In-situ Micro-DCB / Nano-XCT Test to Ensure the Robustness of Leading-edge Cu/ULK BEOL Stacks

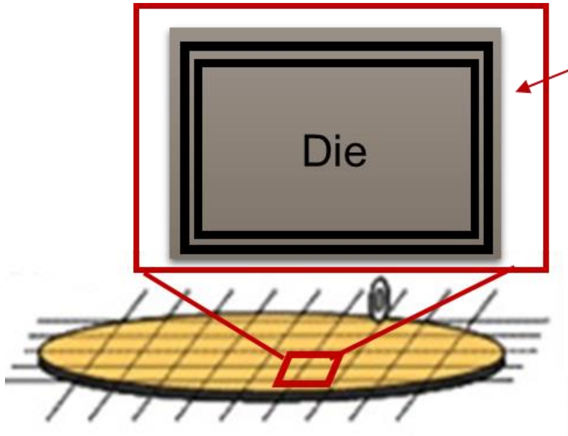
Kristina Kutukova, Ehrenfried Zschech

deepXscan GmbH, Dresden, Germany

FCMN 2022, June 23rd 2022

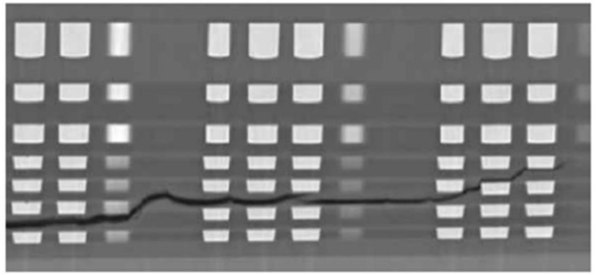
Mechanical Stability Of Leading-edge Cu/ULK BEOL Stacks
Guard Ring Robustness

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



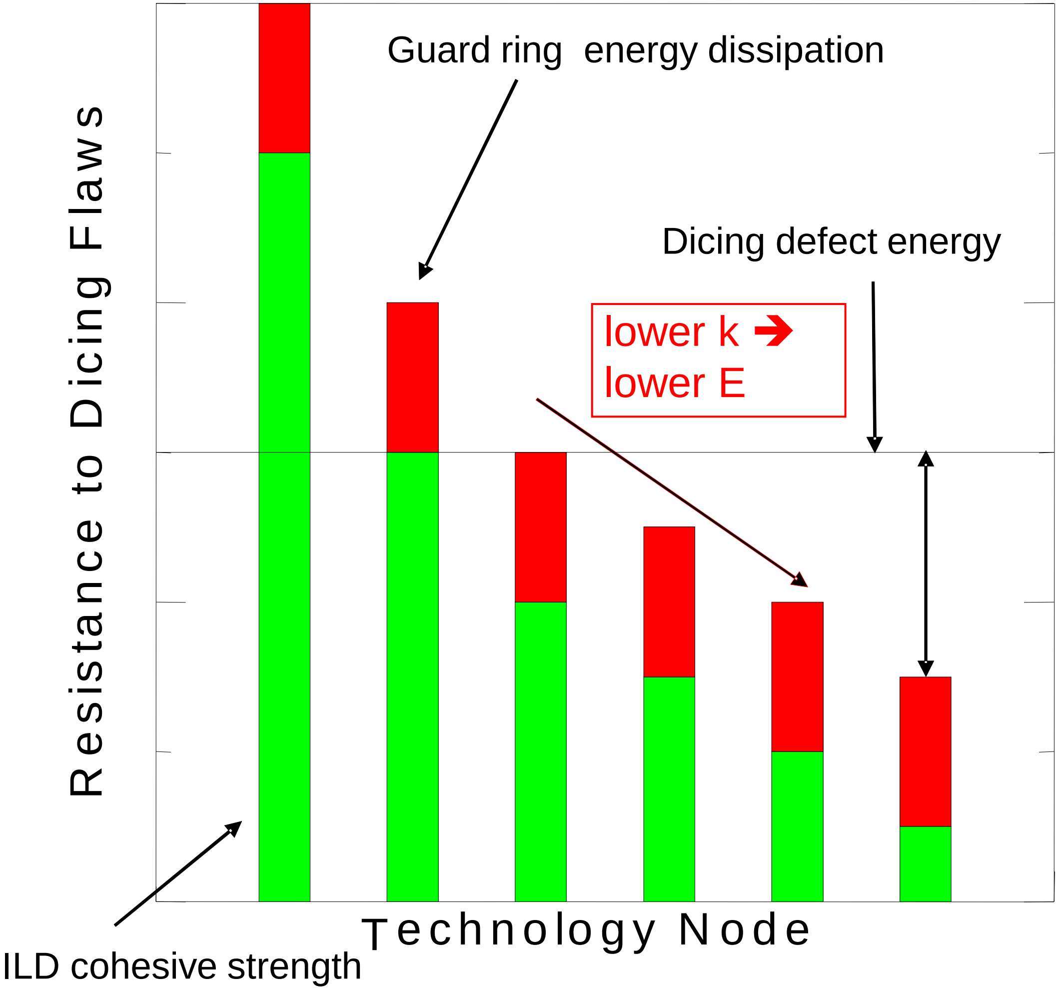
Guard Ring structures on the perimeter of the die (Crack stop)

Dicing process



Crack propagation in interconnects

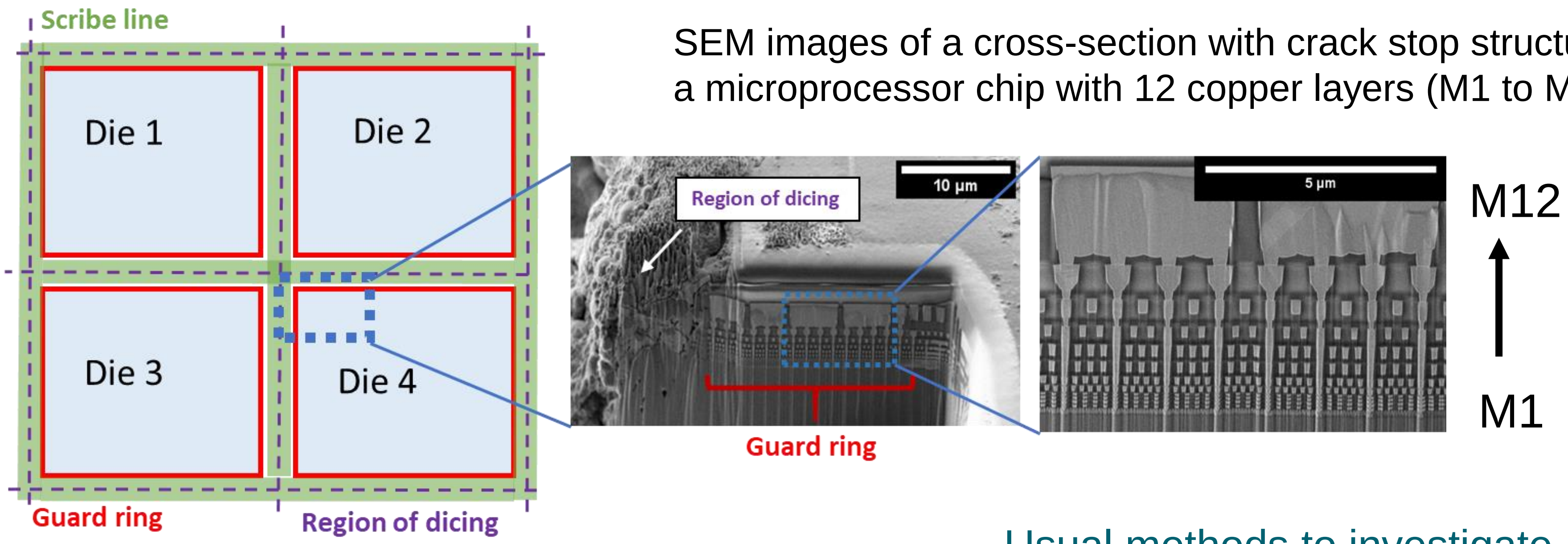
X. Zhang et al. AIP Conf. Pros .2009



M. Lane et al. J. Mater. Res.2000

Cu/ULK BEOL Stack: Mechanical Robustness Of Guard Ring Structures

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



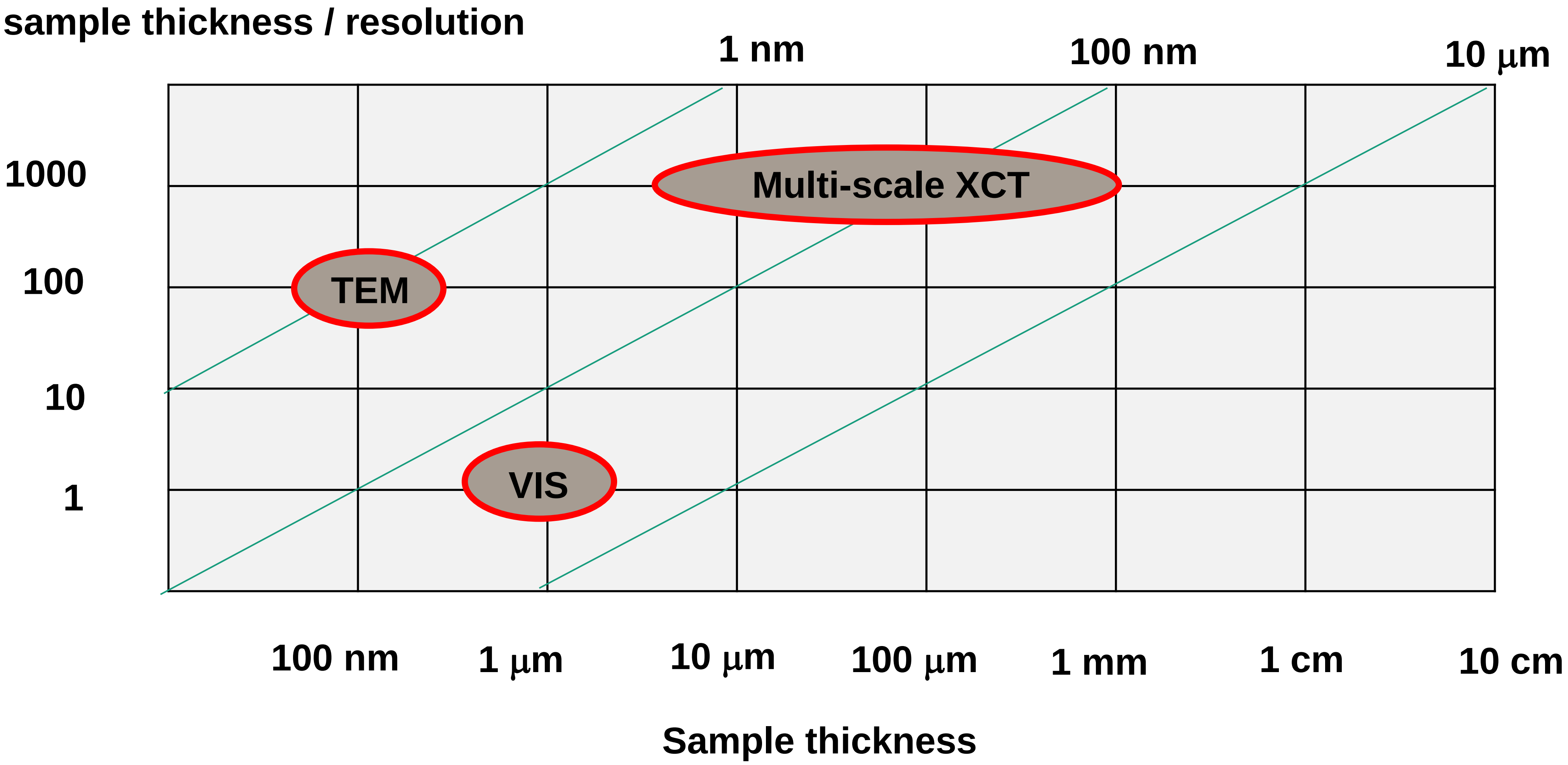
Does 2D studies:

- → reflect the real local crack behavior?
- → provide fracture mechanisms in 3D material systems?
- → Volume vs. Resolution?

Usual methods to investigate **mechanical properties/robustness** of Cu/low-k interconnects:

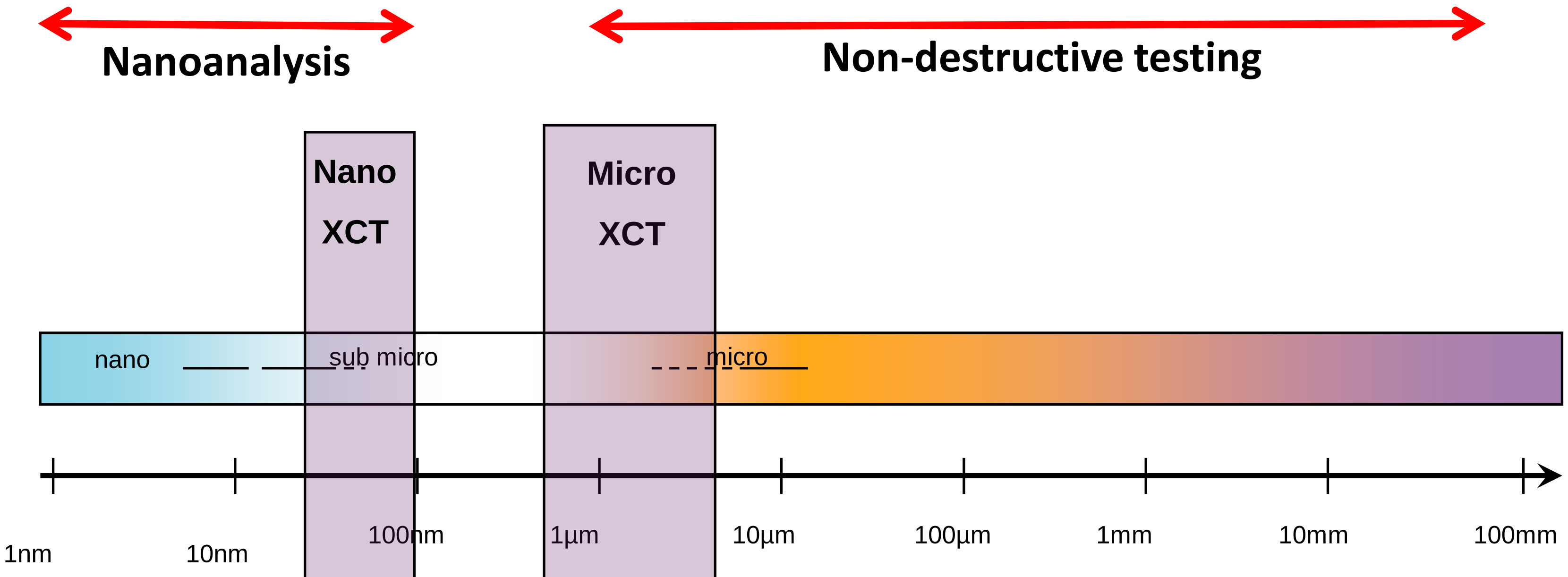
- Double Cantilever beam test (DCB test)
- Three point bending test (3PBT)
- Four point bending test (4PBT)
- Cross-sectional nanoindentation (CSN)

Sample Thickness / Resolution For Several Microscopy Techniques

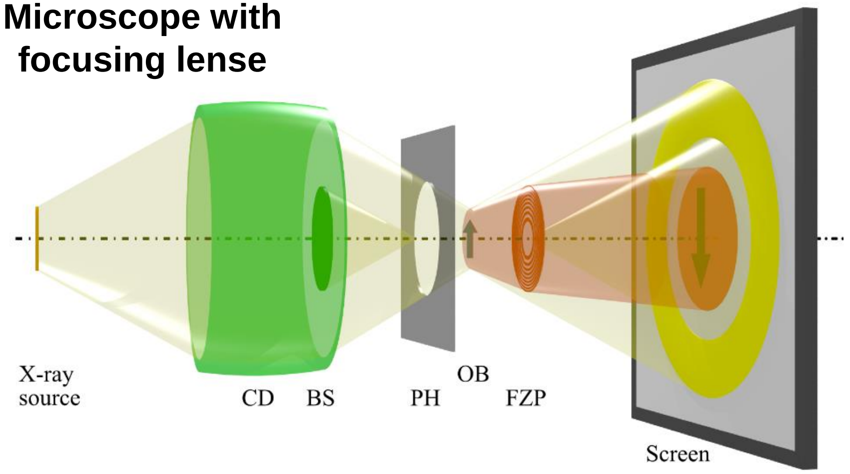


X-ray microscopy: multi-scale, 3D (nano-XCT) and nondestructive

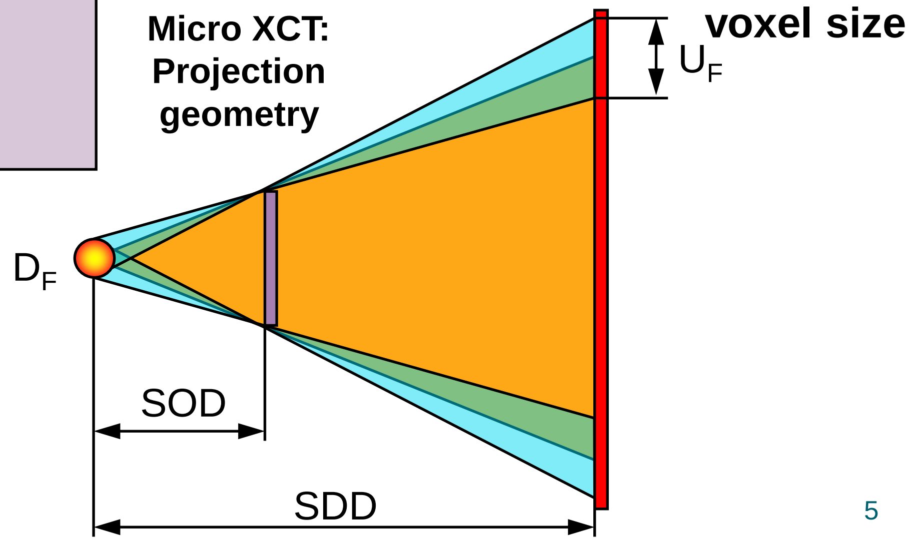
Multi-scale 3D Characterization Of 3D-structured Systems And Materials Using High-resolution Laboratory X-ray Computed Tomography (XCT)



Nano XCT:
Microscope with focusing lense

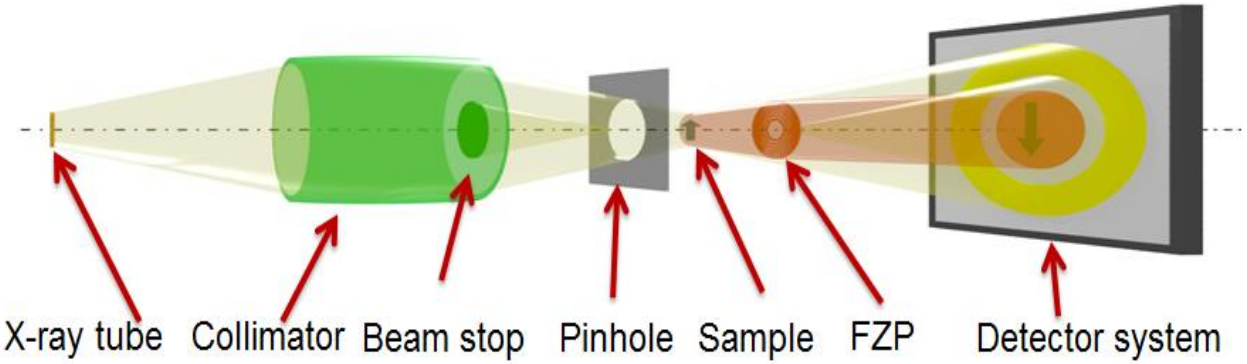


Micro XCT:
Projection geometry



In-situ Mechanical Test Set-up, For Integration Into A X-ray Microscope:

Multi-layered Structures And Thin Films



- **Full-field microscopy**
- **Monochromatic radiation Cu-Kα (8 keV)**

  ➔ Sample thickness ~ 50 μm
- **Resolution ~ 50 nm**

Integration of micromechanical test set-ups into the X-ray microscope

1) Selection of type of experiment – Advantage of micro-DCB (in comparison to 4pt-bending)

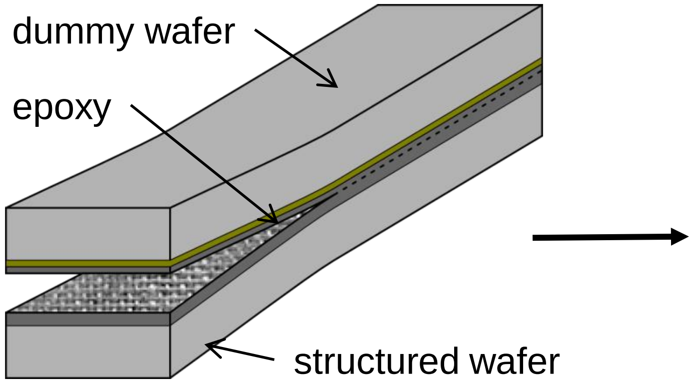
- **Description of fracture modes at the crack tip**
- **Fixed crack position during sample rotation (X-ray tomography)**

2) Requirement of test set-up dimension - Miniaturization

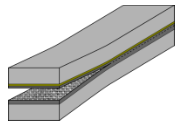
- **Limited space in the X-ray microscope (beam path)**
- **Sample thickness ~ 50 μm ("X-ray transparent" sample @ 8 keV)**

In-situ Mechanical Testing Of BEoL Stacks Using Micro-DCB Test

- Miniaturized Double Cantilever Beam test (micro-DCB) – **Scope: Crack propagation in on-chip interconnect (BEoL) stacks and guard ring structures**
- Displacement-controlled tester → **Critical energy release rate (Gc)** investigation in patterned multilayer systems by measuring crack length and crack opening

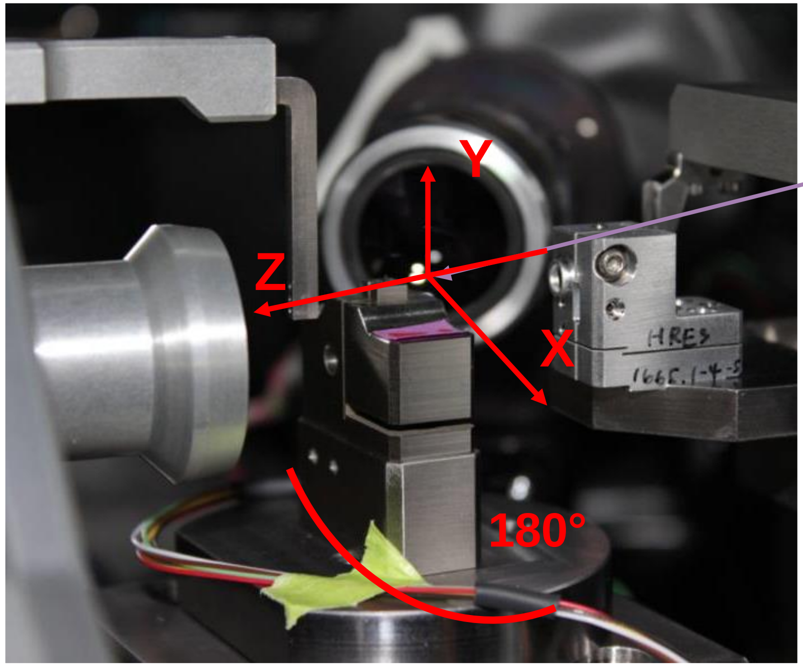


Standard DCB test:
(ex-situ) fracture mechanics
→ G_c

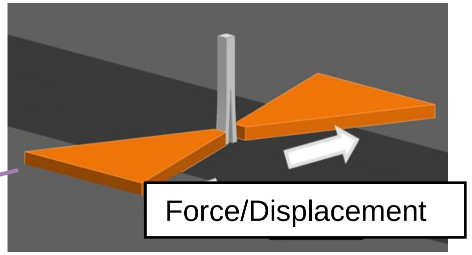


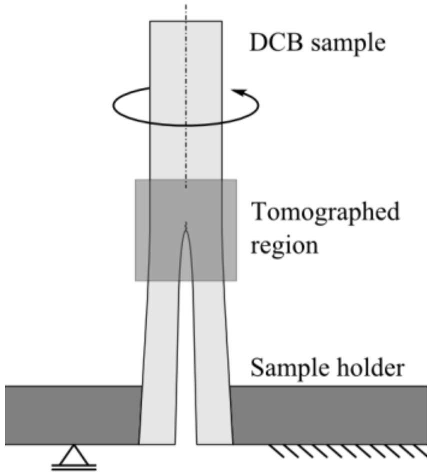
Miniaturized DCB:
in-situ 3D crack evolution using X-ray microscopy

S. Niese, PhD Thesis, BTU Cottbus 2015

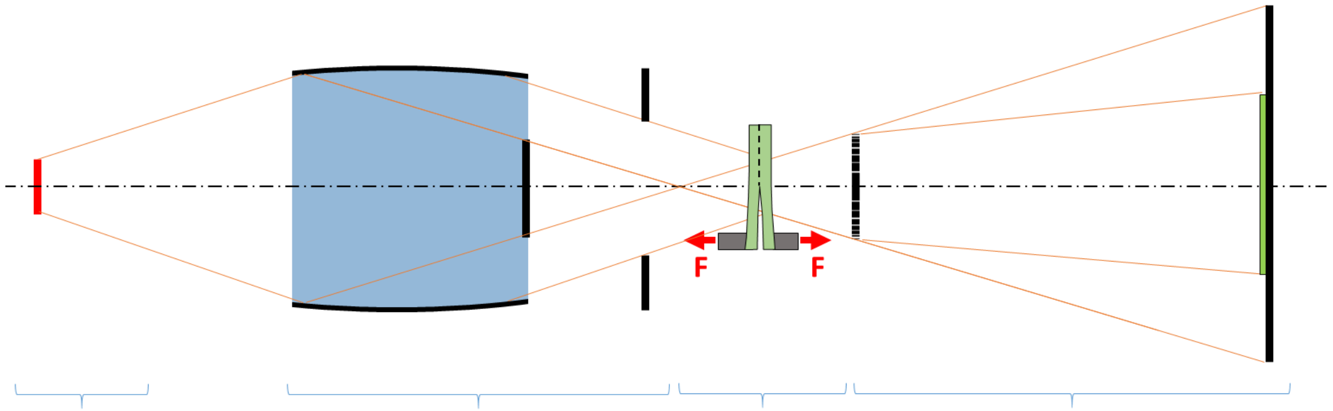


Micro-DCB tester in the nano-XCT tool





Experimental Setup In The Laboratory: Double Cantilever Beam Test (DCB) In The X-ray Microscope



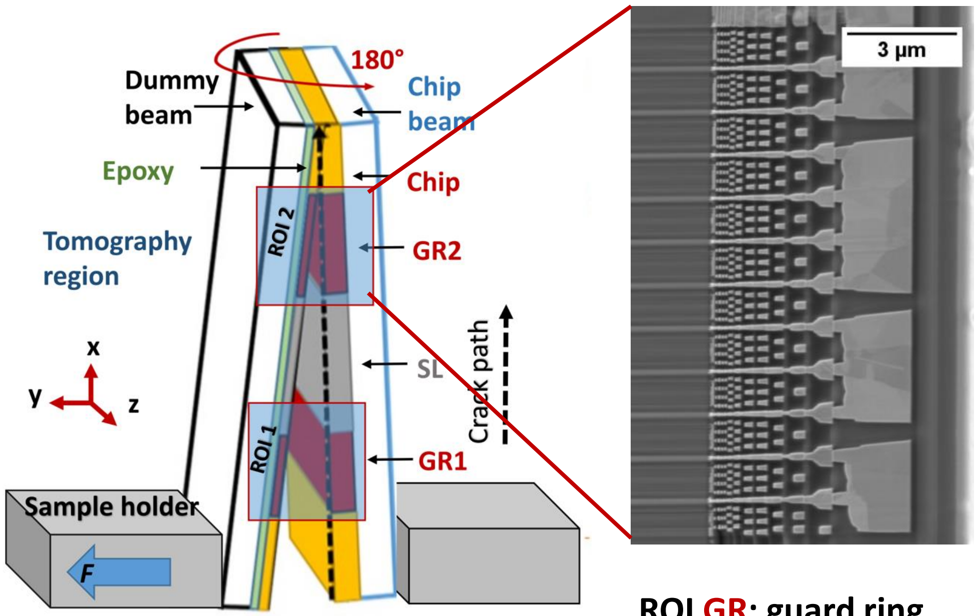
X-ray Source
Rot. anode
Cu-Kα

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



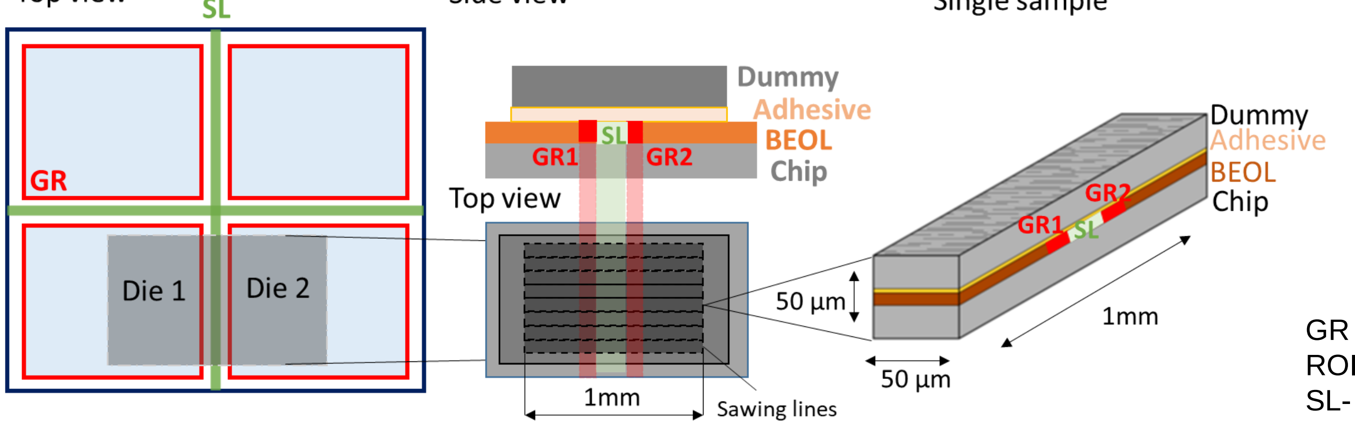
ROI GR: guard ring structure M1 – M12

Process of Mechanical sample preparation

Top view

Side view

Single sample



GR - guard ring
ROI - region of interest
SL- scribe line

S. Niese, PhD Thesis, BTU Cottbus 2015
K. Kutukova, FCMN 2017

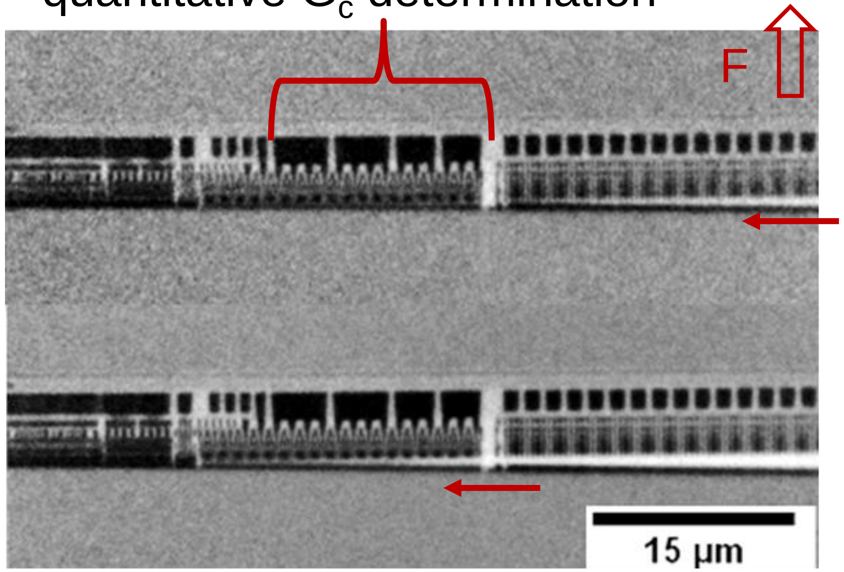
In-situ Micro-DCB Test In The Nano-XCT Tool

Crack propagation in on-chip interconnect (BEoL) stacks and GR structures

→ Quantitative (local) mechanical properties - critical energy release rate (G_c)

→ Crack path localization

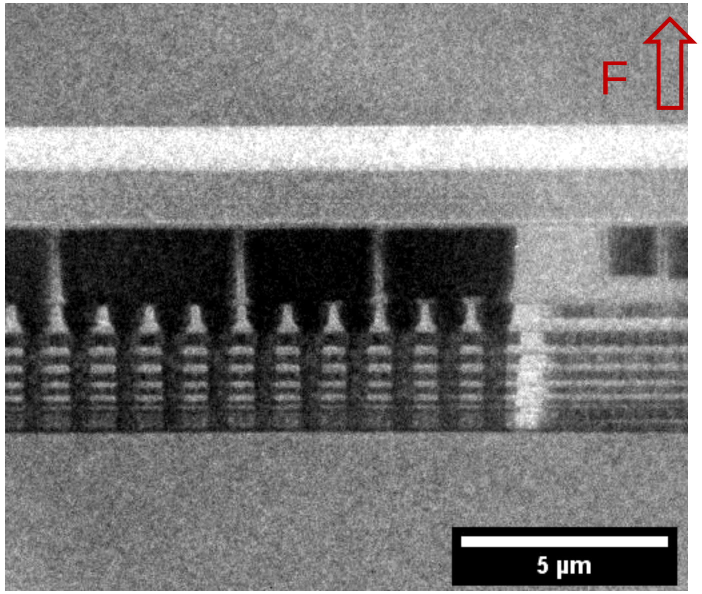
2D radiographs during micro-DCB experiment → stable crack growth and quantitative G_c determination



Crack stops at the GR structure

Crack changes its direction (energy dissipation) →Final cracking

2D radiographs during micro-DCB experiment at high resolution



K. Kutukova et al., APL 2018

FOV: 65 µm or 16 µm; Resolution 100 nm or 50 nm

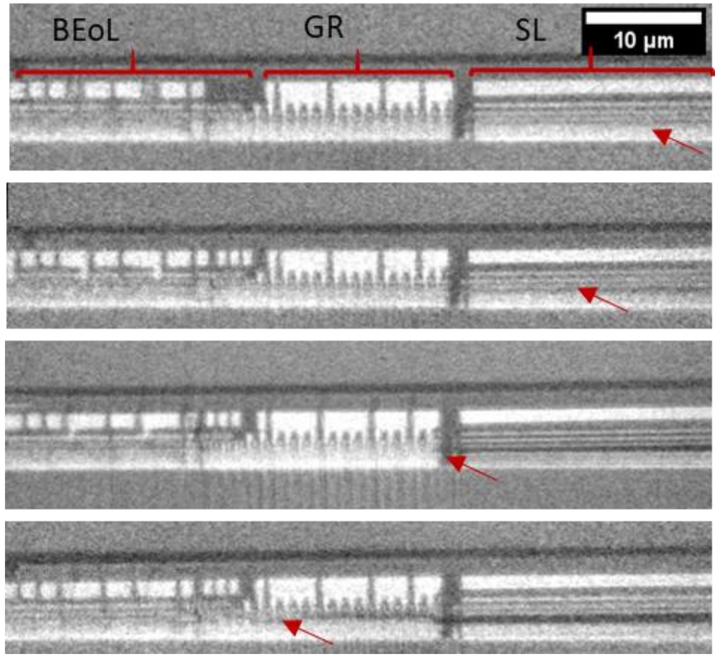
In-situ Micro-DCB Test In The Nano-XCT Tool

Crack propagation in on-chip interconnect (BEoL) stacks and GR structures

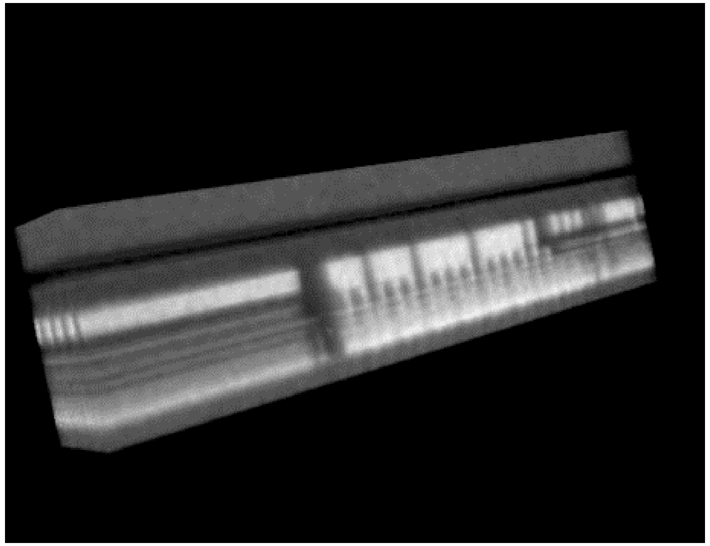
→ **Quantitative (local) mechanical properties - critical energy release rate (G_c)**

→ **Crack path localization**

Virtual cross-sections during micro-DCB experiment at certain loading state



3D data during or after micro-DCB experiment → detailed crack path investigation



3D reconstructed data at different loading steps

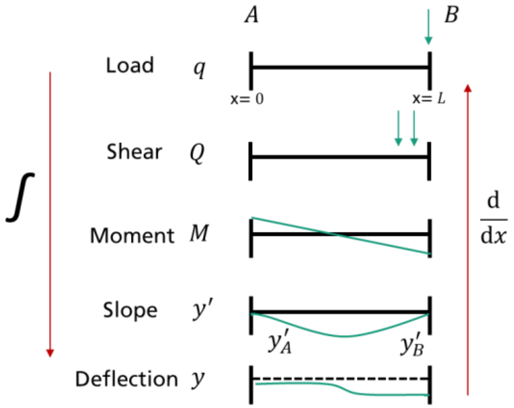
K. Kutukova et al., APL 2018

Specifics Of Micro-DCB Test And Data Analysis For The Determination Of G_c

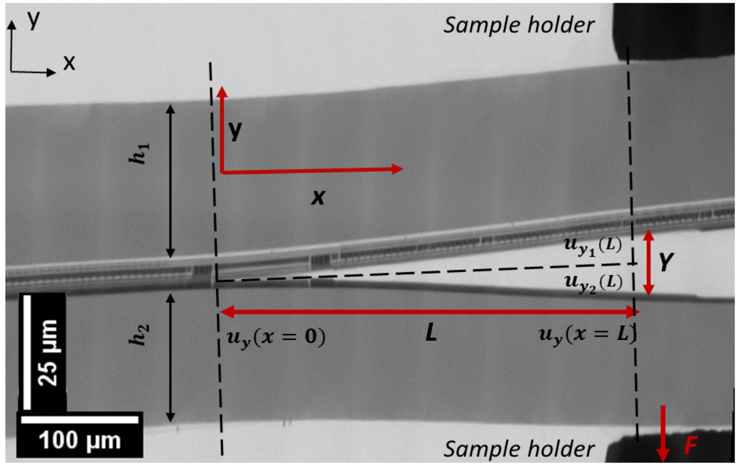
Analytical approach: Euler- Bernoulli beam theory adapted to real bending line of micro-DCB sample ➔ factor A_n (n = {1,2}).

Euler-Bernoulli beam theory:

$$\boxed{\frac{d^2}{dx^2}\left(EI\frac{d^2y}{dx^2}\right) = q}$$



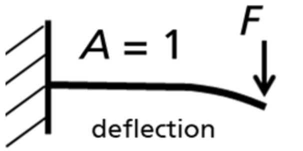
$$u_{y_n}(x) = -\frac{Fx^3}{6EI_n} + \frac{A_n FLx^2}{2EI_n}$$



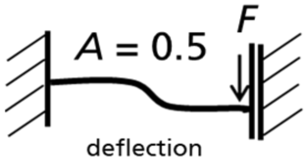
A_n = 0.5 …..1

G_c – critical energy realise rate
F - applied force
q – distributed load
h_n – beam height
u_{y_n}– beam deflection in y

L– max crack length
E – Young's modulus
I_n – second moment of area
A_n – fitting parameter



Free beam end



Fixed beam end

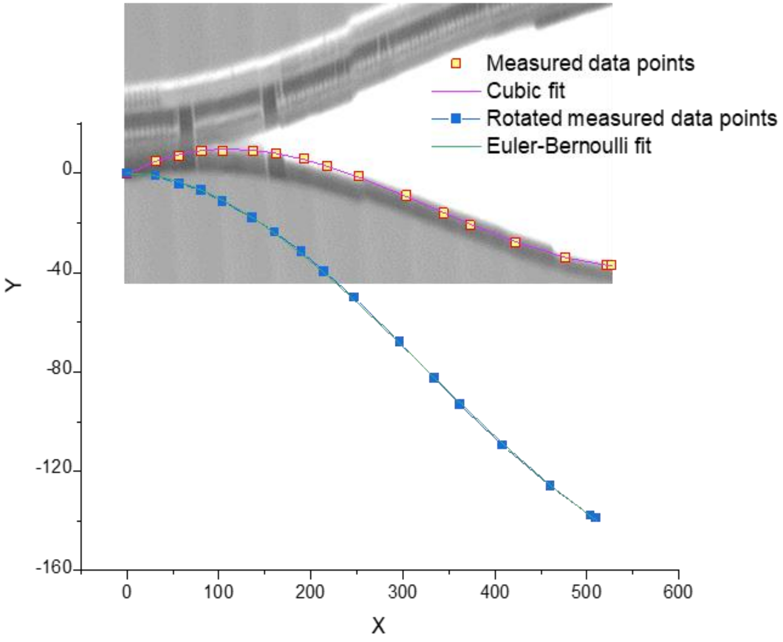
Critical energy release rate G_c

$$\boxed{G_c = \sum_{1}^{n=2} \frac{3Eh_n^3 {u_{y_n}}^2}{4\,L^4\,(3A_n - 1)}}$$

K. Kutukova et al., Materials & Design 2022 (accepted, under review)

Data Analysis And Quantitative Determination Of G_c

- Analytical approach: Euler- Bernoulli beam theory adapted to real bending line of micro-DCB sample
- Fitting geometrical parameter at each loading state based on real 2D image for each beam: chip and dummy



K. Kutukova et al., Materials & Design 2022 (accepted, under review)

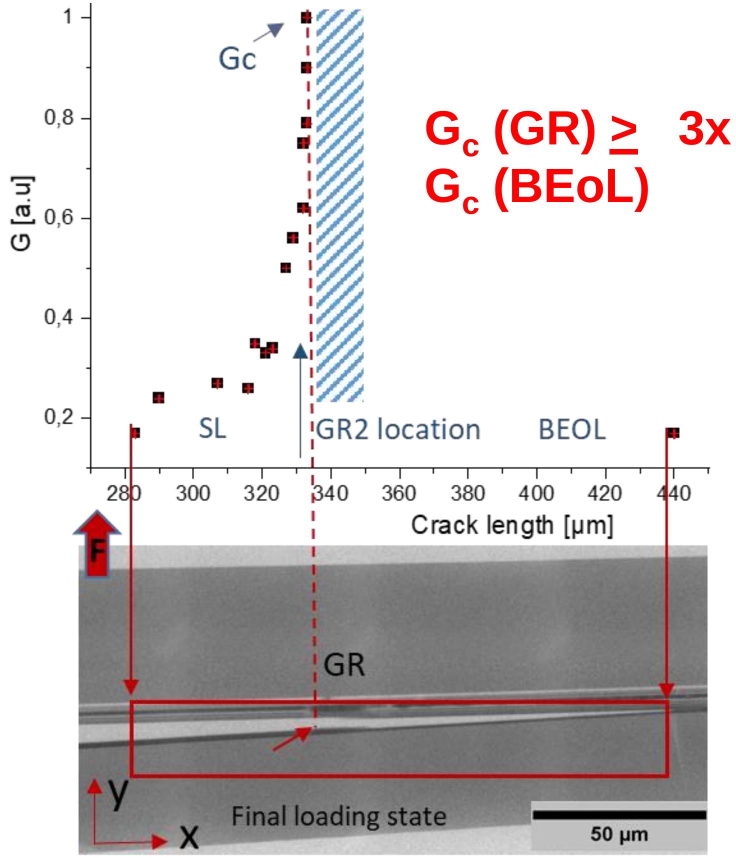
- Equation takes into account geometrical parameters for both cantilevers
- Applicable for symmetric and asymmetric (mode mixity) sample geometries
- Validated on unpatterned reference samples

$$G_c = \sum_{1}^{n=2} \frac{3 E h_n^3 u_{\overline{y}_n}^{2}}{4\, L^4\, (3A_n - 1)}$$

G_c – critical energy realise rate
E – Young's modulus
h_n – beam height
$u_{\overline{y}}$ – beam deflection in Y
L – max crack length
A_n – fitting parameter
$\mathrm{n} = \{\text{cantilevers } 1, 2\}$

→ Quantitative local mechanical properties at certain loading states!

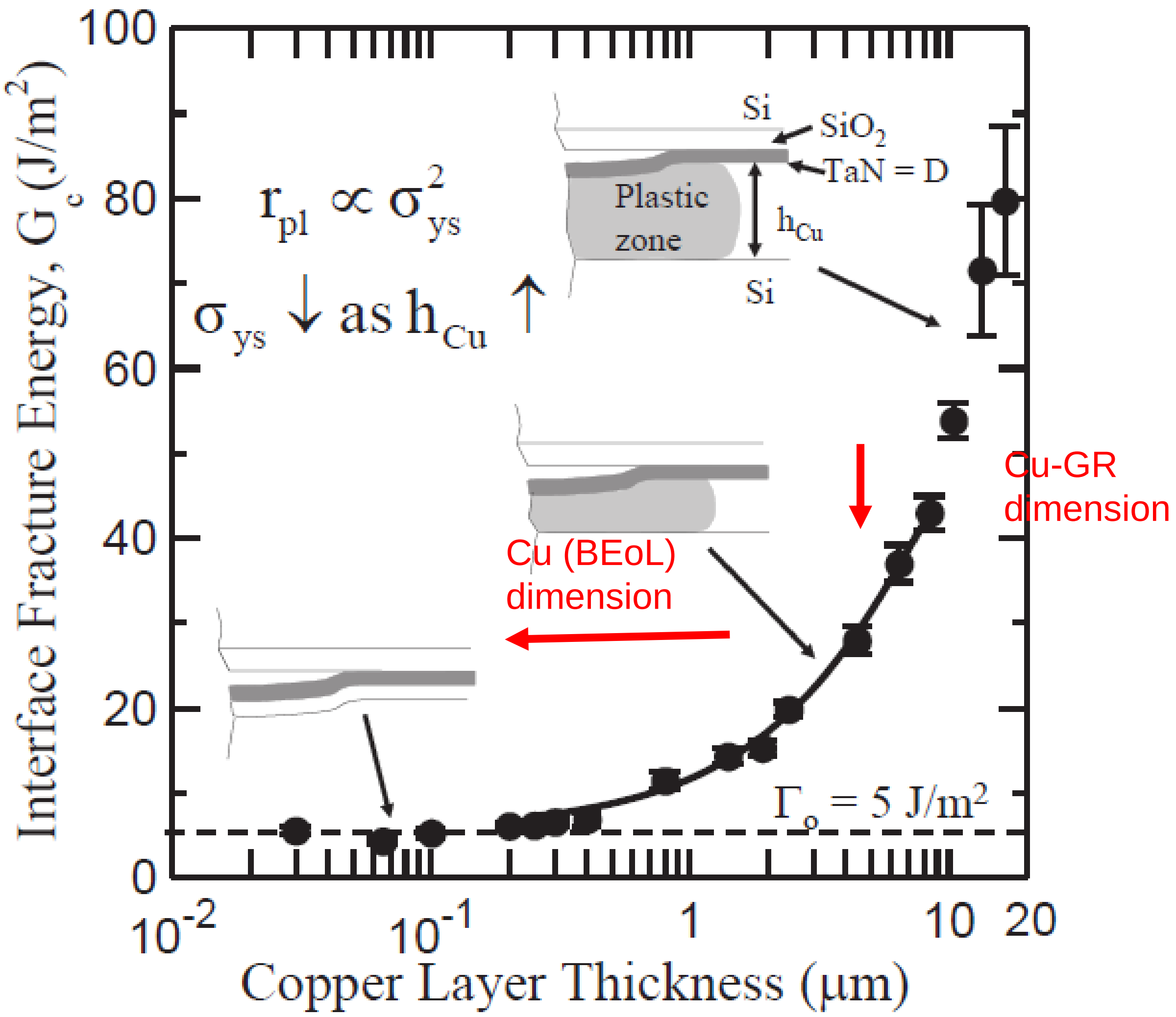
The Effectiveness Of The Guard Ring Structure To Stop Micro-cracks Depends On Materials And Design



G_c (GR) ≥ 3x G_c (BEoL)

Calculated G values at several loading steps (and respective lengths) and stitched image of the final loading stage in the BEoL region

K. Kutukova et al., Materials & Design 2022 (accepted, under review)

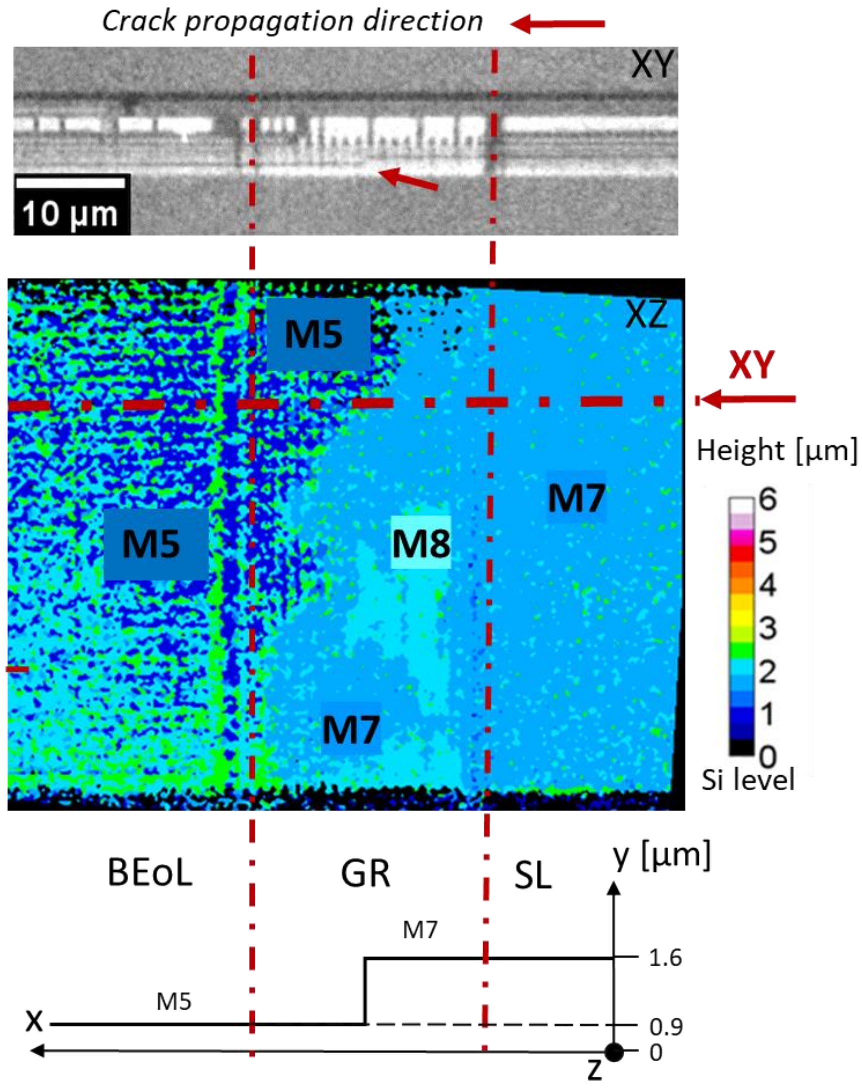


Size-dependent plasticity of Cu

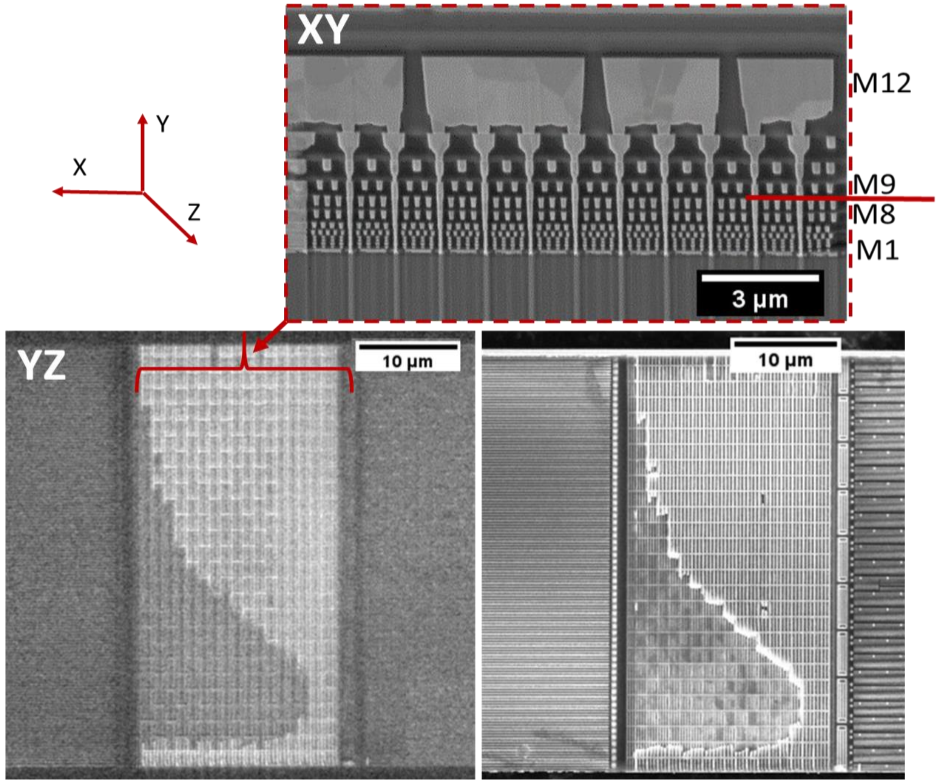
A. Grill et al., MRS Spring 2007

Cu structures > 1 µm: A significant part of the energy is absorbed by plastic deformation!

In-situ Micro-DCB Test In The Nano-XCT Tool



Metallization layers (FIB cross-section)



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

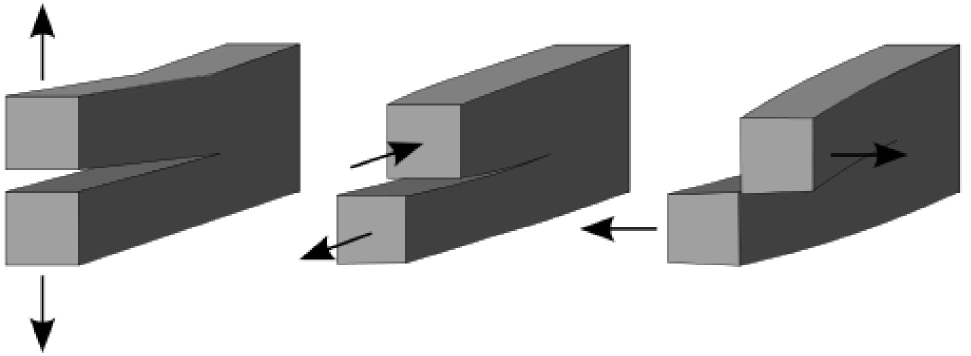
SEM image

K. Kutukova et al., APL 2018

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

Fracture Modes & Mode Mixity

- **Fracture mode and tests:**
  - Mode I (SDCB test)
  - Mixed mode (3PB, 4PB, ADCB)


Mode I
Opening

Mode II
In plane shear

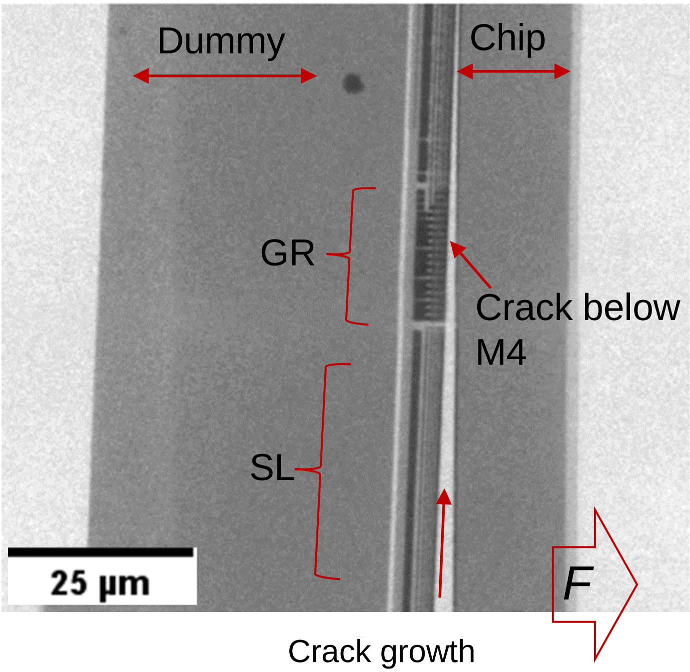
Mode III
Out of plane shear

- **Micro Double cantilever beam test**
  - Mode I D:C-1:1 → e =1
  - Variable mode mix
    (e=2, e=0.5)

e = ratio of dummy D beam and chip beam C

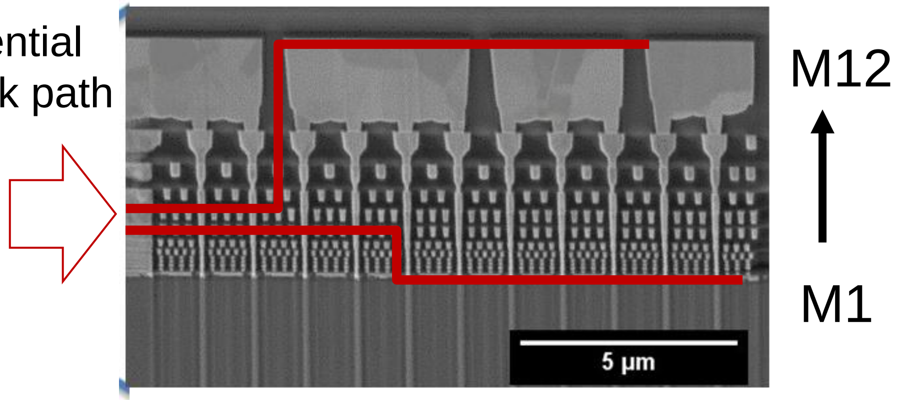
SDCB – symmetric DCB
ADCB – asymmetric DCB
PB – point bend test

Example of test with D:C – 2:1 → **e = 2**



Crack growth direction

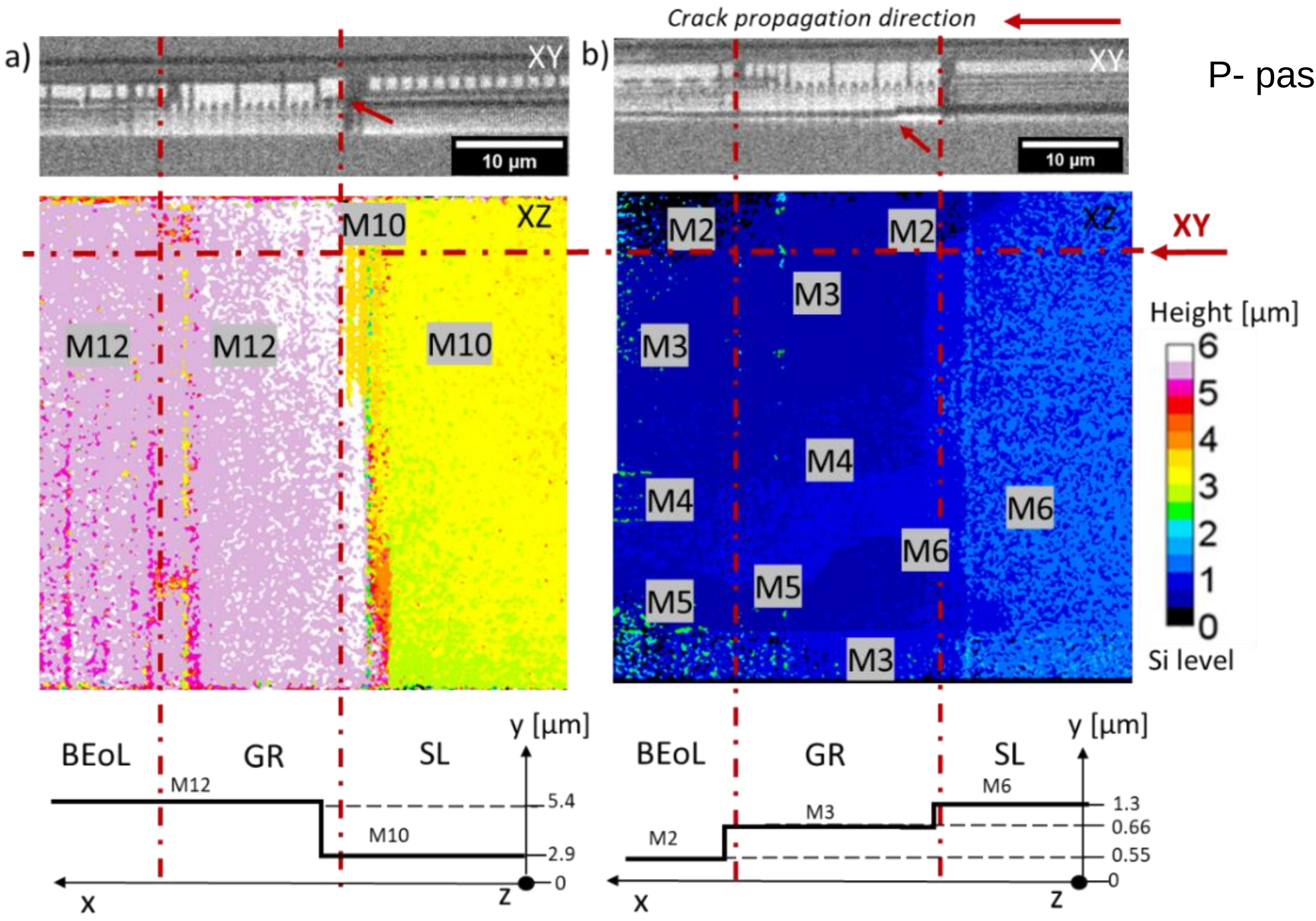
Mode mixity to steer the crack in GR to study different metal layers



Controlled Steering Of Microcrack At GR Structure

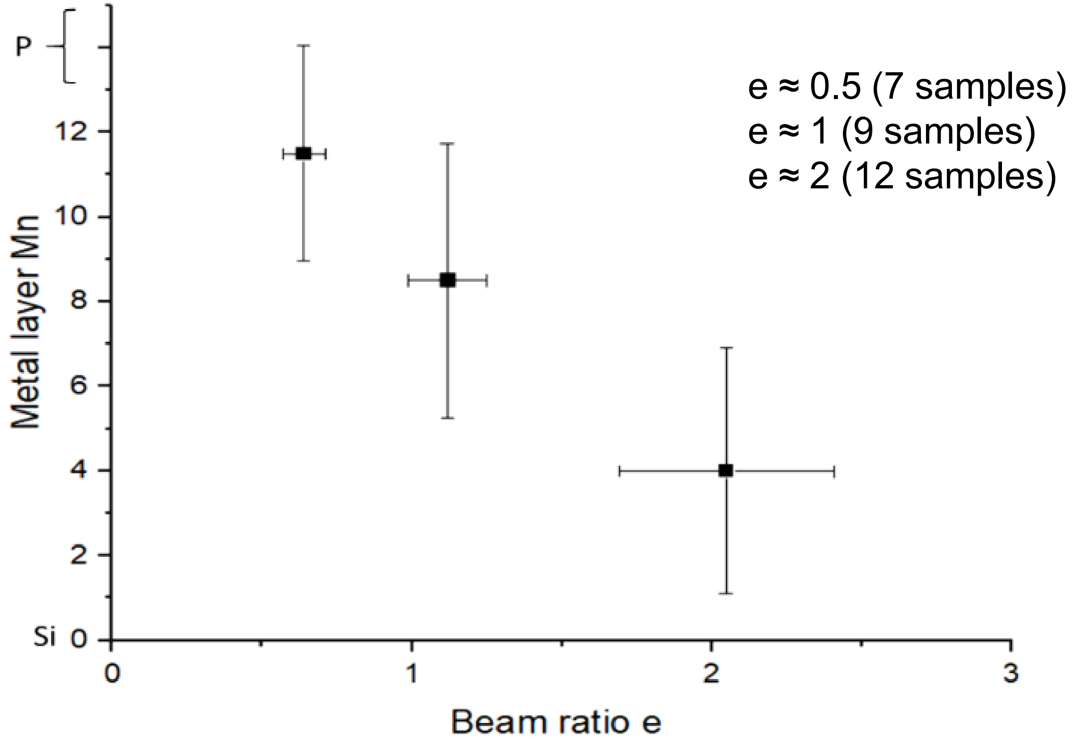
e ≈ 0.5

e ≈ 2



P- passivation

Dominant metal layers of crack propagation for several beam height ratios e



K. Kutukova et al., Materials & Design 2022 (accepted, under review)

Summary: In-situ Micro-DCB Test Integrated Into A Nano-XCT Tool

Kinetic studies of crack propagation in BEoL structures

→ Nondestructive imaging of mechanical damage and failure at high resolution!

Refined mechanical model to determine the critical energy release rate of guard-ring structures

→ Quantitative determination of local mechanical properties at nano-scale!

Demonstration of controlled steering of microcracks into and “trapping” in regions with high fracture toughness, e.g. guard-ring structures

→Design of high-toughness (damage-tolerant) structures, e.g. guard-rings, to stop microcracks!

Nano-XCT is a powerful new technique that provides 3D information about defects and degradation kinetics in ICs (BEoL) and advanced packaging technologies

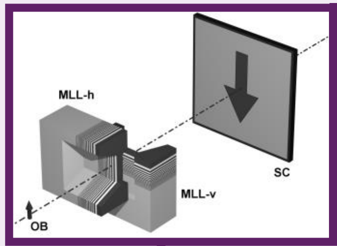
→ fault isolation, physical failure analysis and reliability engineering.

deepXscan GmbH Dresden - product and services

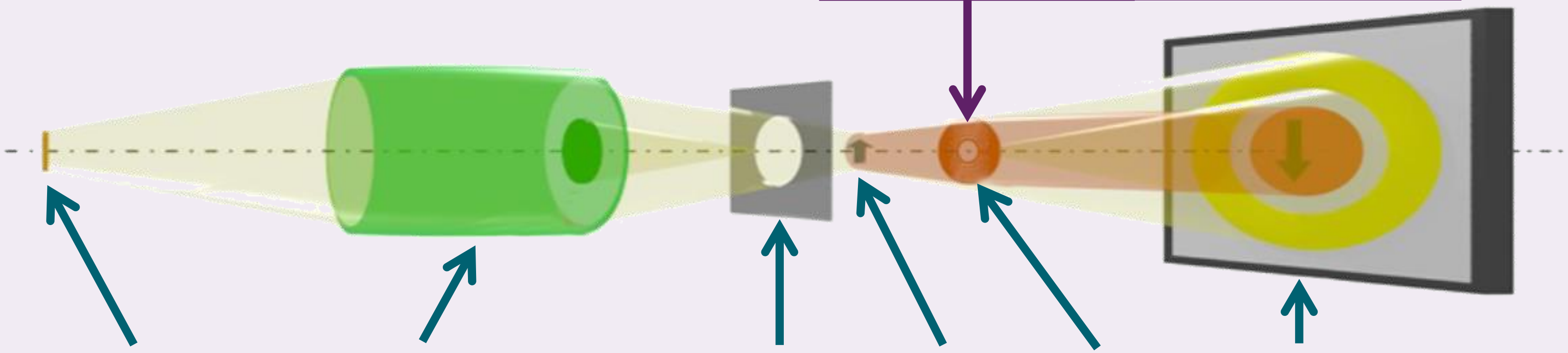
1. X-ray tomography system for high-resolution 3D imaging
   - ➔ process monitoring and quality control solution for industry, resulting in higher manufacturing yield and product quality
   - ➔ unique tool for original research and disruptive innovations

Scheme of a laboratory X-ray microscope with extended photon energy range:

<u>nondestructive 3D imaging of materials and objects</u>



Multilayer Laue lens for high resolution and for E > 10 keV



X-ray source

Collimator

Pinhole

Sample

Lens

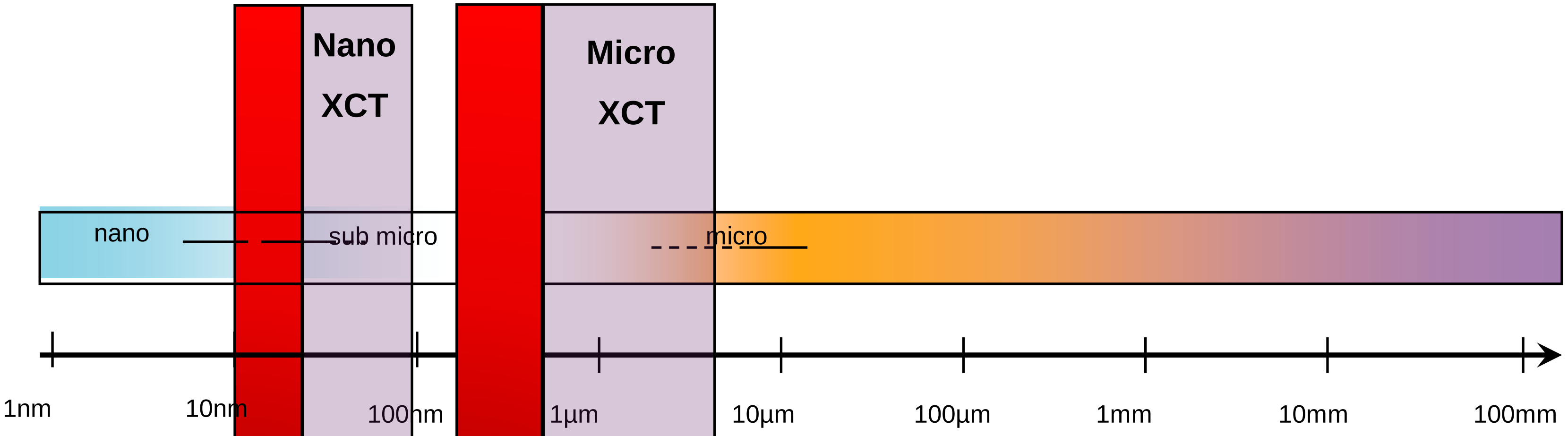
X-ray detector

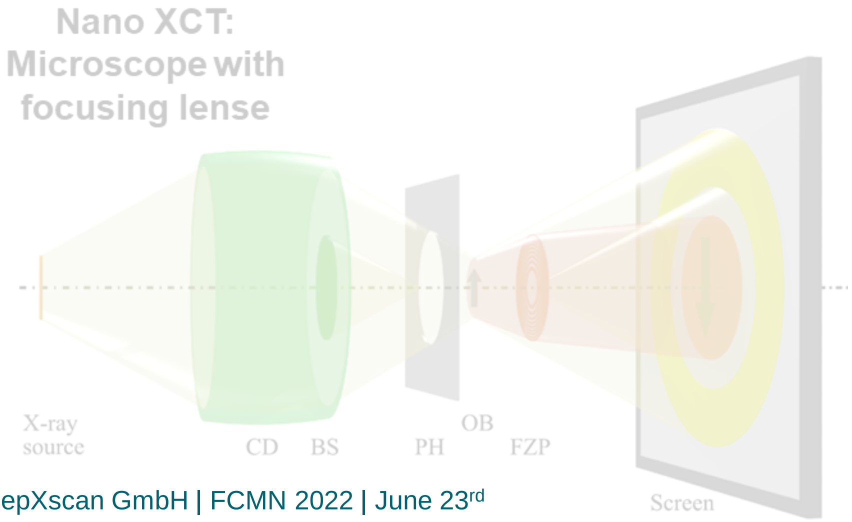
2. 3D imaging service for partners in industry and academia
3. AI-based data analysis using big data / platform

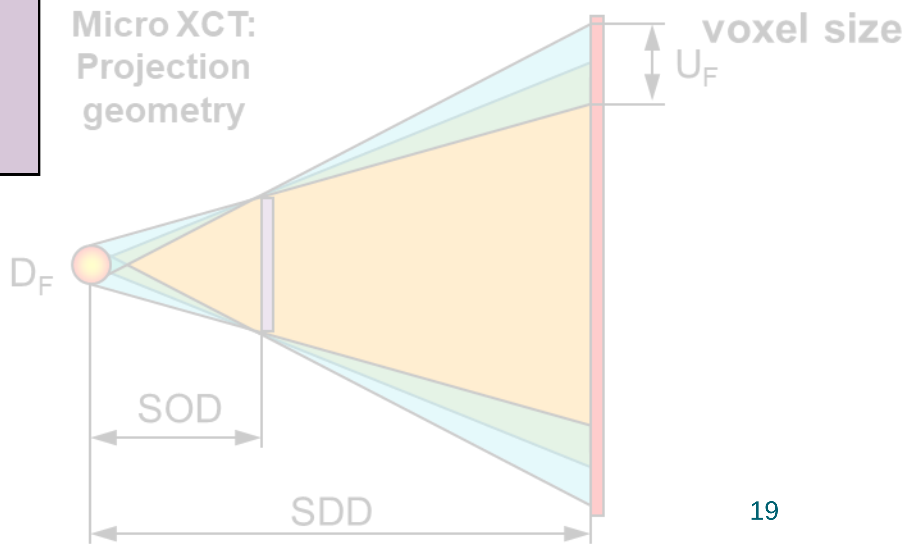
deepXscan Roadmap (Schematic): X-ray Computed Tomography (XCT) With Higher Resolution And Higher Sample Throughput

Nano XCT with new X-ray optics:
➔ 10 nm resolution

Sub-micron XCT with novel X-ray sources:
➔ 0.2 µm resolution




Nano XCT: Microscope with focusing lense


Micro XCT: Projection geometry

1st Announcement

Welcome to Bad Schandau near Dresden, Germany, April 24 – 26, 2023!

17th International Conference

Reliability and Stress-Related Phenomena in Nanoelectronics

New topics:

- **Reliability @ harsh environments (space, automotive)**
- **Materials properties @ low T (quantum computing)**

Contact: ehrenfried.zschech@deepxscan.com

Thank you !

Jürgen Gluch, Andre Clausner, Christoph Sander, Peter Krüger, Yvonne Standke, Matthias Kraatz

Fraunhofer IKTS Dresden, Germany

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

Financial support from SRC under Member-Specific Research Contract P30697 is greatly appreciated.

deepXscan GmbH
Zeppelinstr. 1
01324 Dresden
Germany

www.deepxscan.com