Compliant thin film patterns of stiff materials as platforms for stretchable electronics

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Abstract

A thin film of a stiff material, patterned as a serpentine on a flat elastomeric substrate, can elongate substantially when the substrate is pulled. We show that the film elongates by *twisting out of plane*, accommodated by the compliance of the substrate and the pattern of the film. Consequently, large elongations of the substrate induce small strains in the film, even when the width of the film is much larger than its thickness. Such a wide serpentine, or other compliant patterns of stiff materials, can serve as a *platform* on which electronic circuits can be fabricated. This architecture will make electronics elastically stretchable.

A new direction for integrated circuit technology is to develop deformable electronic surfaces [1-6]. Of various modes of deformation (e.g., bending, twisting and stretching), typically stretching is most demanding, easily inducing a large tensile strain on the surface of a substrate. While an elastomeric substrate can recover from a large strain, most electronic materials, such as metals, dielectrics and semiconductors, fracture at small strains (less than about one percent) [7-11]. How to use these materials to make stretchable electronic circuits remains uncertain. We propose that electronic circuits can be fabricated on a platform, of a stiff material but a compliant pattern, lying on an elastomeric substrate. These circuits will function without appreciable fatigue when the substrate is pulled for many cycles.

A helical spring can elongate substantially, even though the material that makes the spring can only sustain a small strain. One could fabricate electronic circuits on a helical platform, but this approach would require microfabrication in three dimensions, a technology that requires substantial development itself. To be compatible with planar microfabrication technology, the platform must be planar. As an illustration of a principle, Fig. 1 shows a piece of paper cut into a serpentine, and pulled at the two ends. While initially planar, the serpentine elongates by twisting out of plane, so that a large elongation induces only small strains. The serpentine illustrates the principle: *a film of a stiff material can be made compliant if the film is suitably patterned*.

It has been shown that serpentine metal interconnects on elastomeric substrates can sustain more than 200 cycles of elongation by 25% [12]. An existing design for stretchable electronics is to fabricate on a polymeric substrate small functional islands of stiff materials, which are then linked by metal interconnects [4, 6, 13]. While the metal interconnects can be made stretchable [12, 14], the crossovers of the interconnects from the polymer to the islands are susceptible to fracture. In addition, the size of each individual island must be kept small to avert cracking [4, 6, 13].

The metal interconnects used in [12] had cross sections of comparable width and thickness. However, as demonstrated by the serpentine of paper, a large elongation can be achieved for any material, and for serpentines of any width-to-thickness ratio. We propose that a thin film of a *stiff* material (e.g., silicon dioxide, silicon nitride or a metal) can be patterned as a *wide* serpentine on a flat elastomeric substrate, and serve as a platform, on which entire electronic circuits can be fabricated using the planar microfabrication technology. Such a structure can sustain many cycles of large elongation without fracturing the electronic materials. The serpentine can have a much larger surface area than the islands that have been demonstrated to date [4, 6, 13].

For a film on a substrate to elongate substantially by twisting out of plane, two conditions must be met: the substrate must be sufficiently compliant, and the film must be suitably patterned. If the substrate were stiff or the film were straight, the film would deform within the plane, so that a small elongation of the substrate would induce a significant strain in the film. We next quantify the compliance of the substrate and the pattern of the film needed to achieve a large elongation.

Figure 2 illustrates a model which we analyze using the finite element code ABAQUS. The film is of a sinusoidal shape, period L, amplitude A, width W, and thickness h_{film}. The substrate is a $L \times L \times h_{sub}$ block, with displacement u prescribed on the two $L \times h_{sub}$ end surfaces. Marked in the figure is a point P, where the film reaches the maximum strain, $\varepsilon_{\max}$. To avoid confusion with the strain in the film, we call the quantity $2u / L$ the relative elongation of the substrate. The film is meshed with four-node quadrilateral shell elements, with 10 layers of elements along the width; all elements are nearly square. The substrate is meshed with eight-node linear brick elements, with size-matching elements at the film/substrate interface, and coarser elements far away from the interface. We model both the film and the substrate as linear elastic materials, with Young's modulus E_{film} = 100 GPa and E_{sub} = 1 MPa to 100 MPa, so that E_{sub}/E_{film} ranges from 10^{-5} to 10^{-3}. The linear elastic assumption is reasonable for elastomeric substrates within strains of tens of percent. The assumption is also reasonable for the films, as strains are small in the films suitably patterned on compliant substrates. Poisson's ratio is taken to be 0.3 for both materials.

Figure 3 shows the deformed films bonded to substrates of various Young's moduli, subject to a relative elongation of 25%. For visual clarity, the figure does not show the substrates. The state of strain at each point in the film has two principal components, the larger of which is indicated by the shade in the figure. On a very compliant substrate, $E_{sub}/E_{film}=10^{-5}$, the out-of-plane displacement of the surface is *anti-symmetric* with respect to the x_2 axis; that is, to one side of the crest the serpentine pushes the substrate down, and to the other side of the crest the serpentine lifts the substrate up. On a less compliant substrate, $E_{sub}/E_{film}=10^{-3}$, the out-of-plane displacement is *symmetric* with respect to the x_2 axis. As the modulus of the substrate increases, the displacement is gradually confined in the plane, and the strains in the film also increase. For a serpentine with a large width-to-thickness ratio, bending and stretching within the plane leads to a much larger strain than bending and twisting out of the plane.

Figure 4 plots the maximum strain in the film, $\varepsilon_{\max}$, as a function of the relative elongation of the substrate, $2u/L$. For a film on a very compliant substrate (e.g., $E_{sub}/E_{film}=10^{-5}$), $\varepsilon_{\max}$ < 3.5% at a relative elongation of 25%. When the modulus of the substrate increases, so does $\varepsilon_{\max}$. For example, when E_{sub} / E_{film} =10^{-3}, $\varepsilon_{\max}$ = 11.6% at the relative elongation of 25%. Figure 4 also shows that $\varepsilon_{\max}$ increases as the substrate becomes thicker. Further calculations show that, however, $\varepsilon_{\max}$ becomes insensitive to the thickness of the substrate when h_{sub}/L exceeds about unity. This limiting case is shown by the curves for $h_{sub}/L = 5$.

When the substrate is sufficiently compliant, $\varepsilon_{\max}$ is also insensitive to the width and the thickness of the serpentine, and is only sensitive to its amplitude-to-period ratio, A / L. Figure 5 shows $\varepsilon_{\max}$ as a function of A / L. Here we simulate a freestanding film, corresponding to the limiting case of a film on an infinitely compliant substrate. If the film is a straight stripe (A / L = 0), $\varepsilon_{\max}$ is identical to the relative elongation. If $A / L > 0$, the patterned film can benefit from both in-plane bending and out-of-plane twisting. The larger the value of A/L, the smaller the strains level in the film. When $A / L > 1$, $\varepsilon_{\max}$ is more than twenty times smaller than that of a straight stripe.

Figure 6 plots the maximum in-plane strain in the substrate and the maximum interfacial stresses as functions of the relative elongation of the substrate. The maximum in-plane strain in the substrate occurs on its surface near the arms of the film serpentine, with a magnitude slightly higher than the applied relative elongation. The strains in the substrate become uniform about one serpentine period below the surface. As the relative elongation of the substrate increases, the maximum normal stress on the film/substrate interface increases substantially when the film deflects out of plane, and then saturates. The maximum shear stress on the interface increases nearly linearly. The more compliant the substrate, the smaller the maximum interfacial stresses.

As shown in Fig. 6, the maximum interfacial stress is below 1 MPa when a very compliant substrate is used.

As the elongation increases, the serpentine will be finally straightened as shown in Fig. 1b. Further elongation leads to a pure stretch of the film. Let L_{arc} be the arc length of a serpentine of period L. The relative elongation upon which a serpentine is fully straightened can be estimated by $(L_{arc} - L)/L$. For the sinusoidal stripe, the maximum relative elongation is given by

$$\frac{L_{arc} - L}{L} = \frac{1}{\pi}\int_0^{\pi}\left[1 + \left(\frac{A}{L}\right)^2 \pi^2 \sin^2 x\right]^{1/2} dx - 1. \quad (1)$$

This equation is plotted in Fig. 7, which provides an estimate of the A/L ratio needed to achieve a certain relative elongation.

Most electronic materials fracture at strains less than about 1%. To limit strains in a serpentine below 1%, the relative elongation should be kept below 20% for a serpentine of $A/L = 1$ on a very compliant substrate (Fig. 5). Larger relative elongation can be achieved by optimizing the pattern of the film, for example, by increasing the amplitude of the stripe and decreasing its width at crests and troughs. Also, the out-of-plane twisting of a serpentine requires only the compliance of a top layer of the substrate, of a thickness that scales with the feature size of the film pattern, such as the period L and the amplitude A. Underneath such a compliant top layer, a less compliant material may be used as a backing, if some overall rigidity is desired.

We have focused on a serpentine on an elastomeric substrate subject to uniaxial elongation. With suitable choices of length ratios, such a structure can also sustain biaxial elongation. Furthermore, a network of serpentines not only can sustain biaxial elongation, but also has *bidirectional connectivity*. In fact, a large variety of patterns allow substantial elongation by the same principle. In a future study, we will explore such patterns to meet various design requirements.

In summary, we have shown that a thin film of a stiff material, suitably patterned on a sufficiently compliant substrate, elongates by twisting out of plane, so that large elongations of the substrate induce small strains in the film. We propose that such patterned films can serve as platforms, on which entire electronic circuits can be fabricated using the planar microfabrication technology. Such circuits will function without appreciable fatigue when the substrate is repeatedly bent, twisted, and stretched.

Acknowledgements

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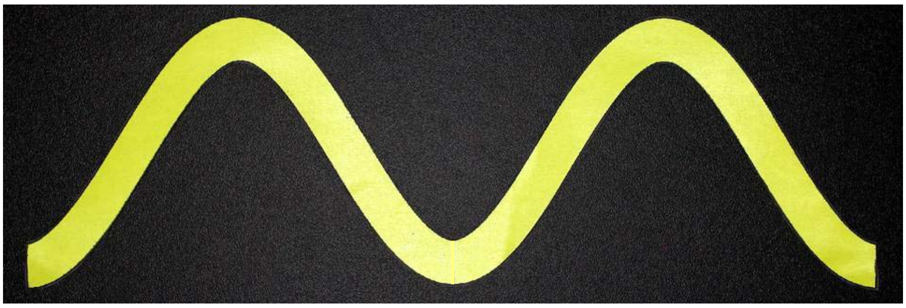
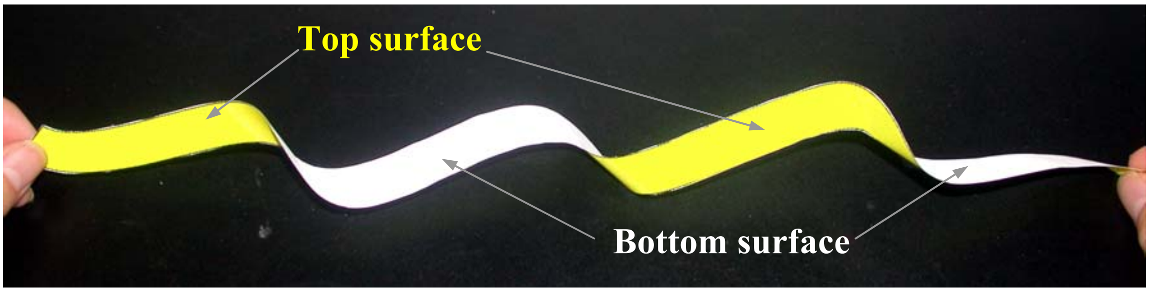


(a)



(b)

Figure 1: (a) A piece of paper is cut into a serpentine. (b) When pulled, the serpentine elongates by twisting out of plane. (The reader may wish to try this experiment to see the serpentine twist in three dimensions.)

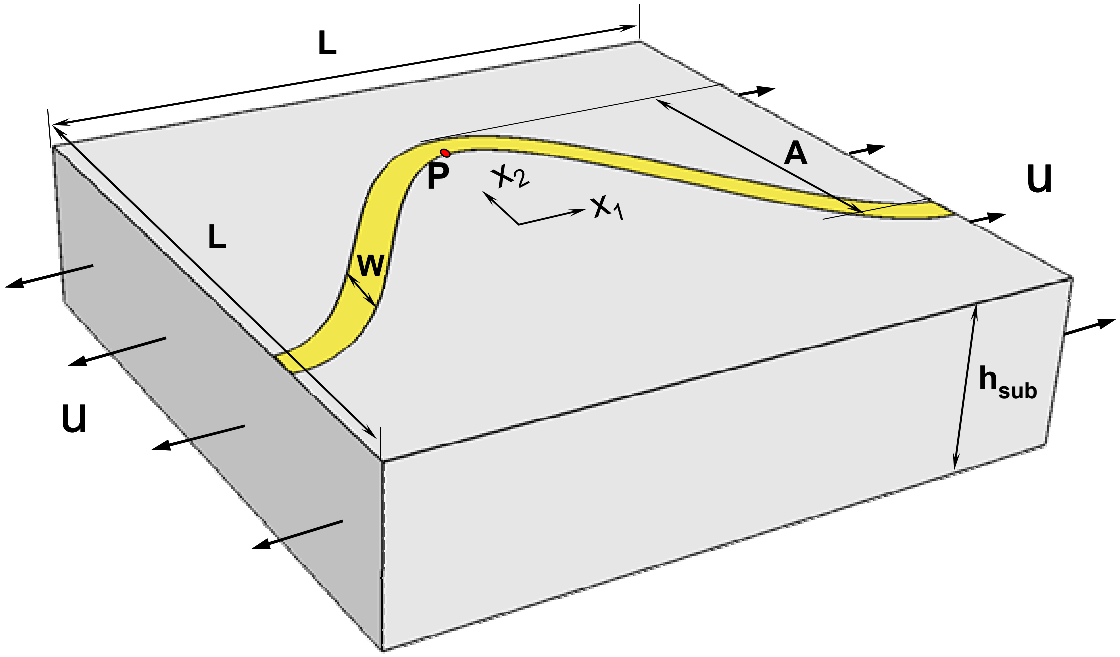


Figure 2: Schematics of a thin film patterned in a sinusoidal shape on a substrate, which is then subject to elongation. The thickness of the film, h_{film} (not shown in the figure), is much smaller than the width of the film, W.

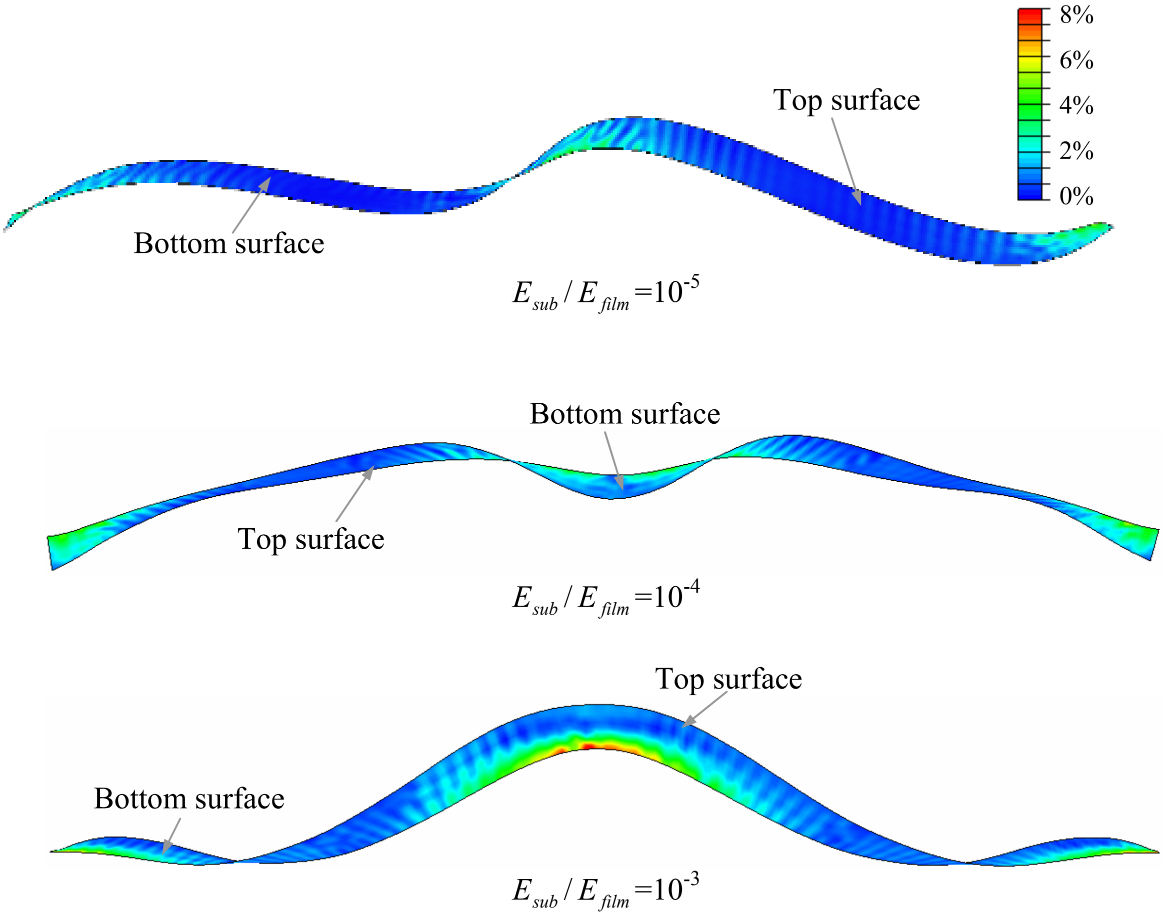
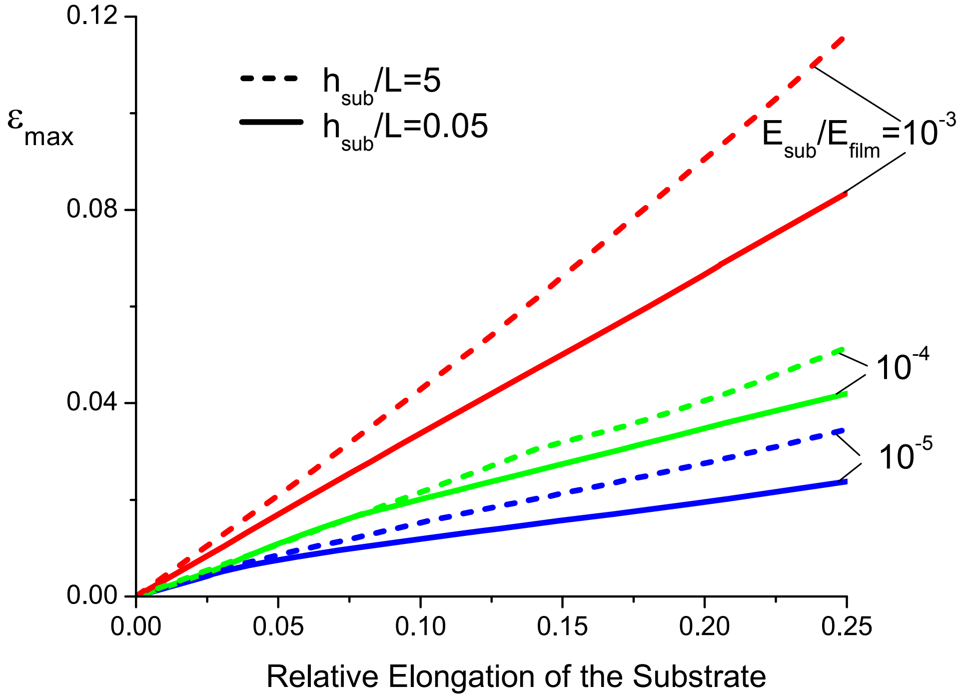


Figure 3: Deformed films on substrates of various Young's moduli, subject to a relative elongation of 25%. For visual clarity, the substrates are not shown. Here W/L=0.05, A/L=0.5, h_{film}/L=0.005, h_{sub}/ h_{film} =10. The shades indicate the levels of the larger principal strain in the film. The three figures are viewed approximately at angles 0^{o}, 15^{o}, -10^{o} from the direction normal to the substrate surface.



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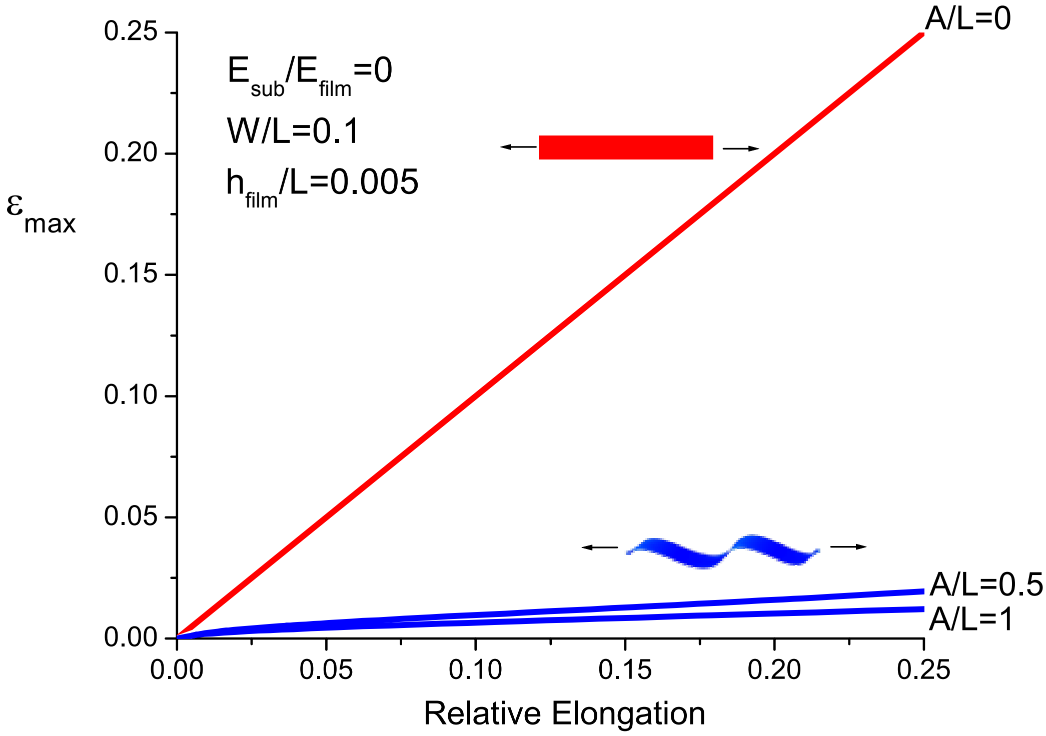

Figure 5: Effect of the sinusoidal pattern on the maximum strain in the film, ε_{max} .

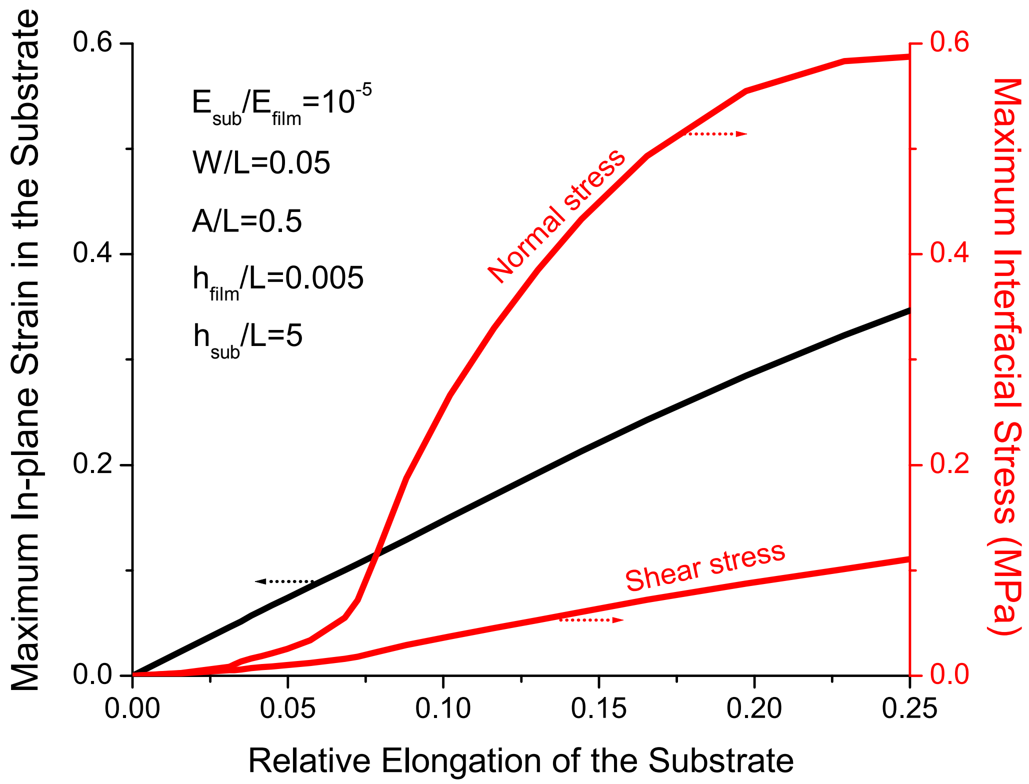

Figure 6: The maximum in-plane strain in the substrate and the maximum interfacial stresses as functions of the relative elongation of the substrate.

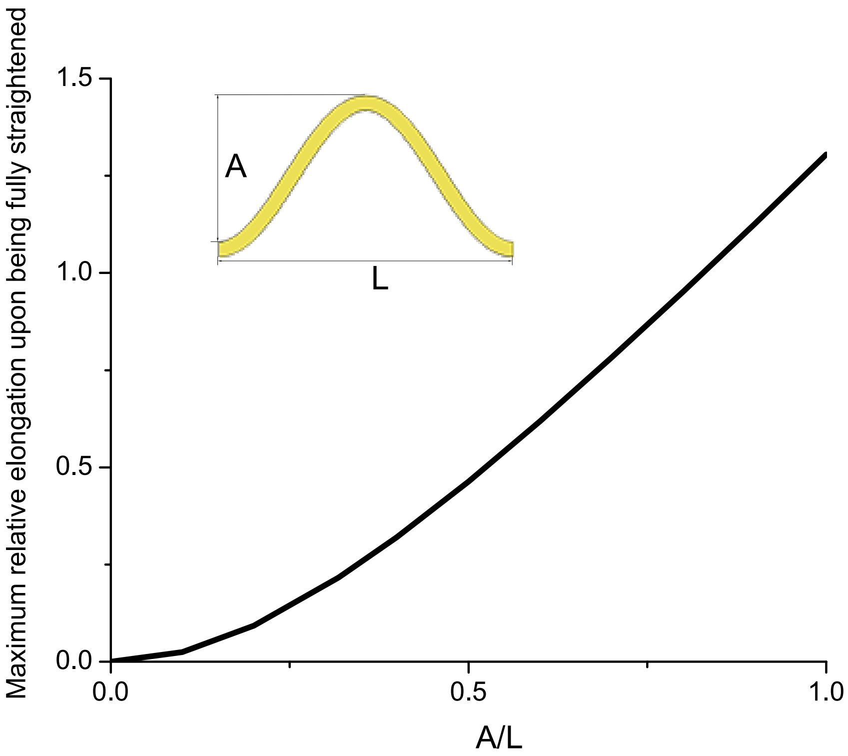

Figure 7: Maximum relative elongation upon which a sinusoid is fully straightened as a function of *A/L*.

Figure Captions

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Figure 5: Effect of the sinusoidal pattern on the maximum strain in the film, $\varepsilon_{\max}$.

Figure 6: The maximum elongation in the substrate and the maximum interface stresses as a function of the relative elongation of the substrate.

Figure 7: Maximum relative elongation upon which a sinusoid is fully straightened as a function of A/L.