TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Zentrum für mikrotechnische Produktion

# Investigations of sintered silver interconnects with multi-energy X-ray imaging methods

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# Outline

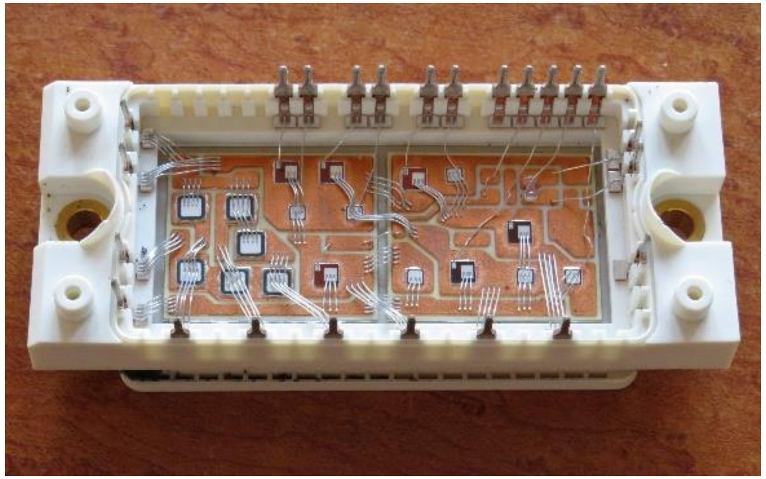
- Motivation & Objectives
- Multi-Energy Approach
- Solution Approach & Procedure
- Example
- Summary & Outlook

# Motivation – Power Electronics

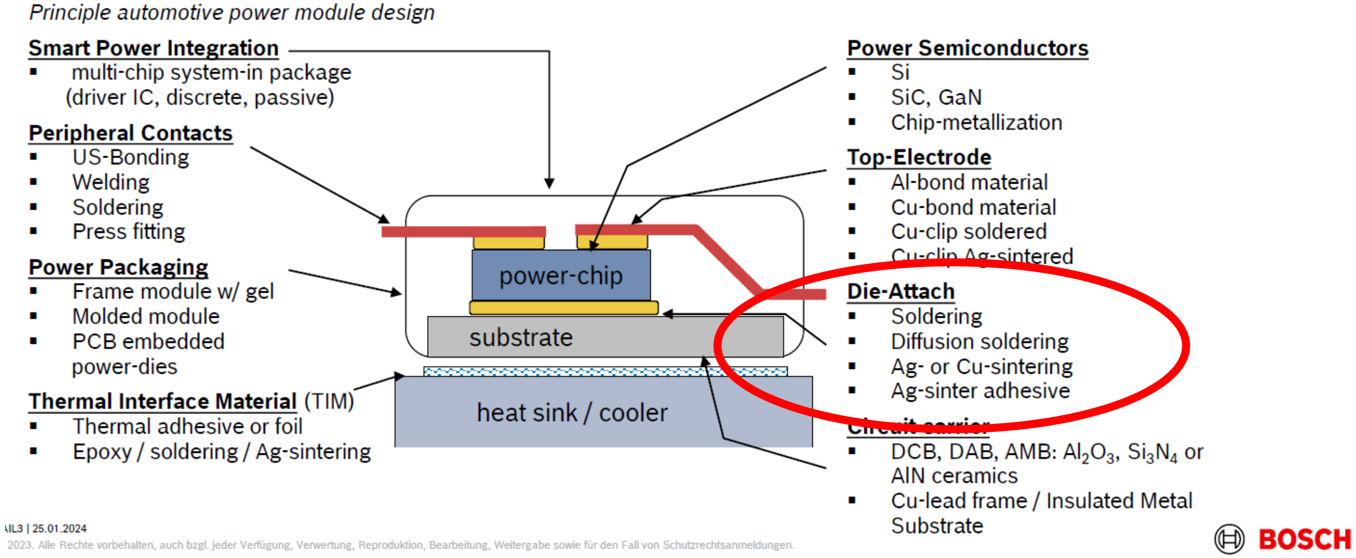
- Conversion of electrical energy into:
  - Light, Motion, Heat

- Main drivers are
  - Electric Vehicles
  - Renewable Energies

- General approaches to increasing power density:
  - Improvement of cooling system (Dissipation of more power loss)
  - Improvement of power devices (Reducing the power loss)
  - Increase of operating temperatures (Increase in temperature difference)



[1] Kraus Hardware

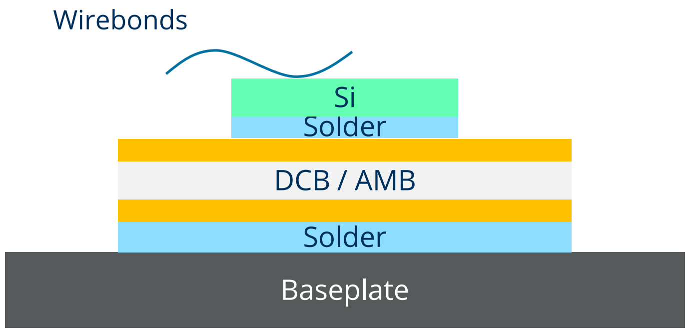



[2] Klemm, Alexander (2024), presentation as part of the 2023/24 Oberseminar at the IAVT

# Motivation – Power Electronics

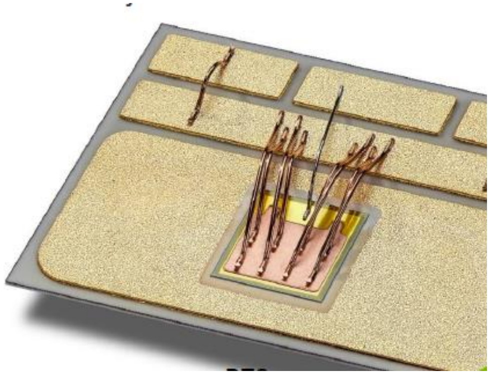
## Present

Operating temperature up to 150°C

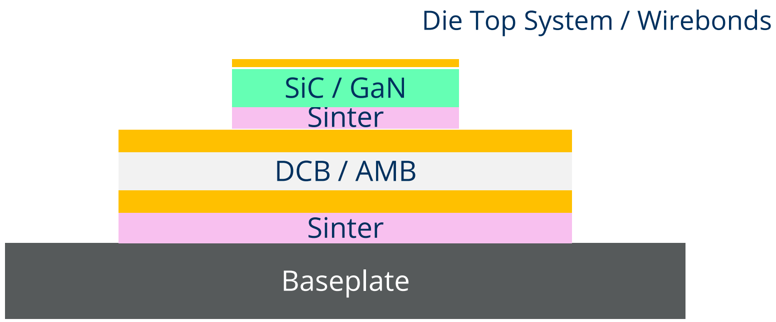



## Near Future

Operating temperature more than 175°C



[3]

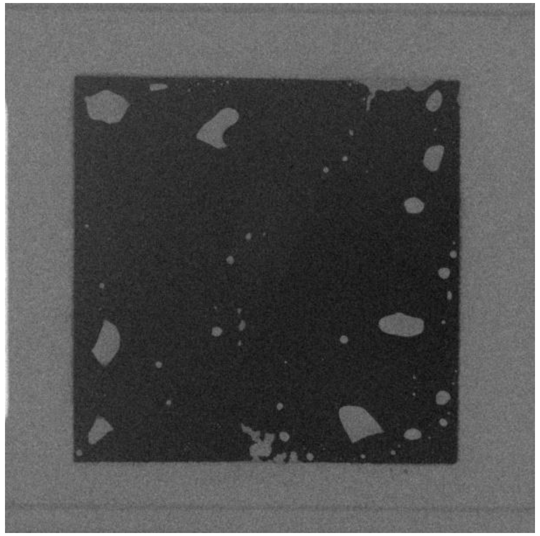



[3] F. Seifert and U. Hauf, “Optimized paste for large area pressure sintering with silver sinter paste,” PCIM 2023

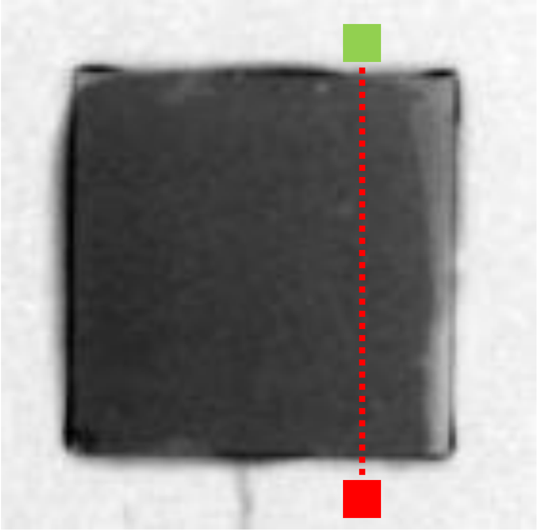
# Motivation – NDT Needs for Power Electronics

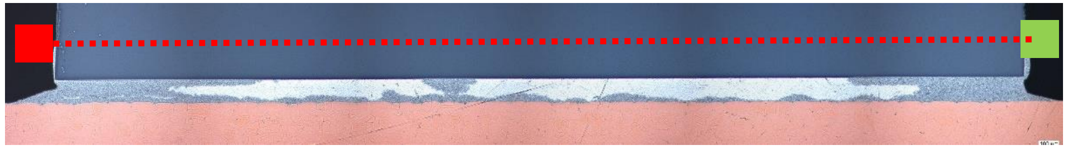
- No NDT methods suitable for series production of (silver-) sintered interconnects available
- X-ray inspection → Grainy structure of sintered interconnects leads to low-contrast signals (compared to solder)
- Precise determination of porosity with SEM after cross-section preparation (destructive)

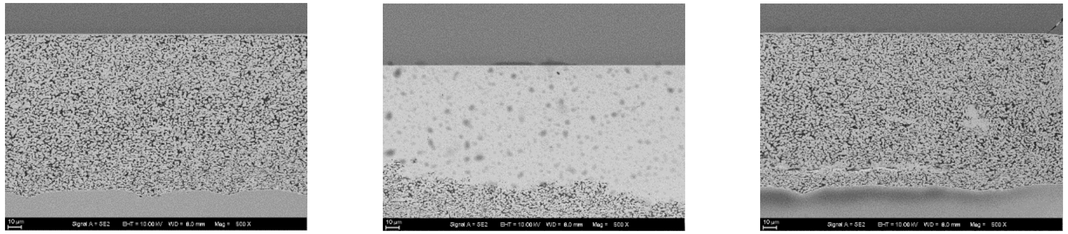
X-ray image
Soldering



X-ray image
Sintering







# Motivation – NDT Needs for Power Electronics

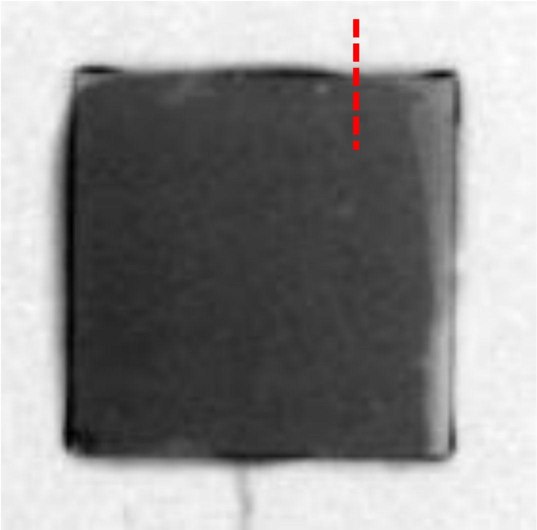
| | Imaging methods | | | Testing / Comparative methods | | |
|---|---|---|---|---|---|---|
| | X-RAY | SAM | LIT | TTA | OLS | KT |
| Automation | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| In-Line capable | ✓ | ✓ | ✓ | ✗ | ○ | ✓ |
| | | | | | | |
| Solder joint | ✓ | ✓ | ✓ / ○ | ✓ | ✓ | ✓ |
| Sintered interconnects | ✗ / ○ | ✓ / ○ | ✓ / ○ | ✓ | ○ | ✓ |
| | | | | | | |
| Restrictions | Superpositon of strutures | Needs contact medium | Surface treatment | Needs Individual contacts | Cycle times | Contact to the surface |

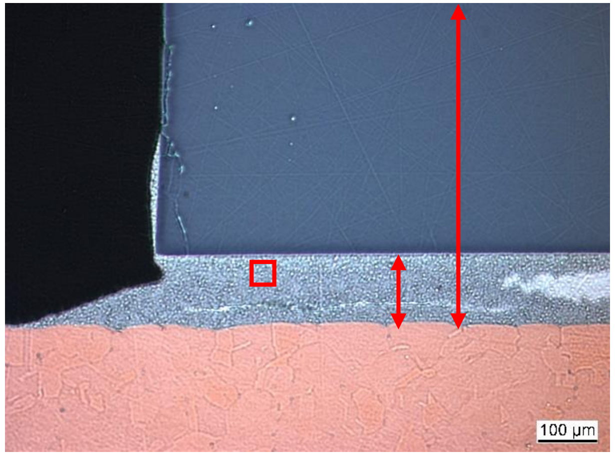
# Objectives

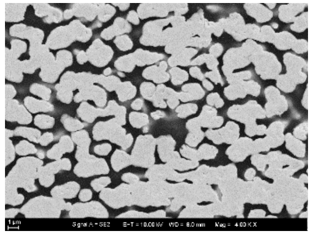
***Is it possible to determine the porosity of silver sintered interconnects non-destructively and with high resolution?***

- Necessary are:
  - Thickness of silver sintered layer
  - Thickness of pure silver
  - → Ratio ≈ porosity
- The challenge!
  - All variables cannot be measured directly!
  - Which influences affect the result?
    - Background
    - Thickness of the die
    - Acquisition parameters

- Idea → Multi-Energy Imaging





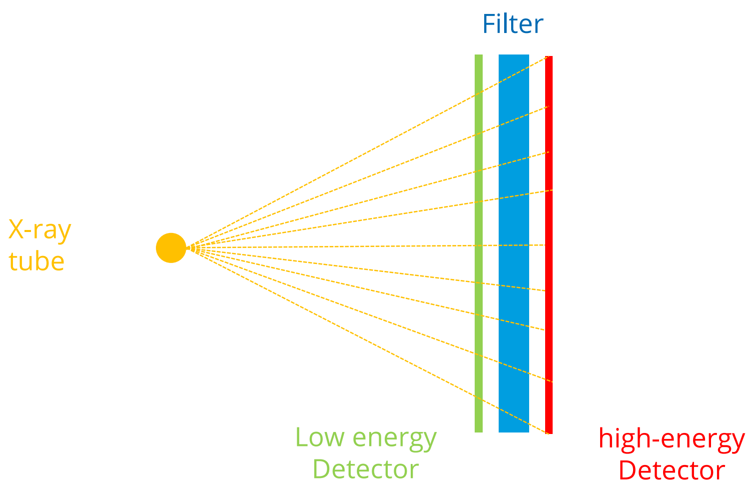



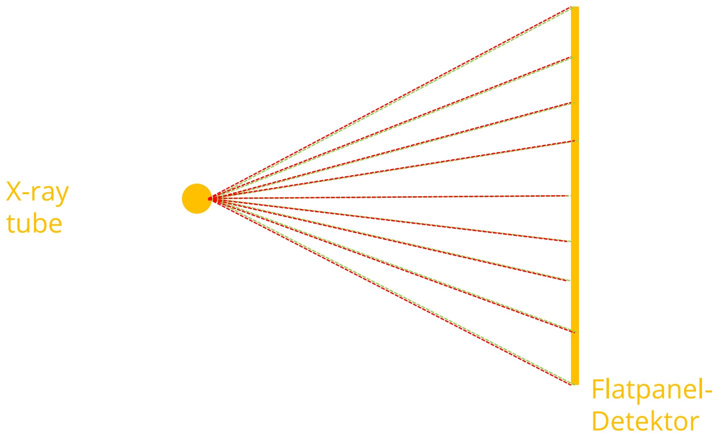
Porosity ≈ 27%

# Multi-Energy Imaging

- Conventional radiography generally uses the attenuation behaviour for a discrete energy level
- The dual-energy method is a common extension
  - Applications in medicine and safety technology
  - Rough separation of materials in dependency of ordinal number
- Available Methods
  - Single-Shot / Sandwich-Detector

Dual-Shot / Flat-Detecor

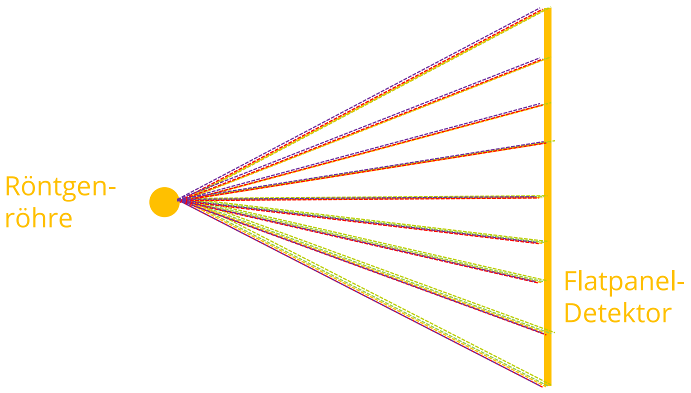


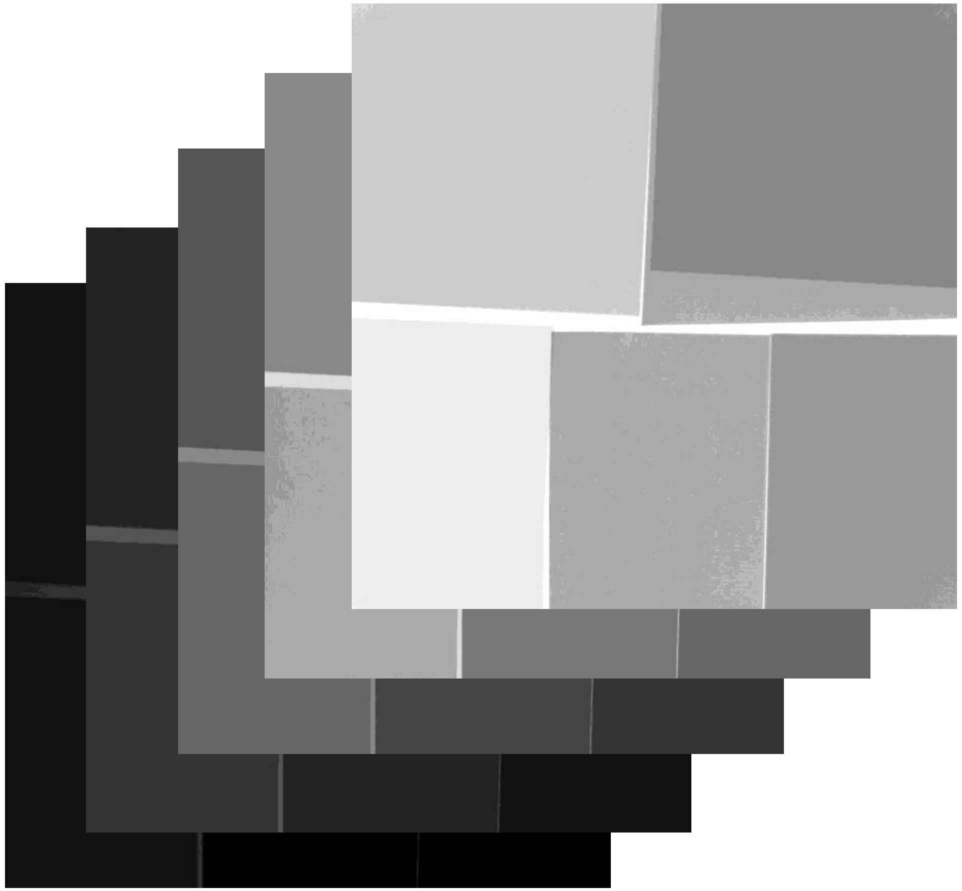



# Multi-Energy Imaging

Basically means…

- Multi-Shot methods with Flatpanel-Detector
- Modification of accelerating voltage or beam current
- single or composite materials
- Evaluation of discrete pixels or defined area



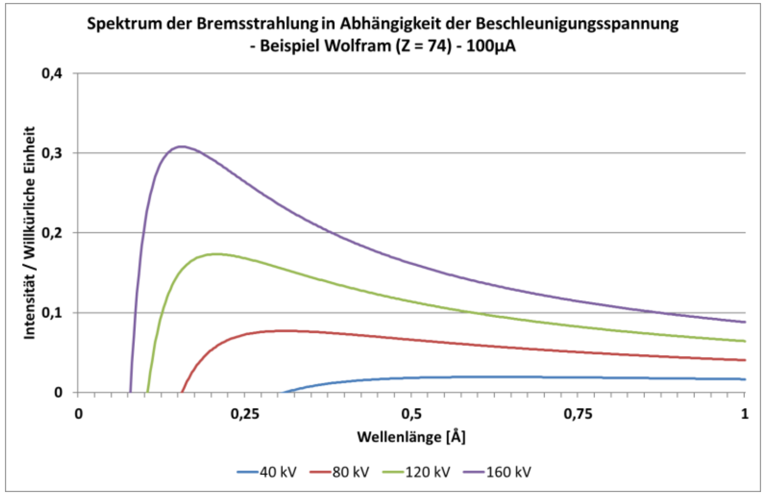



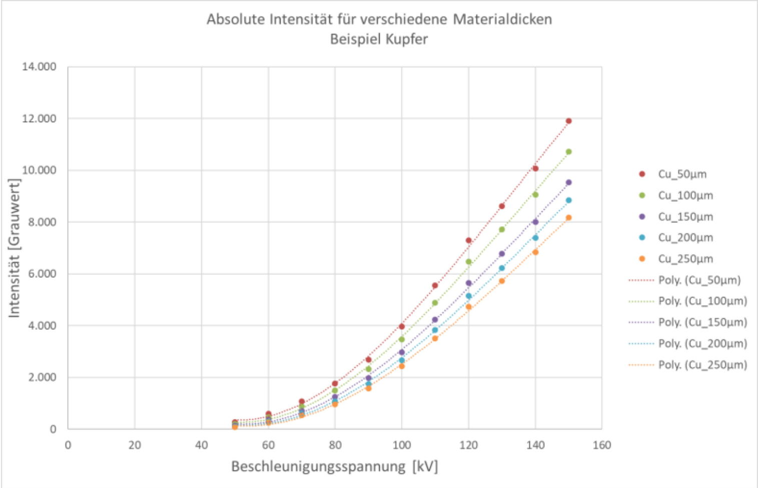
# Multi-Energy Imaging

- To enhance material or thickness/density contrast, new images can be calculated on the basis of several X-ray images at different photon energies…
- usable grey values of the detector can theoretically be described as…

$$GW(E_{max}, t) = \int_0^{E_{max}} D(E) I_0(E) \exp\left(-\int_0^t \mu(E,x)(x)dx\right) dE \quad [4]$$

- Approximate evaluation requires simplified boundary conditions, such as constant detector behaviour and a spectral distribution according to Kramer's rule.
- Equation can be simplified based on empirical experience with polynomial function to fit image data
  - Variable acceleration voltage at constant beam current $GW(U) = aU^3 + bU^2 + cU + d$
  - Variable beam current at constant acceleration voltage $GW(U) = cU + d$

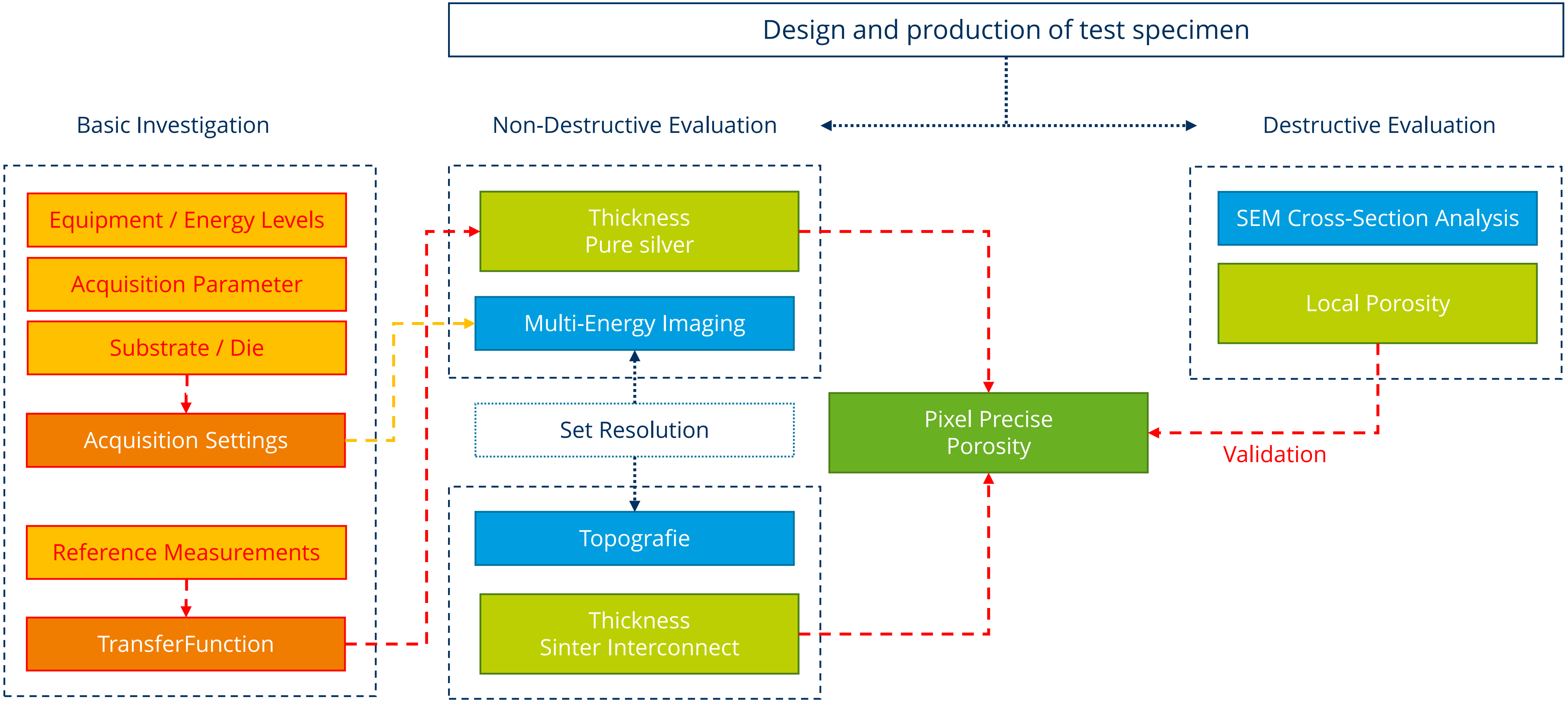




[4] M. Heckert, S. Enghardt, and J. Bauch, "Novel multi-energy X-ray imaging methods: Experimental results of new image processing techniques to improve material separation in computed tomography and direct radiography," *PLoS One*, vol. 15, no. 5, pp. 1–15, 2020, doi: 10.1371/journal.pone.0232403.

# Solution Approach



# Equipment

<u>X-ray microscope nanome|x</u>

- Acceleration voltage 160: 10 – 160kV / 15W
- Beam current: 5 – 880µA
- Digital Detector DXRT250RT
  - Active pixel: 1.000 x 1.000 Pixel
  - Detector area: 200 x 200 mm²
  - Pixel distance: 200 x 200 µm²
  - Grey scale resolution: 14 bit
  - Dynamic: 10.000:1

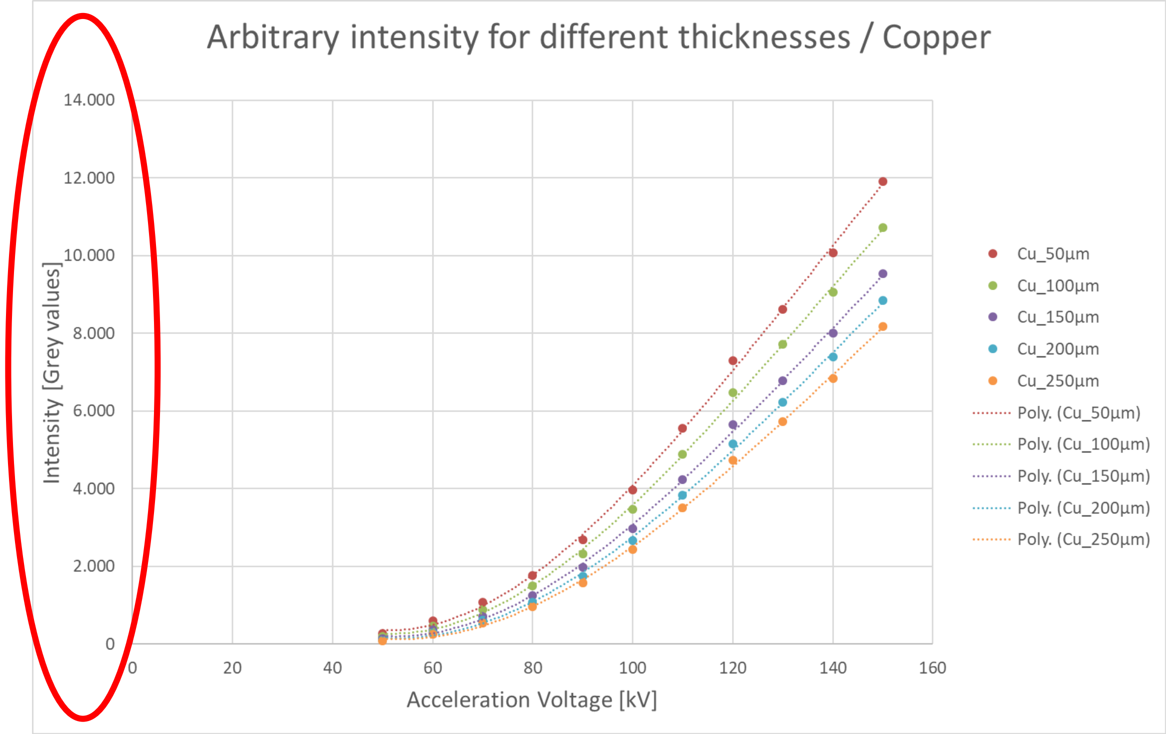
# Investigated Energy Levels

- Investigation of
  - variable acceleration voltage
  - variable beam current
- Investigation of different approaches to "normalise" empirical grey values
- Supporting investigations have shown that the use of variable acceleration voltage is more sensitive to "measure" small differences

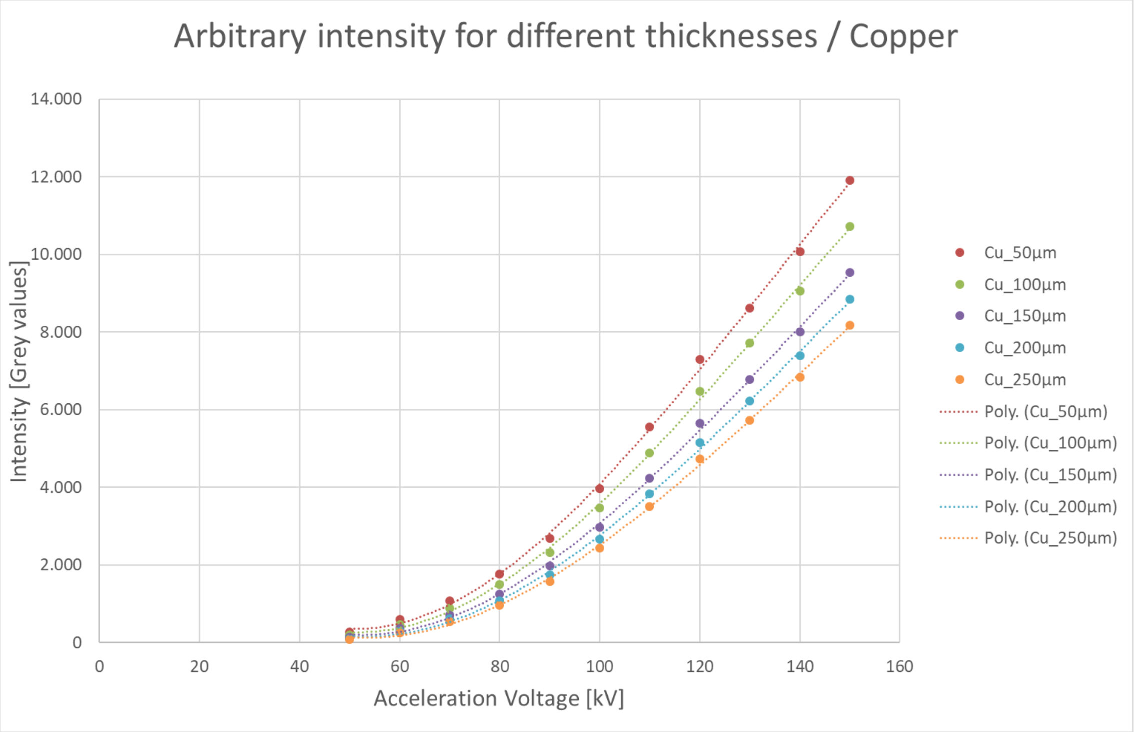
| Variable Acceleration Voltage | | Variable Beam Current | |
|---|---|---|---|
| kV | µA | kV | µA |
| | | 100 | 50 |
| 60 | 100 | 100 | 60 |
| 70 | 100 | 100 | 70 |
| 80 | 100 | 100 | 80 |
| 90 | 100 | 100 | 90 |
| 100 | 100 | 100 | 100 |
| 110 | 100 | 100 | 110 |
| 120 | 100 | 100 | 120 |
| 130 | 100 | 100 | 130 |
| 140 | 100 | 100 | 140 |
| 150 | 100 | 100 | 150 |

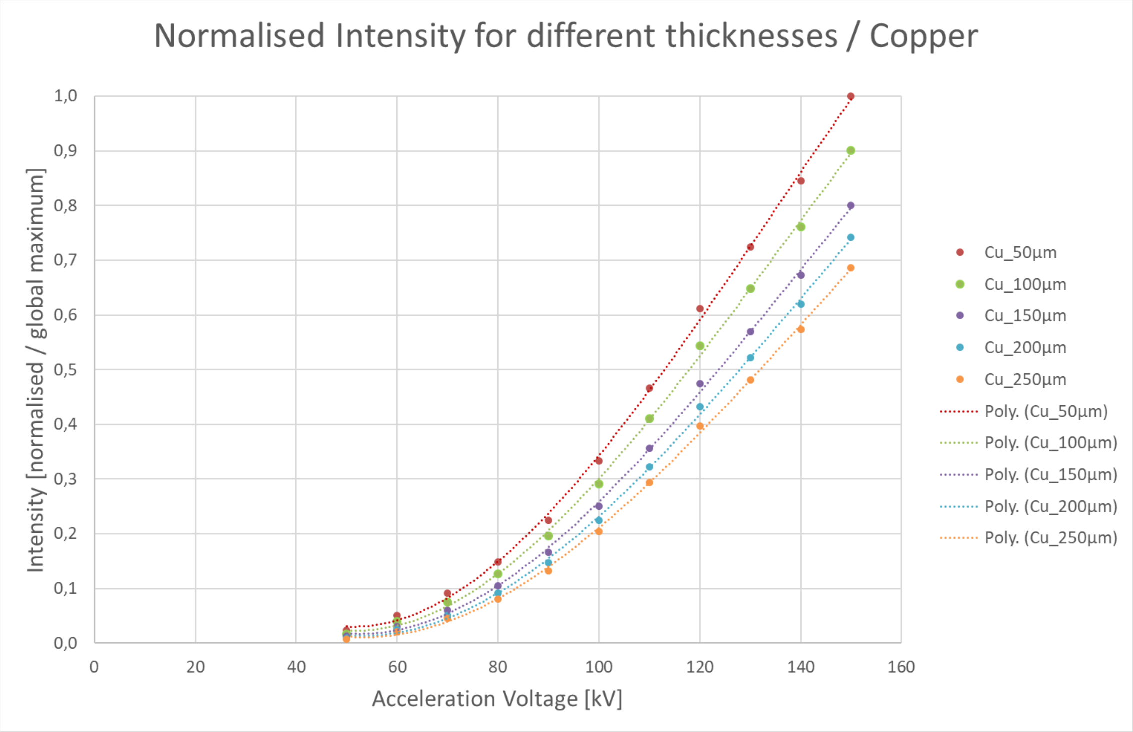
# Basic Investigations – Acquisition Parameter

- Captured grey values are dependent
  - background,
  - exposure time
  - aging of filament,
  - …
- Normalisation is necessary to compare results
- Recommended measures for preparation
  - Warm-up
  - Full-Centering of focus mode
  - Maintain exposure time
  - Saved as…Tiff-Images (16bit)

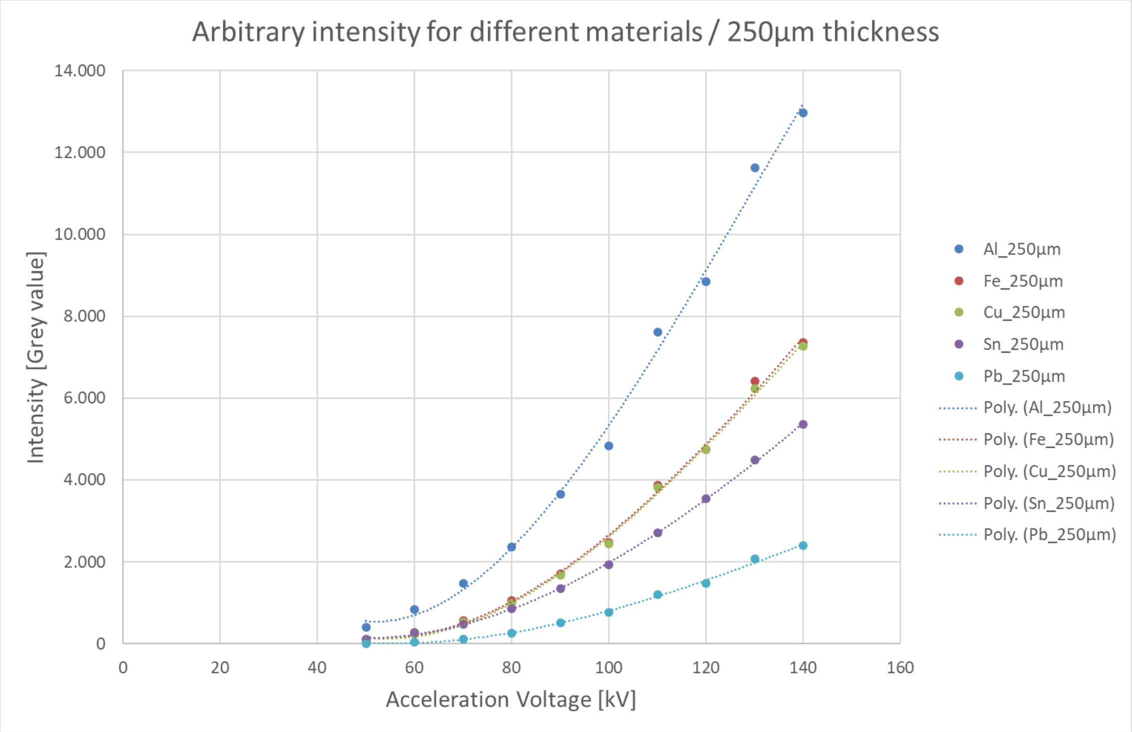


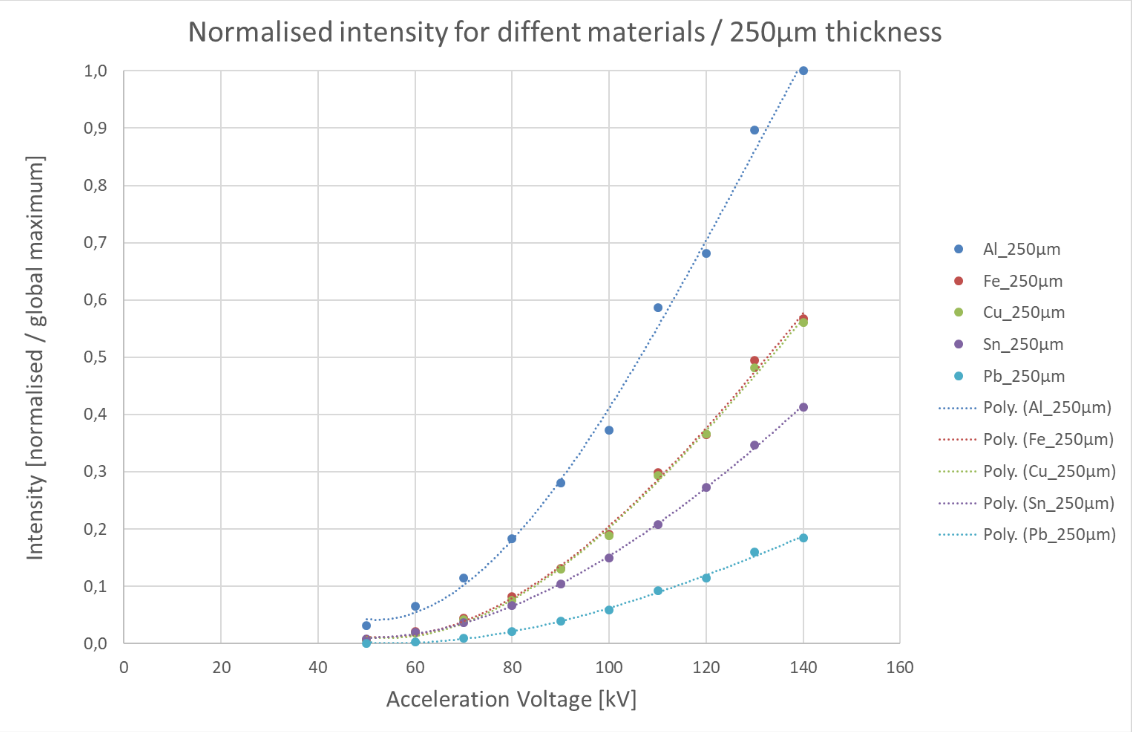
# Basic Investigations – Different thicknesses



# Basic Investigations – Different materials



# Basic Investigations - Influences of Die & Substrat

- Examination of two Die thickness (610µm & 650µm)
  - significant differences were found between the thicknesses, but none within a batch of the same thickness

- Individual properties of single substrats
- Probably deviations in the average copper layer thickness
- Decreasing layer thickness towards the edges
- large defects visible at the interfaces

→ Place single Si-Die as reference area on each substrate

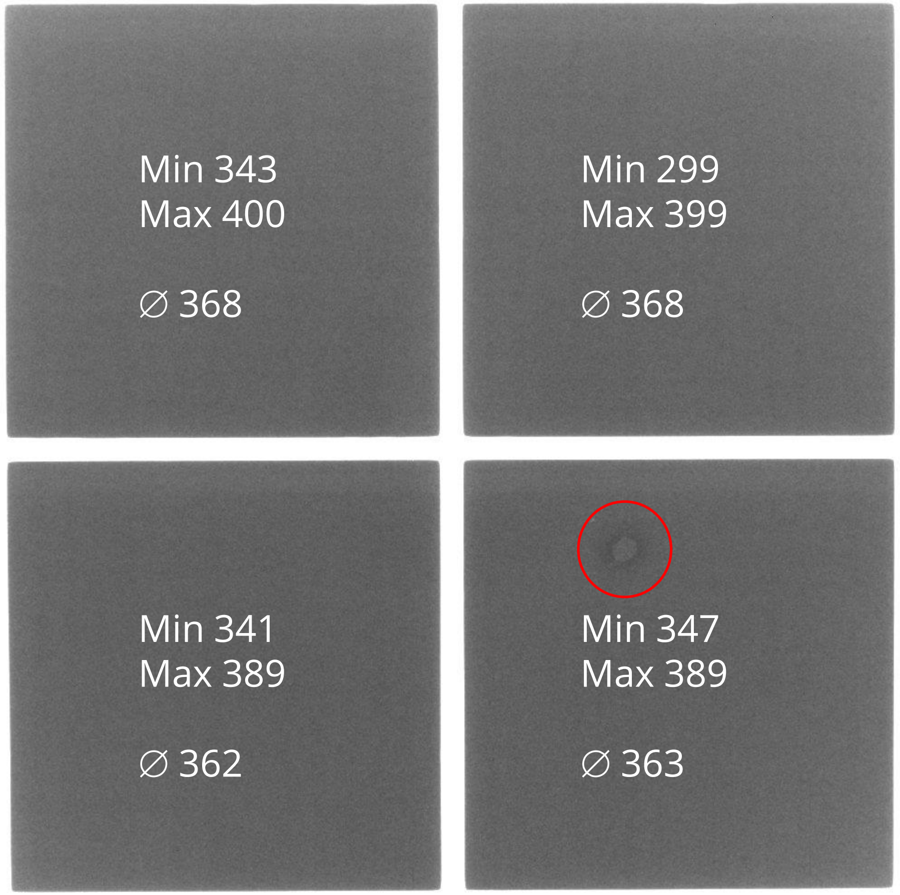
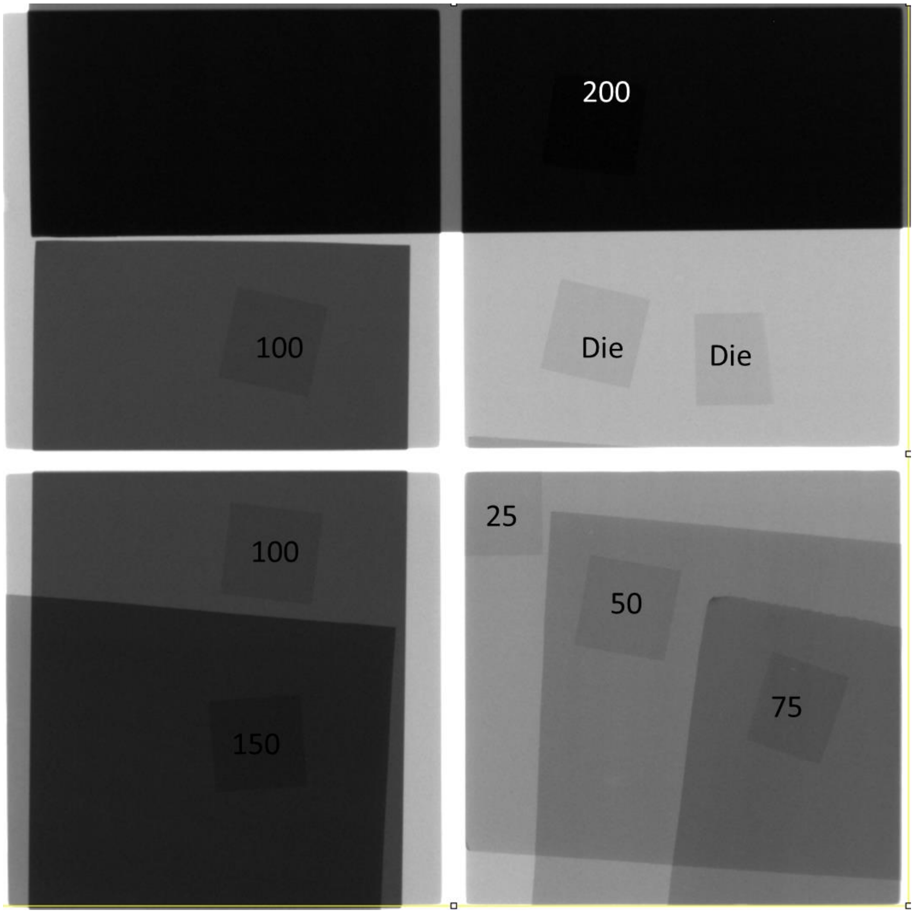



Illustration of the grey value distribution for one example

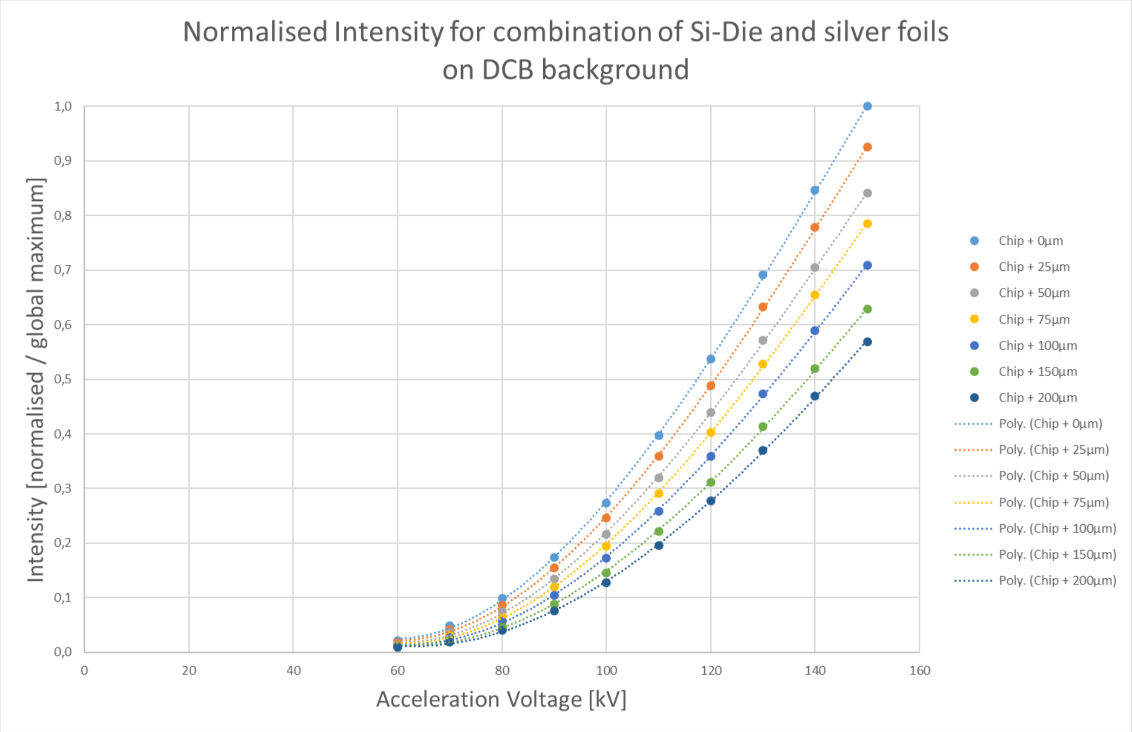
# Basic Investigations – Reference measurements

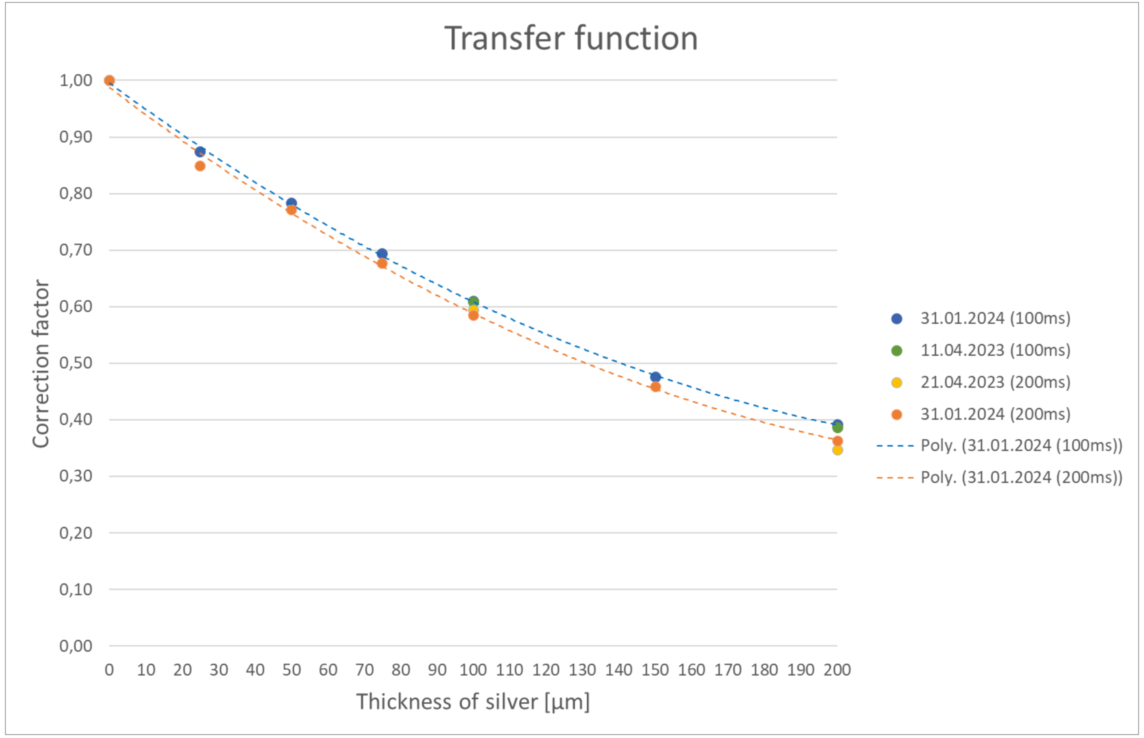
- Manufacturing of silver foils with a defined layer thickness
- Combination of „Substrate & Die“ as background
- Investigation of different influences
- Multi-Energy Imaging
- Calculations of the intensity curves



# Basic Investigations – Transfer Function

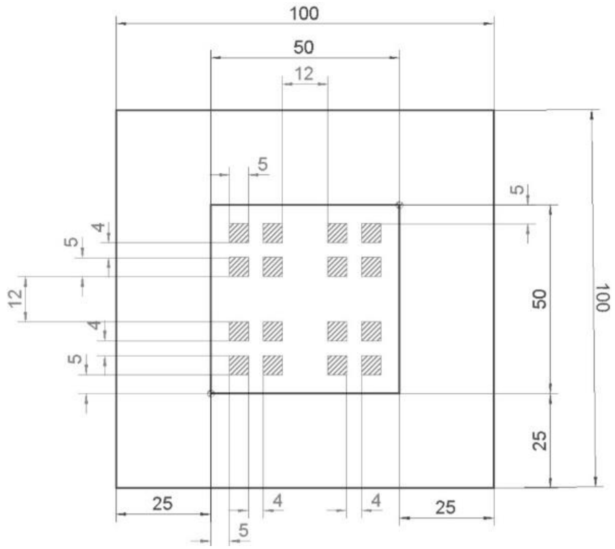
- Calculation of the coefficients of the intensity curves
- Analytical derivation of a transfer function

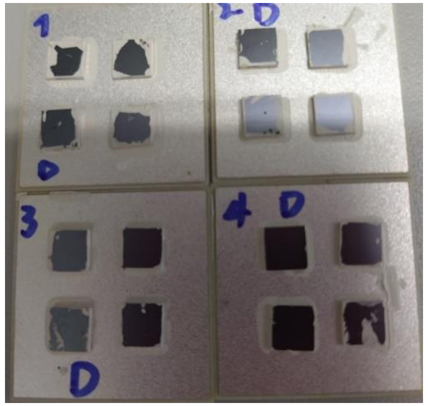


# Design and Manufacturing of Test Specimen

- <u>DCB-Substrat:</u>
  - Area: 25 x 25 mm²
  - Layer structure: Cu 300µm / $Al_2O_3$ 380µm / Cu 300µm
  - Finish: Ag
- <u>Die:</u>
  - Area: 5 x 5 mm²
  - Thickness: 610 µm
  - Metallisation: Ag



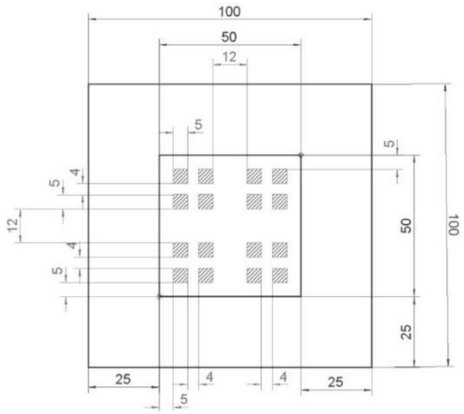



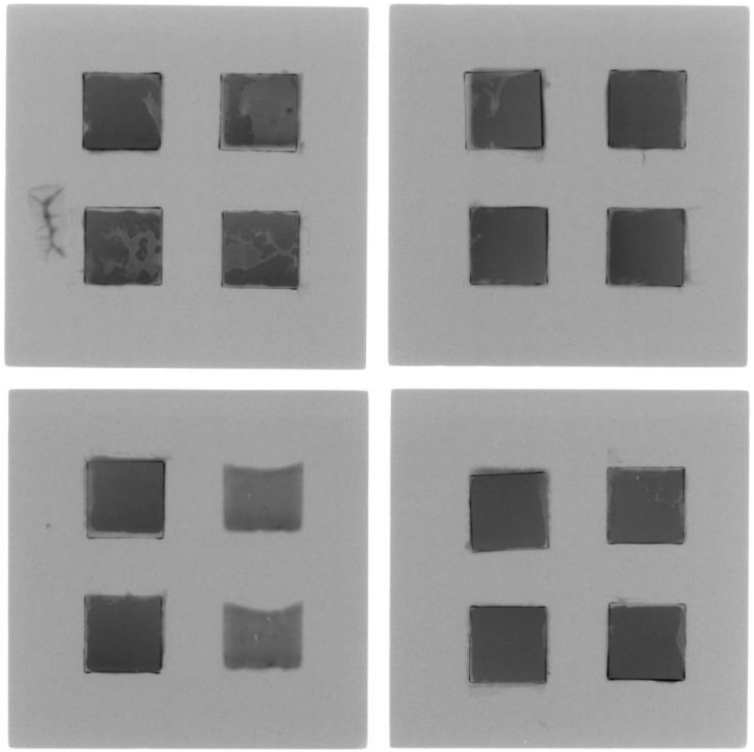
- <u>Experimental variation of the process parameters</u>

| Process Variable | pressureles | | | | | | With pressure (2,4 MPa) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # Dies / Substrat | 4 | | | | | | 1 | | | | | |
| Time [min] | 30 | | | | | | 5 | | | | | |
| Printed sinter layer [µm] | 50 | | 100 | | 200 | | 50 | | 100 | | 200 | |
| Temperature [°C] | 250 | 300 | 250 | 300 | 250 | 300 | 250 | 300 | 250 | 300 | 250 | 300 |

# Non Destructive Evaluation - Set Resolution

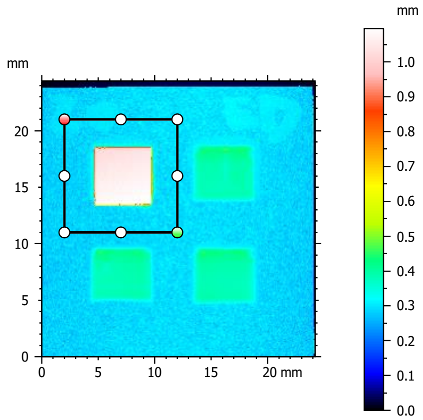
- Full image of 2x2 panel
- Verification of image scale
- Set resolution to 1 Pixel = 50 µm
- Each individual sintered interconnect will represented by a matrix of 100 x 100 pixel



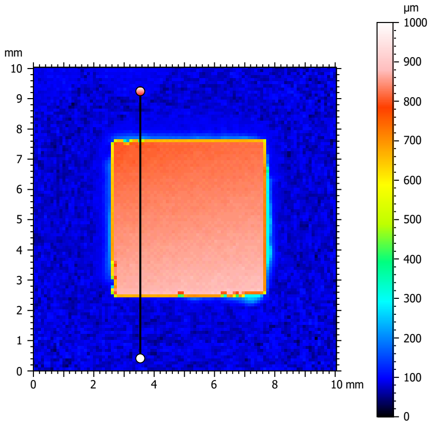



# Measurement - Topography

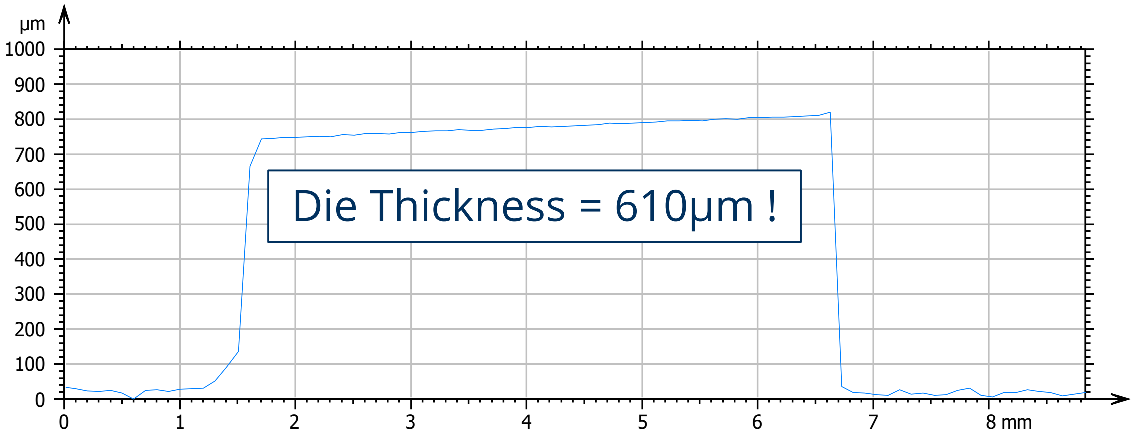
- 3D Scanning Profilometrie with chromatic sensor (resolution out-of-plane: ≈ 25 nm)
- Automated measuring sequence for a substrate (lateral resolution 50 µm → 100 x 100 pixel)
- Alignment / surrounding substrate surface is levelling plane
- Individual analysis (tilt, warpage, etc..)
- Pixel precise determination of the stand-off / sinter layer thickness
- Export for further calculations (e.g. as ASCII surface)



Original / Substrate

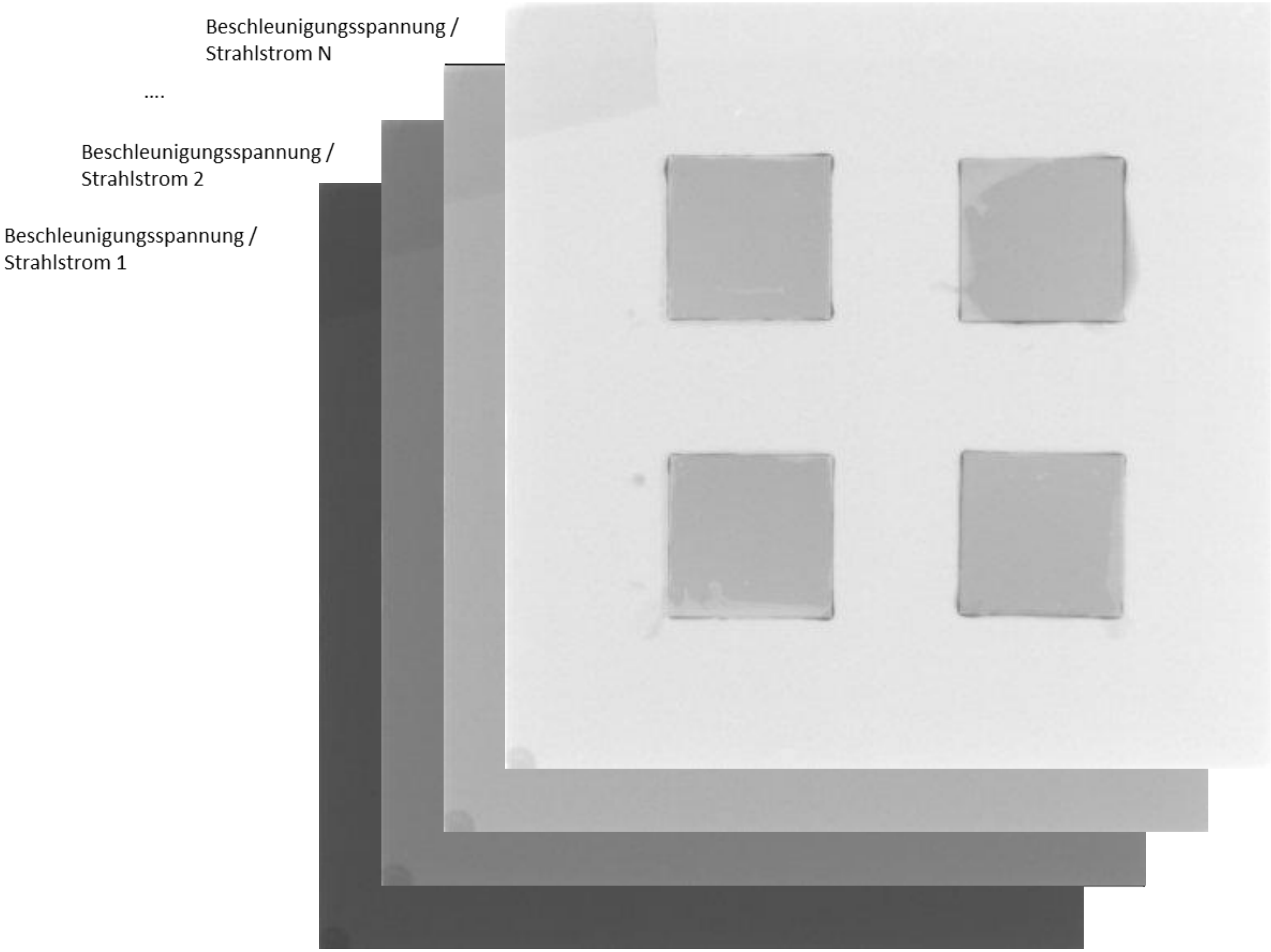


Si-Die (aligned)




Examlpe of a virtual cross-section

# Measurement - Multi-Energy Imaging



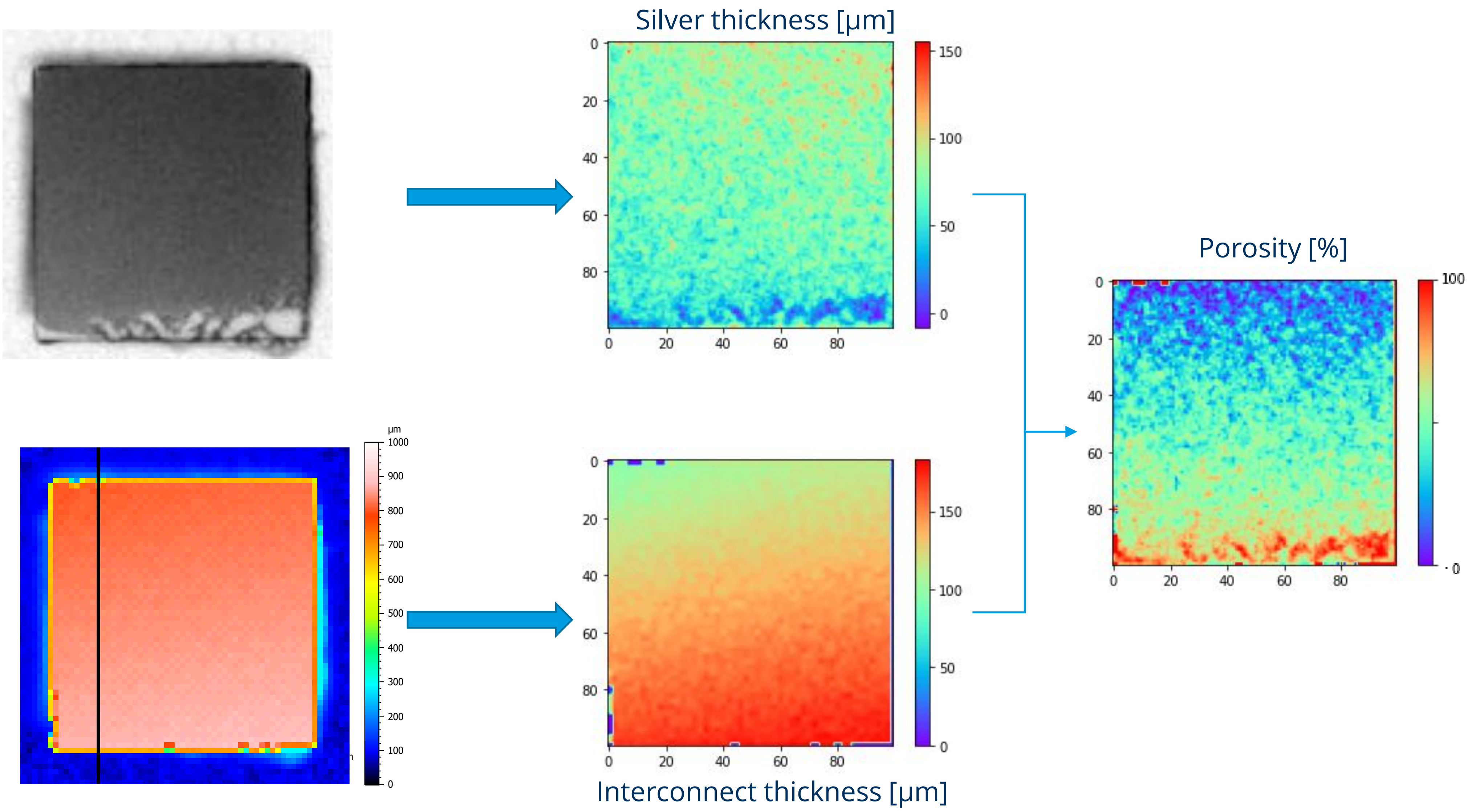

| Low → High | | | | |
|---|---|---|---|---|
| kV/µA | 1 | 2 | ... | N |
| | | | | |
| Acquisition of grey values | | | | |
| Reference | $MW\_Ref_1$ | $MW\_Ref_2$ | ... | $MW\_Ref_N$ |
| Pixel x,y | $GW(x,y)_1$ | $GW(x,y)_2$ | ... | $GW(x,y)_N$ |
| Get intensity curves – approach 1 $y = \frac{GW(x,y)_n}{MW\_Ref_N}$ | | | | |
| Reference | $y\_Ref_1$ | $y\_Ref_2$ | ... | $y\_Ref_N$ |
| Pixel | $y\_(x,y)_1$ | $y\_(x,y)_2$ | ... | $y\_(x,y)_N$ |
| Polynomial regression for reference and each pixel $y = ax^3 + bx^2 + cx + d$ | | | | |
| Reference | $a_{Ref}$ | $b_{Ref}$ | $c_{Ref}$ | $d_{Ref}$ |
| Pixel | $a_{x,y}$ | $b_{x,y}$ | $c_{x,y}$ | $d_{x,y}$ |

Get values for transfer function

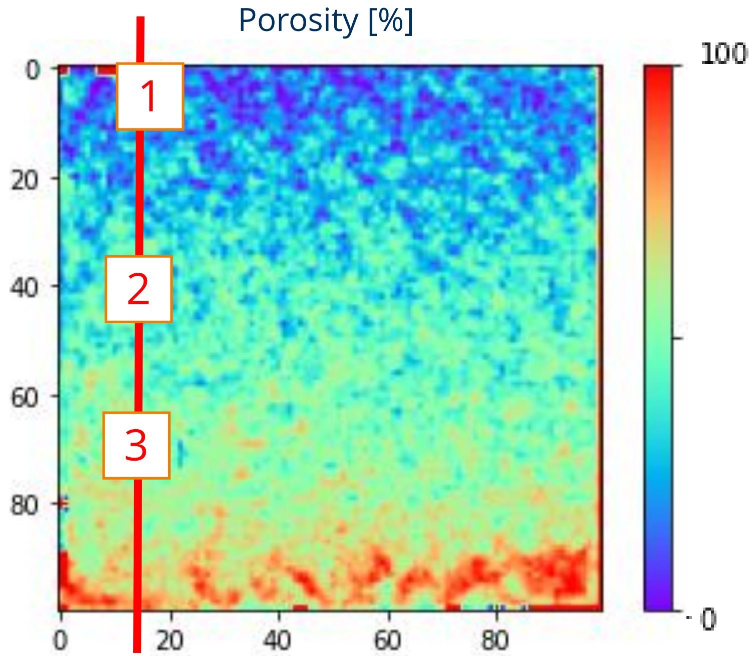
# Example - Results

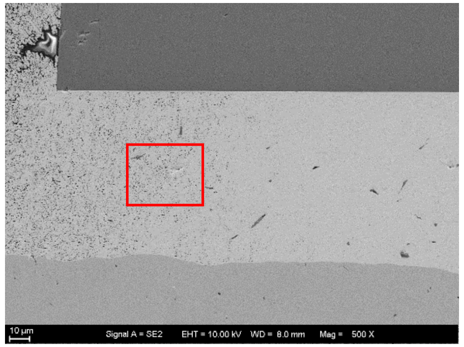
Multi-Energy

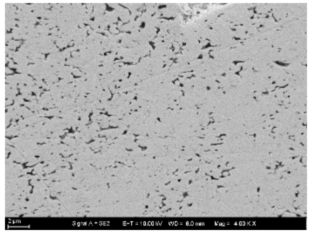
Topography

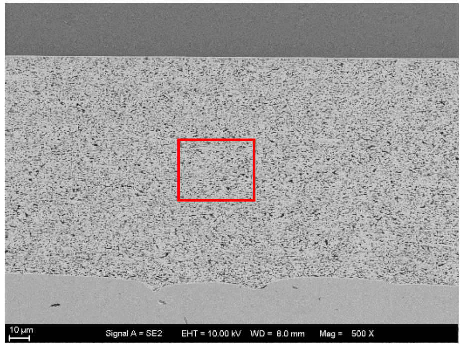


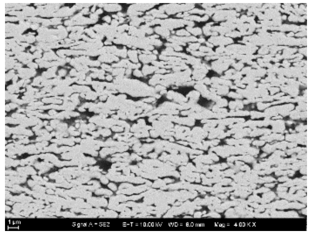
# Example - Validation

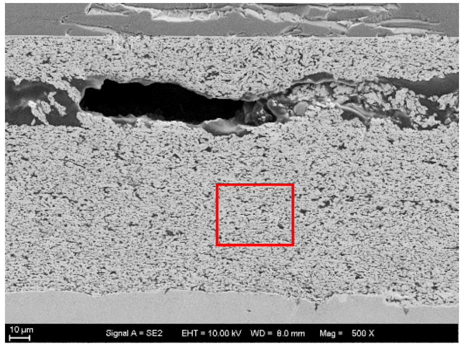


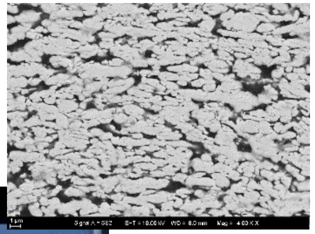



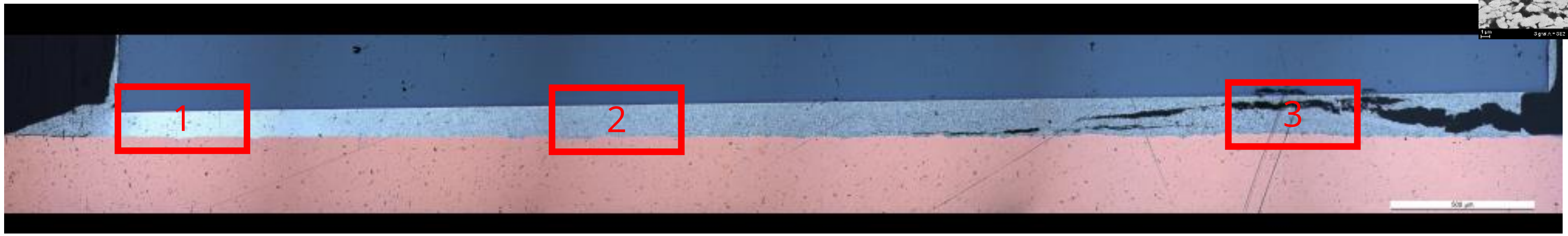




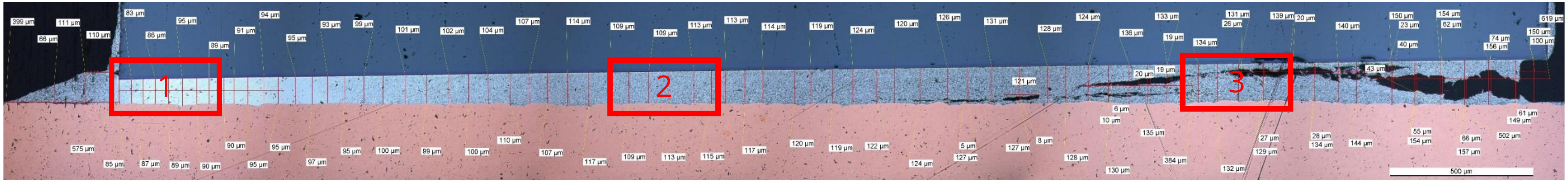


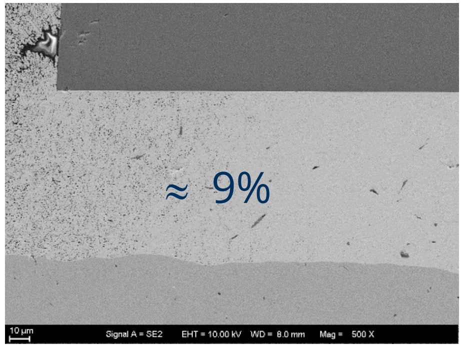


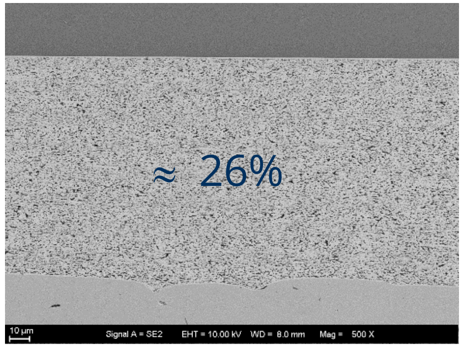


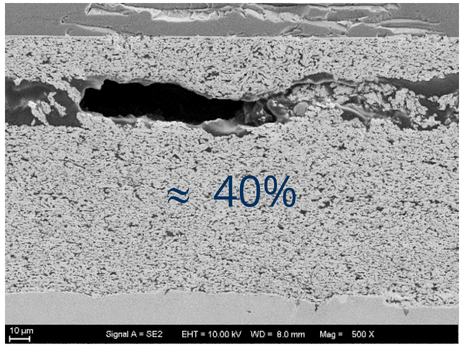


# Example - Comparison




| | 1 | 2 | 3 |
|---|---|---|---|
| Height Optical [µm] | 88 | 115 | 135 |
| Height Topography [µm] | 92 | 118 | 144 |
| | | | |
| Porosity SEM [%] | 9 | 26 | 40 |
| Porosity X-ray [%] | 10 | 35 | 59 |

# Summary & Outlook

- Multi-energy approach for polychromatic X-ray tubes was presented
- Enables separation of elements/material composites and measurement of layer thicknesses
- Can be applied to soldered joints and (silver) sintered interconnects if
  - Structure and topography is known
  - Substrate and Sie-Die are available separately
  - A calibration function is available
- Enables the combination of profilometric and radiographic measurements
- Spatially resolved determination of porosity for the whole area
- High correlation with porosity analysis using SEM

- The measurement process can be automated in principle
- Application possible in the context of process introduction or quality assurance

# Thank you for your attention!