Fracture, Delamination and Buckling of Elastic Thin Films on Compliant Substrates

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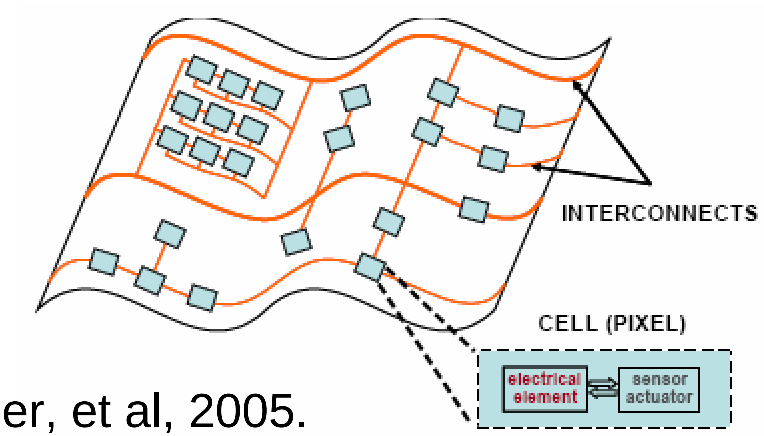
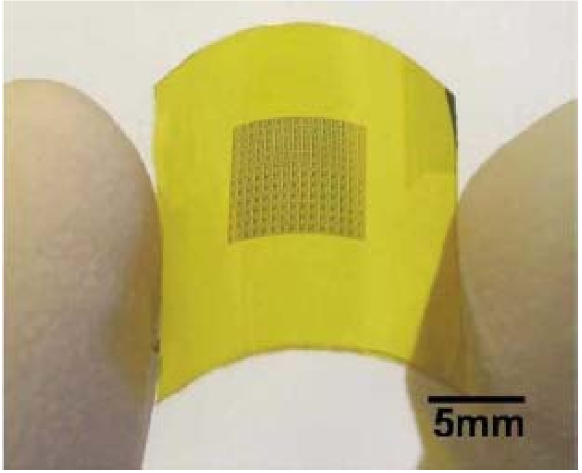
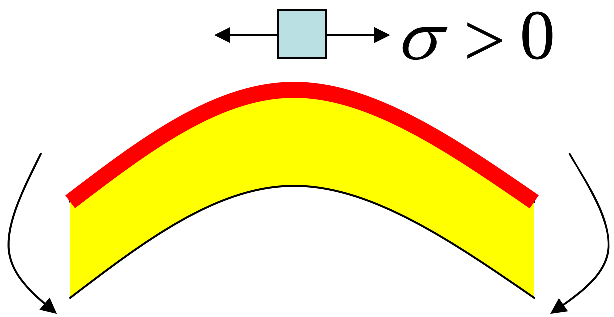
Large-Area Electronics:
flexible, stretchable, compressible

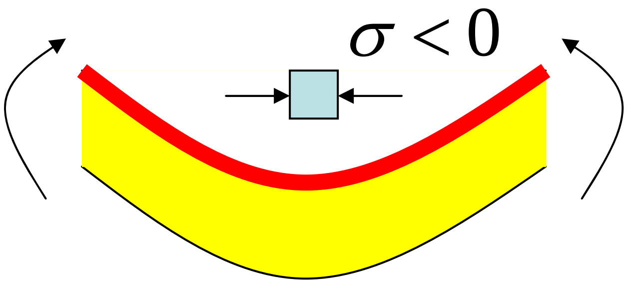


Wagner, et al, 2005.



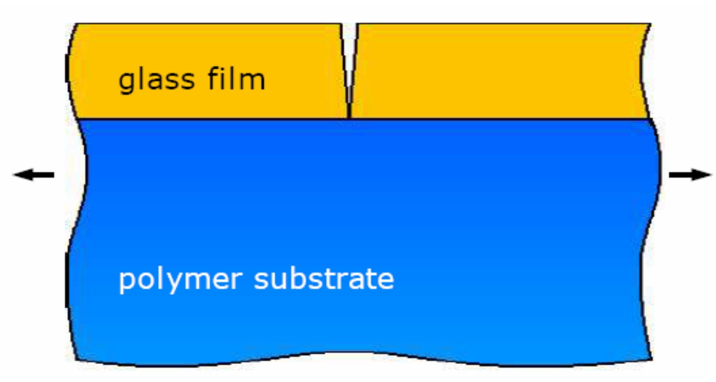
Ahn, et al, 2006

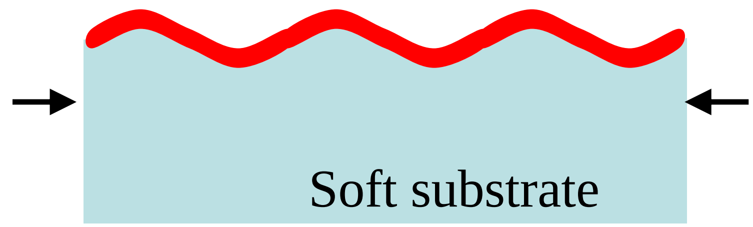


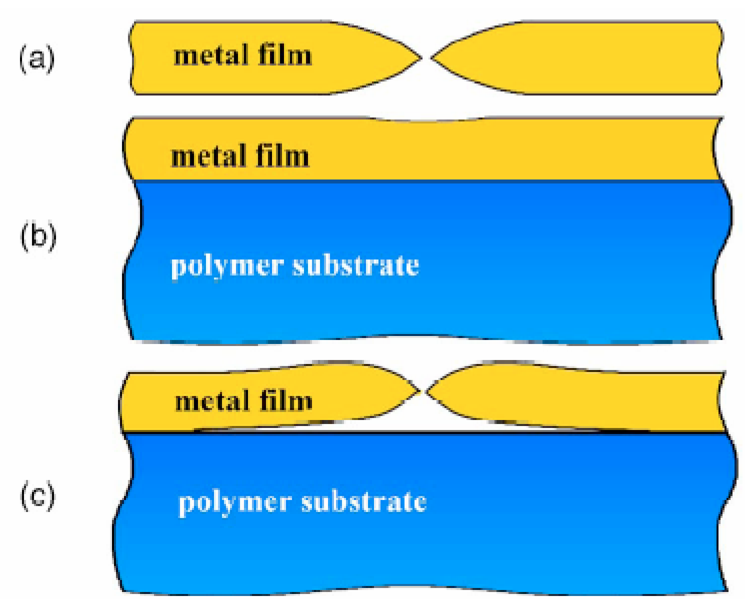


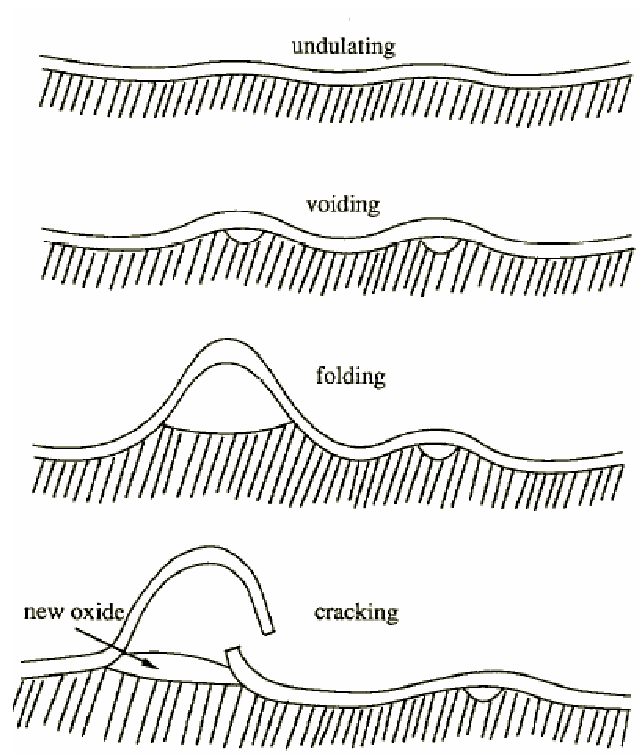
- Not always possible (or practical) to put all the devices on the neutral plane.
- Being flexible requires being both stretchable and compressible!

Mechanics of Thin Films:
Stretch and Compress



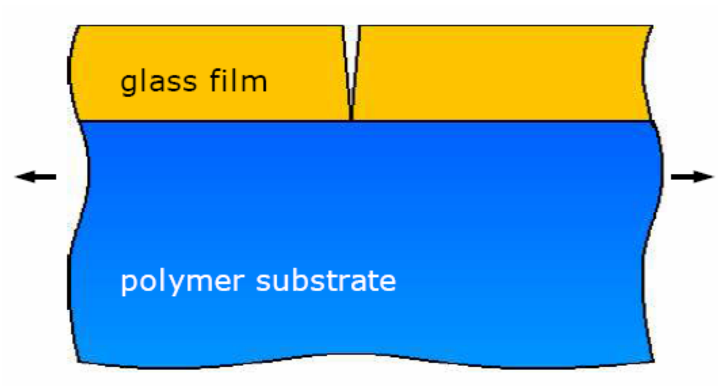


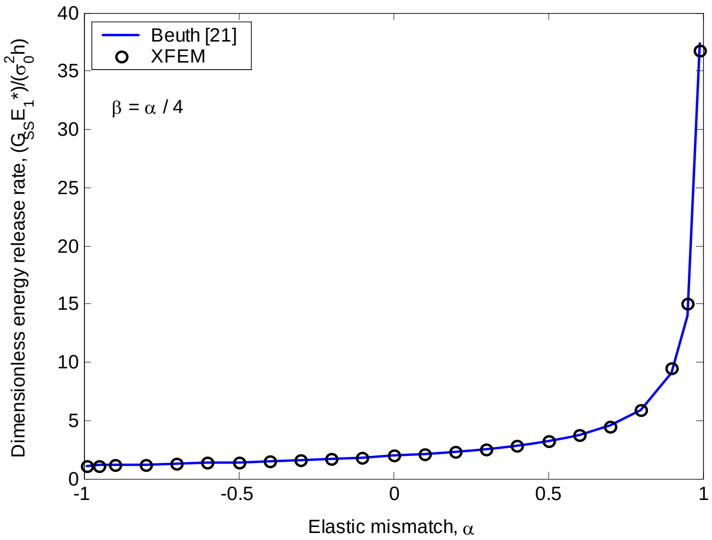




Stretchability

- A brittle thin film on a soft substrate



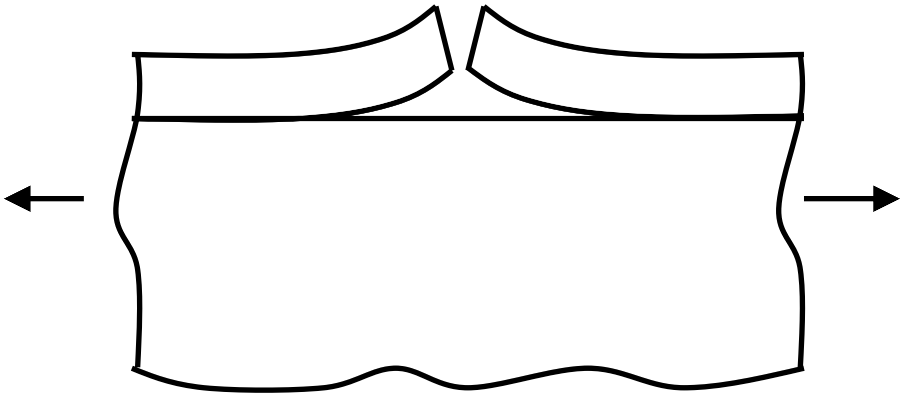


$$G_{SS} = Z(\alpha,\beta)\frac{\sigma_0^2 h}{\overline{E}_f} = Z(\alpha,\beta)\overline{E}_f h\left(\varepsilon_{appl} + \varepsilon_{res}\right)^2$$

$$\Rightarrow \quad \varepsilon_{appl} < \sqrt{\frac{\Gamma_f}{Z(\alpha,\beta)\overline{E}_f h}} - \varepsilon_{res}$$

- **Stretchability decreases with increasing elastic mismatch**
- **Stretchability increases with a compressive residual strain**

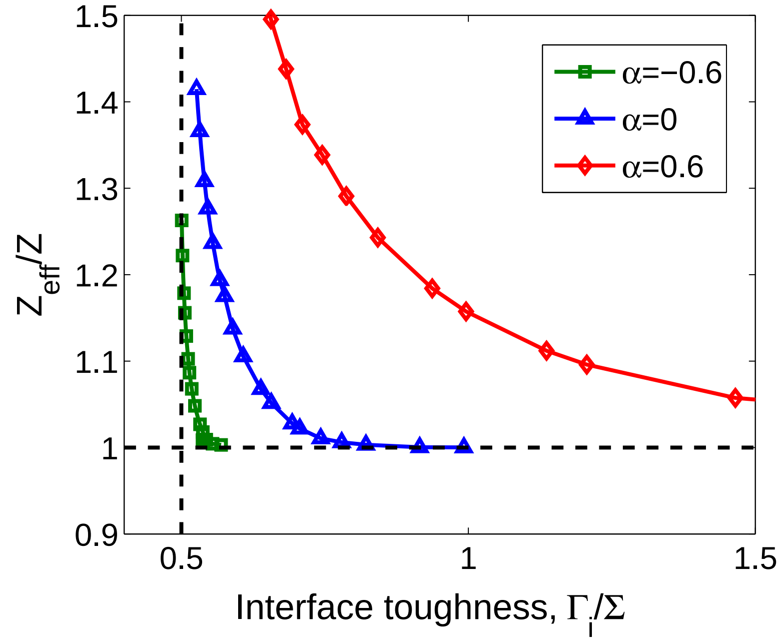
Effect of interface delamination

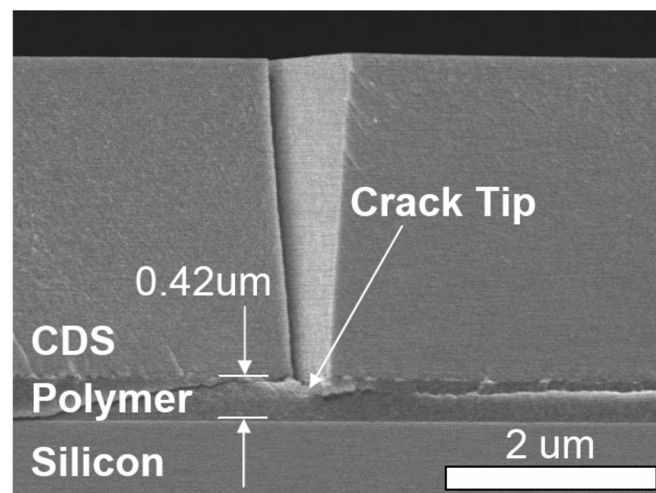


$$G_{eff} = Z_{eff}\left(\bar{\Gamma}_i, \alpha, \beta\right)\frac{\sigma_0^2 h}{\bar{E}_f}$$

$$\varepsilon_{appl} < \sqrt{\frac{\Gamma_f}{Z_{eff}\left(\Gamma_i, \alpha, \beta\right)\bar{E}_f h}} - \varepsilon_{res}$$

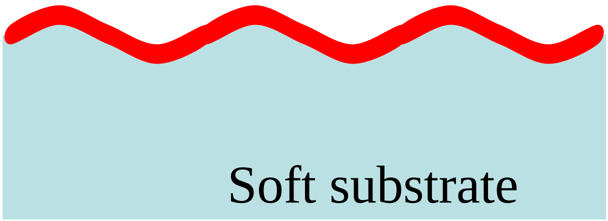
- **Stretchability decreases with decreasing interface toughness**

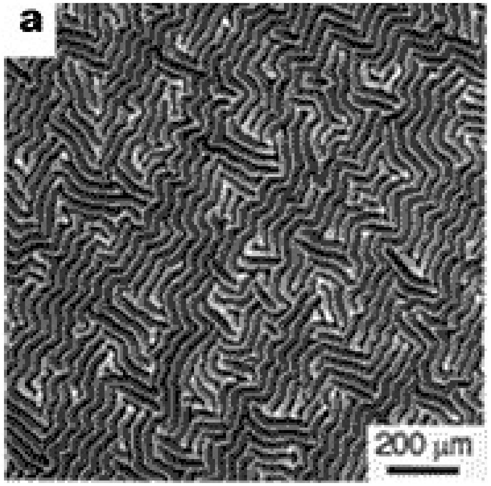


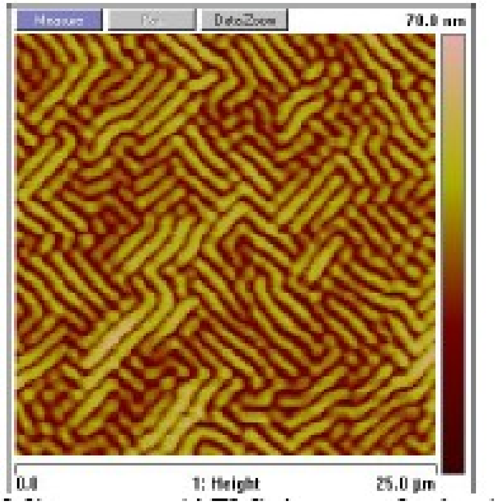


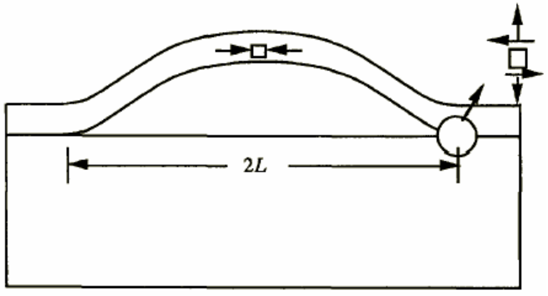
Tsui et al., JMR, 20, 2266 (2005).

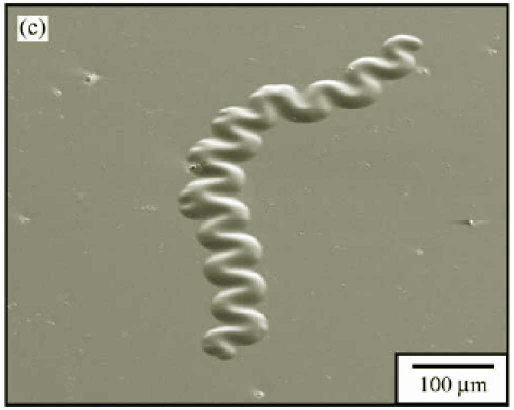
Compressibility: buckling

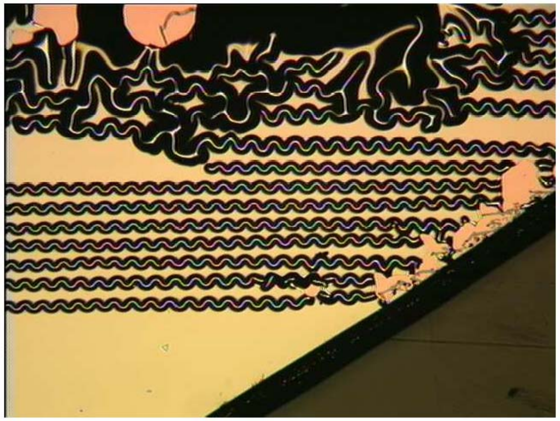












Wrinkling: enhance stretchability, but may fail under compression

Buckle-Delamination: lose interface integrity, may lead to film fracture

Mechanics of buckle-delamination

Hutchinson and Suo (1992):

- 1D buckle (plane strain cross section of a straight blister)
- Assume fixed edges (good for rigid substrates)

Critical strain for buckling:

$$\varepsilon_c = \frac{\pi^2}{12}\left(\frac{h}{b}\right)^2$$

Compressibility 1

Interfacial fracture energy release rate:

$$G = \left[\frac{E_f h}{2\left(1-\nu_f^2\right)}\right]\left(\varepsilon - \varepsilon_c\right)\left(\varepsilon + 3\varepsilon_c\right)$$

Compressibility 2:

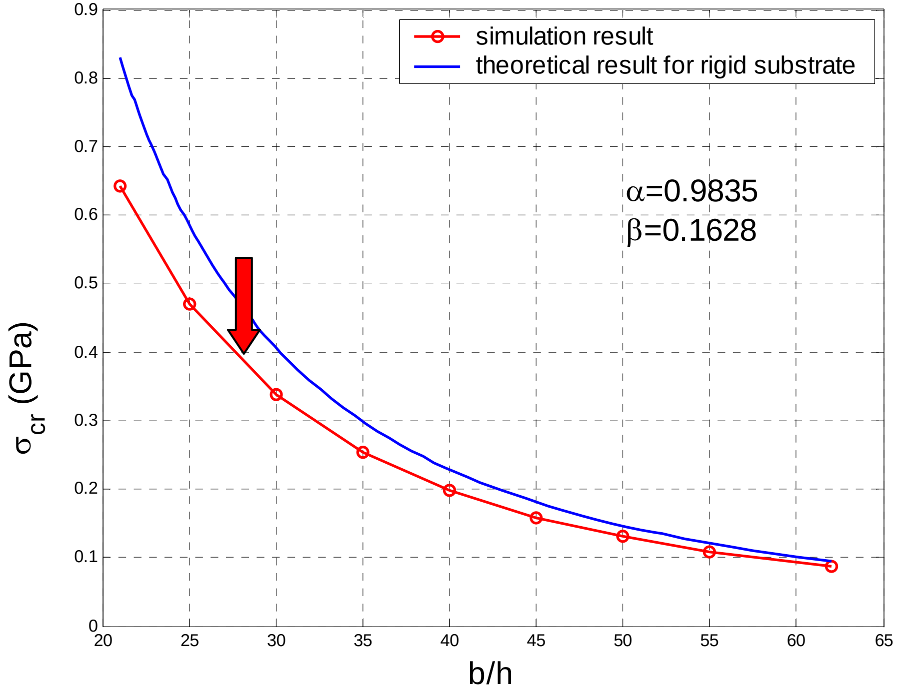
$$G < \Gamma_i \quad \Rightarrow \quad \varepsilon < \sqrt{\frac{2\Gamma_i}{\bar{E}_f h} + 4\varepsilon_c^2} - \varepsilon_c$$

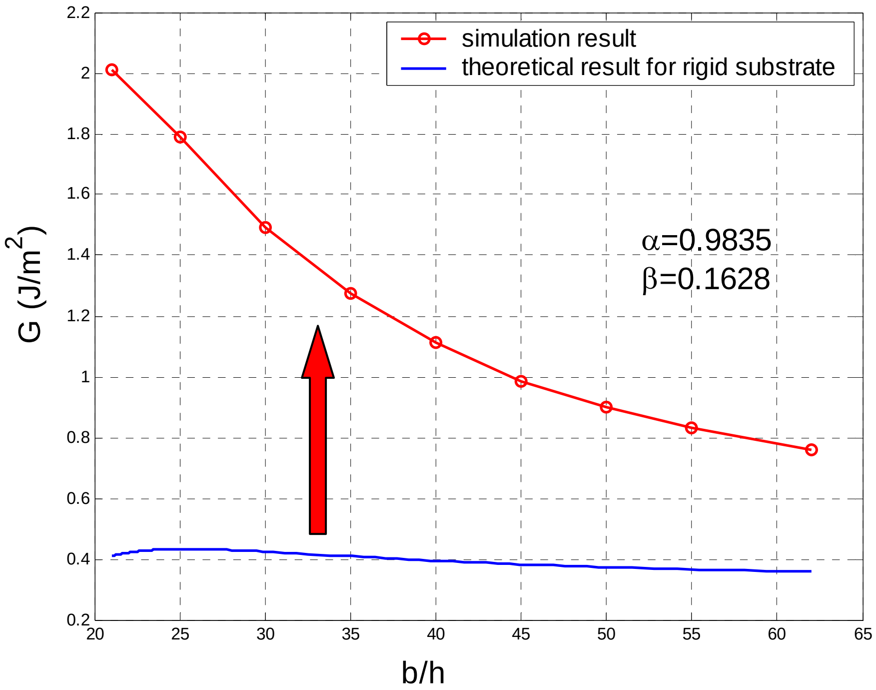
- **Compressibility strongly depends on interface defects and toughness**
- **No effect of elastic mismatch?**

Effect of compliant substrates

Yu and Hutchinson (2002):

- 1D buckle (plane strain cross section of a straight blister)
- Elastic substrate
- Numerical solutions from a finite element model





$$\varepsilon_c = \frac{\pi^2}{12}\left(\frac{h}{b}\right)^2 \xi(b/h, \alpha, \beta)$$

$$G = \frac{E_f \varepsilon^2 h}{2(1-\nu_f^2)} g\left(\varepsilon, \frac{b}{h}, \alpha, \beta\right)$$

Wrinkling: Analytical Solutions

For thick, elastic substrates ($h_s >> h_f$):

For arbitrary thickness: Huang, *J. Mech. Phys. Solids* 53, 63 (2005).

Critical strain:

$$\varepsilon_c = \frac{1}{4}\left(\frac{3\overline{E}_s}{\overline{E}_f}\right)^{2/3}$$

$$\overline{E}_s << \overline{E}_f$$

Small strain!

Equilibrium wavelength:

$$\lambda_{eq} = 2\pi h_f \left(\frac{\overline{E}_f}{3\overline{E}_s}\right)^{1/3}$$

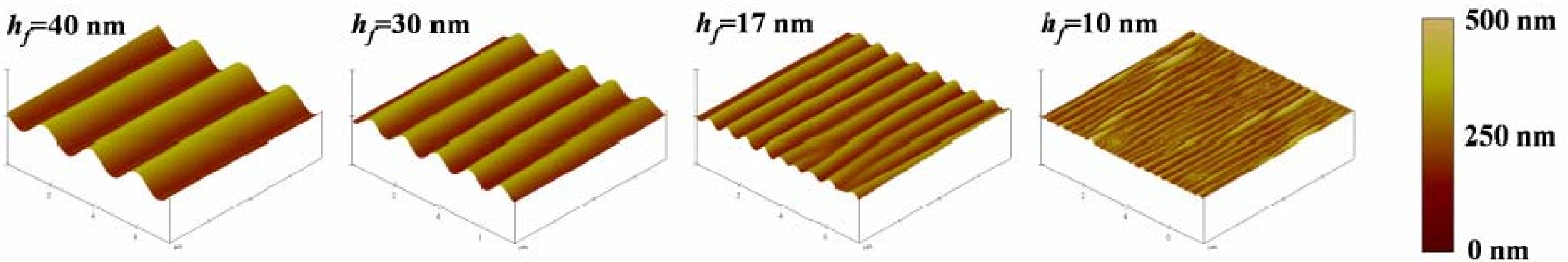
Equilibrium amplitude:

$$A_{eq} = h_f \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)^{1/2}$$

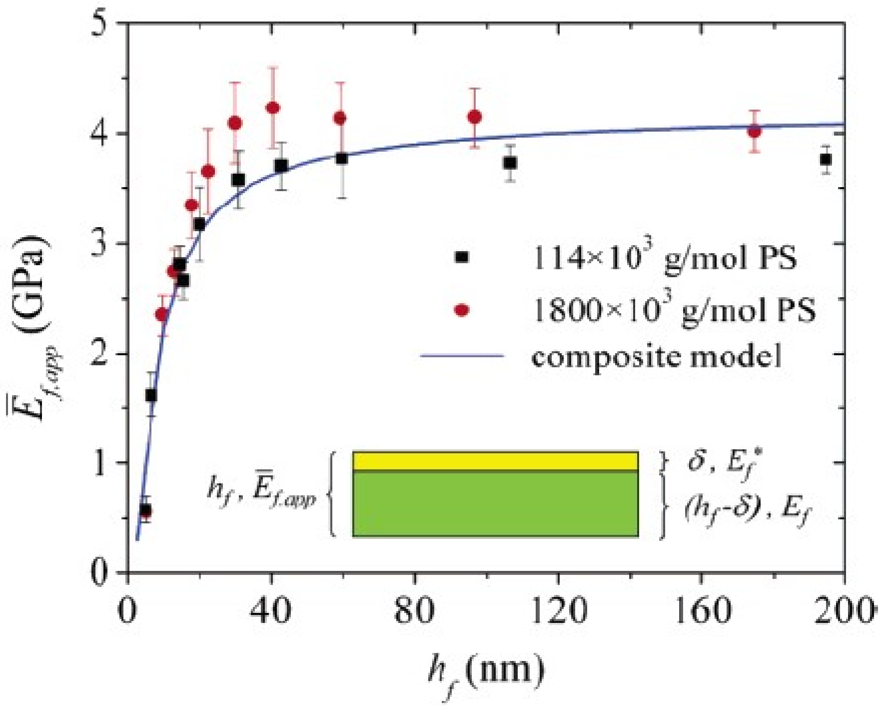
⇒ Measure wavelength to determine film stiffness;

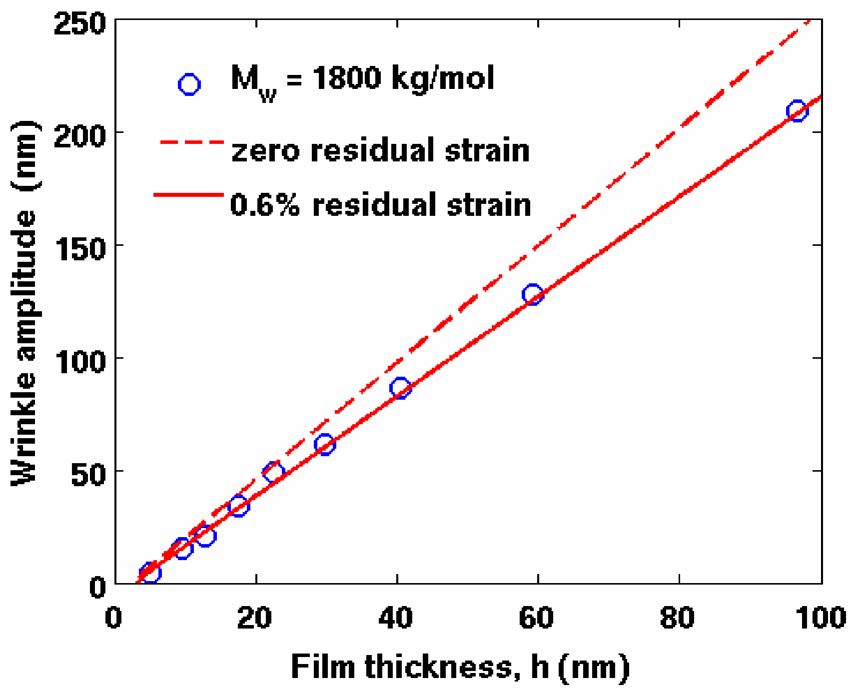
Measure amplitude to determine film stress/strain.

Ultrathin PS Film on PDMS



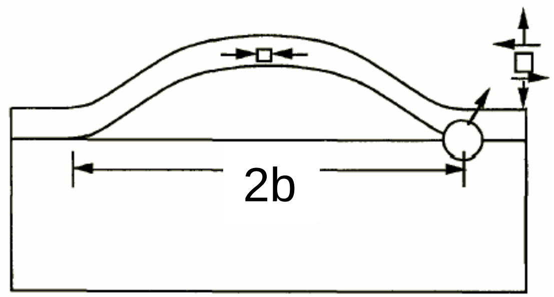
Applied strain: $\varepsilon = 2.5\%$



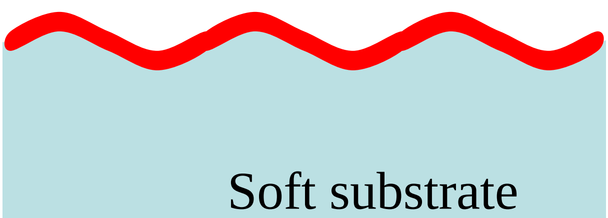


Stafford et al., Macromolecules 39, 5095 (*2006*).

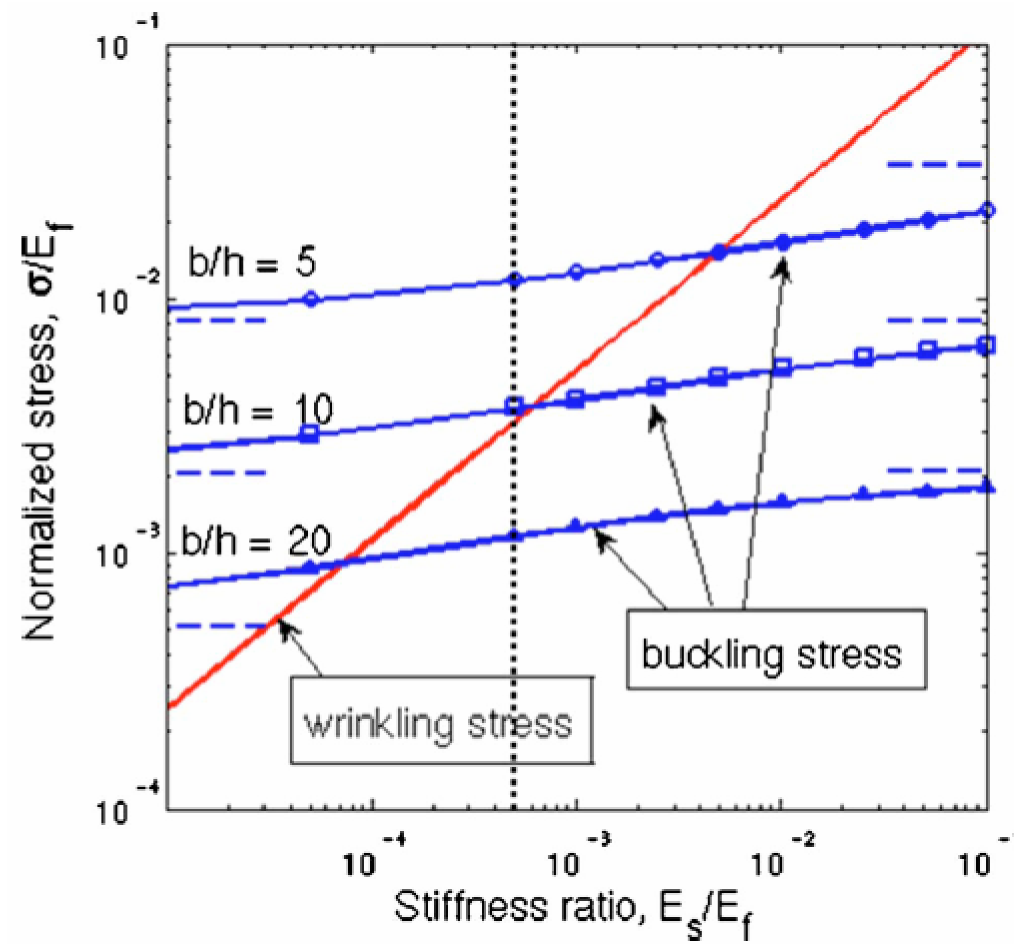
Wrinkling vs Buckling



$$\sigma_B = \frac{\pi^2}{12}\left(\frac{h}{b}\right)^2 \bar{E}_f \xi(\alpha, \beta)$$



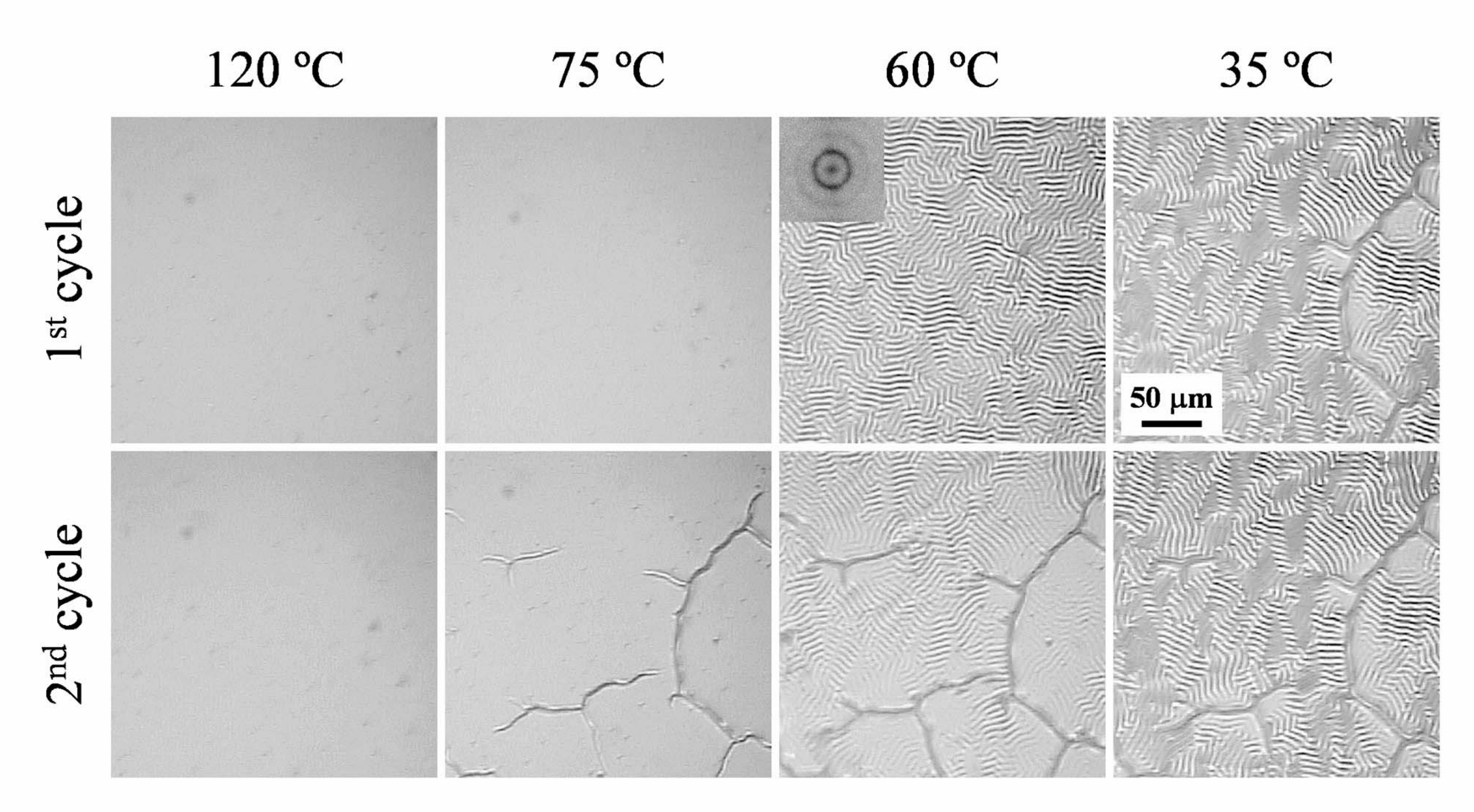
$$\sigma_W = \frac{3^{2/3}}{4}\left(\frac{1-\alpha}{1+\alpha}\right)^{2/3} \bar{E}_f$$



Transition of buckling mode!

Mei et al., Appl. Phys. Lett. 90, 151902 (*2007*).

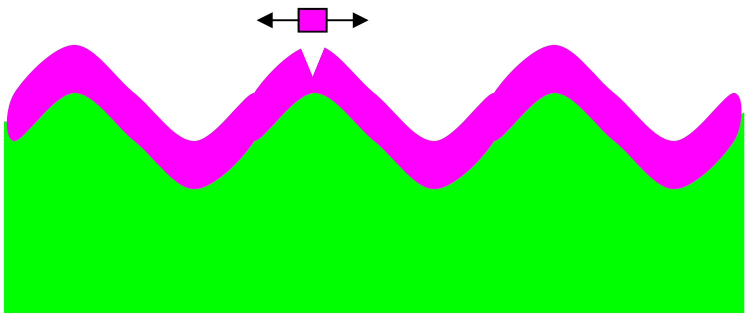
PS thin film on PDMS

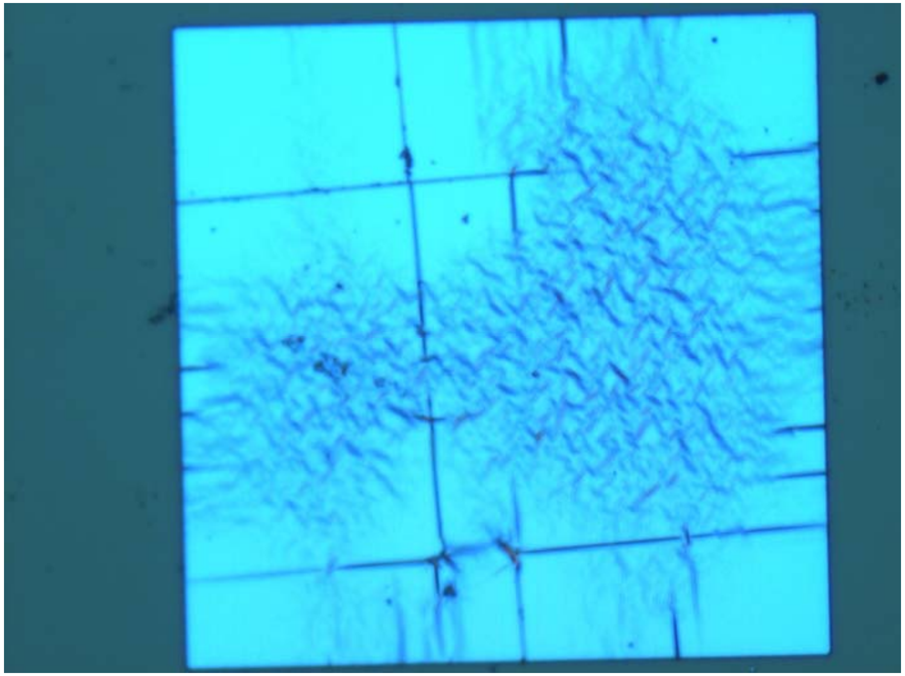


- **1st cycle: small defects, wrinkling followed by buckle-delamination**
- **2nd cycle: large defects, buckle-delamination followed by wrinkling**

Mei et al., Appl. Phys. Lett. 90, 151902 (*2007*).

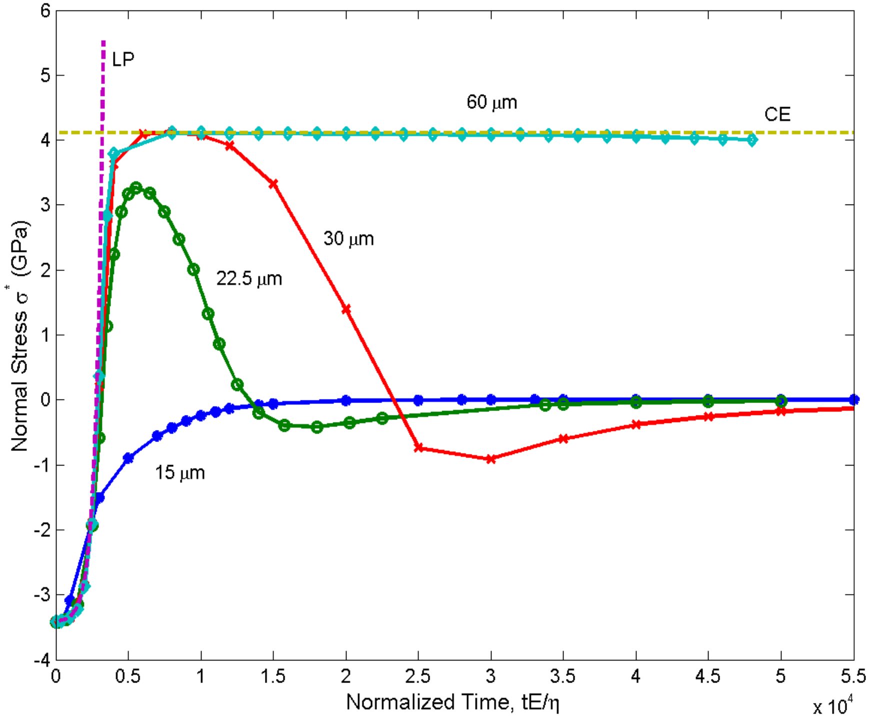
Wrinkle-induced fracture





SiGe film on glass

Yin, et al., *J. Appl. Phys.* **94**, 6875 (2003).



$$\sigma_{eq} = \frac{E(kh)^2}{2(1-\nu^2)}\left[\sqrt{\frac{1}{3}\left[\left(\frac{k_c}{k}\right)^2 - 1\right]} - \frac{1}{6}\right]$$

Liang, et al., *Acta Mater* **50**, 2933 (2002).

Summary

- Large-area electronics requires flexible, stretchable, and compressible design.

- Stretchability is limited by film fracture.
- Compressibility may be limited by buckle-delamination or wrinkle-induced fracture.

- Flexibility requires both!