Nuclear Instruments and Methods in Physics Research B 362 (2015) 62–67

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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

Magnesium aluminate planar waveguides fabricated by C-ion implantation with different energies and fluences

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A R T I C L E I N F O

Article history:
Received 13 March 2015
Received in revised form 31 July 2015
Accepted 18 August 2015

Keywords:
Ion implantation
$MgAl_2O_4$ crystal
Planar waveguide

A B S T R A C T

We report on $MgAl_2O_4$ planar waveguides produced using different energies and fluences of C-ion implantation at room temperature. Based on the prism coupling method and end-face coupling measurements, light could propagate in the C-ion-implanted samples. The Raman spectra results indicate that the $MgAl_2O_4$ crystal lattice was damaged during the multi-energy C implantation process, whereas the absorption spectra were hardly affected by the C-ion implantation in the visible and infrared bands.

1. Introduction

Magnesium aluminate, $MgAl_2O_4$, is a typical spinel material with an isotropic cubic structure that exhibits numerous important properties, including a high melting point (2135 °C), which enables its use as an ultrahigh temperature material, high mechanical strength even at high temperature, high electrical resistivity, wide energy band gap, transparency from the near-UV (ultraviolet) to the mid-IR (infra-red) regime, high resistance against chemical attack, high thermal shock resistance, low thermal expansion coefficient, high hardness (16 GPa), low density (3.58 g/cm^3) that is easier to polish and a lower production cost [1–6]. Because the structure of magnesium aluminate is based on the structure of diamond and its general composition is AB_2O_4, the positions of the A ions are nearly the same as the positions occupied by carbon atoms in the diamond structure; the arrangements of the other ions in the structure are identical to the symmetry of the diamond structure. This structural similarity could explain the reason of the high hardness typical of this material [7]. Because of its good resistance to radiation-induced swelling and strength degradation, magnesium aluminate is a potential fusion reactor power core insulating material [6]. However, this material has a higher IR absorption edge and required light transmission in the wavelength range of 2–5.5 μm and is now being replaced by ZnS, sapphire, AlON, traditional alumina, and lanthanum niobate ceramics in applications including laser ignitors, windows for UV lithography, barcode scanners, spacecraft, watches, and night-vision systems [2,8–14].

Because of its excellent properties, $MgAl_2O_4$ has also been studied for many applications. For example, it has received considerable attention as a ceramic for use in high-radiation environments. Under 180-keV Ne^{2+} ion implantation, $MgAl_2O_4$ undergoes an ordered spinel to disordered rock-salt-like structural phase transformation [15]. After the high-fluence neutron implantation, the A and B cation sublattices are completely disorder in the spinel crystal lattice, the cation disorder likely represents the majority of the retained damage in implanted spinel [16]. However, there are a few of reports that investigate the waveguide structures of $MgAl_2O_4$ crystals. Ion implantation is an excellent technique for modifying the optical properties of materials (e.g. BGO, CaF_2, etc.) because it has superior reproducibility and controllability compared with other techniques [17–20]. This approach typically produces a buried layer within the substrate, and the profile of the buried layer and its index of refraction depend on the energy, the fluence of ions and the ion species used for implantation. In the present work, we report the fabrication of the planar waveguide in $MgAl_2O_4$ crystal using MeV C ion implantation with four different fluences for the first time. The optical properties of the planar waveguides are investigated.

2. Experiment and details

Single-crystal $MgAl_2O_4$ was cut to dimensions of 10 mm × 8 mm × 1 mm and was optically polished before C ion implantation. The energy and fluence are listed in Table 1, which

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http://dx.doi.org/10.1016/j.nimb.2015.08.096
0168-583X/

Table 1
The energies and fluences of the C ion implantation for the five samples.

Sample number	Energy (MeV)	Fluence (ions/cm^2)
S0	–	–
S1	6.0	5×10^{14}
S2	6.0	1×10^{15}
S3	6.0	1.5×10^{15}
S4	5.5 + 6.0	$4 \times 10^{14} + 5 \times 10^{14}$

were obtained using a 2 × 1.7 MV tandem accelerator at Peking University at room temperature. To avoid channeling effects, all of the samples were tilted 7° from the beam direction. The effective refractive indices of the dark modes were investigated using the prism coupling method with a Model 2010 prism coupler at a wavelength of 632.8 nm. The refractive index of the prism used in the measurement was 2.6984, and the index accuracy was less than 0.0001.

The end face coupling method was used to detect the near field intensity distribution of the guided light. Before the end face coupling experiments, the two end facets of the samples were polished carefully. The light from a He-Ne laser at a wavelength of 632.8 nm was coupled into the waveguide with a 25× microscope objective lens. Then, the light coupled out of the waveguide through a 25× microscope objective lens was imaged onto charge coupled device (CCD) cameras connected to a computer. SRIM 2008 was used to calculate the electronic and nuclear power losses in the C-ion-implanted $MgAl_2O_4$ crystal [21].

The micro-Raman spectra of the samples were measured using a confocal micro-Raman system with an excitation wavelength of 473 nm. The light beam was focused to a 2-μm-diameter spot on the implanted end facet of the $MgAl_2O_4$ crystal for comparison. A Hitachi U4100 spectrophotometer was used to measure the absorption spectra of the sample before and after C ion implantation from the UV to the infrared regime.

3. Results and discussion

Fig. 1 presents the measured the effective refractive indices (TM polarized) of the $MgAl_2O_4$ planar waveguides formed by MeV C ion implantation with the different fluence treatments at 632.8 nm. For comparison, the refractive index of the $MgAl_2O_4$ substrate (S0) is also shown in Fig. 1. Fig. 1(a) shows the TM mode of S1, and Fig. 1(b)–(d) show the TM modes of S2, S3, and S4, respectively. A lack of reflected light would result in a dip when the light was coupled into the waveguide region, which may correspond to a real propagation mode. The measured effective refractive indices are reported in Table 2. The surface refractive index (n_{sur}) of the $MgAl_2O_4$ planar waveguide is higher than the refractive index of the substrate (n_0). The effective refractive index (n_{eff}) of the guide mode (S3) is higher than the refractive index of the substrate (S0), and the n_{eff} values of the other sample (S1, S2, S4) are lower than the refractive index of the substrate (S0). According to these analyses, "well" and "barrier" type waveguides could be formed by C ion implantation of $MgAl_2O_4$ crystals with different fluences.

We assume that the refractive index profile of the planar waveguide from the guided modes measured by the prism coupling method can be depicted by two half Gaussian curves. The FWHM (Full Width at Half Maximum) of the two half Gaussian curves, refractive index of the optical barrier, refractive index of the waveguide surface and depth of the optical barrier are the important parameters to reconstruct the refractive index profile [22]. Fig. 2 shows the refractive index profile of samples S3 and S4 at a wavelength of 632.8 nm. The dual-energy implantation results in a wider optical barrier in S4 than that in S3. The index distribution is a "well + barrier" type. To clearly see the experimental and calculated values of the effective refractive indices, the refractive indices of the surface and the mode number for the five samples are listed in Table 2. The experimental and calculated values for the effective indices match well, and the errors for the effective refractive indices of the dark modes between the experimental and calculated values are within 10^{-4} in the calculation.

We simulated the C ion implantation process of the $MgAl_2O_4$ crystal by SRIM 2008; the calculated electronic and nuclear energy loss profiles and the displacement per atom (dpa) distribution of C implanted samples with different energies and fluences are shown in Fig. 3(a) and (b) separately. The electronic energy loss (S_e) occupies a dominant position at the sample surface because the C ions lose most of their energy to electronic ionizations along their paths inside the $MgAl_2O_4$ crystal, which results in the formation of color centers and possibly damage in certain regions. The nuclear energy loss (S_n) governs the end of the ion path, and nuclear collisions lead to the lattice disorder and a decrease in the physical density; therefore, the refractive index is lower than that of the substrate in this region. The peak position of S_n is 3.62 μm. As observed in Fig. 3(b), the damage range of multi-energy C ion implantation is wider than the damage rang of single-energy ion implantation. The damage is low in the near-surface region, and the peak value is approximately 0.08 dpa (displacements per atom) at a depth of approximately 3.37 μm. The results indicate that at the end of ion tracks, nuclear collisions are the main reason for lattice disorder. Additionally, multi-energy C ion implantation can broaden the optical barrier and reduce the leakage of light from the substrate of the $MgAl_2O_4$ crystal through the barrier wall.

Based on the reconstructed refractive index profile (shown in Fig. 2), we used the finite-difference beam propagation method (FD-BPM) [23] to calculate the near-field intensity distribution of TM polarized light in the waveguide at a wavelength of 632.8 nm. Fig. 4(a) shows the near-field light intensity distribution in the S3 planar waveguide simulated with FD-BPM at 632.8 nm. The near-field light intensity distribution of the planar waveguide was obtained using the end-face coupling method at 632.8 nm. Figs. 4(b) and 5(a)–(c) show the 2D near-field light intensity distribution measured from the output facet of the S3, S1, S2, S4 planar waveguides at 632.8 nm, respectively, which indicates that the light could be confined in the $MgAl_2O_4$ waveguide in the visible band and that the optical confinement capability is quite good. As observed in Fig. 4(b), there is almost no light in the substrate area and air layer. Compared with Fig. 4(a) and (b), the simulated result is consistent with our experimental measurement, and the refractive index profile that we selected is reasonable. The propagation losses measured by the end-face coupling method are approximately 2.14, 2.65, 2.84 and 2.19 dB/cm for the planar waveguides S1, S2, S3, and S4, respectively. Compared with the O-implanted waveguide reported in Ref [24], the C-implanted waveguide in this paper has a lower propagation loss.

Raman spectra of the substrate and the waveguide layer in the $MgAl_2O_4$ crystal were collected using a confocal micro-Raman system to obtain a better understanding of the microstructural changes induced by C ion implantation. Fig. 6 presents the confocal micro-Raman spectra of samples 0–4, which were obtained from the substrate and waveguide layer using an excitation beam at 473 nm with a 2-μm-diameter spot on the implanted end facet at room temperature. According to [25,26], the shift of the peak (409 cm^{-1}) was due to the rotational modes of AlO_6 polyhedra and translational modes of Al^{3+} and replotted in Fig.6. The peaks at 668 cm^{-1} and 770 cm^{-1} are caused by stretching modes of AlO_6. As observed in Fig. 6, the single intensity decreases when the single-energy C-ion implantation of the fluences increases slightly, and after multi-energy and multi-fluence C-ion implantation, the Raman spectra intensity decreases, the positions of the peaks shift and the linewidth of the peaks also broaden. The peak