Bragg Gratings in Al_2O_3 Channel Waveguides by Focused Ion Beam Milling

F. Ay, J.D.B. Bradley, R.M. de Ridder, K. Wörhoff, and M. Pollnau

Integrated Optical MicroSystems (IOMS) Group, MESA+ Institute of Nanotechnology,
University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

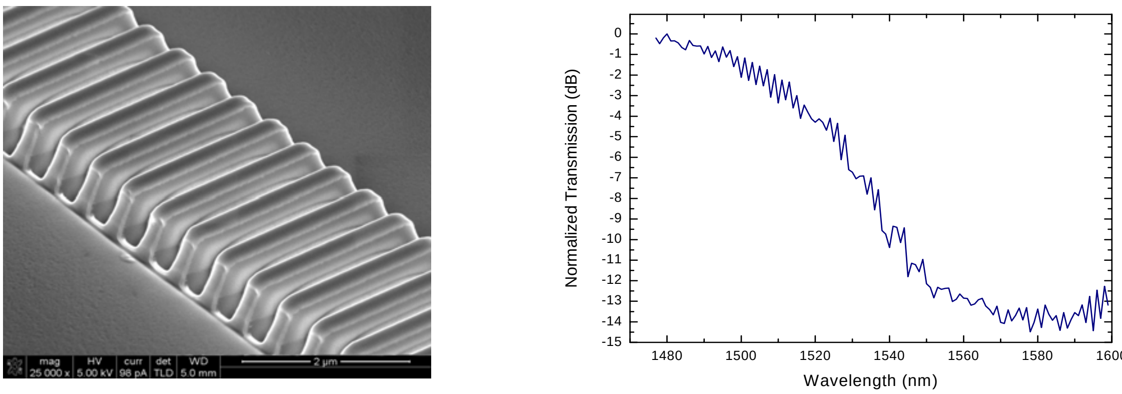
We report on utilization and optimization of the focused ion beam technique for fabrication of nano-structures on Al_2O_3 channel waveguides for applications in integrated photonic devices. In particular, investigation of the effects of parameters such as ion beam current, dwell time, scanning strategy, and dielectric charging effects are addressed. As a result of optimization of these parameters, excellent quality gratings with smooth and uniform sidewalls are reported. The effects of Ga ion implantation during the milling process on the optical performance of the devices are discussed.

Introduction

Focused ion beam (FIB) milling is emerging as an attractive nano-structuring technique and provide an alternative to UV and electron-beam lithographic methods [1]. The main advantage of FIB milling stems from the fact that it is material independent, as the method involves physical removal of a material by a beam of ions, thus making it adaptable to almost any material system. Furthermore, FIB has the benefit of enabling fast prototyping, resulting in considerable reduction of the design-fabrication-characterization cycle time. In this work, utilization and optimization of the FIB technique for fabrication of Bragg grating structures on Al_2O_3 channel waveguides for applications in integrated photonic devices are reported. In addition, the effects of Ga ion implantation during the milling process on the optical performance of the devices are discussed.

Results and discussions

The sub-µm-period surface-relief gratings on dielectric channel waveguides were realized by using a FEI Nova 600 dual beam FIB machine. The acceleration voltage was set to 30 kV and the milling current was chosen to be 93 pA. In order to avoid charging



(a) (b)

Fig. 1. (a) Reflection grating on Al_2O_3 channel waveguide realized by optimized FIB milling procedure; (b) optical transmission spectrum of the depicted grating device

of the structures a Cr layer with thickness ranging from 10 to 40 nm was sputtered on top of the 550 nm thick Al_2O_3 channel waveguides [2]. A study for minimization of the redeposition effects was performed in order to obtain uniform and smooth sidewalls of the grating structures. The dwell time and number of loops were varied while keeping the total dose constant to achieve similar milling depths. The length of the fabricated gratings was about 23 µm and waveguides with widths between 2.0 and 3.8 µm were patterned. The period of the grating was about 550 nm and the milled depths varied between 150 and 200 nm. The gratings were realized using a predefined mask file (stream file) that contains milling time, pixel information, and pixel sequence for the desired geometry. It was found that when the scanning is done along a direction perpendicular to the grating grooves, the cross-sectional profile is distorted due to redeposition effects and the inter-groove space is also milled, resulting in sinking of the entire grating structure. Moreover, using small dwell times and higher number of loops resulted in smoothing out the effects of redeposition. A successful realization of a reflection grating with optimized milling parameters is depicted in Fig. 1 (a). The optical transmission spectrum of the device with a stop band with an on-off ratio of ~14 dB is given in Fig. 1 (b) [3].

The main concern in employing FIB milling in fabrication of photonic structures is the effect of Ga ion implantation during the milling process on the optical performance of the devices. In order to address this issue we have studied the effect of Ga ion implantation into SOI waveguides. Si has proved to be effected much more by the implantation compared to the Al_2O_3 waveguides, making it also easier to study and measure the relevant optical losses [4]. We have implanted Ga ions by performing FIB milling to straight waveguide structures at several lengths. Six different doses between 5×10^{14} and 2×10^{17} ions/cm^2 were studied. The incorporation of Ga^+ ions in Si was analyzed by depth profiled XPS. A representative implantation profile is shown in Fig. 2. For a dose of 1×10^{17} ions/cm^2 we observe that almost all the Gallium is within the first 50 nm of Si. The optical losses at this concentration were identified to be more than 2 dB/µm. As the samples were annealed at 800°C for 60 minutes the optical losses improved by more than an order of magnitude. These results suggest that further improvement is possible.

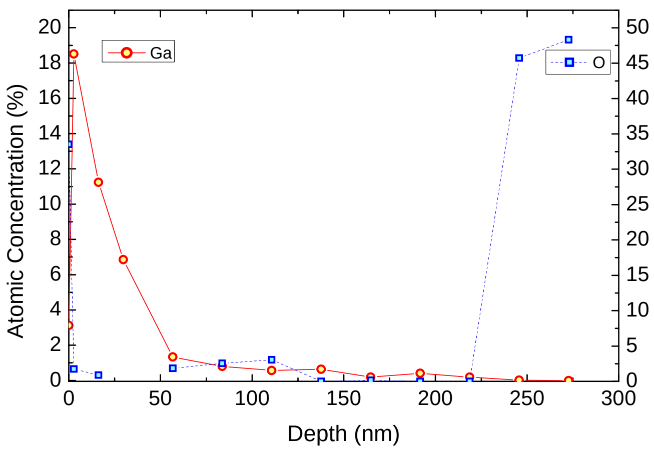


Fig. 2. Variation of gallium and oxygen atomic concentrations through SOI as measured by XPS

Conclusions

Realization of a reflection grating on Al_2O_3 channel waveguide by use of the FIB technique is reported. Smooth and uniform sidewalls of the grating structures were achieved by optimizing FIB milling parameters such as ion current, dwell time, loop repetitions, and the scanning strategy. Furthermore, initial results on the effects of Ga ion implantation during FIB milling of SOI waveguides on optical losses are reported. Reduction of propagation losses by more than an order of magnitude by thermally annealing the SOI waveguides was demonstrated.

Acknowledgments

This work was supported by funding through the European Union's Sixth Framework Programme (Specific Targeted Research Project “PI-OXIDE”, contract no. 017501) and the European Network of Excellence ePIXnet. The authors thank Vishwas Gadgil for his help with operating the FIB machine and Wico Hopman and Edwin Klein for stimulating discussions.

References

[1] M.J. Cryan, M. Hill, D.C. Sanz, P.S. Ivanov, P.J. Heard, L. Tian, S.Y. Yu, and J.M. Rorison, "Focused ion beam-based fabrication of nanostructured photonic devices", IEEE J. Select. Topics Quantum Electron., vol. 11, pp. 1266-1277, 2005.

[2] J.D.B. Bradley, F. Ay, K. Wörhoff, and M. Pollnau, "Fabrication of low-loss channel waveguides in Al_2O_3 and Y_2O_3 layers by inductively coupled plasma reactive ion etching", Appl. Phys. B, vol. 89, pp. 311-318, 2007.

[3] F. Ay, J.D.B. Bradley, W.C.L. Hopman, V.J. Gadgil, R.M. de Ridder, K Wörhoff, M. Pollnau, "Focused Ion Beam Nano-structuring of Bragg Gratings in Al_2O_3 Channel Waveguides", 33rd International Conference on Micro- and Nano-Engineering, Copenhagen, Denmark, 2007, Book of Abstracts, pp. 627-628.

[4] W.C.L. Hopman, F. Ay, W. Hu, V.J. Gadgil, L. Kuipers, M. Pollnau, R.M. de Ridder, "Focused Ion Beam Milling Strategies of Photonic Crystal Structures in Silicon", Proc. European Conference on Integrated Optics, Copenhagen, Denmark, 2007, paper FA1.