Thermomechanical Characterization and Modeling for TSV Structures

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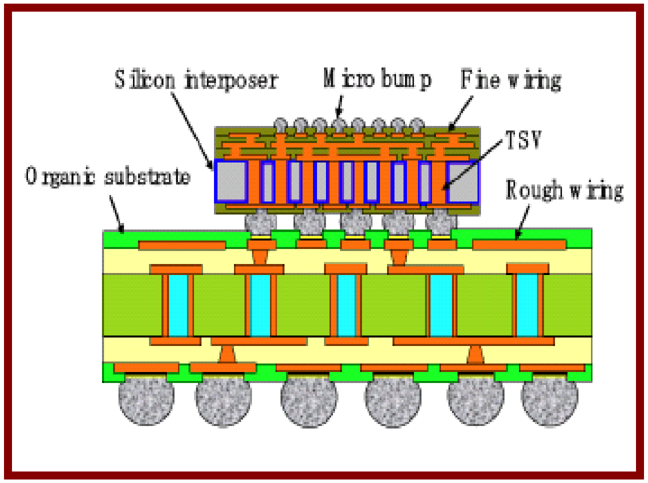
Financial support from Semiconductor Research Corporation is gratefully acknowledged.

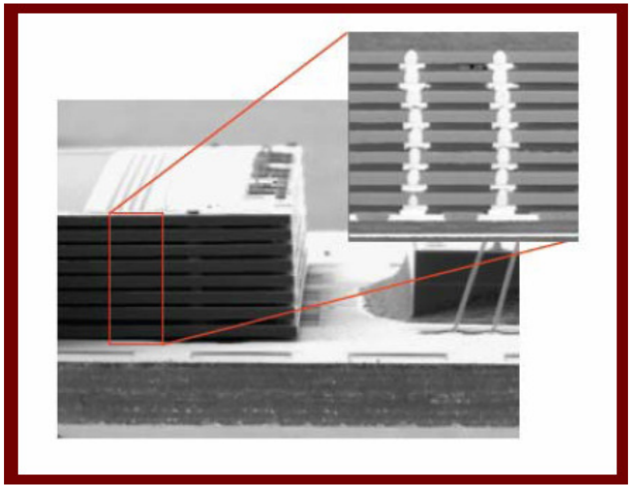
3D Integration

Si Interposer



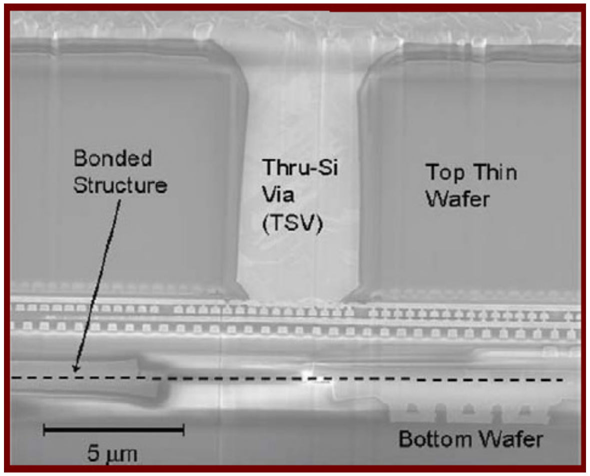
J. Bautista, 3D Technology Workshop 2009

Memory stacks (Samsung)



TSV memory in mobile phones, 30% thinner

Multicore processors (Intel)



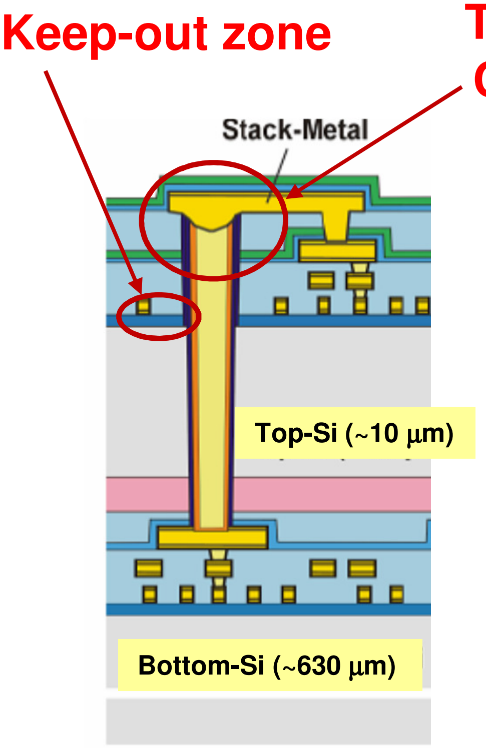
3D integration provides the memory bandwidth required for processors

Thermomechanical issues:

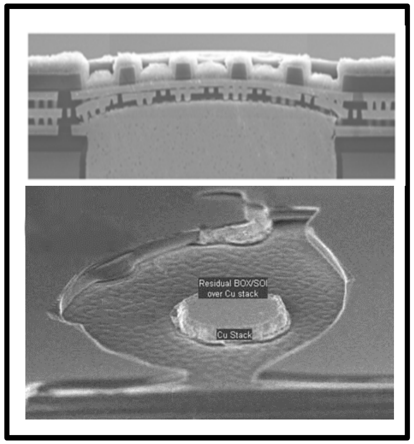
- Stresses induced by TSVs
- Wafer thinning
- Wafer bonding/Chip-package interactions (CPI)

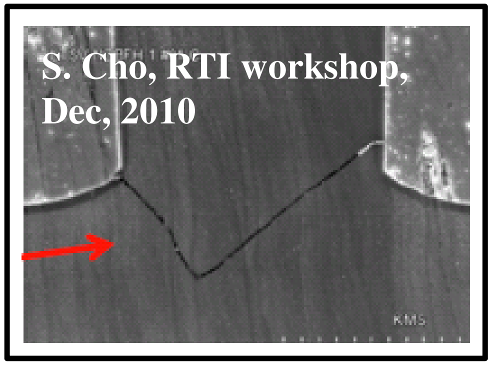
Thermo-Mechanical Issues for TSVs

- ☐ **Stress in vias**
  - plastic deformation
  - stress voiding
- ☐ **Stress in Si:**
  - cracking of Si
  - mobility change
  - keep-out zone
- ☐ **Stress at the interfaces:**
  - interfacial delamination
  - TSV extrusion (pop-up)



Via last TSV (Fraunhoefer)
Handbook of 3D Integration



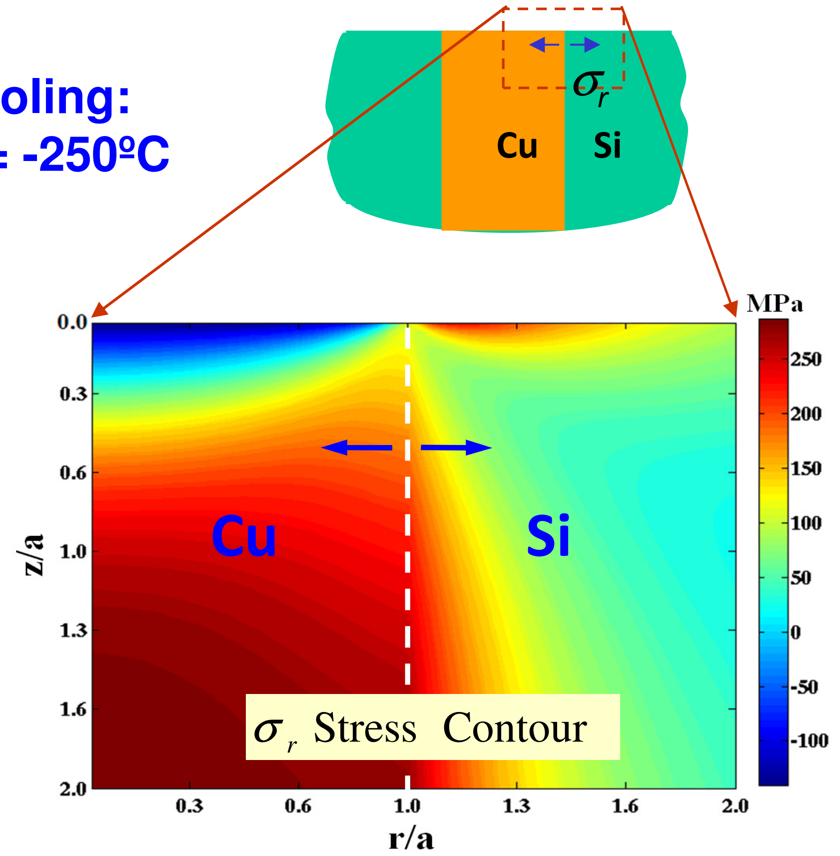

S. Cho, RTI workshop, Dec, 2010

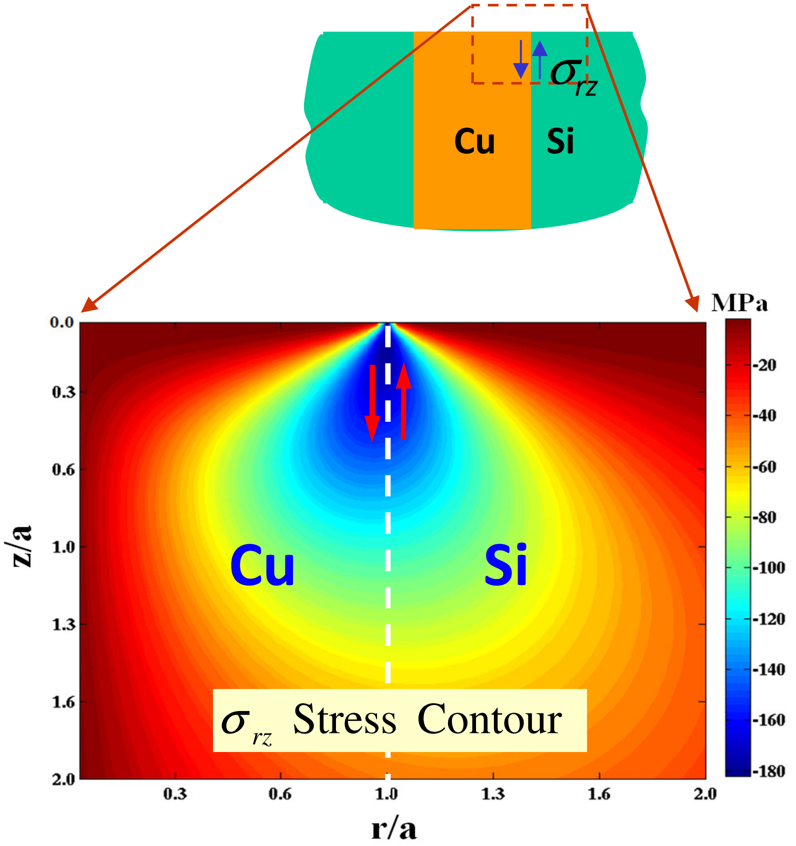

K. Athikulwongse, IEEE, 2010

Stresses near Wafer Surface

S.-K. Ryu, et al., IEEE TDMR 2011.

Cooling:
ΔT = -250ºC





- Positive opening stress along Cu/Si interface
- Concentration of shear stress at the surface/interface junction

Near-surface stresses are 3D in nature with distinct distribution in the radial and depth directions, which may cause degradation of carrier mobility and device performance.

Experimental Measurements

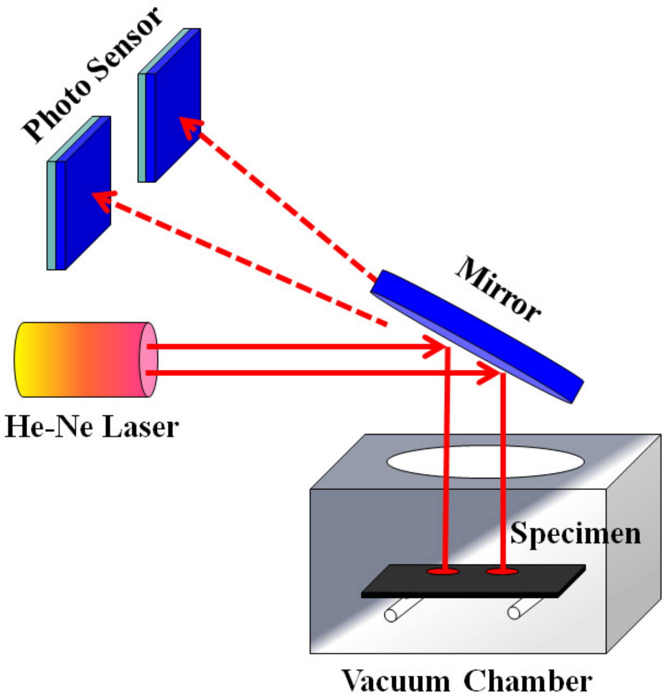
- **Precision wafer curvature technique**
- **Micro-Raman Spectroscopy**
- **Other methods (indentation, synchrotron, etc.)**

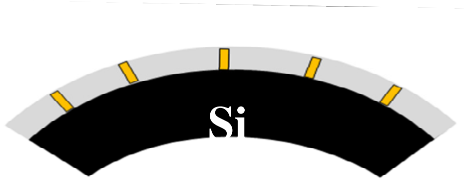
Challenges:

- **Complex geometry** – non-uniform stress and deformation
- **Material aspects** – Si anisotropy, Cu plasticity (nonlinearity), temperature/history-dependent
- **Interfacial properties** – largely unknown

Precision Wafer Curvature Technique

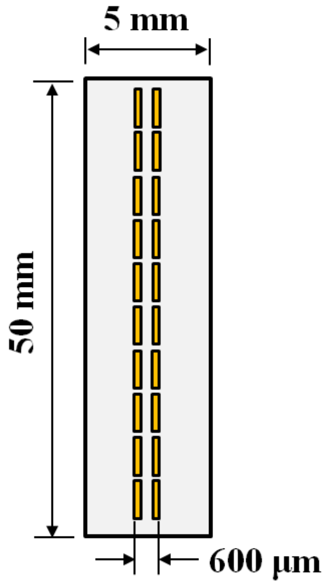
- **Measure the global (averaged) deformation (curvature)**
- **In-situ measurement during thermal cycling.**
- **Direct evidence of nonlinear thermomechanical behavior**
- **Data may be used to study temperature-dependent deformation mechanisms in Cu TSVs**

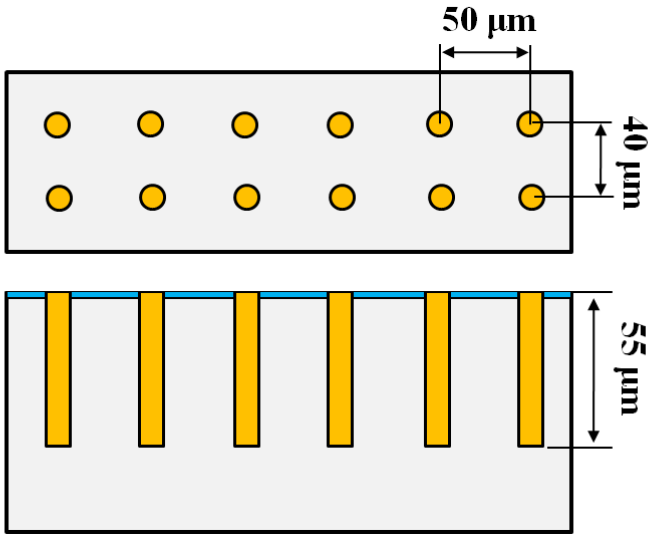


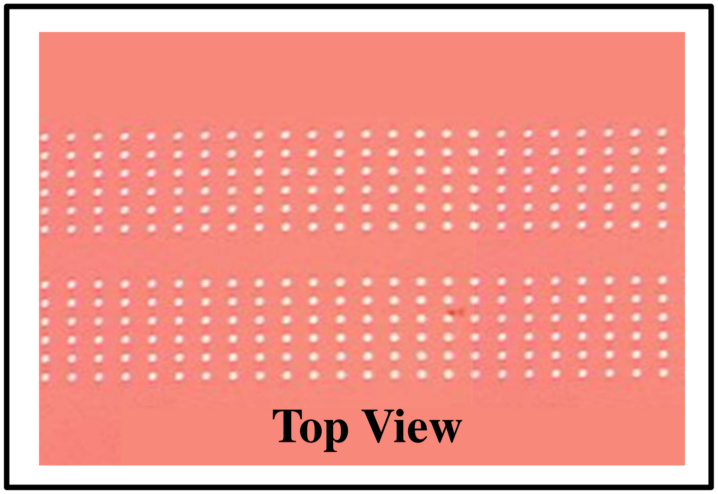


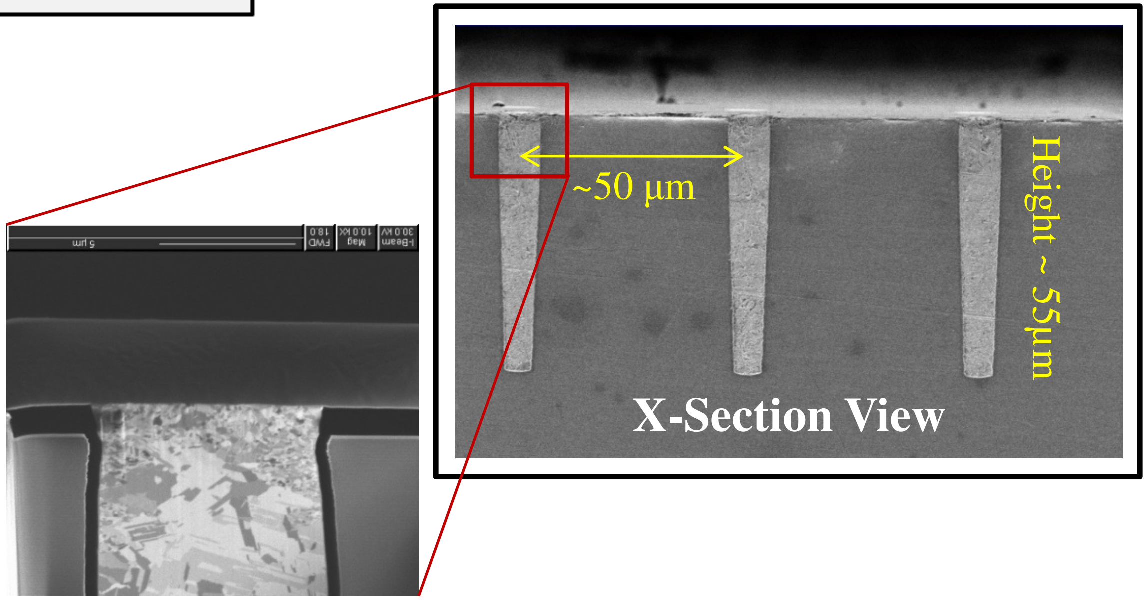
Negative Curvature
(Heating)

TSV Specimen







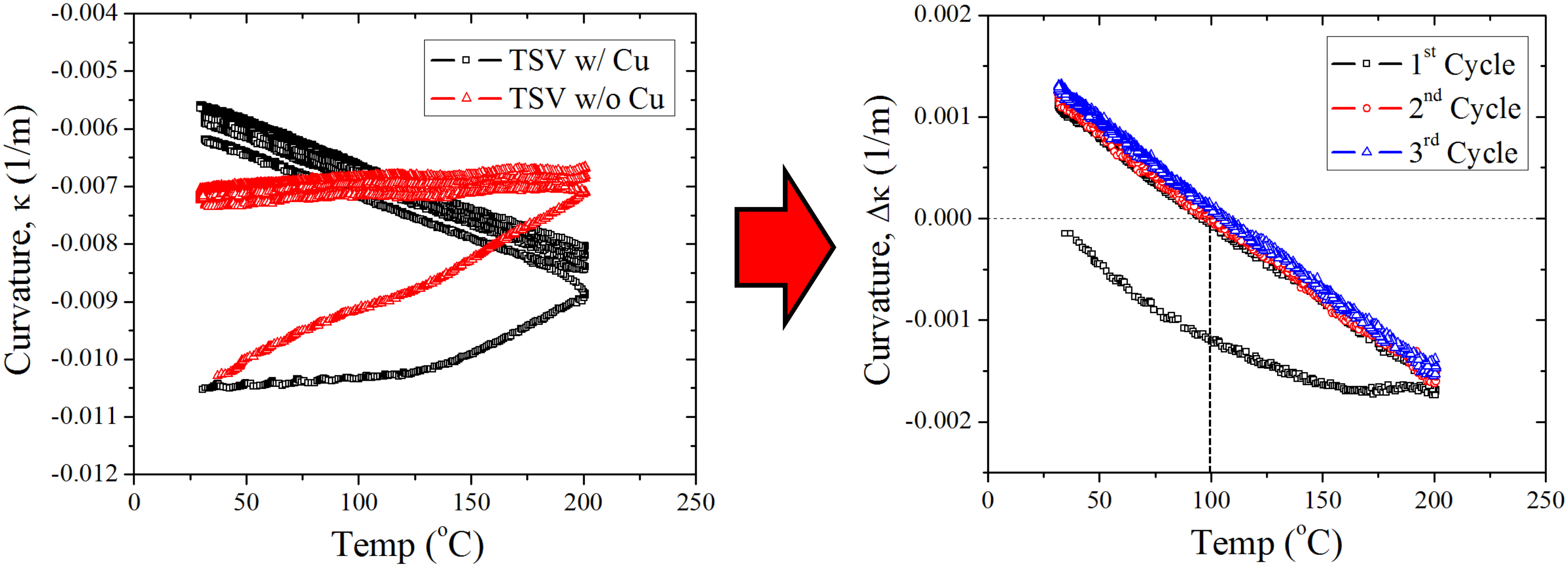


- **Via Diameter ~ 10 µm**
- **Via Height ~ 55 µm**
- **Via pitch 40~50 µm**
- **Si thickness ~ 700 µm**

Work in collaboration with H. Y. Son and K. Y. Byun of Hynix.

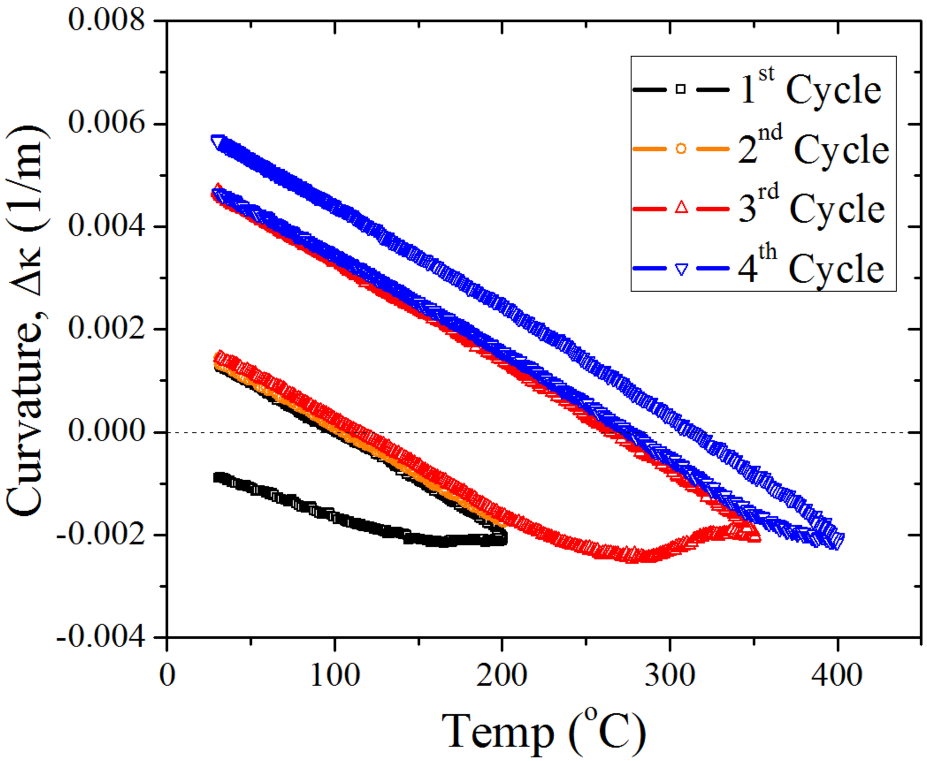
Curvature-Temperature Behavior

S.-K. Ryu, et al., Appl. Phys. Lett. 2012.



- The ***curvature difference*** between the two specimens is attributed to the stress in Cu TSVs.
- ***Linear*** thermo-elastic behavior (***no hysteresis***) except for the first cycle heating.
- Zero curvature difference at around 100 °C, which is taken as the ***reference temperature*****.**

High-Temperature Behavior

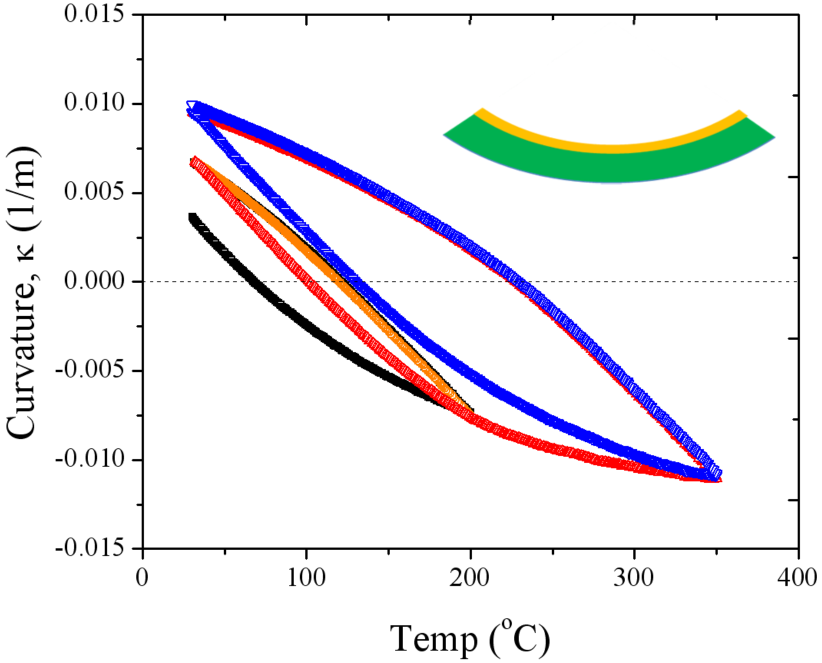


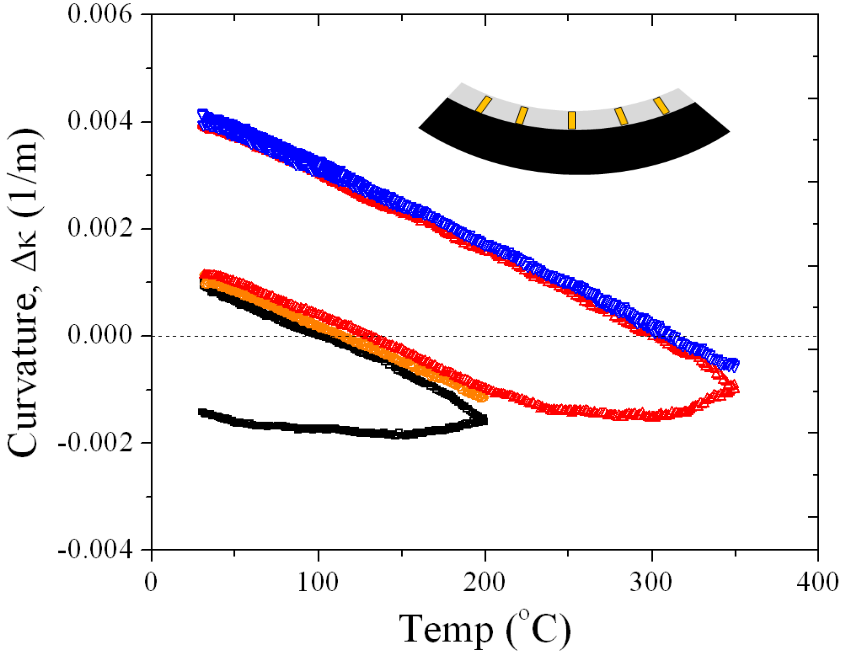
- **4 thermal cycles**

  1st: RT → 200°C
  2nd: RT → 200°C
  3rd: RT → 350 °C
  4th: RT → 400 °C

- ***Nonlinear behavior*** **when heating beyond the highest temperature in the previous cycles**
- ***Linear*** **during cooling and subsequent cycles**
- **Residual stress at RT depends on the thermal history.**

Deformation Mechanisms:
Thin film vs TSV





Electroplated Cu thin film:

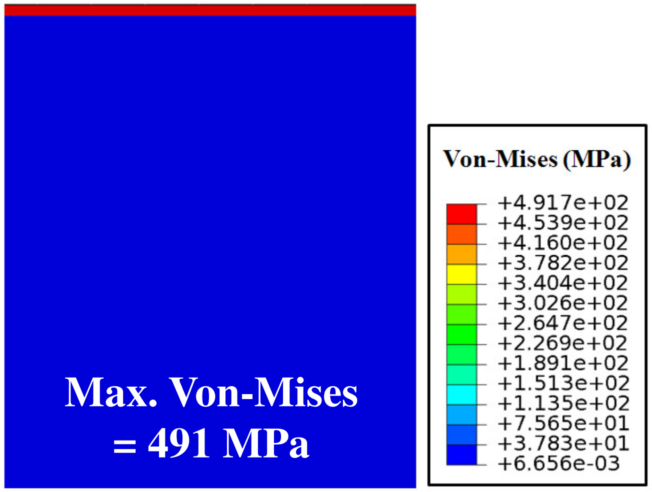
- Hysteresis loop – evidence of plasticity
- Grain growth and diffusional creep may occur at high T

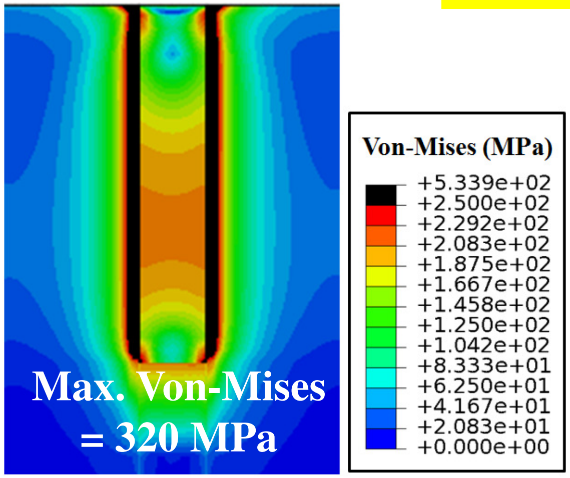
Cu TSVs:

- No hysteresis loop
- Grain growth during heating at high T

Stress and Plasticity

ΔT = 200 °C





Cu thin film:

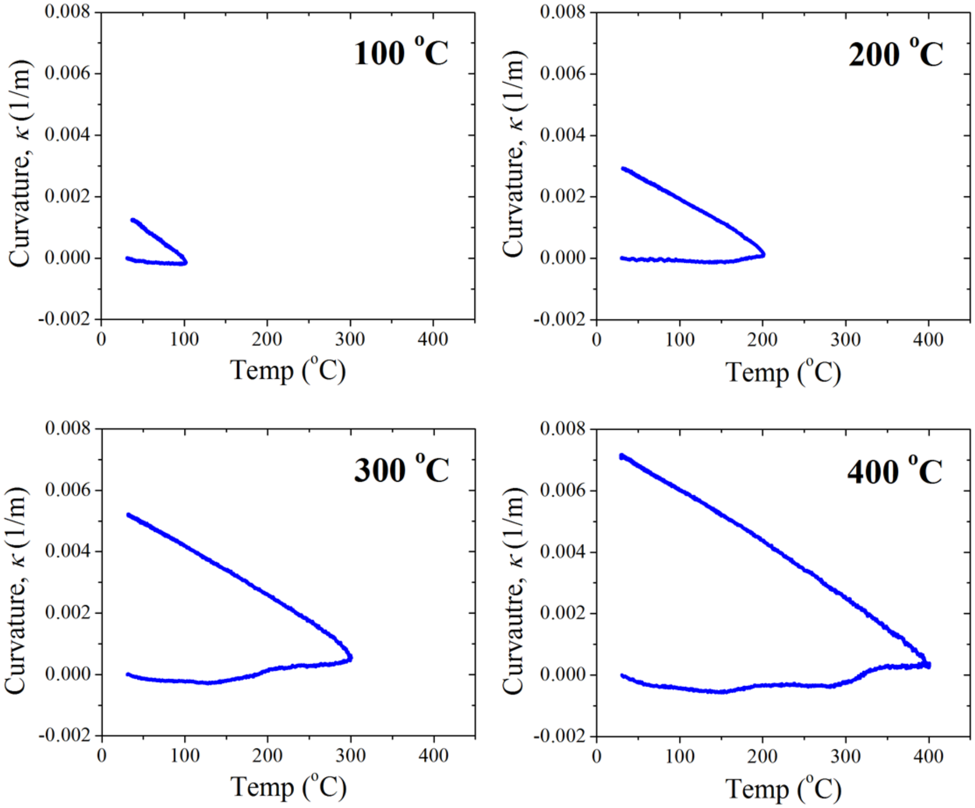
- Uniform, equi-biaxial stress
- High von Mises stress
- Plastic yield lowers the stress and curvature (both heating and cooling)

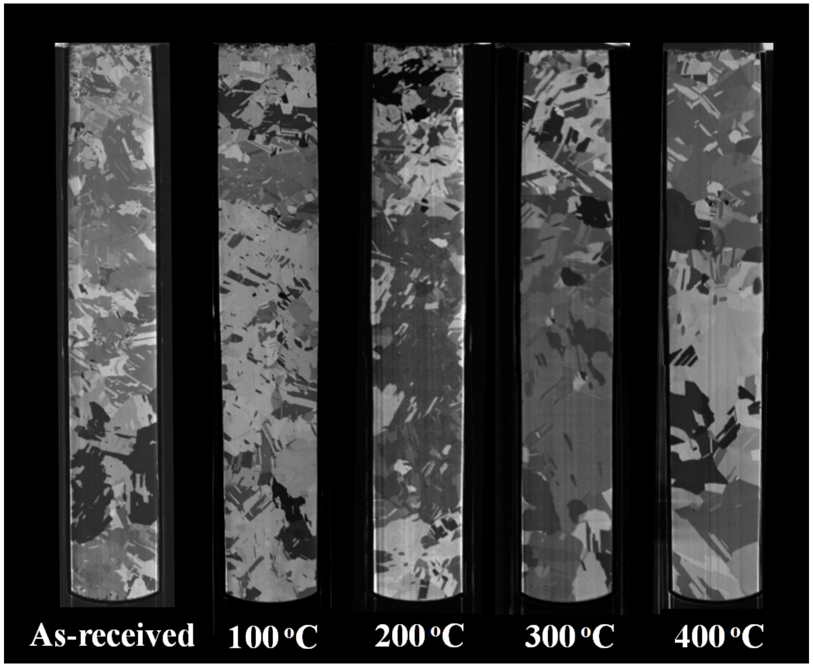
Cu TSV:

- Non-uniform, tri-axial stress
- Relatively low von Mises stress (in Cu)
- Plastic yield occurs locally within a small volume, which has negligible effect on overall curvature

Cu Grain Structures

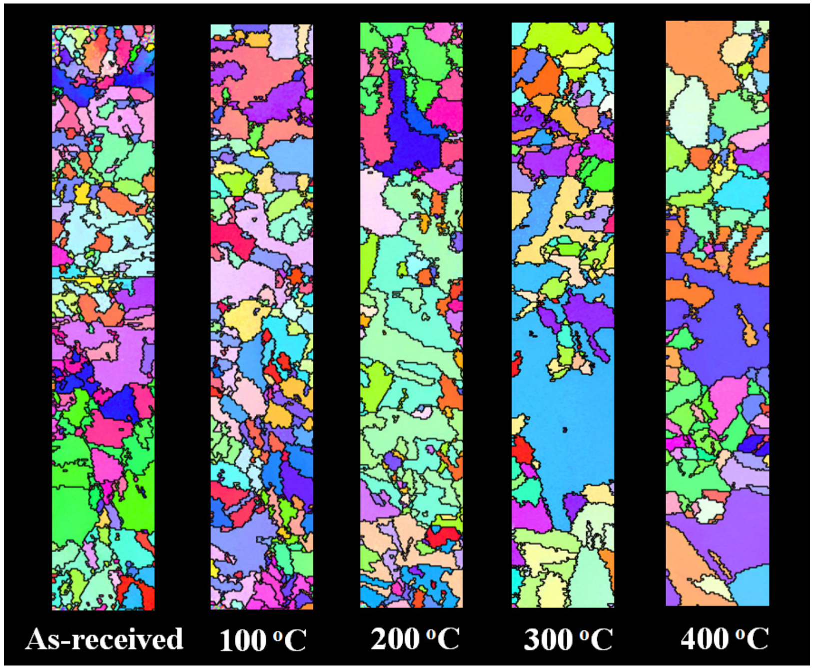
T. Jiang, et al., in press.

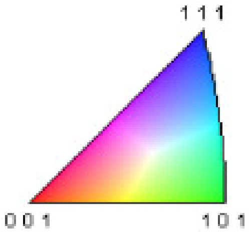


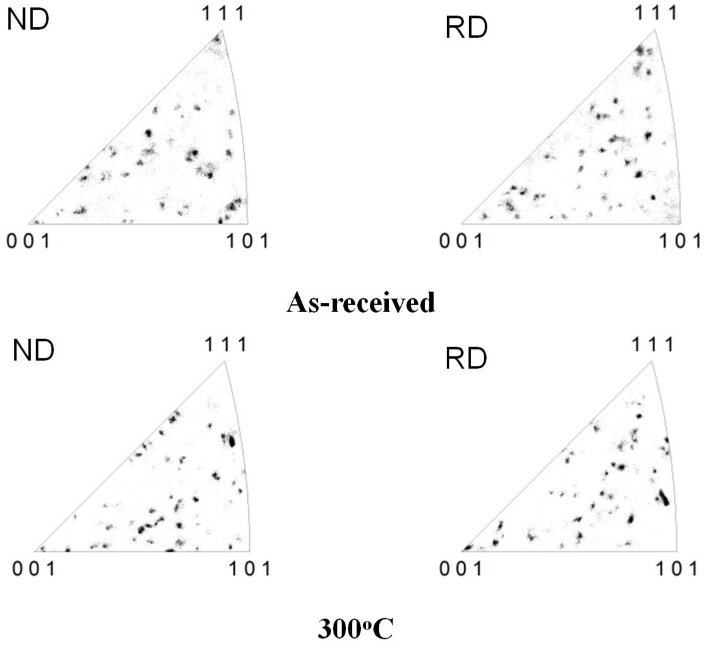


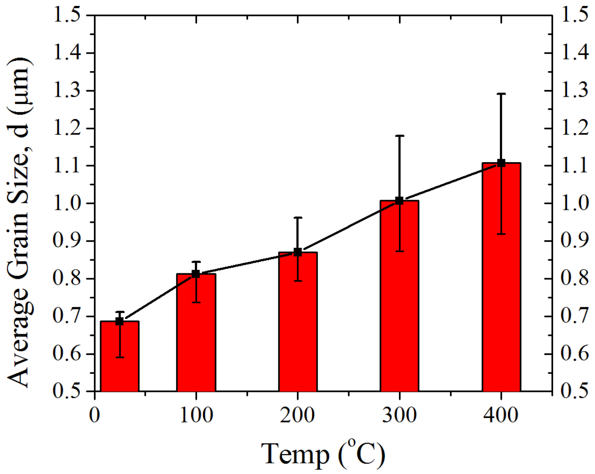
- Similar curvature behavior during the first thermal cycle
- FIB images show that the average grain size increases with the temperature

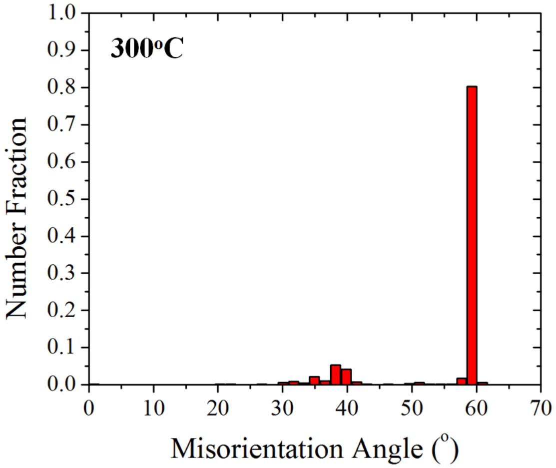
Electron Backscatter Diffraction (EBSD)





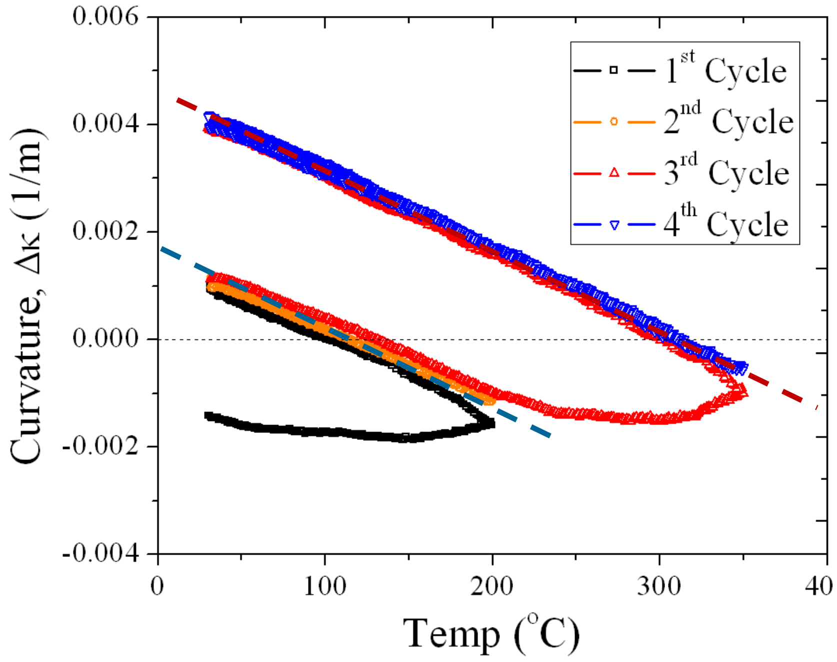


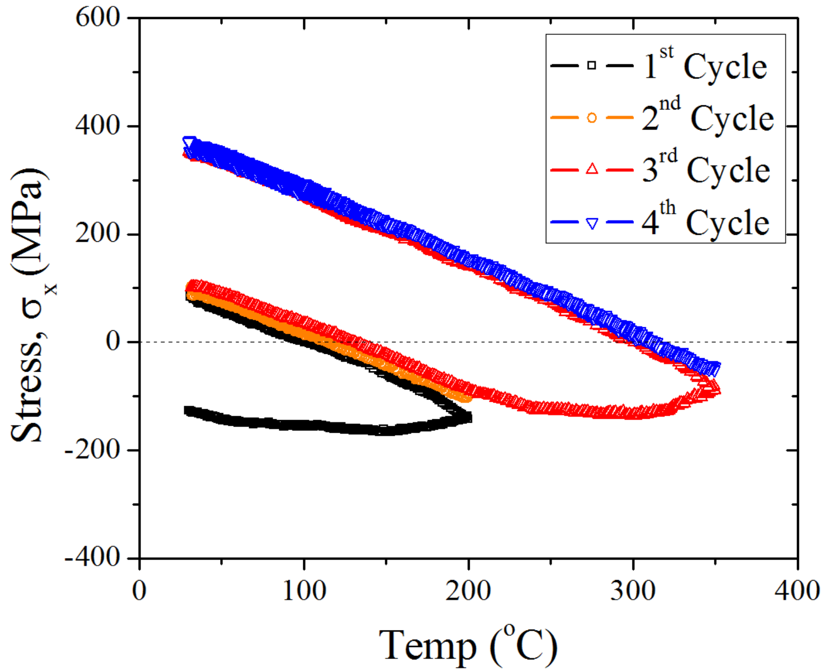




- Average grain size increases with temperature
- A large fraction of twin boundaries (60°)
- No preferred grain orientation (macroscopically isotropic).

From Curvature to Stress



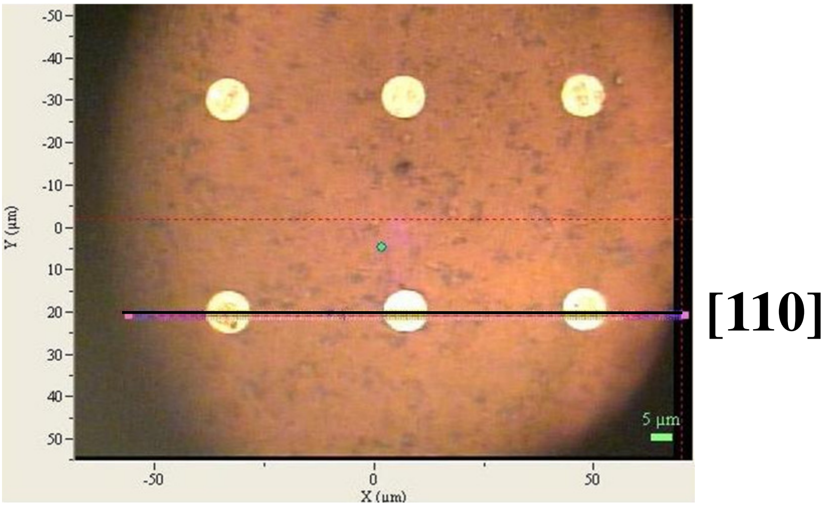


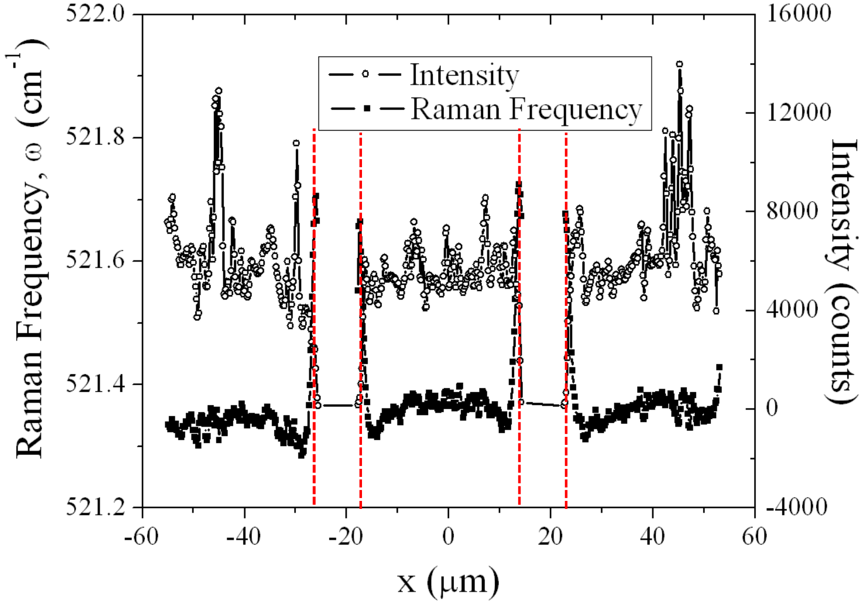
- **The volume-averaged stress in the Cu TSVs is assumed to be linearly proportional to the curvature difference**
- **A linear elastic FEA model agrees reasonably with the curvature slope in the linear region**

Micro-Raman Spectroscopy

S.-K. Ryu, et al., J. Appl. Phys. 2012.

Work in collaboration with Michael Hecker of GF-Dresden.

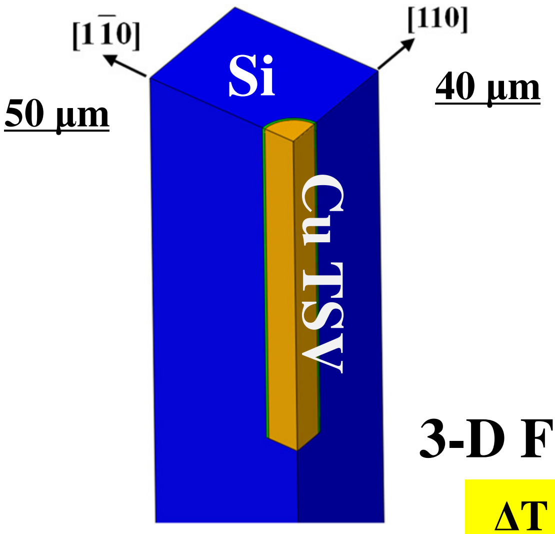




$$\sigma_r + \sigma_\theta \ (\text{MPa}) = -470\,\Delta\omega_3 (\text{cm}^{-1})$$

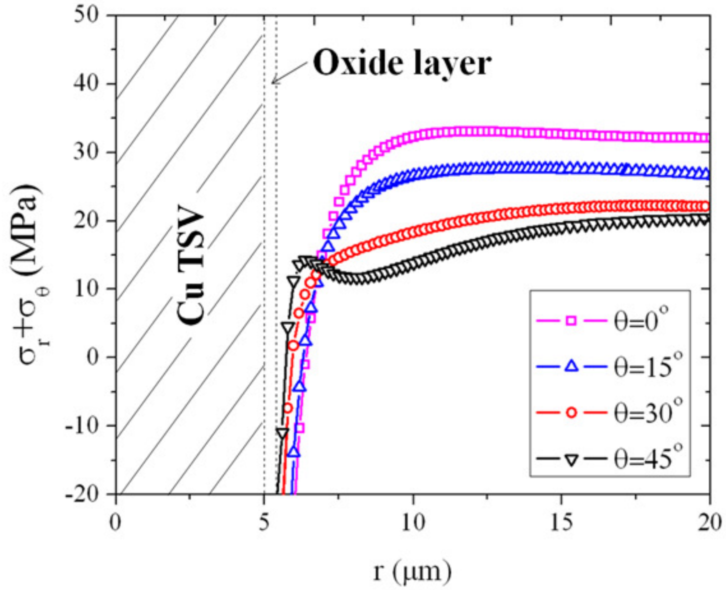
- **Raman frequency shift gives a local measure of the near-surface stress in Si**
- **Correlation between the local Raman measurements and the global curvature measurements offers a complementary approach for thermomechanical characterization of TSV structures.**

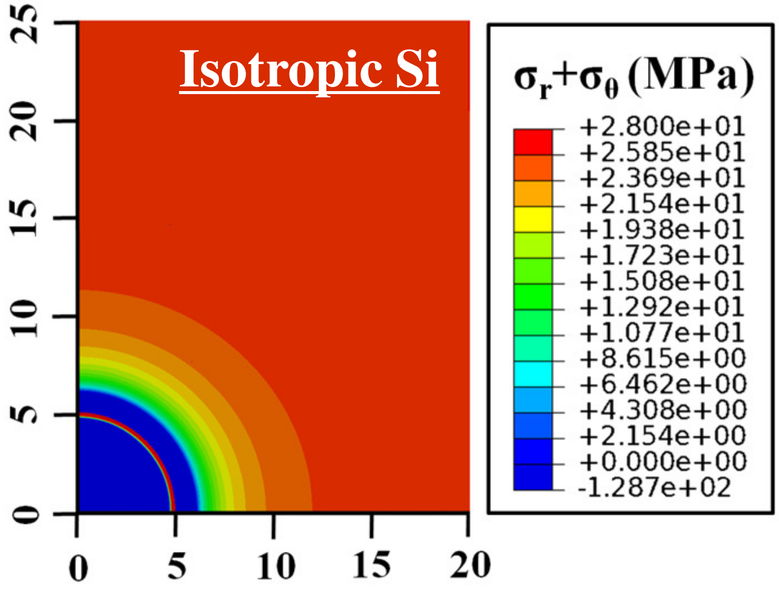
Effect of Silicon Anisotropy

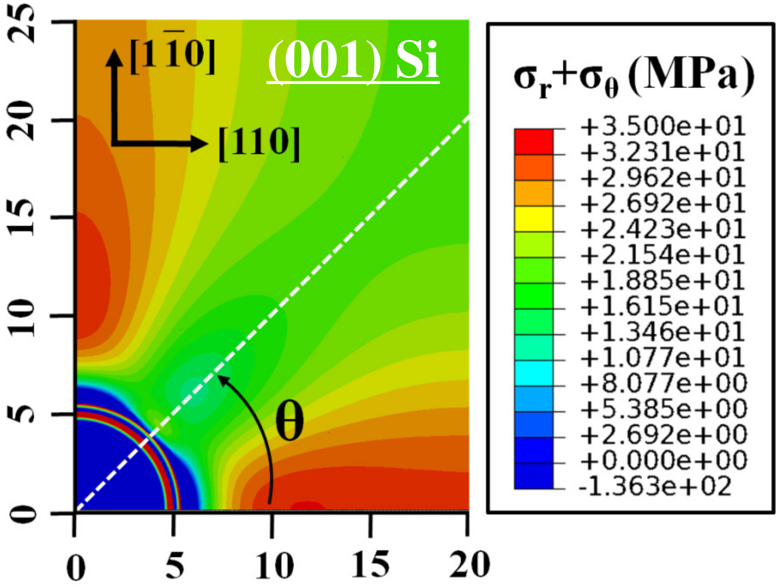


3-D FEA Model

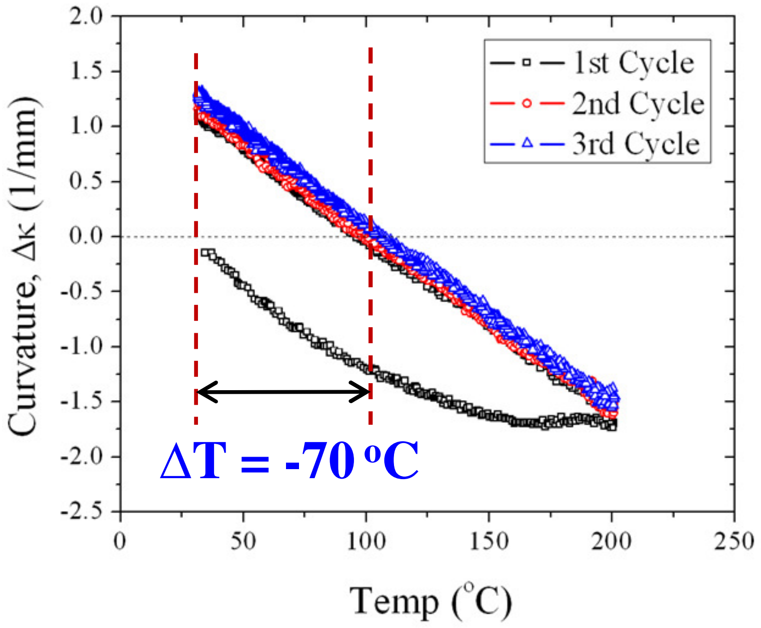
$\Delta T = -100\,^{o}C$

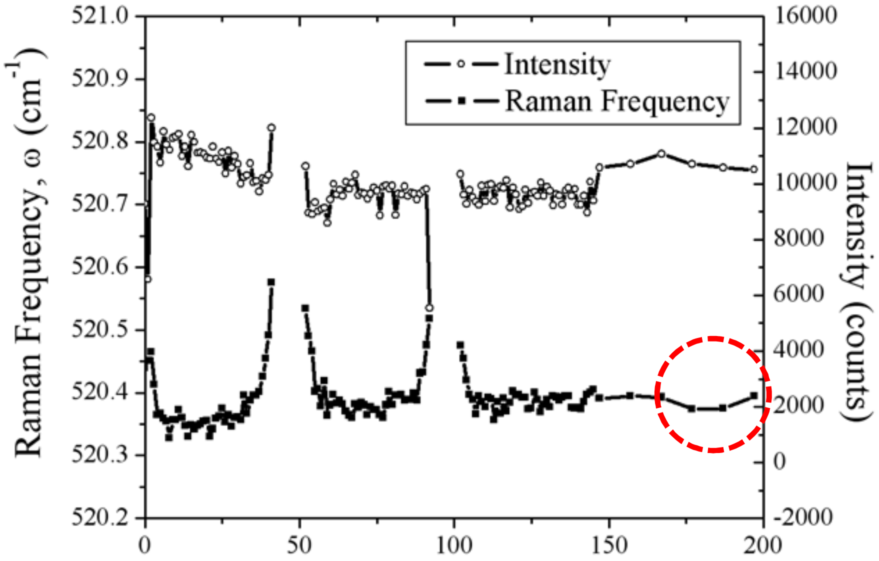




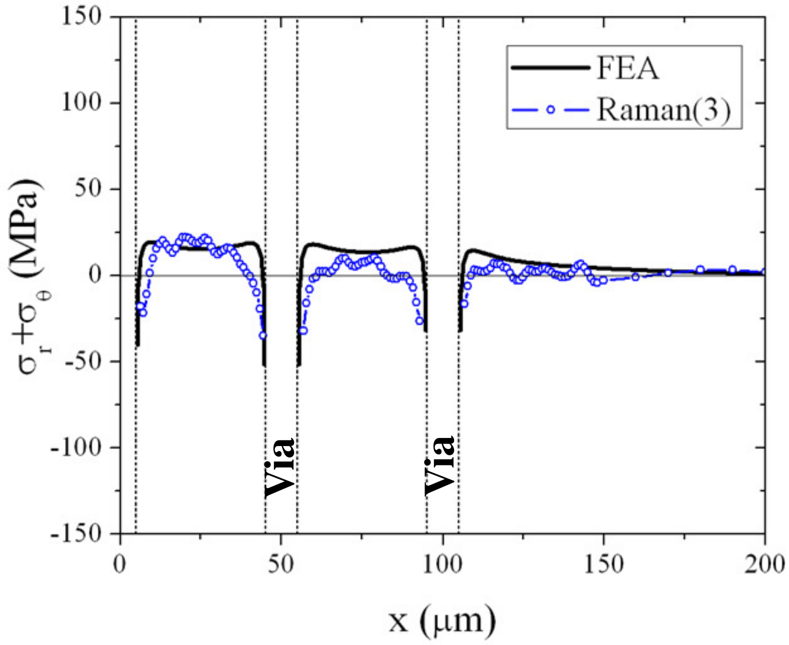


Raman Measurement for TSV (I)

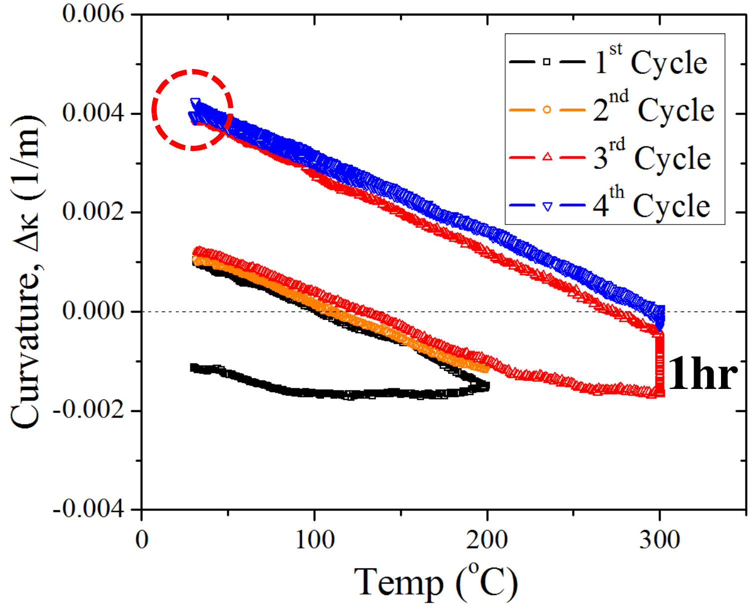


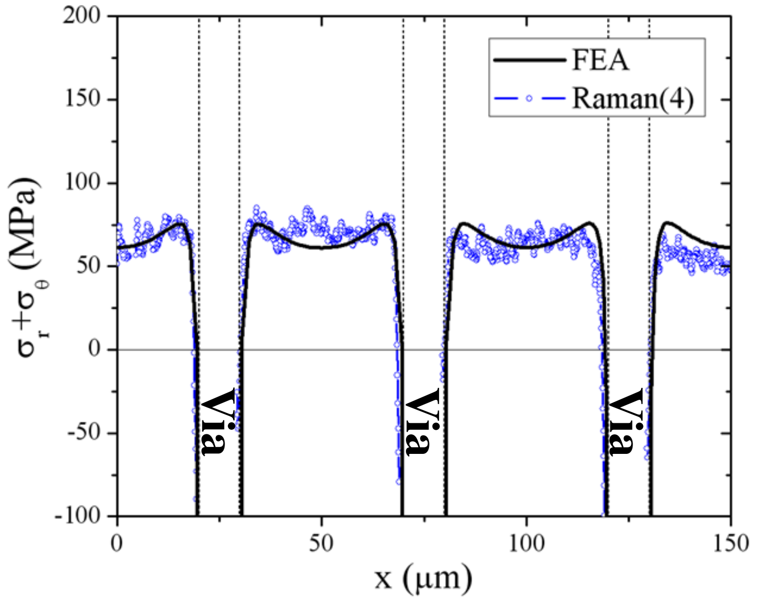


- **Reference frequency: ω_0 = 520.39 cm^{-1}**
- **Thermal load: ΔT = -70 °C**
- **Stress interaction between neighboring vias is notable.**



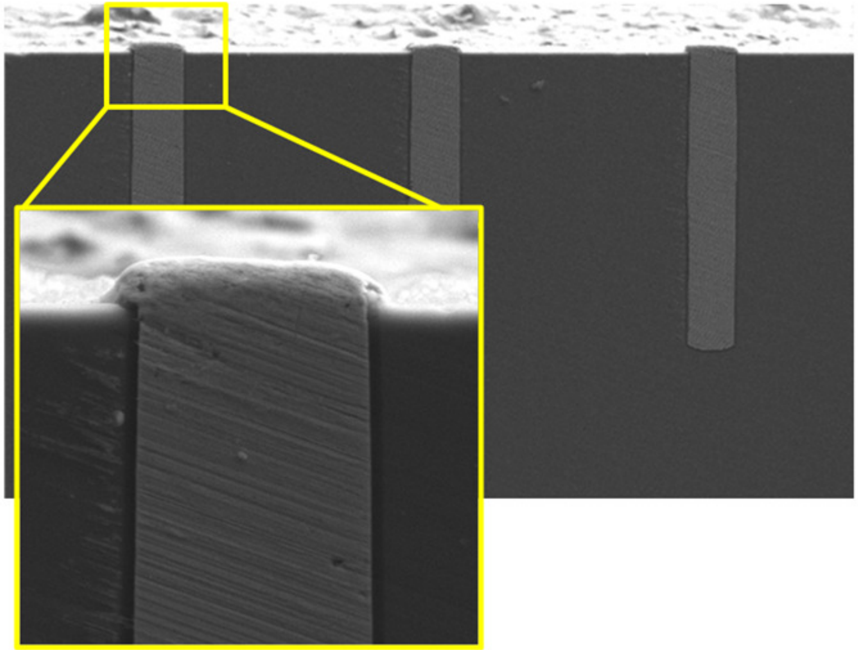
Raman Measurement for TSV (II)

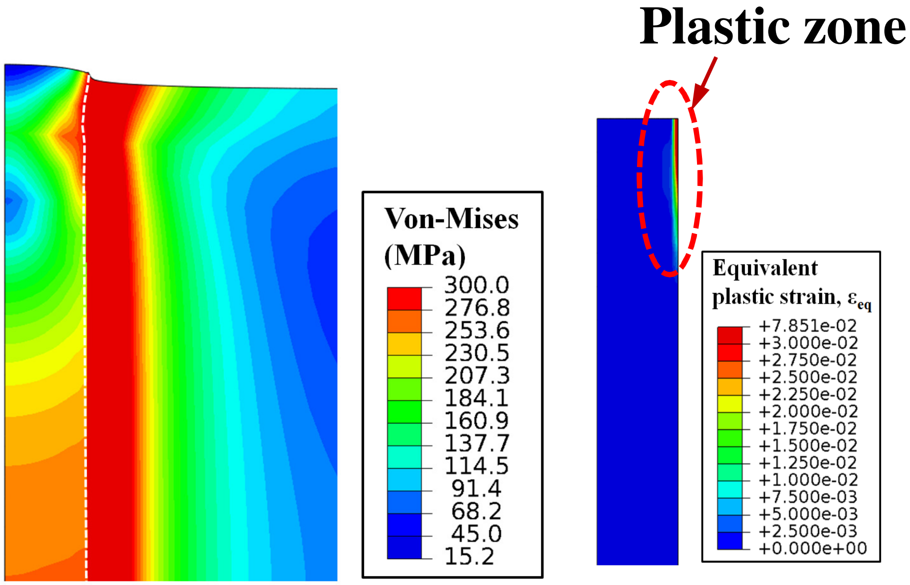




- **The specimen was annealed at 300^{o}C for 1 hour, and then cooled down to RT**
- **ΔT = -270 ^{o}C in the elastic FEA model**
- **Higher stress in Si correlates with higher curvature and higher stress in Cu too.**

Via Extrusion





Elastic-Plastic FEA Model

σ_y = 300 MPa and ΔT = 270^{o}C

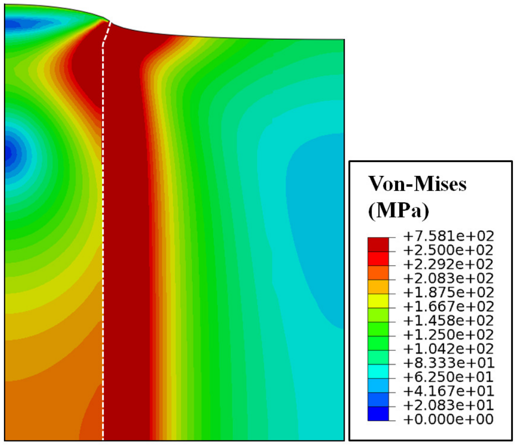
- **Local plastic deformation allows via extrusion.**
- **Yield strength depends on grain size and temperature.**

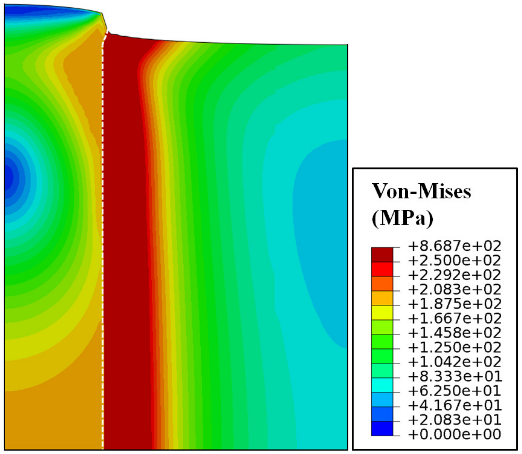
Extrusion or Sinking

Elastic Model

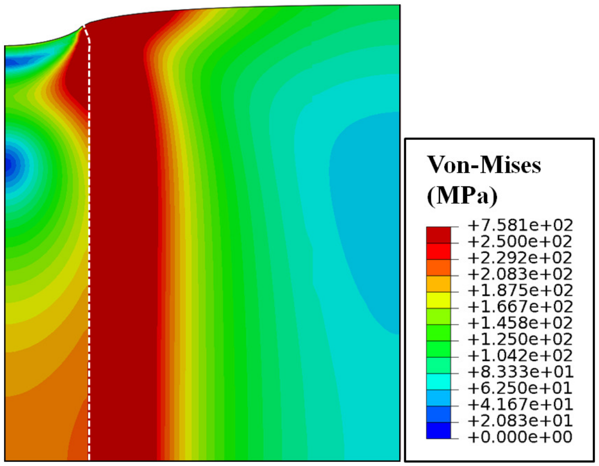
Elastic-Plastic Model

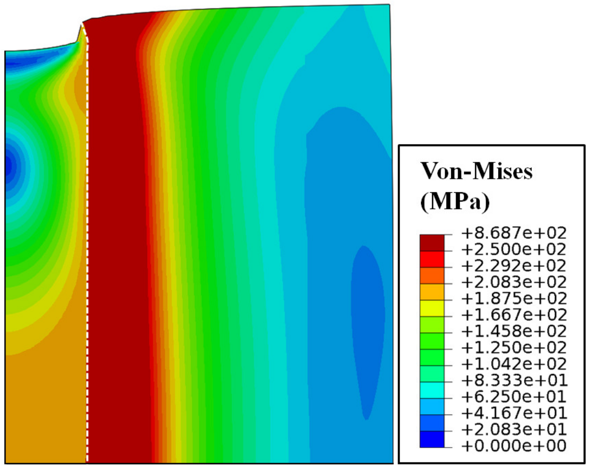
Heating
(ΔT > 0)



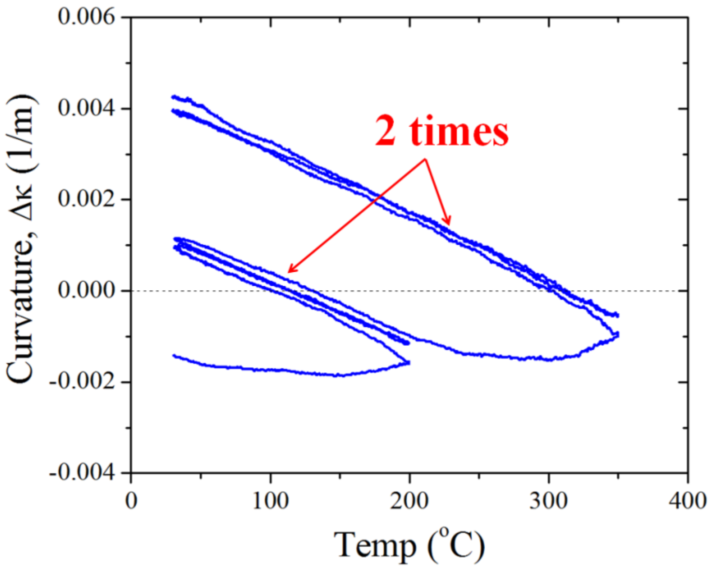


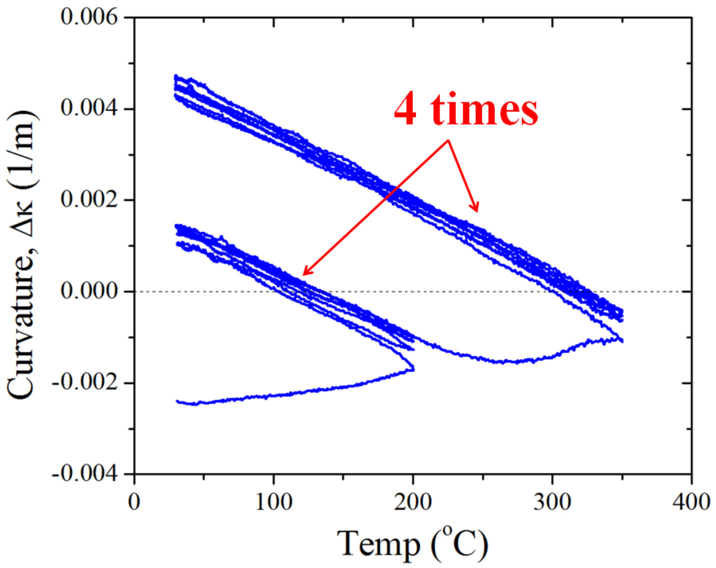
Cooling
(ΔT < 0)





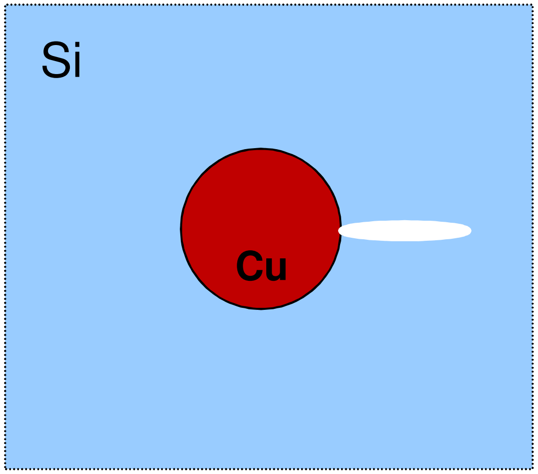
Ratcheting?



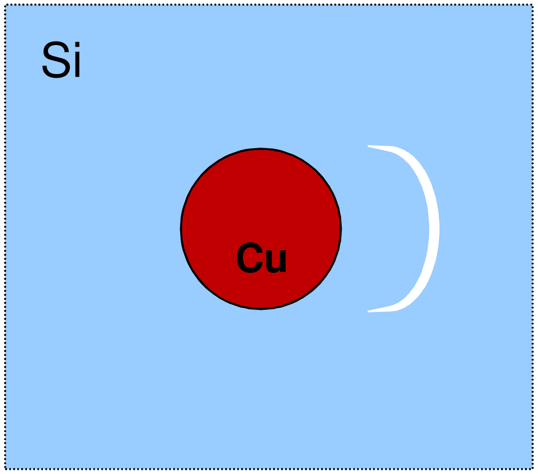


- **Why was via extrusion observed at RT?**
- Plastic ratcheting may induce net deformation (extrusion) after each cycle and accumulate over many cycles
- Grain growth leads to softening (Hall-Patch effect)
- Strain hardening?
- Interfacial sliding/delamination?

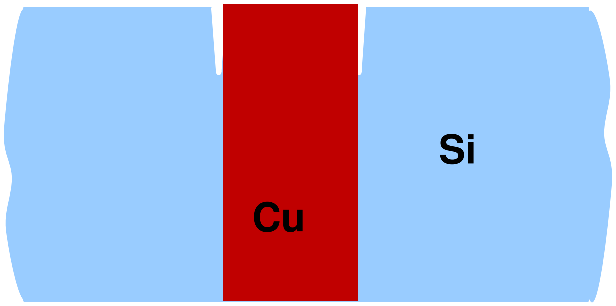
TSV Reliability: Potential Fracture Modes



R-crack



C-crack

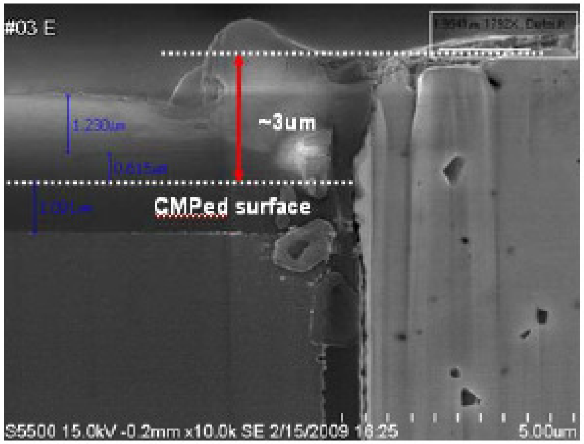


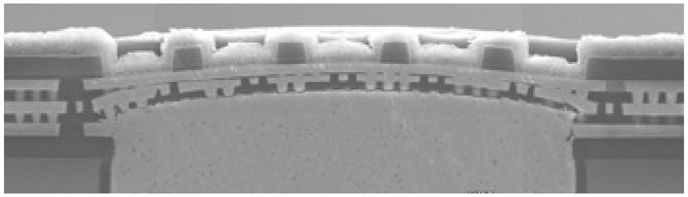
Interfacial crack

- R-crack may grow in Si during heating ($\Delta T > 0$) when the circumferential stress is tensile ($\sigma_\theta > 0$).
- C-crack may grows in Si during cooling ($\Delta T < 0$) when the radial stress is tensile ($\sigma_r > 0$).
- Interfacial crack can grow during both heating (by shear) and cooling (by shear and opening modes).

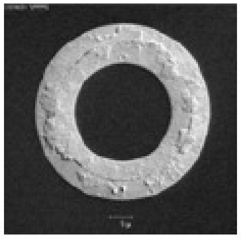
Power of Cu Extrusion

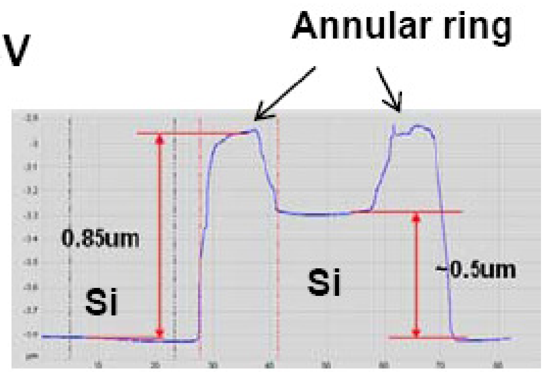
- **Examples**
  - Solid TSV

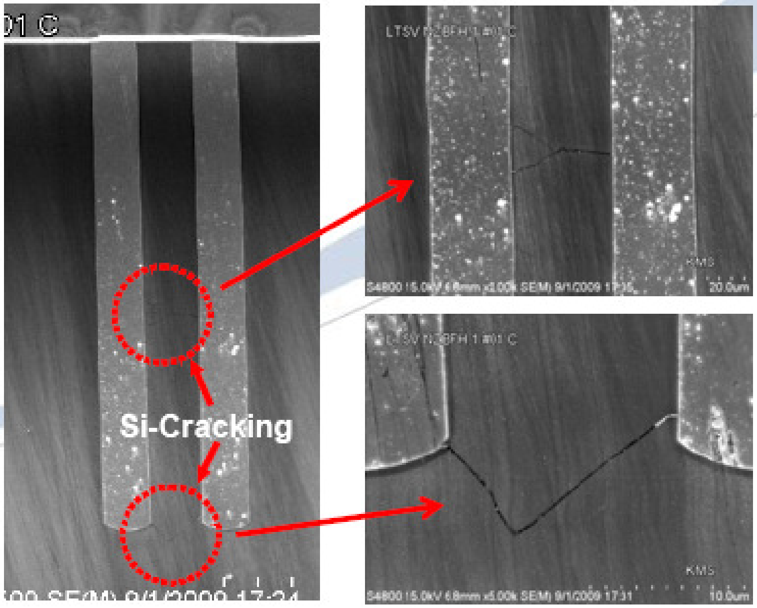




  - Annular TSV







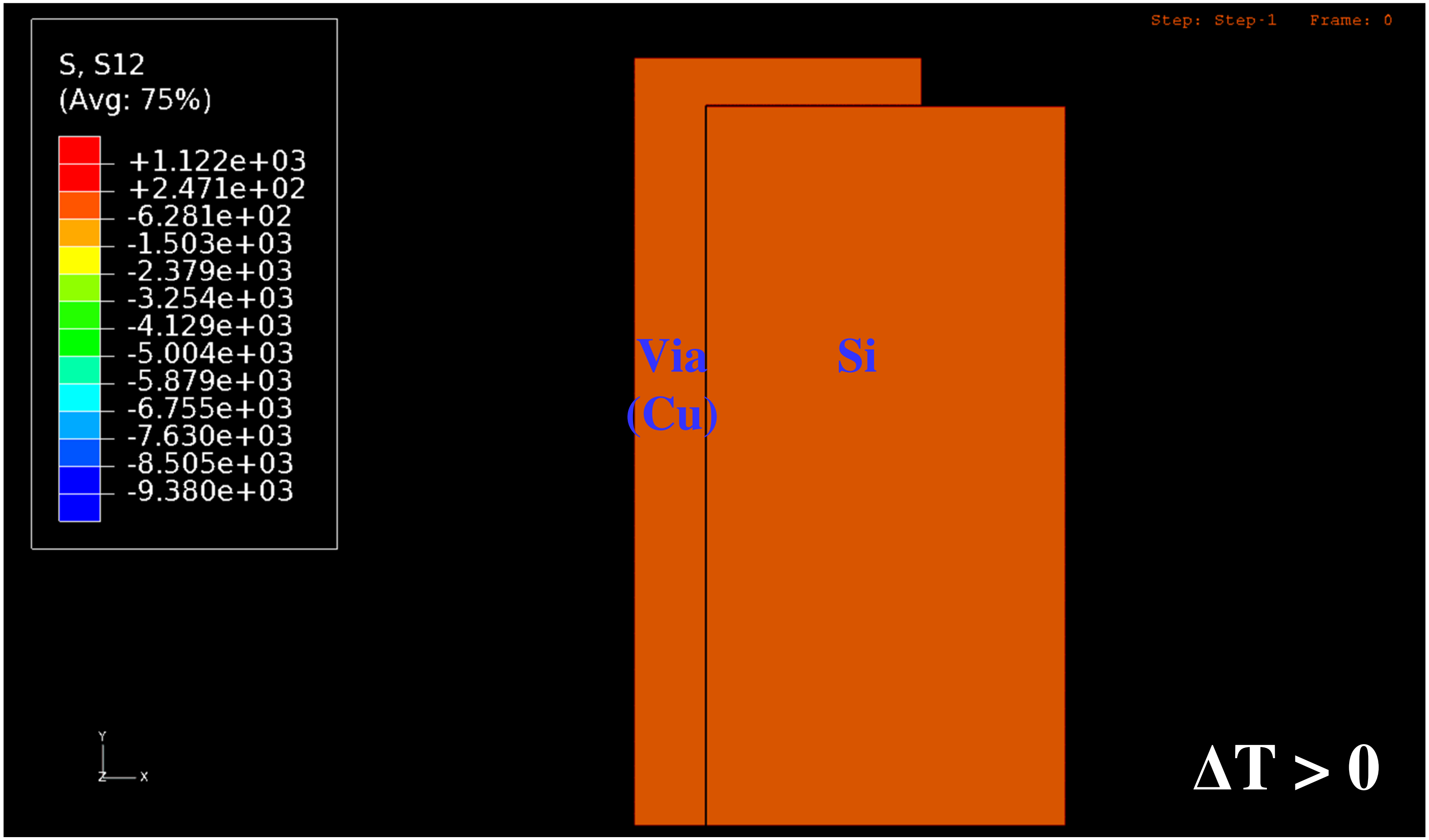
S. Cho, RTI 3D Workshop 12/2010

Basic Fracture Mechanics

$G > or < \Gamma$ Griffith Criterion

- **Energy release rate** (*G*): thermodynamic driving force for crack growth, i.e., the elastic strain energy released per unit area of the crack; calculated by FEA or other methods.
- **Fracture toughness** (Γ): material resistance against cracking, an intrinsic property of the material or interface; measured by experiments.
- Numerical methods are well established, e.g. FEA and cohesive zone modeling.
- **Experimental techniques, test structures and metrology for measuring Γ have to be developed.**

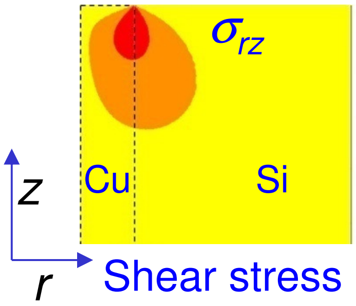
Via extrusion by interfacial delamination



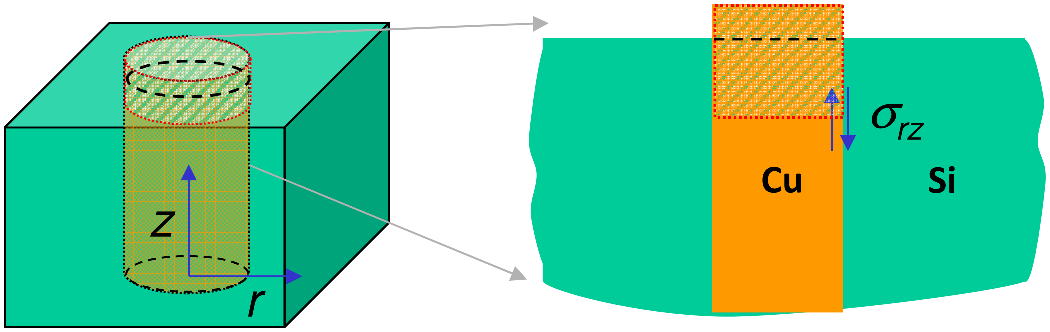
- A cohesive zone model is used to simulate crack nucleation and propagation along the interfaces.

TSV Interfacial Fracture

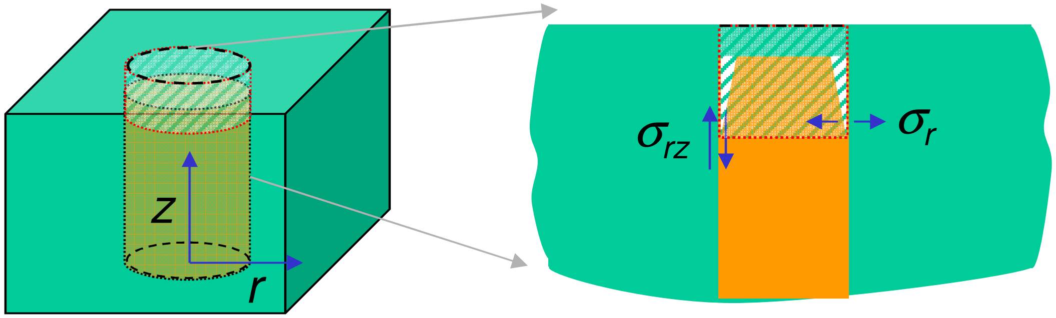
- **Heating cycle: $\Delta T > 0$:**
  - **Interfacial crack driven by shear stress σ_{rz}**



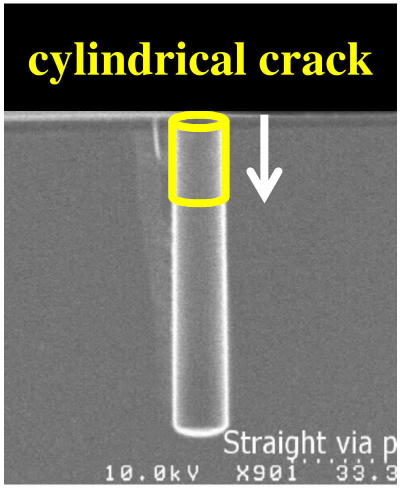
Shear stress σ_{rz} concentration near surface

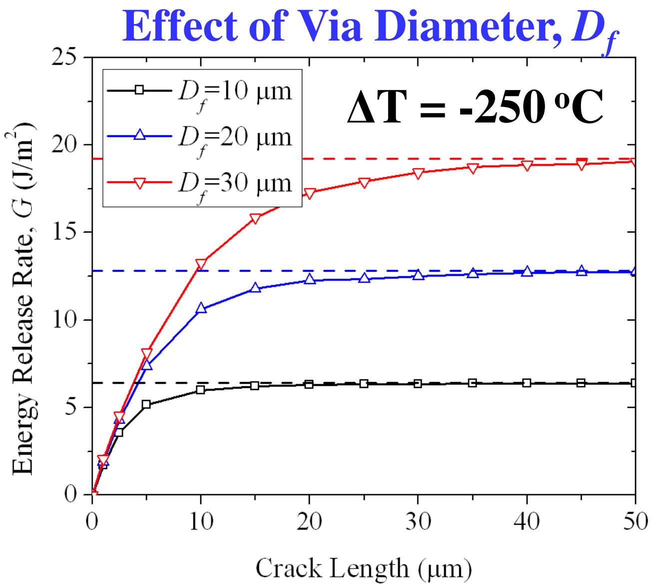


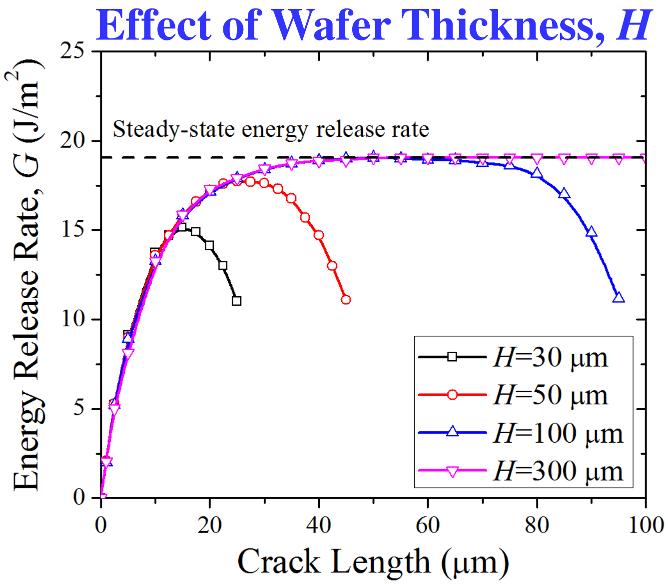
- **Cooling cycle: $\Delta T < 0$:**
  - **Crack driven by both shear stress σ_{rz} and radial stress σ_r**
  - **Mixed mode (Mode I + Mode II)**



Energy Release Rate







Steady-State ERR:

$$G_{SS} = \frac{1}{4} E_{Si} D_f (\Delta\alpha\Delta T)^2 \phi\left(\frac{E_m}{E_{Si}}, \nu_m, \nu_{Si}\right)$$

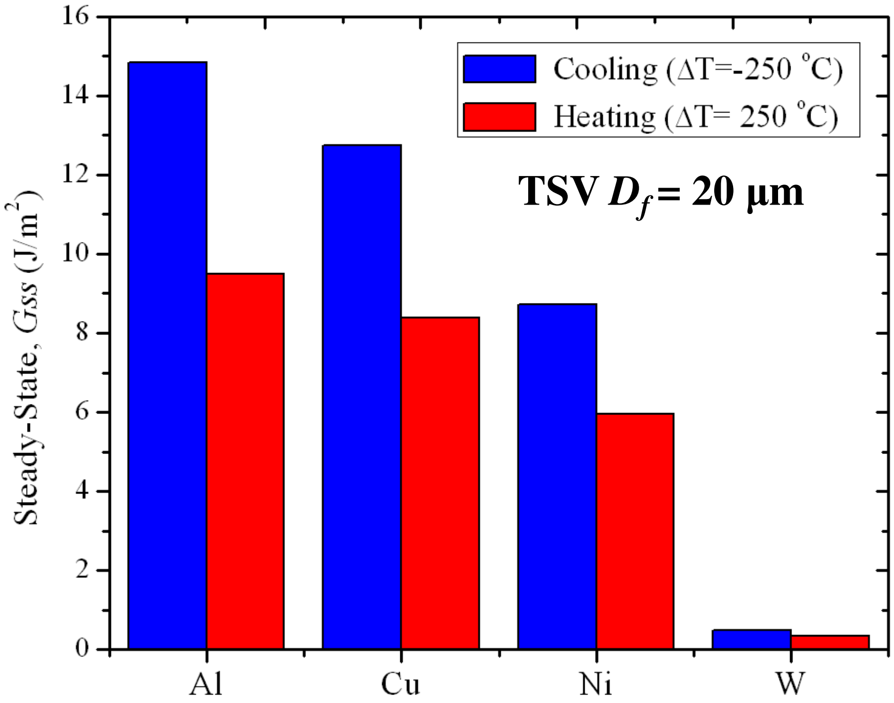
$$G_{SS}^{cooling} > G_{SS}^{heating}$$

Control parameters:

- Thermal mismatch
- Thermal load
- Via diameter
- Elastic mismatch

S.-K. Ryu, et al., IEEE TDMR 2011.

Effect of TSV Metals

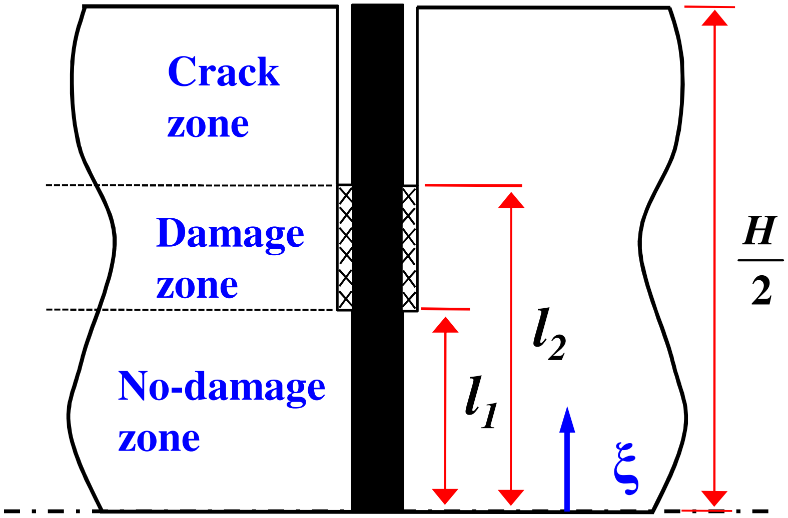


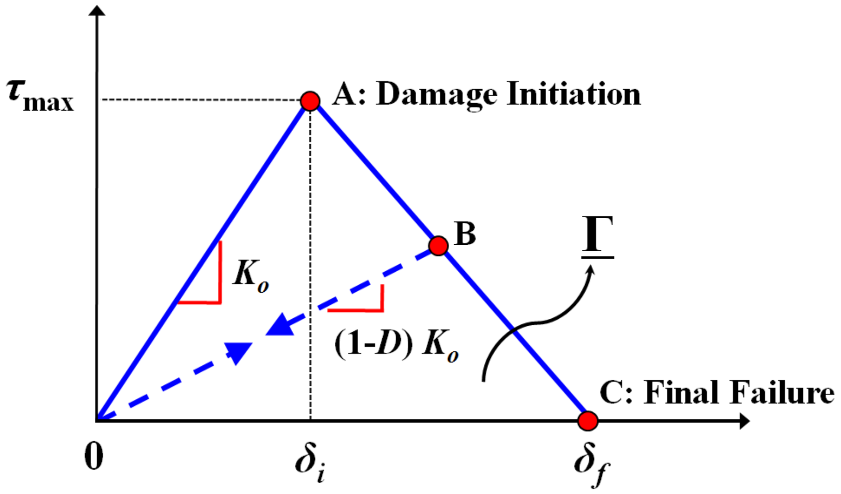
Material	CTE (ppm/K)	Young's Modulus (GPa)	Poisson's Ratio
Al	20	70	0.35
Cu	17	110	0.35
Ni	13	207	0.31
W	4.4	400	0.28
Si	2.3	130	0.28

$$G_{SS} = \frac{1}{4} E_{Si} D_f (\Delta\alpha\Delta T)^2 \phi\left(\frac{E_m}{E_{Si}}, \nu_m, \nu_{Si}\right)$$

- The effect of thermal mismatch dominates the effect of elastic mismatch.
- The advantage of W over Cu may be partly compromised by higher thermal load and lack of plasticity (lower adhesion).

A Shear-Lag Cohesive Zone Model





Two critical temperatures

$$\Delta T_{c1} \approx \frac{2}{\Delta\alpha}\sqrt{\frac{\tau_{\max}\delta_i}{E_f D_f}}$$

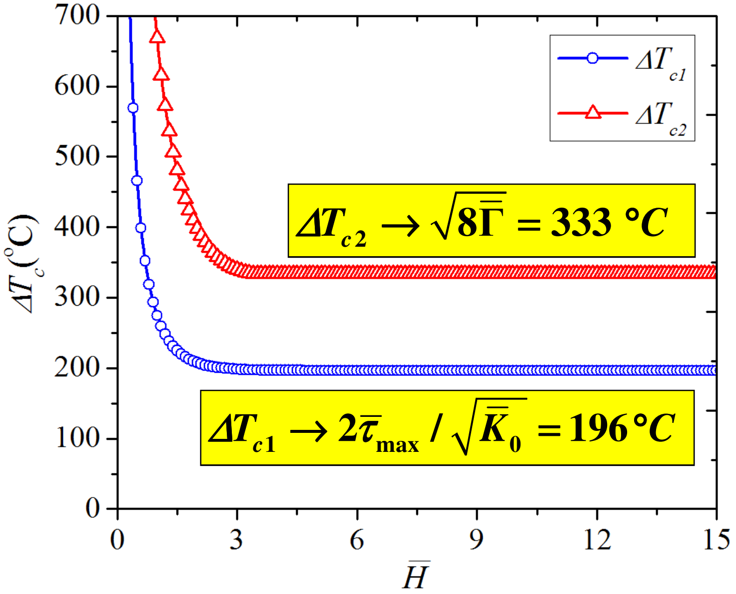
$$\Delta T_{c2} \approx \frac{2}{\Delta\alpha}\sqrt{\frac{2\Gamma}{E_f D_f}}$$

$$\left(H >> D_f\right)$$

Three stages:

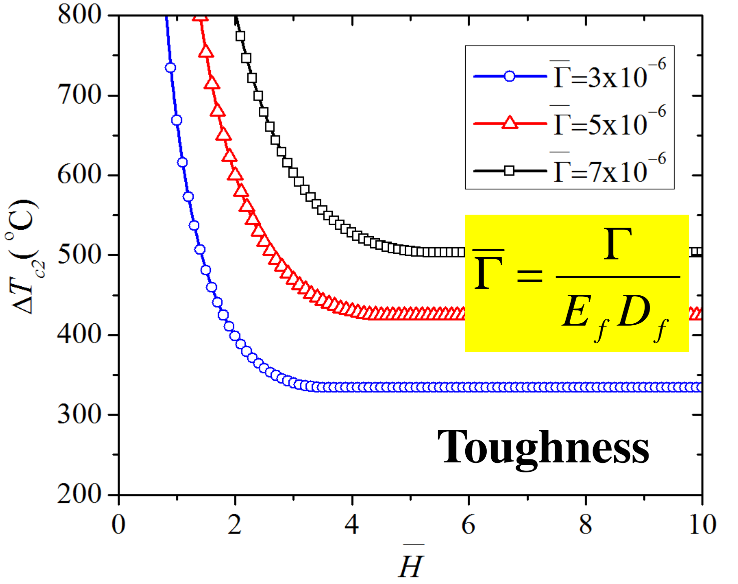
- i) $\Delta T < \Delta T_{c1}$: no damage
- ii) $\Delta T_{c1} < \Delta T < \Delta T_{c2}$: damage evolution
- iii) $\Delta T > \Delta T_{c2}$: crack growth

Critical Temperatures



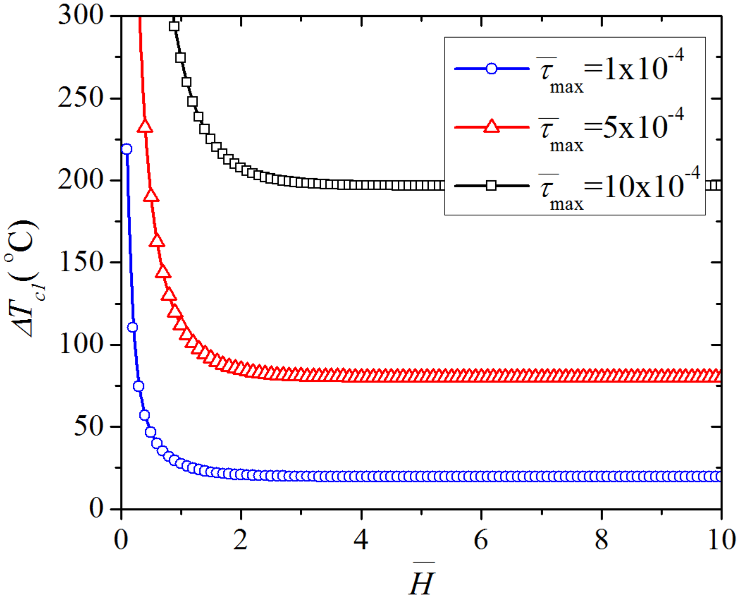
$$\Delta T_{c2} \to \sqrt{8\bar{\Gamma}} = 333\ ^\circ C$$

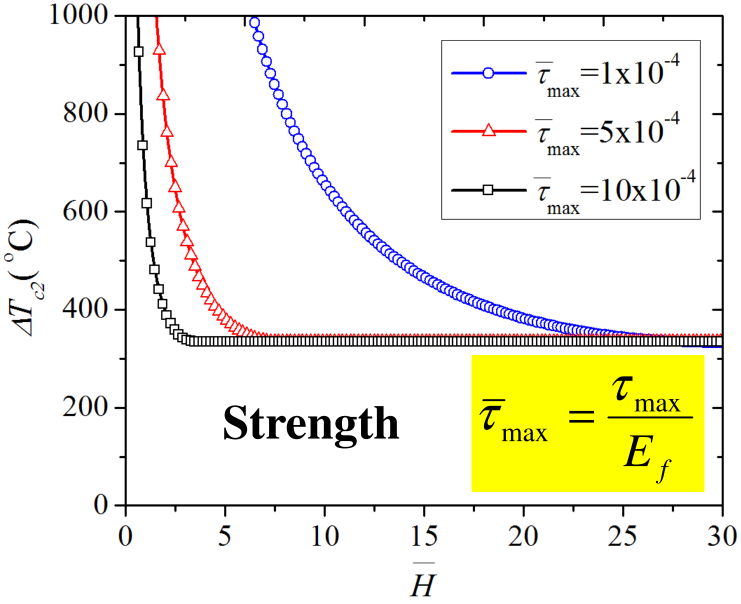
$$\Delta T_{c1} \to 2\bar{\tau}_{\max} / \sqrt{\bar{K}_0} = 196\ ^\circ C$$



$$\bar{\Gamma} = \frac{\Gamma}{E_f D_f}$$

Toughness

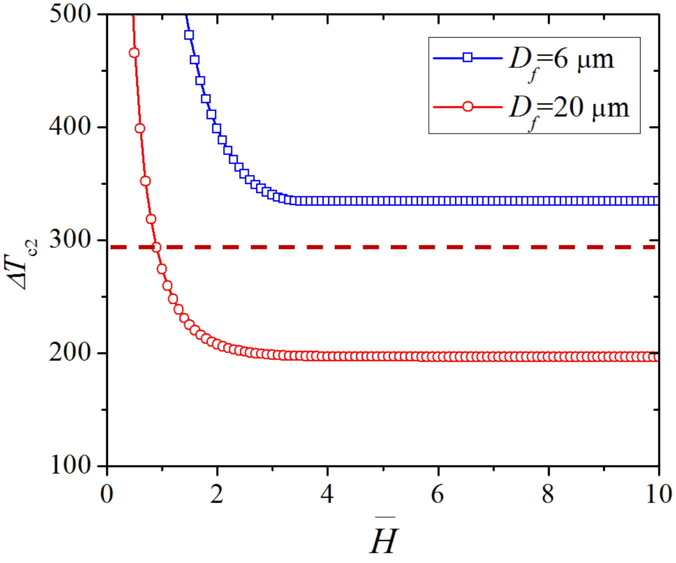


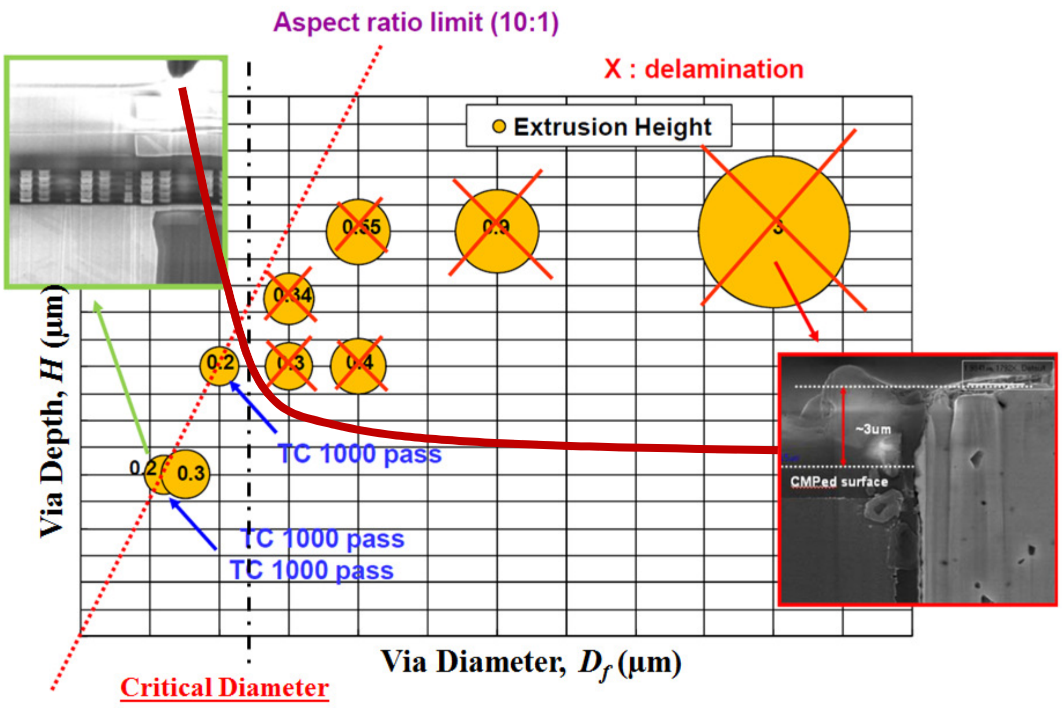


Strength

$$\bar{\tau}_{\max} = \frac{\tau_{\max}}{E_f}$$

Critical TSV Dimensions





S. Cho (Samsung)

- ➢ The critical temperature depends on both the via diameter and the via depth
- ➢ Given the material properties and the thermal load, the critical dimensions can be determined.

Summary

- Thermomechanical reliability of TSV structures has to be addressed by combining experimental characterization with modeling and simulations.
- Precision wafer curvature technique provides in-situ measurements of global deformation during thermal cycles.
- Micro-Raman spectroscopy provides local measurements of near-surface stress in Si, which can be correlated with the curvature measurements.
- Via extrusion may be induced by either local plastic deformation or interfacial delamination, to be further studied.
- Interfacial reliability of TSVs has been studied theoretically; More works are needed to characterize the interfacial properties and correlate modeling with experiments.

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