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Radiation damage study of MeV ions-implanted Nd:YVO_4 crystal

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ABSTRACT

Damage formation mechanism of Nd:YVO_4 implanted with MeV ions is investigated. MeV Si^+ ions were implanted into Nd:YVO_4 crystal, and the lattice damage was measured using Rutherford backscattering spectroscopy/channeling (RBS/C) method. The damage creation kinetic indicates a significant contribution from electronic energy loss to the surface damage. A detailed analysis allows us to deduce the different contributions from electronic and nuclear stopping powers to the lattice damage production. An obvious difference in extent of damage from 1 MeV and 3 MeV Si^+ implantations also implies that there exists a threshold value of the electronic energy deposition for damage formation. The exact value of threshold is obtained by comparison with the experimental data obtained from 3 MeV O^+, F^+ and Si^+ implantation results, which turns out to be (1.7 ± 0.1) keV/nm.

1. Introduction

Neodymium-doped yttrium orthovanadate (Nd^{3+}:YVO_4) is widely used and studied as an outstanding laser medium. It possesses many outstanding properties, like excellent physical performance, wide transparency, large laser emission cross section, low laser threshold, and high efficiency [1,2]. Its applications into stable, cost-effective and powerful diode-pumped solid-state IR, green and blue lasers make Nd:YVO_4 crystal of many attractive values.

Waveguides in Nd:YVO_4 have a significant value for waveguide laser application. Different methods were previously used to form waveguides in Nd:YVO_4, such as thermal diffusion of Nd^{3+} ions into pure YVO_4 [3], femto-second laser inscribe method [4,5], light [6–8] and heavy ion-implantations [9–11]. Among these methods, ion-implantation is one of the efficient approaches due to its superior controllability and reproducibility [12]. Compared to light ion-implantations, waveguide structure formed by implanting heavy ions is more stable because of the enhanced barrier in the waveguide region for the ordinary refractive index (n_o) [13,14], while these refractive index behaviors are closely related to the implantation-induced lattice damage and defects. Although a careful study of damage production is necessary for waveguide analysis, few results are found concerning the properties of lattice damage in YVO_4 crystal induced by ion-implantation. The purpose of this work is to investigate the damage creation in Nd:YVO_4 crystal induced by MeV heavy ion-implantations.

In our previous paper [15], we have investigated some irradiations properties in Nd:YVO_4 implanted with the low energy regime of several hundreds keV Si^+ ions where defect creation is due to elastic collisions of implanted ions with target atoms. While for the MeV energy implantation, the contribution from collective electronic excitation to the lattice damage cannot be ignored [16–18]. In this paper, we intend to analyze the different roles played by nuclear energy loss and electronic energy loss in damage production for MeV heavy ion-implantations, and thus a threshold value of electronic stopping power for damage formation can be estimated.

2. Materials and methods

All the Nd:YVO_4 samples were x-cut single crystals, with size of 10 mm × 10 mm × 0.5 mm, and the Mol concentration of Nd was 2%. Before implantation, they were optically polished and cleaned. Samples were implanted at room temperature with 3 MeV Si^+ ions at fluences of 4×10^{13}, 8×10^{13}, 1×10^{14}, and 2×10^{14} ions/cm^2, and 3 MeV O^+ and F^+ ions, as well as 1 MeV Si^+ ions at ion fluence of 1×10^{14} ions/cm^2, respectively. Table 1 shows the implantation parameters. During the implantation the ion beam was electrically scanned to ensure a uniform implantation over the samples, samples were tilted by 7° off the beam direction in order to minimize the channeling effect. Implantations were performed with a current density at about 6 nA/cm^2. The implantation process was carried out at LC-4 Ion Implanter in Institute of Semiconductors of Chinese Academy of Sciences.

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Table 1
Implantation parameters for Si^+-implanted Nd:YVO_4.

Sample	Dose (ions/cm^2)	Ion	Energy (MeV)
1	1×10^{14}	Si^+	1
2	4×10^{13}	Si^+	3
3	8×10^{13}	Si^+	3
4	1×10^{14}	Si^+	3
5	2×10^{14}	Si^+	3
6	1×10^{14}	O^+	3
7	1×10^{14}	F^+	3

Damage analysis was conducted by using RBS/channeling measurement, which was performed by 2.1 MeV He^{2+} ions at a scattering angle of 165° in 1.7 MV tandem accelerator of Shandong University. Stopping and Ranges of Ions in Matter (SRIM 2003) [19] was used to simulate the depth distributions of the energy transfer to recoils (nuclear energy deposition) and the electronic energy deposition.

3. Results and discussion

3.1. Lattice damage in MeV Si+-implanted samples

Fig. 1 shows the depth distributions of the nuclear and electronic energy deposition per ion and unit depth calculated by SRIM 2003 for the 1 MeV and 3 MeV Si^+-implanted Nd:YVO_4. The maximum of the nuclear energy deposition occurs at the depths of around 0.9 μm and 1.8 μm for 1 MeV and 3 MeV implantation, respectively, whereas the electronic deposition dominates in the near surface region (within 0.5 μm). At the sample surface, the electronic stopping power $(dE/dx)_e$ is 1.2 keV/nm and 2.8 keV/nm for 1 MeV and 3 MeV, respectively, which is much larger than the corresponding nuclear stopping power $(dE/dx)_n$ of 0.24 keV/nm and 0.10 keV/nm. This difference becomes more obvious with the increased implant energy. What we are interested in is the damage formation at near surface region (~0.5 μm), which represents the guiding core of waveguide structure and lies within the detectable range of our RBS/channeling technique.

Fig. 2 indicates the RBS/channeling spectra of samples implanted with 1 MeV Si^+ ions at ion fluence of 1×10^{14} and 3 MeV Si^+ ions at ion fluences of 4×10^{13}, 1×10^{14}, and 2×10^{14} ions/cm^2, as well as the aligned and random spectra from virgin Nd:YVO_4 sample for comparison. It can be found that the backscattering yield of implanted sample increases with Si^+ fluence increasing. For samples implanted with 1 MeV and 3 MeV energy ions, the same ion

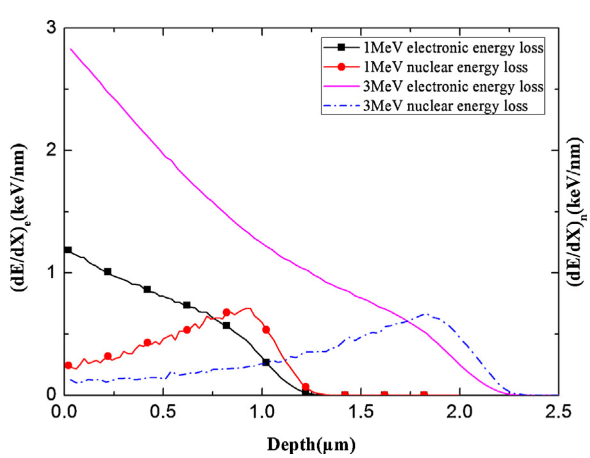

Fig. 1. Calculated distribution of the energy deposition for 1 MeV and 3 MeV Si^+ ion-implantations into Nd:YVO_4.

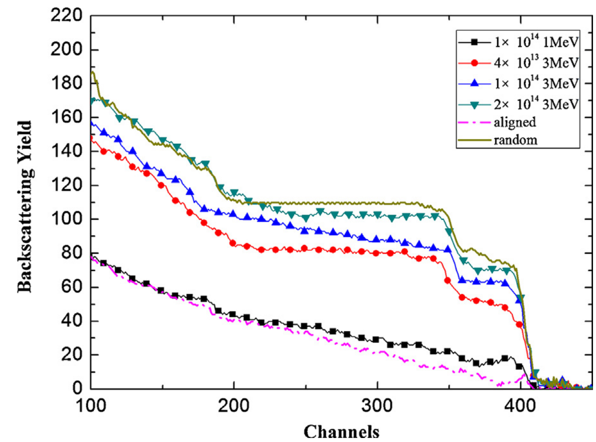

Fig. 2. RBS/channeling spectra of 1 MeV Si^+-implanted Nd:YVO_4 at ion fluence of 1×10^{14} ions/cm^2, and 3 MeV Si^+-implanted samples with fluences of 4×10^{13}, 1×10^{14} and 2×10^{14} ions/cm^2, respectively. The aligned and random spectra are presented for comparison.

fluence of 1×10^{14} ions/cm^2 is applied. In the case of 1 MeV implantation, only slight increase of the backscattering yield is observed in the near surface region with respect to that of the virgin crystal. While for 3 MeV implantation, an obvious increasing dechanneling in the near surface region occurs. If we compare the simulated energy losses from SRIM with the experimental results from RBS, it is easy to deduce that the difference in surface damage should be related to the obvious difference of electronic energy loss for two samples.

For many light ion-implanted optical crystals, lattice damage is mostly determined by nuclear energy loss when keV ions are applied [15,20]. The effect from electronic energy loss usually contributes to the introduction of point defects, which can be removed by following post-implant annealing. But for MeV ion-implantation (between 2 MeV and 5 MeV), the role played by electronic energy deposition in lattice damage production cannot be ignored [16,21]. It is reported that the cumulative process of defects induced by electronic energy loss can also result in obvious lattice damage in the near surface region [22]. This phenomenon is particularly evident in terms of swift heavy ion-implantation (for beam energy larger than 5 MeV). In this case the damage formation is characterized by direct amorphization along each ion path, which is caused mainly by the large electronic energy loss effect [16,23,24]. In our present experiment, only moderate implant energies (between 1 MeV and 3 MeV) are applied, but the lattice damages beneath the surface show obvious difference, which could be referred to Fig. 2. With the same implant fluence, the height of the RBS spectra is close to the random level for implantations with 3 MeV Si^+ ions, but not for 1 MeV Si^+ ion-implantation. Reaching the random level in aligned spectra is commonly taken as an indication for amorphization although the existence of micro-or nanocrystalline structures cannot be excluded when solely the RBS technique is applied. For simplicity the term amorphization is used in the following text. The significant difference in RBS spectra induced by 1 MeV and 3 MeV Si^+-implantations implies that a threshold of electronic stopping power for damage formation exists in the energy range below 3 MeV, and this implant energy is much lower than the value applied in swift ion-implantation. We will subsequently discuss in detail the damage kinetics of 3 MeV Si^+-implanted Nd:YVO_4, and how this threshold value is deduced.

To analyze the lattice damage properties, damage profiles are extracted by using a multiple-scattering dechanneling model, which is based on Feldman's procedure and is applied for all target elements in the crystal [25,26]. The results of samples implanted with 1 MeV Si^+ ions at ion fluence of 1×10^{14} and 3 MeV Si^+ ions