Large area, crystal-bonded $LiNbO_3$ thin films and ridge waveguides of high refractive index contrast

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Abstract: *Large area (30×15 mm^2), high quality "smart cut" $LiNbO_3$ thin films were prepared on a SiO_2/$LiNbO_3$ substrate. By Ar-milling single mode LN ridge guides of high index contrast and of 1-5 µm top width were fabricated. Optical propagation losses are below 3 dB/cm.*

Introduction

Optical waveguides of high index contrast enable small cross section dimensions and small bending radii of curved waveguides, a prerequisite for high density integrated optics [1]. For nonlinear optics in materials like lithium niobate ($LiNbO_3$, LN) the resulting small mode size yields a high guided mode intensity increasing the efficiency of nonlinear interactions.

Recently, strongly guiding LN ridge guides have been reported [2]. They have been fabricated by processing a thin smart-cut LN layer either bonded to a SiO_2 layer on LN [3] or bonded to benzocyclobutene on a LN substrate [4]. We favour crystal bonding to a SiO_2 cladding layer due to its lower refractive index and better thermal stability, which allows thermal annealing at much higher temperatures to recover electro- and nonlinear optical properties after ion implantation. A significant progress is reported to fabricate large area high quality crystal bonded LN thin films on a SiO_2 layer, deposited on a LN substrate. Using such films, ridge guides and photonic "nano-wires" of excellent optical properties were developed.

Fabrication

The fabrication method for crystal bonded LN thin film is similar to the "smart cut" process widely used for silicon-on-insulator (SoI) wafer fabrication [5]. The process is shown in Fig. 1. At first, a Z-cut LN sample was implanted by 250 keV He ions with a dose of 4×10^{16} ions/cm^2 forming an amorphous layer at about 900 nm underneath the surface. Another Z-cut LN handle sample was coated by a SiO_2 layer of 1.8 µm thickness by plasma enhanced chemical vapour deposition (PECVD), and then annealed at 450 ^oC for 8 hours to drive off the gases trapped in the oxide layer. With a chemical mechanical polishing (CMP) process, the surface roughness was reduced from 6 nm to 0.35 nm to enable crystal bonding.

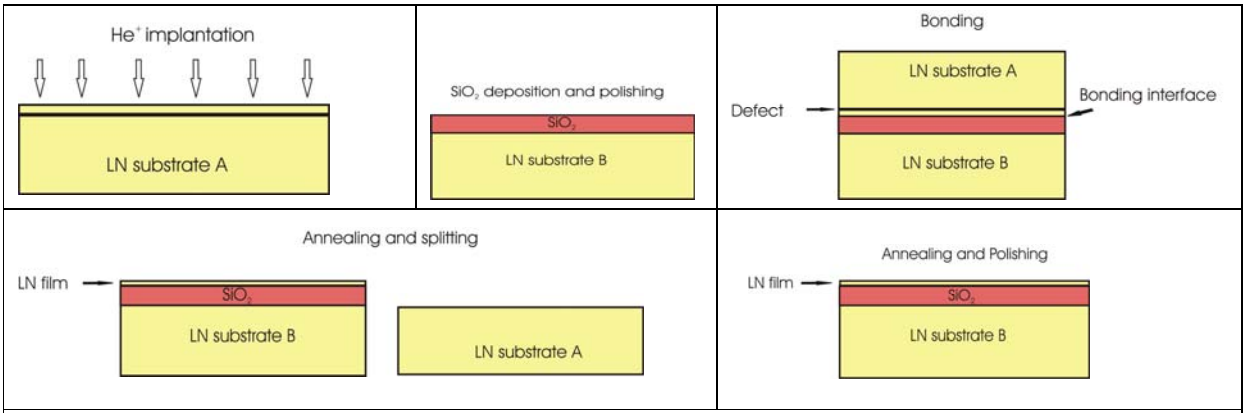

Figure 1: Fabrication scheme of "smart cut" single crystal LN thin films bonded to a SiO_2/LN substrate.

Fig. 2 (left) shows the surface roughness of the polished surface of the SiO_2 layer measured with an atomic force microscope (AFM). After cleaning and before bonding, the surfaces of both samples were covered by NH_4OH solution. The bonded pair of samples was annealed (165 °C, 16 hrs; 190 °C, 6 hrs) to improve the bonding strength. By a further annealing procedure at 228 °C for 2 hrs, a thin LN layer of 900 nm thickness split along the He implanted layer and remained on the SiO_2/LN substrate. Fig. 2 (middle) shows such a “LNoI” film of 30 × 15 mm^2 size. The sample was annealed at 450 °C for 8 hours to increase the bonding strength. After a CMP process, the surface roughness and the film thickness became 0.5 nm and 730 nm, respectively (Fig.2, right).

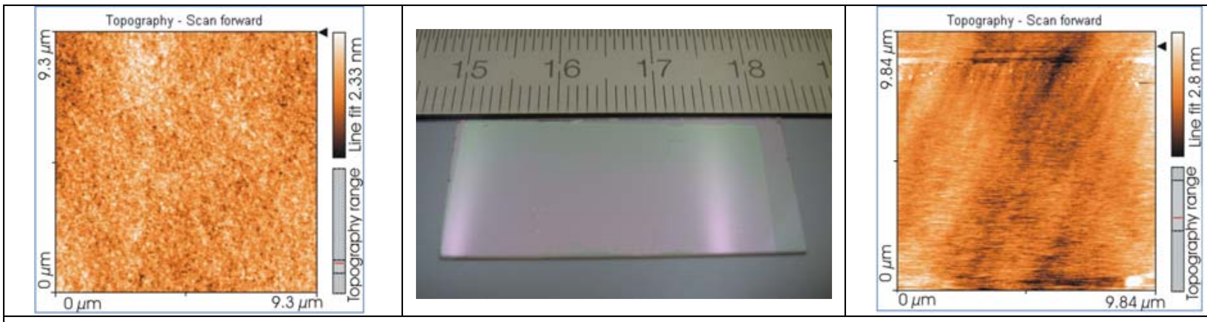

Figure 2: AFM picture of polished SiO_2 surface (left). LN thin film on SiO_2/LN substrate (middle). AFM picture of polished LN surface (right).

High index contrast ridge waveguides and optical “wires”

In single crystal LN thin films, as described above, high quality ridge waveguides of (sub)micrometer cross section dimensions were fabricated by Ar-milling. Photoresist stripes of 1.7 µm thickness and of 1-5 µm width served as etch masks. Adjusting a low etching rate, an etch depth of 470 nm was achieved after one hour of processing. As result, ridge guides of trapezoidal cross sections were obtained with etched trenches along both sides. Finally, the end faces of the sample were carefully polished to enable efficient end-fire coupling. Fig. 3 (left, middle) shows as example SEM micrographs of a ridge guide of 1 µm top width.

To investigate the optical properties, laser light of 1.55 µm wavelength was coupled into the ridge guides by a 60×, 0.6 N.A. objective. The output light was collected by a 100×, 0.9 N.A. objective with a diffraction limit of about 1 µm. Fig. 3 (right) shows a TE mode distribution in a ridge guide of 1 µm top width. The propagation losses in a guide of 2 µm top width are below 3 dB/cm estimated by the Fabry-Perot method at 1.57 µm wavelength.

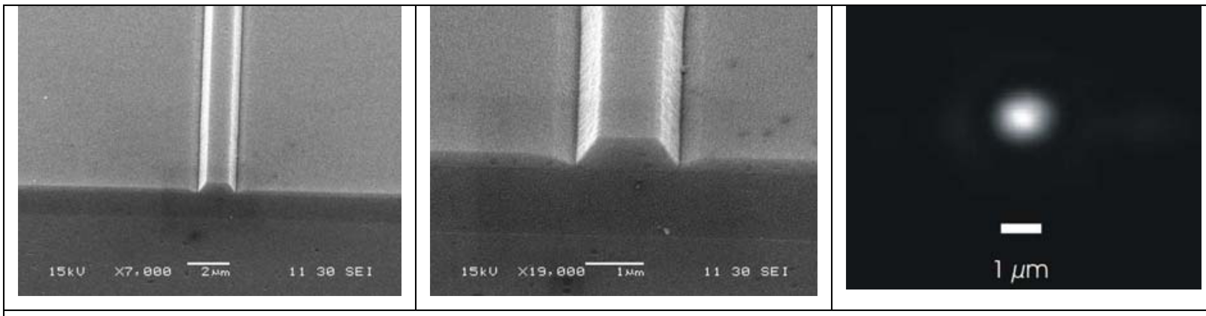

Figure 3: SEM micrographs of a ridge guide of 1 µm top width (left, middle). TE-polarized fundamental mode distribution of the ridge guide shown in the middle (right).

[1] Y. Kokubun, “High Index contrast optical waveguides and their applications to microring filter circuit and wavelength selective switch”, IEICE TRANS. ELECTRON., E90–C, (5), pp. 1037-1045 (2007)
[2] A. Guarino, G. Poberaj, D. Rezzonico, R. Degl’innocenti, and P. Günter, “Electro–optically tunable microring resonators in lithium niobate”, Nature Photonics, vol. 1, pp. 407-410 (2007)
[3] P. Rabiei and P. Günter, “Optical and electro-optical properties of submicrometer lithium niobate slab waveguides prepared by crystal ion slicing and wafer bonding”, Appl. Phys. Lett., 85, (20), pp. 4603-4605 (2004)
[4] G. Poberaj, M. Koechlin, F. Sulser, A. Guarino, J. Hajfler, and P. Günter, “Ion-sliced lithium niobate thin films for active photonic devices”, Opt. Mater., doi:10.1016/j.optmat.2007.12.019 (2008)
[5] M. Bruel, “Silicon on insulator material technology”, Electron. Lett., vol. 31, pp 1201-1202 (1995)