Residual Stress measurement in solar cells

New analytical opportunities for Research and QualityControl

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PANalytical GmbH
Kassel

Workshop 05.11.2013

ABOUT PANALYTICAL

About PANalytical

- Founded in 2003
- Spin-Off from PHILIPS
- Headquarter in Almelo, The Netherlands
- Manufacturer of X-ray equipment since 1920
- 1.100 employees globally
- 220 employees in R&D Almelo
- About 800 X-ray systems per year

PANalytical

PANalytical product portfolio

X-ray fluorescence spectrometers

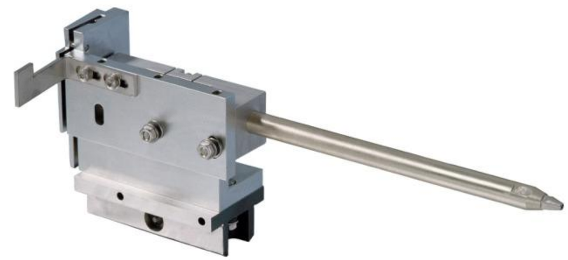
SEMI XRF/XRD

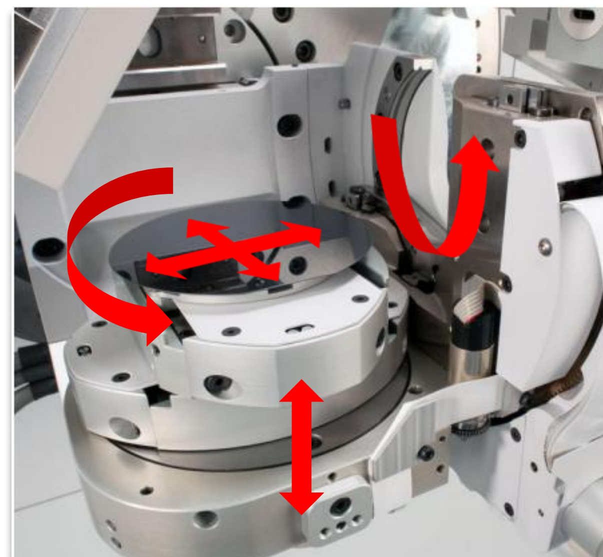
PGNAA

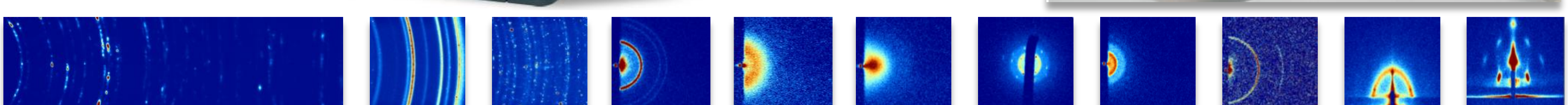
X-ray tubes

Research & Industrial XRD

X-ray diffraction platform: EMPYREAN







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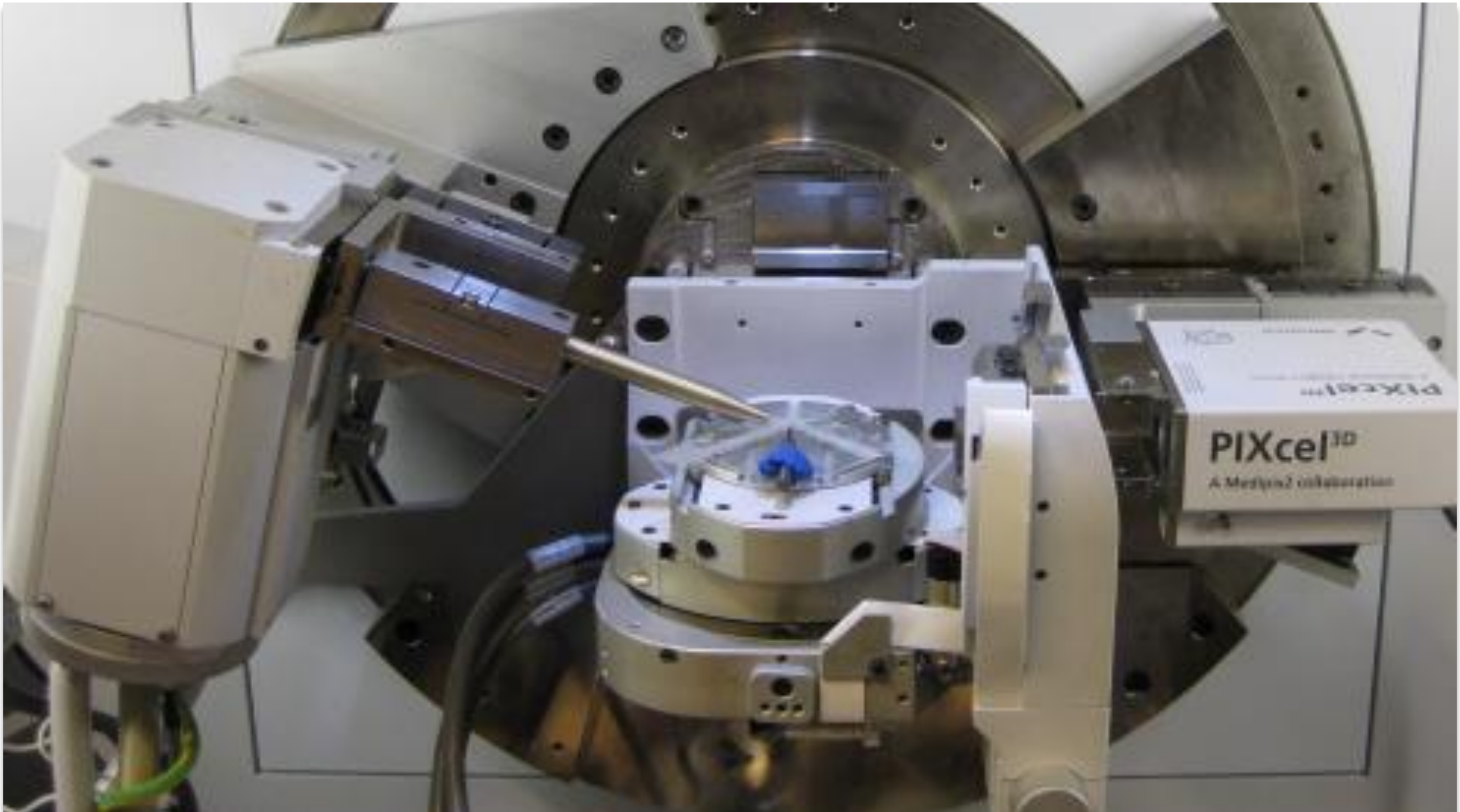
Core components: PIXcel3D x-ray detector & stages



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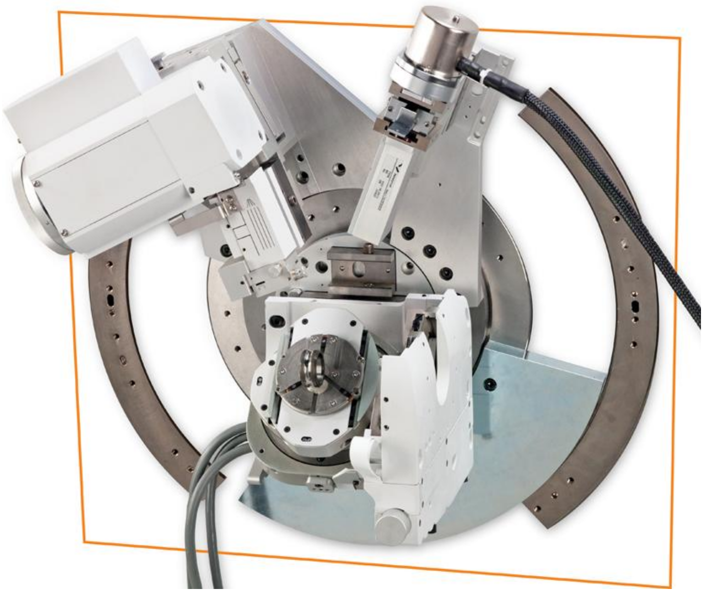
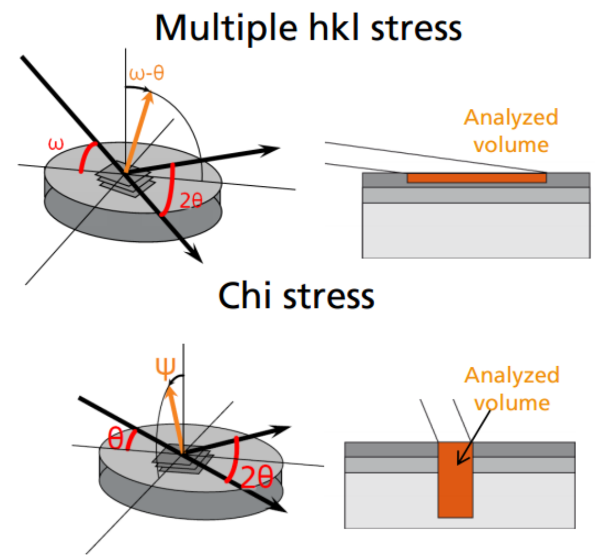
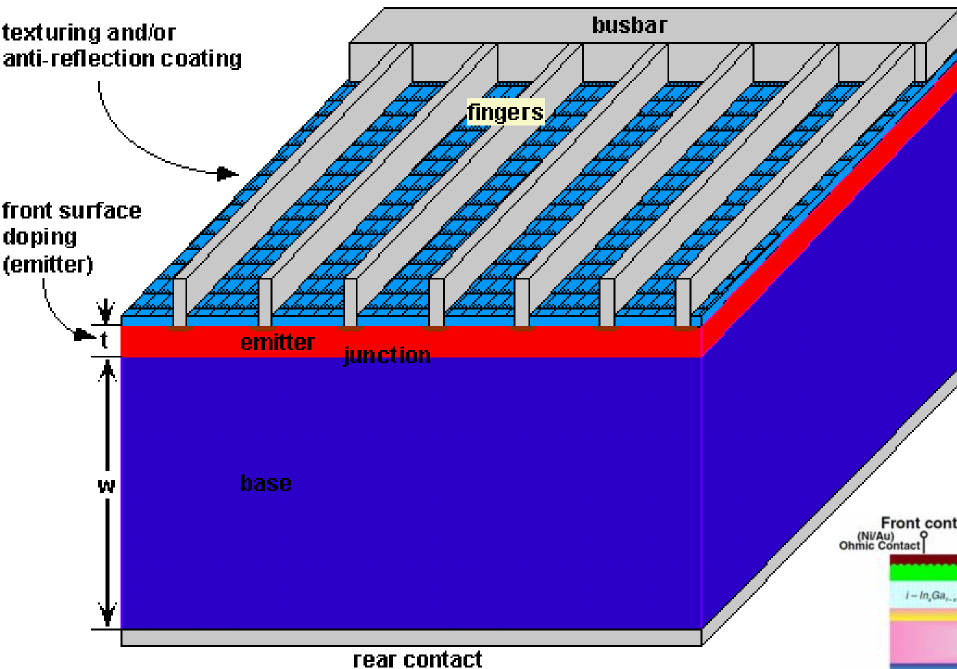
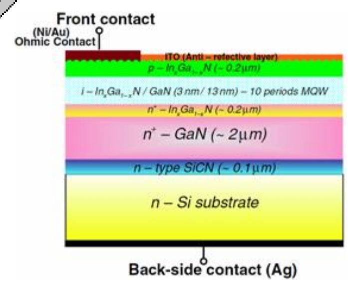


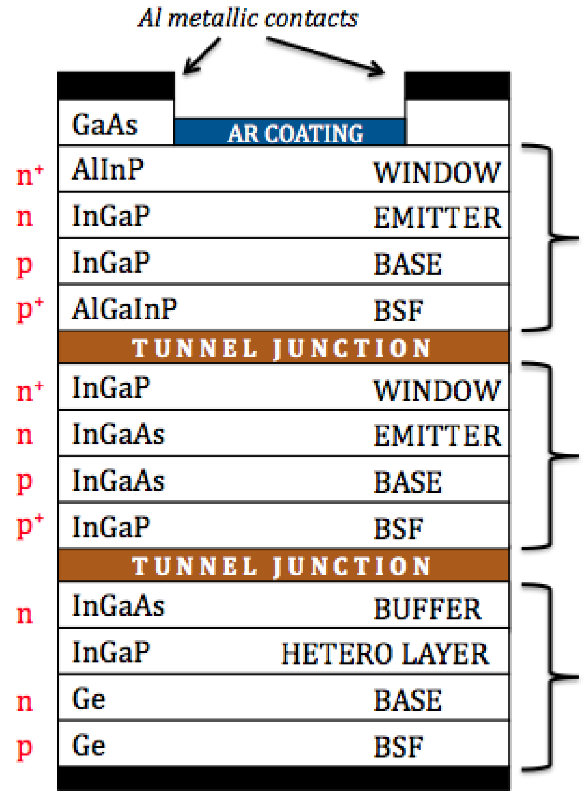


BASICS OF RESIDUAL STRESS ANALYSIS BY X-RAYS

Solar Cells and PV modules – from XRD viewpoint



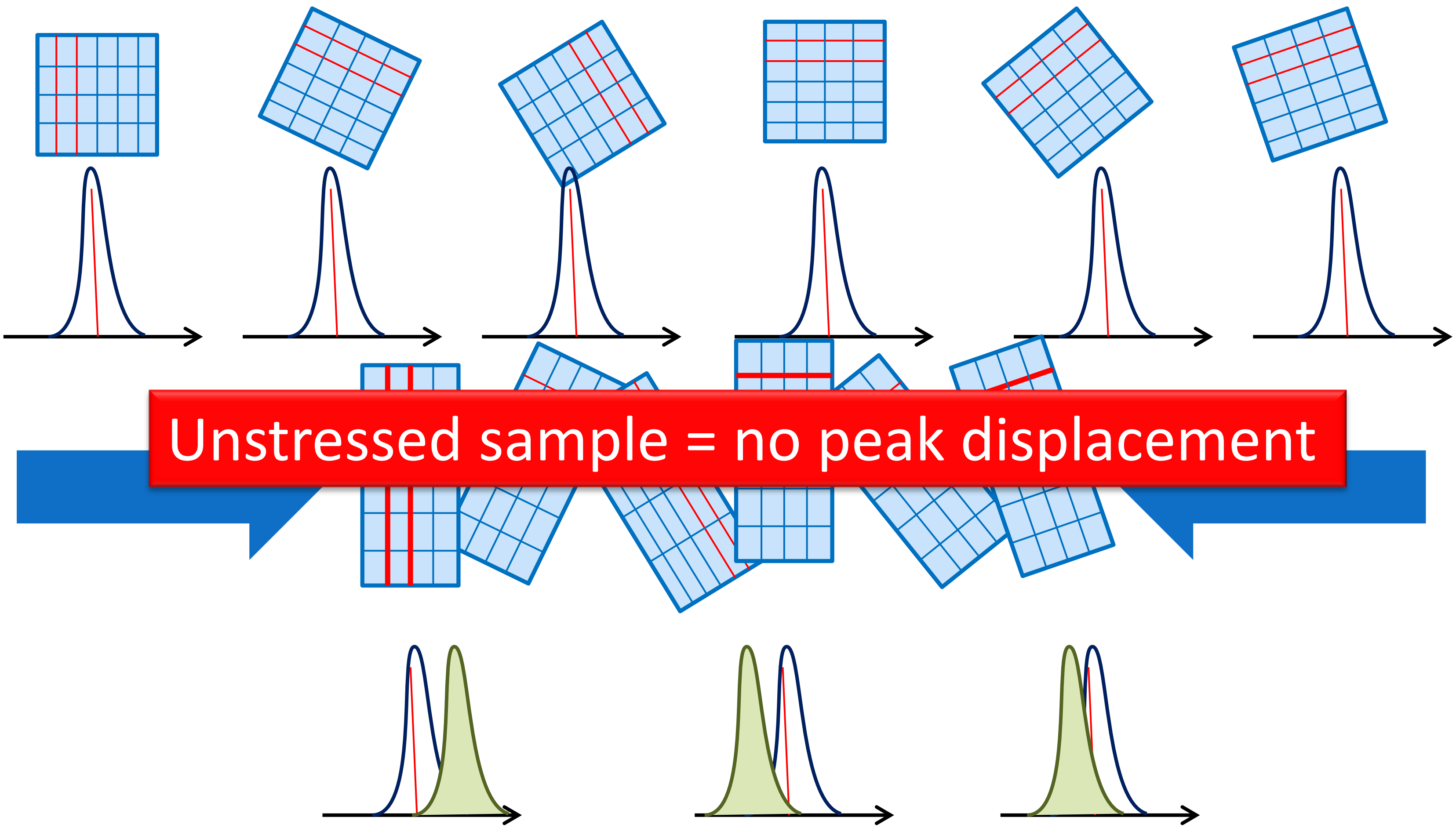




Layered structure | **Thermal processing** | **Residual Stress**

Graphics courtesy of pveducation.org

How to analyze Residual stress by XRD?

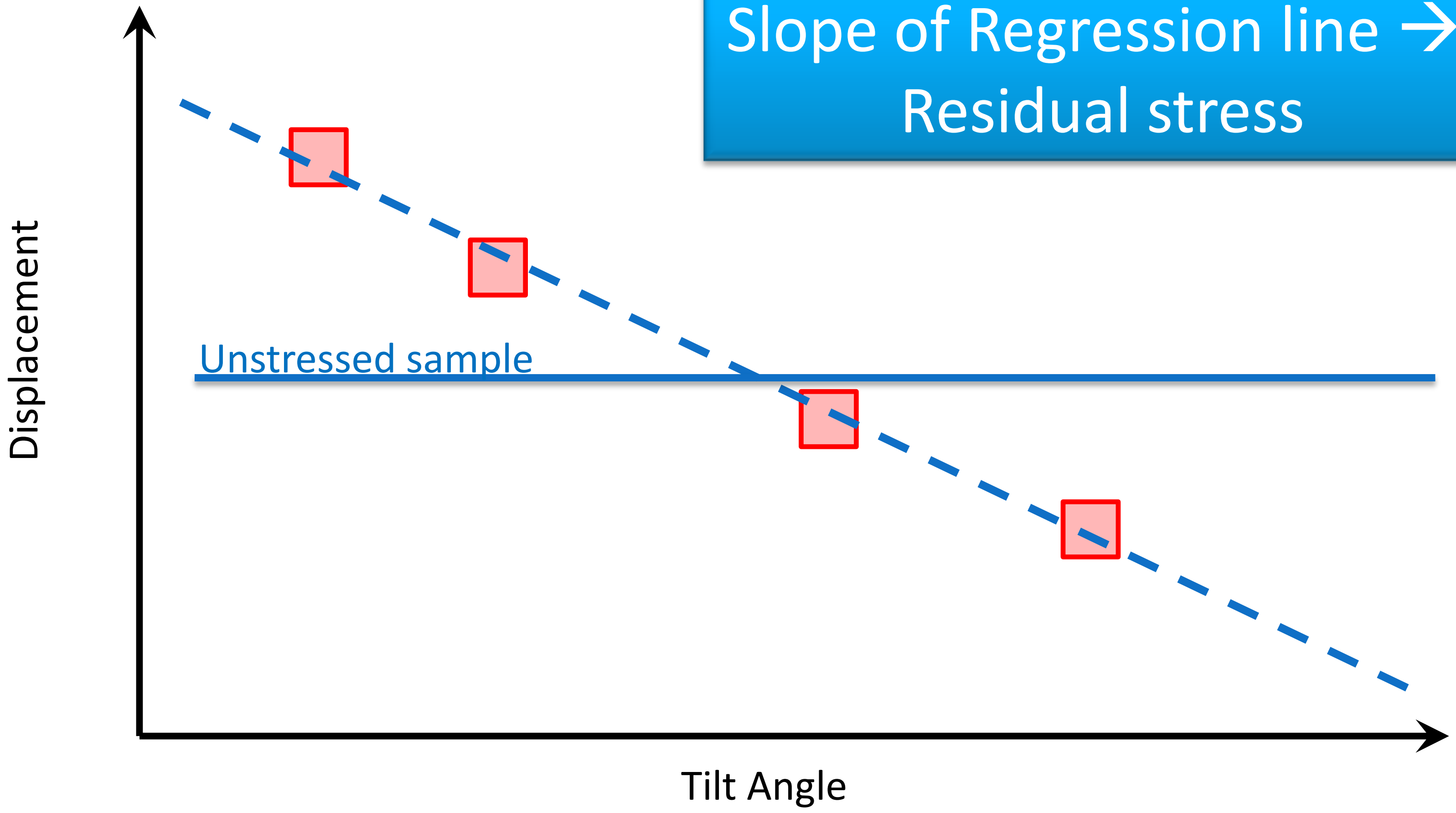


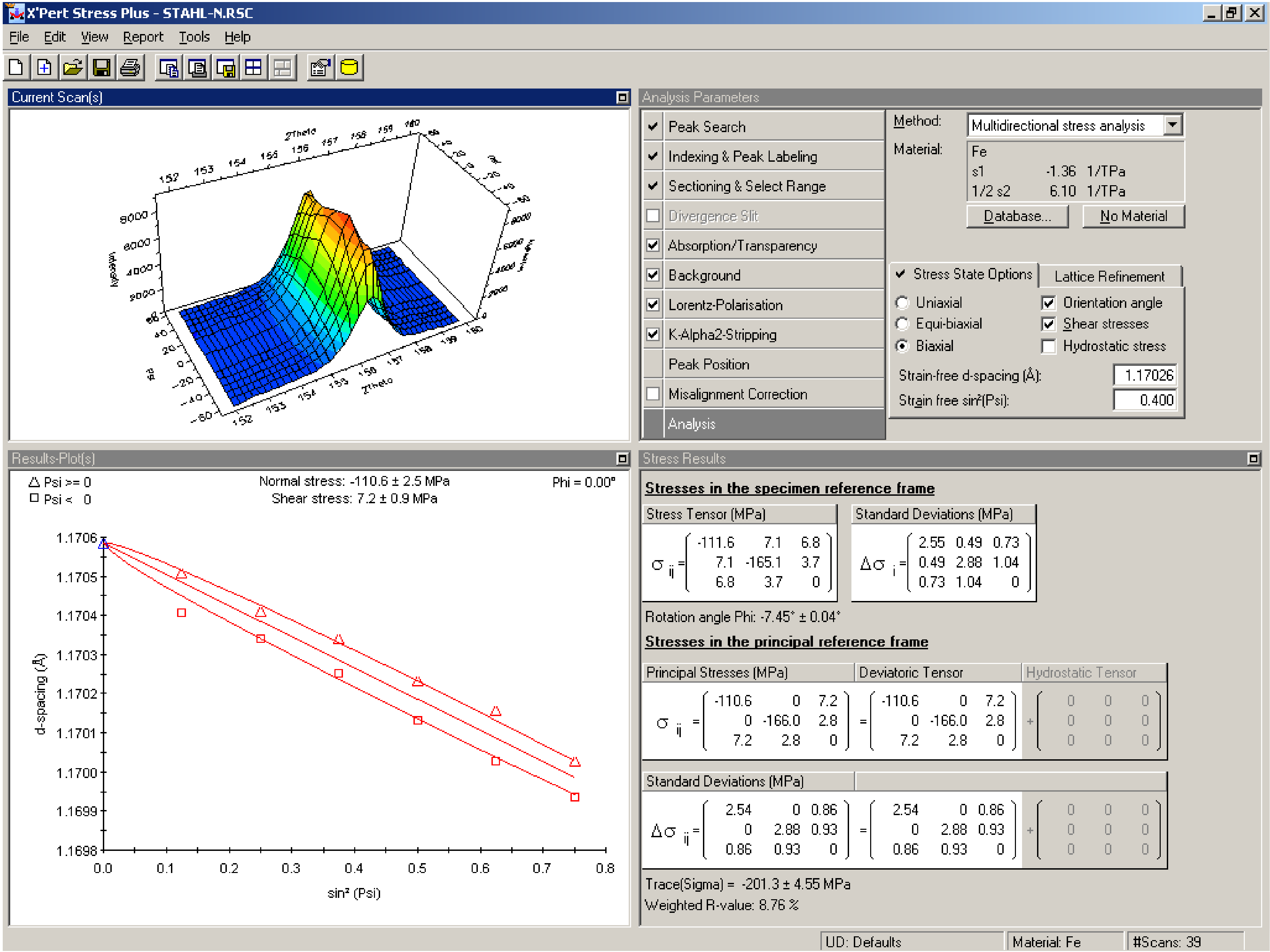
Unstressed sample = no peak displacement

Stress in sample = orientation-dependet peak shift

Displacement plot

Slope of Regression line → Residual stress

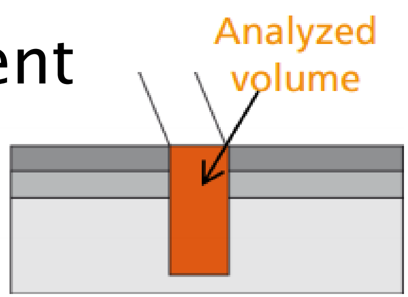


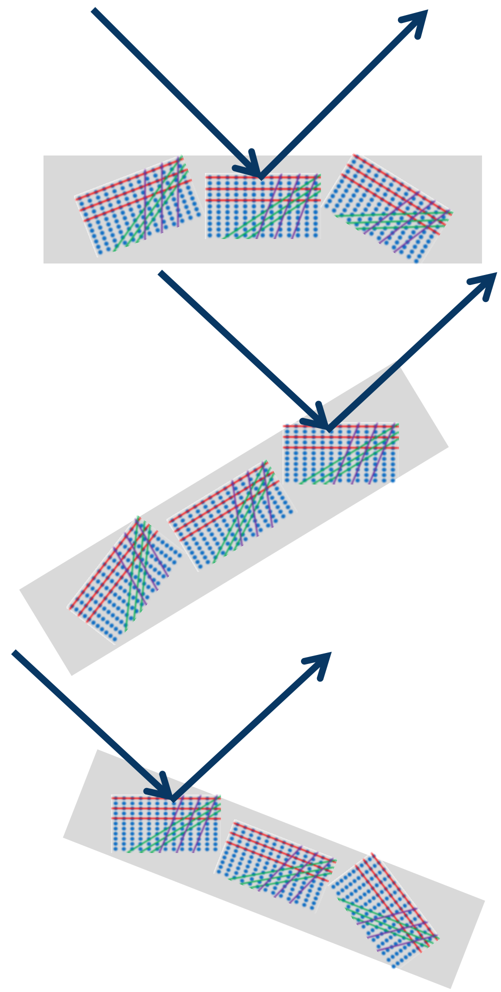

X'Pert Stress Plus - STAHL-N.RSC
File Edit View Report Tools Help
Current Scan(s)
2Theta
152 153 154 155 156 157 158 159 160
8000 6000 4000 2000
Intensity
Psi
60 40 20 0 -20 -40 -60
Analysis Parameters
Peak Search
Indexing & Peak Labeling
Sectioning & Select Range
Divergence Slit
Absorption/Transparency
Background
Lorentz-Polarisation
K-Alpha2-Stripping
Peak Position
Misalignment Correction
Analysis
Method: Multidirectional stress analysis
Material: Fe
s1 -1.36 1/TPa
1/2 s2 6.10 1/TPa
Database...
No Material
Stress State Options
Lattice Refinement
Uniaxial
Equi-biaxial
Biaxial
Orientation angle
Shear stresses
Hydrostatic stress
Strain-free d-spacing (Å): 1.17026
Strain free sin²(Psi): 0.400
Results-Plot(s)
Psi >= 0
Psi < 0
Normal stress: -110.6 ± 2.5 MPa
Shear stress: 7.2 ± 0.9 MPa
Phi = 0.00°
d-spacing (Å)
1.1706 1.1705 1.1704 1.1703 1.1702 1.1701 1.1700 1.1699 1.1698
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
sin² (Psi)
Stress Results
Stresses in the specimen reference frame
Stress Tensor (MPa)
Standard Deviations (MPa)
σ ij = -111.6 7.1 6.8 / 7.1 -165.1 3.7 / 6.8 3.7 0
Δσ ij = 2.55 0.49 0.73 / 0.49 2.88 1.04 / 0.73 1.04 0
Rotation angle Phi: -7.45° ± 0.04°
Stresses in the principal reference frame
Principal Stresses (MPa)
Deviatoric Tensor
Hydrostatic Tensor
σ ij = -110.6 0 7.2 / 0 -166.0 2.8 / 7.2 2.8 0 = -110.6 0 7.2 / 0 -166.0 2.8 / 7.2 2.8 0 + 0 0 0 / 0 0 0 / 0 0 0
Standard Deviations (MPa)
Δσ ij = 2.54 0 0.86 / 0 2.88 0.93 / 0.86 0.93 0 = 2.54 0 0.86 / 0 2.88 0.93 / 0.86 0.93 0 + 0 0 0 / 0 0 0 / 0 0 0
Trace(Sigma) = -201.3 ± 4.55 MPa
Weighted R-value: 8.76 %
UD: Defaults
Material: Fe
#Scans: 39

Principal methods

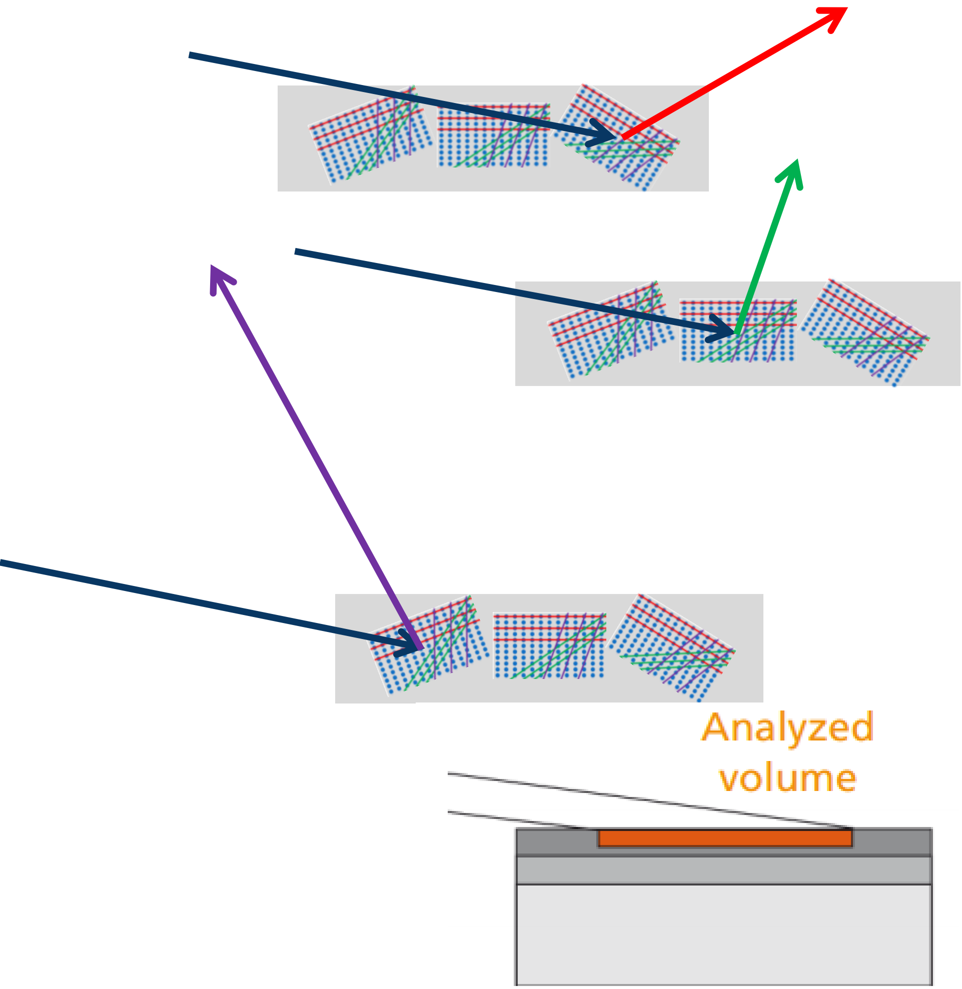
Single-hkl:

- One specific reflection
- Sample needs to be tilted:
  - Omega tilt
  - Chi tilt
- Analytical volume is large and changes with tilt
- Bulk stress measurement





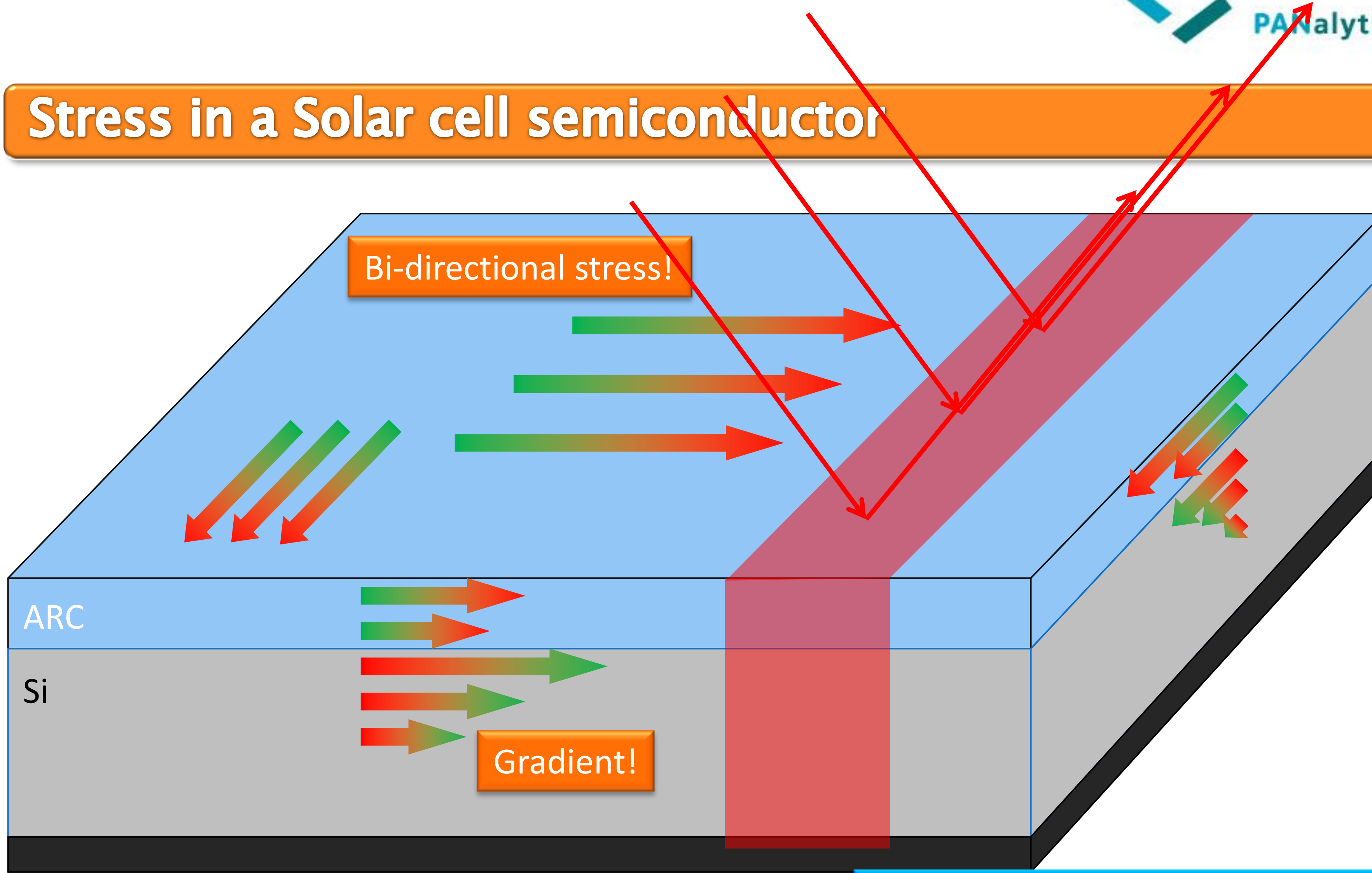
Principal methods



Multi-hkl:

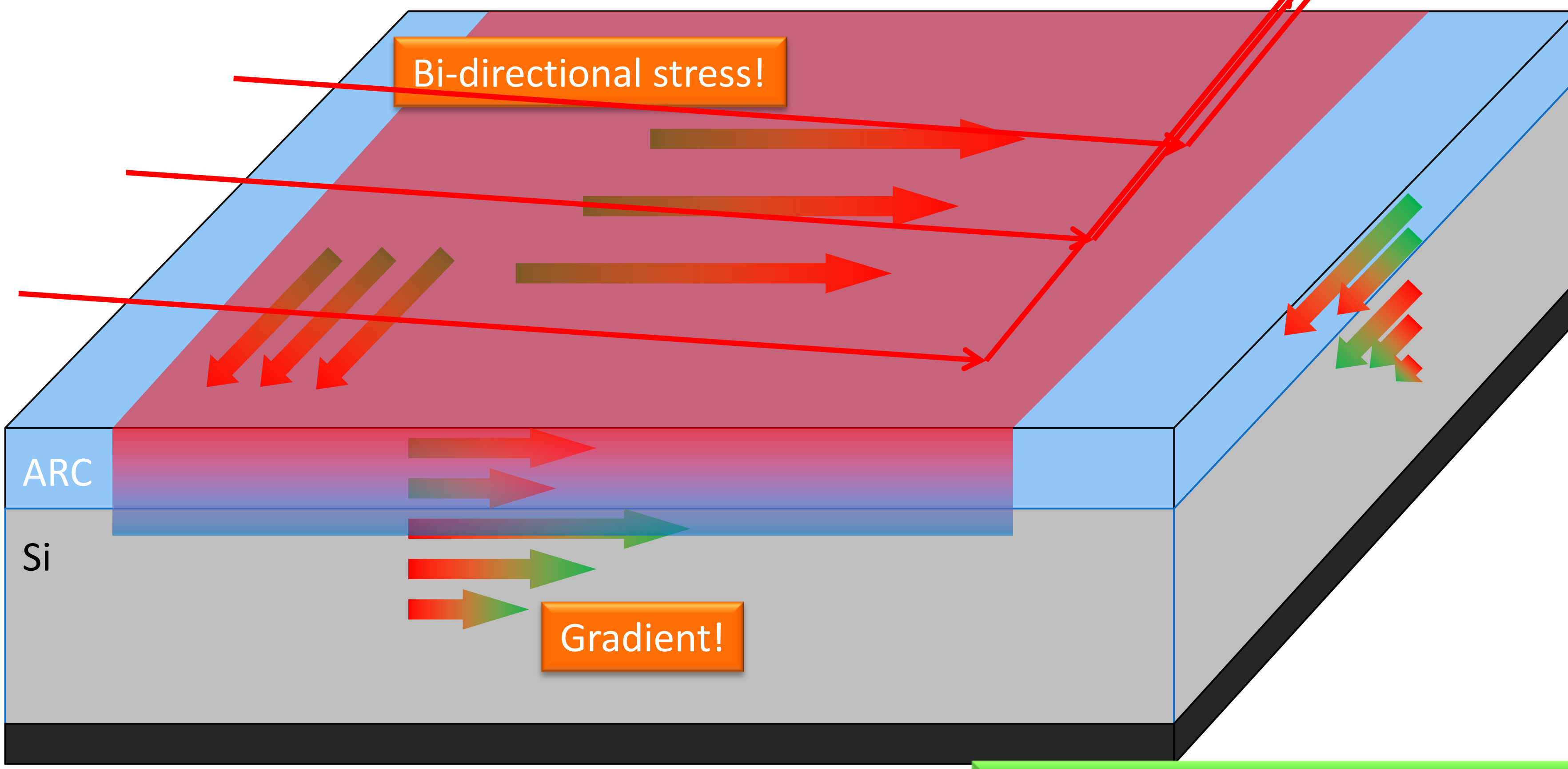
- Several reflections from one phase
- Fixed incident angle
- Fixed analytical volume
  - Thin films
  - Gradients
- Grazing incidence: large analytical area

Stress in a Solar cell semiconductor

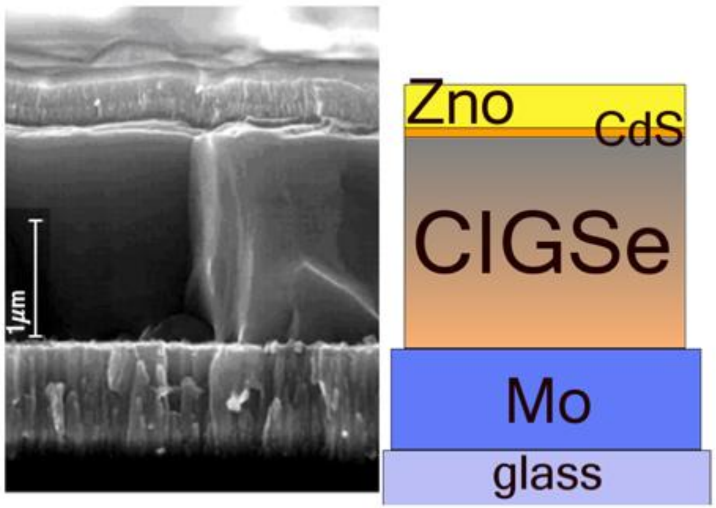


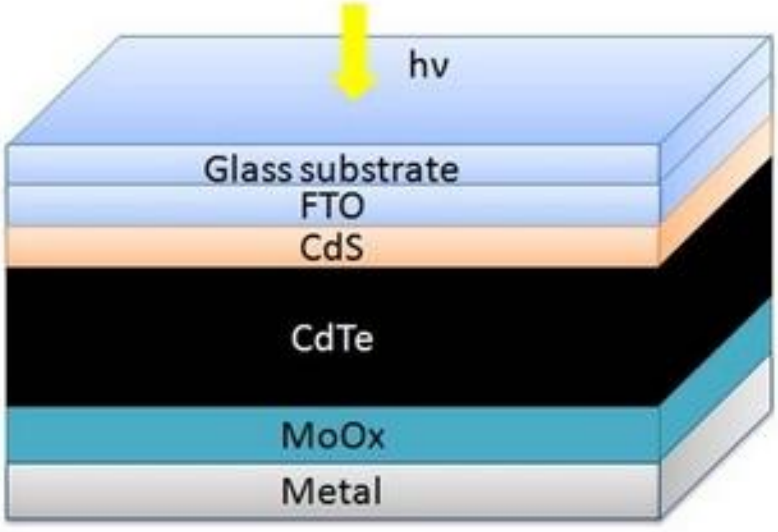
Single-hkl

Stress in a Solar cell semiconductor



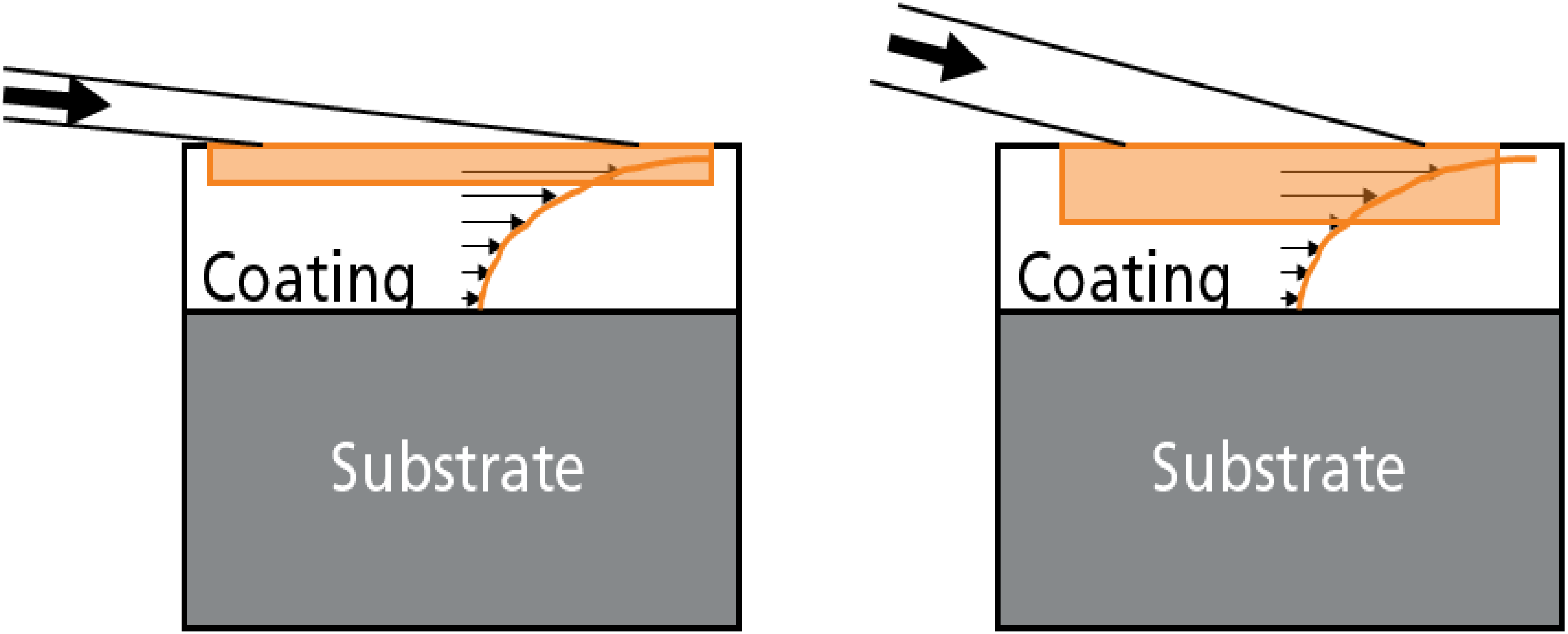
Multi-hkl



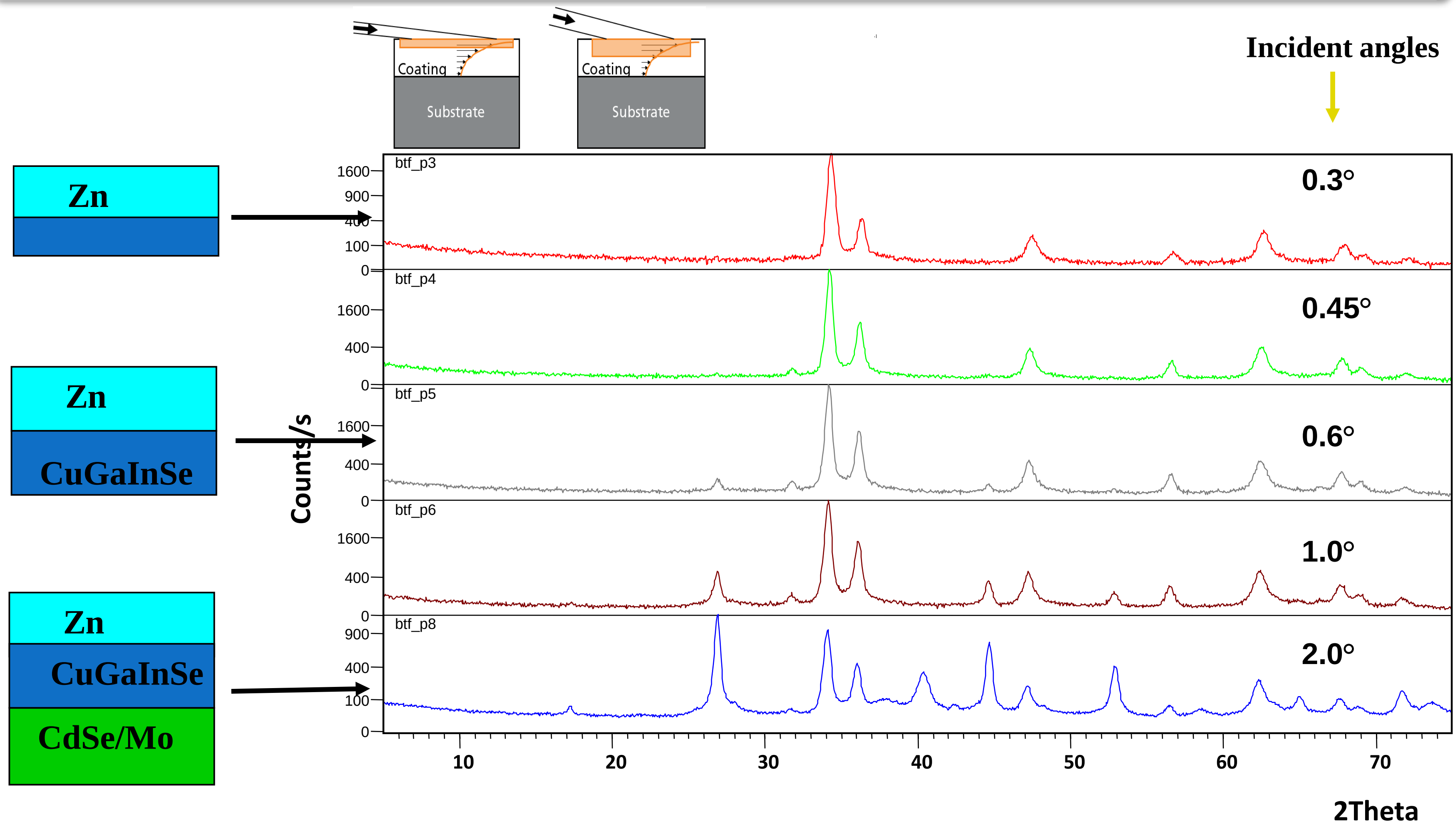


RESIDUAL STRESS & STRESS GRADIENTS IN SOLAR CELLS

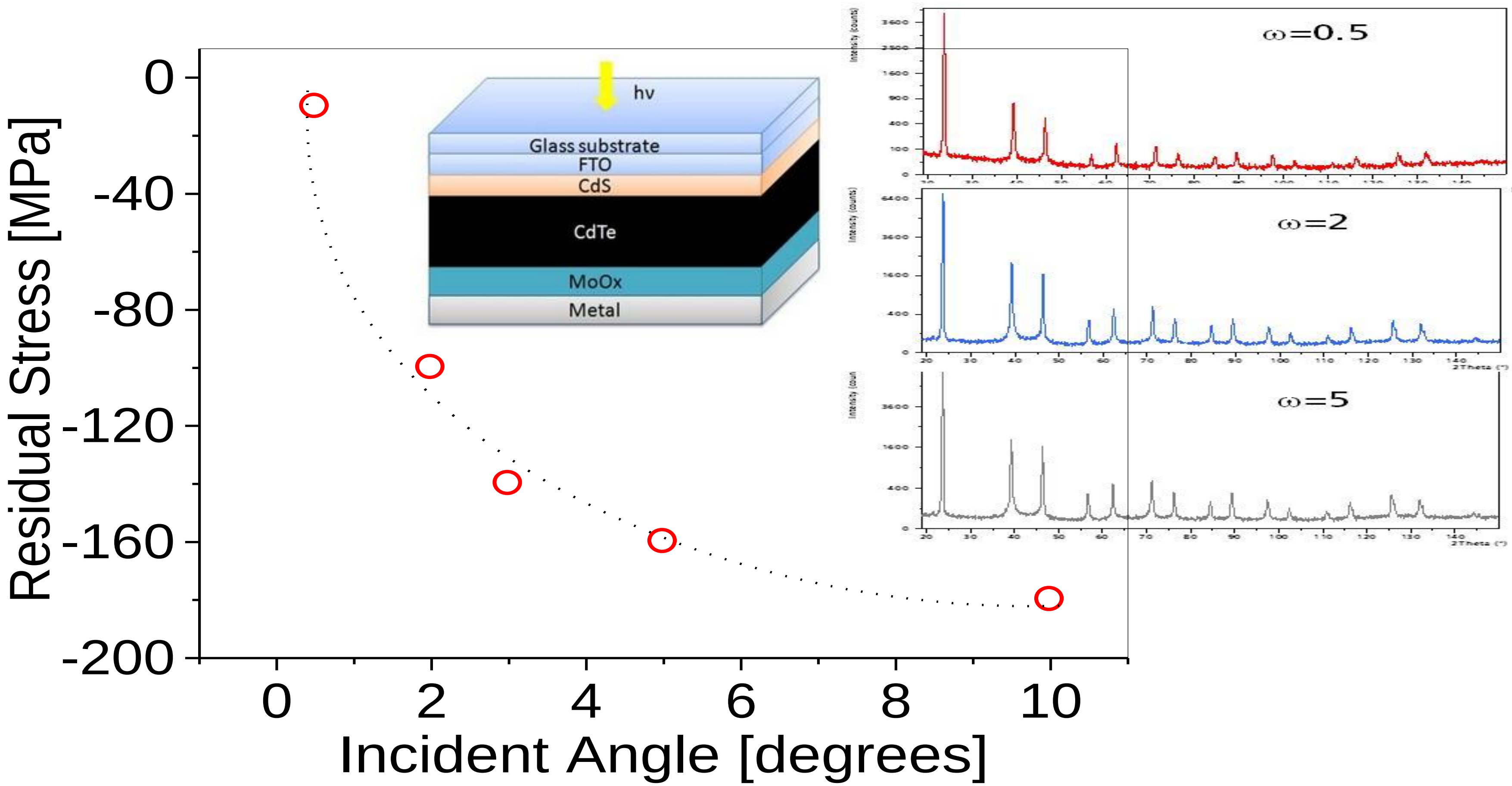
Residual stress analysis in layers



Depth-resolved phase analysis

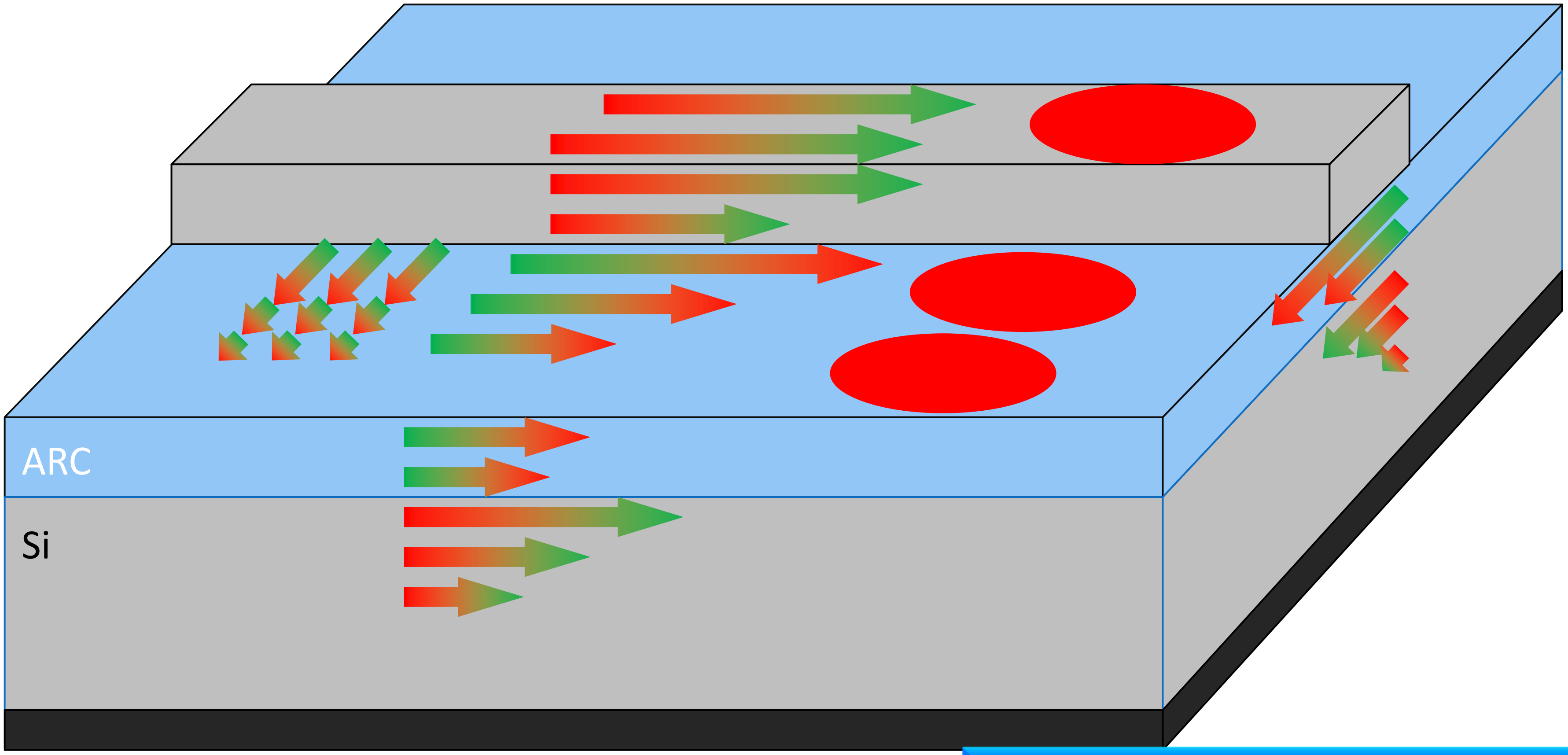


Residual Stress gradient on CdTe cell



RESIDUAL STRESS IN PV MODULE

Stress in a PV module



Single-hkl

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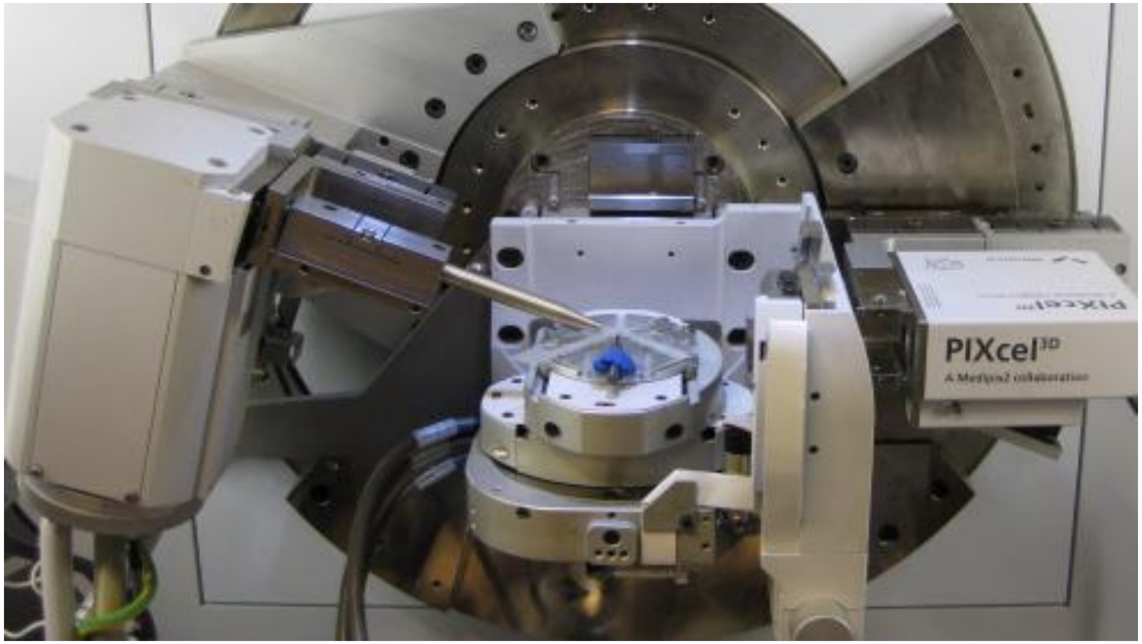
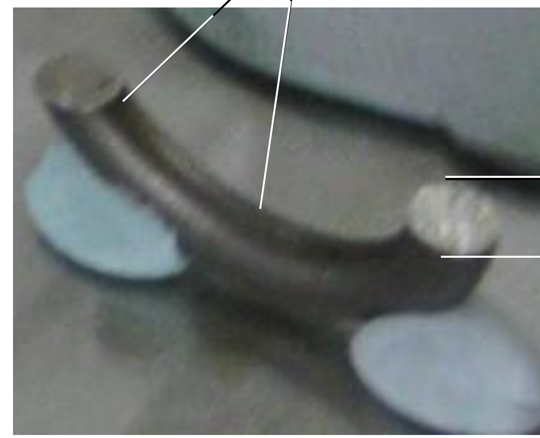
Equipment for micro-analysis



R ~8mm



3mm

Focusing X-ray lens
for intensity boost

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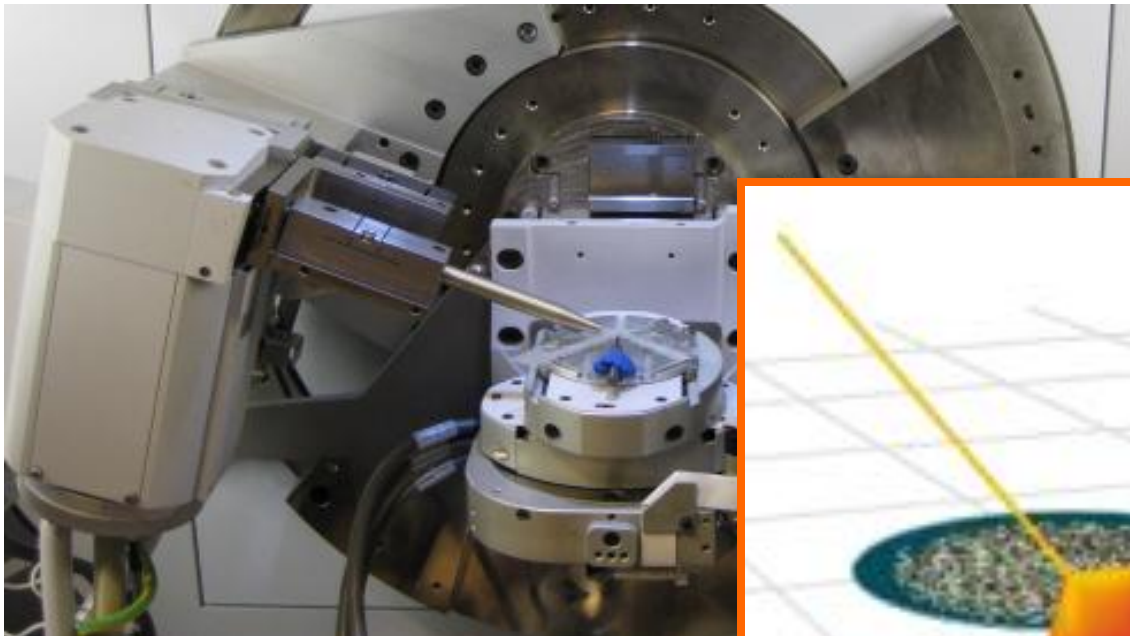
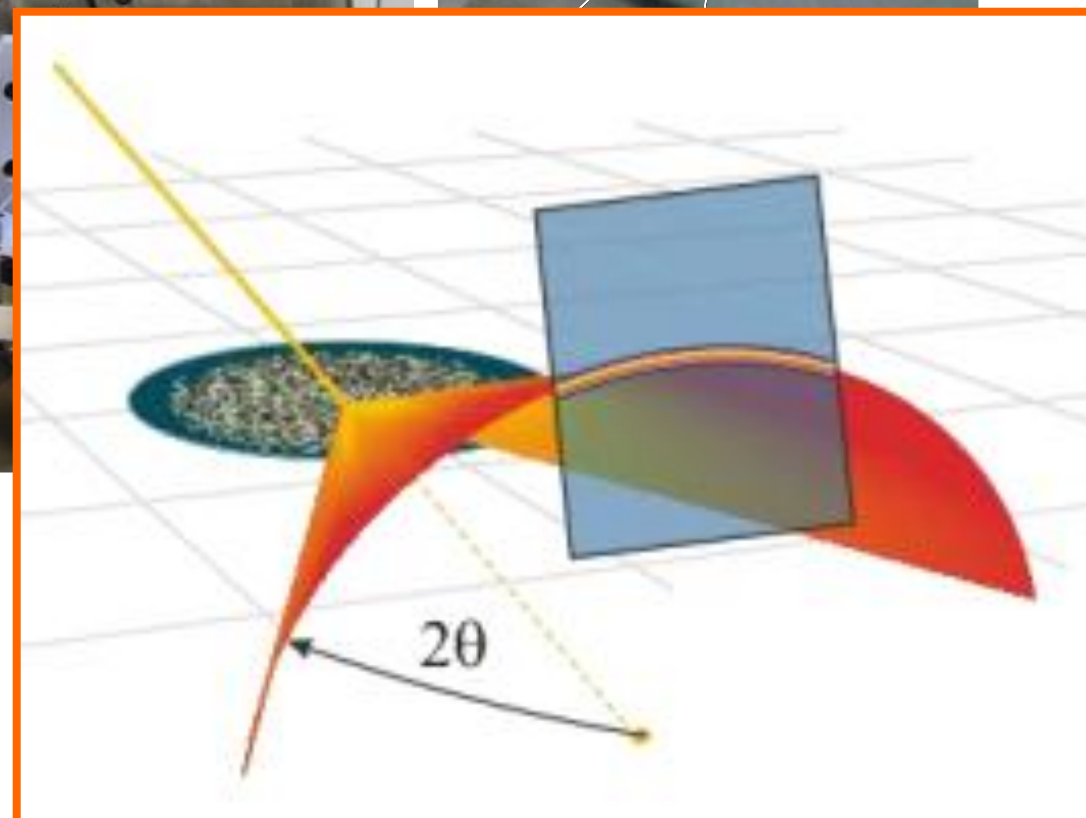
Equipment for micro-analysis

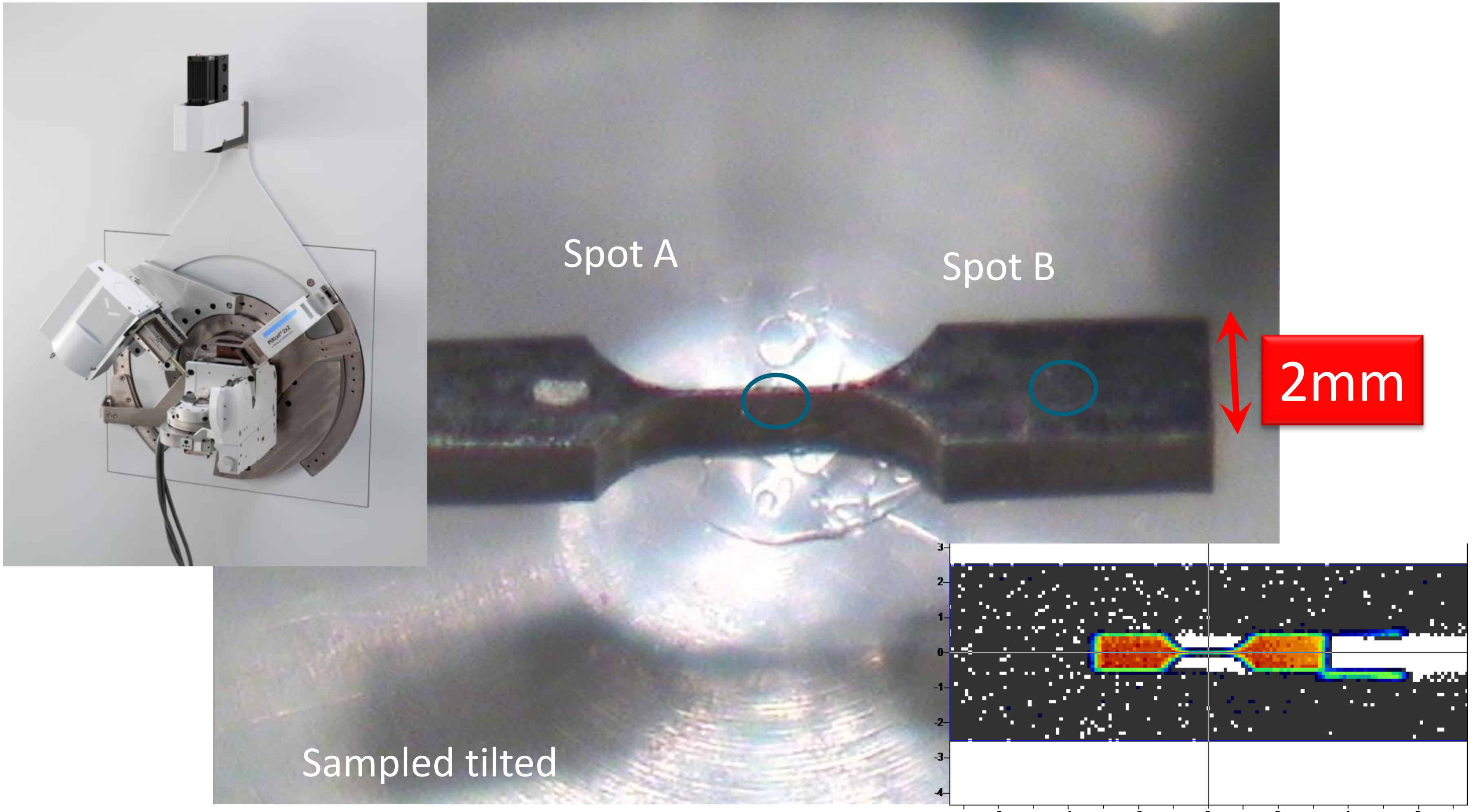


Focusing X-ray lens
for intensity boost

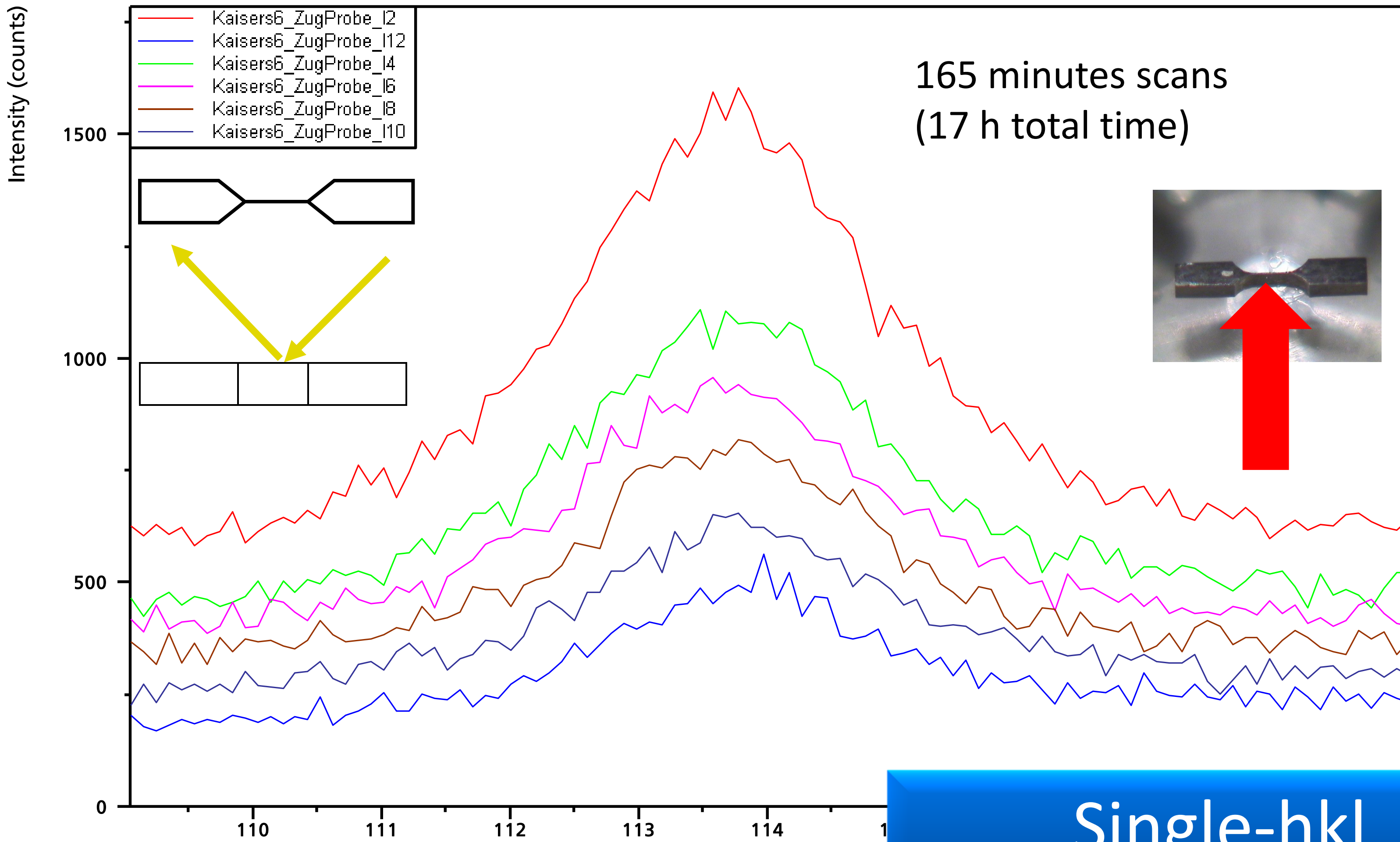
2D data collection to improve measurement time



Micro-Stress analysis on metallic sample

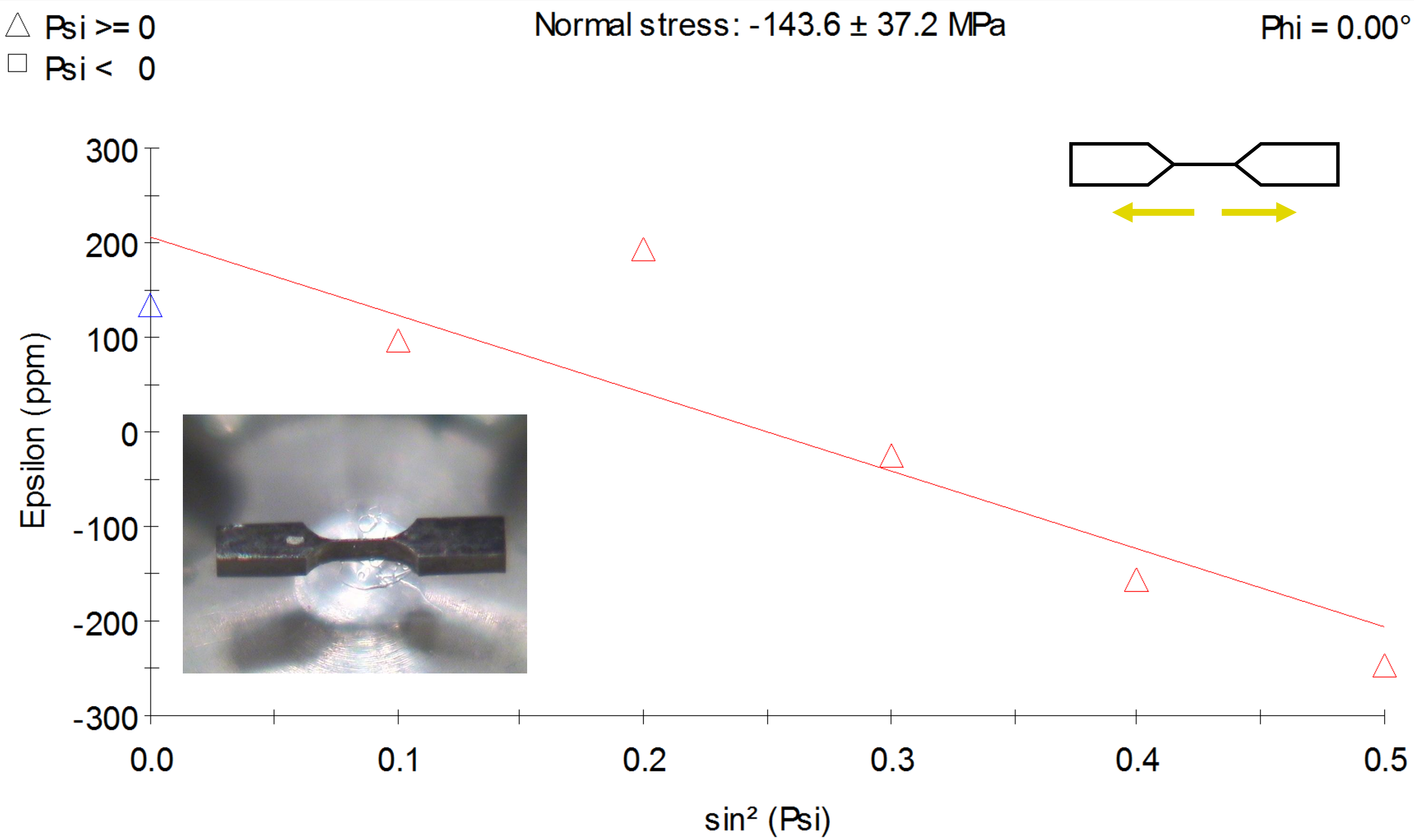


Micro-Stress determination on 50µm strip



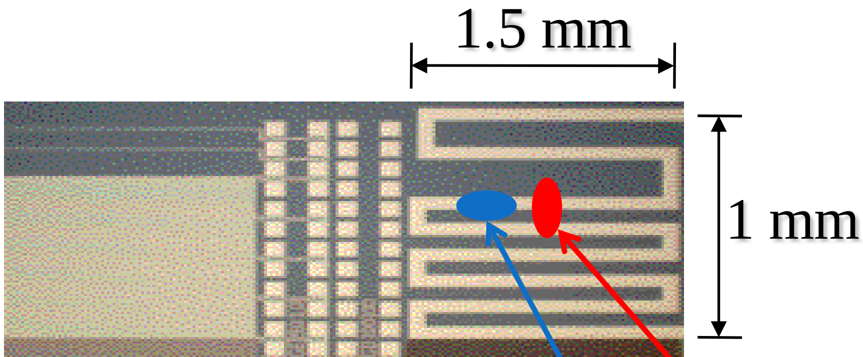
Single-hkl

Single hkl analysis on 50 µm strip



Micro-stress analysis on Cu damascene structure

Single-hkl

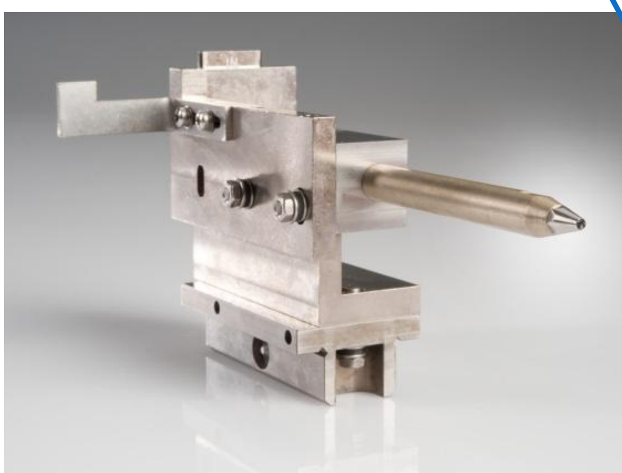


Cu (111) on Si (100)

Highly textured sample!

Stress analysis 90° to wire

Stress analysis along wire



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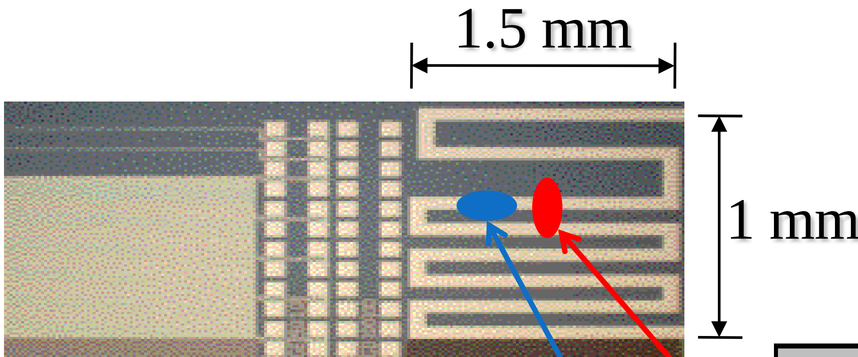
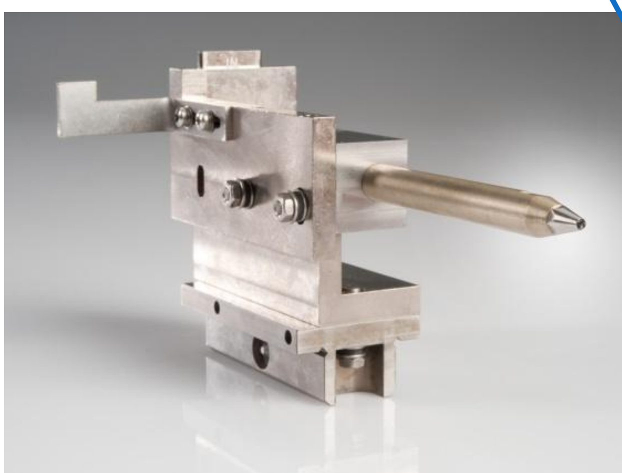
Micro-stress analysis on Cu damascene structure

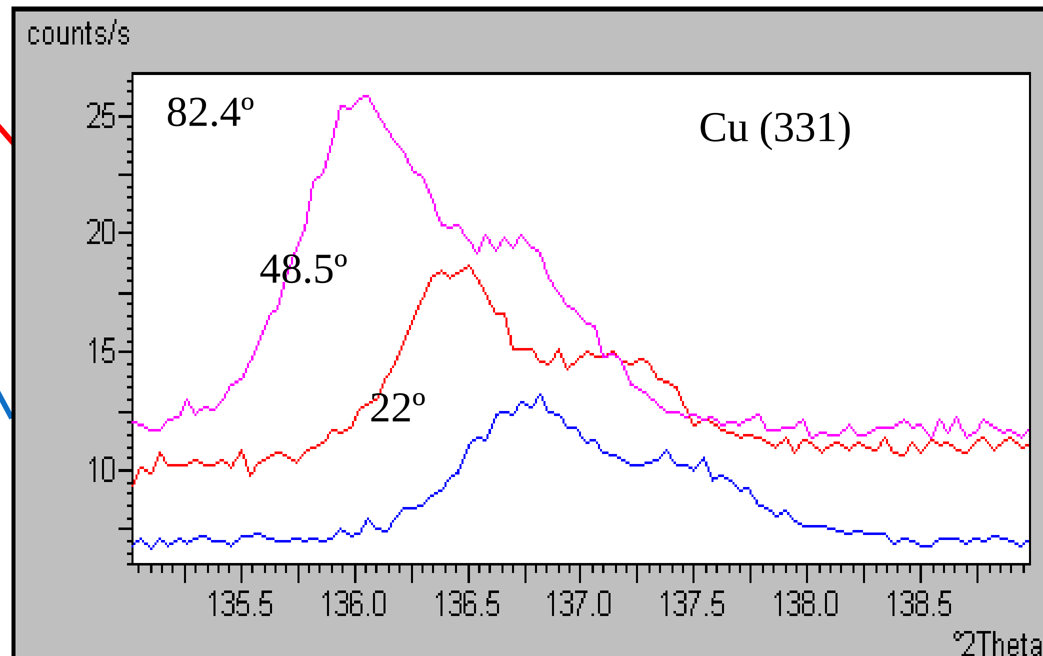


Cu (111) on Si (100)

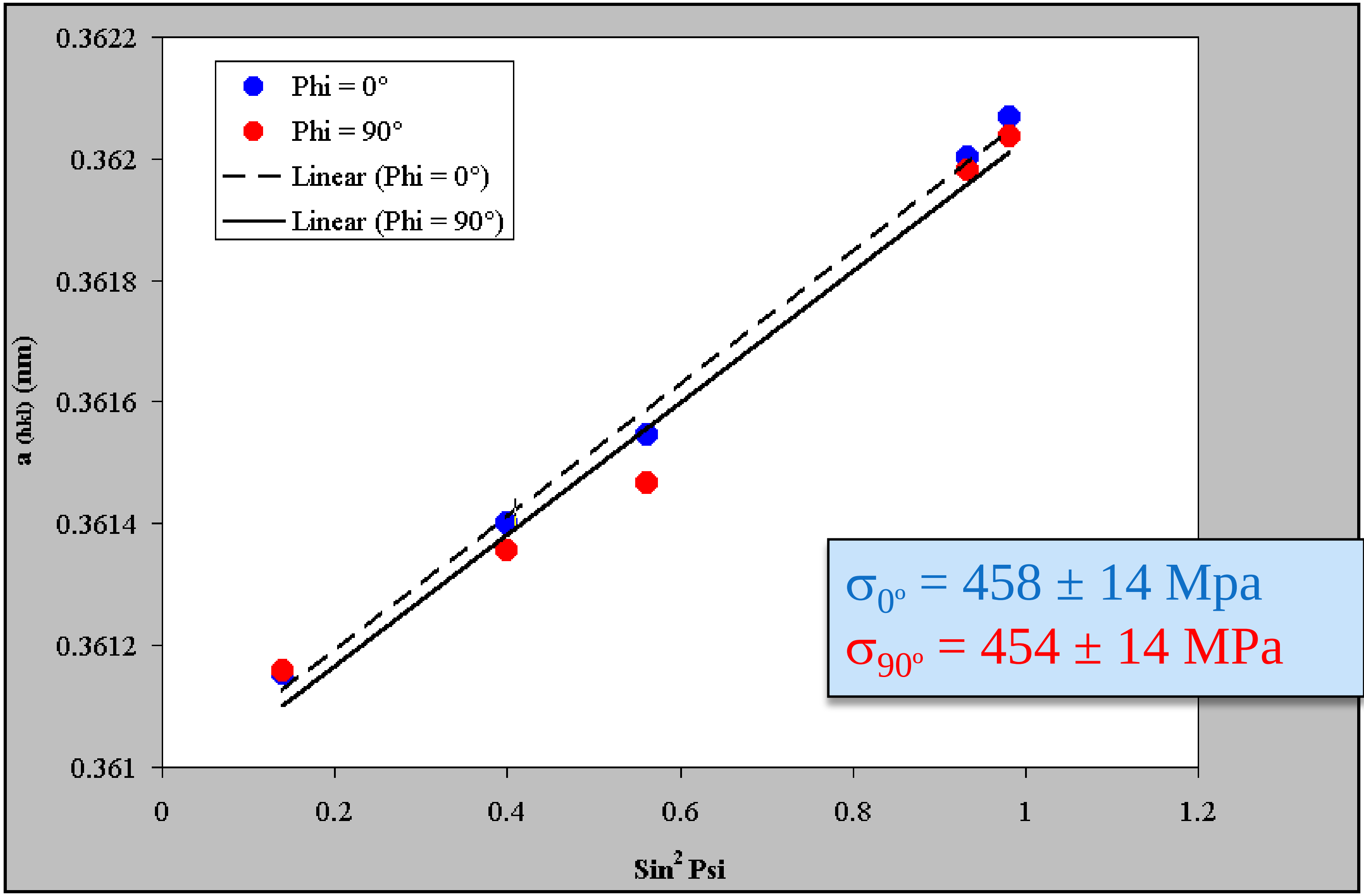
Single-hkl

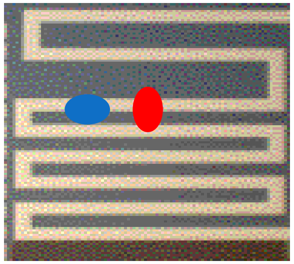
Highly textured sample!





Results on Cu damascene: 2 different orientations

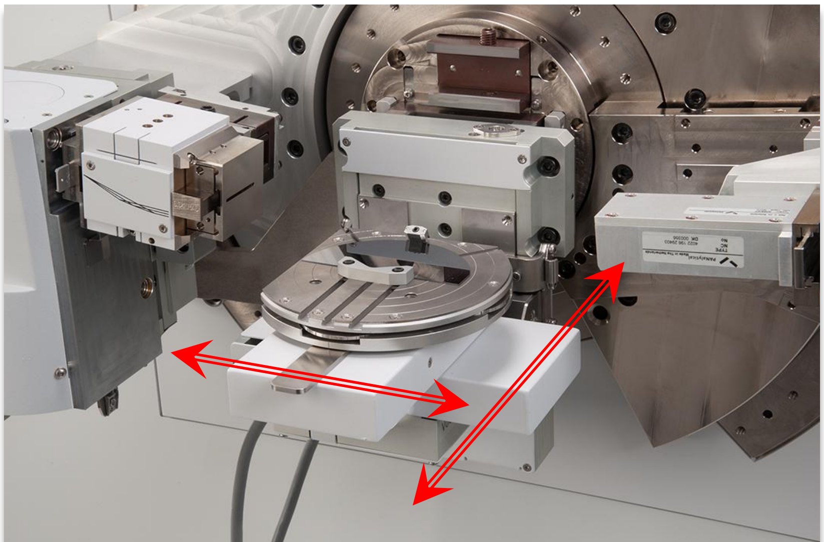


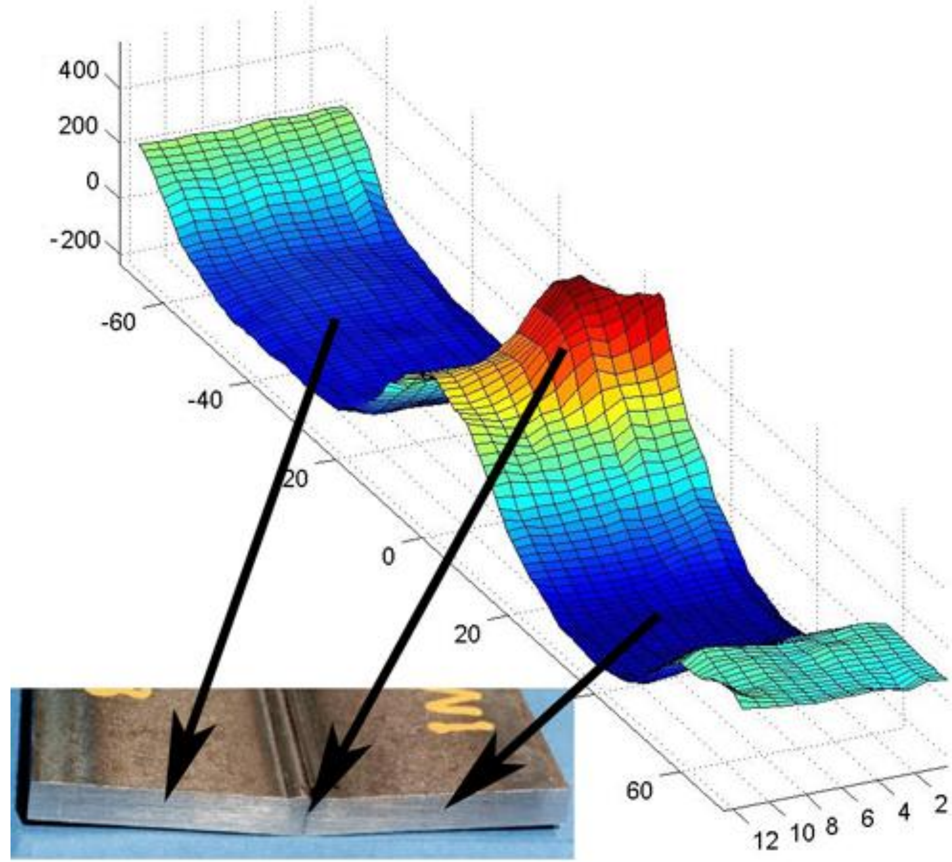


σ_{0^o} = 458 ± 14 Mpa

σ_{90^o} = 454 ± 14 MPa

Mapping & Micro-Stress analysis





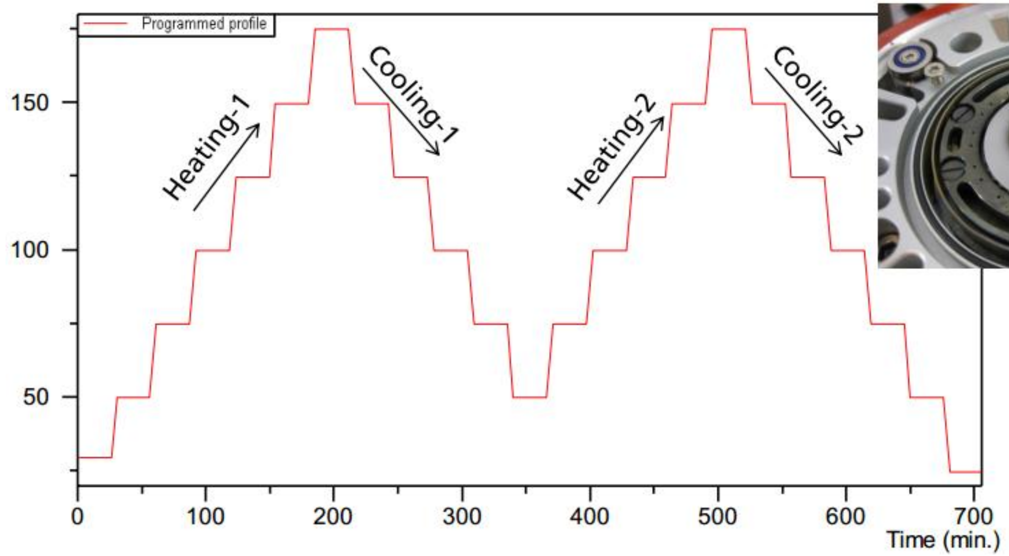
Line Scan

X-Y mapping & Chi/Omega tilt

Line Scan

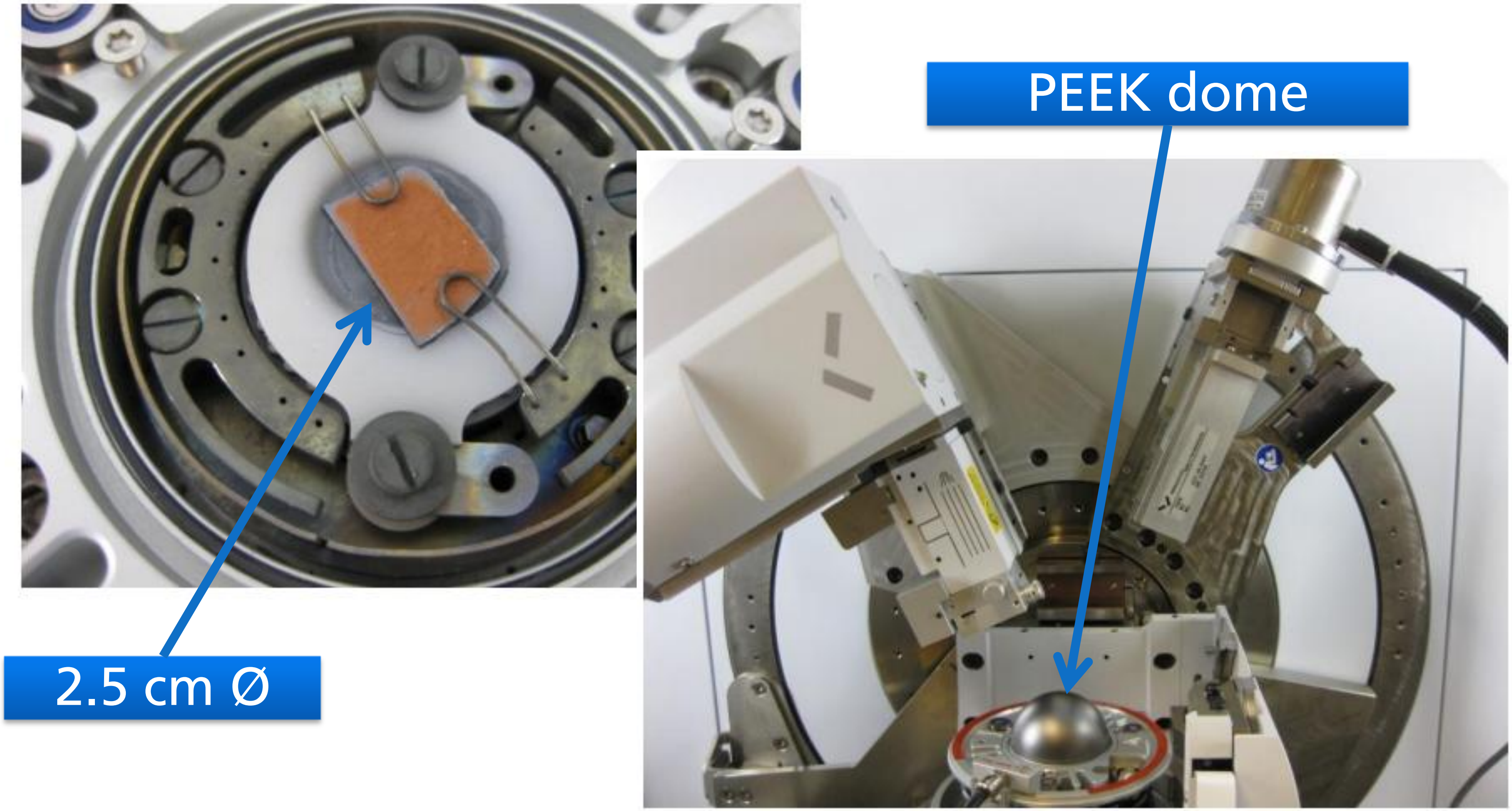
1x step + 6x Omega scan

Grid of 50 x 100 points = 30 000 scans!

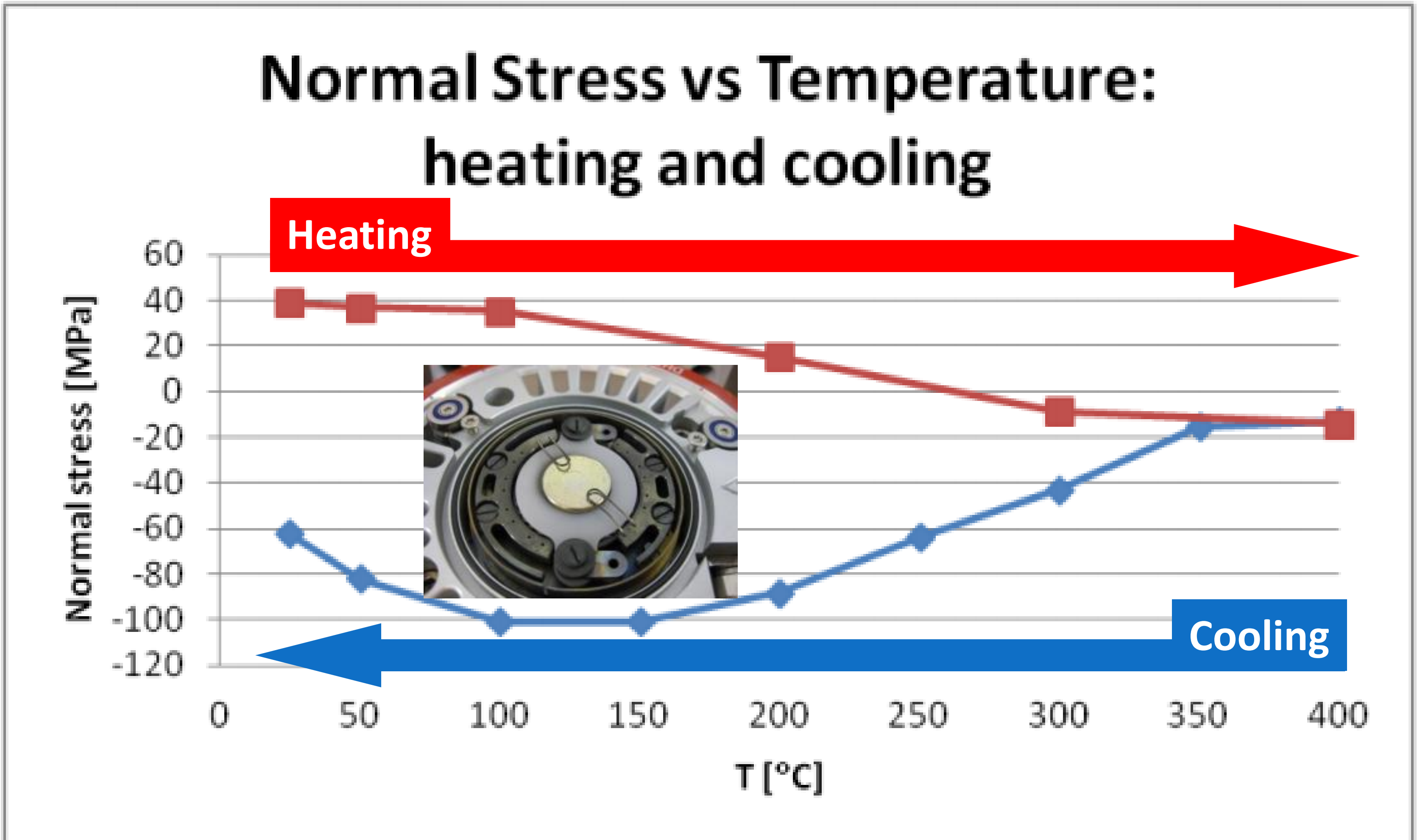


NON-AMBIENT RESIDUAL STRESS

Non-Ambient analysis



DHS1100 study (Cu alloy)



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Summary

X-ray diffraction is a versatile tool to determine residual stress in solar cells and PV modules

Residual stress can be determined both in layers as well as in ohmic contact structures

Stress gradients can be determined in layers (depth-resolved) and on layer surfaces (spatially resolved mapping)

On busbars and ohmic contacts, one can determine bulk stress only (by µ-XRD)

In-situ studies at non-ambient conditions are helpful to understand thermal processes