Wrinkling instability and its applications: From biomimetic tilted pillars to optics grating

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Abstract

Instability of a thin film attached to a compliant substrate often leads to emergence of exquisite wrinkle patterns with length scales that depend on the system geometry and applied stresses. These patterns have potential applications in many areas including tissue engineering, flexible electronics and semiconductor industry. In this talk, we will present several novel techniques for polymer surface engineering, including creation of controlled hierarchical patterns and wrinkles with high amplitude/wavelength aspect ratio. The applications of these techniques in microfluidics, optics, and also in development of biomimetic surfaces will be discussed.

Keywords: Wrinkle; High aspect ratio; Pre-patterning; Ion beam; Optical band gap.

Instability in thin films

Cracking, buckling, wrinkling, and in general mechanical instabilities, in thin films are generally treated as nuisance [1-4]. This view has changed recently with the development of robust techniques for controlled patterning of soft polymer and hard metal surfaces and the emergence of novel applications that benefit from the created patterns [5-8]. These applications range from building cell templates and nanochannels for protein condensation to manufacturing smart adhesives and optical grating devices [9-12].

A common class of these techniques is based on inducing a strain mismatch between a thin film and soft substrate, causing the instability and wrinkling of the stiff film. The wrinkle wavelength is determined by the system geometry (mainly the film thickness) and the relative stiffness of the film and substrate [8,13,14], and is in general much larger than the film thickness and much smaller than the specimen dimensions. The amplitude of the wrinkles depends on the applied stresses and the magnitude of induced strain mismatch [15,16]. The ratio of wrinkle amplitude/wavelength is normally limited to 1/10. In this study, we create buckle patterns with high amplitude/wavelength ratio by the deposition of an amorphous carbon film on a surface of a soft polymer poly(dimethylsiloxane) (PDMS). We employ glancing angle deposition (GLAD) for deposition of an amorphous carbon film on a PDMS surface. Amorphous carbon films are used as a protective layer in structural systems and biomedical components, due to their low friction coefficient, wear resistance, and high elastic modulus and hardness [17]. The deposited carbon layer is generally under high residual compressive stresses (~1GPa), making it...
susceptible to buckle delamination on a hard substrate (e.g. silicon or glass) [3,18] and to wrinkling on a flexible or soft substrate [19]. GLAD is a physical vapor deposition method used to fabricate functional thin films with columnar morphology. The application of the created morphologies range from sensors and actuators to optical filters, microfluidics, and catalysis.

Figure 1a shows the schematic of a PDMS substrate subjected to hydrocarbon ion beam irradiation, and the scanning electron microscopy (SEM) images of the wrinkle patterns created by 50 min amorphous carbon film deposition at three different incident angles. The deposited carbon film is under approximately equi-biaxial compressive stress [3,18], and the created wrinkles are semi-herringbone or semi-labyrinth shapes, Figs 1b-1d. The wavelength of the created patterns is relatively insensitive to the deposition angle and duration and is ~ 750 nm. In contrast, the amplitude of the wrinkles depends on the deposition angle and duration. The wrinkles created by 50 min carbon deposition normal to the substrate surface (i.e. \( \theta = 0^\circ \), Fig. 1b) has an average amplitude 144 nm (i.e. amplitude/wavelength = 1/5) and has the appearance of nonlinear wrinkle configurations observed in a biaxially-compressed film on a compliant substrate [15,19]. The patterns formed by deposition at 45° and 75° have approximately the same wavelength, but much higher amplitudes (amplitude/wavelength ratios of 2 and 2.5, respectively). Figures 2a-2c displays the SEM images of surface patterns created by carbon film deposition at 75° and different deposition durations, showing that the wrinkle amplitude increases for longer deposition durations. In Figure 2d, we measured the amplitude/wavelength ratio of patterns created on the PDMS surface at three different deposition incident angles as a function of deposition time. At incident angle 0° and 45°, the amplitude/wavelength ratio is relatively independent of the deposition time (in the range studied here, 30 sec to 50 min) and is 1/10 and 1/2, respectively. In contrast, the aspect ratio of created patterns with incident angle 75°, increases by increasing the deposition duration, resulting to an amplitude/wavelength ratio aspect ratio as high as 2.5.

![Figure 1 - Surface patterns created by carbon film deposition. (a) Schematic of the experiments, (b-d) SEM images of the PDMS surface after 50 min carbon film deposition at different incident angles.](image-url)
As the next step, we will demonstrate that amorphous carbon deposition of pre-patterned polymeric surfaces that allows fabrication of high aspect ratio wrinkles with a desired wavelength. Figure 3 shows the schematic of the proposed method; first, the surface of the polymer gets pre-patterned with Ar ion beam irradiation. The wavelength of the created patterns depends on the treatment time (varied ~ 200 to 1400 nm in this study). In the next step, an amorphous carbon film gets deposited on the pre-patterned surface using GLAD to elevate the amplitude of the patterns. The details of the proposed method are outlined in the following section. As a part of our discussion, we will demonstrate an interesting application of the created high aspect ratio wrinkles for controlling the optical band gap with respect to the wavelength of wrinkle patterns.

Figure 2 - The effect of deposition angle and time on the morphology. (a-c) SEM images of the PDMS surface after carbon film deposition at 75° incident angles for three different deposition durations. (d) Aspect ratio of the amplitude to wavelength for patterns created by carbon film deposition at different angles, versus the deposition time.

Figure 3 - Schematic of the fabrication of pre-wrinkle patterns on PDMS by Ar ion beam (top) and subsequent carbon deposition using GLAD to increase the amplitude of the pre-patterned surface (bottom).
Summary
We presented a fabrication method of wrinkles with high aspect ratio of amplitude over wavelength using a glancing angle deposition (GLAD). First, we created wrinkle patterns on the PDMS surface using Ar ion beam irradiation with wavelength in the range of 200-1400 nm. An amorphous carbon film was deposited on the pre-patterned PDMS to increase the amplitude of surface features. An application of the polymeric surface patterned with high aspect ratio wrinkles was demonstrated for the optical band gap change, which could have potential usage in fabrication of optical devices.

References