Template fabrication incorporating different length scale features

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Abstract

A cost effective methodology for pattering of Nano Imprint Lithography (NIL) templates with different length scale features is proposed. The approach relies on selecting the optimum processing window of different technologies for cost effective micro and nano patterning. Very promising results were obtained when first fused silica templates were structured by F2 laser ablation at 157 nm without inducing phase transformation of the material. It was demonstrated that nanoscale features and complex 3D microscale features could be machined with a Focused Ion Beam (FIB) over the existing topography produced by laser ablation. Thus, a large area (up to several square centimetres) of the NIL templates is easily patterned with micro- and even meso-scale features by laser ablation while nano- and micro-scale features could be introduced by FIB machining.

Keywords: Focus ion beam (FIB), laser ablation, micromachining, nanostructuring, 3D machining, Nano Imprint Lithography

1. Introduction

Nano Imprint Lithography (NIL) is considered as the next generation lithography (NGL) technology with potential application in integrated photonic devices, nanoelectronics, life sciences, patterned media and next generation memory devices. Today the industry looks to NIL as an enabling technology for novel devices and also as a means for replacing high-end substrate materials with low cost polymers. According to the International Technology Roadmap for Semi-conductors (ITRS) NIL is a as a very promising solution considered for the 32 nm technology node, and beyond. The technology is also envisaged to fulfil the technical requirements of other non-mainstream applications outside of semiconductors, such as in biotechnology.

Recently, Step and Flash Imprint Lithography (S-FIL™) was proposed as one of the most promising nanoimprint techniques for nanopatterning large surface areas [1]. It was demonstrated that in the sub-50 nm regime, the resolution of the S-FIL™ process is only limited by the resolution of the template fabrication processes. Particularly, the resolution of the imprinting technology is strictly dependent on the ability to create a 1x master template, and improvements in feature resolution can be achieved without new light sources, optical systems or resist materials. In this sense, imprint lithography is a multi-generational technique that can be used to facilitate device and process prototyping at several upcoming lithography nodes. Since the patterning process is carried out at room temperature and ambient pressure using UV curable resists it is possible to achieve accurate overlay and reduce significantly process defects [2]. The main advantage of nanoimprinting compared to other high throughput techniques is the ability to replicate accurately 2.5D and 3D structures incorporating features at different length scales, and varying forms from simple shapes to complex diffractive optical elements.

It is worth stressing that thermal NIL is now more widely employed for nano- and micro-pattering, largely because it is cheaper and works with a broad range of polymer materials. However with this imprinting process the replication of features at different length scale (e.g. micro- and nano-scale features in one go) is an issue due to the difference in polymer flow, different effective pressure between nano- and micrometric patterns and varying residual thickness. As a result, uniformity over the entire wafer is difficult to achieve because the applied pressure must be uniform over the wafer surface. Using thermal imprinting a good printing uniformity was demonstrated over an 8-in. wafer for pattern dimensions from 250 nm to 100 μm [3]. Currently, there is demand for fabrication of monolithic devices requiring much smaller features (e.g. sub 50 nm gratings for photonic application combined with micro fluidic channels, etc.).

On the other hand, UV-NIL has advantages including (i) absence of thermal expansion that impedes precise alignment, (ii) low imprint pressure and low viscosity of the uncured resist, which allows uniform pattering over large areas, (iii) almost negligible difference in the residual layer thickness and very importantly (iv) to imprint nanometric and micrometric patterns, simultaneously. The only limitation for the process is the cost effective fabrication of 2.5D and 3D masters/templates. Different pattering techniques can by utilized for nano- and micro-scale structuring in the range from sub 50 nm to hundreds of micrometers. However, all of them have some limitations in terms of either limited resolution or processing speed

Currently, the templates' pattering in mask making facilities is mostly undertaken using e-beam lithography (EBL) employing shaped and Gaussian beam tools. The latter offers finer resolution, but with significantly longer writing time. For direct writing of 3D nanoscale features, single beam FIB technology could be successfully applied but the slow milling speed makes it unacceptable for industrial applications. To achieve cost-effective 3D nanopatterning of large surface areas, any potential solution should integrate the capabilities of high-resolution massively-parallel beam-based technologies with those of high-throughput replication techniques. Projection maskless pattering (PMLP) technology can fulfill all the above mentioned requirements and is, therefore, ideally suited for the fabrication of complex 3D nanoimprint templates. Such

Multi-Material Micro Manufacture
S. Dimov and W. Menz (Eds.)

a system is currently under development within the European Framework Program Six Integrated project CHARPAN [4], where, through a programmable mask, a massive structured beam (incorporating hundreds of thousands highly parallel beams) patterns the wafer at relatively high speed compared to the conventional single beam FIB systems.

In this paper, a feasibility study on an alternative approach for cost effective structuring of UV-NIL templates is reported. The proposed approach combines the capabilities of two complementary technologies with different cost effective processing windows, F2 laser ablation and FIB machining, for 2.5D and 3D structuring of NIL templates incorporating different length scale features.

2 Nano- and micro-structuring of UV-NIL templates by FIB

2.1 Fabrication of templates with 2.5D nano- and micro-scale features

It has already been reported that the FIB technology could be applied for producing complex 2D and 3D micro and nano structures using a layer-by-layer fabrication method [5]. Li *et al* [6] demonstrated the use of FIB milling for structuring fused silica as an alternative solution to EBL for the fabrication of S-FIL™ templates with simple 2D structures. Template fabrication employing FIB is much simpler compared to the processing chains associated with the use of EBL because several processing steps can be omitted. In particular, the processing steps involved in the fabrication of templates when FIB milling is applied are depicted schematically in Fig. 1 .

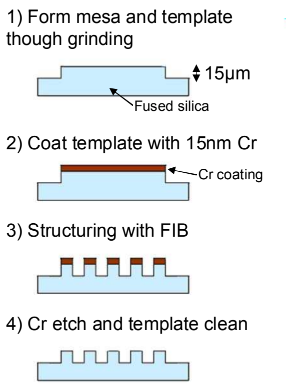

Fig. 1 Main steps for FIB patterning of UV-NIL templates.

Prior to FIB processing, a 15 nm layer of Chrome (Cr) is deposited on the top surface by thermal evaporation. This is required to limit the surface charging effect and pattern drift during ion-beam exposure. Cr was preferred to other evaporation sources such as gold because Cr appears to adhere better to the fused silica surface. Once the evaporation is completed, the template is solvent cleaned again before FIB exposure.

The results of the experimental investigation into the existing functional dependence between the milling depth and ion fluence for fused silica reported in [6] were used to set-up the processing parameters. In this feasibility study a Carl-Zeiss XB 1540 FIB/SEM cross-beam system was used to structure the active area of the template. The FIB patterning was externally controlled by the Raith Eliphy Quantum lithography hardware and software. To speed up the patterning process, especially when 2.5D relief structures have to be produced, FIB milling can be applied only for pattering of a Cr mask on a quartz template followed up by ICP/RIE etching to fabricate them. Gratings fabricated in this way are shown in Fig 2.

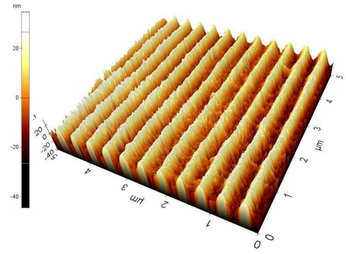

Fig. 2 AFM image of 150 nm grating in fused silica with 40 nm depth realized through dry etching.

Initially, a 15 nm Cr layer was patterned through FIB sputtering. Next, ICP/RIE etching was carried out for 15 min followed up by striping of the remaining Cr layer with Microposit 18 for 300 seconds and then rinsing with deionised water for a further 300 seconds. The sample was further cleaned with solvents to eliminate any other residues from the etching.The carried out AFM measurements showed that the resulting trenches were 40 nm deep, which is more that twice deeper than the Cr pattern.

To prepare the template for S-FIL™ imprinting the process chain includes further processing steps including NMP cleaning and Piranha etch. Finally, the template active area has to be coated with the anti-sticking agent, Relmat, supplied by Molecular Imprints Inc., to facilitate the release of the template from the imprinted polymer.

It is worth stressing that because a FIB/SEM cross-beam system is employed for patterning the template it is possible to carry out a simultaneous inspection of the patterned areas with the integrated SEM. This offers a viable solution for inspecting some critical structures of templates prior to imprinting, and thus to address metrology issues associated with the fabrication of S-FIL™ templates, highlighted by several research groups [7]. In this way, the inspection is performed on the machine and it is not required to use alternative inspection solutions that add complexity to the fabrication process [8].

2.2 Fabrication of NIL templates with complex 3D micro- and nano-structures

Conventional FIB systems operate using bitmap data which define 2D cross-sections. However, to fabricate complex 3D surfaces, it is required to design stacks of layers in order to define the structure accurately. Thus it is impractical to design and import manually the bitmap files required for producing successive layers. One possible way to overcome this problem is to employ GDSII stream format for converting the geometrical design data available in 3D CAD models into a format that can be used to control the FIB milling process through a proper lithography hardware and software, e.g. Elphy Quantum. The method is described in detail elsewhere [9]. The opportunities offered by this CAD-CAM approach were demonstrated by fabricating an array of square micro lenses.

In this research, the same approach was applied for producing complex 3D geometries incorporating different length scale features, nano structures over a micro topography. In particular, the test structure used in this feasibility study was Moth's eye lens. For this a 10x10 µm lens array, was surface patterned with nano-scale lenses (each 150 nm in diameter) in hexagonal arrangement. First, the 3D CAD model of the lens was generated. Then, this 3D model was sliced into layers and exported into GDSII file format. The template fabrication procedure was the same as that described in the previous paragraph. By optimizing the FIB exposure parameters, a 2x2 array of Moth's eye lenses was successfully milled into fused silica, as shown in Fig 3.

Thus, it was demonstrated that by adopting this CAD-CAM approach, complex topographies incorporating micro- and nano-scale features can be fabricated on NIL template with the necessary shape accuracy.

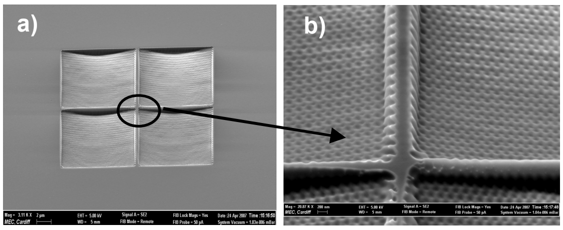

Fig. 3 a) SEM image of a FIB fabricated 2x2 array of Moth's eye lenses and b) SEM image detail of the patterned bottom of the microlenses with nanolenses in hexagonal arrangement.

3 Nano and micro structuring of UV-NIL templates by FIB/laser ablation

Since FIB machining is a very slow process it would be advantageous to apply a faster process for fabrication of large microscale features on relatively big surface areas that do not require nanometer resolution and precision. In this research, laser ablation, which has been used successfully for machining diffractive and refractive microstructures on polymer substrates [10,11] was investigated as a complementary technology to FIB.

3.1 Laser sources and experimental set-up

Dielectric materials, e.g. fused silica and glass, require the use of UV laser sources due to their poor approbation of longer wavelengths. In particular, synthetic quartz that is usually utilised as a UV-NIL template material exhibits over 90% transmission of wavelengths in the range from 180 to 600nm.

An alternative solution to UV laser sources is the use of lasers with ultrashort pulse durations, and thus to achieve energies per photon exceeding the band-gap of fused silica. Therefore, initially in this research the feasibility of structuring directly fused silica employing a pico-second laser source was investigated. The characteristics of the laser source that was used are provided in Table 1.

Table 1 PS Laser source characteristics

Beam quality	M2 <1.5
Pulse duration	~ 8 ps
Wavelength	355 nm
Power	15 mW
Pulse frequency	10 kHz
Spot size	15 µm

Due to relatively long wavelength, 355nm, the absorption coefficient was very low, ~ 92% light transmission. Although it was possible to structure the substrate by increasing the power, the resulting roughness was quite high, in the region of Ra 0.6 µm. In spite of the short pulse duration, a further increase of the power was not possible due the high thermal load on the substrate that triggered a material phase transformation from amorphous to polycrystalline. Polycrystalline materials are not ideal for subsequent dry etching due to the increased roughness of the sidewalls. Thus, this manufacturing route was ruled out as suitable for template fabrication.

To overcome this problem two other possibilities were considered, either a further reduction of the pulse duration, going to the femto-second (fs) range, or the use of deep ultraviolet (UV) laser sources. In this study, the latter was selected due to its relatively high material removal rates in comparison to fs-lasers. In particular, a vacuum UV laser source at 157 nm was chosen because it can provide photon energies exceeding the band-gap of fused silica [12] and material removal rates of about 100 nm per pulse can be achieved.

The set-up used in this research incorporated a LPF220 excimer laser source, summarized in table 2

Table 1 F2 Laser source characteristics

Pulse duration	26 ns
Wavelength	157 nm
pulse energy	40mJ
Frequency	2 kHz
fluence	in excess of 2J/cm2

This was coupled through a 2.5m N2 perfused (<20ppm O_2) enclosed beamline to an x-y-z-ø workpiece holder (50nm lateral resolution) with the beam imaged and focused through a 31x Schwartzfeld reduction lens. The beamline incorporated twin, fly-eye homegenisers for the creation of a uniform beam profiles at the mask plane. A white light through-the-lens viewing system allowed focusing and substrate-beam registration. The 157nm laser beam was shaped using a metal mask, which was fabricated using a Thales Bright 130fs laser with 2µm spot.

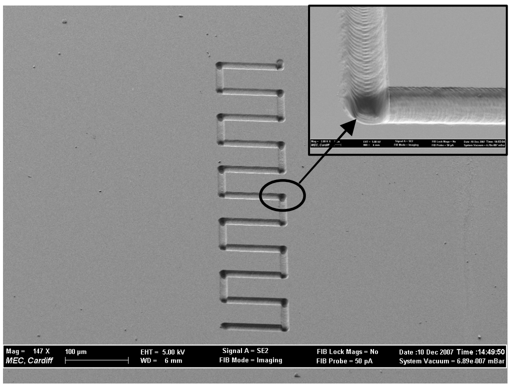

Fig 4. SEM image of grooves with 10 µm width and total length of 1.5 mm machined by F2 laser ablation in fused silica.

3.2 Experiments and results

A fused silica template was successfully patterned using F2 laser at 157 nm wavelength.. Since the set-up described in the previous section uses 31x demagnification projection optics, to ablate the required micro structures, masks were fabricated using the integrated fs laser. In Fig. 4, an example of 10 µm width grooves with a total length of 1.5 mm machined in fused silica is given.

After carrying out some initial test, the capabilities of FIB and F2 laser ablation were combined in order to produce structures that incorporate different length scale features over a relatively large surface area. Fig 5 gives an example of micro and nano features machined by FIB over a pre-existing topography created by F2 laser. In particular, first a 10x6 array of holes were patterned in the fused silica template with pitch of 20 µm with the F2 laser. The holes were 10 µm in diameters and had different dept varying from 150 nm to 3µm. Next, inside the holes 2.5µm and 1.5µm diameter concave microlenses were fabricated by FIB machining utilising the CAD-CAM approach described in Section 2.2. The achieved resolution and shape accuracy of the lenses show clearly that the fused substrate has not undergone phase transformation as a result of the F2 laser ablation. In addition, 100 nm line gratings were machined inside the holes by FIB to test whether the microstructured material is suitable for nanostructuring (bottom right insert in Fig 5.)

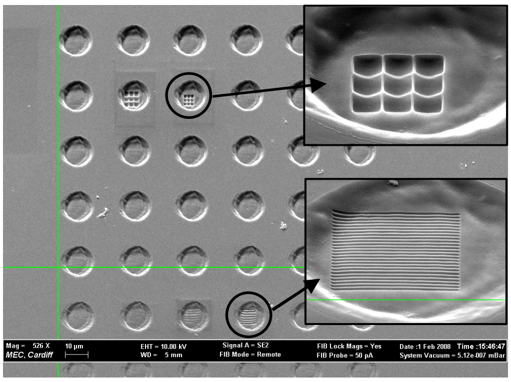

Fig 5. SEM image of a 10x6 array of micro-holes machined by F2 laser in fused silica. The top and bottom right inserts show the FIB machined concave micro lenses and 100 nm line grating, respectively.

4. Conclusions

The paper describes a cost effective method for fabrication of NIL templates incorporating different length scale features by combining the capabilities of laser ablation and FIB machining. It was demonstrated that F2 laser ablation at 157 nm does not trigger any phase transformations in the fused silica substrate. This is a very important point, since this enables the subsequent overlay FIB machining. Different features including both concave micro lenses and nanogratings were FIB machined over the micro features fabricated by laser ablation. Thus, a large area, up to several square centimetres of the NIL templates, can be cost effectively patterned with micro- and even meso-scale features by laser ablation while nano- and micro-features can be added by follow-up FIB machining.

The proposed fabrication route for producing UV-NIL templates incorporating a wide range of micro and nano features simultaneously can find diverse applications. For example, the fabrication of nanogratings onto micro machined features can be used to achieve function integration in novel lab-on-a-chip or point of care devices, where the micofluidic channels can be monolithically integrated within the optical sensing system.

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