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Nuclear Instruments and Methods in Physics Research B xxx (2004) xxx–xxx

NIM B Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

Random energy loss and straggling study of ^{9}Be ions in silicon

L.L. Araujo, M. Behar, P.L. Grande, J.F. Dias *

Instituto de Física, Universidade Federal do Rio Grande do Sul, Caixa Postal 15051, CEP 91501-970, Porto Alegre, RS, Brazil

Abstract

In the present work we have measured the random electronic stopping power and energy straggling of ^{9}Be in Si. In order to achieve this goal, we have employed the Rutherford backscattering technique together with a series of Bi markers implanted into Si. The stopping power measurements were performed in the 500–7000 keV energy range, while the energy straggling ones were done in the 800–5000 keV energy range. The results have been compared with the SRIM predictions and a quite good agreement is observed. Concerning the energy straggling, the experimental results are in general larger than predictions based on Bohr's formalism, and only at higher energies ($E \geqslant 3000$ keV) the present results approach the Bohr values.

1. Introduction

The energy loss of light ions in materials is an important issue. This is not only because of its direct application in ion beam analysis but also in order to improve the understanding of fundamental ion–solid interactions. Furthermore, for accurate ion beam analysis of elemental depth distributions in near surface layers, the stopping power of the respective ion-target combination must be known sufficiently well. The random stopping power is indeed well known for almost any H or He-target combination [1]. In particular, precise values for the stopping power of H, He, B and other light ions in amorphous Si have been already published [2–5]. These data are needed in order to test current theoretical calculation for the electronic energy loss and for analytic techniques such as elastic recoil detection analysis (ERDA) and heavy ion Rutherford backscattering (HIRBS) in order to perform precise energy to depth conversion.

In the present work, we have measured random electronic stopping powers and energy straggling of ^{9}Be ions in Si. We have used the Rutherford backscattering technique (RBS) together with a series of Bi markers implanted into Si wafers. The advantage of this experimental arrangement is that it does not make use of thin selfsupported films as is the case for transmission measurements. Furthermore, this technique allows for stopping power and energy straggling measurements at quite low energies. Consequently, we were able to measure stopping powers over a wide energy range, between 500 keV and 7 MeV, while we observed energy straggling over the 800 keV–5 MeV interval. The present results have been compared with

* Corresponding author. Address: Laboratório de Implantação Iônica, Instituto de Física – UFRGS, Av. Bento Gonçalves, 9500, CP 15051, Porto Alegre 91501-970, Brazil. Tel.: +55-51-3316-7248/7004; fax: +55-51-3316-7286.

E-mail address: jfdias@if.ufrgs.br (J.F. Dias).

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doi:10.1016/j.nimb.2004.01.062

predictions of the SRIM program [6] as well as with other experimental data obtained recently [7].

2. Experimental procedure

2.1. Be stopping power

Bi markers were produced by implanting Bi ions into Si at energies of 200, 400 and 900 keV. The fluences of Bi were kept at low values in order to avoid any influence on the energy loss measurements. The determination of the position of the Bi markers was done using a 1–3 MeV He beam provided by the 3 MV Tandetron of the Instituto de Física of Porto Alegre. A solid state detector situated at 170° with respect to the beam direction detected the backscattered He particles. We used a Canberra premium detector of about 10 keV resolution. Therefore, the overall resolution of the detection system was about 12 keV. The measurements were done with two geometries. One with the beam normal to the sample (normal geometry) and the second with the sample at four different angles between 20° and 60° with respect to the beam (tilted geometry).

The depth to energy conversion was done using the He stopping data as reported by Niemann et al. [2]. The results obtained are displayed in Table 1. It should be stressed that the values quoted were obtained from an average of eight different measurements at normal and tilted geometries. The errors were calculated taking into account (a) the statistical dispersion of the data, and (b) the reported uncertainties in the He stopping power [2] (around 1%). Other sources of errors such as geometry and instability of the electronic system are considered to be much less important. In a second step we have determined the position of the Bi markers by using the RBS technique with a Be beam, in the same conditions as described above.

Table 1
Peak position R_p and half-width of the gaussian Bi distribution ΔR_p of the markers implanted into Si.

Energy (keV)	R_p (Å)	ΔR_p (Å)
200	800	200
400	1400	300
900	2900	450

Considering the expression for the random energy loss factor

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

where K_{Bi} is the kinematic factor for Be ions impinging on Bi atoms, E_0 is the incident beam energy, $E(R_p)$ is the energy position of the Bi marker peak and R_p is the depth of the peak of the Bi implanted in the sample, we can obtain the values for the random stopping of Be in Si through the following relation between the energy loss factor and the energy loss per unit length $\mathrm{d}E/\mathrm{d}x$ (in the surface energy loss approximation):

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

where θ_1 and θ_2 are the angles between the target's normal with the beam direction and detector's normal, respectively. As it can be seen from the expressions above, it is necessary to perform at least two measurements of $E(R_p)$ at different geometries in order to determine the energy losss $\mathrm{d}E/\mathrm{d}x$ at E_0 and $K_{Bi}E_0$ energies. In the present experiment, for each Be energy we have performed five different measurements changing the angle between the incident beam direction and the sample's normal. Fig. 1 shows a RBS spectrum taken with a Be beam impinging on the Si target implanted with Bi. Further details of the analysis procedure can be found in [4].

2.2. Energy straggling

The energy straggling Ω_s of Be ions in Si was determined using also the RBS technique. We have used the ΔR_p values of the Bi distributions determined with the alpha beam. In addition, we have determined the detector and electronic resolution by using an Au film deposited on a Si wafer. Thus

$$\Omega_s = \sqrt{\Omega_m^2 - \Omega_d^2 - \Omega_{Bi}^2},$$

where Ω_s is the straggling and Ω_m is the measured value that includes also the broadenings Ω_d due to the detector plus electronic system and Ω_{Bi} corresponding to the Bi marker.

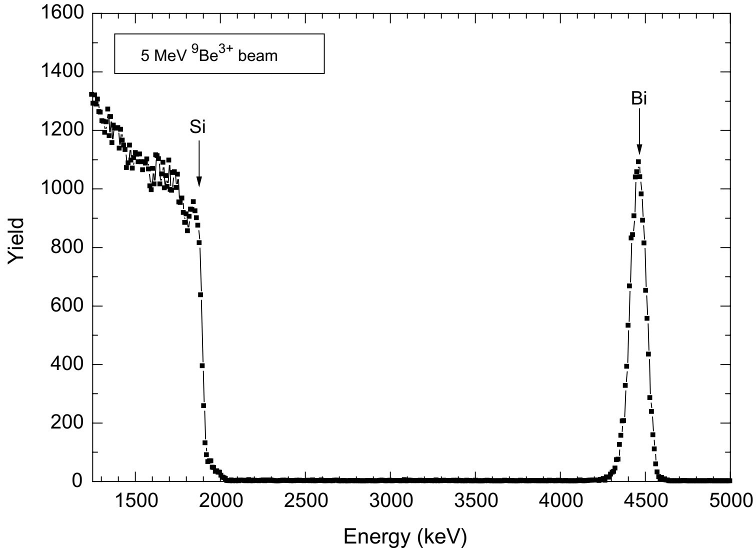

Fig. 1. RBS spectrum of a Bi marker taken with a 5 MeV ^{9}Be beam. The scattering angle was 120°.

3. Results and discussion

The Be random stopping powers obtained in the present experiment in the 500–7000 keV energy range are shown with open circles in Fig. 2. The uncertainties presented in the figure represent the statistical fluctuation of several results obtained for each ion energy under study. Comparing the experimental results with the SRIM predictions [6], it can be observed that for all energies studied

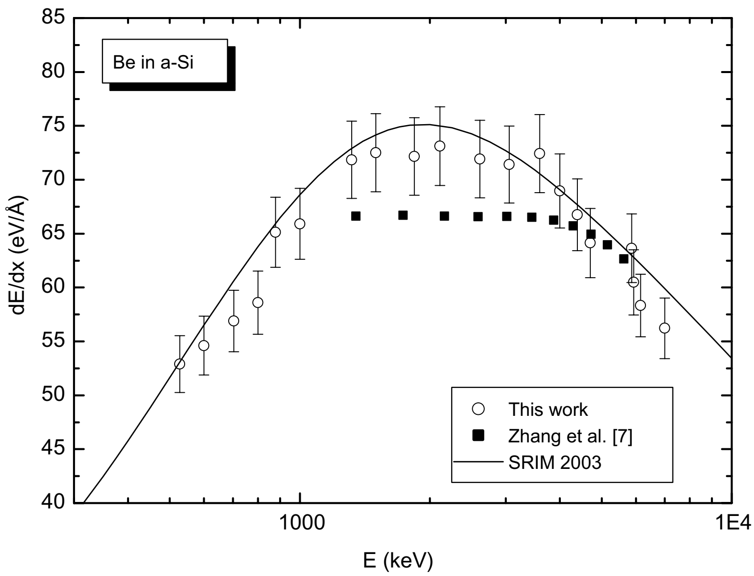

Fig. 2. Present stopping power (open circles) compared with the semi-empirical calculations SRIM 03 [6] (full line) and with data from [7].

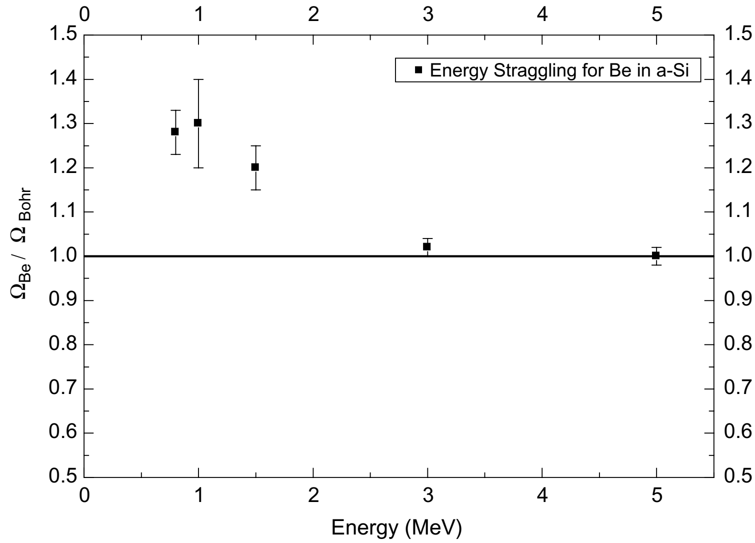

Fig. 3. Present energy straggling data normalized to the Bohr straggling.

in this work the theoretical–experimental agreement is quite good. In the same figure are shown the recent data obtained by Zhang et al. [7] in an energy range smaller than the present one. As can be observed, their stopping power results are smaller than both the present values and the SRIM predictions up to about 4 MeV. However, it must be pointed out that, for energies above 4 MeV, our results are compatible with those obtained in [7].

The Be in Si energy straggling results normalized to the Bohr straggling are presented in Fig. 3. The error bars are basically due to: (a) data statistical fluctuation in the determination of Ω_s and (b) the uncertainty in the Ω_{Bi} determination. As can be observed for low energies ($E \leqslant 3$ MeV) the experimental data is larger than the Bohr predictions, but with increasing energies the data trend approaches the Bohr predictions.

It is interesting to note that this kind of behavior has been observed for other ion-target combinations, where the experimental data only reaches the Bohr value for energies of the order of 500 keV/amu, which agrees with the present results.

4. Conclusions

In the present work we have studied stopping powers for ^{9}Be ions in amorphous silicon over a wide energy range (500 keV $\geqslant E \geqslant$ 7000 keV) and the energy straggling in a more reduced one (800 keV $\geqslant E \geqslant$ 5000 keV).

A comparison with the semi-empirical predictions of the SRIM program shows that there is an overall good agreement with the present data.

Concerning the energy straggling data, a comparison with the Bohr straggling indicates a behavior already observed for other ions: for low energies, an underestimation of the experimental results; and a clear tendency for a good experimental–theoretical agreement for energies equal or above 3 MeV.

Acknowledgements

This work was partially supported by the International Atomic Energy Agency (IAEA), Contract nr. 11313/RO.

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