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Principles and applications of micro and nanoscale wrinkles

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ABSTRACT

In this review, we summarize recent and interesting applications of micro and nanoscale wrinkles. Fluidic studies are comprehensively highlighted for various wrinkled nanochannels. Wrinkling as a mechanical characterization tool is also explained. As a new feature, wrinkles are employed to modify structures or physical properties of nanomaterials. It is promising to apply wrinkling for strain-engineering of graphene. We believe that wrinkling offers entirely new research perspectives in micro and nanotechnologies as well as in material sciences and engineering.

Contents

1. Introduction

1.1. Wrinkles

A wrinkle can be a fold, ridge or crease in the skin and normally appears when one becomes old. It thus enables a huge market for

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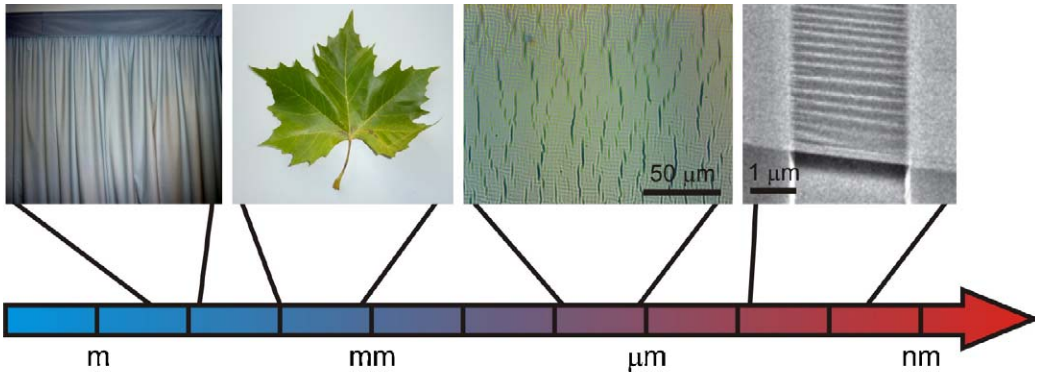

Fig. 1. Observation of wrinkling phenomena in nature. The dimensions (periodicity and amplitude) of wrinkles span across many length scales (from meters to nanometers). For example: (from left to right) a hanging-down curtain, a drying leaf, Al_2O_3 thin films on PDMS substrate, and stretched graphene sheets [1]. Reprinted with permission from Macmillan Publishers Ltd.: *Nature Nanotechnology* [1], copyright (2009).

anti-wrinkle cream etc. Although such wrinkles are very critical for the skin of human beings, wrinkling is a very general phenomenon in nature with dimensions (like periodicity and amplitude) spanning across length scales from meters down to nanometers. Basically, when a layer or sheet is forced to extend or shrink in its plane, it will be wrinkled or buckled in the perpendicular direction if there is limited planar space due to certain geometrical boundary conditions. As shown in the first image of Fig. 1 (from left to right), a curtain hanging down from the ceiling assumes a wrinkled shape on the decimeter scale since the curtain sheet is geometrically constrained in the plane. In the second image, when a leaf drops down to the ground, it dries out and experiences a centimeter-scale buckling at the edge, which is similar to human skin wrinkling or dried wizen fruits. In conventional thin film deposition technology, delaminated films often show buckles (wrinkles or blisters) due to the high compressive stress. As illustrated in the third image of Fig. 1, a thin oxide film deposited on a *poly-(dimethyl)siloxane* (PDMS) substrate shows a regular pattern of wrinkles at a scale of microns after cooling down. Here, the wrinkling is mainly due to the different thermal expansion coefficients between oxides and plastic. People have also created nanoscale wrinkles or buckles with the aim to change the electronic properties of materials. As shown in the right image of Fig. 1, a graphene sheet is wrinkled by controlled thermal treatment, which might open a way to strain-engineer a bandgap in graphene [1].

The study of wrinkles interacts with many other scientific disciplines and establishes a technological platform for plenty of interdisciplinary research. It has been observed by George M. Whitesides that wrinkling of thin metal films on PDMS substrates can be used to create ordered microstructures [2]. After that, a lot of effort has been dedicated to study and understand wrinkled pattern formation [3,4]. Theoretically, wrinkling involves large deformations of thin flat sheets whose behavior is governed by a set of non-linear partial differential equations, known as the Föppl-von Karman equations [5]. In general, these equations cannot be solved analytically except in some one-dimensional cases. Since this topic has been extensively reviewed previously [3,4], we will not focus on the quantitative pattern formation, itself. Instead, we concentrate on the underlying principles and applications of micro and nanoscale wrinkles, leaving out extensive theoretical modeling and computation. We expect that our topical review will be helpful to elucidate the huge application potential of wrinkles in micro and nanotechnologies.

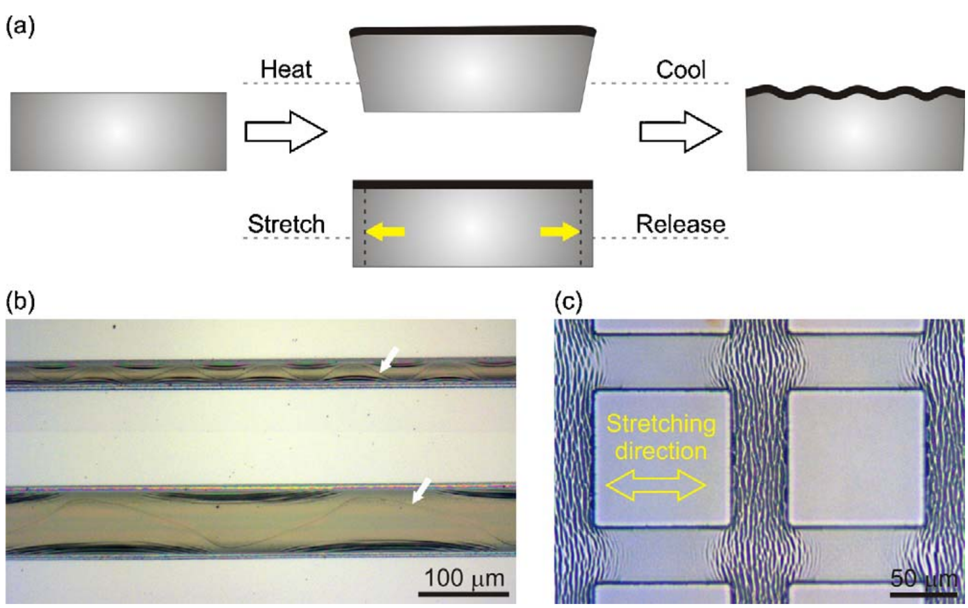

Fig. 2. (a) Procedures for wrinkling on PDMS. The PDMS substrates are heated or stretched for volume expansion and subsequently coated with thin layers. Upon cooling or releasing, the coated layers form wrinkled patterns. (b) Wrinkled patterns exhibit a sinusoidal feature for Al_2O_3-coated photoresist layers fabricated by atomic layer deposition by using the principle of heating and cooling shown in (a). (c) Wrinkled patterns formed by stretching, Al_2O_3 coating and relief of a PDMS substrate.