Thermomechanical Reliability of Microelectronics

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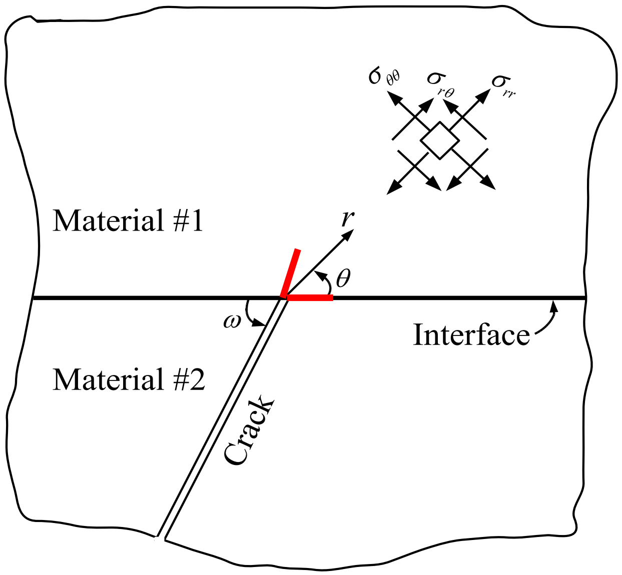
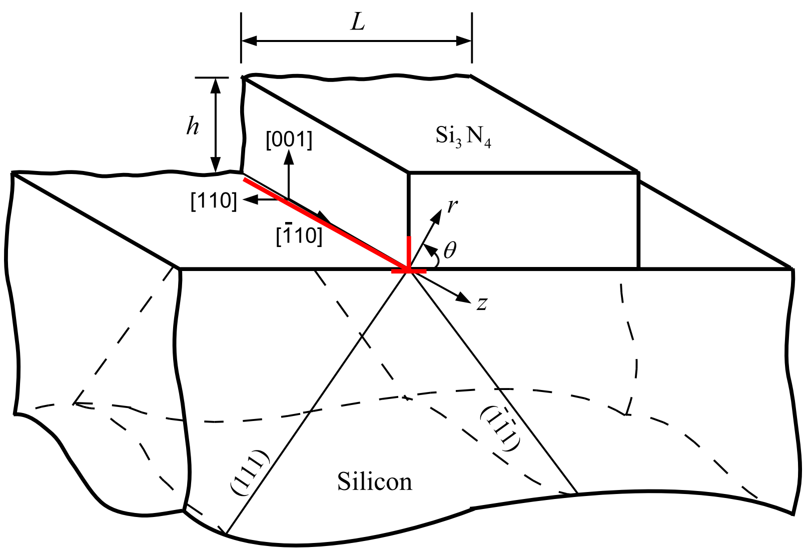
MRSEC

Topics

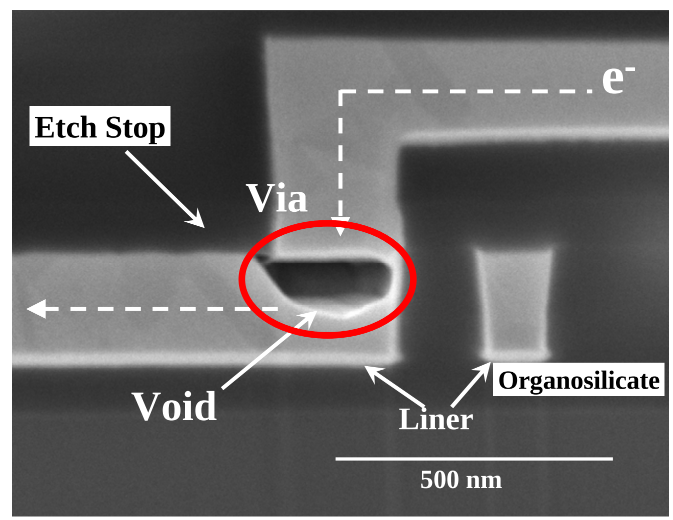


Crack penetration or debonding

Interfacial delamination

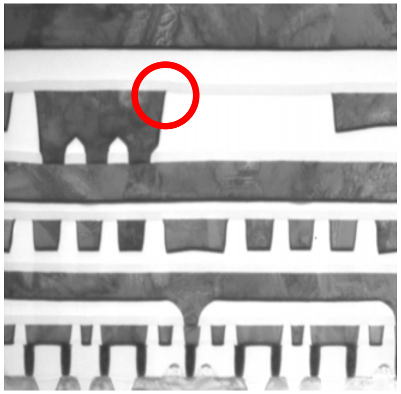


Dislocation injection

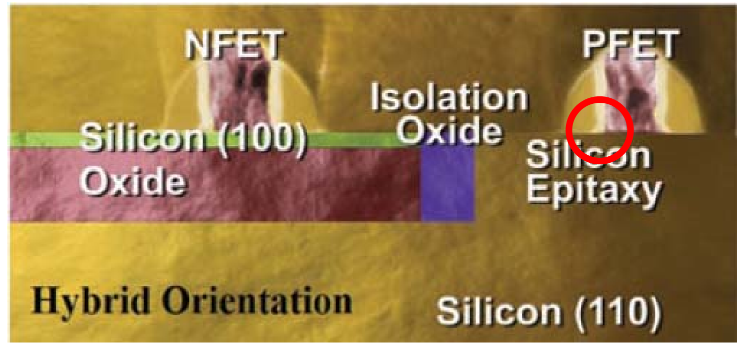


Voiding and electromigraton

Diverse Materials & Sharp Features

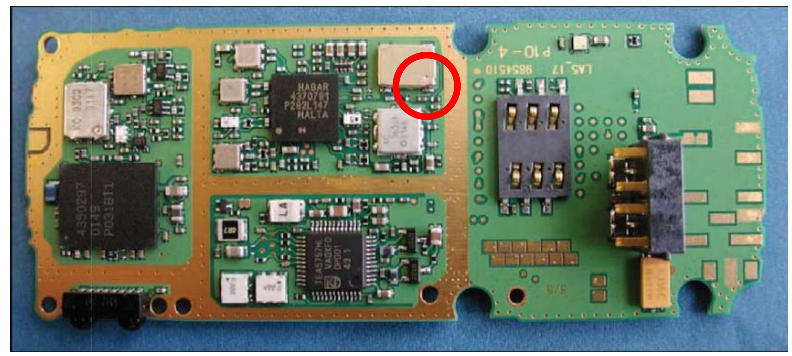


Intel 90 nm interconnect



Ieong et al, Science **306**(2004)p2057.

Intel Pentium III CPU

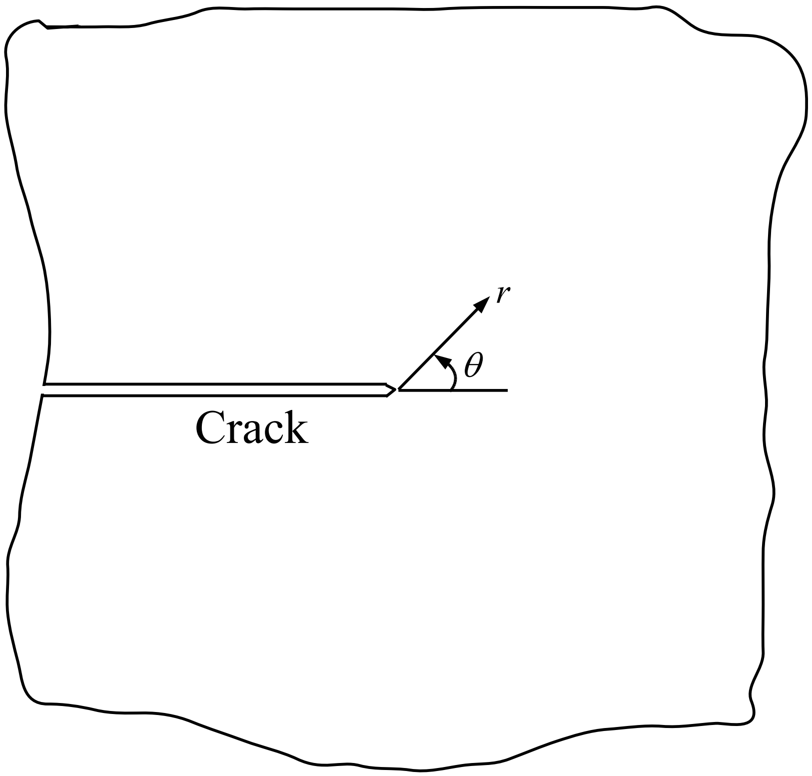


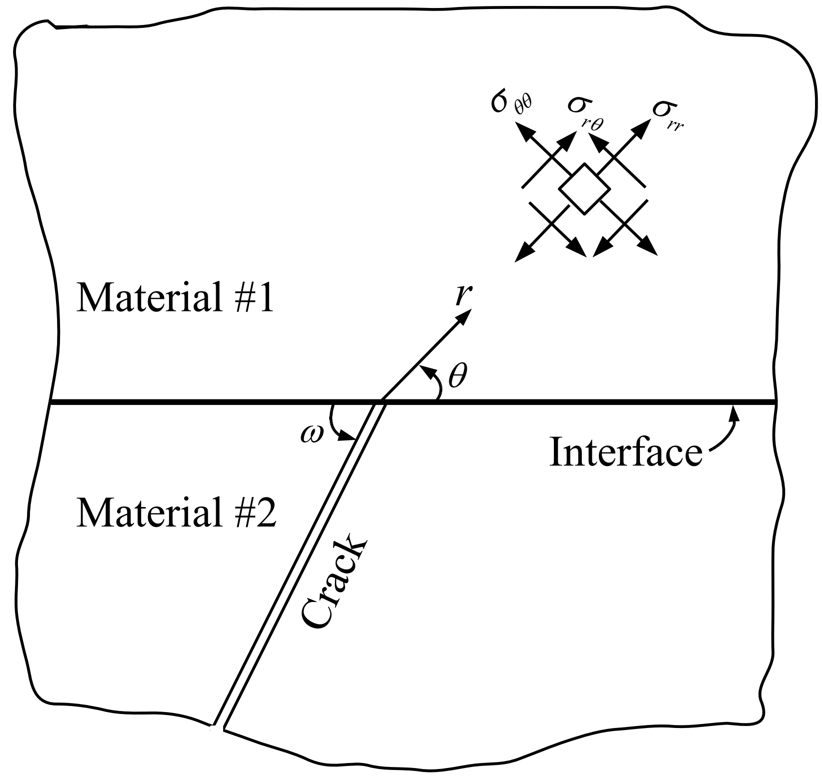
Reuss & Chalamala, MRS bulletin **28**(2003)p11.

Stress concentration ⇨ Failures !

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

Split singularities





Homogeneous material

Two modes have the same exponents --- 1/2

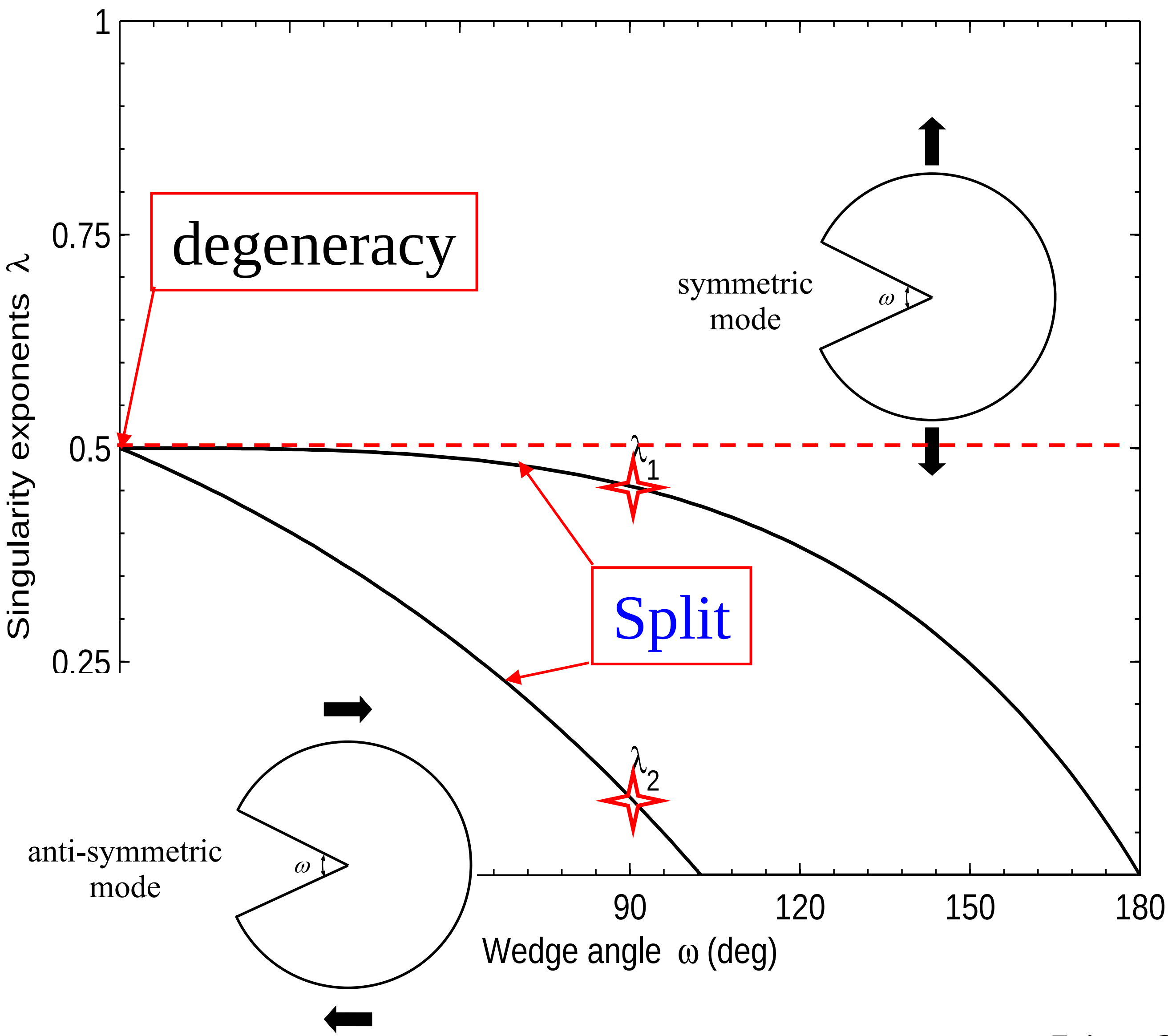
$$\sigma_{ij}(r,\theta)=\frac{K_I}{r^{1/2}}\Sigma_{ij}^{I}(\theta)+\frac{K_{II}}{r^{1/2}}\Sigma_{ij}^{II}(\theta)$$

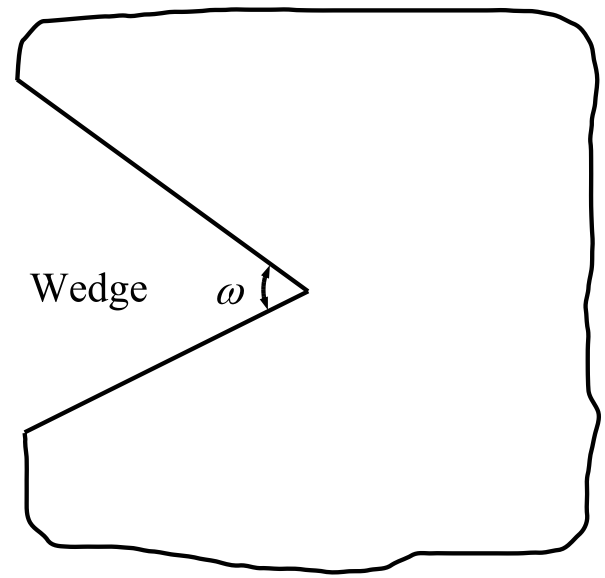
Bimaterial

Two modes have different exponents --- λ_1 and λ_2

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

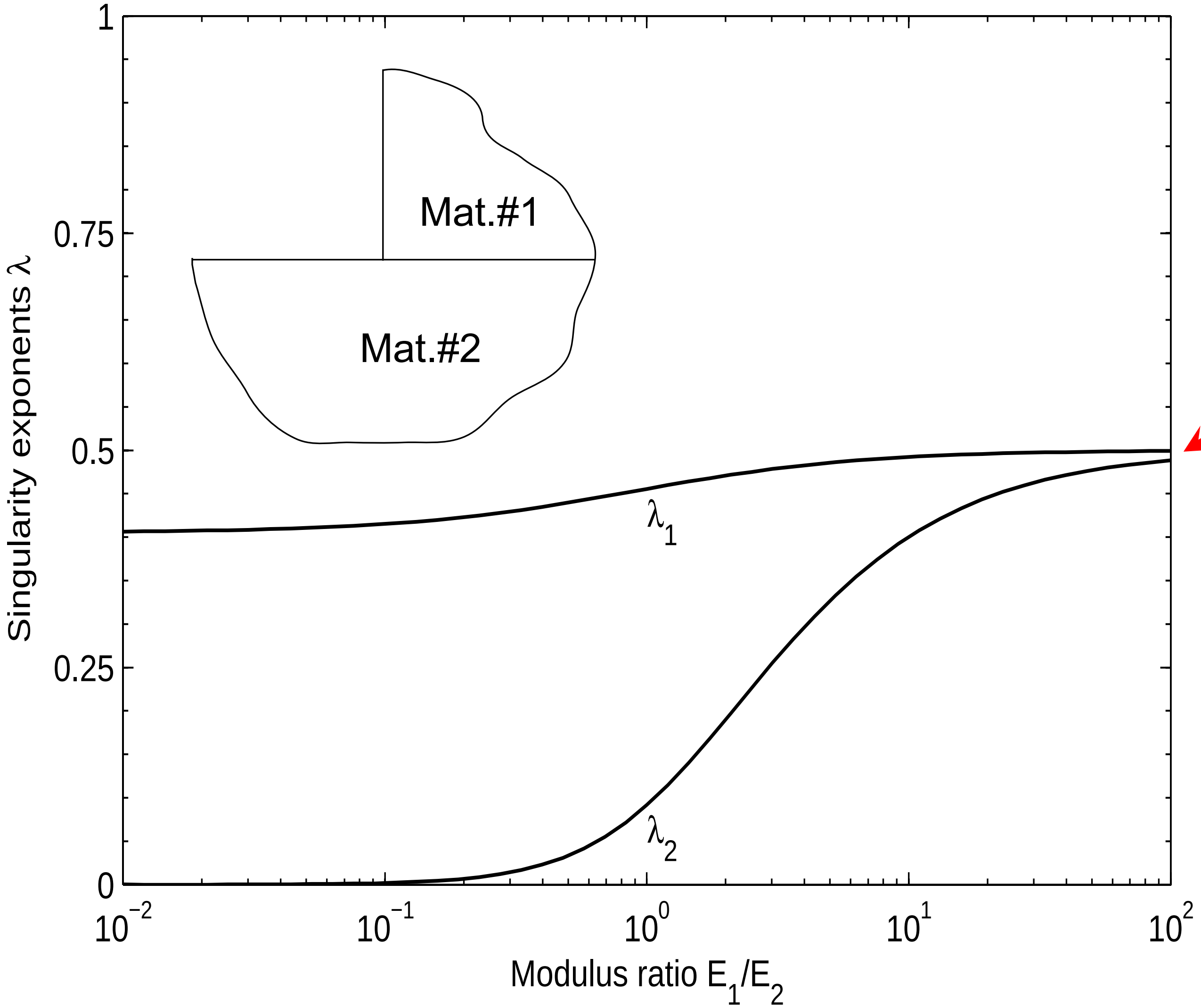
Split due to geometry

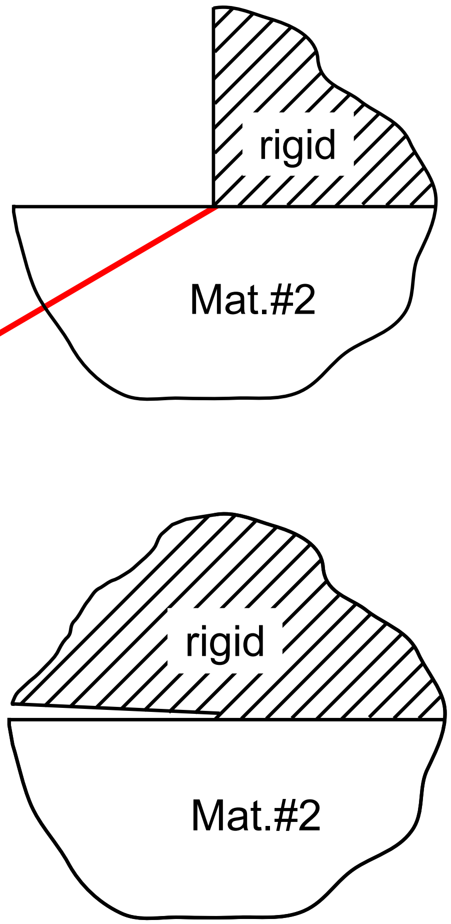




Liu, Suo and Ma, Acta mat. (1999).

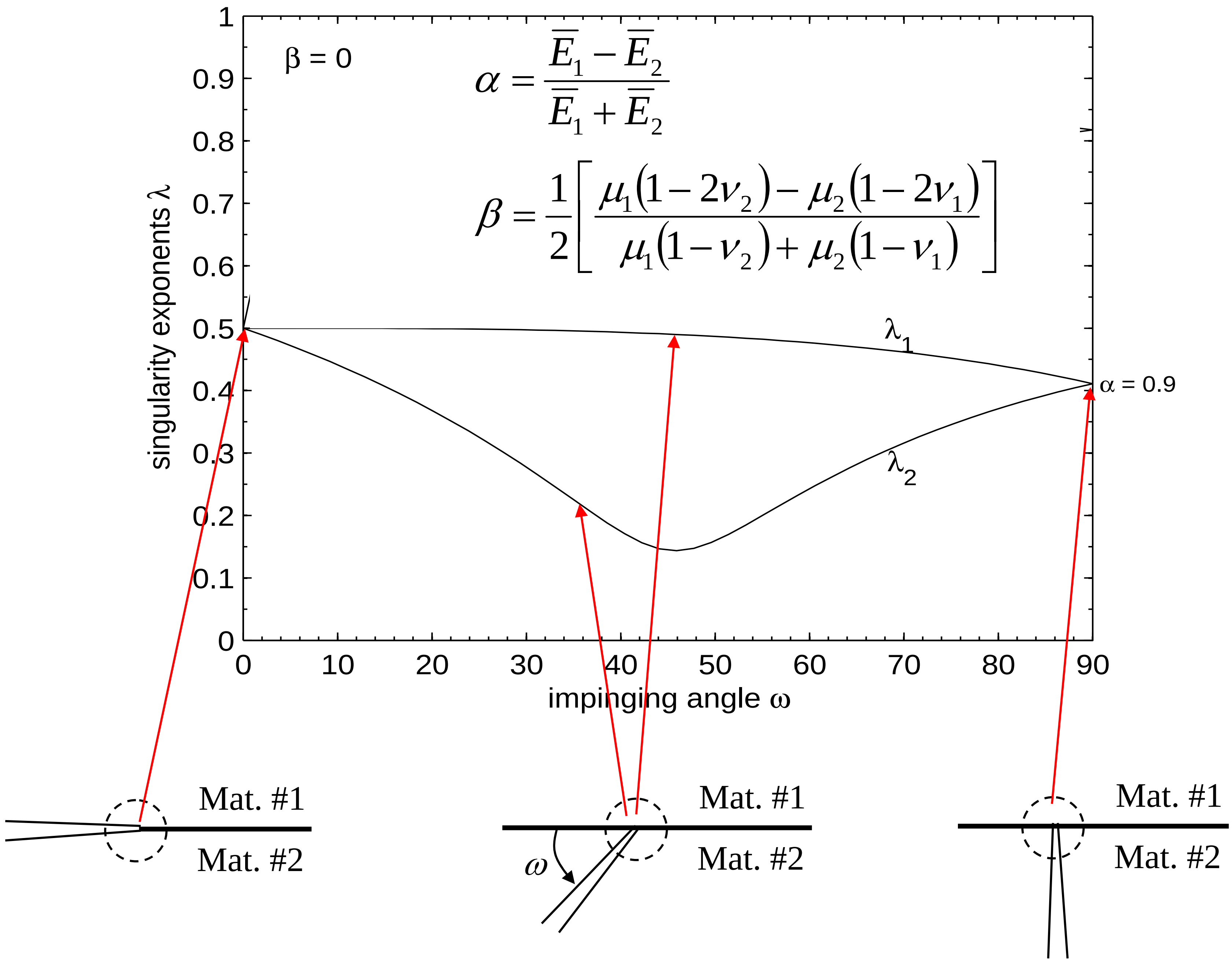
Split due to elastic mismatch





Always split, unless Mat.#1 is rigid.

Split singularities: oblique crack



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?

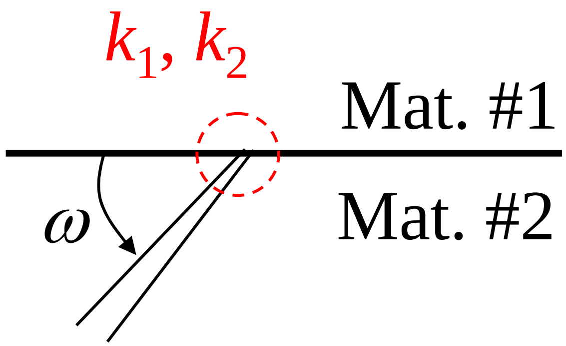
Applications and Implications: **#1**

Crack Penetration or Debonding

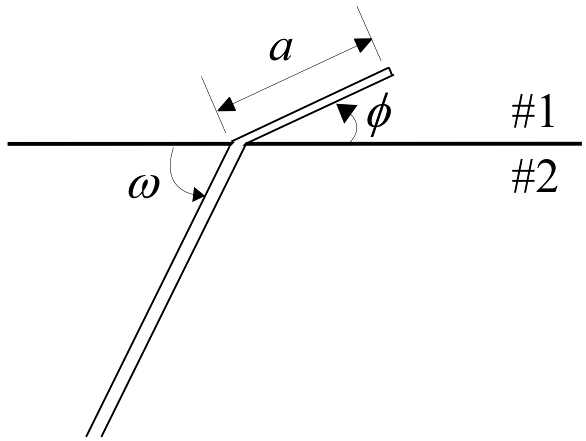
Cracking Path Selection

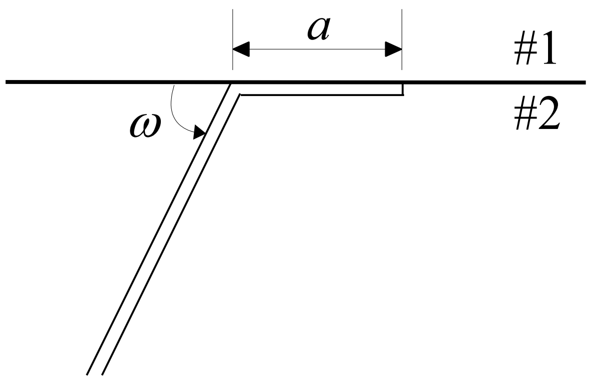
A crack impinges upon an interface.

(He and Hutchinson, *IJSS*, 1989).



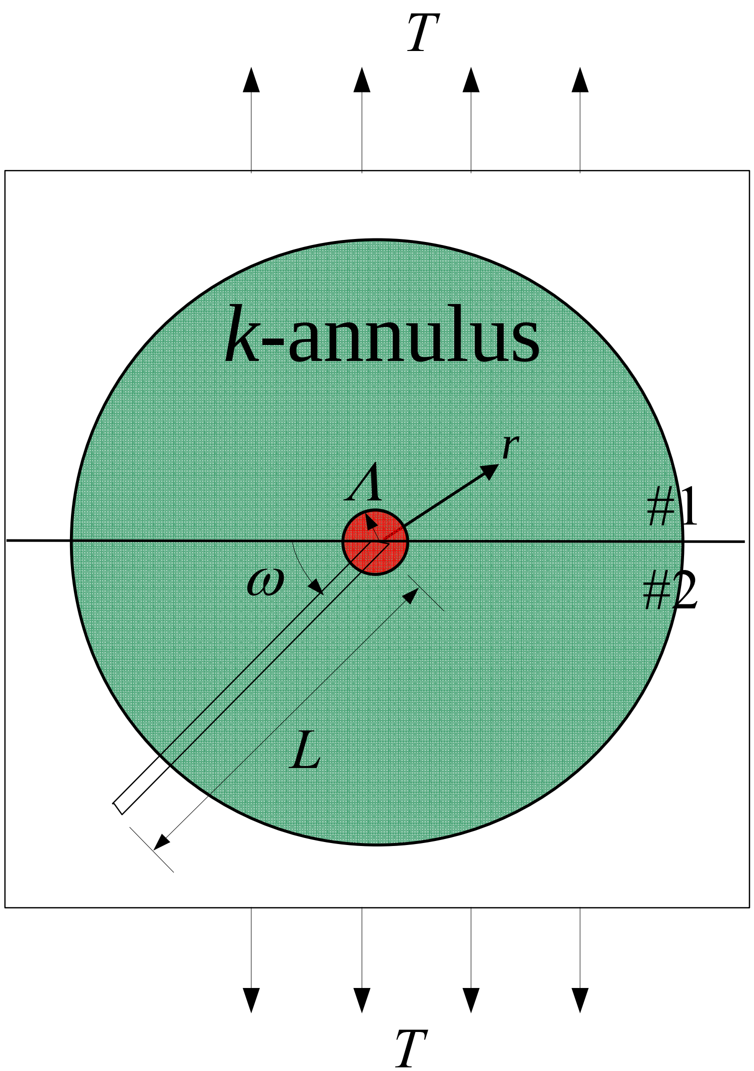
Penetration vs. Debonding





The effect of weaker singularity has not been well studied.

Q: Should we neglect the weaker singularity?



r does NOT go to zero.

Homogeneous material:

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

$$\text{Mode mixity} = \frac{K_{II}}{K_I}$$

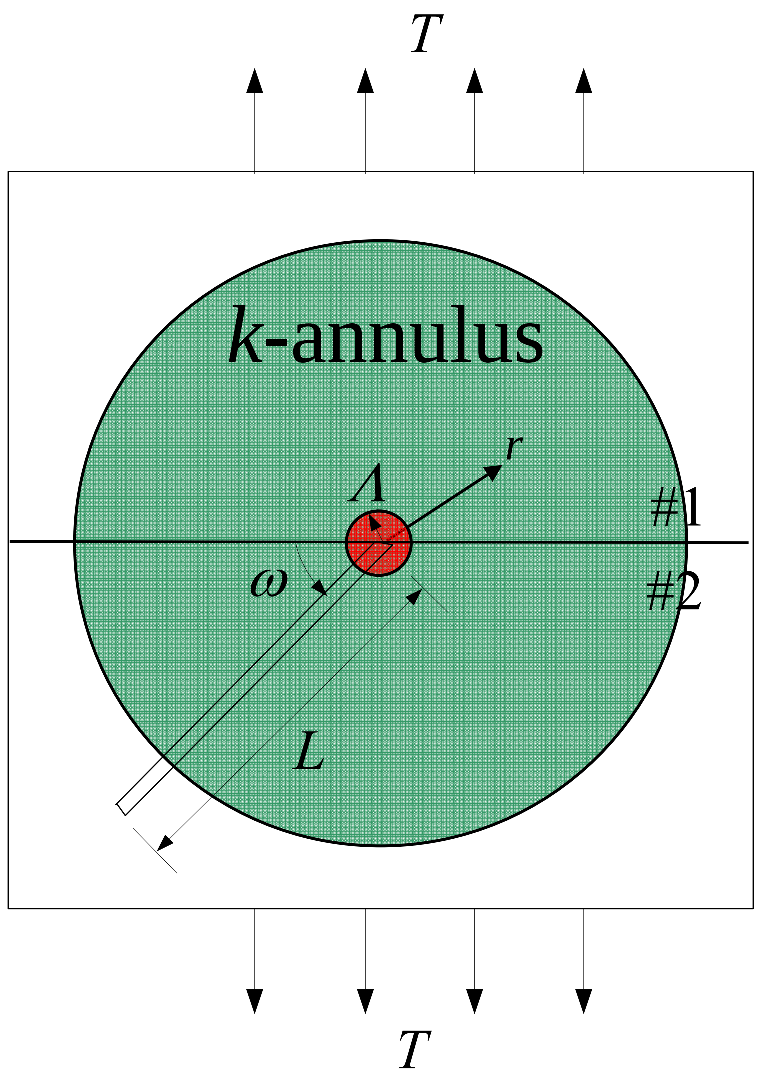
Bimaterial:

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

Stress ratio of two modes $= \dfrac{k_2 r^{-\lambda_2}}{k_1 r^{-\lambda_1}}$

Selection of arbitrary length

Definition of mode mixity



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

Select some length we care:

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

It measures the relative contribution of the two modes to the stress field at length scale Λ

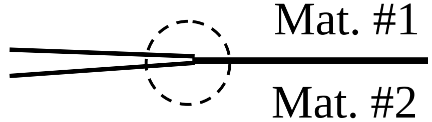
Answer: it depends on the magnitude of the mode mixity.

Two length scales

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

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

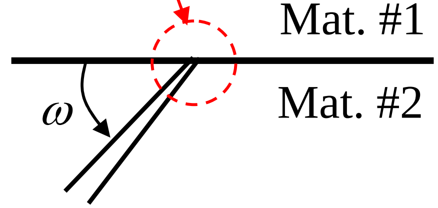
$$\boxed{\eta = \frac{\kappa_2}{\kappa_1}\left(\frac{\Lambda}{L}\right)^{\lambda_1-\lambda_2}}$$



$$\frac{\mathrm{Im}\left(Kl^{i\varepsilon}\right)}{\mathrm{Re}\left(Kl^{i\varepsilon}\right)}$$

(Rice, 1988)

$$\boxed{\Lambda = 1\ \mathrm{nm}}$$



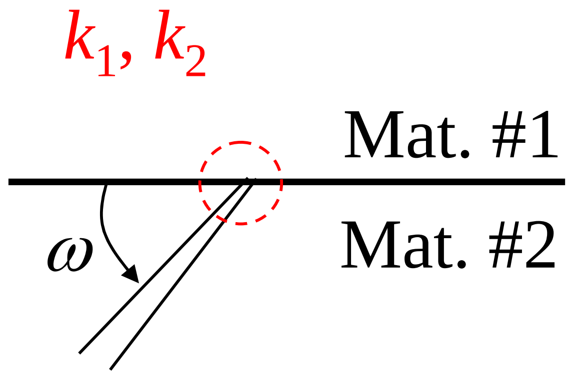
$$\boxed{L = 100\ \mathrm{nm}}$$

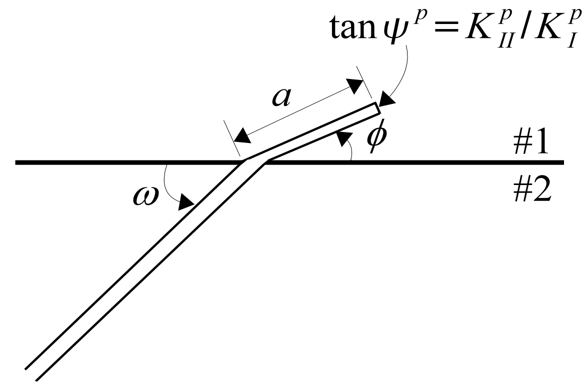
$$\eta = \frac{\kappa_2}{\kappa_1}\underbrace{\left(\frac{\Lambda}{L}\right)^{\overbrace{\lambda_1-\lambda_2}^{0.2}}}_{0.4}$$

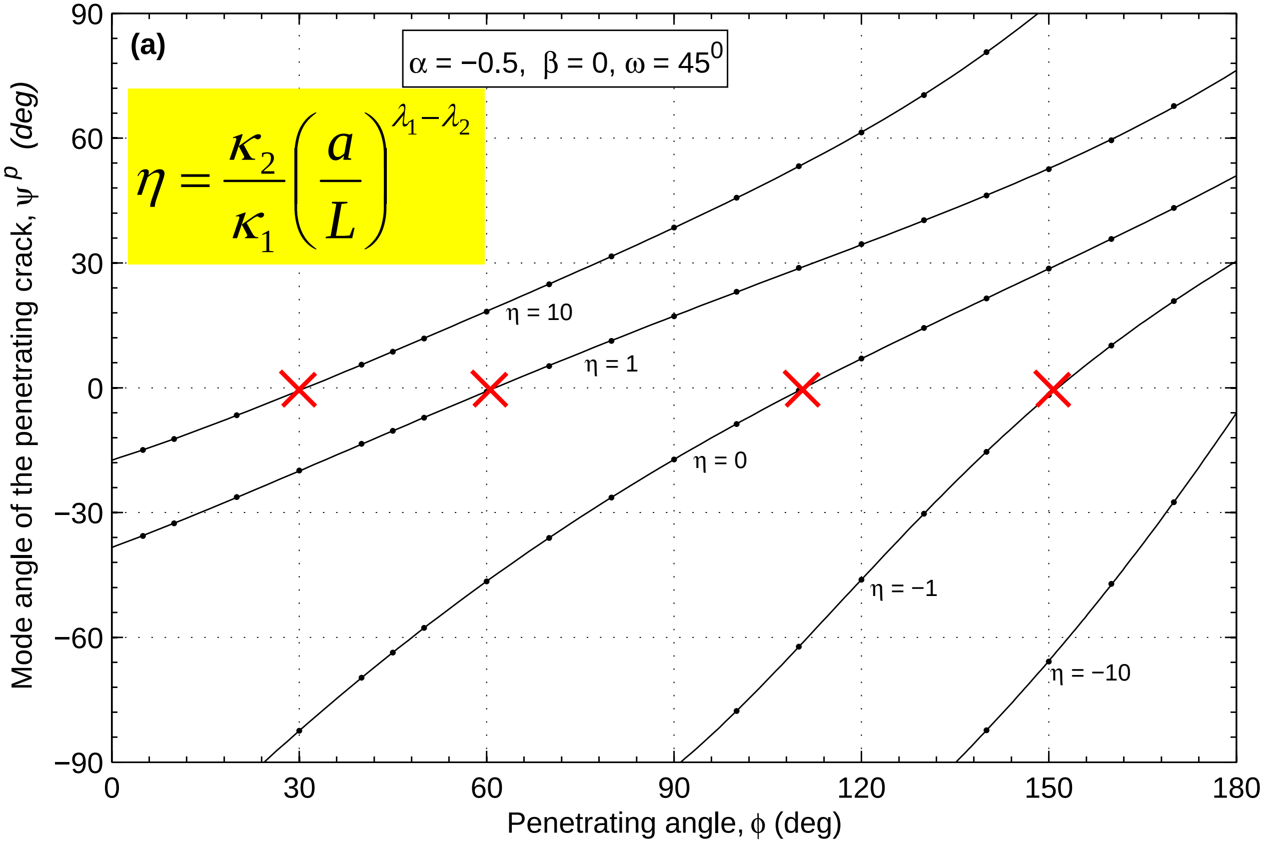
easily on the order of unity.

η is used to assess the effect of weaker singularity.

Crack penetration







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

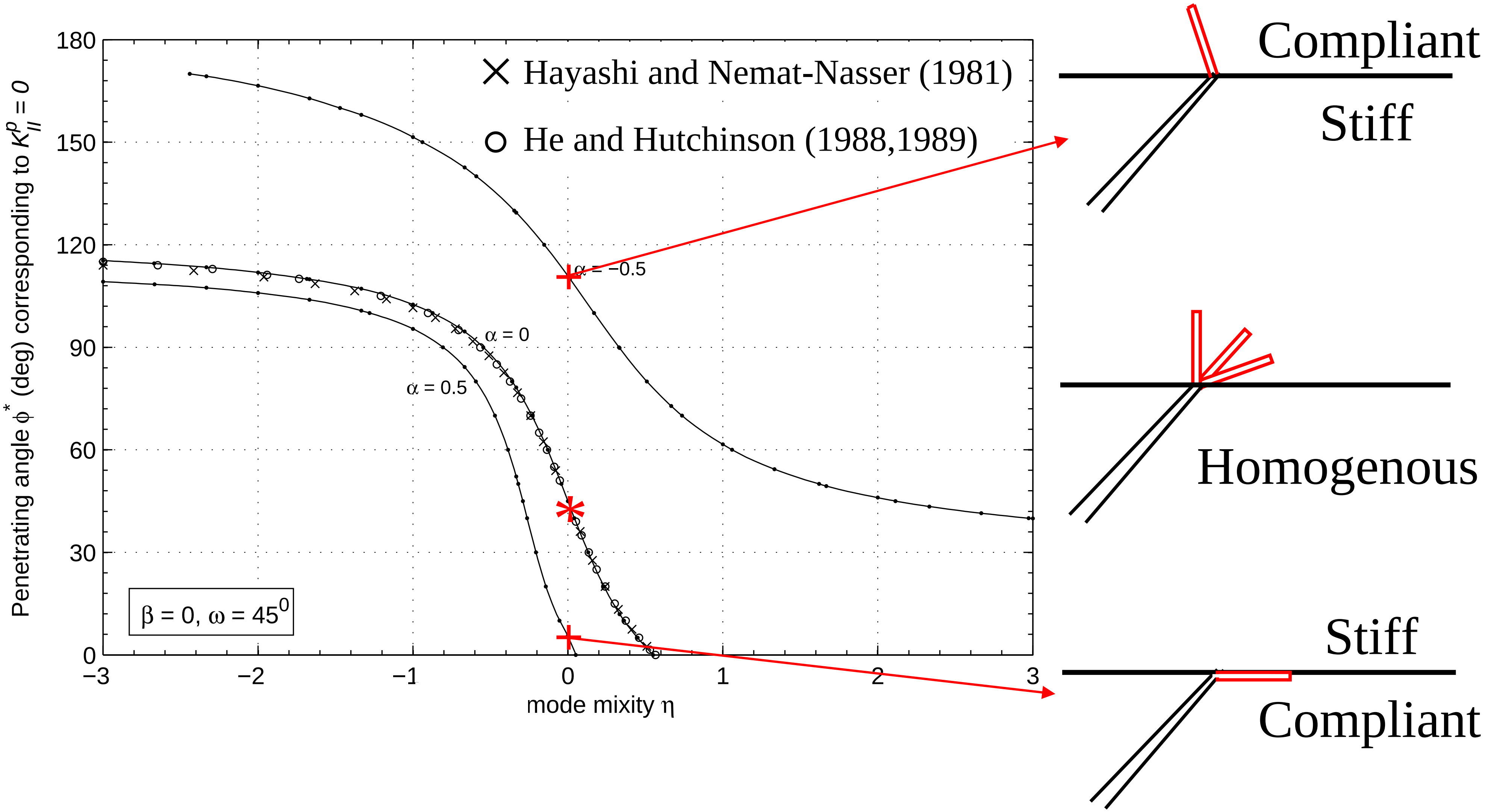
$$\frac{K_I^p}{\sqrt{a}} = b_{11}\cdot\frac{k_1}{a^{\lambda_1}} + b_{12}\cdot\frac{k_2}{a^{\lambda_2}}$$

$$\frac{K_{II}^p}{\sqrt{a}} = b_{21}\cdot\frac{k_1}{a^{\lambda_1}} + b_{22}\cdot\frac{k_2}{a^{\lambda_2}}$$

Selection of penetrating angle:

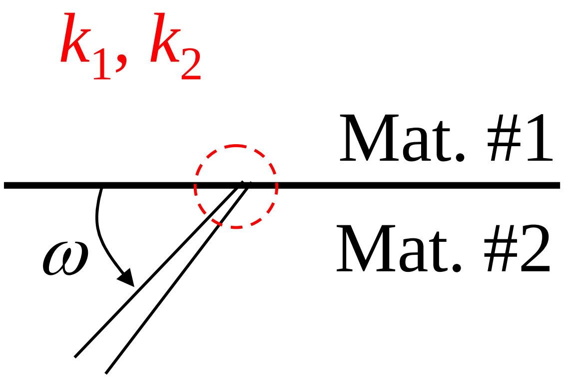
$$\boxed{K_{II}^p = 0}$$

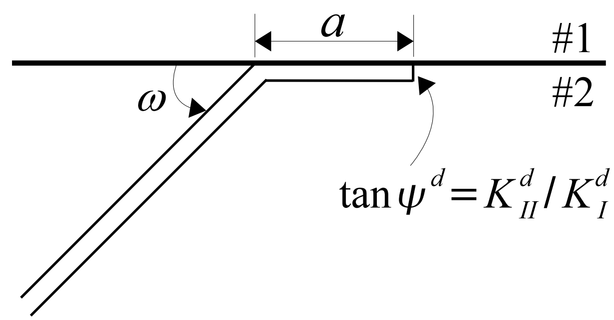
Penetrating angle vs. mode mixity

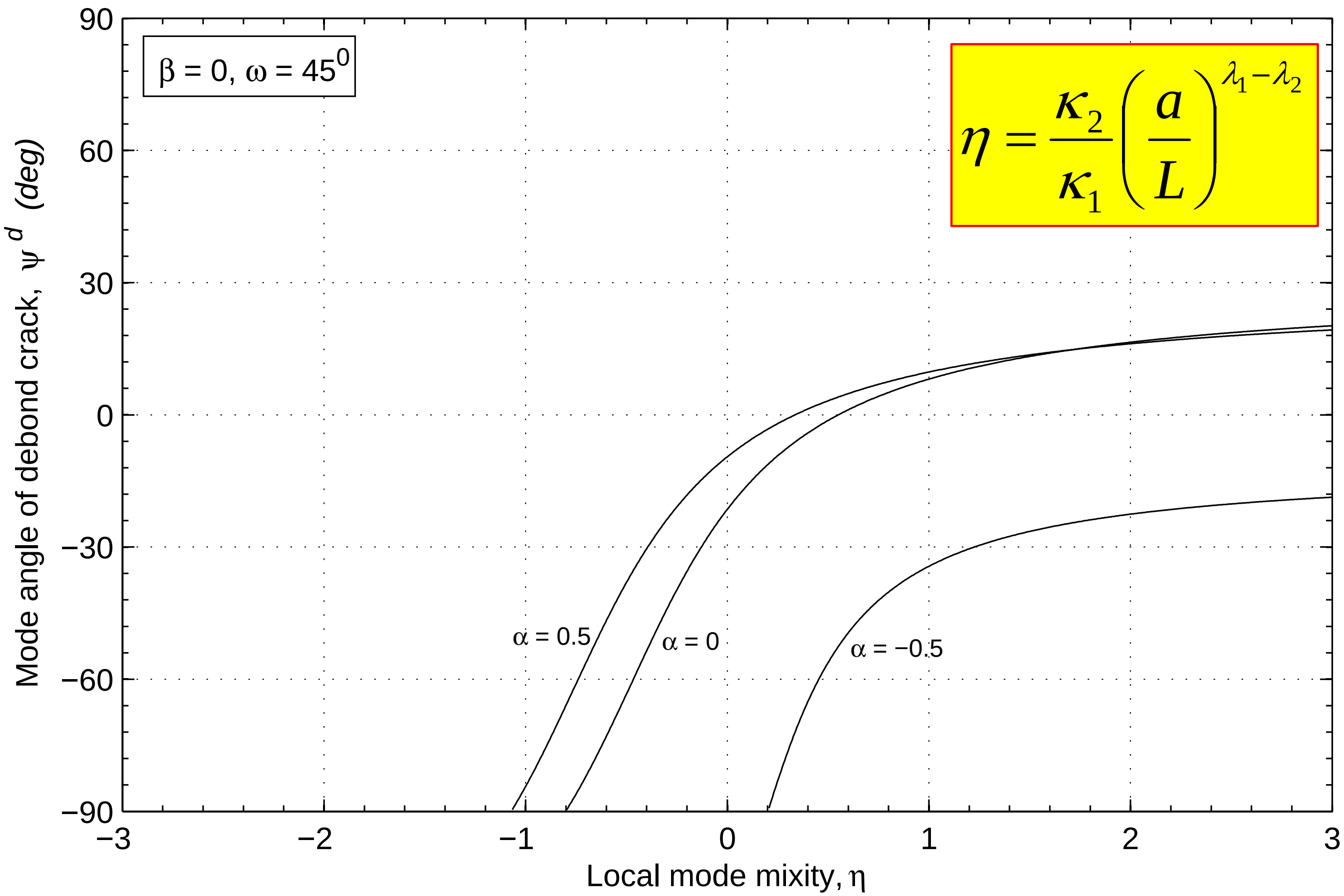


Weaker singularity plays role via mode mixity.

Debonding







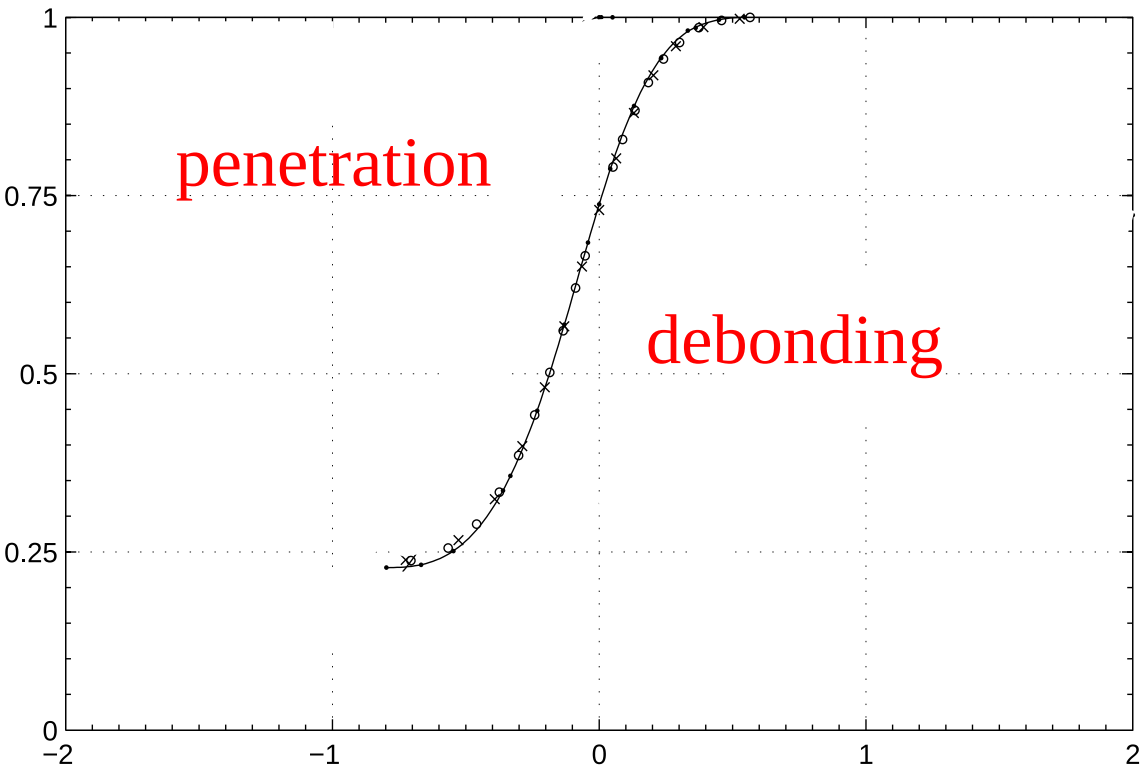
$$\frac{K_I^d}{\sqrt{a}} = c_{11}\cdot\frac{k_1}{a^{\lambda_1}} + c_{12}\cdot\frac{k_2}{a^{\lambda_2}}$$

$$\frac{K_{II}^d}{\sqrt{a}} = c_{21}\cdot\frac{k_1}{a^{\lambda_1}} + c_{22}\cdot\frac{k_2}{a^{\lambda_2}}$$

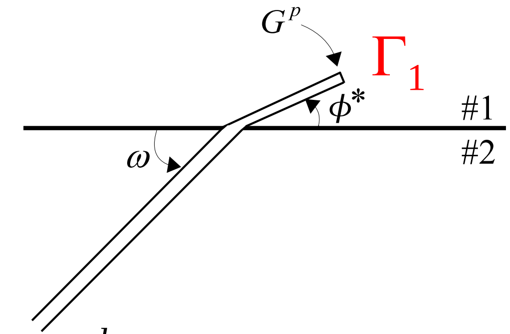
Penetration vs. Debonding

$$\frac{G^d}{G^p} = \frac{1}{1-\alpha} \cdot \frac{\left(c_{11}^2 + c_{21}^2\right) + 2\left(c_{11}c_{12} + c_{21}c_{22}\right)\eta + \left(c_{12}^2 + c_{22}^2\right)\eta^2}{\left(b_{11}^2 + b_{21}^2\right) + 2\left(b_{11}b_{12} + b_{21}b_{22}\right)\eta + \left(b_{12}^2 + b_{22}^2\right)\eta^2}$$

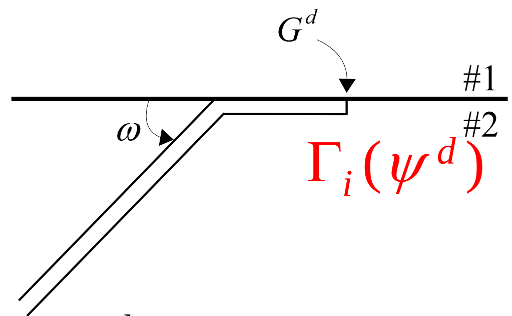
$$\frac{\Gamma_i}{\Gamma_1}$$



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



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

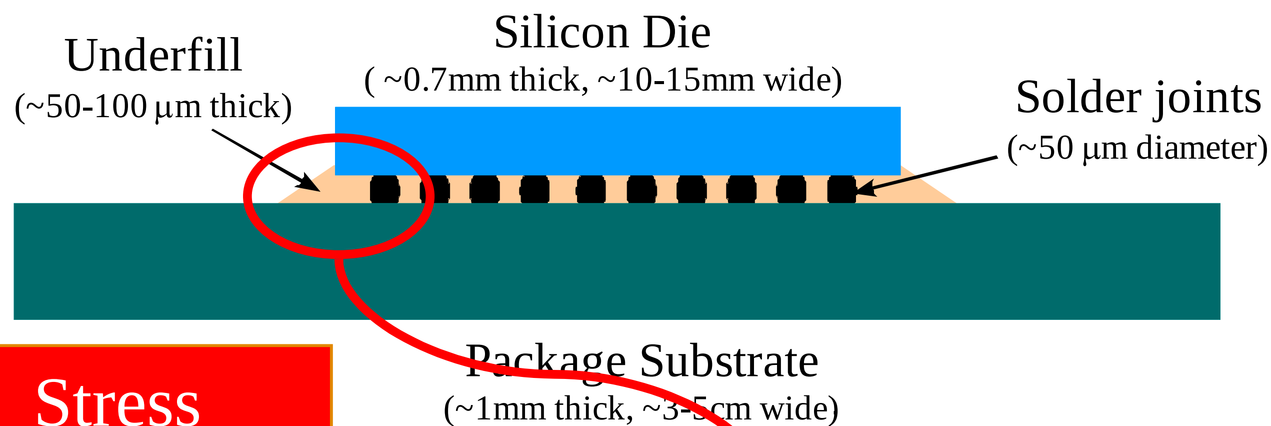
Applications and Implications: **#2**

Interfacial Delamination

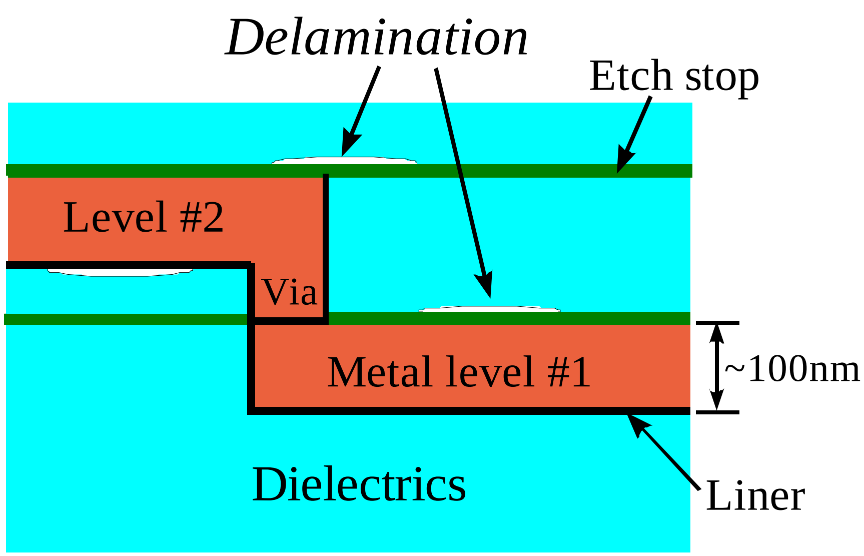
due to

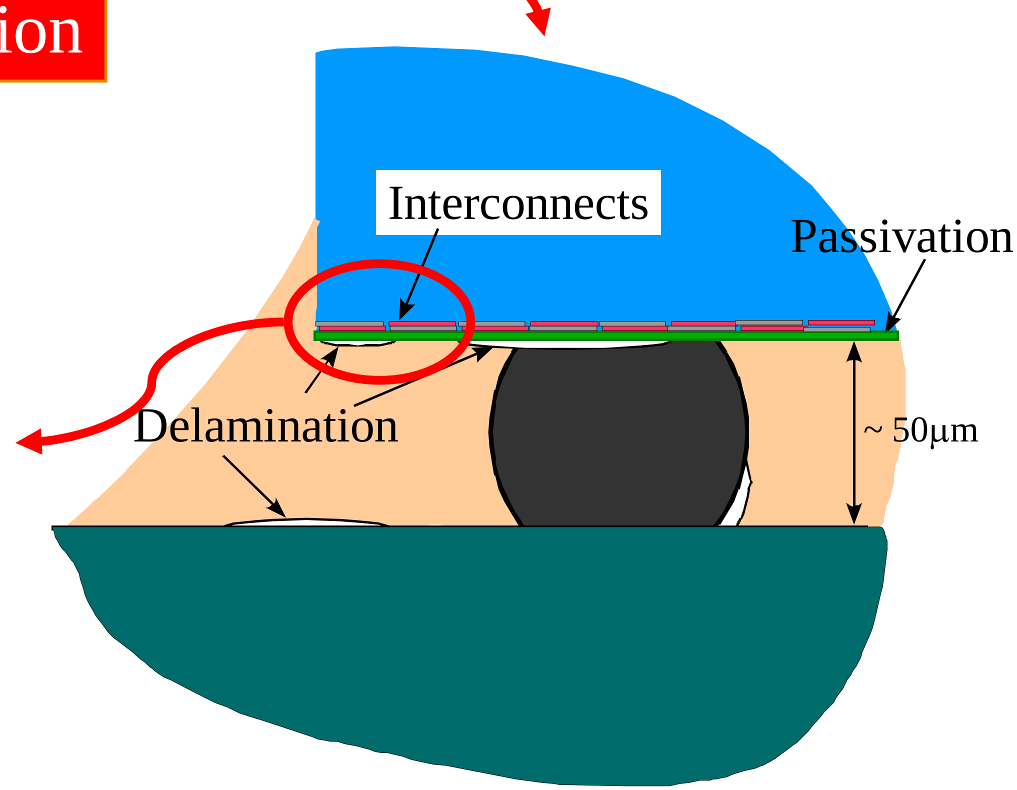
Chip-Package Interaction

Multi-level structure of flip-chip



Stress concentration





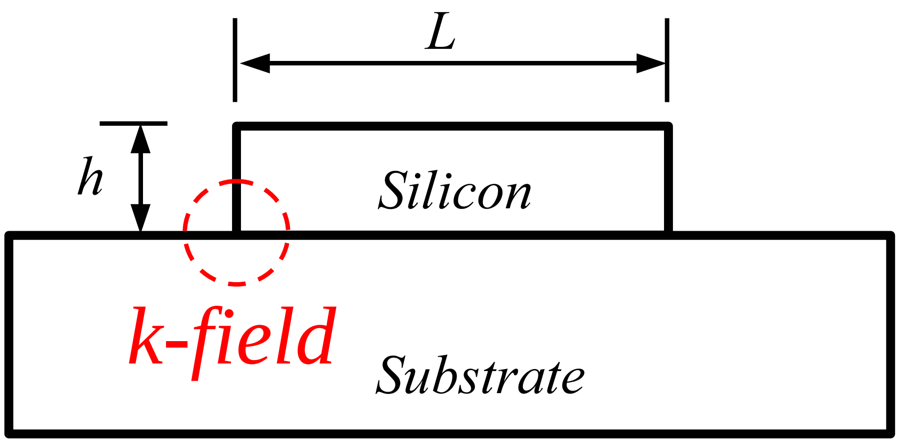
Observations:

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

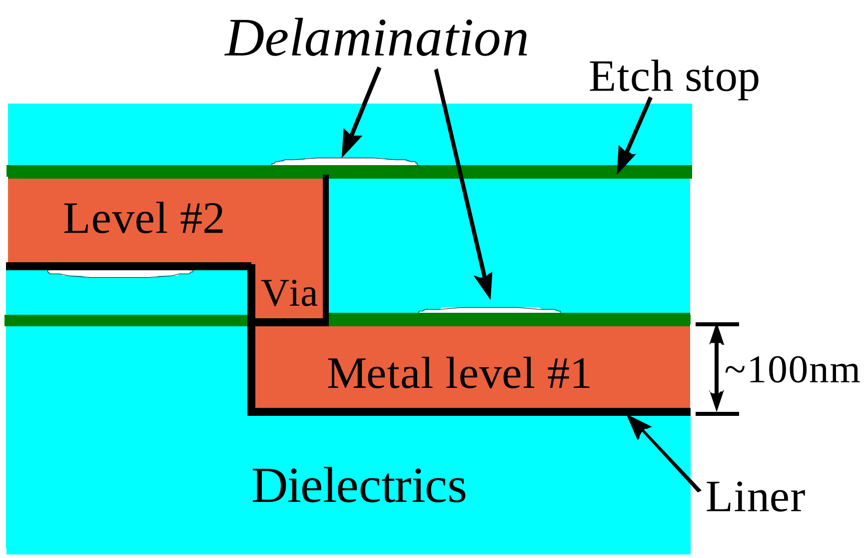
Challenges:

- Huge variation in length scales: ~nm *to* ~cm
- 3D multilevel structures
- Diverse materials interaction
- Global-local FEM is adopted in industry.

Simplified model



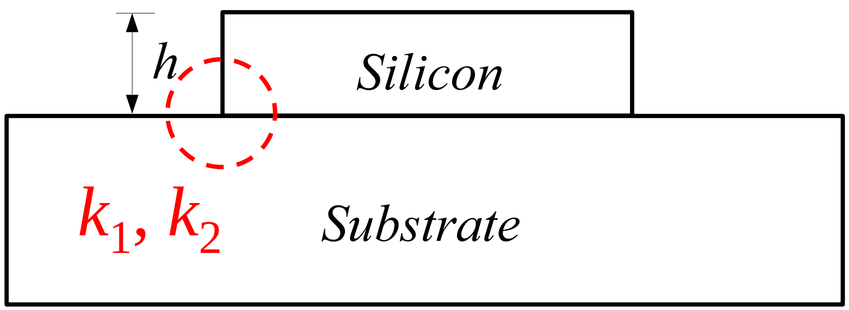
$$\sigma_{ij}(r,\theta)=\frac{k_1}{r^{\lambda_1}}\Sigma^1_{ij}(\theta)+\frac{k_2}{r^{\lambda_2}}\Sigma^2_{ij}(\theta)$$



- *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.

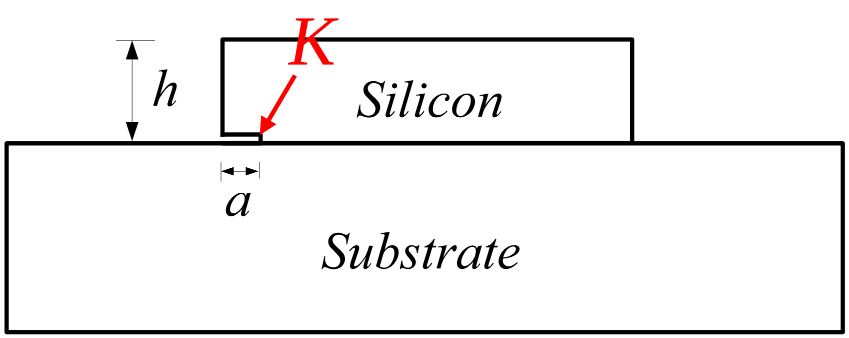
k-field and K-field

Chip-package interaction:



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

Interfacial delamination:



$$\frac{\mathrm{Re}\left(Ka^{i\varepsilon}\right)}{\sqrt{a}}=c_{11}\cdot\frac{k_1}{a^{\lambda_1}}+c_{12}\cdot\frac{k_2}{a^{\lambda_2}}$$

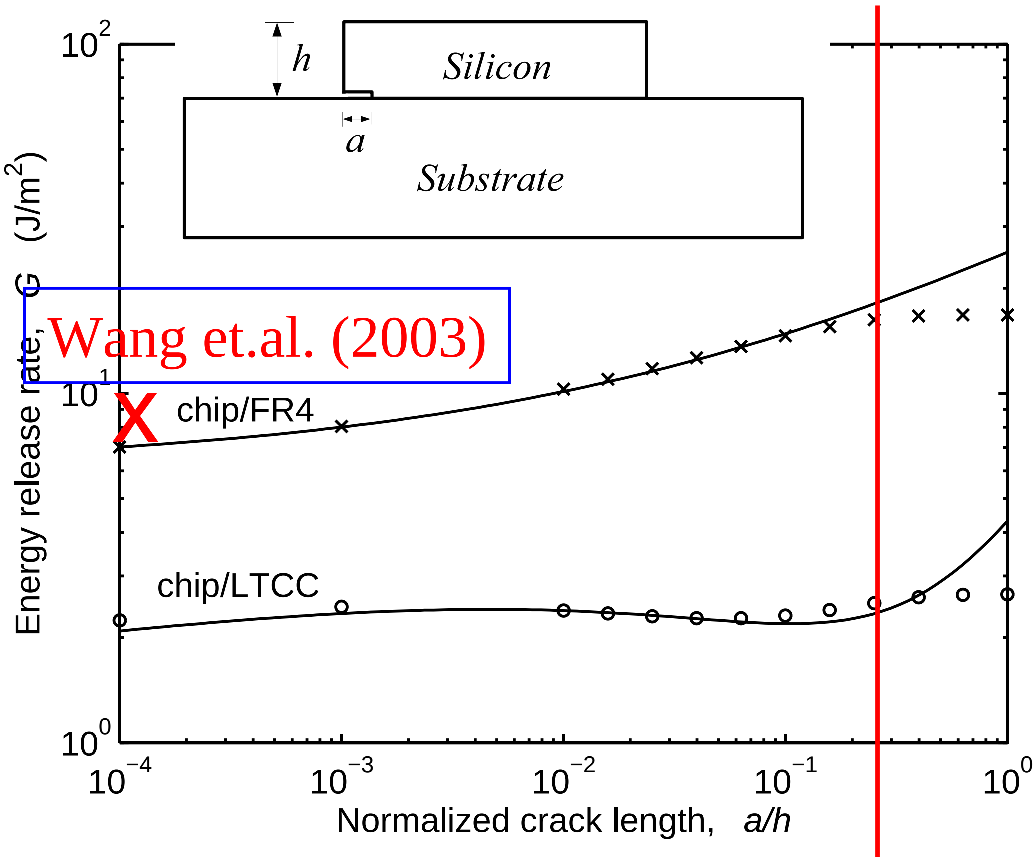
$$\frac{\mathrm{Im}\left(Ka^{i\varepsilon}\right)}{\sqrt{a}}=c_{21}\cdot\frac{k_1}{a^{\lambda_1}}+c_{22}\cdot\frac{k_2}{a^{\lambda_2}}$$

Length dependence of mode mixity

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

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

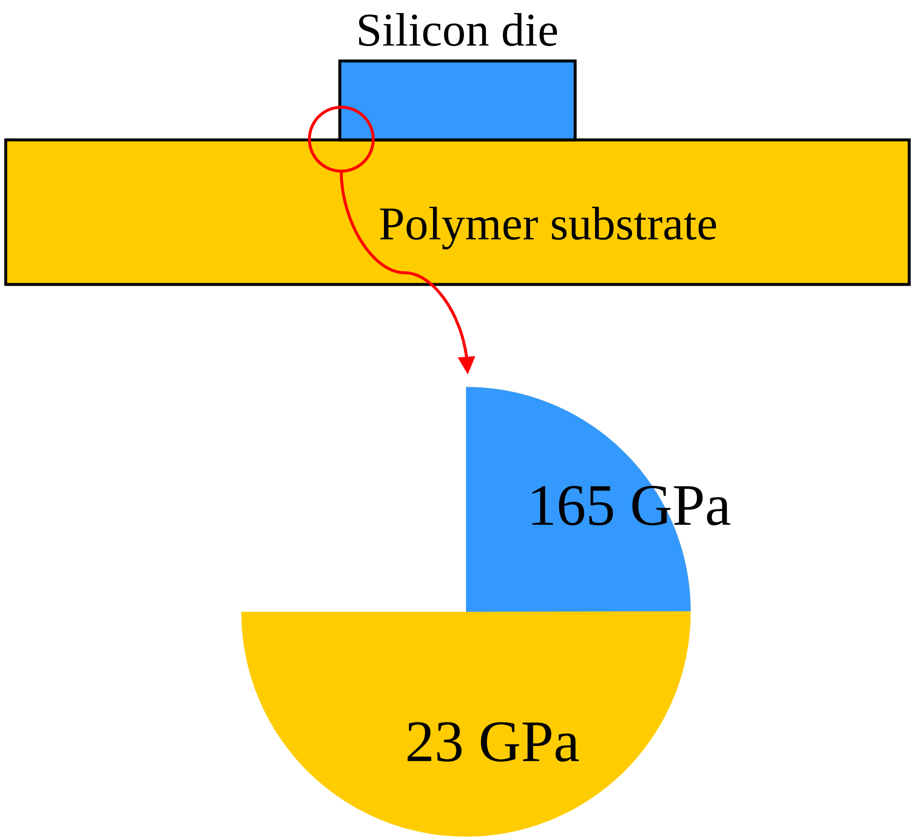
Thermal excursion $\Delta T=140^0C$



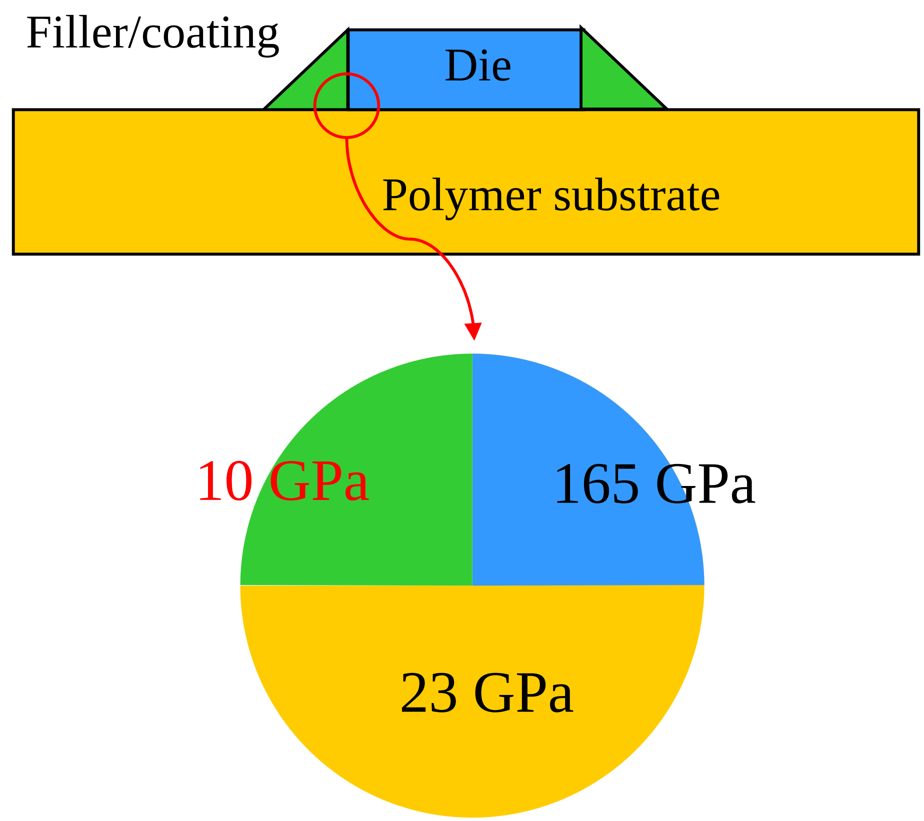
Wang et.al. (2003)

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

Reduction in singularity



$\lambda_1 = 0.497 \qquad \lambda_2 = 0.346$



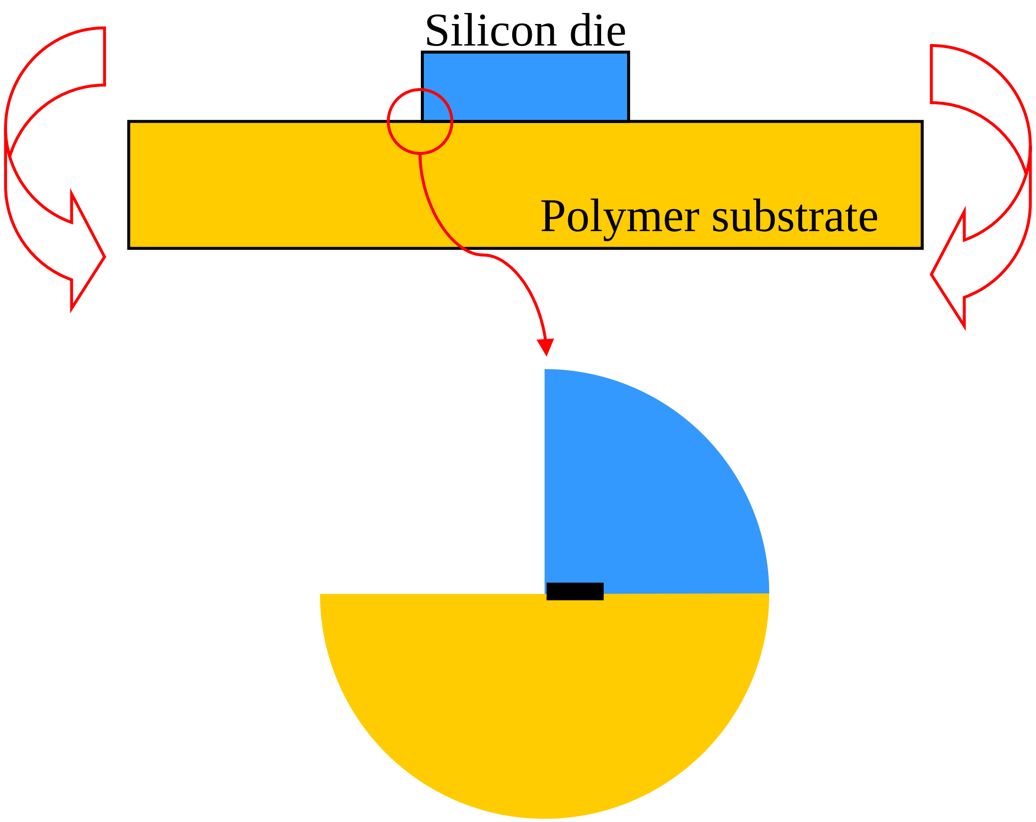
$\lambda_1 = 0.3 \qquad \lambda_2 = 0.247$

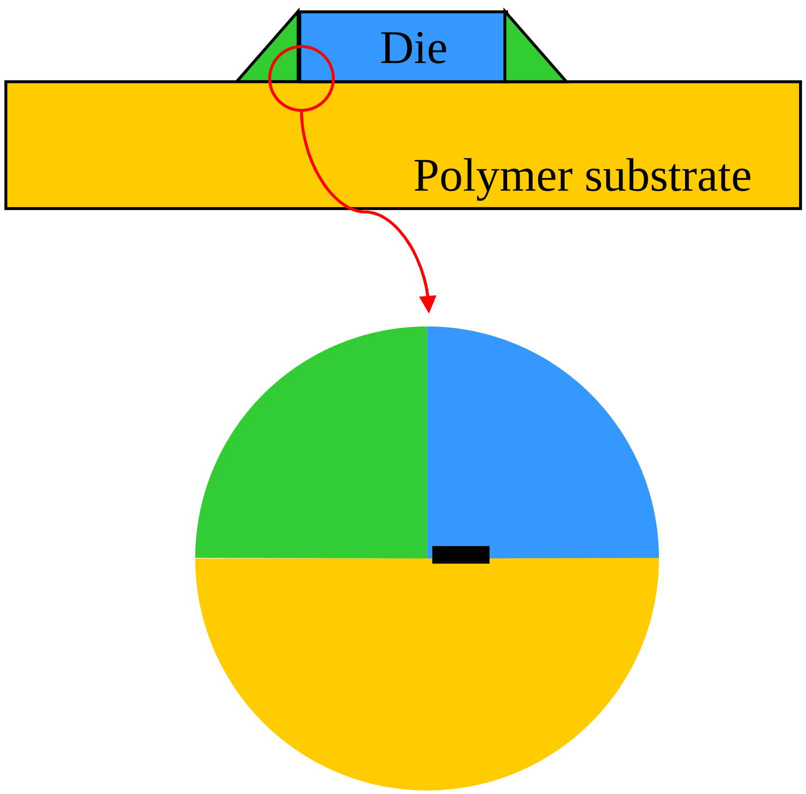
Singularities are reduced a lot by using a filler or coating.

Why?

Elastic mismatch is reduced and geometric discontinuity is closed.

Suppression of debonding

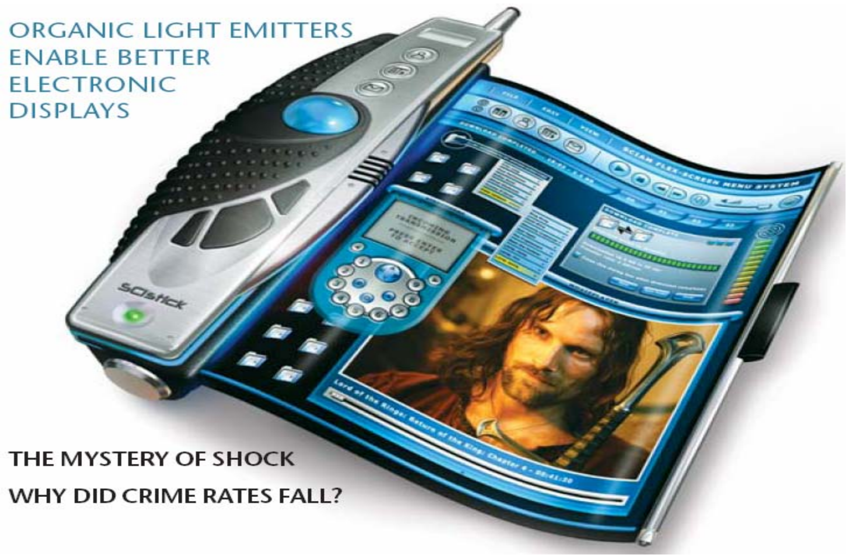


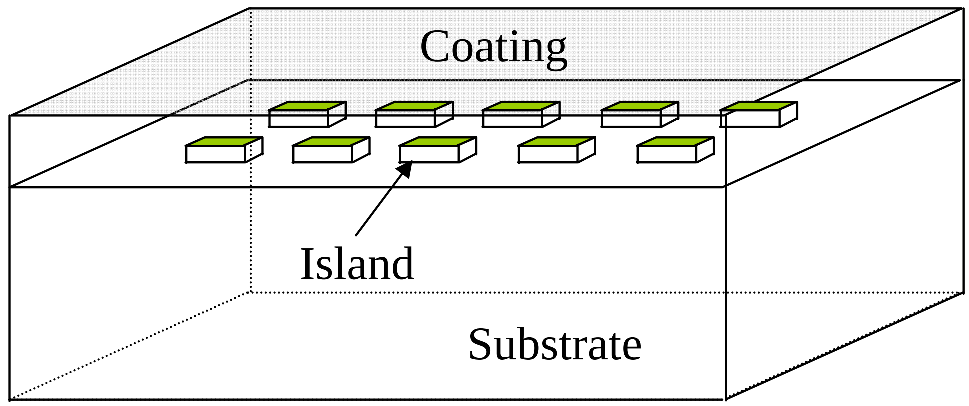


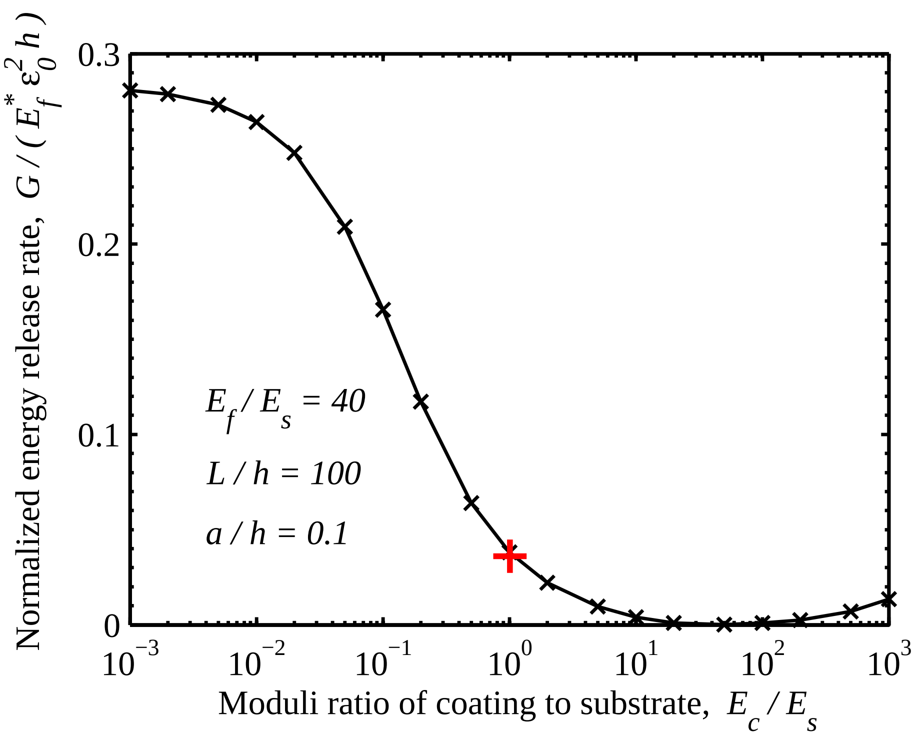
Free surfaces are easy to deform, interfacial flaw is easy to open.

The opening of the debonded interface is suppressed.

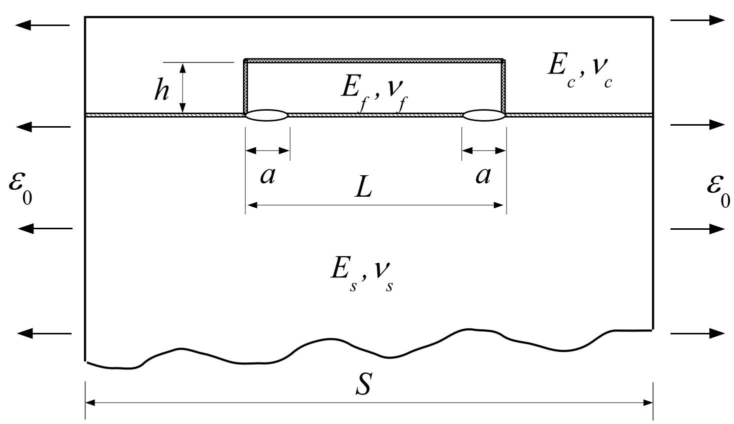
Example in flexible electronics







- Enhance the survival rate
- Increase the island size

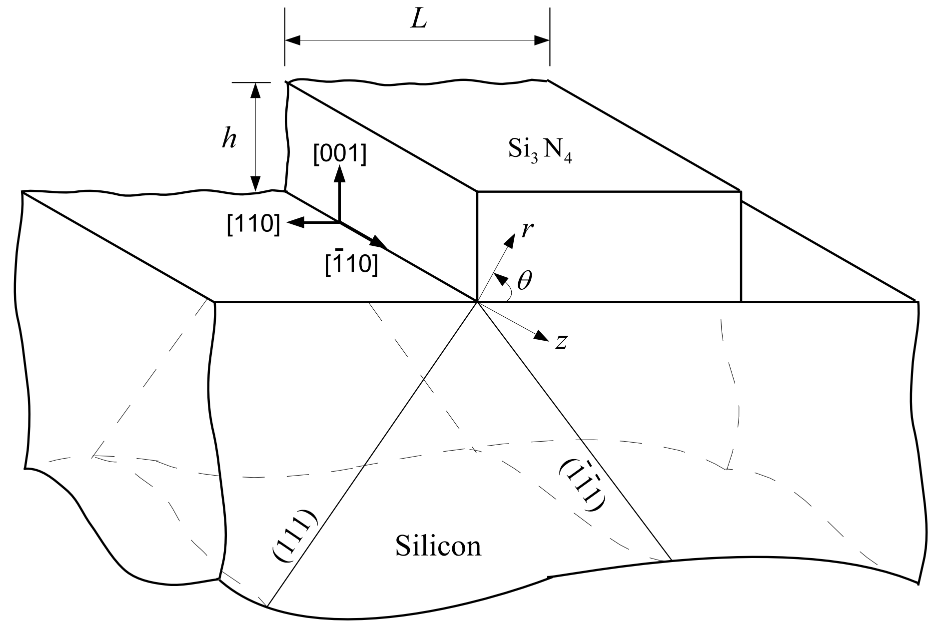


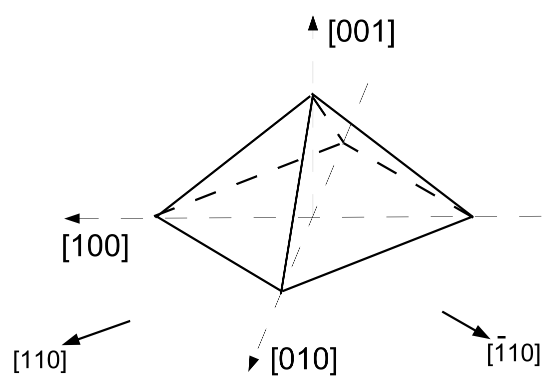
Applications and Implications: **#3**

Dislocation Injection From Sharp Features In Strained Silicon Structures

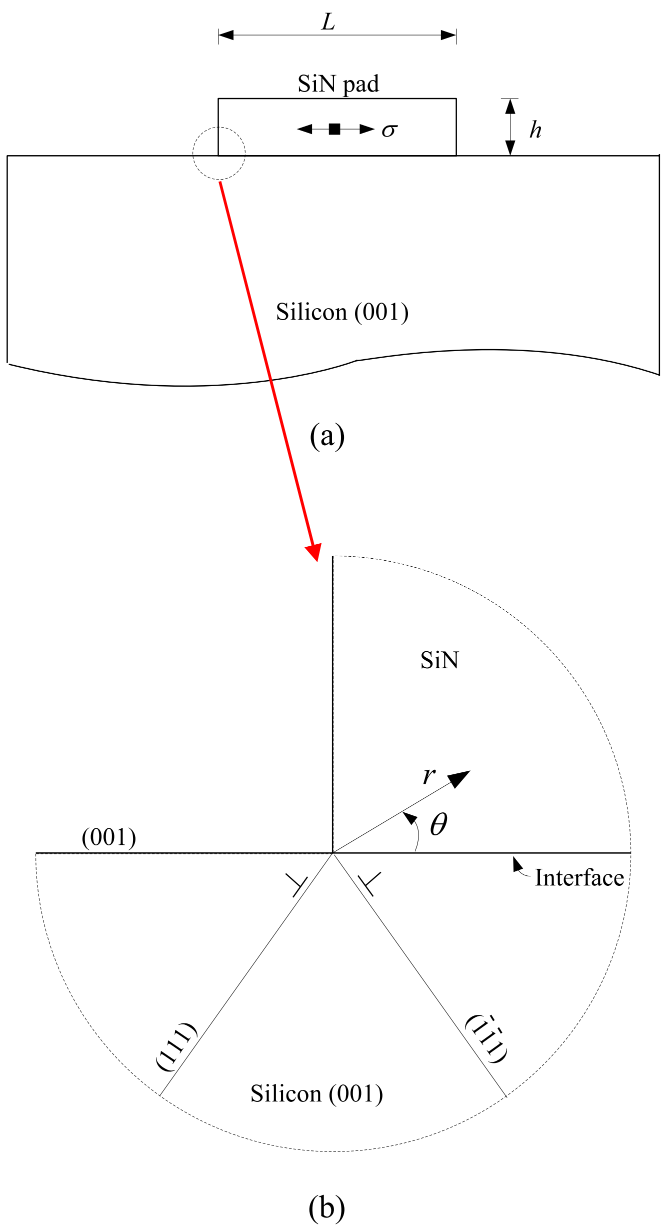
Strained silicon structure

- 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



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

$$\lambda_1 = 0.4514 \qquad \lambda_2 = 0.0752$$

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

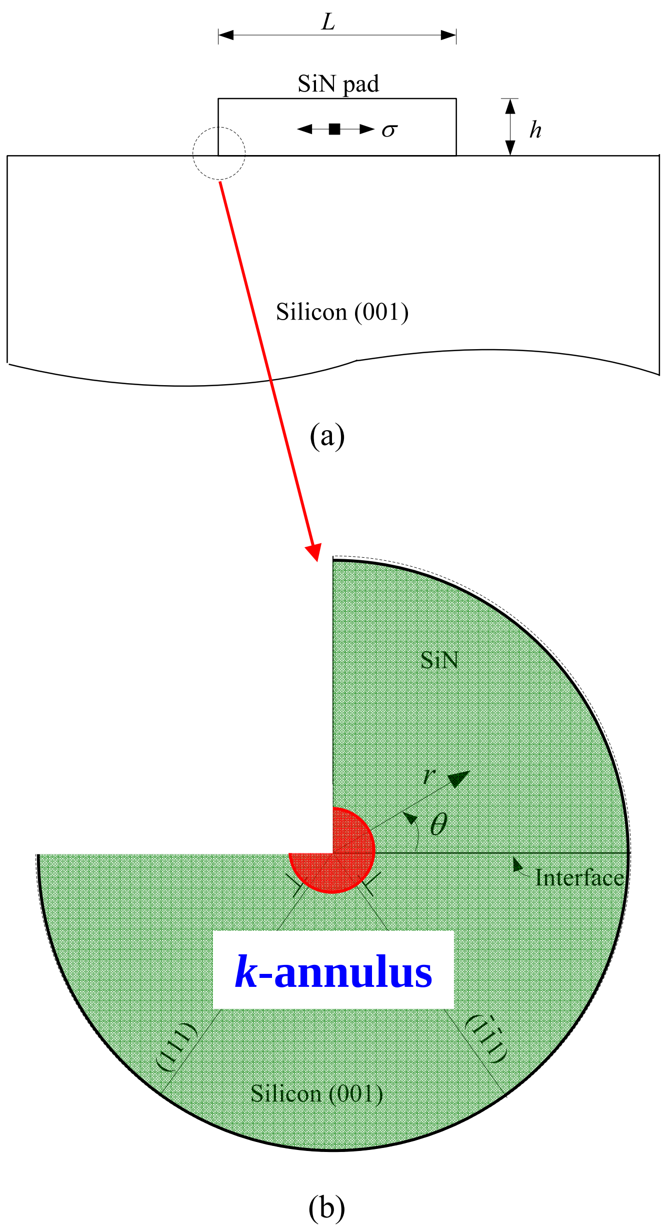
b = 0.383 nm

h = 100 nm

$$\eta \sim 0.02$$

$$\boxed{\sigma_{ij}(r,\theta) = \frac{k}{r^{\lambda}}\Sigma_{ij}(\theta)}$$

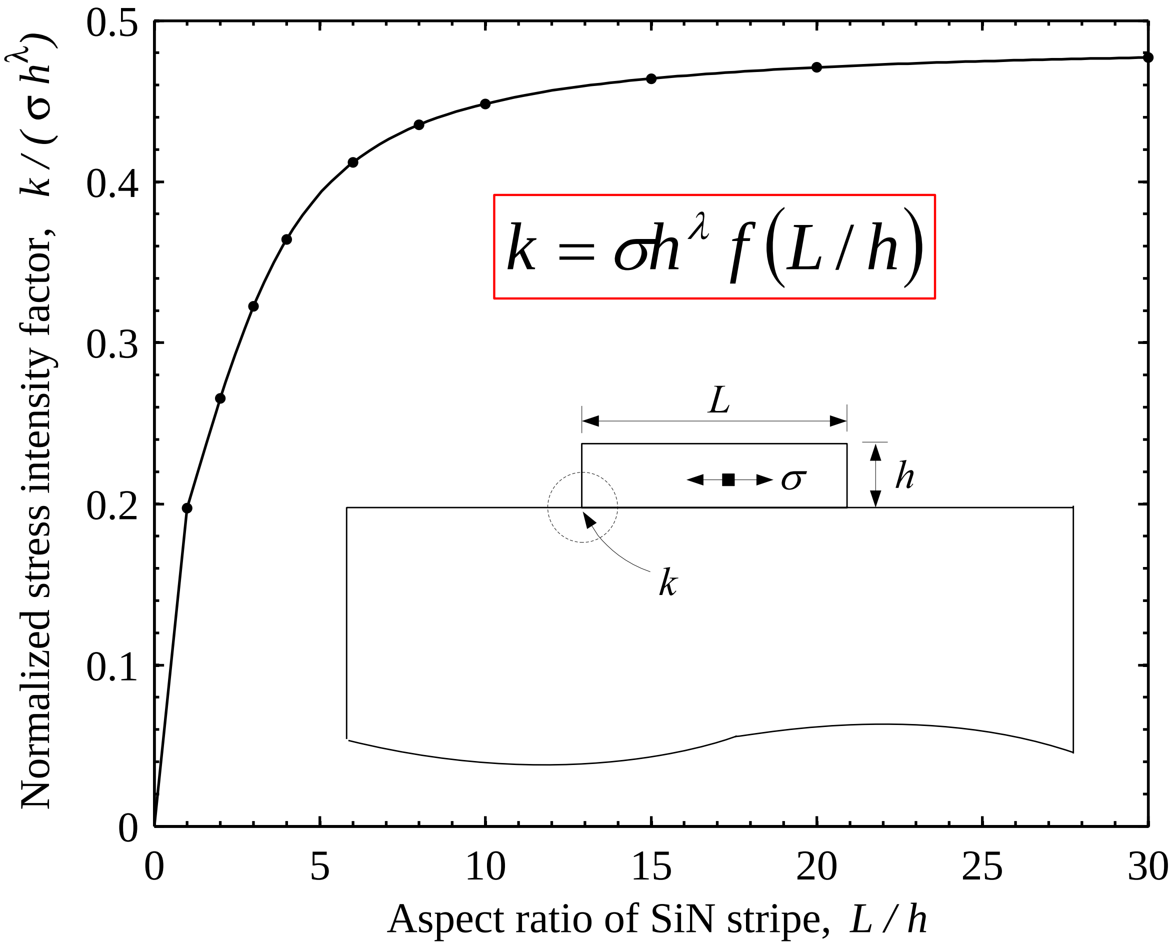
Stress intensity factor *k*



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

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

Critical stress intensity factor k_c



Critical condition:

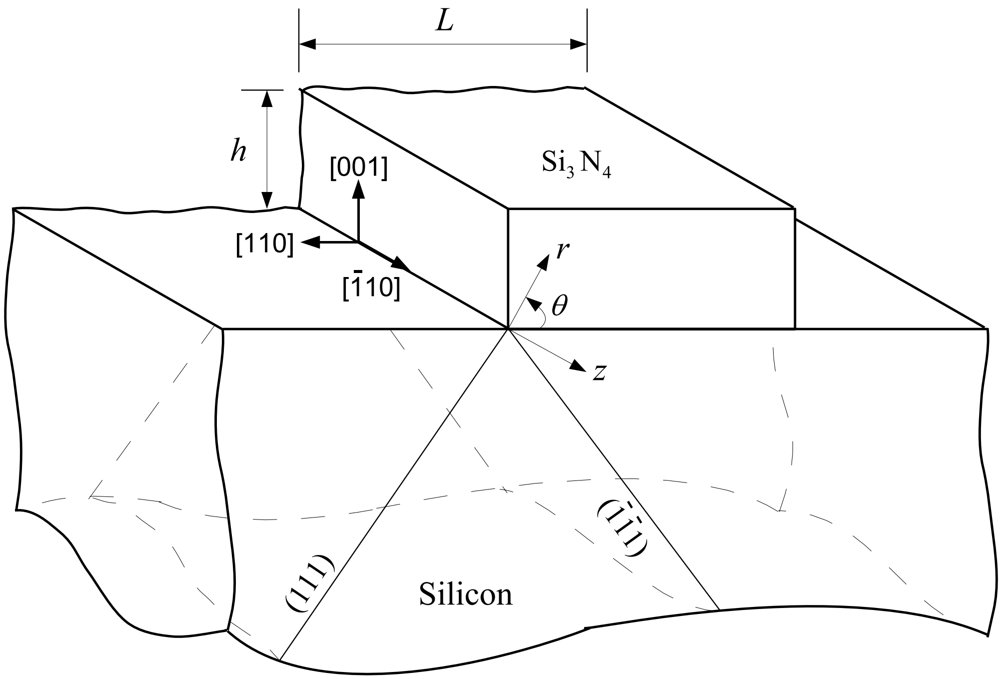
$$k = k_c$$

Driving force

Resistance

k_c is specific to the materials and wedge angle, like fracture toughness.

An estimate of k_c



$$\sigma_{ij}(r,\theta)=\frac{k}{r^{\lambda}}\Sigma_{ij}(\theta)$$

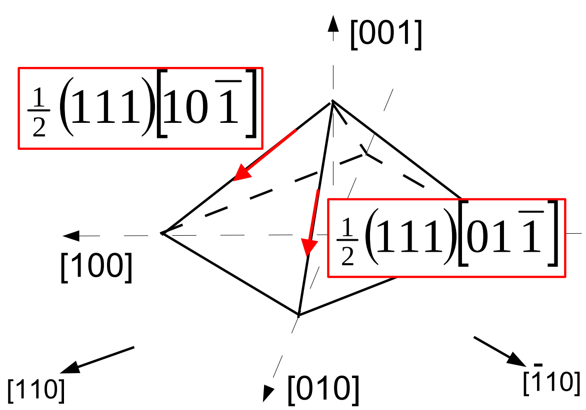
$$\tau_{nb}=\sigma_{ij}n_i b_j$$

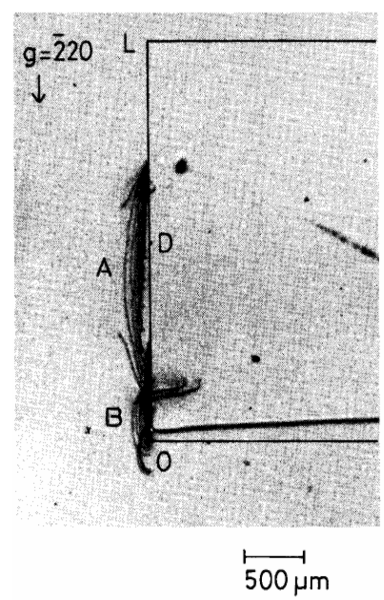
$$\tau_{th}=\frac{\mu b}{2\pi d}\cong 0.2\mu$$

Criterion:

$$\tau_{nb}\big|_{r=b}=\tau_{th}$$

$$\boxed{k_c=0.5\mu b^{\lambda}}$$



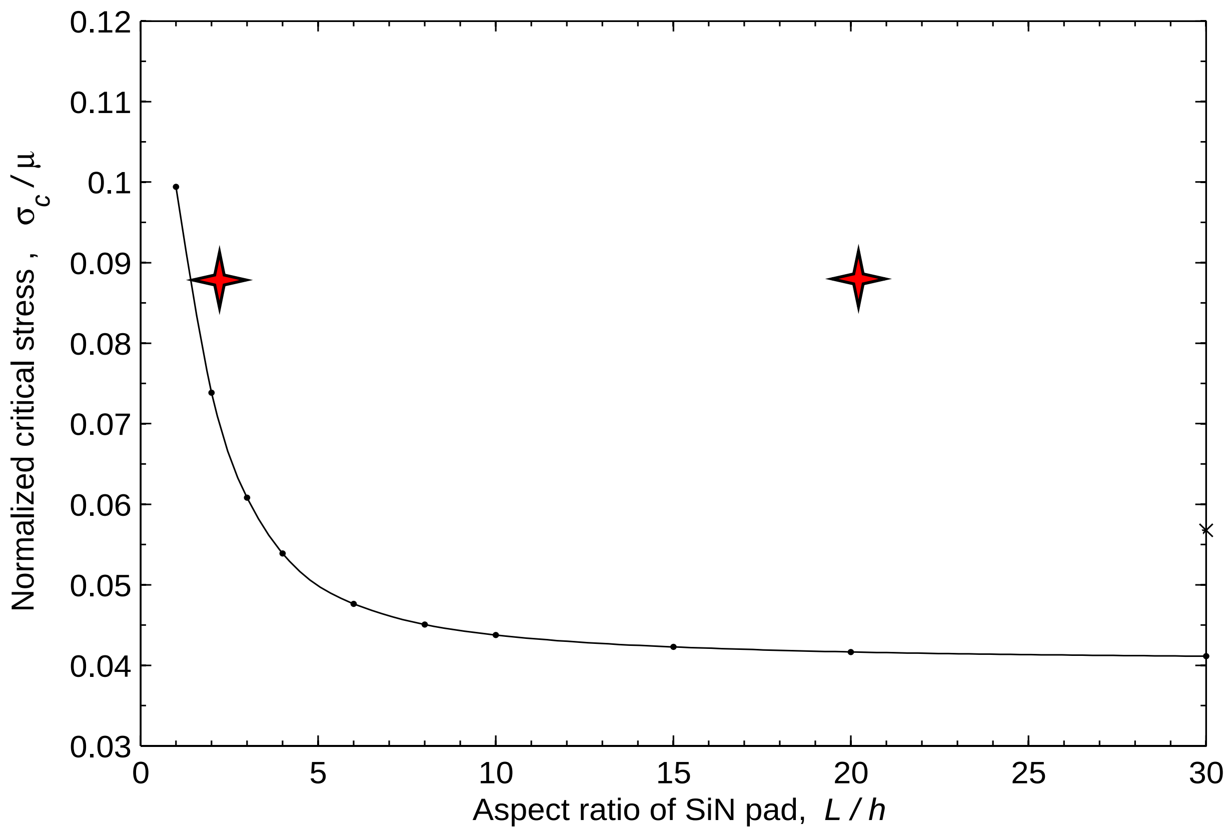


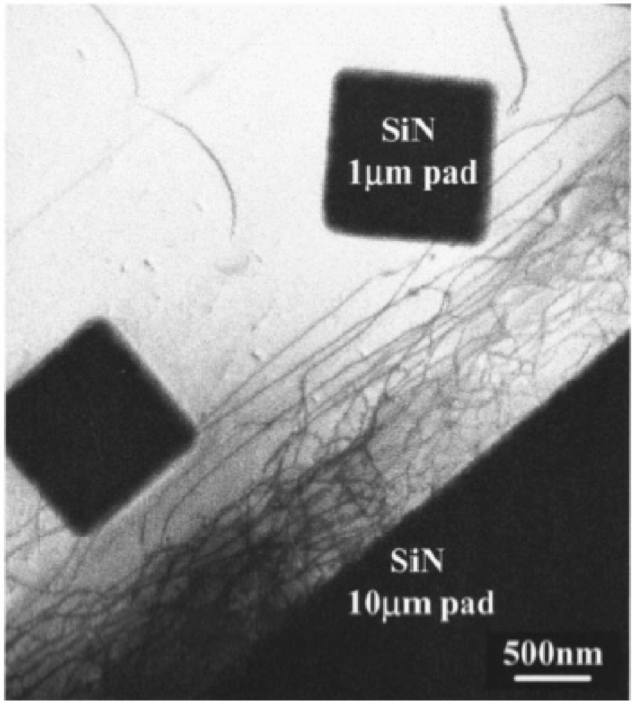
Isomae (1981)

Critical stress in SiN stripe

$$\sigma_c = \frac{0.5\mu}{f(L/h)}\left(\frac{b}{h}\right)^{\lambda}$$

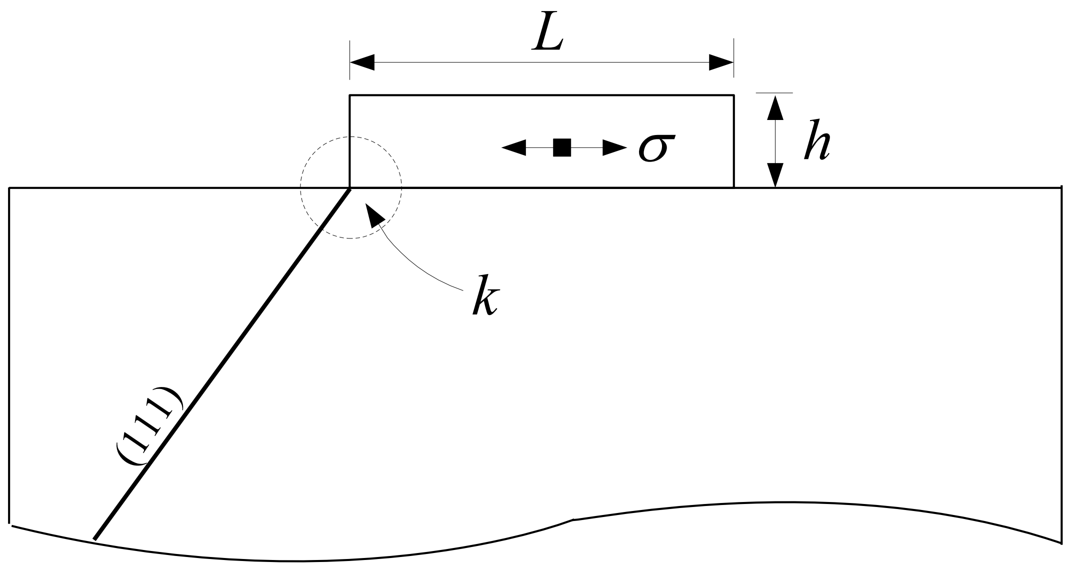
The wider and thicker,
The easier to inject dislocation.





Kammler et al (2005)

Measurement of k_c



Measure k_c :

Calculate k:

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

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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  Joost Vlassak
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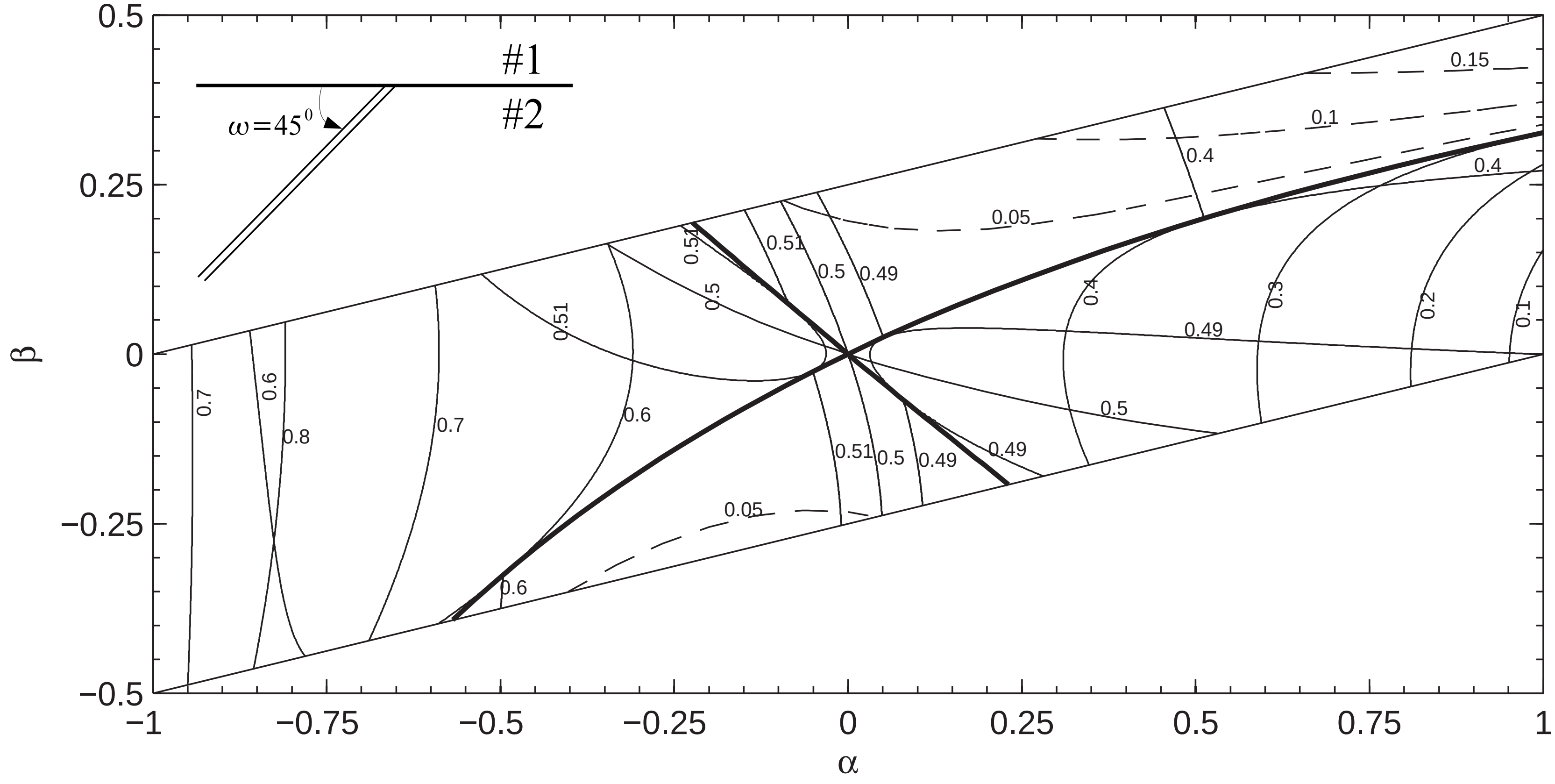
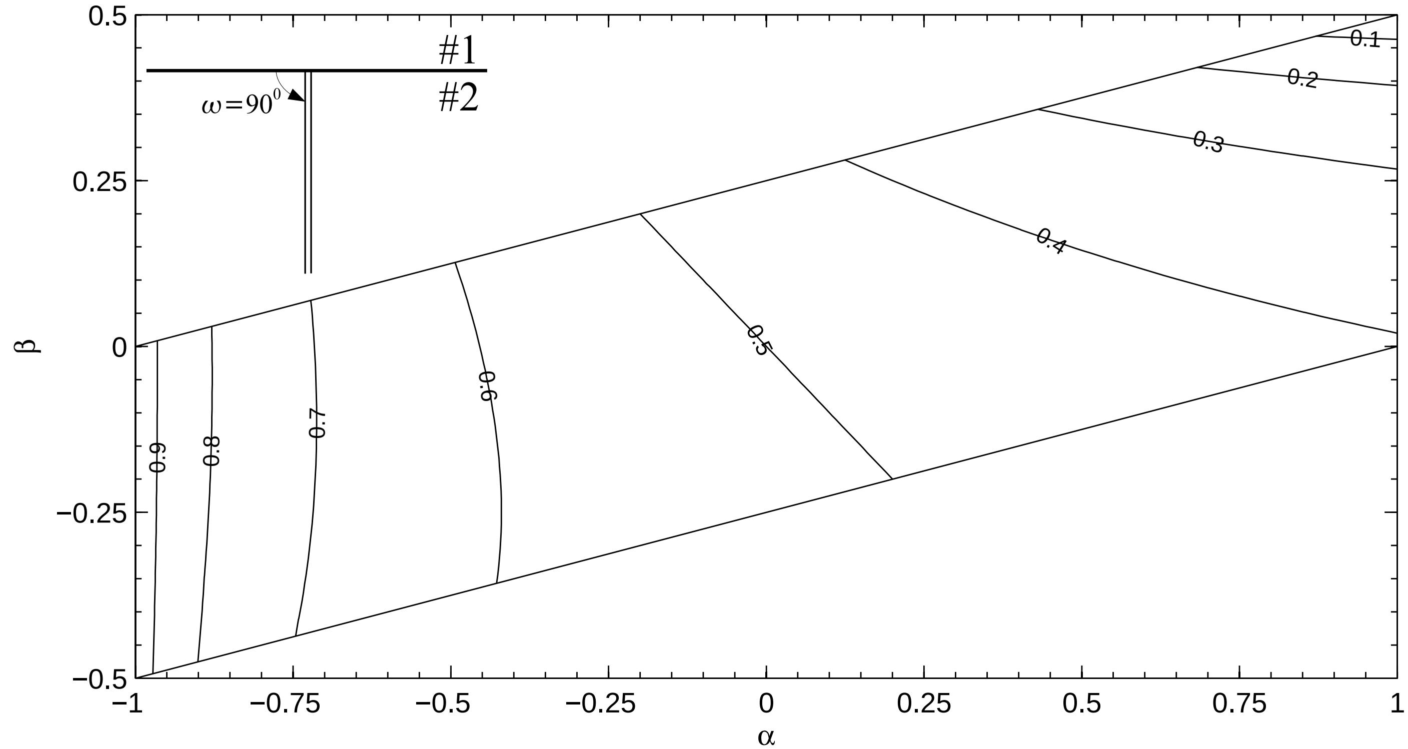
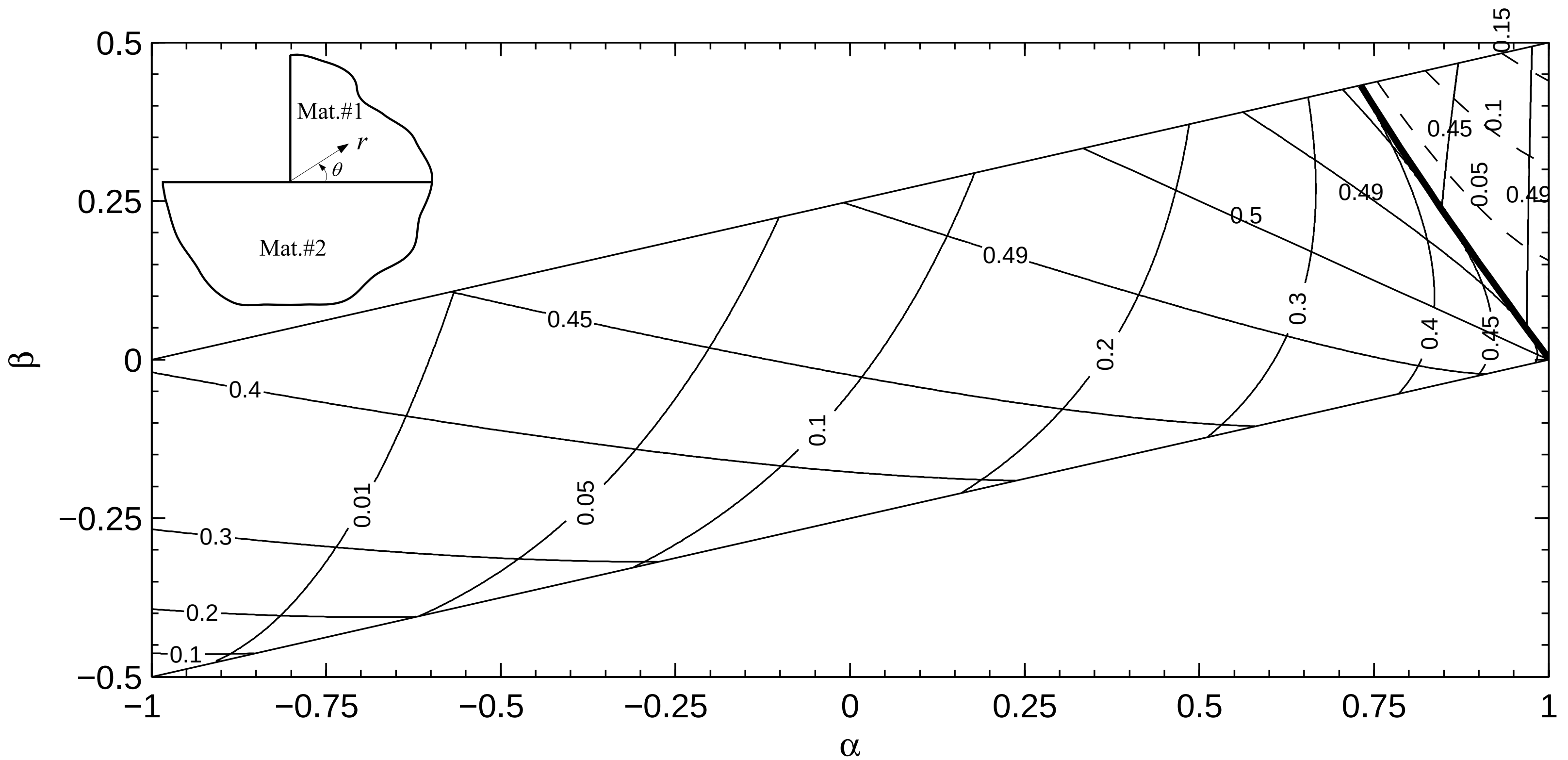
- Group members: Wei Hong, Xuanhe Zhao, Jinxiong Zhou, Dunming Liao, etc.

Backup slides for split singularities

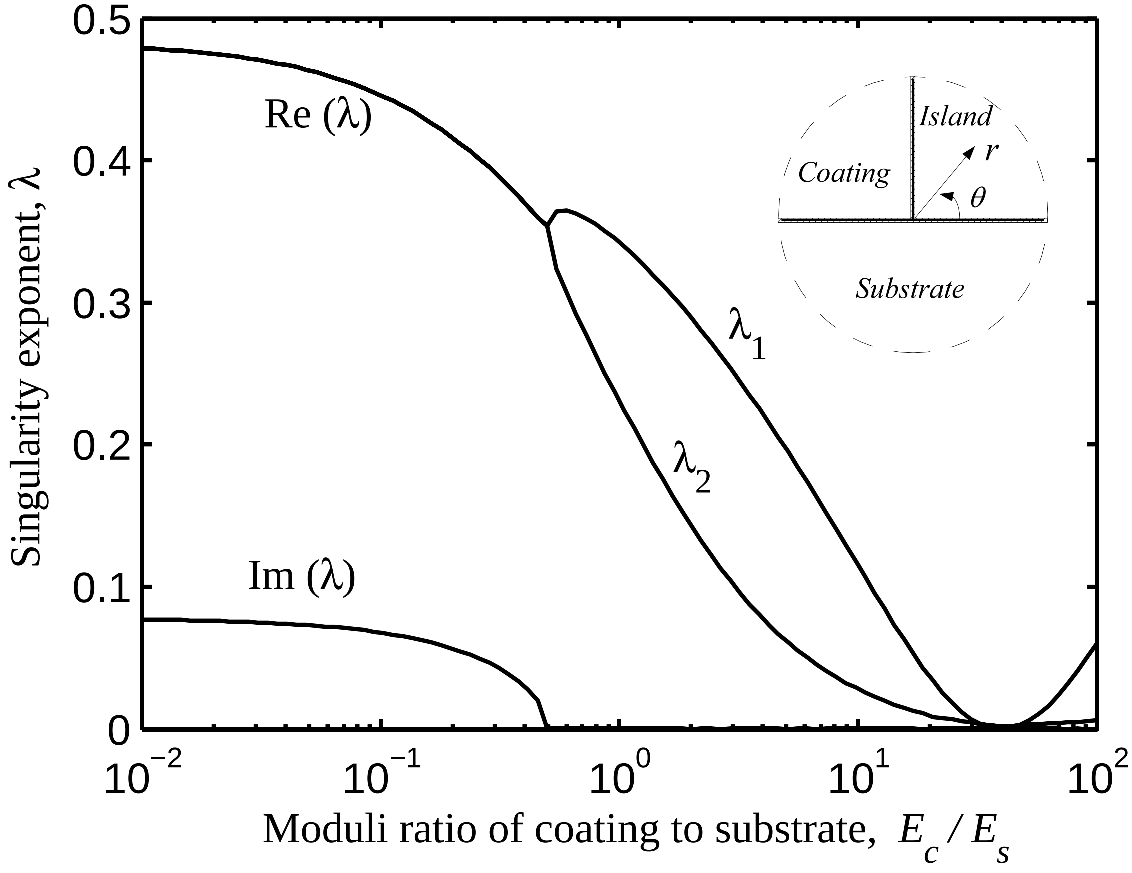
Split singularties



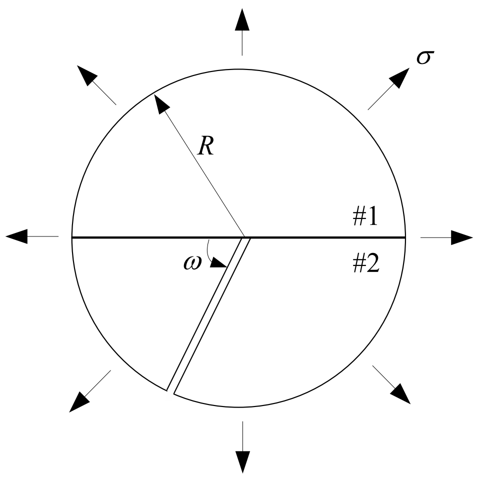

#1
#2
ω=90°
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
β
α
0.5
0.25
0
−0.25
−0.5
−1
−0.75
−0.5
−0.25
0
0.25
0.5
0.75
1



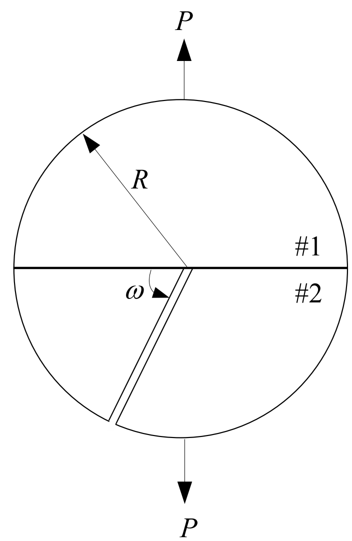
Mat.#1
Mat.#2
r
θ
β
α
0.5
0.25
0
−0.25
−0.5
−1
−0.75
−0.5
−0.25
0
0.25
0.5
0.75
1
0.01
0.05
0.1
0.2
0.3
0.4
0.45
0.49
0.5
0.15


0.5
0.4
0.3
0.2
0.1
0
Singularity exponent, λ
Re (λ)
Im (λ)
λ1
λ2
Island
Coating
r
θ
Substrate
10^−2
10^−1
10^0
10^1
10^2
Moduli ratio of coating to substrate, Ec / Es

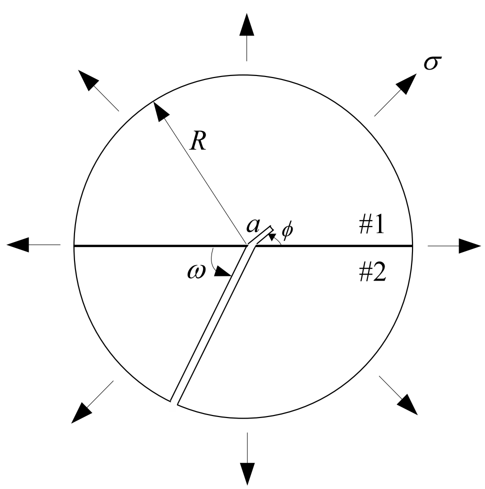
(a)



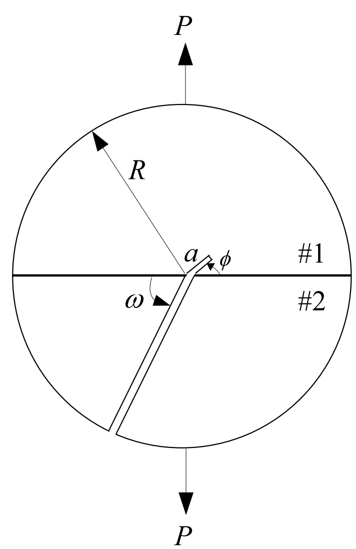
(b)



(a)



(b)

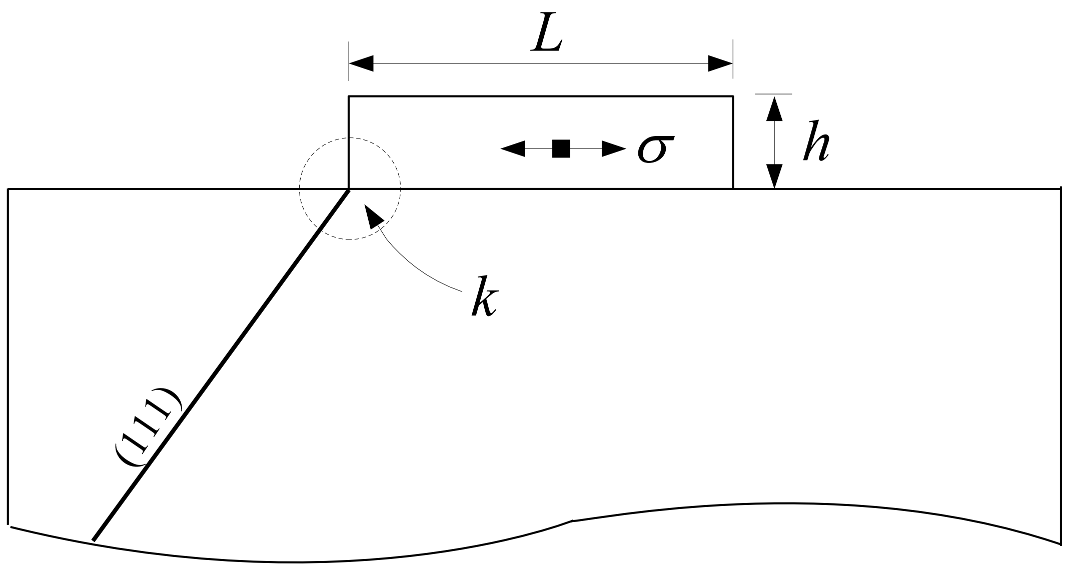


$$\frac{K_I^p}{\sqrt{a}} = b_{11} \cdot \frac{k_1}{a^{\lambda_1}} + b_{12} \cdot \frac{k_2}{a^{\lambda_2}}$$

$$\frac{K_{II}^p}{\sqrt{a}} = b_{21} \cdot \frac{k_1}{a^{\lambda_1}} + b_{22} \cdot \frac{k_2}{a^{\lambda_2}}$$

Backup slide for strained silicon

Measurement of k_c



Dimensional requirement:

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

A series of experiments:

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

Find a critical condition to obtain coefficient c by:

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

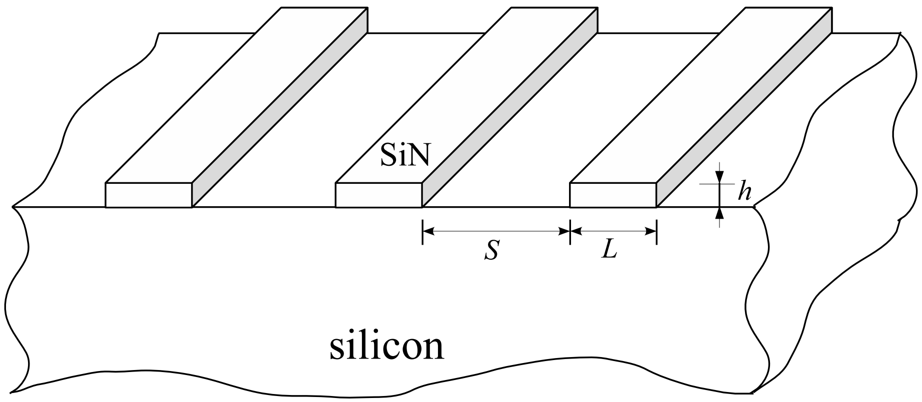
Other concerns from industry

- 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.

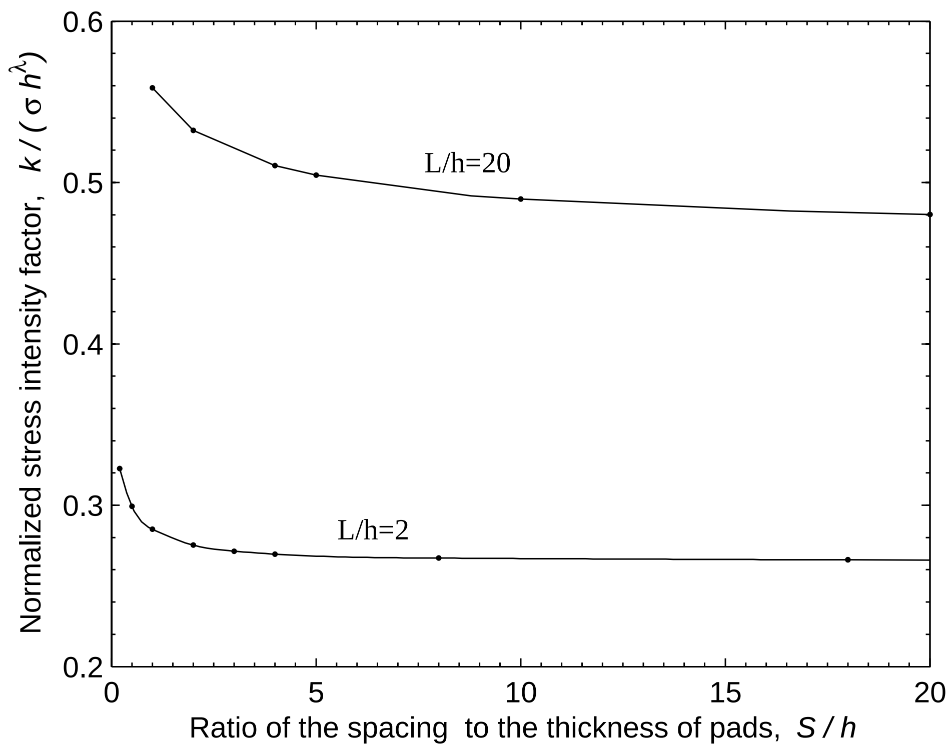
Spacing effect



$$\sigma_{ij}(r,\theta) = \frac{k}{r^{\lambda}} \Sigma_{ij}(\theta)$$

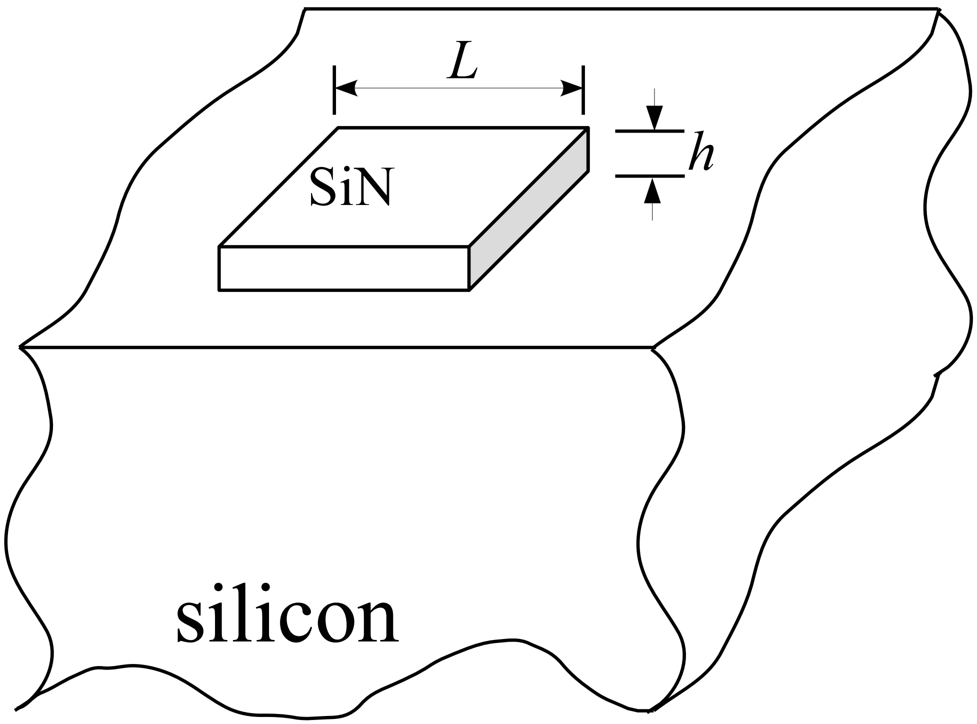
with $\lambda = 0.4514$

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



In practice, *S/h* doesn't go to zero, so the spacing effect is quite small.

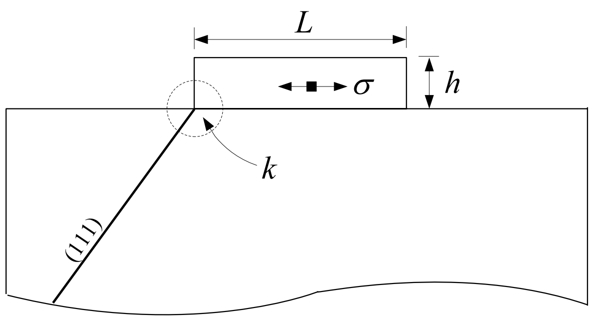
3D Corners



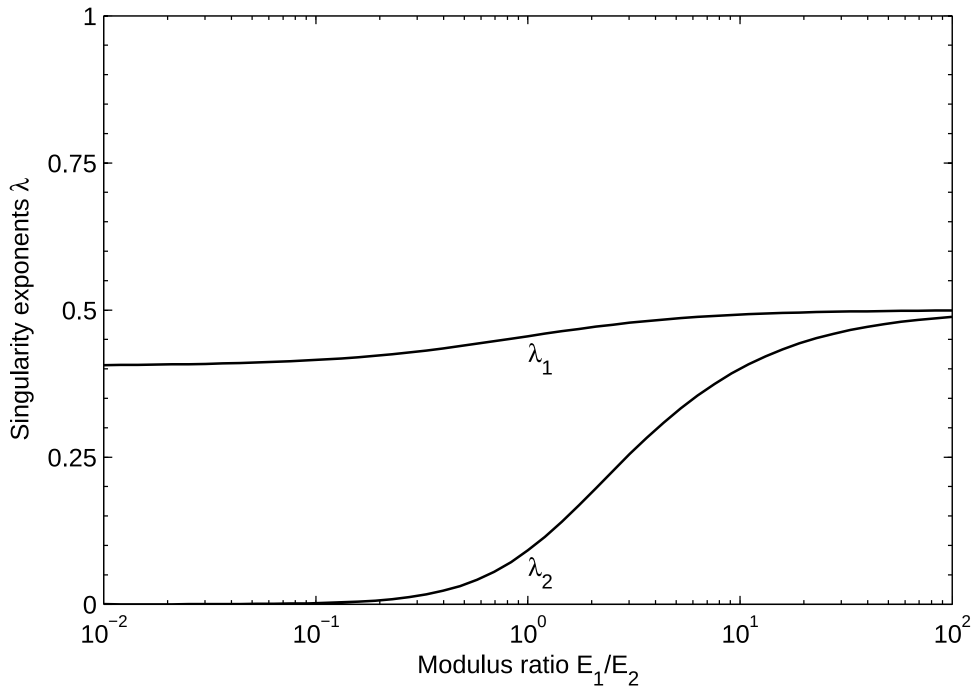
$$\boxed{k = \sigma h^{\lambda} \cdot f\left(\frac{L}{h}, \frac{S}{h}, \frac{R}{h}\right)}$$

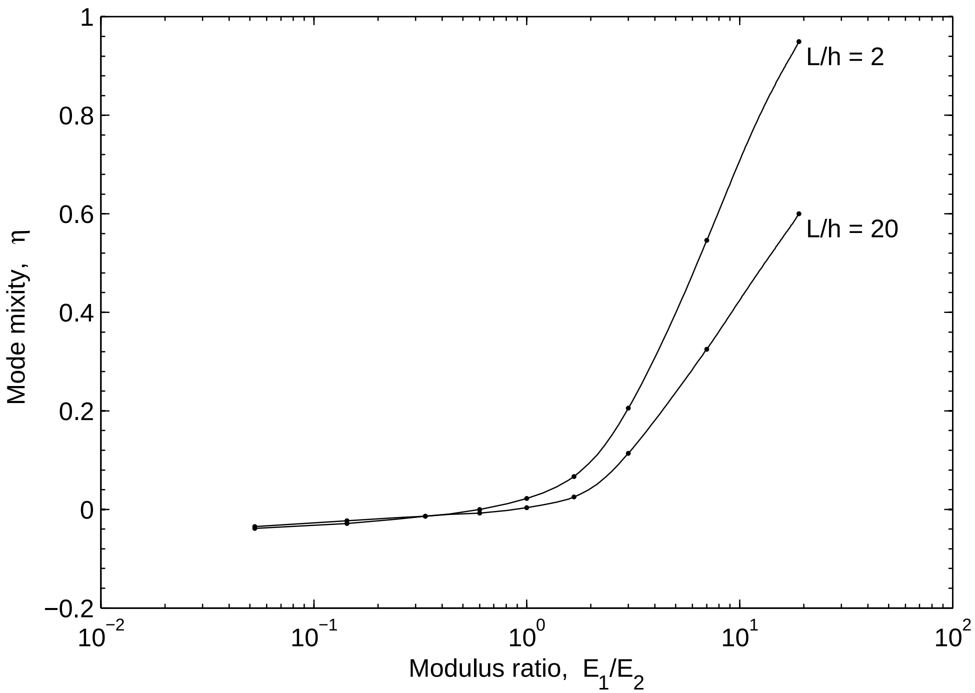
- The method still applies. What changes is the coefficients.
- 3D corner singularities. Measurement of k_c and calculation of $f(L/h, S/h, R/h)$.
- 3D calculation is expensive for academia, but very cheap for industry. *Do it.*

Effect of weaker singularity if not SiN



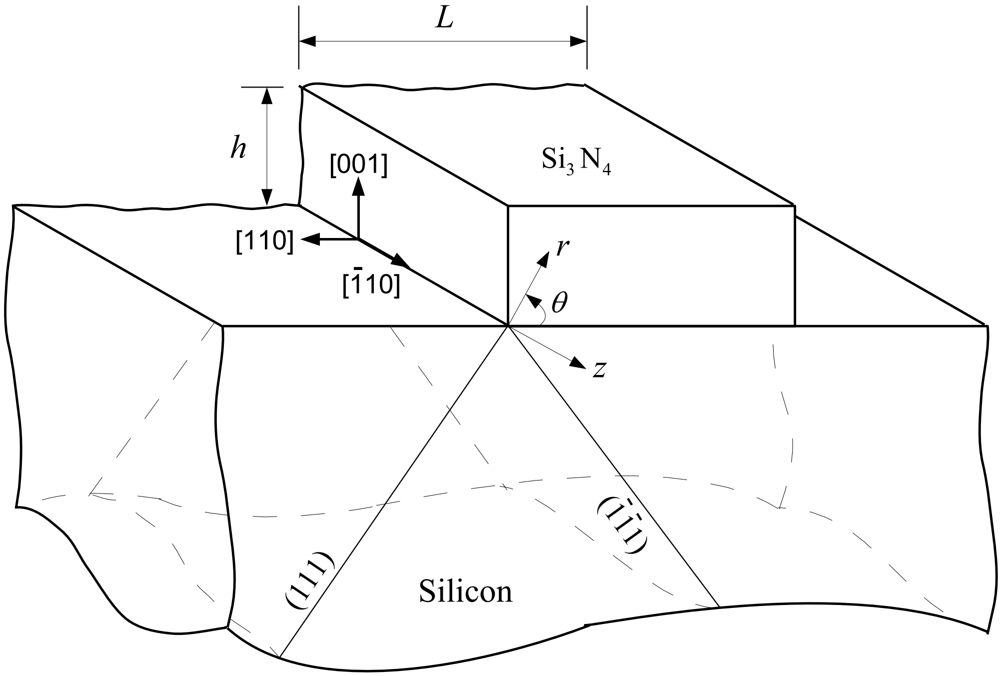
Local mode mixity: $\boxed{\eta = \frac{\kappa_2}{\kappa_1}\left(\frac{b}{h}\right)^{\lambda_1-\lambda_2}}$

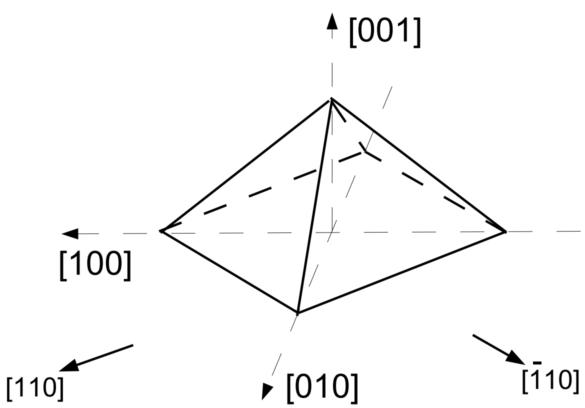


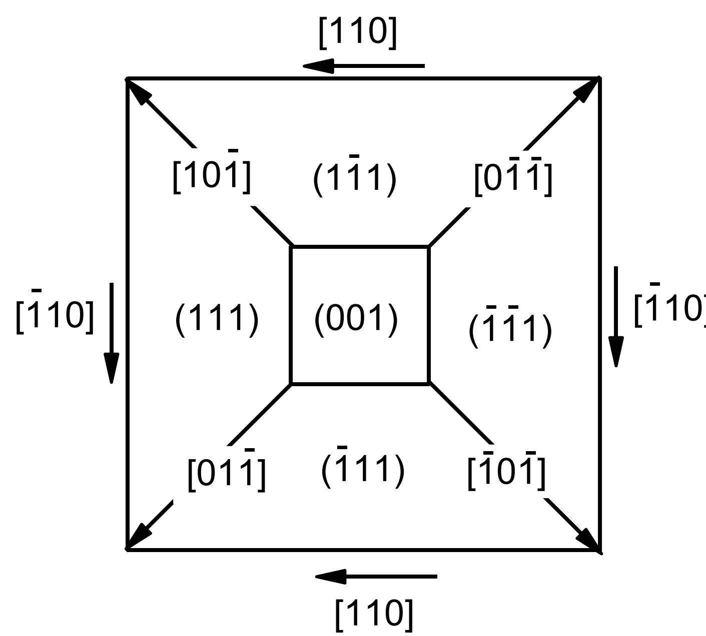


Evaluate it case by case.

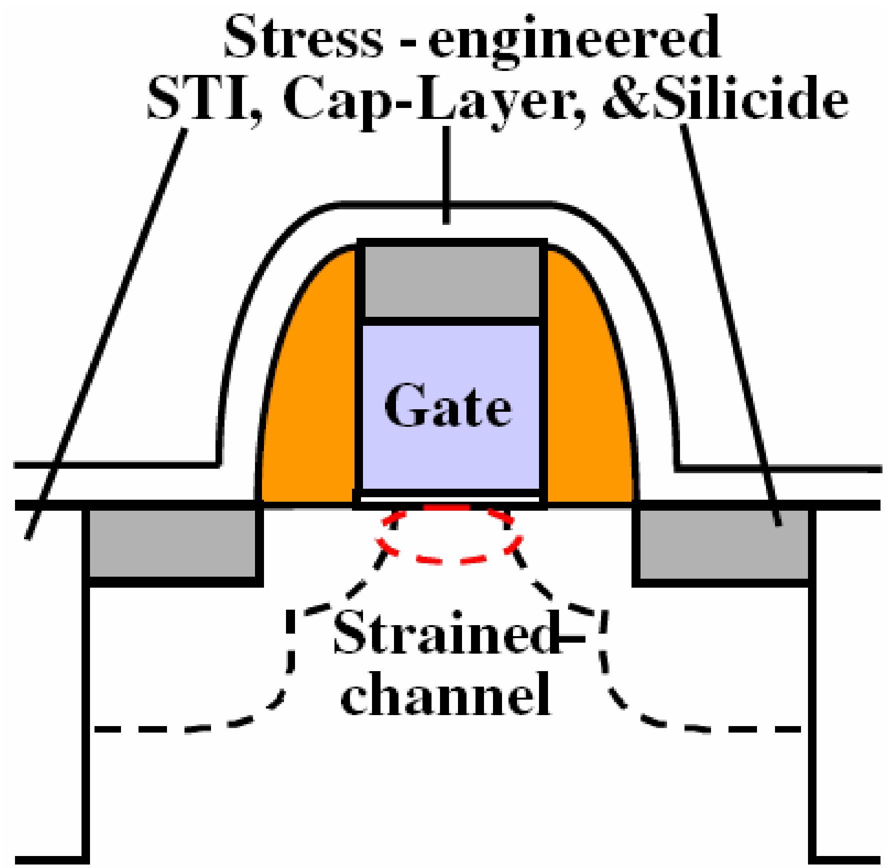
Slip systems







Future focus



Ge et al, IEDM 2003.

- Stress driven dislocation motion under channel.