Thermomechanical Reliability of Microelectronics

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Topics

- Crack penetration or debonding
- Interfacial delamination
- Dislocation injection
- Voiding and electromigration
Diverse Materials & Sharp Features

The study of the singular stress filed around the sharp features draw a lot of attention.

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Intel  90 nm interconnect

Intel  Pentium III CPU


Stress concentration  ➔  Failures!
Split singularities

Homogeneous material
Two modes have the same exponents --- $1/2$

$$\sigma_{ij}(r, \theta) = \frac{K_I}{r^{1/2}} \Sigma^I_{ij}(\theta) + \frac{K_{II}}{r^{1/2}} \Sigma^{II}_{ij}(\theta)$$

Bimaterial
Two modes have different exponents --- $\lambda_1$ and $\lambda_2$

$$\sigma_{ij}(r, \theta) = \frac{k_1}{r^{\lambda_1}} \Sigma^1_{ij}(\theta) + \frac{k_2}{r^{\lambda_2}} \Sigma^2_{ij}(\theta)$$
Split due to geometry

Split due to **elastic mismatch**

Always split, unless Mat.#1 is rigid.
Split singularities: oblique crack

\[ \beta = 0 \]

\[ \alpha = \frac{\overline{E}_1 - \overline{E}_2}{\overline{E}_1 + \overline{E}_2} \]

\[ \beta = \frac{1}{2} \left[ \frac{\mu_1 (1 - 2\nu_2) - \mu_2 (1 - 2\nu_1)}{\mu_1 (1 - \nu_2) + \mu_2 (1 - \nu_1)} \right] \]

singularity exponents \( \lambda \)

impinging angle \( \omega \)

Mat. #1

Mat. #2

Mat. #1

Mat. #2

Mat. #1

Mat. #2
Split singularities:

Rule rather than exception:

\[
\sigma_{ij}(r, \theta) = \frac{k_1}{r^{\lambda_1}} \Sigma_{ij}^1(\theta) + \frac{k_2}{r^{\lambda_2}} \Sigma_{ij}^2(\theta)
\]

Questions:

• Should we neglect the weaker singularity?
• How do we study the failure phenomena with consideration of weaker singularity?
Applications and Implications: 

Crack Penetration or Debonding
Cracking Path Selection

A crack impinges upon an interface.
(He and Hutchinson, *IJSS*, 1989).

Penetration vs. Debonding

The effect of weaker singularity has not been well studied.
Q: Should we neglect the weaker singularity?

Homogeneous material:

\[ \sigma_{ij}(r, \theta) = \frac{K_I}{r^{1/2}} \Sigma^I_{ij}(\theta) + \frac{K_{II}}{r^{1/2}} \Sigma^II_{ij}(\theta) \]

Mode mixity \( = \frac{K_{II}}{K_I} \)

Bimaterial:

\[ \sigma_{ij}(r, \theta) = \frac{k_1}{r^{\lambda_1}} \Sigma^1_{ij}(\theta) + \frac{k_2}{r^{\lambda_2}} \Sigma^2_{ij}(\theta) \]

Stress ratio of two modes

\[ = \frac{k_2 r^{-\lambda_2}}{k_1 r^{-\lambda_1}} \]

\( r \) does NOT go to zero.
Definition of **mode mixity**

\[
\sigma_{ij}(r, \theta) = \frac{k_1}{r^{\lambda_1}} \Sigma^1_{ij}(\theta) + \frac{k_2}{r^{\lambda_2}} \Sigma^2_{ij}(\theta)
\]

Select some length we care:

Mode mixity: \[
\eta = \frac{k_2 \Lambda^{-\lambda_2}}{k_1 \Lambda^{-\lambda_1}}
\]

It measures the relative contribution of the two modes to the stress field at length scale \( \Lambda \)

**Answer:** it depends on the magnitude of the mode mixity.
Two length scales

\[ k_1 = \kappa_1 T L^{\lambda_1} \sim [\text{stress}][\text{length}]^{\lambda_1} \]

\[ k_2 = \kappa_2 T L^{\lambda_2} \sim [\text{stress}][\text{length}]^{\lambda_2} \]

\[ \eta = \frac{\kappa_2}{\kappa_1} \left( \frac{\Lambda}{L} \right)^{\lambda_1 - \lambda_2} \]

\[ \text{Mat. #1} \]

\[ \text{Mat. #2} \]

\[ \text{Mat. #1} \]

\[ \text{Mat. #2} \]

\[ L = 100 \text{ nm} \]

\[ \Lambda = 1 \text{ nm} \]

\[ \text{Im} \left( K_i^{ie} \right) \]

\[ \text{Re} \left( K_i^{ie} \right) \]

(Rice, 1988)

\[ \eta \]

\[ 0.2 \]

\[ 0.4 \]

easily on the order of unity.

\[ \eta \] is used to assess the effect of weaker singularity.
Crack penetration

\[ k_1, k_2 \]

Mat. #1

\[ \omega \]

Mat. #2

\[
\tan \psi^p = \frac{K_{II}^p}{K_I^p}
\]

\[ \alpha = -0.5, \ \beta = 0, \ \omega = 45^\circ \]

\[
\eta = \frac{\kappa_2}{\kappa_1} \left( \frac{a}{L} \right)^{\lambda_1 - \lambda_2}
\]

Selection of penetrating angle:

\[ K_{II}^p = 0 \]
Penetrating angle vs. mode mixity

Weaker singularity plays role via mode mixity.
Debonding

\[ \eta = \frac{\kappa_2}{\kappa_1} \left( \frac{a}{L} \right)^{\lambda_1 - \lambda_2} \]

\[ \frac{K_I^d}{\sqrt{a}} = c_{11} \cdot \frac{k_1}{a^{\lambda_1}} + c_{12} \cdot \frac{k_2}{a^{\lambda_2}} \]

\[ \frac{K_{II}^d}{\sqrt{a}} = c_{21} \cdot \frac{k_1}{a^{\lambda_1}} + c_{22} \cdot \frac{k_2}{a^{\lambda_2}} \]
Penetration vs. Debonding

\[ \frac{G^d}{G^p} = \frac{1}{1 - \alpha \left( \frac{c_1^2 + c_2^2}{b_1^2 + b_2^2} \right) + \frac{2(c_{11}c_{12} + c_{21}c_{22})}{b_{11}b_{12} + b_{21}b_{22}}} \eta + \frac{(c_{12}^2 + c_{22}^2)}{b_{12}^2 + b_{22}^2} \eta^2 \]

- If \( \frac{G^d}{G^p} < \frac{\Gamma_i}{\Gamma_1} \), Penetrate.
- If \( \frac{G^d}{G^p} > \frac{\Gamma_i}{\Gamma_1} \), Debond.

Weaker singularity can readily change the outcome of the penetration-debond competition.
Applications and Implications: #2

Interfacial Delamination due to Chip-Package Interaction
Multi-level structure of flip-chip

Solder joints (~50 µm diameter)

Underfill (~50-100 µm thick)

Silicon Die (~0.7mm thick, ~10-15mm wide)

Solder joints (~50 µm diameter)

Package Substrate (~1mm thick, ~3-5cm wide)

Delamination

Passivation

Interconnects

Stress concentration

Level #2

Metal level #1

Dielectrics

Etch stop

~100nm

Liner

Via

Delamination

~ 50µm
Observations:

• Failure mode: *interfacial delamination*
• Driving force: *chip-packaging interaction*

Challenges:

• Huge variation in length scales: $\sim$nm to $\sim$cm
• 3D multilevel structures
• Diverse materials interaction
• Global-local FEM is adopted in industry.
Simplified model

- **$k$-field** scales with $h$.
- Small feature size is within $k$-field.
- Same macroscopic driving force motivates different flaws to grow.
- The same flaw size and orientation, the same ERR.
- Maybe different toughness.
- Local driving force is much smaller than global driving force.
$k$-field and $K$-field

**Chip-package interaction:**

\[
\sigma_{ij}(r, \theta) = \frac{k_1}{r^{\lambda_1}} \Sigma^1_{ij}(\theta) + \frac{k_2}{r^{\lambda_2}} \Sigma^2_{ij}(\theta)
\]

**Interfacial delamination:**

\[
\frac{\text{Re}(Ka^{i\varepsilon})}{\sqrt{a}} = c_{11} \cdot \frac{k_1}{a^{\lambda_1}} + c_{12} \cdot \frac{k_2}{a^{\lambda_2}}
\]

\[
\frac{\text{Im}(Ka^{i\varepsilon})}{\sqrt{a}} = c_{21} \cdot \frac{k_1}{a^{\lambda_1}} + c_{22} \cdot \frac{k_2}{a^{\lambda_2}}
\]
Length dependence of mode mixity

\[ G = \frac{1 - \beta^2}{1 - \alpha} \frac{\kappa_1^2 \sigma^2 h}{E_{Si}} \left( \frac{a}{h} \right)^{1-2\lambda_1} \left[ (c_{11} + c_{12} \eta)^2 + (c_{21} + c_{22} \eta)^2 \right] \]

\[ \eta = \frac{\kappa_2}{\kappa_1} \left( \frac{a}{h} \right)^{\lambda_1 - \lambda_2} \]

- Similar value as multi-scale calculation.
- \( k \)-field applies if \( a/h < 1/4 \).
- Break-down of power law of \( G \sim a \) relation.
- \( G \) hardly goes to zero.

Thermal excursion \( \Delta T = 140^\circ C \)
Reduction in singularity

Singularities are reduced a lot by using a filler or coating. **Why?**

Elastic mismatch is reduced and geometric discontinuity is closed.
Suppression of debonding

Free surfaces are easy to deform, interfacial flaw is easy to open.

The opening of the debonded interface is suppressed.
**Example in flexible electronics**

- Enhance the **survival rate**
- Increase the **island size**

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**Diagrams:***

- Substrate
- Coating
- Island

**Graph:***

- Normalized energy release rate, $G / (E_f^* \varepsilon_0^2 h)$
- Moduli ratio of coating to substrate, $E_c / E_s$

- $E_f / E_s = 40$
- $L / h = 100$
- $a / h = 0.1$

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**Organic Light Emitters Enable Better Electronic Displays**

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**The Mystery of Shock: Why Did Crime Rates Fall?**
Applications and Implications: #3

Dislocation Injection
From Sharp Features
In Strained Silicon Structures
Strained silicon structure

- **Stresses** are deliberately introduced to increase carrier mobility.
- **Edges and corners** intensify stresses, inject dislocations and fail the device.
- **Objective:** critical conditions that avert dislocations, on the basis of singular stress fields near the sharp features.
Simplification

\[ \sigma_{ij}(r, \theta) = \frac{k_1}{r^{\lambda_1}} \sum_{ij}^1(\theta) + \frac{k_2}{r^{\lambda_2}} \sum_{ij}^2(\theta) \]

\[ \lambda_1 = 0.4514 \quad \lambda_2 = 0.0752 \]

\[ \eta = \frac{\kappa_2}{\kappa_1} \left( \frac{b}{h} \right)^{\lambda_1-\lambda_2} \quad b = 0.383 \text{ nm} \]

\[ h = 100 \text{ nm} \]

\[ \eta \sim 0.02 \]

\[ \sigma_{ij}(r, \theta) = \frac{k}{r^{\lambda}} \sum_{ij}(\theta) \]
Stress intensity factor $k$

The driving force of dislocation injection is stress field in $k$-annulus, which is characterized by $k$.

$$k = \sigma h^\lambda f(L/h)$$
Critical stress intensity factor $k_c$

$k = \sigma h^\lambda f(L/h)$

Critical condition:

$k = k_c$

Driving force

Resistance

$k_c$ is specific to the materials and wedge angle, like fracture toughness.
An estimate of $k_c$

\[
\sigma_{ij}(r, \theta) = \frac{k}{r^2} \sum_{ij} (\theta)
\]

\[
\tau_{nb} = \sigma_{ij} n_i b_j
\]

\[
\tau_{th} = \frac{\mu b}{2\pi d} \approx 0.2\mu
\]

Criterion:

\[
\tau_{nb} \bigg|_{r=b} = \tau_{th}
\]

\[k_c = 0.5\mu b^\lambda\]

Isomae (1981)
The wider and thicker, 

The easier to inject dislocation.

\[ \sigma_c = \frac{0.5\mu}{f(L/h)(\frac{b}{h})^\lambda} \]

Kammler et al (2005)
Measurement of $k_c$

Measure $k_c$:

Calculate $k$:

$$k = \sigma h^\lambda f\left(\frac{L}{h}\right)$$
Summary

• Split singularities:

\[ \sigma_{ij}(r, \theta) = \frac{k_1}{r^{\lambda_1}} \Sigma_{ij}^1(\theta) + \frac{k_2}{r^{\lambda_2}} \Sigma_{ij}^2(\theta) \]

• Mode mixity depends on two lengths:

\[ \eta = \left( \frac{\kappa_2}{\kappa_1} \right) \left( \frac{\Lambda}{L} \right)^{\lambda_1 - \lambda_2} \]
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Backup slides for split singularities
Split singularities
Singularity exponent, $\lambda$

Moduli ratio of coating to substrate, $E_c / E_s$
\[ K_I^p = b_{11} \cdot \frac{k_1}{a^{\lambda_1}} + b_{12} \cdot \frac{k_2}{a^{\lambda_2}} \]
\[ K_{II}^p = b_{21} \cdot \frac{k_1}{a^{\lambda_1}} + b_{22} \cdot \frac{k_2}{a^{\lambda_2}} \]
Backup slide for strained silicon
Measurement of $k_c$

Dimensional requirement:

$$k_c = c \cdot \mu b^\lambda$$

A series of experiments:

$$k = \sigma h^\lambda f\left(\frac{L}{h}\right)$$

Find a critical condition to obtain coefficient $c$ by:

$$c = \frac{\sigma}{\mu} \cdot \left(\frac{h}{b}\right)^\lambda \cdot f\left(\frac{L}{h}\right)$$
Other concerns from industry

- Periodic patterned, so how is the spacing effect?

- 3D corner is more singular than 2D wedge. Does the current method apply?

- What if I don’t use SiN? I chose other materials as stressors.
Spacing effect

\[ \sigma_{ij}(r, \theta) = \frac{k}{r^\lambda} \sum_{ij}(\theta) \]

with \[ \lambda = 0.4514 \]

\[ k = \sigma h^\lambda \cdot f\left(\frac{L}{h}, \frac{S}{h}\right) \]

In practice, \( S/h \) doesn’t go to zero, so the spacing effect is quite small.
3D Corners

• The method still applies. What changes is the coefficients.

• 3D corner singularities. Measurement of $k_c$ and calculation of $f(L/h, S/h, R/h)$.

• 3D calculation is expensive for academia, but very cheap for industry. *Do it.*

\[ k = \sigma h^\lambda \cdot f \left( \frac{L}{h}, \frac{S}{h}, \frac{R}{h} \right) \]
Effect of weaker singularity if not SiN

Local mode mixity:

\[ \eta = \frac{\kappa_2}{\kappa_1} \left( \frac{b}{h} \right)^{\lambda_1 - \lambda_2} \]

Evaluate it case by case.
Slip systems
Future focus

- Stress driven dislocation motion under channel.