Focused ion beam nano-structuring of photonic Bragg gratings in Al_2O_3 waveguides

Amaia Uranga, Feridun Ay, Jonathan D.B. Bradley, René M. de Ridder, Kerstin Wörhoff, and Markus Pollnau

Integrated Optical MicroSystems (IOMS) Group, MESA+ Institute for Nanotechnology, University of Twente, 7500 AE Enschede, The Netherlands
phone: +31-53-4891037, e-mail: a.urunga@student.utwente.nl

Focused ion beam (FIB) etching is receiving increasing attention for the fabrication of active integrated optical components such as waveguide amplifiers and lasers. Si-technology compatible low-loss Al_2O_3 channel waveguides grown on thermally oxidized silicon substrates have been reported recently. We used FIB milling for reflection grating definition on Al_2O_3 channel and ridge waveguides. Structural optimization has been achieved by experimentally adjusting FIB patterning parameters such as ion current, dwell time, loop repetitions, scanning strategy, and applying a top metal layer for reducing charging effects and sidewall definition improvement. Optical properties of these devices are currently being studied.

Introduction

Both passive and active integrated photonics have been subjects of substantial research in recent years. While the field of passive devices can be considered rather mature and developed with proven achievements, active integrated optics still require considerable progress for the development of reproducible layer deposition methods as well as high-quality and low-optical-loss micro-structuring techniques.

In this work we report on the development and realization of sub-µm-period reflection gratings which, together with micro-ring resonators, may be considered as the most promising devices for a fully integrated optical approach for on-chip laser resonators. Si-compatible Al_2O_3 waveguide technology has been used in order to achieve the previously reported optical quality and low losses together with uniform and reproducible layer growth [1]. Regarding the structure patterning, focused ion beam milling has been considered as an interesting techinque which enables rapid and flexible nanometer-scale feature size fabrication.

Design of grating structures

A grating structure is mainly characterized by its spatially periodic variation of the refractive index, which generates a specific photonic band gap for each different parameter configuration. From the numerous theoretical methods that have been reported in the literature to calculate the photonic band structure [2], the transfer matrix method (TMM) is used in this case as a one-dimensional (1D) approach that reduces the grating structure into two different cross-section profiles (the waveguide itself and the patterned part) and field propagation properties are calculated for each case by using the effective index method. Then the grating structure is represented as a periodic stack of the mentioned sections so that, after calculating the layer-to-layer boundary conditions, all the field propagation parameters can be analyzed.

This simulation tool allows the optimization of three input parameters in order to achieve the desired stop band: milled depth (represented by the effective index of the corresponding cross section), aspect ratio between the top and milled parts of the grating and finally the length of the structure. Figure 1 provides the result of a 1D simulation that shows a typical grating transmission response; the selected parameters are shown in Table 1. As a final step, all the results from the 1D simulation were gathered and plotted in a two-dimensional surface plot (see Fig. 2). The plot shows how the achieved maximum reflectivity evolves as a function of milled depth and length of the grating (this value is represented as a number of periods); an aspect ratio of 50% was fixed.

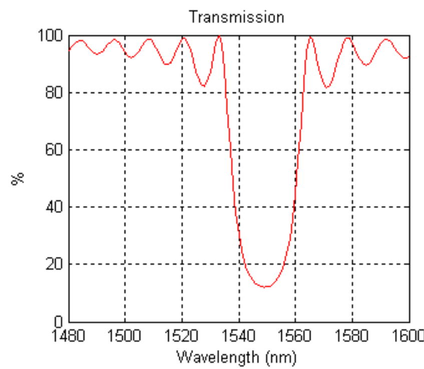

Fig. 1. Example of 1D grating simulation

Waveguide Width	2 μm
Waveguide Height	562 nm
Reflection Peak Centre	1550 nm
Periodicity	520 nm
Duty Cycle	50%
Milled Depth	517 nm
Number of Periods	120

Table 1. Details of the 1D simulation example

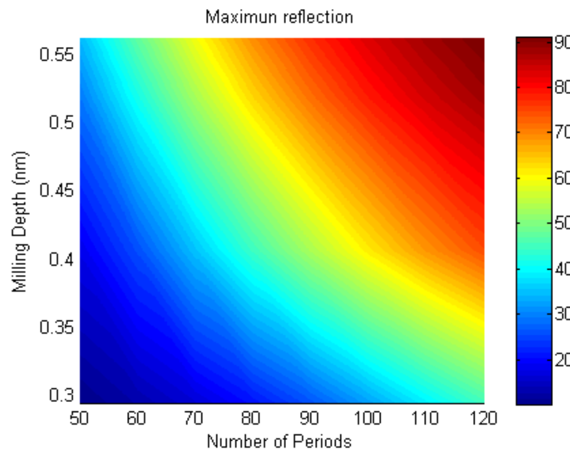

Fig. 2. Two-dimensional surface plot showing reflection dependence on milling depth and grating length

Focused ion beam milling of Al_2O_3

FIB processing is a well established technique with unique capabilities to locally sputter-etch ion implant and deposit metals or insulators with a nanometer-scale feature size, without the need of a mask. Even if is not suitable for large-scale production, it provides the best frame for study, research and development. In this case a Nova 600 NanoLab Dual Beam TM-SEM/FIB has been used for nanoscale prototyping, machining, characterization and analysis.

Despite the flexibility and speed that this tool offers, FIB milling is not a straightforward process; many variables and undesired effects must be taken into account in order to obtain a match between the designed and the fabricated structures [3]. The most important FIB parameters are grouped as follows:

- Total dose/dose per area: total ion current applied to the target area. The structure can be different if the same dose is achieved by diverse combinations of dwell times and loops due to the redeposition effects.
- Beam current: it defines the milling speed as well as the diameter of the Gaussian shaped beam.
- Magnification: it determines the field of view, i.e. the maximum area that can be scanned by the ion beam at once.

Optimization study

Sample preparation: We have observed two adverse effects during this research; both of them can be avoided by preparing the sample before milling. First of all, since Al_2O_3 is an amorphous material, no milling is possible at high magnifications such as x2.5K due to the severe charging which will be present on the surface. This charging can be avoided by sputtering a >10 nm thickness Cr layer on the top of the sample. Moreover, due to the drifts caused by the carbon double side sticker used for holding the sample, the milled pattern shows significant amount of drift comparing to the predefined design. In order to solve this, we used silver paste for achieving a firmer fixation that also allows conductive connection between the holder and the sample.

Cross sectioning: This destructive method which simply consists of deep milling the grating will allow for a clear and fast inspection of the structure by tilting the sample in a certain angle and inspecting it with SEM. In order to prevent redeposition while milling the cross section, a layer of Pt is deposited by using FIB. As can be seen in Fig. 4, this technique permits the further study of redeposition and parameters such as side-wall angles, milling depth and degradation of the top of the structure.

Dwell time and loop number optimization: A clarifying study has been performed in order to define de optimum value of these parameters that directly influence the final quality of the milled structure. All the experiments consisted of several dwell time and loop number combinations that always led to the same value of dose per area. As Fig. 4 shows, small dwell times together with high number of loops resulted in better defined gratings with more vertical walls and smoother profile.

Scanning strategy: As it is described in Figs. 3 and 4, two different scanning strategies have been found and tested during this research work. In the so-called perpendicular strategy the ion beam scans the sample perpendicularly to the grooves; since the beam does not totally switch off from one pixel to the closest one, this scanning procedure results in a deepened structure and a rounded grating shape. Better results have been achieved with the groove-parallel scan; the ion beam does not step over the non-milled structure, so straight sidewalls are achieved.

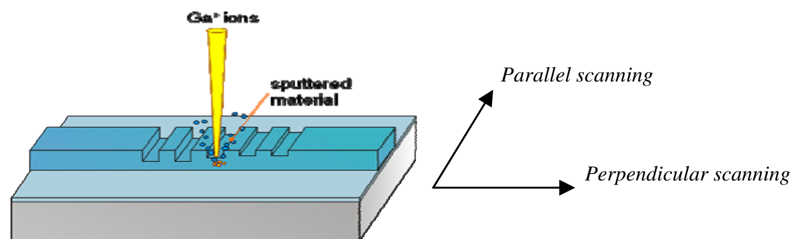

Fig. 3. Picture showing how the ion beam performs the scanning

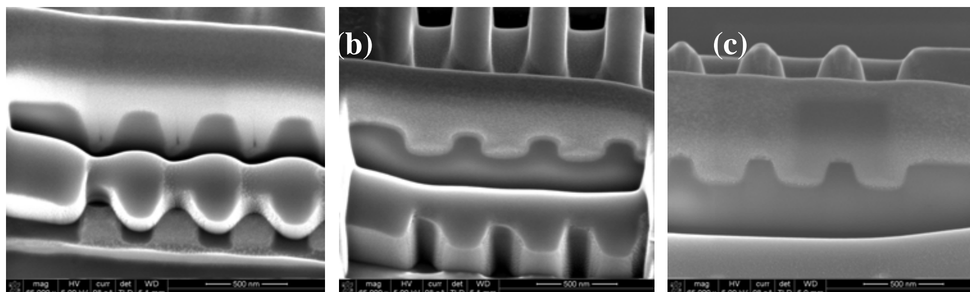

Fig.4. Cross-section of the grating structure obtained (a) with perpendicular scanning strategy (dwell time of 0.1 ms and 8 loops) (b) with perpendicular strategy (dwell time of 0.001 ms and 800 loops) and (c) when the scanning is done along the y-axis (parallel to the grooves) for the same conditions as in (b).

Optimized structures

The optimum Ga^+ current and specific magnification for reasonable length of the grating structure and acceptable sidewall smoothness were specified; 93 pA beam current (22.4 nm beam diameter, approximately 1.5 times the inter-pixel distance) is optimum for such a structure, while the actual magnification was fixed to 5000 times, resulting in a writing field of about 25x25 μm^2 and a grid spacing of 6.2 nm. Apart from these first steps, dwell time and loop repetitions were optimized in order to avoid charging effects and obtain the most favorable sidewall angle, edge roundness and wall smoothness. As a result, excellent quality gratings were patterned. Table 2 and Fig. 5 show optimum parameter values and the milled grating.

Table 2. Optimized milling parameters.

Ion current	Magnification	Dwell time per pixel	Pixel #	Loop#	Dose/Area ($pC/\mu m^2$)	Mill depth (nm)
93 pA	5000	0.001 ms	647094	710	1864	~190 nm

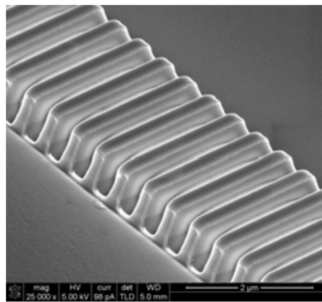

Fig. 5. Structure milled with the parameters of Table 2.

Conclusions

The 1D TMM simulation method was applied for detailed parameter variation and an optical result study of Bragg gratings in Al_2O_3 channel waveguides. As a consequence, the target grating for achieving the expected optical output was designed. In the second stage of our work, FIB parameters were optimized in order to realize the designed structure. Small dwell times and high number of loops were chosen for achieving better sidewalls, and also redeposition and Ga implantation effects were minimized by using Cr layer deposition. As a result, excellent quality gratings were obtained after a successful optimization of the FIB milling parameters and adequate propagation of light has already been observed.

Acknowledgement

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References

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