Ratcheting Induced Slow Crack (RISC)

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Work with

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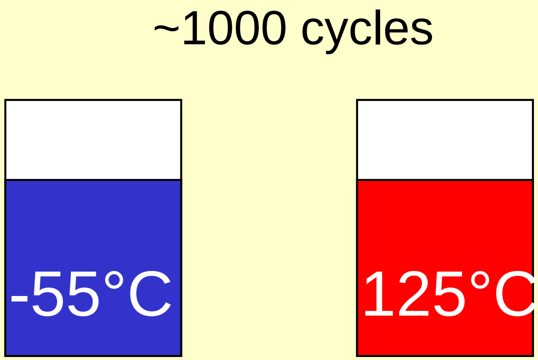
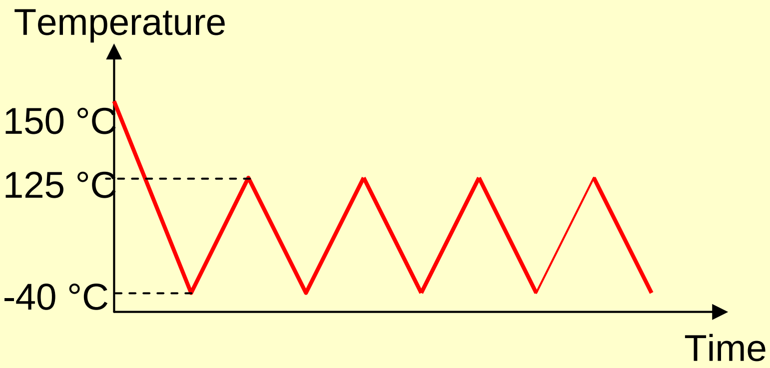
Princeton University

Q. MA, H. Fujimoto, J. He

Intel Corporation

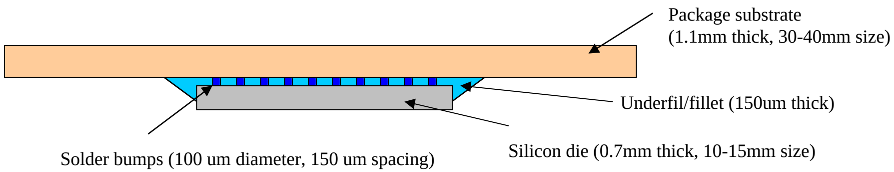
Thermal Cycling: Qualification Test

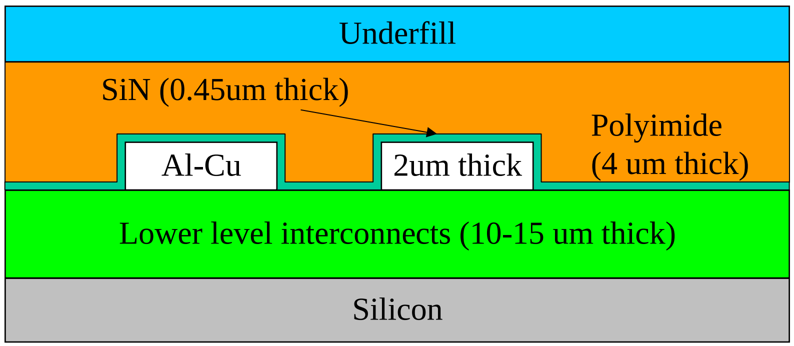




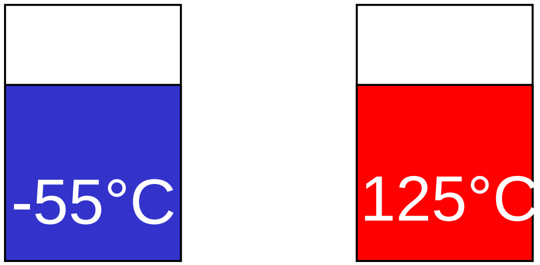
- Make-and-break
- Time consuming, a **bottleneck**
- Multiple failure modes
- Little understanding of mechanisms
- **New materials**

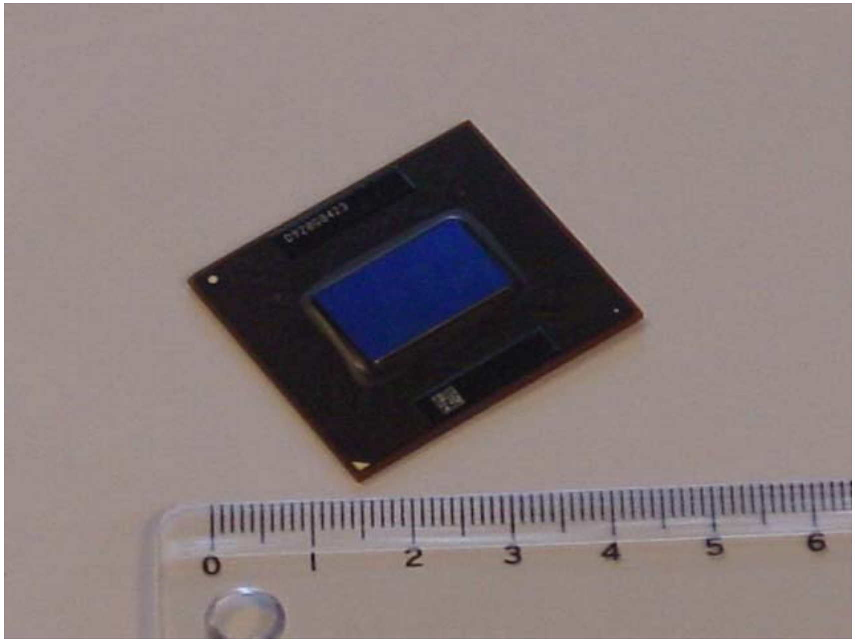
Flip-chip structure

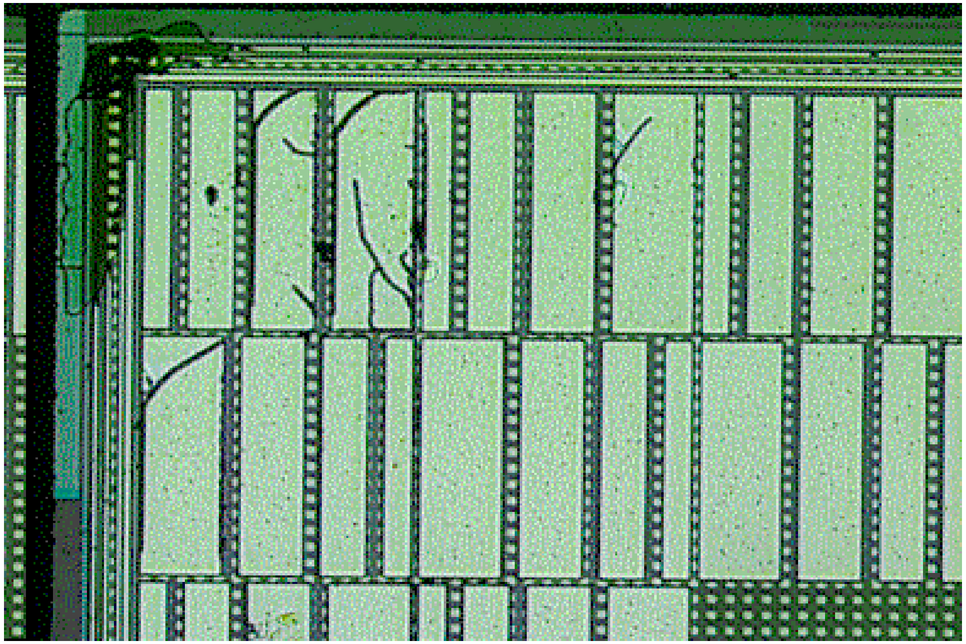




~1000 cycles

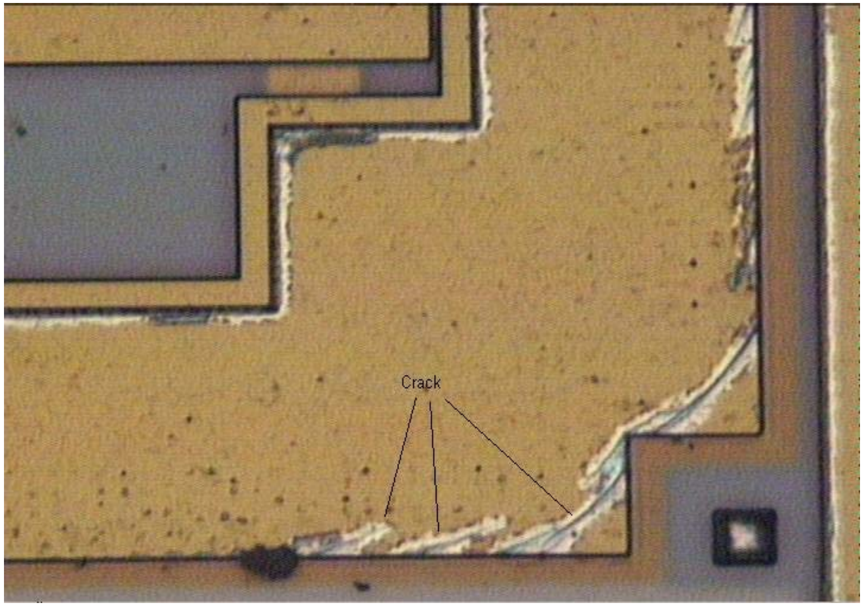




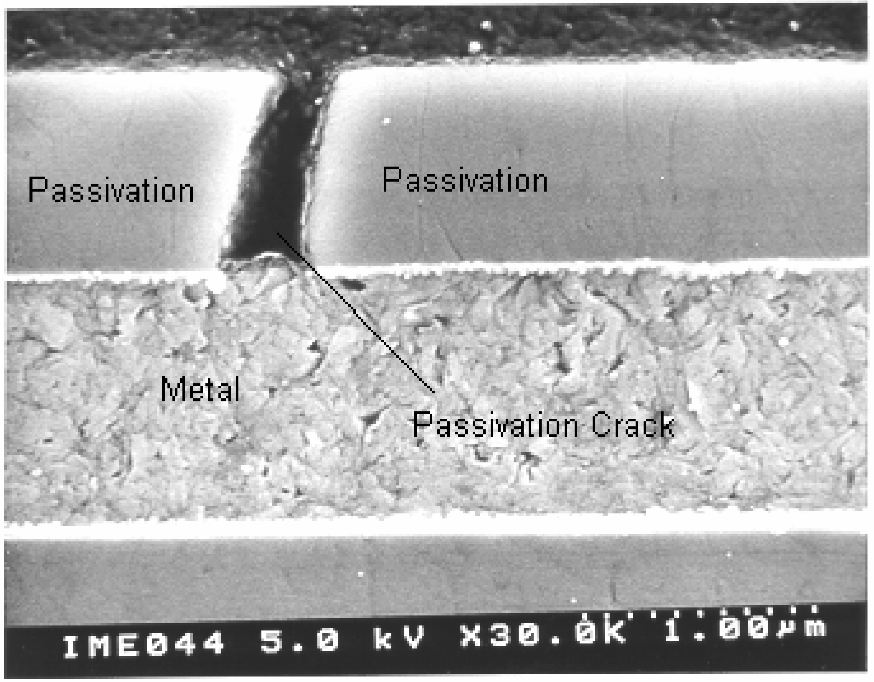


500 cycles between -55°C and 125°C

Plan view

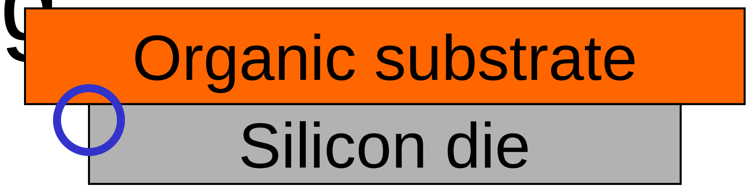


Edge view

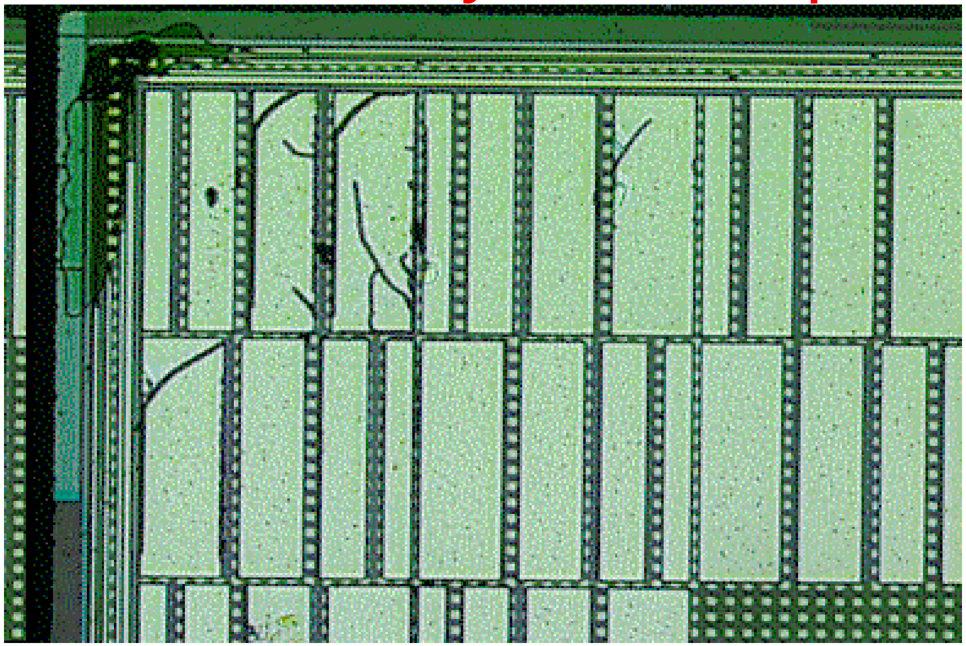


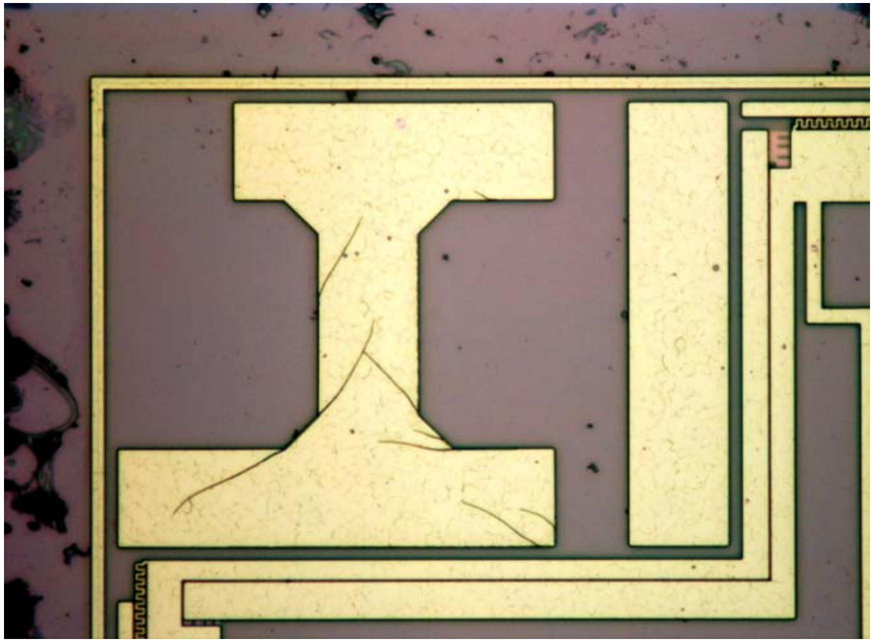
Courtesy of Dr. **J.B. Han** , Agilent Technologies Singapore

Empirical Observations of Cracking



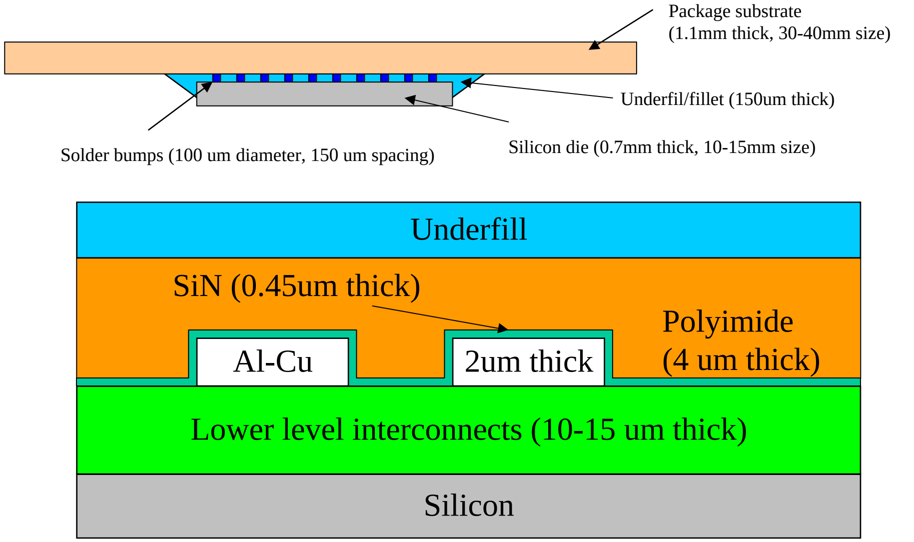
- At die corners
- After temperature cycles
- In SiN film over Al pads, but not in SiN film over silica
- More likely when Al pad is wide





Questions

Flip-chip structure



- **Why cycling?**
  SiN does not fatigu

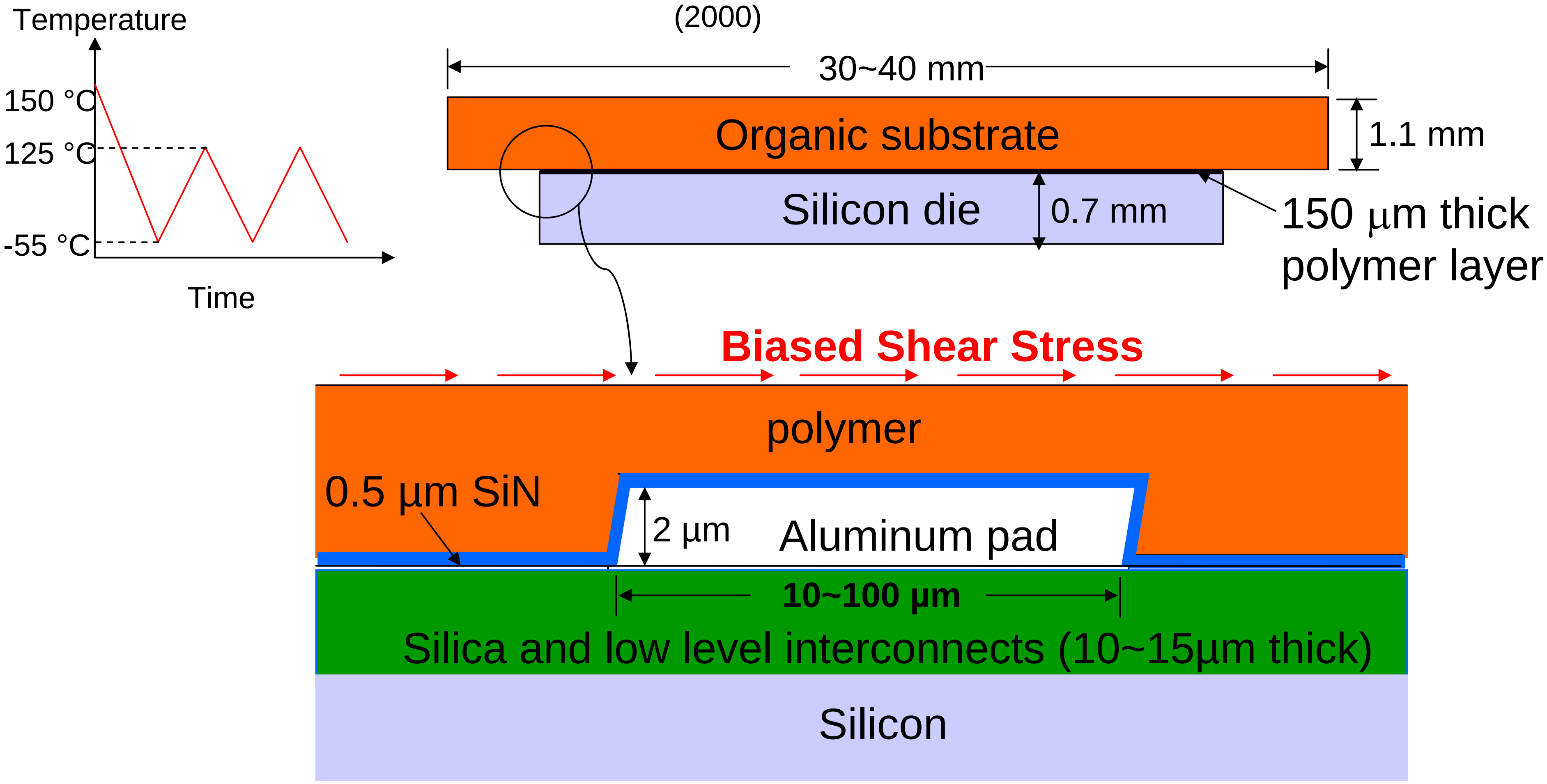
- **Why cracking?**

*Shear stress is limited by the yield strength of polymer, say 100 MPa.

*Breaking strength of SiN is 1000 MPa.

Ratcheting Plastic Deformation

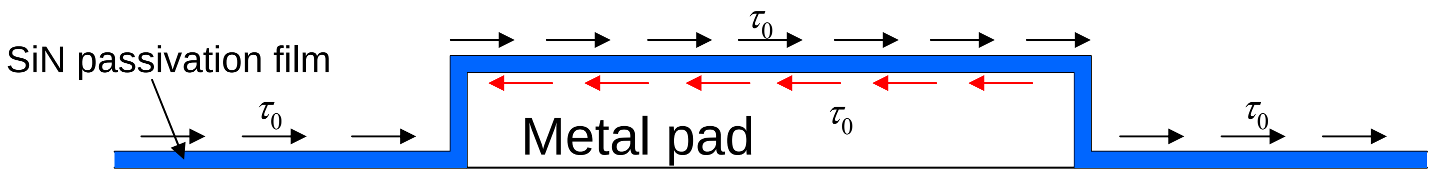
Huang, Suo, Ma, Fujimoto, *J. Mater. Res.*, **15**, 1239 (2000)



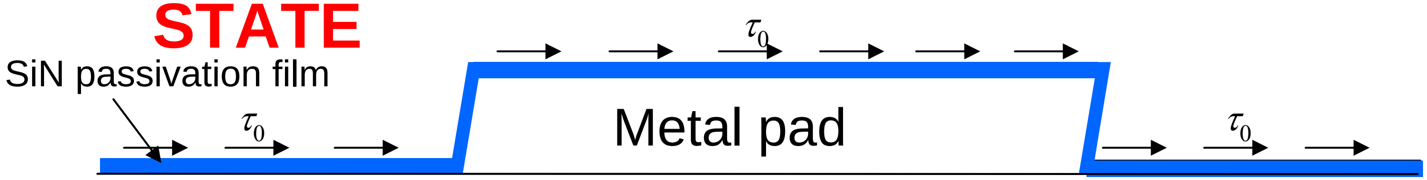
- **Biased shear stress, from organic substrate**
- **Metal yields, from CTE mismatch with**

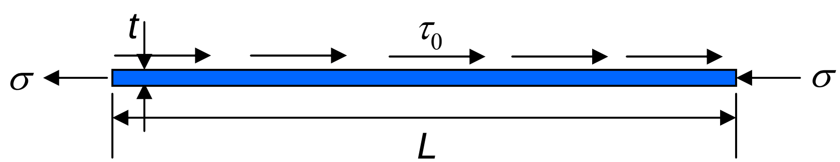
Stress builds up in SiN. STEADY STATE

First cycle



Many cycles, **STEADY STATE**





$$2\sigma t = \tau_0 L$$

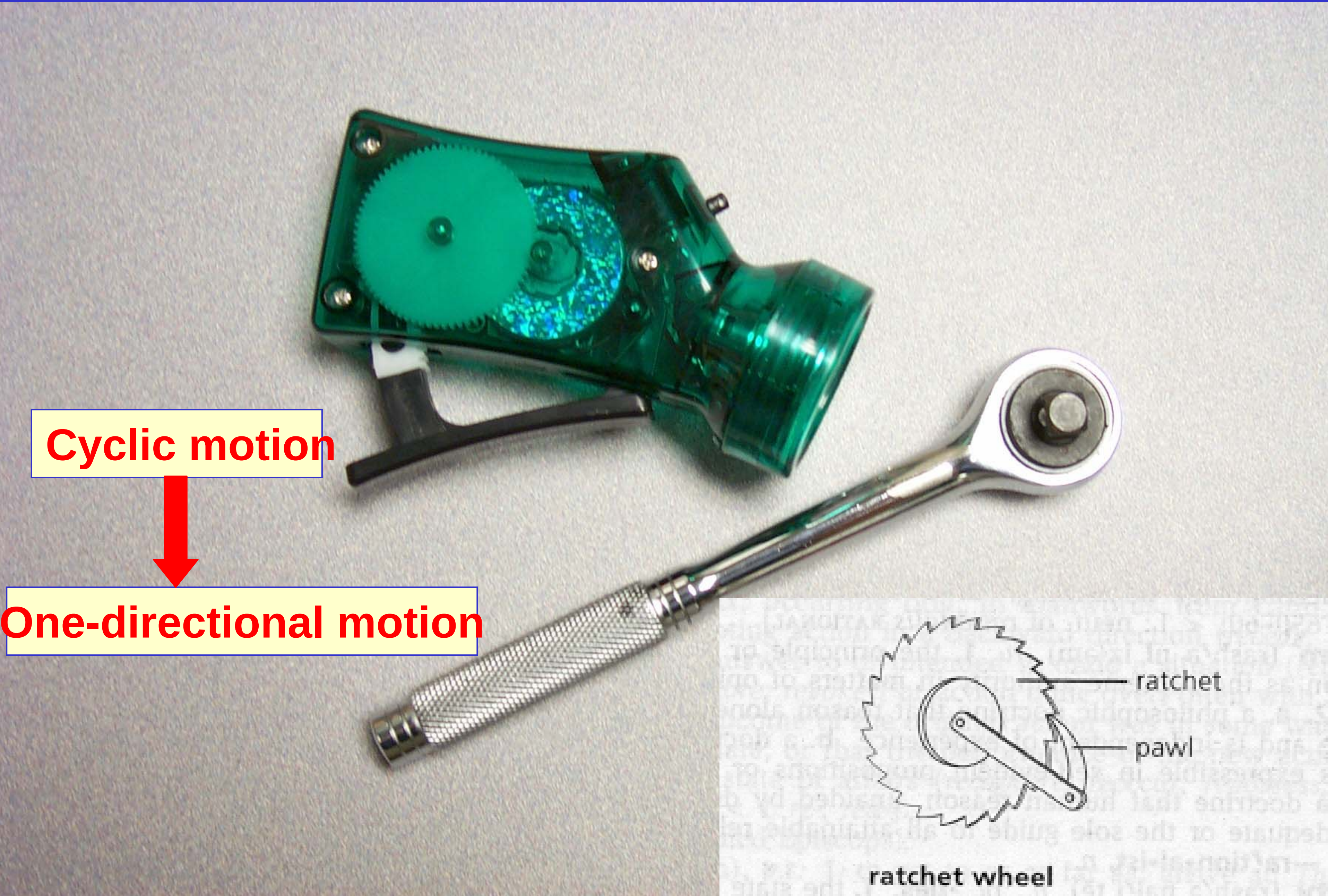
$$\sigma = \frac{\tau_0 L}{2t}$$

Ratchet and Pawl

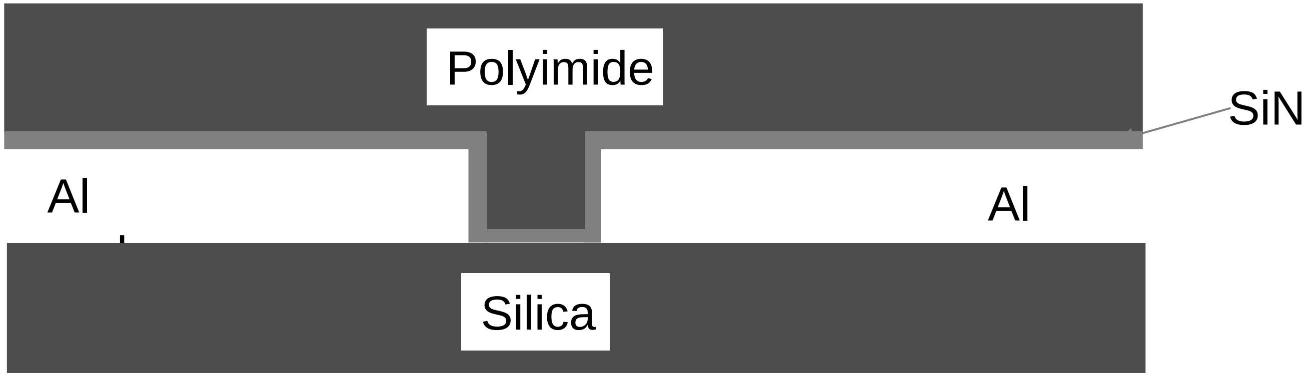
Cyclic motion

↓

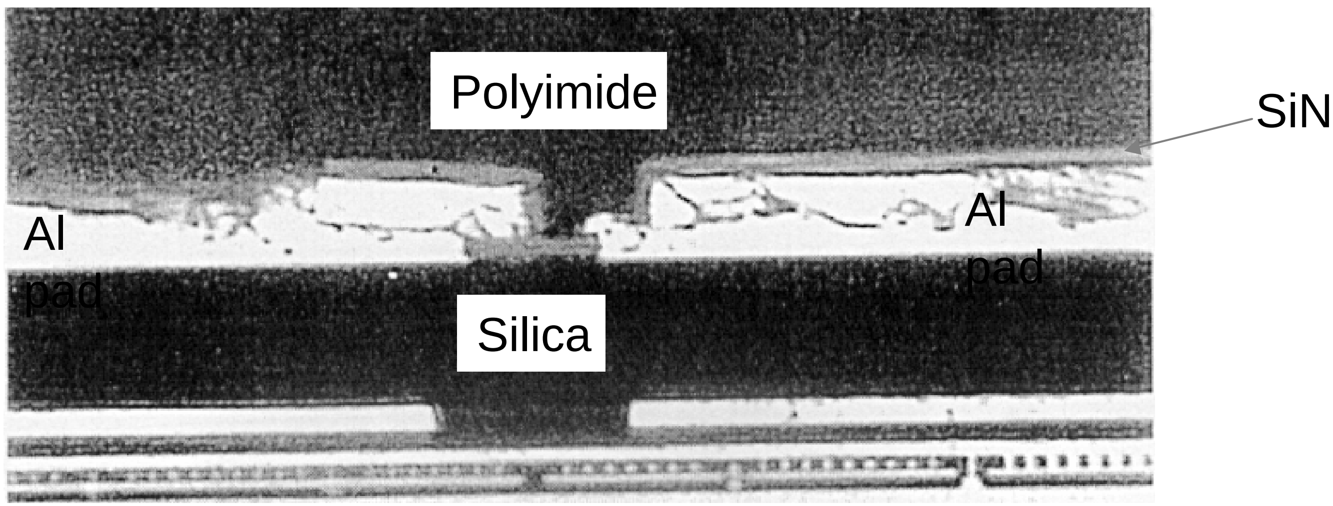
One-directional motion



Metal Pad Crawling



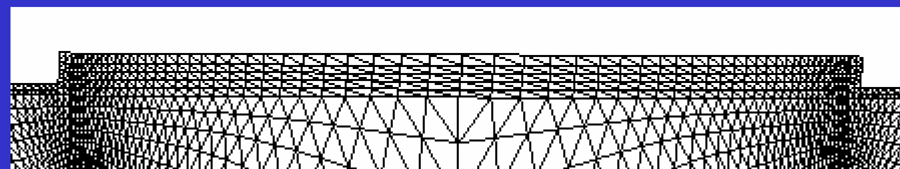
After ~1000 thermal cycles



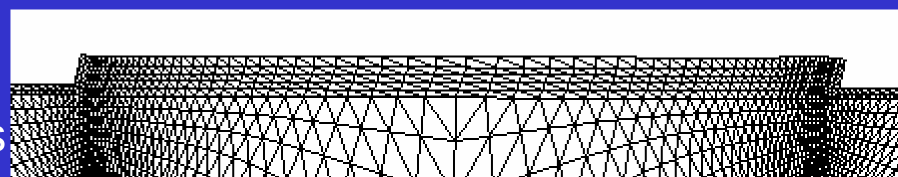
Large plastic deformation over many thermal cycles

Finite Element Simulation

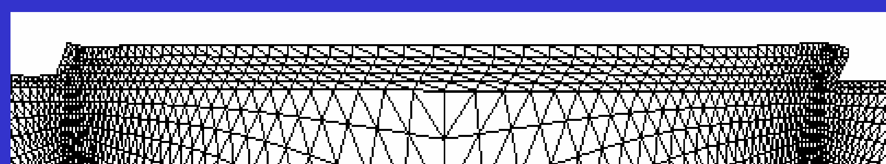
1 cycle



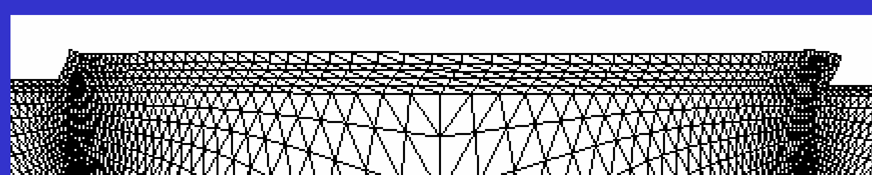
10 cycles



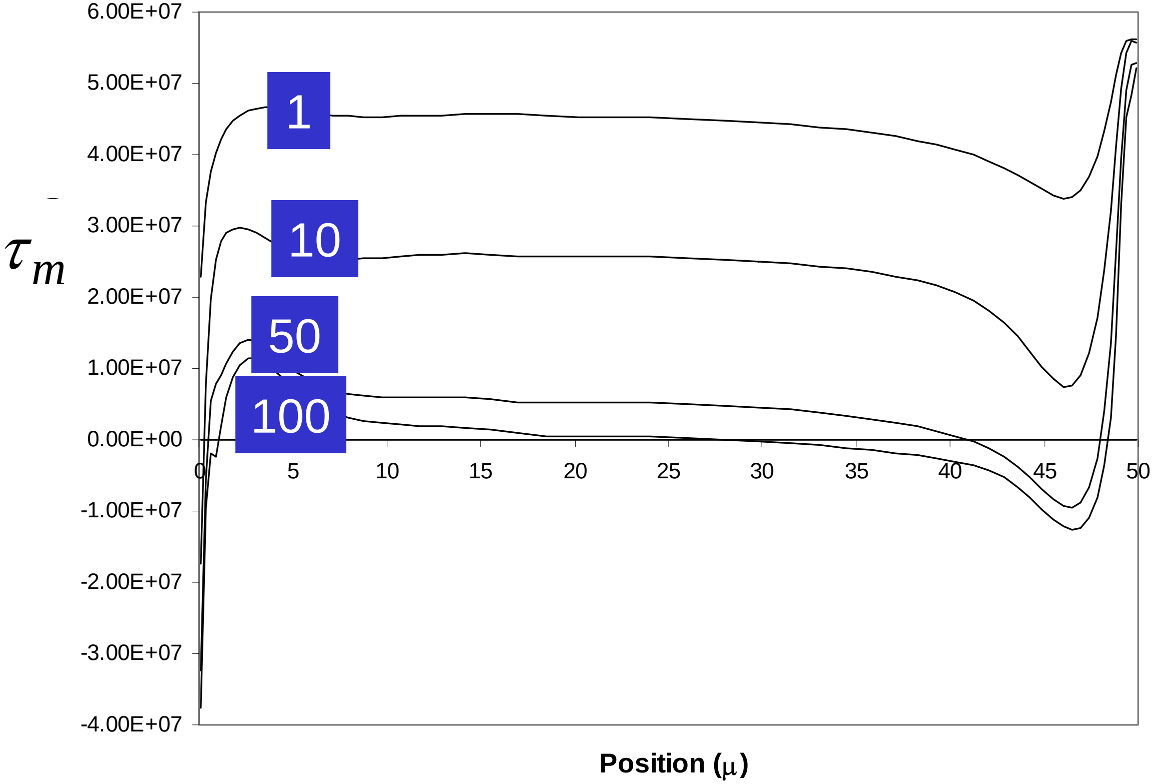
50 cycles

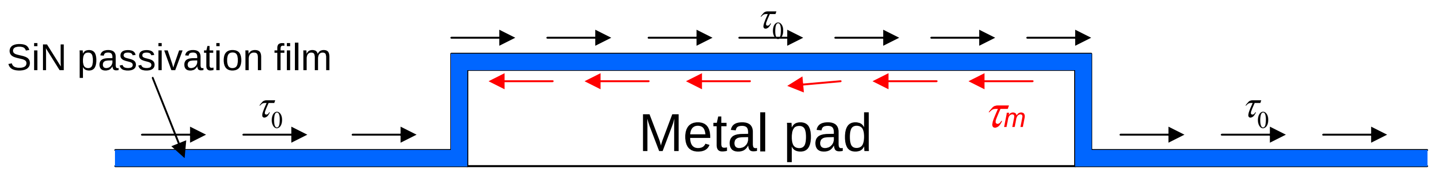


100 cycles

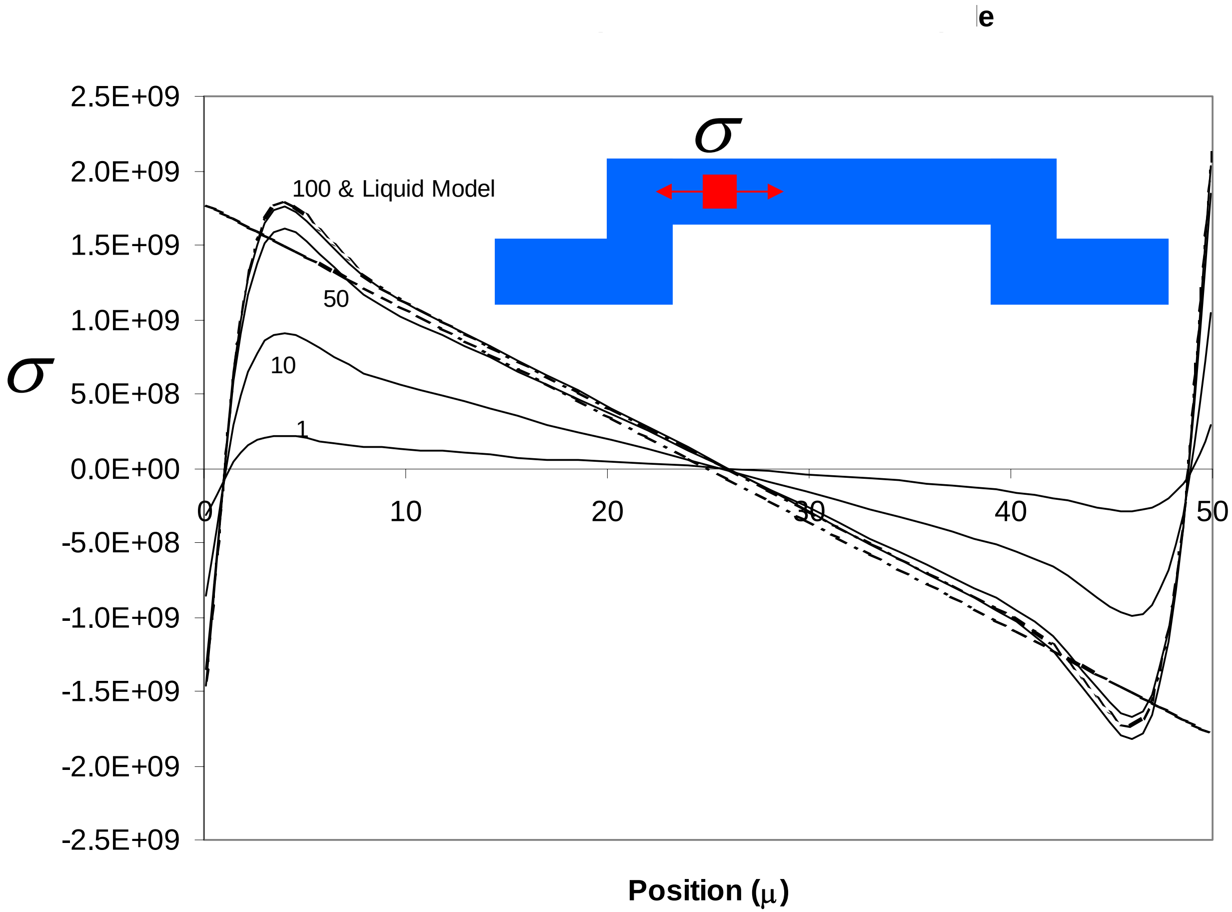


Shear stress in metal relaxes as temperature cycles

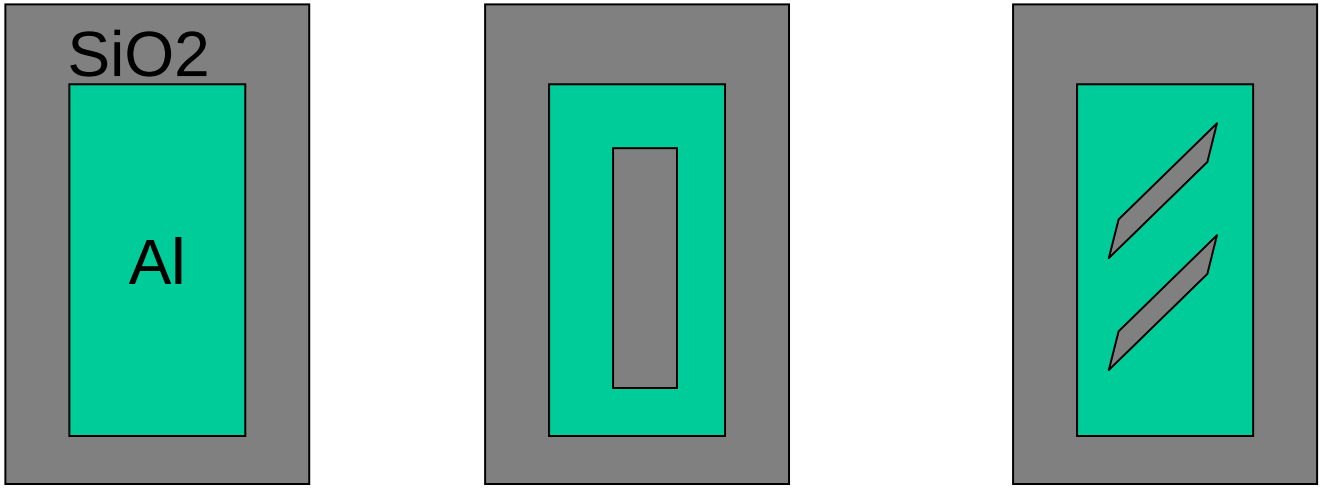


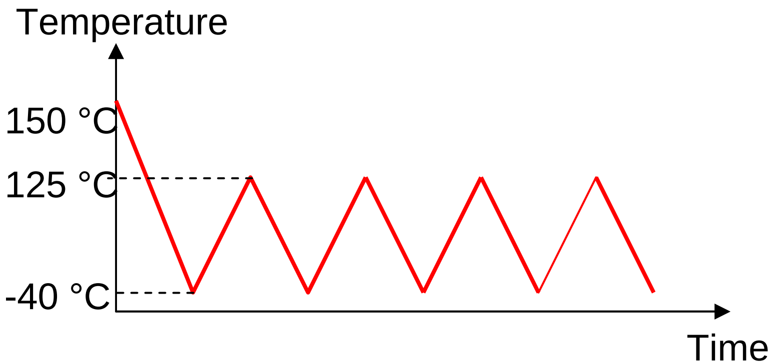


Membrane stress in SiN builds up as temperature cycles



Metal pad geometry. Slots.

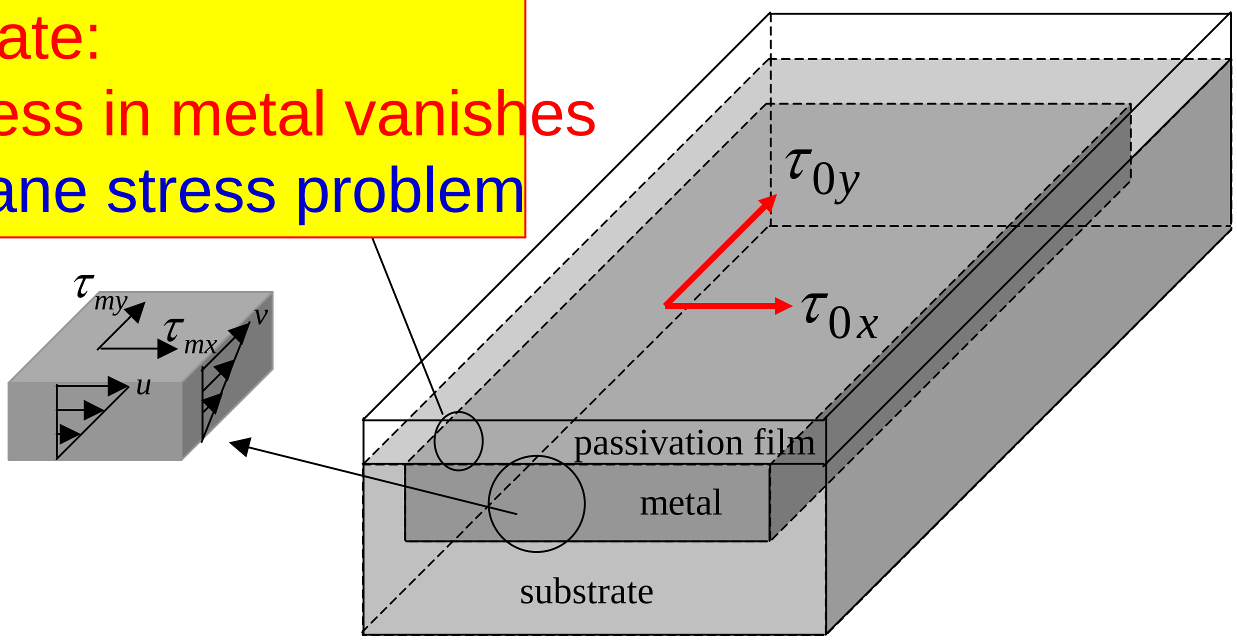




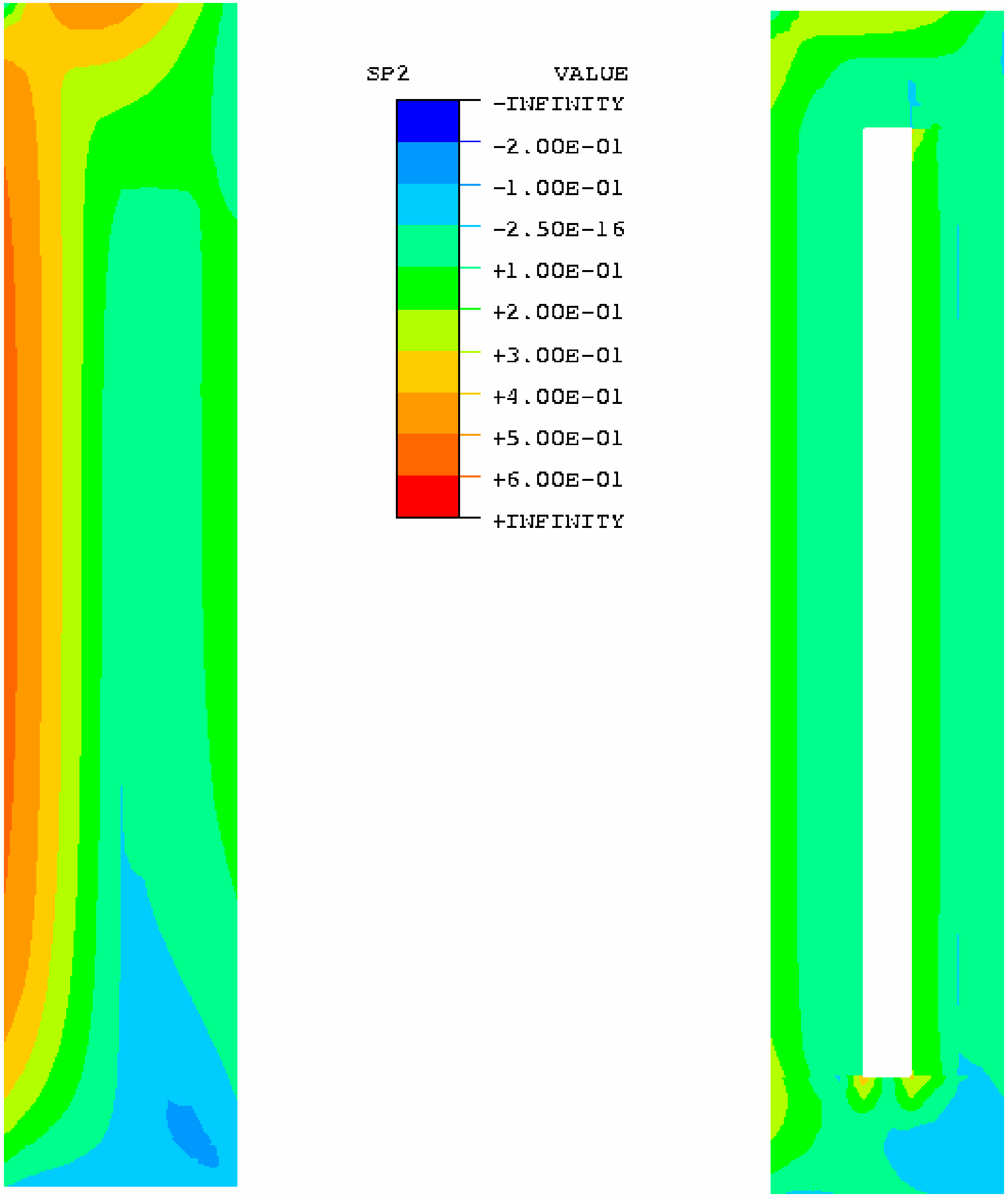
- Direct finite element calculations for 3D, many cycles take VERY long time.

3D Structure

Steady-state:
Shear stress in metal vanishes
Elastic plane stress problem



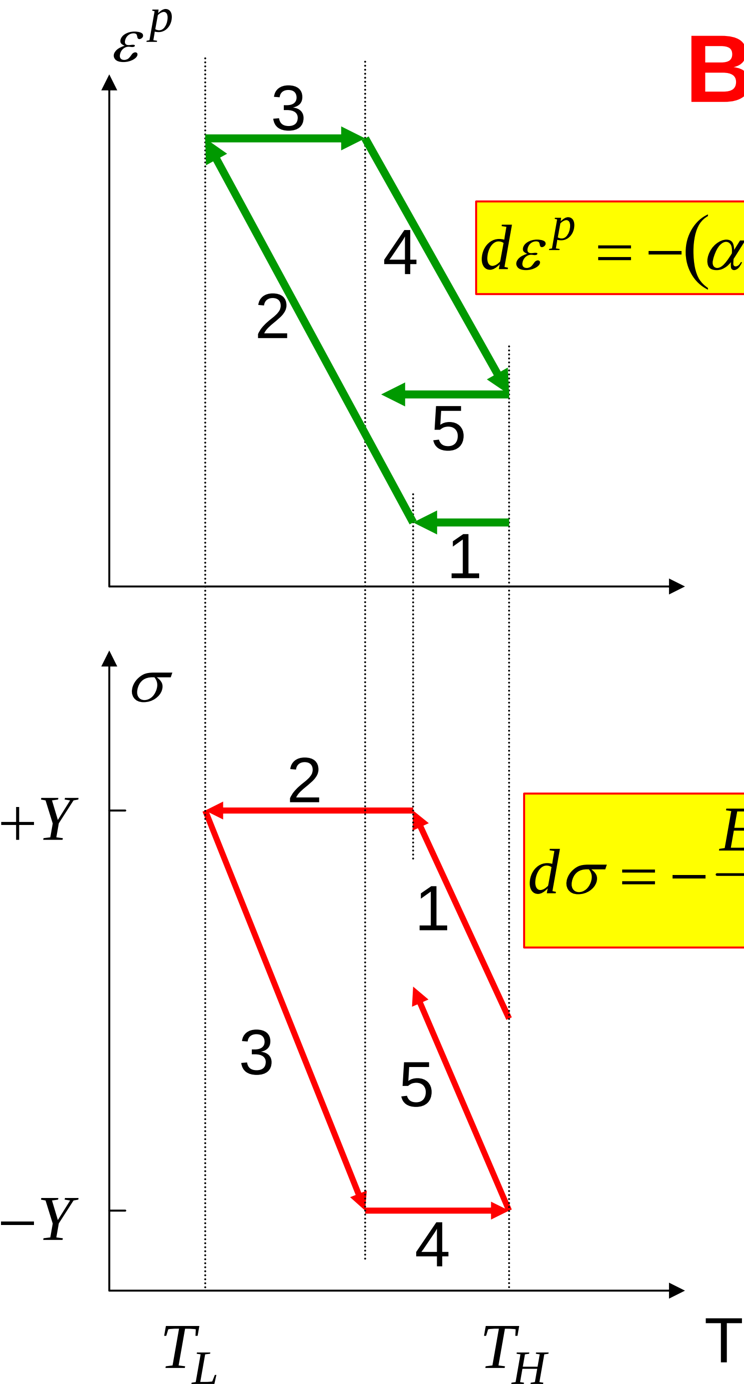
Slot!


SP2
VALUE
-INFINITY
-2.00E-01
-1.00E-01
-2.50E-16
+1.00E-01
+2.00E-01
+3.00E-01
+4.00E-01
+5.00E-01
+6.00E-01
+INFINITY

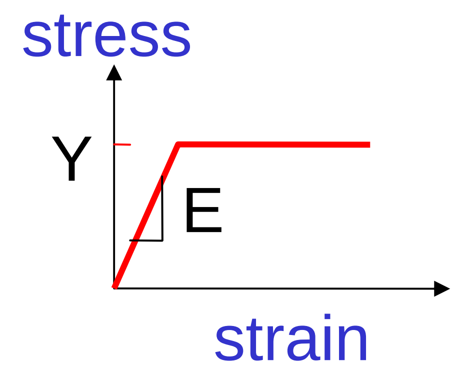
Further Issues

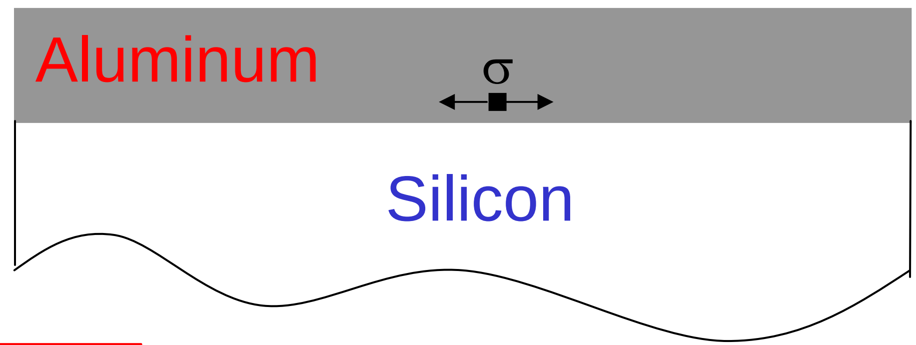
- Why cycle, again? Why not just plastic collapse?
- Number of cycles to approach the steady state.

Blanket film



$$d\varepsilon^p = -(\alpha_m - \alpha_s)dT$$

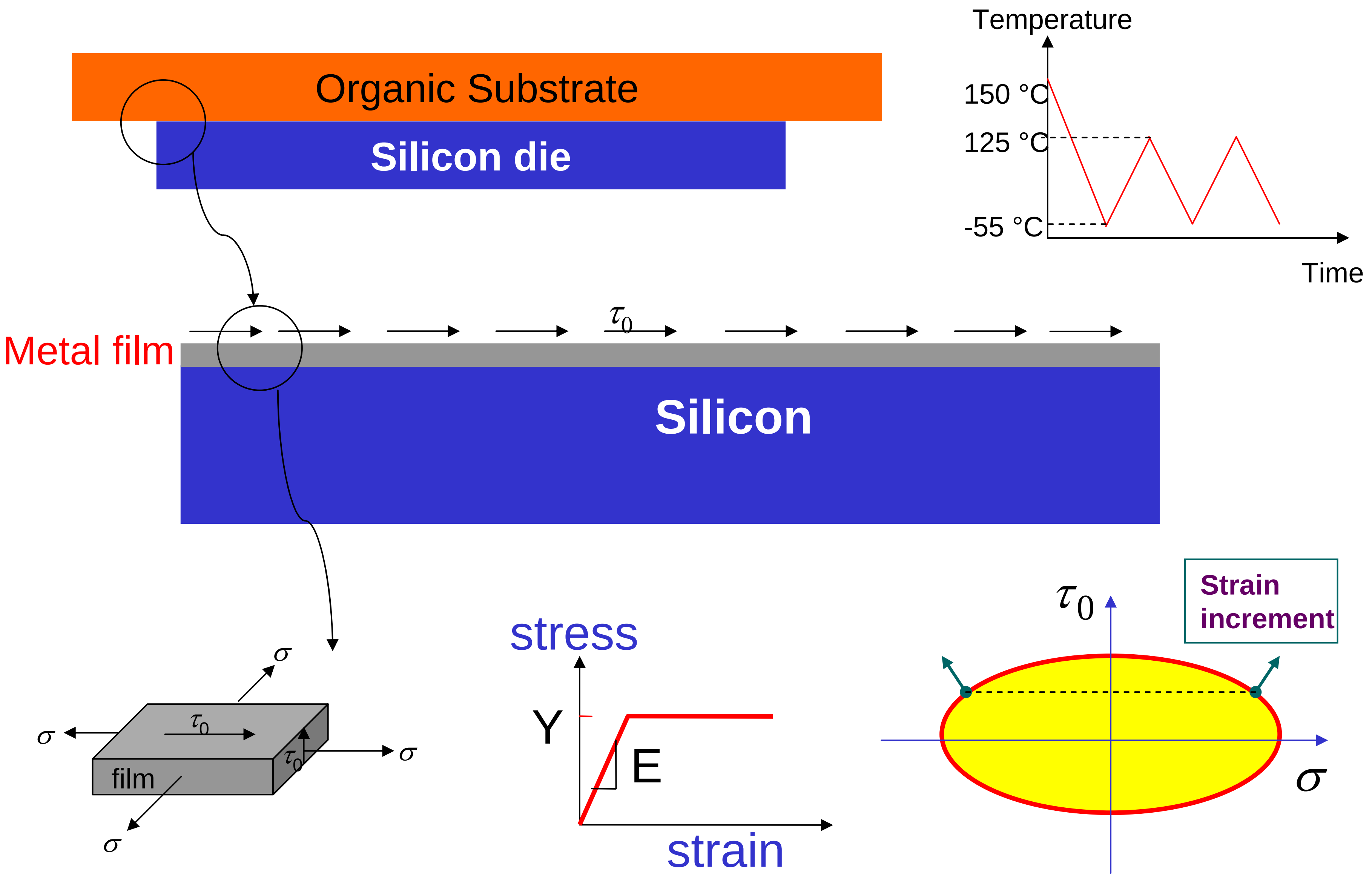




$$d\sigma = -\frac{E(\alpha_m - \alpha_s)}{1-\nu}dT$$

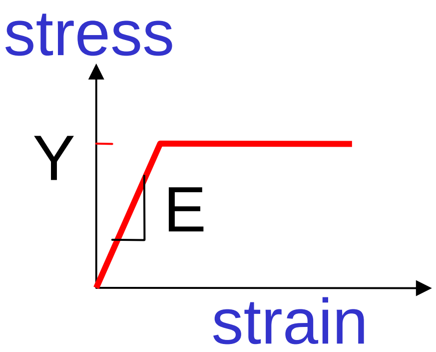
$$\frac{E(T_H - T_L)(\alpha_f - \alpha_s)}{(1-\nu)Y}\begin{cases} > 2, & \text{cyclic plasticity} \\ < 2, & \text{shakedown} \end{cases}$$

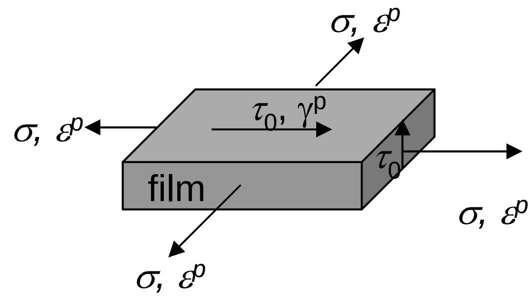
Why Crawling?

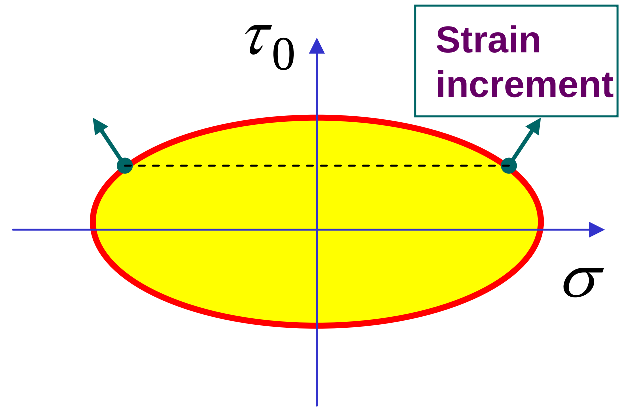


Huang, Suo, Ma, *Acta Materialia*, **49**, 3039-3049 (2001

Elastic-Plastic Model







$$\sigma^2 + 3\tau_0^2 = Y^2$$

Yield condition

Matching strains of film & substrate

$$d\varepsilon^p = -\left(\alpha_f - \alpha_s\right)dT$$

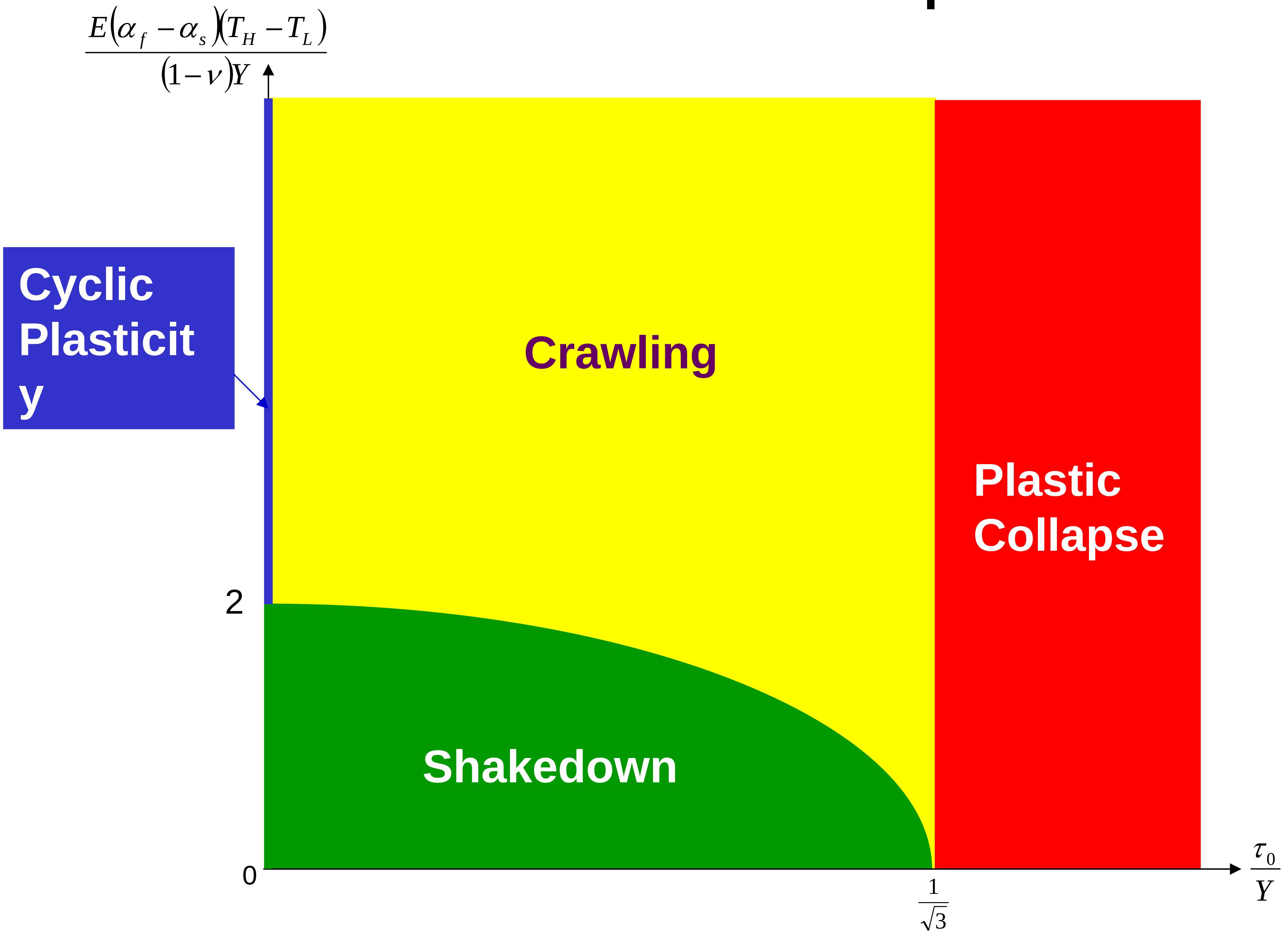
J2 flow theory

$$d\varepsilon_{ij}^p = s_{ij}d\lambda \qquad \frac{d\varepsilon^p}{\sigma/3} = \frac{d\gamma^p}{2\tau_0}$$

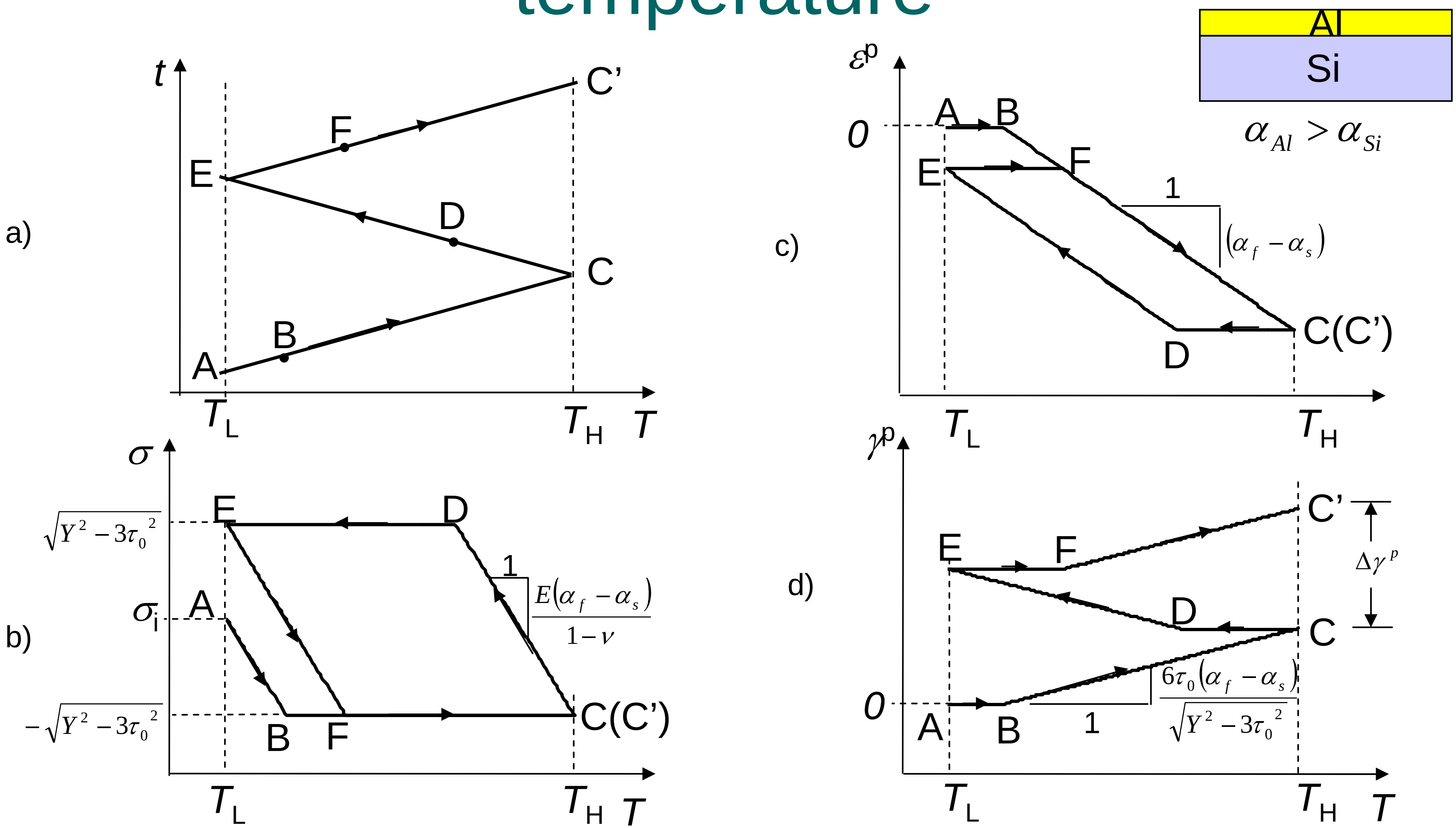
Shear strain increment

$$d\gamma^p = -\frac{6\tau_0}{\sigma}\left(\alpha_f - \alpha_s\right)dT$$

Four-color map

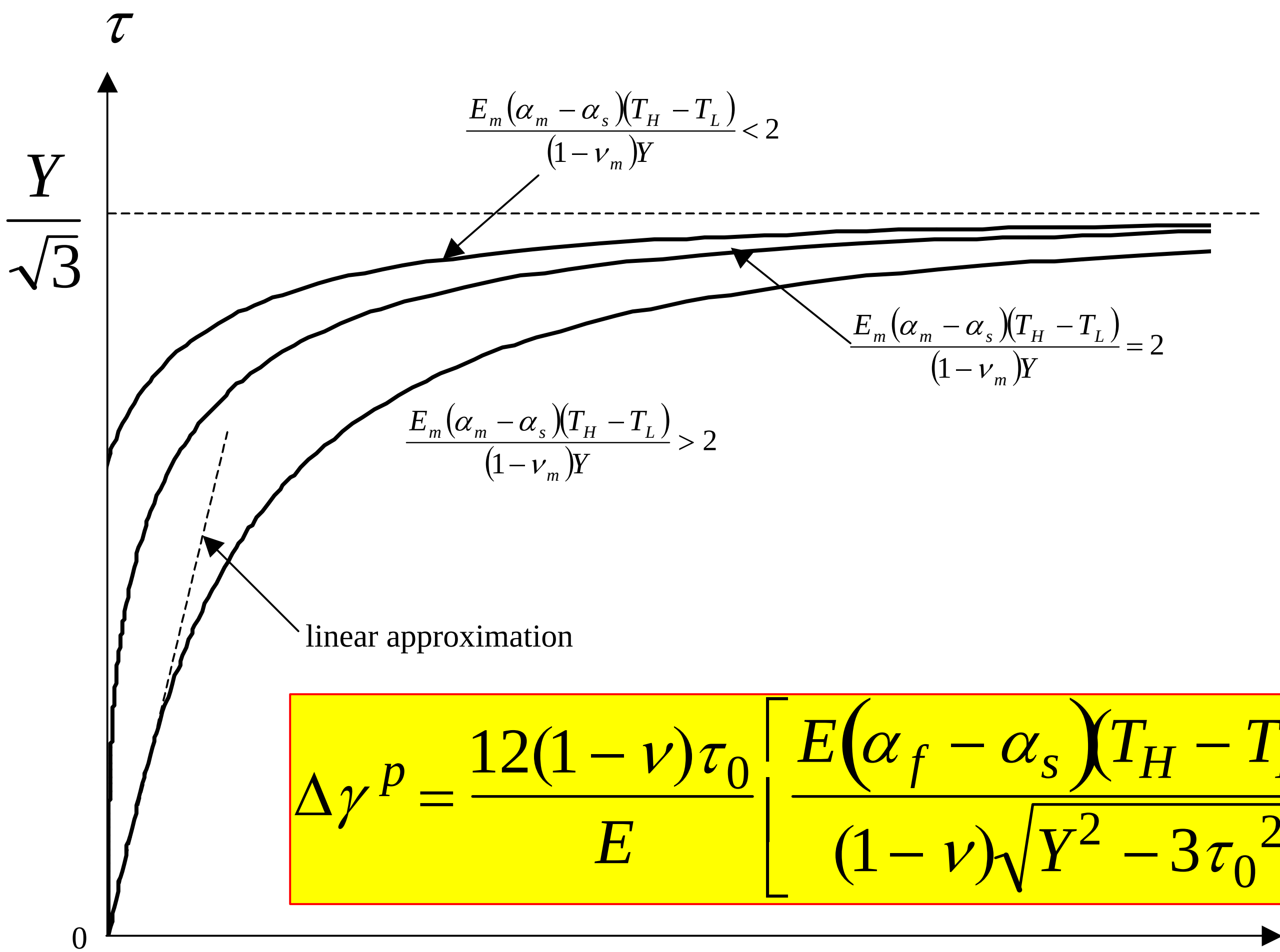


Stress and strain change with temperature



Strain per cycle
$$\Delta\gamma^p = \frac{12(1-\nu)\tau_0}{E}\left[\frac{E(\alpha_f - \alpha_s)(T_H - T_L)}{(1-\nu)\sqrt{Y^2 - 3\tau_0^2}} - 2\right]$$

Ratcheting-Creep Analogy

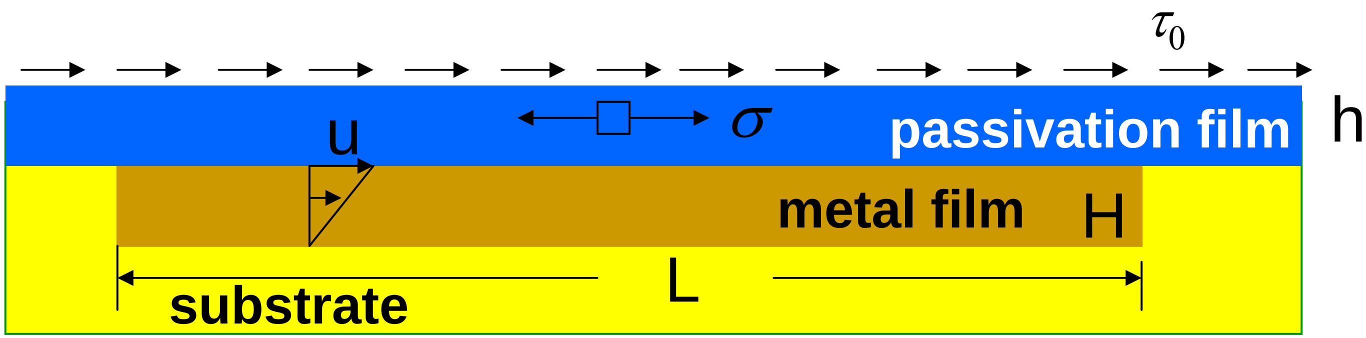


$$\Delta\gamma^p = \frac{12(1-\nu)\tau_0}{E}\left[\frac{E(\alpha_f-\alpha_s)(T_H-T_L)}{(1-\nu)\sqrt{Y^2-3\tau_0{}^2}}-2\right]$$

Strain per cycle $\Delta\gamma^p$

$$\frac{d\gamma}{dN} \Leftrightarrow \frac{d\gamma}{dt}$$

Number of cycles to reach steady-state



Elastic passivation film

Equilibrium $$h\frac{\partial \sigma}{\partial x} = \tau - \tau_0$$

Elasticity $$\sigma = E_p \frac{\partial u}{\partial x}$$

Ratcheting metal film

$$\tau = \frac{\eta}{H}\frac{\partial u}{\partial N}$$

$$\eta = \frac{E_m}{12}\left(\frac{E_m \Delta\alpha \Delta T}{Y} - 2\right)^{-1}$$

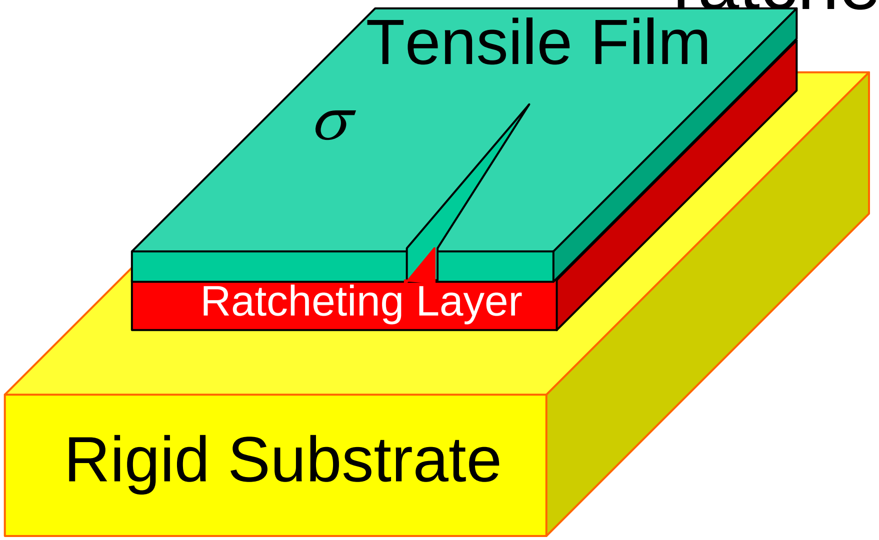
$$\frac{\partial u}{\partial N} = D\frac{\partial^2 u}{\partial x^2} - \frac{H\tau_0}{\eta}$$

$$D = \frac{EHh}{\eta}$$

$$N_0 \sim \frac{L^2}{D} \sim \frac{L^2}{Hh}\frac{E_m}{E_p}\left(\frac{E_m \Delta\alpha \Delta T}{Y} - 2\right)^{-1}$$

Huang, Suo, Ma, *J Mech.Phys. Solids*. **50**, 1079 (200

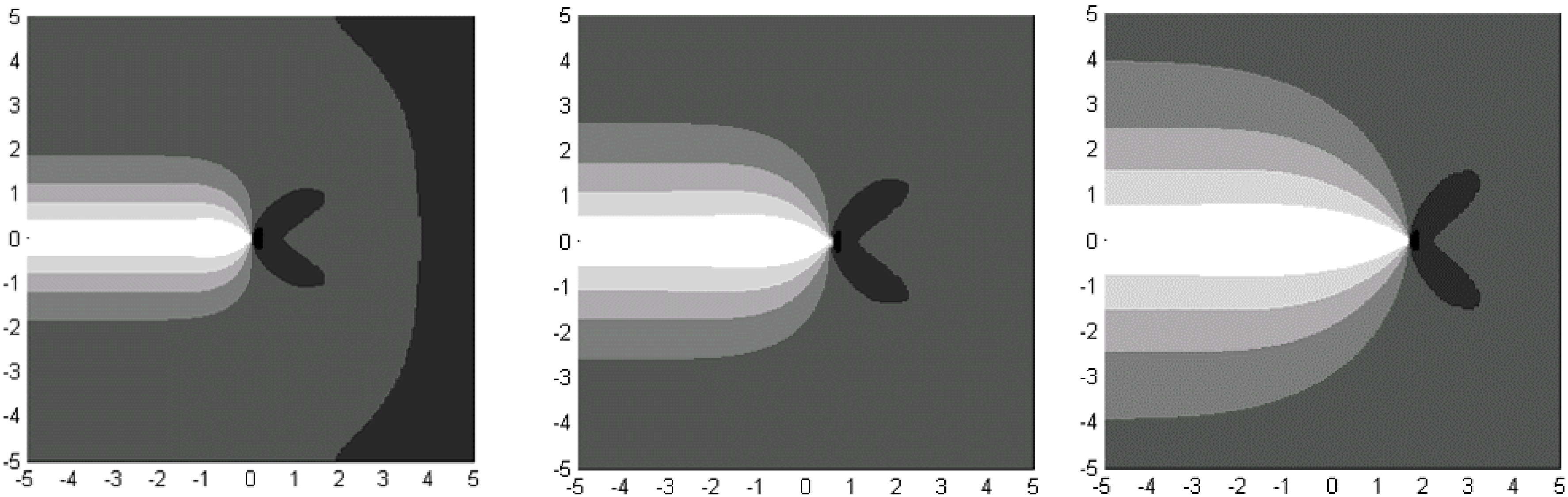
Concomitant crack extension and underlayer ratcheting



$$\frac{da}{dN} = 0.6\frac{Hh\sigma^2}{\eta G_c}$$

$$\eta = \frac{E_m}{12(1-\nu_m)}\left[\frac{E_m \Delta\alpha\Delta T}{(1-\nu_m)Y} - 2\right]^{-1}$$

J. Liang, R. Huang, J.H. Prevost, Z. Suo, submitted



Conclusions

- **Thermal cycling test is a bottleneck.**
- **Ratcheting:** **cyclic temperature**, aided by **biased shear stress**, causes uni-directional deformation.
- Stress relaxes in metal, and builds up in SiN.
- Ductile, low k dielectrics may ratchet.
- Need **thin film data** on large plastic deformation over many cycles, and long time.