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Mechanics for stretchable sensors

Nanshu Lu *, Shixuan Yang

Center for Mechanics of Solids, Structures and Materials, Department of Aerospace Engineering and Engineering Mechanics, Center for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies (NASCENT), Texas Materials Institute, The University of Texas at Austin, Austin, TX 78712, USA

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ABSTRACT

In the past decade, high performance stretchable sensors have found many exciting applications including epidermal and *in vivo* monitors, minimally invasive surgical tools, as well as deployable structure health monitors (SHM). Although wafer based electronics are known to be rigid and planar, recent advances in manufacture and mechanics have made intrinsically stiff and brittle inorganic electronic materials stretchable and compliant. This review article summarizes the most recent mechanics studies on stretchable sensors composed of ceramic and metallic functional materials. The discussion will focus around the most popular "island plus serpentine" design where active electronic or sensing components are housed on an array of isolated, micro-scale islands which are interconnected by electrically conductive, stretchable, serpentine thin films. The mechanics of polymer supported islands, freestanding serpentines, and polymer supported serpentines will be introduced. The effects of feature geometry and polymer substrate on the stretchability, compliance, as well as functionality of the sensor system will be discussed in details. The tradeoff between mechanics and functionality gives rise to the challenge of simultaneously optimizing the structure and performance of stretchable sensors.

1. Introduction

Research on flexible electronics started almost 20 years ago [1,2] with the demand of macroelectronics [3], such as paperlike displays [4,5]. Organic semiconductors and conducting polymers were appealing materials for large-area electronics attributing to their intrinsic flexibility, light weight, and low fabrication cost in roll-to-roll processes [6,7]. The other branch of flexible and even stretchable electronics based on high-quality inorganic semiconductors started to emerge in the mid-2000s [8,9]. Inorganic semiconductors exhibit high carrier mobility and excellent chemical stability [8]. Natural abundance and well-established manufacturing processes make them even more appealing. Their intrinsic stiffness and brittleness, however, greatly hindered their application in flexible electronics. Mechanics of stiff/brittle membranes integrated with deformable polymeric substrates have offered insights and solutions to overcome the intrinsic limitations of these materials.

For example, bendable and foldable inorganic electronics including integrated circuits [10,11], solar cells [12], light emitting diodes [13], thin film battery [14], and bio-integrated nanogenerator [15] have been successfully developed by placing fragile materials along the neutral axis of a multilayer stack. Neutral axis is defined as the line (or the plane for 3D problems) whose strain remains zero when the system is under pure bending. Using Euler–Bernoulli beam theory [16], the position of the neutral axis of an n-layer laminate can be determined by the following equation [10].

$$b = \frac{\sum_{i=1}^{n} \bar{E}_i h_i \left[\left(\sum_{j=1}^{i} h_j \right) - \frac{h_i}{2} \right]}{\sum_{i=1}^{n} \bar{E}_i h_i}, \tag{1}$$

where b denotes the distance between the top surface of the laminate to the neutral axis, $i = 1$ represents the top layer, $\bar{E}_i = E_i/(1-\nu_i^2)$ is the plane strain Young's modulus with ν_i being the Poisson's ratio of the ith layer, and h_i represents the thickness. Bending-induced strain can be calculated analytically using:

$$\varepsilon = \frac{y}{\rho}, \tag{2}$$

where ρ represents the radius of the neutral axis and y is the distance from the neutral axis to the point of interest. Therefore, when the median plane of a brittle layer of thickness h is aligned with the neutral axis, the maximum bending induced tensile strain in this brittle layer can be calculated by substituting $y = h/2$ in Eq. (2), which indicates that even when the brittle layer is placed along the neutral axis, the maximum strain is still proportional to the thickness of this brittle layer. However, we have to be careful when

* Corresponding author. Tel.: +1 512 471 4208.
E-mail address: nanshulu@utexas.edu (N. Lu).

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using Eqs. (1) and (2) because they are only applicable to a laminate with small elastic mismatch between different layers. With flexible photonic strain sensors [17], we find that the Euler–Bernoulli beam theory breaks down when a soft layer is sandwiched between two stiff layers because significant shear can develop in the soft layer, leading to the so called "split of neutral axis", i.e. multiple neutral axes can appear within one multilayer laminate. This finding breaks the limit of conventional flexible electronics where all the brittle materials have to be placed along one neutral plane. Instead, it suggests a possibility to build flexible electronics with multiple layers of active components because of the presence of multiple neutral axes.

Compared with flexible electronics, the mechanics for stretchable electronics are more complicated. An earlier strategy to achieve stretchable circuits is to harness the wrinkling (i.e., no delamination between film and substrate) and buckling delamination of stiff nanoribbons or nanomembranes on soft elastomeric substrates [10,18–25]. The controlled wrinkle formation of stiff membranes on elastomeric substrates dated back to late 90s [26–28]. Wrinkled conductors were later found to be useful as stretchable interconnects [22–25]. Wrinkled semiconductor nanoribbons were first realized in 2006 [18,19]. While some analysis on the critical membrane force to initiate wrinkle [29] and buckling delamination [30–32] were even earlier than above experiments, these experiments have stimulated numerous mechanics studies to predict the wavelength and amplitude of the wrinkled patterns [33–45].

Due to difficulties associated with the fabrication, encapsulation, and bio-integration of wrinkled or buckled circuits, a new mechanics strategy to build stretchable electronics, the "island plus serpentine" design [46], became more popular. The idea is simple: instead of using continuous nanomembranes or straight nanoribbons, inorganic materials can be patterned into isolated micro-islands and serpentine-shaped meandering ribbons. As the Young's moduli of elastomers are four to six orders lower than inorganic semiconductors, when the elastomer substrate is stretched, it cannot generate large enough stress to be transferred to the stiff islands which are bonded to the elastomer. Therefore strains in the islands remain very small and the brittle materials housed on the islands can stay intact even under very large applied strains to the substrate. To complete the circuits, isolated islands have to be interconnected by extremely stretchable conductors. While straight thin metal films well adhered to polyimide substrate have demonstrated stretchability up to 50% [47–49], the deformation is enabled by plastic mechanism, which is not reversible. One way to enable reversible resistance of straight thin metal film with applied loading and unloading is through a microcrack facilitated mechanism [50], but their fatigue behavior could be a concern. Wrinkled stretchable interconnects have been studied extensively [23–25] but they are difficult to encapsulate and are easy to fracture even under very slight over stretch. Buckled, encapsulated interconnects have successfully linked the isolated islands to complete the circuits [10,51–53] but the fabrication requires transfer printing circuits on pre-stretched elastomer and the buckled interconnect bridges make it difficult to integrate the device with other surfaces. In-plane, serpentine-shaped interconnects can get rid of both troubles – they can be transfer printed onto relaxed elastomers and as fabricated sensors have a flat surface which is easy to encapsulate or to integrate. Serpentines are stretchable because they are like in-plane springs, which can achieve large end-to-end displacement through geometric reconfiguration instead of straining the interatomic distance of the material [54,55]. What's more convenient is that the geometric reconfiguration can be highly reversible due to the small induced strains.

The "island plus serpentine" strategy and its more stretchable variation, the "filamentary serpentine" network, have enabled an explosion of stretchable electronics [56,57] in the late 2000s when the concept of bio-integrated electronics was proposed. So far, bio-integrated electronics has demonstrated exciting applications including epidermal electronic systems (EES) for vital sign monitoring and human machine interface [58–64] (Fig. 1A), conformal epicardial mapping/treatment sheet [65] (Fig. 1B) or sock [66], and instrumented balloon catheter for minimally invasive surgery [67] (Fig. 1C). More detailed materials and mechanics strategies for bio-integrated electronics have been summarized in several recent review articles [68–73]. In addition to bio-integrated electronics, stretchable sensors based on freestanding "island-plus-serpentine" network (i.e., not bonded to polymer substrates) have also found use in structure health monitors (SHM) for their extreme extensibility so that microfabricated, wafer sized sensor network can be deployed hundreds of times to cove huge civil or aerospace structures [74,75] (Fig. 1D). As bending eventually induces tensile strains on the surface of the structure, the "island-plus-serpentine" structure has also enhanced the bending and folding capability of silicon electronics integrated on stiff substrates (e.g., Kapton, printing papers, fabrics, etc.) through a soft strain isolation interlayer [76,77].

This review will summarize some recent studies of the fundamental mechanics of polymer-supported stiff islands and serpentines either freestanding or bonded to polymer substrates. The tradeoff between mechanics and functionality will also be discussed and some optimization strategies will be offered. This review is organized as follows: Section 2 will focus on the mechanics of polymer-supported stiff islands. Section 3 will investigate freestanding and polymer-supported serpentine, respectively. Concluding remarks will be given in Section 4.

2. Stretchable islands on polymer substrates

Mechanics of stiff islands on polymer substrate is important to not only the mechanical reliability of the stretchable device, but also the functionality of the electronics and sensors. In terms of mechanical reliability, failure modes such as channel cracking in ceramic islands [78] and island/substrate delamination [79] are commonly seen. In terms of functionality, semiconductor mobility [80,81] and strain gauge gauge factor [58,64,65,82,83] can be greatly affected by the strain transferred from substrates to islands. In this section, we will use stretchable strain gauges made of piezoresistive silicon strips bonded on polymer substrates (Fig. 1B) as an example to illustrate the tradeoff between mechanics and functionality.

Strain gauges are widely applied to measure mechanical deformation of structures and specimens. Stretchable strain gauges offer unique capability of measuring large strains in soft materials and bio-tissues. While metallic foil gauges usually have a gauge factor slightly over 2 [84], single crystalline silicon demonstrates intrinsic gauge factors as high as 200 due to their piezoresistive property [85–87]. Although silicon is an intrinsically stiff and brittle material, flexible and even stretchable strain gauges have been achieved by integrating thin silicon strips on soft and deformable polymer substrates [64,65,83]. Compared with polymer based stretchable strain gauges [88,89], silicon based ones exhibit less drift, better reversibility, and faster time response. But depending on the substrate material, the behaviors of silicon strain gauges are very different: their gauge factors spanned from 0.23 [64,65] to 43 [83] and stretchability from less than 1% [83] to more than 25% [64,65].

To achieve a fundamental understanding of the large variation in gauge factor and stretchability of reported flexible/stretchable silicon-on-polymer strain gauges, 2D plane strain finite element models (FEM) and semi-analytical models are established to reveal the effects of the length of the silicon strip, and the thickness and