Available online at www.sciencedirect.com
ScienceDirect
International Journal of Solids and Structures 45 (2008) 2014–2023
INTERNATIONAL JOURNAL OF SOLIDS AND STRUCTURES
www.elsevier.com/locate/ijsolstr

Post-buckling analysis for the precisely controlled buckling of thin film encapsulated by elastomeric substrates

Hanqing Jiang [a,*], Yugang Sun [b], John A. Rogers [c,d], Yonggang Huang [e]

[a] *Department of Mechanical and Aerospace Engineering, Arizona State University, Tempe, AZ 85287, USA*
[b] *Center for Nanoscale Materials, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA*
[c] *Department of Materials Science and Engineering, Beckman Institute, and Seitz Materials Research Laboratory, University of Illinois at Urbana-Champaign, 1304 West Green Street, Urbana, IL 61801, USA*
[d] *Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
[e] *Department of Civil and Environmental Engineering and Department of Mechanical Engineering, Northwestern University, Evanston, IL 60208, USA*

Received 31 July 2007; received in revised form 10 November 2007
Available online 3 December 2007

Abstract

The precisely controlled buckling of stiff thin films (e.g., Si or GaAs nano ribbons) on the patterned surface of elastomeric substrate (e.g., poly(dimethylsiloxane) (PDMS)) with periodic inactivated and activated regions was designed by Sun et al. [Sun, Y., Choi, W.M., Jiang, H., Huang, Y.Y., Rogers, J.A., 2006. Controlled buckling of semiconductor nanoribbons for stretchable electronics. Nature Nanotechnology 1, 201–207] for important applications of stretchable electronics. We have developed a post-buckling model based on the energy method for the precisely controlled buckling to study the system stretchability. The results agree with Sun et al.'s (2006) experiments without any parameter fitting, and the system can reach 120% stretchability.

Keywords: Stretchable electronics; Buckling; Mechanics

1. Introduction

Buckling of a stiff thin film (e.g., silicon) on a compliant substrate [such as poly(dimethylsiloxane) (PDMS)], was first observed by Bowden et al. (1998), where the stiff thin films were attached on the unembellished surface of compliant substrate that is subject to pre-strain. Relaxation of the pre-strain in compliant substrate leads to buckling of stiff thin films with highly periodic, sinusoidal wavy patterns. The wavelength of the buckled film ranges from 10 to 100 μm. The buckling of stiff thin film/compliant substrate system has then been attracting lots of attentions due to its many important applications. For example, these applications include stretchable electronic interconnects (Lacour et al., 2004, 2005, 2003, 2006; Wagner et al., 2004), and stretch-

* Corresponding author.
E-mail address: hanqing.jiang@asu.edu (H. Jiang).

0020-7683/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsolstr.2007.11.007

able electronic devices (Choi and Rogers, 2003; Choi et al., 2007; Jiang et al., 2007a,b; Khang et al., 2006), microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) (Fu et al., 2006), tunable phase optics (Efimenko et al., 2005; Harrison et al., 2004), force spectroscopy in cells (Harris et al., 1980), biocompatible topographic matrices for cell alignment (Teixeira et al., 2003), modern metrology methods (Stafford et al., 2005, 2004, 2006; Wilder et al., 2006), and other micro/nanofabrication (Bowden et al., 1999; Huck et al., 2000; Schmid et al., 2003; Sharp and Jones, 2002; Yoo et al., 2002).

The geometry of buckled thin film, however, is completely determined by the thin film thickness and the elastic moduli of the thin film and substrate, and therefore cannot be controlled once the thin film and substrate are specified. This "un-controlled" buckling may lead to some restrictions in applications. For stretchable electronics, the stretchable strain may reach 20% (Khang et al., 2006), which is much larger than the failure strain of silicon (∼1%), but is still too small for certain applications. In order to control the buckle geometries and improve the stretchability, Sun et al. (2006) designed a mechanical strategy to fabricate precisely controlled buckle geometries for GaAs and Si nanoribbons on PMDS substrate, by using the photolithograph method to pattern PDMS surface and a buckling process similar to that reported in Khang et al. (2006).

We briefly summarized the fabrication procedure (Sun et al., 2006) in the following. Fig. 1a illustrates the photolithograph process that defines the bonding chemistry on a stretched PDMS substrate subject to prestrain $\varepsilon_{\mathrm{pre}} = \frac{\Delta L}{L}$ in the ribbon direction. The standard photolithograph method was used to form periodic interfacial patterns with activated sites where strong chemical bonds can form between PDMS substrate and thin

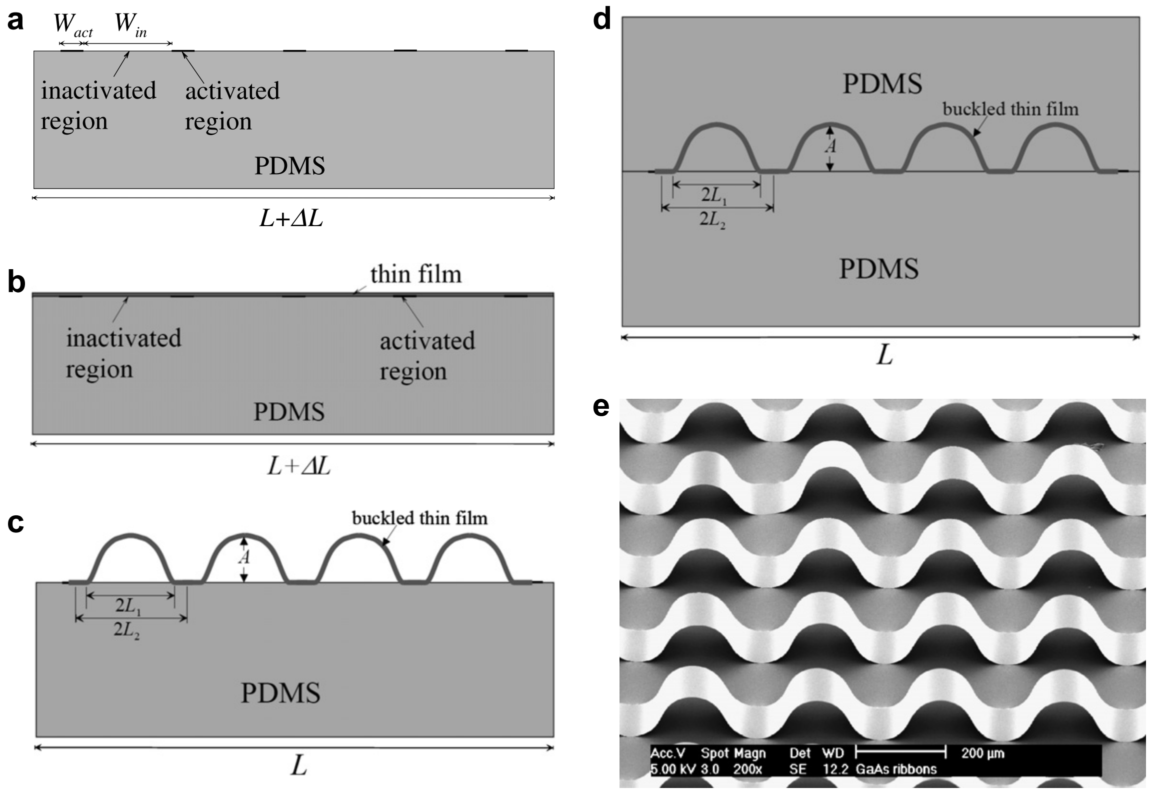

Fig. 1. Processing steps for precisely controlled thin film buckling on PDMS substrate. (a) Pre-strained PDMS with periodic activated and inactivated patterns. L is the original length of PDMS and ΔL is the extension. W_{act} and W_{in} denote the widths of activated and inactivated sites, respectively. (b) A thin film parallel to the pre-strain direction is attached to the pre-strained and patterned PDMS substrate. (c) The relaxation of the pre-strain $\varepsilon_{\mathrm{pre}}$ in PDMS leads to buckles of thin film. The wavelength of the buckled film is $2L_1$, and its amplitude is A. $2L_2$ is the sum of activated and inactivated regions after relaxation. (d) Casting and curing a liquid prepolymer to encapsulate the buckled nanoribbons into PDMS substrates. (e) Scanning electron microscope (SEM) image of buckled GaAs thin films formed using the previous procedures.