Suitably patterned thin stiff films as general platforms for flexible electronics

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Abstract

We propose a general principle to make thin films of stiff materials compliant by suitably patterning. Such a principle is demonstrated by three patterns: a film in serpentine shape, a film with distributed branched cracks, and a film with distributed parallel cracks. We show that such a patterned film elongates by deflecting and 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. We further propose that such a patterned film with large area can serve as a platform, 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.

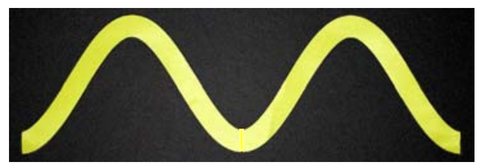
1. Introduction

Enormous interests are gathering in recently years in the nascent technology area of flexible electronics, with an exiting array of applications that will impact everyone's daily life from multiple fronts, ranging from rollable, large area displays, printable thin-film solar cells, flexible radio frequency identification (RFID), to sensitive textiles [1, 2]. Future success of this promising technology largely relies on the reduced cost and enhanced portability of the flexible electronic devices, attributes that will come from new choice of materials and of manufacturing processes. For example, electronic materials (metals, dielectrics and semiconductors) can be fabricated into micro/nano structures on polymer substrates, through a roll-to-roll printing, resulting in lightweight, rugged and flexible device [3]. These devices will have diverse architectures, hybrid materials, and small features. Moreover, such devices will be subject to large, repeated deformation during manufacturing and service. The mechanical behaviors of such micro/nano structures of electronic materials on soft substrates pose significant challenges to the functionality and reliability of flexible and stretchable electronic devices. For example, thin films of electronic materials rupture at small strain (e.g., <1%) [4-7]. How to fabricate flexible circuits by using traditional electronic materials remains unclear. To address these concerns, we propose a general platform for flexible electronics by suitably patterning thin films of electronic materials.

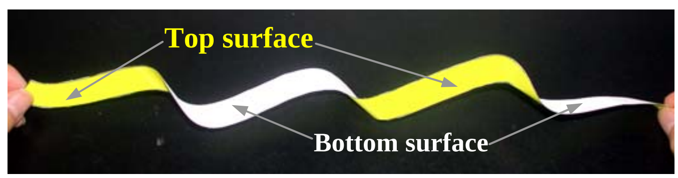
The rest of the paper is organized as follows. Section 2 illustrates a general principle to make a thin film of a stiff material compliant by patterning it into a serpentine. The effects of the compliance of the substrate and the pattern of the film on the deformability of the serpentine are then studied in Section 3. Section 4 explores two other possible compliant patterns of stiff materials, inspired by recent experiments. The concluding remarks are given in Section 5.

2. Illustration of a principle

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.



(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.

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.

3. Effect of substrate compliance and film pattern

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.

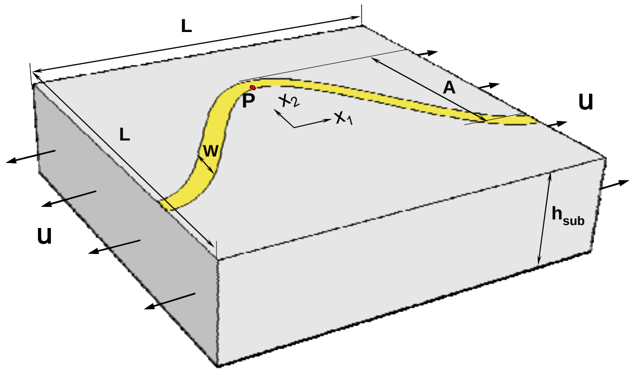


Figure 2: Schematics of a thin film patterned in a sinusoidal shape on a substrate, which is then subject to elongation. The thickness of the film, h_{film} (not shown in the figure), is much smaller than the width of the film, *W*.

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}. Poisson's ratio is taken to be 0.3 for both materials.

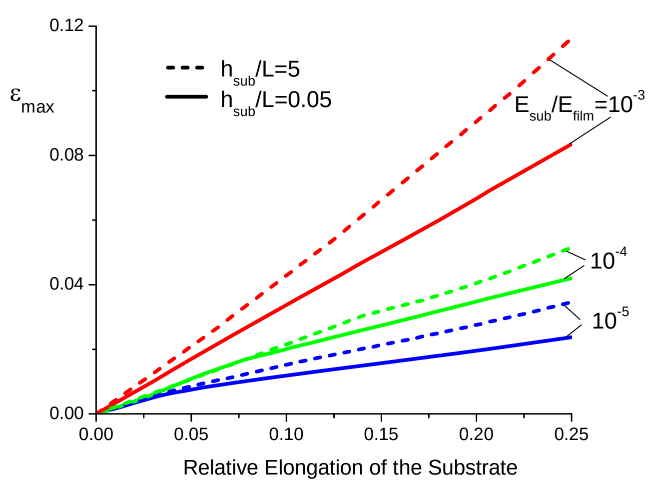


Figure 3: The maximum strain in the film, $\varepsilon_{\max}$, as a function of the relative elongation of the substrate. Here *W/L*=0.05, *A/L*=0.5, h_{film}/L=0.005.

Figure 3 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%. The out-of-plane displacement of the film is anti-symmetric with respect to the x_2 axis (similar to the elongated paper serpentine in Fig. 1 (b)); when the modulus of the substrate increases, the displacement is gradually confined in the plane, and $\varepsilon_{\max}$ also increases. For example, when $E_{sub}/E_{film} = 10^{-3}$, $\varepsilon_{\max}$ = 11.6% at the relative elongation of 25%. 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 3 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 4 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.

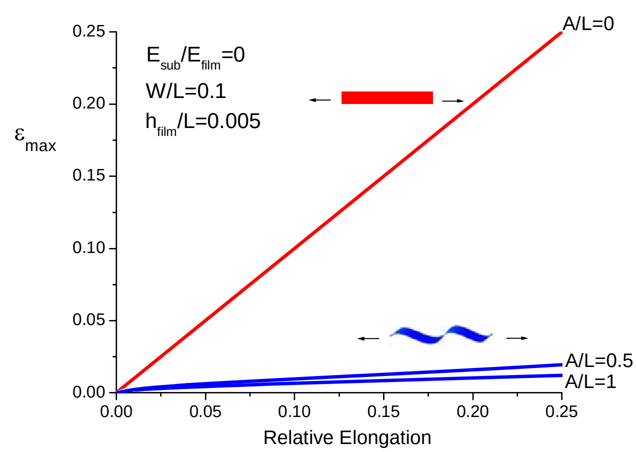


Figure 4: Effect of the sinusoidal pattern on the maximum strain in the film, $\varepsilon_{\max}$.

4. Other compliant thin film patterns

In Section 3, we have focused on a thin film patterned as a serpentine on an elastomeric substrate [8]. In fact, a large variety of patterns allow substantial elongation by the same principle. In this section, we will explore other stretchable patterns of thin stiff films, inspired by recent experiments.

Lacour et al. recently observed that thin gold films on polydimethylsiloxane (PDMS) substrates can sustain one-time elongation up to twice their length, or repeated elongations of 32% over one hundred cycles, while retaining electrical continuity [9,10]. Scanning electronic microscopy showed that such thin gold films have randomly distributed tri-branched microcracks of 1μm length or less as deposited. By contrast, continuous (crack-free) thin gold films on PDMS usually rupture at an elongation less than 1% [11]. The deformation mechanism of the stretchable thin gold films with distributed microcracks can be explained by the same principle illustrated by the paper serpentine in Section 2. As visualized by a macroscopic experiment (Fig. 5), an array of tri-branched cuts is made in a piece of transparency foil in the pattern of Fig. 6a, and the foil is pulled at two opposite edges. The patterned foil elongates by deflecting and twisting out of the plane. The strain induced in the foil remains so small that it does not tear the foil. Upon release, the foil becomes flat again.

Figure 5: A transparency foil with tri-branched cuts becomes stretchable by deflecting and twisting out of the plane.

To quantify the strain levels in the stretchable film, we simulated the deformation of the patterned films as in Fig. 6a under elongation, using the finite element code ABAQUS. The centers of the tri-branched cracks in Fig. 6a coincide with a hexagonal lattice of lattice spacing L. The branches of the Y-shaped cracks, of length a, lie along the lines that connect adjacent lattice points. Due to the symmetry of the structure, we only simulate part of the film (marked by the shaded area in Fig. 6a), with displacement u applied on the ligaments along the two parallel edges of the shaded area (Fig. 6b). Again, to avoid the confusion with the microscopic strain in the film, we call the quantity $2u/L$ the relative elongation. The film is meshed with eight-node quadrilateral shell elements, with densified mesh near the crack tips. We model the film as a linear elastic material with a Young's modulus E. In simulations, a/L = 0.75 and h/L = 0.01, where h is the film thickness.

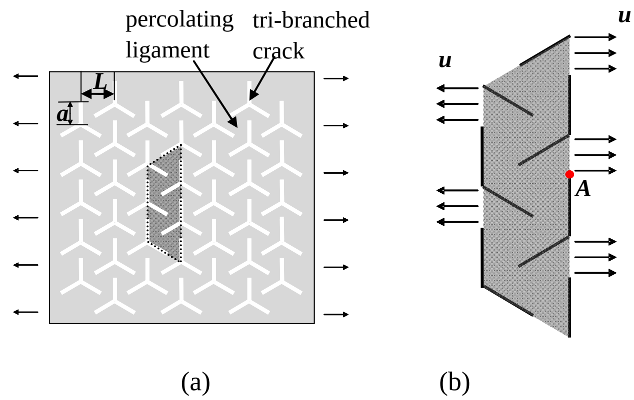


Figure 6: (a) Schematic of the film patterned with the tri-branched cracks. (b) Simulation model (corresponding to the shaded part in (a)).

Results are presented for the cell demarcated in Fig. 6b at a relative (macroscopic) elongation of 25% (Fig. 7). At each point in the film the strain has two principal components, the larger of which is indicated by the shade in Fig. 7.

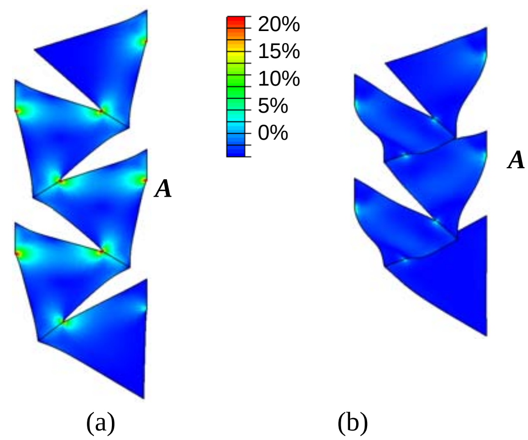


Figure 7: Under a relative elongation of 25%, the percolating ligaments (a) bend in the plane, leading to the openings of the cracks, or (b) deflect and twist out of the plane. The shades indicate the levels of the larger principal strain in the film. Note the overall low strain level in (b).

If the patterned film is bonded to a sufficiently less compliant substrate, the out of plane deflection of the ligaments can be constrained. Therefore, a small elongation would induce a significant strain in the film. Such a limiting case is illustrated in Fig. 7a. If the deformation is confined in the plane, the film accommodates the elongation by the in-plane bending of the ligaments, leading to the opening of the cracks. The resulting strains near the crack tips are significant. By contrast, if the patterned film is bonded to a sufficiently compliant substrate, it can accommodate a large elongation by deflecting and twisting the ligaments out of plane. The resulting strain is much smaller than that of in-plane deformation mode. Such a limiting case is illustrated in Fig. 7b. Therefore, most part of the film only deforms elastically under a large elongation. Without much plastic deformation, the film can then be elongated repeatedly, and does not fatigue.

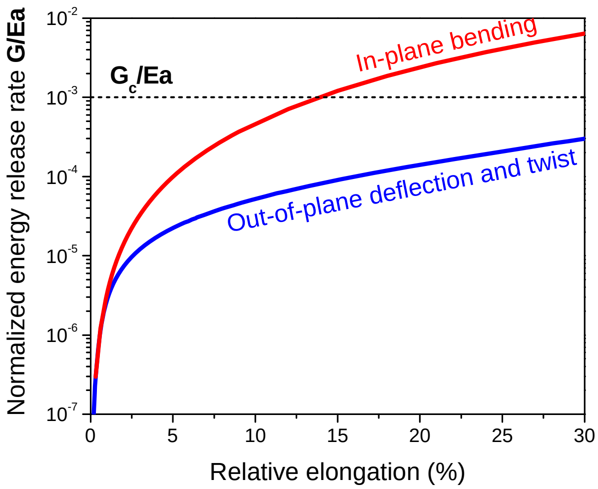


Figure 8: Normalized energy release rate *G/Ea* at crack tip A as a function of relative elongation. Note the order of magnitude difference in the driving force of crack propagation for the two deformation modes. G_c denotes the threshold value above which the crack branch will grow under monotonic loading.

To further quantify the critical condition of the growth of the tri-branched cracks, Figure 8 plots the energy release rate *G*, normalized by *Ea*, at the crack tip *A* marked in Fig. 6b, as a function of the relative elongation. The quantity *G*/*Ea* measures the driving force for crack growth. Once *G* reaches a critical value G_c, the crack grows. The larger the relative (macroscopic) elongation of the film, the larger the driving force for crack propagation. Figure 8 reveals that, if the film can deflect and twist out of the plane (blue curve), the energy release rate at the crack tips is much smaller than that due to bending in the plane (red curve). For example, at a relative elongation of 30%, the energy release rate of out-of-plane deflection is one-twentieth of that of in-plane bending. For a thin metal film, G_c scales with σ_Y and *h*, where σ_Y is the yield strength of the metal and *h* the film thickness. With σ_Y = 1GPa, *h* = 30nm, *E* = 100GPa, and *a* = 0.3μm, we have $G_c / Ea = 10^{-3}$. With such a critical value, the maximum relative elongation without crack growth is far beyond 30% when the metal film can deflect and twist out of the plane, while it is only 13.5% when the film is confined to the plane.

We further simulate the deformation of a film patterned with distributed parallel cracks (comparable to Fig. 6a). The crack pattern is defined in Fig. 9. Vertical cracks of length *a* are evenly distributed with vertical spacing of *L* and horizontal spacing of S. The centers of the cracks coincide with two interpenetrating rectangular lattices (*L* by *S*), each one of which is at the centers of the rectangles defined by another lattice. Such a film is subject to elongation in horizontal direction. In the simulation, we use *L/S*=5, *a/S*=4, which is comparable to the crack geometry in Fig. 7a. We calculate the energy release rate *G*, normalized by *Ea*, at the crack tips. The results are plotted in Fig. 10 in a similar manner as in Fig. 8. Figure 10 also shows dramatic decrease in the driving force of crack propagation if the film can deflect and twist out of the plane (blue curve) instead of bending in the plane (red curve). Such a decrease is more substantial than that for the film with tri-branched crack pattern. For example, at a relative elongation of 30%, the energy release rate of out-of-plane deflection is about one-fortieth of that of in-plane bending.

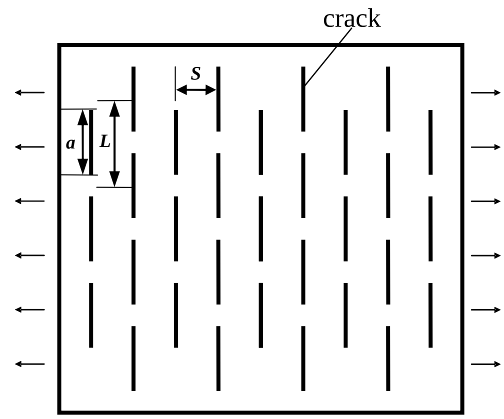


Figure 9: Schematic of the film patterned with the parallel cracks.

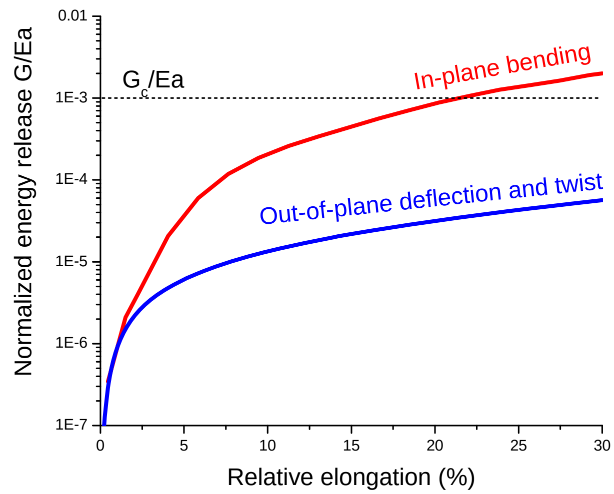


Figure 10: Normalized energy release rate *G/Ea* at the tips of parallel cracks in Fig. 10 as a function of relative elongation.

G_c estimates the threshold of crack growth under monotonic elongation. Under cyclic loading, the fatigue crack growth threshold G_{th} is not well understood for thin metal films, but nonetheless is a fraction of G_c [12]. From Fig. 8, for G_{th} = G_c/10, a film patterned with tri-branched cracks can still be cyclically elongated up to 16.3% without crack growth if it can deform out-of-plane. From Fig. 10, for a film patterned with distributed parallel cracks, the maximum relative elongation without crack growth is ~30% even for G_{th} = G_c/20.

Section 5: Concluding remarks

In this paper, we propose a general principle of making a thin film of stiff material stretchable by suitably patterning. We show that such a patterned film elongates by deflecting and 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. We further propose that such a patterned film with large area can serve as a platform, 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.

We have explored several stretchable thin film patterns, and quantified the relation between their stretchability and pattern geometry. In practice, the stretchability of such patterns is limited by the fracture strain of electronic materials (less than about 1%). For example, 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. 4). 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. The randomly distributed tri-branched cracks in the gold films are spontaneously formed during the fabrication. The crack pattern can be fabricated in a more controlled manner through mature fabrication technology, i.e. lithography and imprinting. The crack tips can be blunted, therefore the driving force for crack propagation can be further decreased and even better stretchability can be achieved.

The simulations also show that, the out-of-plane deflection and twist of a patterned film 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 for a serpentine. Underneath such a compliant top layer, a less compliant material may be used as a backing, if some overall rigidity is desired in practice (i.e., rollable display).

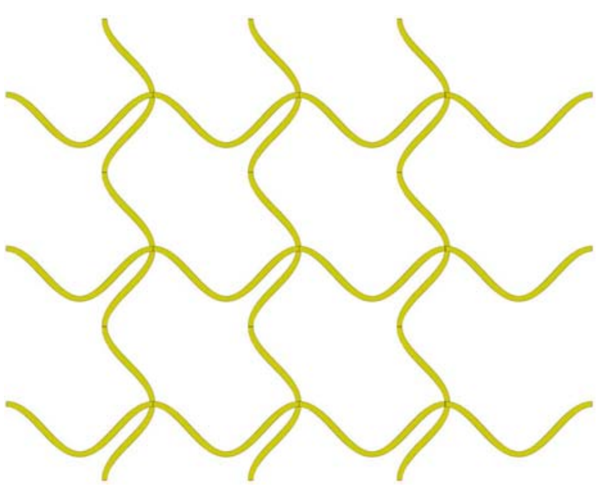


Figure 11: A network of serpentines with bidirectional connectivity.

We have focused on a patterned film on an elastomeric substrate subject to uniaxial elongation. With suitable choices of length ratios, such a structure can also sustain biaxial elongation (i.e., Fig. 11). 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 future studies, we will explore such patterns to meet various design requirements.

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