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Mechanical Reliability

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EPFL-IMX LPAC

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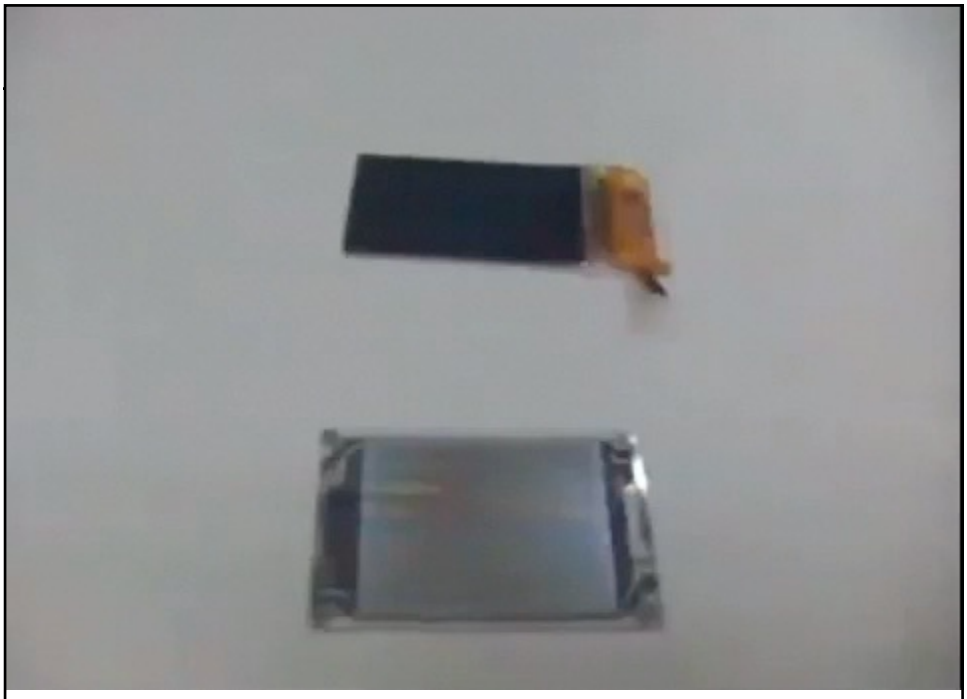

http://www.youtube.com/watch?v=DPF9Kp7W_s0&feature=related

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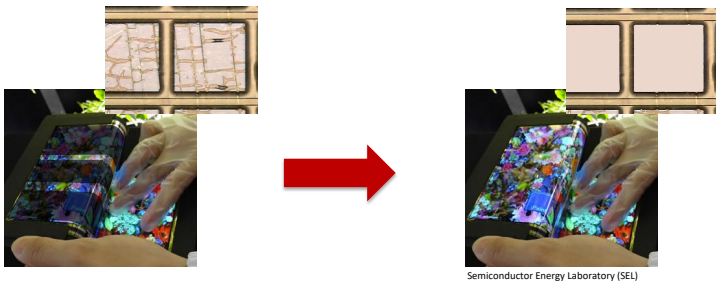
Objectives

- understand the key factors, which control the mechanical integrity of soft microsystem and flexible electronic devices.
- learn the essential ingredients to design and produce reliable devices on soft substrates with examples of ongoing research.

Defective display with cracked layers

Robust display with intact layers



Semiconductor Energy Laboratory (SEL)

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Objectives

- understand the key factors, which control the mechanical integrity of soft microsystem and flexible electronic devices.
- learn the essential ingredients to design and produce reliable devices on soft substrates with examples of ongoing research.

Key questions

- What factors determine the critical strain at which damage initiates in soft microsystems?
- How can you measure the mechanical properties of thin films on polymers and why is it challenging?
- How does environmental conditions (temperature, moisture) impact the critical failure strain?
- How to reduce cracking of brittle layers in soft devices, and how to increase lifetime stability of such devices?

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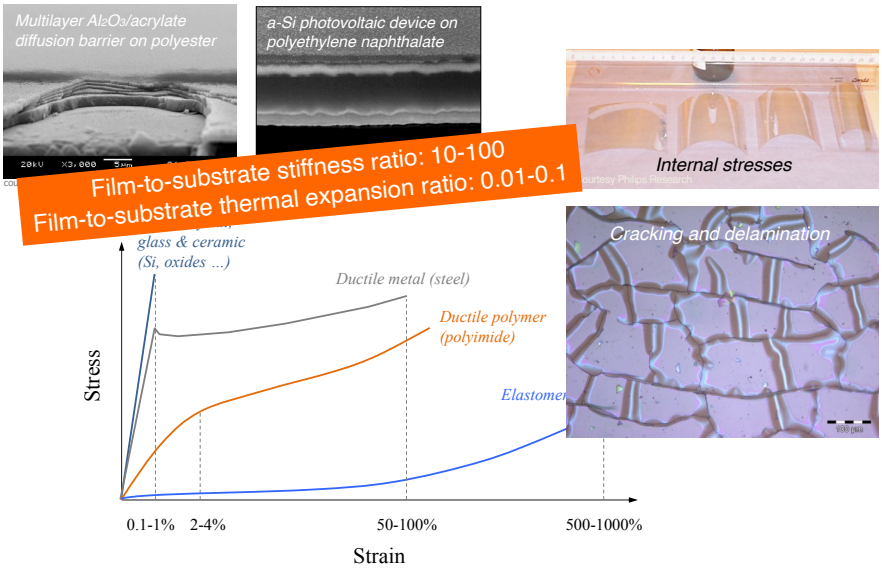
Challenge = huge property contrast in multilayers!



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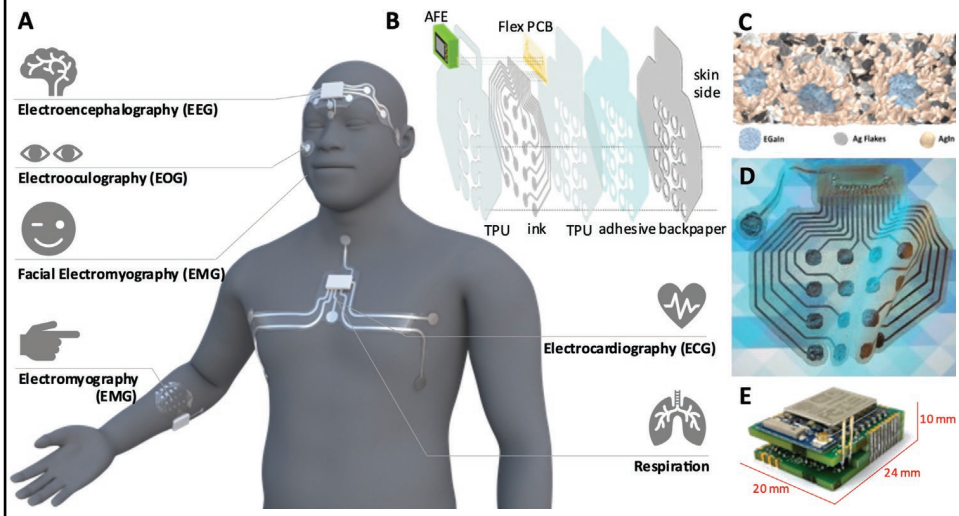
Challenge = mechanical reliability!

Multi-Electrode Printed Bioelectronic Patches for Long-Term Electrophysiological Monitoring



Manuel Reis Carneiro, Carmel Majidi, Mahmoud Tavakoli, Adv. Funct. Mater. **2022**, 2205956

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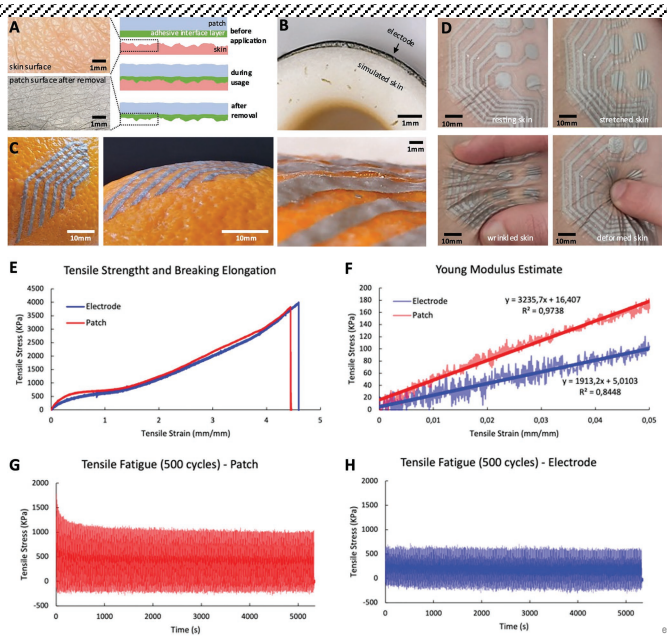
Challenge = mechanical reliability!



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Outline

1. Introduction: critical strain
2. Stress and strain analyses
3. Failure mechanisms under tensile and compressive stress
4. Durability influences
5. Summary

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Critical strain

The critical strain ε_{crit} is the strain at which film failure occurs due to mechanical damage (cracking, delamination).

- flexible electronics, which comprise films with $\varepsilon_{crit} < 2\%$, are based on substrate materials that are thin enough (100 µm) to be safely bent to radius of curvature down to 10 mm, but cannot be stretched.
- compliant electronics, for which $2\% < \varepsilon_{crit} < 10\%$, can be flexed to radius of curvature of few mm, allow some in-plane loading and can be used with thicker substrates.
- stretchable electronics, for which $\varepsilon_{crit} > 10\%$, can be conformed to a broad diversity of surfaces with 2D curvatures and small radius below few mm.

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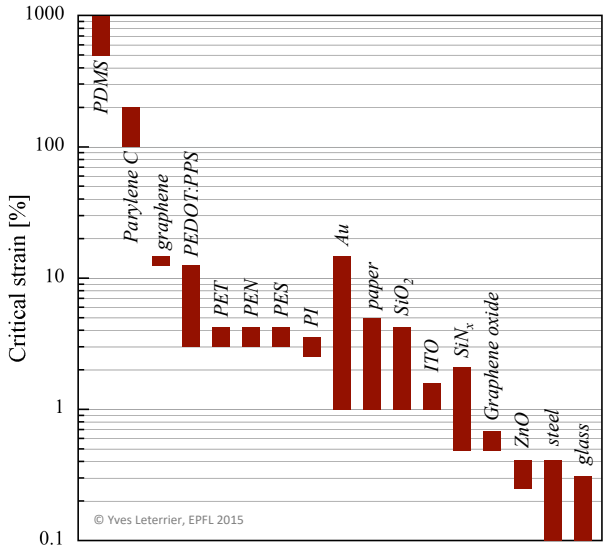
Relevant material properties: critical strain



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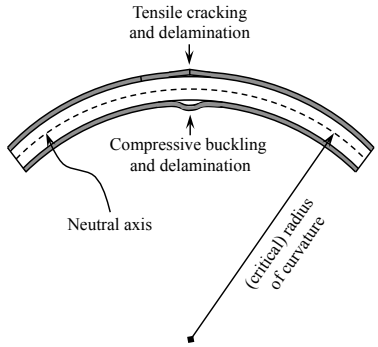
Critical strain and critical radius of curvature



The critical radius of curvature is determined by

- the architecture of the device (e.g., position of neutral axis, layer thickness …)
- the *critical strain*, ε_{crit} , controlled by:
  - Cohesive properties of brittle layers, and related tensile failure
  - Interfacial adhesion, and related adhesive failure (delamination)
  - Process-induced internal stresses

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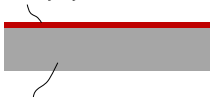
Critical strain and critical radius of curvature

For a bilayer film/substrate structure

film: h_f, E_f



substrate: h_s, E_s

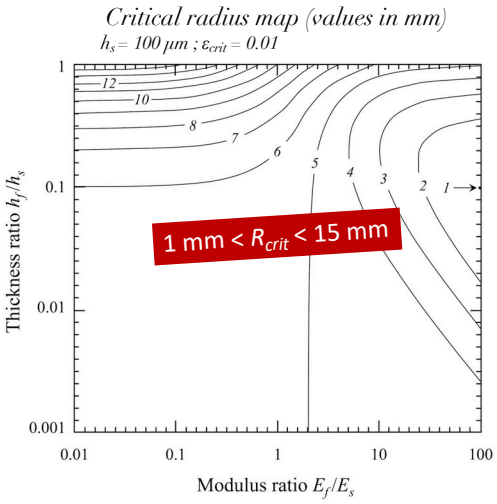
$$R_{crit} = \left(\frac{h_f + h_s}{2\,\varepsilon_{crit}}\right) \cdot \left(\frac{1 + 2\eta + \chi\eta^2}{(1+\eta)(1+\chi\eta)}\right)$$

$\eta = h_f / h_s$ and $\chi = E_f / E_s$

E_i Young's moduli

h_i thicknesses

ε_{crit} critical strain



Suo et al. *Appl. Phys. Lett.*, **74**, 1177 (1999)
Leterrier, in *Handbook of Flexible Organic Electronics: Materials, Manufacturing and Applications*, Woodhead (2015)

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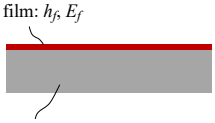
Critical strain and critical radius of curvature

For a bilayer film/substrate structure

film: h_f, E_f



substrate: h_s, E_s

$$R_{crit} \cong \frac{h_s}{2\,\varepsilon_{crit}} \text{ for } h_f << h_s \text{ and } E_f >> E_s$$

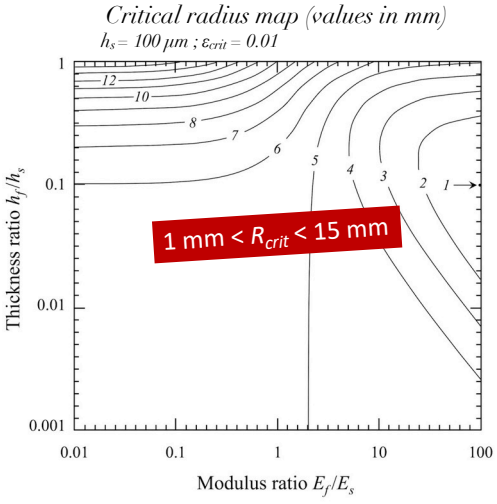
$\eta = h_f / h_s$ and $\chi = E_f / E_s$

E_i Young's moduli

h_i thicknesses

ε_{crit} critical strain

thinner substrates enable smaller critical radii



Suo et al. *Appl. Phys. Lett.*, **74**, 1177 (1999)
Leterrier, in *Handbook of Flexible Organic Electronics: Materials, Manufacturing and Applications*, Woodhead (2015)

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Critical strain and critical radius of curvature

Material	Thickness [µm]	ε_{crit} [%]	R_{crit} [mm]
Glass	600	0.1	300
Steel	100	0.2	25
Polymer	100	2	2.5
Thin inorganic film	0.1	1	0.005 (5 µm)
Thin inorganic film on polymer	100.1	1	5

Suo et al. *Appl. Phys. Lett.*, **74**, 1177 (1999)
Leterrier, in *Handbook of Flexible Organic Electronics: Materials, Manufacturing and Applications,* Woodhead (2015)

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Relevant material properties

The calculation of the critical radius requires to know the critical strain (usually associated with film cracking or delamination) and, for all layers, their:

- thickness (*h*)
- Young's modulus (*E*)
- Poisson's ratio (ν)
- coefficient of thermal expansion (*CTE*)
- coefficient of hygroscopic expansion (*CHE*)

} *a priori* *T* and *RH* dependent properties, especially for polymers
(*E* may also depend on strain and on time)

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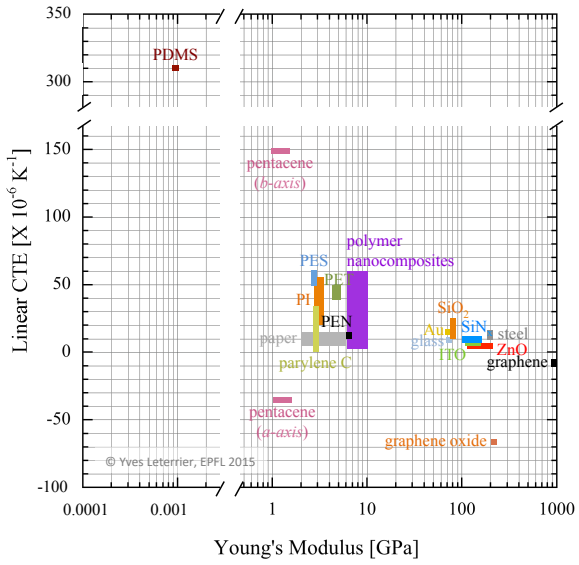
Relevant material properties: CTE and Young's modulus



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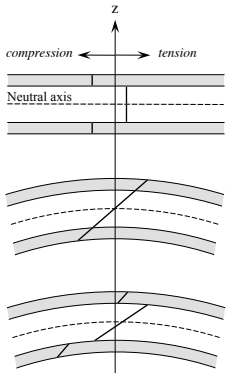
Stress and strain analyses

Bending mode

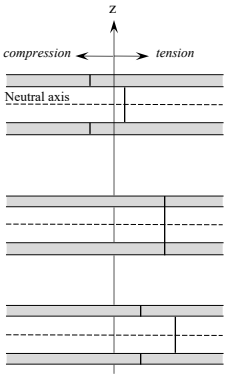


Internal strain

Bending strain

Total strain

Tensile mode



Internal strain

Tensile strain

Total strain

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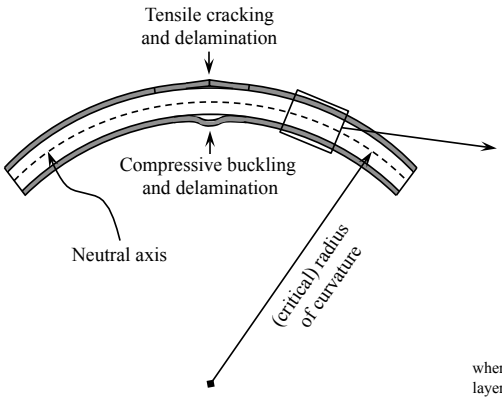
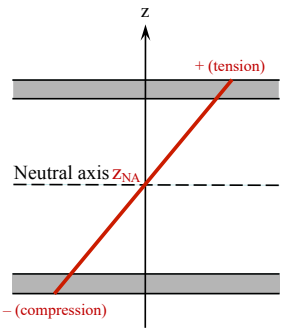
Bending strain

Bending strain $\varepsilon(z) = \frac{z - z_{NA}}{R}$ where $z_{NA} = \frac{\sum_{i=1}^{N} \bar{E}_i h_i \bar{z}_i}{\sum_{i=1}^{N} \bar{E}_i h_i}$





where $\bar{E}_i = E_i / (1 - \nu_i^2)$ is the plane strain modulus of layer i (E_i and ν_i are its Young's modulus and Poisson's ratio, respectively), $\bar{z}_i$ is the position of the mid-plane of layer i, h_i is the thickness of layer i, and N is the number of layers.

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Neutral axis design

'Neutral axis design' approaches to minimize strain in brittle layers under bending:

1) Thin substrate (ε(z) ~ z/R)

2) Compliant substrate (shift of neutral axis)

3) Encapsulation

$$z_{NA} = \frac{\sum_{i=1}^{N} \bar{E}_i h_i \bar{z}_i}{\sum_{i=1}^{N} \bar{E}_i h_i}$$

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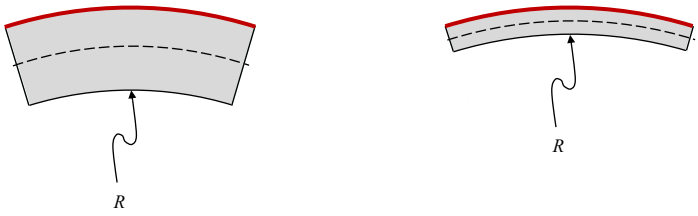
Neutral axis design: Thin substrate

Strain in film: $\varepsilon \cong \frac{h_s}{2R}$



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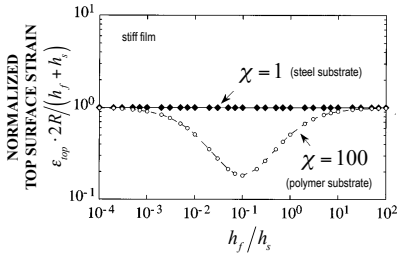
Neutral axis design: compliant substrate

'Neutral axis design' approaches to minimize strain in brittle films under bending:

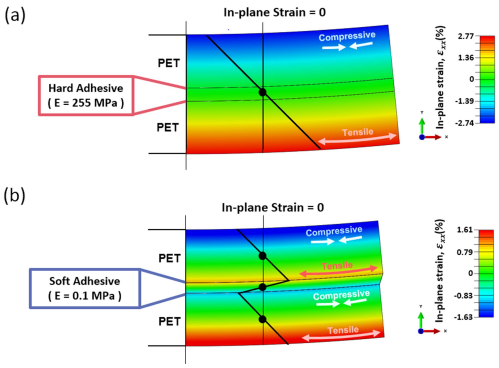
Compliant substrates can reduce the bending strain by as much as a factor of 5 owing to the shift of the neutral axis towards the film

$$\varepsilon_{top} = \left(\frac{h_f + h_s}{2R}\right) \cdot \left(\frac{1 + 2\eta + \chi\eta^2}{(1+\eta)(1+\chi\eta)}\right)$$

$$\eta = h_f / h_s \quad and \quad \chi = E_f / E_s$$



Multilayer design with multiple neutral axes based on soft adhesives



Kim et al., Nanotechnology 28, 194002 (2017)

Suo et al., *Appl. Phys. Lett.* 74 (1999)

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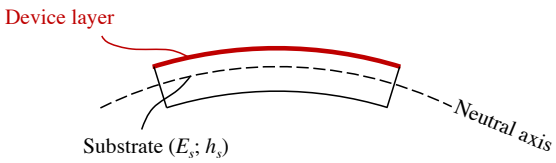
Neutral axis design: encapsulation



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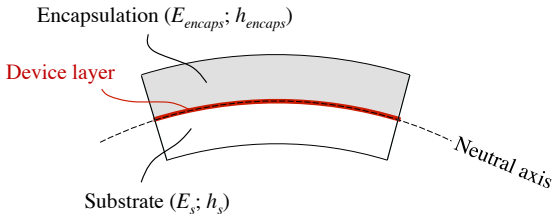
Neutral axis design: encapsulation



For negligible film thickness, the film is placed at the neutral plane when $E_s \cdot h_s^2 = E_{encaps} \cdot h_{encaps}^2$

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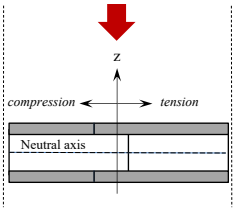
Internal stresses and strains

initial 'stress free' state

Differential change of dimensions
(e.g. thermal contraction upon cooling)

Force and momentum balance



Final equilibrium state
with internal strains

thermal strain

$$\varepsilon_i^{thermal} = \left(\alpha_s - \alpha_f\right) \cdot \Delta T$$

α_i = CTE_i

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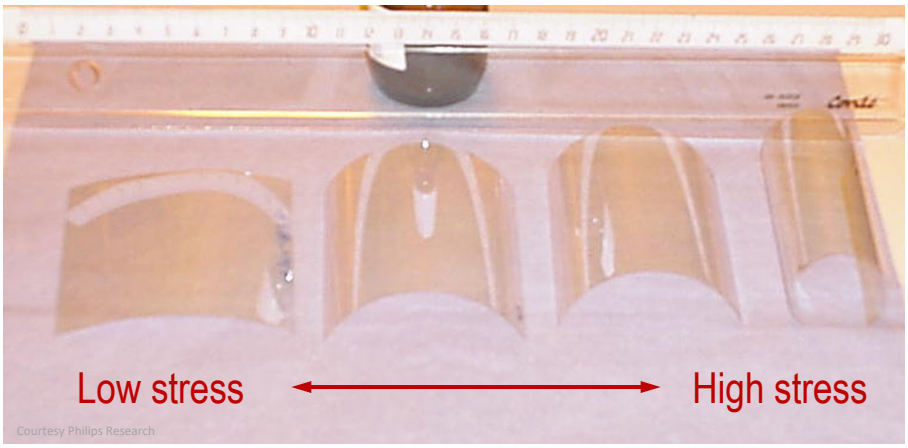
Internal stresses and strains



(Internal stress = Internal strain x Elastic modulus)

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Internal stresses and strains

$$\varepsilon_i = \sigma_i / \overline{E_f} \quad \rightarrow \quad \varepsilon_{crit} = \varepsilon^*_{crit} - \varepsilon_i$$

σ_i; ε_i : internal stress; strain

ε_{crit}; ε^*_{crit} : critical strain; critical intrinsic strain

$\overline{E_f}$: effective film modulus

- plane stress: $\overline{E_f} = E_f$ (Young's modulus)
- plane strain: $\overline{E_f} = E_f / \left(1 - \nu_f^2\right)$ (ν_f Poisson's ratio)
- biaxial stress: $\overline{E_f} = E_f / \left(1 - \nu_f\right)$

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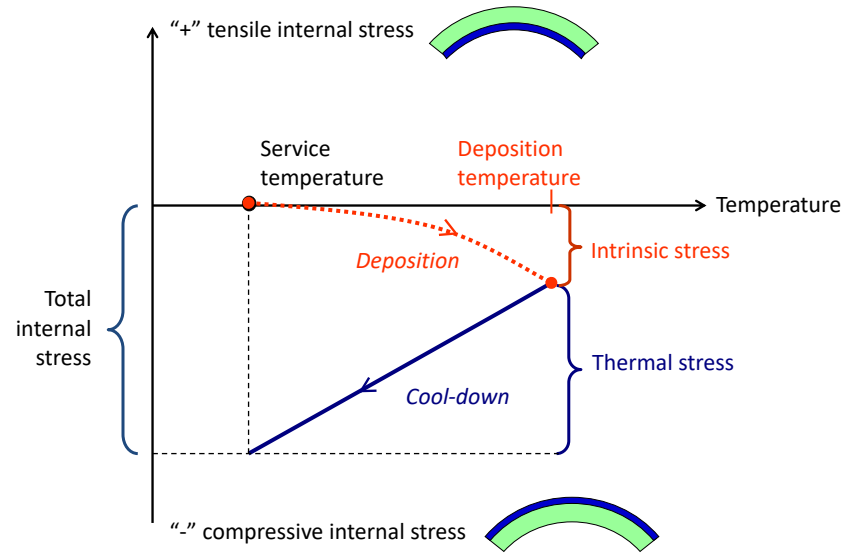
Internal stresses and strains



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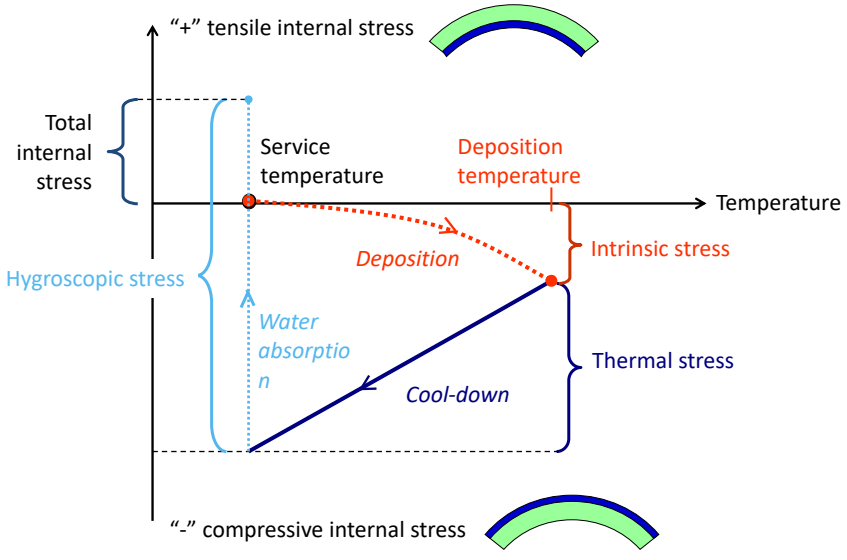
Internal stresses and strains



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Internal stresses and strains

Stress component	Origin	Inorganic films	Organic films
Intrinsic	Film formation (vapor deposition, solution processing)	– or +	+
Thermal	Difference in CTE between film and substrate and temperature changes	–	– or +
Hygroscopic	Difference in CHE between film and substrate and relative humidity changes	+	– or +

– stands for compressive stress
+ stands for tensile stress

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Internal stresses and strains

- Tensile internal stresses may lead to premature cracking
- Compressive internal stresses may lead to premature delamination
- *Low stress* materials and processes are to be favored:
  - low shrinkable inks to limit intrinsic stress
  - room temperature processes to avoid thermal stresses
  - atmospheric processes to limit hygroscopic stresses
  - solution processing, ink-jet, photopolymerization …

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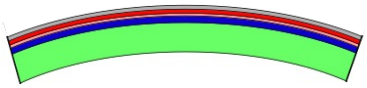
Multilayer Strain Analysis



1 radius of curvature …
∞ number of admissible stress states …

1 thermoelastic solution

$$\frac{1}{R} = \frac{\sum_{k=1}^{N} E_k t_k \sum_{i=1}^{N} E_i t_i \varepsilon_{k,i} \left(\sum_{j=1}^{k} t_j - t_k / 2 \right)}{\frac{1}{12} \sum_{k=1}^{N} E_k t_k \sum_{i=1}^{N} E_i t_i^3 + \frac{1}{2} \sum_{k=1}^{N} E_k t_k \sum_{i=1}^{N} E_i t_i \left(t_i - t_k + 2 \sum_{j=1}^{k} t_j - 2 \sum_{j=1}^{i} t_j \right) \left(\sum_{j=1}^{k} t_j - t_k / 2 \right)}$$

PET substrate (75 µm)
- E_{PET} = 4.8 GPa
- ν_{PET} = 0.4
- α_{PET} = 50 ppm/K

Hard Coat (HC 3 µm)
- E_{HC} = 10 GPa
- ν_{HC} = 0.35
- α_{HC} = 30 ppm/K
- process @ 20°C

SiN_x (200 nm)
- ε_{crit} = 1%
- E_{SiNx} = 200 GPa
- ν_{SiNx} = 0.20
- α_{SiNx} = 3 ppm/K
- process @ 120°C

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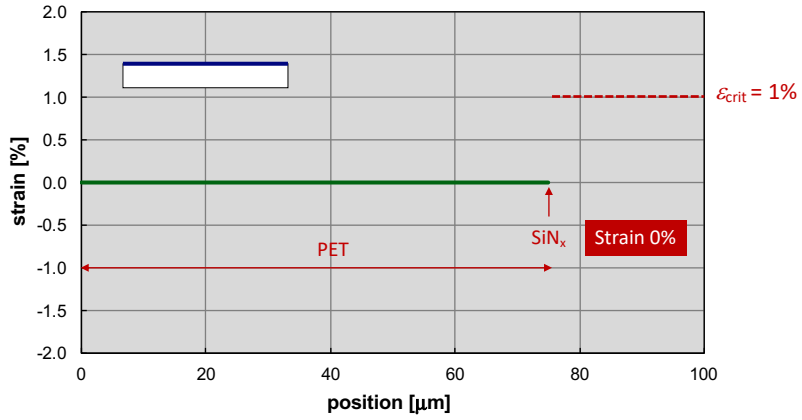
Multilayer Strain Analysis

PET (75 µm) + SiN_x (200 nm) @ 120°C (no HC layer)
Radius of curvature R = ∞ (‘*stress free*’ state)



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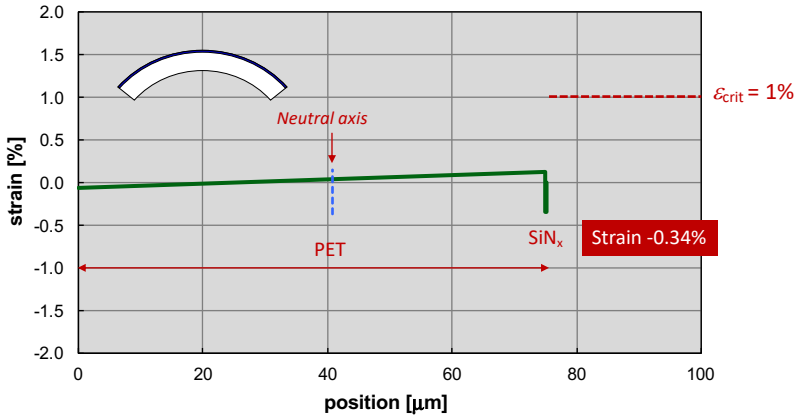
Multilayer Strain Analysis

PET (75 µm) + SiN_x (200 nm) @ 20°C (no HC layer)
Radius of curvature R = 37.9 mm



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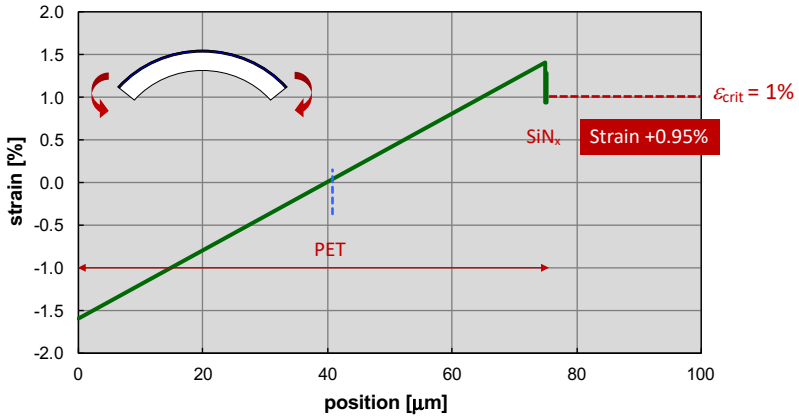
Multilayer Strain Analysis

PET (75 µm) + SiN_x (200 nm) @ 20°C (no HC layer)
Radius of curvature R = 2.5 mm with applied moment



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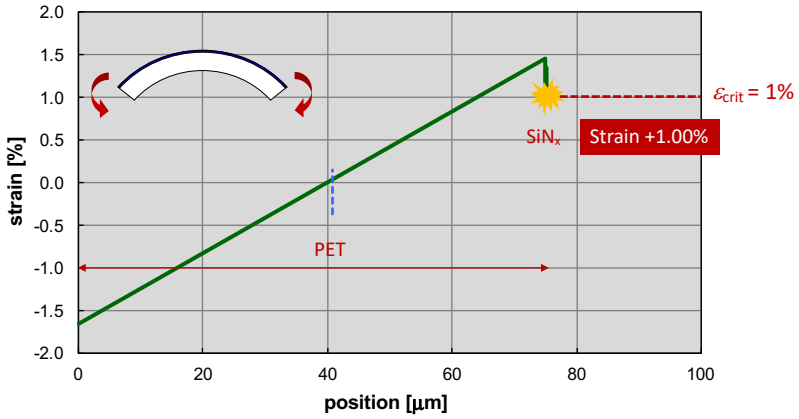
Multilayer Strain Analysis

PET (75 µm) + SiN_x (200 nm) @ 20°C (no HC layer)
Radius of curvature R = 2.4 mm with applied moment: Critical radius!



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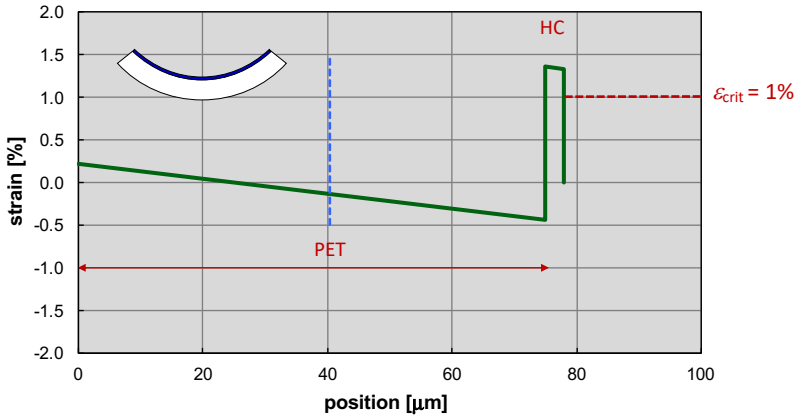
Multilayer Strain Analysis

PET (75 µm) + hard coat HC (3 µm) @ 20°C
Radius of curvature R = -11.2 mm



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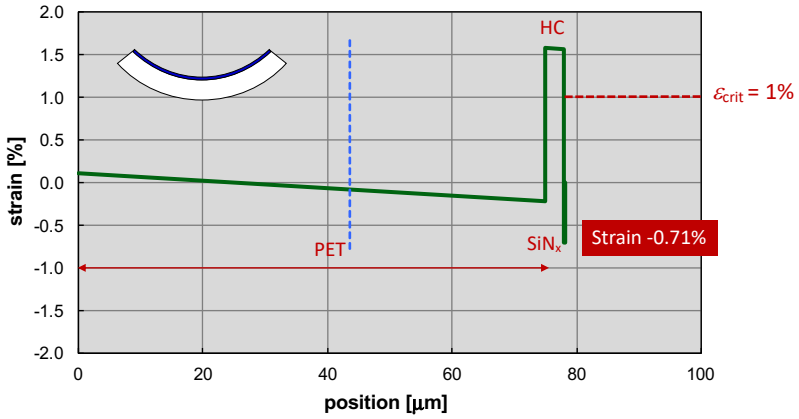
Multilayer Strain Analysis

PET (75 µm) + hard coat HC (3 µm) + SiN_x (200 nm) @ 20°C
Radius of curvature R = -22.4 mm



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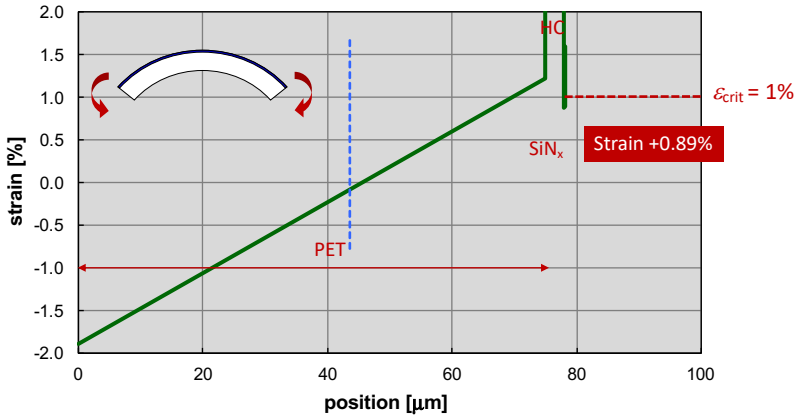
Multilayer Strain Analysis

PET (75 µm) + hard coat HC (3 µm) + SiN_x (200 nm) @ 20°C
Radius of curvature R = +2.4 mm using bending moment: *quasi* safe!



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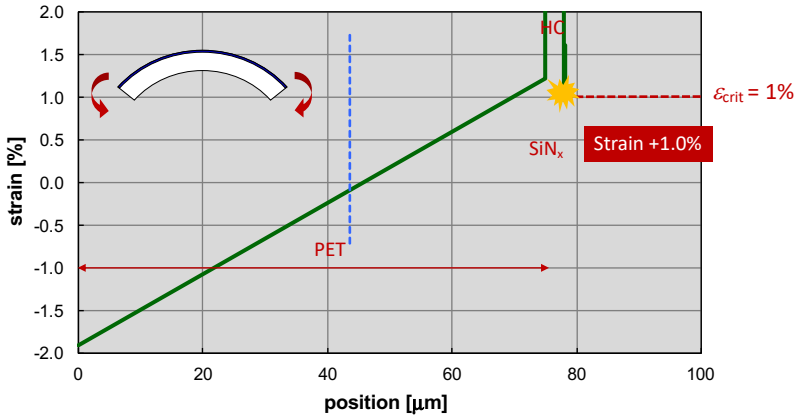
Multilayer Strain Analysis

PET (75 µm) + hard coat HC (3 µm) + SiN_x (200 nm) @ 40°C
Radius of curvature R = +2.4 mm using bending moment: *failure*!



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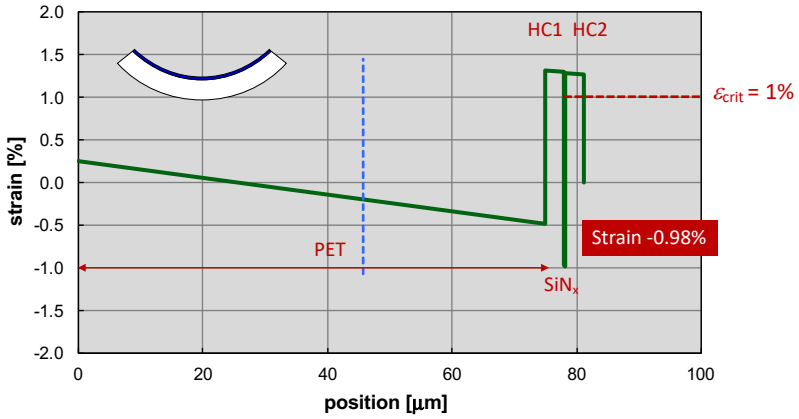
Multilayer Strain Analysis

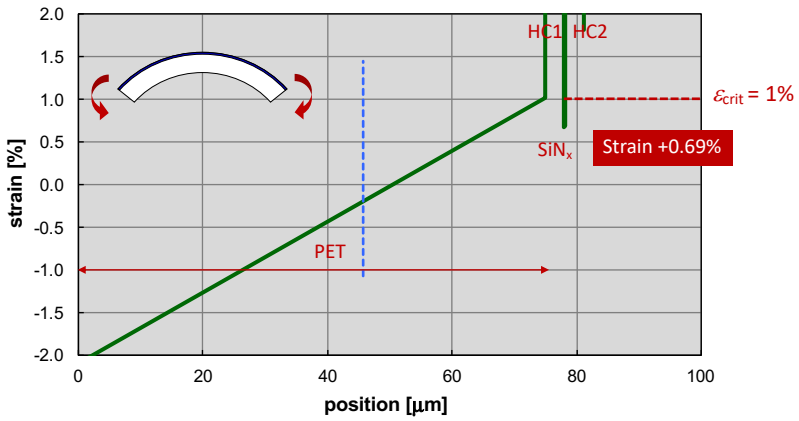
PET (75 µm) + HC1 (3 µm) + SiNx (200 nm) + HC2 (3 µm) @ 20°C
Radius of curvature R = -10.3 mm



42

Multilayer Strain Analysis

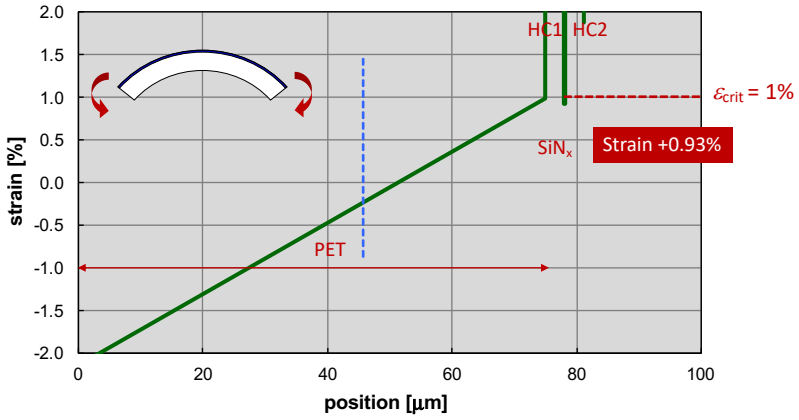
PET (75 µm) + HC1 (3 µm) + SiNx (200 nm) + HC2 (3 µm) @ 20°C
Radius of curvature R = +2.4 mm using bending moment: safe!



43

Multilayer Strain Analysis

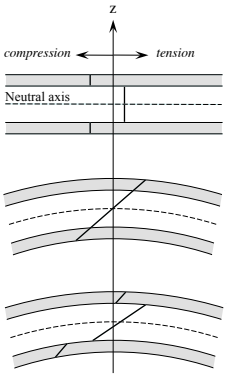
PET (75 µm) + HC1 (3 µm) + SiNx (200 nm) + HC2 (3 µm) @ 80°C
Radius of curvature R = +2.4 mm using bending moment: still safe!



44

Stress and strain analyses

Bending mode

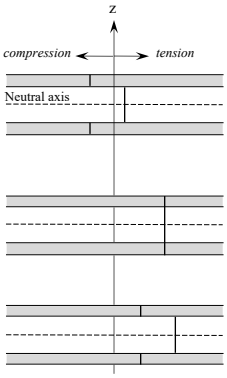


Internal strain

Bending strain

Total strain

Tensile mode



Internal strain

Tensile strain

Total strain

45

Outline

1. Introduction: critical strain
2. Stress and strain analyses
3. Failure mechanisms under tensile and compressive stress
4. Durability influences
5. Summary

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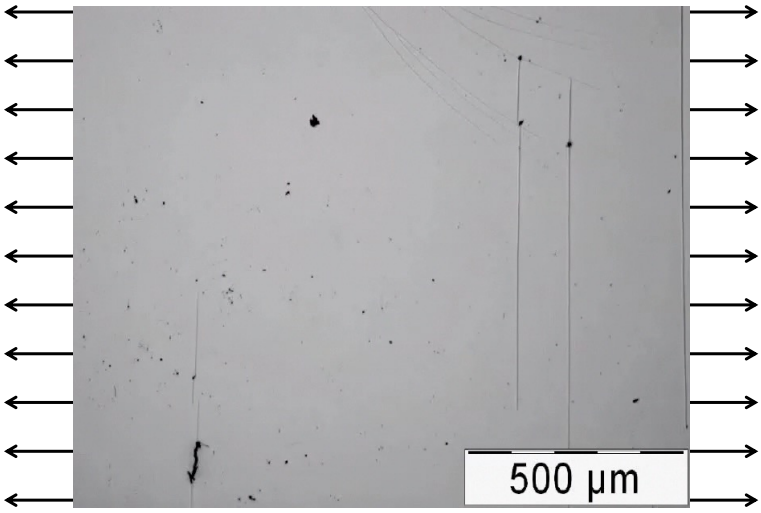
Failure under tensile stress



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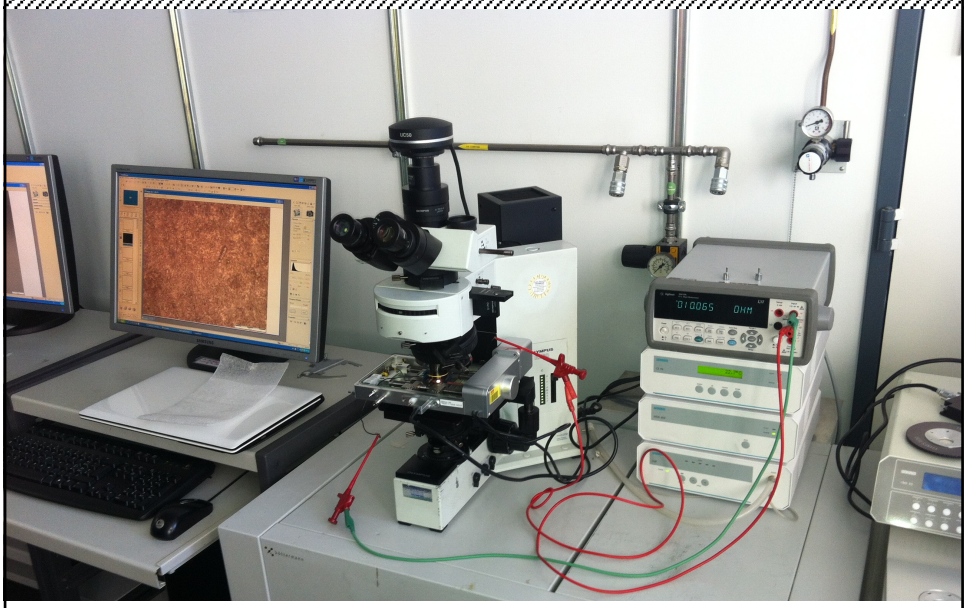
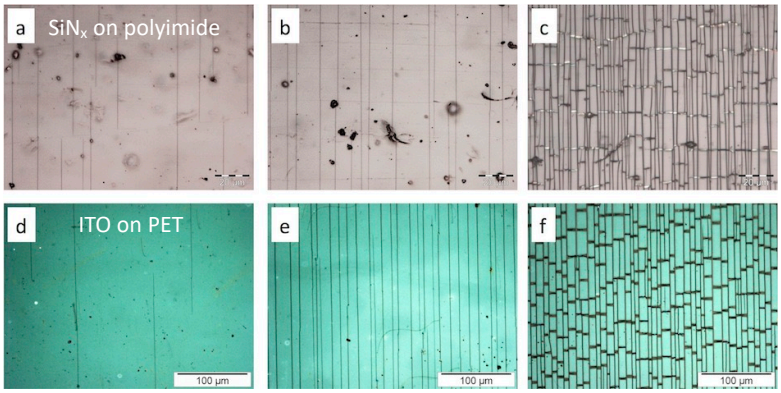
(Electro)-fragmentation test *in-situ*



48

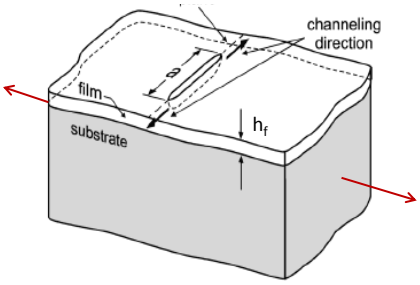
The three stages of tensile fragmentation

Stage 1	Stage 2	Stage 3
Crack initiation on film defects and stable propagation	*Mid-point cracking and unstable crack propagation*	*Saturation of tensile cracking and transverse buckling*



SiN_x on polyimide at a: 1.2%, b: 1.5% and c: 14.7% strain
ITO on PET at d: 1.1%, e: 2.2% and f: 11.6% strain

Failure under tensile stress



Cracks initiate at pre-existing flaws and propagate perpendicular to the loading direction

- In bending the top surface of the film experiences the largest strain
- In tension both film and substrate experience the same strain

Failure under tensile stress

$$G_{ss} = -\left[\frac{\partial U}{\partial a}\right] = \frac{\pi\sigma^2 a}{E} \quad \geq \quad G_c = 2\gamma_s$$

Energy release rate (ERR)

U elastic energy
σ applied stress
a crack length
E Young's modulus

Fracture energy (toughness)

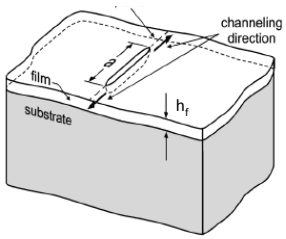
γ_s surface energy

A.A. Griffith, "The phenomena of rupture and flow in solids", Philosophical Transactions of the Royal Society of London, A 221: 163–198 (1921).

53

Failure under tensile stress: film on substrate

$$G_{ss} = \frac{\pi\sigma_f^2 h_f}{2\bar{E}_f} g(\alpha,\beta)$$



σ_f *film stress*

$\bar{E}_f$ *film plain strain modulus*

$\left(\bar{E}_f = E_f / (1-\nu_f^2)\right)$

ν_f *film Poisson's ratio*

h_f *film thickness*

$g(\alpha;\beta)$ *non – dimensional ERR*

(function of Dundurs parameters)

Beuth, IJSS (1992)
Hutchinson & Suo, Adv. Appl. Mech (1992)

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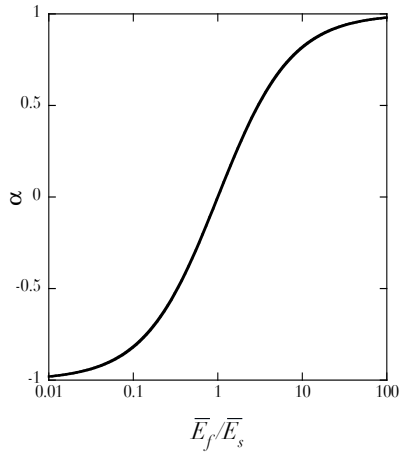
Dundurs parameters α and β



$$\alpha = \frac{\bar{E}_f - \bar{E}_s}{\bar{E}_f + \bar{E}_s}$$

Soft on stiff: $\alpha \to -1$

Stiff on soft: $\alpha \to +1$

$$\bar{E}_i = E_i / \left(1 - \nu_i^2\right) \quad (plane\ strain)$$

$$\beta = \frac{\mu_f\left(1-2\nu_s\right) - \mu_s\left(1-2\nu_f\right)}{2\mu_f\left(1-\nu_s\right) + 2\mu_s\left(1-\nu_f\right)} \qquad 0 < \beta < \frac{\alpha}{4}$$

μ_i *shear moduli*

Same film and substrate materials : $\alpha = \beta = 0$

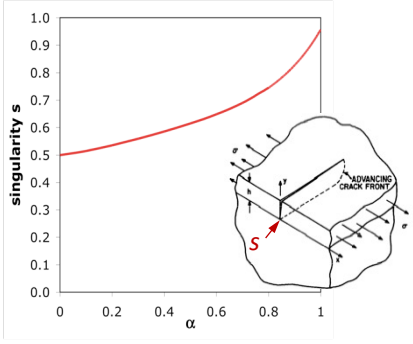
Dundurs, J. Appl. Mech. 36 (1969) 650

55

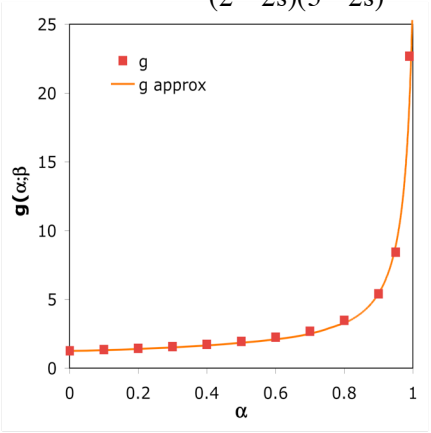
Elastic contrast function $g(\alpha,\beta)$

Crack tip singularity $0 < s < 1$ root of

$$\cos(s\pi) - 2\left[\frac{\alpha-\beta}{1-\beta}\right](1-s)^2 + \left[\frac{\alpha-\beta^2}{1-\beta^2}\right] = 0$$



$$g(\alpha;\beta) \simeq \frac{+2.5155}{(2-2s)(3-2s)}$$



Zak & Williams, J. Appl. Mech. (1963)

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Elastic contrast function $g(\alpha,\beta)$

Substrate (Young's modulus [GPa]; Poisson's ratio [–])	Film (Young's modulus [GPa]; Poisson's ratio [–])	α	β	g(α;β)
Steel (200; 0.30)	SiN_x (100; 0.26)	-0.344	-0.124	1.01
	Polyimide (3; 0.34)	-0.970	-0.234	0.72
Polyimide (3; 0.34)	SiN_x (100; 0.26)	0.939	0.225	7.74
	Parylene (2.8; 0.40)	-0.009	0.036	1.27

$$\varepsilon_{crit} = \sqrt{\frac{2G_c}{\pi h_f E_f \left(1-\nu_f^2\right) g(\alpha;\beta)}} \propto \frac{1}{\sqrt{g(\alpha;\beta)}}$$

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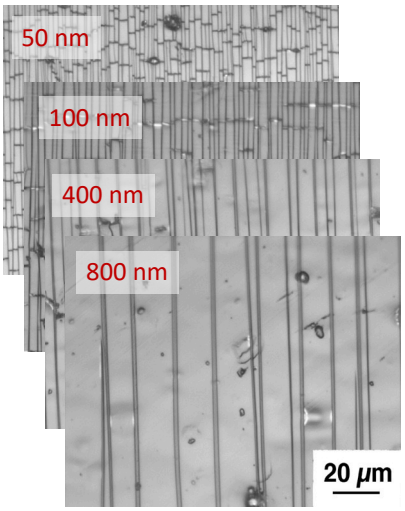
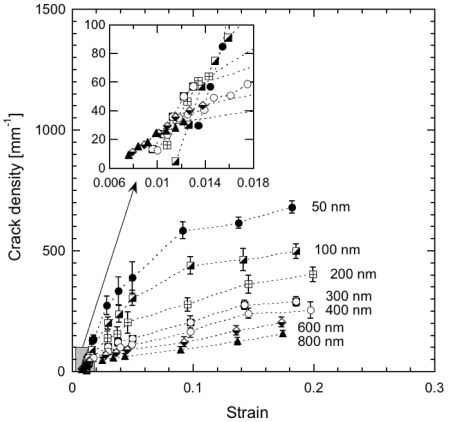
Influence of film thickness: thinner is stronger

SiN_x barrier films on PI





Andersons et al, *Mech Mater* (2007)

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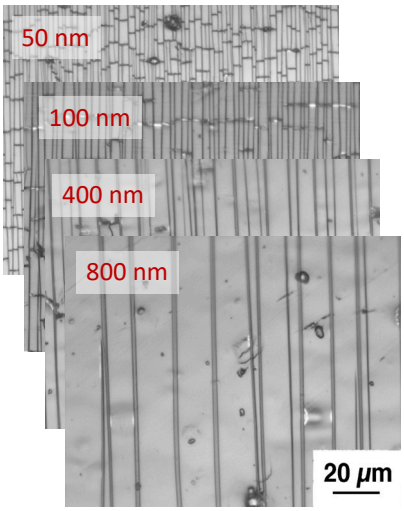
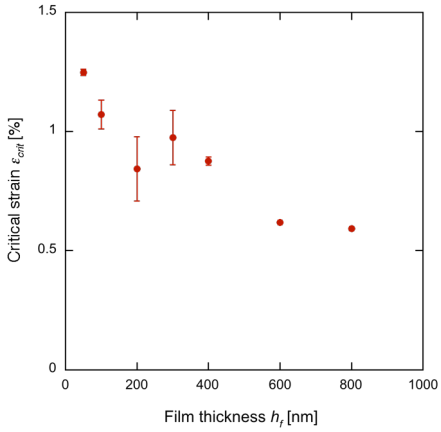
Influence of film thickness: thinner is stronger

SiN_x barrier films on PI





Andersons et al, *Mech Mater* (2007)

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Influence of film thickness: thinner is stronger

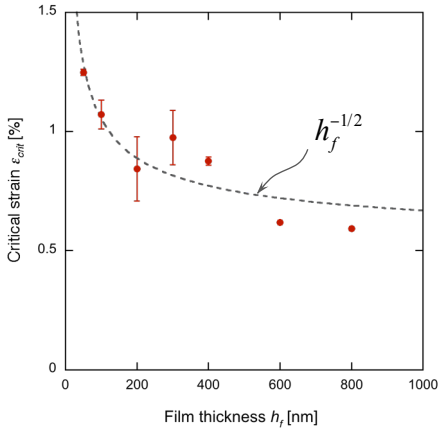
SiN_x barrier films on PI

$$G_{ss} = \frac{\pi\sigma_f^2 h_f}{2\bar{E}_f} g(\alpha;\beta) = G_c$$

$$when \quad \sigma_f = \sigma_{crit} = E_f \varepsilon_{crit}$$

$$\Leftrightarrow \quad \varepsilon_{crit} = \sqrt{\frac{2G_c}{\pi h_f E_f (1-\nu_f^2) g(\alpha;\beta)}} \propto h_f^{-1/2}$$

$$\Leftrightarrow \quad R_{crit} \propto h_f^{1/2}$$



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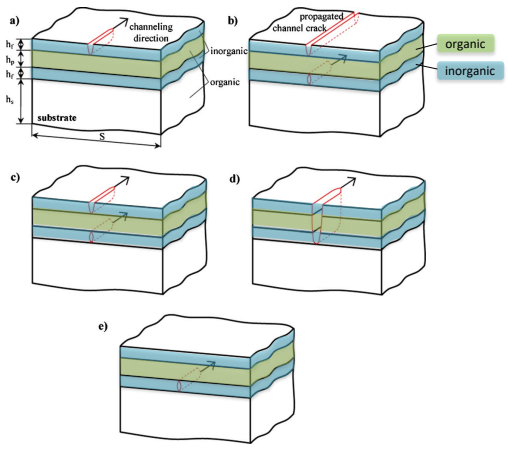
Optimizing Critical Strain with Organic Interlayers

Organic interlayers (also called hardcoats) can be designed to increase the critical strain

How the thickness of the organic layer, h_p, affects the critical strain?



Cordero, Yoon, Suo. *Applied Physics Letters* 90, nº 11 (2007): 111910
Kim, et al., ACS Appl. Nano Mater. 2019, 2, 2525−2532

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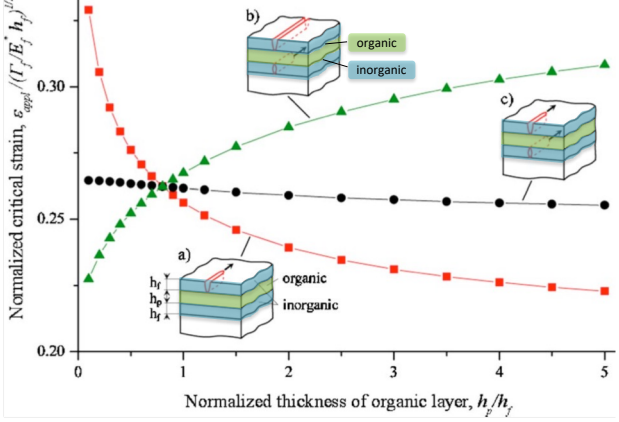
Optimizing Critical Strain with Organic Interlayers

Organic interlayers (also called hardcoats) can be designed to increase the critical strain

How the thickness of the organic layer, h_p, affects the critical strain?

$$U = E_f^* \varepsilon_{\text{appl}}^2 h_f^2 f\left(\frac{h_p}{h_f}, \frac{E_p}{E_f}\right)$$

f dimensionless function (calculated using e.g. ABACUS)



Cordero, Yoon, Suo. *Applied Physics Letters* 90, nº 11 (2007): 111910
Kim, et al., ACS Appl. Nano Mater. 2019, 2, 2525−2532

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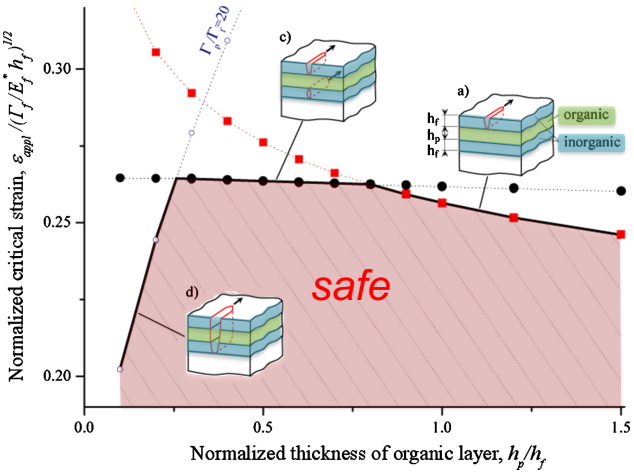
Optimizing Critical Strain with Organic Interlayers

If the organic layer is too thin, it cannot stop the propagation of a crack across the organic/ inorganic interfaces.

If the organic layer is too thick, the constraint between the two inorganic layers is removed, so that channel cracks can readily form in either inorganic layer.

There exist an intermediate thickness of organic layer, which maximizes the critical strain



Cordero, Yoon, Suo. *Applied Physics Letters* 90, no 11 (2007): 111910
Kim, et al., ACS Appl. Nano Mater. 2019, 2, 2525−2532

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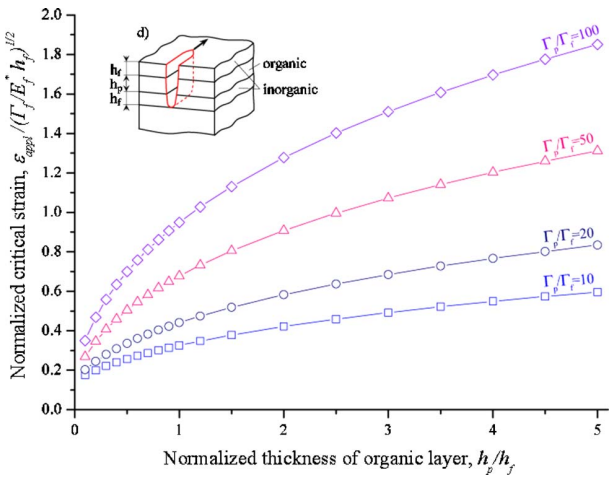
Optimizing Critical Strain with Organic Interlayers

One of the key material properties to increase the critical strain is the fracture toughness of the organic interlayer, which should be much greater than that of the inorganic layer



Cordero, Yoon, Suo. *Applied Physics Letters* 90, no 11 (2007): 111910
Kim, et al., ACS Appl. Nano Mater. 2019, 2, 2525−2532

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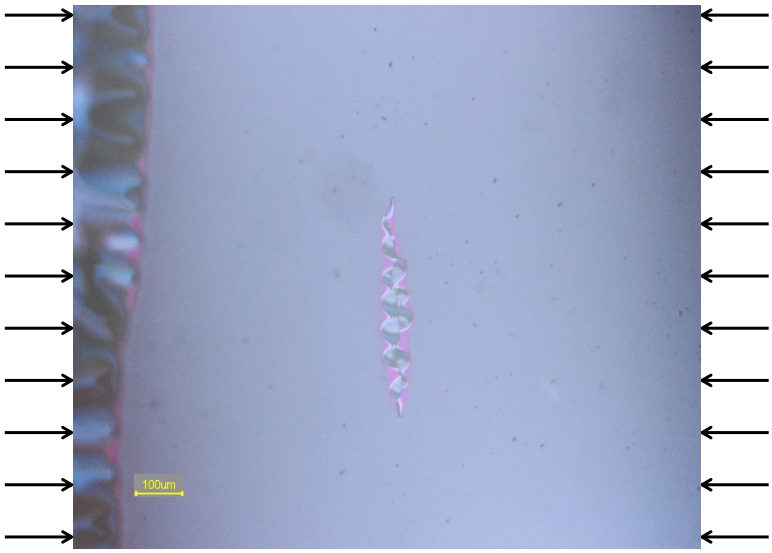
Failure under compressive stress



Courtesy A. Abdallah, U. Eindhoven

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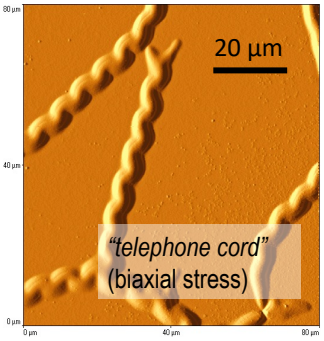
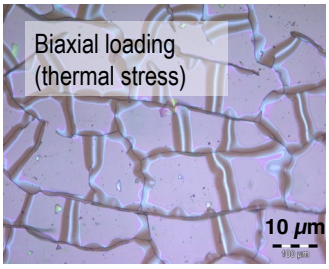
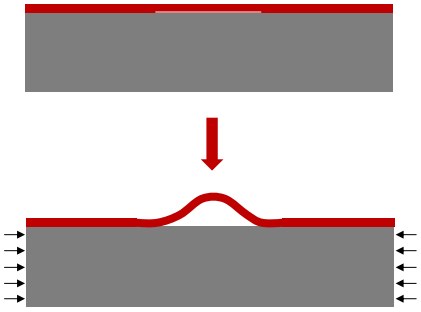
Failure under compressive stress





Cracks initiate at pre-existing debonded areas, followed by buckling



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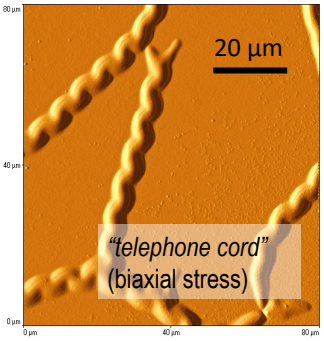
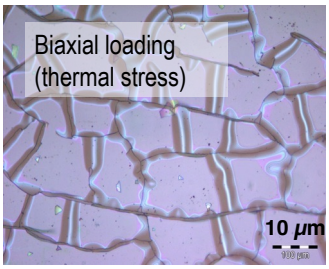
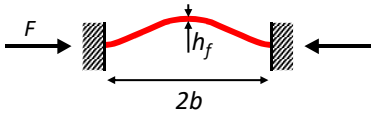
Failure under compressive stress

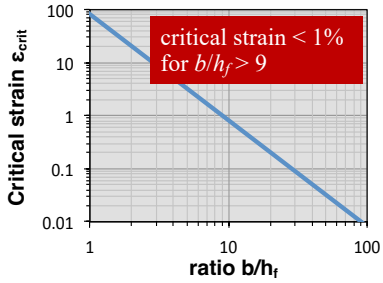




edge clamped plate



Critical buckling strain $\varepsilon_{crit} = \frac{\pi^2}{12}\left(\frac{h_f}{b}\right)^2$



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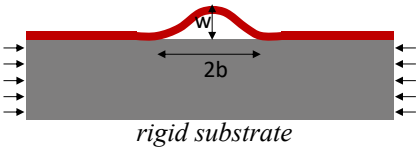
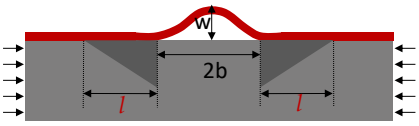
Failure under compressive stress



rigid substrate



compliant substrate

Adhesion energy

$$G_{ss} = G_0\left[1-\left(\frac{\varepsilon_{crit}}{\varepsilon}\right)^2\right]; \quad G_0 = \frac{\sigma_f^2 h_f}{2\bar{E}_f}$$

$$l = \frac{2h_f}{1-\alpha} \qquad G_{ss} = G_o\left[1-\left(\frac{\varepsilon_{crit}}{\varepsilon}\right)^2\right]\left(\frac{b+l}{b}\right)$$

Failure of films under compressive stress depends on adhesion quality

Hutchinson, Suo, Adv. Appl. Mech. 29 (1992) 63-191
Cotterell, Chen, Int. J. Fracture 104 (2000) 169

Bouten, Slikkerveer, Leterrier, in 'Flexible Flat Panel Displays', Wiley (2005)
Abdallah et. al, Thin solid films 503 (2006) 167-176

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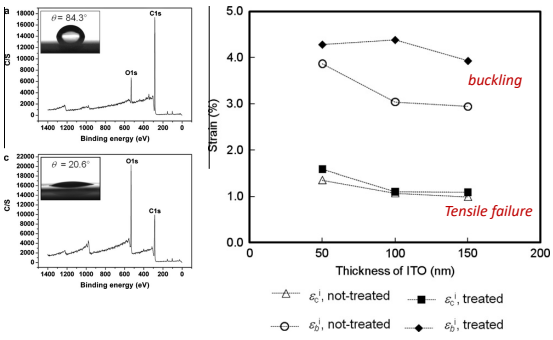
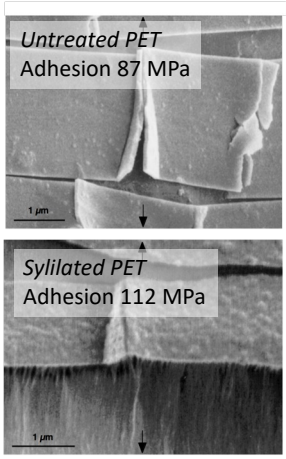
Failure under compressive stress

Oxygen plasma treatment (ITO films on PET)



Organosilane treatment (SiO_2 films on PET)



Leterrier, Sutter, Månson, J. Adhesion, 69, 13 (1999)
Kim et al, Current Applied Physics 10 (2010) S510–S514

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Outline

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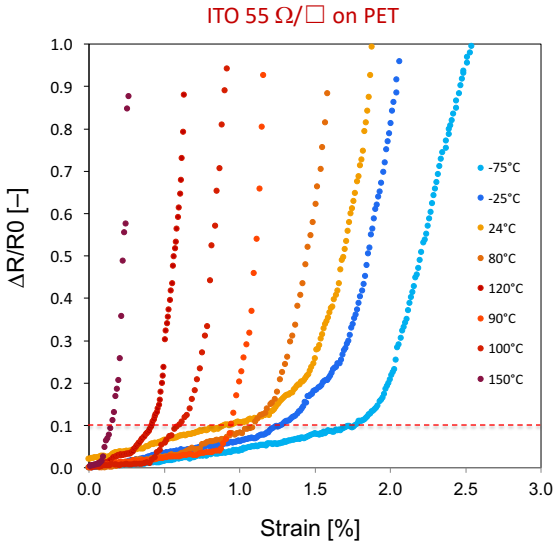
Influence of temperature on film cracking



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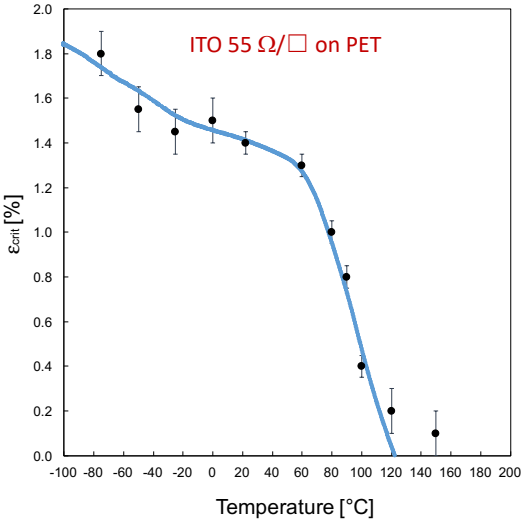
Influence of temperature on film cracking



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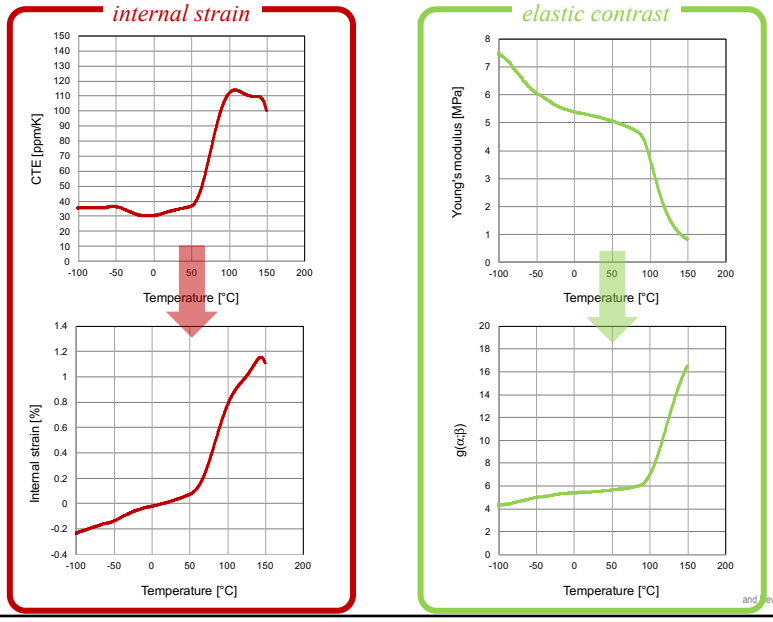
Influence of temperature on film cracking



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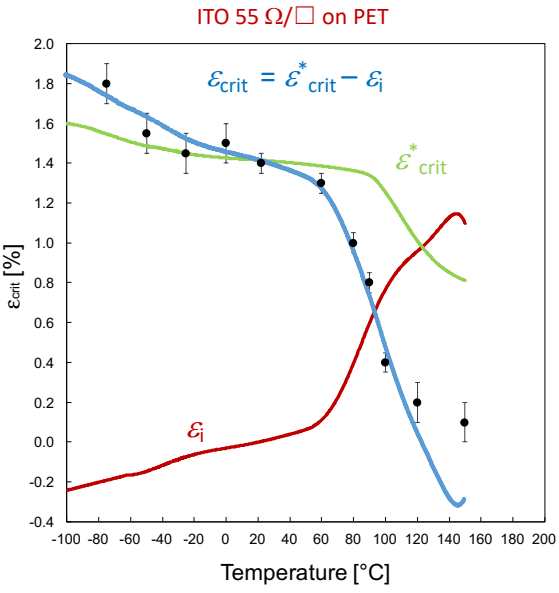
Influence of temperature on film cracking



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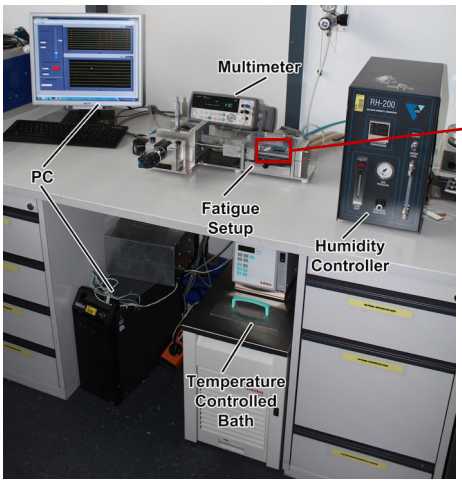
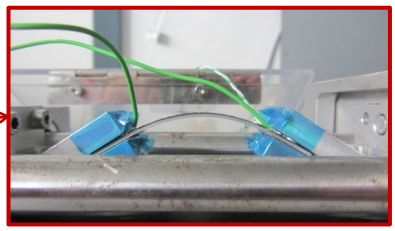
Automatic electro-fatigue analysis





Device performance

- Displacement accuracy better than 5 µm over more than 500'000 cycles
- True displacement measurement (LVDT)
- In-situ in a microscope (video-extensometry)
- Frequency up to 3Hz (sinusoidal loading)
- Stand-alone system with LabVIEW monitoring

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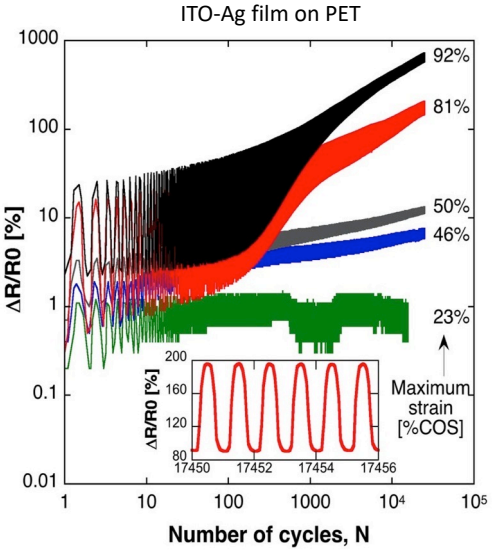
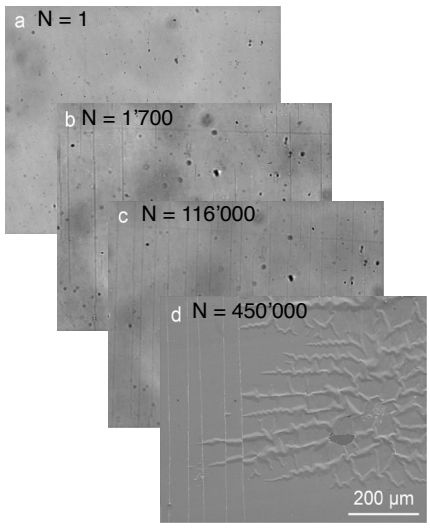
Automatic electro-fatigue analysis

ITO-Ag film on PET



Maximum strain = 92% ε_{crit}



Pinyol et al., *MRS Fall Meeting* (2007)
Leterrier et al., *Thin Solid Films* (2010)

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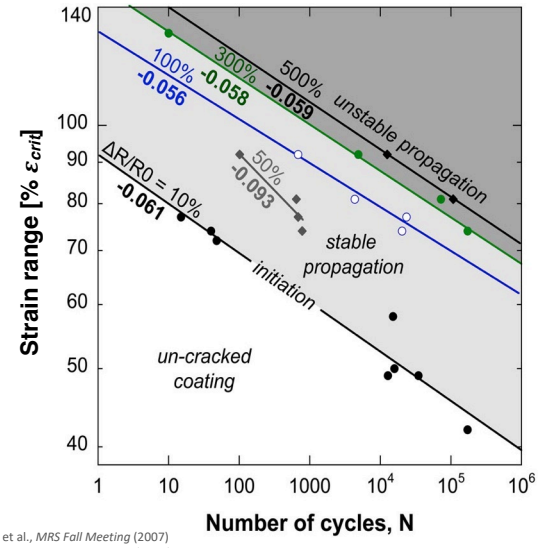
Durability influences: Fatigue

ITO-Ag film on PET



High cycle fatigue exponents (Modified Basquin Law for non-zero mean stress)
(Morrow, Fatigue Design Handbook 1968)

ITO-Ag films -0.06

Cu films -0.07
(Park et al., Mat wis u Werk 2008)

Si films -0.03
(Muhlstein et al., Sens Act A 2001)

Pinyol et al., *MRS Fall Meeting* (2007)
Leterrier et al., *Thin Solid Films* (2010)

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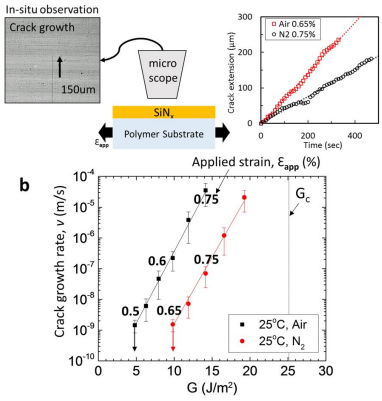
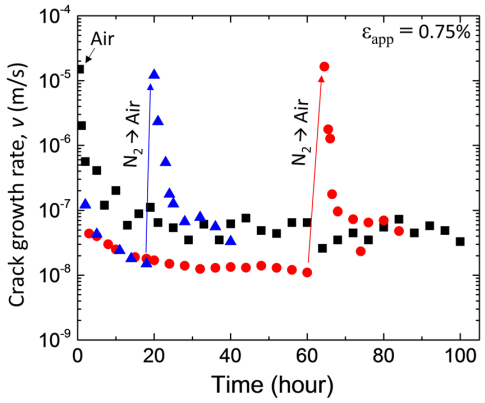
Durability influences: Corrosion

SiN_x/PET films under air (30%RH) and N_2





Kim et al., Scientific Reports (2018) 8:4560

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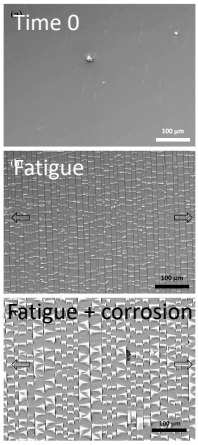
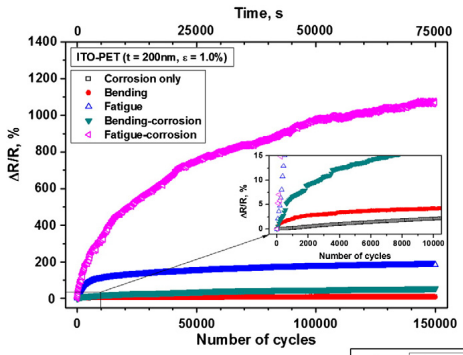
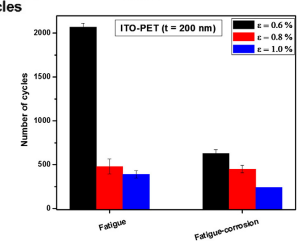
Durability influences: Corrosion and fatigue

ITO/PET films
- 0.6-1% fatigue loading
- 0.05 M acrylic acid solution (pressure sensitive adhesive)







T.S. Bejitual, et al, Thin Solid Films Thin Solid Films 528 (2013) 229–236 & 549 (2013) 251–257

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Outline

1. Introduction: critical strain
2. Stress and strain analyses
3. Failure mechanisms under tensile and compressive stress
4. Durability influences
5. Summary

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You have learned …

Key factors, which control the critical radius of curvature (and associated critical strain) of flexible electronics:

- Film cohesive properties (fracture toughness) ⟺ tensile failure
- Film / substrate adhesive properties ⟺ compressive failure
- Film / substrate elastic contrast (the 'g' function)
- Process and service induced internal stresses

To avoid failure, flexible devices should:

- be designed to be as thin as possible (avoid premature cracking)
- be designed with brittle layers close to neutral axis (avoid premature cracking)
- be based on surface-treated substrates (avoid delamination)
- include 'hardcoat' interlayers to minimize elastic contrast
- be processed with tailored cycles to minimize internal stresses

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Nomenclature

a	Crack length
CD, CD_{sat}	Crack density, crack density at saturation
CHE	Coefficient of hygroscopic expansion
CTE	Coefficient of thermal expansion
E, E_f, E_s	Young's modulus, of film, of substrate
$\bar{E}_f$, $\bar{E}_s$	Plane strain modulus of film, of substrate
$g(\alpha; \beta)$	Normalized energy release rate
G_c , G_{adh}	Film toughness, interfacial toughness
h	Indentation depth
h_i, h_f , h_s	Thickness of layer i, of film, of substrate
R, R_0	Electrical resistance, of unstrained film
R_1, R_2	Radii of curvature of substrate, of coated substrate
R_{crit}	Critical radius of curvature
RH	Relative humidity
T	Temperature
α, β	Dundurs parameters
χ	Film-to-substrate Young's modulus ratio
δ	Substrate deflection in internal stress measurement
ε	Strain
ε_{crit}	Critical strain
ε_{crit}^*	Intrinsic crack onset strain
ε_i	Film internal strain
η	Film-to-substrate thickness ratio
μ_f , μ_s	Shear modulus of film, of substrate
ν_f , ν_s	Poisson's ratio of film, of substrate
σ_i	Film internal stress
ξ	Adjustable factor in nano-indentation tests

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Thank you!
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