In-situ nano-XCT study of the local energy release rate for crack propagation in advanced ICs

Kristina Kutukova, Ehrenfried Zschech

deepXscan GmbH, Dresden, Germany

Jürgen Gluch, Matthias Kraatz, André Clausner

Fraunhofer IKTS, Dresden, Germany

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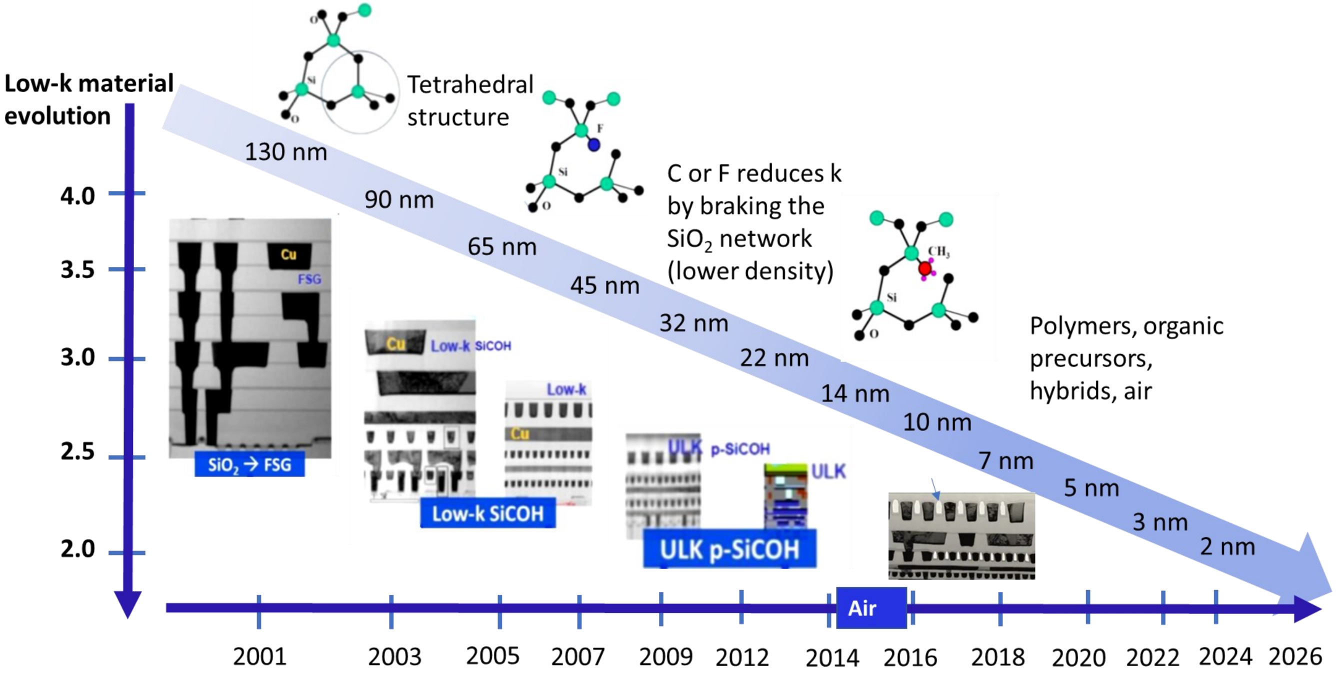
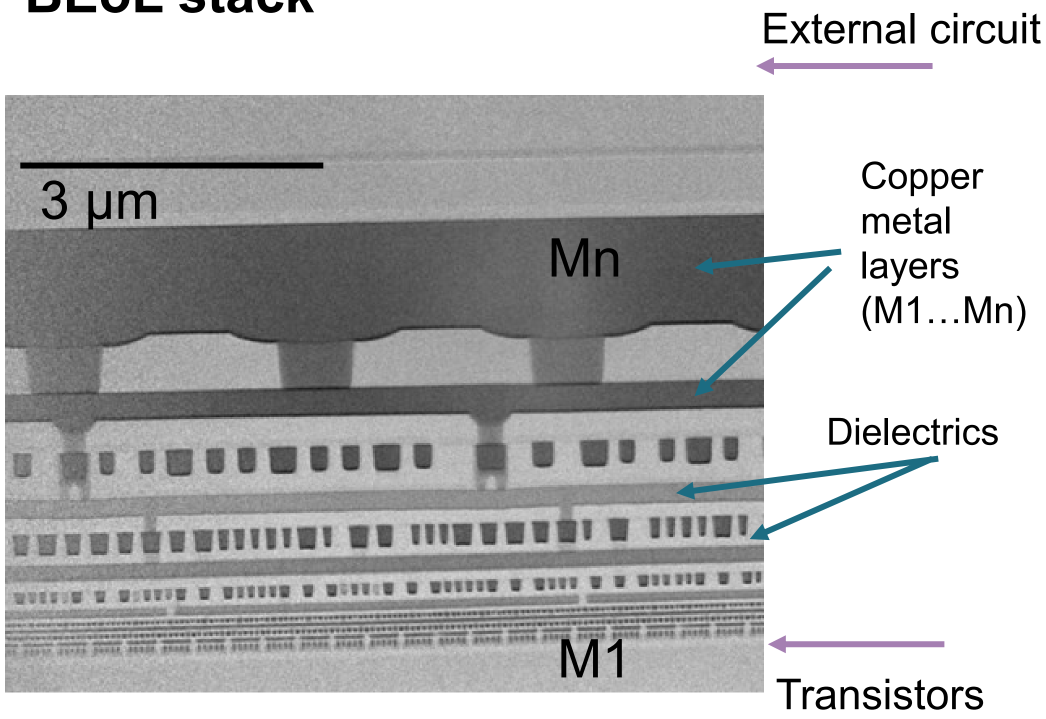
Advanced ICs : On-chip interconnect stack materials & design

- Decreasing on-chip interconnect pitch (including inter-layer dielectrics dimensions) in nano-electronic products → higher signal delay, power loss, …
- Need of dielectric materials with ultra low k-values (ULKs)
- **Nano-porous organosilicate glasses (OSGs)** for k-values below 3,0 or less



FSG: Fluorosilicate glass
OSG: Organosilicate glass

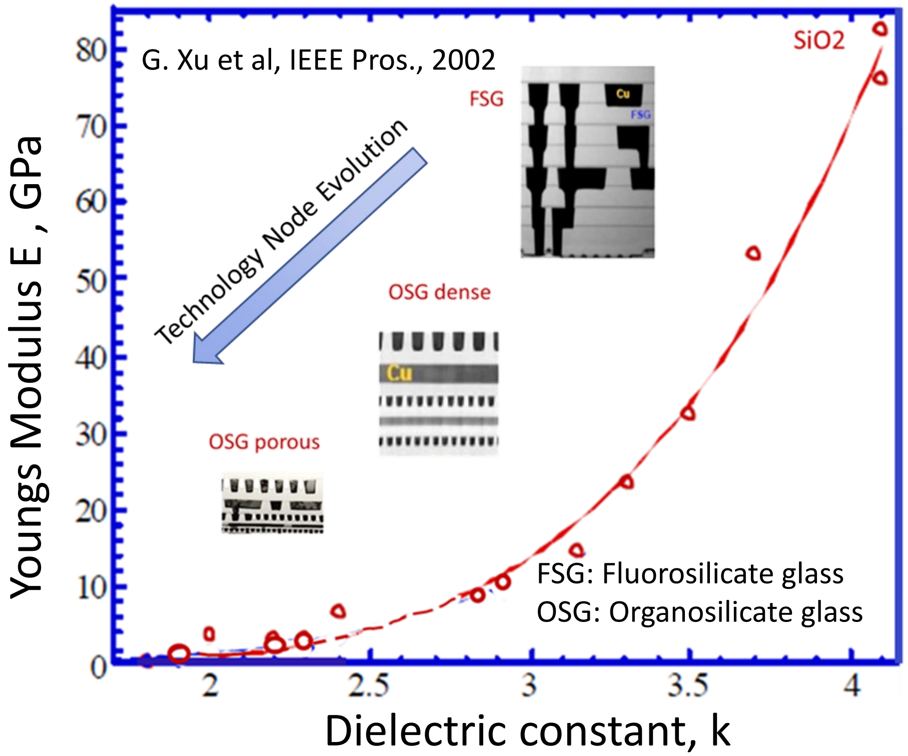
High resolution radiograph of microchip X-section: BEoL stack



Example: Cu/ dielectric on-chip interconnect stack of advanced ICs (14 nm CMOS technology node)

Ultra Low-k nano-porous materials in nano-electronics: mechanical properties

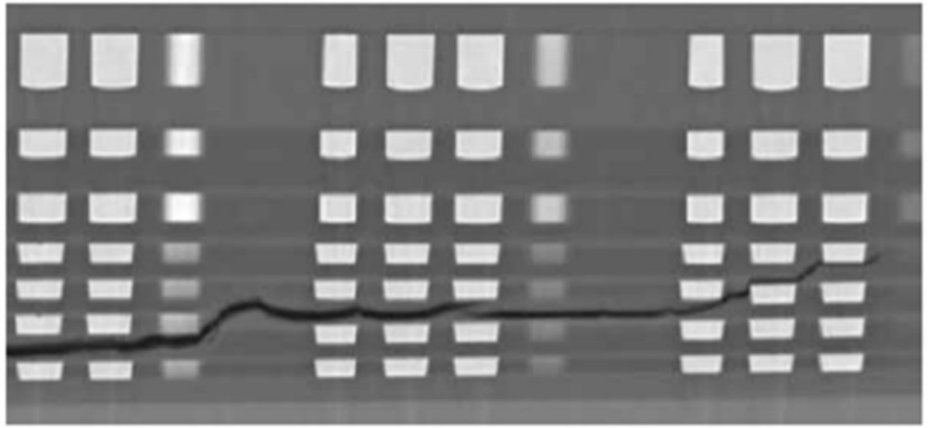
Dielectric materials



Criterion for crack propagation:

$$\frac{\pi\sigma^2 a}{E} \geq 2\gamma$$

Low E leads to easy crack Propagation.



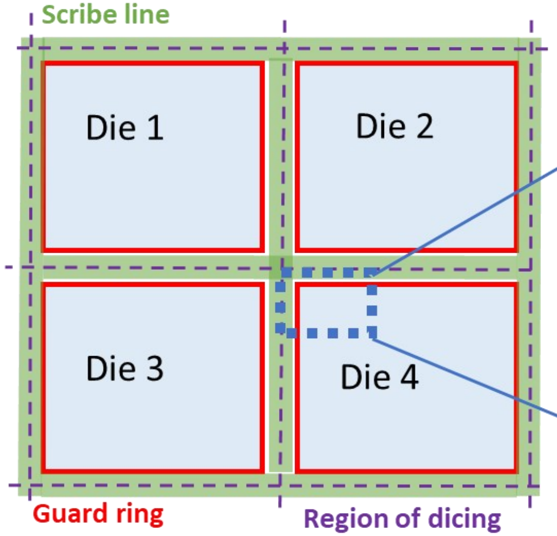
Crack propagation in a multilevel interconnect.

- Reliability issues caused by crack propagation (CPI, thermo-mech. stresses)

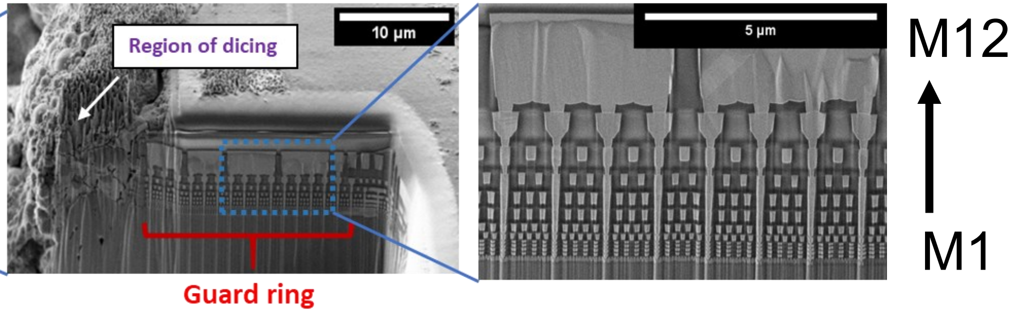
➢ **Mechanical characterization of the Cu/ULK films of nano-electronics is important!**

Cu/ULK BEOL Stack: Mechanical Robustness of Microchip

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



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?

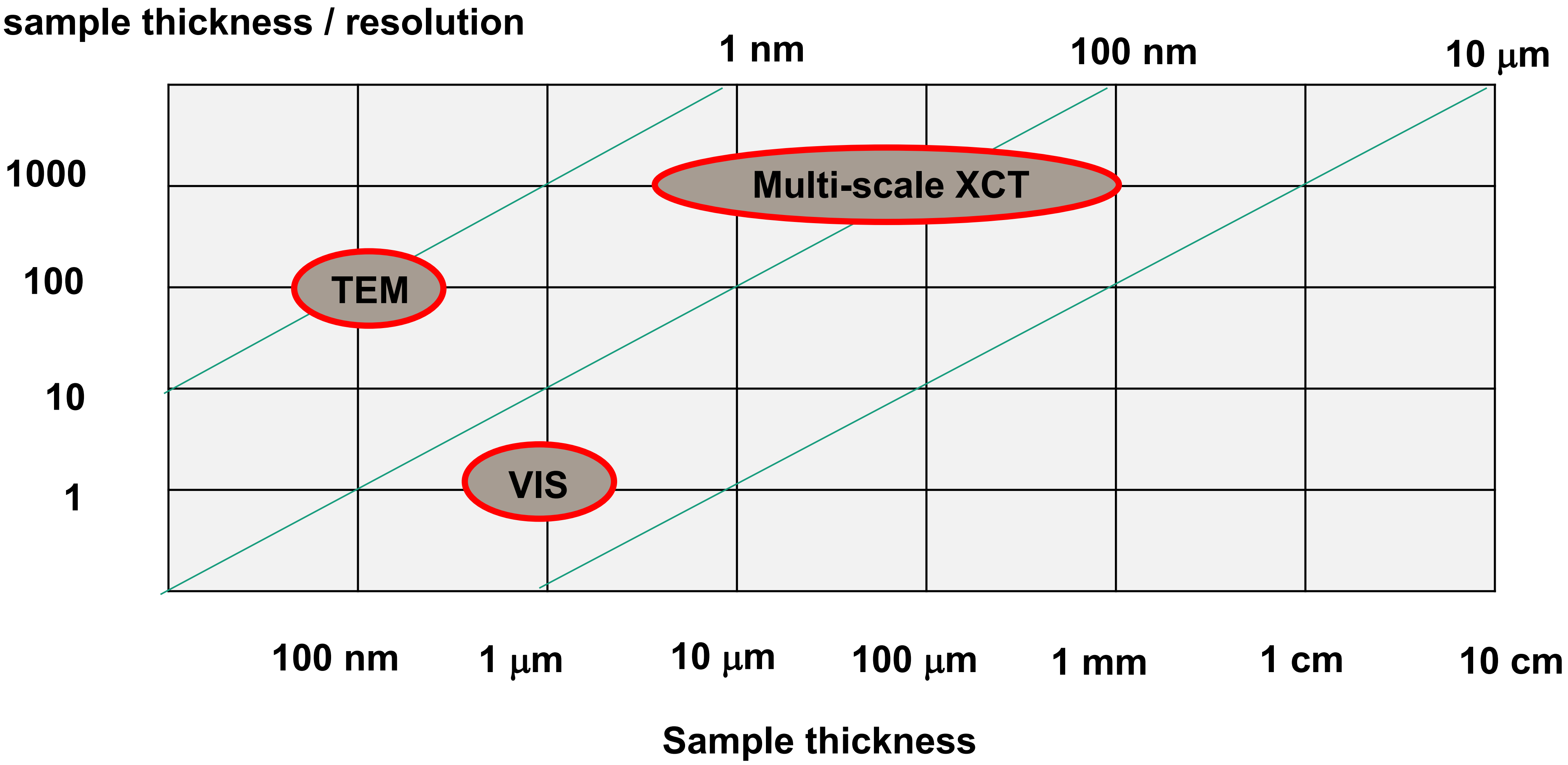
→ provide fracture mechanisms in 3D material systems?

→ 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

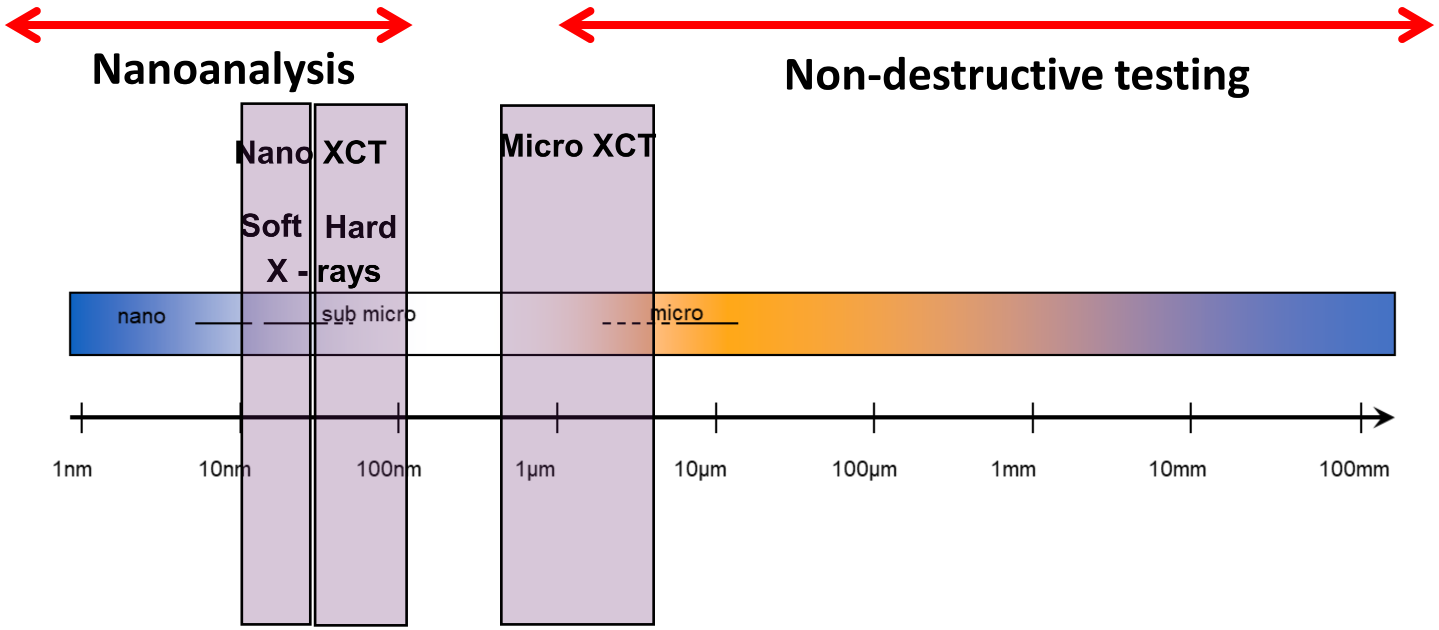


X-ray microscopy: multi-scale, 3D (nano-XCT) and nondestructive

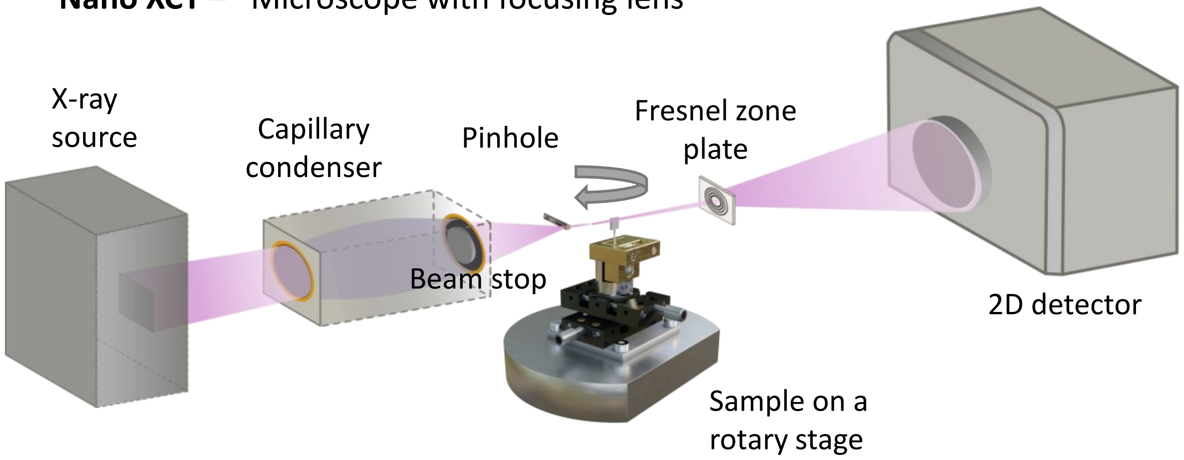
TEM – transmission electron microscopy
XCT – X-ray Computed tomography
VIS – visible light microscopy

Transmission X-ray microscopy and 3D-XCT

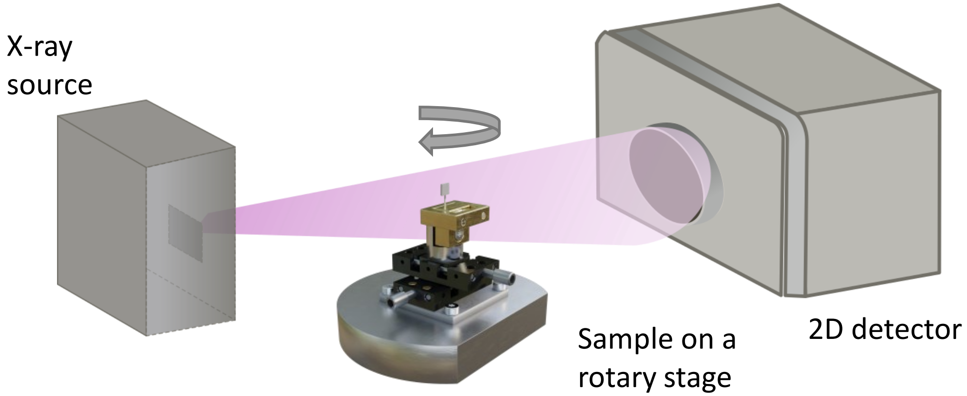
Energy	Resolution	X-ray microscope source
E < 3 keV	~ 10 nm	Synchrotron radiation (SR)
E > 5 keV	~ 50 nm	Laboratory or SR source



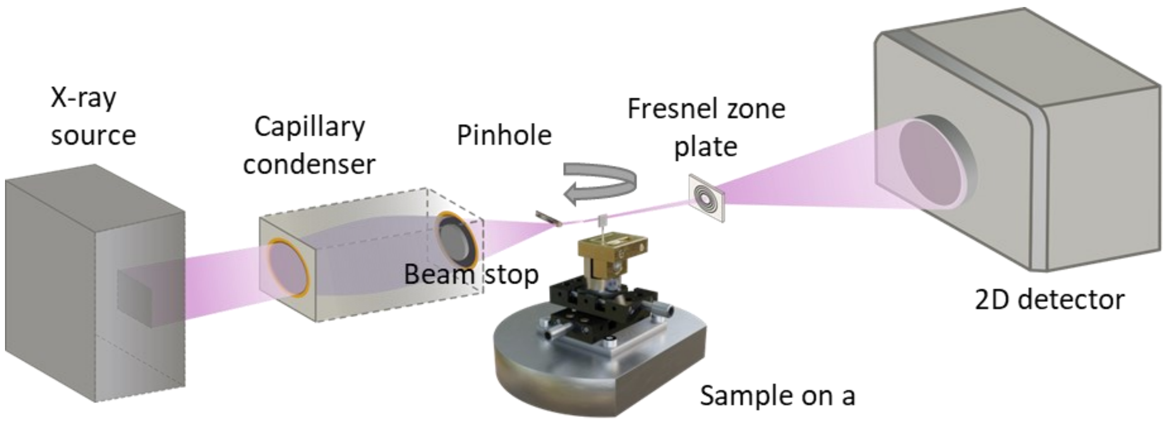
Nano XCT – Microscope with focusing lens



Micro XCT: Projection geometry



In-situ experiments in lab nano-XCT



Or micro-manipulator on rotary stage

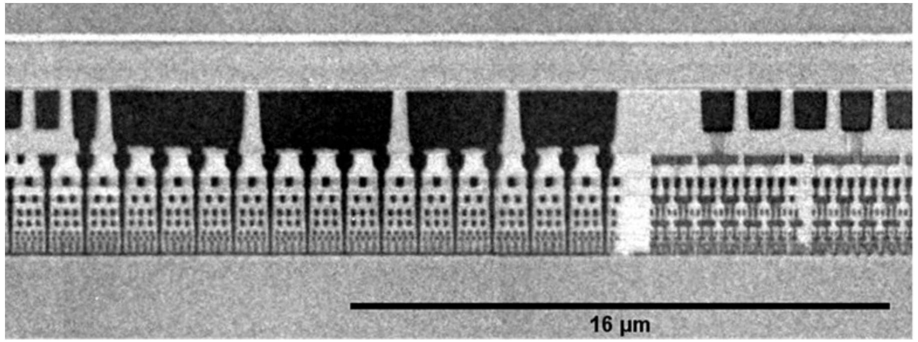
- **X-ray source**: Rotating anode, monochromatic radiation: Cu-Kα (8 keV)
- **X-ray optics**: Capillary condenser and Fresnel zone plate
- **Field of view width**: 65 µm or 16 µm
- **Spatial resolution:** 50 nm

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

1) 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)

2) Type of the micromechanical set-up - Concept
   - Description of fracture modes at nano-scale
   - Fixed feature position (e.g. crack) during sample rotation (X-ray tomography)
   - Reasonable load/displacement range/ applied force
   - Stable operation and repeatability of the experiment

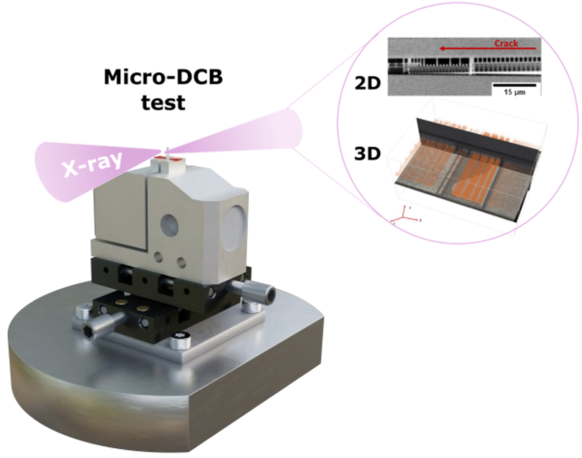
Stitched radiograph of the guard ring structures in HR mode at lab nano-XCT
Sample thickness ≈ 50 µm

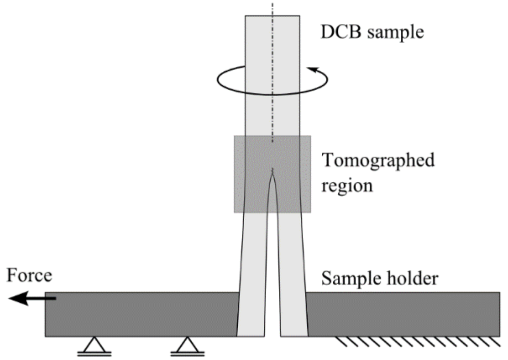


In-situ mechanical testing of multilayered structures using micro-DCB test

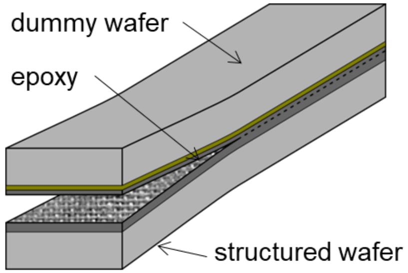
- Miniaturized Double Cantilever Beam test (micro-DCB)
  → **Crack propagation in 3D nano-patterned structures**

- Displacement-controlled tester → **Critical energy release rate (G_c)** determination of nanopatterned structures by measuring **crack length and crack opening (sum beam of deflection)**



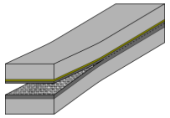


- Sample dimension: 1.7 × 5 × 50 mm³
- Post-mortem crack path study
- G_c : Defined beam theory



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

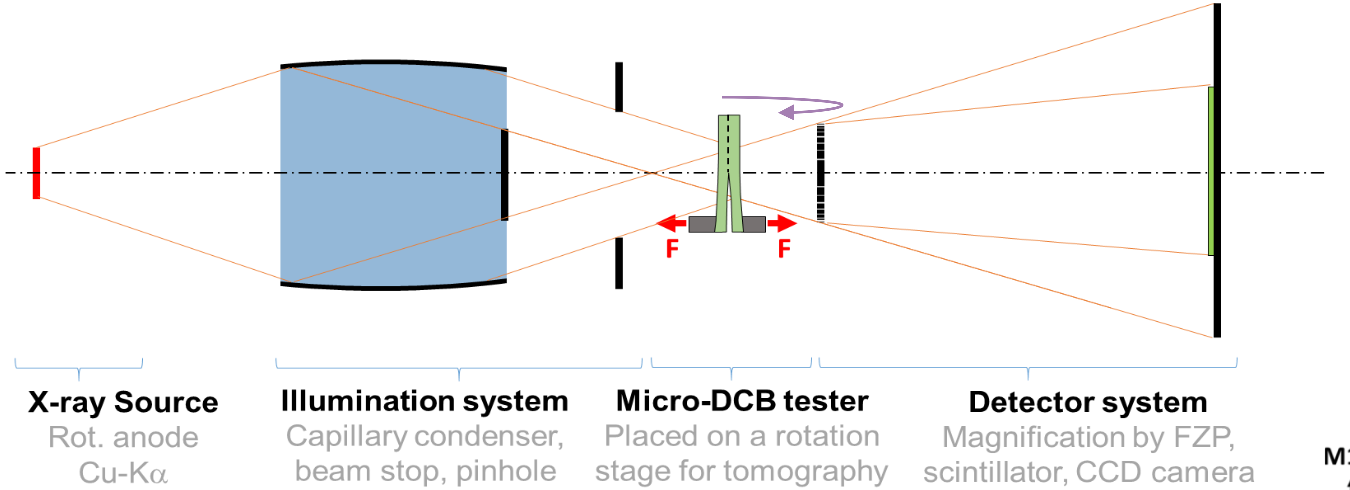
- Sample dimension: ~ 50 × 50 × 1000 µm³
- **In-situ 2D and 3D study → requires an experimental workflow!**
- **G_c : Beam Theory needs to be adapted!**



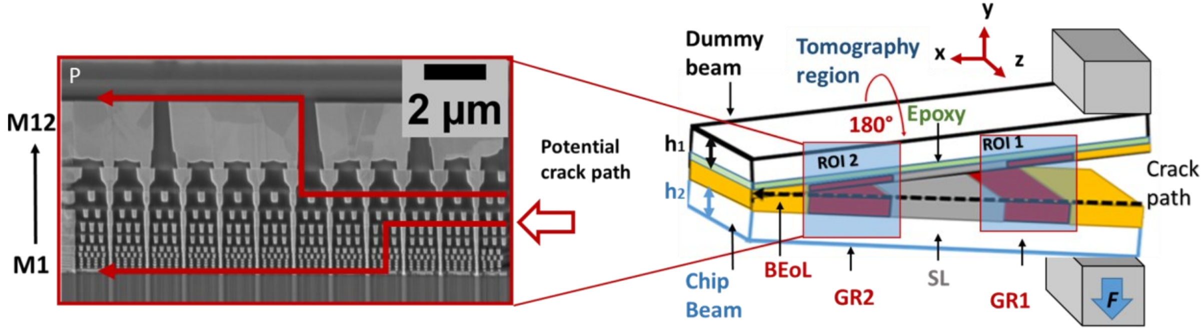
Miniaturized DCB:
in-situ 3D crack evolution
using X-ray microscopy + G_c

K. Kutukova, S. Niese et al., Mater. Today Commun. 2018

Experimental setup in the laboratory microscope: micro Double Cantilever Beam Test (micro-DCB)



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

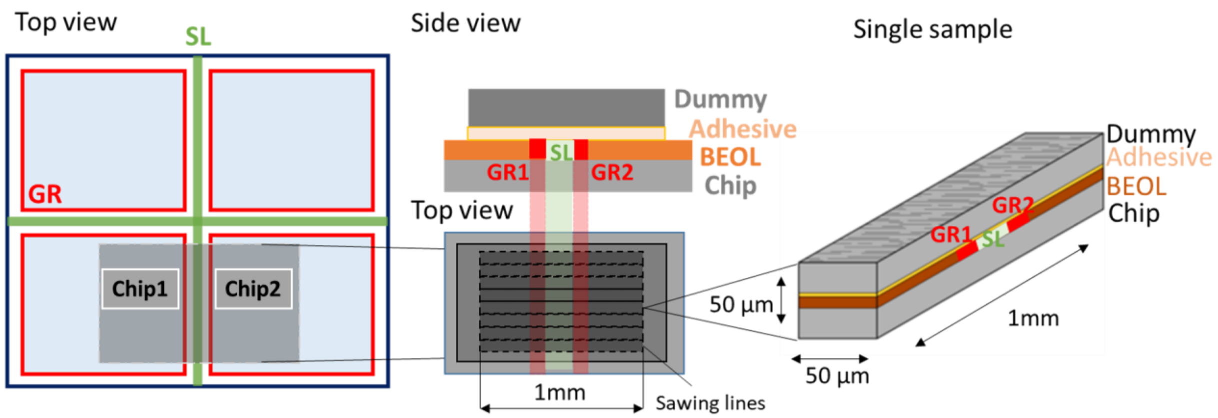


ROI GR: guard ring structure M1 – M12

GR - guard ring
ROI - region of interest
SL- scribe line
BEoL – Back end of line

Scheme of the sample geometry

Process of Mechanical sample preparation



K. Kutukova et al., Materials & Design 2022

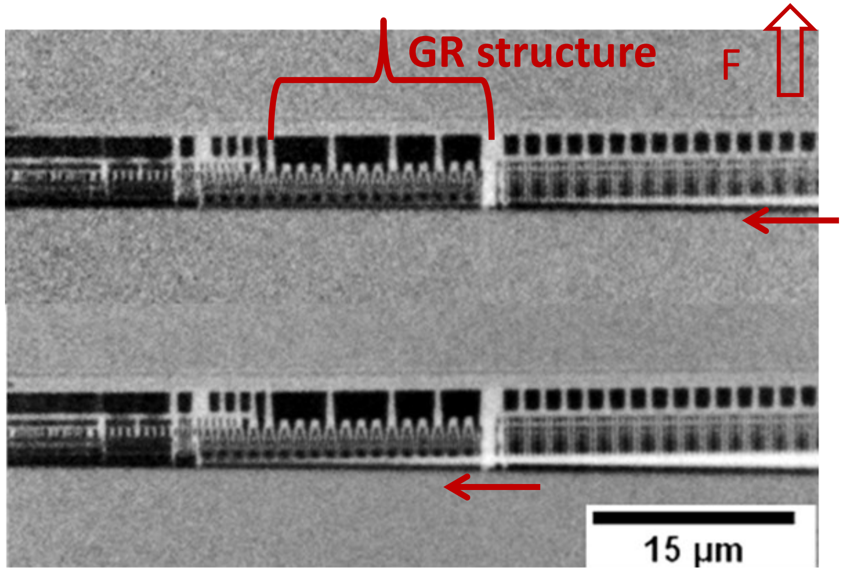
In-situ micro-DCB test in the nano-XCT tool: 2D

- Crack propagation in on-chip interconnect stacks and GR structure of microchip
  - → **Crack path localization in 2D**
  - → **Quantitative (local) mechanical properties - critical energy release rate (G_c)**

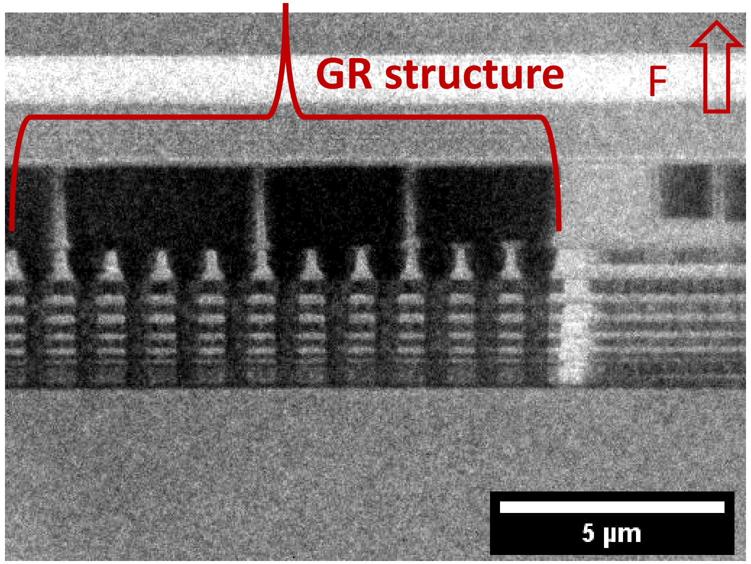
2D radiographs during micro-DCB experiment → stable crack growth and quantitative G_c determination

Crack stops at the GR structure

Crack changes its direction (energy dissipation) →Final cracking



2D radiographs during micro-DCB experiment at high resolution

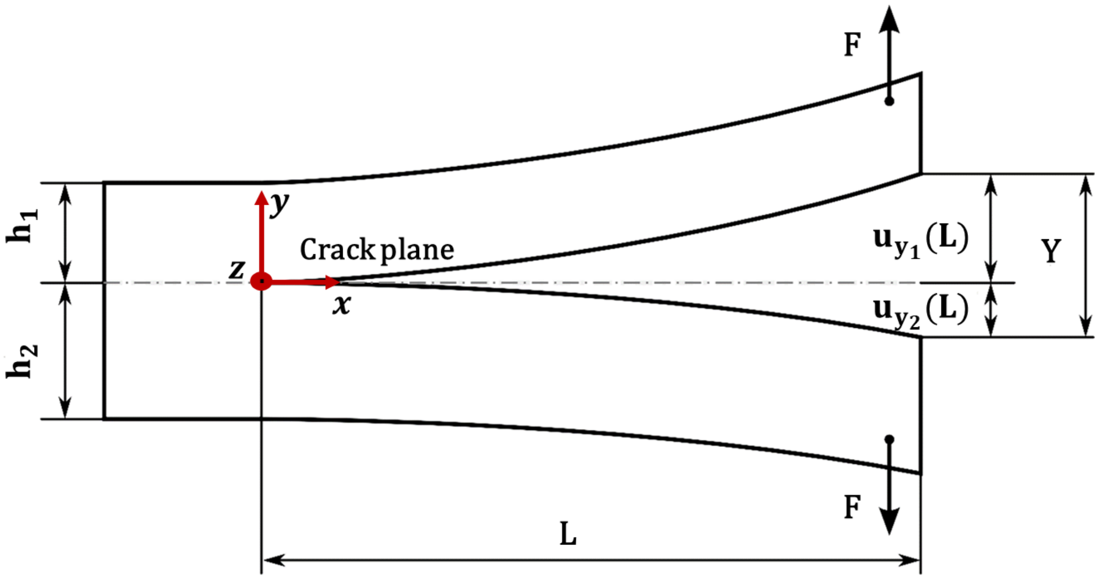


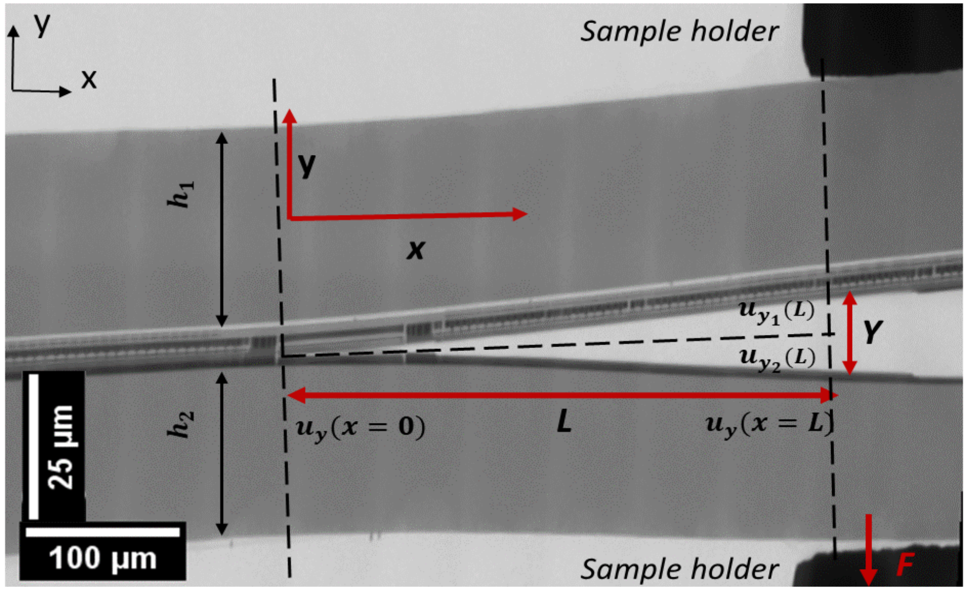
FOV: 65 µm or 16 µm; Resolution 100 nm or 50 nm

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 → boundary conditions (BC)**





G_c – critical energy realise rate
F - applied force
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

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Specifics of micro-DCB test and data analysis for the determination of G_c

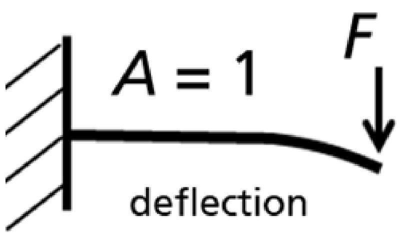
- **Analytical approach: Euler- Bernoulli beam theory adapted to real bending line of micro-DCB sample → boundary conditions (BC)**

Euler-Bernoulli beam theory:

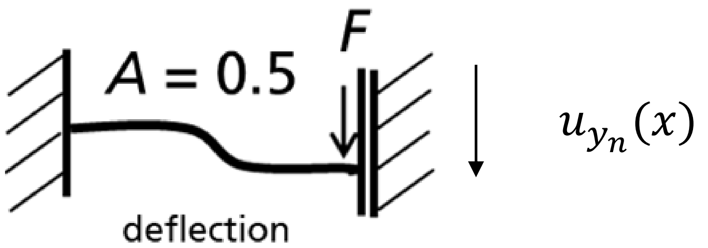
$$\frac{d^2}{dx^2}\left(EI\frac{d^2y}{dx^2}\right) = q$$

Deflection according BC

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

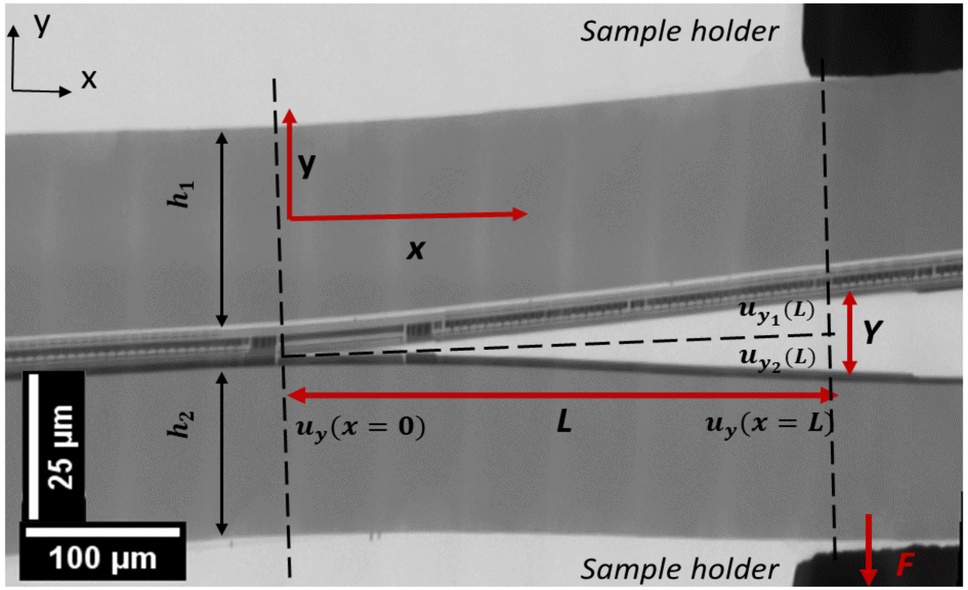


Free beam end



Fixed beam end

A_n = 0.5… 1



G_c – critical energy realise rate
F - applied force
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 for n-beam

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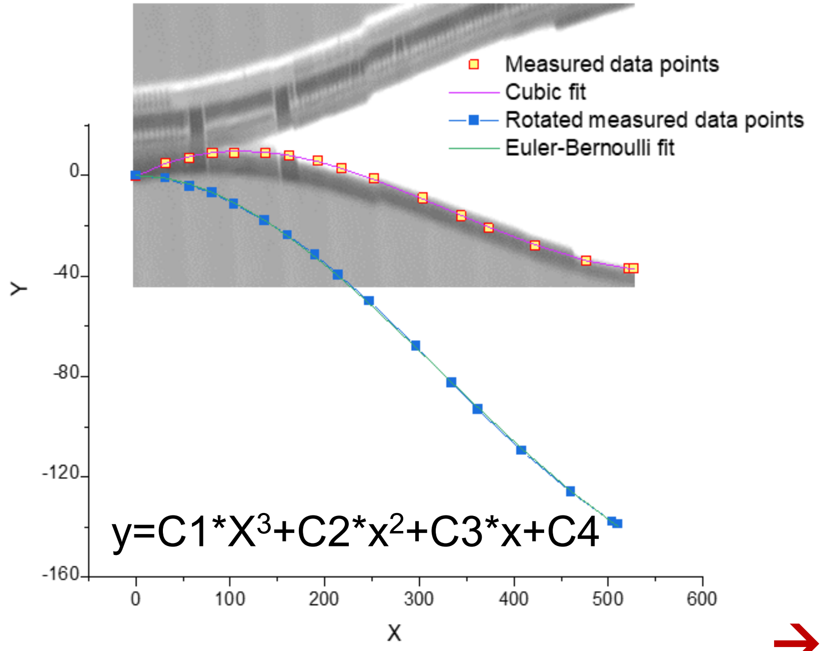
Data analysis and quantitative determination of G_c

- 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



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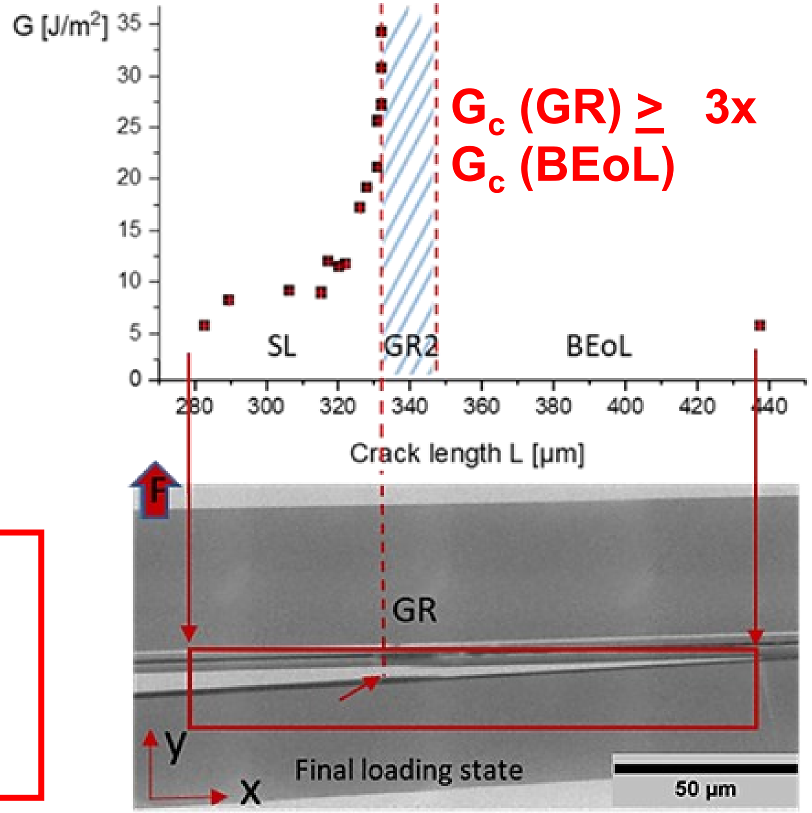
- Equation takes into account geometrical parameters for both cantilevers
- Applicable for symmetric and asymmetric (mode mixity) sample geometries
- **Validated on unpatterned reference samples**

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

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



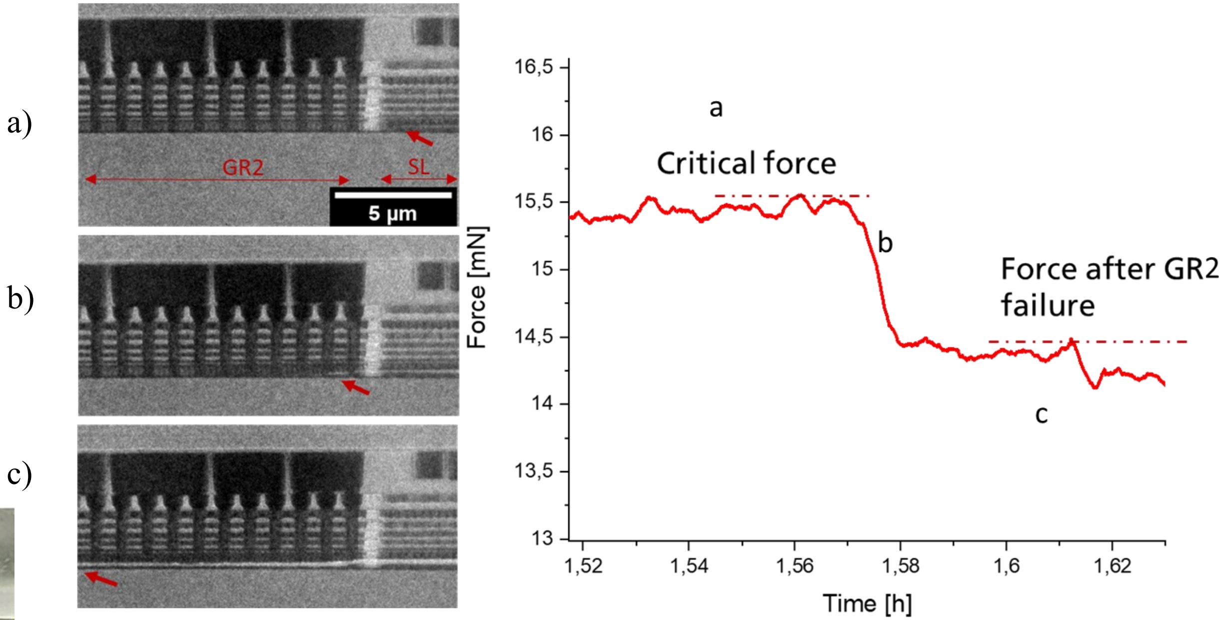
G_c (GR) ≥ 3x G_c (BEoL)

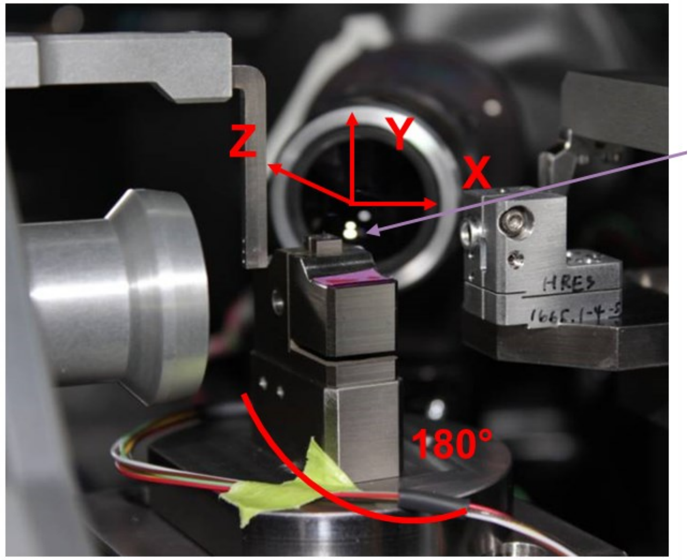
Calculated G values at several loading steps (and respective crack lengths) and stitched image of the final loading stage in the BEoL region

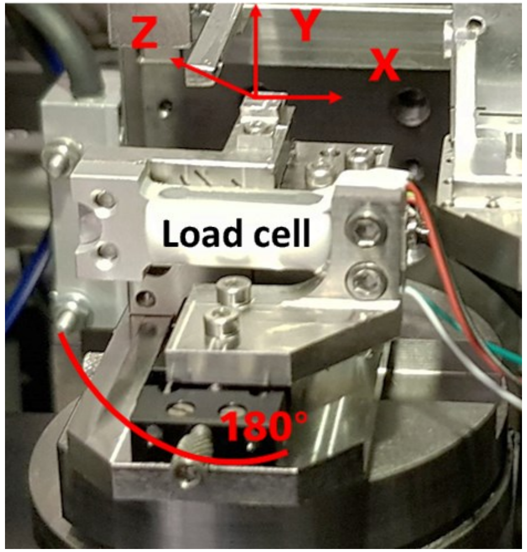
→ Quantitative local mechanical properties at certain loading states!

Data analysis and quantitative determination of G_c – micro-DCB tester set-up with force sensor

- Integrated load sensor to Micro-DCB set-up
  → continuous force measurements
  → faster data synchronization
  → better control of the crack propagation process







Micro-DCB testers in the nano-XCT tool

- Equation takes into account geometrical parameters for both cantilevers – linear parameter dependence!
- Reduced analyses time due to direct force measurements
- **Validated on unpatterned reference samples**

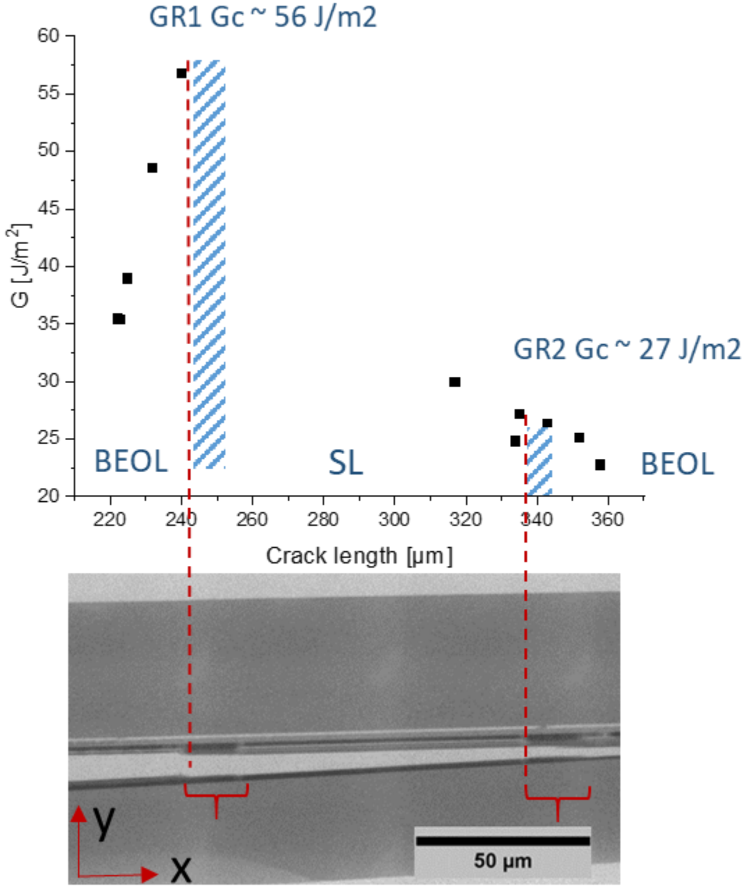
$$G_c = \sum_{1}^{n=2} \frac{3Fu_{y_n}(L)}{2bL}$$

G_c – critical energy realise rate
F - applied force
b– beam width
u_{y_n}– beam deflection in y
L– crack length

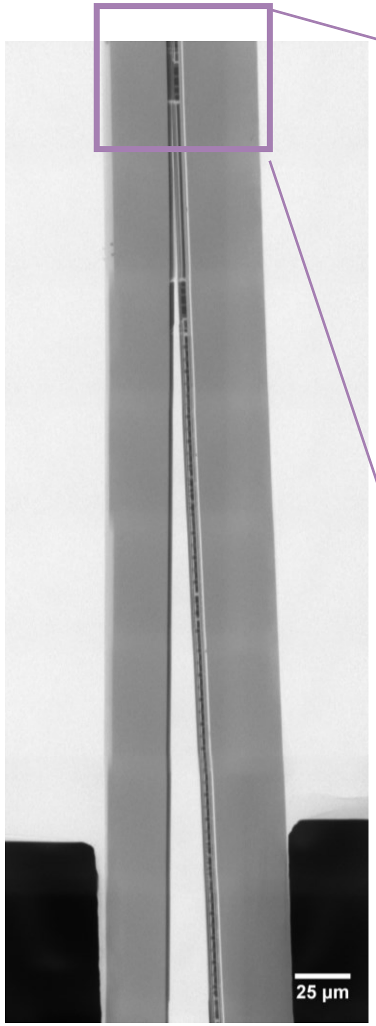
K. Kutukova PhD thesis, 2023

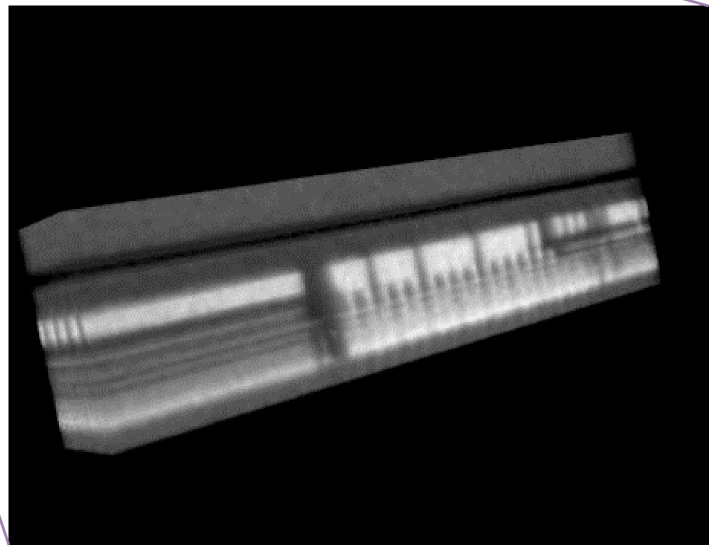
Data analysis and quantitative determination of G_c– micro-DCB tester set-up with force sensor

Integrated load sensor to Micro-DCB set-up:
→ study at several Guard Rings (GR 1 and GR2):



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





3D reconstructed data at different loading steps

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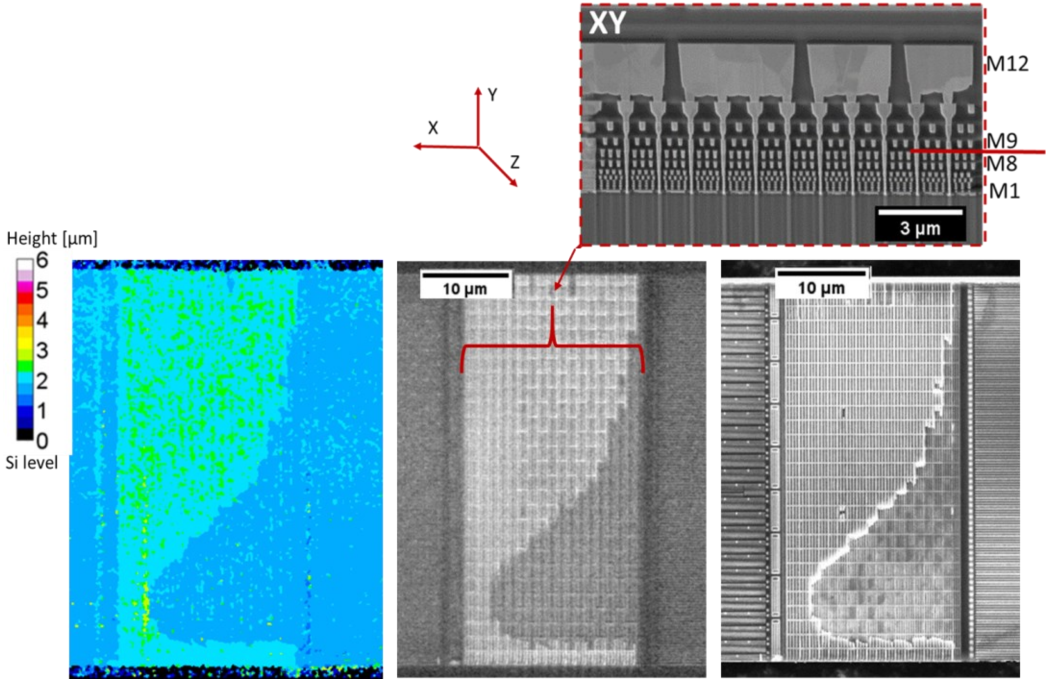
In-situ Micro-DCB Test In The Nano-XCT Tool

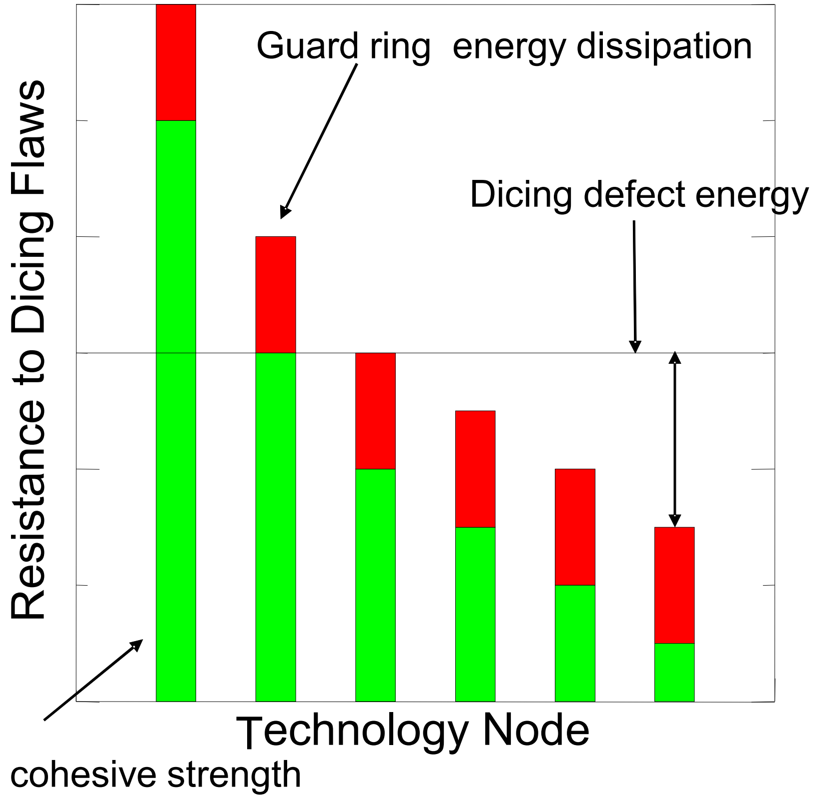
Crack propagation in on-chip interconnect (BEoL) stacks and GR structures

→ Quantitative (local) mechanical properties - critical energy release rate (G_c) to study GR resistance to dicing flaws

→ Correlation to the damaged layers in 3D – input to the GR design



3D data SEM



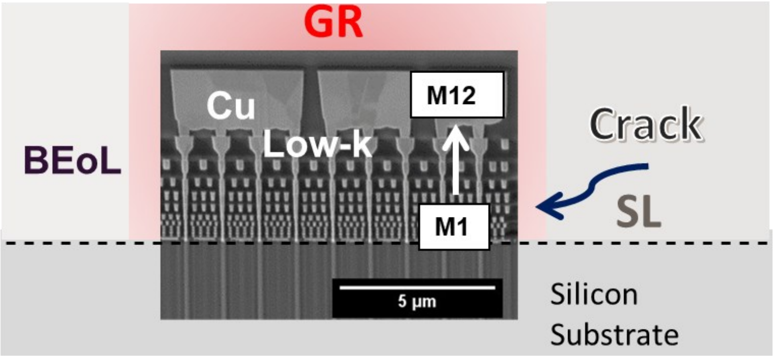
K. Kutukova et al., Materials & Design 2022

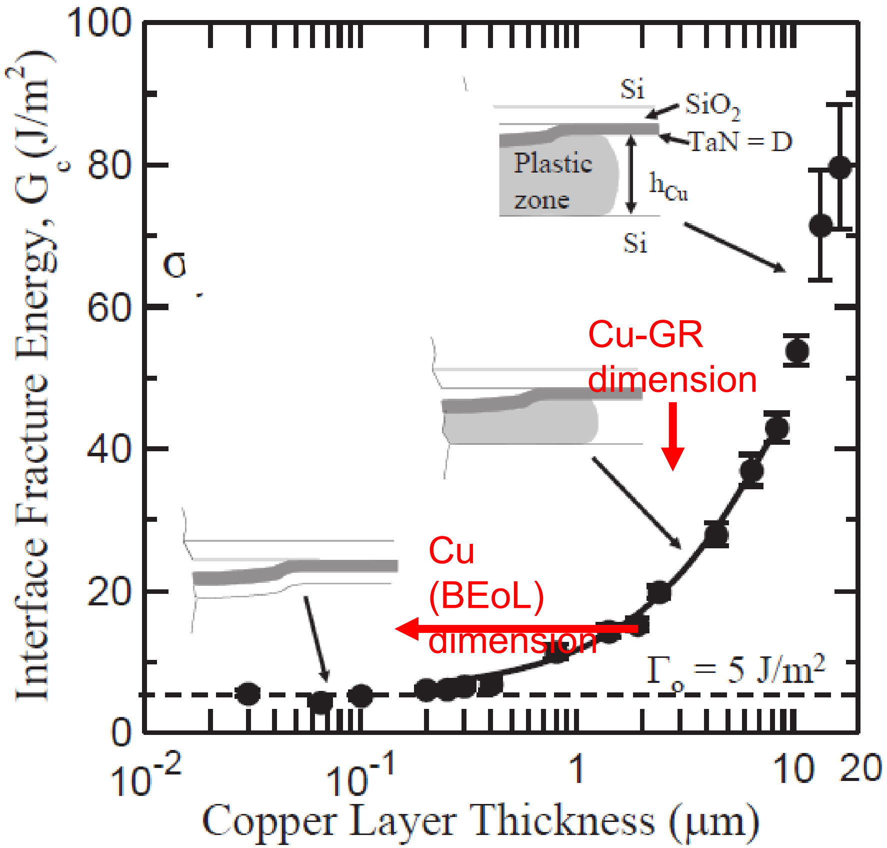
M. Lane et al. J. Mater. Res.2000

The effectiveness of the GR to stop micro-cracks depends on materials and design

Displacement-controlled micro-DCB tests at nano-XCT:

→ **Experimentally studies** show significantly **larger G_c** for crack propagation at special protective GR structure in a microchip of **G_c > 30 J/m²**, compared to values in patterned regions with **G_c < 10 J/m²**





M. Lane, R. Dauskardt et al, J. Mater. Res., 2000

Steer microcrack to stop ? →
more in talk by Ehrenfried Zschech

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Summary: In-situ Micro-DCB Tests 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 based on two approaches:

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

Demonstration of two set-ups for Gc quantification in regions with high fracture toughness locally, e.g. guard-ring structures

→ evaluation of process-induced materials changes and a pathways to study the scaling of mechanical properties of interconnect stack materials of advanced ICs!

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.

Thank you !

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

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deepXscan GmbH
Zeppelinstr. 1
01324 Dresden
Germany

www.deepxscan.com