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Press and release imprint: Control of the flexible mold deformation and the local variation of residual layer thickness in soft UV-NIL

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ABSTRACT

We report on a two step soft UV nanoimprint process termed "Press and Release Imprint (PRI) that enables the reduction of both the mold deformation and the local variation of the residual layer thickness, thereby allowing high fidelity pattern replication with a uniform local residual layer thickness. The effect of imprint pressure on the mold deformation, local variation of residual layer thickness as well as required mold release time has been investigated for microscale patterns in the range of 10–100 μm. The potentials of PRI are demonstrated by high fidelity replication of micro-patterns with a uniform residual layer of minimum thickness.

1. Introduction

Nanoimprint lithography (NIL) [1] has been considered as an alternative technology to optical lithography for the fabrication of micro- and nano-structures. Its potential for nanoelectronics and photonic devices has already been demonstrated [2,3]. In particular, UV nanoimprint using flexible molds (soft UV-NIL) enables simple fabrication of micro-and nano-patterns at low cost [4,5]. One of its advantages is that flexible molds can be easily fabricated with only one patterned master via molding processing [6,7]. The distortion of flexible molds, however, is a drawback to be solved for high fidelity pattern fabrication in soft UV-NIL. The applied imprint pressure is the main cause for the mold deformation, which leads to inadequate pattern fidelity as well as local variation of the residual layer thickness in soft nanoimprint. On the other hand, a certain amount of imprint pressure is necessary to ensure fast pattern replication, i.e. efficient conformal mold contact and sufficient mass transport for a fast filling of mold cavities.

Principally, the deformation of flexible molds can be avoided if no external pressure is applied. This is the extreme case of capillary force lithography (CFL), where the resist is driven into the cavities of the mold by capillary forces alone [8,9]. Due to the absence of an external imprint pressure, there is no mechanical distortion of flexible molds. It takes, however, quite a long time to achieve conformal mold contact for large areas (wafer scale) and to fill the mold cavities with resist by capillary action only.

In "Press and Release Imprint (PRI)", which is basically a two step soft UV-NIL process, the advantages of both soft UV-NIL and CFL are utilized. In PRI, the process during which the resist flow takes place is split in two separate phases. In the first step, a certain amount of imprint pressure is applied for quick conformal mold contact with the resist layer. However, the exerted pressure leads to elastic mold deformation and to a local variation of the residual layer thickness. In conventional soft UV-NIL, the resist is cured by UV-exposure at this point resulting in a deformed resist pattern. In PRI, the pressure is completely released prior to the polymerization of the resist. During this step the distorted mold resumes its original unstressed shape due to its elasticity while the resist starts to flow into the now recovering mold cavities, allowing them to completely fill with resist. This simple additional step of pressure release avoids the replication of deformed mold structures and reduces local thickness variations of the residual layer, two important features for high fidelity imprints.

The influence of PRI on both the mold deformation and the local variation of the residual layer thickness have been analyzed by the comparison of imprint results of single step soft UV-NIL and PRI. Since any *in situ* observation of the mold deformation during the process itself is very difficult, the two processes were compared by evaluating imprinted resist structures via AFM and SEM.

2. Experimental

The test pattern for the investigation of mold deformation on a micro scale contains the arrays of square pillars as well as holes with sizes ranging from 100 down to 2 μm. The patterns were

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defined by optical contact lithography and transferred into the silicon wafer by reactive ion etching (RIE). A thin anti-adhesion layer is deposited on the surface of the patterned master for easy separation of the flexible molds from the master during the mold fabrication. PDMS (Sylgard 184, Dow Corning) is used as flexible mold material. The base material was blended with 10 wt.% curing agents. This mixture is poured onto the silicon master and degassed in a vacuum chamber for 30 min. The master with PDMS is placed onto a hot plate and the PDMS is cured at 120 °C for 30 min. The cured PMDS mold is then peeled off the master and used for single soft UV-NIL and PRI.

In Fig. 1 the PRI process is illustrated in six steps. The local variations on the mold pattern are defined by cavities (C) and protrusions or pillars (P). At first, a PDMS mold is pressed into the liquid polymer layer on a substrate (Fig. 1a and b) for 30–60 s. During this time, the resist begins to fill the mold cavities that are distorted to some extent due to the pressure-induced mold deformation. The expected mold deformation is depicted in exaggerated form in Fig. 1b where the dashed line represents the mold's original contour. As PDMS is essentially incompressible, the volume of the PDMS mold remains constant. Its shape, however, is deformed due to the elastic properties of PDMS. A uniaxial compression of the mold along the vertical axis will lead to an inward bulging at the protrusions of the mold accompanied by an outward bulging of their sidewalls and the cavity roofs as illustrated in Fig. 1b. In conventional soft UV-NIL, the deformations in the resist are solidified by the following UV-exposure. In the case of PRI, however, a release step is introduced (Fig. 1c) where the imprint pressure is released for a certain amount of time ("release time", t_r) prior to the UV exposure. Due to the elasticity of the PDMS mold, the cavities and protrusions are restored close to their original unstressed shape. During this recovery, the liquid resist resumes flowing, filling the space left by distorted mold features. This flow of resist is driven not only by capillary forces but also by a pressure gradient in the resist built up between depressed regions and cavities induced by local changes in resist volume during mold recovery. In addition, reflow of resist into the released state leads to a more uniform residual layer thickness. After mold filling is completed, the polymer is cured by UV exposure (Fig. 1d) and the mold is separated from the cured resist layer (Fig. 1e), leaving high fidelity resist replications on the substrate. The defined resist patterns can be used as an etch barrier for pattern transfer after removal of the residual layer (Fig. 1f).

Micro-patterns were replicated under PRI conditions that are compared with the results of soft UV-NIL using the same soft mold. Since the same PDMS mold is used for both imprint processes, any influence of mold fabrication itself can be excluded. The fidelity of replicated patterns is only related to the topography of the PDMS mold during imprint processing. The imprint process was carried out with the EVG 620. A UV-curable polymer (AMONIL, AMO GmbH) with a viscosity of 50 mPas at RT was chosen as imprint resist, because its low dynamic viscosity is important for the reflow of resist into the recovering mold cavities during the elastic reformation of soft molds under PRI conditions.

3. Results and discussion

Conventional soft UV-NIL and PRI patterns are compared by analyzing AFM scans and SEM images. In Fig. 2 AFM images of square holes (mold protrusions) and pillars (mold cavities) imprinted with an imprint pressure of 900 mbar are compared. In Fig. 2a the AFM scan of an array of square holes with a size of

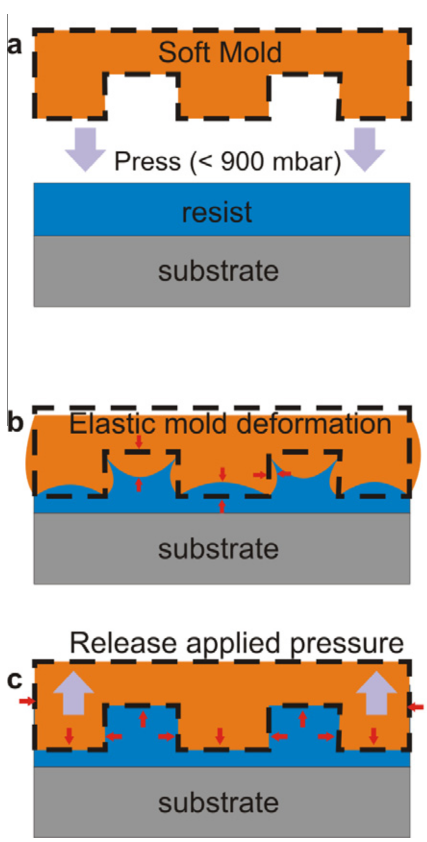

Fig. 1. Process sequence of PRI. (a) Pressing mold into the liquid resist layer, (b) elastic mold deformation, (c) complete release of the applied pressure, which returns the distorted mold cavities into their unstressed state, (d) curing of the resist via UV-exposure, (e) separation of the mold from the cured resist layer, leaving resist patterns on the substrate, (f) removal of the residual layer.