Mechanical Stresses and Reliability Study of Cu Through-Silicon Via (TSV) Samples Fabricated by SK Hynix vs. SEMATECH using Synchrotron X-Ray Microdiffraction for 3-D Integration and Reliability

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Outline

- Background – Mechanical Stresses and Reliability/Performance Implications in 3-D Cu TSV Integration Schemes
- The Technique – Synchrotron X-Ray Submicron Diffraction (White and Monochromatic Beam)
- Experimental –
  - Mechanical Stresses in Cu TSV and Their Potential Impacts on 3-D Interconnect Reliability: SK Hynix vs. SEMATECH
  - Mechanical Stresses in Silicon Surrounding TSV and Their Potential Impacts on 3-D Interconnect Performance as well as Reliability: SK Hynix vs. SEMATECH
- Conclusions & Future Work

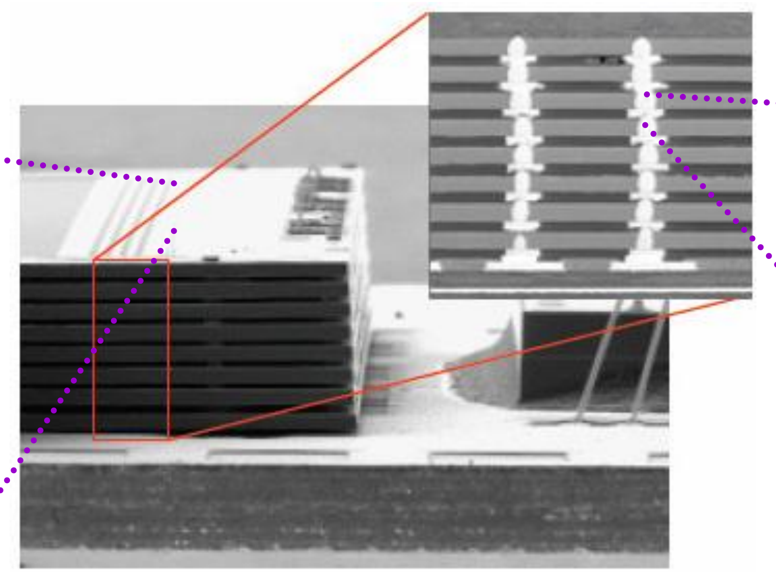
Impact to Reliability and Performance of Device

Si stress

Keep-away zone

Device must be kept away from the zone in which mobility is changed.

Si cracking

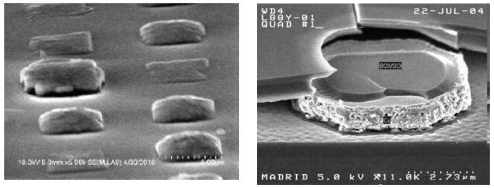


<Samsung Electronics>

Cu stress

Debonding, TSV cracking

TSV Pop-up, Bulging-up → Integration Issues

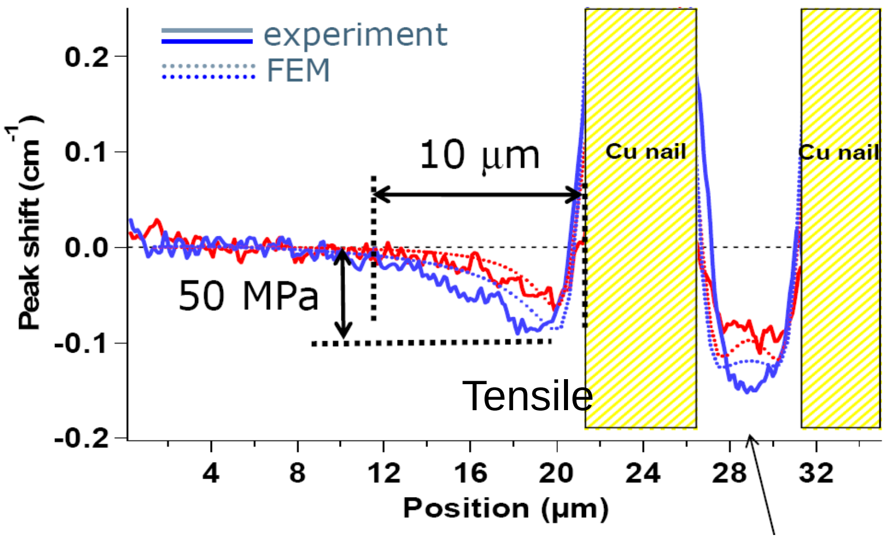


<Source: SEMATECH>

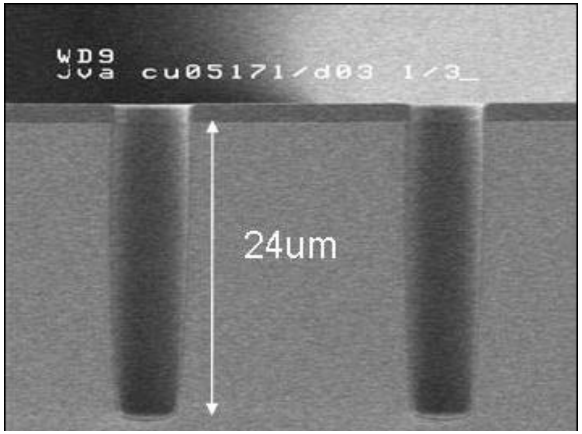
- Thermal stress of TSV → Si stress and Cu stress.
- Si stress (residual stress) → degradation of device performance.
- Cu stress (thermal stress) → mechanical failure of Cu TSV.

Stress of Si : µ-Raman spectroscopy

Okoro, *et al*., IRPS, 2010

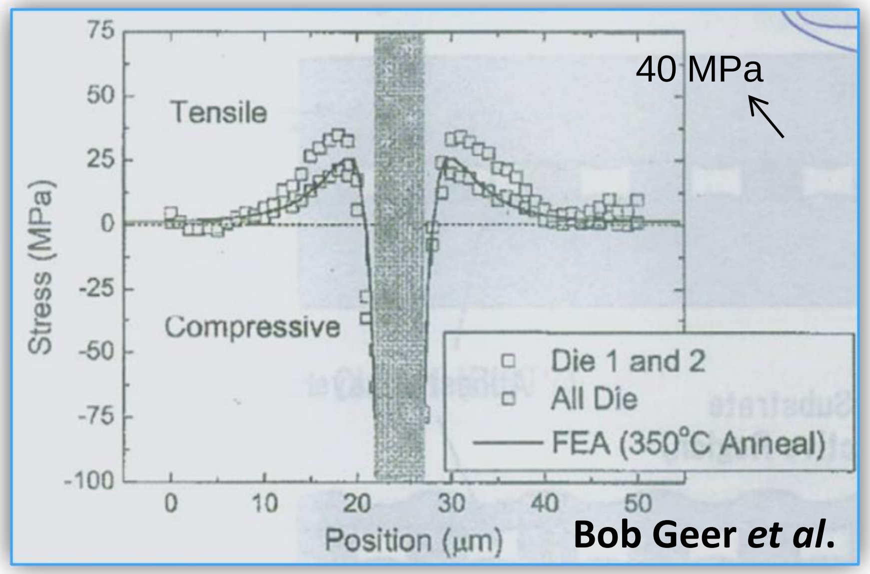


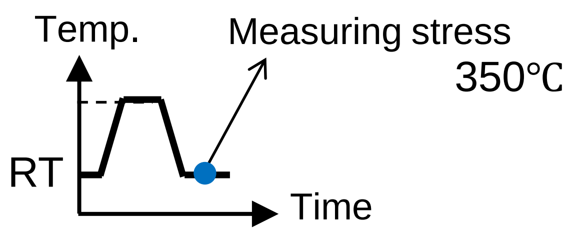
Diameter 5 µm,
pitch 10 µm,
depth 24 µm



- TSV-induced stress extends about 10 µm in Si
- 50 MPa tensile stress in Si after cycling

Lee, *et al*., TSV 3D Packaging Technology Workshop, 2010

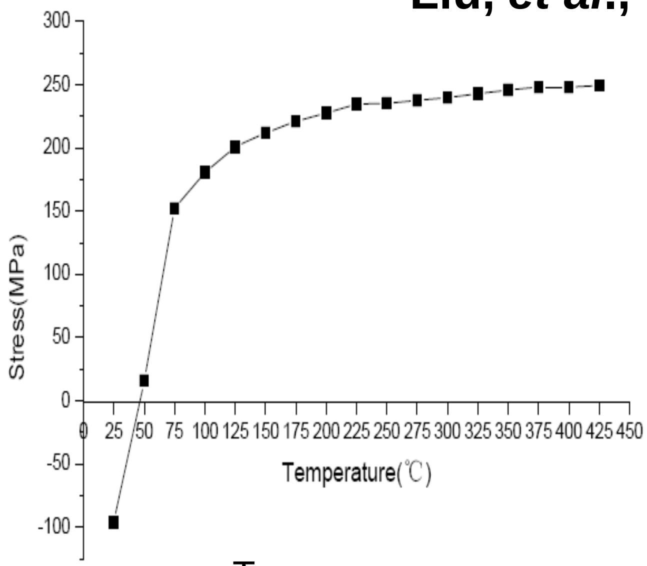


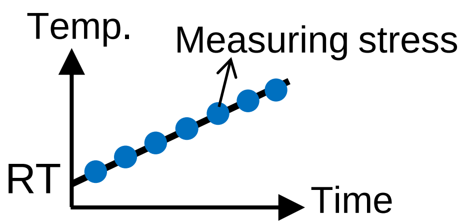


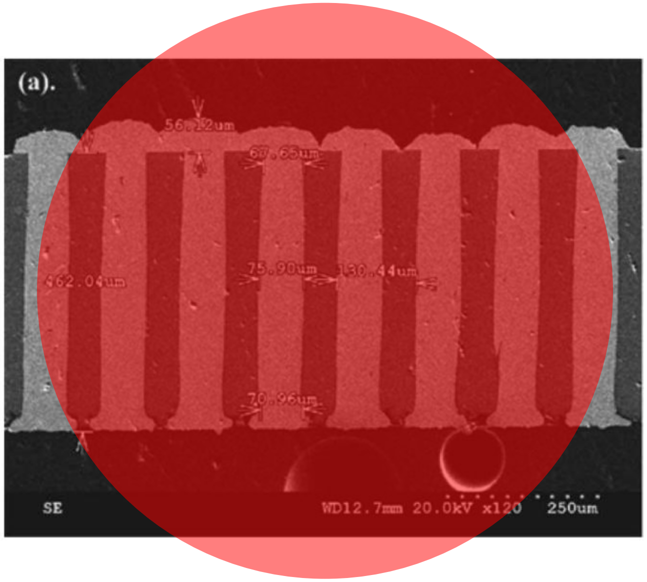
- 40 MPa tensile stress in Si was developed near Cu TSV after cycling.

Stress of Cu : Laboratory XRD
Lack of micron resolution

Liu, *et al*., ECTC, 2009



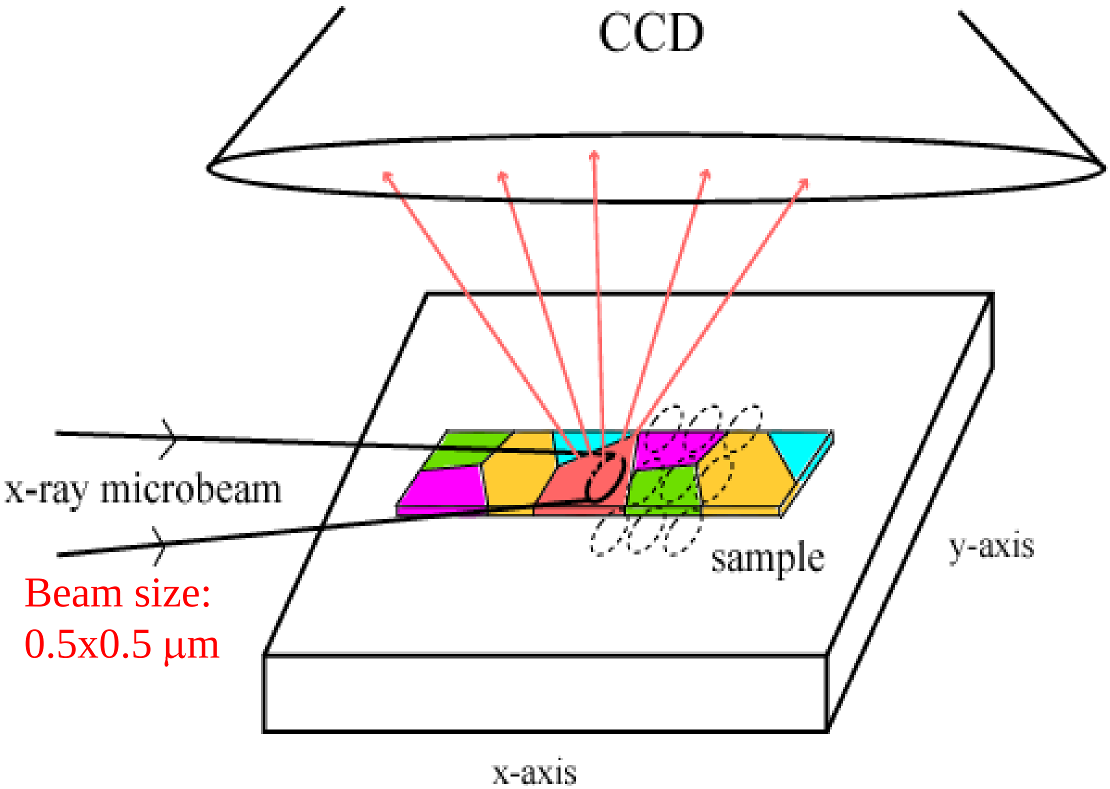




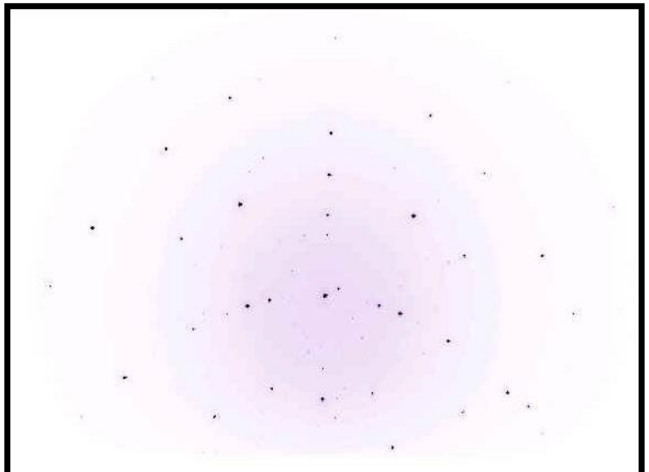
Diameter 70 μm , pitch 140 μm, depth 460 μm

- + 225 MPa at 200 ℃.
- - 100 MPa at 25 ℃.

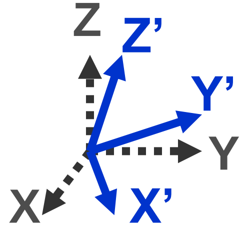
Synchrotron X-Ray Sub-micron Diffraction



Beam size:
0.5x0.5 μm



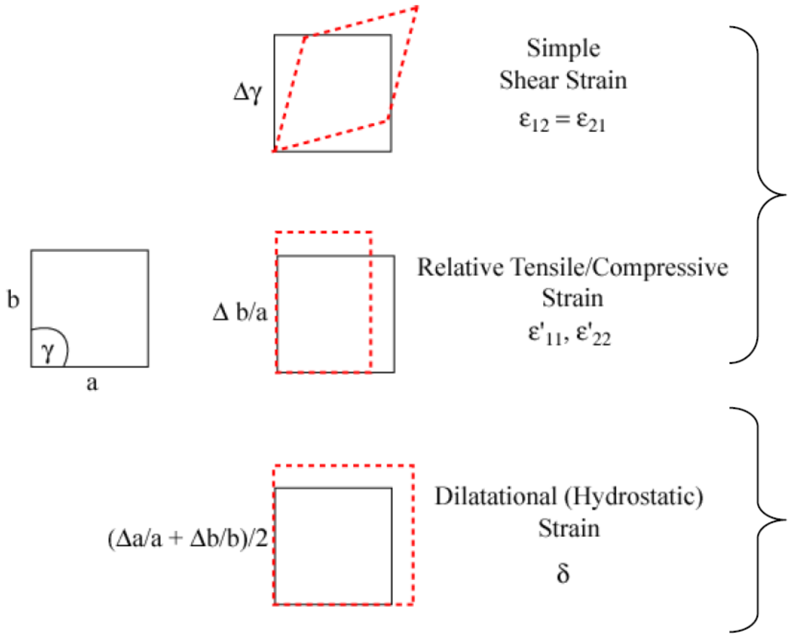
CCD frame w/ Laue patterns



X-ray source: ALS Synchrotron, Berkeley Lab (Beamline 12.3.2)

Deviatoric strain tensor: Small shifts in spot <u>relative</u> positions ➡ Crystal deformation at constant volume (~ 1 x10^{-4} accuracy)

Laue pattern and energy scanning analysis



Deviatoric Strains:

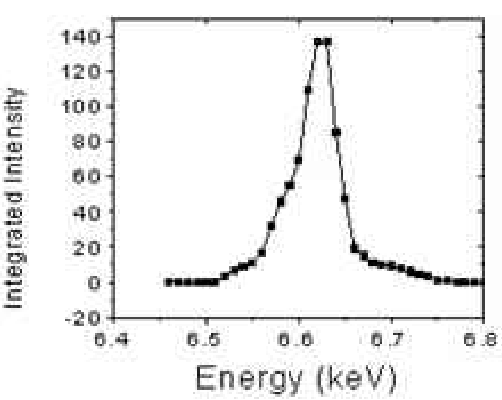
Angles between atomic planes change, causing a shift in the positions of the Laue reflections

Dilatational Strain:

Volume of unit cell changes, Laue reflections do not shift positions, energy of the Laue reflection changes

Laue pattern

Energy scanning



Total strain = dilatational + deviatoric

(Energy scan) + (Laue pattern)

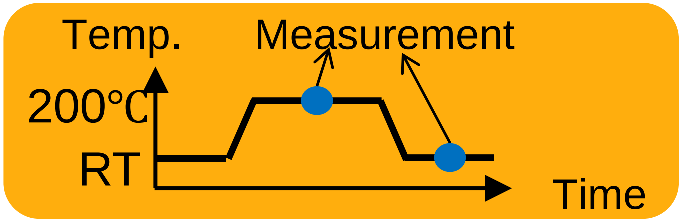
$$\varepsilon_{ij} = \begin{pmatrix} \delta & 0 & 0 \\ 0 & \delta & 0 \\ 0 & 0 & \delta \end{pmatrix} + \begin{pmatrix} \varepsilon'_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon'_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon'_{33} \end{pmatrix}$$

Experimental

- Sample

  <u>Hynix</u>: 20 µm TSV diameter, 90 µm pitch, 90 µm height

  <u>SEMATECH</u>: 5.5 µm TSV diameter, 80 µm pitch, 50 µm height



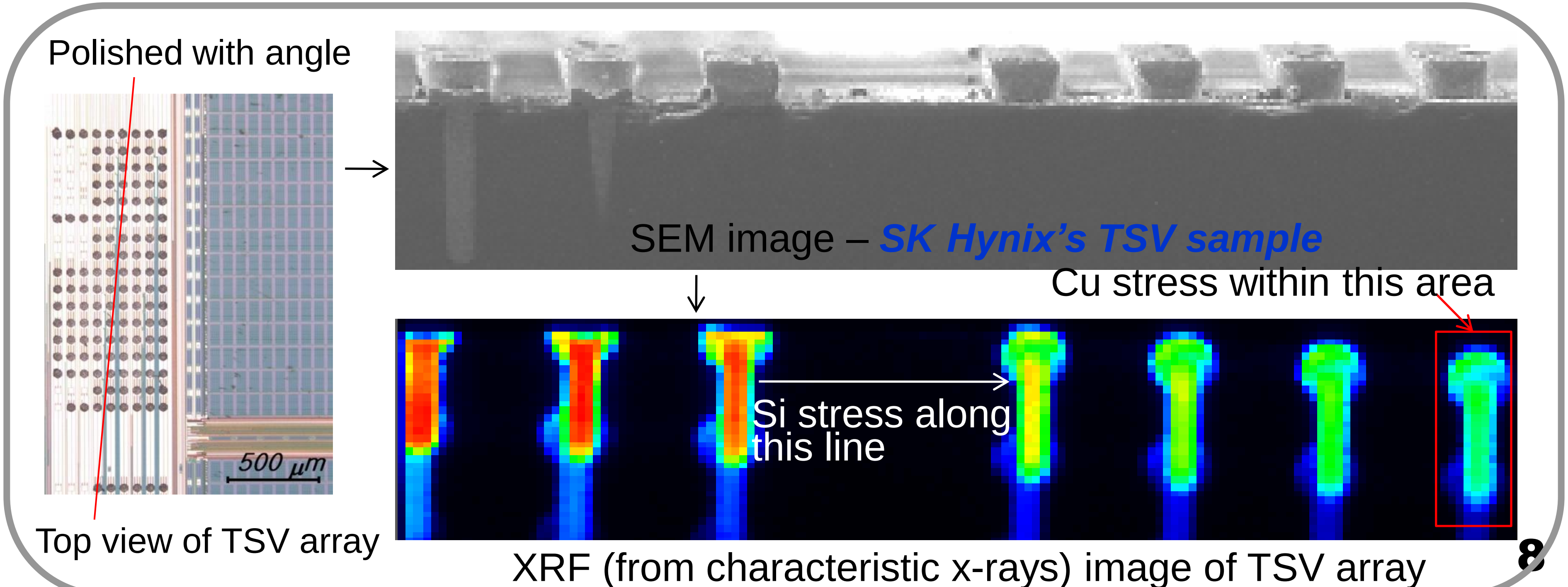
- Condition of measurement

  - Measurement of stress for : Si, Cu TSV

  - Thermal treatment: *in situ* at 200 ℃ (**SK *Hynix***)

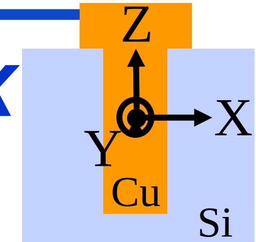
  ex situ post-annealed (200 ℃ for 1 hour) sample (**SK *Hynix***)

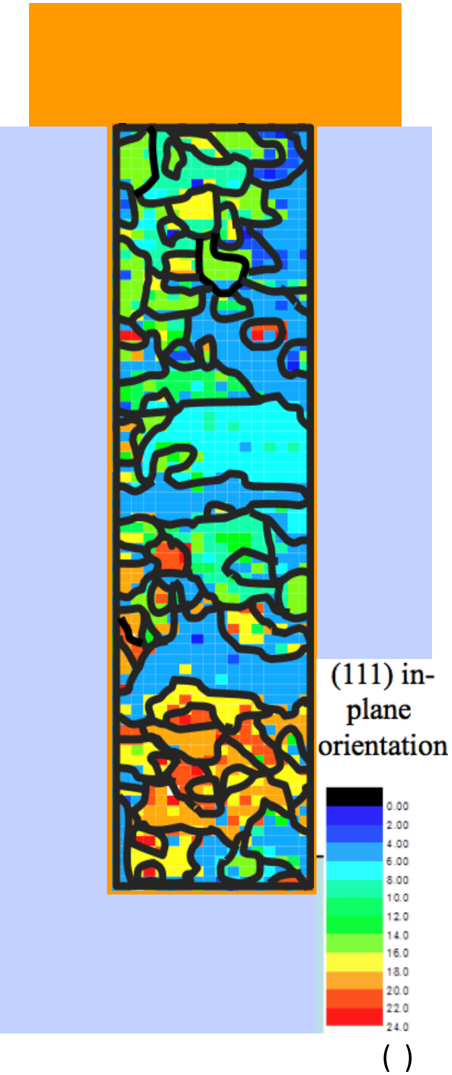
  ex situ post-annealed (350 ℃ for 30 mins) - ***SEMATECH***

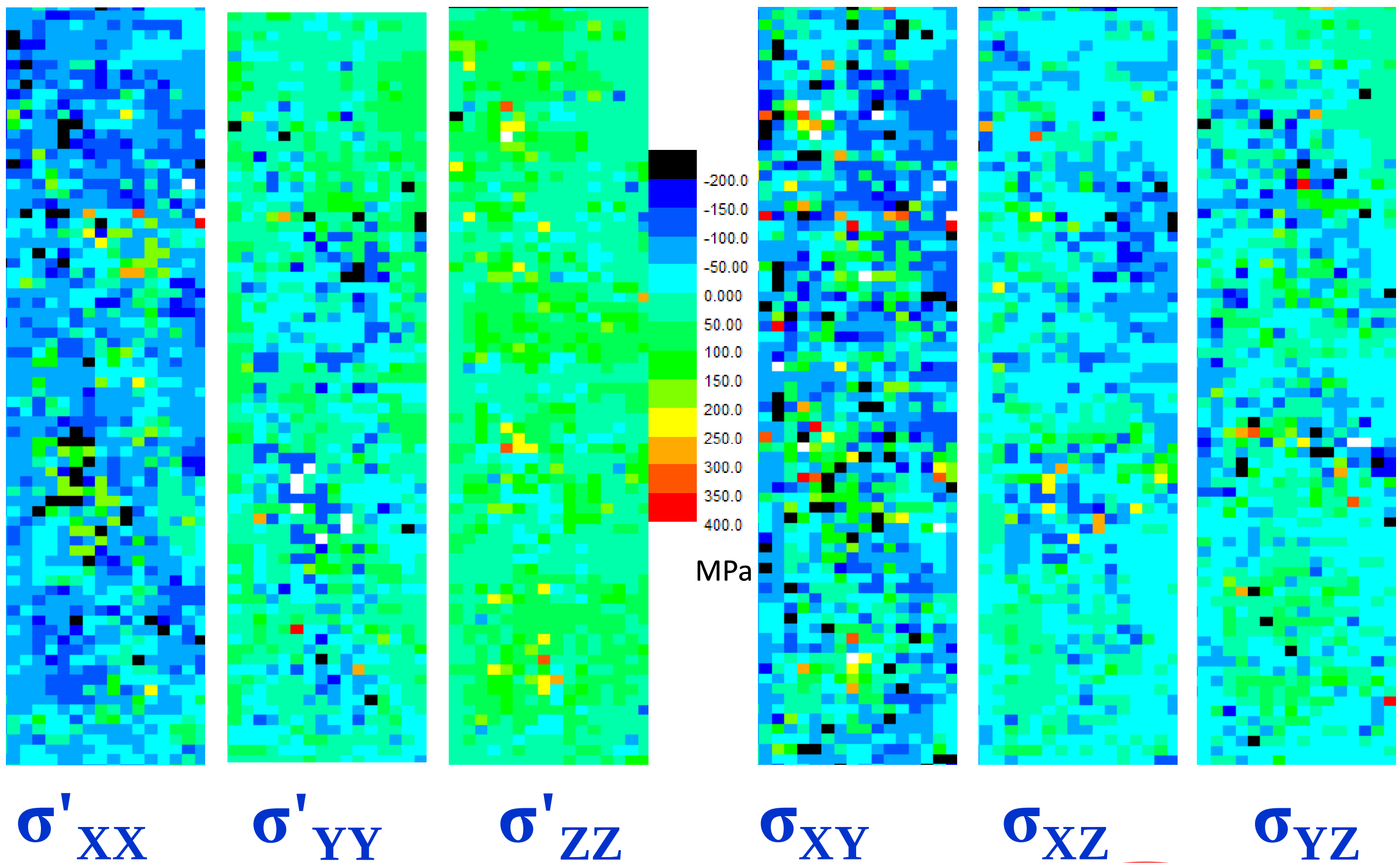


Cu Stress State in TSV – *SK Hynix*

- Post Annealed Sample (measure at RT)



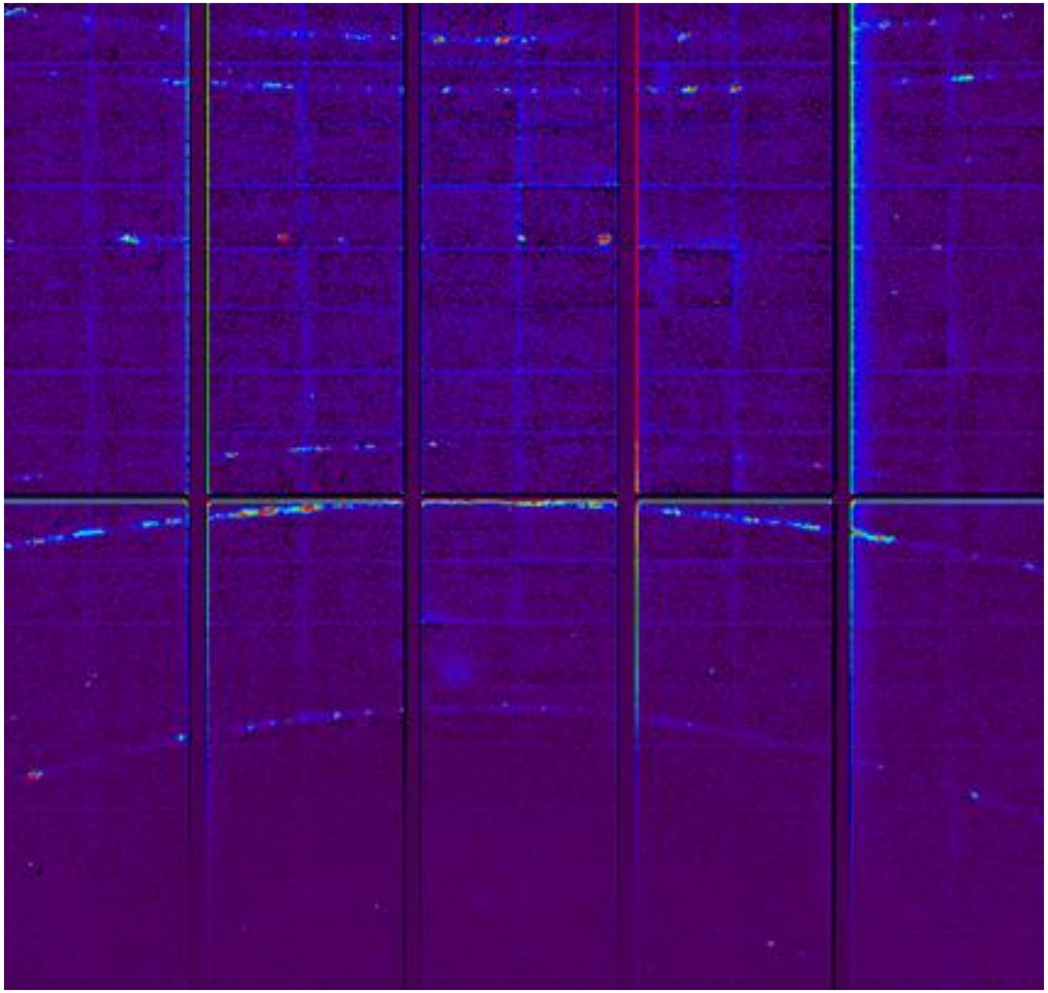


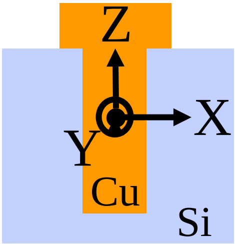


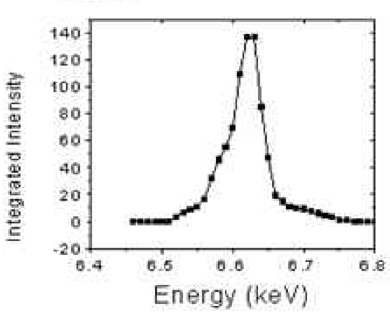
Only deviatoric components of stress

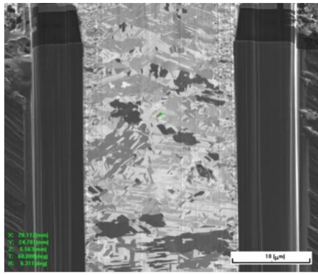
$$\varepsilon_{ij} = \begin{pmatrix} \delta & 0 & 0 \\ 0 & \delta & 0 \\ 0 & 0 & \delta \end{pmatrix} + \begin{pmatrix} \varepsilon'_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon'_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon'_{33} \end{pmatrix}$$

Cu Hydrostatic Stress State in TSV – *SK Hynix*
- Post Annealed Sample (measure at RT)







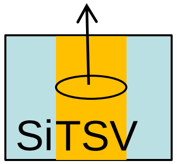


$$\varepsilon_{ij} = \begin{pmatrix} \delta & 0 & 0 \\ 0 & \delta & 0 \\ 0 & 0 & \delta \end{pmatrix} + \begin{pmatrix} \varepsilon'_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon'_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon'_{33} \end{pmatrix}$$

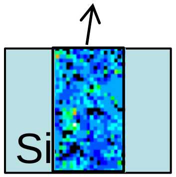
Hydrostatic stress = +166.6 MPa

- Hydro + deviatoric

One area



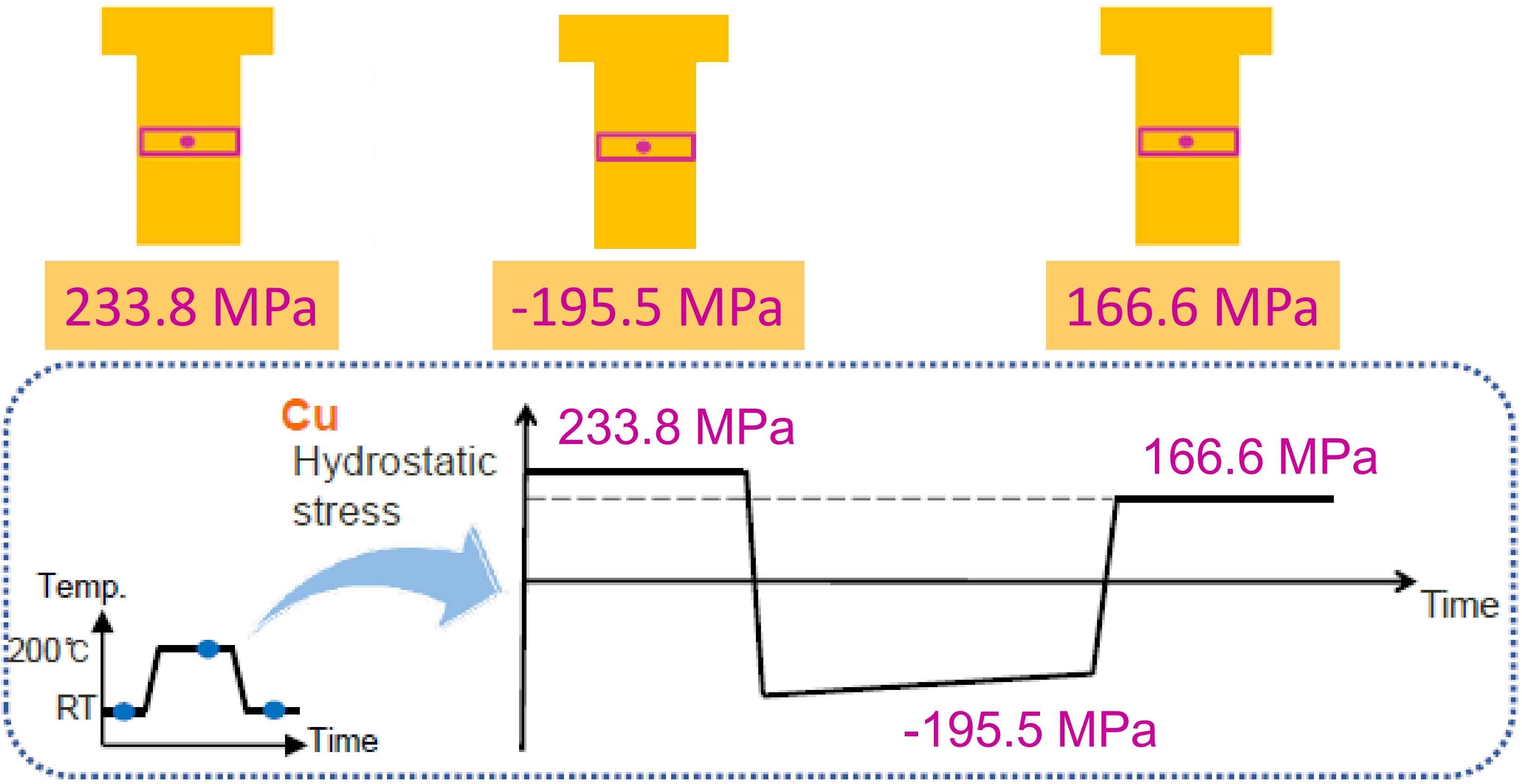
All area scan



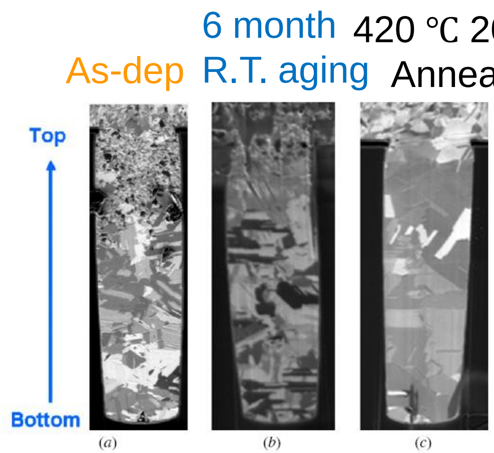
Stress Evolution in Cu TSV – *SK Hynix*

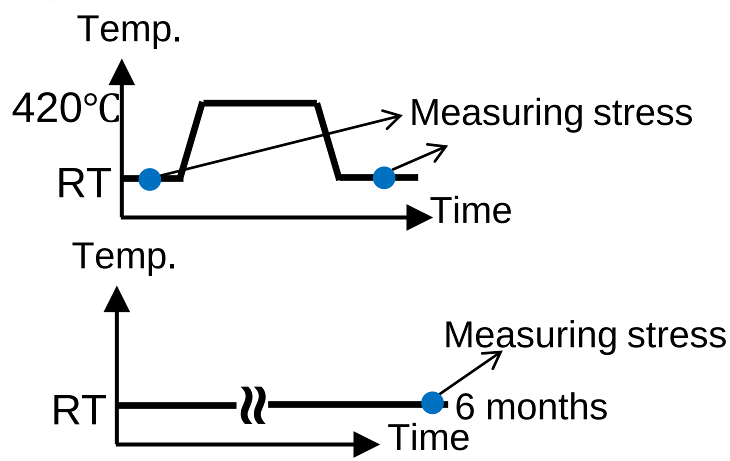
Cu hydrostatic stress

- As-received
- at 200℃
- After anealing

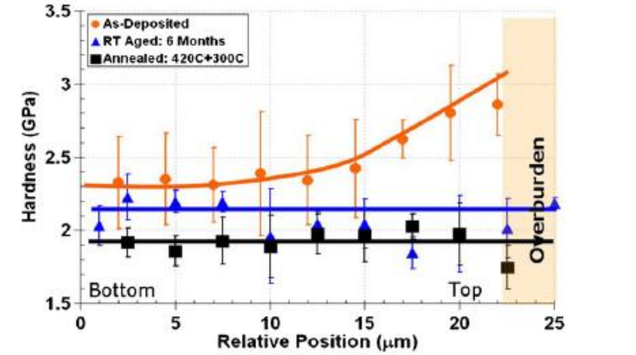


High Tensile in As-Received → Cu RT Grain Growth

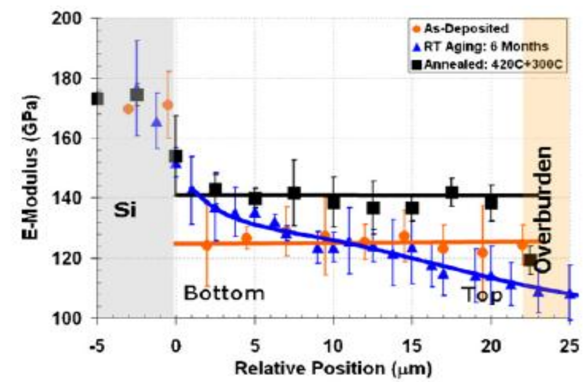




- Hardness change by annealing



- Elastic modulus

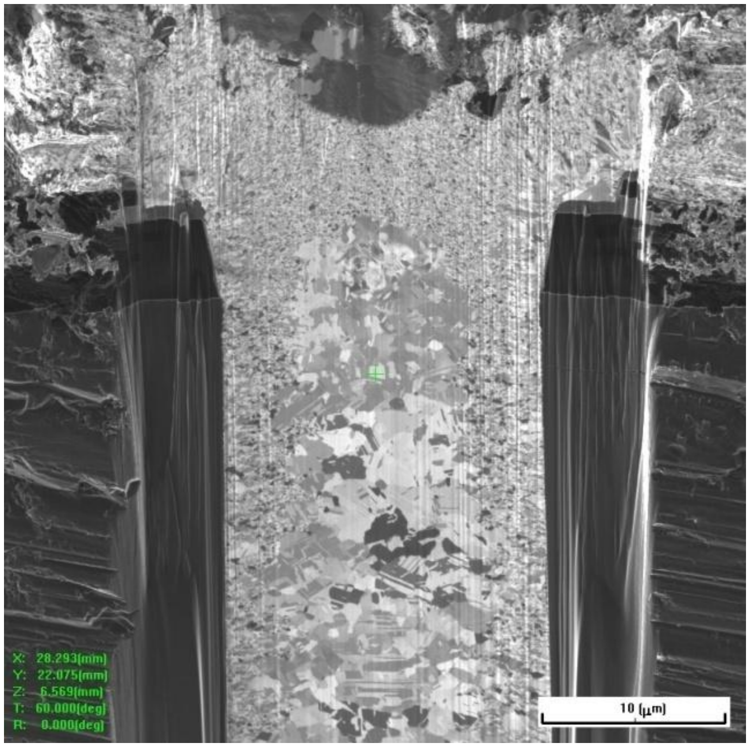


- Decreasing hardness → Cu stress toward more tensile stress after annealing and R. T. aging.

- **Okoro *et. al.*, J. Micromech. Microeng. (2010)**

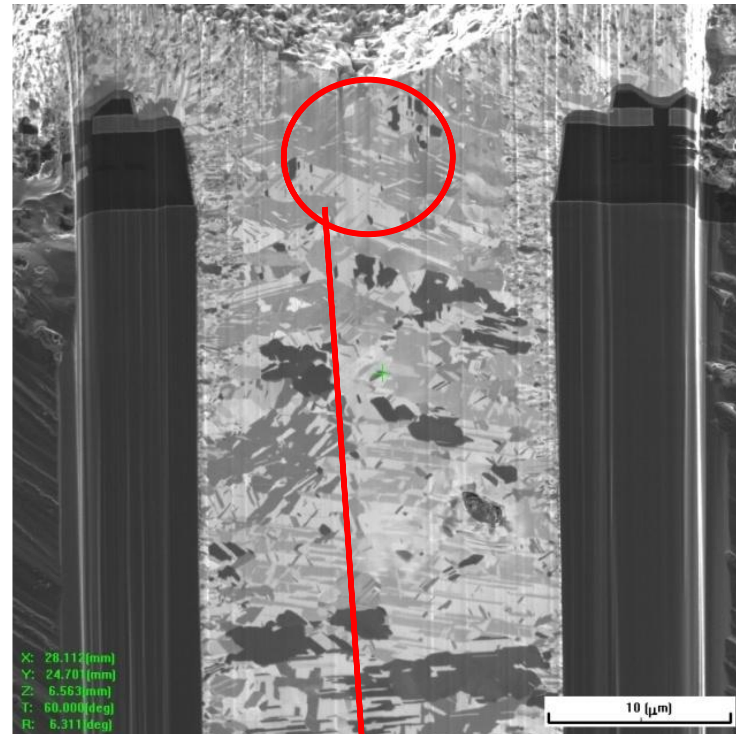
Microstructure change of Cu during annealing leads to tensile stress – SK Hynix

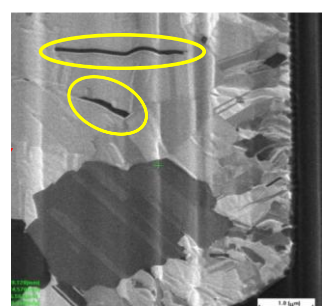
As received



Grain growth

200℃ 1hr annealing





Crack

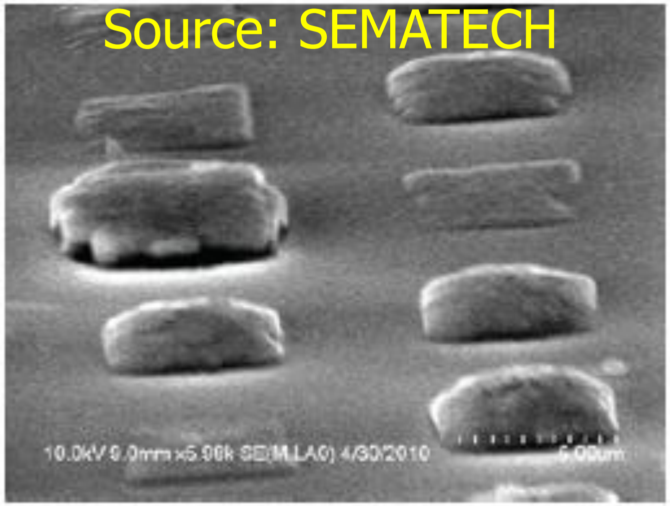
Void

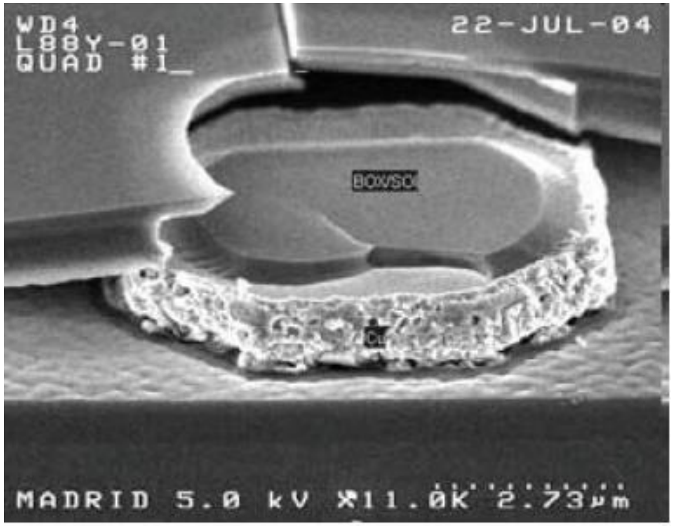
Compressive Hydrostatic Stress in Cu TSV during Annealing

Cu TSV Protrusions:

- Popping out, bulging out during high-temp processing steps
- Cracking/flaking of dielectrics over Cu TSV and open vias to above metallization lines

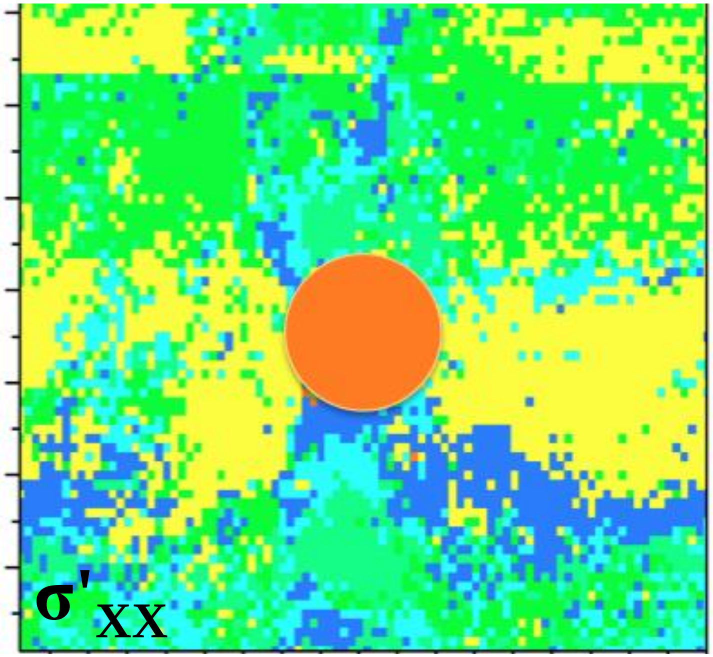
→ **Integration issues as well as serious reliability concerns!**

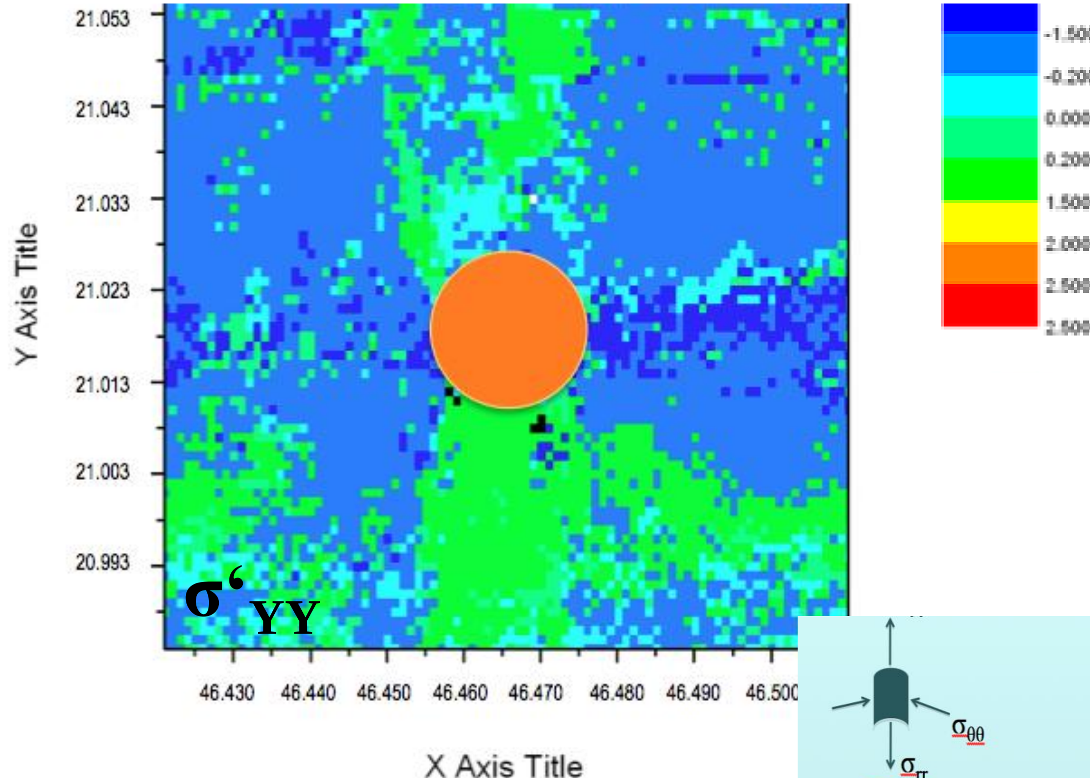


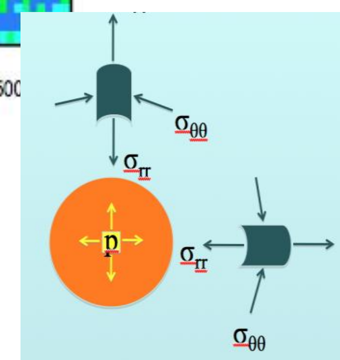


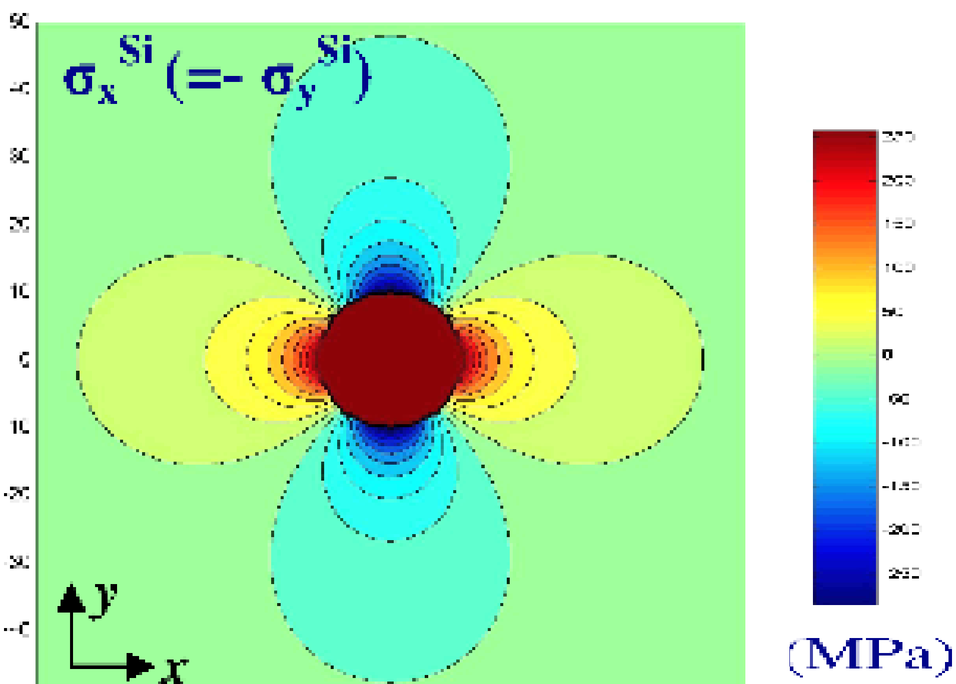
Copper expansion can fracture the oxide layer above. (Source: Tezzaron)

Si Stress State in TSV – *SK Hynix* (Post Annealed)







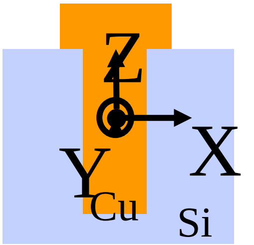


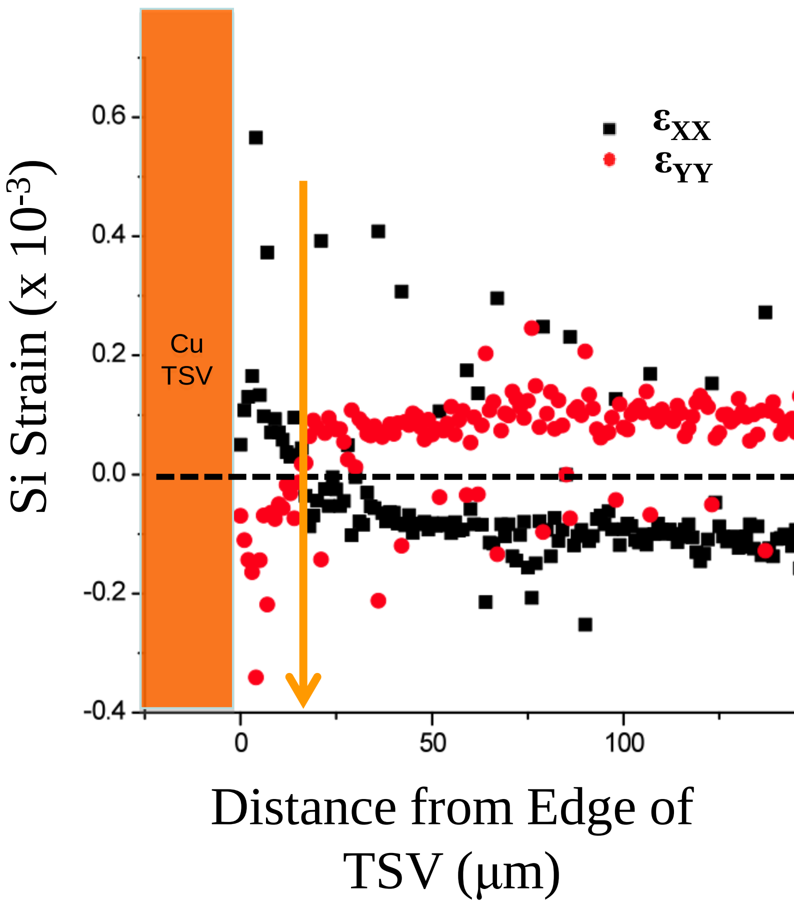
$$\sigma_{xx} = -\sigma_{yy} = -\frac{R^2 B \Delta\alpha \Delta T (x^2 - y^2)}{2(x^2 + y^2)^2}$$

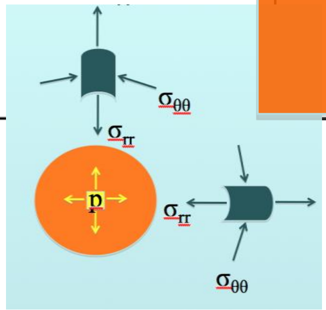
Lu et al., AIP, 2009;
TSV diam. = 20 μm
Stress Map = 100 μm x 100 μm

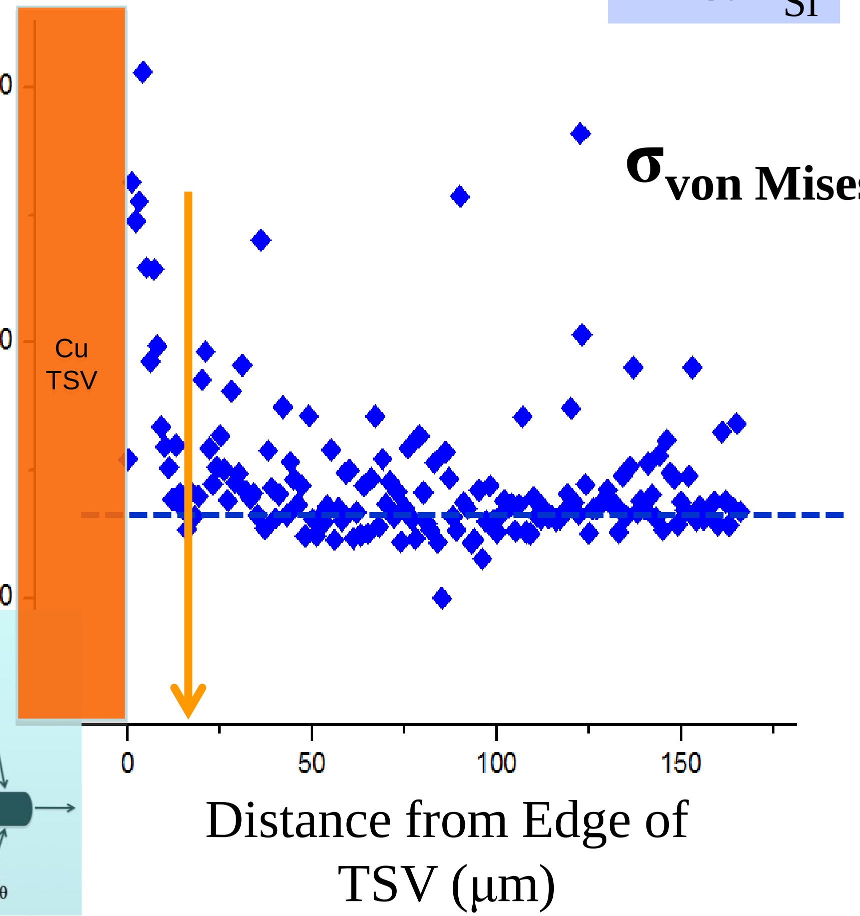
Si Strain Profile from Edge of TSV

- SK Hynix (Post Annealed)



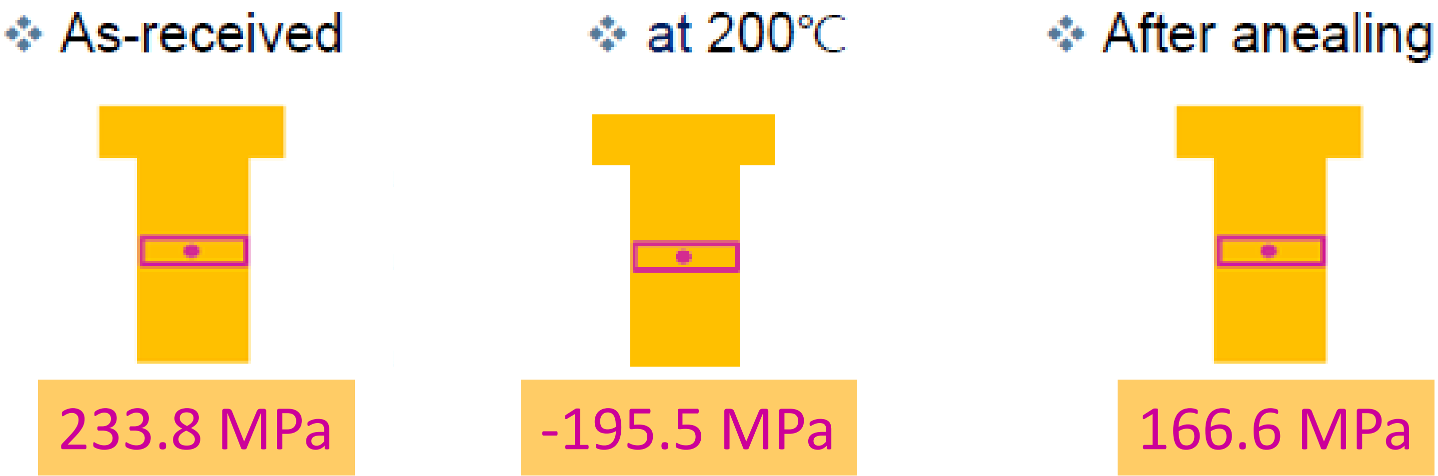


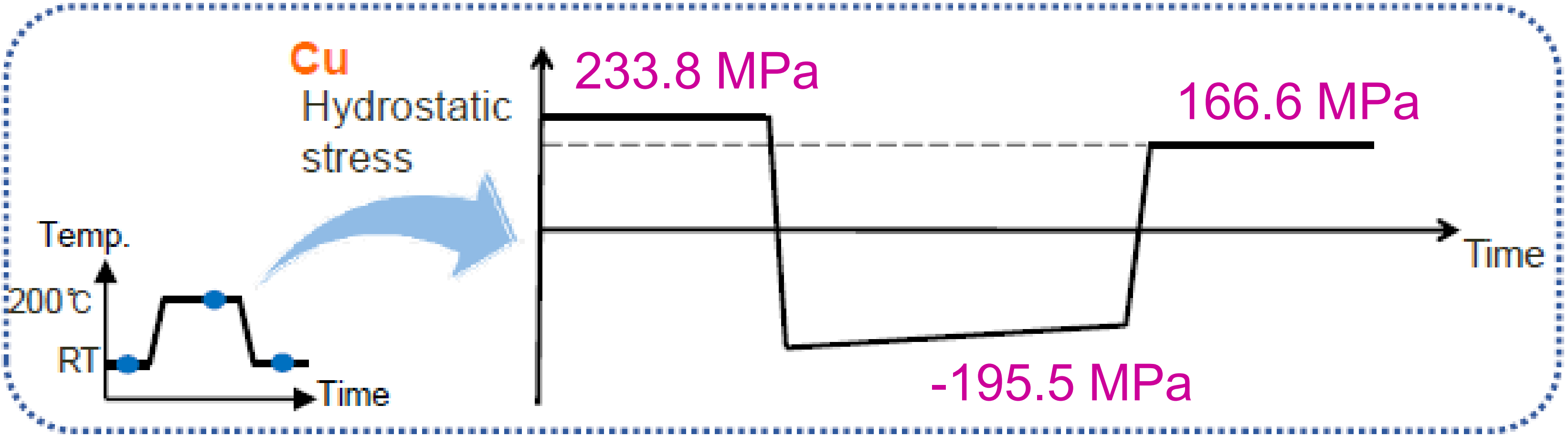




<u>Si Keep-Away Zone</u>: ***<u>SK Hynix</u>***: 17 μm

→ Reduce as-received Cu TSV high tensile stress!!





Electroplating process? Thermal treatment? Reduce Cu RT grain growth?

Summary

- Synchrotron X-ray submicron diffraction (white + monochromatic beam) has proven to be a powerful tool to measure stress states in TSV *in situ* and while the Cu via is still ***buried under Silicon***

- Cu stress state is mostly in tensile and considerable shear stresses at the post-annealed state:
  - Comparison SK Hynix vs. SEMATECH samples → RT grain growth leads to high tensile stress in the as-received state
  - How to reduce stress-induced reliability/integration → reduce Cu hydro stress in the as-received state

- Stress in Si surrounding Cu TSV was found to follow Cu hydrostatic stress: higher Cu hydrostatic stress → higher Si stress → larger “keep-away zone”
  - Si stress in array of TSV’s → important for design/layout
  - Stress scanning from the top would be valuable → to optimize layout!

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