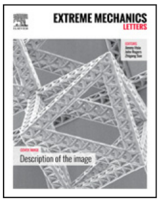
Extreme Mechanics Letters 15 (2017) 44–50

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml



Optimization of compound serpentine–spiral structure for ultra-stretchable electronics

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ARTICLE INFO

Article history:
Received 27 January 2017
Received in revised form 4 April 2017
Accepted 22 May 2017
Available online 30 May 2017

Keywords:
Stretchable electronics
Flexible electronics
Serpentine structure
Spiral structure
Finite element analysis

ABSTRACT

Stretchable electronics is a rising technology, promising to replace the conventional, brittle and rigid electronics for applications that demand mechanical compliance to irregular, complex and mobile shapes. Several approaches have been proposed to find an optimum balance between electrical and mechanical characteristics. These include finding new flexible electronic materials, integrating both organic and inorganic materials or incorporating structural modifications to conventional materials, thus achieving flexibility and stretchability. Previously, the use of spiral-based structures made entirely out of silicon, a well-mature and high-performing material, has been proposed as a platform for ultra-stretchable electronic applications. In this paper we have demonstrated the use of spiral-based compound, fractal-inspired structures to optimize and greatly reduce the stress and strain distribution along them. The integration of double-arm spirals with variants of serpentine and horseshoe structures has been considered and their mechanical response to an applied deformation has been performed through finite element analysis (FEA). The proposed compound structures provide outstanding stretching capabilities and demonstrate up to ∼55% reduction in stress/strain, as well as a more uniform distribution as compared to the original, un-optimized spiral-based structure. These results show the remarkable potential of combining structures to optimize their mechanical behavior, thus accomplishing more robust platforms that will leverage the development of stretchable electronics.

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1. Introduction

With the continuous advancement of electronic systems, new potential and innovative areas of engineering have emerged to cover an exciting range of novel applications from bio-integrated devices and wearable technologies to smart cybernetics and soft-robotics, or self-powered sensor networks as enablers of the Internet-of-Everything (IoE) and Internet-of-Things (IoT) [1–8]. Along with this surge of application areas, electronic systems are being presented with tough challenges in terms of new mechanical requirements and demands. For example, bio-integrated devices and wearable electronics, which deal with complex, mobile, soft, flexible and stretchable biological systems, demand the devices to be conformal to irregular surfaces and to be able to exhibit certain degree of flexibility and stretchability while retaining the high electrical performance of conventional electronics, thus still enabling fast and efficient processing of high amount of information [9–11]. Unluckily, conventional electronics, mostly based on silicon, are rigid and brittle in nature, thus lacking the ability to stretch or flex. This makes conventional electronics inherently incompatible with all these applications where mechanical compliance is not only useful but essential. Research work is underway to overcome such challenges, finding innovative ways to achieve both high electrical and mechanical performance. A number of ground-breaking ideas have been proposed, where two main approaches can be identified; (I) the use of unconventional materials with conventional electric designs, or (II) use of novel strategies and structures to adapt conventional electronics with new mechanical characteristics [10,12–15].

In relation to unconventional materials, organic or polymeric materials are the natural choice due to their excellent mechanical characteristics, giving birth to the notion of flexible, organic electronics, which can provide great flexibility and even stretchability, in contrast to conventionally brittle, inorganic-based devices [10,16–18]. However, their range of applications is, at the moment, limited due to their lower electrical performance, evidently lower compared to silicon, and inability to handle high temperature processing [19,20]. Alternatively, 1D structures, such as nanowires or carbon nanotubes, and 2D atomic structures, such as graphene or transition metal dichalcogenide nanosheets (TMDC), are still far from achieving the integration level and layout complexity of current silicon-based electronics despite their excellent potential electronic properties [20].

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http://dx.doi.org/10.1016/j.eml.2017.05.004
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The alternative second approach, on the other hand, exploits the fact that the flexural rigidity of most stiff materials can be drastically reduced by reducing their thickness down to microscopic or nanoscopic features, thus becoming flexible and able to bend to even very small radii [21]. For example, silicon, which is brittle and rigid in nature, becomes flexible when its thickness is reduced to micro- or nanoscale, thus enabling devices made on ultra-thin silicon sheets to display even high levels of flexibility, while retaining their excellent electric characteristics [10,19,22–26]. Further structural modifications and smart architectures in the thin membranes can expand their mechanical characteristics to go beyond flexibility and even reach stretchability. For instance, ultra-thin silicon sheets can be structured to have a wavy profile, stretchable in nature, when transferred onto a pre-strained polydimethylsiloxane (PDMS) sheet. This wavy shape in the structure provides end to end stretchability and offers elastic response when strain is applied to the structure [10,15,27–30]. A similar strategy is applied by replacing the straight silicon sheets with serpentine traces. In this case the level of stretchability can be carefully designed and improved, because higher elongation can be reached by the buckling-induced, twisting deformation and sequential unfolding of the serpentine structures [31]. An immediate extension to these strategies consist in arranging the brittle semiconducting materials, containing the active electronics, in arrays of rigid islands, which are spatially distributed over an elastic substrate and electrically joined through especially designed metallic interconnects [32–37]. The design of these interconnects is prepared in a way to mitigate the strain induced during the flexing, stretching, or even twisting. The main idea behind this arrangement is to minimize the stress localization at the brittle region of the electronics [13]. Another benefit of this scheme is that it provides the freedom to separate and reorganize the different components of the system, such as power management, sensing modules, communication, etc.

Unlike the islands, interconnects can be stretched due to their structure. Designing interconnects into stretchable forms can result in structures that can withstand large strain deformations. Kim et al. [38] developed a concept to build a network of islands on an elastomer and then connecting the islands through buckled-arch shaped interconnects. Upon the application of applied strain, interconnects move out of the plane to mitigate the effect of the applied pressure. In the same work, an alternative structure was also proposed by replacing the straight-arch-shaped, buckled interconnects with effectively longer serpentine bridges such that the effect of external strain is compensated by the change in height and geometry of non-coplanar serpentines. A powerful alternative configuration comes from naturally occurring structures known as fractals, a self-repeating structure that can provide stretchability to a larger extent. The use of fractal structures, such as Peano, Greek cross or Vicsek, for stretchable electronics was demonstrated by Fan et al. [39] in a health monitoring and communication application. It also showed that higher order fractal structures demonstrate better stretchability; for example, third order Peano layout showed more than 20% stretchability which is even higher than skin's elastic limit. Recently, Yan et al. [40] developed a novel technique to build complex 3D out-of-plane topologies using multilayer 2D precursors on a pre-strained substrate, studying the use of a variety of geometries, such as circular cages, blooming flower, entangled wavy arcs, etc., with the potential for innovative out-of-plane, stretchable applications, like a demonstrated spiral-based tunable inductor for wireless communication. Similarly by using compressive buckling Xu et al. [41] demonstrated to transform 2D structures into 3D. Several 3D geometries were studied that resulted from their 2D precursors like Helix, toroids and spirals.

The use of spiral structures is of especial interest for us due to their advantageous mechanical characteristics. For instance, it has been recently demonstrated by Lv et al. [42] that spiral-based structures can provide larger stretchability as compared to serpentine-based structures with the same in-plane area (plastic deformation reached at ∼100% applied strain with serpentine-based structures, compared to 200% for the spiral). In fact, the use of spirals as ultra-stretchable interconnects has been already proposed by Huang et al. [22] earlier on, where a topology of silicon-based circular islands, meant to host electronics, were physically interconnected through silicon spiral springs in a 2D network. In this work, a very large area expansion ratio of 51 times the original size was achieved, which can be extremely advantageous in macro-electronics applications. Expanding on this, it has been demonstrated that the stretchability ratio can be even further improved by increasing the number of the spiral springs in an area-efficient way. Thus, an all silicon-based network with hexagonal islands was proposed, where the islands were physically interconnected with double-arm spiral structures, such as the one shown in Fig. 1(a), reaching an unprecedented stretch ratio of more than 1000%. Additionally, the base of spring arms were modified with serpentine-like structures to mitigate the effect of high strain at both ends, thus reducing the localized strain at these points by half and evenly distributing it throughout the spiral structure [19]. Practical implementations that use spiral structures to build highly stretchable systems for diverse applications have been demonstrated as well. For instance, Mamidanna et al. [43] demonstrated the excellent mechanic and electric performance of spiral-shaped, reactive ink-based interconnects, showing outstanding stretchability (160%–180%) with only ∼2.5% variation in electrical resistance after being subjected to 1000 elongation cycles. More recently, a spiral-inspired stretchable thermoelectric generator (TEG) was shown to, interestingly, generate higher electric power while being stretched. This can be easily explained since the temperature gradient increases at stretching, given the adequate conditions [44].

Inspired by these all-silicon, spiral-based structures and by the concept of fractals, this letter studies, through finite element analysis (FEA), the effect of replacing the spiral's arms with serpentine and horseshoe structures for maximum stress and strain reduction, while maintaining an efficient use of area. This fractal inspired concept, although not self-repeating, consists of the effective, combined use of spiral, serpentine and horseshoe structures (a structure within a structure). The simulation results showed a considerable reduction in stress and strain, up to 42%, for the compound serpentine–spiral structure compared with the original spiral. Moreover, even further reduction was achieved, up to ∼55% compared with the original spiral, through the optimized compound serpentine–spiral with horseshoe structures at the arms' start and end.

2. Finite element analysis

In general, serpentine/horseshoe structures contain periodic cells; one unit cell with equal halves with each unit cell containing two half circles of radius R, thickness t, arch angle α, width w, S is the end-to-end distance and length l between the half circles (reference schematic can be seen at the inset of Fig. 3(a)). The analytical solution of the in-plane serpentine/horseshoe mechanic behavior has been studied in detail in previous works [45–47].

The general equation for end-to-end distance, S, in case of horseshoe serpentine structure, presented in [45], is given as,

$$S = 4\left(R\cos\alpha - \frac{l}{2}\sin\alpha\right). \tag{1}$$

The above equation shows that for higher stretchability, the radius R of the half-circle plays a vital role and is directly proportional to the end-to-end displacement, whereas the thickness t of the structure will have no effect.

Additionally, a useful non-linear theoretical model for fractal-inspired horseshoe microstructures has been already developed

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