Understanding the Damage and Microstructural Evolution in Cu Metallizations during Thermo-mechanical Fatigue

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Infineon at a glance

Growth areas

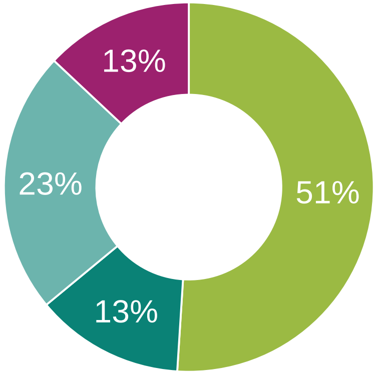
Energy
green and efficient

Mobility
clean and safe

IoT
smart and secure

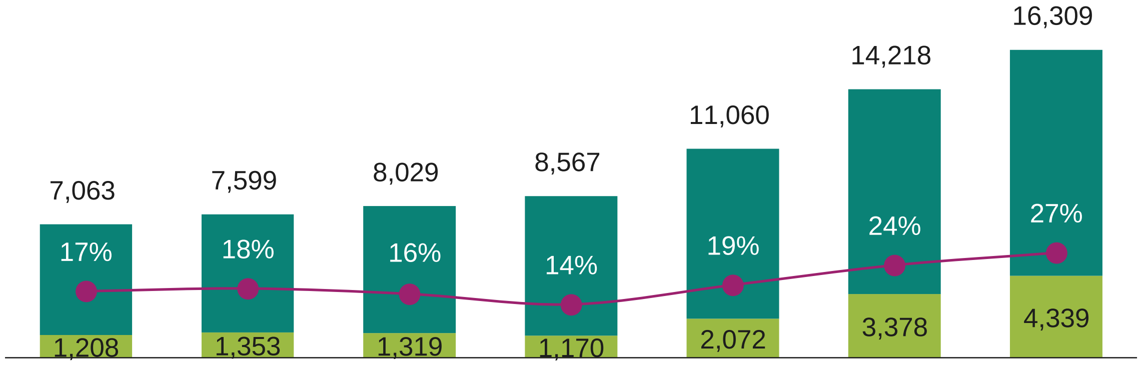
FY23 revenue by segment[1]

- Automotive (ATV)
- Green Industrial Power (GIP)
- Power & Sensor Systems (PSS)
- Connected Secure Systems (CSS)



Financials

[EUR m]



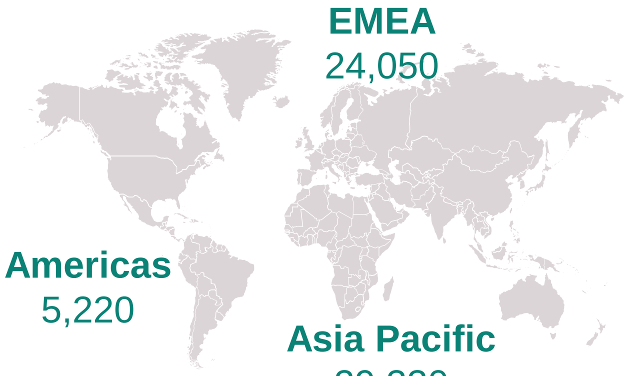
Revenue | Segment result | Segment result margin

Employees[2]

58,600
employees worldwide

69
R&D and

17
manufacturing locations[2]



For further information: Infineon Annual Report.

[1] 2023 Fiscal year (as of 30 September 2023) | [2] As of 30 September 2023

AddMorePower

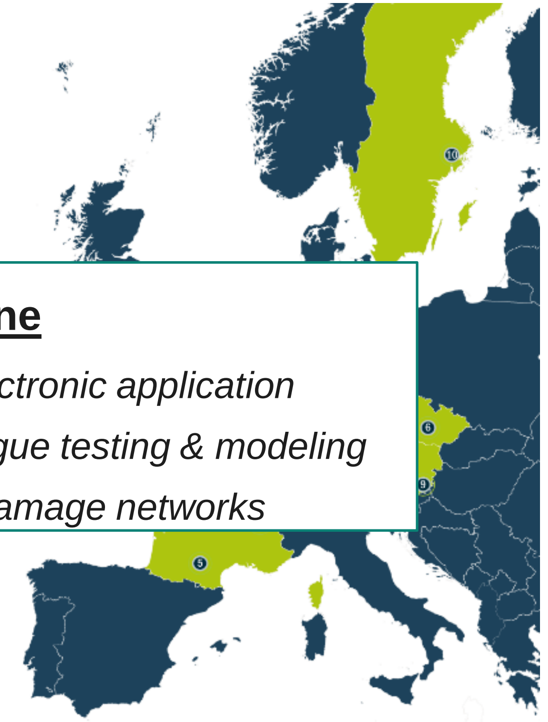
EU funded research project: 01/2023 – 12/2026

Motivation

- Materials integration and development for the next generation of power semiconductor technologies
- Digitalization and electrification of our society and its supply with sustainable energy
- European Green Deal for climate neutrality by 2050

Project objectives

- Develop a defect characterization workflow using advanced X-ray and electronprobe related techniques
- Modelling approaches to new wide bandgap power semiconductor materials and 3D integrated power technologies
- Using FAIR (findable, accessible, interoperable and reuseable) data principles required for digitalization and industry 4.0



Outline

- *Challenges in power electronic application*
- *Thermo-mechanical fatigue testing & modeling*
- *3D characterization of damage networks*

10/11 partners in 5 countries

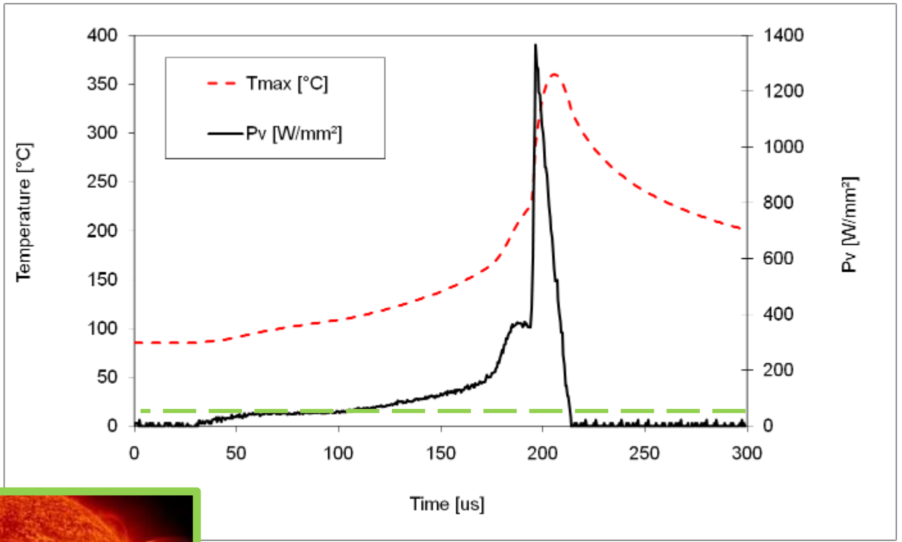
[1] Consortium partner until: 01/2024
[2] Designated consortium partner

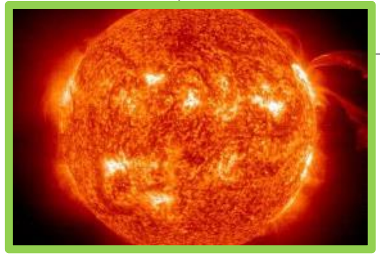
Challenges in power electronic applications

Thermo-mechanical fatigue

In power electronic applications, malfunction and short circuit events cause high overload pulses, leading to rapid heating up to high temperatures.

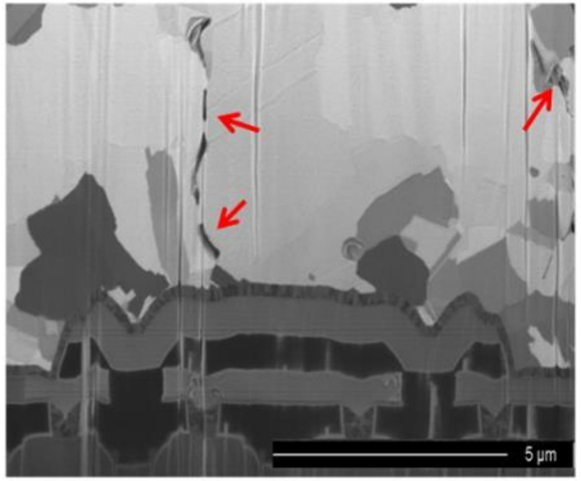
Typical overload pulse in a power electronic device

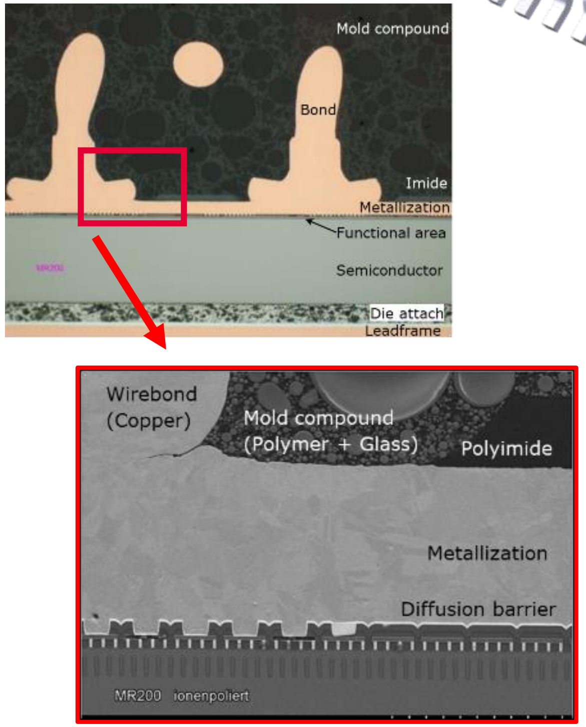




surface of the sun: 63 W/mm²

After thermo-mechanical cycling [2]





Structure of a power electronic device [1]

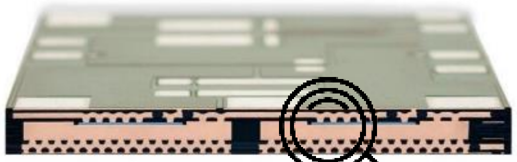
Degradation of the metallization layer due to multiple overload pulses and final device failure.

[1] M. Nelhiebel, *Microelectronics Reliability* (2011)
[2] M. Nelhiebel, *Microelectronics Reliability* (2013)

Challenges in power electronic applications

Thick Cu as enabler for aggressive device shrink

30 years of shrinkage in subsequent generations in „automotive high-side smart power switch“



Infineon embedded MOSFET half bridge power module [1]

Example: Power electronic switches for 12V board net

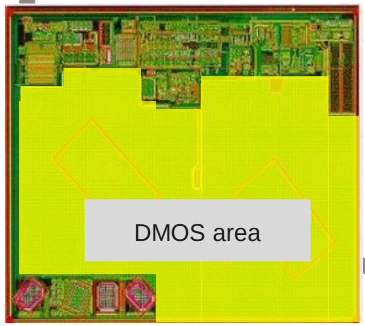
- self-protecting (temperature, current, voltage) to guarranty reliably functioning
- low-ohmic

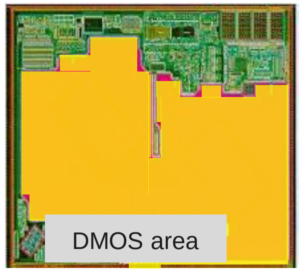
→ Advanced materials characterization metrology

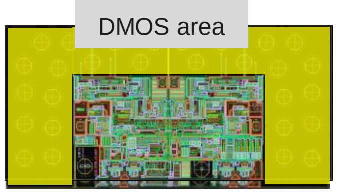
→ Understand the dominant degradation mechanism

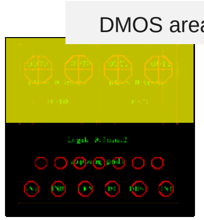
→ Multiphysics and multiscale modeling of Cu metallization degradation

MOS-FET area reduction



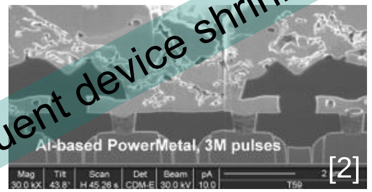




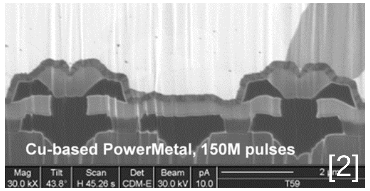


Future

Subsequent device shrinkage – power density increase (chip level)



[2]



[2]

** Devices tested with identical loading condition*

Years

Al era **Cu era** **+ 3D integration**

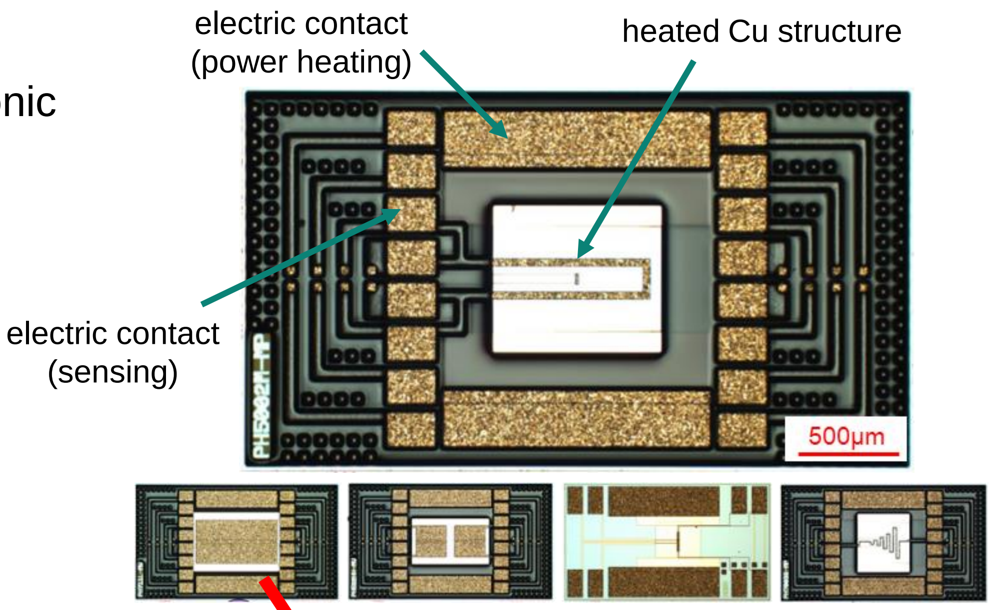
[1] https://eps.ieee.org/technology/heterogeneous-integration-roadmap/2023-edition.html

[2] M. Nelhiebel, *Microelectronics Reliability* (2011)

Thermo-mechanical fatigue testing + modeling

Polyheater test structures

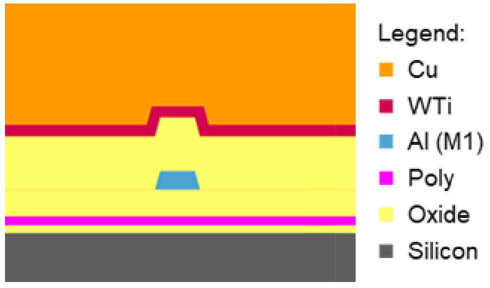
Test chip to investigate the thermo-mechanical degradation of power electronic metallization layers via repetitive fast heat pulsing

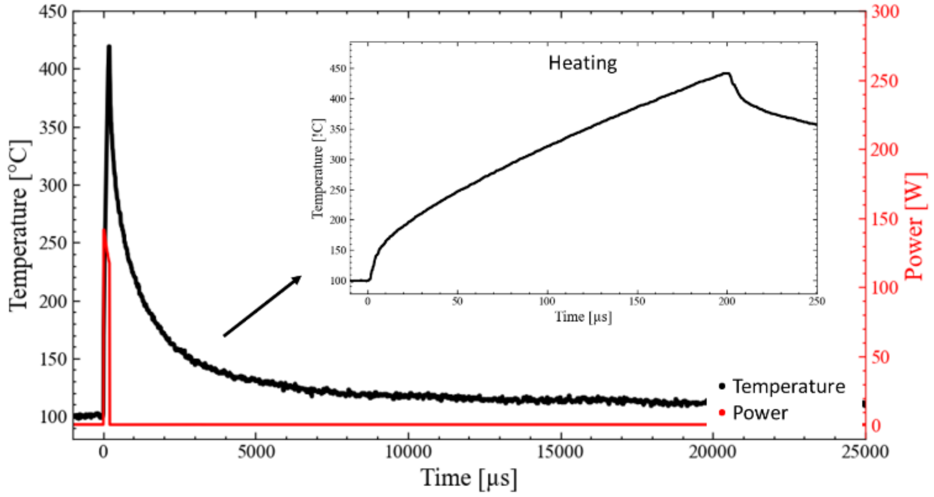


<u>Test Parameters which can be varied:</u>

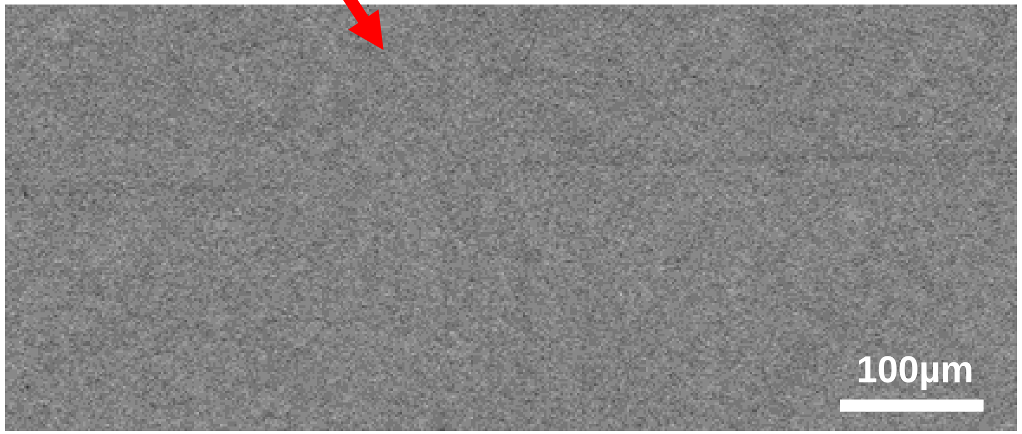
- T_{Base} (RT - 150 °C)
- T_{Max} (up to 650 °C)
- Pulse Length (200µs (*) – 20ms)
- Ambient: Air, Vacuum, Forming gas
- Repitition rate: 5 pulses/sec - ...

(*) Heating rate of ~1.5*10^6 K/sec (ΔT = 300°C)





50000 cycles

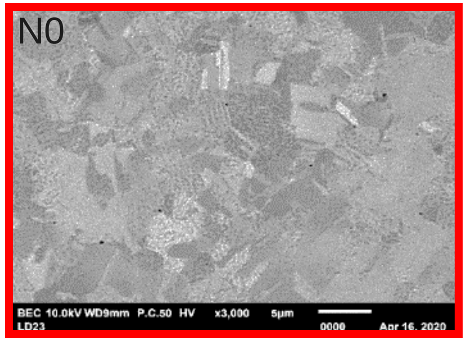


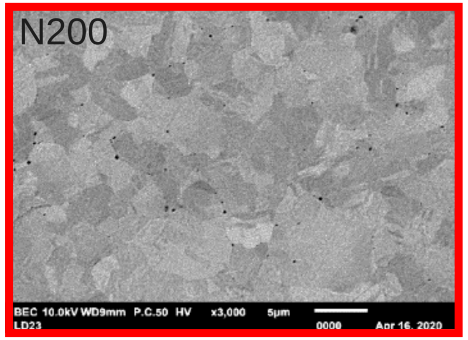
In-situ experiment showing the damage evolution on the Cu surface

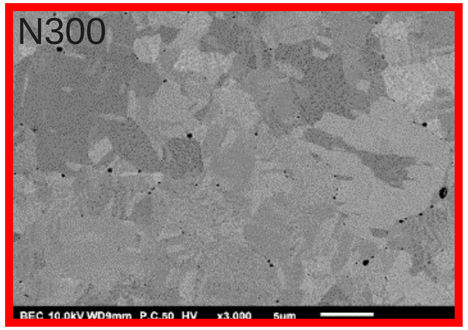
S. Moser, *JOM* (2019)

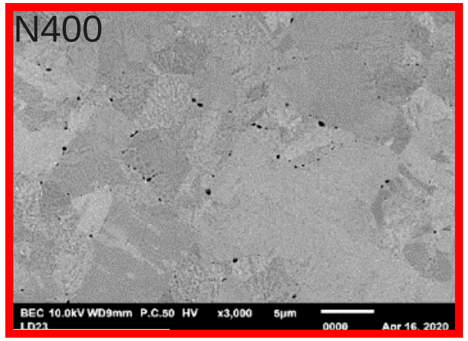
Thermo-mechanical fatigue testing + modeling

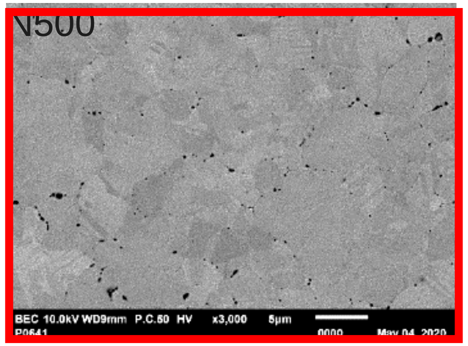
Post-testing 2D Scanning electron microscopy study

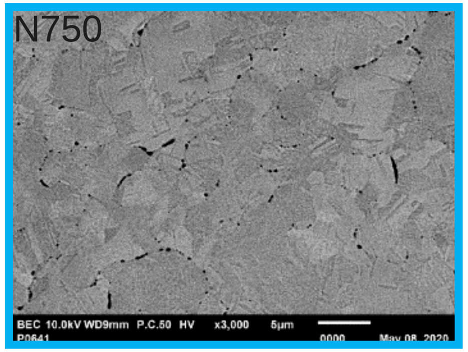


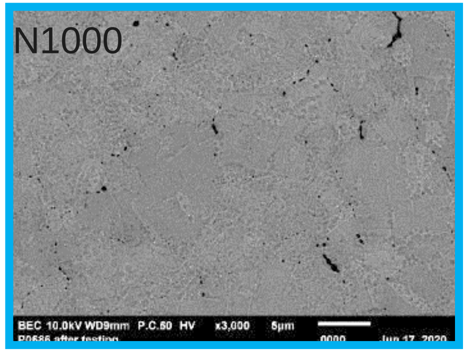


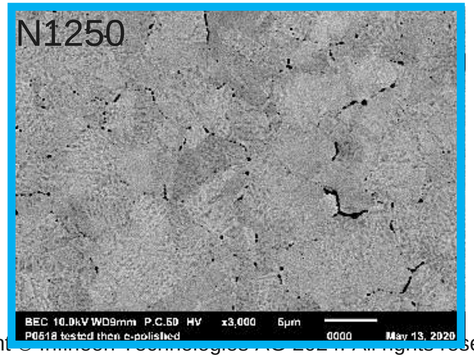


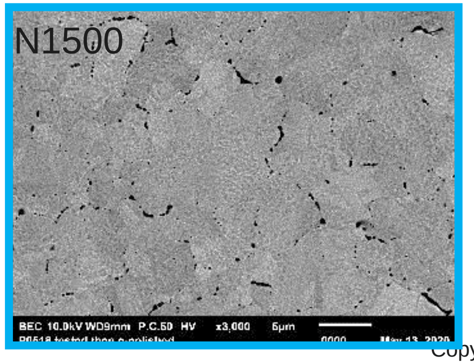


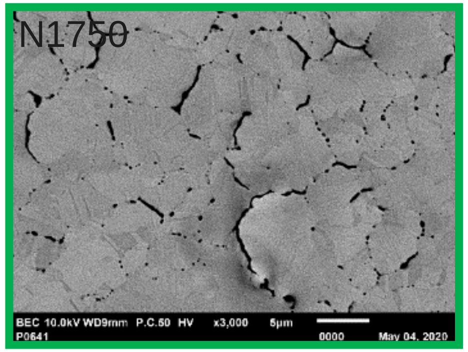


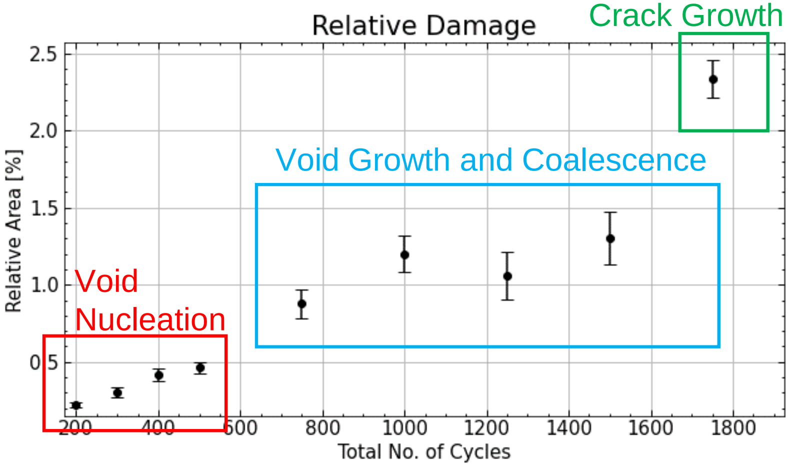












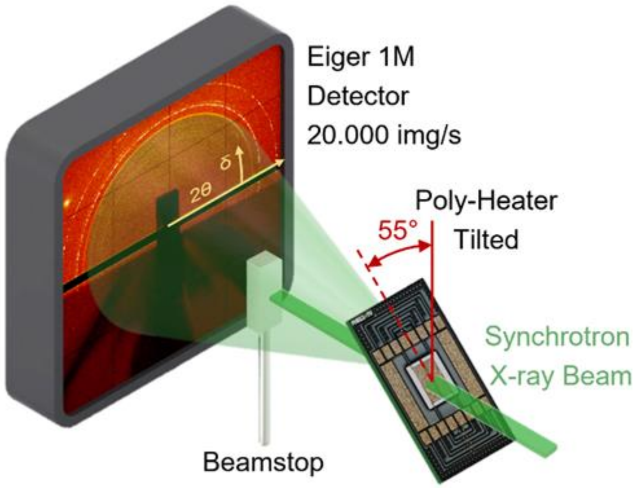
Applied test conditions:

- T_{base}: 100 °C - T_{max}: 400 °C
- Pulse Length: 200 µs
- Repittion rate: 1 Pulse/sec

M. Kleinbichler, *Microelectronics Reliability* (2021)

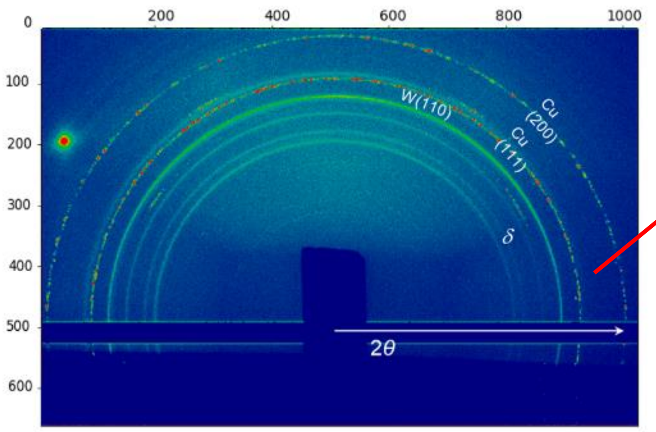
Thermo-mechanical fatigue testing + modeling

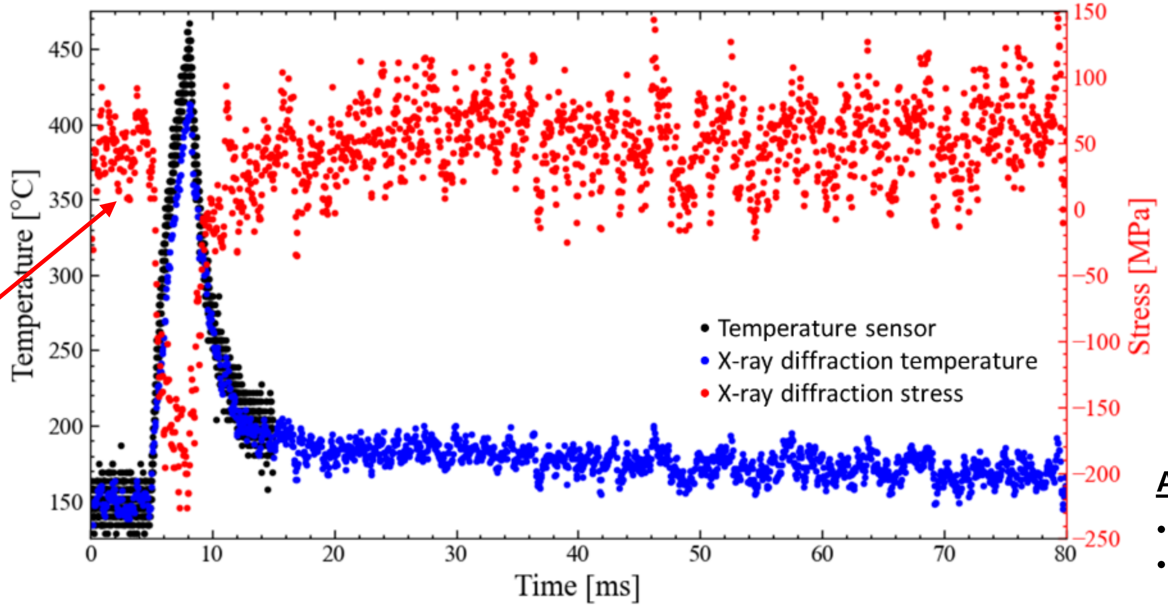
Thermo-mechanical stress in metallization layers



Ultra-fast 20 kHz X-ray diffraction (Synchrotron: PSI - MS-Powder)

- In-situ time resolved X-ray diffraction to determine the stress within Cu metallization with 20.000 fps (every 50µs)
- Acquisition of diffraction patterns (DP) allows to determine *temperature* and thermo-mechanical stress throughout the course of a single heating pulse





Applied test conditions:

- T_{base}: 150 °C - T_{max}: 400 °C
- Pulse Length: 3200 µs

T. Ziegelwanger, *In Prep.*

Thermo-mechanical fatigue testing + modeling

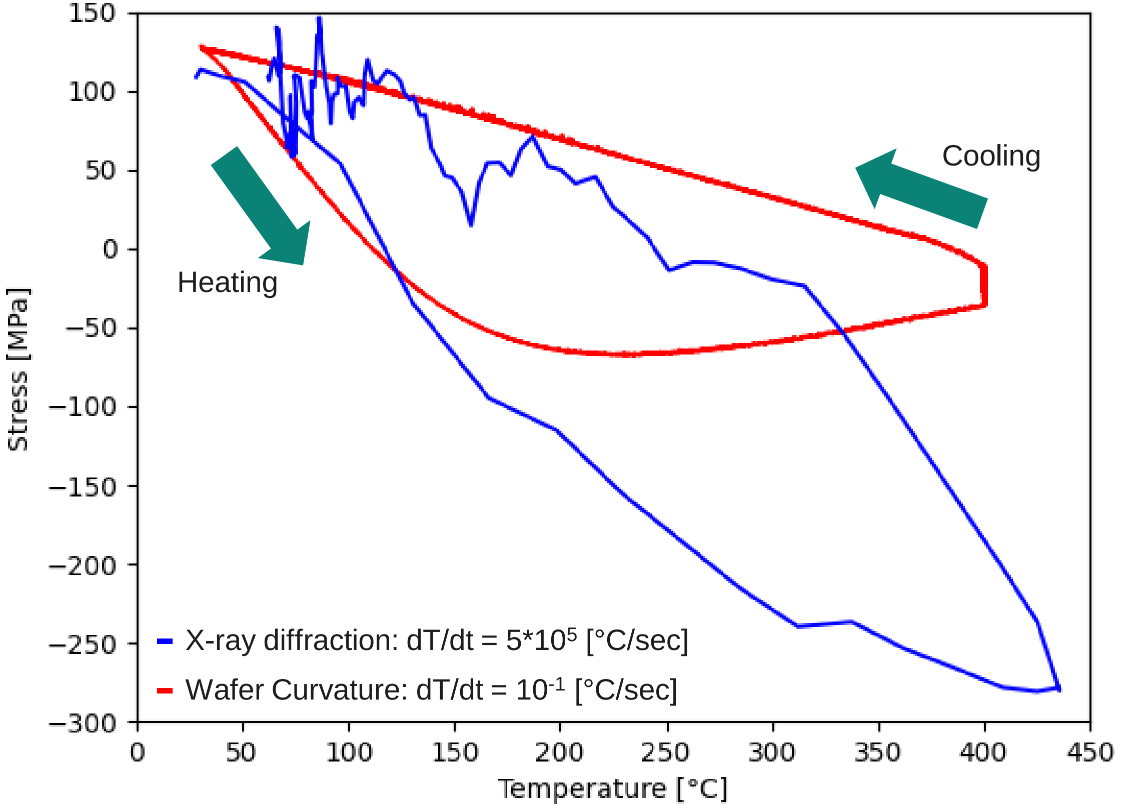
Thermo-mechanical stress in metallization layers

Slow heating vs. rapid heating

- Different deformation mechanisms are activated in high strain rate regime
- High thermo-mechanical stresses were measured but data evaluation is challenging
- Slow heating experiments (e.g.: Wafer Curvature) are not representative for application-relevant stresses

Coefficient of thermal expansion

Cu : Si
6.5 : 1



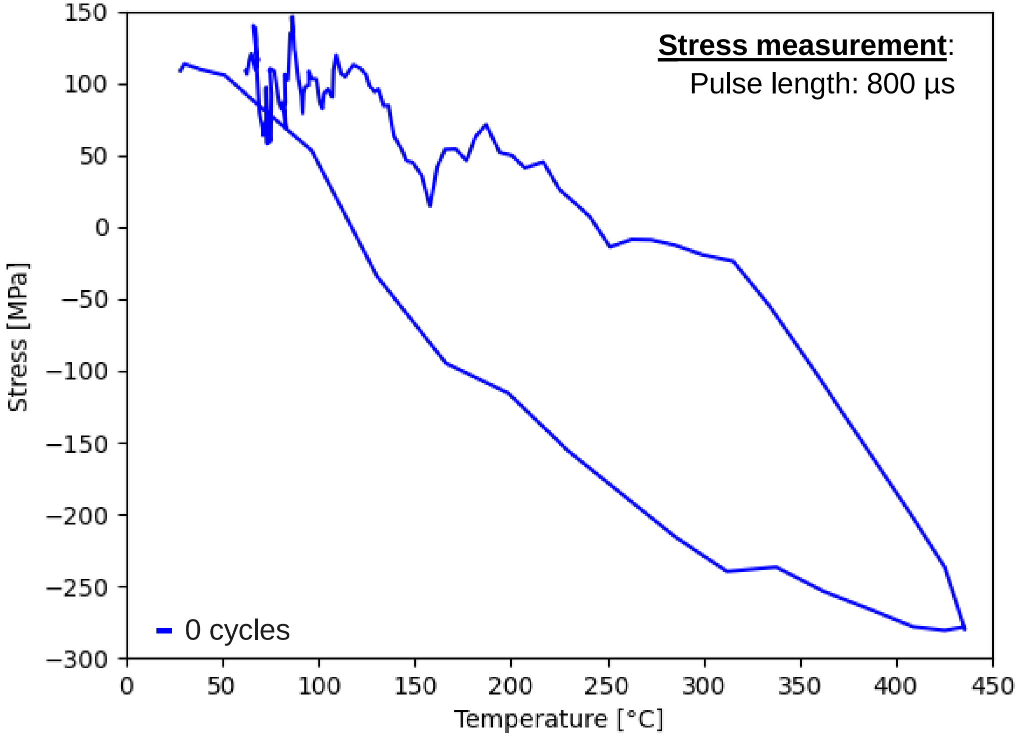
Evolution of the thermo-mechanical stress in a 20 µm Cu metallization through the course of a heat cycle

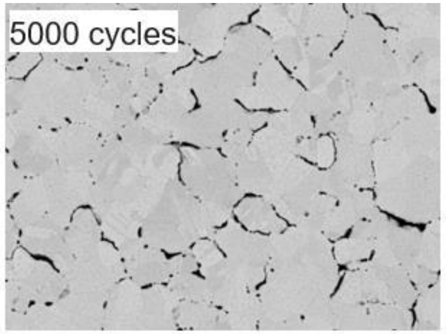
T. Ziegelwanger, *In Prep.*

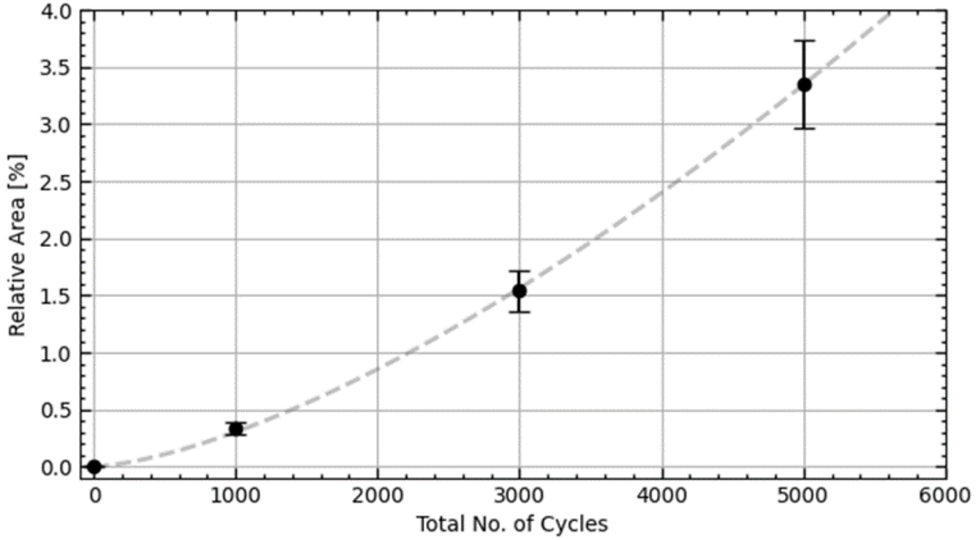
Thermo-mechanical fatigue testing + modeling

Thermo-mechanical stress in metallization layers

Thermo-mechanical stress evolution:







TMF cycling:

- T_{base}: 100 °C - T_{max}: 400 °C
- Pulse Length: 200 µs
- Repitition rate: 1 Pulse/sec

The damage formation leads to a cyclic softening in the metallization layer and a decrease of total thermo-mechanical stress.

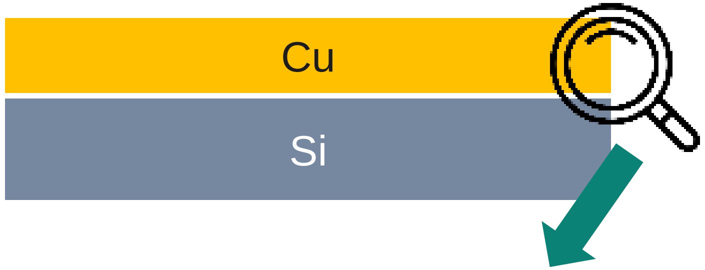
T. Ziegelwanger, *In Prep.*

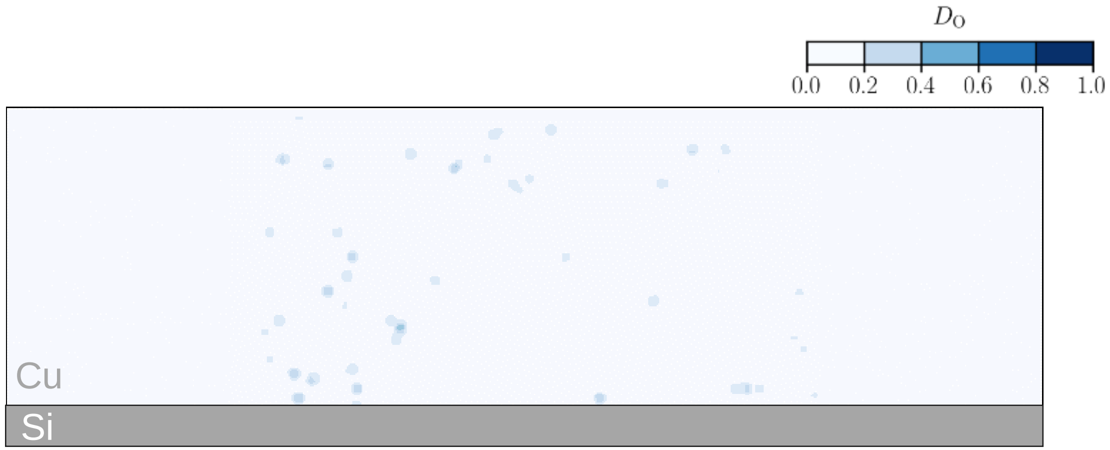
Thermo-mechanical fatigue testing + modeling

2D Modeling based on SEM imaging

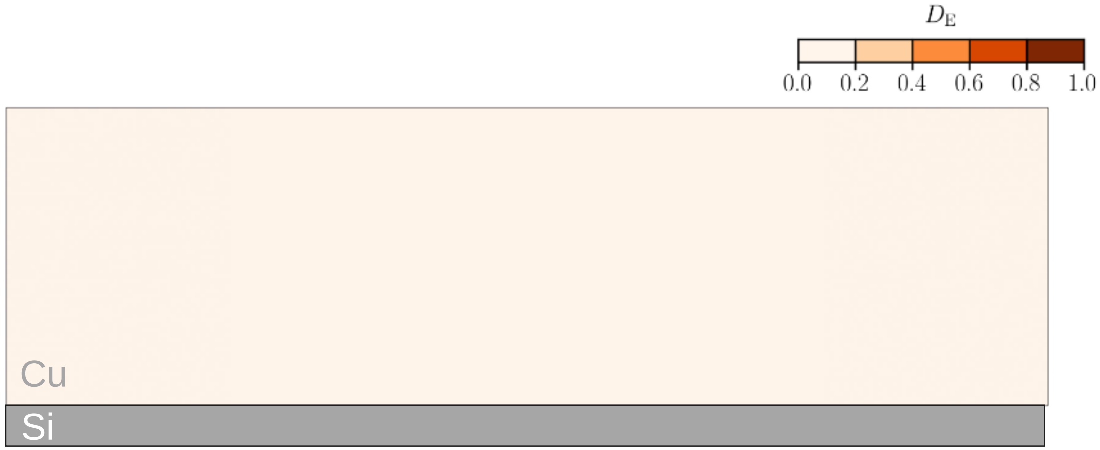
Today: 2D Damage Modelling

- SEM imaging to determine weak spots in microstructure
- Input for 2D FEM-based damage modeling
- Calibration based on Top view and Cross-Section view SEM images





Initial distribution of the damage onset variable D_0 [1]



Evolution of the damage variable D_e during cycling [1]

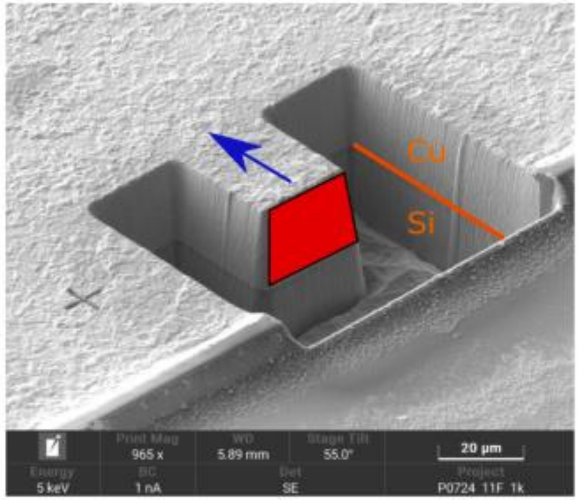
Future: 3D Modelling

- To consider complex 3D integrated structures for damage model
- 3D characterization techniques to study the damage network formation

[1] P. Hoffmann, *PhD thesis* (2023)

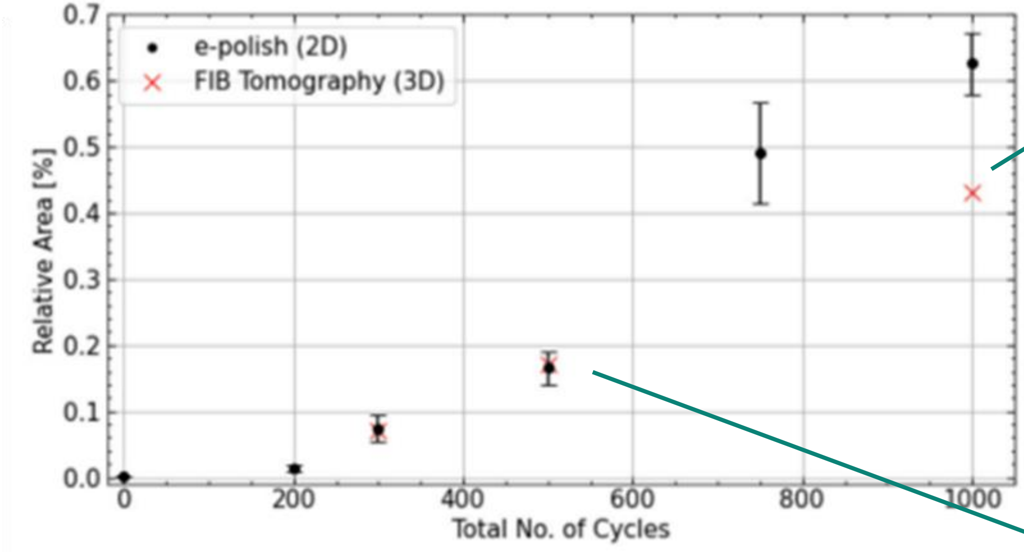
3D characterization of damage networks

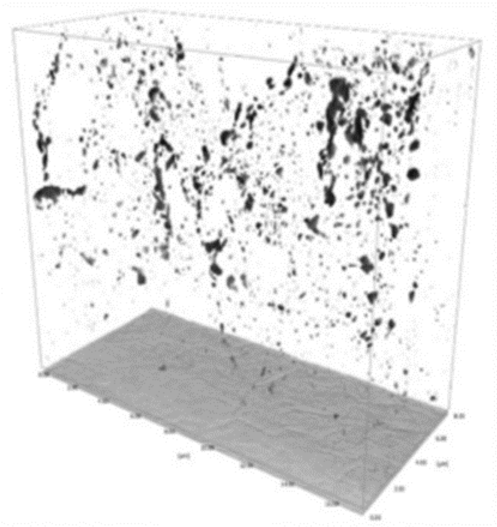
FIB Tomography – Comparison of 2D and 3D

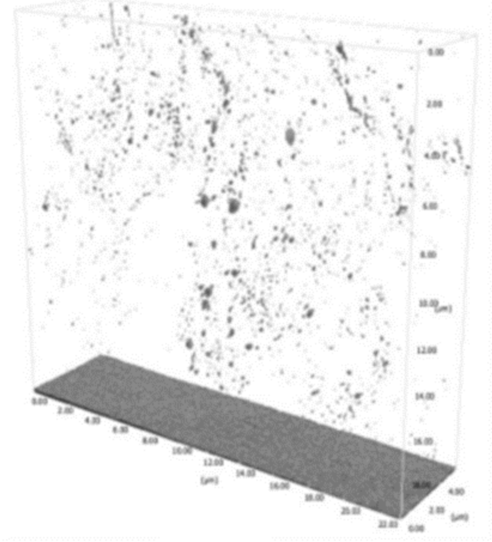


Laboratory FIB Tomography

- Voxel Volume: 30 × 30 × 30 nm³
- SE and FIB images were recorded
- Enhanced information for void/crack detection and quantification







- Damage network revealed in laboratory and good correlation between 2D and 3D data
- Very time consuming and destructive

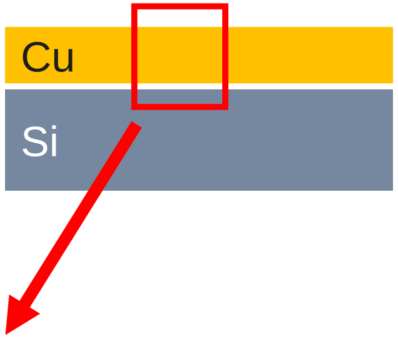
M. Kleinbichler, *Microelectronics Reliability* (2021)

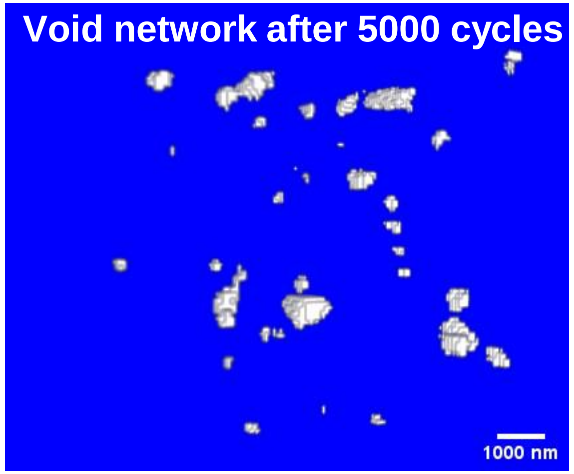
3D characterization of damage networks

Nano-Tomography – Preparation artefact-free ground truth

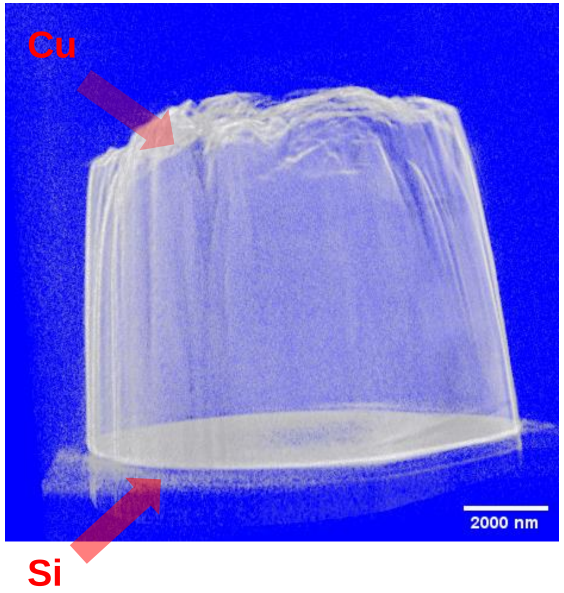
Synchrotron: Tomography (DESY P05)

- Post testing characterization of the resulting damage network
- Voxel volume: 14.8 × 14.8 × 14.8 nm³
- 3D damage network and alignment of vertical features
- Continuous increase of damaged volume

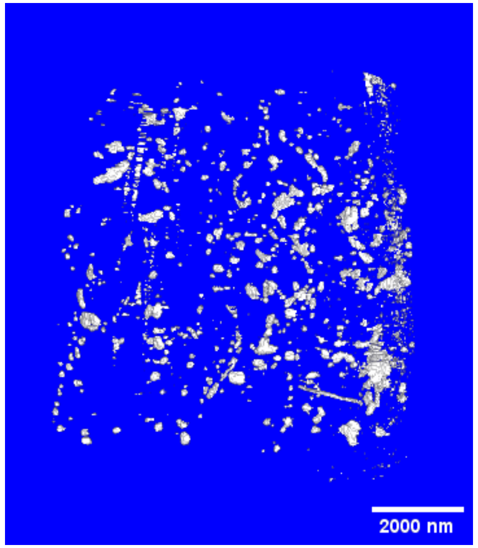




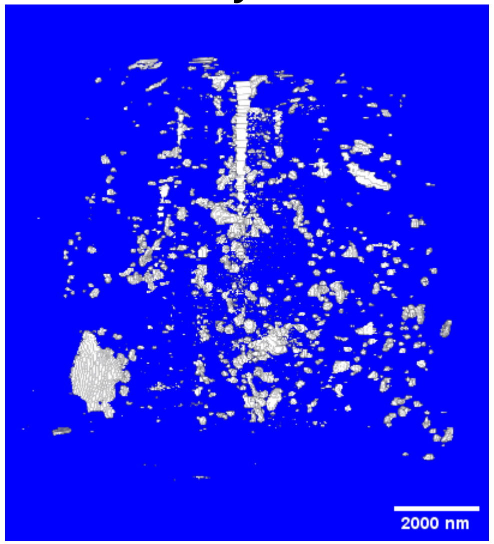
0 cycles

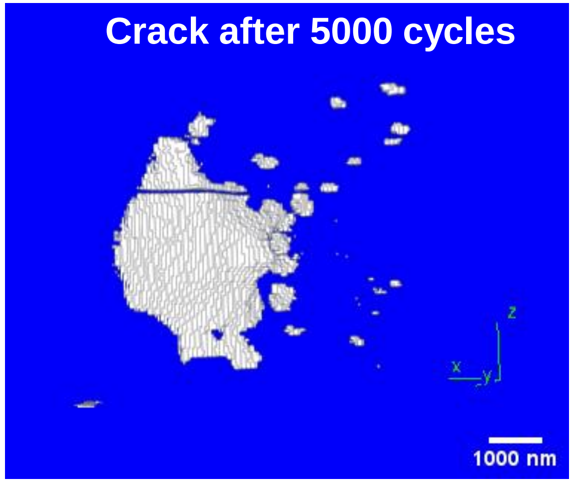


1000 cycles



5000 cycles





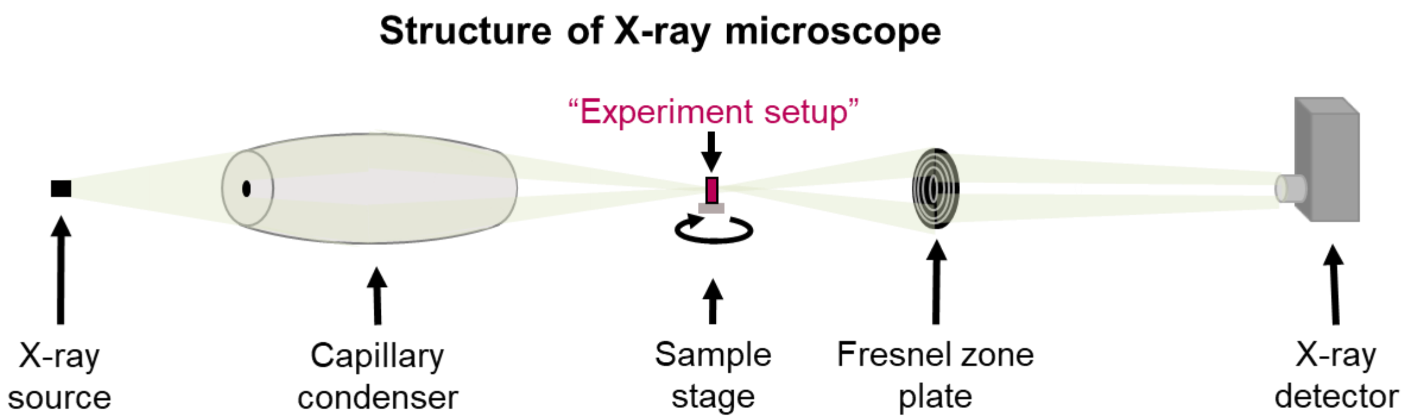
Applied test conditions:

- T_{base}: 100 °C - T_{max}: 400 °C
- Pulse Length: 200 µs
- Repittion rate: 1 Pulse/sec

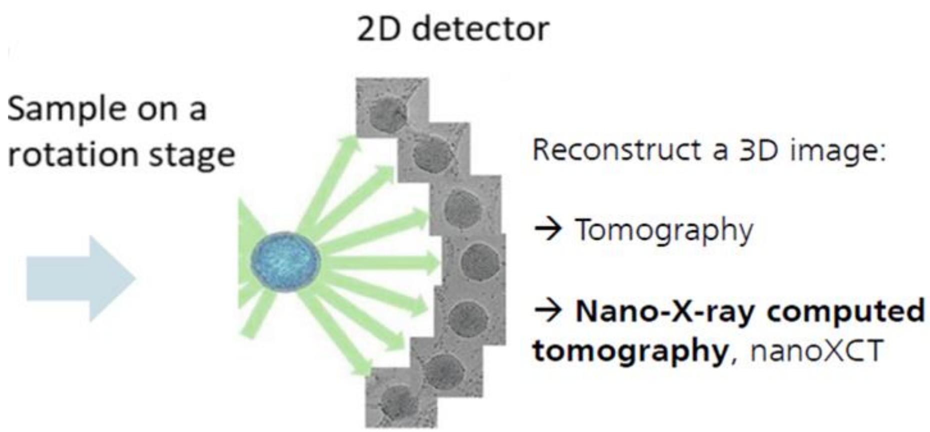
T. Ziegelwanger, *In Prep.*

3D characterization of damage networks

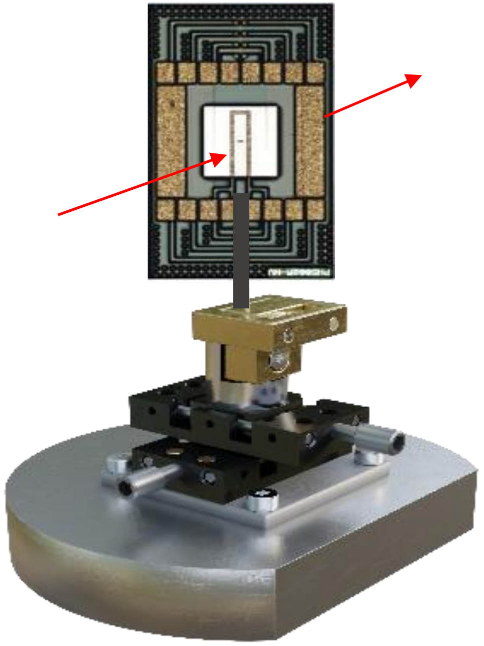
Lab X-ray microscopy – Introduction



Optical beam path of state-of-the-art TXM/nano-CT tool



- Varying X-ray absorption inside sample results in 2D-radiographies
- Sample mounted on a rotating stage
  - Rotates inside the beam to allow complete view of sample
- Only 180° rotation necessary because of the nearly parallel-beam geometry
  - Nondestructive 3D-imaging technique
  - Preparation artefact free volume information



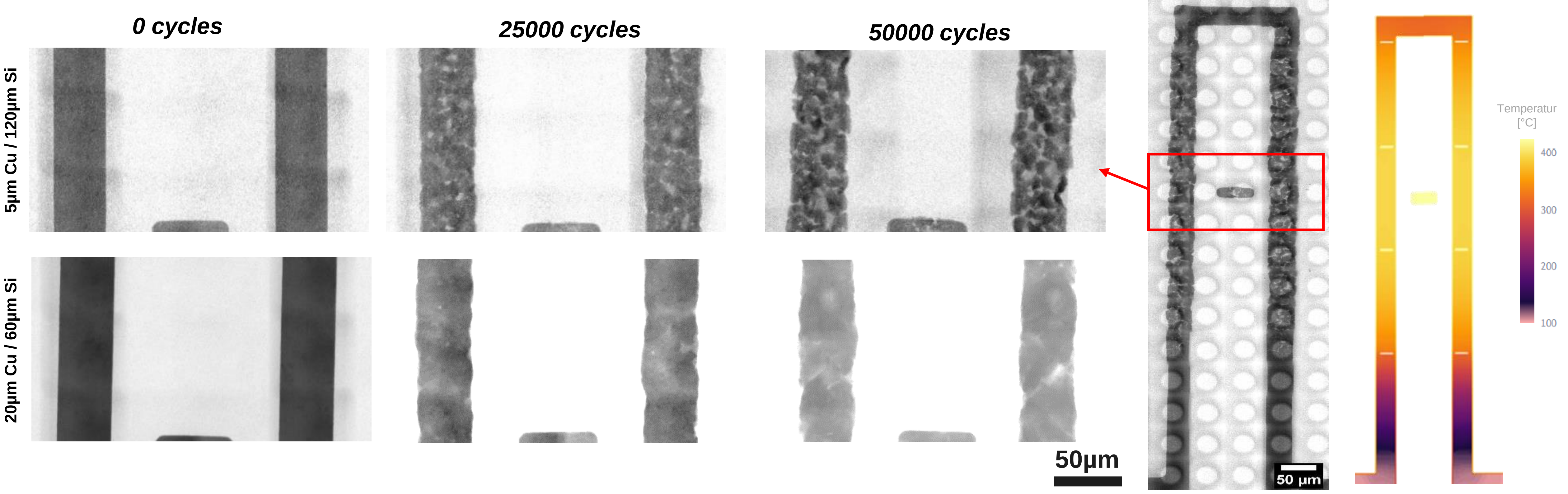
3D characterization of damage networks

Radiography to reveal damage evolution

- Radiography mapping after different cycling states: 126 single mosaic images with 65µm FoV
- Spatial damage destribution correlates well with temperature
- Degradation details are missing due to projection view
- Radiographs of the sample geometry with thinner copper providing more detailed information

Applied test conditions:

- T_{base}: 100 °C - T_{max}: 400 °C
- Pulse Length: 200 µs
- Repitition rate: 1 Pulse/sec



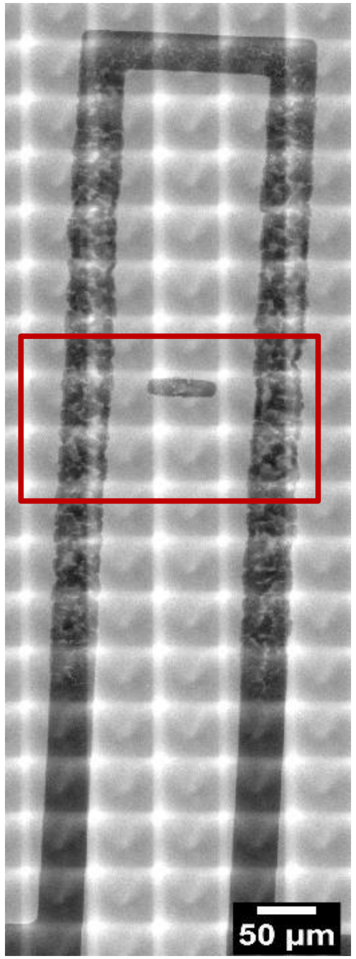
FEM temperature simulation

3D characterization of damage networks

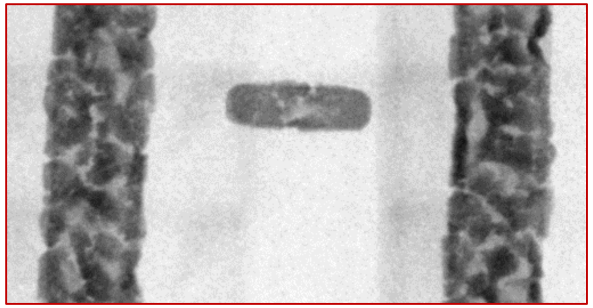
Radiography using multi-photon energies (Cu-Kα, Ga-Kα) on 5µm Cu

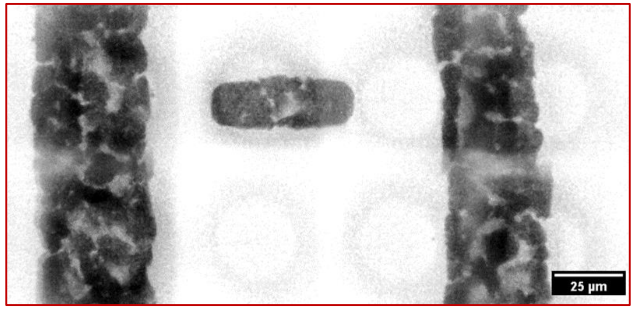
Fraunhofer IKTS · deepXscan · AI · Infineon

Cu-Kα (8.05 keV)

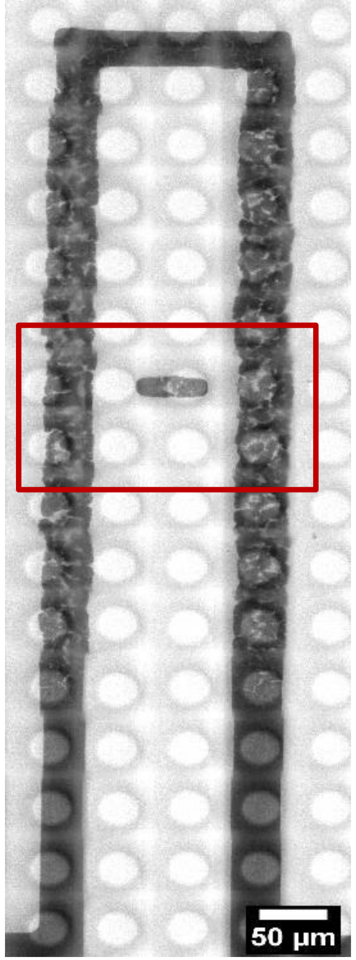


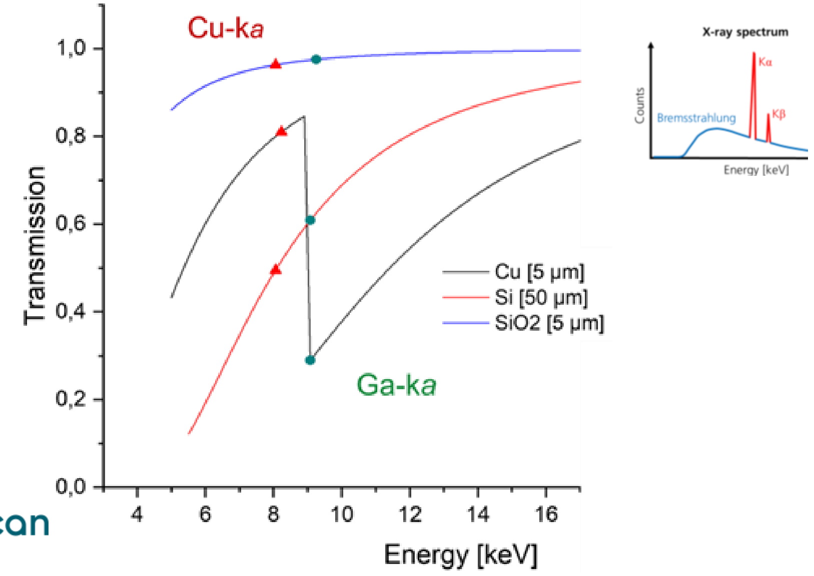
- Innovative liquid metal-jet X-ray source technology (Ga-Ka) with 9.05 keV provides enhanced contrast for Cu structures in dielctrics
- Use high energetic source such as In to enable the characterization of thick Cu structures

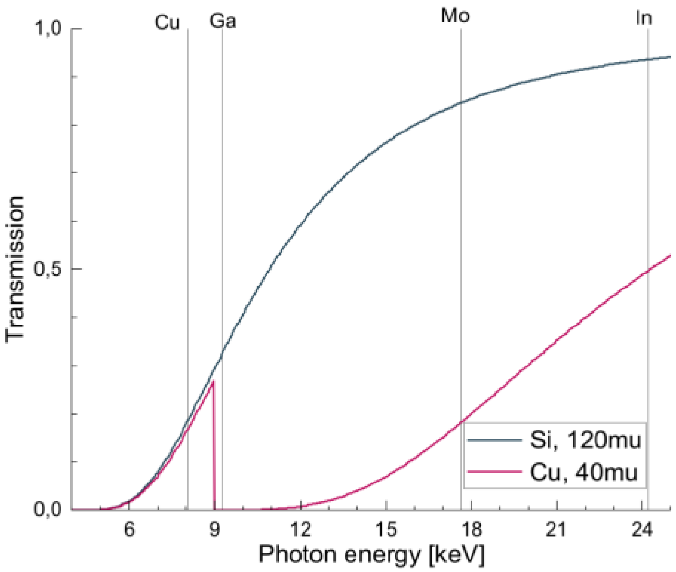




Ga-Kα (9.25 keV)





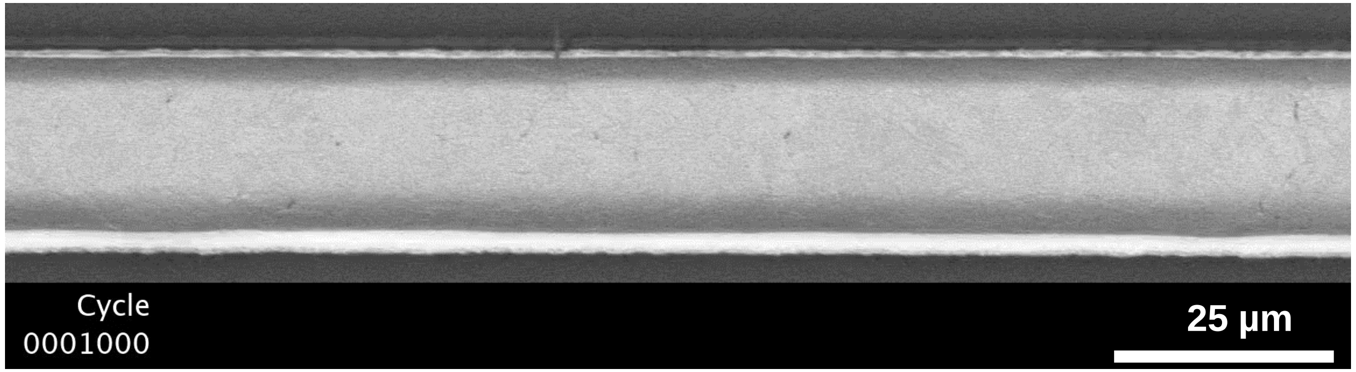


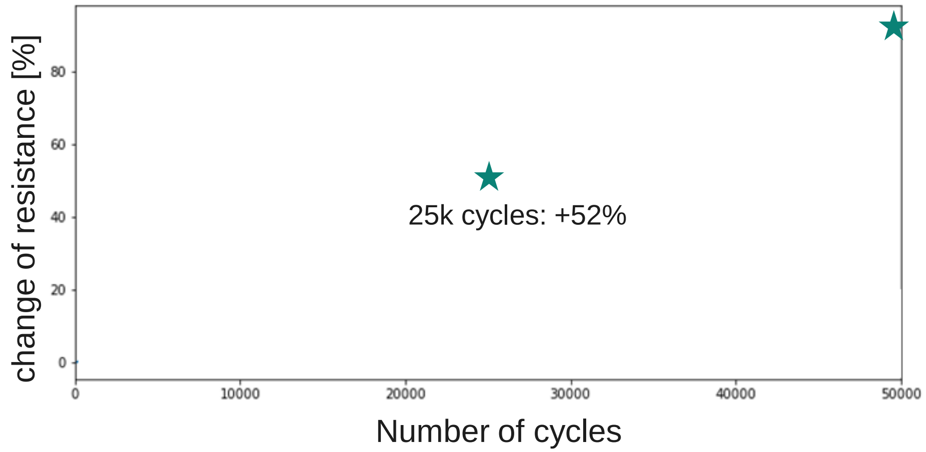
deepXscan

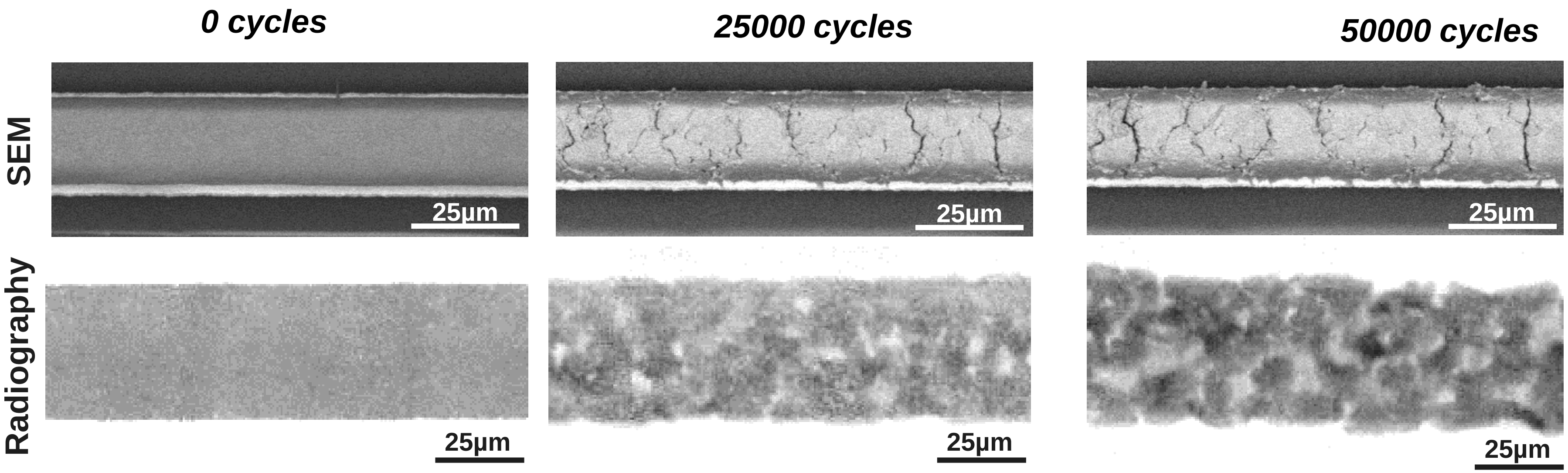
K. Kutukova, *Nanomaterials* (2024)

3D characterization of damage networks

Radiography vs. in-Situ SEM







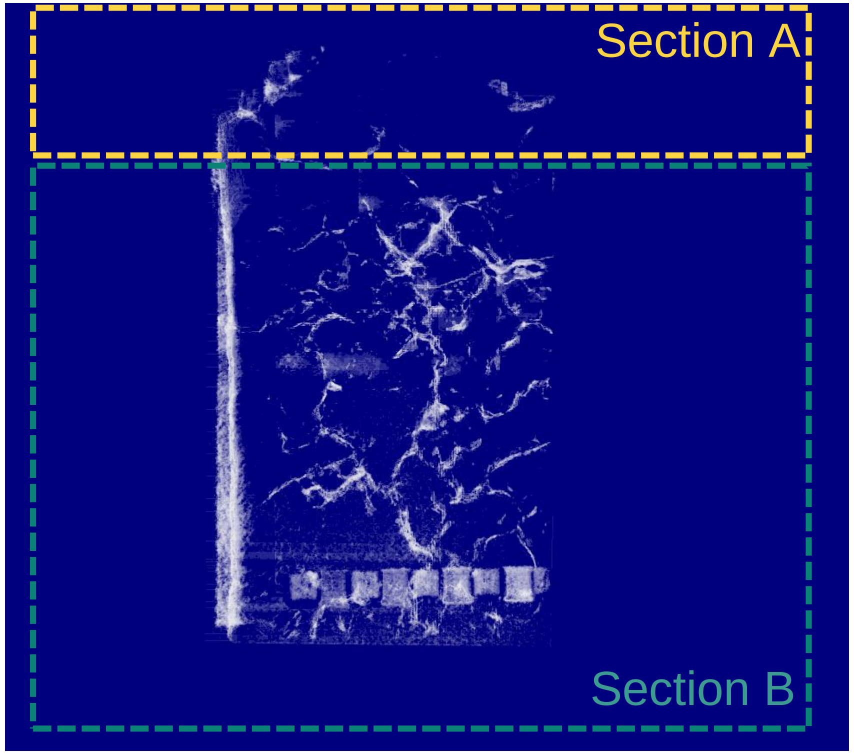
Applied test conditions:

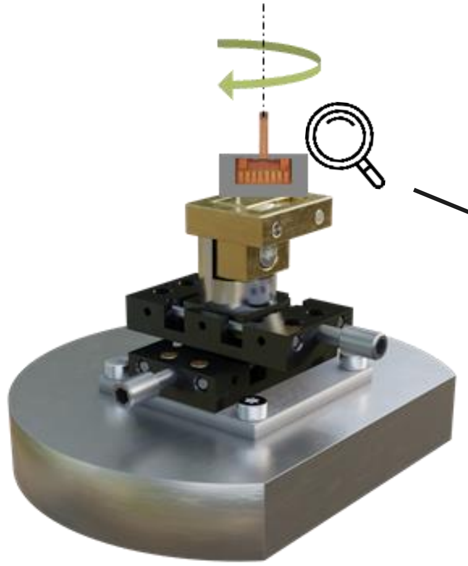
- T_{base}: 100 °C - T_{max}: 400 °C
- Pulse Length: 200 µs
- Repittion rate: 1 Pulse/sec

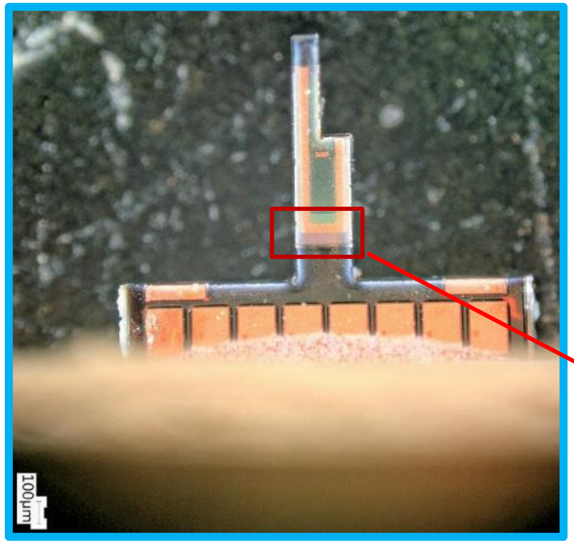
3D characterization of damage networks

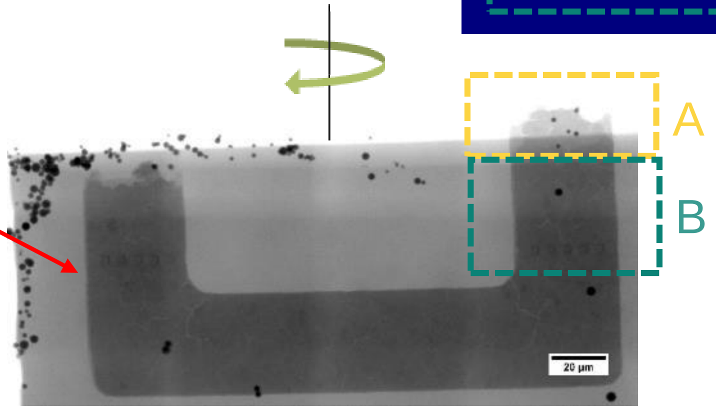
Lab X-ray tomography of realistic test structure

- Modified sample geometry enables a section for a tomography with an angular range of 180°
- Two sections within on sample:
  - Section A: Single line
  - Section B: 2 parallel lines with limited transparency
- Smearing effect leads to damage overestimation
- Tomography on „real structures“ requires higher energetic X-ray source and the corresponding optics









Applied test conditions:

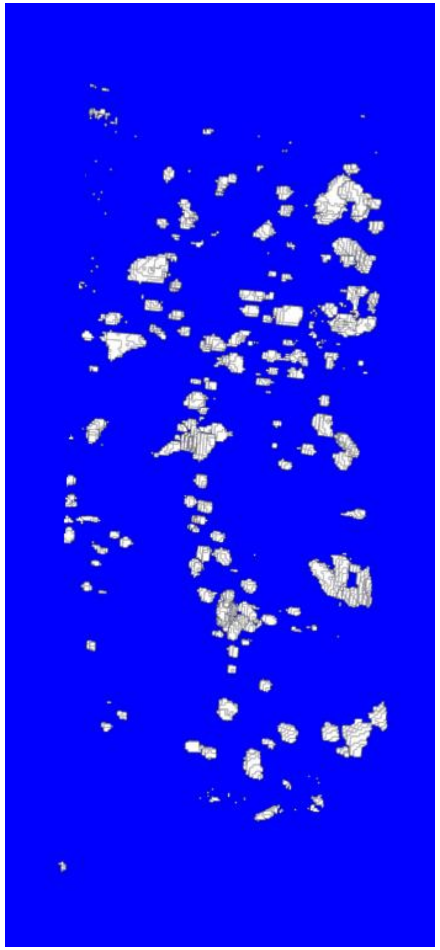
- T_{base}: 100 °C - T_{max}: 400 °C
- Pulse Length: 200 µs
- Repittion rate: 1 Pulse/sec
- 25000 cycles

Conclusion

- **Thermo-mechanical fatigue leads to the formation of complex 3D damage networks.**
  - Void nucleation → Void growth and coalescence → Crack growth
  - Grain boundaries and triple junctions are weak spots
  - Vertical alignment of damage features identified by 3D techniques
  - Radiography reveals damage progression within the volume after surface damage saturation.

- **Large thermal stresses due to high heating rates and cyclic softening due to degradation**
  - Dedicated test structures are required to achieve application relevant conditions
  - In-Situ experiments necessary to monitor evolution

- **Lab X-ray microscopy has a high potential for damage monitoring in semiconductor industry**
  - Using In-Kα radiation (24 keV) and Ga-Kα (9.2 keV) radiation X-ray sources
    - Non-destructive investigation of thick metallization's or complex 3D integrated structures
    - Enhanced contrast and detailed information
  - New test structures design for in-situ X-ray microscopy and in-situ damage monitoring
  - Advanced damage segmentation algorithms are required for quantification of 3D data
  - Input for predictive 3D damage modeling



Lab X-ray microscopy is a key characterization method to enable the 3D integration of future power electronic technologies!

Thank you for your attention!

Questions?

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