Film in tension

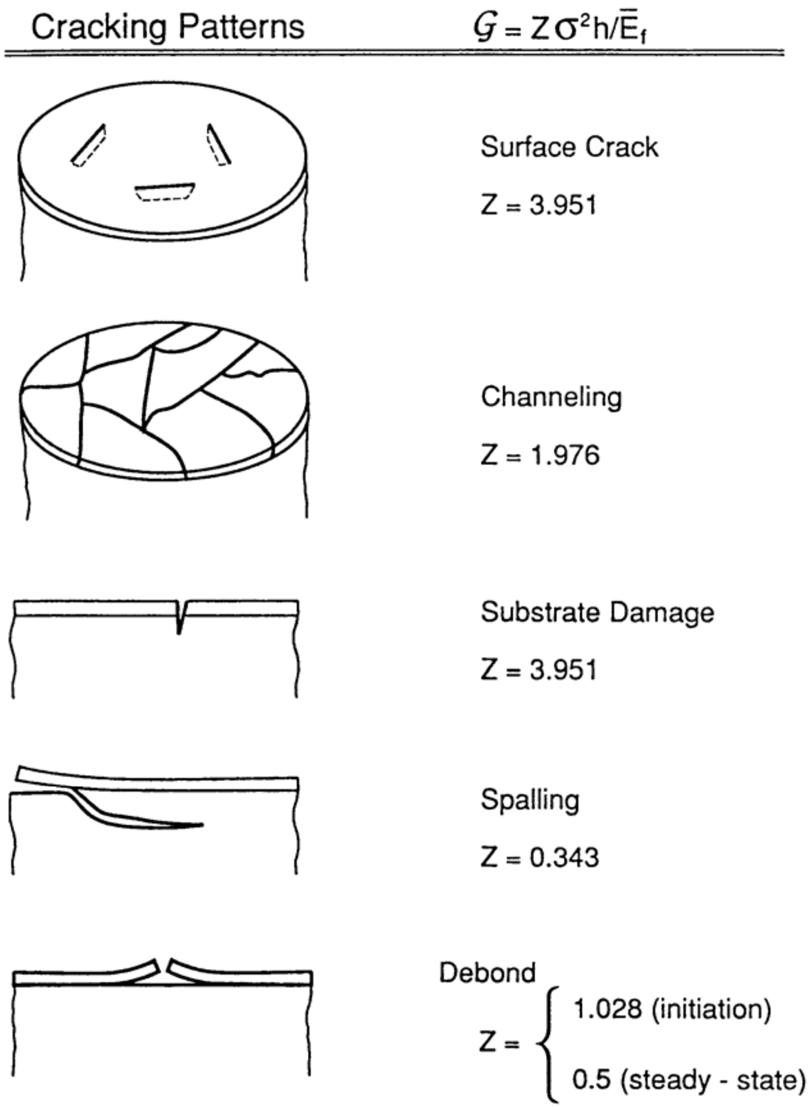


FIG. 43. Commonly observed cracking patterns. The dimensionless driving force for each pattern is listed, assuming that the film–substrate is elastically homogeneous, and the substrate is infinitely thick.

Film in compression

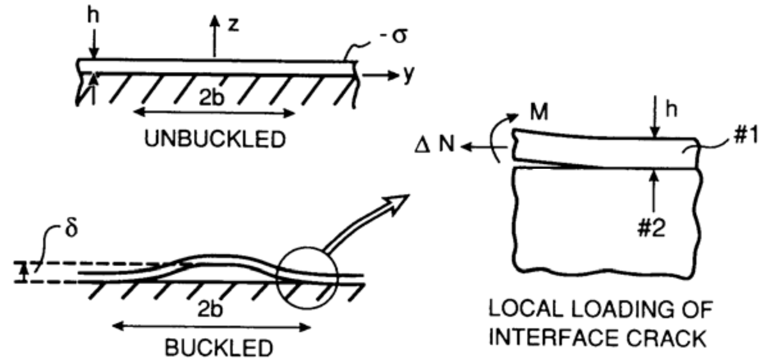
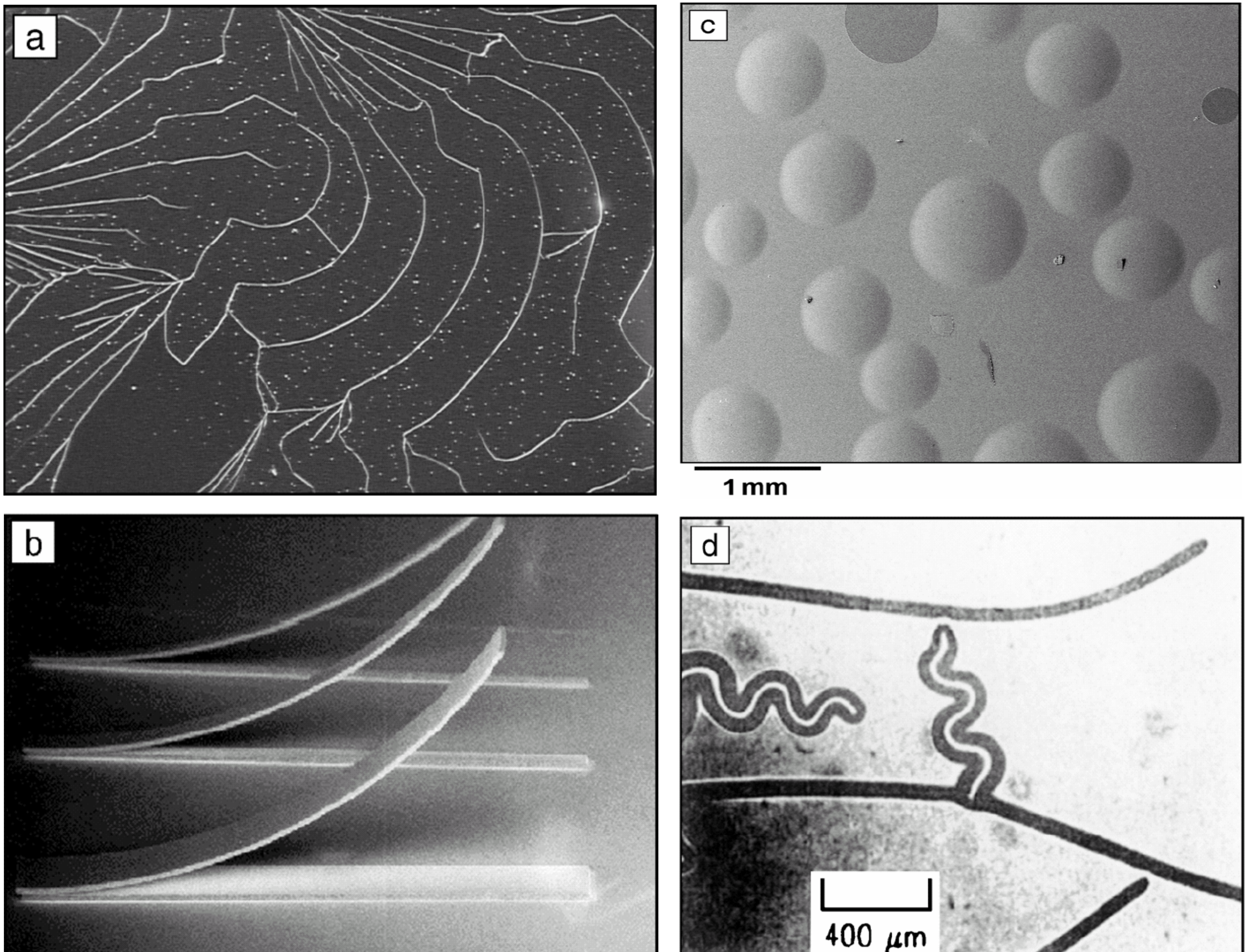


FIG. 57. Geometry of the one-dimensional blister, and conventions for the elasticity solution characterizing conditions near the tip of an interface crack between a thin film and an infinitely thick substrate. Top left: unbuckled; bottom left: buckled; right: local loading of interface crack.

Hutchinson, Suo
Advances in Applied Mechanics
29, 64-192 (1992).

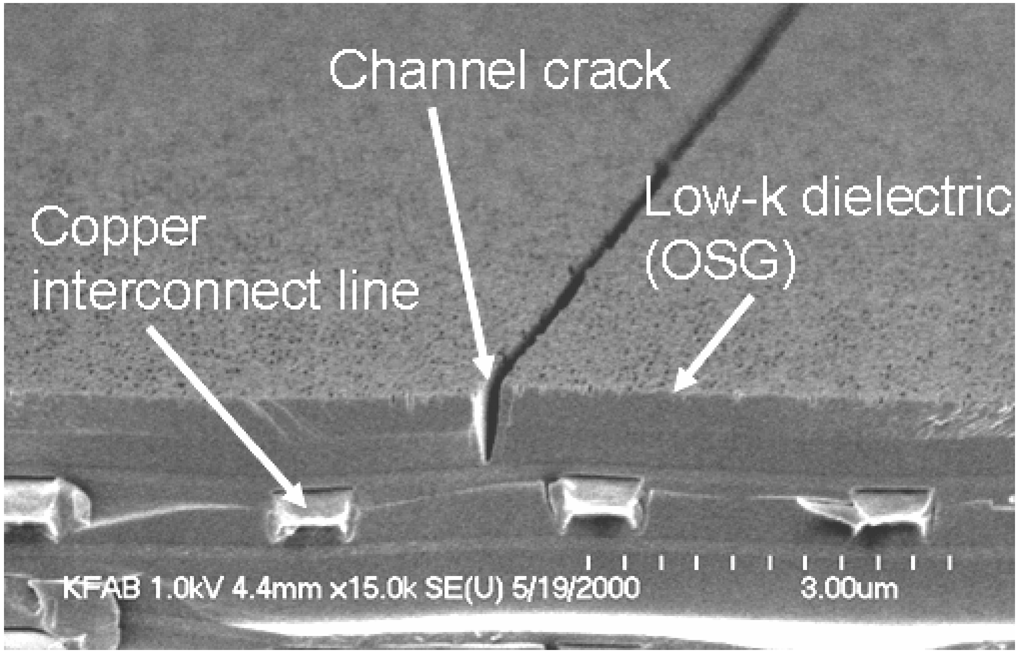
pdf file: www.deas.harvard.edu/suo

Variety of Thin Film Fracture Patterns



Cook, Suo, MRS Bulletin, 27, 45 (2002)
Courtesy J. Sturn (a), (c); Q. Ma (b); M.D. Thouless (d)

A channel crack



T. Tsui (http://www.imechanica.org/node/248)

The origin of stress in a film

- Deposition process (intrinsic stress)
- Mismatch due to lattice constant
- Mismatch in the coefficient of thermal expansion
- Bending

W.D. Nix, Mechanical Properties of Thin Films (http://imechanica.org/node/530)

Stress in a thin film due to mismatch in the coefficients of thermal expansion

- The film is very thin compared to the substrate (h << H).
- The substrate is nearly stress free.
- The film is in a state of equal biaxial stress, σ.
- At T_{ref}, the film is stress free.
- The film deforms elastically as the temperature changes

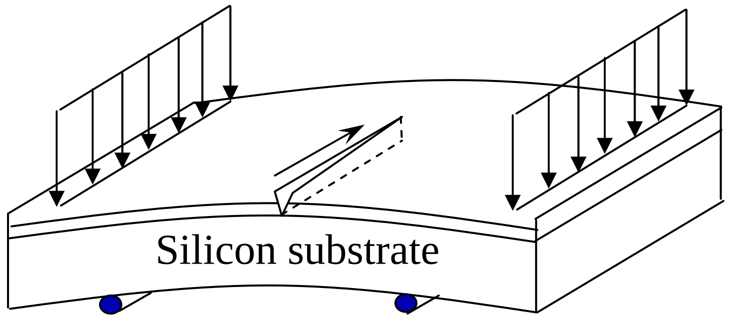
$$\varepsilon_s = \alpha_s \left(T - T_{ref} \right) \qquad \varepsilon_f = \alpha_f \left(T - T_{ref} \right) + \frac{\left(1 - \nu_f\right)\sigma}{E_f}$$

As the temperature changes, the substrate and the film remains bonded

$$\varepsilon_s = \varepsilon_f \qquad \sigma = \frac{E_f}{\left(1 - \nu_f\right)} \left(\alpha_f - \alpha_s \right)\left(T_{ref} - T \right)$$

When $\alpha_f > \alpha_s$, upon cooling, the film is under tensile stress, $\sigma > 0$.

Stress in film due to bending



$$\frac{1}{R}=\frac{M}{\frac{E_s}{12\left(1-\nu_s^2\right)}BH^3}$$

$$\varepsilon=\frac{H/2}{R}$$

$$\sigma=\frac{E_f}{1-\nu_f^2}\varepsilon$$

$$\sigma=\frac{6E_f\left(1-\nu_s^2\right)M}{E_s\left(1-\nu_f^2\right)BH^2}$$

M = applied moment

B = width of the beam

H = thickness of the substrate

R = radius of curvature

ε = strain in the film

σ = stress in the film

Measure residual stress using wafer curvature

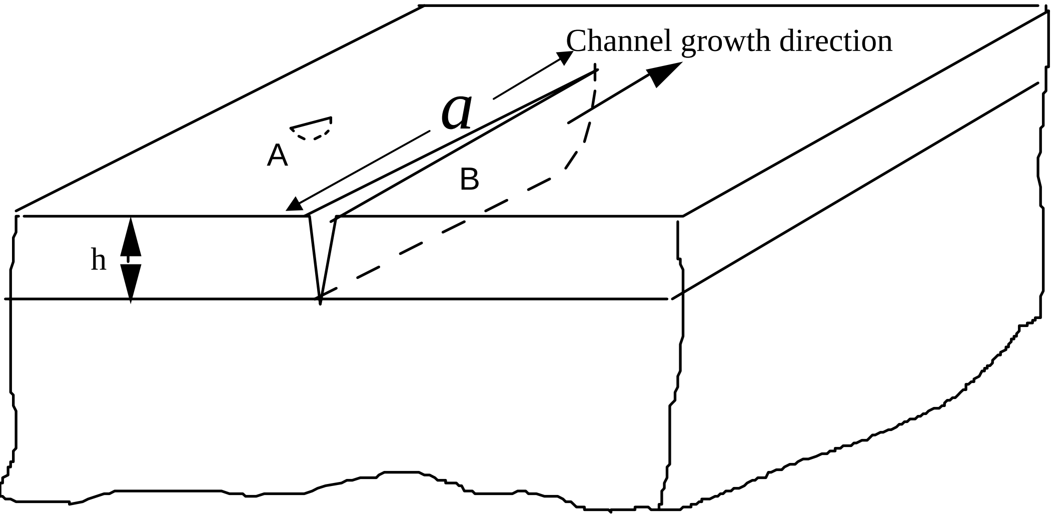
Line tension $$f = \int \sigma dz$$

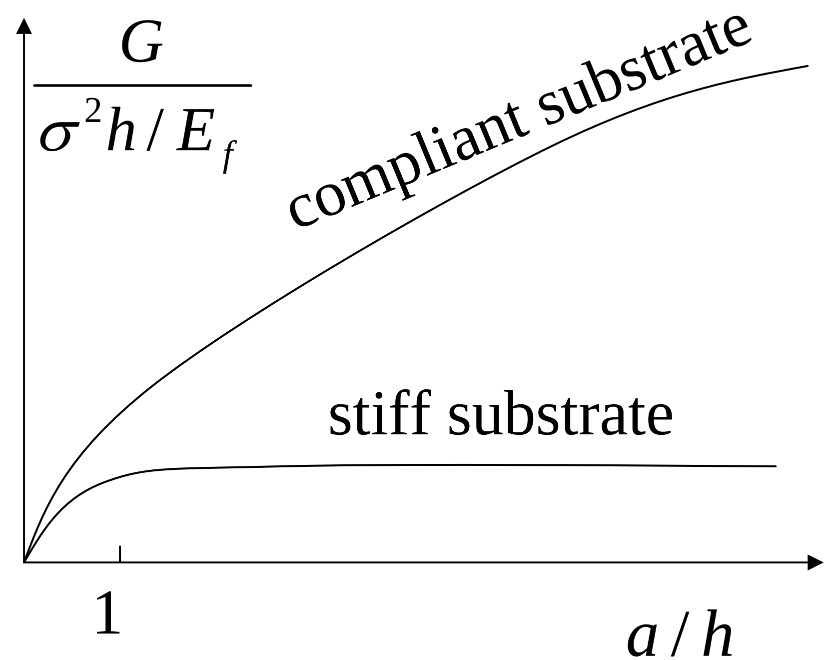
Bending moment $$M = fBH/2$$

Radius of curvature $$\frac{1}{R} = \frac{1-\nu_s}{E_s}\frac{12M}{BH^3}$$

Stoney's formula $$f = \left(\frac{E_s}{1-\nu_s}\right)\frac{H^2}{6R}$$

Channel crack: Initiation vs. steady propagation



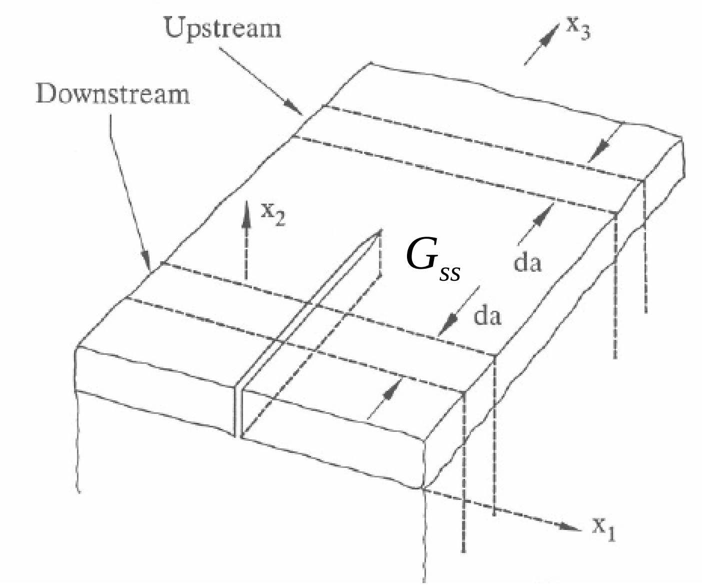


A. Initiation $G_{initiation} = Y\sigma^2 a / E_f$

B. Steady propagation $G_{ss} = Z\sigma^2 h / E_f$

When the substrate is compliant, steady state is attained at a large a/h and a large energy release rate.

Steady-state energy release rate of a channel crack

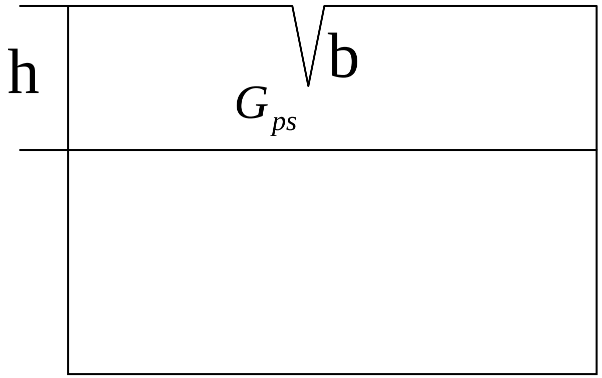


Reduction in elastic energy for the crack to advance a unit distance

$U = SE_{upstream} - SE_{downstream}$

$$U = \int_0^h G_{ps}(b)$$

Steady-state energy release rate



$$hG_{ss} = U \qquad G_{ss} = \frac{1}{h}\int_0^h G_{ps}(b)\,db$$

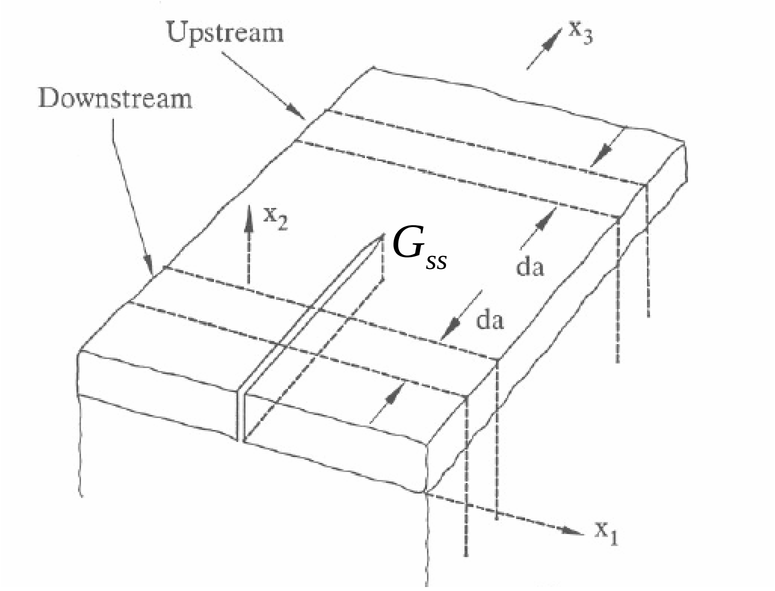
Example: film and substrate have similar elastic modulus

$$G_{ps}(b) = \frac{1-\nu^2}{E}(1.1215)^2 \pi b \sigma^2 \qquad G_{ss} = 2\frac{(1-\nu^2)}{E} h\sigma^2$$

Steady-state energy release rate of a channel crack

Reduction in elastic energy for the crack to advance a unit distance

$U = SE_{upstream} - SE_{downstream}$



$$U = \frac{1}{2}\int_0^h \delta(z)\sigma(z)dz$$

$\delta(z)$ Crack opening downstream

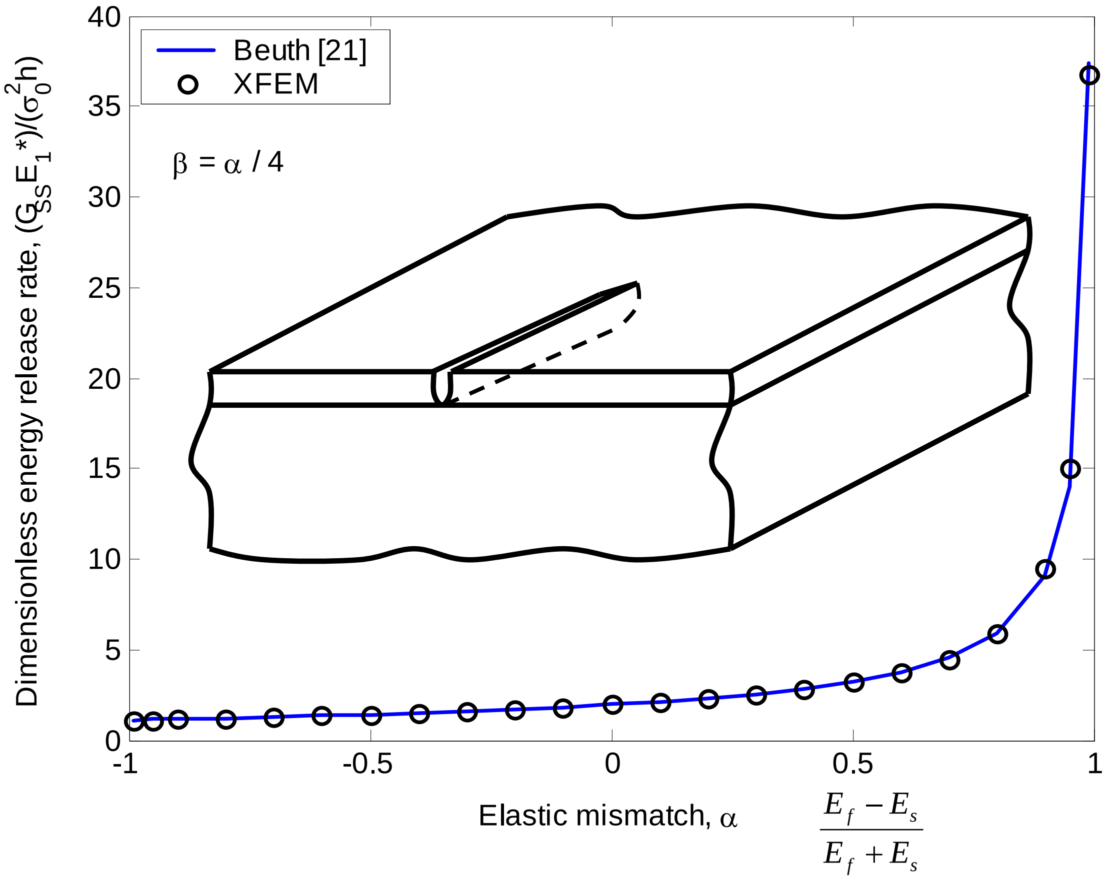
$\sigma(z)$ Stress upstream

$$hG_{ss} = U$$

$$G_{ss} = \frac{1}{2h}\int_0^h \delta(z)\sigma(z)dz$$

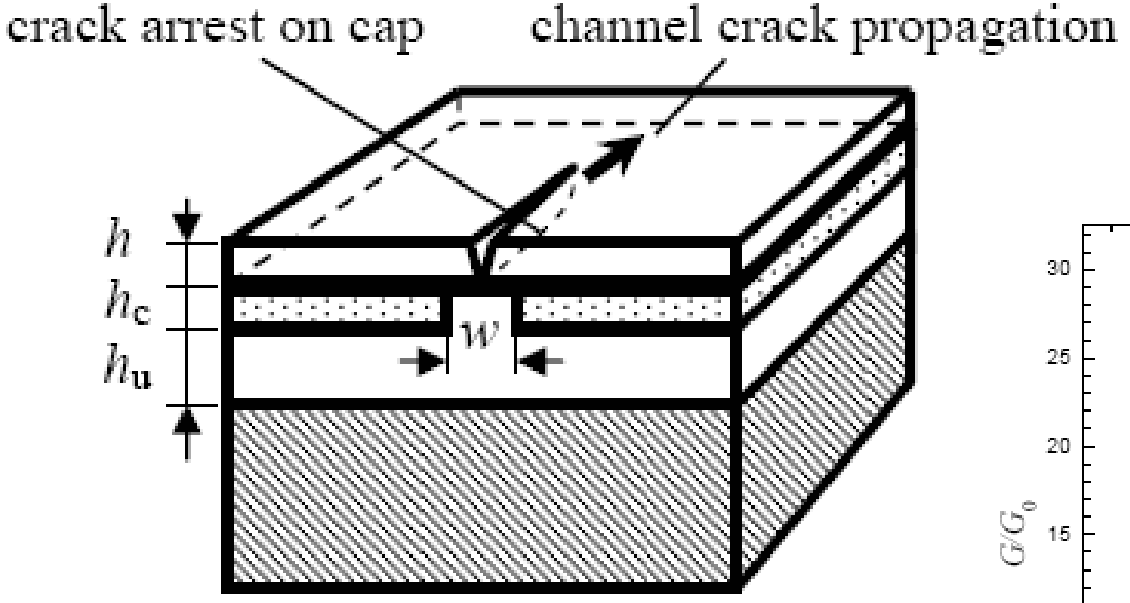
Driving force for steady propagation

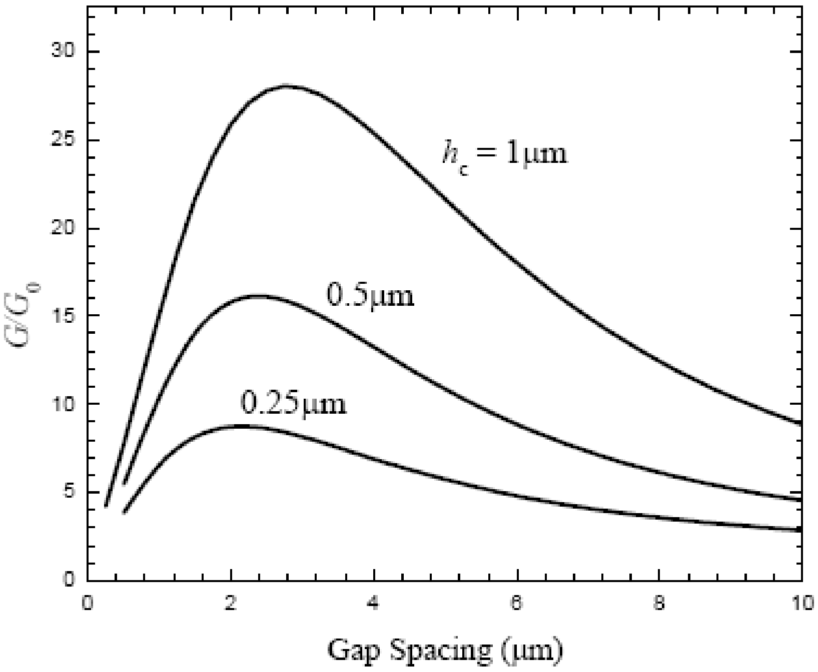
$$G_{ss} = Z\frac{\sigma^2 h}{E_f}$$



An advantage of being nano: thin films can sustain large stains.
e.g., 7 nm silica film can sustain strains of ~5%.

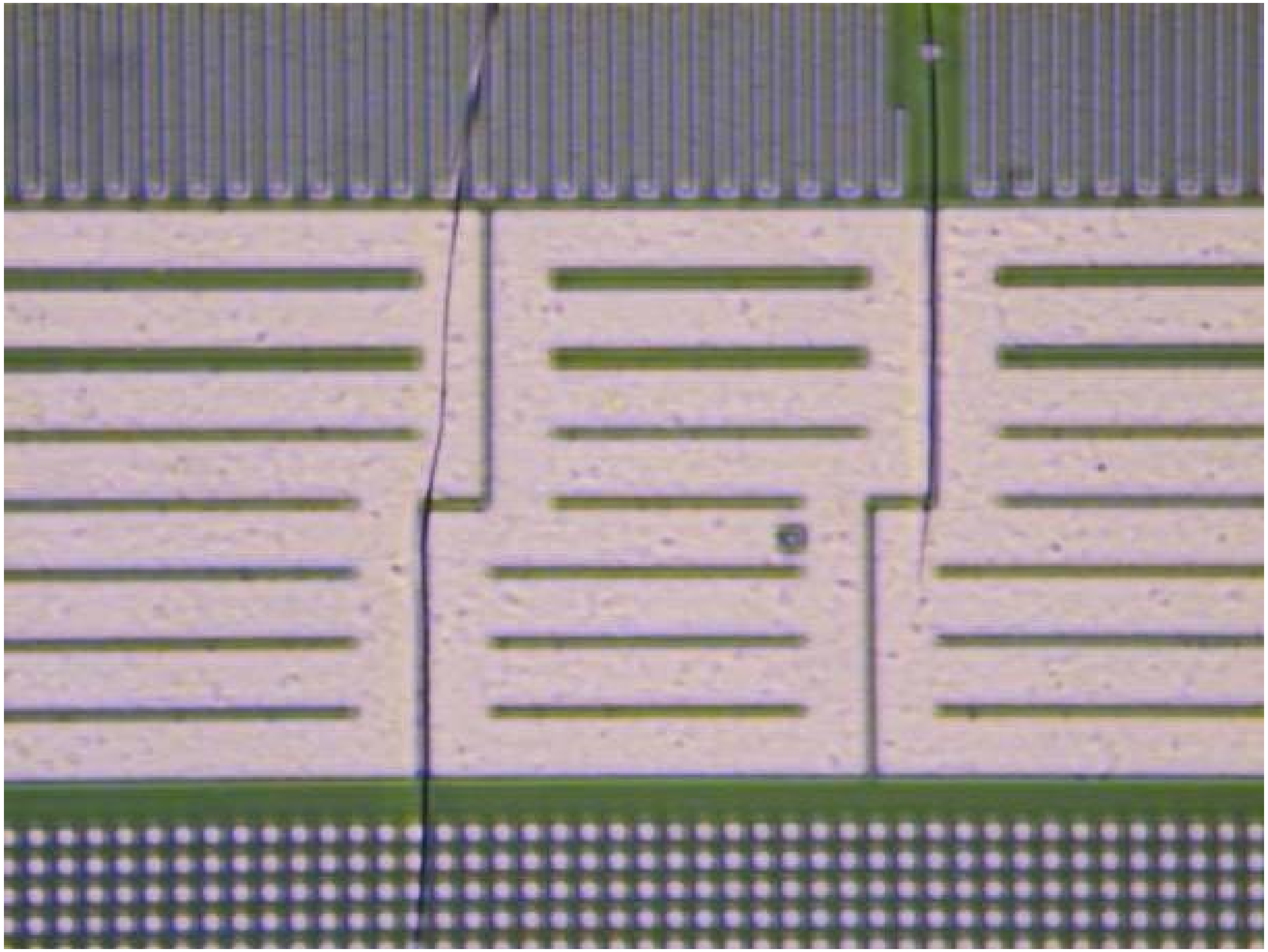
Channel crack in patterned structure





X.H. Liu (http://www.imechanica.org/node/379)

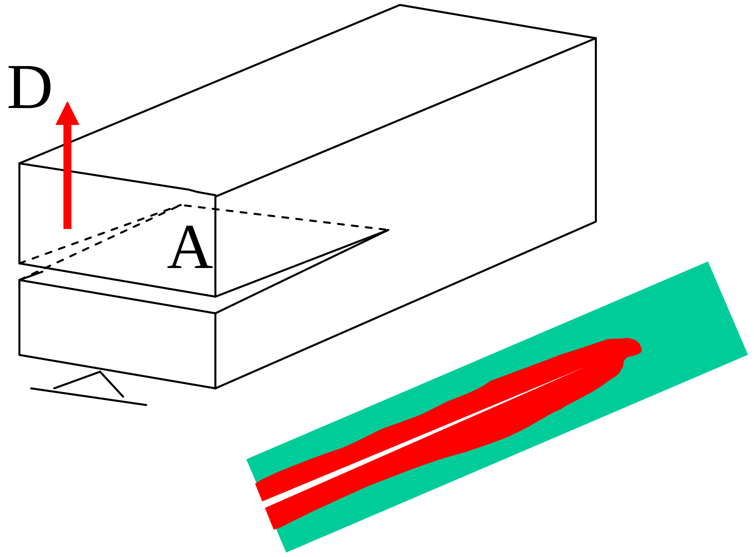
Cracking in low k dielectrics



Also see a thread of discussion at http://www.imechanica.org/node/165

Crack driving force, G

Generalized coordinates: D = displacement, A = crack area



Elastic energy

$$U(D,A)$$

$$dU = FdD - GdA$$

$$G = -\frac{\partial U(D,A)}{\partial A}$$

Work supply = elastic energy + excess

In *steady state*, the excess is proportional to crack area, ΓA

$$FdD = dU + \Gamma dA$$

$$G = \Gamma$$

Fracture mechanics as a division of labor

George Rankin Irwin (1907-1998)

Crack driving force, G.   Crack resistance, Γ

$$G = \Gamma$$

Solve an elasticity BVP
to calculate *G* of a structure

$$G = Y\sigma^2 a / E$$

Run a test to
measure Γ of a material

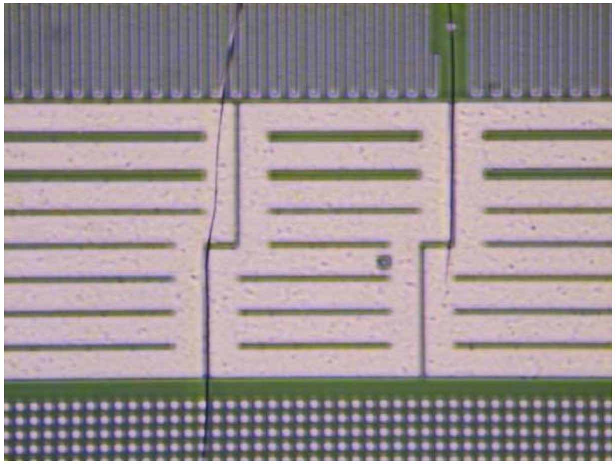
Determine
load σ

Determine
crack length *a*

Small structures: a new economy

- Calculating G is prohibitively expensive

•3D architecture
•uncertain flaws
•uncertain residual stress field
•uncertain material properties

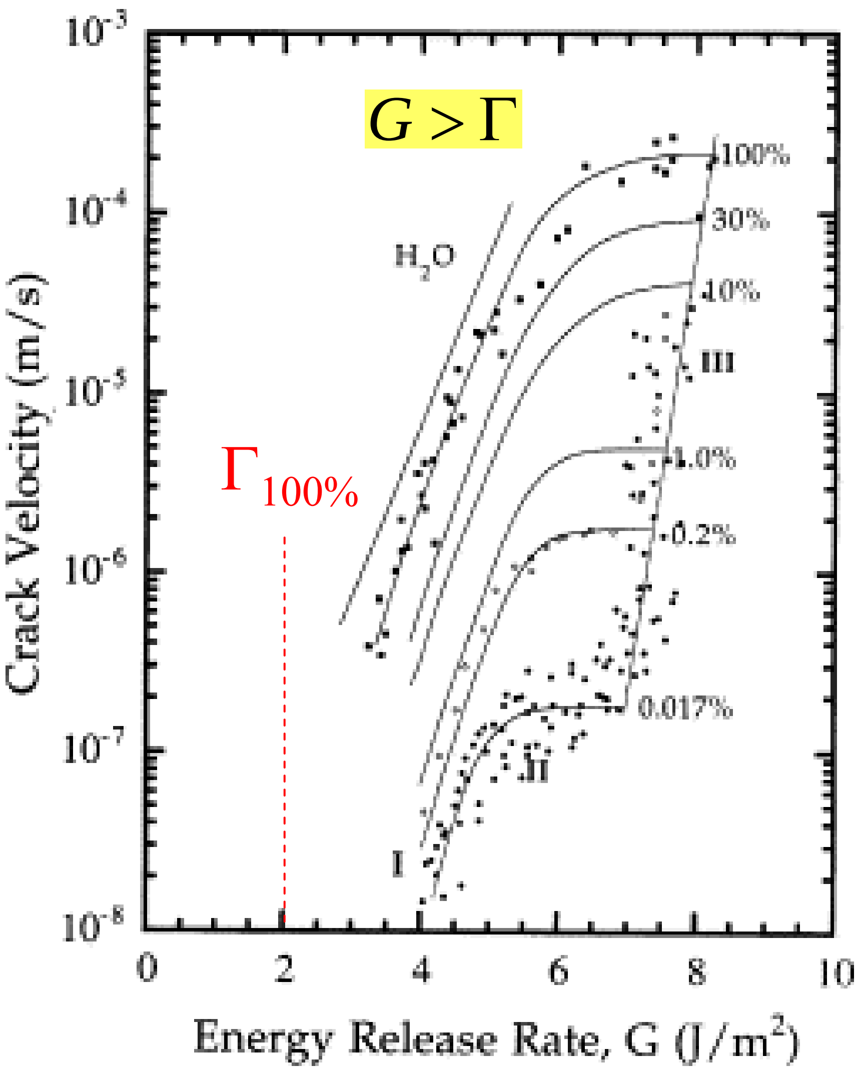


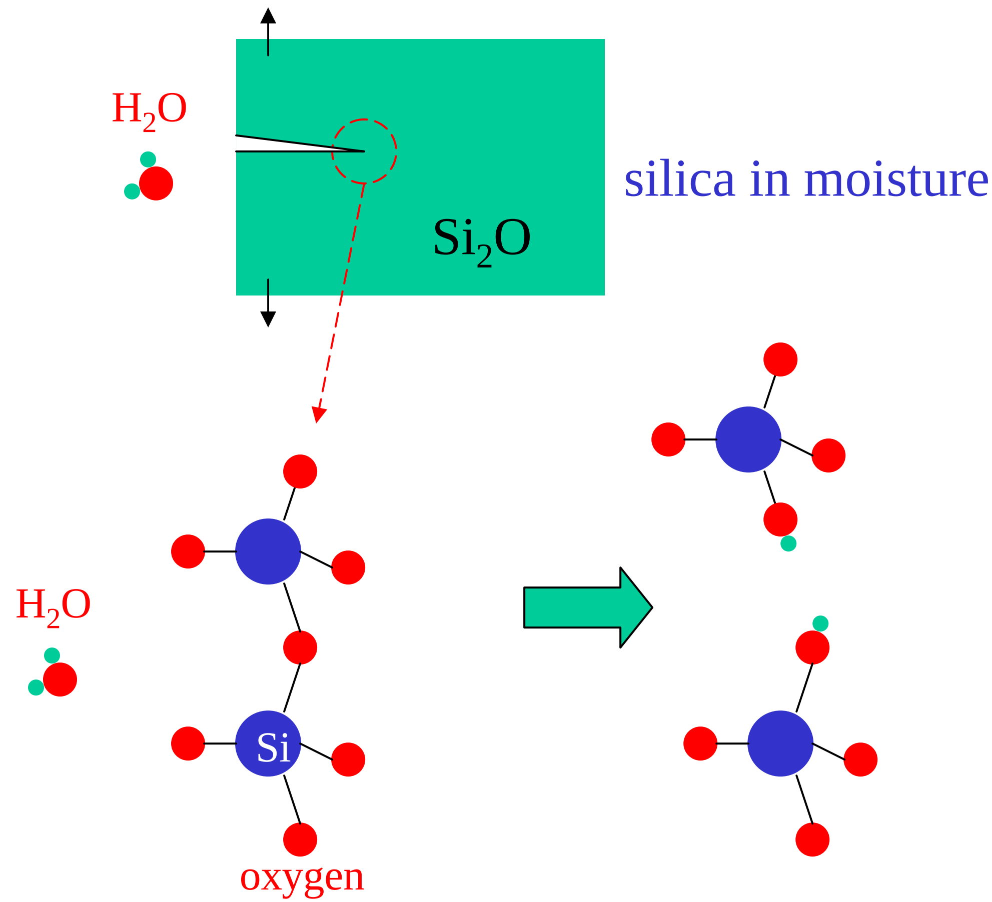
- Massive testing is cheap.

A new division of labor: run test to measure G!

Moisture-assisted crack growth: the V-G function

Weiderhorn, J. Am. Ceram. Soc. **59**, 407 (1967)





The load opens crack and strains bonds
H_2O transports to crack tip and assists in breaking bonds

A method to measure G

V-G function is specific to material and environment, and remains the same when the material is integrated into a structure.

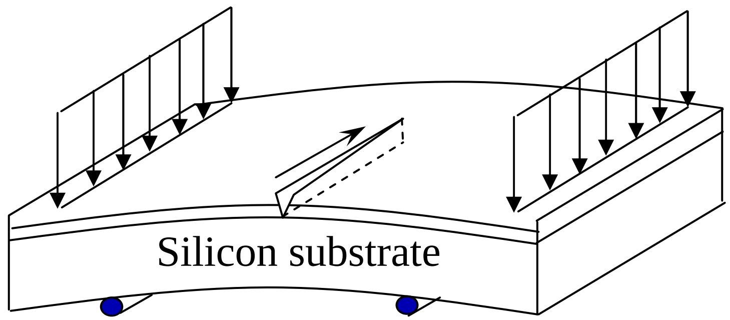
Use a simple structure to measure V-G function.

In a complex structure, an observed V gives a reading of G.

…in a way analogous to measuring temperature

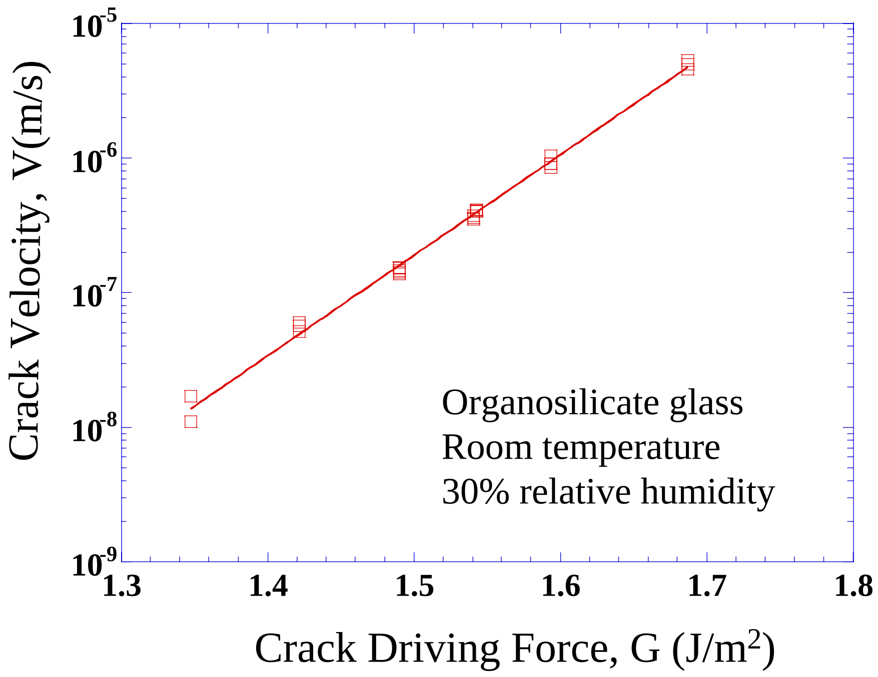
Thermometer → G-meter

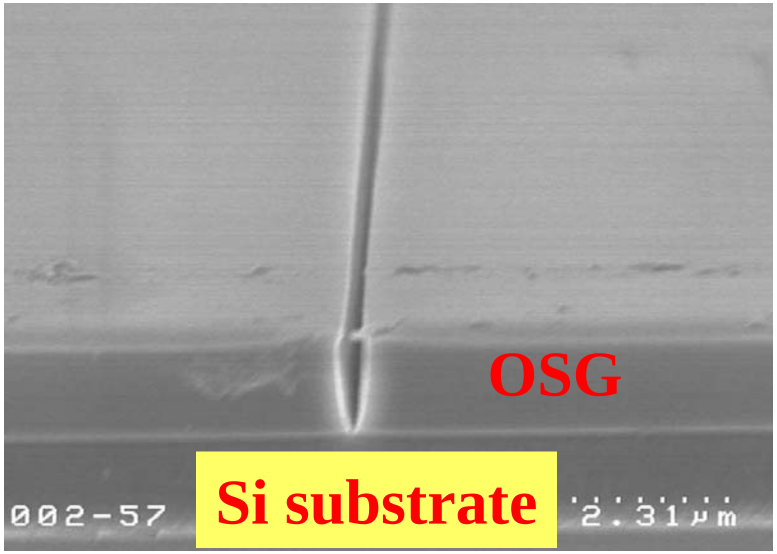
Measure the V-G function



- Scratch and bend
- Channel crack

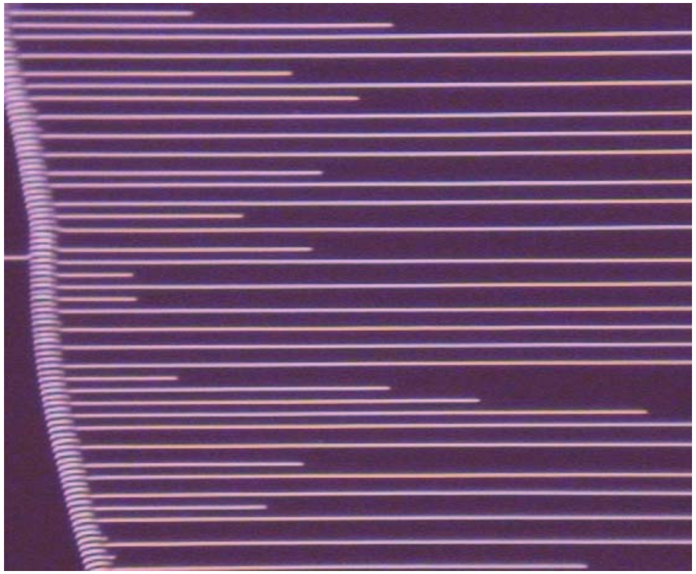
$$G = Z\sigma^2 h / \overline{E}$$

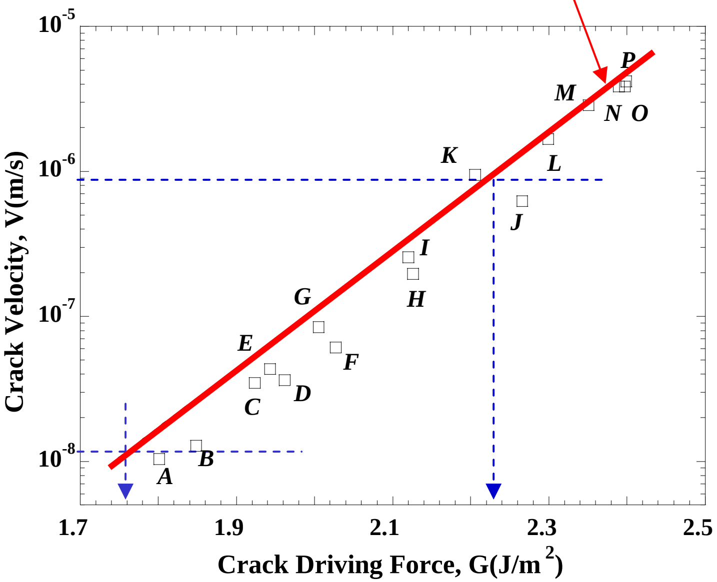




Read G

Known V-G function





$$G = \frac{\sigma^2 Zh}{\bar{E}}\left(\tanh\left(\frac{S_1}{2Zh}\right) + \tanh\left(\frac{S_2}{2Zh}\right) - \tanh\left(\frac{S_1+S_2}{2Zh}\right)\right)$$

Xia, Hutchinson, *J. Mech. Phys. Solids* **48**, 1107 (2000).

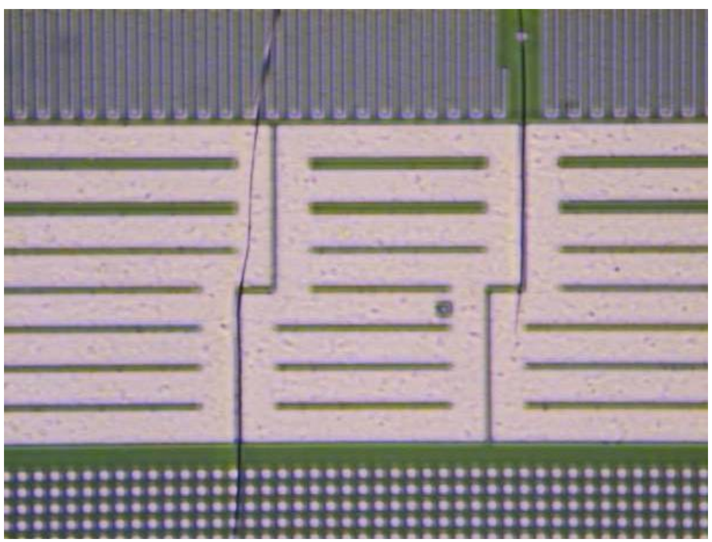
Measure crack driving force due to residual stress field, G_R

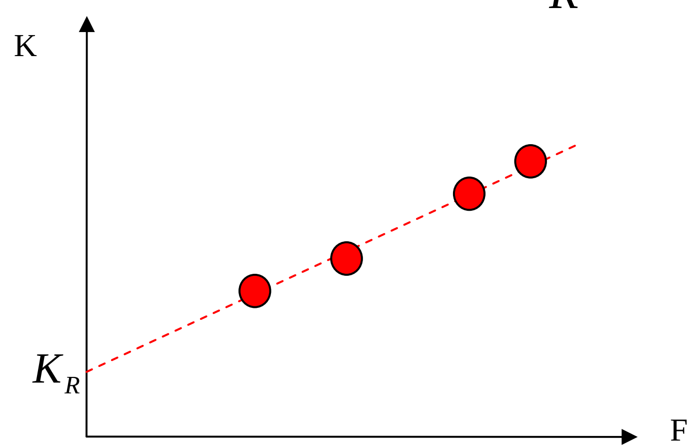
At G_R, the crack velocity is too low to be observed.

- Bend structure, observe crack velocity, and read G.
- Extrapolate the data to obtain G_R

$$G = K^2 / \bar{E}$$

$$K = K_R + BF$$





To be immortal, $G_R < \Gamma$