Prediction of radiation degradation of Si detectors irradiated by relativistic ions of different masses

D Mitina, E Verbitskaya, I Eremin and N Fadeeva

Division of Solid-State Electronics, Ioffe Institute,
26 Politekhnicheskaya, St Petersburg, 194021 Russian Federation

E-mail: daria.mitina@cern.ch

Abstract. The presented paper is focused around radiation damage of silicon material under the different ions irradiation. The ion total energy range is 0.7 GeV for ^{7}Li to 208 GeV for ^{208}Pb. The results of TRIM modeling for the set of six ions are presented. The extracted information about vacancy production allows making first assumptions of the Si degradation dependence on mass and energy of the incident ion.

1. Introduction

Radiation hardness of silicon heavy ion detectors is an important issue for the development of the nuclear physics instrumentation. The current situation is similar to the one that existed at the beginning of work on building the experiments at Large Hadron Collider ae CERN, when the deterioration of silicon detectors characteristics under the influence of light relativistic particles was not thoroughly studied. As a result, application of Si detectors operating at fluences of $(1-10)\times10^{14}$ p/cm^2 was challenging and put forward a question on the detailed study of long-term degradation of the detector performance.

The experiments planned in nuclear physics deal with a similar problem of Si detector radiation hardness, now concerning the impact of heavy ions, while the variety of exposure conditions to radiation significantly increases. Different ions ranging from relatively light ones like ^{7}Li to extremely heavy ^{238}U, become the influencing factor. Obviously, the impact of different particles requires an individual analysis of ion interaction with the detector material, since the results depend on the ratio of their masses and ion charge. The damage of the silicon lattice can be characterized by the concentration of primary defects, vacancies, which makes it possible to compare the effects of ions and protons. In [1], this approach allowed scaling the characteristics of Si P-I-N structures irradiated with ^{40}Ar ions with respect to the expose with 23 GeV protons, including such as radiation-stimulated transformation of the electric field. Therefore, the studies on the interaction of ions with a solid are in demand being the basis for the quantitative evaluation of special detectors characteristics.

The presented research contain theoretical predictions of the primary effect of different ions on silicon structure. All results were obtained via TRIM modeling [2] and following data processing.

2. Concentrations and profiles of primary vacancies

The approach based on scaling the radiation effects of ions and protons comes from the hypothesis that the changes in the silicon detector characteristics are proportional to the concentration of radiation-

induced vacancies, which works at proton fluences up to 10^{15} cm^{-2}. However, the difference in the concentrations of numerous deep energy levels induced by radiation leads to nonlinearity of the processes in the detector sensitive volume, such as current generation through radiation defects, the formation of an electric field via the interaction of equilibrium carriers and defects and electron and hole transport in the space charge region.

The interaction of ions with the crystal lattice is a complex process, and the total integration of individual mechanisms cannot be fully described theoretically. Therefore, in this work, interaction of ion with silicon atoms is considered using the TRIM program, which simulates an ion transverse through the silicon by the Monte Carlo method, taking into account the possible mechanisms of its interaction with silicon atoms. The calculations were performed for ions in the energy range from 100 MeV/u to 1 GeV/u and nuclei with the atomic mass from ^{7}Li to ^{208}Pb. The results represent a spatial distribution of primary defects concentration and statistically averaged number of vacancies along an individual track; for the latter, selected data are specified in table 1. The calculations were carried out with the statistics of events that ensured the accuracy of 1%. The ion charge corresponded to the complete ionization of the atom.

Table 1. The number of vacancies introduced by the set of ions into silicon

	A	[V] at 100 MeV/u	Total energy (GeV)	[V] at 1 GeV/u	Total energy (GeV)
^{7}**Li**	**7**	18	0.7	2	**7**
^{12}**C**	12	71	1.2	6	12
^{28}**Si**	28	388	2.8	36	28
^{40}**Ar**	40	617	4	65	40
^{131}**Xe**	131	5198	1.3	561	131
^{208}**Pb**	208	11014	20.8	1184	208

The common tendency is a rise in the number of vacancies created by an ion with its mass increase, and its reduction with an increase in energy. This correlates with the physics of displacement damage produced by particles in solid and is associated with the corresponding changes in the interaction cross-sections [3].

In figure 1a, the dependence of the ratio $R = [V](E)/[V](1 \text{ GeV/u})$ (where $[V]$ is the concentration of primary vacancies) on the atomic mass includes the results for light ions added to the data in table 1. A specific feature of the curves is the region in which the ratio of vacancies concentration created by the ion is independent of the ion mass. The region starts from carbon and includes all elements of the transuranium group. In turn, in the energy range below 100 MeV/u, this regularity is violated, and the curves are nonmonotonic, showing a maximal ratio increase within the 30% for ^{12}C followed by reduction of R to a constant value for ^{40}Ar and heavier elements.

We have to admit that the physical reason of the constant ratio of vacancy concentrations induced by ions of different masses is not yet clear. However, its practical importance is beyond doubt since the calculation of radiation effects on silicon detectors may be significantly simplified for ions with an atomic mass $A \geq 40$. For this, it is sufficient to have relevant data for any ion with $A > 40$ and a known energy and a dependence describing the effect of energy ion on the introduction of vacancies. For the normalized number of introduced vacancies $[V](E)/[V](1 \text{ GeV/u})$, this dependence is shown in figure 1b and its approximation is expressed as

$$R(E) = \frac{1}{c + b \cdot E}, \tag{1}$$

where E is the energy of incident ion, $c = 5.2 \times 10^{-3}$ and $b = 1.02 \times 10^{-3}$ (MeV/u)$^{-1}$ are the approximation parameters independent on the ion mass. The last evidence underlines that the (1) dependence is universal. Discussion of the physical reasons for the observed regularities is beyond the scope of this study.
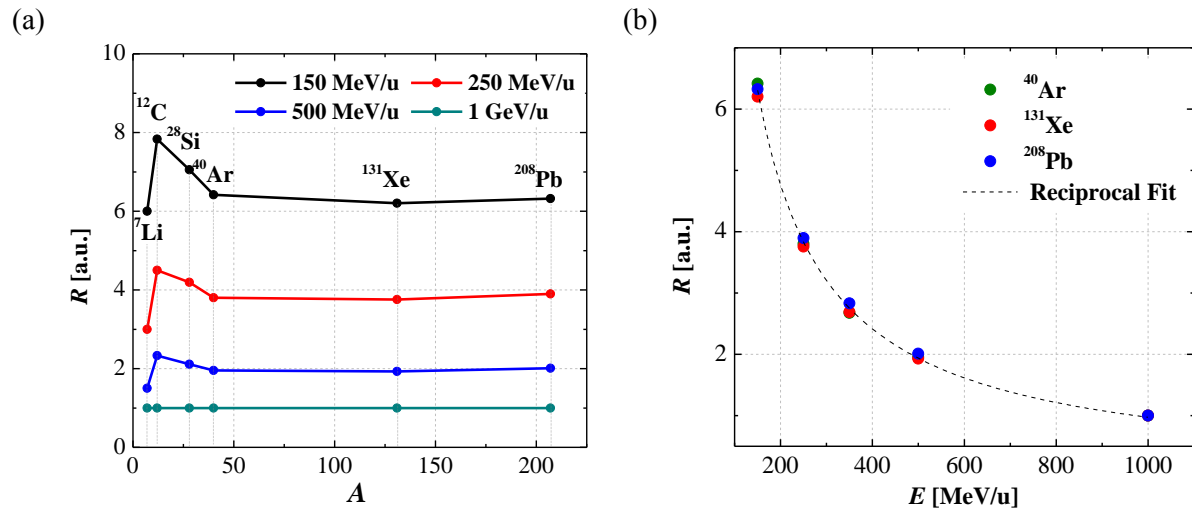
(a)

(b)

Figure 1. The relative amount of vacancies R dependence on (a) atomic mass and (b) ion energy

In addition to the number of vacancies, simulation of the interaction by the TRIM determines their distribution along the track. To trace the initial stage of collision events for ions with different masses in silicon, the TRIM data on modeling the generation of vacancies along the ion track were used. The results of calculations of vacancy density distributions for 10 impinging ions are demonstrated in figures 2a – 2d, which show significant nonuniformity in the density of vacancies along the track for an ion of any mass and energy. The distributions contain local regions with peak values of their concentration against the background of almost uniform vacancies density. The density of vacancies in the peak with respect to the background depends on the ion mass and energy, which is illustrated in figures 2a and 2b for ^{12}C ion. At ion energy of 100 MeV/u, the background is clearly visible being about 10% of the local peak height. The carbon ion with an energy of 1 GeV/u also creates regions with peaks; however, the background is significantly less or negligible. For heavier ions, such as ^{208}Pb, the background is noticeably higher even at an energy of 1 GeV/u.

It is obvious that the peak origin is associated with the appearance of recoil atoms in the collision events, i.e., low-energy silicon atoms creating dense aggregations of vacancies. Their identification as vacancies clusters or disordered regions depends on the dimensions of the local regions; however, the TRIM data cannot resolve this issue.
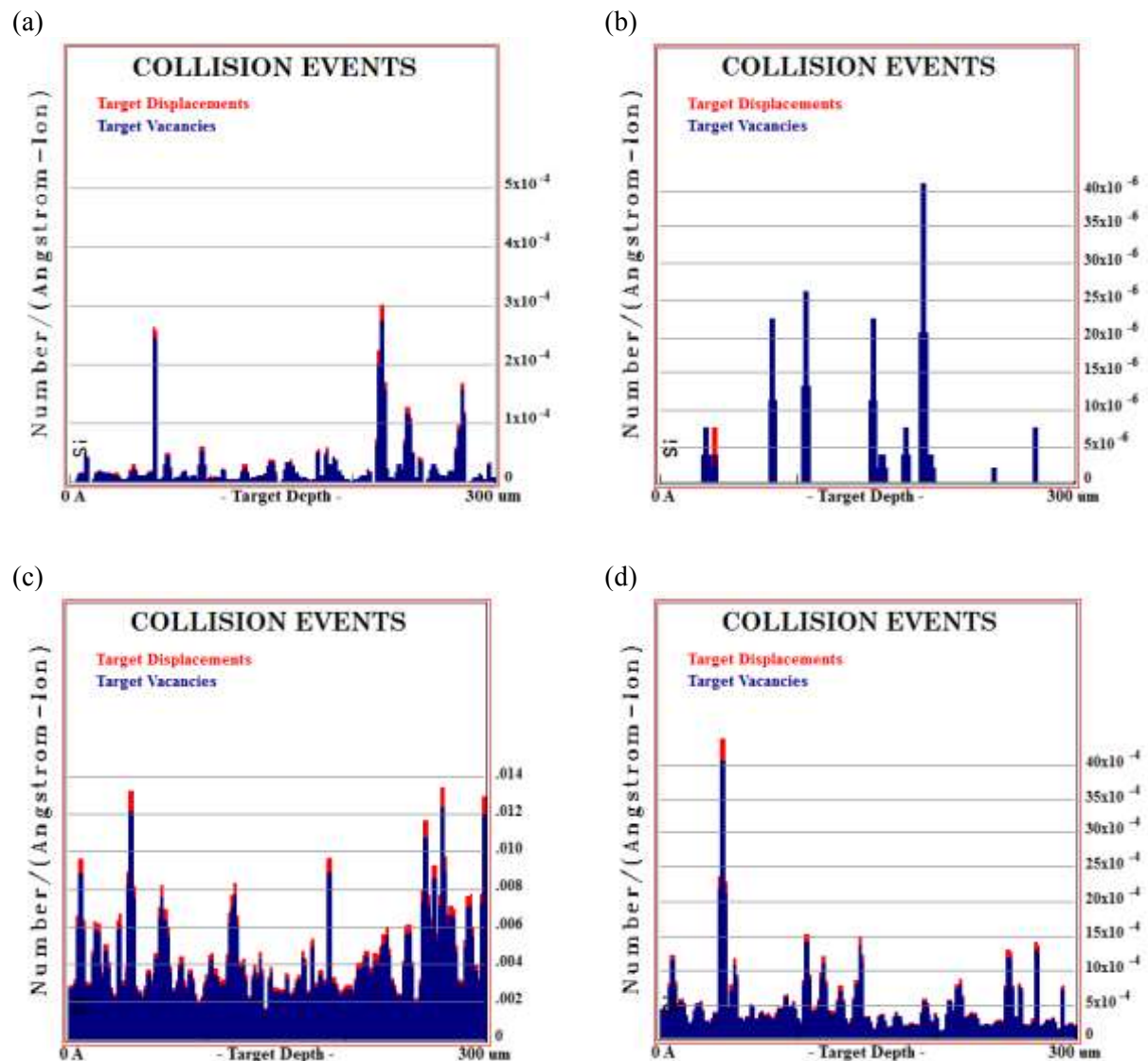
(a)   (b)

(c)   (d)

Figure 2. Profile of vacancies linear density along the track of ^{12}C (a and b) and ^{208}Pb (c and d) with different energy (a and c – 100 MeV/u, b and d – 1.0 GeV/u).

3. Summary

Modeling of vacancy formation in silicon was carried out for a set of ions with different masses and energies in the range 50 MeV/u to 1 GeV/u. It is found that there is a range of ion masses and energies in which an analytical parameterization demonstrates independence of normalized vacancy concentration on the ion mass. The observed law of vacancy generation facilitates the scaling of radiation effects on silicon and degradation of Si detectors. The physical interpretation of the revealed regularity and its correlation with the detector degradation scenario is included in the future plans.

References
[1]   V Eremin et al 2018 *JINST* **13** P01019
[2]   Ziegler J F, Biersack J P and Ziegler M D 2008 *The Stopping and Range of Ions in Solids*
[3]   Van Lint V A J 1987 *The Physics of Radiation Damage in Particle Detectors NIM* **A 253**