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Mechanics of stretchable electronics with high fill factors

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ABSTRACT

Mechanics models are developed for an imbricate scale design for stretchable and flexible electronics to achieve both mechanical stretchability and high fill factors (e.g., full, 100% areal coverage). The critical conditions for self collapse of scales and scale contact give analytically the maximum and minimum widths of scales, which are important to the scale design. The maximum strain in scales is obtained analytically, and has a simple upper bound of $3t_{scale}/(4\rho)$ in terms of the scale thickness t_{scale} and bending radius ρ.

1. Introduction

Stretchable and flexible electronics have performance equal to established technologies that use rigid semiconductor wafers, but have mechanical properties of a rubber band (Rogers et al., 2010). They enable many new application possibilities, such as structural health monitoring devices (Nathan et al., 2000), flexible sensors (Lumelsky et al., 2001; Mannsfeld et al., 2010; Someya et al., 2005; Someya and Sekitani, 2009), smart surgical gloves (Someya et al., 2004), flexible display (Crawford, 2005; Forrest, 2004; Gelinck et al., 2004); electronic eye camera (Jin et al., 2004; Ko et al., 2008); stretchable and foldable circuits (Kim et al., 2008a; Sekitani et al., 2010), and flexible solar cell (Yoon et al., 2008) and LED (Park et al., 2009; Sekitani et al., 2009). Stretchable and flexible electronics have recently been applied to medicine, such as to cardiac electrophysiology (Viventi et al., 2010), bio-integrated electronics (Kim et al., 2010a), water-proof optoelectronics for biomedicine (Kim et al., 2010b), advanced catheter technology (Kim et al., 2011a), epidermal electronics (Kim et al., 2011b), and flexible and foldable surface electrodes for measuring brain activity (Viventi et al., 2011).

Fig. 1a shows the mesh design of stretchable and flexible electronics (Kim et al., 2008b; Song et al., 2009; Su et al., 2012). The device islands connected by interconnect bridges are structured into a mesh and bond to a pre-stretched elastomeric substrate of PDMS only at the islands. Release of pre-stretch in the substrate leads to buckling of bridges to form arc-shaped bridge structures (Fig. 1b) that can move freely out of the plane to accommodate large applied strains (e.g., >100%), even to values that approach the fracture limits of the PDMS. Serpentine interconnect bridges have also been used to reach even higher stretchability (Kim et al., 2008b).

The island-bridge design in Fig. 1, however, reduces the fill factor (number of devices per unit area) of stretchable electronics since the area outside the device islands is not effectively used. Kim et al. (2012) proposed an imbricate scale design that can provide mechanical stretchability and high fill factor (e.g., full, 100% areal coverage). As illustrated in Fig. 2, scales (rigid plates on which electronics are fabricated) were transfer printed from a donor substrate onto a PDMS backing layer with molded posts. A stamp with microtips at corners was first pressed with high preload against a scale on a donor substrate, which led to mechanical collapse of the stamp and therefore large stamp/scale contact region between microtips. The stamp was then rapidly retracted to lift the scale from the donor. Shortly afterward the compressed microtips relaxed back to their original shape due to restoring forces in PDMS, leaving small stamp/scale contact region only at the microtips. The scale was then gently placed on a post of the PDMS backing layer,

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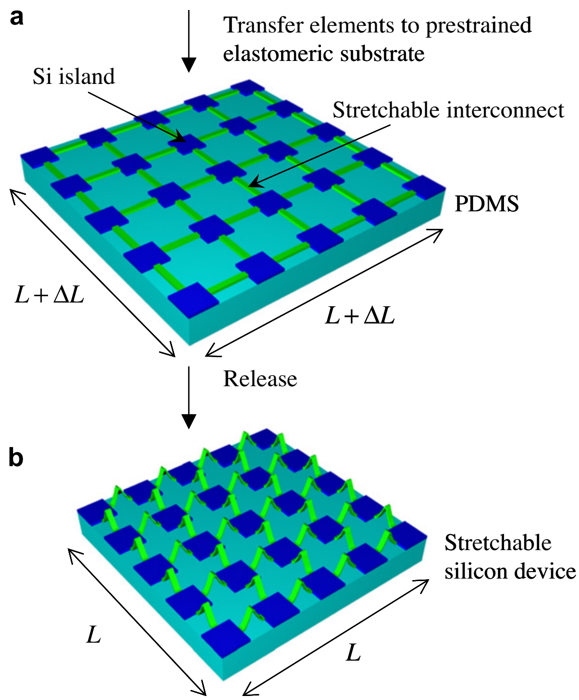

Fig. 1. Schematic illustration of fabrication process for stretchable electronics with the noncoplanar mesh design on a compliant substrate; (a) mesh on a pre-stretched substrate; and (b) buckled mesh after the release of pre-stretch in the substrate. (Copyright 2009 American Institute of Physics.)

followed by slow retraction of the stamp. The scale/post bonding was accomplished using surface hydroxyl condensation reactions. The lateral dimensions of scales (600 × 600 μm) exceeded the post spacing (500 μm), which yielded imbricate layouts with overlaps (of 100 μm) for adjacent scales, as illustrated in Fig. 3a and b. The overlaps changed in size during deformation, but they never disappeared, which enabled full, 100% effective area coverage, i.e., reaching the maximal fill factor of one.

Mechanics models for imbricate scales are established in this paper. An important design consideration is to prevent the scales from self collapsing onto the PDMS backing layer due to scale/PDMS adhesion. A simple, analytical expression for the maximum width of scale is obtained in Section 2. Section 3 gives analytically the maximum stretchability and bendability of scales that still remain in contact during deformation. The maximum strain in scales is obtained in Section 4 via both analytical model and finite element method.

2. Self collapse of the scale onto PDMS backing layer

Fig. 4 illustrates self collapse of a scale onto the PDMS backing layer due to scale/PDMS adhesion. For simplicity the scale is modeled as a beam with the bending stiffness $\overline{EI}_{scale}$, width w_{scale}, and thickness t_{scale}. The post width and thickness are denoted by w_{post} and t_{post}, respectively. Deformation of the post is negligible, as to be shown at the end of this section. The PDMS backing layer is much thicker than the scale and post.

Let y denote the deflection of scale over the part L (Fig. 4) that does not contact the post and backing layer. Only the right half of scale is analyzed due to symmetry. The equilibrium equation of the beam gives $\overline{EI}_{scale} d^4y/dx^4 = 0$, where x is the coordinate with origin at the top right corner of the post. The boundary conditions are $y|_{x=0} = 0$, $y|_{x=L} = -t_{post}$, and $y'|_{x=0} = y'|_{x=L} = 0$. This gives the deflection

$$y = t_{post}\left[2\left(\frac{x}{L}\right)^3 - 3\left(\frac{x}{L}\right)^2\right]. \tag{1}$$

The bending energy in the beam is $\int_0^L (\overline{EI}_{scale}/2) y''^2 dx = 6\overline{EI}_{scale} t_{post}^2/L^3$. The total energy is

$$U = \frac{6\overline{EI}_{scale}}{L^3} t_{post}^2 - \gamma\left(\frac{w_{scale} - w_{post}}{2} - L\right), \tag{2}$$

where γ and $(w_{scale} - w_{post})/2 - L$ are the work of adhesion and contact length between the scale and PDMS backing layer, respectively. Minimization of energy $\partial U/\partial L = 0$ gives

$$L = \left(\frac{18\overline{EI}_{scale}}{\gamma} t_{post}^2\right)^{1/4}. \tag{3}$$

The total energy is obtained by substituting Eq. (3) into Eq. (2), which must be larger than the energy without collapse (i.e., zero) to prevent self collapse of the scale. This gives the maximum width of scale as

$$w_{scale} \leqslant w_{post} + 8\left(\frac{2\overline{EI}_{scale} t_{post}^2}{9\gamma}\right)^{1/4} \tag{4}$$

to prevent self collapse of the scale. For $\overline{EI}_{scale} = \overline{E}_{scale} t_{scale}^3/12$ with $\overline{E}_{scale} = 140$ GPa and $t_{scale} = 3$ μm, $w_{post} = 140$ μm, $t_{post} = 80$ μm, and $\gamma = 0.15\ \mathrm{Jm}^{-2}$ in experiments (Kim et al., 2012), the above equation gives $w_{scale} \leqslant 2.01$ mm. The scale width in experiments $w_{scale} = 600$ μm, at which no self collapse is observed, indeed satisfies this condition.

The change of post thickness due to self collapse of the scale can be estimated the compression due to the scale/post contact force

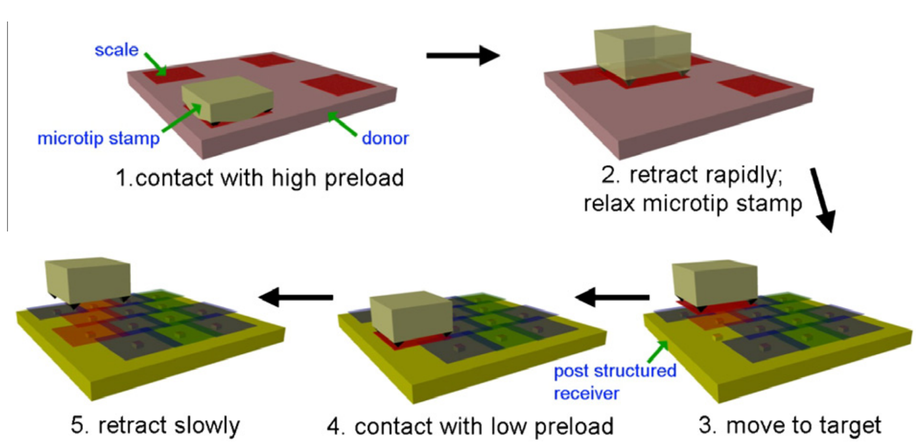

Fig. 2. Schematic illustration of fabrication process for stretchable electronics with an imbricate scale design on a compliant backing layer.