Journal of the Mechanics and Physics of Solids 95 (2016) 25–43

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

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

Helical coil buckling mechanism for a stiff nanowire on an elastomeric substrate

Youlong Chen [a], Yilun Liu [a,*], Yuan Yan [a], Yong Zhu [b], Xi Chen [c,**]

[a] International Center for Applied Mechanics, State Key Laboratory for Strength and Vibration of Mechanical Structure, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China
[b] Department of Mechanical and Aerospace Engineering, North Carolina State University, NC 27695, USA
[c] Columbia Nanomechanics Research Center, Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, USA

ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form
15 April 2016
Accepted 16 May 2016
Available online 24 May 2016

Keywords:
Helical buckling
Energy landscape
Nanowires
Continuum mechanics approach
Stretchable electronics

ABSTRACT

When a stiff nanowire is deposited on a compliant soft substrate, it may buckle into a helical coil form when the system is compressed. Using theoretical and finite element method (FEM) analyses, the detailed three-dimensional coil buckling mechanism for a silicon nanowire (SiNW) on a polydimethylsiloxane (PDMS) substrate is studied. A continuum mechanics approach based on the minimization of the strain energy in the SiNW and elastomeric substrate is developed. Due to the helical buckling, the bending strain in SiNW is significantly reduced and the maximum local strain is almost uniformly distributed along SiNW. Based on the theoretical model, the energy landscape for different buckling modes of SiNW on PDMS substrate is given, which shows that both the in-plane and out-of-plane buckling modes have the local minimum potential energy, whereas the helical buckling model has the global minimum potential energy. Furthermore, the helical buckling spacing and amplitudes are deduced, taking into account the influences of the elastic properties and dimensions of SiNWs. These features are verified by systematic FEM simulations and parallel experiments. As the effective compressive strain in elastomeric substrate increases, the buckling profile evolves from a vertical ellipse to a lateral ellipse, and then approaches to a circle when the effective compressive strain is larger than 30%. The study may shed useful insights on the design and optimization of high-performance stretchable electronics and 3D complex nano-structures.

1. Introduction

Recently, stretchable electronics has attracted wide research interests and holds great potential applications, such as precision metrology (Stafford et al., 2004; Wilder et al., 2006), electronic eye cameras (Ko et al., 2008; Rogers et al., 2010), flexible displays (Chen et al., 2002; Crawford, 2005), stretchable electronic circuits (Kim et al., 2008; Song et al., 2009a; Yao and Zhu, 2015), and conformable skin sensors (Lacour et al., 2005; Someya et al., 2004), to name a few. In stretchable electronics the fragile and stiff elements (e.g. silicon, metal films or wires) are usually placed on the elastomeric substrates

---

[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: yilunliu@mail.xjtu.edu.cn (Y. Liu), xichen@columbia.edu (X. Chen).

http://dx.doi.org/10.1016/j.jmps.2016.05.020
0022-5096/

and pre-compressed to some fundamental buckling modes (Annabattula et al., 2010; Audoly and Boudaoud, 2008; Charlot et al., 2008; Chen and Yin, 2010, 2013). The buckling conformation of the brittle and stiff elements can provide large deformability and tolerance for stretching, compression, bending, twisting and even combined loading modes of the stretchable electronics (Rogers et al., 2010).

In essence, through buckling the compressive strain is released and replaced by relative small bending strain of the slender compressed structure. In this way, the brittle component of electronics can be fabricated into complex buckled form by precisely adjusting the geometrical structures of the stiff components and the elastomeric substrates, the mechanical properties of every constitutive component and the adhesion between the stiff components and the substrates (Ko et al., 2008; Song et al., 2009b; Xu et al., 2015). Further reduction of the thickness or radius of the buckling members, although beneficial for accommodating more compressibility (Song et al., 2009a; Xiao et al., 2010), is unfortunately limited by the fabrication processes and functionality of the flexible electronics. Besides, the bending strain is localized at the crest and valley of the buckling configurations for sinusoidal buckling such as out-of-plane buckling of nanowires and films. Hence, the failure of the brittle components usually initiates at the stress concentration region. Furthermore, the electronic properties of silicon components are closely dependent on the strain applied in the components and the localized strain may cause non-uniform electronic properties in the components (Peng et al., 2009; Sajjad and Alam, 2009; Sajjad et al., 2008). An alternative solution to further enhancing the deformability of the buckling mode is to make the buckles go three-dimensional, such as the helical buckling model of nanowire that has been successfully applied to silicon nanowire (SiNW) which can sustain very large stretchability up to the failure strain of polydimethylsiloxane (PDMS) (Xu et al., 2011). This helical buckling mode can easily handle diverse loading models, including multi-axial stretching, compression, bending, and twisting, and extend the usefulness of stretchable electronic elements. Furthermore, systems at micro or even nano scales were fabricated (Chen and Yin, 2010), and coaxial electrospinning with the helical configuration and other spring-like structures were obtained based on buckling of nanofibers and films on curved substrates (Chen et al., 2009; Chen and Yin, 2010; Yin et al., 2009; Yin and Chen, 2010).

The buckling of nanowires on elastomeric substrate is a very common phenomenon and has important applications in stretchable electronics (Durham and Zhu, 2013; Kim et al., 2008; Ryu et al., 2009; Sun et al., 2006; Wang et al., 2013), and different buckling structures have been reported. For example, the buckled nanowire could lie within the plane of the substrate (in-plane buckling), or perpendicular to the substrate (out-of-plane buckling), or of special interest here is the helical configuration (combination of the in-plane and out-of-plane modes, Fig. 1) (Xiao et al., 2008, 2010; Xu et al., 2011). The adhesion strength between SiNW and elastomeric substrate may have an important role in regulating the buckling mode of SiNW on PDMS substrate. It has been reported that the ultraviolet/ozone (UVO) treatment may strengthen the interaction between SiNW and PDMS by forming strong covalent bonds, and without the treatment, there only exist much weaker Van der Waals forces (Efimenko et al., 2002; Qin and Zhu, 2011). Consequently, no debonding between SiNW and PDMS is observed after proper UVO treatment and SiNW buckles in the helical mode. While sliding at the interface is distinctly detected without UVO (with low adhesion strength) and hence SiNW shows the in-plane buckling mode with lower strain energy to the out-of-plane buckling; such a transition between the in-plane and helical buckling modes based on the sliding and debonding has been studied in our parallel work (Chen et al., 2016).

In particular, it is worthwhile to mention that SiNWs in helical buckling mode can handle very large strain up to the failure strain of PDMS (~104%) that is much larger than the failure strain (~27%) of in-plane buckled SiNW (Xu et al., 2011). The buckling behavior of a slender beam has long been studied, such as the classical Euler buckling, the buckling of a beam in lateral constraints or spatial confinements, the sinusoidal buckling of a nanowire on elastomeric substrates (Domokos et al., 1997; Euler, 1952; Goriely et al., 2008; Xiao et al., 2008, 2010; Xu et al., 2011). Although the initial curved nanoribbons

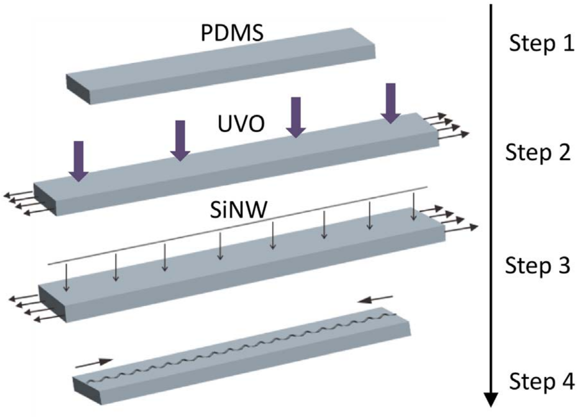

Fig. 1. Schematic diagram of the helical buckling of SiNW on PDMS substrate (Xu et al., 2011). First, the PDMS is pre-stretched and radiated by ultraviolet/ozone (Step 2) which improves the adhesion strength between PDMS and SiNW. Then, the SiNW is transferred to the surface of PDMS (Step 3) using contact printing. After releasing the pre-strain in PDMS, helical buckling occurs in the SiNW (Step 4).