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Stamp design towards instability-induced 3D patterning

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Instability-induced pattern formation is easily realized during thermal nanoimprint when a temperature difference is provided between stamp and substrate. The use of this effect for pattern definition requires spacers between stamp and substrate to install a gap of definite height. We test the use of silica particles to serve as spacers with variable height for such an approach. Then, there is no need to prepare stamps with a specific design especially for this purpose, as any stamp available can be used. It turns out that the silica particles are not ideally suited to serve as reliable spacers – they are too soft, when Si stamps are used, but too hard when replica stamps made from OrmoStamp are used. The experiments allow to roughly estimate the mechanical properties of the particles. Nonetheless, it is demonstrated that a formation of isolated polymeric bridges of 5 μm in height is feasible.

1. Introduction

Nanoimprint Lithography (NIL) has become a strong candidate for the definition of patterns in the micron and submicron range. Already in the initial phase an aspect related to its mechanical nature, the development of instabilities was described theoretically [1] as well as experimentally. Instabilities result in the development of physically self-assembled structures of the polymer between the substrate and the stamp. Chou introduced LISA (lithography induced self-assembly) [2] and LISC (lithography-induced self-construction) [3] during T-NIL with an electric field between the stamp and the substrate [4], where micron-sized dot structures develop below elevated stamp structures. The dot structures may also coalesce to form continuous bridges between the substrate and the stamp to minimise the surface energy of the polymer.

According to Schäffer [1], the formation of bridges is due to the instability of a layer and may be driven by different interactions, the main cause depending on the gap height between the elevated stamp structures and the polymer surface. When the gap is higher than about 50 nm, potential differences as well as temperature differences between the stamp and the substrate are the main drivers. When the gap is smaller than about 50 nm, Van der Waals forces dominate [5]. Typical geometries of bridges have been shown to be in the micron range in lateral direction, and in the range of some 100 nm in height; a formation of the structures over 2 h was demonstrated [6].

The development of bridges due to instabilities is not restricted to T-NIL (thermal NIL), they are found in processes like capillary force lithography (CFL) [7] or UV-nanoimprint (UV-NIL) [8], too. The self-assembled structures observed there are quite similar to the ones described with thermal NIL. Typically in case of linear cavities and under conditions of incomplete filling broken lines are found as replica, instead of continuous lines with a mean filling height [9]. Often these structures are ascribed to the long processing times involved (several hours with CFL [7]). In cases where nanoimprint is used as a lithography technique instability-induced structures are classified as defects [10], as the stamp cavities are not replicated to scale.

In contrast, it is intended here to make use of instabilities for pattern definition rather than avoiding them. But different from the study by Chou et al. we will show that it is possible to induce the formation of bridges between stamp and substrate by using a temperature difference between the stamp and the substrate. The technique has the potential of forming isolated polymeric structures in one step.

This manuscript will discuss the requirements for the successful formation of isolated polymeric structures induced by instabilities. A low cost flexible approach to realize the process configuration is proposed and tested and the respective results are analysed. Finally it is shown that bridges with a height of some microns can be obtained.

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2. Requirements

In order to form bridges of a defined height, a 3-level stamp is required to define the width of the gap between the elevated stamp structures and the polymer surface. The schematic of Fig. 1 illustrates the principle. The stamp provides elevated structures (target structures), defining the position as well as the lateral dimensions of the bridges. In addition, the stamp provides spacer structures. In Fig. 1b the final stage is shown. The spacers are imprinted to full depth and the polymer has built bridges between the elevated stamp structures (target structures) and the substrate with de-wetted regions in between the bridges.

Our view of bridge formation is the following. Initial formation of bridges is induced by the temperature difference between stamp and substrate, resulting in modulations of the polymeric surface below the elevated stamp structures. When the air gap remaining between polymer surface and stamp structures is about 50 nm in height, first contact is induced by attractive van der Waals forces. Starting from initial contact points, the bridge broadens and forms full contact with the elevated stamp structures by a suction of the polymer from the surrounding non-contact area. In this last stage the process is driven by surface energy minimisation (Laplace pressure). When polymer supply from the surrounding is hampered, e.g. due to local de-wetting, the process stops and a final, stable situation is reached. The time to bridge formation is controlled by the viscosity of the polymer.

The challenge in getting isolated bridges is the correct choice of the thickness of the initial layer (h_0), which depends on the height of the spacers and the geometries of the target structures of the stamp. When the initial layer chosen is too low, the gap between the elevated stamp structures and the initial layer surface is wide; then the interaction is small and the bridges may not form. When the initial layer chosen is too high, there may be no de-wetting between the bridges; then the bridges do not become isolated. We estimated the initial layer thickness required from volume conservation of the polymer, considering the contact area of the elevated stamp structures, their lateral distances and the spacer height.

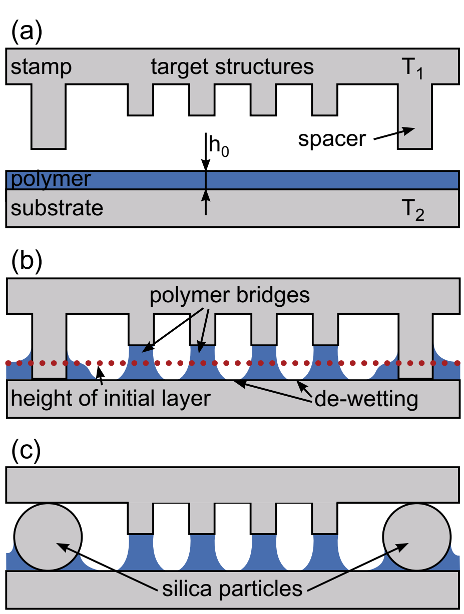

Fig. 1. Schematics illustrating the principle of a process forming isolated polymeric bridges with a 3-level stamp. (a) Before the process. (b) After the process. Initially there is a gap between the elevated stamp structures and the initial layer. Finally the polymer builds isolated bridges between stamp and substrate. (c) Realisation with 2-level stamp; silica particles were used as spacers.

A disadvantage of the 3-level stamp is that it is prepared with a fixed height of the spacers. Any change of the final bridge height then requires its own stamp. To eliminate this disadvantage it would be better to have variable spacers. With variable spacers it will be possible to get different heights of the bridges with one single stamp.

We used small silica particles as spacers (see Fig. 1c), because these particles are available in many different diameters and can easily be deposited at the substrates. During this deposition process it is even possible to use shadow masks to place the particles in specific regions of the substrate only. In order to test the suitability of this approach, namely to use silica particles as spacers, the experiments reported here were performed without a shadow mask.

3. Experimental

We used two different stamps with positive structures. One stamp is made from silicon ($2 \times 2\,cm^2$) with 3 patterned fields which are identical. The fields have lines with a length of 1 cm and a varying width of 5 μm up to 100 μm. The stamp height is 850 nm and the spacing between the lines is 300 μm. This stamp serves to test the approach with lateral geometries of some 10 μm. The other stamp featuring micron-sized structures is a replica stamp ($2 \times 2\,cm^2$) made from OrmoStamp (micro resist technology GmbH) which consists of a 5 μm thick OrmoStamp layer on top of a 500 μm thick silicon substrate. The stamp has fields of lines and fields of squares (both $50 \times 100\,\mu m^2$) with structures of similar geometries (2–5 μm elevated structures and cavities) and a height of 1.3 μm. For both stamps we used fluorinated trichlorosilane as an anti-sticking agent.

For all our experiments silicon substrates ($2.5 \times 2.5\,cm^2$) were pre-treated by a dehydration bake (10 min at 200 °C) and spin-coated with polystyrene (PS, 350 kg/mol, Sigma–Aldrich). The thickness of the layers varies with different experiments. After spin-coating the samples were baked for 15 min at 120 °C to remove most of the solvent. Silica particles with 2 μm and 5 μm diameter were used as spacers. To deposit the particles on the spin-coated substrates, we used a dusting chamber (laboratory set up). The main density of particles at the sample surface amounts to $5.6 \times 10^8\,m^{-2}$ as estimated from SEM investigation after four deposition shots.

The experiments were performed in a motor-driven imprint system [11]. In all experiments we heated the top hotplate to 160 °C and the bottom hotplate to 190 °C to get a low enough viscosity of the PS 350 kg/mol ($\approx 10^4$ Pas). When the temperatures are reached, the pressure is applied and after 5 min of imprint the cool down is initialized. The pressure is released when the temperature is about 70 °C. Most experiments were performed at a pressure of 25 bar. This pressure is adequate to provide contact between stamp and substrate across the whole area, despite the waviness of all components involved (stamp, substrate, hotplate).

The samples and the stamps were inspected with a white light interferometer (Micro XAM 100, KLA-Tencor) and by SEM (XL30s FEG, Philips/Quanta 450 FEG, FEI).

4. Results and discussion

To test the formation of some 10 μm wide bridges we used the silicon stamp, a pressure of 25 bar and a substrate with a 50 nm thick PS layer. Fig. 2 shows a linear bridge with a width of 60 μm and a height of about 80 nm. Inspection of the bridge along the line shows that no full contact exists over the whole width of the line.