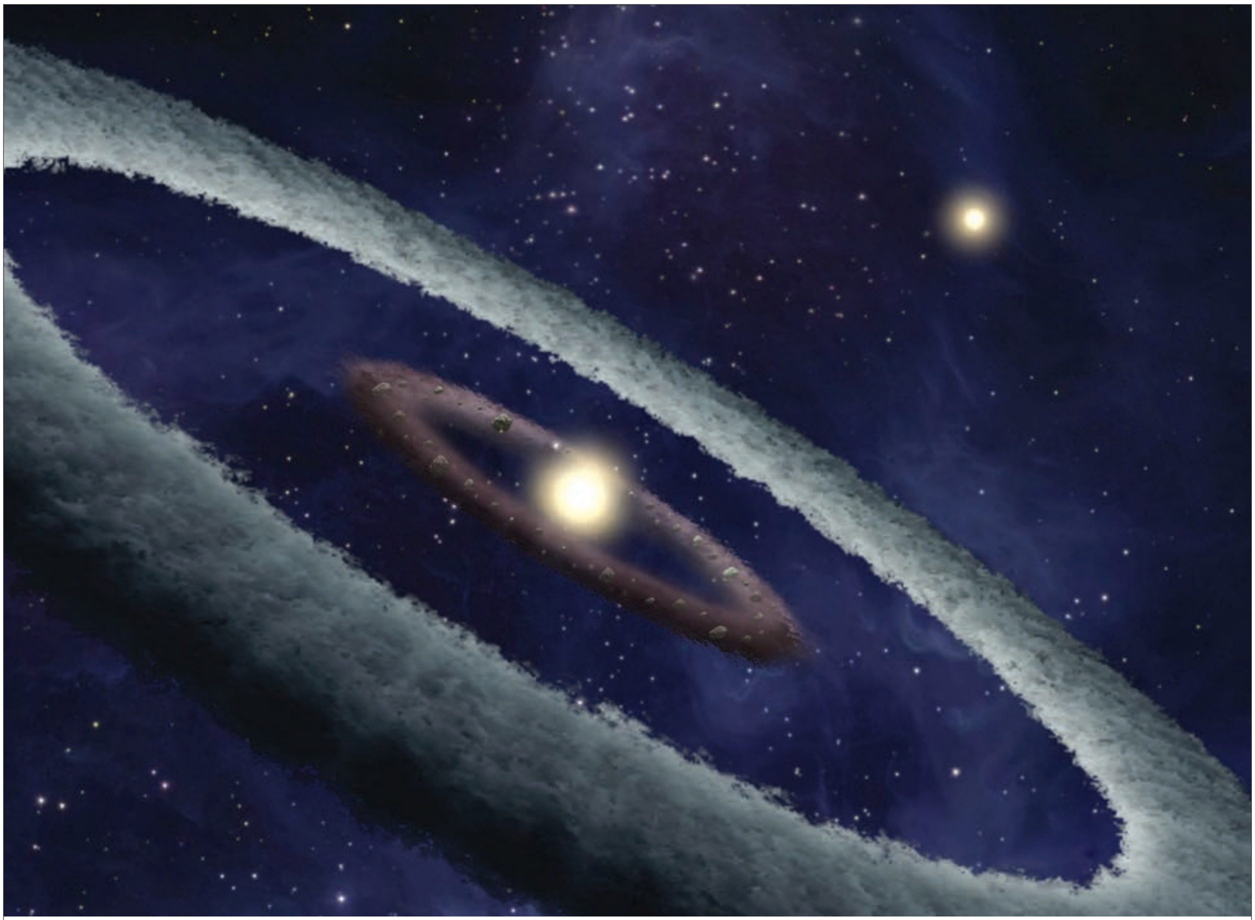

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Copper Implantation in Lithium Niobate for Active Optical Waveguides*

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Abstract: The optical properties of $LiNbO_3$ are very important material parameters and related with others such as applied voltage, strain and temperature. The important idea in integrated optics is the use of such waveguides as the basic structures of all the optical components, including lasers, modulators, detectors, prisms, lenses, polarisers and couplers. The knowledge of the refractive index profiles and the correlation between them and the fabrication parameters are prerequisites for desiguing efficient integrated electro-optic and non-linear optical devices. $LiNbO_3$ crystals were implanted at room temperature with 1 and 1.5 MeV Cu ions at a flow of 5×10^{14} ions cm^{-2} and beam densities of 45 and 6nA cm^{-2} respectively. We have used the TRIM transport of ions in matter code to simulate the damage profile in $LiNbO_3$ by Cu ions implantation with indicated dose and energies. This is helpful for choosing the functionality of planar optical waveguides. In this study, the correlation between the profiles of Cu distribution and refractive index is discussed; moreover we reported a doping of $LiNbO_3$ with Cu atoms by MeV ion implantation and the subsequent fabrication of planar optical waveguide. Comparing the optical properties of samples implanted with 1 and 1.5 MeV would give more concrete insights into what happens in the implanted layer and from these points of view we examined differences in the optical properties of these samples.

Key words: Ion implantation, lithium niobate, optical waveguides, defects

INTRODUCTION

Ion implantation is a superb method for modifying the surface properties of materials since it offers accurate control of dopant composition and structural modification, at any selected temperature (Townsend, 1984). Some rare earth ions have been used as ion implantation doping for a laser or amplifier action (Cristiani *et al*., 1999; Maeda *et al*., 1999). As in semiconductor technology, the local doping of rare earth ions- medium or heavier ions-and induced damage to in opto-electrical crystals can produce a laser source and integrated optical circuits on the same wafer. Metal ions implanted in dielectric materials can change optical properties, such as colour, reflectivity, transmission, refractive index, etc, in the near surface (Gea and Boatner, 1996). How these changes of properties occur depends on the combinations of ions and host materials and some subsequent thermal treatments. Some metal ions implanted in transparent and colourless crystals give vivid and beautiful colours, for instance Nb^+ or Fe^+ in quartz, Au^+ in silica glass, Cu^+, Ag^+, or Au^+ in $LiNbO_3$ (Shang *et al*., 1996). The mechanisms of optical absorption considered to be responsible for these colorations are crystal field coloration, absorption by metal colloids formed in the crystal, colour centers, (Glass, 1969) etc. In ion implanted waveguide, the poor transmission efficiency mainly results from the high defect density in guiding layer and the narrow optical barrier tunneling. Generally, the defects maiuly arise from the ionization process, which can be easily annealed. The possible index profile in waveguides formed by heavy ion

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**Originally Published in Research Journal of Physics, 2007* implantation has been demonstrated according to a theoretical model, which is considered to have a correlation with the damage to some extent (Brice, 1975). Generally, this refractive profile allows the leakage of energy due to tunneling effect through the barrier layer. Then, optical devices, such as waveguide lasers involve mode locked, Q switched, self-frequency doubled, tunable and waveguide amplifiers, can in principle be realized; and the monolithic integration of passive and active devices on one chip may become possible.

Due to its high electro-optical, acousto-optical, piezoelectric and nonlinear optical coefficients, lithium niobate $LiNbO_3$ is widely used in a variety of photonic devices (Sarkisov *et al.*, 2000). For its low cost and outstanding physical properties such as high Curie temperature and high rigidity, $LiNbO_3$ has been successfully used in integrated optics applications. In order to combine this attribute with the excellent nonlinear, electro-optical and acousto-optical properties of $LiNbO_3$, the doping of $LiNbO_3$ with copper becomes an interesting task. In heavy ion-implanted waveguide in $LiNbO_3$, the extraordinary refractive index in guiding region may be increased with moderate implanted doses. As a result, the light is confined in the index-raised region. It is known that monovalent metal ions implanted into insnlators, frequently lead to the formation of metal colloids. Metal colloids have been the object of continuously growing interest in colloid science or nonlinear optical effects of colloids. Some articles on metal colloid formation in $LiNbO_3$ by ion implantation have been published, but little work has been done on the energy dependence. Therefore, knowledge of the damage to distribution and waveguide formation of heavier ions implanted in opto-electrical crystals is necessary. Are there any differences or similarities in the characteristics of the behaviours of Cu implanted in $LiNbO_3$ with different energies? In this research of Saito *et al.* (1997), a study of Cu implantation in $LiNbO_3$ was done at two largely different energies that are 25 keV and 3 MeV to examine differences in the optical properties of these samples. In this paper, MeV Cu ions were chosen as candidates for implantation into a $LiNbO_3$ crystal to study heavy ion induced damage to distribution and waveguide formation.

MATERIALS AND METHODS

X-cut Y propagating $LiNbO_3$ single crystals with optically polished surfaces were used in this research. The MeV Cu ion implantations were performed at room temperature with the 2×1.7 MV tandem accelerator. Deionised water was used to cool the samples during implantation. The ion beam density was maintained below 50 nA cm^{-2} to avoid excessive heating. The ion beam was scanned to ensure a uniform implantation over the sample. During implantation, the normal to the top face of the sample was tilted 7° off the beam direction to avoid the channelling effect. The implant dose was 5×10^{14} ions cm^{-2} for 1.5 and 1 MeV Cu^+ implantations, respectively. Rutherford backscattering in a channelling geometry was performed using a 2.1 MeV $^4He^{2+}$ beam generated by a 2×1.7 MV tandem accelerator, with a beam current around 20 nA. The samples were mounted on a three-axis goniometer driven by pulse motors in a vacuum chamber. A surface barrier detector at an angle of 165° with respect to the incident beam was used to detect the backscattered particles. All the experiments were performed in a vacuum of 2×10^{-6} Torr.

RESULTS AND DISCUSSION

The dominant effect of ion implantation on refractive index is due to the partial lattice disorder or damage to produce in the collisional processes. The ion irradiation causes a substantial decrease in the refractive index but only near the end of the implanted ion's range (Carruthers *et al.*, 1974). Moreover, the results demonstrate that a graded refractive index depth profile may be produced by implantation (Townsend, 1984; Wang *et al.*, 2000). In heavy ion-implanted waveguide in $LiNbO_3$, the extraordinary refractive index in guiding region may be increased with moderate implanted doses as in case of 5×10^{14} Cu implanted ions cm^{-2}. So, the refractive index profile depends on the range

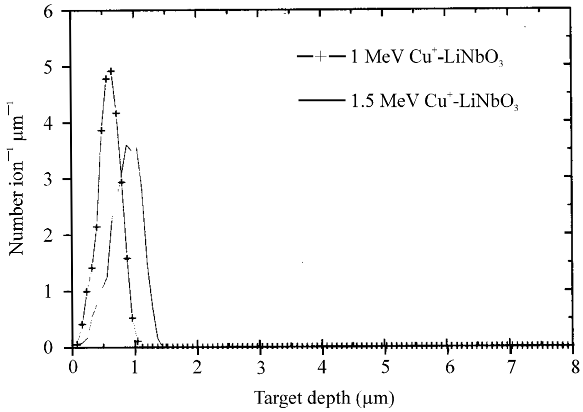

Fig. 1: Final distribution density versus the penetration depth of 1 MeV and 1.5 MeV Cu^+ ions implanted into $LiNbO_3$ at a tilt angle of 7° and doses of 5×10^{14} ions cm^{-2}

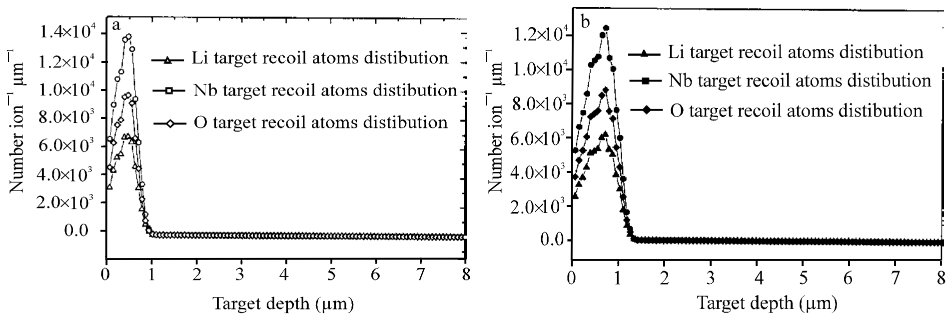

Fig. 2: Final distribution of $LiNbO_3$ ion recoils target versus the penetration depth induced by a 1 MeV and b 1.5 MeV Cu ion implantation to doses of 5×10^{14} ions cm^{-2}

profile of implanted ions and damage to profile created by ions. The thickness and feature of the waveguide is controlled by the ion energy, from Fig. 1 to 6a and b; therefore it can be estimated from the projected range of the implanted ions and ions recoils target, as shown in Fig. 1 and 2a and b, the width of the optical barrier created by Cu^+ ions as well the contribution of ions recoils target in the waveguide is related on the damage to profile. The Fig. 1 and Fig. 2a and b show acomparison of damage to distributions in $LiNbO_3$ produced in two different implantation processes at a tilt angle of 7°, which is simulated by TRIM code. Initially we can notice in both figures that the distribution density level in the case of 1 MeV is greater than one of 1.5 MeV. In Fig. 1, a uniform damage to around 35% is produced in depth approximately ranging from 0.88 μm to 104 μm in 1.5 MeV energy implanted waveguide, which maybe results to an even low-index barrier region at the end of ion track. The barrier in 1.5 MeV implanted $LiNbO_3$ is thick enough comparable with that of 1 MeV implantation so that the tunneling effect can be reduced or neglected. Accordingly, the leakage of light will be reduced or neglected through barrier when it is excited to propagation in 1.5 MeV implanted $LiNbO_3$. Having the reduced tunneling effect, enhanced transmission efficiency can be expected. So the heavy ion-implanted waveguides should synthesize the characteristics of index-raised region and optical barrier. A broadened index barrier would play an important role in reducing the leakage of light. The multi-energy heavy ion implantation provides an alternative method for fabricating low-loss waveguides. Furthermore, the two profiles of Fig. 1 are clearly different. The peak seems to evolve to a bimodal distribution in the case of 1.5 MeV Cu implantation. This phenomenon is somewhat similar to the one observed by Alford *et al.* (1990) who reported that Au^{2+} implantation into silicon with an energy above 1.8 MeV shows a splitting in the Au concentration profile (Carruthers *et al.*, 1974). There is no accepted explanation for this double-peak phenomenon. One speculation is that aggregation into extended defects is more likely for the tilt-angle implantation because the localized defects are nearer to the surface and the subsequent back diffusion of Cu^+ ions in addition to ions recoils target in Fig. 2a and b towards the surface gives rise to the evolution from a shoulder feature to a twin peak in tilting the implantation angle of 7°.

To the first approximation, this is the concentration profile of the implanted ions. In any case, the depth profile of ions in the as-implanted state is of prime importance. Propagation loss is an important parameter for evaluating the properties of a waveguide. In ion-implanted waveguide, the poor transmission efficiency mainly results from the high defect density in guiding layer and the narrow optical barrier tunneling. Generally, the defects mainly arise from the ionization process, as we can see in Fig. 3a and b, where in some cases they can be easily annealed (Tien, 1977). The energy loss distribution due to ionizations by ions recoils target in the case of 1 MeV implantation is greater than one for 1.5 MeV, whilst for the Cu^+ ions the energy loss distribution is higher in the case of 1.5 MeV than one of the 1 MeV. In addition, the tunneling effect may be reduced if a broadened barrier is built at the end of ion track. Damage to induce by ion implantation normally results in isolated point defects and ionic displacements as shown in Fig. 4a and b. In this Fig. 4a and b the collision events distribution of ions lithium niobate target vacancies in the case of 1 MeV is superior to the distribution in the case of 1.5 MeV, for the reason that the energy transferred by Cu^+ implanted ions to ions recoils target in the case of 1 MeV is more important than the case of 1.5 MeV as given away in Fig. 5a and b).

In ion-implanted waveguides, it is reasonable to get some information on barrier by simulating damage to profile caused by both electronic and nuclear collisions. As is well known, waveguide is characterized by a region of high-refractive index bounded by regions of lower index. The confinement of the light, as well as the spatial distribution of optical energy inside the guiding layer depends on the refractive index profile. Consequently, the investigation of index profile is significant for tailoring a waveguide structure. In heavy ion-implanted $LiNbO_3$, the changes of extraordinary index are generally dominated by two different types of mechanisms. In the near surface, the spontaneous polarization of lattice is usually degraded on account of electronic interactions which will results in an increase of extraordinary index. At the end of ion track, a reduced density is caused by the nuclear collisions, as shown in Fig. 6a and b which bring on a decrease of extraordinary index. In heavy ion implanted $LiNbO_3$, a possible index profile has been investigated and constructed according to a theoretical model.

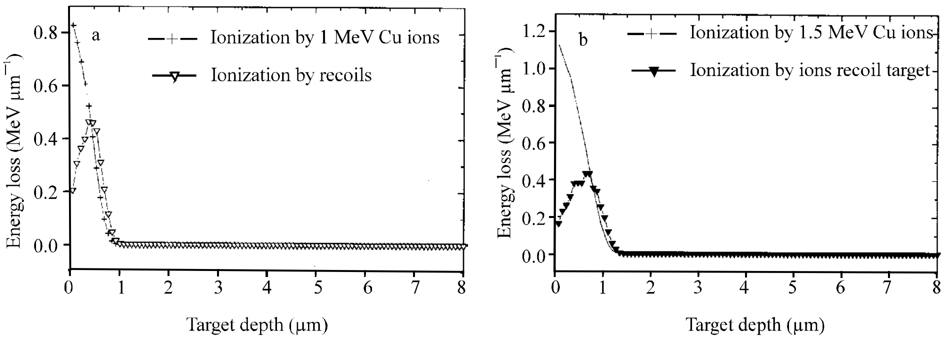

Fig. 3: Energy loss distribution versus the penetration depth in lithium niobate due to ionizations by ions recoils target and Cu ions at both energies of 1 and 1.5 MeV in a and b, respectively to doses of 5×10^{14} ions cm^{-2}

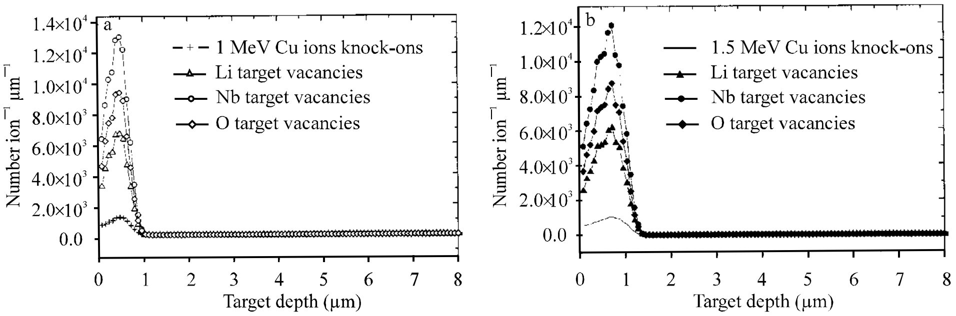

Fig. 4: Collision events distribution of ions lithium niobate target vacancies and Cu ions knock-on versus the penetration depth at energies of (a) 1 MeV and (b) 1.5 MeV and doses of 5×10^{14} ions cm^{-2}

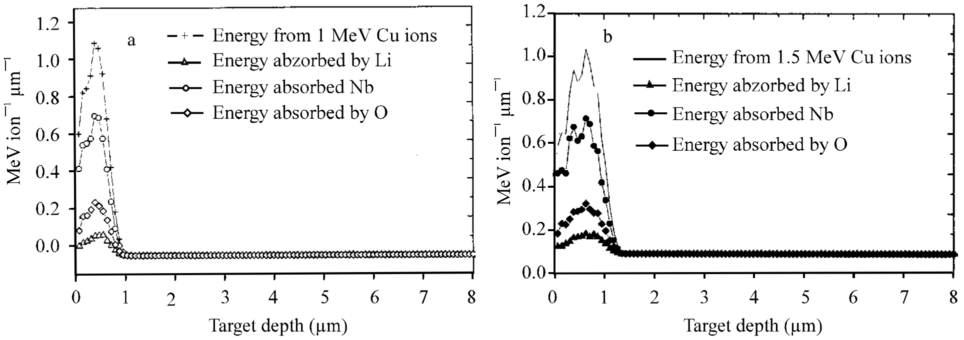

Fig. 5: Energy transferred versus the penetration depth to ions recoils target by implantation of 5×10^{14} Cu ions per cm^2 at energies of a 1 MeV and (b 1.5 MeV in lithium niobate

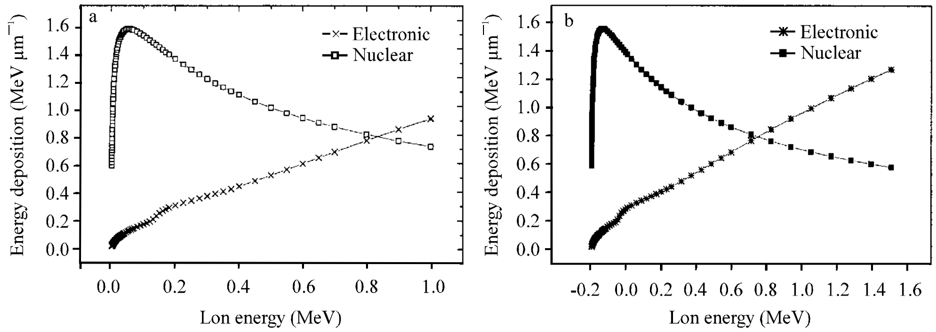

Fig. 6: Electronic and nuclear energy deposition as a function of ion energy induced by a 1 MeV and b 1.5 MeV Cu ion implantation in $LiNbO_3$ target at doses of 5×10^{14} ions per cm^{-2}.

As mentioned, damage to induce by implantation plays an important role in index changing. In order to get some information on the damage to by nuclear energy deposition, we used TRIM simulation to reproduce the process of the ion implantation. Fig. 6a and b) shows the nuclear and electronic energy leakage as a function of the energy deposition of MeV Cu^+ ions in $LiNbO_3$ target. The primary remark one can make is that the electronic energy deposition in the case of 1 MeV is more important than the one of the 1.5 MeV, whereas the nuclear energy deposition is comparable for the two energy's implantations. In the peak position optical barrier is built up, it shows for ordinary polarization decreasing of refractive index has the same trend with implantation damage too. For the extraordinary index which is specific of the guide region, slight damage to leads to lattice disorder, which means part of electronic dipoles in $LiNbO_3$ were dislocated. Well ordered dipoles are the main reason $LiNbO_3$ has the large birefringence. Slight damage to make the extraordinary index increase and the ordinary one decrease. If other factors were omitted, as the ion dose became larger these two indices would approach the same value and the crystal would become glassy. But for high-dose implantation damage to also reduces the density. So at the end of the ion track an optical barrier is also built, which come into a lower index region too. Because of the higher index in the waveguide region, four modes of extraordinary light could be confined in the relatively lower optical barrier (Tien *et al*., 1969).

CONCLUSIONS

The waveguides are defined by the air and the low-index optical barrier. Recently, substituting for light ions, energetic MeV heavy ions such as copper implanted into lithium niobate has been demonstrated to be a suitably alternative method for the fabrication of waveguides. It is important to recall that low mass (He) ion implantation generates the maximum nuclear recoil damage to near the end of the ion range, while the near-surface regime remains relatively undamaged. Therefore MeV He ions will always be used to generate a buried layer of reduced optical index within essentially all optical crystals. In most cases, when energetic (1-2 MeV) light ions with dose in the range of 10^{16} ions cm^{-2} are implanted into optical materials, an optical barrier is built up at the end of the ion track because of the elastic energy deposition from ions to the lattices. The heavy ion implanted lithium niobate waveguide is more efficient to confine the transmitted signal by a region where the extraordinary index is increased. We find that one characteristic of the heavy ions implantation in the fabrication of lithium niobate waveguide is that usually it requires much lower dose and better confinement of propagating light compared with light ions implantation (Townsend *et al*., 1994). Indeed, the tunneling effect may be reduced if a broadened barrier is built at the end of the ion track. Consequently, high transmission efficiency can be expected in a waveguide fabricated by multi-energy implantation with moderate dose. Materials created with properties different from those of the bulk in the surface layer may find useful applications in various fields. Slightly measurable surface damage to have been demonstrated when energetic Cu ions are implanted into $LiNbO_3$, which means the characteristics of crystals in guiding region possibly can be well preserved with low-dose implantation.

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