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Mechanics of stretchable electronics

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ABSTRACT

Recent advances in mechanics and materials provide routes to develop stretchable electronics that offer performance of conventional wafer-based devices but with the ability to be deformed to arbitrary shape. Many new applications become possible ranging from electronic eye cameras to wearable electronics, to bio-integrated therapeutic devices. This paper reviews mechanics of stretchable electronics in terms of two main forms of stretchable designs. One is wavy design, which can provide one-dimensional stretchability. The other is island-bridge design, which can be stretched in all directions. Mechanics models and their comparisons to experiments and finite element simulations are reviewed for these two designs. The results provide design guidelines for the development of stretchable electronics.

1. Introduction

The vast majority of development in electronic research community has been focused on smaller and faster devices. These devices are confined to the planar surface of silicon wafers, and are hard, rigid and flat. An emerging research direction is stretchable electronics, which offers the performance of conventional wafer-based devices, but with mechanical properties of a rubber band that would enable many new applications, particularly the intimate integration of electronics with human body [1,2]. Examples include electronic eye cameras [3–5], wearable photovoltaics [6], flexible displays [7], epidermal electronics [8,9], flexible piezoelectric sensor [10], stretchable strain gauge [11], energy harvester [12], and bio-integrated therapeutic devices [13–15]. Circuits that use organic semiconductor materials can sustain large deformations [16–18], but their electrical performance is relative poor comparing with the inorganic semiconductors such as silicon, gallium arsenide, and gallium nitride. Compatibility with well developed, high performance inorganic electronic materials represents a key advantage in stretchable electronics. The main challenge is the mismatch between the soft and elastic requirements of applications and the intrinsic hard and rigid features of inorganic materials with a fracture strain ~1%. Several mechanics strategies have been developed to make inorganic electronic materials and devices stretchable on elastomeric substrates. They can be classified into two categories.

(1) *Wavy design:* The thin films of inorganic materials are transfer-printed to a prestretched elastomeric substrate. Releasing the prestrain leads to the formation of wavy configuration, which can accommodate external deformations (~20%) through changes in wavelength and amplitude. Fig. 1 shows scanning electron micrographs of wavy design with ribbons perfectly (Fig. 1a) and partially (Fig. 1b) bonded to an elastomeric poly(dimethylsiloxane) (PDMS) substrate. This strategy has been demonstrated in different film systems such as gold [19], platinum [20], silicon nanoribbon [21,22] and nanomembranes [23], silicon nanowires [24–26], carbon nanotubes [27,28], graphene [29], and ferroelectrics [30].

(2) *Island-bridge design:* The island-bridge mesh design is transfer-printed to a biaxially prestretched elastomeric substrate with strong chemical bonds at the locations of island (i.e., active device) and weak bonds at the locations of bridge (i.e., interconnect). The release of prestrain causes the bridge to buckle out of the plane to accommodate the deformations (~100%) such that the relatively rigid island experiences very small deformations. Fig. 2 shows scanning electron micrographs of island-bridge design with straight interconnects (Fig. 2a) and serpentine interconnects (Fig. 2b). The recent optimization of the bridge by using the type of fractal interconnect further increases the system stretchability [31]. This design has been widely used to various types of stretchable electronics due to the large stretchability that it can provide. Examples include electronic eye cameras [4–6], integrated circuits [32], silicon curvilinear electronics [33], LED system [34], and stretchable lithium-ion batteries [31].

Various mechanics models associated with the above designs have been developed to study the key effects on deformation modes and strain distribution. There exist several reviews of

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mechanics and materials for stretchable electronics [1,2,35,36]. This article provides a brief review of the fundamental aspects of the mechanics in the wavy and island-bridge designs for stretchable electronics, through discussions of theoretical models and their quantitative comparisons to experiment. The mechanics theories for wavy design are described in Section 2 and island-bridge design in Section 3. It should be noted that the focus of island-bridge design in this article is on straight interconnects. Mechanics of serpentine or fractal interconnects is reviewed by others in this issue.

2. Mechanics of wavy design

The fabrication of stretchable wavy ribbons is illustrated in Fig. 3. The flat ribbon is transfer-printed to a prestrained compliant substrate with a perfect bond interface. When the prestrain is released, the substrate shrinks, which leads to a compression in ribbon to form the wavy layout through a nonlinear buckling response. These wavy layouts can accommodate external deformations along the ribbon direction through changes in wavelength and amplitude.

2.1. Wavy ribbon in small deformation

The thin ribbon is modeled as an elastic nonlinear von Karman beam since its thickness is much smaller comparing with other characteristic lengths (e.g., wavelength). The substrate is modeled as a semi-infinite solid because its thickness (∼mm) is much larger than that (∼μm) of film. The total energy consists of the bending energy U_b and membrane energy U_m in the thin film and strain energy U_s in the substrate.

For a stiff thin film (ribbon) with thickness h_f, Young's modulus E_f and Poisson's ratio ν_f on a prestrained compliant substrate with prestrain ε_{pre}, modulus E_s, and Poisson's ratio ν_s, where $E_f \gg E_s$ (e.g., $E_f = 130$ GPa for silicon and $E_s = 1.8$ MPa for PDMS), the wavy profile forms with the out-of-plane displacement

$$w = A\cos(kx) = A\cos\left(\frac{2\pi x}{\lambda}\right), \quad (1)$$

when the prestrain is released. Here, x is the coordinate along the ribbon direction, A is the amplitude, λ is the wavelength and $k = 2\pi/\lambda$ is the wave number. The bending energy U_b can be obtained by

$$U_b = L_0 \frac{1}{\lambda}\int_0^{\lambda} \frac{\bar{E}_f h_f^3}{24}\left(\frac{d^2 w}{dx^2}\right)^2 dx = \frac{\pi^4 \bar{E}_f h_f^3 A^2}{3\lambda^4} L_0, \quad (2)$$

where L_0 and $\bar{E}_f = E_f/\left(1-\nu_f^2\right)$ are the length and plane-strain modulus of thin film, respectively.

The membrane strain ε_m, which determines the membrane energy in the ribbon, is related to the in-plane displacement u and out-of-plane displacement w by $\varepsilon_m = du/dx + (dw/dx)^2/2 - \varepsilon_{pre}$. The membrane force N_m is given by $N_m = \bar{E}_f h_f \varepsilon_m$. The interfacial shear is negligible [37] and the force equilibrium then gives a constant membrane force and therefore a constant membrane strain

$$\varepsilon_m = \frac{\pi^2 A^2}{\lambda^2} - \varepsilon_{pre}, \quad (3)$$

The membrane energy U_m in the film can then be obtained by

$$U_m = L_0 \frac{1}{\lambda}\int_0^{\lambda} \frac{1}{2} N_m \varepsilon_m dx = \frac{1}{2}\bar{E}_f h_f \left(\frac{\pi^2 A^2}{\lambda^2} - \varepsilon_{pre}\right)^2 L_0. \quad (4)$$

The strain energy in the substrate is obtained by solving a semi-infinite solid subjected to the normal displacement in Eq. (1) and vanishing shear on its boundary as

$$U_s = \frac{\pi}{4\lambda}\bar{E}_s A^2 L_0, \quad (5)$$

where $\bar{E}_s = E_s/(1-\nu_s^2)$ is the plane-strain modulus of the substrate.

The buckle amplitude A and wavelength λ are obtained by minimizing the total energy, i.e., $\partial(U_m + U_b + U_s)/\partial A = \partial(U_m + U_b + U_s)/\partial\lambda = 0$, as

$$\lambda = 2\pi h_f \left(\frac{\bar{E}_f}{3\bar{E}_s}\right)^{1/3}, \quad A = h_f\sqrt{\frac{\varepsilon_{pre}}{\varepsilon_c} - 1}, \quad (6)$$

where

$$\varepsilon_c = \frac{1}{4}\left(\frac{3\bar{E}_s}{\bar{E}_f}\right)^{2/3}, \quad (7)$$

is the critical strain for buckling and is extremely small (e.g., 0.034% for silicon/PDMS system). When $\varepsilon_{pre} < \varepsilon_c$, no buckling occur and the ribbon remains flat. When $\varepsilon_{pre} > \varepsilon_c$, the ribbon buckles with a constant membrane strain $\varepsilon_{membrane} = -\varepsilon_c$. The maximum bending strain is given by $\varepsilon_{bending} = 2\sqrt{(\varepsilon_{pre} - \varepsilon_c)\varepsilon_c}$. The peak strain ε_{peak}, which is the sum of membrane strain and bending strains, is approximated by

$$\varepsilon_{peak} \approx 2\sqrt{\varepsilon_{pre}\varepsilon_c}, \quad (8)$$

for small ε_c.

For the buckled system subjected to the applied strain $\varepsilon_{applied}$, the wavelength and amplitude become

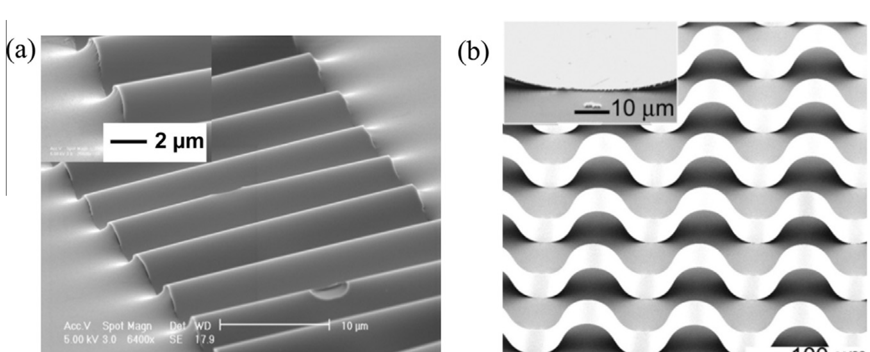

Fig. 1. Scanning electron microscope (SEM) images of wavy design with ribbon (a) perfectly and (b) partially bonded to a compliant substrate. (Reprinted with permission from Ref. [35].)