The production of optical waveguides by ion implantation: the case of rutile

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With the purpose of developing optoelectronic devices, optical waveguides have been produced by ion implantation in many solids. The implantation process creates a damaged layer near the end of the ion trajectories, with a consequent reduction of density and index of refraction. This produces an optical barrier at a depth of a few microns, depending on the type of ion and its energy. The barrier and the surface constitute a planar waveguide. Rutile (TiO_2 tetragonal structure) single crystals were implanted with 7 MeV carbon ions using the Instituto de Física 3 MV Pelletron Accelerator, in the (100) and (001) directions, and Poly Allyl Diglycol Carbonate (PADC) as detection material. The waveguides were observed using the coupled prism technique, which indicated differences in the waveguides produced for different directions due to crystal anisotropy.

Keywords: Optical waveguides; ion implantation; rutile.

En un gran número de sólidos se han producido guías de onda ópticas por implantación de iones, con el propósito de desarrollar dispositivos opto-electrónicos. La implantación produce una capa con daños en la estructura, reduciendo la densidad y el índice de refracción. Esto da lugar a una barrera óptica a una profundidad de algunos micrómetros, dependiendo del tipo de ion y su energía. La barrera y la superficie forman una guía de onda. Se produjeron guías de onda planas en rutilo (TiO_2 con estructura tetragonal) por implantación de iones de carbono de 7 MeV con el Acelerador Pelletron del Instituto de Física de 3 MeV, en las direcciones (100) y (001), usando policarbonato allil diglicol (PADC) como material detector. Las guías de onda producidas fueron observadas usando la técnica de prisma acoplado, y se observaron diferencias debidas a la anisotropía de los cristales.

Descriptores: Guías de onda ópticas; implantación de iones; rutilo.

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1. Introduction

Waveguides in optical materials are a promising way to help couple electric and optical signals in opto-electronic devices. Many types of waveguide have been produced in these materials, including YAG (yttrium-aluminum garnet), YVO (yttrium-vanadium oxide), $LiNbO_3$, quartz and others [1]. One way of producing waveguides in some of these materials is by implanting ions from a particle accelerator. When this technique is used, parameters such as purity of the ion species, beam energy (and thus penetration of the ions), and fluence (quantity of ions implanted) can be strictly controlled, giving clean, homogeneous and reproducible results.

Single crystal rutile (TiO_2) is transparent and birefringent. It has a very high refraction index (ordinary and extraordinary refractive indices 2.5837 and 2.8725 respectively for 632.8 nm light) and is used for special optical applications, such as polarizers. Its crystal structure is tetragonal with lattice parameters a= 0.459 nm and c= 0.296 nm. The purpose of this work is to investigate whether optical waveguides can be produced in rutile by ion implantation, and determine the conditions.

When energetic ions penetrate a sample, they travel a distance (in our case a few μm) which depends on their initial kinetic energy. Along this path they deposit their energy mainly through two processes: ionization and structural damage. The amount and location of the ionization and damage produced, as a function of type of ion, type of absorber, and ion energy, can be calculated using the code SRIM [2], which is based on a good understanding of the mechanisms of passage of ions through matter. Most of the structural damage is produced near the end of the ion's path, producing a disordered region with reduced density and consequently a zone of reduced refraction index which constitutes an optical barrier. One can choose the depth at which the barrier appears by adjusting the ion energy. If a thick barrier is required, implantations at several nearby energies can produce the effect. The waveguide is formed between the polished sample surface and the barrier.

Carbon ion implantation has been used to produce waveguides in some materials. The barrier thickness produced is larger than with protons or He ions, making the barrier more effective. Also, C ions produce more damage, so less fluence is required to form the barrier. On the other hand, some damage is produced in the guide region, producing absorption and scattering of the light. Some of this damage can be reduced annealing the sample. Ions heavier than C produce considerably more damage, and it is to be determined whether they generate useful effects.

2. Experiment

Single crystal 10×10 mm rutile samples with polished faces normal to the (100) and (001) directions were purchased from MRI Corporation. The structure was verified by observing

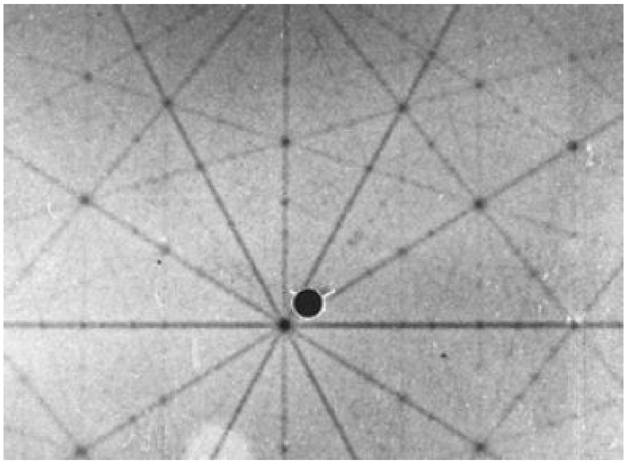

FIGURE 1. Rutile single crystal blocking pattern obtained with 2 MeV He ions, and CR39 polycarbonate sheet 10 cm from the sample. The ions entered approximately in the (100) direction.

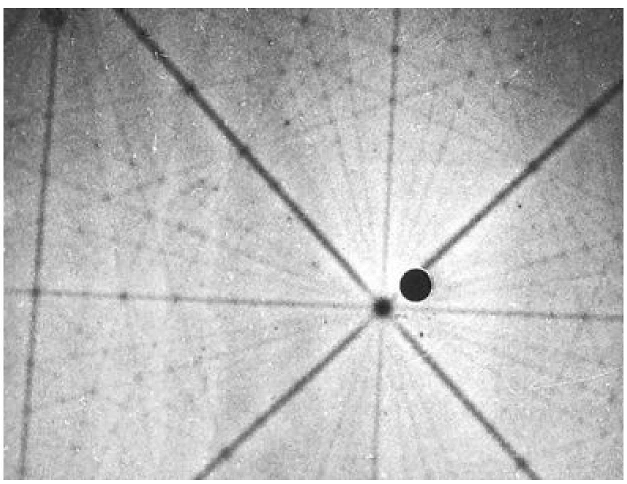

FIGURE 2. Blocking pattern in the (001) direction.

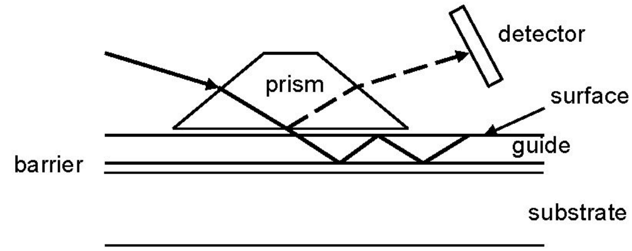

FIGURE 3. Geometry of the prism coupling method used to observe the waveguides.

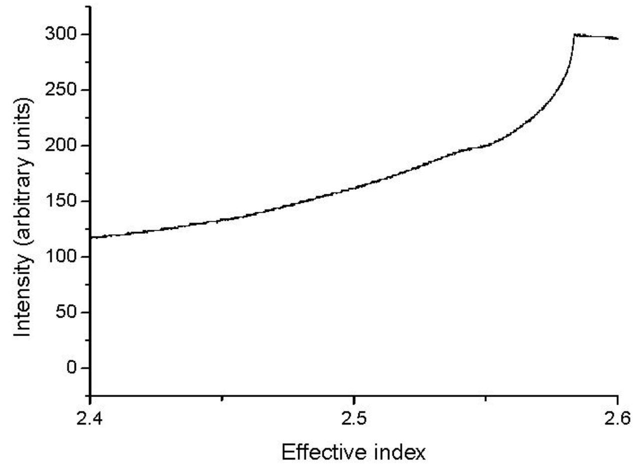

FIGURE 4. Reflected intensity *vs* effective refractive index curve obtained from an unimplanted rutile crystal, using 632.8 nm light. The step corresponds to the ordinary refractive index (2.5837). No waveguide is observed.

backscattered blocking patterns using 2 MeV He ions from the Instituto de Física 3 MV 9SDH-2 Pelletron accelerator. The blocking patterns were recorded using Nuclear Track Methodology [3,4], on CR39 polycarbonate sheets (Pershore®) which were later chemically etched with 6N KOH solution at 60°C $\pm$ 1°C, during 6 hours to reveal the particle tracks. Examples of the (100) and (001) blocking patterns obtained are shown in Figs. 1 and 2. The crystal planes are easily identified.

The samples were implanted with 7 MeV C^{3+} ions from the Pelletron accelerator, rastered over the whole surface to produce planar waveguides. They were tilted 8° during implantation to avoid channeling. The corresponding SRIM calculation indicates the production of an asymmetrical damaged region with a maximum at a depth of 3.79 μm and an average width of 0.32 nm. The fluence was 1×10^{15} cm^{-2} (1×10^{19} m^{-2}), which would produce 0.61 displacements per atom at the damage maximum.

The optical properties were studied using the coupled prism technique [5,6]. Due to the high refractive index of rutile, a special high refractive index prism was required. A laser beam is coupled to the waveguide (Metricon Model 2010 analyzer in the TE mode) with the geometry shown in Fig. 3. The reflected light (632.8 nm) intensity is recorded as the incoming angle is varied. When the angle is such that light enters the waveguide, a minimum is produced for each propagation mode. An effective refractive index can be calculated for each mode.

3. Results and discussion

Figures 4 and 5 show the reflected light intensity as a function of effective refractive index for the (001) sample (optical axis), before and after implantation. In the unimplanted case (Fig. 4), the drop in intensity corresponds to the critical angle and there is no guide. The implanted sample (Fig. 5) shows up to ten minima after the initial drop, indicating the presence of a waveguide, each minimum corresponding to a propagation mode within the waveguide. When the sample was rotated around the 001 axis the same light intensity pattern was observed.

Figure 6 shows the pattern obtained for the sample implanted in the (100) direction. The minima are an indication

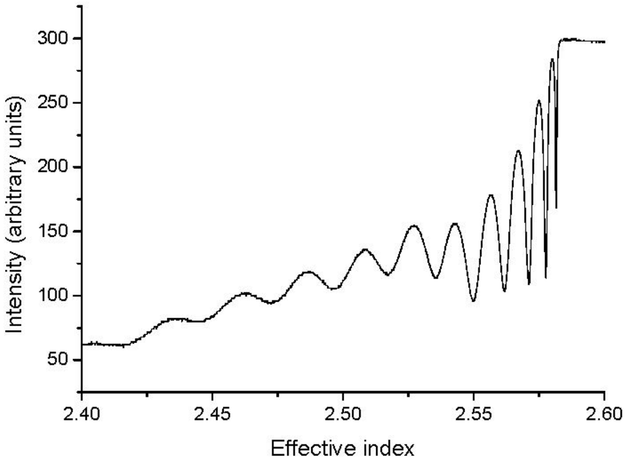

FIGURE 5. Reflected intensity *vs* effective refractive index curve from a rutile crystal implanted with 1×10^{15} cm^{-2} 7 MeV C ions in the (001) direction. The minima correspond to the different modes of propagation in the waveguide.

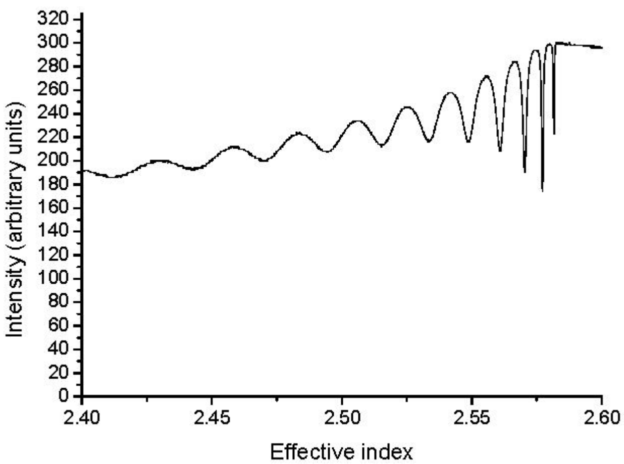

FIGURE 6. Reflected intensity *vs* effective refractive index curve from a rutile crystal implanted in the (100) direction.

that a waveguide is produced. However, on rotating the sample 90° around the (100) axis, the pattern is modified, presenting minima typical of the higher modes, and suggesting that the first modes are off scale and beyond the apparatus useful range (Fig. 7). They would correspond to the extraordinary index. (2.8725), whereas in the previous cases the ordinary index (2.5837) is relevant. Due to the crystal birefringence, the ordinary ray is guided in one direction and the extraordinary ray in the perpendicular direction.

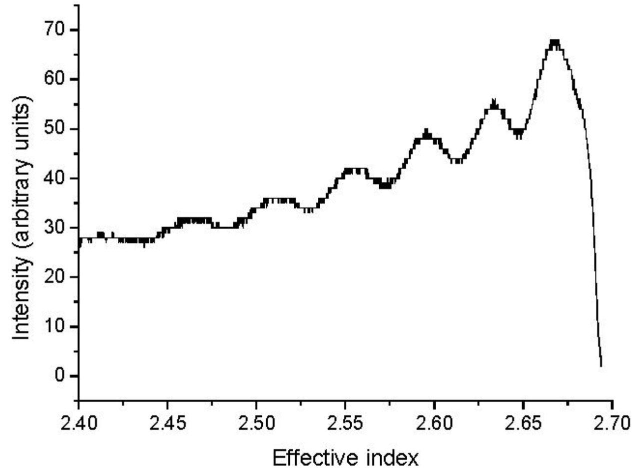

FIGURE 7. Reflected intensity *vs* effective refractive index curve from a rutile crystal implanted in the (100) direction, when the crystal was rotated perpendicular to the (100) direction.

4. Conclusions

Planar optical waveguides were produced in rutile single crystals by 7 MeV C ion implantation in different crystallographic directions, (001) and (100), at a fluence of $1{\times}10^{19}$ m^{-2}. The prism coupling method was used to analyze the waveguide modes. In the (100) case the ordinary index gives rise to the wave propagation in one direction and the extraordinary index to propagation in the perpendicular direction.

Acknowledgements

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