Nuclear Instruments and Methods in Physics Research B 272 (2012) 121–124

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Planar waveguides in magnesium doped stoichiometric $LiNbO_3$ crystals formed by MeV oxygen ion implantations

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ARTICLE INFO

Article history:
Available online 2 February 2011

Keywords:
Lithium niobate
Ion implantation
Waveguide

ABSTRACT

The planar waveguides were formed in magnesium doped stoichiometric $LiNbO_3$ crystals by means of 4.5 MeV oxygen ion implantations at different fluences. The dark mode spectra were measured by the prism coupling method. The annealing behaviors of the formed waveguides were characterized by a series of annealing treatments. The Rutherford backscattering/channeling technique was used to investigate the damage produced by the ion implantation.

1. Introduction

Interest in $LiNbO_3$ waveguide devices remains high in applications requiring reduced or enhanced photorefractive efficiency [1–4]. Decreasing the photorefractive efficiency is very important in the case of avoiding optical damage, particularly in second-harmonic generation and other high-intensity waveguide applications [5].

Up to now several strategies have been applied to decrease the photorefractive efficiency. The metal elements, for example Magnesium (Mg), Zinc (Zn) could be doped in the bulk material during the crystal growth process to increase the optical damage threshold dramatically [6–8]. The researchers also found that the proton exchanged (PE) region (PE waveguide) in congruent lithium niobate present excellent anti-optical damage ability [1,9]. Compared to the congruent one, the stoichiometric $LiNbO_3$ (SLN) keeps the Li/Nb ratio is closer to one. The density of defects related to the photorefractive process is decreased due to the more perfect crystal structure [10]. As a result higher damage threshold has been achieved by Mg doping in SLN [11].

Considering the excellent properties of Mg doped SLN, especially the high optical damage threshold, it is necessary to establish a reliable method to fabricate waveguide structure on it. The PE method is not recommended because this process decreases the content of Li element in the near surface region (PE guiding region). For the titanium diffusion, the diffusion coefficient between Ti and SLN is much lower than that of congruent LN (CLN). Therefore, much more fabrication time is required to form the usable guiding structure, and the Li-outdiffusion problem will be more severe under this situation.

The former investigations have suggested that the ion implantation, especially implantation of ions with medium mass, is an alternative method to form waveguide structures in various substrates [12–18]. In this paper, we will show that the implantation of oxygen ions with 4.5 MeV energy is an effective process to fabricate guiding structure on Mg doped SLN crystals. The dark mode properties and the annealing behaviors of fabricated planar waveguides are included in this paper.

2. Methods and experimental details

The *z*-cut Mg doped SLN crystals from Nankai University were fabricated by vapor transport equilibration method from Mg doped CLN. The new fashioned wafers were then polished and diced into $5 \times 10 \times 1$ mm pieces. Compared to CLN crystal, the extraordinary refractive index (n_e) of SLN decreased to 2.1886 at 632.8 nm (2.1264 at 1539 nm) and the ordinary one was nearly unchanged. This result was also confirmed by the former investigations [14].

The oxygen ion implantations were performed by a 1.7 MV tandem accelerator at Peking University. The fluences of the implantations were list at Table 1. The ion beam was electrically scanned on the sample in order to ensure a uniform implantation. After the implantation, the samples were thermally treated to investigate the annealing behaviors. The annealing conditions were listed at Table 2. The dark mode spectra were measured by a Model 2010 prism coupler. The end faces of the samples were polished carefully to perform the end-firing coupling measurement.

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doi:10.1016/j.nimb.2011.01.046

Table 1
The implanted fluences of Mg doped SLN samples.

Number of samples	Fluence (ions/cm^2)
S1	5×10^{13}
S2	1×10^{14}
S3	2×10^{14}
S4	4×10^{14}
S5	8×10^{14}

Table 2
The annealing conditions of Mg doped SLN samples.

Annealing number	Annealing condition
1	As implanted
2	200 °C 30 min
3	240 °C 30 min
4	270 °C 30 min
5	300 °C 30 min
6	300 °C 60 min
7	320 °C 30 min

3. Results and discussions

Fig. 1 shows the effective refractive index (N_{eff}) of the fabricated planar waveguides at wavelength of 632.8 nm versus the annealing conditions. One can see that the N_{eff} of the S1 and S2 sample without annealing are slightly higher than that of the substrate. The N_{eff} of these two samples are somewhat stable under the annealing treatments. However, the guiding behavior of S1 sample disappeared after No. 5 annealing and S2 after No. 6 annealing. This implies that the index change in the implanted region is removed by the progressive annealing.

The tendency of S3 and S4 samples are very different to S1 and S2 samples in Fig. 1. Firstly, the N_{eff} of the S3 and S4 are higher that of the substrate, the index change is in the order of 10^{-2}. This change is enough for the light guiding and we confirmed it by the following end firing coupling measurement. The index changes of S3 and S4 decrease after each annealing treatment. However, the index changes are still higher than the substrate even after the last annealing treatment. The results imply that S3 and S4 samples are more stable than S1 and S2 samples at high temperature. The tendency of S3 and S4 show in Fig. 1 implies that the guiding properties of both samples will be eliminated by the annealing treatment at higher temperature.

S5 sample shows an entirely different tendency to the others. The index change is elevated by the first four annealing treatments. After the No. 4 annealing the N_{eff} reaches its maximum (2.2044). Then the index decreased dramatically under the following annealing treatment.

Fig. 2 shows the N_{eff} at wavelength of 1539 nm. The N_{eff} of S1, S2 and S3 samples are less than that of the substrate. We believe that these three samples cannot support effective guiding at wavelength of 1539 nm. Maybe the measured mode is the resonant result of the optical barrier formatted at the end of the projected range. The N_{eff} of S4 is higher than that of the substrate till the No. 6 annealing treatment. S5 sample shows the similar tendency to Fig. 1. The N_{eff} at 1539 nm also reaches its maximum after No. 4 annealing.

SRIM2006 (the stopping and range of ions in matter) simulations were performed to model the implantation process. The former investigations imply that the electronic energy deposition is the dominant mechanism in the formation of CLN waveguide implanted by medium ions with MeV energy. The damage ratio in the near surface region depends on the energy and fluence of the injected ions. It should also be noted that there is an accumulation process which means that only point like defects are formed at the low fluence and the disorder will raise and lead to an ultimate amorphous phase at a certain high fluence. Fig. 3a shows the electronic energy deposition of the 4.5 MeV oxygen ion implantations. It is found that the surface guiding region, which is revealed by the prism coupling measurement and the refractive index profile reconstruction, coincide with the surface electronic energy deposition region. Fig. 3b shows the reconstructed refractive index profiles of S5 before after the first annealing treatment. This figure clearly shows that the electronic excitation is the responsible mechanism of the guiding behavior.

Another physical model related to the implanted lithium niobate waveguide is the self spontaneous polarization mechanism (P_S model) [19–21]. This model was firstly introduced to explain the guiding behavior of proton exchanged $LiTaO_3$ and $LiNbO_3$ waveguide [22]. In 2001, Hui et al. revised this model considering the physical process of the ion implantation on lithium niobate. They found that the N_{eff} of the Si^+ implanted waveguides increased with the implanted fluences. The highest fluence they used is 4.3×10^{14} ion/cm^2 [23]. They also implanted lithium niobate with Cu ions. The results showed that the N_{eff} increased to its maximum

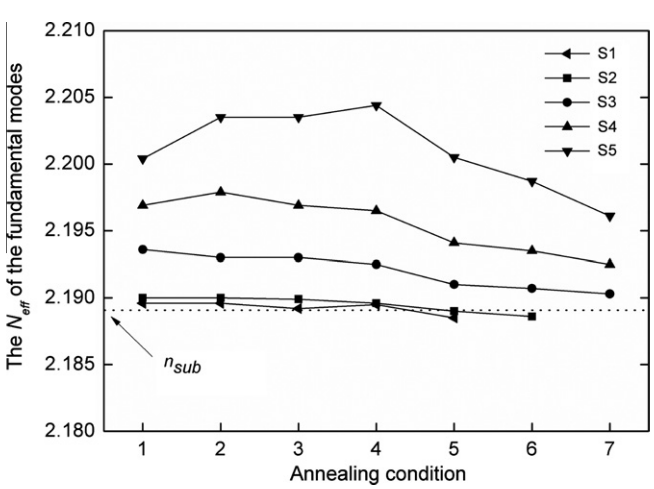

Fig. 1. The effective refractive indices of the Mg-doped SLN waveguides at 633 nm versus the annealing conditions (see the fluence list in Table 1).

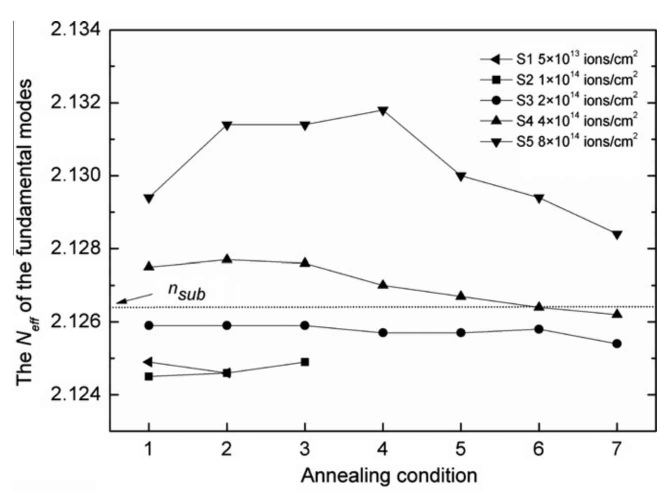

Fig. 2. The effective refractive indices of the Mg-doped SLN waveguides at 1539 nm versus the annealing conditions (see the fluence list in Table 1).