Optical Waveguide Couplers Fabricated by Nano-Imprint Lithography

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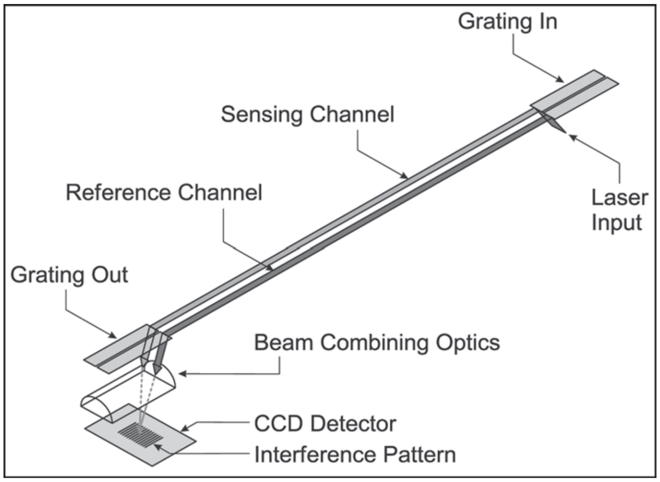

Figure 1: Schematic of the optical interferometric sensor.

Introduction:

A chemical sensor can be created based on optical planar waveguide interferometry. Since waveguides have evanescent fields sensitive to index of refraction changes, optically combining a guided sensing beam with a reference beam generates an interference pattern that depends on the relative phases of the two beams. Applying a chemically selective film over the sensing arm of the interferometer provides the basis for a sensor (Figure 1). While achievements have been made using grating-coupled silicon nitride waveguides [1], further research is needed in development of inexpensive and more versatile fabrication methods. In particular, fabrication of the grating couplers poses the greatest challenge, as the line width of the gratings is only 360 nm. Nano-imprint lithography offers a solution to this problem, with the ability to replicate three dimensional patterns inexpensively at nanometer resolution. Using standard and grayscale electron-beam lithography, imprint templates for both the standard square grating and blazed gratings were successfully fabricated.

Experimental Procedure:

The process development consisted of two basic stages. The first was creating the imprint template by electron-beam lithography (EBL). The second was transferring the pattern into quartz via nano-imprint lithography (NIL). EBL required the determination of exposure, developing, and plasma etching parameters, while NIL required the determination of imprint, exposure, and plasma etching parameters.

Silicon was chosen as the template material because of its low cost and compatibility with EBL. Hydrogen silsesquioxane (HSQ) was chosen as the resist due to its high etch selectivity over silicon (~ 8.5:1). While contrast data for HSQ for various developer concentrations and immersion times has previously been collected, this data does not account for over-exposure due to back-scattered electrons from the substrate (proximity effect). Because of this, writing multiple grating patterns with a wide range of doses and developing parameters was necessary to determine a reliable process.

The proximity effect can be accurately modeled by a Gaussian distribution with a half-maximum radius of 31.2 μm. With the smallest dimension of the sensor couplers being 200 μm, the majority of the couplers' area will have the maximum over-exposure from the proximity effect. Appropriate sized test patterns were determined to have dimensions of 200 μm by 200 μm and verified by numerical computation of the proximity effect in MATLAB, showing that an approximately 100 μm by 100 μm area in the center of these patterns would show the maximum proximity effect (Figure 2). The patterns were written with doses ranging from 290 μC/cm^2 to 1680 μC/cm^2 on multiple wafers with resist thicknesses

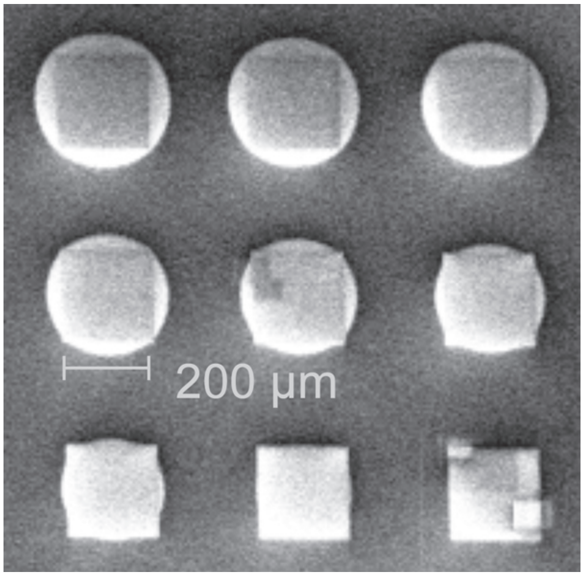

Figure 2: SEM of square grating test patterns (HSQ on Si).

ranging from 45 nm to 105 nm. These were then developed in tetramethlyammonium hydroxide (TMAH) in concentrations ranging from 2.3% to 25% with times from 7 seconds to 70 seconds.

Several successful formulas were found after these patterns were etched in a Cl_2/Ar based inductively coupled plasma and remaining resist was stripped. The optimal formula was found to be exposure with 290 μC/cm^2, 45 nm resist thickness, and development in 2.3% TMAH for 70 s. The criteria for selecting this formula was based on minimizing cost of production: the shortest fabrication time with minimal material costs.

Process development of the pattern transfer into quartz was the more difficult of the two stages. No previous work had been done towards this goal, so several imprint resists and etching gases were tested for selectivity. The first resist tested was polymethyl methacrylate (PMMA). This is a common thermally curable resist used for imprinting and is relatively inexpensive. The second was a proprietary UV curable resist (mr-UVCur06) from Micro Resist Technology. Both of these resists were tested as quartz etch masks in two different types of inductively coupled plasmas. PMMA was ineffective as an etch mask for both etch recipes. The mr-UVCur06 resist proved to be much more effective. The Cl_2 based plasma yielded low selectivity of ~ 4:1 over quartz, while the CF_4/C_4F_6 based plasma yielded a much higher selectivity of 1:1.33.

The imprinting process was tested with arbitrary trench depths, but the sensor couplers require a trench depth of 70 nm for the maximum coupling efficiency of light to the waveguide. In order to accomplish this, accurate data was taken for the etch rates of both the resist and quartz substrate. Measurement of the resist etch rate was necessary because a residual layer of the resist remains after imprinting and must be etched down to the quartz surface. The required etch time was then calculated to be 65 s, and several substrates for actual sensors were fabricated.

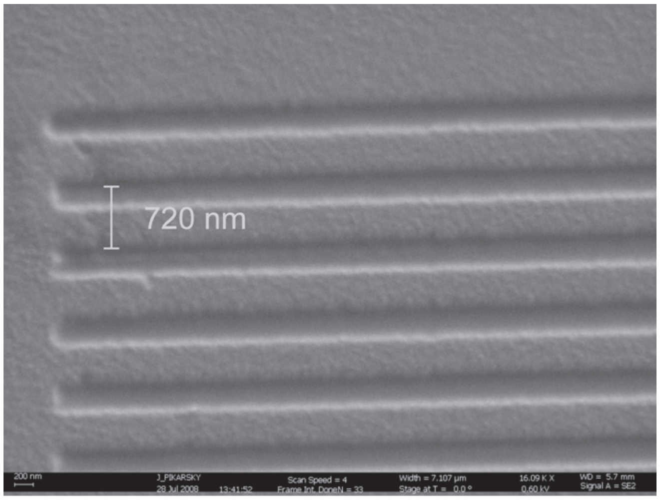

Figure 3: SEM of square grating pattern etched into quartz.

Results and Future Work:

The square and blazed grating patterns for the waveguide couplers were demonstrated successfully with nano-imprint lithography. SEM images taken of the quartz after etching (Figure 3) show that the line widths are reproduced accurately to ± 2 nm. AFM images of the blazed grating template and etched quartz (Figure 4) show some degradation in pattern transfer. While the square and blazed grating shapes have been successfully transferred in quartz, there have yet to be any quantitative measurements of the coupling efficiency. The silicon nitride waveguide material will be deposited by plasma enhanced chemical vapor deposition (PECVD). A HeNe laser will then be used as the light source, and the relative intensity of light output from the waveguides will be measured by a CCD camera.

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References:

[1] J. Xu, D. Suarez, D.S. Gottfried. Analytical and Bioanalytical Chemistry. 2007 Oct; 389(4): 1193-9.

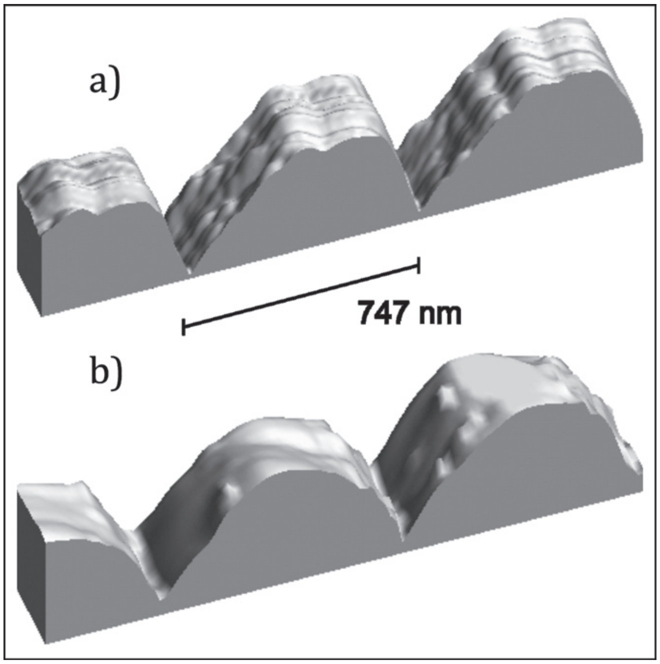

Figure 4: AFM scans of a) HSQ template of blazed gratings, and b) blazed gratings etched into quartz.