Advances in X-ray Metrology under MADEin4

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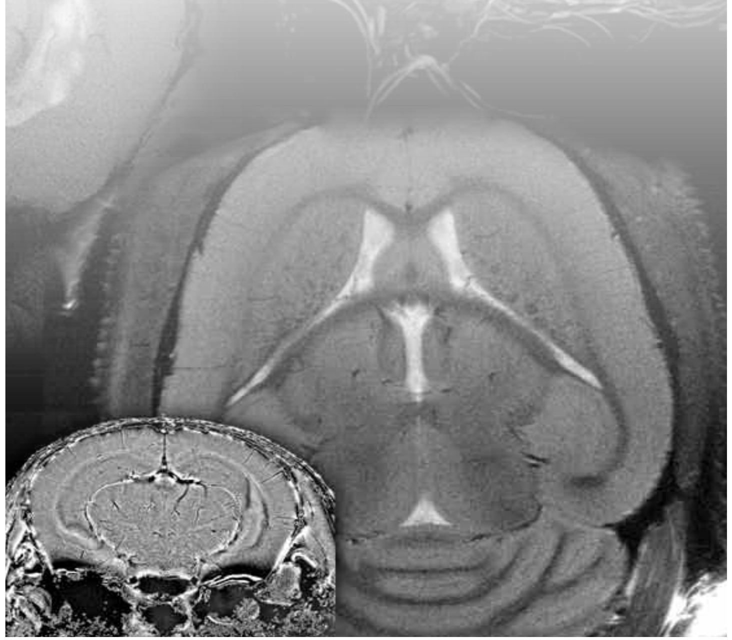
Overview

Bruker Organization

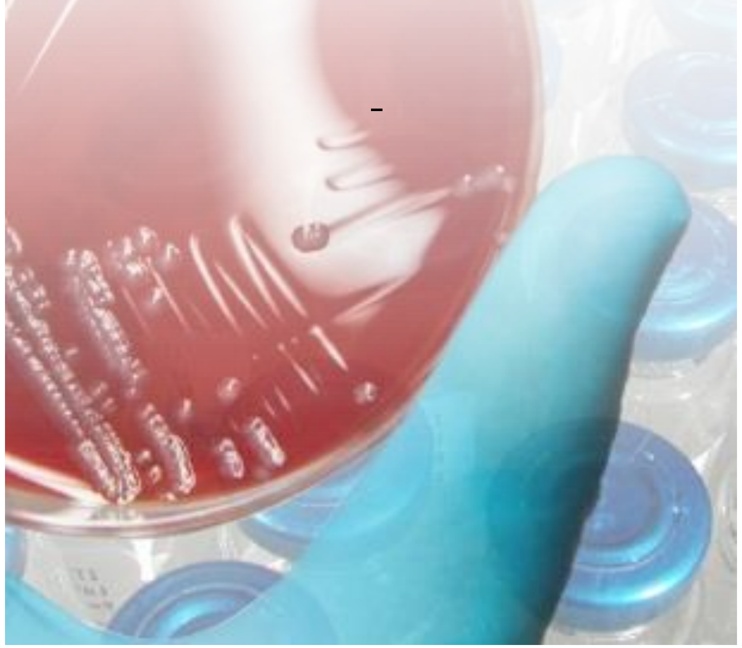
Bruker BioSpin Group

- NMR/EPR for Research & Pharma
- Applied, Industrial & Clinical MR
- Preclinical Imaging
- Services & Life-Cycle Support



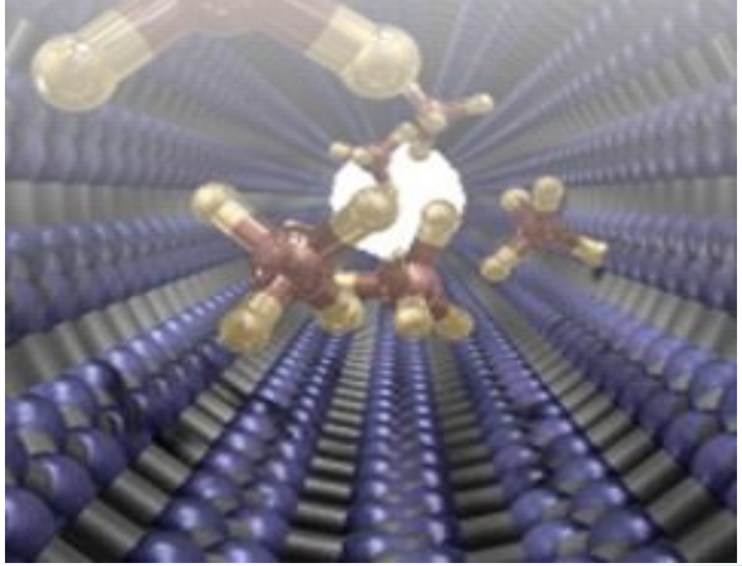
Bruker CALID Group

- Mass Spectrometry for Proteomics, Applied & Pharma
- FTIR/Raman for Applied Markets
- CBRNE Detection for Security

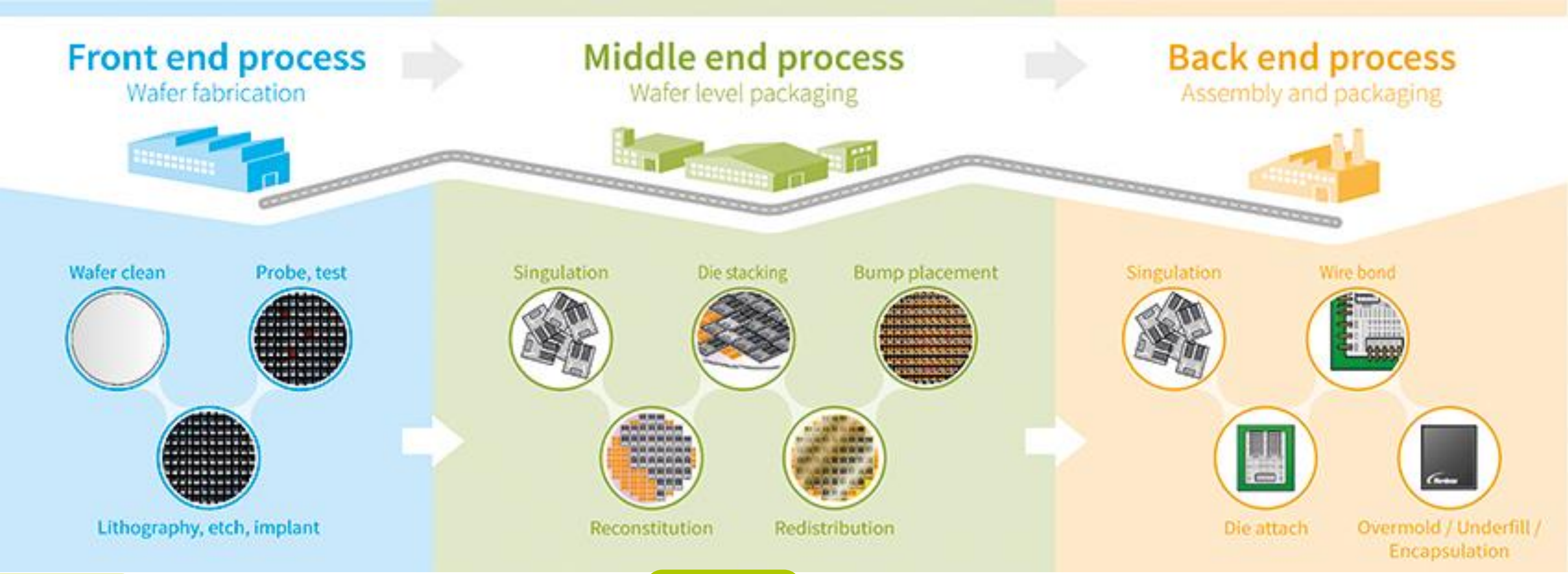


Bruker NANO Group

- Advanced Semiconductor Metrology
- 3D Optical and Stylus profiling
- Atomic Force Microscopy
- X-Ray for Materials Research, QC
- Tribology and mechanical testing



Bruker Semiconductor X-ray Metrology and Inspection Techniques



Bruker X-ray solutions

- Front end process: µXRF, XRD, XRDI, TXRF, SAXS, XRR
- Middle end process: µXRF, XRI
- Back end process: XRI

Scope and Goals MADEin4

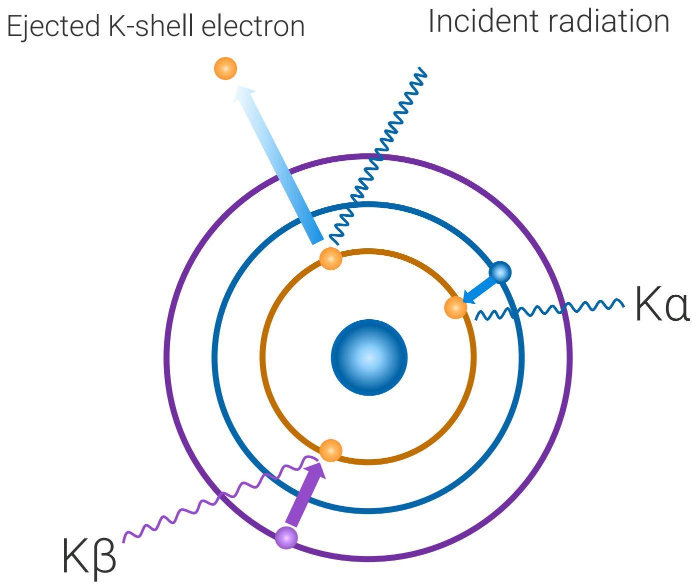
- Bruker is partner in the Metrology work package of MADEin4
- WP3: Metrology platform developments for enhanced productivity
- Subtask 3.1.2: Metrology for front-and back-end process characterization
  - µXRF for metal thickness and composition
  - Assessing prototype of latest Liquid Metal Jet X-ray source from Excillum
  - Goal: increase µXRF flux with 10x, keeping the small spot size

- Subtask 3.1.4: Metrology for contamination control
  - TXRF for metal contamination monitoring
  - Goal: increase light element sensitivity by 10x; increase throughput by 2x

Thickness, Composition by XRF

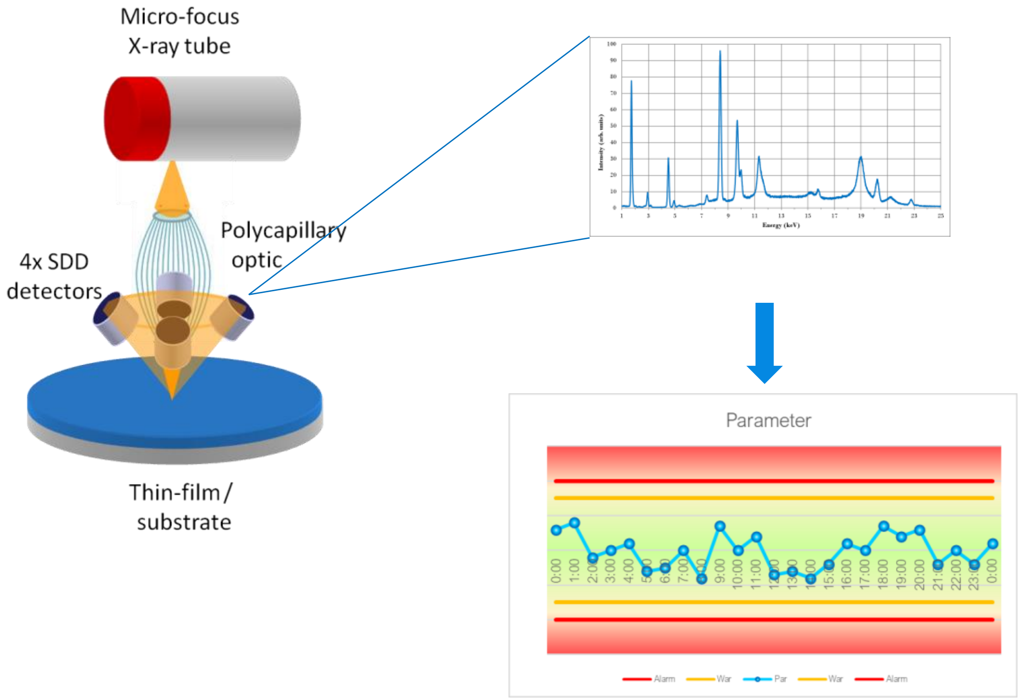
X-ray Fluorescence Principle

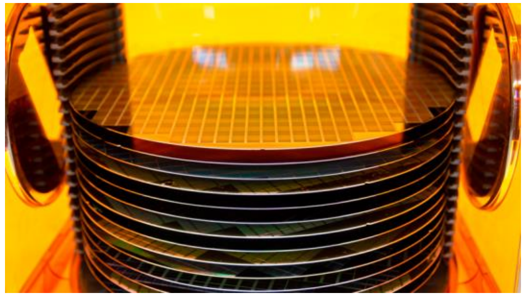
- Radiative transitions between different atomic shells result in a discrete series of X-ray energies (lines).
  - K or L lines are commonly used for XRF analysis of metals in air.
- Each element has a unique series of lines and the intensity is proportional to the number of atoms.
  - Qualitative analysis
  - Quantitative analysis –after calibration-
    - Thickness
    - Concentrations



µXRF Metrology Channel for Inline Process Monitoring

- Microfocus X-ray sources, anode material depends on applications
  - Mo, Cu, Rh, W are common state-of-the-art materials
  - Small spot (FWHM of 25µm, optional 15µm or 35µm)
  - Low sensitivity to Z-errors
  - Small edge exclusion
- Detection
  - Up to four quadrant SDD detectors for efficient photon collection
- Accurate positioning
  - Automatic pattern recognition for accurate positioning on small features
- Benefits
  - Fast
  - Non-destructive



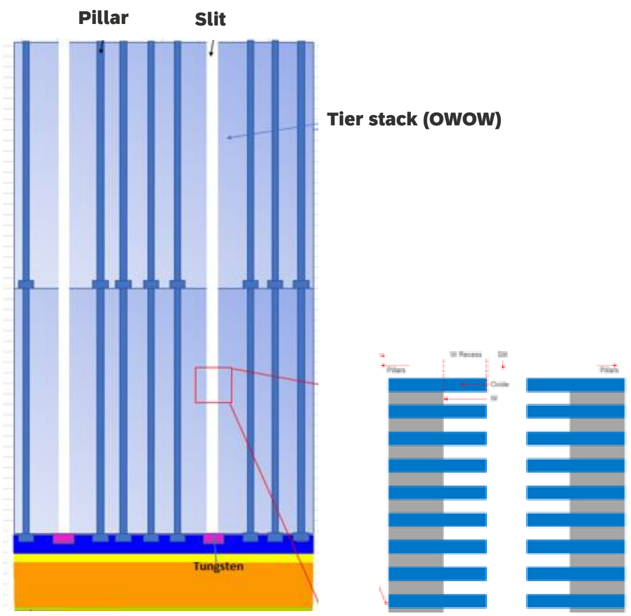


3D-NAND: W Recess Control with µXRF

- Changes in W recess are ~ 1% of volume, therefore very high sensitivity is required (3σ <0.15%)
- Fast measurements allow creation of very dense maps, small beam enables EE <1mm

Sample	Recess	POR vs DOE (ΔI)	center and edge (ΔI)
A	High	-0.5%	1.1%
B	POR	0%	1.6%
C	Low	+0.9%	2.0%

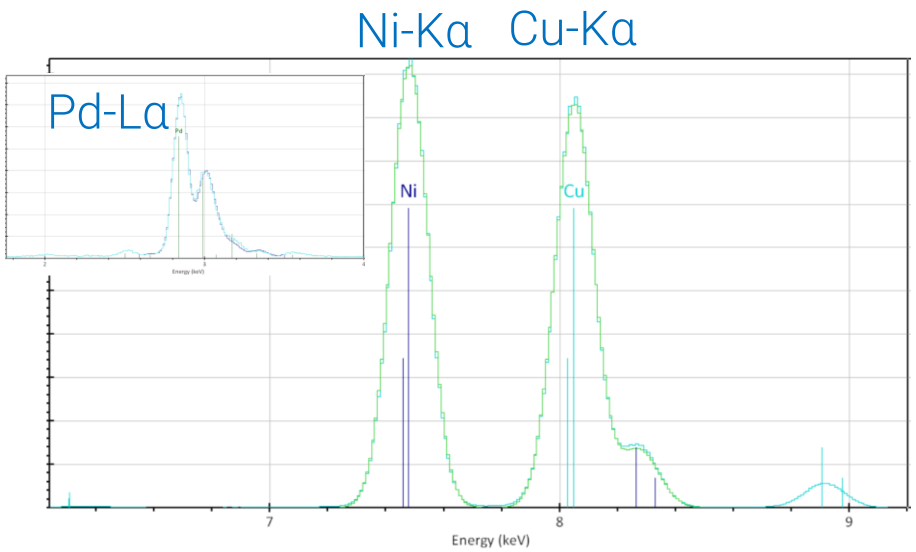
Intensity differences comparison at the wafer center



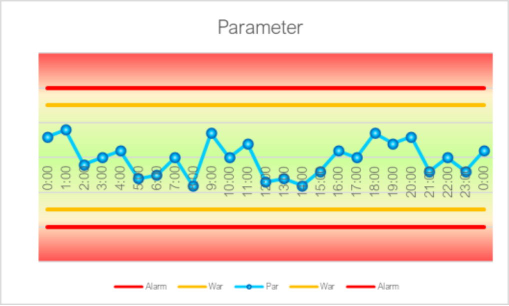
Typical 3D-NAND stack (left); W recess in OWOW pairs (Right)

Thickness of Electroless Plating Stacks with µXRF

- Pad metallization
- 200-300nm Pd on 2000-3000 nm of Ni on thick Cu
- Thickness of each layer in tens of seconds
  - <1% for Pd
  - 0.3% for Ni

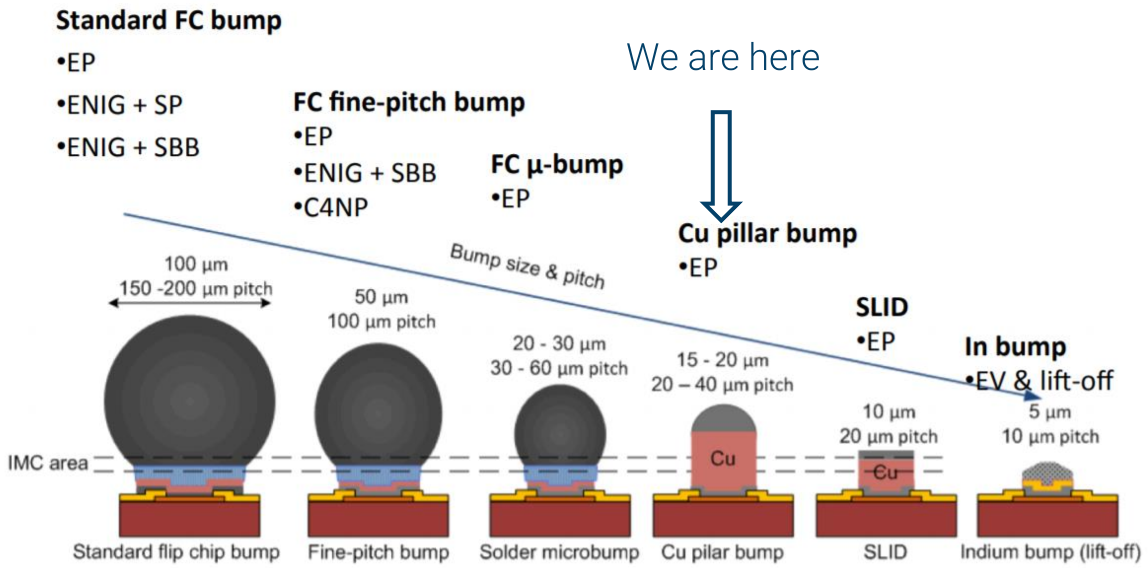


Typical µXRF spectrum from Pd/Ni on Cu stack



Advanced Wafer Level Packaging Process Control with µXRF

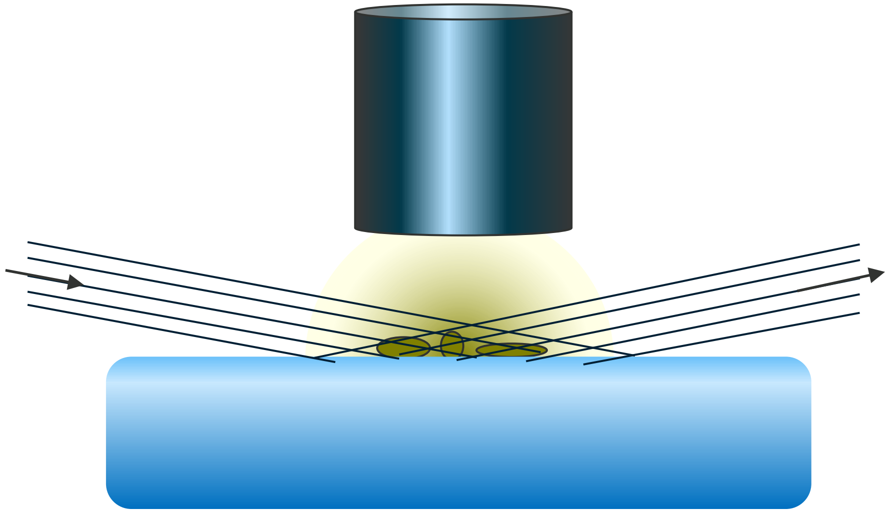
- Applications
  - % Ag in Sn-Ag solders – controls reflow temperature
  - Solder and under-bumps metal height (thickness) – resistivity and planarity
- µXRF for advanced WLP, specifically for next bumps generation



Contamination Control by TXRF

Total Reflection and the Standing Wave

- Total Reflection: incident angle < critical angle
- Generation of X-ray Standing Wave Field over the surface of the reflector
  - Constructive interaction of the incident monochromatic beam and the totally reflected beam
- Contaminant is excited twice: once by the incident X-ray beam and again by the reflected beam
  - Amplification of the X-ray fluorescence signals
- Background contribution is minimized
  - Monochromatic excitation
  - No penetration into the substrate
  - Working in vacuum (in most cases)
- Excellent detection limits



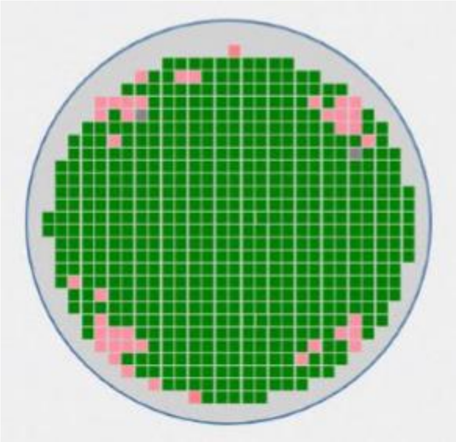
Yield Optimization is the Key Driver

- Yield is the "single most important factor in overall costs", thus optimization gives a competitive advantage (*McKinsey 2018*)
  - "one semiconductor player in Asia and America" saved $12M in 6 months by improving yield monitoring

- Contamination control is essential, as contamination counts for 10% of overall yield loss

- Metallic contaminants degrade silicon device performance in a variety of ways

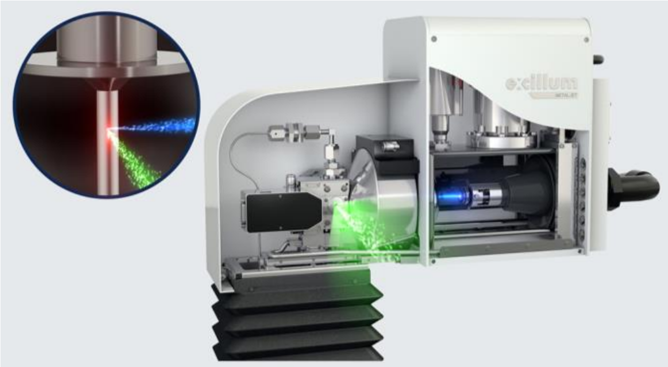
- Every processing step can contribute to contamination
  - Equipment: deposition systems, mechanical, gas piping
  - Human: process engineers or factory operators
  - Materials: chemicals, etchants, D.I. water
  - Process: contamination from all above sources



Advances Made in MADEin4

Subtask 3.1.2 µXRF Enhancements

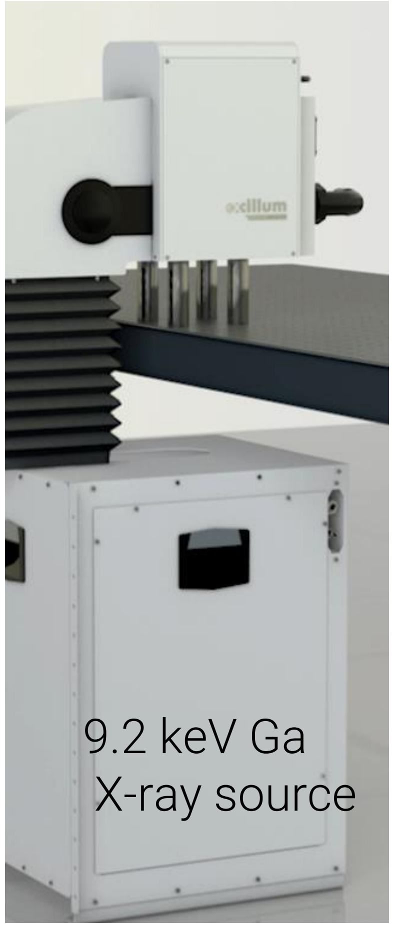
- Assessment of Excillum‘s Liquid Metal Jet source with Ga liquid anode
- Benchmark against state-of-the-art solid anodes



- With use of
  - Similar optics as in a conventional µXRF system
  - State-of-the-art SDD (Silicon Drift Detector)

excillum MADEin4 BRUKER

Increased Intensity with the Excillum Liquid Metal Jet X-ray Source



µXRF tests with MetalJet

Layer	Projected improvement*
TiN 100Å (DRAM)	5-10X
W 2000Å (W plug)	>10X

*in acquisition time, compared to state-of-the-art maintaining 3σ<1% .

End User Advantage

- Increased throughput of µXRF metrology for nanoelectronics process control
- Enhanced productivity for at-line and in-line µXRF metrology

Initial Findings

- Great improvement in fluorescence intensity on known samples.
- Spot size fits the requirements.

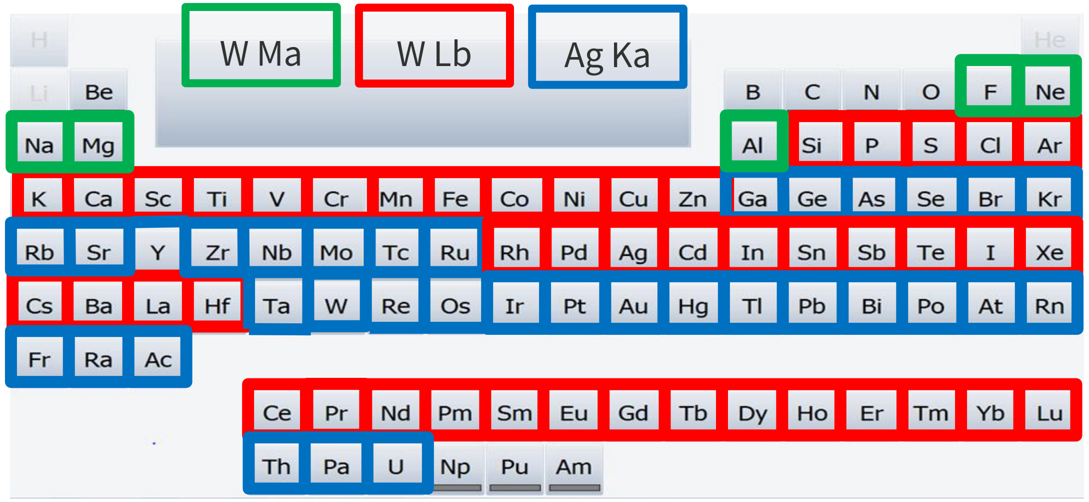
	Liquid Metal Jet	Common solid anode
Power density	Superior to SotA anodes	Limited
Optics	May need adaption	Optimized
Beam path	Horizontal	360° freedom

3.1.4 TXRF Enhancements

- Optimization of the light element beam path to boost the sensitivity for Na, Mg, Al.
- Implementation of optical sensor-based wafer alignment for increased throughput.

Improved Light Element Analysis with TXRF

- 3 X-ray sources for optimum elemental sensitivity
  - ME (W-Lb): transition elements
  - HE (Ag-Ka): best sensitivity for heavy elements
  - LE (W-Ma): optimized channel for light elements
- Optimized detectors for each element range
  - Large SDD for transition/heavy elements
  - Optimized thin window SDD for light elements

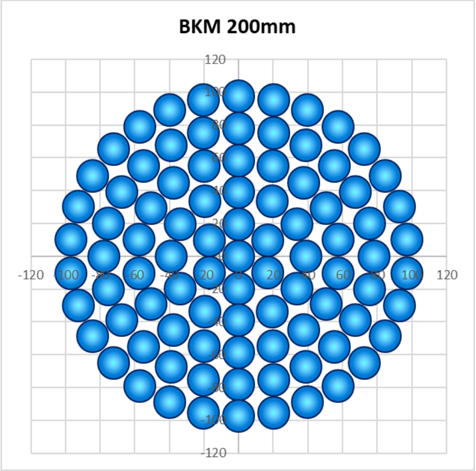


Element	LLD (at/cm²)*	Channel
Al	<1E11	LE (W Ma)
Ni	1E9	ME (W Lb)
Zr	1E9	HE (Ag Ka)

* Acquisition time 1000s

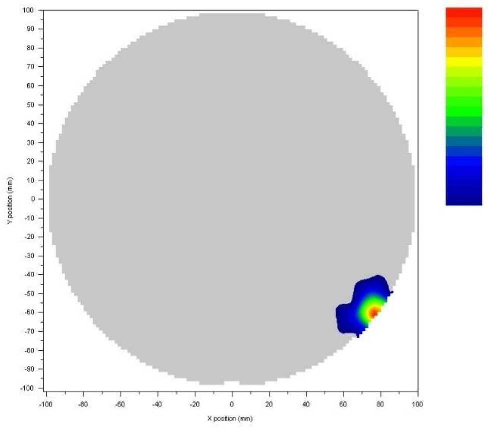
Fast Full Wafer Maps with 0 mm Edge Exclusion

- Identification of the contamination <u>and</u> of its location on the wafer
  - Identify root cause of contamination, e.g. suspect process equipment
- Non-destructive analysis
- Zero edge exclusion
- Fast: 100% coverage of 200mm wafer in <27 min
  - With sample alignment at every site



Full wafer coverage

Na (E10 at/cm²)



Output: wafer map per element, at 2x higher throughput.

Outlook

- µXRF is already in HVM, but if the performance can be improved compared to the state-of-the art system, it opens the door for more applications, especially in advanced logic and memory.
- Bruker will continue to collaborate with Excillum to push the sensitivity of µXRF.
- Future focus on localized hazardous elements and metal contamination detection.

Thank you!

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