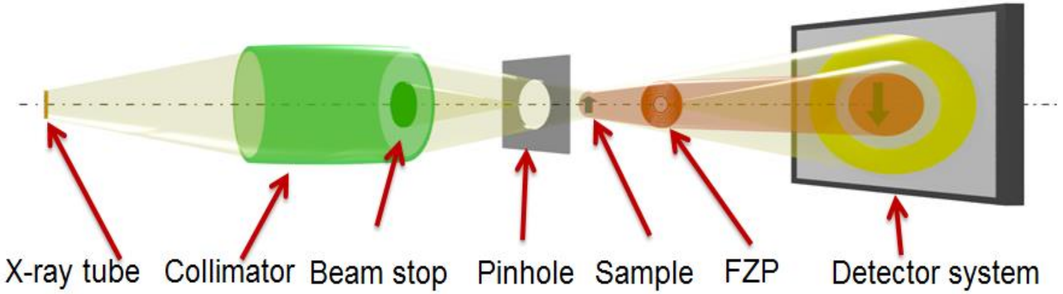
Larger working distance (~ 5 cm)
➔ *chambers (temperature, humidity, …), mechanical tests (crack propagation)*

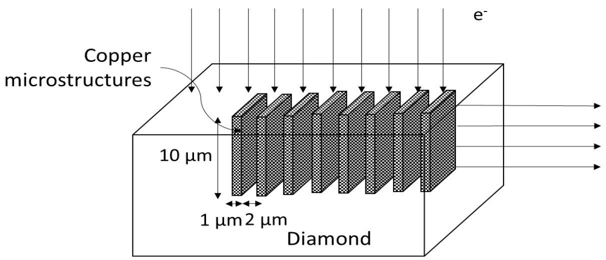
Higher X-ray energies (e. g. Mo source)
➔ *penetration of whole wafers, wafer stacks*

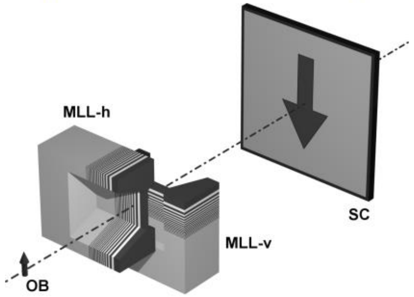


Outlook: Laboratory nano XCT for advanced packaging/interconnect imaging: Nondestructive & 3D, higher resolution, higher throughput

Development Parameters	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:

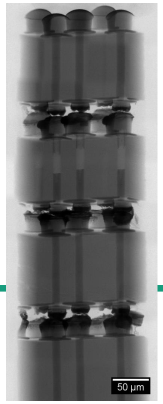
Novel nano X-ray tomography system with

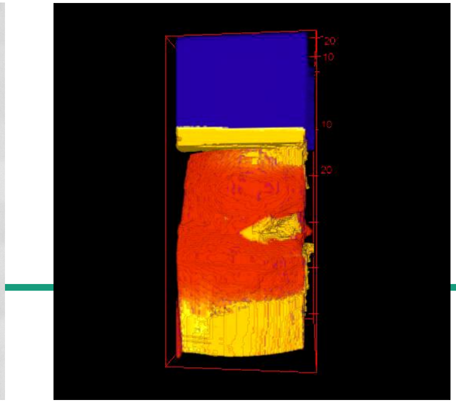
- High-flux X-ray source (Sigray Inc., Concord/CA, USA)
- Novel multilayer Laue lens X-ray optics (Fraunhofer IKTS + IWS Dresden)

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

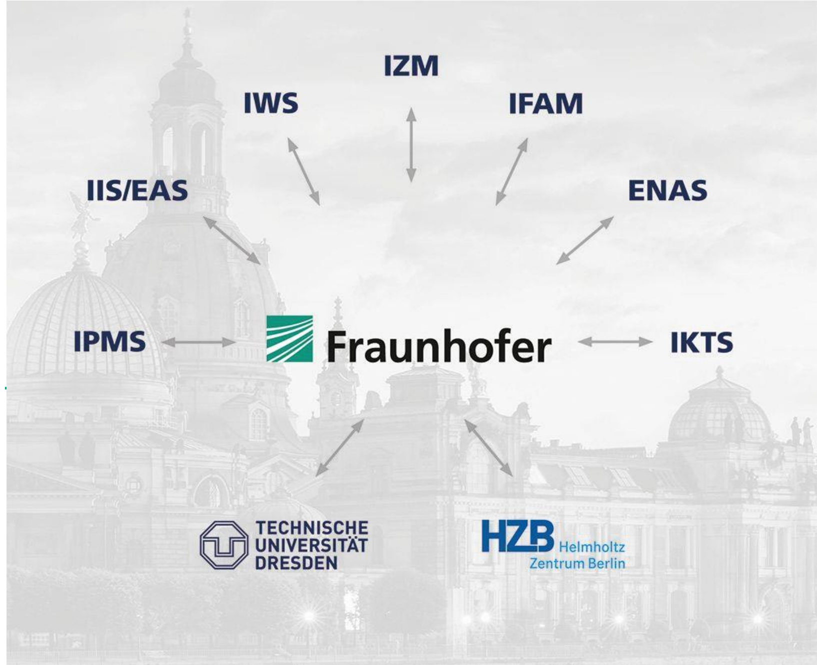




3D stack w/ Cu TSVs and AgSn microbumps

E. Zschech et al, FCMN 2017

www.nanoanalysis.fraunhofer.de



Thank you !

Jürgen Wolf, Fraunhofer IZM-ASSID Dresden, Germany

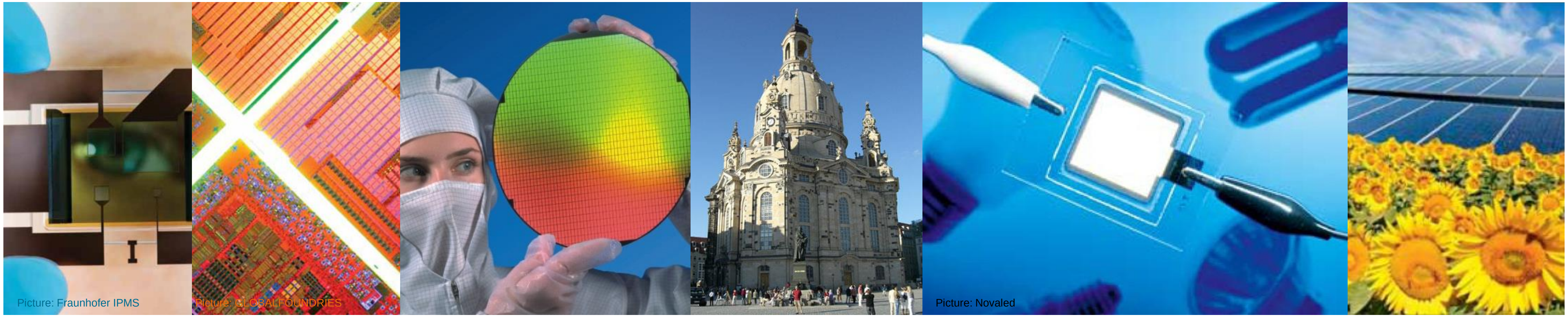
Markus Loeffler, TU Dresden, Germany

Gerd Schneider, Peter Guttmann, Stephan Werner, HZB Berlin, Germany

Sven Niese, Reiner Dietsch, AXO Dresden, Germany

Wenbing Yun, Sigray Concord/CA, USA

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


Picture: Fraunhofer IPMS
Picture: GLOBALFOUNDRIES
Picture: Novaled

Contact: ehrenfried.zschech@ikts.fraunhofer.de

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