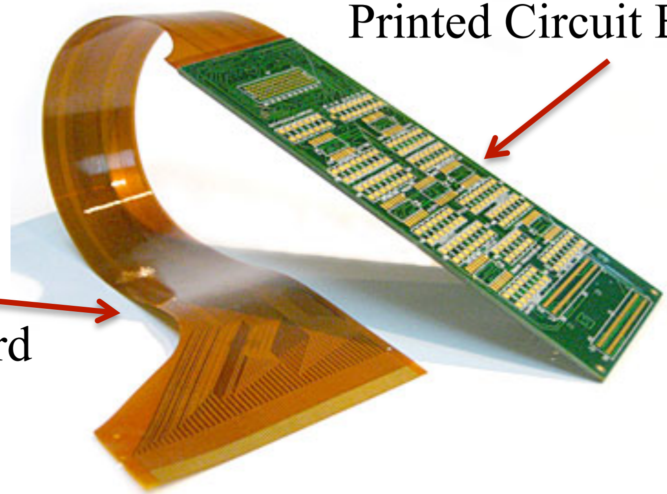
MICRO-514
Flexible electronics

Lecture 2
Mechanical concepts
Wednesdays, 8am to 10am
BM 5202

Concepts

- Flexible electronics is not:
  - Large, passive, PCBs
  - Flexible connectors

Rigid
Printed Circuit Board



Flexible
Printed Circuit Board

http://pcb-prototyping.ready-online.com/pcb-prototypes.html

Inkjet cartridge with flex connector

A flexible circuit is a pliable counterpart to a rigid printed circuit board.

Shaping electronic circuits

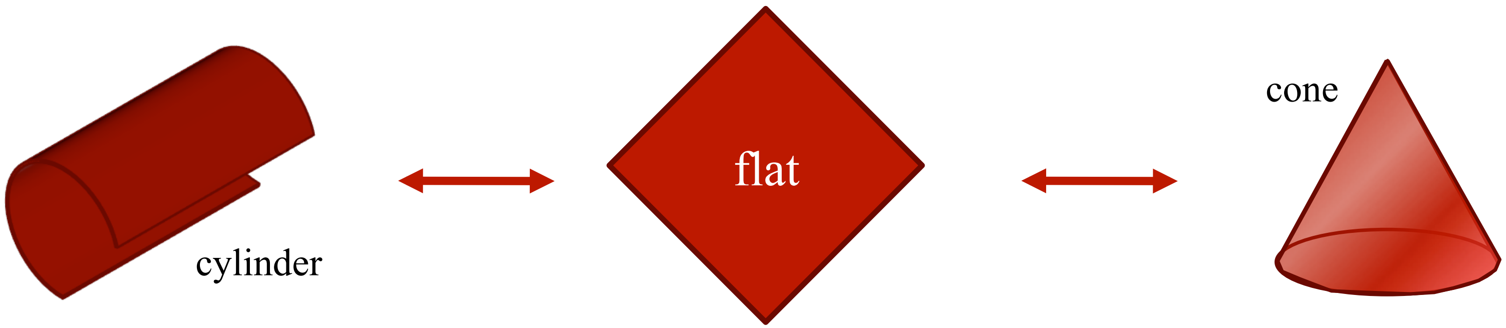
- From 2D, flat surface to 3D, volumetric structure
- Once, permanently or many times

Key mechanical concepts/parameters

- Deforming a surface
- Stress/strain
- Elasticity/plasticity
- Mechanical failure

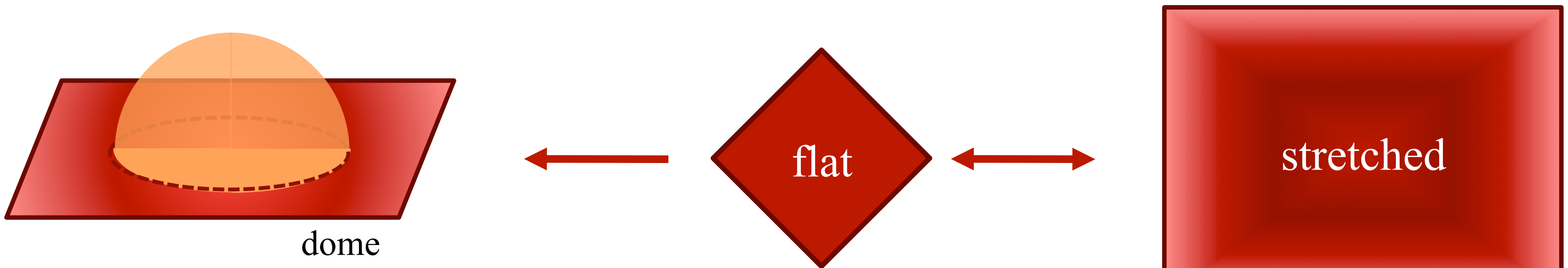
Deforming a surface: Flexibility

- Developable surfaces
  - surfaces that can be flattened onto a plane without distortion



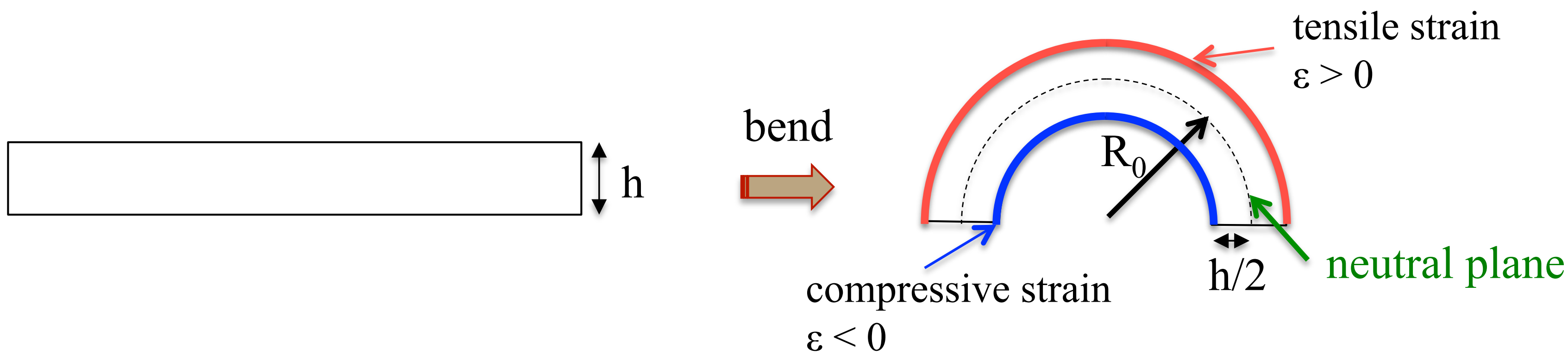
Deforming a surface: Stretchability

- Deformable surfaces
  - Surfaces that can conform complex shapes once or many times
  - Surfaces that can expand and relax reversibly



Mechanical strain

$$strain\ (\varepsilon) = \frac{change\ \ in\ \ length}{original\ \ length} = \frac{\delta L}{L} \times 100\%$$



$$surface\ \ bending\ \ strain = \varepsilon = \pm \frac{h}{2\ R_0}$$

Critical strain

- The critical strain is the maximum applied strain before mechanical fracture

$$\varepsilon_{crit} = \pm \frac{h}{2\,R_{0,\min}}$$

design parameter
10µm to 250µm

material property
Brittle glass: <0.2%
Ductile metal: <20%

application driven
1mm to cm

Example: how thick should a foil be when the critical strain is 0.5%, to allow for a 1cm bending radius?

Critical strain : ε_{crit} = 0.5%
Min. bending radius: R_0 = 1cm

➢ Foil thickness: h = 100µm

True vs engineering strain

- e: true strain

$$e = \int_{L_0}^{L_f} \frac{dL}{L} = \ln\left(1 + \frac{\Delta L}{L_0}\right)$$

ΔL: net elongation
L: instant length, $L_0 < L < L_f$

- ε: engineering strain

$$\varepsilon = \frac{1}{L_0} \int_{L_0}^{L_f} dL = \frac{\Delta L}{L_0}$$

ΔL: net elongation
$L \approx L_0$

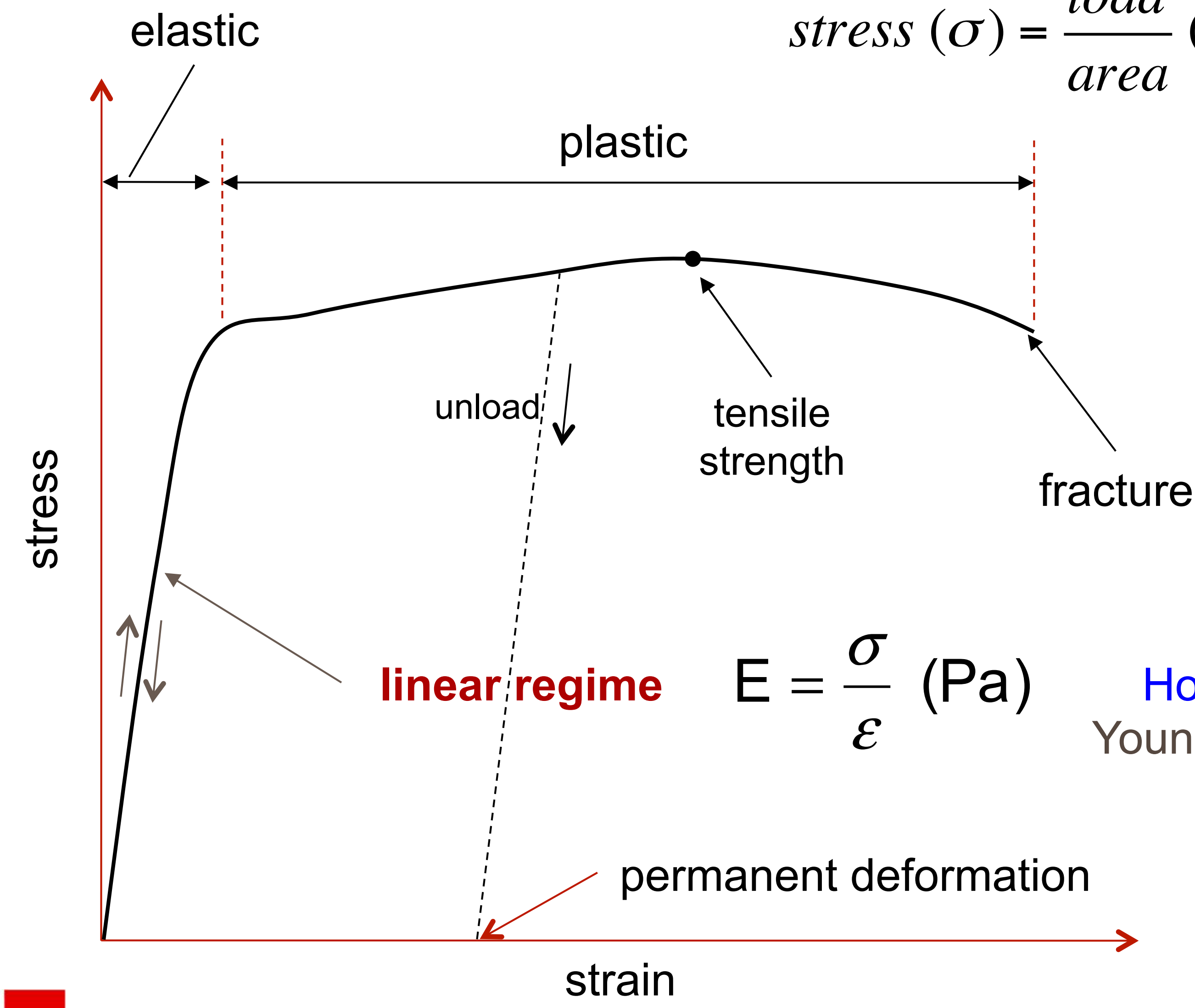
$$e = \ln(1 + \varepsilon)$$

For “small” elongation, i.e., strain < 10%, **$\varepsilon \approx e$**

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Mechanical stress

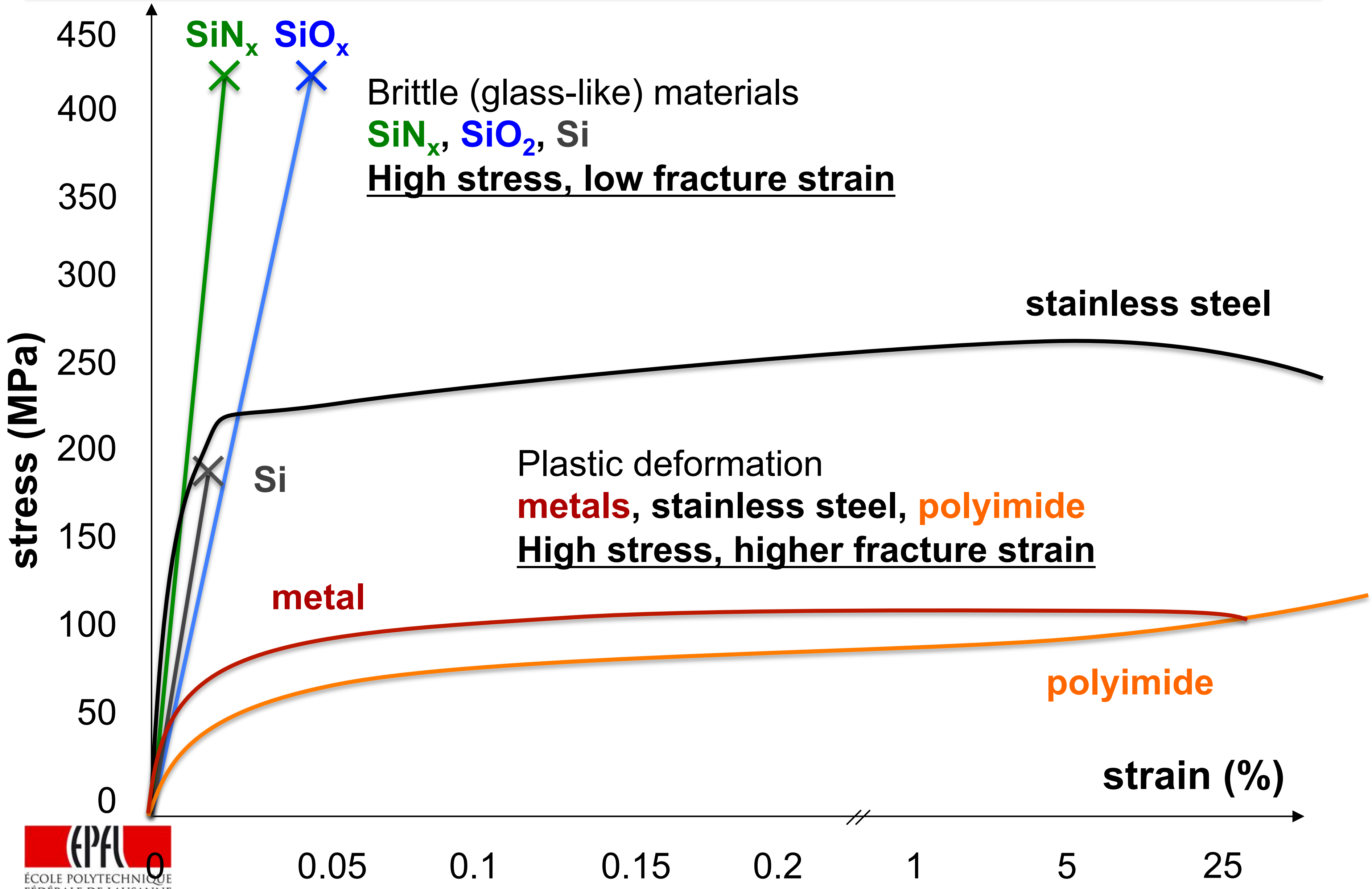
$$stress\ (\sigma) = \frac{load}{area}\ (N/m^2\ or\ Pa)$$



$$E = \frac{\sigma}{\varepsilon}\ (Pa)$$

Hookes' law
Young's modulus

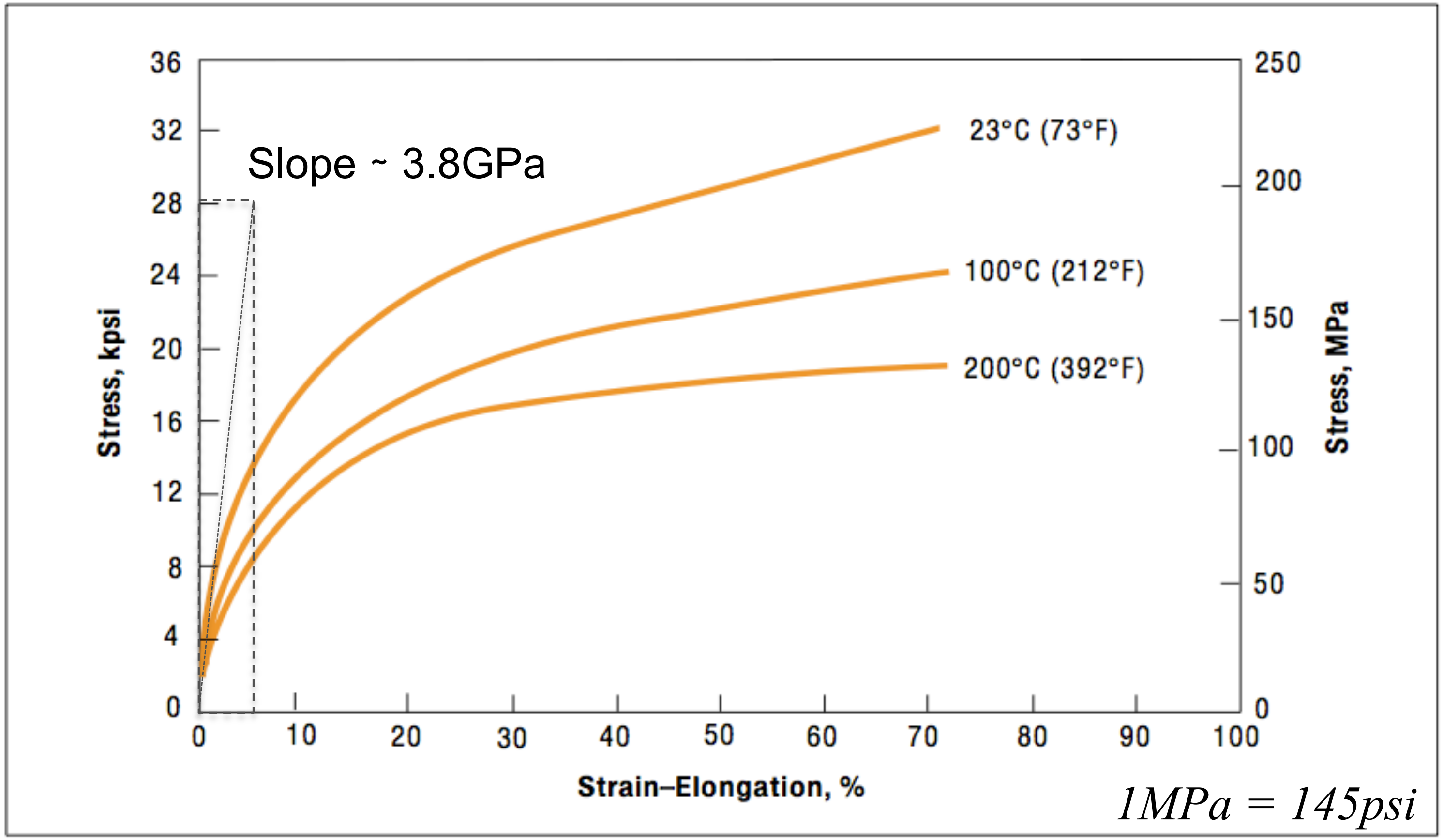
Typical Stress(strain) curves



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Dupont, Polyimide foil (Kapton®)

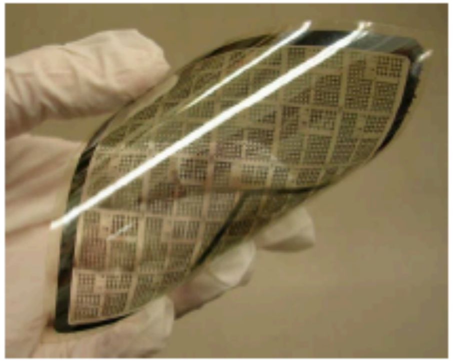
Figure 1. Tensile Stress–Strain Curves, Type HN Film, 25 µm (1 mil)



www2.dupont.com/Kapton/en_US

Substrates for flexible transistor backplane

polymer foil substrate

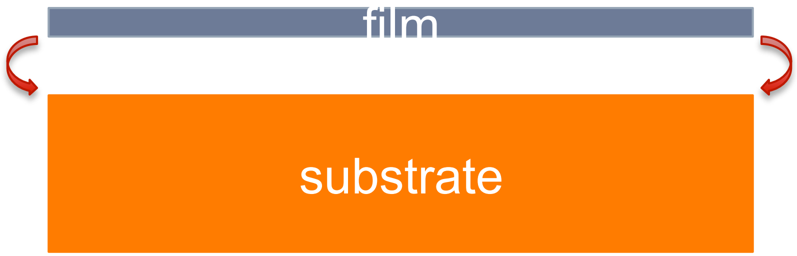


steel foil substrate

<280°C	**process temperature**	up to ~1000°C
low	**dimensional stability**	>10 times higher
yes	**permeable to O_2 or H_2O**	no
no	**electrical conductor**	yes
some	**visually clear**	no
moderate	**surface roughness**	rough

Courtesy Prof. S. Wagner, Princeton University

Film-on-substrate



Young's modulus, thickness

Film: E_f, d_f

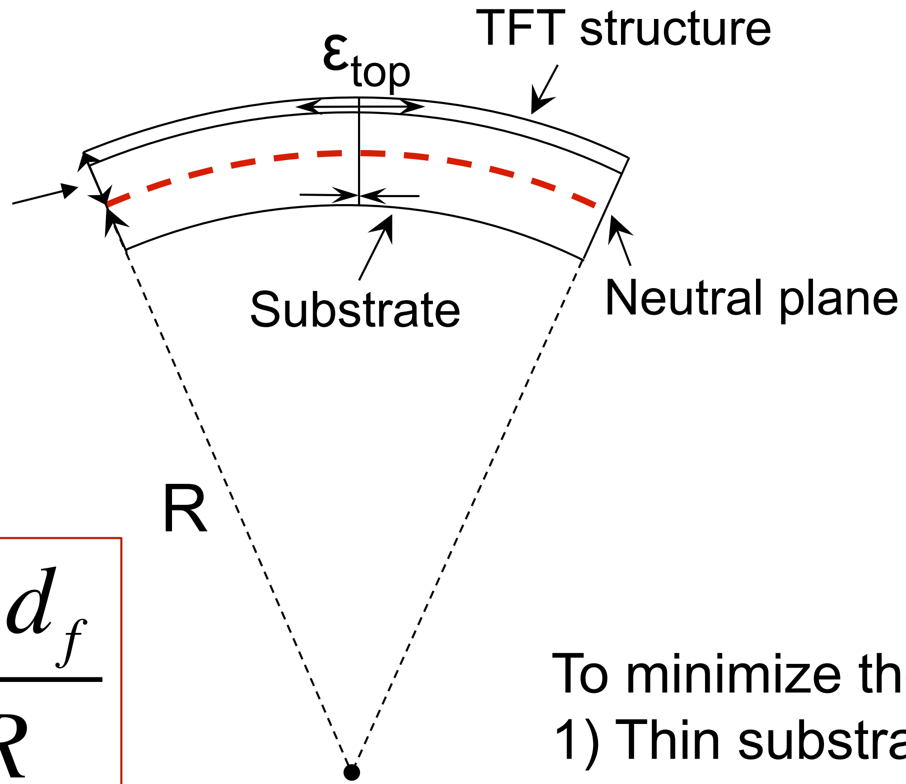
Substrate: E_s, d_s

$E_f \cdot d_f \ll E_s \cdot d_s$	The substrate dominates; The film complies with it.	Ex. Film on glass
$E_f \cdot d_f \approx E_s \cdot d_s$	Equal strength of film and substrate	Ex. Film on plastic
$E_f \cdot d_f \gg E_s \cdot d_s$	The film dominates, The substrate complies with it	Ex. Film on rubber

Bending a film-on-substrate stack

Stiff substrates $E_f \cdot d_f \ll E_s \cdot d_s$

Distance from top to neutral plane $d = \frac{d_f + d_s}{2}$



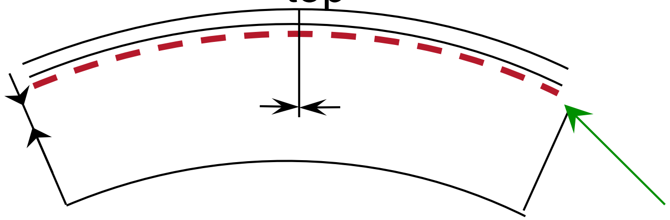
$$\varepsilon_{top} = \frac{d}{2R} = \frac{d_s + d_f}{2R}$$

To minimize the strain use:
1) Thin substrate
2) Compliant substrate
3) Encapsulation

Bending a film-on-substrate stack

Compliant substrates $E_f \cdot d_f \approx E_s \cdot d_s$

Distance from top to neutral plane $d < \frac{d_f + d_s}{2}$



$$\varepsilon_{top} = \left(\frac{d_s + d_f}{2R}\right)\frac{1+2\eta+\chi\eta^2}{(1+\eta)(1+\chi\eta)}$$

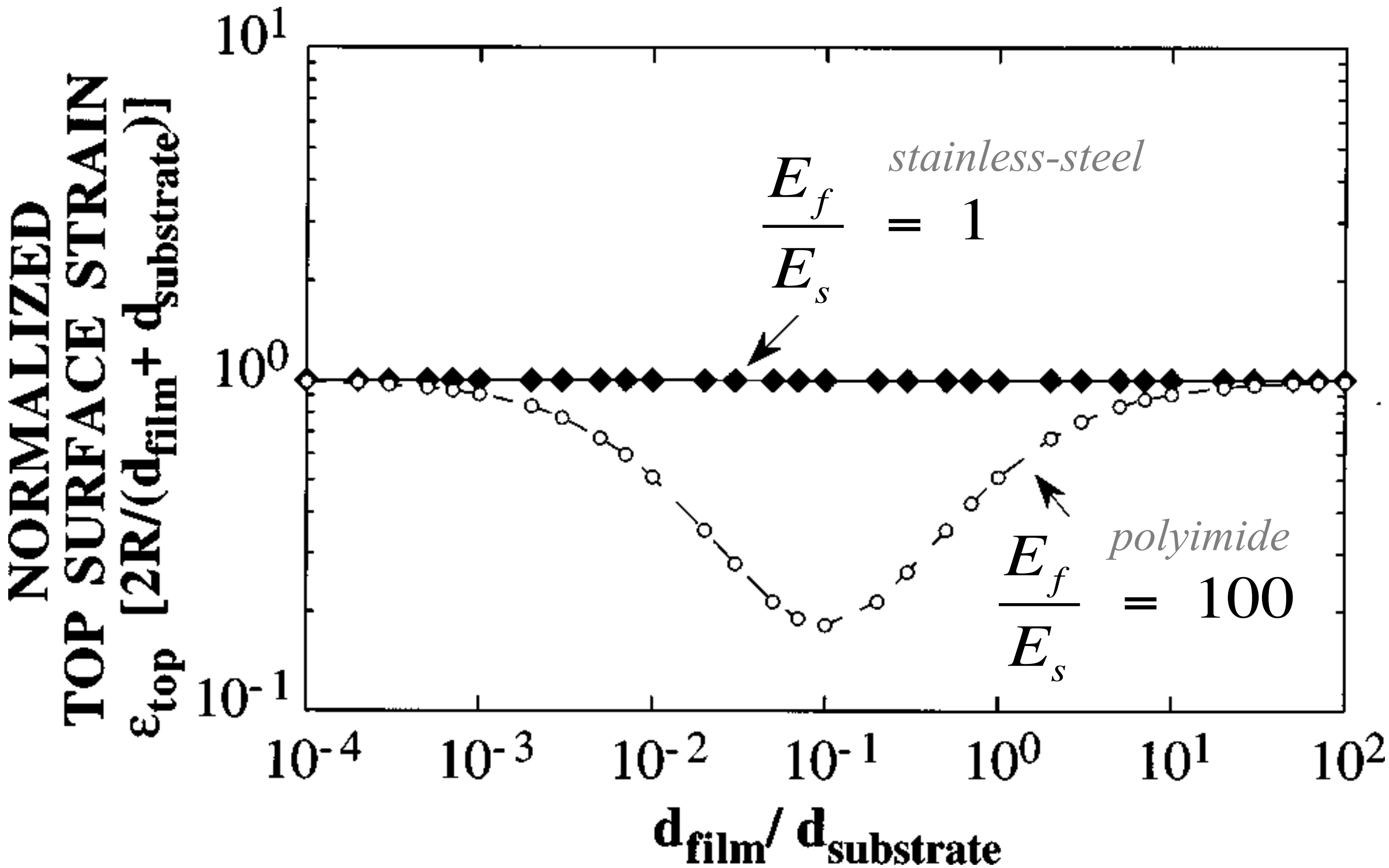
with $\eta = d_f / d_s$

$\chi = E_s + E_f$

Z. Suo et al, 1999, Applied Physics Letters, 74 8, 1177-1179.

Film on compliant substrate

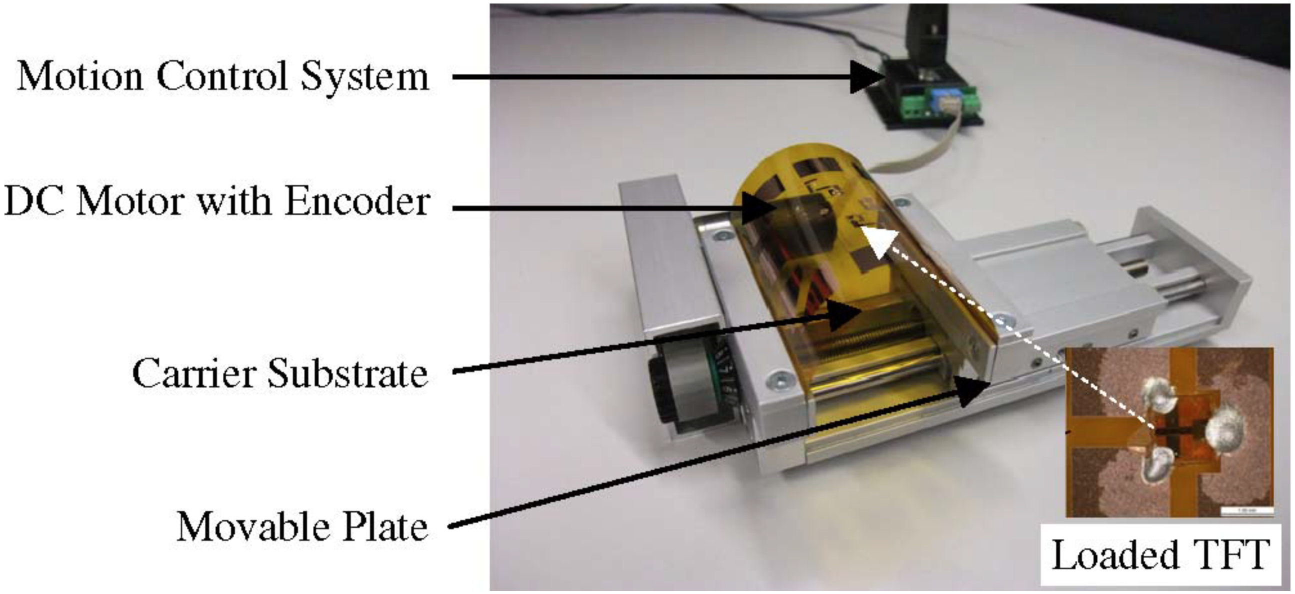
Strain in the film as a function of film/substrate thickness ratio

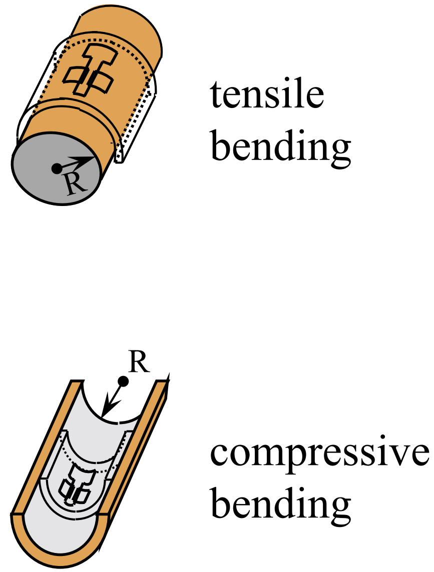


Z. Suo et al, 1999, Applied Physics Letters, 74 8, 1177-1179.

Bending experiments

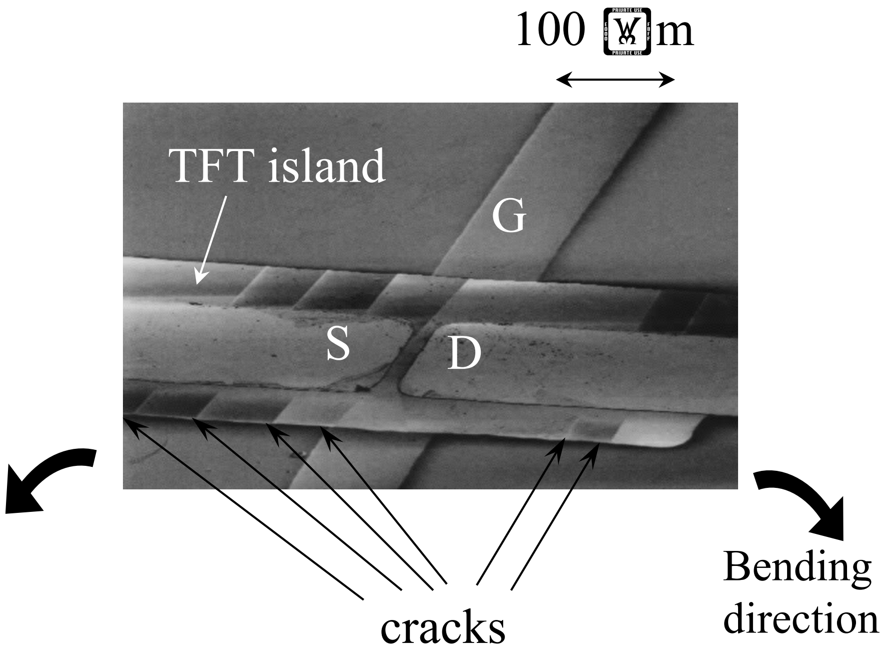
- Thin Film Transistor (TFT) on foil probed during bending
- The uniaxial strain in the TFT depends on the bending radius R





K. Cherenack et al, 2010, IEEE Electron Device Letters, 31 11, 1254-1256.

Mechanical failure at large strain

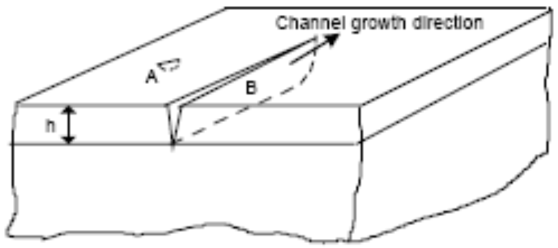


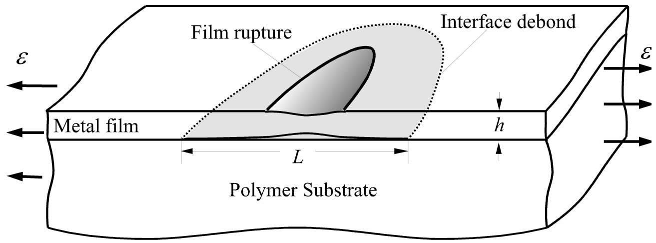
Tensile strain: **fracture** of the thin films at ~ **0.5%** strain (2mm = R)

H. Gleskova et al, 1999, Applied Physics Letters, 75 19, 3011-3013.

Mechanical failure in thin films of device materials

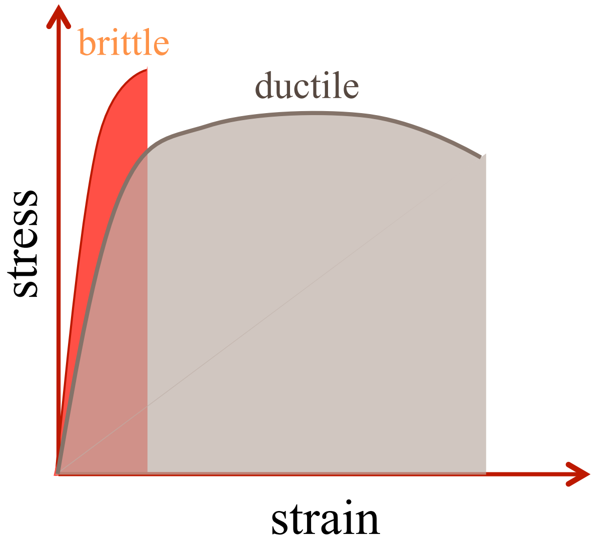
- Brittle behaviour
- Ductile behaviour





Crack propagates

– Semiconductors
– Dielectrics
– Metal oxides



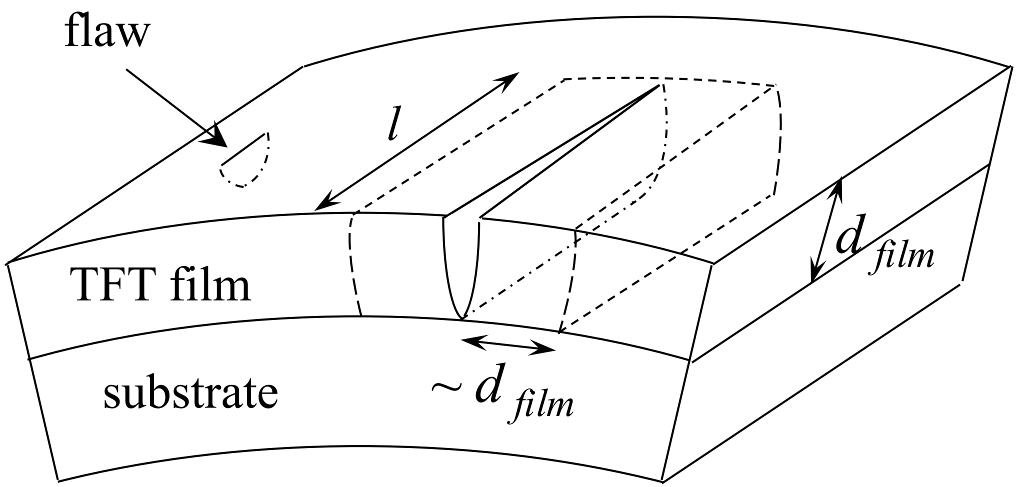
Film necks

– Metals

Z. Suo, Harvard University,
http://www.seas.harvard.edu/suo/

Fracture mechanism under tension

- Crack formation starts at a pre-existing flaw
- The top surface of the TFT film withstands the highest strain



Elastic energy released:

$$2\beta\frac{\left(1-\upsilon_{film}\right)\sigma_{film}^{2}d_{film}^{2}l}{Y_{film}}$$

Energy of formed crack:

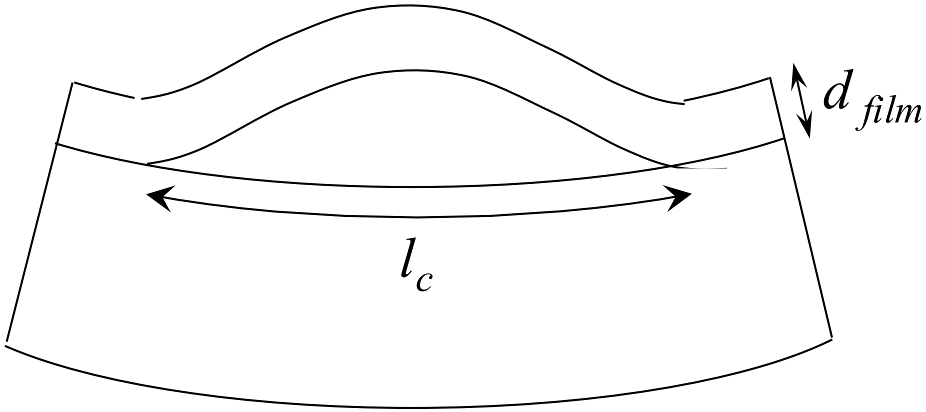
$$2\Gamma l d_{film}$$

⇒ Passivate surface to suppress crack initiation

H. Gleskova, Princeton University

Fracture mechanism under compression

- Crack formation starts from a pre-existing debonded area, followed by buckling



Critical unbonded length:

$$l_c = \frac{\pi d_{film}}{\sqrt{3\left(1-\upsilon_{film}^2\right)}}\sqrt{\frac{Y_{film}}{\sigma_{film}}}$$

For $\varepsilon = \frac{\sigma_{film}}{Y_{film}} \sim 0.02$

$$l_c \sim 10 d_{film} \sim 10 \mu m$$

$\Rightarrow$ Good adhesion is important

H. Gleskova, Princeton University

Summary of lecture 2

- Thin $\Rightarrow$ flexible
- Device materials and substrates have very different mechanical properties
- Maximum bending depends on the thickness and elastic modulus of the film and substrate