Synchrotron Radiation X-Ray Microdiffraction of Pb-free solders

N. Tamura

Advanced Light Source,

Lawrence Berkeley National Laboratory

Collaborators:

W.J. Choi, T.Y. Lee, A. Wu, K.-N. Tu, UCLA

W.A. Caldwell, R. S. Celestre, LBNL

Y. Y. Bong, and Luu Nguyen, National Semiconductor Corporation

Outline

1.- Introducing Scanning X-ray Microdiffraction (μSXRD)

2.- Beamline 7.3.3. description

3.- Diffraction data analysis

4.- Study of Sn whiskers on Pb-free surface finish

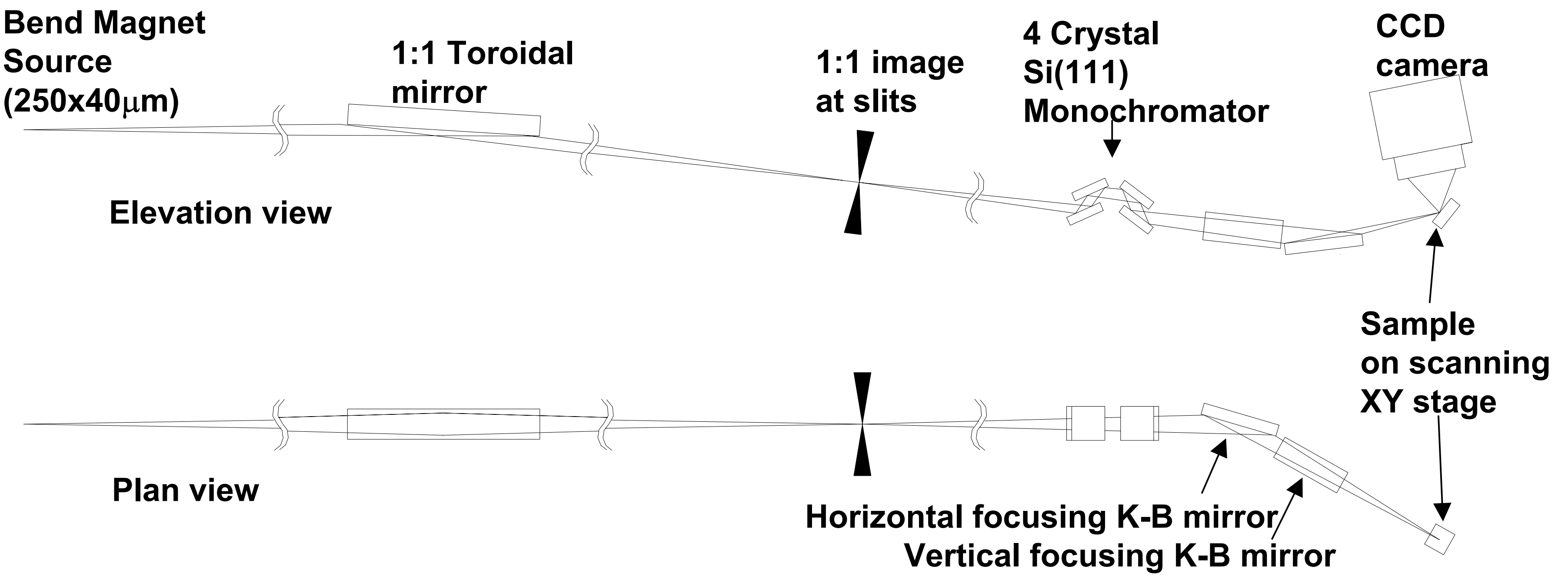
5.- Stress measurements in solder joints

6.- Conclusions

Scanning X-Ray Microdiffraction (μSXRD)

- Availability of high intensity submicron X-ray beam
  - High brilliance synchrotron sources
  - Progress in white/mono beam focusing optics
- Fast diffraction patterns collection with no sample rotation
  - Large 2D X-ray detector (CCD) with fast readout
- Automation
  - High precision XY sample stage
  - On-line diffraction pattern analysis algorithm

Schematic layout of the X-ray Microdiffraction Beamline (7.3.3.) at the ALS



Beam size on sample: 0.8x0.8 μm^2

Photon energy range: 5-14 keV

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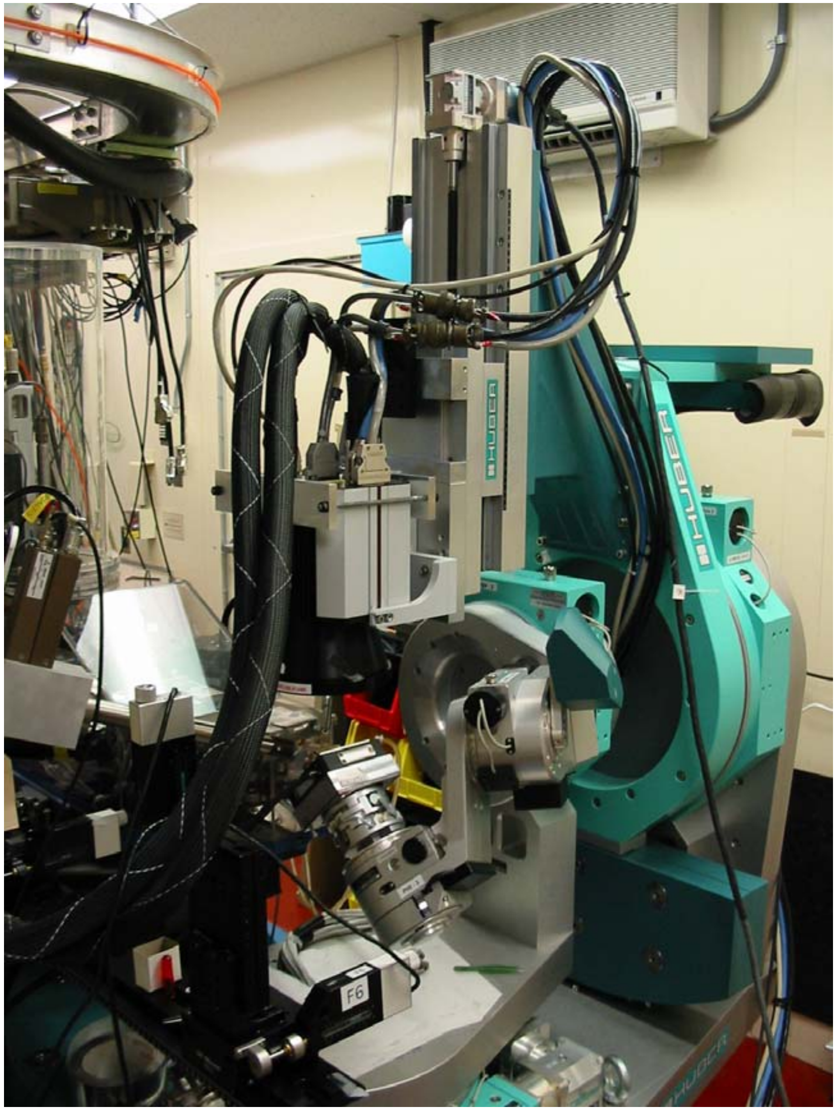
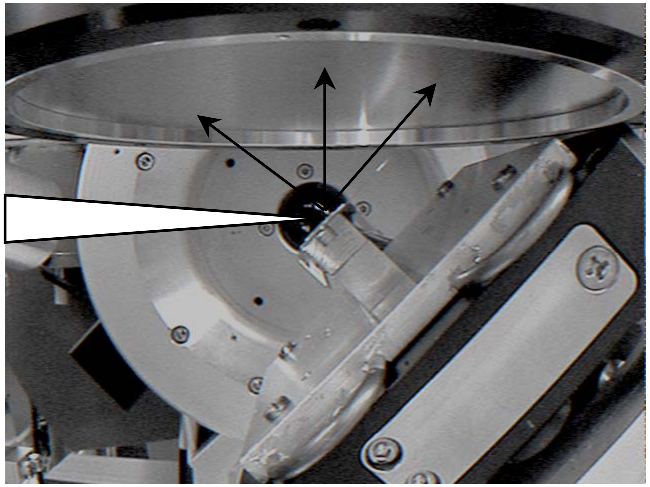




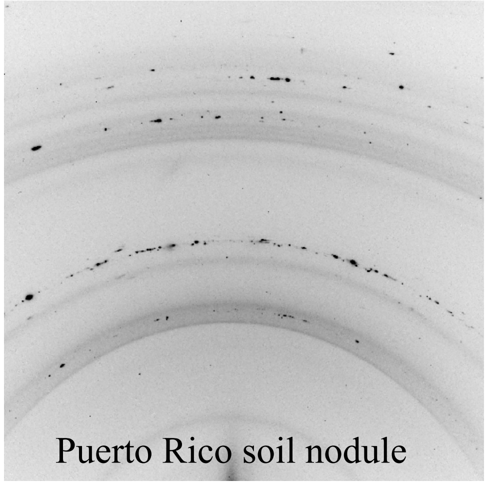
- Huber 6-circle diffractometer
- Bruker SMART 6000 CCD (9x9 cm^2 active area)
- HP Ge EG&G ORTEC detector
- Sample mounted on a XYZ Huber stage and a PI Piezo stage
- Heating/Cooling stage

What information could be extracted from white/monochromatic μSXRD data ?

$La_{0.95}Sr_{0.05}Ga_{0.90}Mg_{0.10}O_{3-x}$

White beam (Laue) patterns

- Orientation imaging
- Stress mapping (complete stress tensor)
- Microtopography



Puerto Rico soil nodule

Monochromatic beam (Debye Scherrer Rings) patterns

- Crystalline phases distribution
- Stress mapping

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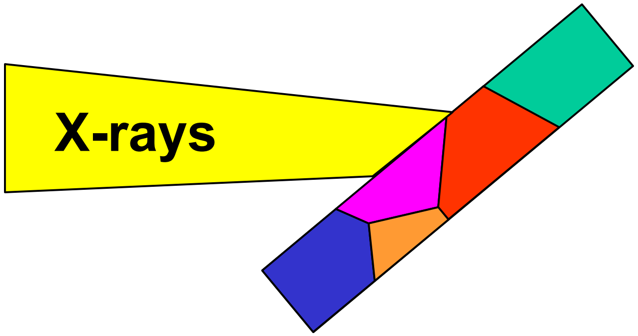
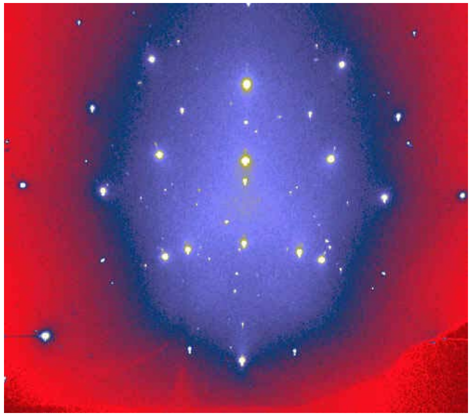
Grain size > or ~ beam size

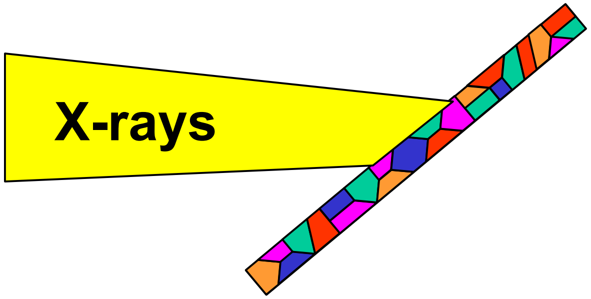


White beam μSXRD

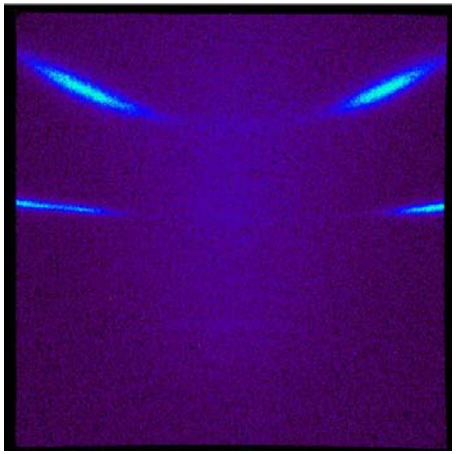


- Orientation imaging
- Strain/Stress map
- Microtopography

Grain size << beam size

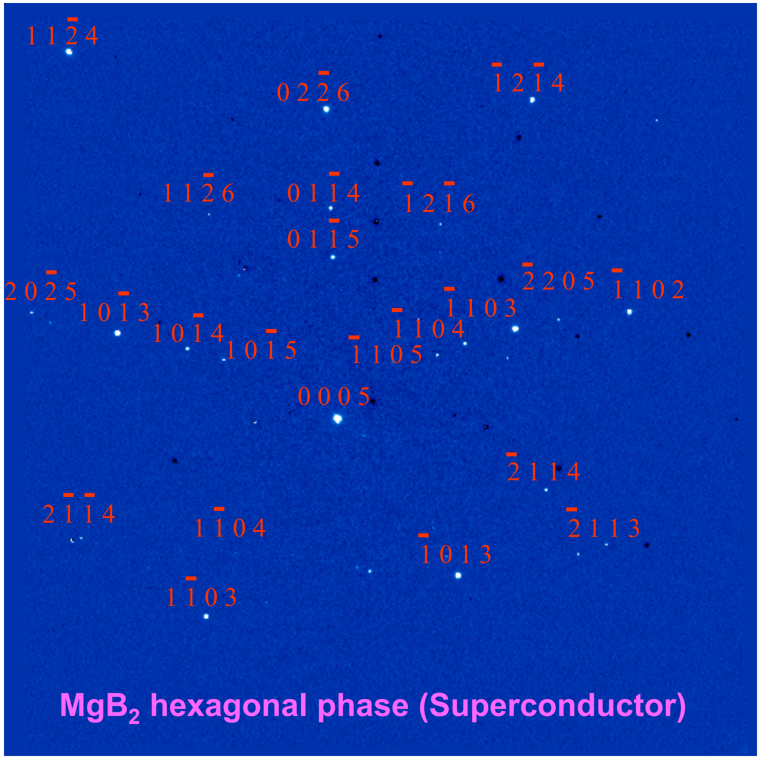


Monochromatic μSXRD



- Strain/Stress map
- Phases distribution map

White Beam (Laue) pattern analysis



MgB_2 hexagonal phase (Superconductor)

- Automated Peak finding and fitting routines

- Geometrical calibration of distances using an "unstrained" reference

- Automated indexation (single or multi-grains)

  • Orientation matrix

- Peak position deviations from unstrained positions

  • Unit cell deformation/Deviatoric strain tensor ε'_{ij}:

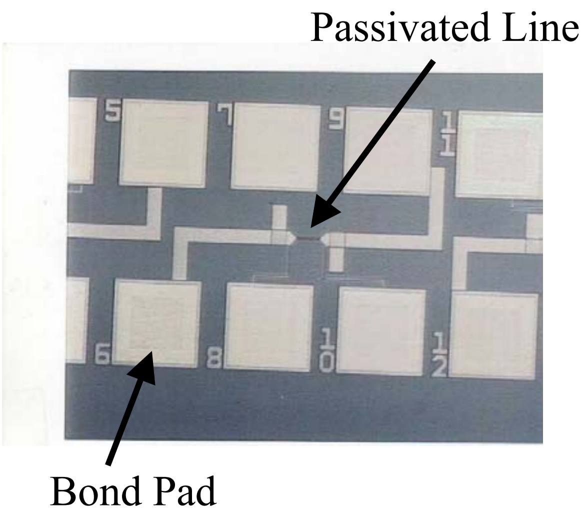
$$\varepsilon_{ij} = \varepsilon'_{ij} + \Delta\,, \qquad \Delta = \delta\, I_{ij}$$

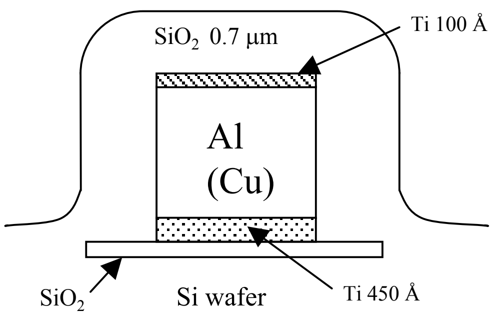
$$\varepsilon'_{11} + \varepsilon'_{22} + \varepsilon'_{33} = 0$$

  • One energy measurement will determined the absolute strain tensor

- Stress tensor: $\sigma_{ij} = C_{ijkl}\,\varepsilon_{kl}$

Orientation imaging and stress mapping of Al (0.5 wt%Cu) thin films and lines

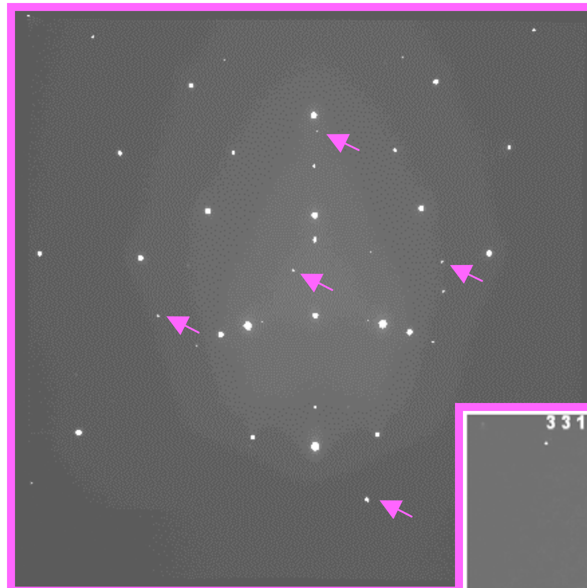




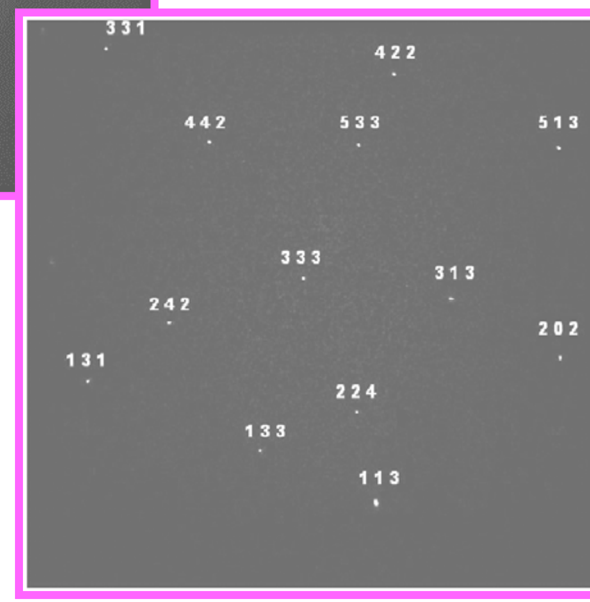
Thickness: 0.75 µm

Length: 30 µm

Width: 0.7, 4.1 µm



Si + Al "raw" pattern



Indexed Al pattern (Si peaks digitally subtracted)

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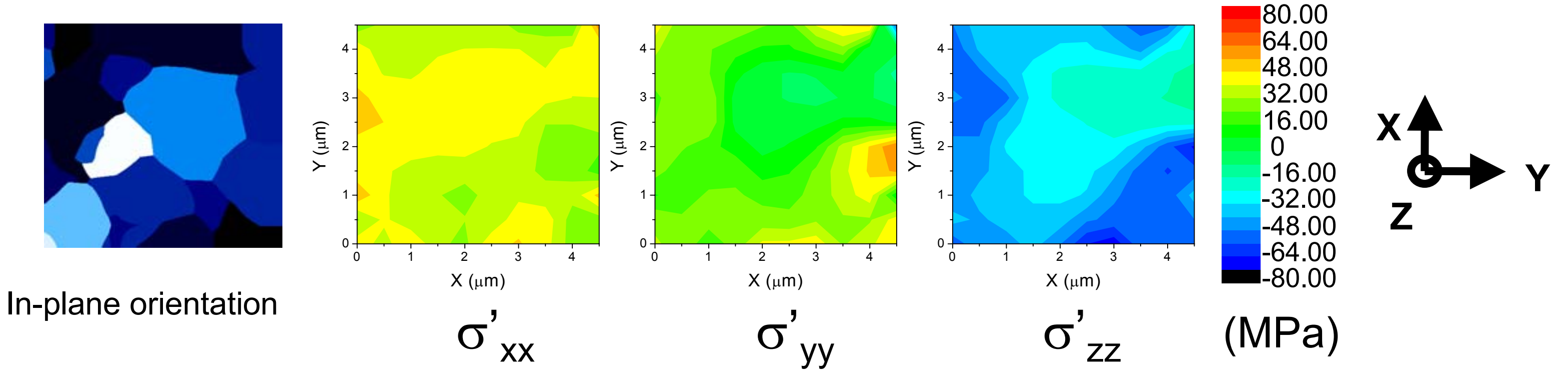
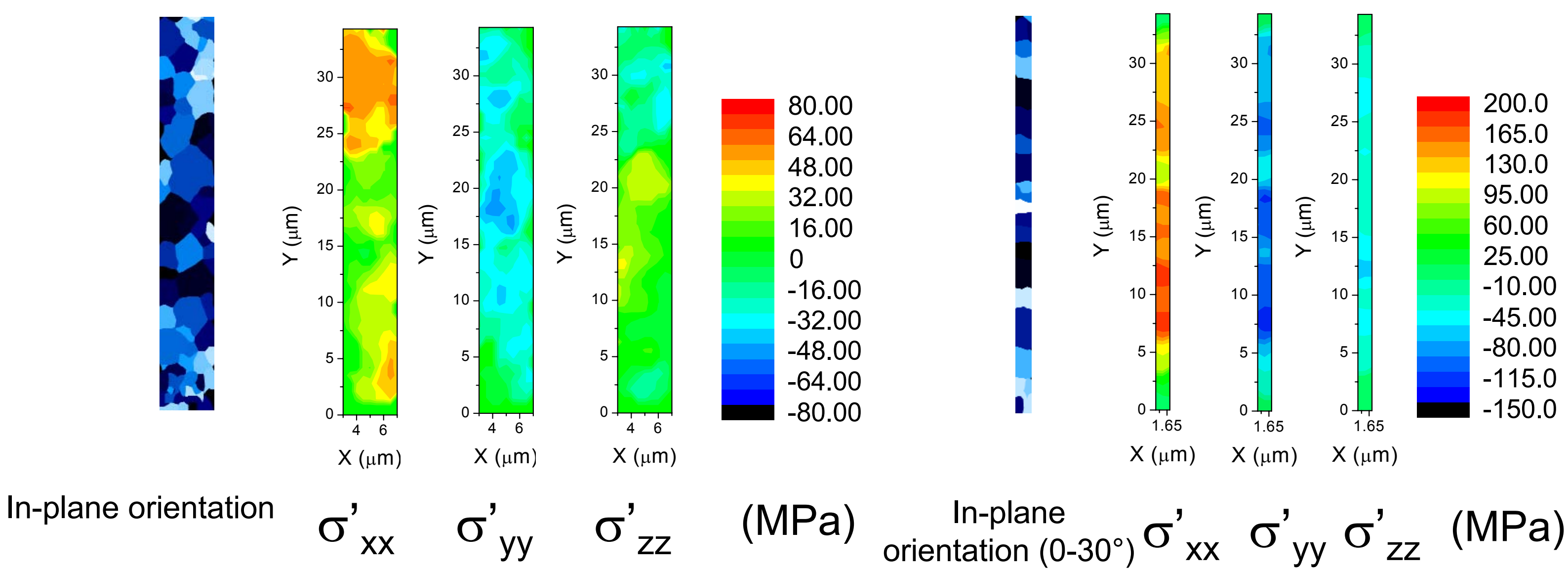
Orientation imaging and stress mapping of Al (0.5 wt%Cu) thin films and lines

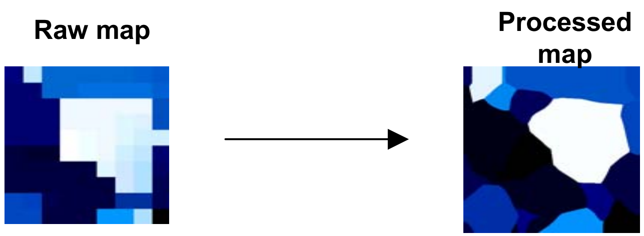




N. Tamura et al., *Rev. Sci. Inst.* **73** (2002) 1369

Orientation imaging and stress mapping of Al (0.5 wt%Cu) thin films and lines: remarks

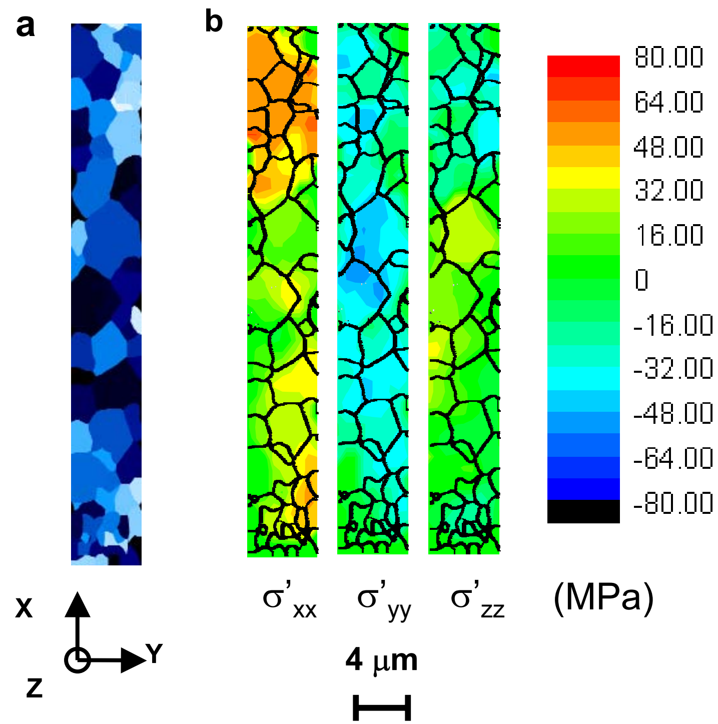
1) "Smoothing" by intersecting the interpolated profiles of each grain



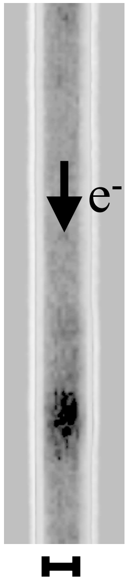
Al(Cu) pad: 5x5 μm, 0.5 μm step

2) Advantage over EBSD and FIB for buried samples and stress sensitivity

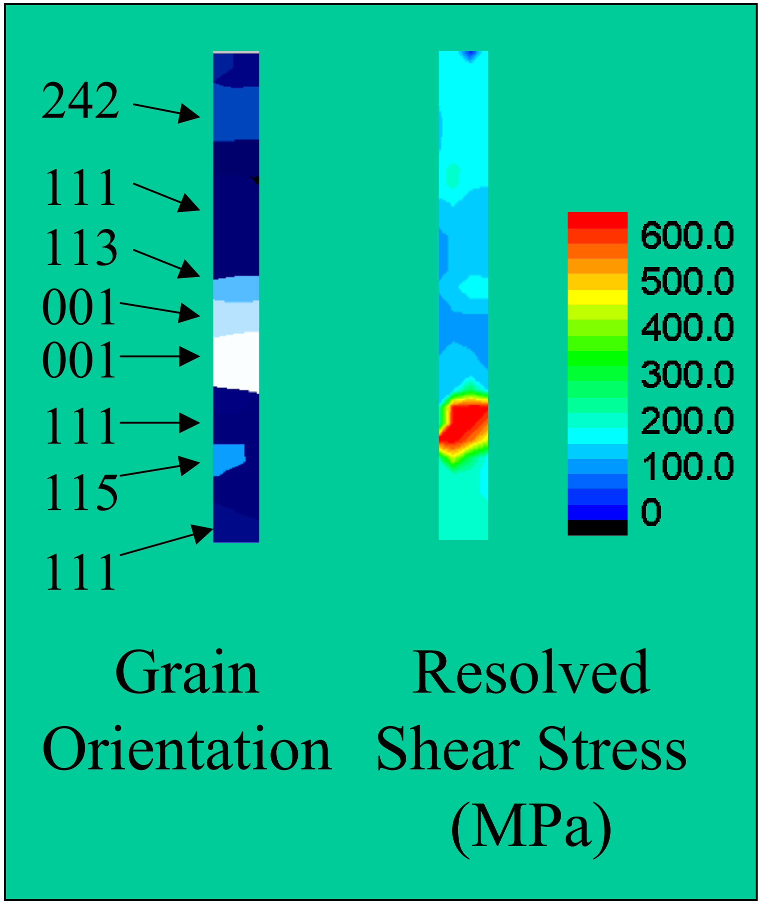
3) Stress and grain orientations can be directly correlated. Inhomogeneities in the stress distribution with large inter and intragranular stress gradients



Electromigration induced build-up regions in Damascene Cu lines (length: 300 μm, width: 1.1 μm, thickness: 0.75 μm)

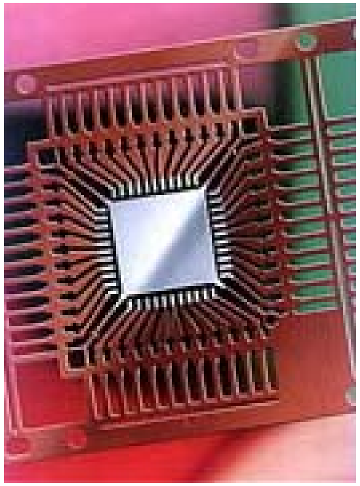


HVSEM



- Bamboo Type structure
- HVSEM shows electromigration induced metal accumulation regions
- μSXRD shows dramatic stress increase at build ups
- Anisotropy of surface diffusion
- Grain orientations show that localized metal accumulation appears at flux divergence points on the surface (necessary condition)

N. Meier Chang, PhD Thesis, Stanford University (2002)



Whisker growth on Pb-free solder coated leadframe

- Cu leadframe for external connection of packaged chip
- Use of Pb-free solder (Sn, SnCu, SnAg, SnBi, …) finish to enhance wetting
- Problem: spontaneous growth of Sn whisker (ex: growth rate of 1 mm/yr for SnCu finish) leading to short circuits

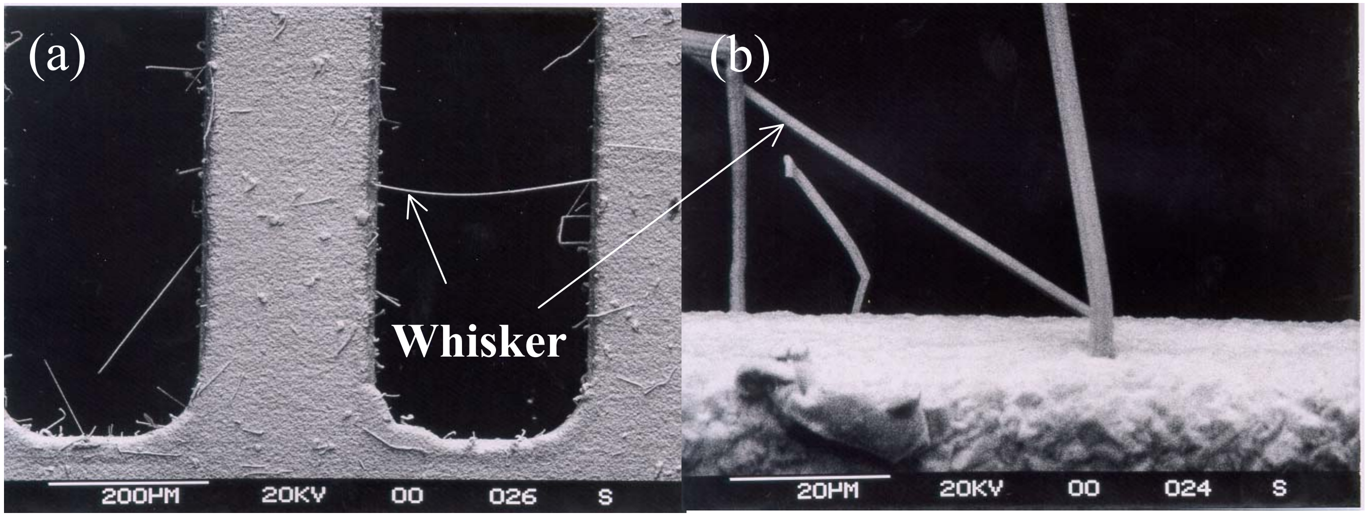
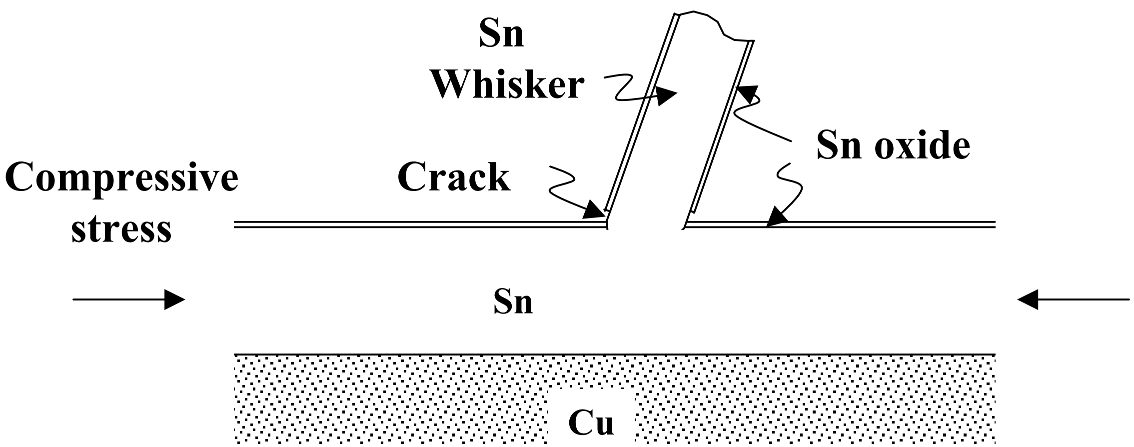


Fig. (a) Short circuit due to whisker (b) Magnified picture of whisker

Why do whisker grows ?

"Toothpaste" effect



Three necessary and sufficient conditions:

- a compressive stress

- a protective layer

- "weak" spots on the protective layer (structural discontinuities)

Protective layer: Sn oxide

• Whiskers and hillocks only grow when there is a protective oxide layer (ex: Sn, Al but not Au, Cu)

Origin of the compressive stress

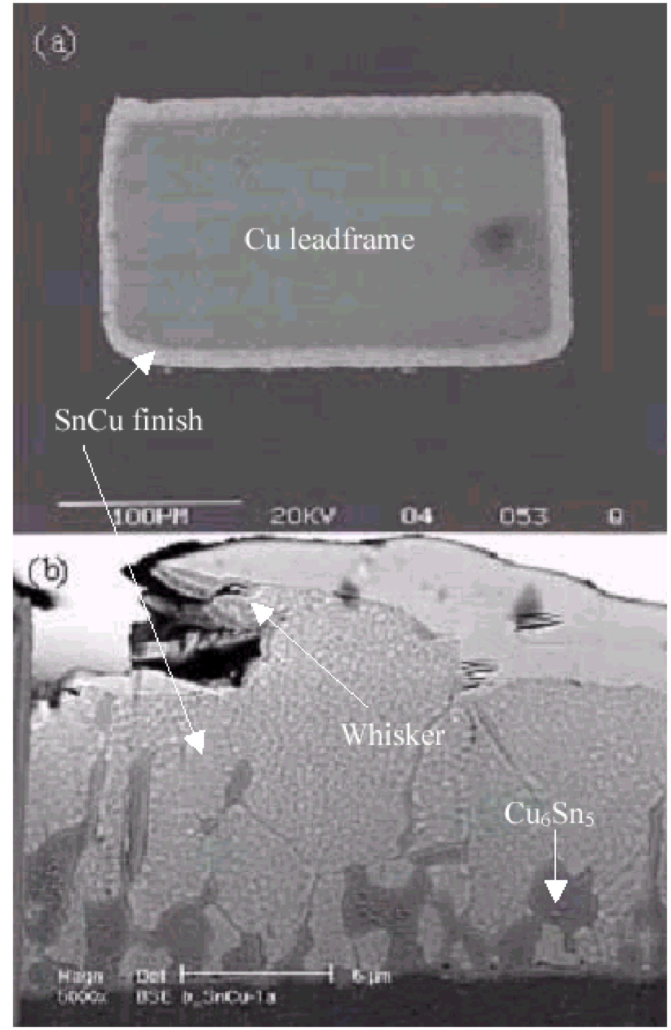
- Thermal stress: $CTE_{Sn} > CTE_{Cu}$

- Mechanical stress

Tm(Sn)= 232 °C => fast atomic diffusion at RT quickly relieve thermal and mechanical stress

- Chemical stress: formation of Cu_6Sn_3

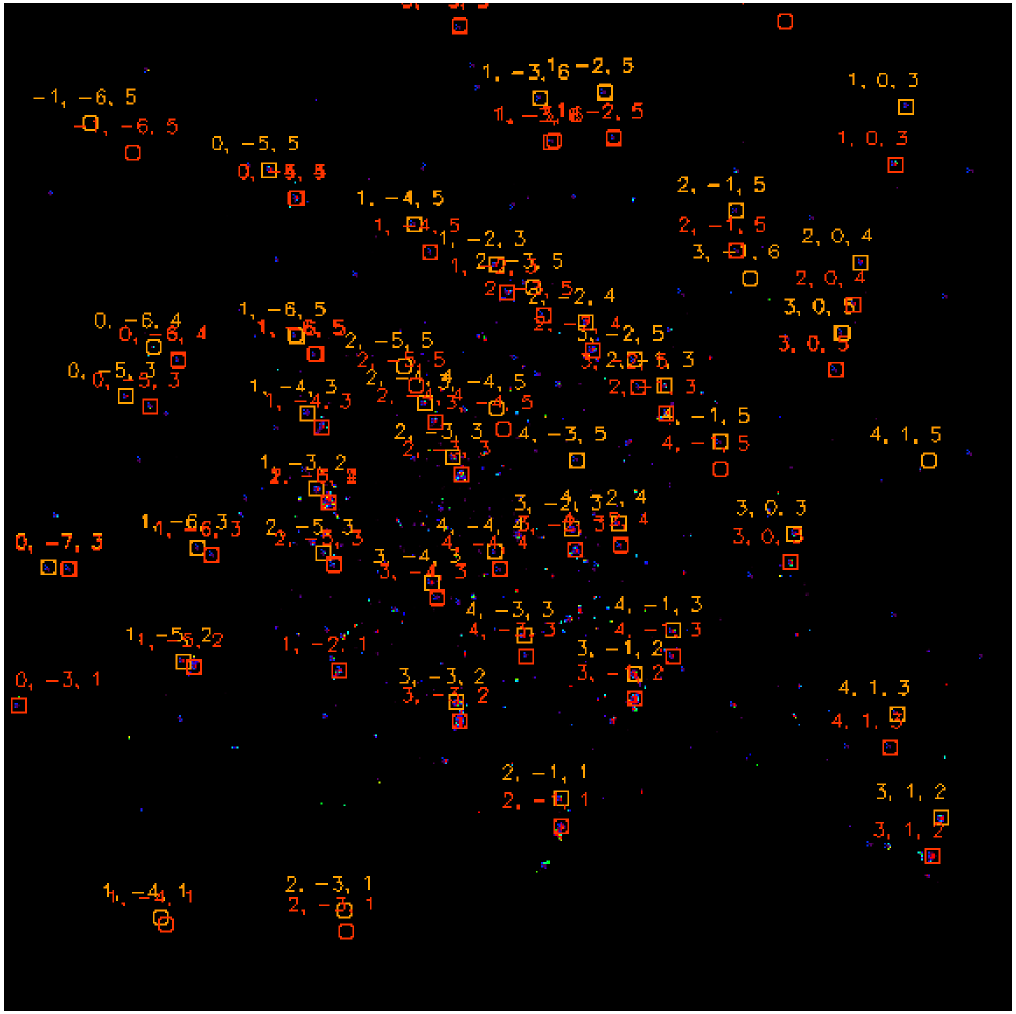
Poster: G.T.T. Sheng et al., Tin Whiskers Studied by Focused Ion Beam Imaging and Transmission Electron Microscopy



Cross sectional SEM

- To avoid whisker growth, a precise understanding of its mechanism is needed
- Experimental requirements:
  - – Detect structural discontinuities at the micron scale (what are the weak spots ?)
  - – Measure local stress gradients at the micron scale
- Sample is polycrystalline (grain size: ~ 1-5 μm)

=> well matched problem to be studied by μSXRD

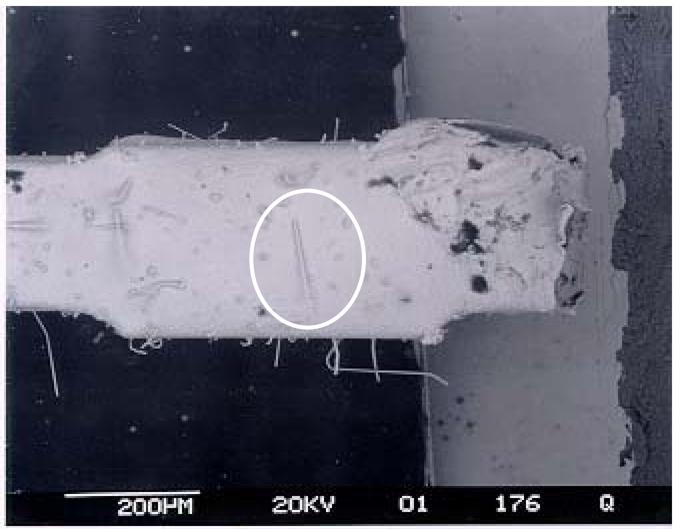


W.J. Choi et al., *IEEE, 52 ECTC Proc.* (2002) 628

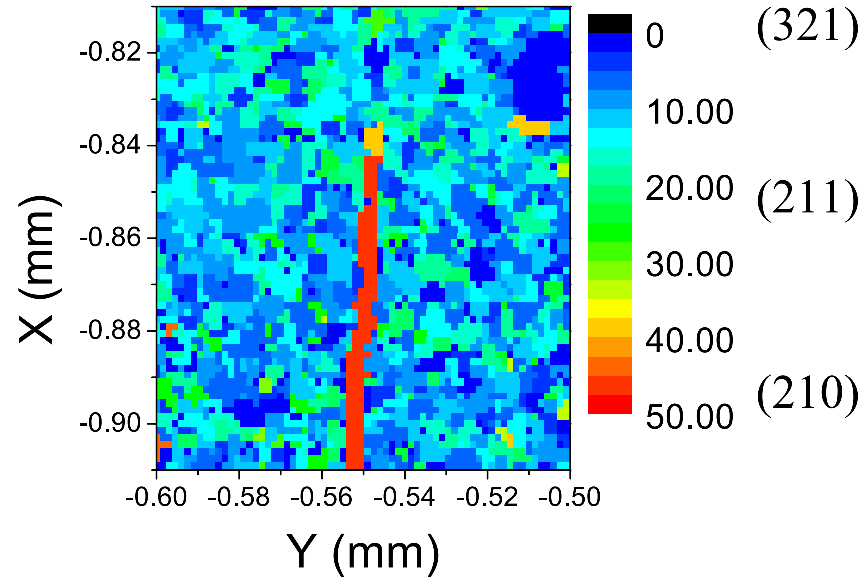
W.J. Choi et al., *J. Appl. Phys.* (2002) submitted

μSXRD grain orientation study: where do whiskers grow ?

μSXRD scan of a whisker root, 1.5 μm step size, 100x100 μm^2 area, 4489 Laue patterns



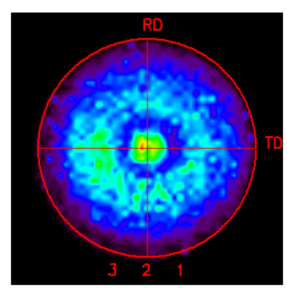
SEM image



μSXRD Orientation map

- Coating has a bad (321) fiber texture

- Whiskers grow from off-textured grains (structural discontinuities)



(321) pole figure

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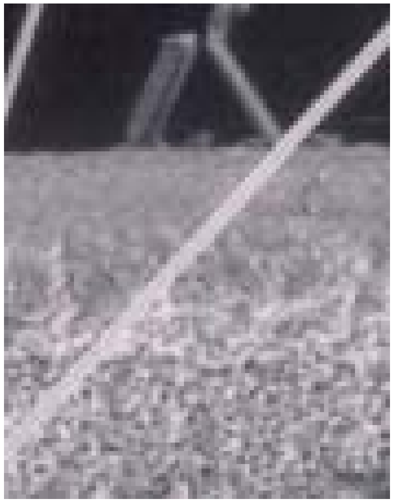
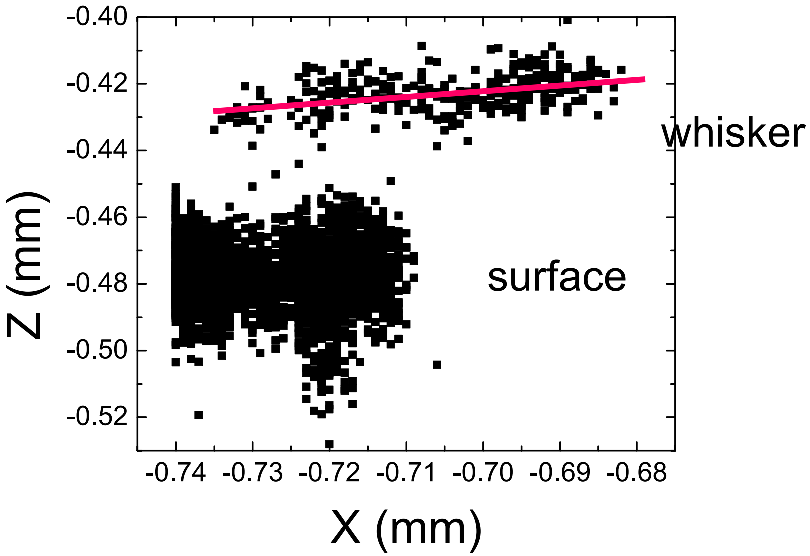
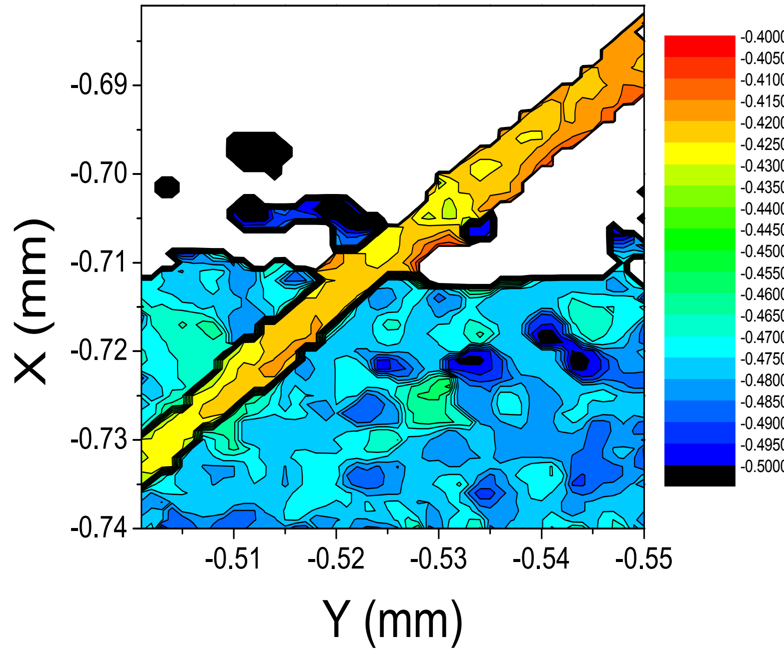
μSXRD grain orientation study: what is the growth direction ?





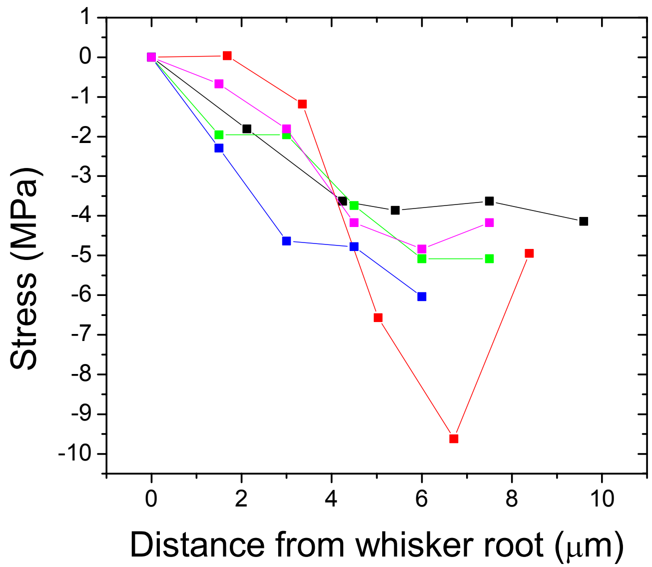


Whisker grain indexation => orientation matrix

Z position (depth) fits => Angle between whisker and sample surface

=> whisker growth direction (c-axis)

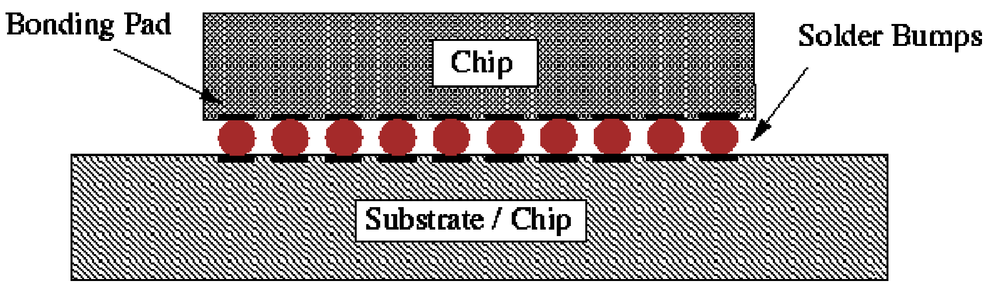
μSXRD Local stress measurements: what is the driving force for whisker growth ?



- Stress is inhomogeneous with intra and intergranular variations
- Stress is biaxial and confirmed to be compressive in average (~ - 15 MPa)
- Stress gradient observed around whisker root

Poster: W.J. Choi et al.
Synchrotron radiation Scanning X-ray micro-diffraction study of Sn whiskers on Pb-free surface finish

Future work: stress measurements in solder joints



• Flip-chip technology connects chip to substrate via solder bumps

• Although current density is low (~10 000 A/cm^2), diffusion in Sn-based solder is fast => electromigration induced failure is possible

• Current crowding effect, dissolution of IMC and UBM, local Joule heating, compositional gradient, ...

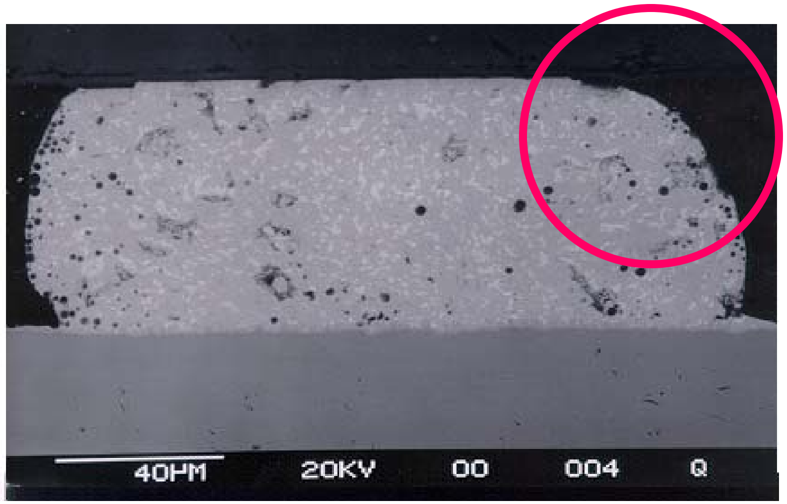
• Difference between chip CTE and substrate CTE can put solder joints under shear stress

• Thermal fatigue due to creep strain or plastic strain can also cause failure

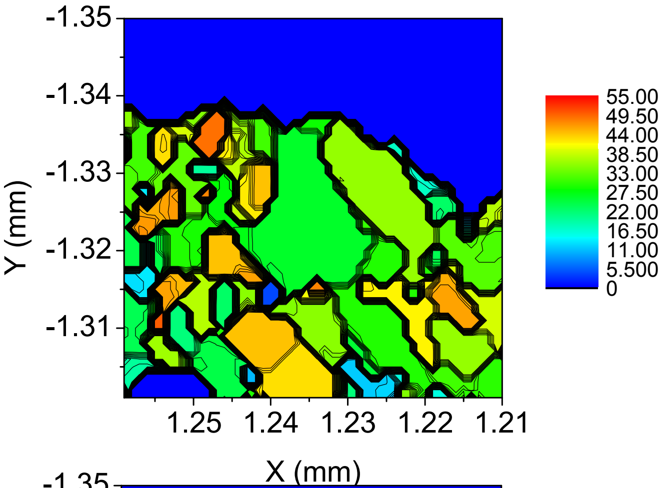
• Proposed study: local stress and stress gradient measurements in and in the vicinity of solder joints under applied constraints

μSXRD study of solder joints: preliminary data and feasability

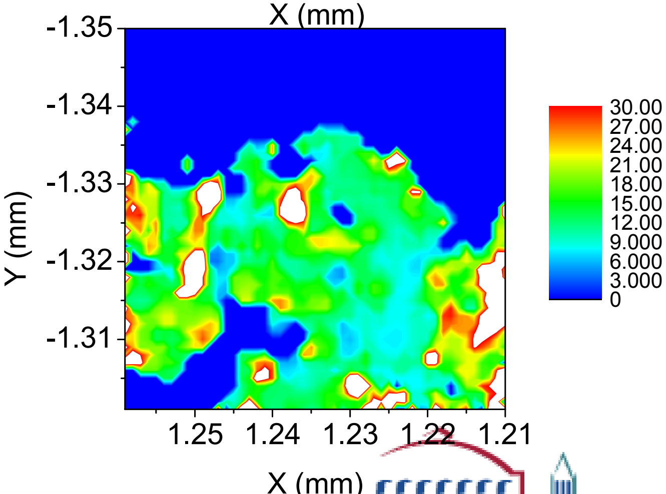
Orientation map



SnPb solder joint



Stress map



CONCLUSIONS

• μSXRD is a new experimental tool to study microstructure at the mesoscale range (0.1 - 100 mm)

• Application to the problem of whisker growth in Pb-free leadframe finish

  – stress in the finish is compressive in average

  – local stress gradient is the driving force for whisker growth

  – average texture of the finish is (321)

  – whisker grows at structural discontinuities (ex: off-oriented grains)

  – growth direction of whisker is mainly the c-axis

• Future work: spatially resolved stress measurements under applied constraints in Pb-free solder joints