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Invited Article

Fabrication of micron and submicron gratings by using plasma treatment on the curved polydimethylsiloxane surfaces

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ABSTRACT

Here, a simple and low-cost fabrication strategy to efficiently construct well-ordered micron and submicron gratings on polymeric substrates by oxygen plasma treatment is reported. The Polydimethylsiloxane (PDMS) substrate is prepared on the polyethylene (PET) by spin-coating method, then the curved PDMS-PET substrates are processed in oxygen plasma. After appropriate surface treatment time in plasma the curved substrates are flattened, and well-ordered wrinkling shape gratings are obtained, due to the mechanical buckling instability. It is also demonstrated that changing the curvature radius of PDMS-PET substrates and the time of plasma treatment, the period of the wrinkling patterns and the amplitude of grating also change accordingly. It is found the period of the wrinkling patterns increased with the radius of curvature; while the amplitude decreased with that. It also shows good optical performance in transmittance diffraction testing experiments. Thus the well-ordered grating approach may further develop portable and economical applications and offer a valuable method to fabricate other optical micro strain gauges devices.

1. Introduction

Folding structures are ubiquitous in the natural environment, such as human skin, dehydrated fruit skin and rolling hills, etc. Recently these folding structures have been imitated to fabricate nanostructure self-assembly templates [1,2], twisted liquid crystal displays [3], stretchable electrodes or interconnects [4,5], optical devices [6,7], microfluidic devices [8], thin film metrology [9–11], etc.

At present, there are two methods commonly used to fabricate the periodic structure, i.e. lithography and self-assembly technologies. However, lithography technology is relatively expensive, not suitable for the large scale production. In contrast, self-assembly method is low cost, and thus it is a commonly used method.

Polydimethylsiloxane (PDMS) is a commercially available clean room compatible type of elastic polymer material with awide range of applications, due to the low glass transition temperature, low surface energy, high transparency, excellent insulating performance and chemical stability performance. In most of the published research works, PDMS has been used as an elastomeric substrate. Several creative methods have been developed to improve its surface properties, including heating [13,14], mechanical stretching, compression [15–18], and chemical oxidation [12,20,21], which contribute to the formation of various layer on the surface. When the PDMS films are properly stretched and the residual stresses exceed the critical value, the PDMS wrinkles could be formed on the surface of the substrate. Using these techniques, various wrinkling patterns could been produced, including gratings [6], microlenses [7], checkerboard patterns [19], etc. Especially, the grating based on PDMS has good tunability and excellent diffraction effects in the visible light wave band. There are many feasible methods have been widely used to form uniform wrinkles of grating.

For example, Masashi Watanabe and Koujirou Mizukami [21] reported using a mixture of sulfuric acid and nitric acid on a

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PDMS substrate formed wrinkles with a well-ordered stripe pattern. However, when the oxidation duration varies, the stripe patterns appear substantially different, and the required experimental high-temperature environment is difficult to control. Unlike chemical oxidation, oxygen plasma treatment is commonly used to create a stiff surface layer. Later, Cunjiang Yu et al. [6] reported a simple method to fabricate the tunable gratings on prestretched PDMS substrate by oxygen plasma treatment. In this paper, we propose a simple method to manufacture micron and submicron scale grating patterns on the curved PDMS surface by combining surface stress control and oxygen plasma treatment. And there are not any cracks on the grating patterns surface. After diffraction testing, the tunable elastic polymeric grating exhibits good tunability, and the self-formed grating could further serve as a strain sensors.

2. Experiment

The transparent PDMS substrates were prepared by casting the mixture of base and curing agent at the ratio of 10:1 by weight (Sylgard-184, Dow Corning); then, the mixture was degassed in a vacuum chamber and spin coated on a clean polyethylene (PET) substrate (~0.5 mm), then cured at 65 °C for 3 h. Finally, the obtained PET-PDMS sheets (~0.8 mm) were cut into $10 \times 30\ mm^2$ and $10 \times 50\ mm^2$ slabs.

Experimental schedule is listed in Fig. 1. Both ends of the PET-PDMS sheets are clamped by using a custom-made jig and applied prestress to obtain a symmetrical bending of the sheet; the L values are 0.5 cm and 2.5 cm, respectively, $\triangle$L are 0.4 cm and 1 cm, r (radius of curvature of the center area) are 1.4 mm and 5.6 mm, respectively. The prestretched PET-PDMS specimens are treated by using oxidation plasma (PVA TePla ION Wave 10) with input power of 150 W and oxygen flow rate of 150 sccm; the reaction time is systematically set in the range of 60–540 s. After plasma treatment, the surface is capped with a glassy layer; when the sheet is released from the bending restriction, the strain mismatch between the hard coating and the polymer substrate leads to buckling of the surface glassy layer. In addition, we find that in the process of the grating fabrication, the period *d* and amplitude *A* are almost unchanged when the radius of curvature and plasma treatment time are controlled well and remain unchanged. As shown in Fig. 2, we carry out 50 experiments under the same conditions that the errors on period and amplitude are basically floating in 60 and 5 nm, respectively. Therefore, we conclude that the method has good repeatability.

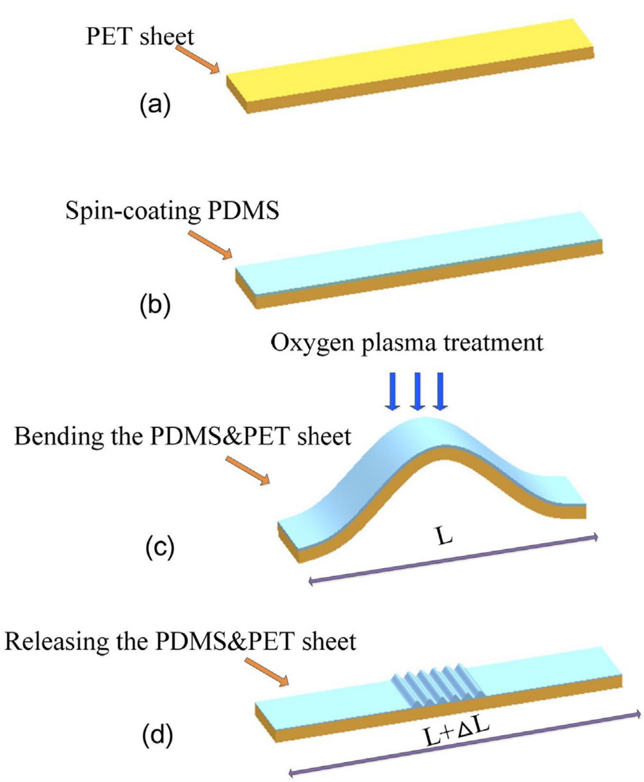

Fig. 1. Scheme of the fabrication of the micron and submicron gratings. (a) Prepared a polyethylene (PET) substrate (~0.5 mm); (b) The mixture of base and curing agent was spin coated on the PET substrate; (c) The prestretched PET-PDMS specimens were treated by using oxidation plasma (PVA TePla ION Wave 10); (d) Well-ordered wrinkles formed when the substrate was made flat again.

3. Results and discussions

3.1. Morphology

The surface morphology was analyzed by using atomic force microscopy (AFM; CSPM-5000, Benyuan) and laser scanning confocal microscopy (LEXT OLS4100, OLYMPUS). After the oxygen plasma treatment, the surface of PDMS became brittle. Notably, owing to the thermal expansion instability and the influence of the Poisson effect, the period and shape of the wrinkling patterns were difficult to control. Thus, in this work, the PDMS-PET sheets were bent and the stress was exerted very homogeneously, which is different from the study that stretching PDMS slab along a single planar direction [18].

Fig. 3(a) shows a PET-PDMS sheet (180 s, r = 1.4 mm) after releasing the strain from the oxygen plasma treated PET-PDMS sheet. The usable surface area of the film is the center area (about 1 cm long) where the curvature is relatively close. The diffraction wavelengths induced by the gratings could be modulated by deforming and bending the flexible substrates under the indoor light. The photograph of the colorful PDMS grating clearly shows that all different parts of the wrinkling pattern had diffraction peaks; these peaks were symmetrically distributed with respect to the center of the sheet. We attributed this phenomenon to the changing of the grating period. Well-ordered stripe patterns are observed via optical microscopy, as shown in Fig. 3(b). In order to demonstrate grating parameters clearly, the profile and side of this

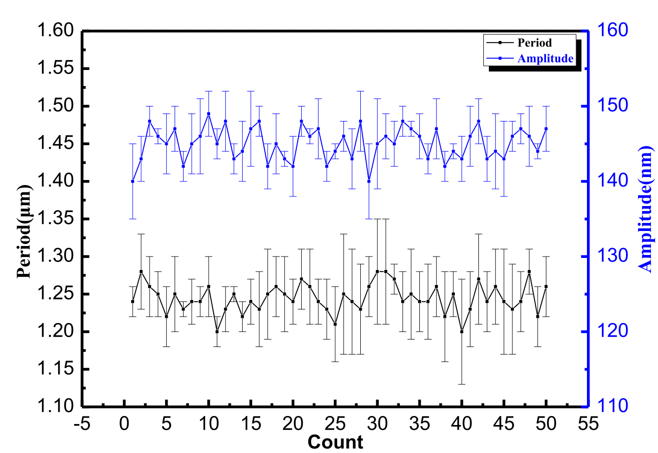

Fig. 2. The 50 experiments under the same conditions were carried out to test the repeatability of the grating. The error of period (left axis) and amplitude (right axis) is basically floating in 60 and 5 nm, respectively.