Thermomechanical Reliability Challenges for 3D Interconnects

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Wafer Level 3D Integration

**Mechanical effects:**
- Through silicon vias (TSVs)
- Wafer thinning
- Wafer (die) bonding

*Philip Garrou, Microelectronic Consultants of NC*
**TSV Mechanical Reliability**

- **Stress around TSVs:**
  - *Keep-away zone* for FEOL
  - Cracking of silicon

- **Stress at the interfaces:**
  - Debonding, TSV pop-up

- **Stress inside TSVs:**
  - Plastic deformation
  - Stress-induced voiding
  - Stress migration

- **Sources of stress:**
  - Process-induced stress
  - Thermal stress – BEOL process
  - Packaging induced stress

**TSV stress and reliability depends on both materials processing and structural design.**
Stress and Reliability Analysis of TSV

- **Analytical solutions**
  - 2D approximation
  - Near-surface stress distribution by method of superposition

- **Finite element analysis**
  - Effect of liners/barrier layers
  - Effect of wafer thickness
  - Effect of elastic mismatch
  - Effect of nail head

- **Fracture analysis**
  - Calculation of ERR
  - Cohesive crack simulations
Process Induced Stress Simulation

- TEOS/barrier layer deposition at 400~430°C
- Cu electroplating @ 30°C
  - Annealing @ 200°C
  - Cooling down to 30°C
    - Cu CMP
  - Capping layer deposition at 150°C
  - CVD of TEOS @ 400°C
  - Cooling down to 25°C

TSV diameter: ~2 μm

Critical steps for interfacial delamination and silicon cracking
Thermal Stress: 2D Approximate Solution

Thermal Strain:
\[ \varepsilon_T = (\alpha_{Cu} - \alpha_{Si}) \Delta T \]

Uniform thermal stress in Cu via (triaxial):
\[ \sigma_r = \sigma_\theta = \frac{-E \varepsilon_T}{2(1-\nu)}, \quad \sigma_z = \frac{-E \varepsilon_T}{1-\nu} \]

Stress distribution in Si (biaxial):
\[ \sigma_r = -\sigma_\theta = \frac{-E \varepsilon_T}{2(1-\nu)} \frac{a^2}{r^2}, \quad \sigma_z = 0 \]

- The magnitude of the stresses in the via is independent of the via size.
- The stresses in Si decay with the distance \((r)\), with the decay length proportional to the via size \((a)\).
Method of Superposition

Problem A:
uniform thermal stress in Cu

Problem B:
3D Stress redistribution near surface

- For a high aspect-ratio TSV, the stress field away from the surfaces can be obtained from a 2D plane-strain solution (Problem A).
- The stress field near surface is 3D in general, which can be determined by superimposing an opposite surface loading (Problem B) onto the 2D field (Problem A) to satisfy the boundary conditions at the surface.
2D Stress Field of Single Via

- Assume stress free at high temperature (reference)
- Cooling from the reference temperature ($\Delta T = -175^\circ C$) leads to tensile stresses in the via.
- Around the via, the stress is tensile in the radial direction and compressive in the circumferential direction, both concentrated near the via.
Proximity Effect on Keep-away Zone

- Proximity of TSVs increases the area with high thermal stress and affect the keep-away zone.

![Diagram of Normal Stress $\sigma_x$](image1)

![Diagram of Normal Stress $\sigma_x$ (MPa)](image2)
3D Stress Field near Surface (Problem B)

Uniform surface pressure over a circular area

\[ p = \sigma_z^T = \frac{E \varepsilon_T}{1 - \nu} \]

- Stress decays with the distance from the surface.
- Triaxial stress in the via center \((r = 0)\).
- Radial and circumferential stresses on the surface \((z = 0)\).
- Shear stress at the interface.

\[
\sigma_z(r = 0) = \frac{E \varepsilon_T}{1 - \nu} \left[ \frac{z^3}{(a^2 + z^2)^{3/2}} - 1 \right] = \frac{E \varepsilon_T}{1 - \nu} f\left(\frac{z}{a}\right)
\]

\[
\sigma_r(r = 0) = \sigma_\theta(r = 0) = \frac{E \varepsilon_T}{2(1 - \nu)} \left[ -2\nu + \frac{(1 + 2\nu)z}{\sqrt{a^2 + z^2}} + \frac{a^2z}{(a^2 + z^2)^{3/2}} \right]
\]
Stresses near Wafer Surface

Positive opening stress along Cu/Si interface

Concentration of the shear stress at the surface/interface junction
At the Cu/Si interface, the opening stress ($\sigma_r$) decreases but the shear stress ($\sigma_{rz}$) increases as the aspect ratio H/D decreases.
Effect of Liner Interlayer

\( \sigma_r \)
opening stress

\( \sigma_{rz} \)
shear stress

Without liner

With liner
Potential Fracture Modes of TSVs

- R-crack may grow in Si during heating ($\Delta T > 0$) when the circumferential stress is tensile ($\sigma_{\theta} > 0$).
- C-crack may grow in Si during cooling ($\Delta T < 0$) when the radial stress is tensile ($\sigma_r > 0$).
- Interfacial crack can grow during both heating and cooling.
Concepts of Fracture Mechanics

- **Energy release rate** (ERR or $G$): thermodynamic driving force for crack growth, the elastic strain energy released per unit area of the crack; calculated by FEA or other methods.

- **Fracture toughness** ($\Gamma$): material resistance against cracking, an intrinsic property of the material or interface; measured by experiments.

- *An simple comparison between $G$ and $\Gamma$ predicts crack growth or not.*

- **Cohesive zone modeling**: use a nonlinear traction-separation relationship to describe the interactions across the interface, including crack nucleation and growth.
TSV-induced R-crack in Si

Energy release rate:

\[ G(c) = \frac{\pi E(\Delta \alpha \Delta T)^2}{8(1-\nu)^2} \frac{c}{(1+c/a)^3} \]

- The energy release rate for a R-crack increases as the via diameter increases.

- The maximum energy release rate occurs at the crack length \( c = 0.5a \):

\[ G_{\text{max}}(a) = \frac{\pi(\Delta \alpha \Delta T)^2}{54(1-\nu)^2} Ea \]
TSV Interfacial Delamination

- Heating cycle ($\Delta T > 0$): Interfacial crack driven by shear stress ($\sigma_{rz}$); Mode II fracture

- Cooling cycle ($\Delta T < 0$): Crack driven by both shear stress ($\sigma_{rz}$) and radial stress ($\sigma_r > 0$); mixed mode fracture (Mode I + Mode II)
Via pop-up upon heating

- Cu TSV subjected to heating up to +400K
- Cohesive interface elements are used to simulate crack initiation and growth
- The simulation results depend on input of interfacial properties (strength and toughness)
Interfacial Delamination during Cooling

- Cu TSV subjected to cooling up to -400K
- Cohesive interface elements are used to simulate crack initiation and growth
Energy Release Rate (ERR)

\[ \Delta T = 250 \text{ K} \]

\[ \Delta T = -250 \text{ K} \]

\[ G_{cooling}^{SS} \approx \frac{E(\Delta \alpha \Delta T)^2 D_f}{4(1-\nu)} \]

\[ G_{heating}^{SS} \approx \frac{1+\nu}{8(1-\nu)} E(\Delta \alpha \Delta T)^2 D_f \]

- The steady-state ERR sets an upper bound for the crack driving force, which may be used for conservative design.
Effect of TSV Metals

![Graph showing the effect of different metals on thermal mismatch.]

<table>
<thead>
<tr>
<th>Material</th>
<th>CTE (ppm/K)</th>
<th>Young’s Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>20</td>
<td>70</td>
<td>0.35</td>
</tr>
<tr>
<td>Cu</td>
<td>17</td>
<td>110</td>
<td>0.35</td>
</tr>
<tr>
<td>Ni</td>
<td>13</td>
<td>207</td>
<td>0.31</td>
</tr>
<tr>
<td>W</td>
<td>4.4</td>
<td>400</td>
<td>0.28</td>
</tr>
<tr>
<td>Si</td>
<td>2.3</td>
<td>130</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The effect of thermal mismatch dominates the effect of elastic mismatch.

\[
G_{SS} = \frac{E_S (\Delta \alpha \Delta T)^2 D_f}{4} f\left(\frac{E_{TSV}}{E_S}, \nu_{TSV}, \nu_S\right)
\]
Annular TSV

Diameter ratio: \( \eta = \frac{D_i}{D_f} \)

Steady-State ERR for interfacial delamination:

\[
G_{SS} = \frac{E_{Si} (\Delta \alpha \Delta T)^2 D_f}{4} f\left( \eta, \frac{E_{TSV}}{E_{Si}}, \nu_{TSV}, \nu_{Si} \right) \approx \frac{E(\Delta \alpha \Delta T)^2 D_f}{4(1 - \nu)} \left(1 - \eta^2\right)
\]
TSV with Nail Head

- Shear stress at both interfaces
- Opening stress at the NH/Si interface (heating)

\[ D_f = 6 \mu m \]
\[ \Delta T = 400 K \]
Cu TSV/NH subjected to heating up to +400K
Cohesive interface elements are used to for both via/Si and NH/Si interfaces
Delamination typically initiates from the corner (site of stress concentration) and grows simultaneously along both interfaces.
Summary

- Thermal expansion mismatch induces stresses in TSV and surround materials. TSV geometry and material combination can generate complex 3D stress fields that affects the determination of keep-away zone.
- Interfacial delamination of TSV can occur under both heating and cooling while r-crack in Si could occur under heating. In both cases, the crack driving force increases with the TSV diameter and scales with the square of thermal loading.
- The reliability of TSV structure can be improved by optimizing the materials and geometry to reduce the crack driving force.
- Cohesive zone modeling could be useful in the study of crack nucleation and growth, for which experimental measurements of the interfacial properties (toughness and strength) are needed.