Influence of crystal-orientation effects on pulse-shape-based identification of heavy-ions stopped in silicon detectors

L. Bardelli a,b,* M. Bini a,b G. Casini b G. Pasquali a,b G. Poggi a,b S. Barlini c,d A. Becla e R. Berjillos f B. Borderie d R. Bougault c M. Bruno g,h M. Cinausero i M. D’Agostino g,h J. De Sanctis g,h J.A. Dueñas f P. Edelbruck d E. Geraci g,h F. Gramegna i A. Kordyasz j T. Kozik e V.L. Kravchuk k L. Lavergne d P. Marini g,h A. Nannini h F. Negoita k A. Olmi b A. Ordine l S. Piantelli b E. Rauly d M.F. Rivet d E. Rosato m,l C. Scian i A.A. Stefanini a,b G. Vannini g,h S. Velica k M. Vigilante m,l

a University of Florence, Italy
b I.N.F.N. Sezione di Firenze, Italy
c LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, Caen, France
d Institut de Physique Nucléaire, CNRS/IN2P3, Université Paris-Sud 11, F-91406 Orsay cedex, France
e Jagiellonian University, Institute of Physics, Reymonta 4, 30-059 Krakow, Poland
f Departamento de Física Aplicada, Universidad de Huelva, E-21071 Huelva, Spain
g University of Bologna, Italy
h I.N.F.N. Sezione di Bologna, Italy
i I.N.F.N. Laboratori Nazionali di Legnaro, Italy
j Heavy Ion Laboratory, Warsaw University, Pasteura 5a, 02-093 Warsaw, Poland
k NIPNE, RO-077125 Bucharest-Magurele, Romania
l I.N.F.N. Sezione di Napoli, Italy
m University of Napoli, Italy

For the FAZIA Collaboration

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ABSTRACT

Current and charge signals have been collected for Se ions at 408 MeV, S at 160 MeV and Ni at 703 MeV, all stopped in silicon detectors. Some detectors were cut off the (1 1 1) axis and some off the (1 0 0) axis. Important effects on the shape of the silicon current and charge signals have been observed, depending on the orientation of the impinging ion relative to the crystal axes and planes.

A degradation of the energy and risetime resolution of about a factor ~3 with respect to the measured optimal values (for example 7° off-axis orientation) is observed for ion impinging directions close to crystal axes and/or planes, i.e. the common scenario for normal incidence on 0° cut detectors.

For Pulse Shape Analysis applications, the necessity of using such “random” oriented silicon detectors is demonstrated.

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1. Introduction

One of the main research topics of the recently established FAZIA Collaboration [1] is the study of the pulse shape properties of silicon detectors. The use of digital sampling and processing methods is under investigation for obtaining Z and A identification of charged particles stopped in a silicon detector, in the 1–10 MeV/u energy range.

It is well known from the literature (see for example Ref. [2–8] and references therein) that crystal-orientation related effects play a major role in contributing to pulse-height defect, both at low (few MeV [2–7]) and higher energy (1–10 MeV/u [8]). In this work experimental tests have been carried out in order to study the influence of crystal orientation effects on signal pulse shape.

Parallel tests are being also performed by the collaboration to quantitatively study the influence of the residual doping non-uniformities: with respect to the contents of the present paper this problem was kept under control because the used collimated detectors have a measured non-uniformity smaller than ~1% [9].

The paper is organized as follows: Section 2 describes the used experimental setup. The analysis of the collected data, in terms of energy and signal risetime fluctuations correlated with the direction of the impinging ions with respect to crystal axes and planes is shown in Section 3. In Section 4 the importance of

* Corresponding author at: University of Florence, Italy. Tel.: +39 055 4572693.
E-mail address: bardelli@fi.infn.it (L. Bardelli).

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controlling crystal orientation effects in applications relying on Pulse Shape Analysis to discriminate amongst stopped ions in silicon is addressed, showing some perspicuous identification results. An overview of the work done and perspectives is given in Section 5.

2. Experimental setup

Experiments have been carried out at the INFN Laboratori Nazionali di Legnaro, using $^{80,82}\text{Se}$ at 408 MeV, $^{32}\text{S}$ at 160 MeV and $^{58,60}\text{Ni}$ at 703 MeV beams, elastically scattered by a gold target.

As sketched in Fig. 1, collimated silicon detectors are mounted, one at a time, on a two-axis remote-controlled precision goniometer, which permits to tilt the detector with 0.01° steps. The relevant rotation angles will be referred to in the following as $(\theta_H, \theta_V)$. Laser alignment permitted to calibrate the system in such a way that $(\theta_H, \theta_V) = (0°, 0°)$ corresponds to normal incidence of the scattered particles on the mounted detector. With this setup, the response of the detector as a function of the direction of the impinging particles with respect to the crystal orientation is explored.

The detector is connected to a PACI preamplifier [10], that provides charge and current outputs. The two signals have been acquired using the 12 bit 125 MS/s digitizer described in Ref. [11]. Detectors cut 0° of the (1 1 1) and (1 0 0) axes have been used. They are of nTD type and have been manufactured by Canberra—they will be referred to in the following as detector A ((1 1 1)), B ((1 0 0)), C ((1 1 1)), D ((1 1 1)) and E ((1 0 0)), respectively.

During all measurements, in view of Pulse Shape applications, all detectors were used most of the time in the rear injection configuration (see for example Ref. [12] and references therein).

In order to define at best the direction of the impinging ions, the goniometer was mounted about 130 cm far from the target, the detector was collimated with a diaphragm having a diameter of 3 mm and the gold target was spot-evaporated (spot of 3 mm in diameter) on a carbon backing. Elastic scattering was the largely dominant contribution in all examined cases. The used geometry allows to define the impinging ions direction with an uncertainty smaller than ±0.1° and to keep the kinematic spread well below 0.1 MeV for all tests. The observed counting rate was of the order of few counts/s—the total duration for a typical angular scan extended over a few hours, thus collecting about 10⁶ events for each $(\theta_H, \theta_V)$ position. The scanning step in both directions was 0.5°.

3. Data analysis: energy and risetime

Direct on-line inspection of the collected waveforms (both current and charge signals at the output of the preamplifier) showed that a very different behavior was present as a function of the goniometer orientation, i.e. the direction of the impinging ions with respect to the detector crystal. As an example, Fig. 2 shows, on the left side, the distribution of current waveforms collected by detector B, when the $^{80}\text{Se}$ ions are stopped in the detector entering the crystal at $(\theta_H, \theta_V) = (0°, 0°)$. In spite of the monochromaticity of these stopped ions, a large spread of waveforms is observed. On the contrary the distribution, for the same number of events, observed for another orientation of the goniometer $(\theta_H, \theta_V) = (-9°, 3°)$, is shown on the right side of the same figure and it is clearly much less dispersed. Very similar behavior in terms of fluctuations is also observed for the charge signals.

In order to make the preceding observations quantitative, the following analysis has been performed on all the collected waveforms—for each waveform the measured energy of the detected particles is extracted with digital filtering [13], and the current/charge signal risetime with digital CFD algorithms [14]. For each $(\theta_H, \theta_V)$ configuration, the standard deviation of these quantities with respect to the mean value has been extracted and reported in the $(\theta_H−\theta_V)$ plane. The angular scanning range was extended also to regions far from the crystal axes and planes in order to determine the angular region(s) where the best PSA performances are reached, that is the main goal of this work.

As far as energy measurement is concerned, the analysis described in this section closely follows the approach discussed in Ref. [8], whereas that of the risetime of the signals is totally new.

The energy and current risetime measurements if $^{32}\text{Se}$ ions at 408 MeV, for (1 1 1) detector (A) and (1 0 0) detector (B), are shown in Figs. 3 and 4. In each figure the standard deviation of the measured energy as a function of the two goniometer angles is reported on the left side. On the right side the standard deviation of the measured risetime of the current signal associated to elastically scattered ions is reported, as a function of the same two angles. Please note the different crystal structure for the detectors, related to the two tested different crystal orientations—(1 1 1) and (1 0 0).

The sensitivity of both the energy and risetime measurements to crystal orientation effects is evident: in particular one observes that for ions entering the detector along directions parallel to major crystal planes and axes a size-able increase of fluctuations is present with respect to other directions. This is true for both energy and current risetime determinations.

Impinging directions far from any crystal axis or plane correspond to minimal fluctuations in energy and risetime—in the following they will be referred to as “random directions”.

As far as the centroid of energy and current risetime is concerned, they also show a marked sensitivity to the crystal orientation, although the effects are not as much pronounced as the associated standard deviations.

It is apparent that the effect on the current signal risetime is so important that a higher sensitivity with respect to the energy observable is reached, allowing to perceive finer details of the silicon crystal structure (see Fig. 4).

The resulting sensitivity in both the energy and the risetime observables exploits the used high resolution digitizer [11], providing both high resolution energy measurement [13] and sub-ns resolution timing [14].

As far as the energy measurements reported in left side of Figs. 3 and 4 are concerned, the results are compatible with the observations presented in Ref. [8], even though for Au ions and different beam energy (but similar velocity, i.e. 11 MeV/u),

1 The behavior of current and charge risetimes well represents the general trend of signal fluctuations as a function of the two goniometer angles that we observed for many other shape-related quantities (time-over-threshold, current maximum, ...), not reported here.
The present findings confirm the close relationship between crystal orientation and Pulse Height Defect in this ion-velocity range (1–10 MeV/u). The connection between channeling and the various contributions to Pulse Height Defect is mainly known in the literature from studies performed at much lower energies [5–7], thus referring to ion ranges in the μm region.

In order to see how the standard deviations presented in Figs. 3 and 4 build up, Fig. 5 (left) shows the measured energy distribution of elastically scattered 82Se ions for detector A, corresponding to three different tilting-angle regions of the crystals (full detector, (0°, 0°) or “channeling” and “random”). One clearly sees that over angular regions where crystal orientation effects are present (i.e. (i) and (ii) selections), the energy distribution is not only much wider than along “random” directions (iii), but it also splits in two bumps, i.e. it is bimodal. On the contrary, the “random” incidence region shows a better resolution with a regular Gaussian shape.

In Table 1 the measured RMS energy and risetime resolutions are reported for the two used detectors and for the various selected regions. From the reported data it is clear that a
significant improvement of the experimental resolutions (about a factor of 3) for both quantities can be achieved by using a proper "random" configuration.

In Fig. 6 the results obtained for (1 1 1) detector (C) with a $^{32}$S beam are shown (similar to Figs. 3 and 4). In this case no significant effect is observed for the measured energy fluctuations as a function of the rotation angles (left part of the figure). The different behavior of the energy observable shown in Fig. 6 with respect to the previous ones can be ascribed to the much smaller Pulse Height Defect for the considered ions and energies [15,16], which basically prevents any significant effect of the measured energy as a function of crystal orientation.

The right part of the figure, on the contrary, shows that the risetime of the current signals, even for $^{32}$S beam, is still very sensitive to the crystal orientation.

In the literature (see for example Ref. [17]) crystal-orientation-and/or channeling-related effects are usually quantified by defining the angle $\psi_{1/2}$ for which the experimental observable drops to one half of the value corresponding to the maximum effect.

The following procedure has been used—for each detector-ion-variable configuration, a standard deviation vs ($\theta_H, \theta_V$) plot is built (see for example Fig. 3). By using a graphical cut, ($\theta_H, \theta_V$) regions covering part of a primary crystallographic plane are selected (excluding ($\theta_H, \theta_V$) = (0°, 0°)). This data is projected on the direction orthogonal to the examined crystal plane and a Least

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**Table 1**

<table>
<thead>
<tr>
<th>Energy resolution (RMS)</th>
<th>Risetime resolution (RMS)</th>
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<tbody>
<tr>
<td>(i) Full detector ($\pm 4^\circ$)</td>
<td>2.2</td>
</tr>
<tr>
<td>(ii) (0°, 0°) direction</td>
<td>2.9</td>
</tr>
<tr>
<td>(iii) &quot;Random&quot; incidence</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The same angular selections (i), (ii), (iii) as in Fig. 5 have been used.
Squares fit provides the desired $\psi_{1/2}$ value. Results are finally corrected for the finite size of the experimental angular step and for the finite angular resolution of our setup ($\pm 0.13^\circ$, see Section 2). All the studied observables and ions provided an experimental value for $\psi_{1/2}$ in the $0.3 - 0.7^\circ$ range. These values are significantly larger than the ones calculated in the hypothesis of pure channeling for the initial beam energy according to Ref. [17], i.e. $0.02 - 0.05^\circ$. This observation has been already reported [8], although only for the energy observable and front-side injection.

We have verified that the simulation used in Ref. [8] is able, also for the ions considered in this work, to reproduce $\psi_{1/2}$ values in the experimentally observed range. This speaks in favor of fluctuating electronic losses due to close atomic collisions associated with multiple scattering process along the ion path, that are the major included ingredients in Ref. [8].

4. Importance of controlling crystal orientation effects in Pulse Shape Analysis applications

In order to show the importance of controlling crystal orientation effects in Pulse Shape Analysis applications, we present in Fig. 7 some results obtained for the PSA-based discrimination of stopped $^{58}$Ni and $^{60}$Ni ions, both of exactly the same nominal energy of 703 MeV, in order to provide a significative bench-test.

In Fig. 7 (left) the sum of the $^{58}$Ni and $^{60}$Ni risetime distributions is shown, obtained in the configuration $(\theta_H, \theta_N) = (0^\circ, 0^\circ)$—in the inset, the two separately collected distributions are shown (log scale) for $^{58}$Ni (black) and $^{60}$Ni (red). Similarly, the right side reports the distributions collected for “random” regions. The improvement in the PSA identification capabilities associated to the “random” orientation of the detector is evident. In the $(\theta_H, \theta_N) = (0^\circ, 0^\circ)$ configuration both the increased widths and the significant tails of the distributions prevent an experimental separation between the two isotopes. Similar quality degrading effects are expected also for lighter ions, where $\Delta \theta = 1$ resolution is aimed at—tests are indeed scheduled to check the identification performances.

On the basis of the results shown in Fig. 7, one concludes that detectors to be used for PSA applications must ensure “random” incidence for impinging particles, i.e. a proper silicon-ingot cut must be used for producing the detectors—see for example Ref. [18].

5. Conclusions

Experimental tests have been carried out in order to study the importance of crystal-orientation effects in silicon detectors for Pulse Shape applications—the detector output signals have been digitized and collected as a function of the ion impinging angle with respect to the detector crystal orientation. Large fluctuations in the signal shape (current and charge) and the measured energy have been observed when the stopped ions enter along directions parallel (within tenths of degree) to crystallographic axes and/or planes.

For these directions the energy and risetime resolutions are about a factor of $\sim 3$ with respect to the case of “random direction” (for example $7^\circ$ off-axis incidence).

These results make it mandatory, for applications where the detailed shape of the signal is studied (like in A and Z discrimination approaches based on Pulse Shape Analysis [1]), to use silicon detectors made of wafers cut at specific (“random”) angles with respect the crystal axes. As an example, a Pulse-Shape-based discrimination between $^{58}$Ni–$^{60}$Ni (same total energy) has been presented, where clear improvement in the particle identification performances is observed for “random” configurations.

The effects on the energy resolution have been studied as well, confirming [8] that in order to exploit the optimum energy resolution attainable with silicon detectors, stopped heavy ions $Z \geq 20$ of a few AMeV must enter the crystal along selected directions (“random”), far from crystallographic planes and axes.

A careful interpretation of the observed data is beyond the scope of the present paper, which is mainly aimed at demonstrating the importance of controlling the crystal orientation effects when identification of stopped ions in Silicon, having an energy range of 1–10 MeV/n, is planned, based on PSA. Although the large measured $\psi_{1/2}$ value associated to the observed waveform fluctuations makes it reasonable to associate the observed phenomena to strongly varying electronic densities for trajectories close (within the measured $\psi_{1/2}$ values) to directions parallel to crystal axes and/or planes, we are aware that a detailed interpretation of the data, aiming at quantitatively reproducing the effect on the pulse shape is very complicated. In fact, at variance with studies performed at very low energies, an ion entering the crystal along directions close to major crystal axes or planes and stopped after a hundred-micron-long path is subject to significant channeling, dechanneling, feeding-in and multiple scattering effects, whose relative importance is not yet well established in the examined energy regime.
From another point of view, one expects, given the shown high sensitivity of PSA observables to crystal orientation effects (addressed in this work in order to keep it at a minimum), that the presented time-domain signal analysis could rather be exploited in channeling-physics oriented experiments as a probe to quantitatively determine the relative importance of all the involved contributions in this energy regime, possibly complementing the standard approach based on energy measurements.

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