ADVANCED FUNCTIONAL MATERIALS

Supporting Information

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Design of Strain-Limiting Substrate Materials for Stretchable and Flexible Electronics

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Design of mechanically strain-limiting substrates for stretchable and flexible electronics

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Supplementary Note 1. Maximum pre-strain for the substrate with finite thickness

For a thick substrate, the strain in the film reaches a maximum when the substrate is released from the pre-strained length L_2 to the initial length L_1. This shrinkage, corresponding to $\varepsilon_{pre} = (L_2 - L_1)/L_1$, is imposed on the film. For a relatively thin substrate, the substrate only shrinks to L_0, and therefore the shrinkage of the film corresponds to $\varepsilon_{transition} = (L_2 - L_0)/L_0$. Therefore, ε_{pre} in Eq. (1) should be replaced by $\varepsilon_{transition}$ for a substrate with finite thickness in order to avoid plastic yielding, i.e., $\varepsilon_{transition} < \varepsilon_Y^2/(4\varepsilon_c)$. Together with Eq. (3) this gives the maximum pre-strain for a substrate with finite thickness

$$\varepsilon_{pre} < \frac{\varepsilon_Y^2}{4\varepsilon_c} + \frac{1}{4}\left(\frac{9\overline{E}_f h^3}{\overline{E}_s H^3}\right)^{1/3}\left(\frac{\varepsilon_Y^2}{4\varepsilon_c} + 1\right). \quad \text{(S1)}$$

Supplementary Note 2. Local wrinkling versus global buckling

The critical length L_{cr} that separates local wrinkling from global buckling is given by [20]

$$L_{cr} = 4\pi\sqrt{EI\left(\frac{\left(\overline{E}_f/3\overline{E}_s\right)^{2/3}}{\overline{E}_s H + \overline{E}_f h} - \frac{1.2}{\overline{E}_s(H+h)}\right)}, \quad \text{(S2)}$$

where the effective bending rigidity EI is

$$EI = \frac{\left(\overline{E}_s H^2 + \overline{E}_f h^2\right)^2 + 4\overline{E}_s H \overline{E}_f h (H+h)^2}{12(\overline{E}_s H + \overline{E}_f h)}. \tag{S3}$$

For $H \gg h$, Eqs. (S2) and (S3) degenerate to Eqs. (5) and (6), respectively. For a substrate thickness reduced to a critical value, L_{cr} reaches zero, corresponding to global buckling at all lengths of the film. This critical value is given by $\left(\overline{E}_s / \overline{E}_f\right)^{2/3} + \left[\overline{E}_f h^3 / \left(\overline{E}_s H^3\right)\right]^{1/3} = 0.064^{1/3}$. For $\overline{E}_s / \overline{E}_f \ll 1$, it becomes $\overline{E}_f h^3 / \left(\overline{E}_s H^3\right) = 0.064$.

Supplementary Note 3. Effect of delamination

Figure S4a shows a model of interfacial delamination between a $1\mu\text{m}$-thick PI film and a 1mm-thick Silbione substrate with 36.0% unidirectional pre-strain. The length of the crack (interfacial delamination) is $195\mu\text{m}$, which is about half of the buckling wavelength $\lambda = 390\mu\text{m}$ for the system of materials without a crack. A crack is placed at the peak of each wrinkle (Fig. S4a) where the strain reaches the maximum for the system of materials without delamination. Stress-strain curves with and without the crack, obtained by FEA, are very close, which confirms that the effect of delamination on the stress-strain curve is small.

SI figure captions

Figure S1. Normalized length L_0/L_1 versus thickness ratio H/h for the PI film on several substrates.

Figure S2. Numerical results of morphologies (scale bar, 1mm) for 1μm-thick PI film on 1mm-thick Silbione substrate subjected to **a)** 15.1%, **b)** 25.6% and **c)** 36.0% pre-strains.

Figure S3. a) Interfacial delamination morphologies of 1μm-thick PI film on 1mm-thick Silbione substrate subjected to 36.0% pre-strain (crack length: a , $a/\lambda = 0.5$). **b)** Comparison of stress-strain curves for cases with and without delamination.

Figure S4. Stress-strain curves for *x*-, 30°-, 45°-, 60°-, and *y*-stretching of a 1μm-thick PI mesh (width $W = 0.1\text{mm}$ and spacing $S = 0.4\text{mm}$) on 1mm-thick Silbione substrate subjected to pre-strains of ε_{pre}^{x} =30.8% and ε_{pre}^{y} =15.7%.

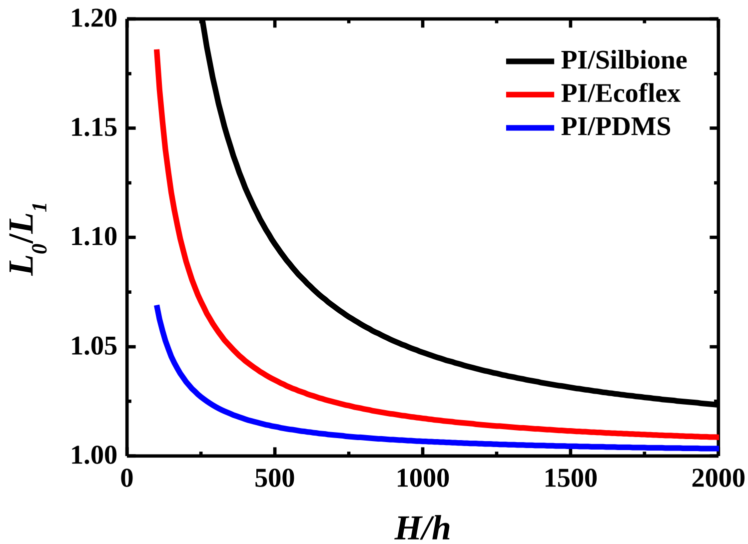

PI/Silbione
PI/Ecoflex
PI/PDMS
L_0/L_1
H/h
1.20
1.15
1.10
1.05
1.00
0
500
1000
1500
2000

Figure S1

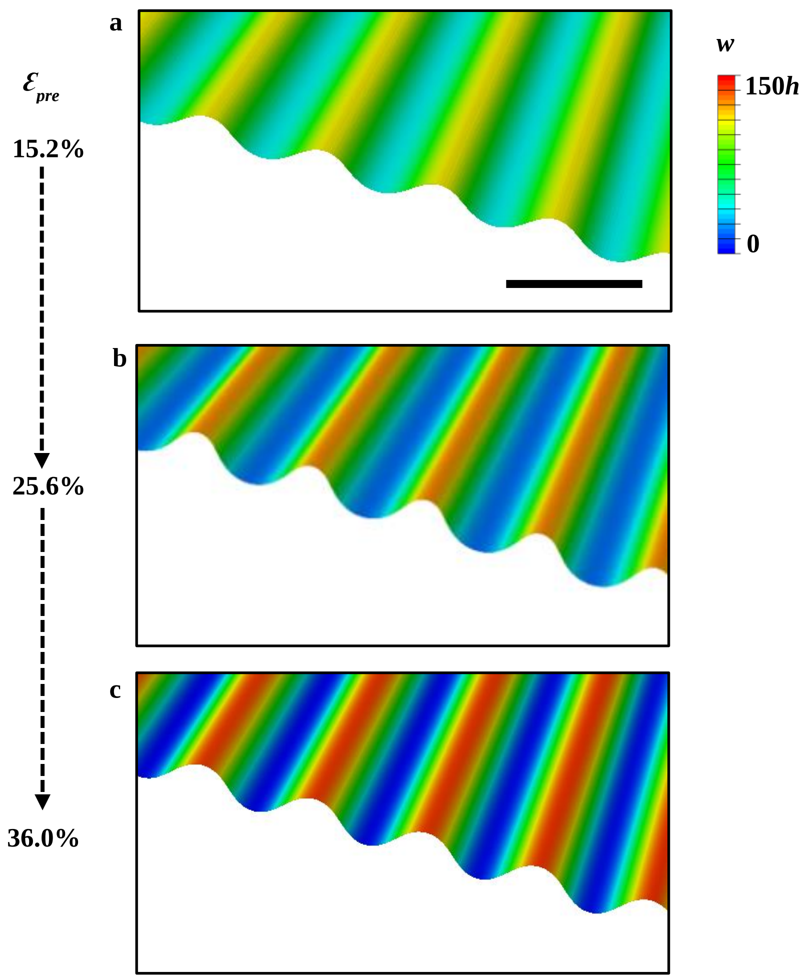
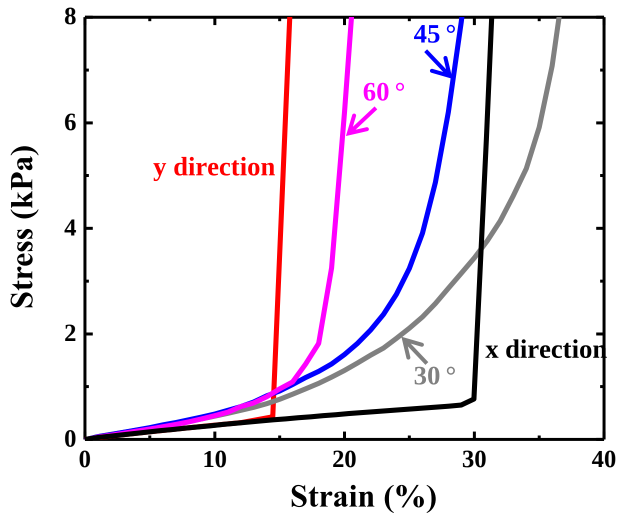


Figure S2



Stress (kPa)
Strain (%)
y direction
60 °
45 °
30 °
x direction
0
2
4
6
8
0
10
20
30
40

Figure S3

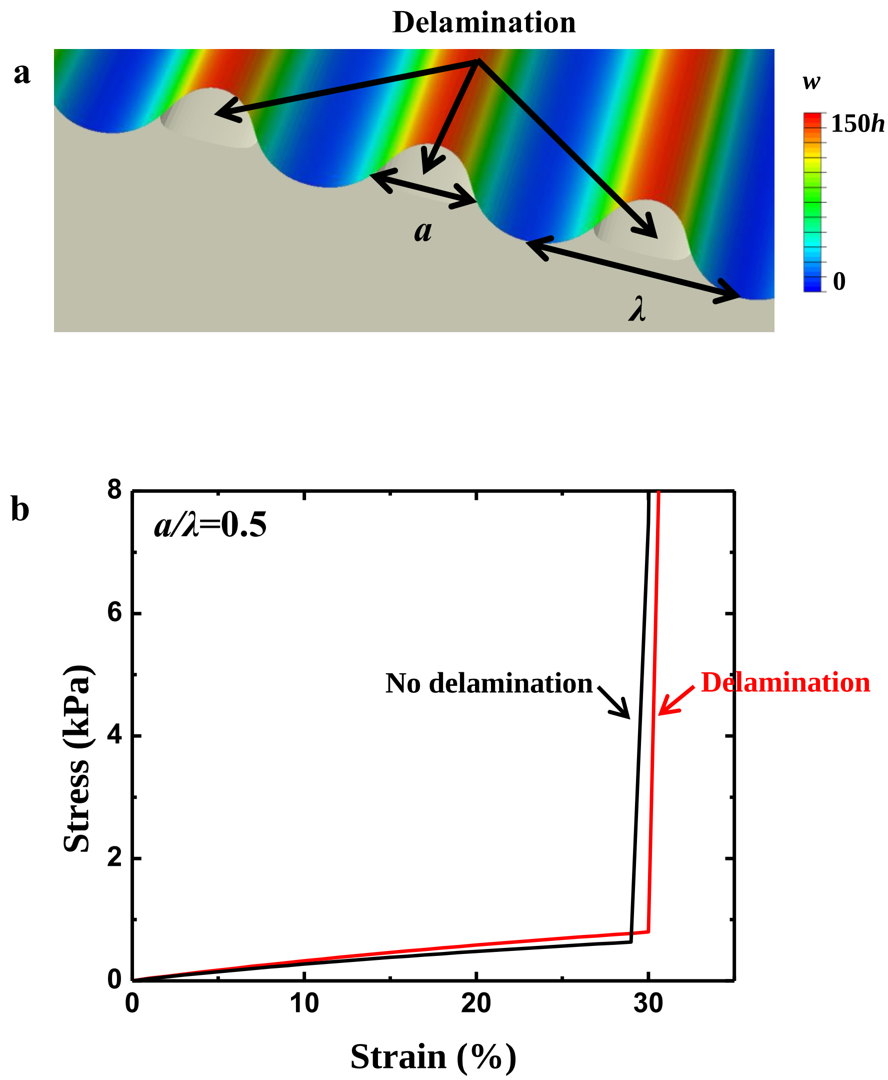

Delamination
a
w
150h
0
a
λ
b
a/λ=0.5
No delamination
Delamination
Stress (kPa)
Strain (%)
0
2
4
6
8
0
10
20
30

Figure S4