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Indirect determination of the energy loss of protons channeled in silicon single crystals

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SEZIONE II
(Fisica, chimica, geologia, paleontologia e mineralogia)

Fisica. — *Indirect determination of the energy loss of protons channeled in silicon single crystals* (*). Nota di GIANANTONIO DELLA MEA, ANTONIO V. DRIGO, SERGIO LO RUSSO e PAOLO MAZZOLDI, presentata (**) dal Socio A. ROSTAGNI.

RIASSUNTO. — La perdita di energia di protoni incanalati in monoscristalli di silicio viene misurata con un metodo indiretto basato sullo studio della reazione nucleare Si^{28} (p, γ) P^{29} e dello scattering Rutherford dei protoni in condizioni di « channeling » del fascio incidente.

Il rapporto tra la perdita di energia nella direzione assiale $\langle 111 \rangle$ e la perdita di energia « normale » risulta essere $\alpha = 0.58 \pm 0.04$ per protoni di 1600 Kev.

Viene anche studiata la dipendenza dallo spessore della frazione del fascio deincanalata.

1. INTRODUCTION

The energy loss of light ions in silicon single crystals under channeling conditions was investigated by several Authors using the transmission technique, i.e. by studying the energy distribution of the transmitted particles [1, 2, 3, 4].

An indirect method to determine the energy loss of the channeled particles has been used by D. Blanchin *et al.* [5] in aluminium single crystals. We used a similar method, with suitable modifications, in order to determine the " energy loss coefficient "

$$\alpha = (\mathrm{dE}/\mathrm{d}x)_C/(\mathrm{dE}/\mathrm{d}x)_N$$

for protons channeled along the $\langle 111 \rangle$ axial direction of silicon; $\left(\frac{\mathrm{dE}}{\mathrm{d}x}\right)_C$ and $\left(\frac{\mathrm{dE}}{\mathrm{d}x}\right)_N$ are the stopping powers in silicon for channeled and non-channeled protons respectively.

The results are compared with those observed using the transmission technique.

2. PRINCIPLE OF THE EXPERIMENT

The main channeling effect is the reduction in the yield of the small impact parameter processes.

By studying this reduction with respect to the " normal " yield we can obtain the beam dechanneling rate along an energy scale, which cannot be converted into a depth scale, if the " energy loss coefficient " α is unknown.

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(**) Nella seduta del 13 maggio 1972.

In order to determine this coefficient for protons channeled along the ⟨111⟩ axial direction of silicon, we used two different processes, which are both governed by small impact parameter: the $Si^{28}(p, \gamma) P^{29}$ resonant nuclear reaction and the large angle Rutherford scattering of the protons. From the comparison of the dechanneling yields obtained independently from the two processes at the same depth in the crystal, we determined the α coefficient with the help of a computer iterative process.

We studied the $Si^{28}(p, \gamma) P^{29}$ nuclear reaction at the resonance energy $E_r = 1650$ Kev. By varying the incident energy E_p of the channeled protons, the depth x, at which the reaction occurs, increases according to the equation:

$$x = \int_{E_p}^{E_p - (\Delta E)_{p\gamma}} \frac{1}{\alpha} \left(\frac{dE}{dx} \right)_N^{-1} dE, \tag{1}$$

where $(\Delta E)_{p\gamma} = E_p - E_r$ is the energy excessing the resonance energy, α is the unknown energy loss coefficient and $\left(\frac{dE}{dx} \right)_N$ is the "normal" stopping power tabulated by Williamson *et al.* [6]. We studied the dechanneling of protons along the ⟨111⟩ axis of silicon as a function of $(\Delta E)_{p\gamma}$, i.e. along an energy scale, by varying E_p from E_r to $E_r + 200$ Kev. We assume that the dechanneling rate does not change in this energy range.

Dechanneling along the ⟨111⟩ axis has been also studied by means of the Rutherford scattering of protons incident at 1600 Kev, and then compared with the results from the (p, γ) nuclear reaction.

The best experimental condition should be to measure the dechanneling yields of the two processes at the same incident energy.

However we have used for the backscattering spectra the fixed incident energy of 1600 Kev to avoid the contribution of the elastic proton channel, which appears at energies higher than 1650 Kev.

Such experimental conditions are justified by the previous assumption that the dechanneling rate does not vary significantly in the energy range considered.

The energy at the detector of protons dechanneled and backscattered at the depth x is determined by the equation:

$$E_C = K \left[E_0 - \int_x^0 \alpha \left(\frac{dE}{dx} \right)_N dx \right] - \int_0^{x/\cos\theta} \left(\frac{dE}{dx} \right)_N dx, \tag{2}$$

where E_0 is the energy of the incoming protons, $\theta = 160^\circ$ the angle between the beam and the detector and K the Rutherford scattering constant:

$$K = \left\{ \frac{M_1 \cos\theta}{M_2 + M_1} + \left[\left(\frac{M_1 \cos\theta}{M_2 + M_1} \right)^2 + \frac{M_2 - M_1}{M_2 + M_1} \right]^{1/2} \right\}^2 . \tag{3}$$

M_1 and M_2 are respectively the masses of the incoming particles and of the tangent nuclei.

From eqs. (1) and (2) we can calculate x and α in the following way: for a fixed value of $(\Delta E)_{p\gamma}$, using an arbitrary α–value, we calculate the depth x at which the reaction should occur from eq. (1). E_C is then calculated by inserting into eq. (2) the x value so obtained. Now the dechanneled fractions $N_R\%$ and $N_\gamma\%$ are measured respectively by the backscattering and (p, γ) spectra and compared.

The correct α value is the one which makes $N_R\% = N_\gamma\%$ when inserted into eqs. (1) and (2).

By varying the $(\Delta E)_{p\gamma}$ values, we obtained the coefficient α as a function of the depth.

The used (p, γ) resonance has a width $\Gamma = 53$ Kev which causes an uncertainty in the analysis of the data relative to $(\Delta E)_{p\gamma} < 80$ Kev and consequently the calculations are limited to the depth range 4 to 12 μm. A study is in progress to overcome this difficulty. In the analysis of the backscattering experimental data we introduced corrections to account for the different energy-depth conversion for aligned and random spectra and for the energy dependence of the Rutherford cross section [7], because at a given depth channeled and non-channeled protons have not the same energy. This correction becomes considerable with increasing depth.

3. Experimental technique

The incident collimated beam of protons, obtained from the 5.5 Mev Van de Graaff accelerator of Laboratori Nazionali di Legnaro, had an energy resolution better than 1 Kev and an angular divergence better than 0.1°.

The silicon single crystals were 200 μm thick and cut perpendicular to the ⟨111⟩ axial direction within a few degrees. The silicon samples were mounted on a three-axis goniometer which allowed orientation of the crystal with an accuracy better than 0.05°.

The backscattering protons were energy-analysed by a solid state surface-barrier detector associated with a multichannel analyzer. The open area of the detector was 7 mm². The typical target current was 10 *n*A.

The target was polarized to avoid secondary electron emission. The gamma rays from the (p, γ) nuclear reaction were detected by a NaI (T*l*) 4″×4″ detector.

A lead screen was used to reduce the gamma background; the residual gamma background and the gamma contribution from the $C^{12}(p, \gamma)N^{13}$ reaction was subtracted from the gamma spectra.

The target current for this spectra was typically of the order of 150 *n*A.

4. Experimental results

The yields of the (p, γ) reaction at different incident energies for channeled and random protons are shown in fig. 1 as a function of the energy excess $(\Delta E)_{p\gamma}$.

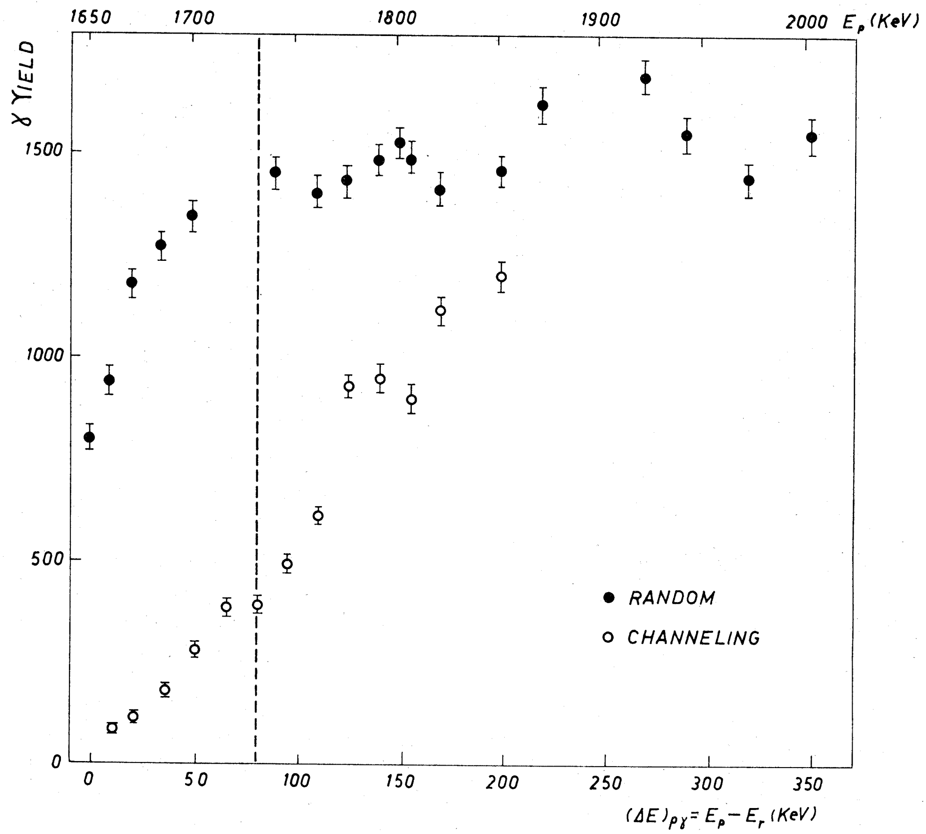

Fig. 1. – Yield of the Si^{28} (p, γ) P^{29} nuclear reaction versus proton incident energy along a random direction and along a $\langle 111 \rangle$ direction.

Fig. 2 shows the scattered proton spectra for 1600 Kev protons incoming *a*) along a random direction, *b*) along the $\langle 111 \rangle$ axis.

The α coefficient computed from experimental results is plotted in fig. 3 versus the crystal depth.

In the range 4 to 12 μm α is constant, in agreement with the results of Blanchin *et al.* [5] in aluminium single crystals.

The mean α value is 0.58 ± 0.04.

Such value is in good agreement with our results obtained from transmission measurements [3], [4].

Fig. 4 shows the dechanneling rate as a function of the crystal depth obtained from the backscattering spectra, taking into account the correction in the energy-depth conversion as outlined before. The dechanneled fraction at the surface, obtained by extrapolating the value of experimental curve at the origin of fig. 4, is $\chi_{min}(0) = 2.8 \pm 0.3\,\%$. This value is in good agreement both with the experimental results obtained by Davies *et al.* [8] using 3 Mev-protons and with theoretical estimates by Lindhard [9].

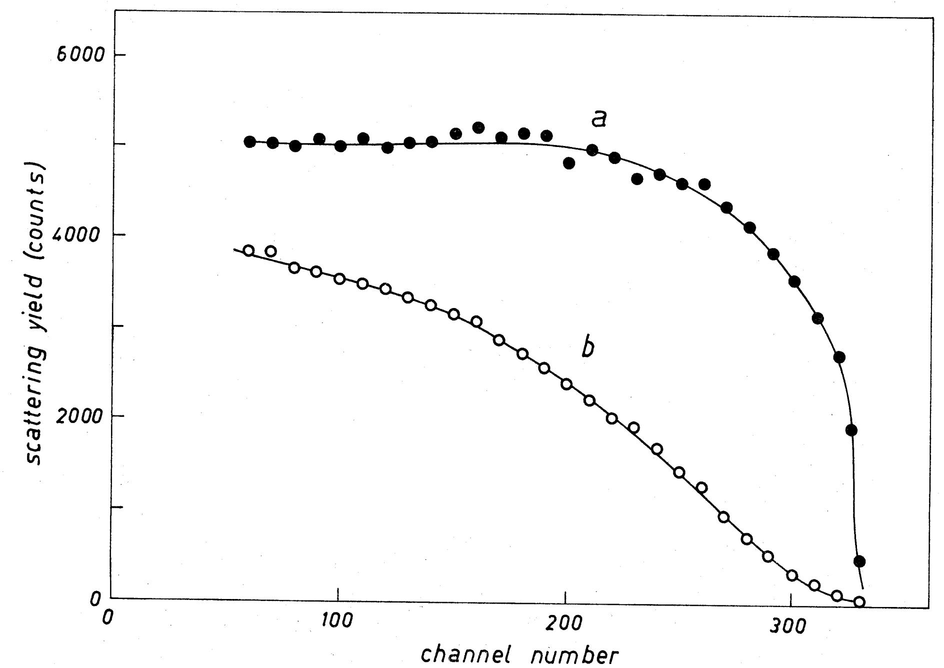

Fig. 2. – Backscattering energy spectra of 1600 Kev protons incident in silicon: (*a*) along a random direction; (*b*) along a ⟨111⟩ direction.

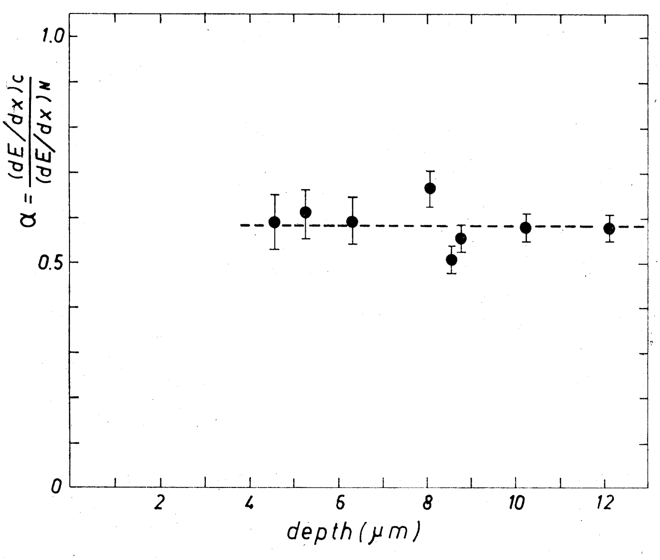

Fig. 3. – Depth dependence of the coefficient α computed fror experimental results on (p, γ) reaction and Rutherford scatterinᵹ

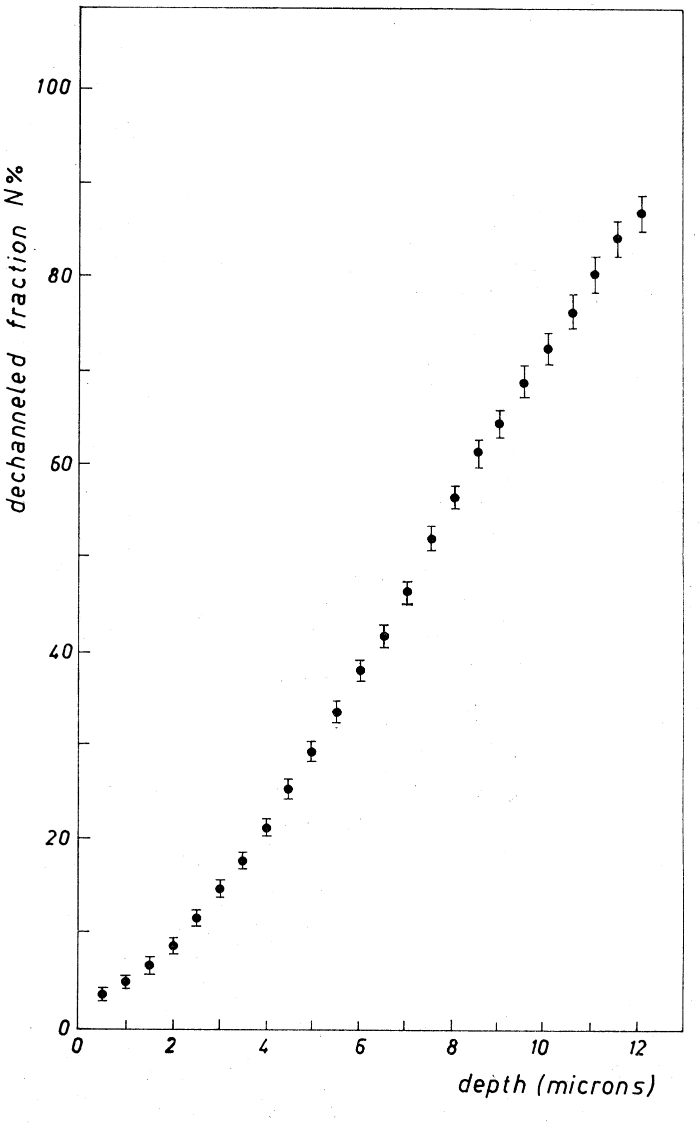

Fig. 4. – Dechanneling depth dependence from backscattering spectra for a 1600 Kev proton beam incident in Si along the ⟨111⟩ direction.

Further measurements are in progress to investigate other axial and planar directions of silicon and the temperature dependence of the coefficient α.

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