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Random stopping power and energy straggling of ^{16}O ions into amorphous Si target

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Abstract

In the present contribution, we report results on random stopping power and range straggling of ^{16}O ions into amorphous Si target. The measurements were performed in a 300 keV–13.5 MeV energy interval by using the Rutherford backscattering technique together with a marker system. The present stopping results were compared with the TRIM predictions based on the Ziegler, Biersack and Littmark calculations, the theoretical values being always higher than the experimental ones. On the other hand, the calculated straggling data are compared with the Bohr predictions. For low energies, the calculated values over-estimate the experimental ones. For energies larger than 2 MeV, the experimental results became larger than the Bohr predictions. However, with increasing energies, the experimental results approach the Bohr values, and above 12 MeV a quite good theoretical experimental agreement was found. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The slowing down of energetic ions penetrating into the matter has been intensively studied for many years. As a consequence, a large number of range measurements on a variety of projectile–target combinations have been performed in order to test current theories [1]. On the other hand, in the same period of time much less stopping power measurements have been reported.

An accurate knowledge of stopping powers is important from two points of view. First, the data can test inter-atomic potentials and/or electronic excitation models used in range and atomic displacement calculations. Second, from the practical point of view, the data can be used as input of analytical or Monte-Carlo type of programs that calculate depth distributions and damage produced by ions implanted into a given target.

Usually the energy loss of ions has been performed by measuring the final energy of ions transmitted through thin foils. However, the use of this method strongly depends on the preparation of homogeneous self-supporting films. In particular, in order to measure the energy loss of ions heavier than protons or He at low or intermediate energies, extremely thin films must be employed.

The random stopping power data for O in Si are scarce and incomplete. First measurements were performed by Santry and Werner [2] in a 200–2000 keV energy range. More recently, Jiang et al. [3]

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have also measured the O random stopping in Si in 5–20 MeV energy interval. Both experiments have been done using the transmission technique. Consequently, we decided to measure the O random stopping in Si in a wide energy range between 350 keV and 13.5 MeV by using the Rutherford backscattering (RBS) technique together with a set of markers. In addition, we have determined, for the first time, the range straggling of O in a Si.

The stopping power data were compared with the previous measurements as well with the predictions of the sub-routine RSTOP of the TRIM program [4]. On the other hand, the straggling data were compared with the Bohr predictions [5].

2. Experimental procedure

2.1. Stopping power measurements

For this experiment, we have used Bi markers implanted into an amorphized Si wafer. First, we have determined the projected range R_p of the Bi ion distribution using a He beam. Then, we have determined the energy position of the same marker by using an O beam at different energies. With this information, we were able to determine the random stopping of O in Si as described below.

The sequence of experiments was the following. First, we have amorphized a Si⟨1 0 0⟩ wafer by using an Ar beam ($\Phi = 3 \times 10^{14}$ Ar/cm^2, $E = 400$ keV). After that, we have prepared a series of markers by implanting Bi in different pieces of the wafer at several energies, $E = 30$, 50, 100, 200, 400 and 900 keV. In this way, we have obtained different markers to be used for different energies of the analyzing O beam. Then, we have determined the range of the implanted Bi markers by using a 1200 keV He^{2+} beam provided by the 500 kV ion implanter of the Instituto de Física, Universidade Federal Rio Grande do Sul. The backscattered He particles were detected by a Si surface barrier detector placed at 170° with respect to the beam direction. The overall resolution of the system was better than 12 keV. The range measurements were done in two types of geometries namely (a) with the sample at normal angle with respect to the beam and (b) with the sample at six different angles (between 15°and 60°) with respect to the beam normal. A typical RBS spectrum is shown in Fig. 1(a).

The energy to depth conversion was carried out using the He stopping power values as reported by Niemann et al. [6]. The obtained R_p values are quoted in Table 1. Each one has been obtained as a result of 10 measurements done at different geometries. The quoted errors are the ones which arise from the statistical treatment of the individual measurements plus those which came from the uncertainties in the determination of the He stopping (estimated at a 1% level).

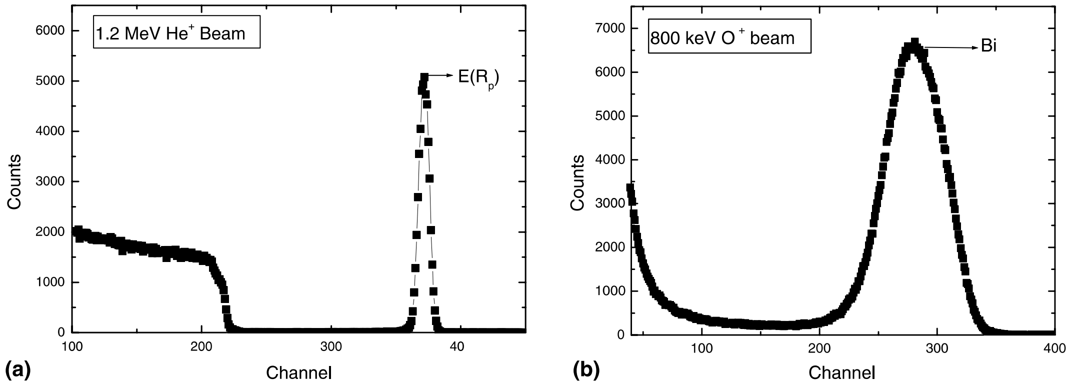

Fig. 1. (a) RBS spectrum of a 50 keV marker implanted in Si obtained with a 1200 keV He beam. (b) Same as (a) but obtained with a 800 keV ^{16}O beam.

Table 1
Bi implanted into a-Si characteristics

Energy (keV)	Fluence (Bi/cm^2)	R_p (Å)
30	2×10^{16}	195 ± 30
50	2×10^{16}	267 ± 30
100	2×10^{16}	442 ± 50
200	2×10^{16}	757 ± 60
400	2×10^{16}	1486 ± 80
900	1×10^{16}	2972 ± 100

In a next step, we have determined the energy position $[E(R_p)]$ of the implanted Bi peak by using O beams with energies that varied between 350 and 13 500 keV. For the 900–13 500 keV energy range, we have used the O beam provided by the 3MV Tandetron accelerator of our institute. Fig. 1(b) displays a RBS spectrum taken with a 800 keV O beam. The energy position corresponding to the maximum of the Bi distribution is marked in the figure as $E(R_p)$. Considering the expression for the random energy-loss factor,

$$[S(B)]_{\mathrm{Bi}}^{\mathrm{Si}} = \frac{K_{\mathrm{Bi}}E_0 - E(R_p)}{R_p}, \tag{1}$$

we can obtain the values for the random stopping of O in Si through the relation between the energy-loss factor and the energy loss per unit length $\mathrm{d}E/\mathrm{d}x$ (in the mean energy-loss approximation [7]),

$$[S(B)]_{\mathrm{Bi}}^{\mathrm{Si}} = \frac{K_{\mathrm{Bi}}}{\cos\theta_1}\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{E_0} + \frac{1}{\cos\theta_2}\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{K_{\mathrm{bi}}E_0}. \tag{2}$$

It can be observed from expressions (1) and (2) that at least two measurements of $E(R_p)$ (performed at different geometries) must be done in order to determine the energy loss $\mathrm{d}E/\mathrm{d}x$ at E_0 and $K_{\mathrm{BiE_0}}$ energies. In the present experiment, for each O energy we have performed six different measurements changing the angle between the incident beam direction and the sample's normal. For each energy, the set of measurements were reproducible at a 5% level.

2.2. Straggling measurements

For the straggling measurements, we have proceeded as follows. The spectra of the implanted Bi markers were analyzed with He beams as described in Section 2.1. Then, for each marker, we have de-convoluted the He obtained spectrum with the detector plus electronic system resolution and He in Si straggling as determined in [8]. Consequently, we have obtained the "true" Bi in Si distribution. In a next step, the markers were analyzed with an O beam. The as-obtained spectra were de-convoluted with the detector plus electronic resolution of the system (28 keV full width half-maximum) and the "true" Bi in Si distribution. The remaining Bi distribution should be ascribed to the O in Si straggling.

3. Results and discussion

In Fig. 2, we show the present random stopping results together with the previous ones obtained by Santry and Werner [2] and Jiang et al. [3]; in addition, we show the predictions of Ziegler, Biersack and Littmark as provided by the sub-routine RSTOP of the program TRIM version 1991 and 2000 [4]. An inspection of the figure shows the following features: (a) the present results are in excellent agreement with those of Santry and Werner [2]; (b) the Jiang et al. [3] data are systematically higher than the present ones, the difference being of the order of 8–10% and (c) the predictions of the TRIM program are also systematically higher than the present measurements, increasing the difference with increasing energy and being of the order of 15% for the highest energy.

In addition, we show with a full line a polynomial curve as proposed by the Kalbitzer group [9] of the form

$$S = \frac{E^S \ln(e + \beta E)}{\alpha_0 + \alpha_1 E^{1/2} + \alpha_2 E + \alpha_3 E^{1+S}}, \tag{3}$$

with $S = 0.66$, $\beta = 15.7$, $\alpha_0 = 10.2$, $\alpha_1 = -0.23$, $\alpha_2 = 0.006$ and $\alpha_3 = -0.2 \times 10^{-5}$. As can be observed, expression (3) fits very well the present data and consequently describes analytically the present results.

In Fig. 3, we show the present straggling results normalized to the straggling of Bohr. For low

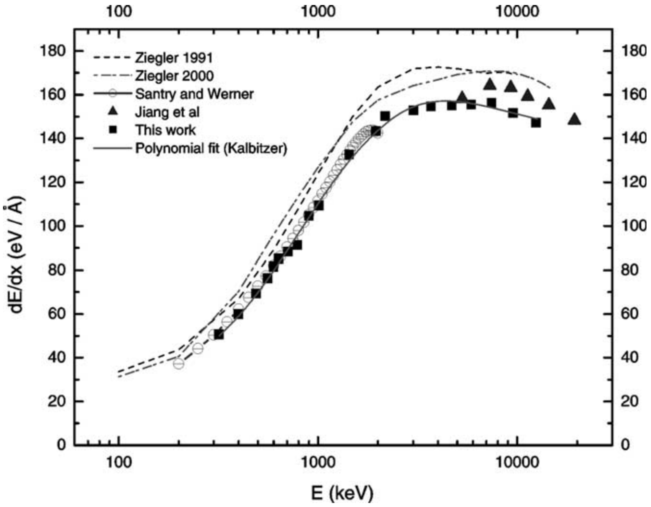

Fig. 2. Random stopping powers of ^{16}O in Si as a function of energy. With squares are represented the results of the present experiment; circles correspond to the data of Santry and Werner; triangles to the ones of Jiang et al. dashed lines are the predictions of TRIM 1991 and dashed-dotted to the ones of TRIM 2000. Full line corresponds to the fitting of the "universal" expression from the Kalbitzer group.

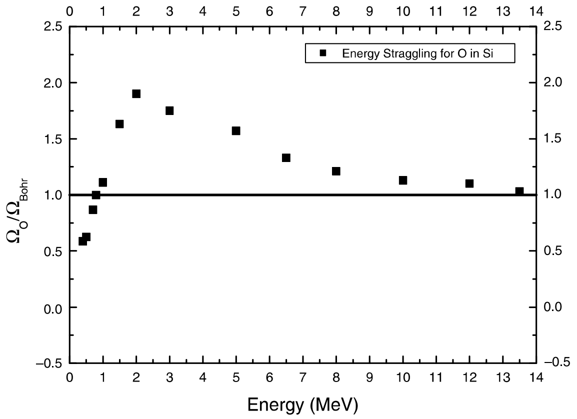

Fig. 3. Present results of range straggling of ^{16}O in Si normalized to the straggling of Bohr.

energies, the calculated values over-estimate the experimental ones. Then, for energies larger than 2 MeV the experimental values became larger than the Bohr predictions. However, with increasing energies the experimental results approach the Bohr calculations, and above 12 MeV a quite good theoretical experimental agreement was found. This behavior was observed for H, He, Li in Si and could be observed to the fact that in the Bohr theory it is assumed that the ion velocity is much larger than velocity of the electrons bound to the target atoms. This feature is only true at high ion velocities, typically between 400 and 800 keV/amu.

4. Conclusions

In the present contribution, we present random stopping power results as well as range straggling of O in Si in a 300 keV–13.5 MeV energy interval. The measurements were done by using the RBS technique together with marker samples.

Previous random stopping data have been measured using the transmission technique in a restricted and complementary energy range. The present data compares quite well with those of Santry and Werner [2] measured in a 200–1200 keV energy range. On the other hand, the data of Jiang et al. [3] obtained for a 5–20 MeV energy interval is systematically higher than the present one, the difference being of the order of 10%. A comparison with the TRIM predictions indicate that the calculated values are always larger than the experimental ones. The difference increases with increasing energy being of the order of 15% for the highest measured energy.

Concerning the straggling results, they are the first reported in the literature. When compared with the Bohr predictions they show, for energies smaller than 2 MeV to be lower than the calculations. For larger energies, the experimental values became larger than the Bohr predictions. However, with increasing energies the experimental results approach the Bohr calculations, and above 12 MeV a quite good theoretical experimental agreement is achieved.

Acknowledgements

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