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The lattice expansion, damage effect and propagation loss of $KTiOPO_4$ waveguides formed by ion implantation

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A B S T R A C T

We investigated the damage effect on the refractive index as well as the lattice expansion induced by C^{3+} ion implantation into $KTiOPO_4$ crystals. A $KTiOPO_4$ channel waveguide was formed by area-selective 6.0 MeV C^{3+} ion implantation at a fluence of 5×10^{13} ions/cm^2 using photoresist masking, and planar waveguides were formed by ion implantation with 6.0 MeV C^{3+} ions at fluences from 8×10^{12} ions/cm^2 to 6×10^{14} ions/cm^2. The propagation loss of the $KTiOPO_4$ planar waveguides at 633 nm fabricated at fluences of 2×10^{13} ions/cm^2 and 5×10^{13} ions/cm^2 after annealing is as low as 0.38 and 0.54 dB/cm, respectively. Prism coupling and refractive index profile reconstruction using the reflectivity calculation method were used to investigate the anisotropy of the refractive indices in the $KTiOPO_4$ waveguides region before and after annealing. The lattice expansion induced by ion implantation was investigated by combining X-ray rocking curves with atomic force microscopy. Rutherford backscattering spectrometry and channeling was applied for damage analysis, and the relationship between effective refractive index and relative defect concentration was studied.

1. Introduction

Potassium Titanyl Phosphate ($KTiOPO_4$, KTP) with its large optical nonlinearity, high optical damage threshold and outstanding thermal stability, is an important material for integrated optics [1]. Optical waveguides, as basic component of modern integrated photonic circuits, can confine light propagation in small volumes and reach much higher optical density with respect to bulk materials [2–4]. Optical waveguides have been fabricated in various materials by ion exchange [5], ion implantation [6–9], swift heavy-ion irradiation [10] and femtosecond laser inscription [11,12]. For the implantation of KTP with medium mass ions, such as C, an increase of the refractive indices n_x and n_y occurs in the near surface region, which is called an “enhanced well + barrier” index distribution [13]. The “enhanced well + barrier” waveguide has three advantages compared to typical “barrier” waveguide: lower ion fluences are needed for fabrication, mono-mode waveguide can be obtained and tunneling effect can be prevented [14,15]. It was reported that in KTP waveguides formed by 6.0 MeV C^{3+} ion implantation with a fixed fluence of 1×10^{14} ions/cm^2, the values of effective refractive index $n_{x,eff}$ (1.7576) and $n_{y,eff}$ (1.7667) are lower but near the ones of virgin KTP crystal ($n_{xsub} = 1.7621$, $n_{ysub} = 1.7716$) before annealing. Both $n_{x,eff}$ (1.7635) and $n_{y,eff}$ (1.7727) refractive indices are higher than the ones of substrate after annealing [13].

A major effect of ion irradiation in optical materials is the modification of the refractive index, which depends on the radiation damage produced by ion implantation [16–19]. Ion implantation induced radiation damage is caused by the displacement of lattice atoms and excitation and ionization of target atoms [20,21]. Lattice strain and stress induced by H and He coimplanted into KTP crystal was reported by Ma et al. [22]. However, there has little research on lattice expansion of KTP induced by ion implantation and the lattice damage effect on the properties of the KTP waveguides been done.

In this work, we investigate the effect of implantation damage

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on the properties of the KTP waveguides. The main purposes of this paper are first, to show the effective refractive indices of the KTP waveguides as a function of the ion fluence before and after annealing; second, to investigate the implantation damage and lattice expansion induced by ion implantation; third, to give the relationship between effective refractive index and relative defect concentration.

2. Experimental details

Z-cut KTP crystals with size of 7 × 7 × 1.5 mm^3 and 5 × 20 × 1.5 mm^3 were provided by the School of Chemistry and Chemical Engineering, Shandong University. The channel waveguide structures were created in KTP by depositing a specially designed photoresist mask. The masked sample was implanted with 6.0 MeV C^{3+} ions at an ion fluence of 5×10^{13} ions/cm^2 using a 1.7 MV tandem accelerator at Peking University. Unmasked KTP samples were implanted with 6.0 MeV C^{3+} ions in the fluence range from 8×10^{12} ions/cm^2 to 6×10^{14} ions/cm^2. All implantations were carried out under an angle of 7° and the beam current density was 200 nA/cm^2. After ion implantation the photoresist mask was removed with acetone. The end faces along *y* direction of the sample were precisely polished to optical quality to allow for direct end-face coupling of light. All samples were annealed at 260 °C for 30 min.

The effective refractive indices of the planar KTP waveguides were measured by prism coupling methods at 633 nm with a resolution better than 0.0002 [23]. Both the transverse electric (TE) and transverse magnetic (TM) modes can be measured through the insertion of actuator driven waveplates. The TE modes are polarized parallel to the surface of the sample, while TM modes are polarized normal to it. An end-coupling-in and end-coupling-out system was set up to measure the near-field intensity distribution of the waveguide, which is a direct way to determine whether the waveguide has the capability of confining the light in a guided mode. The propagation loss of the KTP planar waveguides was measured by the fiber probe technique using the instrument Metricon Model 2010. Laser light with a wavelength of 633 nm is coupled into the waveguide. A fiber optical probe with detector is scanned parallel to the sample surface along the direction of propagating laser light. Thus the intensity of light scattered out of the surface of the waveguide is measured as a function of distance. In order to prevent light scattering through the remaining five surfaces of the sample, these surface were blackened before analysis. The lattice expansion induced by ion implantation is measured by high resolution X-ray diffraction (HR-XRD) rocking curves and atomic force microscopy (AFM). The rocking curves from the (400) plane were obtained on a HR-XRD (AXS HRXRD D5005 system; Bruker Inc.) in the Bragg geometry with Cu $K_{\alpha 1}$ radiation. The samples were analyzed by means of Rutherford backscattering channeling (RBS/C) spectrometry using 1.4 MeV He^{+} ions at a backscattering angle of 170°. The RBS/C was performed in a special target chamber at the Institute für Festkörperphysik in Jena.

3. Results and discussion

3.1. Optical properties of KTP waveguides

Fig. 1(a) and (b) show the TE and TM dark mode spectra respectively of a KTP planar waveguide formed by 6.0 MeV C^{3+} ion implantation at a fluence of 5×10^{13} ions/cm^2 after annealing. The refractive indices of substrate are marked for comparison. The sharp dip at an effective refractive index of 1.7724 and 1.8461 for TE and TM modes, respectively, indicates that a waveguide structure has been formed in this sample. From Fig. 1 (a) and (b) it can be seen that n_y is higher and n_z is lower than the corresponding refractive

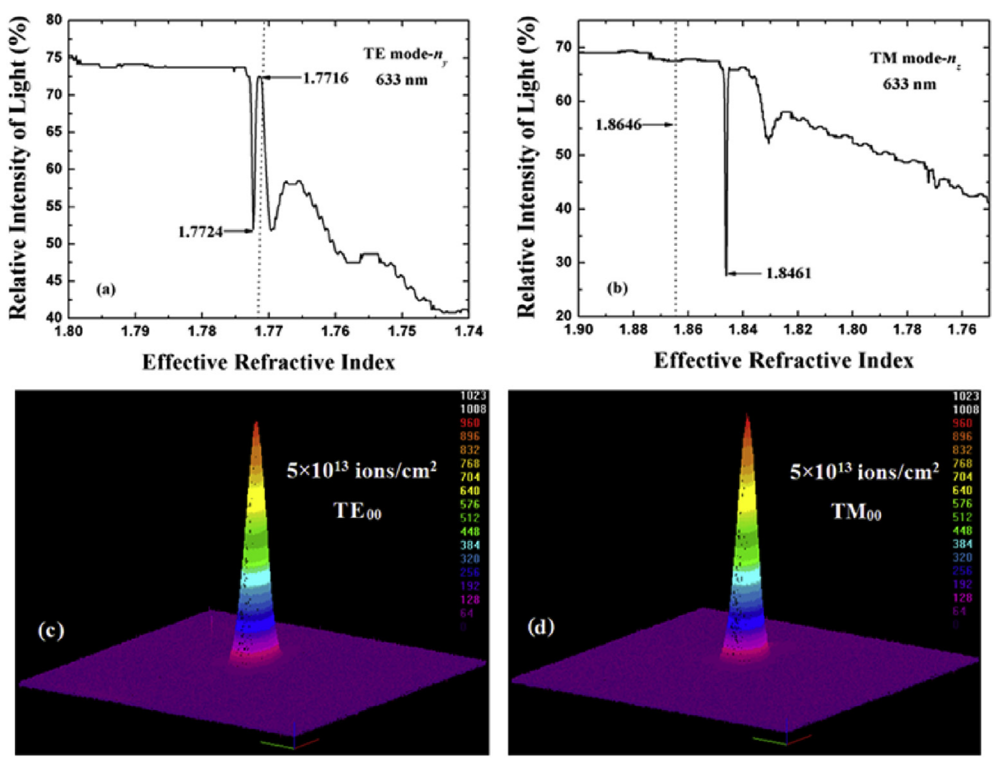

Fig. 1. Measured relative intensity of light in (a) TE and (b) TM polarization reflection from the prism as a function of the effective refractive index for the KTP planar waveguide, (c) TE and (d) TM field intensity distribution of the KTP channel waveguide formed by 6.0 MeV C^{3+} ion implantation with a fluence of 5×10^{13} ions/cm^2 after annealing, respectively.