Fabrication Process of 3D-Photonic Crystals via UV-Nanoimprint Lithography

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ABSTRACT

In recent years the standard lithography reached its limits due to the diffraction effects encountered and the necessary complexity of compatible masks and projection optics. The restrictions on wavelength, in combination with high process and equipment costs, make low cost, simple imprinting techniques competitive with next generation lithography methods. There are several NIL techniques which can be categorized depending on the process parameters and the imprinting method – either step & repeat or full wafer imprinting. A variety of potential applications has been demonstrated by using Nanoimprint Lithography (e.g. SAW devices, vias and contact layers with dual damascene imprinting process, Bragg structures, patterned media) [1,2]. UV-NIL has been selected for the fabrication process of 3D-photonic crystals. Results with up to three layers will be demonstrated.

Keywords: Nanoimprint Lithography, UV-NIL, 3D-Photonic Crystals, Woodpile Structure

1 INTRODUCTION

UV-based Nanoimprint Lithography (UV-NIL) offers several decisive technical advantages concerning overlay alignment accuracy, simultaneous imprinting of micro- and nanostructures and tool design. 3D-photonic crystals have been fabricated using e-beam lithography [3] with high precision alignment stages for achieving sub-100 nm overlay alignment needed to exhibit full photonic bandgap structures for woodpile rod line width ranging from 200 nm to 400 nm. In order to increase the patterned area which is clearly restricted to about 100 µm x 100 µm for most the e-beam lithography equipment to an area in the range of 25 mm x 25 mm UV-NIL has been selected for this application. Quartz glass templates were fabricated in such a way that the first layer as well as subsequent layers can be imprinted with the same template by rotating the template by 90° and a following optical alignment procedure. In order to get a sufficiently high refractive index difference between rods and the spacing in between Si respectively Al - for better contrast - and SiO_2 were deposited. A woodpile structure with 3 layers is demonstrated in this contribution, which does not exhibit a photonic bandgap, however it demonstrates the capability of 3D stacking by using UV-NIL.

2 EXPERIMENTAL

UV-NIL consists of the following main process steps which were performed predominantly on an EVG®620:

- Spin coating of substrate with UV-NIL resist
- Loading of template and substrate
- Non contact wedge compensation of template and substrate
- 3-step alignment in proximity and in soft contact of template and spin coated substrate
- Imprinting of the features using vacuum contact
- Exposure – photo polymerization of imprinted resist
- Detachment of template and substrate

The tooling of the EVG®620 consists of a template holder with a glass backplane and a substrate chuck for substrate sizes of up to 100 mm in diameter. A compliant layer on the substrate chuck was used to ensure a full contact of template to resist which resulted in a residual layer deviation of +/-5 nm for a residual layer thickness of 20 nm in average across the 25 mm template width (at an imprinting depth of 400 nm).

NSTI-Nanotech 2007, www.nsti.org, ISBN 1420061828 Vol. 1, 2007

The template contains 16 squares (each 3 mm x 3 mm) with elevated structures with a height of nominally 200 nm or 400 nm and periods ranging from 800 nm to 2400 nm (lines are ranging from 200 nm to 600 nm). The Moiré alignment features are placed in the center of each rim indicated with arrows (Figure 1). The alignment features are designed in such a way that all 5 layers can be built up with the same template by simply rotating the template by 90° for every subsequent layer to be imprinted.

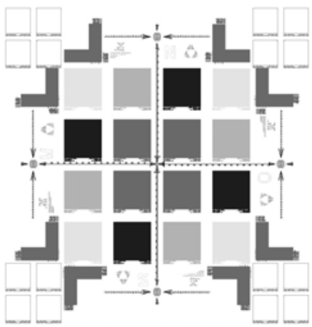

Figure 1: Template design containing 16 fields of lines and space structures for the woodpile structure; other features are used for alignment and test purposes

In order to transfer the imprinted features into the substrate by dry etching with superior pattern fidelity the residual layer after imprinting needs to be thinner than 50 nm. Actually, residual layers as small as 20 nm could be achieved by using the resist mr-UVCur06 from micro resist technology; www.microresist.de, Germany. The quartz glass templates were treated with an anti-adhesive layer based on a fluorosilane polymer that was applied by spin coating. The imprinted and etched features were characterized by scanning electron microscopy (SEM) (Figure 2,3).

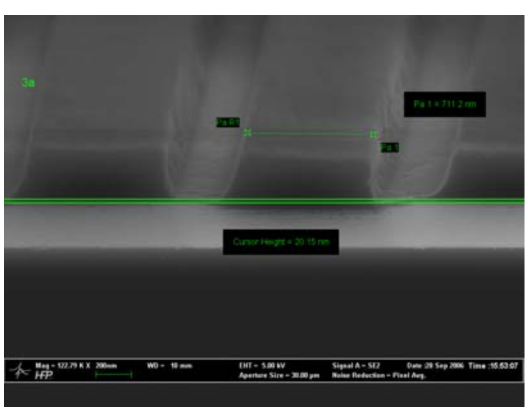

Figure 2: SEM picture of imprinted lines in UV-NIL resist; 1st layer of photonic crystal imprinted with elevated template structures with 200 nm line width and 700 nm space

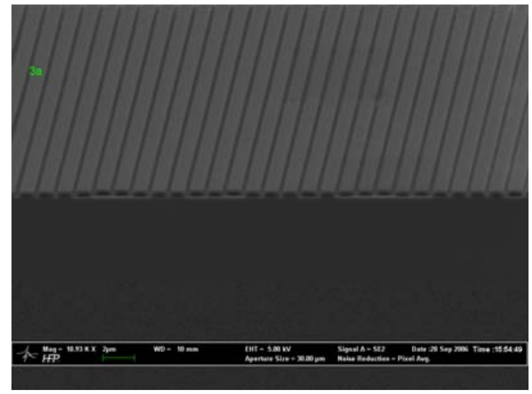

Figure 3: SEM picture of imprinted lines, close-up of lines is shown in figure 2

2.1 Process Flow for the woodpile structure

The process consists of 25 process steps for getting five layers of the 3-dimensional photonic crystal, which consists of Si (n=3.4) rods separated by SiO_2 (n=1.4) (Figure 4). There has to be a refractive index difference of at least 1.7 in order to get a full photonic bandgap independent on the direction of light propagation as shown by simulations.

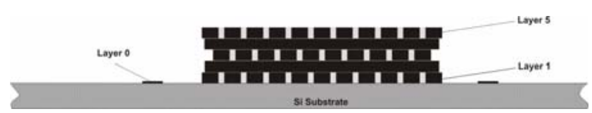

Figure 4: Cross-sectional view of the woodpile structure, black: SiO_2; grey: Si

In order to get a photonic bandgap the structures have to be aligned with an overlay alignment accuracy of 100 nm for the 300 nm rod width. The alignment is performed in 3 stages using Vernier and Moiré pattern resulting in overlay alignment accuracies better than 100 nm [4,5]. The 5^{th} layer has to be exactly above the 1^{st} layer. Alignment marks are defined in the 0^{th} layer by imprinting with a dedicated template containing only the alignment keys which are used as a reference for the subsequent layers. This has the advantage that the inevitable alignment errors are not summed up from layer to layer during the consecutive imprinting steps. The alignment keys are defined by UV-NIL and then etched into the Silicon substrate. Subsequently this structure is covered with a layer of 400 nm SiO_2. After spin coating of the UV-NIL resist the first layer is imprinted with a different template containing the structures for all subsequent layers. The imprinted structures are dry etched into the SiO_2 layer, covered with Si, the surface is then planarized via chemical mechanical polishing (CMP). During the CMP process the end point detection is performed in such a way that the planarization process is stopped after reaching the Si-SiO_2 interface. Next the deposition of SiO_2 follows to be ready for the next layer. The next layer is imprinted onto 400 nm SiO_2 by rotating the template by 90° referring to the alignment keys of the 0^{th} layer.

2.2 Moiré Alignment

In order to achieve a full photonic bandgap the 3^{rd} layer needs to be aligned to the 1^{st} layer with a precision of d/4, i.e. 150 nm for 600 nm line width.

The template contains 4 areas with linear and circular Moiré pattern for high precision manual alignment of substrate and template. The alignment procedure is performed in 3 stages: (1) rough alignment in separation of template and substrate by using the cross and its corresponding square (2) fine alignment in soft contact of resist and template and (3) Moiré alignment in close proximity of resist and template and if necessary final corrections in soft contact.

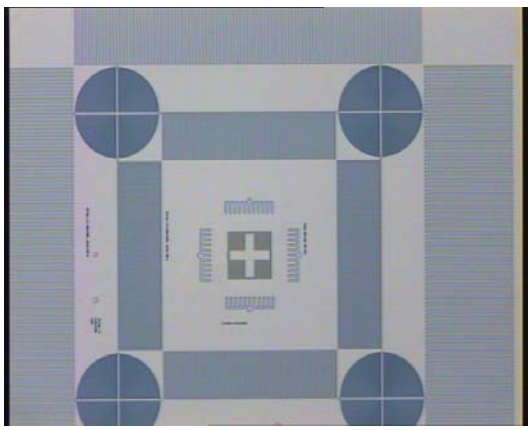

Figure 5: Microscope picture of imprinted Moiré and Vernier patterns around the cross sputtered with Al

The evaluation of the alignment accuracy is performed via the Vernier patterns located next to the cross in the center in figure 5. Alignment accuracies in x- and y-direction of certainly better than 100 nm have been achieved, since a misalignment by one increment on the Vernier would correspond to 200 nm offset. The concentric appearance of the circular Moiré patterns is a further indication of the excellent alignment. For clarity we include in Fig. 6 a zoomed area of the Vernier comb, indicated with a red arrow.

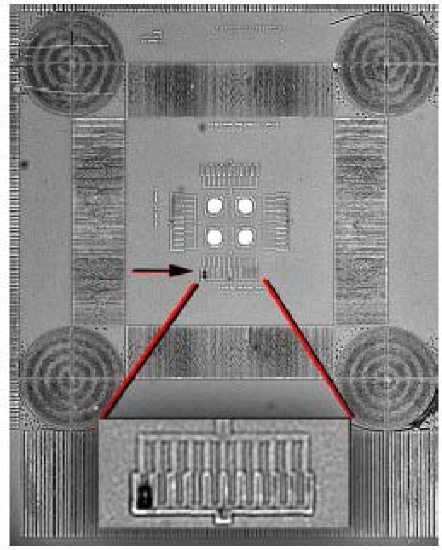

Figure 6: Result of an alignment process

3 RESULTS

The woodpile structure was not only built up by processes described above, but also in subsequent layers of UV-NIL resist and deposited Al. Although this woodpile structure does not exhibit a photonic bandgap, this sequence was selected in order to demonstrate the 3D-stacking capability by using UV-NIL with much less process steps than the process described previously. Only UV-NIL into the spin coated resist and deposition of about 400 nm thick Al layers was necessary for the realization.

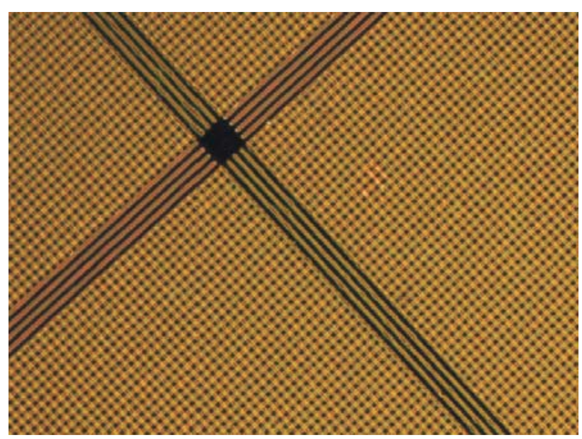

Figure 7: Microscope picture of two imprinted layer perpendicular to each other, smallest features are 300 nm

Figure 7 shows an optical microscope picture of a top view of a microscope picture of two imprinted layers consisting of Si rods embedded in SiO_2 for the first layer and the imprinted polymer for the second layer.

NSTI-Nanotech 2007, www.nsti.org, ISBN 1420061828 Vol. 1, 2007

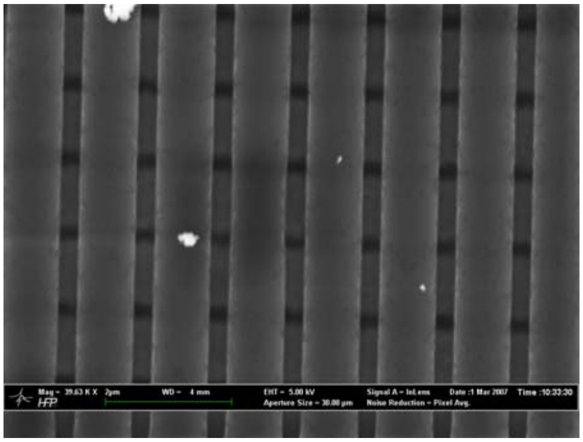

Figure 8: SEM picture of 2 layers imprinted perpendicular to each other

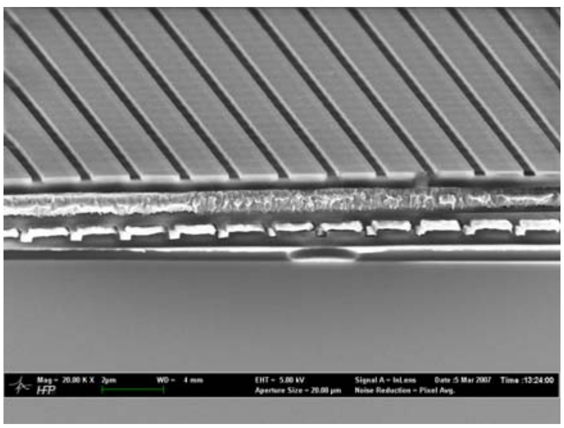

Figure 9: SEM cross section of 3 layers imprinted perpendicular to each other spaced with Al

Figure 8 shows a top view SEM picture of a stack of 2 layers imprinted on top of each other. The bottom layer is imprinted and covered with ~ 400 nm thick Al and the top layer is imprinted. In Figure 9 a stack of 3 imprinted layers spaced with Al is shown in a cross sectional SEM. It can be noticed that the deposited Al layer on top of the first imprinted layer is planarized by the imprinting resist during spin coating or imprinting, so that a flat layer is achieved after each imprinting process. The imprinted first layer is partially covered by Al due to cleaving of the substrate for SEM measurement.

4 CONCLUSION

A concept for the fabrication of 3D-photonic crystals has been described. Up to three layers of the woodpile structure have been realized by using UV-based nanoimprint lithography, dry etching and deposition techniques in order to achieve Si rods separated by SiO_2 on top of each other in a woodpile structure. Alternatively, the 3D-stacking of imprinted lines & space structures was demonstrated by using UV-NIL and sputtered Al layers in between due to SEM contrast considerations. The required alignment accuracy of below 150 nm was realized by using linear and circular Moiré patterns. Alignment accuracies in the range even below 100 nm were achieved. The next steps are the stacking of 5 layers in order to get the 3D-photonic crystal. In parallel the process with resist rods separated by Al will be continued.

5 ACKNOWLEDGEMENTS

The authors acknowledge funding from the European Community´s 6^{th} Framework program (COOP-CT-2004-512667 3DNanoPrint, www.3Dnanoprint.org) and the support from Dr. Marko Vogler from micro resist technology.

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