Ratcheting deformation in thin film structures

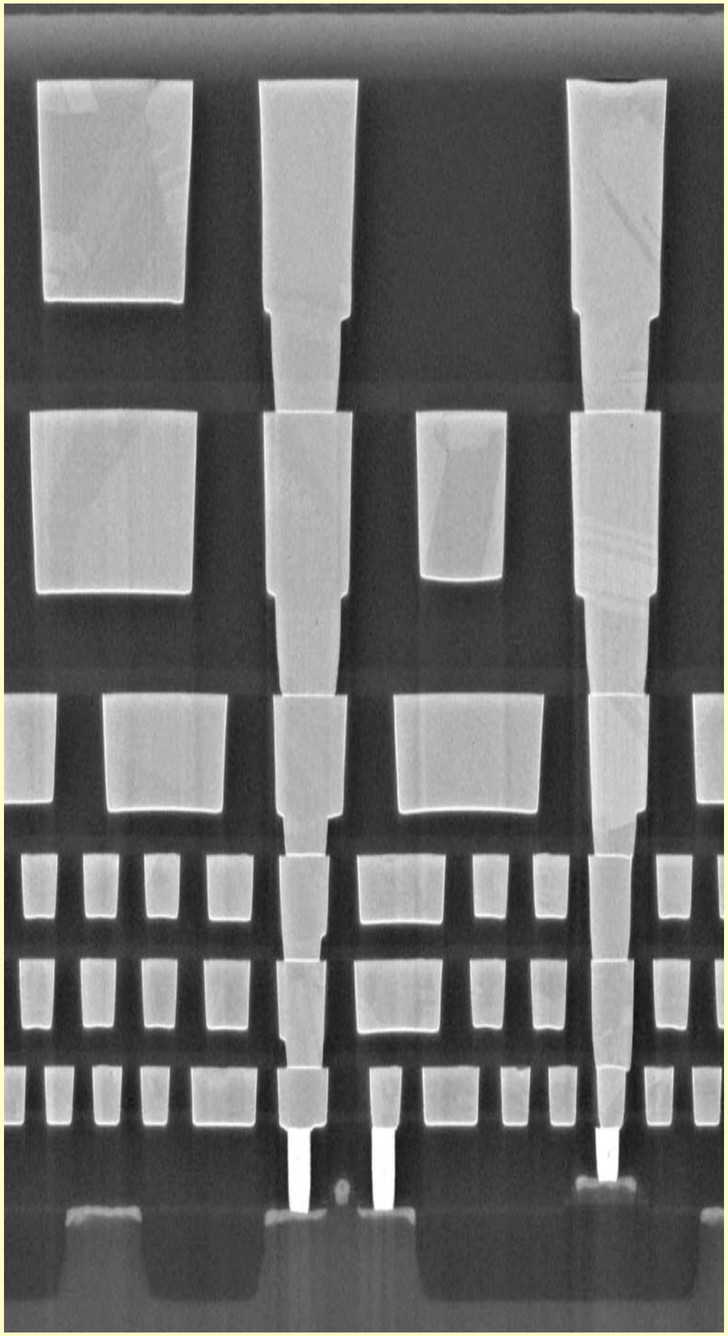
Z. SUO
Princeton University

Work with
MIN HUANG, Rui Huang, Jim Liang, Jean Prevost
Princeton University

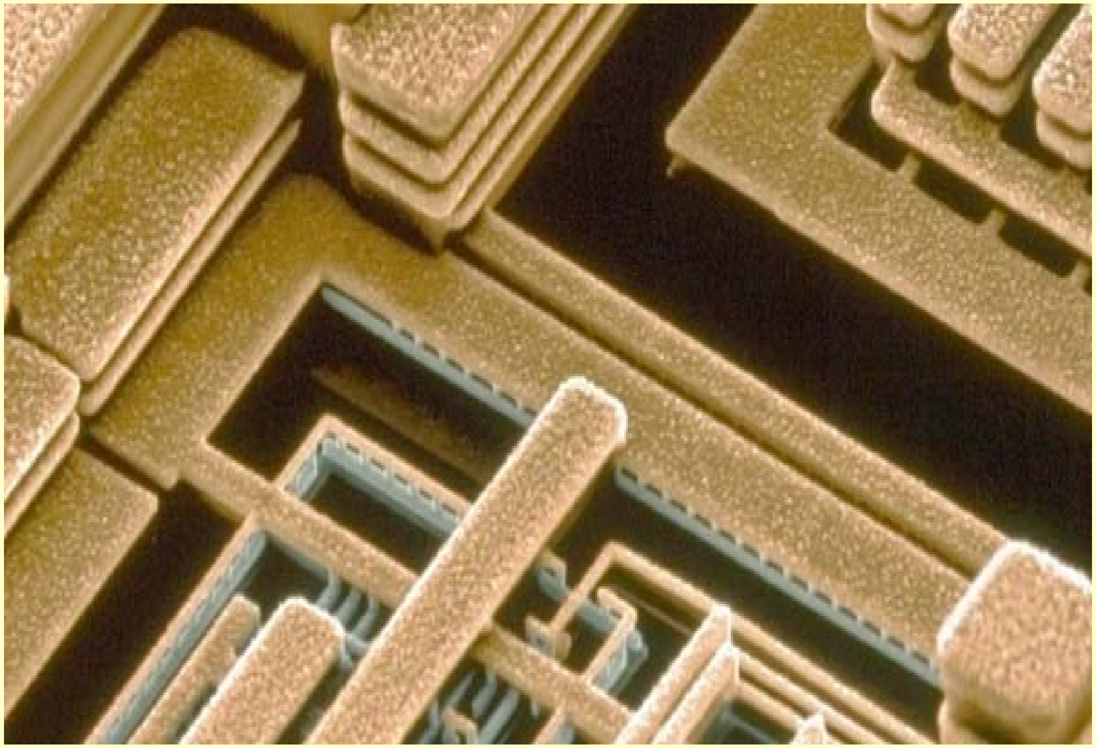
Q. MA, H. Fujimoto, J. He
Intel Corporation

Interconnect Structures

- Complex architecture
- Small feature sizes
- Diverse materials



Intel: 130nm technology



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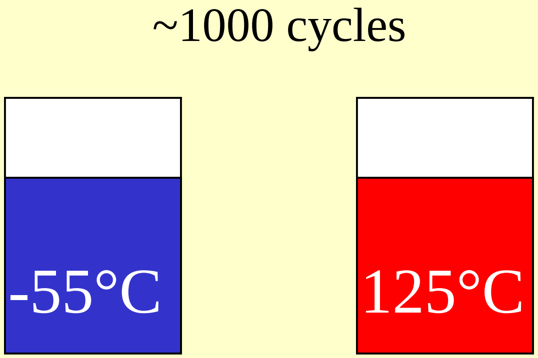
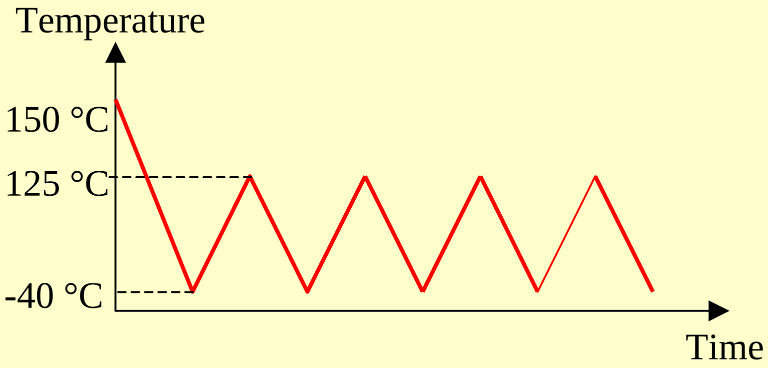
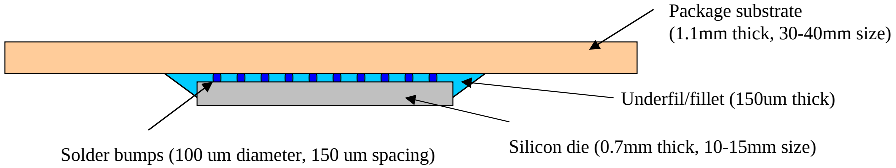
Thermal Cycling: Qualification Test





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

Flip-chip structure

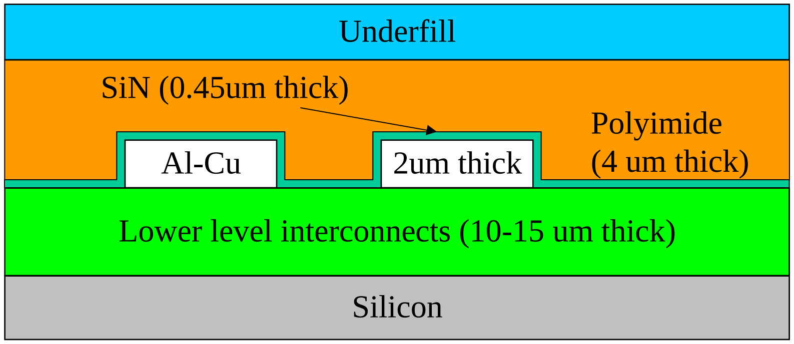


Package substrate
(1.1mm thick, 30-40mm size)

Underfil/fillet (150um thick)

Silicon die (0.7mm thick, 10-15mm size)

Solder bumps (100 um diameter, 150 um spacing)



Underfill

SiN (0.45um thick)

Polyimide
(4 um thick)

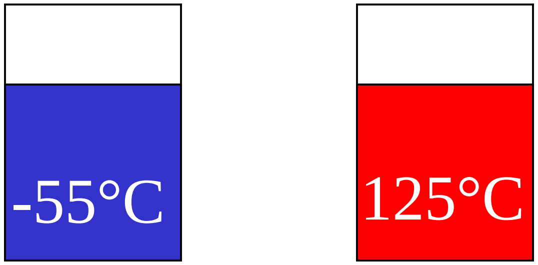
Al-Cu

2um thick

Lower level interconnects (10-15 um thick)

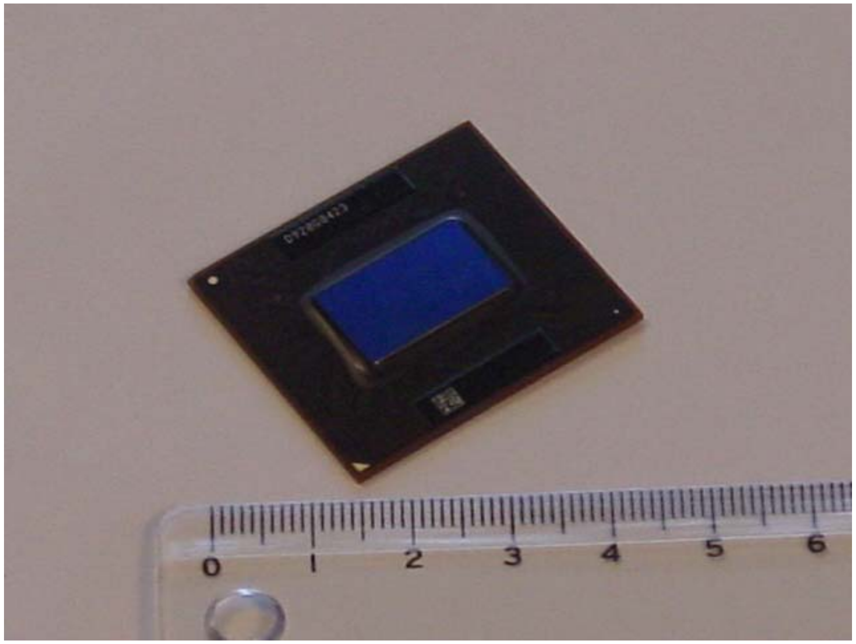
Silicon

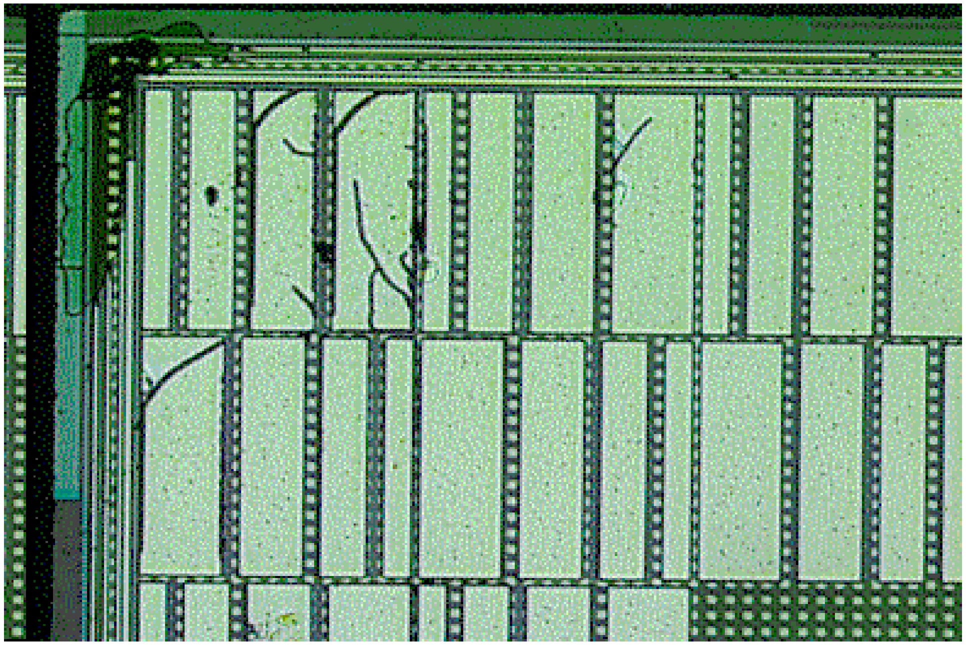
~1000 cycles



-55°C

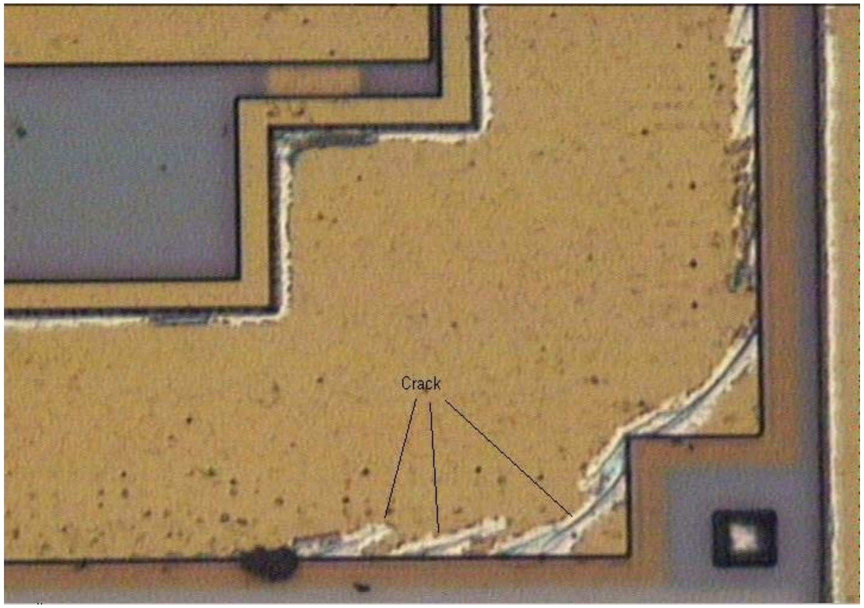
125°C



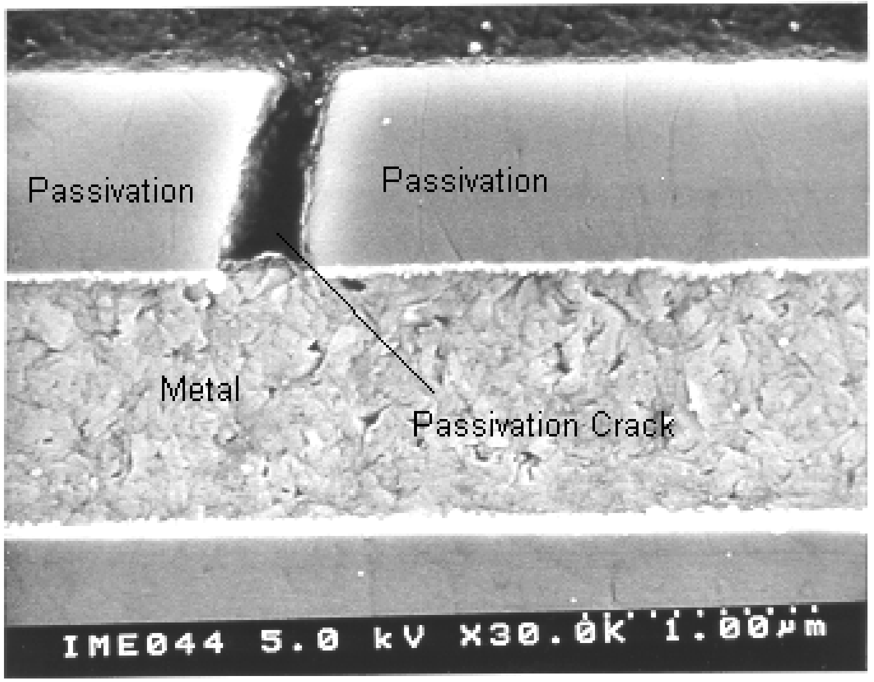


500 cycles between -55°C and 125°C

Plan view



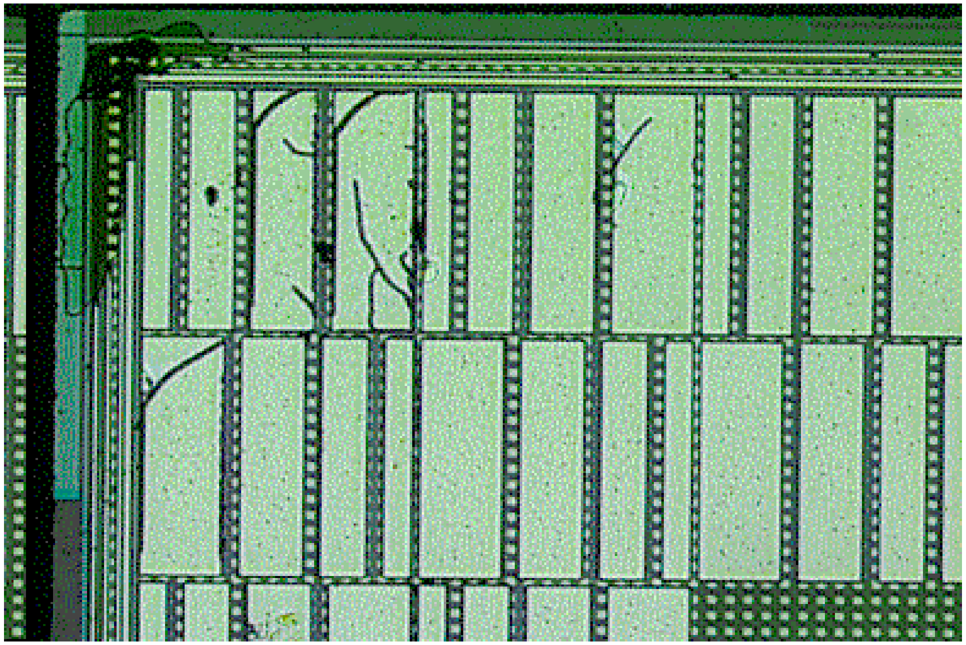
Edge view

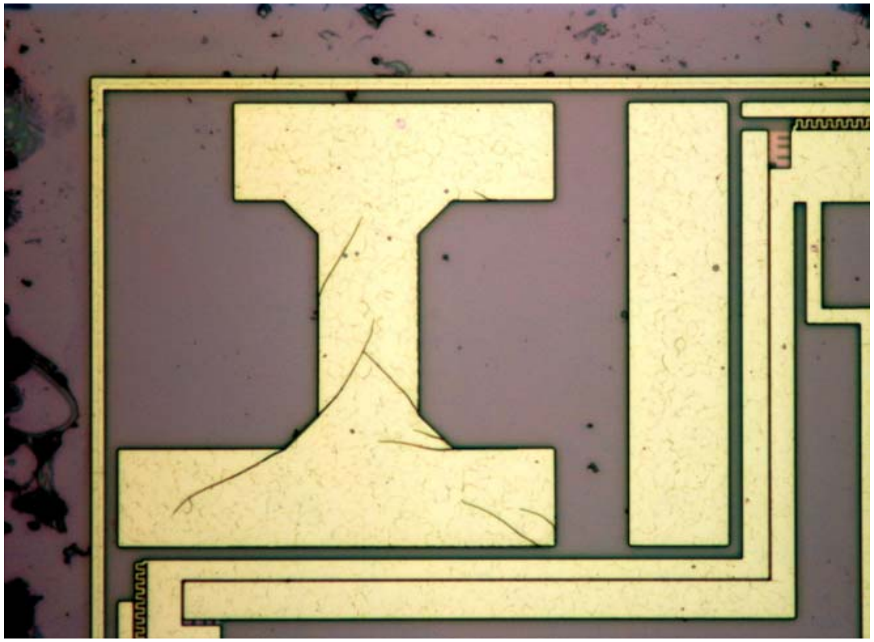


Courtesy of Dr. **J.B. Han** , Agilent Technologies Singapore

Empirical Observations of Cracking

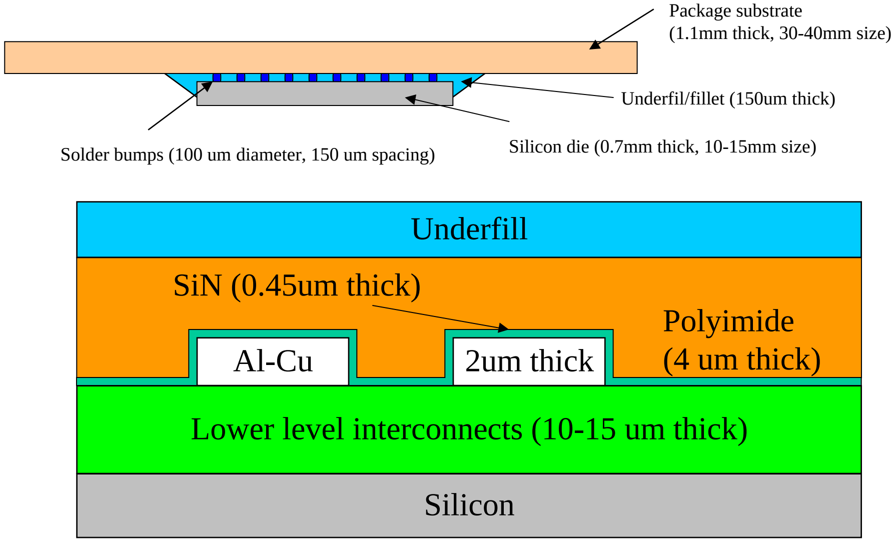
- At die corners
- After temperature cycles
- In SiN film over Al pads, but not in SiN film over silica
- More likely when Al pad is wide





Questions

Flip-chip structure



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

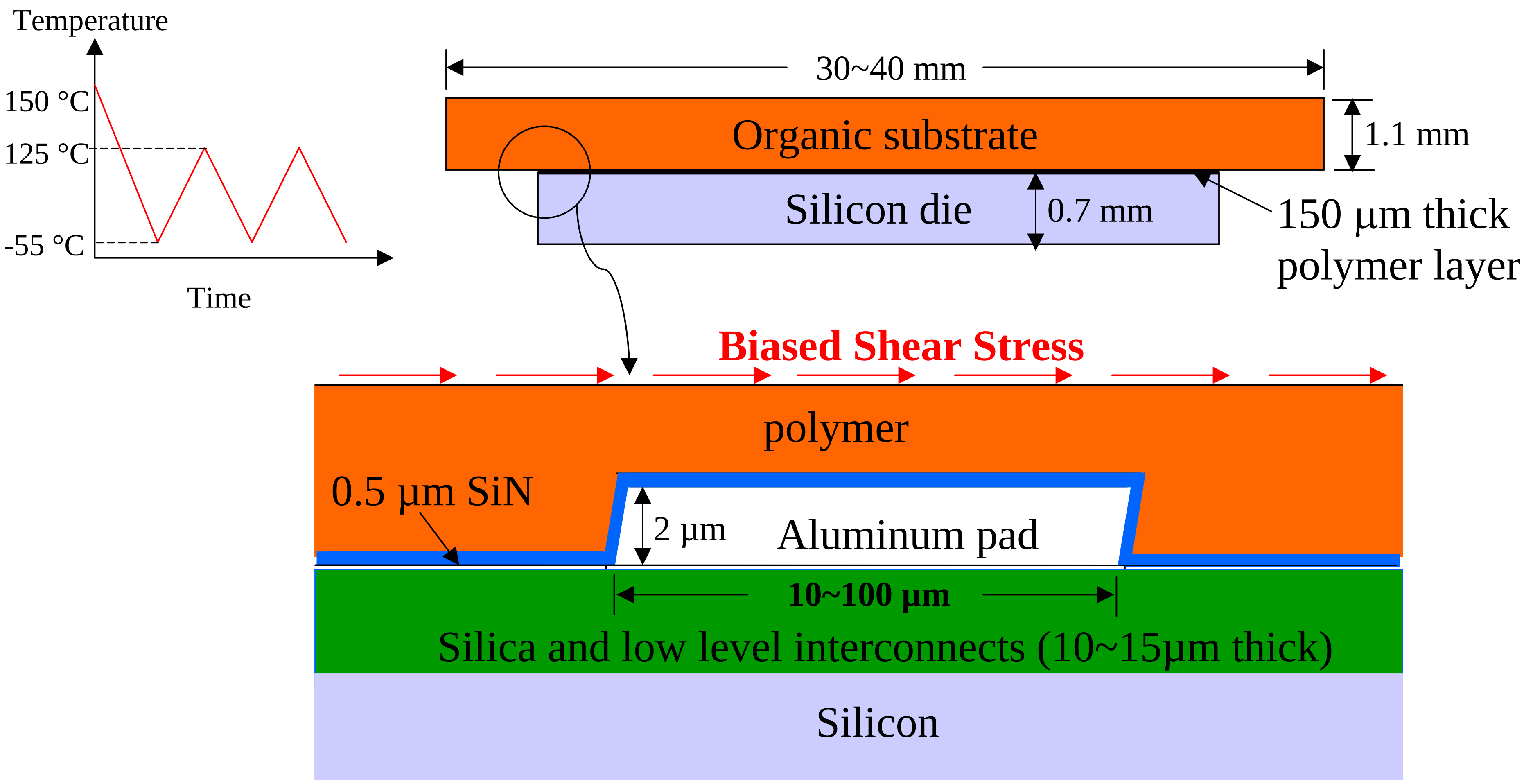
- **Why cracking?**

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

*Breaking strength of SiN is 1000 MPa.

Ratcheting Plastic Deformation

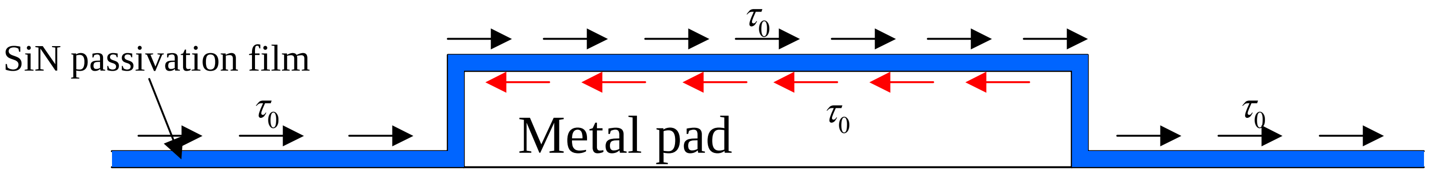
Huang, Suo, Ma, Fujimoto, *J. Mater. Res.*, **15**, 1239 (2000)



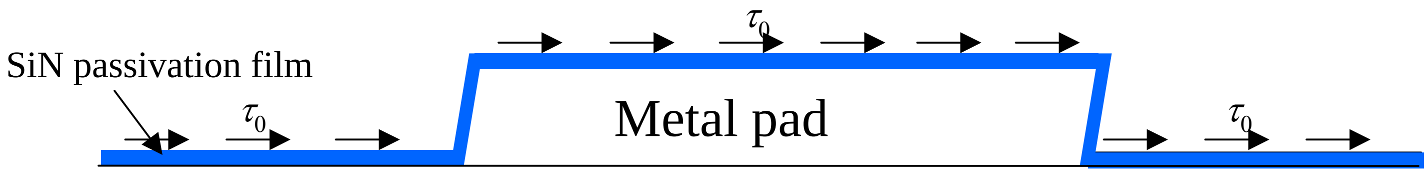
- **Biased shear stress, from organic substrate**
- **Metal yields, from CTE mismatch with SiO2**

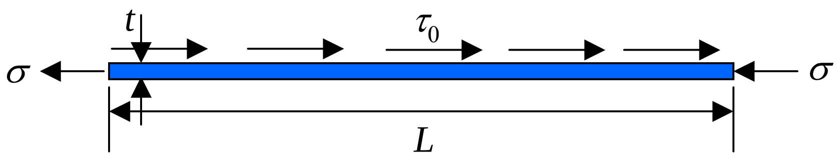
Stress builds up in SiN. STEADY STATE

First cycle



Many cycles, **STEADY STATE**

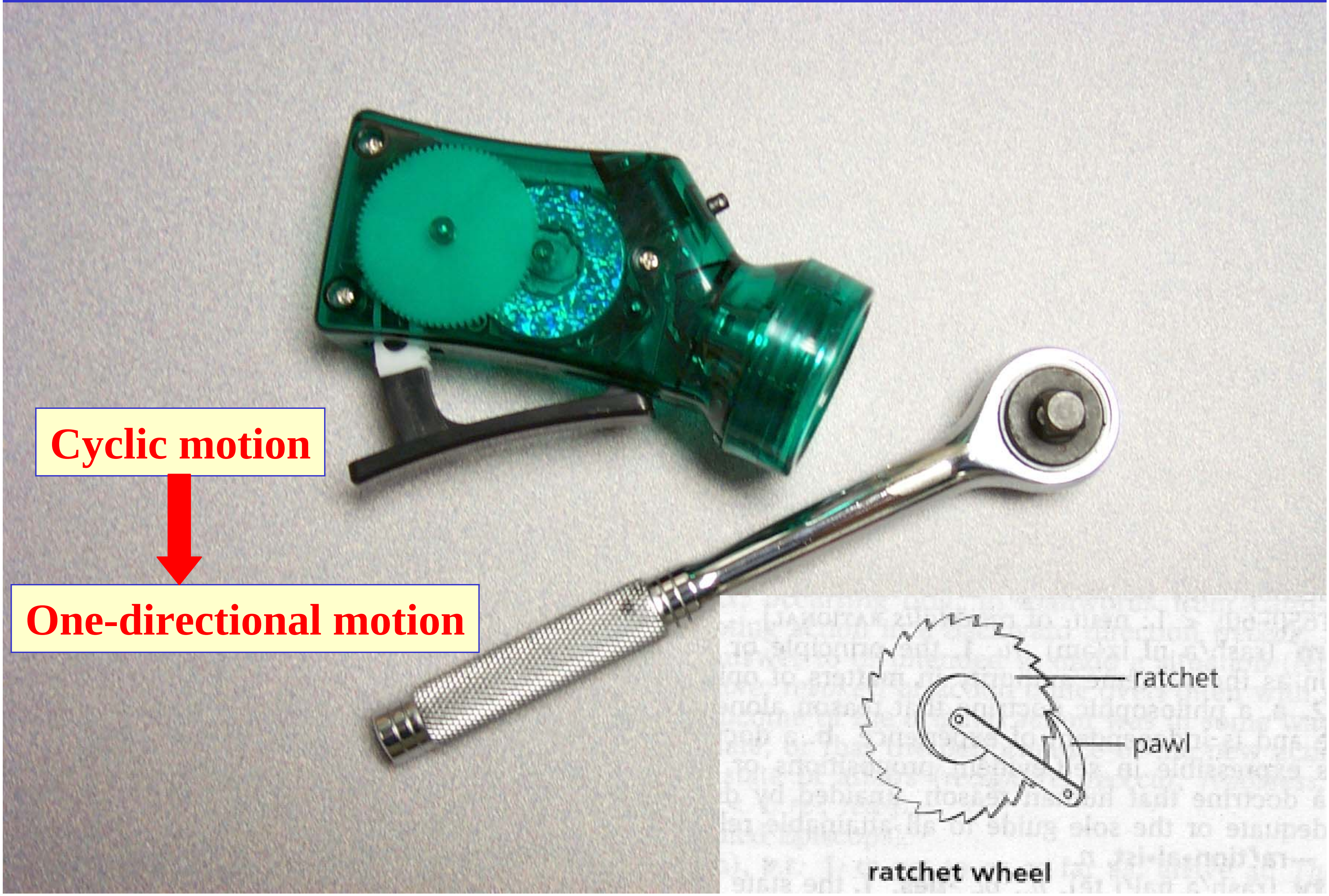




$$2\sigma t = \tau_0 L$$

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

Ratchet and Pawl

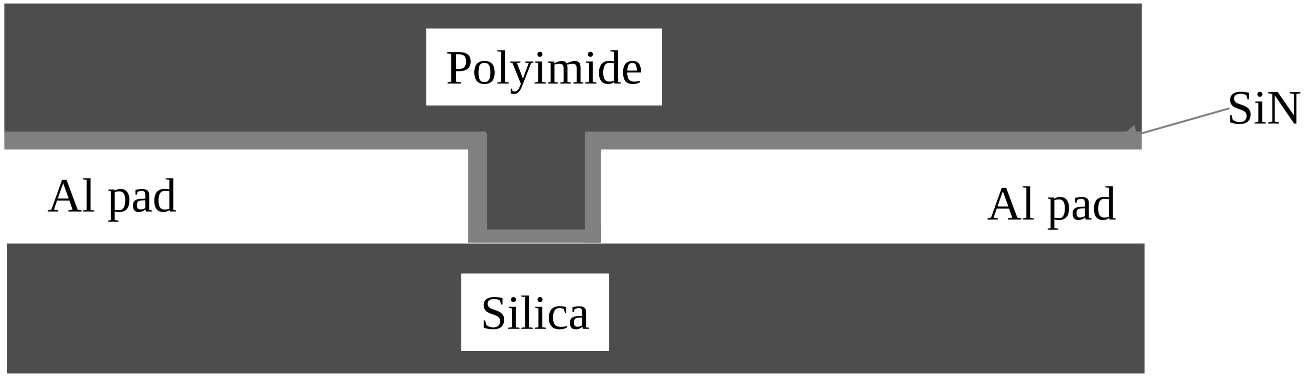


Cyclic motion

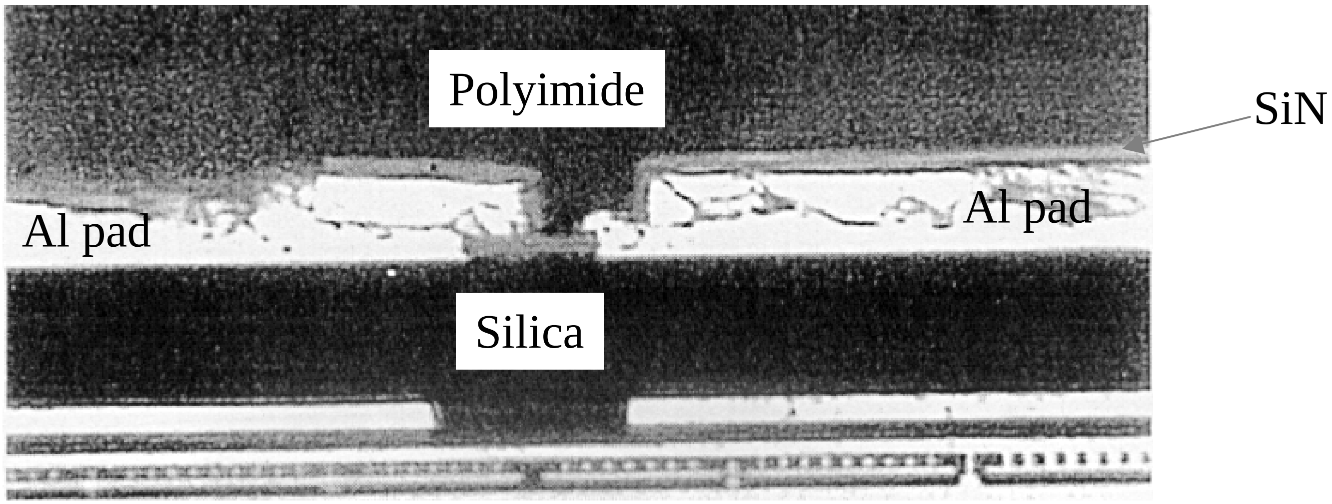
↓

One-directional motion

Metal Pad **Crawling**

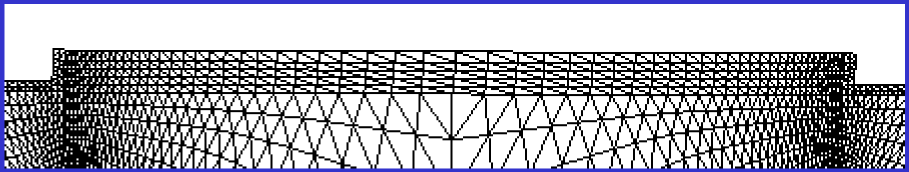


After ~1000 thermal cycles

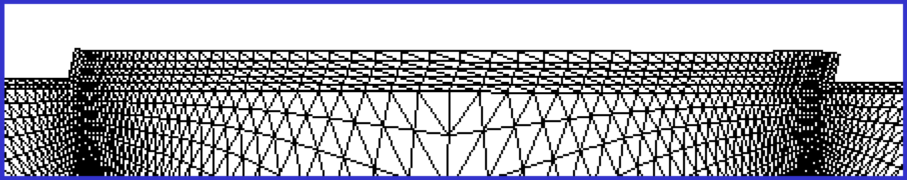


Large plastic deformation over many thermal cycles

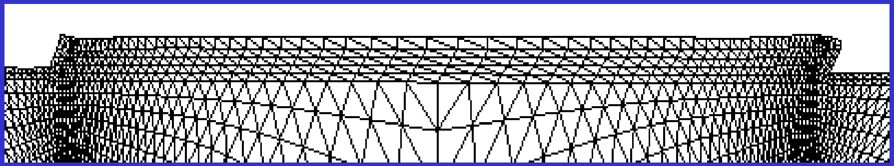
Finite Element Simulation



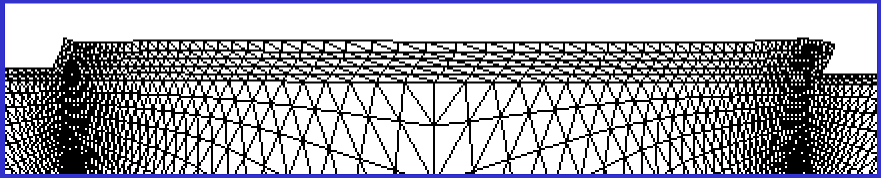
1 cycle



10 cycles

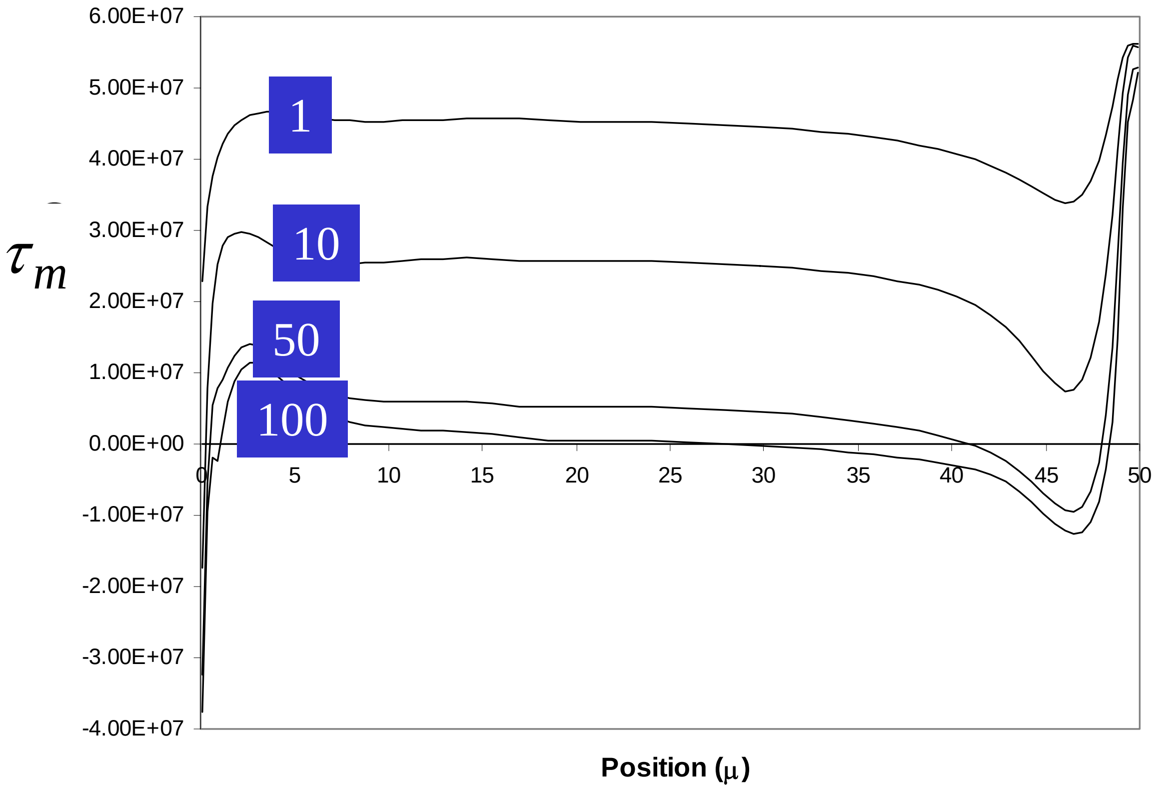


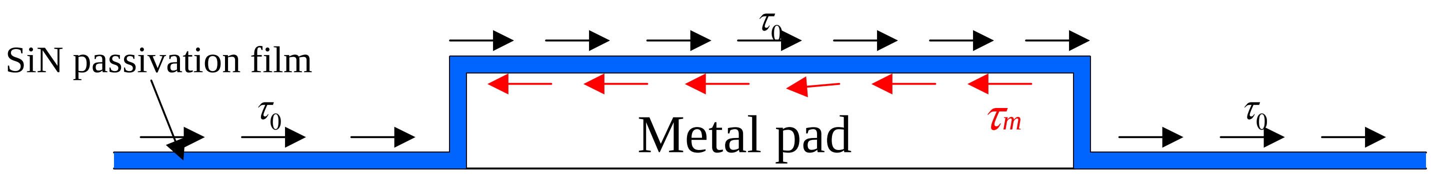
50 cycles



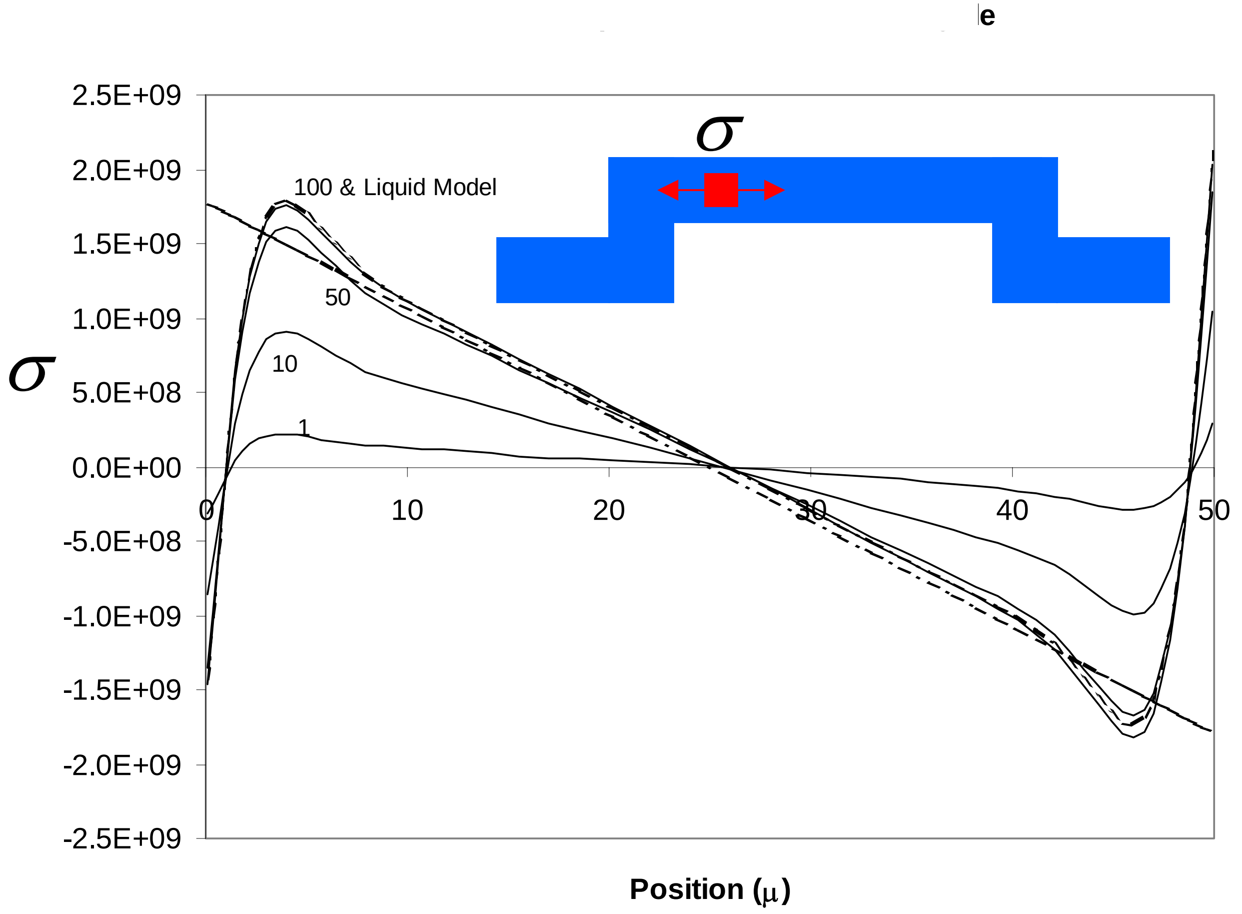
100 cycles

Shear stress in metal relaxes as temperature cycles

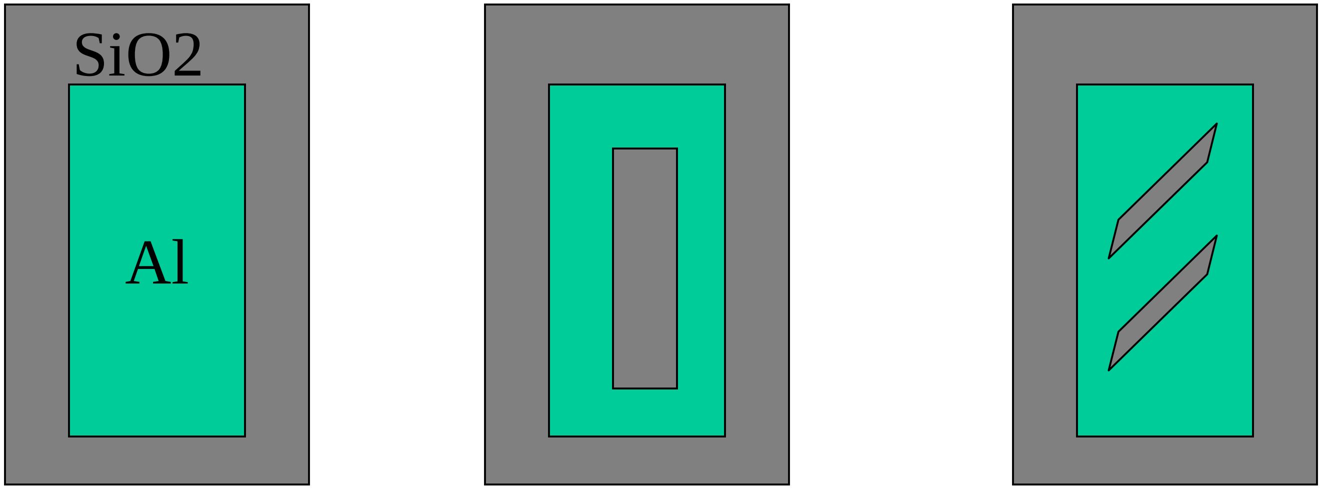


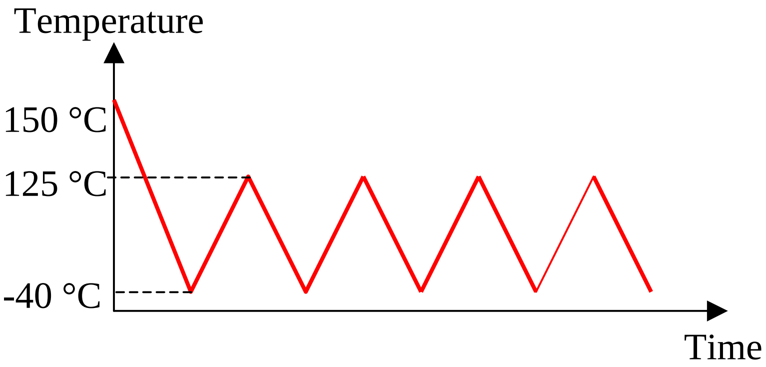


Membrane stress in SiN builds up as temperature cycles



Metal pad geometry. Slots.





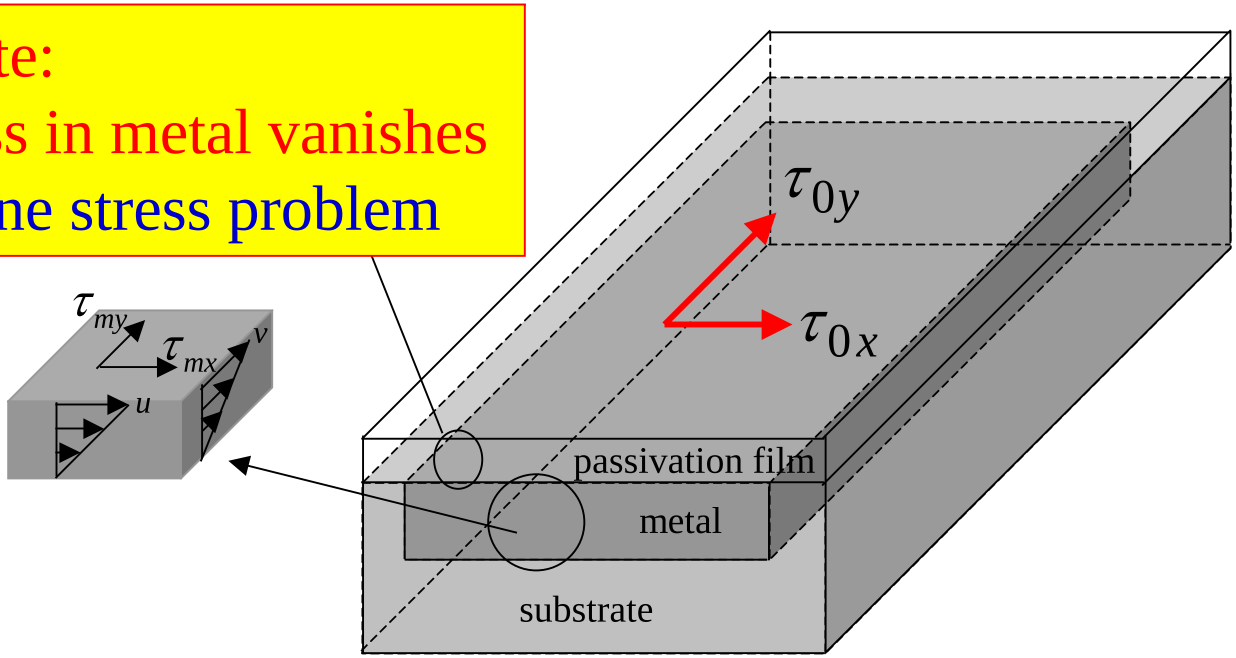
- Direct finite element calculations for 3D, many cycles take VERY long time.

3D Structure

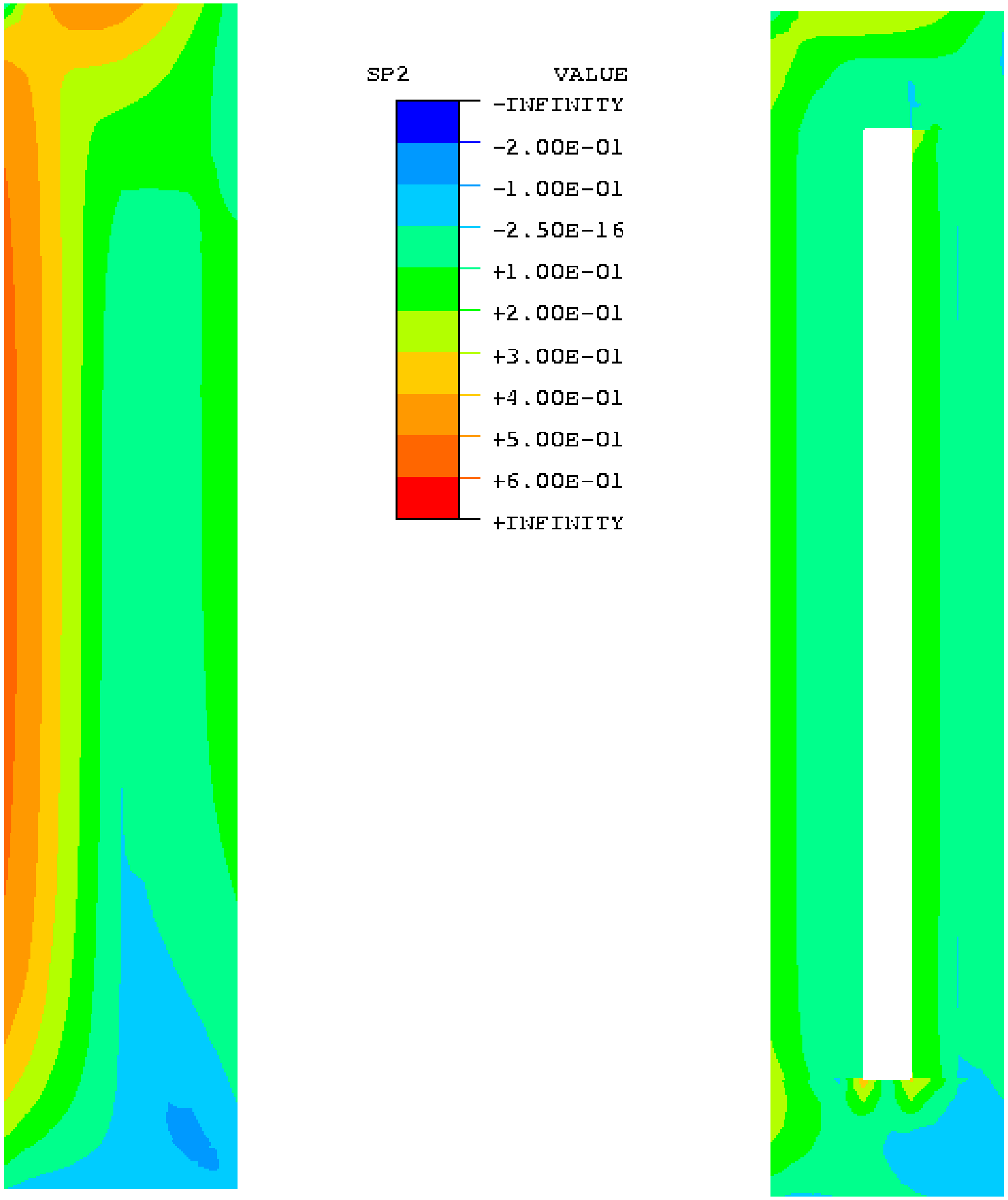
Steady-state:

Shear stress in metal vanishes

Elastic plane stress problem



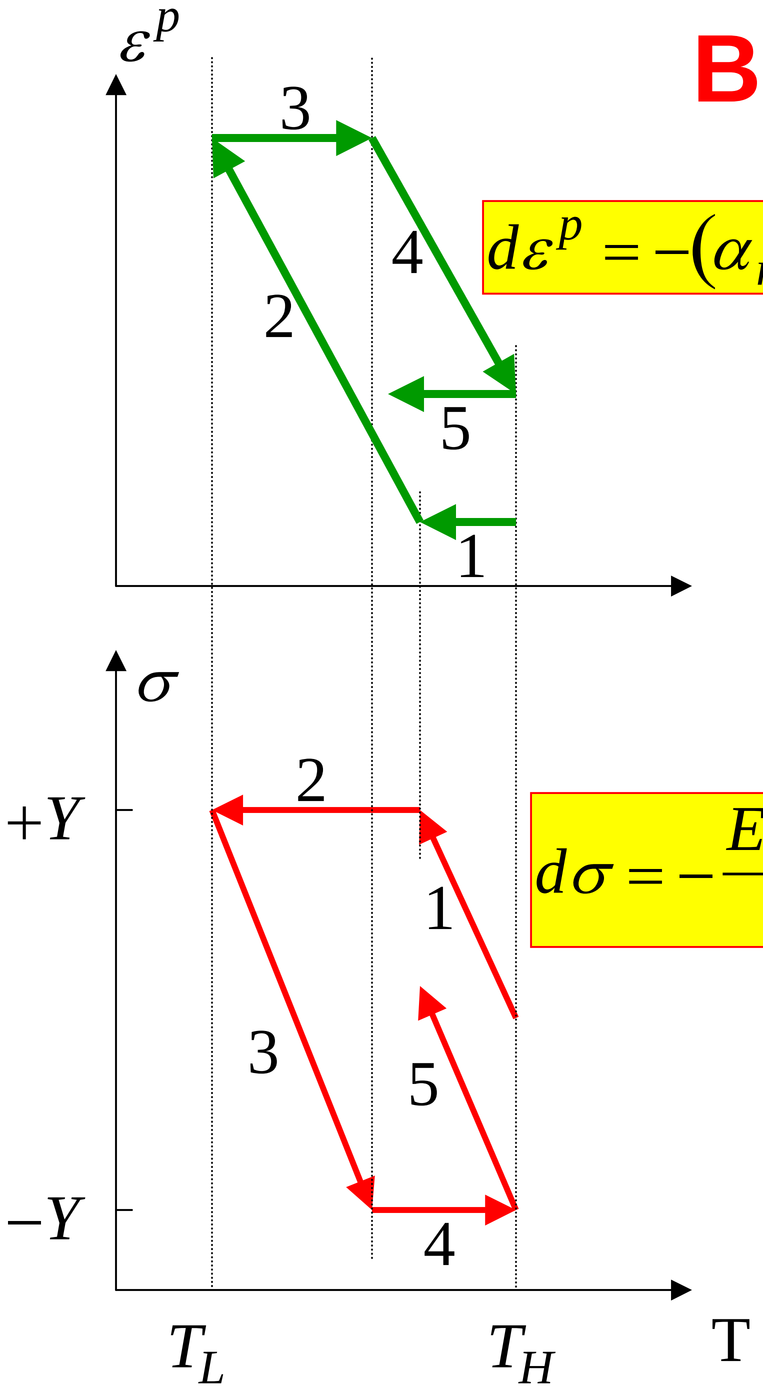
Slot!

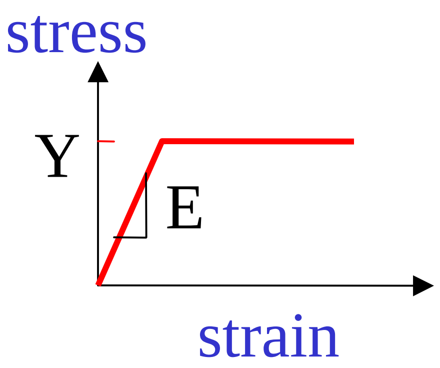

SP2
VALUE
-INFINITY
-2.00E-01
-1.00E-01
-2.50E-16
+1.00E-01
+2.00E-01
+3.00E-01
+4.00E-01
+5.00E-01
+6.00E-01
+INFINITY

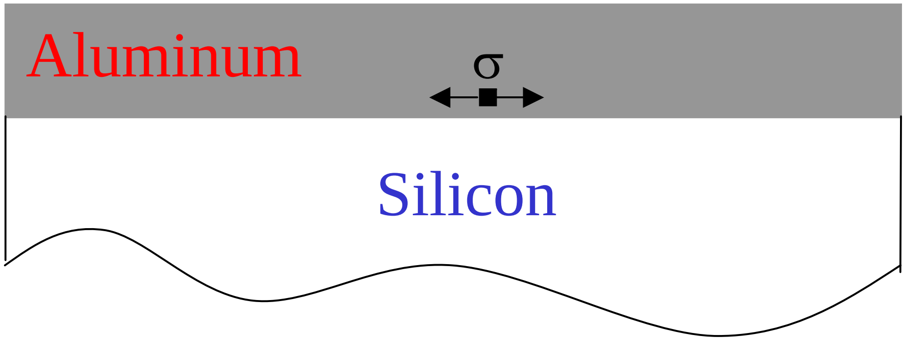
Further Issues

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

Blanket film





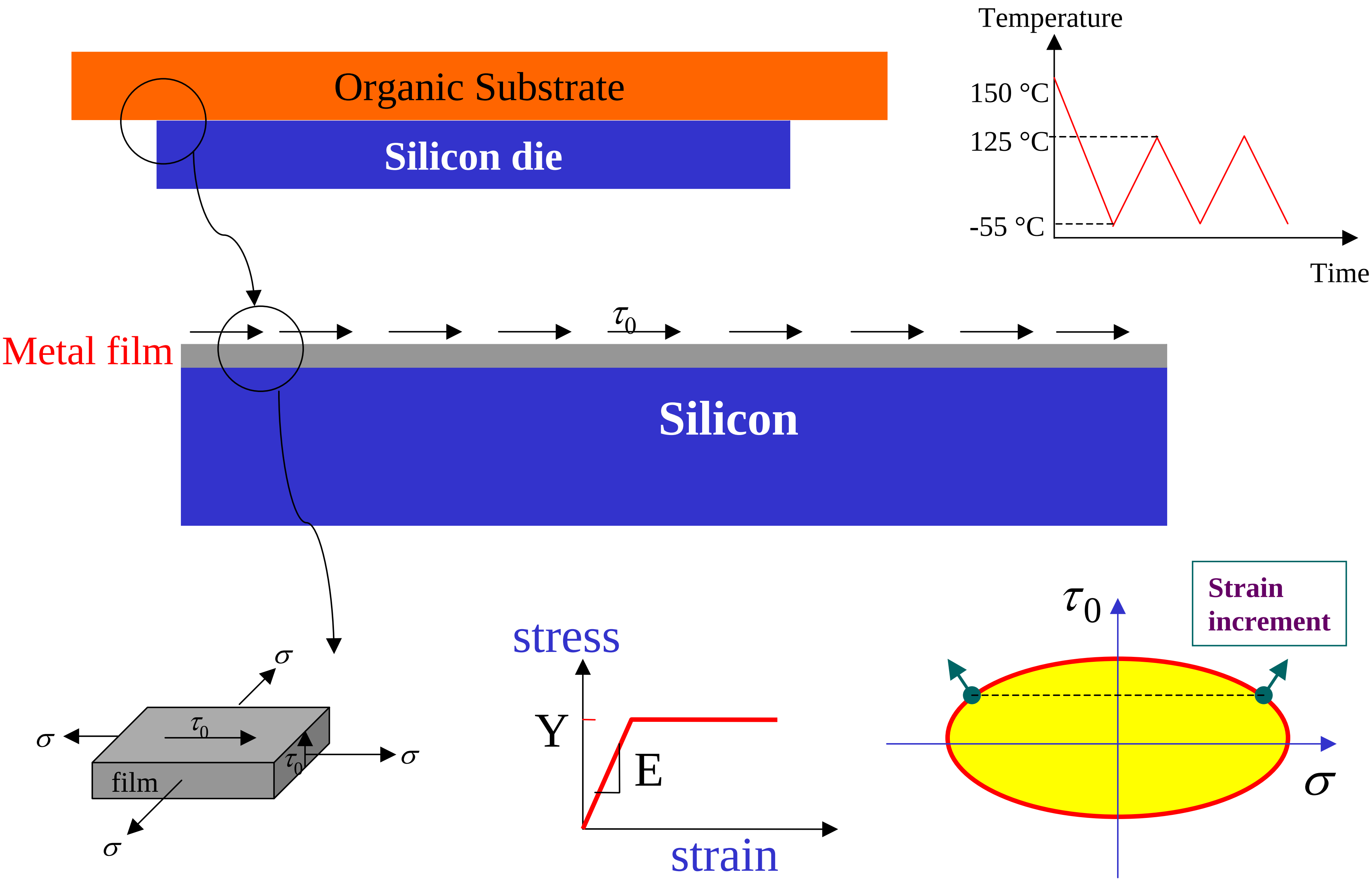


$$d\varepsilon^p = -(\alpha_m - \alpha_s)dT$$

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

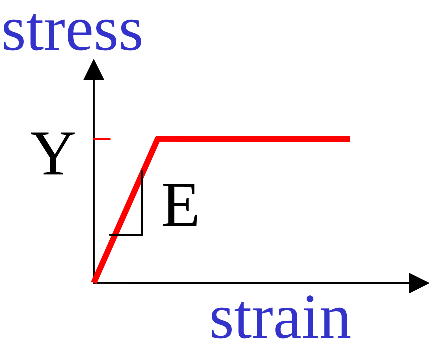
$$\frac{E(T_H - T_L)(\alpha_f - \alpha_s)}{(1-\nu)Y}\begin{cases} >2, & \text{cyclic plasticity} \\ <2, & \text{shakedown} \end{cases}$$

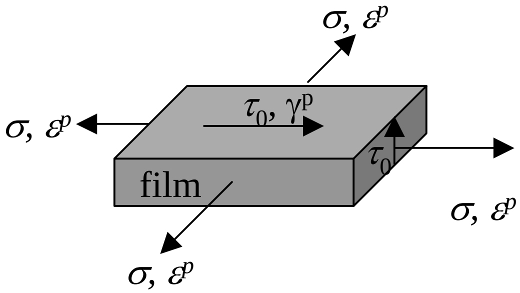
Why Crawling?

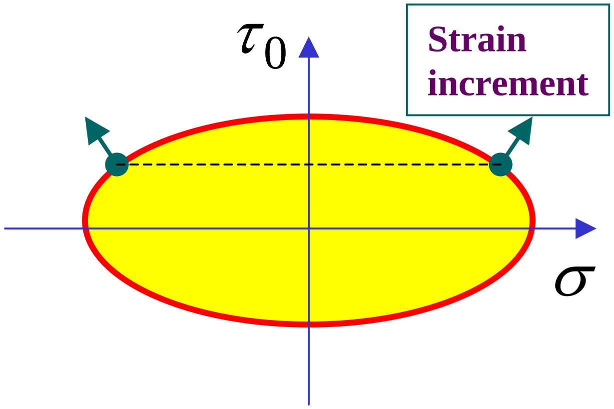


Huang, Suo, Ma, *Acta Materialia*, **49**, 3039-3049 (2001)

Elastic-Plastic Model







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

Yield condition

Matching strains of film & substrate

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

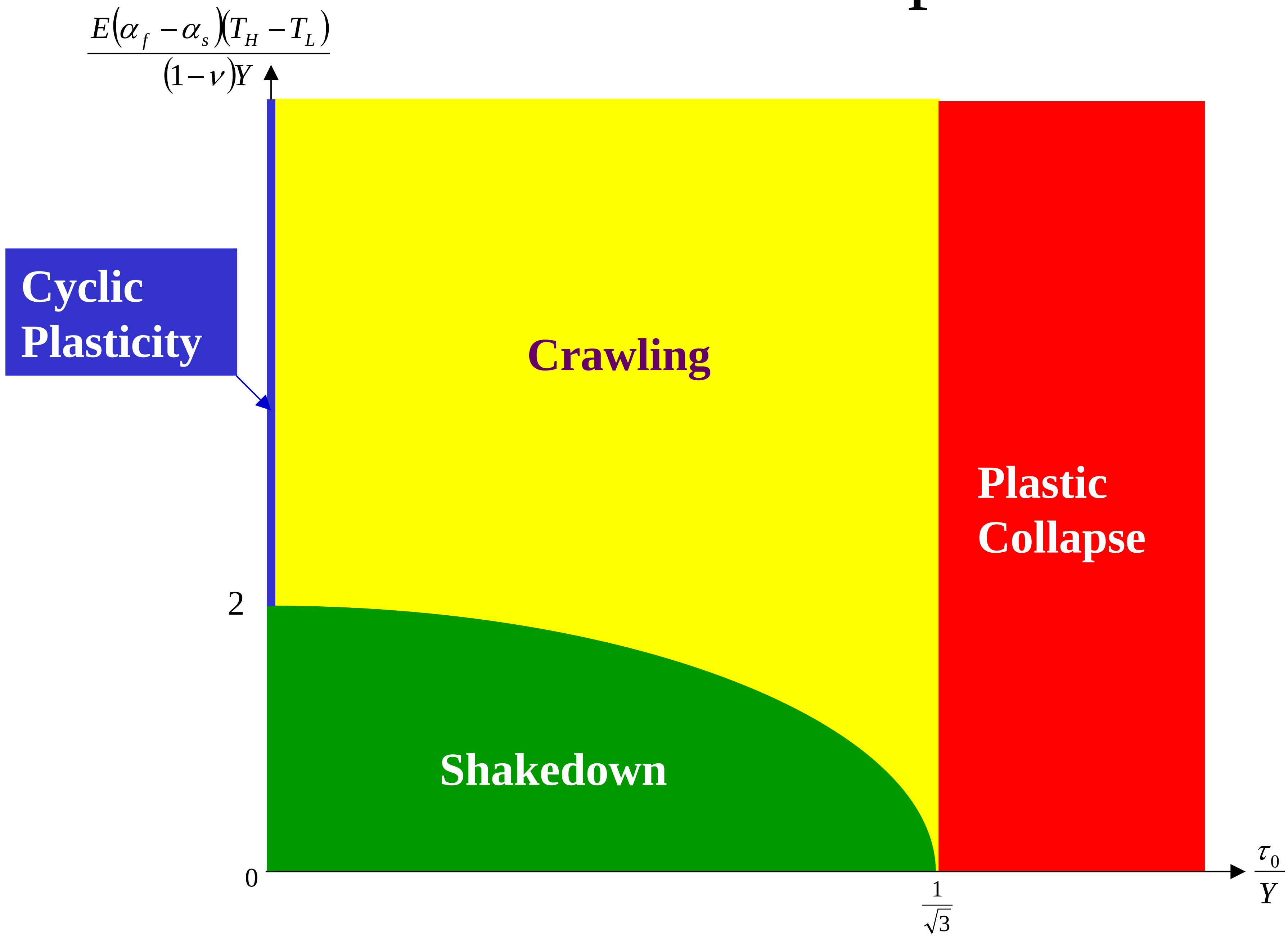
J2 flow theory

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

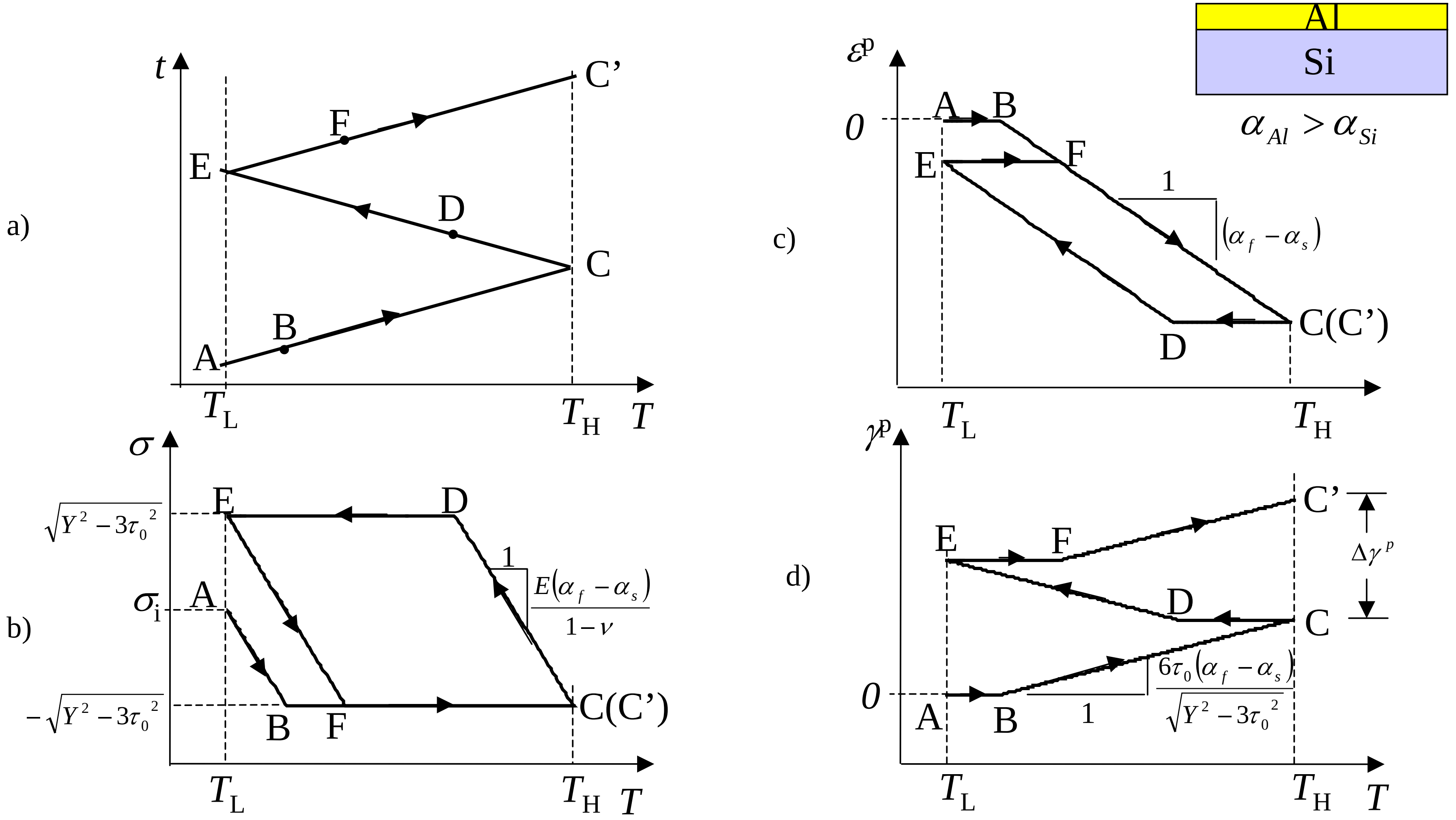
Shear strain increment

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

Four-color map



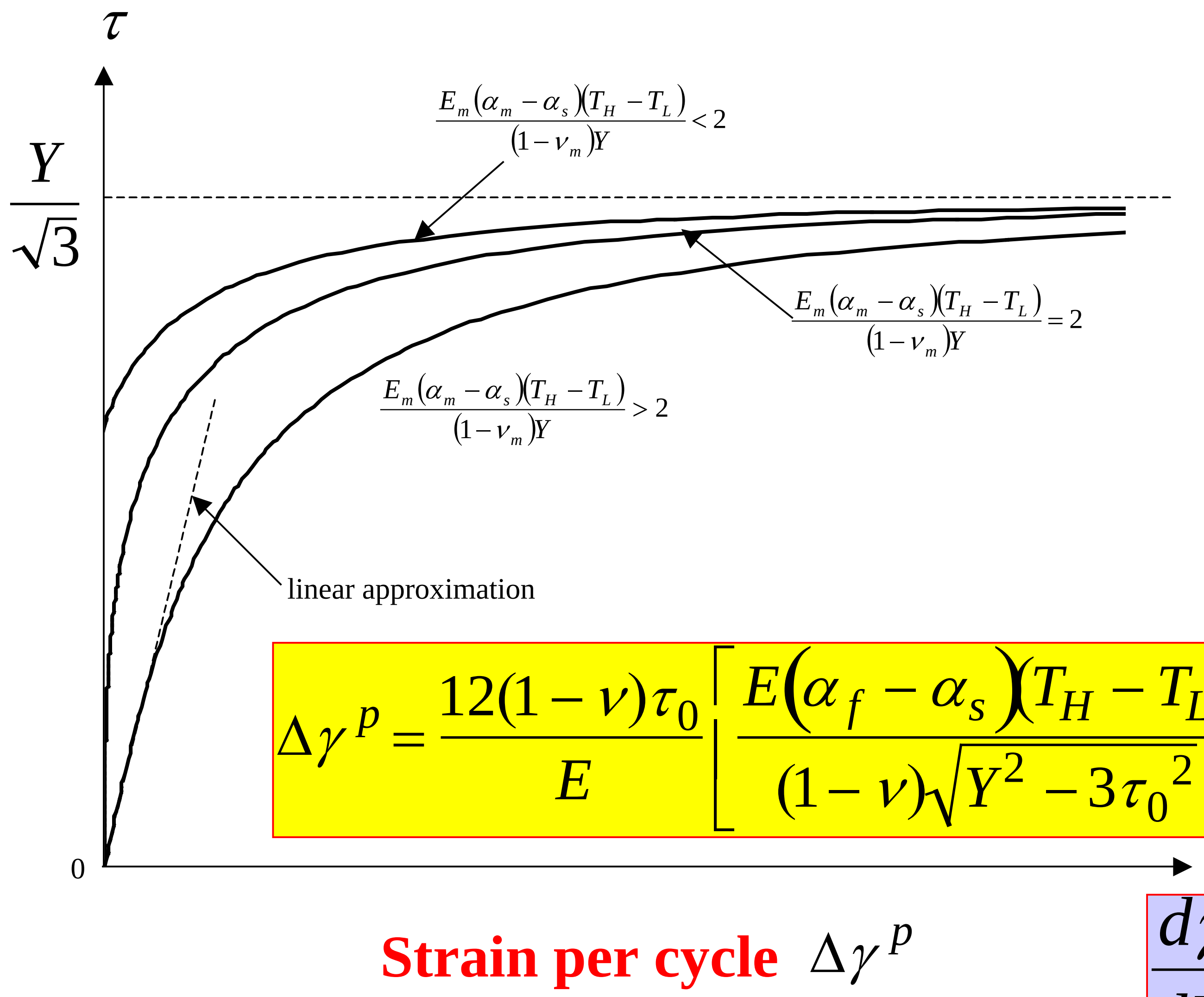
Stress and strain change with temperature



Strain per cycle

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

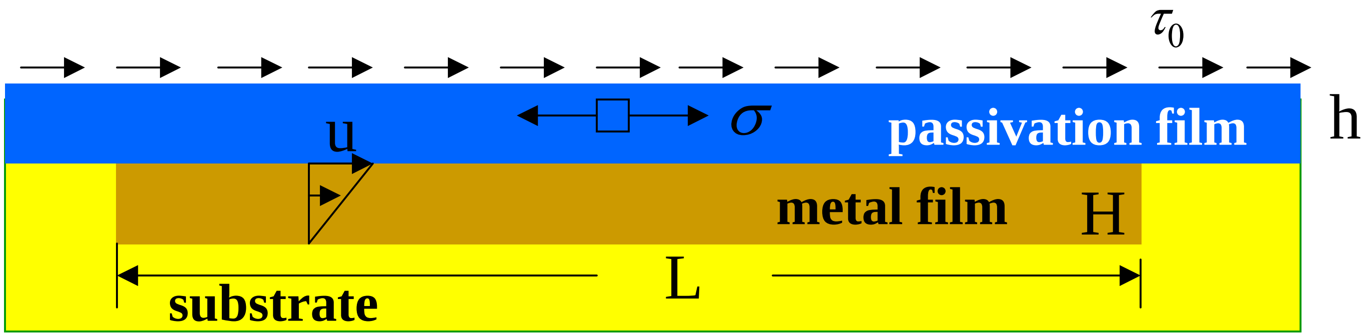
Ratcheting-Creep Analogy



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

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

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

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

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

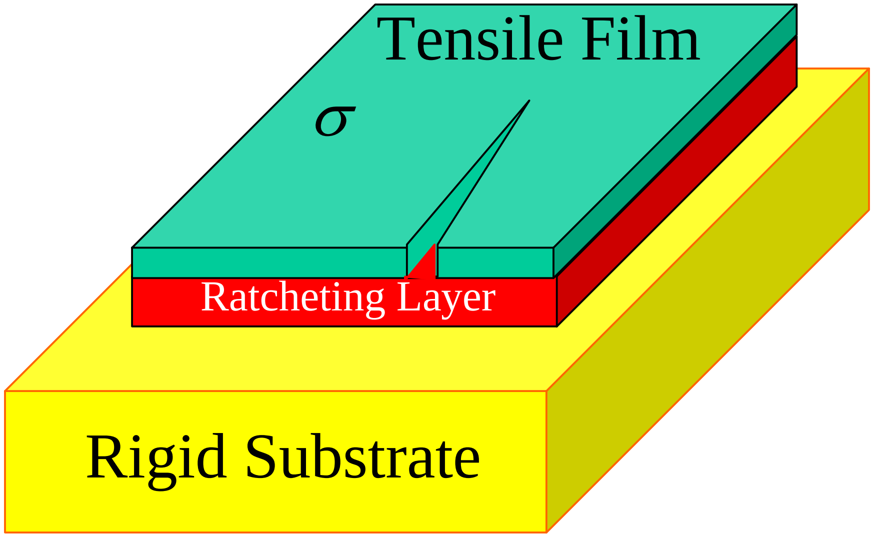
$$\frac{\partial u}{\partial N}=D\frac{\partial^2 u}{\partial x^2}-\frac{H\tau_0}{\eta}$$

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

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

Huang,Suo, Ma, *J Mech.Phys. Solids*. **50**, 1079 (2002)

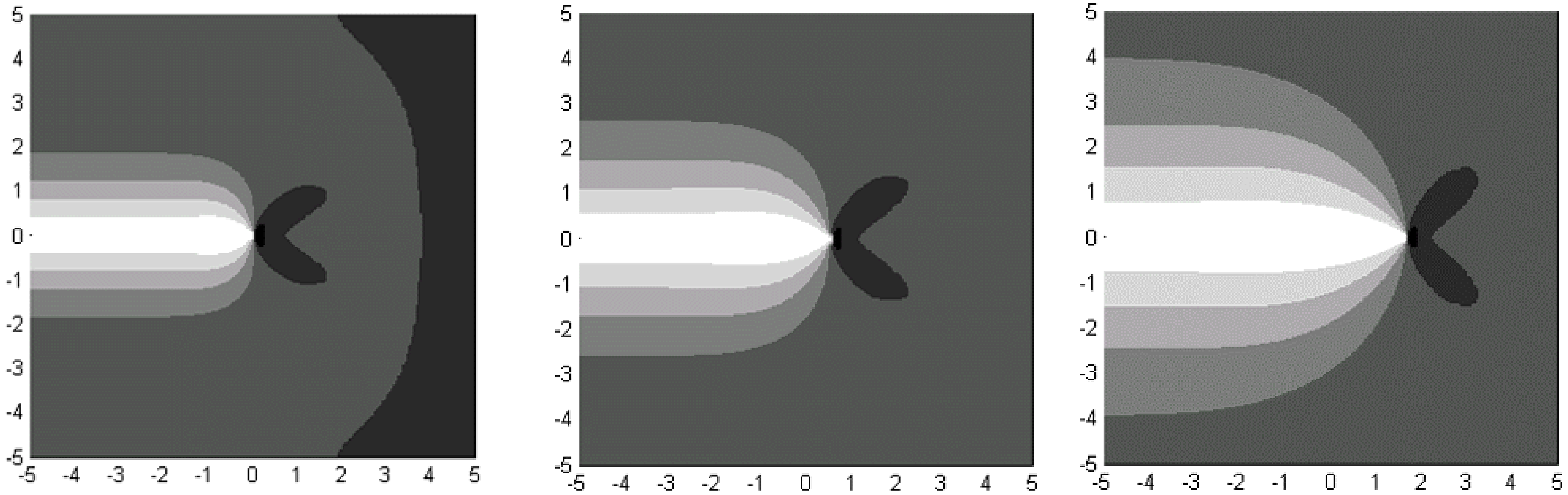
Concomitant crack extension and underlayer ratcheting



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

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

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.

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