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Abnormal diffusion behavior of Yb^+ and Er^+ implanted in $KTiOPO_4$

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400 keV Yb^+ and 300 keV Er^+ were implanted into potassium titanyl phosphate ($KTiOPO_4$ or KTP) with doses of 3×10^{15} and 1×10^{15} ions/cm^2, respectively. The samples were annealed in the temperature range 600 to 800 °C in Ar ambient. The diffusion behaviors of implanted Yb^+ and Er^+ in $KTiOPO_4$ were investigated by Rutherford backscattering of 2.0 MeV He ions. The results show that no obvious diffusion of Yb^+ and Er^+ in $KTiOPO_4$ is detected at 600 °C annealing, but there are three and two peaks of implanted rare-earth ion distribution after 800 °C annealing for the case of Yb^+ and Er^+, respectively. An explanation of these phenomena is suggested.

Potassium titanyl phosphate ($KTiOPO_4$ or KTP) is an attractive and new material which has superior properties for several nonlinear optical applications. Its high nonlinear optical d coefficients, high optical damage threshold, and thermally stable phase-matching properties make it useful for second-harmonic generation and optical waveguides. $KTiOPO_4$ has several potential advantages for optical waveguide devices compared with other materials.[1–5]

Optical properties of rare-earth ions incorporated in insulators such as glass or $LiNbO_3$ are of great interest in optoelectronic technology.[6,7] Erbium is of particular interest because of its intra-4f transition with a wave length (λ) of 1.54 μm, coinciding with the low-loss window of standard optical telecommunications silica fiber. The lifetime of the $^4I_{13/2}$ excited state is a critical parameter for the application of Er-implanted silica glass in waveguide lasers and amplifiers. According to the report by Polman *et al.*,[8] the fluorescence lifetime is in the order of 10 ms. This long lifetime suggests that application in optical amplifiers and other integrated electro-optic devices might be possible.

Ion implantation is an accurate method for modifying the refractive index of surfaces of insulators with the aim of forming waveguides and waveguide lasers.[9] In the present letter, we report results on the diffusion behavior of implanted Yb^+ and Er^+ in $KTiOPO_4$. Perhaps these results will be useful in the development of a waveguide laser in $KTiOPO_4$.

$KTiOPO_4$ of (100) orientation was polished before implantation. The sample was provided by the Institute of Crystal Material, Shandong University. 400 keV Yb^+ and 300 keV Er^+ were implanted in $KTiOPO_4$ (100) to doses of $3\times10^{15}$and 1×10^{15} ions/cm^2, respectively. The ion implantation was performed at room temperature. In order to ensure uniformity over the implanted area, a two-directional electrostatic scanning system was used. Thermal annealing was carried out in a standard tube-furnace in Ar ambient. The annealing temperature ranged from 600 to 800 °C for 30 or 90 min.

The implantation profile was measured by Rutherford backscattering (RBS) of 2.0 MeV He ions with a scattering angle of 170°. The energy resolution of the detector was 14 keV. The beam current of He was 50 nA with a beam size about 1.5 mm diameter. The ion implantation was performed at the Institute of Physics at Changchun, Chinese Academy of Sciences. The Rutherford backscattering measurements were carried out at the Dynamitron accelerator of the University at Albany, USA.

Potassium Titanyl Phosphate is a quadriatomic target made of Ti, K, P, and O. Figure 1 shows a RBS spectrum for 400 keV Yb^+ implanted into $KTiOPO_4$. The implanted Yb profile is a Gaussian. Experimental mean projected range R_p and range straggling ΔR_p are 1080 and 330 Å, respectively.

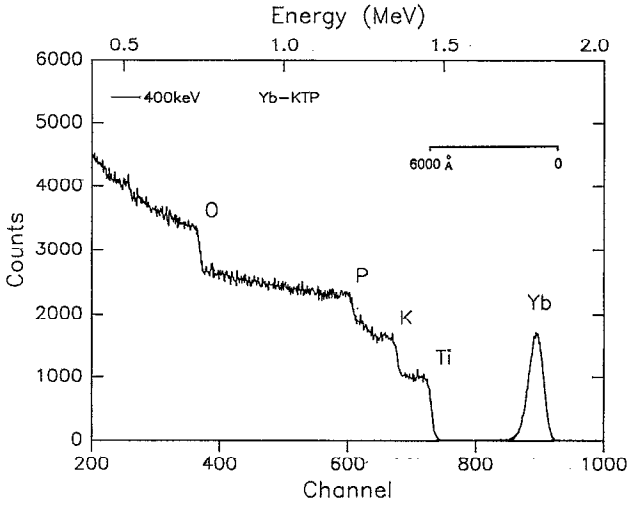

FIG. 1. Rutherford backscattering spectrum of $KTiOPO_4$ (100) implanted with 400 keV Yb^+ to a dose of 3×10^{15} ions/cm^2 at room temperature.

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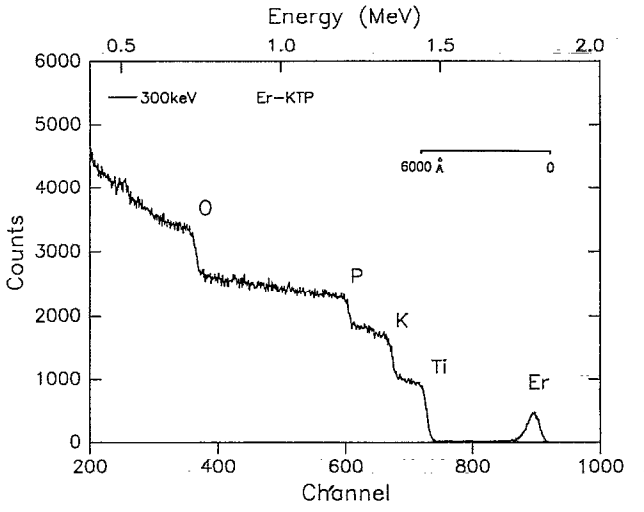

FIG. 2. Rutherford backscattering spectrum of $KTiOPO_4$ (100) implanted with 300 keV Er^+ to a dose of 1×10^{15} ions/cm^2 at room temperature.

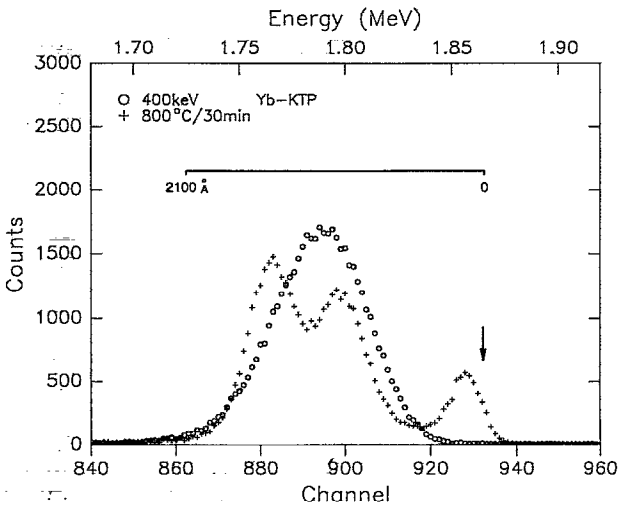

FIG. 3. Depth distributions of implanted Yb ions in $KTiOPO_4$ (100) before and after 800 °C annealing obtained by Rutherford backscattering of 2.0 MeV He^+. The arrow indicates the Yb surface position. The peak position of Yb depth distribution before annealing is 1080 Å.

The theoretical values by TRIM'91 code[10] are 1084 and 259 Å, respectively. Figure 2 shows the RBS spectrum for 300 keV Er^+ implanted in $KTiOPO_4$. Also, the implanted Er^+ has a nearly Gaussian distribution. The mean projected range R_p and range straggling ΔR_p obtained in the present measurement are 900 and 285 Å, respectively. The predicted values by TRIM'91 code are 861 and 213 Å, respectively. In the analysis of RBS data, we assume that Bragg's rule is valid for evaluating the stopping power of the compound and we have deconvoluted the energy resolution of the detector and energy straggling of He ions in the $KTiOPO_4$ to obtain the range straggling. We consider the agreement (indicated above) between the TRIM'91 calculations and our results to be good in the cases of 400 keV Yb^+ and 300 keV Er^+ implanted in $KTiOPO_4$ for the mean projected range.

Figure 3 shows the high energy (Yb) portion of RBS spectra for 400 keV Yb^+ in $KTiOPO_4$ before and after annealing at 800 °C for 30 min. As seen, unusual dopant profiles are observed. The Yb concentration profile looks entirely different from that of implanted Yb at room temperature. The original Gaussian profile has developed into a three peaked profile. It should be noted that no obvious diffusion of Yb was detected after 600 °C annealing for 30 min. After 800 °C annealing, some of the Yb has migrated toward the surface of the crystal. A small amount of Yb starts diffusing into the $KTiOPO_4$ region deeper than R_p. Most of the Yb has been trapped in the damage region. In order to explain this phenomenon, we therefore propose the following picture. After 400 keV Yb^+ at a dose of 3×10^{15} ions/cm^2 has penetrated the $KTiOPO_4$, the crystal matrix is amorphized over a depth of about 1000 Å. Severe lattice defects are generated in the regions near the maximum concentration profiles of doped impurities.[11,12] There exists an interface between the implanted region and the $KTiOPO_4$ substrate. The implanted Yb atoms in the crystal are rapidly redistributed through an annealing process and are trapped first within the damaged region. The remaining Yb atoms have migrated toward the surface (air-solid surface) and the interface.

Figure 4 shows the Er distribution in $KTiOPO_4$ (after 800 °C annealing) by Rutherford backscattering. The situation is a little different from the case of Yb^+ implanted in $KTiOPO_4$. There are two peaks of Er distribution. Some of the Er has migrated toward the surface of the crystal. This phenomenon is very similar to the case of Yb. The remained Er was trapped at damage region. But there is no third peak in the distribution of Er. One possible reason is that there is no obvious interface formation after the annealing because of the lower dose compared with the case of Yb implanted in $KTiOPO_4$.

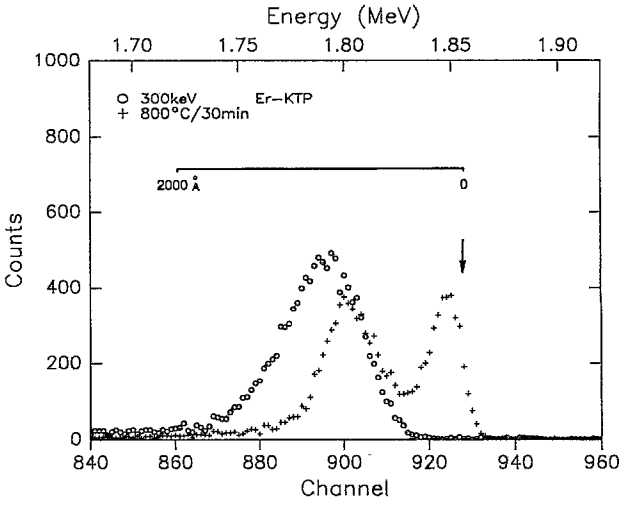

FIG. 4. Depth distributions of implanted Er ions in $KTiOPO_4$ before and after 800 °C annealing obtained by Rutherford backscattering of 2.0 MeV He^+. The arrow indicates the Er surface position. The peak position of Er depth distribution before annealing is 900 Å.

In summary, 400 keV Yb^+ with a dose of 3×10^{15} ions/cm^2 and 300 keV Er^+ with a dose of 1×10^{15} ions/cm^2 were implanted in $KTiOPO_4$(100), respectively. The distributions of implanted Yb^+ and Er^+ have Gaussian shapes. The experimental mean projected range is in good agreement of predicted value by TRIM'91. Three peaks of Yb distribution and two peaks of Er distribution were found after 800 °C annealing, but no obvious diffusion of Yb and Er in $KTiOPO_4$ for 600 °C annealing was detected. It suggests that the implanted Yb and Er were first trapped by the defects in the damaged region, the remained Yb and Er migrated toward the surface or interface.

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