UV curing imprint lithography for micro-structure in MEMS manufacturing

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Abstract. Imprint lithography has been gaining popularity as a new method to fabricate micro-electro mechanical systems. The main advantages of the IL are its extremely low set-up cost, high replicating accuracy and extended fabricating critical dimension. Compare to traditional optical lithography, IL has the advantages of being able to fabricate complex pattern structure with high-aspect ratio. However, the thermal and loading errors can reduce pattern transferring fidelity. In this paper, UV curing method is used in IL process which can avoid the heat distortion of tools. Additionally, a six-step loading process for template pressing into resist film is developed. The performance of this process include: the loading locus is continuous with very high accuracy (10nm), the press releasing control (accuracy up to 1 psi) can reduce and avoid the distortion of template structure and stage supports. This process can achieve a residual layer with thickness of 20nm and avoid the elastic stamp distorted (under 20nm) at the same time. The press force can reach up to 300 psi for 6 cm² pattern size but the friction force during demould process can be reduced to 30 psi. Experimental results reveal that it is a novel and robust process with high fidelity in micro/nano structures manufacturing.

1. Introduction
Due to the recent advancements in micro-electro mechanical systems (MEMS), many studies have been carried out to fabricating process and tools (such as UV, x-ray, ion, e-beam lithography and corresponding tools). In the past decade, much attention has been focused on how to fabricate MEMS’s three-dimensional structure with high ration of depth/width, because the fabricating method always uses optical lithography which has been popular in integrated circuit (IC) manufacturing[1, 2]. The expensive cost of manufacturing equipments and the optical diffracting limitation under 100nm critical dimension (CD) always limit the MEMS achieve a popular development (such as sub-100nm transistor structure always included in MEMS circuit). Imprint lithography (IL) technology has been explored in the recent years, its low set-up cost and extended fabricating CD, i.e. from 10nm to several hundred microns, are remarkable advantages[3−5].

Commonly, the hot embossing with the advantages of larger pattern transferring area always be used in single layer structure manufacturing, the limited factor is the thermal distortion error produced in fabricating tools and the multi-layer alignment. Thus, the cool IL, such as UV curing IL, comes into vogue for fabrication of complex micro-structure. Although, The UV curing IL avoids the heat distortion of tools caused by hot embossing, the mechanical action as common problem can reduce pattern transferring fidelity also. Additionally, the depth/width ration of micro-groove structure is not easy to match the need of subsequent etching process, because the press force in room temperature is
lower than hot embossing, and at the same time the imprint area is limited\cite{6~11}. In this paper, the adaptable IL loading process, flexible supporting structure, and elastic mould will be researched to effectively release the mould distortion stress, avoid the conflict between keeping rigidity of resist film structure, and reduce the demoulding force.

2. IL loading and distortion error control

As same as the optical lithography, the IL has the same subsequent process, etching. The different factor between IL and optical lithography is that the residual resist layer caused by IL must be cleared first, and too large thickness of residual resist can make great trouble in pattern transferring from resist to wafer. So, using an adaptable loading process to keep high fidelity pattern replication and thin residual resist layer is very necessary. Fig.1 is the AFM image of elastic stamp and pattern transferring results in different loading conditions. The mould structure’s feature size is 0.1µm in width and 0.1µm in height. As shown in fig1b, the pattern can be accurately transferred into resist film. Because the loading force is deficient, the thickness of resist film is almost not reduced. This result will make it impossible that the pattern transferring from resist to wafer during subsequent etching process. To reduce the residual resist thickness, when adding the loading force to be sufficient, as shown in fig1c, the residual resist film thickness can be reduced to 0.01µm, but the feature size in width enlarged to 1µm, and the feature size in depth is reduced to 0.04µm, all pattern structure is demolished.

Additionally, observing the partial characteristic in fig.1c, the sidewall in resist groove has collapsed and the thickness of residual resist is random. As a rule, pressing force can make the template structure distort and un-precise curing time may induce the resist structure collapse. In this experiment, the causes of above result are that the loading process is blind and the curing time is not enough, which make the resist structure distorted and un-curing resist flowing slowly. The distortion behaviour of resist pattern caused during IL process is very harmful, and the errors will be transferred into final functional structures. Thus, optimizing the loading control and creating new IL process is precondition of solving the conflict.

Because the real mould patterns of MEMS are of mixed sizes, during the pressing process the calculations of the imprint time, velocity, acceleration, and forces are very complex. To simplify the problem, the assumptions can be made as follows: parallel contact between the surfaces of the mold and the substrate, no waviness on both of mold and substrate, neglecting surface tensions and capillary forces, and regarding the polymer during imprint as a non-compressible Newtonian liquid. So based on the stationary solution of the Navier-Stokes equations for the force required to press two parallel plates together through a liquid with the viscosity \(\eta\) at a velocity \(v\), an equation for the force \(F\) and residual resist thickness \(h_r\) can be derived as follow:

\[
F = 3\pi\eta R^4 \left(\frac{1}{4(h_f - h_r/2)}\right)
\]  

(1)
\[ h_i = \exp\left(\ln\left(\frac{3\pi R^4}{4F}\right)/3\right) \]

Where \( h_i \) is the initial film thickness of the resist as spin-coated onto the substrate, and \( h_s \) is the structure height. \( R \) is radius of the elevated area of the mould. Fig.2 is dynamics process of IL, which is calculated from equation 1 and 2. If the conditions based on above assumptions, i.e. loading locus, UV curing time, and demould speed, are all matched each other, the transferring pattern will be uniform. The results are that along with increase of loading pressure, the depth of imprint and filling ration will trend to constants. So, the un-precise loading locus will make the mould’s structures distort or un-complete resist fill, short or long curing time may arose the resist sidewall collapsing or more difficult demoulding. The contribution of this research is that a high precise multi-step loading process for template pressing into resist film based UV IL has been developed. Shown as figure 3, this process includes pattern transferring step, resist thickness reducing step, press releasing step, UV curing step, and demoulding step. Different from the conventional IL process, it divided the demoulding factor from the press releasing process, and makes the distortion releasing factor as the single process. The advantages of this process are as follow: the loading locus is continuous with very high accuracy (10nm), the press releasing control (accuracy up to 1 psi) can reduce and avoid the distortion of template structure and stage supports, through adjusting UV curing time (minimum period 5ms) the converting process from liquid to solid state of resist can be controlled, which is helpful to refill the cavity between micro-structures of mould and resist film caused by press release, and before the resist curing step the distortion of the elastomeric stamp has been released and the residual resist film thickness is accurately controlled through the confirmation of the dividing line in the pressing process. It can achieve a residual layer with thickness of 20nm and avoid the elastomeric stamp distorted (under 20nm) at the same time. The press force can reach up to 300 psi for 6 cm² pattern size but the friction force during demould process can be reduced to 30 psi. Experimental results reveal that it is a novel and robust process with high fidelity in micro/nano structures manufacturing.

Considering the need of force during IL process, if there is not an accuracy alignment system the multi-layer pattern replication is very difficult, the positioning error will transfer to replicating result and the MEMS’s structure may be destroyed because of the failed alignment. Fig.4 is the alignment and nano-actuators structures of IL, which can monitoring the whole loading process and combine the loading step with fine position alignment to make a close loop control. Fig.5 is the UV curing tool, besides the nano-alignment system, it includes the loading system, CCD alignment, mould fixture, wafer stage, and flexure supports, etc. In IL tool, the flexure supports and elastic stamp are designed and used to compensate the unparallel error produced by waveness on wafer surface. Thus, the press area can be enlarged from 1.5 cm² to 6 cm². Through precisely adjusting UV curing time (minimum
The converting process from liquid to solid state of resist can be controlled, which is helpful to refill the cavity between micro-structures of mold and resist film caused by press release, and reduce the trend of islandlike polymerization in resist surface layer.

3. Result

Fig.6 is the images of AFM. The CD of fig.6a–c is about 5 microns, which can be used in optical device, bio-sensors, and panel display. Due to the symmetrical structure, its fabricating process is greatly matched to IL technique. But, if the IL control is blind, the pattern transferring fidelity from mould will be very low, such as fig6a and6b. It is very clear that the pressing force (10 psi) did not satisfy the requirement of resist filling, and the curing time (20 ms) is also not enough. Thus the top of the structure is not flat and the sidewall exist collapse. The structure in fig6b, the top surface has sunken. The cause is the curing time is over long (1.5 s), so during the demoulding process the friction between mould and resist is very big, and the top edges of resist structure are pulled up. Through analyzing experimental results and calculating simulation, when the pressing force is added to 35 psi and the curing time is reduced to 50 ms, the replicating pattern is very well, shown as fig6c. The top and bottom surface is very flat and the sidewall’s collapse is avoided also. So, using the above pattern replicating parameters, as shown in fig.6d, the micro-electro with 250nm CD can be fabricated and the electro’s consistency is good.

Up to now, attempts have been made to apply the IL tool and DRPPR process to fabricate optical communication, bio-sensor, super-density magnetic storage media, and semiconductor fabrication.
Fig. 6 Replicating pattern
a: lack of loading and curing time, b: over curing, c: result of DRPPR, d: micro-fluid tunnel and micro-electrodes

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