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Characteristics of Refractive Index Profiles at Different Temperatures in $LiNbO_3$ and $KTiOPO_4$ Waveguide Formed by 350 keV Light Ions

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Abstract

Both $LiNbO_3$ and $KTiOPO_4$ samples were implanted with 350 keV H^+ and He^+ ions at different doses ranging from 1×10^{16} to of 5×10^{16} ions/cm^2. Single and multi-energy implantations were performed at room temperature. Mono-mode or a few modes in both $LiNbO_3$ and $KTiOPO_4$ waveguides were observed. The effect of temperature on the refractive index profiles of $LiNbO_3$ and $KTiOPO_4$ waveguids was studied. The temperature covered from room temperature, 200℃, 194.5 K (dry ice) and 77K (liquid nitrogen). Different mechanisms are needed to interpret the observed behavior. A n_e increased mono-mode $LiNbO_3$ waveguide was formed by multi-energy keV He^+ ions.

Keywords : Ion implantation, Optical waveguide, Refractive index profile

1. Introduction

Lithium niobate ($LiNbO_3$) is of great interest for the formation of integrated optical elements and devices. This is due to excellent nonlinear properties and relatively large domain crystals which are available at low cost. $KTiOPO_4$ (KTP) is attractive nonlinear material. It is especial important for integrated optics to produce low loss waveguides. There are different methods to fabricate the waveguides including diffusion, ion exchange, pulsed laser deposition (PLD) and ion implantation. To use the waveguides in device applications two criteria must be considered. First it must be possible to construct a low-index barrier which is thick enough to prevent significant tunneling; second the waveguide should be stable below and above normal working temperature [1]. Ion implantation is an attractive method to form optical waveguides for integrated optics. Ion implantation can change the refractive index of crystalline materials due to the chemical presence of the dopant ions or the radiation damage induced during the ion implantation. Now MeV light ions such as He^+ and H^+ ions have been successfully used to fabricate planar optical waveguides in opto-electrical crystals at room temperature or 77 K [2-5]. An accelerator with several MeV is needed. However in practical applications, mono-mode waveguide is common, or guide with very few modes [6]. Ion implantation with several hundreds keV is less cost, simple and useful. The present work is mainly to study characteristics of refractive index profiles at different temperatures in ion implanted $LiNbO_3$ and $KTiOPO_4$ waveguide formed by 350 keV H^+ and He^+ ions.

2. Experimental

X-cut $LiNbO_3$ and $KTiOPO_4$ crystals were optically polished and cleaned before ion implantation. The samples were kept in disk with a conducting paint to

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avoid the surface charging during the implantation. The H^+ and He^+ ion implantation was done at room temperature. To have uniform implantation, the beam was scanned over the area of the sample. During ion implantation, the samples were tilted with respect to the H^+ and He^+ ion beam by 7^0 to minimize channeling effect. $LiNbO_3$ and $KTiOPO_4$ crystals were implanted at 350 keV H^+ and He^+ ions with different doses from 1×10^{16} to 5×10^{16} ions/cm^2. To study the effect of different temperature on the refractive index profile in $LiNbO_3$, samples implanted with 350 keV H^+ to a 4×10^{16} ions/cm^2 were annealed at 200℃ for 30 min, kept at 194.5 K (dry ice) and 77 K (liquid nitrogen) for 2 hours, respectively. Multi-energy implantation is needed to broaden the optical barrier and reduce the tunneling loss. H^+ ion implantation with a total dose of 6×10^{16} ions/cm^2 was carried out at different energies: 350 keV (4×10^{16} ions/cm^2), 340 keV (1×10^{16} ions/cm^2) and 330 keV (1×10^{16} ions/cm^2). He+ ion implantation with a total dose of 3×10^{16} ions/cm^2 was carried out at different energies: 350 keV (1.5×10^{16} ions/cm^2), 340 keV (0.5×10^{16} ions/cm^2) and 330 keV (0.5×10^{16} ions/cm^2) and 320 keV (0.5×10^{16} ions/cm^2). Ion implantation was performed at 400 kV implanter of Beijing Normal University.

The prism coupling method was used to measure the bright and dark modes in the waveguide films [7]. In the present work, the mode observation was done with a model 2010 prism coupler (Metricon corporation, USA) A He-Ne laser with the wavelength of 632.8 nm struck the base of a prism which was brought into contact with $LiNbO_3$ and $KTIOPO_4$ samples. The reflected beam was detected by a silicon photodetector. The intensity of light striking the photo detector was changed as a function of the incident angle. A sharp drop in the intensity corresponds to a propagation mode (dark mode).

3. Results and discussion

In all cases, modes in both $LiNbO_3$ and $KTiOPO_4$ crystals were observed after 350 keV H^+ and He^+ ion implantation. Fig. 1 shows the relative light intensity as a function of the effective refractive index obtained by the model 2010 prism coupler for $LiNbO_3$ waveguide formed with 350 keV H^+ ions to the dose of 4×10^{16} ions/cm^2 at room temperature. At least 6 drops in the intensity were observed which correspond the modes in $LiNbO_3$ waveguide. The confinement of the light as well as the spatial distribution of optical energy within the guiding region is related to the refractive index profile. WKB (Wentzel-Kramers-Brillouin) approximation is used to derive simple equation that predicts the shape of the refractive index profile from measured mode indices of a planar optical waveguide [8]. This method is useful in the study of diffused waveguides. However it appears to have major limitation in the case of ion implanted waveguide which depends on the reduced index barrier at the end of incoming ions range. Chandler and Lama have developed the reflectivity calculation method (RCM) to analyze the refractive index profile [9]. This method can analyze the refractive index profile in ion implanted waveguides remarkably well. RCM uses a parametrized index profile to describe the index profile of the waveguide. Fig. 2 shows the refractive index profile no in LiNbO3 waveguide formed

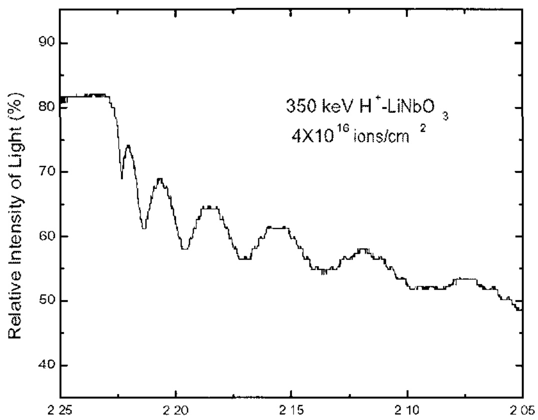

Fig. 1. Light relative intensity as a function of effective refractive index for $LiNbO_3$ waveguide formed with 350 keV H^+ ions to the dose of 4×10^{16} ions/cm^2.

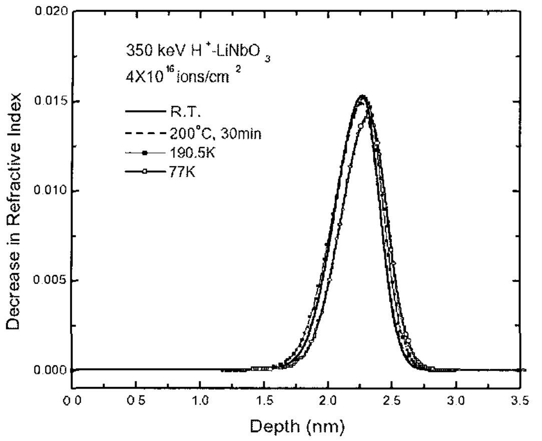

Fig. 2. The refractive index profile no in $LiNbO_3$ waveguide formed with 350 keV H^+ ions to the dose of 4×10^{16} ions/cm^2 at different temperature: room temperature, 200℃, 194.5 K (dry ice) and 77K (liquid nitrogen).

with 350 keV H^+ ions to the dose of 4×10^{16} ions/cm^2 at different temperature: room temperature, 2000 C for 30 min, 194.5 K and 77K for 2 hours. It is found that after annealing at 200℃ for 30 min, the peak height of the refractive index profile is decreased, this can be caused by the partial recovery of the damage, but after keeping at 194.5 K for two hours, the peak height of the refractive index profile is nearly the same as one at room temperature, however after keeping at 77 K for two hours, the peak height is remarkably decreased and the optical barrier has moved towards the substrate. The reason is not clear for us, one possible reason is due to a stress-induced mechanism. The solid line represents the fit curve based on the RCM in $LiNbO_3$ waveguide formed with 350 keV H^+ ions to the dose of 4×10^{16} ions/cm^2 at room temperature. It is seen that there is little refractive index change in the guiding region, and (1.5 % refractive index decrease at the end of ion range, building up a barrier to confine the light. It is found that the measured effective refractive index is in agreement with calculated values within 10^{-4}. For an ion implanted waveguide, the width of the waveguide is related to the mean projected range of implanted ions, and the optical barrier depends on the range straggling of implanted ions and damage profile created by coming ions. We have used the TRIM (transport of ions in matter) to calculate the mean projected range and range straggling [10]. The mean projected range and range straggling of 350 keV H^+ ions implanted into $LiNbO_3$ obtained by TRIM'98 are 2.31 μm and 161.8 nm, respectively. It is found that the mean projected range is in good agreement with the peak position of the refractive index profile.

Fig. 3 shows light relative intensity as a function of effective refractive index for $KTiOPO_4$ waveguide formed with 350 keV H^+ ions to the dose of 5×10^{16} ions/cm^2. It was found that there are 6 modes in $KTiOPO_4$ waveguide. Fig. 4 shows light relative intensity as a function of effective refractive index for $KTiOPO_4$ waveguide formed with multi-energy keV H^+ ions to the total dose of 6×10^{16} ions/cm^2 (350 keV with 4×10^{16} ions/cm^2, 340 keV with 1×10^{16} ions/cm^2 and 330 keV with 1×10^{16} ions/cm^2). Also 5 modes in $KTiOPO_4$ waveguide were observed. Compared with Fig. 3, the dip is getting deeper and the corresponding effective refractive index is getting smaller. It indicates that for the case of multi-energy implantation, there is better confinement for light.

Fig. 5 shows the refractive index profile n_x in $KTiOPO_4$

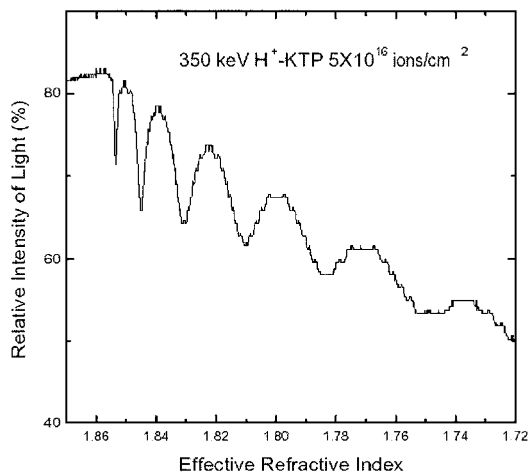

Fig. 3. Light relative intensity as a function of effective refractive index for $KTiOPO_4$ waveguide formed with 350 keV H^+ ions to the dose of 5×10^{16} ions/cm^2.

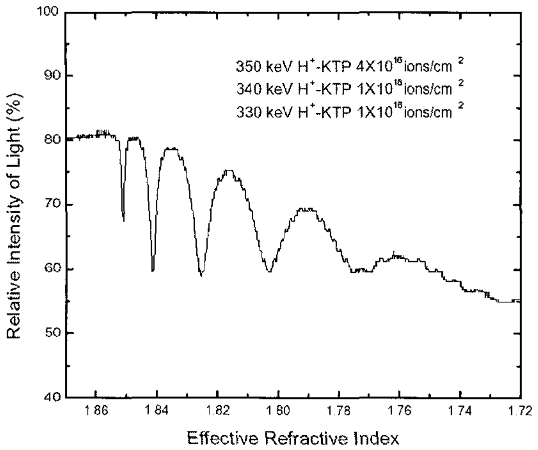

Fig. 4. Light relative intensity as a function of effective refractive index for $KTiOPO_4$ waveguide formed with multi-energy keV H^+ ions to total dose of 6×10^{16} ions/cm^2.

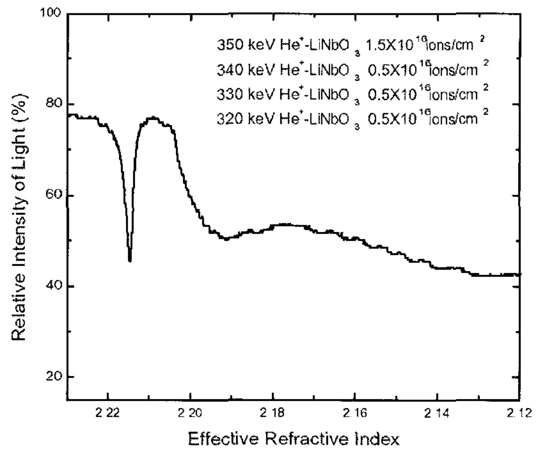

Fig. 6. shows the light relative intensity as a function of the effective refractive index for $LiNbO_3$ waveguide formed with multi-energy keV He^+ ions to the total dose of 3×10^{16} ions/cm^2.

waveguide formed with 350 keV H^+ ions to the dose of 5×10^{16} ions/cm^2 at different temperature: room temperature and 77K. The solid and dashed lines represent the refractive index profiles at RT and 77 K for 2 hours, respectively. It is observed that after keeping at 77 K for 2 hours, the shape of the refractive index profile is somewhat different from one at room temperature. The height of the refractive index profile at 77 K is decreased. Similar behavior to the case of $LiNbO_3$ is found.

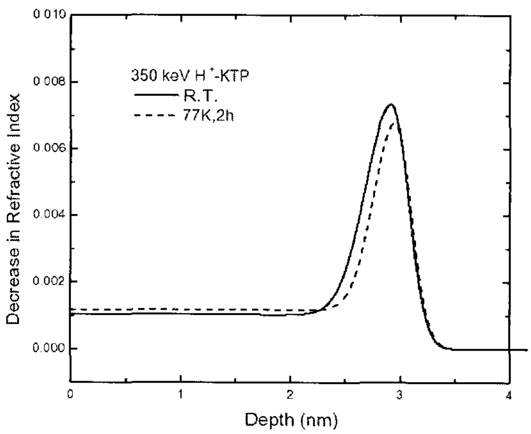

Fig. 5. The refractive index profile nx in $KTiOPO_4$ waveguide formed with 350 keV H^+ ions to the dose of 5×10^{16} ions/cm^2 at different temperature: room temperature and 77K.

Fig. 6 shows the light relative intensity as a function of the effective refractive index for $LiNbO_3$ waveguide formed with multi-energy keV He^+ ions to the dose of 3×10^{16} ions/cm^2 at room temperature. It is found that there is a ne increased mono-mode waveguide formation in $LiNbO_3$ by multi-energy keV He^+ ions.

4. Summary

$LiNbO_3$ and $KTiOPO_4$ crystals were implanted with 350 keV H^+ and He^+ ions at room temperature using different doses from 1×10^{16} to of 5×10^{16} ions/cm^2. Single and multi-energy implantation were performed. The modes in $LiNbO_3$ and $KTiOPO_4$ waveguides were measured by prism coupling method. The effect of temperature on the refractive index profiles of $LiNbO_3$ and $KTiOPO_4$ waveguids were studied. It is found that after annealing at 200℃ for 30 min, the peak height of the refractive index profile is decreased, this can be caused by the partial recovery of the damage, but after keeping at 194.5 K for two hours, the peak height of the refractive index profile is nearly the same as one at room temperature, however after keeping at 77 K for two hours, the peak height is remarkably decreased and the optical barrier has moved towards the substrate.

The reason is not known, perhaps the decrease of the refractive index is caused by stress at lower temperature. A ne increased mono-mode waveguide in $LiNbO_3$ is fabricated by multi-enegy keV He^+ ions.

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