Direct patterning of micro-optical structures by combined nanoimprinting and lithography

Jarkko Tuominen*[a], Jussi Hiltunen[a], Antoine Wojdyla[a], Mikko Karppinen[a], Antti Suutala[b], Heli Jantunen[b], Renaud Bouffaron[c], Ludovic Escoubas[c]

[a]VTT Technical Research Centre of Finland, PO Box 1100, FI-90571 Oulu, Finland;
[b]University of Oulu, Microelectronics and Materials Physics Laboratories, PO Box 4500, FI-90014 University of Oulu, Finland;
[c]Université Paul Cezanne Aix Marseille III Laboratoire, TECSEN UMR CNRS 6122, Service 231 - Domaine Universitaire de Saint Jérôme, 13397 Marseille Cedex 20, France

ABSTRACT

The driving force behind combining the nanoimprinting and photolithography is to effectively utilize the advantages of both patterning techniques simultaneously. Conventional shadow-mask UV-lithography can be used to pattern micron-scale structures uniformly over large areas, whereas nanoimprinting enables patterning of nanoscale features, which can also be tilted or round-shaped. We present the work on direct patterning of micro-optical structures by combined nanoimprinting and lithography using modified mask aligner, hybrid mask mold and directly patternable, UV-curable materials. Patterning of structures is carried out in wafer-level fashion. Hybrid mask mold fabrication can be realized for example by modifying conventional shadow-mask using focused ion beam (FIB) milling, or by patterning a mold area on shadow-mask surface by nanoimprinting. One of the advantages of proposed fabrication method is that there is no need for reactive ion etching (RIE) process steps. We present also near-field holography (NFH) as a method of grating mold fabrication. Fabricated micro-optical structures include directly patterned waveguides with light coupling gratings, and also pyramid-shaped gratings which show antireflection properties in the mid-infrared spectral region.

Keywords: polymer waveguide, UV-NIL, diffractive grating, direct patterning, infrared, antireflection coating

1. INTRODUCTION

Photolithography, in its all forms from shadow-mask lithography to projection lithography, has become the most established technique for patterning micron- and nanoscale structures in micro-device fabrication. Microelectronic industry has efficiently used photolithography as a standard technique for years, and also optical and photonics industry has adopted the same production method, especially in the fields of integrated and micro-optics. So far, photolithography can be used to produce size-shrinking microelectronic and photonic devices efficiently, but when entering sub-100 nm structures region, a strong need is seen for a cost-efficient production method compared to expensive and complicated techniques, e.g. extreme UV lithography or projection electron-beam lithography.

Nanoimprint lithography (NIL)[1] has shown potential to become such a method that large-scale, low-cost, high-throughput and simple patterning of nanostructures is possible. NIL is a technique where a surface-patterned mold is physically imprinted into a material on a substrate, and after deforming and separation, the mold pattern replica is created. This process can be carried out with relatively low-cost equipment, and several varieties of NIL have been developed, such as thermal, soft and UV-NIL. For optical and photonic device fabrication, where surface quality, high aspect ratios and direct patterning can have great importance, UV-NIL is a very suitable technique. In general, UV-transparent stamp is imprinted into a layer of photo-curable resin, and after an UV-light exposure, resin is hardened to a solid layer having stamp-defined replicated structures on top. Further processing includes in almost every case a reactive ion etch (RIE) step for residual layer removal, which is also seen as one of the problems of UV-NIL at the moment.

* jarkko.tuominen@vtt.fi; www.vtt.fi

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UV-NIL is capable of replicating micron- or nano-scale structures uniformly over large areas, but problems occur when large structures in mm-scale and beyond need to be replicated. As UV-NIL is a physical deform process, larger structures must displace larger amounts of material, leading to a non-uniform residual layer thickness over large area, which causes problems during RIE step. Nanoscale features next to larger ones are also very hard to pattern with high quality due to non-uniform material flow. Arbitrary-sized features next to each other are common in most modern microtechnology application devices. When direct patterning of structures is concerned, techniques that leave no residual layer after imprinting are the most wanted, and their development is strongly supported.

To overcome the proposed problem and to also add flexibility to UV-NIL processing, different schemes have been developed earlier. Mix and match of photolithography and nanoimprinting[2] relies on separate processing steps, UV lithography *after* nanoimprinting, which makes it feasible to create multistep profiles. More sophisticated approach is the combined nanoimprinting and photolithography (CNP) scheme presented by Cheng and Guo[3]. The essential part of the scheme is the hybrid-mask-mold (HMM), which integrates a nanoimprinting stamp with a conventional shadow mask. Processing with HMM is very simple, and modified inexpensive UV exposure tools can be used. CNP is capable of defining nm-scale features together with µm- or mm-scale features simultaneously, and shadow-masked areas are clean from residual layers of photopatternable material. This scheme has already been applied in fabricating finger-shaped nanoelectrodes to demonstrate nanoscale pentacene organic thin film transistors[4], and in the demonstration of wafer scale fabrication process for integration of polymer DFB lasers and waveguides[5]. Similar to CNP, but replicating microstructures rather than nanofeatures, has also been demonstrated in the field of optical MEMS and micro-optics fabrication[6]. Refractive lenses were fabricated on top of sol-gel cantilevers, and diffractive lenslets were replicated onto a VCSEL device using integrated mask-mold master.

As the CNP relies on HMM, the fabrication of the mold is an essential part of the scheme. In general, the fabrication of a HMM is similar to a NIL mold fabrication, so standard microelectronic fabrication processes are used, such as UV lithography, e-beam lithography, RIE and metallization[4],[5]. Other possible process methods would be focused ion beam (FIB) milling, FIB-CVD or nanoimprinting. NIL mold fabrication by FIB-CVD has been demonstrated with diamond-like carbon[7], and FIB milling, or lithography, has been demonstrated with silicon for thermal NIL[8]. Boron nitride NIL molds have been fabricated for UV-NIL by FIB-milling[9]. Even a method for NIL mold defect repairing has been demonstrated using FIB lithography and FIB-CVD[10].

We present the work on wafer level direct patterning of micro-optical structures by CNP scheme using a modified mask aligner, hybrid mask molds and photopatternable materials. Nanoimprinting is used to fabricate HMMs, and FIB milling and near-field holographic (NFH) lithography are studied as potential fabrication methods. Fabricated micro-optical structures include surface-patterned waveguides and antireflection-type gratings.

2. MOLD FABRICATION METHODS

2.1 Photopatternable materials

Polymer optical waveguides are generally fabricated using photopatternable materials, UV exposure tools and standard lithography fused silica shadow masks with a patterned Cr layer on top. After UV exposure, shadowed areas are washed away during development step, whereas exposed areas remain hardened on substrate. Further processing, e.g., nanopatterning of waveguide sides, would need time-consuming, costly and potentially damaging process step, e.g., NIL and RIE. Nanoimprinting would also require alignment steps and material compatibility. However, using CNP scheme, for example light coupling grating can be integrated into a waveguide simultaneously with direct patterning.

The photopatternable materials used in this work were organically modified ceramics (ORMOCER®) inorganic-organic hybrid polymer family products, sold by Micro Resist Technology GmbH, Berlin, Germany. ORMOCER®s are versatile materials for UV-exposure-based processing at room temperature, and their material characteristics are suitable for optical and photonics devices working in UV, visible or NIR wavelengths. ORMOCER®s are processed in liquid form, so also molding and nanoimprinting are possible. In our work, version Ormocore was used in waveguide core fabrication, and Ormocomp was used as a general nanoimprinting and molding material. Negative masters were also fabricated with Ormocomp.

2.2 Nanoimprinting

CNP scheme requires a hybrid-mask-mold for operation. When fabrication of nanostructures is concerned, expensive equipment and processes are generally needed to fabricate a HMM. For the fabrication of integrated grating waveguide HMM, our approach was to modify a standard waveguide-patterned chromium shadow-mask by nanoimprinting. Using a quartz NIL mold (400 nm period binary grating, grating depth 300 nm), Ormocomp material, and the modified mask aligner (Suss MA6) suitable for imprinting process, grating area on top of shadow mask was defined. Processing scheme and a photograph of the fabricated HMM are shown in Figure 1. After grating patterning, an anti-adhesion layer was deposited on HMM using the material (F_{13}-TCS) and the vapor phase deposition process described by Beck et al.[11]. Other possibility is to use a PDMS-based anti-adhesion layer and its deposition process described by Lee et al.[12]. In addition to binary grating mold, also a NIL mold with blazed gratings (20 μm period, grating depth 10 μm) was used to fabricate a different HMM.

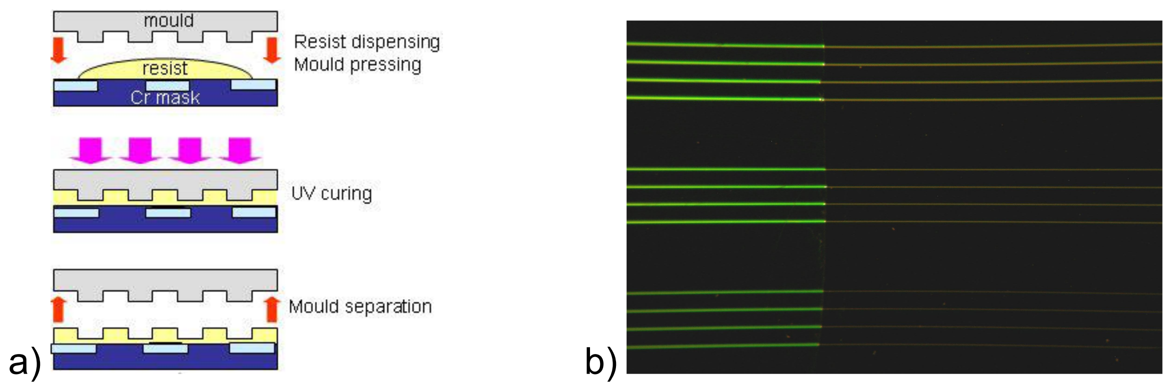

Fig. 1. HMM fabrication by nanoimprinting. (a) Processing scheme. (b) Photograph of the fabricated HMM. On the left, the grating area (400 nm period) is shown in green. Line apertures are 25, 50, and 100 μm wide.

2.3 Focused ion beam milling

Standard equipment used in NIL mold fabrication includes e-beam lithography and RIE systems. One novel possibility to fabricate nanostructures is to use the FIB milling method. FIB equipment uses highly focused ion beam, normally composed of Ga^+-ions, to scan the surface according to the programmed pattern design. This maskless and resistless direct-write fabrication method has a resolution down to 7 nm, and is also capable of milling and depositing materials in 3D. Direct analysis of fabrication quality is possible with the use of integrated scanning electron microscope (SEM). Milling on different materials is possible, such as silicon and quartz.

In our experiment, binary and blazed gratings with a depth of 400 nm and 1000 nm, respectively, and with a period of around 1 μm were fabricated onto quartz substrate using FEI Nova series FIB with Nanometer Pattern Generation System (NPGS). Each patterned area was 5 μm wide and 20 μm long. After successful nanoimprinting tests with Ormocer materials, it was shown that FIB milling method could be used to fabricate NIL molds. It would be also possible to modify conventional shadow masks to CNP molds, e.g., fabricating a grating area into a line aperture area of a waveguide mask. SEM micrographs of a FIB milled blazed grating are shown in Figure 2.

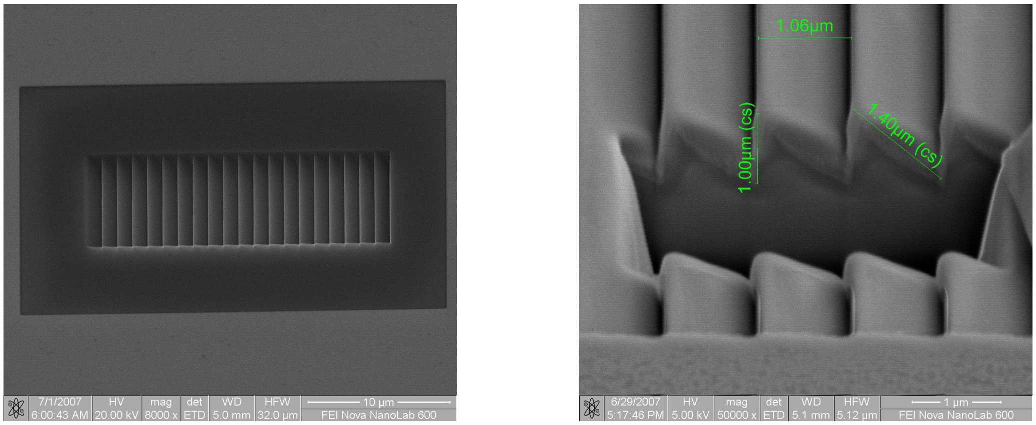

Fig. 2. SEM micrographs of a blazed grating mold fabricated by FIB milling.

2.4 Near-field holography

Near field holography (NFH) is a technique for the manufacturing of planar grating structures with period between 200 and 600 nm. Such structures are typical, for example, in devices used in guided wave optical communications, where very narrow optical bands are required. The method uses a mask and holographic exposure to transfer the grating period into photoresist on a substrate, as illustrated in Figure 3(left). The zeroth diffraction order passes through the phase mask plate whereas the first diffraction order is diffracted under an angle that has the same value as the impinging beam but is directed to the opposite side. When these diffraction orders have same intensity, the resulting interference pattern has the same pitch as the original grating. The method is called the near field holographic lithography, because a conventional mercury lamp with band narrowing filter is used in illumination having limited coherence and, thus, the interference pattern formation is limited close to the mask.

The first step on NIL grating mold fabrication by NFH method was to pattern positive resist on silicon wafers. Transparent fused silica phase mask with a grating period of 400 nm and a pattern area diameter of 2 inches was used. As our NFH exposure module is a part of SUSS MA6 mask aligner, the proposed method is suitable for wafer-scale volume production. Phase mask was contact-printed on a prebaked resist-coated wafer and after exposure and developing, a grating with the same period as on the phase mask was created. The second step was to transfer the grating onto the silicon wafer by reactive ion etch process. Figure 3(middle) shows an example of periodic photoresist pattern on silicon by NFH. Fabricated silicon mold is shown in Figure 3(right), where the 400-nm-period grating is transferred by RIE process; NFH-patterned resist was used as an etch mask.

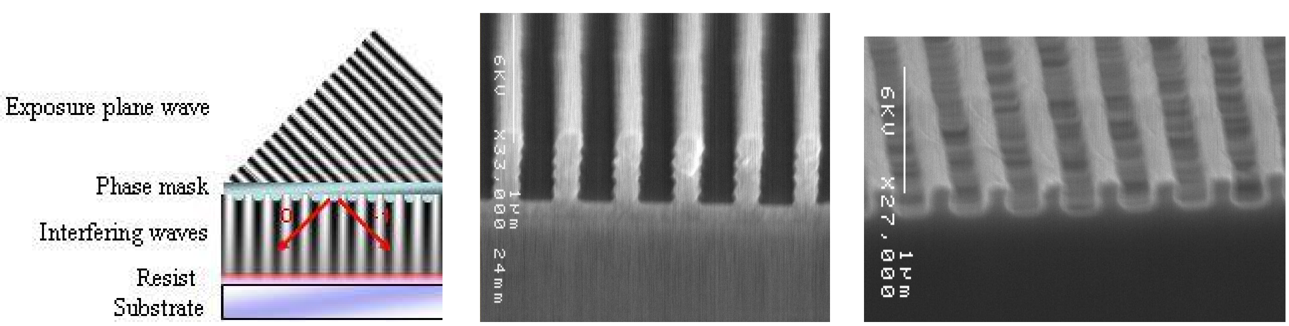

Fig. 3. (left) NFH principle. Distance between the phase mask and the resist is exaggerated for visual reasons, contact printing is a normal process condition. SEM micrographs of (middle) patterned positive resist by NFH and (right) RIE-etched grating on silicon wafer.

3. DIRECT PATTERNING RESULTS

3.1 Waveguides with gratings

In several devices, such as backlights and integrated optical components, source-emitted light is intended to be exploited as efficiently as possible. In addition to light-guiding element material issues, optical couplings are perhaps the most challenging parts of the devices. Efficient light in- and outcoupling to and from the guiding element, respectively, is a key issue regarding the general functionality of the fabricated device. As the integration and the miniaturization of optical devices is an ongoing process, diffractive elements are seen as one solution for replacing larger components. However, mass production of integrated diffractive elements in light-guiding applications is still in its infancy due to expensive processing equipment and processes. Replication of diffractive elements from masters, composed of either binary[13] or slanted gratings[14], is seen as a potential mass-production method.

Using the HMMs described earlier in Section 2.2, gratings on top of a waveguide and integrated onto a waveguide were fabricated to demonstrate the feasibility of the CNP scheme, which is also displayed in Figure 4 (left). SEM micrographs of replicated blazed gratings integrated onto an Ormocore waveguide are shown in Figure 4 (middle) and (right). Replicated binary grating with a period of 400 nm on top of an Ormocore waveguide is shown in Figure 5. Height of the waveguide is 50 μm. In both examples, the replication and waveguide patterning were successful in one step showing feasibility of the proposed method. The structures were not optimized in this case, but for different applications optimized structures can be found through modeling and simulation.

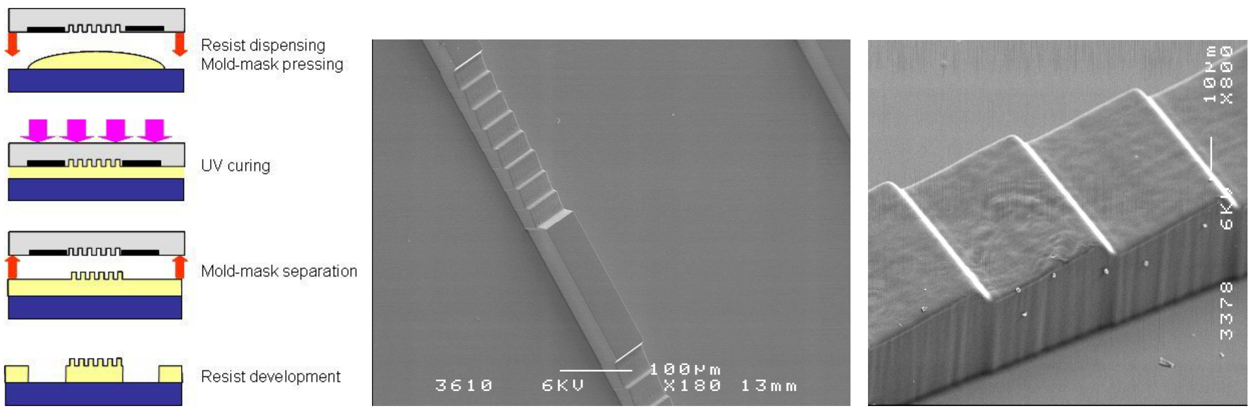

Fig. 4. (left) CNP scheme. (middle), (right) SEM micrographs of blazed gratings integrated onto waveguides using CNP scheme.

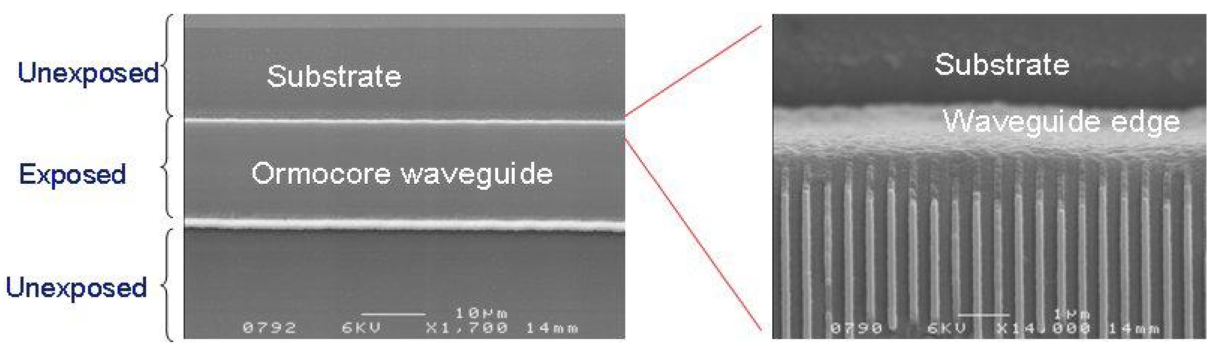

Fig. 5. SEM micrographs of 400 nm binary grating on top of a waveguide fabricated by CNP scheme.

3.2 Antireflection gratings

Reflection of light from optical surfaces can be problematic in several devices such as displays and lens systems. Lower transmission and stray light are caused by reflections, which impair the efficiency of the optical devices. On the other hand, reducing the reflections to minimum can arise from the need not to be seen, i.e., in stealth applications. Anti-reflective surfaces are thus used extensively, and their importance will remain in the future. Standard method of fabricating AR surfaces is the vacuum-deposited coating of dielectric material layers, but this method is rather expensive and resulting layer thicknesses can be way over several micrometers. To reduce fabrication costs and to meet the demands of miniaturization and integration, sub-wavelength grating structures patterned on reflecting surfaces has been shown as a potential alternative for coating methods. Their advantages include a wide operation wavelength range, UV light suitability and possibility to replicate the structures by mass production techniques such as injection molding, hot embossing or nanoimprinting. Replication of nanostructured AR surfaces by hot embossing in polycarbonate operating in visible spectral range has been demonstrated[15], and also UV-replication of sub-wavelength AR-structures in ORMOCERs on glass has been demonstrated[16].

In the following, the work on replication of pyramid-shaped gratings, which show antireflection properties in the mid-infrared spectral region, is presented. Theory of operation, simulation results and the fabrication process of the silicon masters based on photolithographic patterning and wet anisotropic etching, as well as characterization of optical properties have been presented in more detail by Escoubas et al.[17]. Reflectance of silicon wafers was reduced to around 2 % in the spectral range from 4 μm to 6 μm.

Silicon masters, fabricated in Institut Fresnel, Marseille, France, had surface grating structures consisting of 4- and 8-sided flat-topped pyramids (i.e. frustums of pyramids) with the heights of 870 and 670 nm, respectively, and with the individual flat-topped pyramid lateral spacing of 5 μm. After anti-adhesion layer material (F_{13}-TCS) deposition, negative replicas were fabricated using the imprinting tool of Suss MA6, Ormocomp material and glass substrates. In order to get the proper structure for the measurements, negative replica was used as a replication master, thus, anti-adhesion layer was deposited on negative replicas. Using the same process as with master replication, an Ormocomp replica of silicon master was fabricated on glass substrate. AFM characterization pictures of the 8-sided structures are shown in Figure 6, and SEM micrographs of the replicated 8-sided structures are shown in Figure 7. The replication is shown to be a successful process, and the quality of the replicas is good in comparison with the master structures.

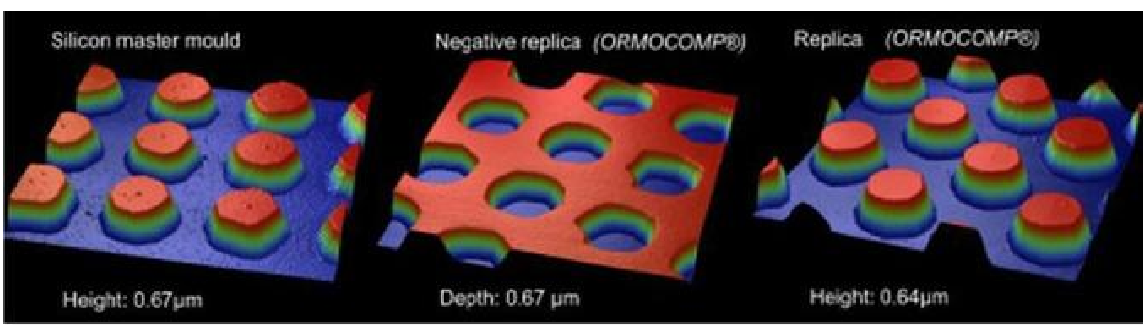

Fig. 6. AFM pictures of the AR silicon master with 8-sided flat-topped pyramids, its negative replica and replica of the Si master. Negative replica was used as a mold to fabricate the Si master replica.

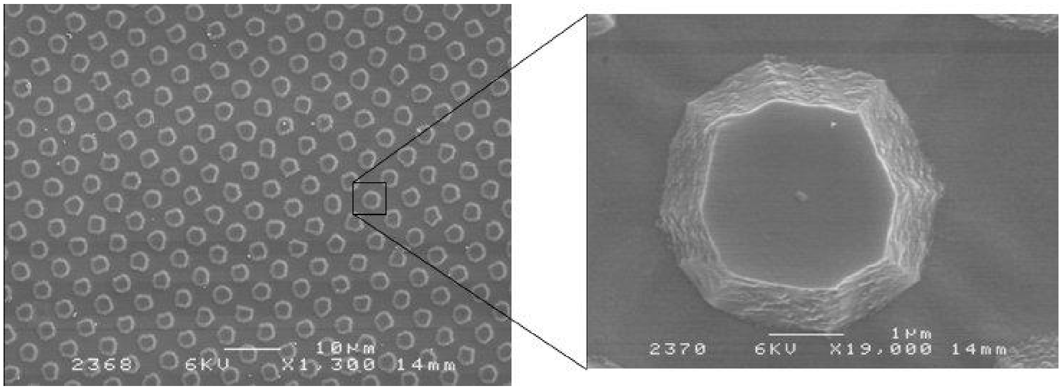

Fig. 7. SEM micrographs of ORMOCOMP-replicated AR structures with 8-sided flat-topped pyramids.

Optical measurements were carried out to test the operation of the replicas as anti-reflective surfaces. Samples were measured with FT-IR spectrometer by Biorad. Measurement wavelength range from 1.5 µm to 3.3 µm was chosen as it is in mid-infrared region and suitable for Ormocomp, i.e., Ormocomp is not working properly in longer wavelength region. Reflection measurement relative-to-glass results in the mentioned wavelength range are displayed in Figure 8., showing that both replicated structures have anti-reflection properties, and 8-sided flat-topped pyramid structures have better performance.

Fig. 8. Relative-to-glass reflectance versus the wavelength of ORMOCOMP-replicated AR-structures.

4. CONCLUSIONS

In this work, we have shown that wafer-level direct patterning of micro-optical structures by CNP scheme using a modified mask aligner, hybrid mask molds and photopatternable materials is feasible. Nanoimprinting was used to fabricate binary and blazed grating HMMs through modification of conventional lithography waveguide shadow mask. FIB milling was used to fabricate binary and blazed grating NIL quartz molds to demonstrate the capabilities of a potential direct-write NIL mold fabrication equipment. Near-field holographic (NFH) lithography was used to fabricate a NIL mold through positive resist patterning, presenting a cost-efficient wafer-scale method for replication of masters and for fabrication of HMMs. Fabricated micro-optical structures included waveguides with binary and blazed gratings integrated on top of waveguides, and antireflection-type gratings consisting of 4- and 8-sided flat-topped pyramidical structures fabricated on glass. Replicas having pyramid-shaped gratings were shown to have antireflection properties in the mid-infrared spectral region.

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