RESEARCH Revista Mexicana de Física **64** (2018) 251–253 MAY-JUNE 2018

Planar waveguides produced by implanting Si and C ions in rutile

J. Mejía[a,*], E. Flores-Romero[b], R. Trejo-Luna[c], and J. Rickards[c]
[a]*Posgrado en Ciencias Físicas, Instituto de Física, Universidad Nacional Autónoma de México,*
Apartado Postal 20-364, Ciudad de México, 01000, México.
[*]*e-mail: julianmejia@ciencias.unam.mx*
[b]*CONACyT, Instituto de Física, Universidad Nacional Autónoma de México,*
Apartado Postal 20-364,Ciudad de México 01000, México.
[c]*Departamento de Física Experimental, Instituto de Física, Universidad Nacional Autónoma de México,*
Apartado Postal 20-364, Ciudad de México, 01000, México.

Received 13 December 2017; accepted 21 February 2018

Planar waveguides were generated in samples of rutile crystal ($\mathrm{TiO_2}$) by bombarding with two types of ion: silicon and carbon. Rutile is used because of its anisotropic properties, particularly its birefringence. The guide is generated due to damage caused by the ions in the crystal which change its index of refraction. Three parameters were used: the implantation ion energy, the implantation fluence, and the orientation of the crystallographic planes. The refractive index profile of the irradiated sample was calculated and together with the value of the optical barrier the comparison was made between the different waveguides generated.

Keywords: Optical Waveguides; Ion Implantation; Rutile; Important Optical properties of Crystals; Various Crystal Faces; Ions; Fluences; Two Different Ions-Damage; Reduce Fluence With Si Ions.

PACS: 42.82; 41.75

1. Introduction

Ion implantation has been used extensively to generate planar optical waveguides in crystals [1,2], as part of the development of miniature optical and optoelectronic devices.

Implanting ions from a particle accelerator is a useful method for producing waveguides. The nuclear stopping of the ions in the implantation process creates a damaged layer in the crystal near the end of the ion trajectories, with a consequent reduction of material density and index of refraction. This produces an optical barrier at a depth determined mostly by electronic stopping, and which can be controlled by the mass, charge and energy of the ion [3]. The amount of implanted ions and the thickness of the barrier determine the effectiveness of the produced optical barrier. The planar waveguide is formed between the optical barrier and the crystal surface.

Single crystal rutile ($\mathrm{TiO_2}$) is transparent in the visible spectrum and is birefringent. It has a very high refraction index (ordinary and extraordinary refractive indices are 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.

Most waveguides in crystals have been produced by implanting H or He ions. Heavier ions allow wider optical barriers and require less ion fluence for comparable results. Waveguides with C implantation have been produced before in rutile [4] and other crystals [5,6]. Yet, the increase of the damage in the crystal due by the increase of the mass of the ion may result detrimental for the confinement of the light into the waveguide [1]. The purpose of this work is to compare resulting waveguides formed by implanting C and Si ions, and determinate if the increase of mass of the ion allows wider optical barriers keeping the optical characteristics, besides analyze the effect of the anisotropy of the crystal in the waveguide generated.

Here we report on the production of waveguides in rutile single crystals ($\mathrm{TiO_2}$, an anisotropic and high refraction index material with tetragonal crystal structure). A comparison is made of conditions for producing waveguides with two types of ions: carbon and silicon. Also is noticed the effects of tow different fluences of implantation.

2. Generation and measurements of waveguides

Oriented (001) and (100) polished single rutile crystals were purchased from MTI Corporation. The structure was verified by observing backscattered blocking patterns using 2 MeV He ions (Not showed). They were implanted with either 7 MeV C ions or 12 MeV Si ions using the 9SDH-2 Pelletron accelerator. The implanted faces were tilted 8° to the perpendicular to the beam to avoid channeling effects. The ion beam (with a typical current of 200 nA) was scanned over the whole 1×1 cm surface of the crystal. The energies were selected such that the ion ranges in both cases were comparable, as determined with the SRIM [7,8] code. Fluences of 1×10^{14} cm^{-2} and 1×10^{15} cm^{-2} were applied for both ions.

The produced optical waveguides were measured using a Metricon 2010/M prism coupler, at a wavelength of 632.8 nm in the dark line mode. A Transversal Electric (TE) light beam is directed onto a prism coupled to the surface to be studied and is totally reflected onto a detector.

Inside the Metricon the sample coupled to the prism is rotated to vary in angle of incidence of the light source until the critical angle is attained, and light enters the sample. As the sample is rotated further, a series of dark values are observed in the detector, corresponding to the different propagation modes in the waveguide [9-10].

A high refraction index prism is required, since rutile is highly refractive; in the present case a GaP prism with a refraction index of 3.314 at 632.8 nm was used.

3. Waveguide analysis

An example of the refractive index variation obtained in these conditions from a sample implanted in the (100) direction is the Fig. 1, with the waveguide produced for the extraordinary ray (crystal's larger refractive index direction).

The distribution of the damage produced by the ion beam in the target may best be described by the number of displacements per atom (dpa) vs depth. The number of dpa, that is the average number of displacements a target atom undergoes subject to a given ion fluence, can be obtained from the SRIM code [7]. In general, the maximum dpa lies slightly below the ion projected range, and it is distributed along the path length as depicted in Fig. 2, which is a calculated plot of dpa vs depth, for a fluence of 10^{15} cm^{-2}, 7 MeV C ions and 12 MeV Si ions implanted in TiO_2. The waveguide is expected to be formed in the region between the maximum dpa and the surface, the maximum acting as an optical barrier.

Refraction index contours were obtained experimentally for each of the implantation parameters studied. These data were analyzed using the code WGII [11], adjusting the calculation parameters to obtain the best fit to the propagation modes.

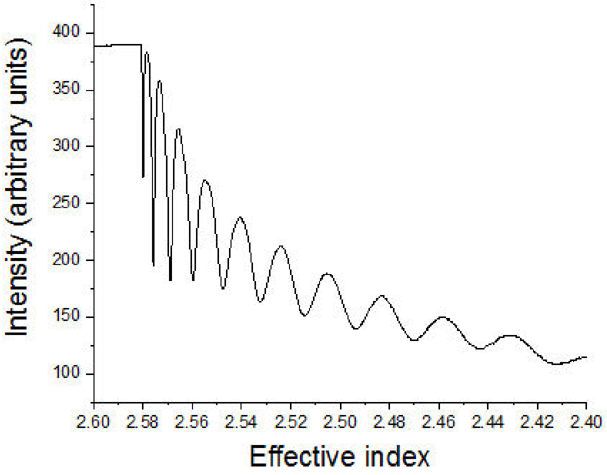

FIGURE 1. An example of the index variation obtained from a rutile sample implanted in the (100) direction, with a waveguide produced for the extraordinary ray.

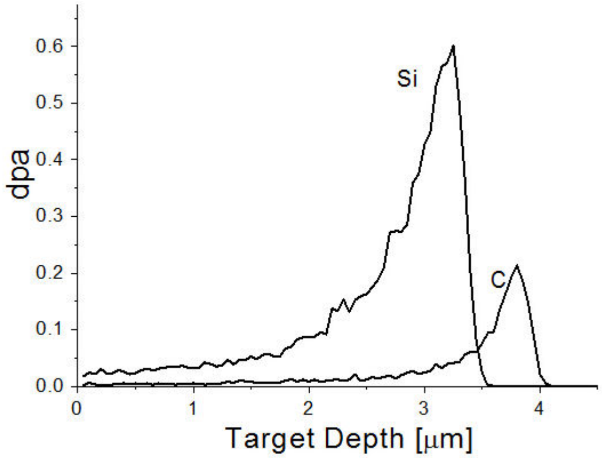

FIGURE 2. Calculated plots of dpa vs depth, for a fluence of 1×10^{15} cm^{-2}, 7 MeV C ions and 12 MeV Si ions implanted in rutile.

4. Results and Discussion

The result of the calculation is an index profile as shown in Fig. 3 for the same case as that of Fig. 2. Here we are defining the height B as a measure of the barrier effectiveness and therefore the usefulness of the waveguide. The height B is the difference of values of the refractive index between the minimum value of the optical barrier and the region of minimum ionic damage in the substrate.

Previous research results [2,12] convinced that the "well plus barrier" confined waveguide has better light confinement effect than "barrier" confined because it could avoid the tunneling effect. The B height synthesizes this information.

The two used directions has different atomic densities due to the anisotropic crystal lattice. In the (100) direction the atomic density is larger and hence the dpa is largest, which results in a better optical barrier. The ordinary ray in the direction (100) has a upper B value than the direction (001),

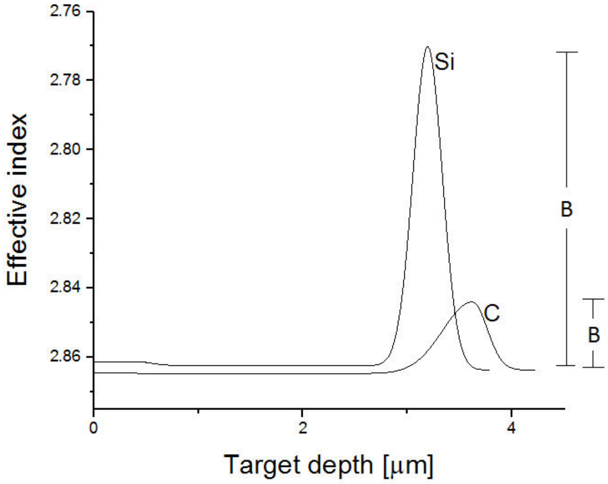

FIGURE 3. Index profile obtained from the code WGII for the same cases as those in Fig. 2.

TABLE I. B values of four waveguides in the orientation with the larger optical barrier.

Ion	Fluence [cm^{-2}]	Orientation	B value
C	1×10^{14}	100	0.018
C	1×10^{15}	100	0.025
Si	1×10^{14}	100	0.032
Si	1×10^{15}	100	0.039

in spite of that they have the same refractive index. Unfortunately this noticed effect over the dpa is not possible to confirm with the SRIM computation since is not allowed to specify the implantation direction in the software.

The optical barriers are better defined in the orientation (100) in the extraordinary ray, the values for those optical barriers are shown in Table I.

The waveguides generated with both types of ions show an increase in their B value by increasing the fluence (see Table I), however the B value for Si improves only a 21.87% while the improvement for C is 38.88%. The two main causes for this effect are; the larger amount of colour centres caused by the increasing of the ion mass [5], and the change in the dpa distribution by changing the fluence and energy of the ion implantation.

Typically, as the fluence and the implantation energy increases the dpa distribution becomes wider and reaches a lower maximum [3], leading to a lessening in the effectiveness of the optical barrier.

The observed differences in the B value gains suggest that the solely increase of one of the waveguide generation parameters may not lead to a significant improvement of the light confinement. Thus, the combined effect of the implantation parameters variation would result better for the B value optimization.

5. Conclusions

In the planar waveguides generated by ion implantation, substrate anisotropy, fluence, implantation energy and ion mass are control parameters that significantly affect the confinement of light. In general, Si implantation produces better results than C implantation (in the B value and hence in the confinement of light) especially in the extraordinary ray (100).

Of all the cases, the best is the extraordinary ray in the (100) direction with a Si ion and a fluence of 1×10^{15} cm^{-2}. This being the case in which there was a higher refractive index in the crystal, the heavier ion was used and, the higher fluence was applied. However, this was not true for the best relative increase in the B value.

Acknowledgements

The technical support of K. López and F. Jaimes is gratefully acknowledged also Program PAPIIT UNAM project IN113111 and SNI III researcher assistants program of CONACyT.

---

1. P. Chandler P. Townsend and L. Zhang, *Optical Effects of Ion Implantation* (Cambridge University Press, 1994).
2. Jin-Hua Zhao, Xi-Feng Qin, Feng-Xiang Wang, Yang Jiao, Jing Guan, and Gang Fu, *Nucl. Instr. Meth. B 409* (2017) 163.
3. H. Márquez *et al*., *Opt. Mater.* **35** (2013) 927.
4. J. Rickards, R. Trejo-Luna, E. Flores-Romero, J. Golzarri, and G. Espinosa. *Rev. Mex. Fis. S* **57** (2011).
5. M.E. Sánchez-Morales, G.V. Vázquez, G. Lifante, E. Cantelar, J. Rickards, and R. Trejo-Luna. *Opt. Spectrosc.* **110** (2011) 885.
6. Mei Qiao *et al*., *Nucl. Instr. Meth. B* **9** (2017).
7. J. Biersack J. Ziegler and U. Littmark, *The Stopping and Range of Ions in Solids*. Pergamon Press, (New York, 1985).
8. James F. Ziegler, M.D. Ziegler, and J.P. Biersack, *Nucl. Instr. Meth. B* **268** (2010) 1818.
9. P.J. Chandler and F.L. Lama, *Opt. Acta.* **33** (1986) 127.
10. F.L. Lama and P.J. Chandler, *J. Mod. Opt*. **35** (1988) 1565.
11. G. Lifante, *Integrated Photonics: Fundamentals. Southern Gate*, Chichester,West Sussex PO19 8SQ, (England, 2003).
12. Feng Chen, Xue-Lin Wang, and Ke-Ming Wang, *Opt. Mater.* **29** (2007) 1523.