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Application of NRA/Channeling to study He^+ implanted waveguides

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ABSTRACT

Four different techniques (RBS/channeling, NRA/channeling, prism coupling, and TRIM) for estimating the depth and width of a damaged layer created by ion implantation in $LiNbO_3$ are compared. Waveguides can be created in $LiNbO_3$ by lattice disruption damage with light ions (protons, alphas) or by implantation with Ti. End of range damage results in a decrease in refractive index that acts as a low index barrier to create a waveguide. In the electronic stopping region the ordinary index of $LiNbO_3$ is decreased while the extraordinary index is increased. The damage in the electronic stopping regime is removed by annealing to a temperature lower than that needed to remove the nuclear damage. RBS/channeling is used to examine displacement of Nb atoms and NRA/channeling is used to study displacement of Li atoms using Li(p,α) and Li(p,γ) reactions. We have analyzed waveguides producedby implantation of 1.7 MeV He^+. Comparison of the NRA/Channeling results of as implanted and 175°C and 400°C annealed crystals suggest that electronic stopping induced lattice distortion is responsible for the increase in the extraordinary index in the electronic stopping region.

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1. INTRODUCTION

Lithium niobate is a commercially important electro-optical material, part of the advanced technology effort in optical communication and computing. Electro-optical devices are now used to substitute traditional electronic devices in communications and in information processing. Integrated optical $LiNbO_3$ devices include couplers, switches, modulators, multiplexers and others.[1,2] Three different techniques have been employed to create waveguides in lithium niobate: proton exchange, Ti diffusion and Ti implantation[3,4,5]. Ion implantation allows tighter control over device geometry, dopant concentration and dopant profile than the diffusion and proton exchange methods[6]. Moreover, ion implantation is the only technique to create regions with modified refractive index deep inside the crystal. It makes possible the fabrication of 3-D waveguide structures in one bulk crystal including rather simple vertical stack multichannel waveguides, directional couplers, etc. In this paper we analyze waveguides created by implantation of 1.7 MeV He^+ ions.

In crystalline materials ion implantation typically reduces the refractive index with the maximum reduction occuring at the end of range of the ion in the nuclear damage region. This change in index is due primarily to a decrease in density caused by the disordering of the lattice[7,8]. The implantation thus creates a narrow region of reduced refractive index up to several micrometers below the surface that can act as an optical barrier to create a waveguide. The guiding region between the surface and the barrier is also damaged, but to a much lesser extent than at the end of range and this damage can be annealed out at a temperature of 200-250°C, about 200°C lower than that needed to remove the damage in the barrier region[9,10,11]. Computer simulation and prism coupling [12,13,14] are usually used to correlate implant damage with refractive index changes. Prism coupling has also been combined with surface removal by hand polishing to verify refractive index change versus depth[9]. In this work we use TRIM92[15] and RBS and NRA-Channeling to investigate the depth and distribution of damage due to implanting lithium niobate with 1.7 MeV He^{+}. The TRIM and ion beam analysis results are compared to prism coupling results.

2. EXPERIMENTAL

The optically polished x-cut crystals were purchased from Deltronic Crystal Industries, Inc. The implantation was carried out using the Surface Modification and Characterization Facility at Oak Ridge National Laboratory. Prior to ion beam analysis the crystals were coated with a thin film of aluminum to prevent charge buildup.

The waveguides were tested and characterized at 632.8 nm with a Metricon 2010 automated prism coupler equipped with a rutile prism. Analysis of the number, intensity and angular spacing of the modes yields information on the index and thickness of the guide. Due to the limitations of the prism coupler only TE modes could be investigated in $LiNbO_3$ crystal.

He^{+} ions at an energy of 1.7 MeV and a fluence of 1.5×10^{15} /cm^2 were used to create a refractive index barrier predicted by TRIM to be 3.6 μm below the surface. The implantation was done at approximately 0° C to ensure that the samples remained at or below room temperature during implantation.

2.1 ION BEAM ANALYSIS

The implanted crystals were analyzed using a 1.03 MeV H^+ ion beam from the NEC 5SDH-2 Pelletron at Alabama A&M University. The beam current of 12-17 nA on the target passed through 2.4 and 2.0 mm collimators spaced 20 cm apart and 15 cm from the sample. The data aquisition system was set up to permit simultaneous operation of Silicon Surface Barrier(SSB) detectors for RBS or Li(p,α) analysis and a 2" × 2" NaI detector for PIGE analysis in a channeling configuration[16]. For NRA of the Li(p,α) reaction the SSB detector was placed at a backangle of 130° to yield a large energy loss for the alpha particle to enhance depth resolution. For RBS a separate detector at a backangle of 170° was used. The NaI detector was positioned 2 cm behind the sample to give a large solid angle and a correspondingly high count rate. The H^+ energy was chosen to take advantage of the 478 keV (FWHM 60 keV) Li(p,p'γ) reaction resonance at 1.03 MeV and to maximize yield from the surface region and minimize background gammas from deeper regions.

The results of RBS-Channeling after annealing the sample to 175°C and 400°C are shown in Figure 1. The RBS-Channeling results are skewed somewhat by an overly thick aluminum layer that reduced channeling. A electronic artifact is responsible for the approximately 10 channel difference in the spectra. Disorder due to the He^+ implant, which should appear to the left of the O signal, is not visible because the amount of disorder, , was too low to overcome the background from the Nb and O signals.

Figure 2 shows the Li(p,α) results in random and aligned configurations for the He^+ implanted crystal. The effect of channeling is seen in the reduced yield in the spectra.

Some surface disorder or Li accumulation at the surface can be seen in the spectrum taken prior to annealing but the expected increase in yield at 3.6 μm due to disorder is not readily apparent in these spectra.

However, in contrast to the RBS-C results the NRA-C sprectra of Figure 2 show a reduction in surface yield. The degradation of channeling is apparent in the decrease in the length of the tail of the alpha spectrum. But the front end of the spectrum shows improved channeling and a marked reduction in Li in the first 500 nm. The yield reduction may indicate an improvement in the lattice due to the low temperature anneal. By analogy to results of x-ray diffraction studies of Na^+ implanted MgO [17] we can attribute the poor channeling to ion beam induced elastic strain. This would be in agreement with the hypothesis [18] that the increase in the extraordinary index and decrease in ordinary index is due to contraction in one direction and expansion in the other induced by the implantation. While Figure 2 shows a decrease in lattice disorder, the decrease in near surface Li might suggest that Li has segregated to the surface during implantation. This would be counter to the results of the study of missing or extra 'strange' modes[18] in He^+ implanted $LiNbO_3$ that suggest that Li is more likely to diffuse towards the amorphized nuclear stopping region than away from it.the efffect however is complex and it is possible that Li diffuses both towards the surface and towards the nuclear damage region. Because the changes in refractive index in the electronic stopping region are mostly removed with annealing temperatures below 250°C the NRA-C results suggest that lattice distortion is responsible for the index changes between the surface and the end-of-range of the implanted ions.

2.2 MODES IN WAVEGUIDES

For samples implanted with a single 1.7 MeV implant and with a two energy implant (1.5 and 1.7 MeV) substantial differences were noted between modes traveling in the y direction (the refractive index in virgin crystal for TE polarization is 2.286) and in the z direction, 2.206), with the y direction supporting more modes.

Five propagating modes were supported in the y direction, and two in the z direction, for the 1.5-1.7 MeV implanted guide. The guide thickness computed from the prism coupling using a simple step index, asymmetric waveguide model [19]was 2.7 μm, and the ordinary refractive index reduction was 0.017. The thickness approximately agrees with TRIM which predicted He range of 3.0 μm.

Better agreement is obtained between TRIM and prism coupling using Townsend's reconstruction of a 1.75 MeV He^+ implanted guide. TRIM predicts a damage maximum at 3.65 μm while the prism coupling yields a maximum at 3.75 μm [18].

CONCLUSIONS

This work indicates that channeling analysis may prove to be a valuable means to assess to what degree electronic energy induced lattice disorder is responsible for the anamolous increase in the extraordinary index in lithium niobate in the electronic stopping region.

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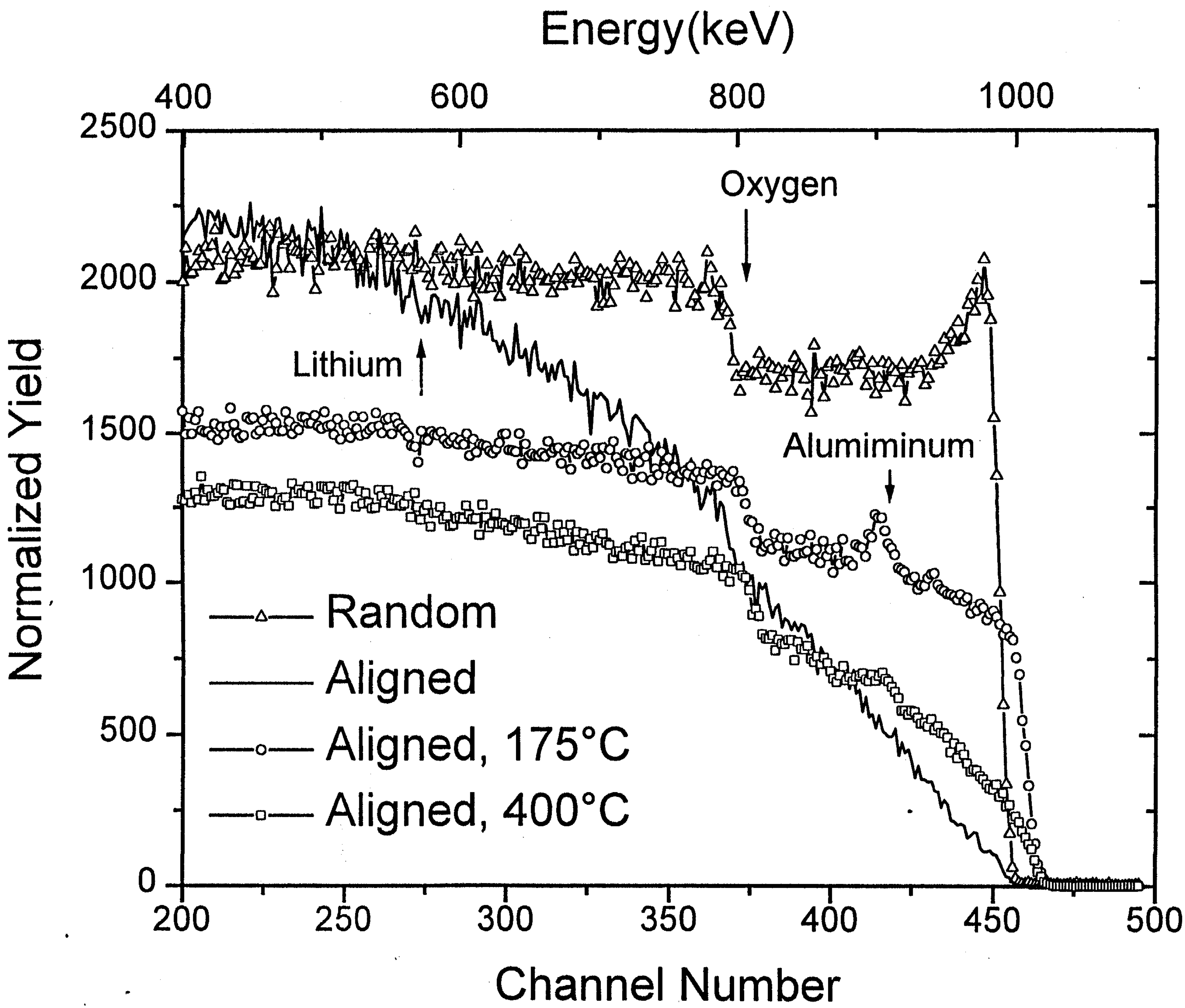
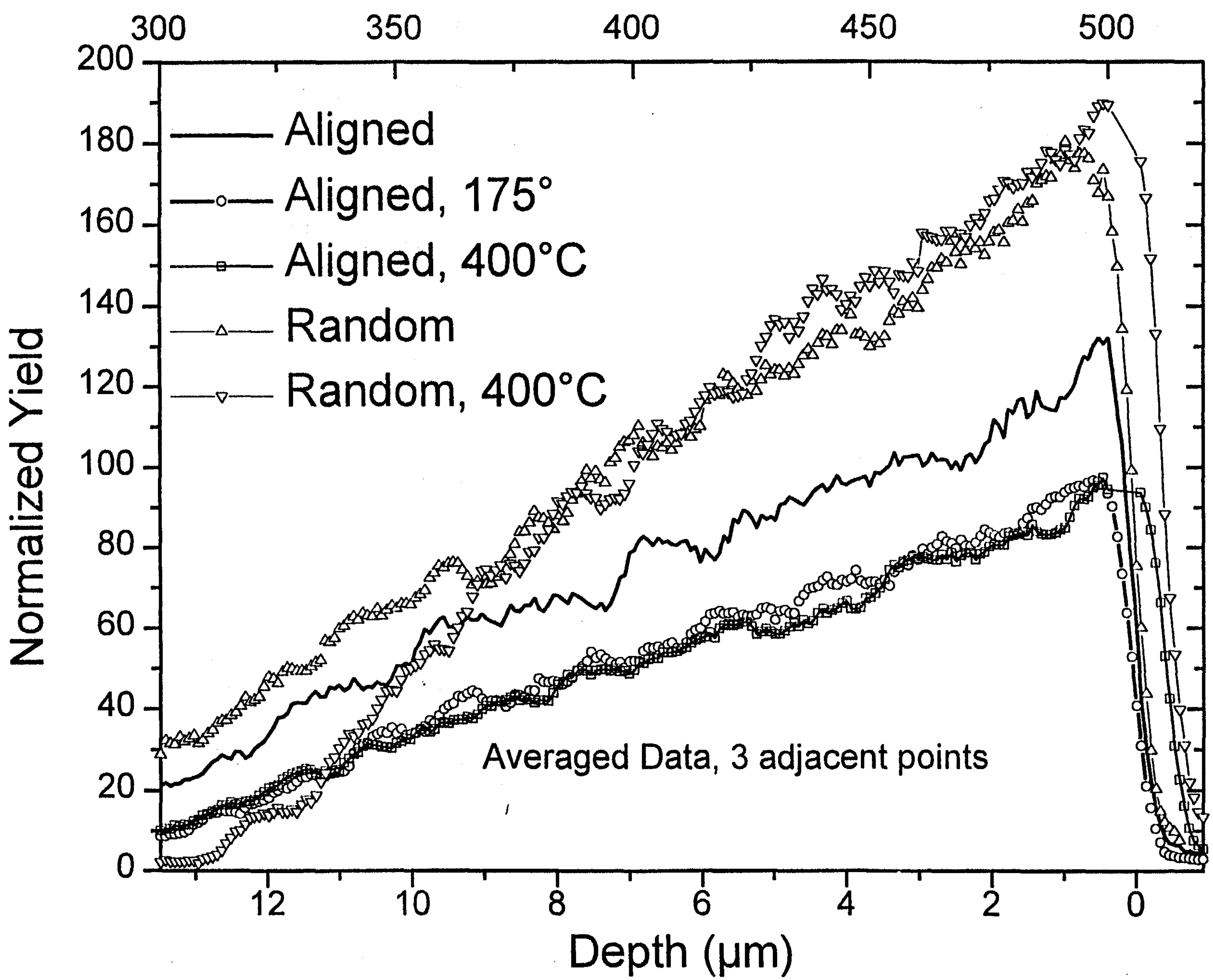
Figure captions

Figure 1. RBS-Channeling from He^+ implanted $LiNbO_3$ after implantation and after 30 minute 175°C and 400°C anneals. The mismatch in channel number at the surface is due to an error in the electronics

Figure 2. NRA-Channeling spectra from Li(p,a) reaction from He^+ crystal analyzed prior to annealing and after 30 minute anneals at 175°C and 400°C in air. .



Energy(keV)
400
600
800
1000
Oxygen
Lithium
Aluminimum
Random
Aligned
Aligned, 175°C
Aligned, 400°C
Normalized Yield
2500
2000
1500
1000
500
0
200
250
300
350
400
450
500
Channel Number



Aligned
Aligned, 175°
Aligned, 400°C
Random
Random, 400°C
Averaged Data, 3 adjacent points
Normalized Yield
Depth (µm)
300
350
400
450
500
200
180
160
140
120
100
80
60
40
20
0
12
10
8
6
4
2
0