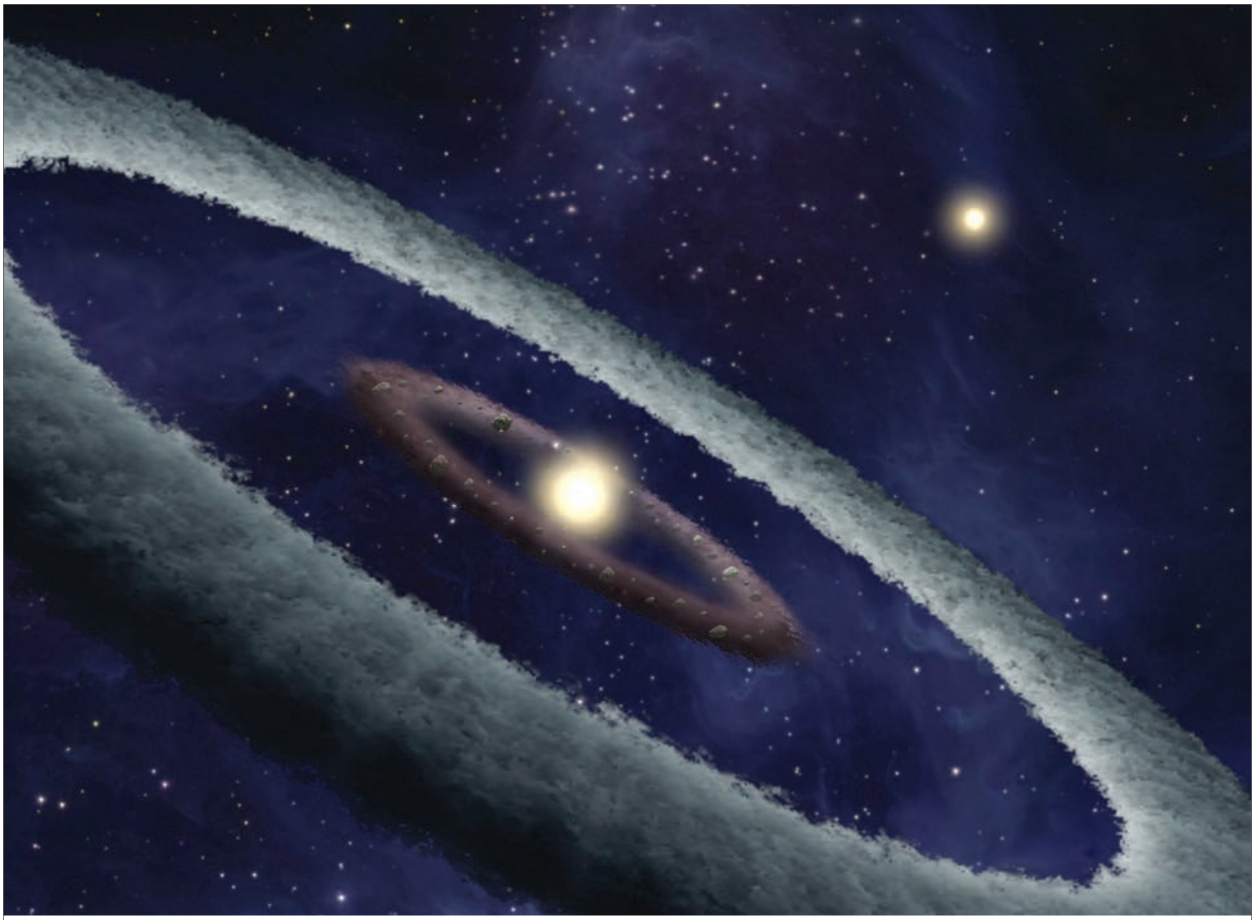

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Evaluation of MeV Ion-Implanted Planar Optical Waveguides in Fused Silica

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Abstract: Ion irradiation of silica causes compaction of the substrate over the extent of the ion range and the resulting increase in refractive index has applications to optical waveguide fabrication. Several analytical techniques have been utilized to characterize implantation-induced structural and surface modifications of silica with the aim of yielding further insight into this technologically relevant process. Fused silica samples were implanted at room temperature by 2.6 MeV Ni^+ ions with a dose of 9×10^{14} ions cm^{-2} and 2 MeV He^+ ions with a dose of 1.5×10^{16} ions cm^{-2}, respectively. A comparison of the MeV Ni^+ ion implanted planar waveguide formation was made with the MeV He^+ ion implanted one. TRIM simulation was used to simulate the damage profile in silica by MeV Ni^+ and He^+ ions implantation. It is found that the refractive index profile in MeV Ni^+ ions implanted waveguide is somewhat different in shape from that in MeV He^+ ions implanted waveguide.

Key words: Optical waveguide, ion implantation, refractive index profile

INTRODUCTION

Silica is of importance for the manufacture of optoelectronic components, forms the basis of a worldwide fibre network and is compatible with established Si processing techniques (Benaïssa *et al*., 2006). Ion implantation is a routine processing methodology for the microelectronics industry with numerous potential applications for optoelectronic device and circuit fabrication including the formation of silica based waveguides, couplers and dividers. However, a thorough understanding of implantation-induced effects in silica is first necessary if the potential advantages of this combination of processing and materials system are to be realized. Ion implantation has now become a recognized technique for the fabrication of optical waveguides and has obtained great success in more than 50 crystalline materials (Townsand *et al*., 1976; Ziegler, 1984). Compared with other techniques, for example, diffusion, ion exchange and surface epitaxy, ion implantation also may be applied to fabricate waveguides with lower loss and better optical quality (Smith and Dexter, 1972; Benaïssa *et al*., 2006). Ion implantation of high-energy light ions, example MeV He^+ has become a relatively mature method to produce refractive index changes and hence optical waveguide. In this case, a low refractive index "optical barrier" has happened at the end of the track where most of the displacement damage occurs. And such an optical barrier confines the light to a narrow layer or optical well between itself and the surface (Townsend *et al*., 1994). However, as for waveguide formed by high-energy heavy ion implantation, the refractive index profiles usually represent somewhat from that of light ions implanted one. So it is significant to make a comparison between optical waveguides by light ion implantation and those formed by heavy ion implantation. Silica (SiO_2) is an ideal material for making such a comparison of waveguide formation between the two kinds of implantation. Ni^+ is a suitable heavy ion to fabricate waveguides in many crystals such as $LiNbO_3$ (Fink *et al*., 1987; Wang *et al*., 2000). The knowledge of the index profile of waveguides as well as its dependence on fabrication parameters is

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a prerequisite for tailoring waveguiding structures for applications. The effective indices of the waveguide modes need to be accurately known for devices relying on phase-matching applications such as traveling-wave modulators or frequency doublers. The index profile also determines the optical field distribution which needs to be known to optimize field overlap in electro-optic and nonlinear optical applications (Verhaegen *et al*., 1995). In the present paper, we represent the formation of planar optical waveguides in silica by MeV Ni^+ ions implantation and compare the results to those that obtained from MeV He^+ ion-implanted waveguides in silica. This study has addressed the influence of ion implantation on the structure and surface of silica. A critical review of the numerous results on range profiles obtained with our Monte Carlo TRIM simulation in its latest version showed that there exist several, as yet unknown, universal relations between the moments of range and damage profiles. In combination with the well-known PRAL Algorithm (Ziegler *et al*., 1985) or other recently developed analytical formulae for the energy range relation, one may use these relations to obtain improved range and damage profile simulation predictions. For dominant nuclear and dominant electronic interactions mostly different relations are used. The influence of various effects on the range parameters is additionally demonstrated to evaluate for some test measurements. As the relations derived from theoretical results are intended essentially to help experimenters in their work, we find it appropriate to give the reader a feeling for the accuracy of experimentally obtainable range profile parameters to compare with the theoretical calculations.

WAVEGUIDE FABRICATION

Our investigations were carried out using implanted samples, which an example of elaboration is well described by Benaïssa *et al*. (2006), by 2.6 MeV Ni^+ ions with dose of 9×10^{14} ions cm^{-2} and 2 MeV He^+ ions with dose of 1.5×10^{16} ions cm^{-2} at room temperature, respectively. To reduce heating of the sample surface it is preferable to work with a relatively low ion beam flux. The ion beam was scanned to ensure a uniform implantation over the silica samples. During the implantation the samples were tilted off by 7° the beam direction in order to minimize the channeling effect. Prism-coupling method was used to observe the modes in waveguide. A laser beam at 633 nm from a He-Ne laser struck at base of a rutile prism and hence the laser beam was coupled into the waveguide region. A silicon photodetector was used to detect the reflected beam. The prism, waveguide and the photodetector were mounted on a rotary table so that the angle of incident laser beam could be changed. The intensity of light striking the photodetector was plotted as a function of the incident angle, where a sharp drop in the intensity profile would correspond to a propagation mode. A computer was used to control the measure system via an interface attached to the control pad (Townsend *et al*., 1994).

RESULTS AND DISCUSSION

A numerical TRIM (transport of radiation in matter) simulation, as given by Ziegler *et al*. (1985) of the implantation process, is given for viewing and insight into different physical processes in the fabricated silica sample. Optical waveguides have been fabricated in a wide variety of materials using ion implantation. A refractive index change is induced by modification of the substrate density, polarisability or structure produced by the radiation damage or the stoichiometric changes (Townsend *et al*., 1994) as shown in Fig. 1 and 2. Ion implantation is one relevant fabrication technology that has been used to modify the physical and optical properties of silica, yielding an increase in both density and refractive index over the extent of the ion range, as pointed out in Fig. 1 and 2, as ones can see a furrowed optical waveguide in the penetration depth of 2.5-2.75 μm by implantation of 1.5×10^{16} ions cm^{-2} He^+ with energy of 2 MeV and another one furrowed in the penetration depth of 2.75 ~ 3.25 μm by implantation of 9×10^{14} ions cm^{-2} Ni^+ with energy of 2.6 MeV in silica, where ion implantation produces compaction of the glass network resulting in positive

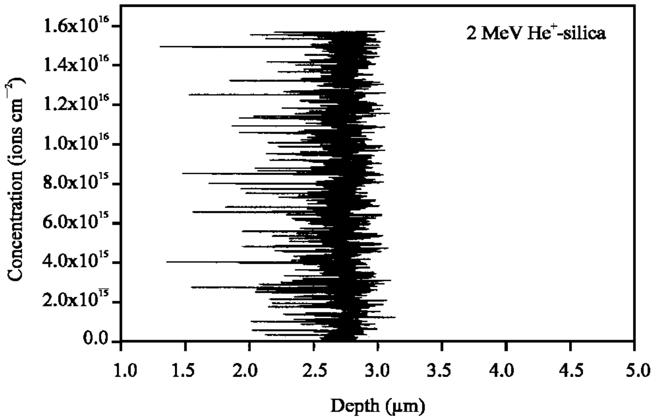

Fig. 1: Formation of planar waveguides with a 1.5×10^{16} ions cm^{-2} He$^+$ implantation into silica due to the decrease of the refractive index in the buried index barrier as a function of the penetration depth

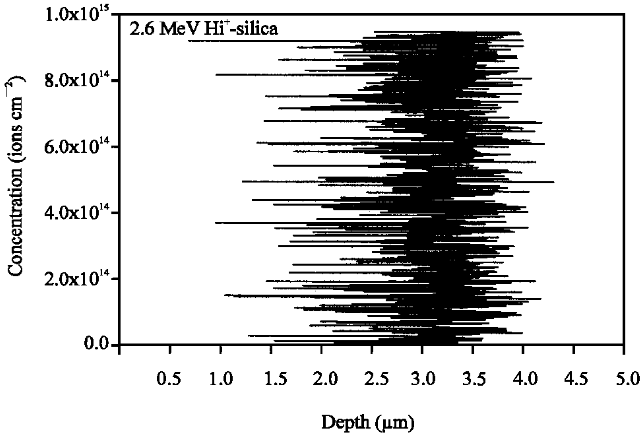

Fig. 2: Formation of planar waveguides with a 9×10^{14} ions cm^{-2} Ni$^+$implantation into silica due to the decrease of the refractive index in the buried index barrier as a function of the penetration depth

refractive index changes of typically 1-2%. In this case, the implanted layer constitutes the optical waveguide. For example, low loss channel waveguides have been fabricated by implantation of MeV ions, Ge, Si or P (Benaïssa *et al.*, 2006). The implantation of light ions with high energy of some MeV into oxide crystals results in the formation of a buried damaged layer of reduced refractive index compared to the substrate material.

The ions lose most of their energy by electronic ionizations during their path inside silica and for low kinetic energy of the ions, a large number of nuclear collisions occur that can result in a significant reduction of the refractive index, as indicated in Fig. 3a and b for implanted He$^+$ and Fig. 4a and b for implanted Ni$^+$. Note that the refractive index decrease is related to this nuclear damage; the concentration of deposited silica atoms is of minor importance. And as shown in Fig. 3 and 4, both electronic and nuclear energy losses with implantation of Ni ions are greater than ones with He ions. That means that correspondingly large decrease of refractive index took place in silica waveguide region by 2.6 MeV Ni$^+$ ion implantation and the shapes of the refractive index between the two waveguides are quite different.

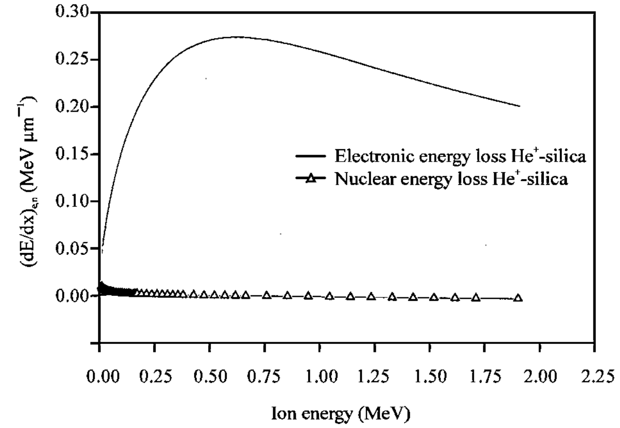

Fig. 3a: Maximum energy losses of He$^+$ ions in silica due to nuclear collision and electronic excitation as a function of the ion-beam energy

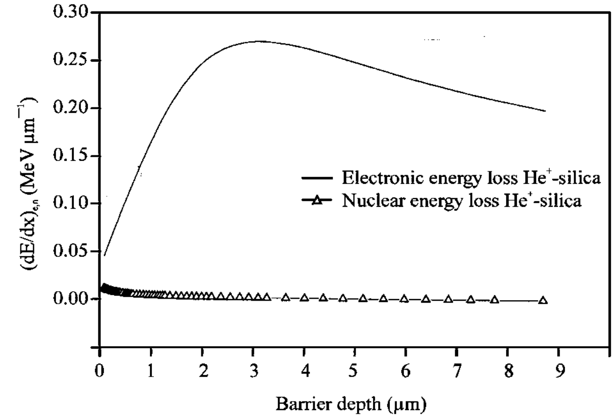

Fig. 3b: Maximum energy losses of He$^+$ ions in silica due to nuclear collision and electronic excitation as a function of the barrier depth

Despite the applicability of the implantation technique to form waveguides in a large variety of materials, the magnitude and even the sign of the index change strongly depend on the material. The major change in refractive index in He$^+$ and Ni$^+$ implanted waveguides in this silica material is primarily due to collision damage caused by the ion beam, so that the index profile is strongly related to the damage profile. With increasing implanted helium and nickel dose, both electronic and nuclear damage of the waveguiding layer grows and the photorefractive properties of the waveguides are considerably degraded.

It seems reasonable that the lattice damage produced by ion implantation plays the most important role in refractive index change in ion implanted silica. Lattice damage brings on a decrease in physical density and hence to a reduced refractive index. However, lattice damage due to light ions irradiation is different from that induced by heavy ions implantation. Figure 5 and 6 represents the vacancy distribution in the 2.6 MeV Ni$^+$ and 2 MeV He$^+$ ions implanted silica. As far as heavy ions implantation is concerned, the two shapes shown in Fig. 5 and 6 are different to a certain extent. The reason is that the contribution to change of the refractive index by the electronic excitation is not neglected in the case of heavy ions implantation, whilst energetic light ions causes little or negligible structural damage by electronic interaction with the first microns in the waveguide region.

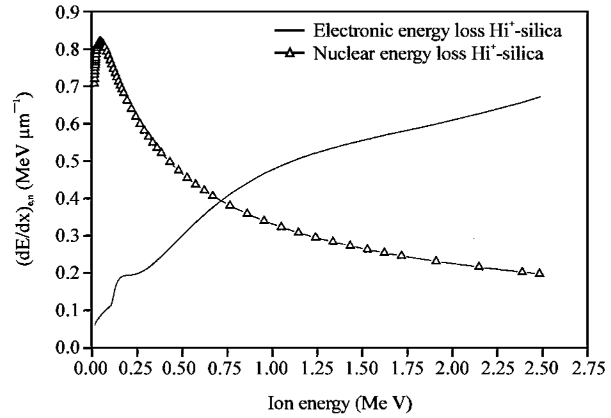

Fig. 4a: Maximum energy losses of Ni^+ ions in silica due to nuclear collision and electronic excitation as a function of the ion-beam energy

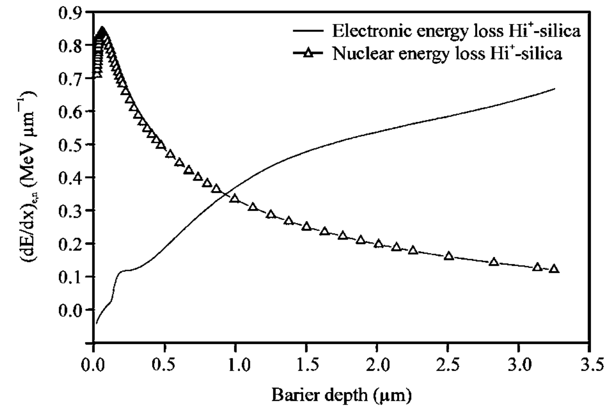

Fig. 4b: Maximum energy losses of Ni^+ ions in silica due to nuclear collision and electronic excitation as a function of the barrier depth

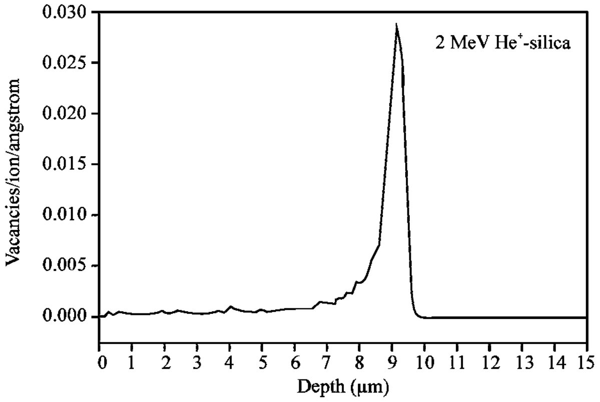

Fig. 5: The vacancy density versus the depth in silica for 2 MeV He^+ ions to the dose of 1.5×10^{16} ions cm^{-2} as a function of the penetration depth

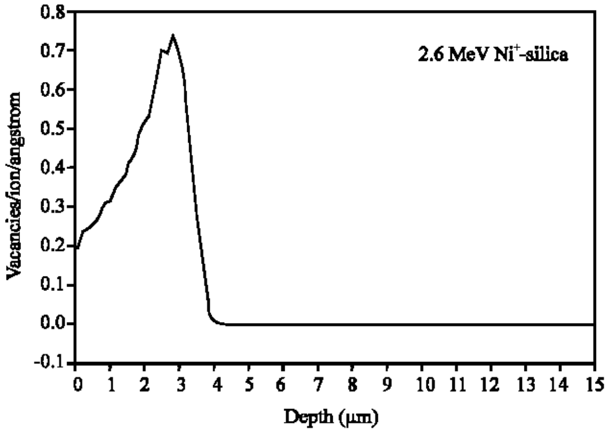

Fig. 6: The vacancy density versus the depth in silica for 2.6 MeV Ni^+ ions to the dose of 9×10^{14} ions cm^{-2} as a function of the penetration depth

CONCLUSIONS

Planar optical waveguides were formed by 2.6 MeV Ni^+ ions with dose of 9×10^{14} ions cm^{-2} and 2 MeV He^+ ions with dose of 1.5×10^{16} ions cm^{-2} in fused silica. The present results also show that the shape of the refractive index profile in silica waveguide by MeV Ni^+ ion implantation is different from one by MeV He^+ ion implantation owing to the ions density vacancies and loss deposited electronic (ionization) energy and nuclear energy in the silica target.

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