Issues of TRIM program as a tool for developing a silicon detectors radiation degradation scenario

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Abstract. The presented study is focused around the TRIM program issues and its applications for prediction of silicon detectors degradation under heavy ions of $^{40}$Ar. Results of the simulations of low-energy ion (53.4 MeV) and high-energy ion (1.62 GeV) irradiation are demonstrated. Experimental data for silicon p$^-$-n$^-$-n$^+$ detectors irradiated by the low energy are also presented. Reliability of TRIM simulations application for studying silicon detectors degradation under heavy ion irradiation is discussed.

1. Introduction
Silicon detectors are one of the most important elements of detection systems located in the largest research centers such as The European Organization for Nuclear Research (CERN) and The GSI Helmholtz Centre for Heavy Ion Research. The inevitable impact of the detected radiation leads to the degradation of the detector characteristics, which in turn puts forward the task of predicting the long-term scenario of their work. For relativistic protons, the process of degradation is well-studied [1]; however, the question of the impact of heavy ions on Si detectors, which is relevant for the work on the FAIR program [2] in GSI, remains open. One of the possible ways to solve it is to introduce a scaling factor that allows one to simulate the degradation of detectors irradiated by ions based on the available data for relativistic protons. Since the experiments at GSI imply the use of ions in a wide range of mass ($^7$Li to $^{238}$U) and energies ($10^8$ eV to $10^{12}$ eV), the scaling factor must depend on the characteristics of ions. In this study the concentration of Frenkel pairs, i.e. vacancies, mainly forming the spectrum of radiation defects, will be examined as the appropriate parameter for scaling. This vacancy concentration can be obtained using the TRIM program (Transport of Ions in Matter) [3].

Note here that also, the value of the Non-Ionizing Energy Losses (NIEL) can be calculated from the TRIM data. Most of this NIEL is responsible for the Frenkel pair creation so that it is commonly used for bulk damage scaling [4]. There is a lot of studies for light and medium mass ions which are stopped in the sample, up to a complete loss of energy [5]. As a result, maximum energy losses to nuclear scattering take place at the end of the track, which in turn leads to the formation of highly nonuniform vacancy distribution with the Bragg peak near the end of the track. It is clear that such nonuniformity can dramatically disturb the electric field distribution that will increase uncertainty in the sample characteristics dependence on the NIEL.

In order to extract reliable results cleaned-up from the mentioned secondary factors, the scaling issue was investigated for ions which uniformly homogeneously generate Frenkel pair.
2. Samples and Experiments
Both experimental and simulated data are presented for silicon p-n-p-n+ pad detectors with a thickness of 300 µm and 25 mm² of active region area. Low energy ion irradiation was carried out at the Ioffe Institute Cyclotron, Saint Petersburg, Russia. The detailed information about samples under investigation is listed in table 1.

Table 1. Parameters of Si detectors

| Irradiation Energy | Ion Range (µm) | Dopant Concentration (cm⁻³) | Detector # | Fluence (cm²) |
|--------------------|----------------|-----------------------------|------------|--------------|
| ⁴⁰Ar 53.4 MeV      | 15.2           | 6.93x10¹³                  | F1         | 1x10⁹       |
|                   |                |                             | F2         | 2x10⁹       |
|                   |                |                             | F3         | 4x10⁹       |

3. High Energy Ion Irradiation
As the first step, the simulation of specified irradiation was performed. The energy of incident particles was 1.62 GeV and their number was 10⁵. The number of incident particles increases the statistics of both trajectories of the particles and the results of scattering events along the paths. Analysis of damage processes requires the information about energy loss to vacancy formation. The creation of target vacancies results from both ion/target atom collisions, and also from the collision cascades of recoiling target atoms. Simulated evolution of collision events and the ions energy loss to vacancy production over the depth are presented in figure 1a and 1b, respectively. Simulation was performed for silicon 300 µm thick sample. The results clearly indicate that the range of ⁴⁰Ar ions with 1.62 GeV energy is much more than the sample thickness and the most tracks looks like a lines normally to the sample surface with the small deviations around. The mean rate of the vacancy generation β_TRIM is defined from the statistics of their introduction (figure 1b) and is 3.5x10⁹ cm⁻¹.

(a) (b)

Figure 1. TRIM simulation of high energy ion irradiation. (a) Collision plot (b) Energy loss to vacancy production
Now one can establish correlation the results of simulations in TRIM for various types of incident particles. The scaling coefficient, based on the comparison of damage parameters for irradiation with 1.62 GeV $^{40}$Ar ions and 23 GeV protons was obtained in [6]. The following parameters were compared: the introduction rates for a single effective deep level acting as a current generation center and introduction rates of each deep level. The scaling coefficient turned out to be about 10. Also, the Hamburg model was applied to analyse the effective concentration dependence on fluence (figure 2). According to the model, effective concentration decreases with irradiation fluence via the following expression: $N_{\text{eff}} = N_0 e^{-\gamma F - \beta F}$, where $N_0$ is the effective concentration for a nonirradiated structure, $c$ the donor removal coefficient, and $\beta$ the acceptor introduction rate. The latter can be an appropriate parameter for comparison with the rate of the vacancy generation, extracted from TRIM simulation. Following the hypothesis on linear dependence of concentration for all radiation-induced levels on the fluence, the rate can be calculated from the proportionality law. The calculated value of $\beta_{\text{prop}}$ for proton irradiation is given and bold:

- 1.62 GeV $^{40}$Ar ions $\beta = 0.11$ [6] $\beta_{\text{prop}}^{\text{TRIM}} = 3.5 \times 10^4$
- 23 GeV protons $\beta = 0.019$ [7] $\beta_{\text{prop}}^{\text{prop}} = 6.05 \times 10^3$

If the proportional is correct, the calculated value has to be similar to the vacancy generation rate obtained from the simulation. Note here that TRIM provides the simulation of proton interaction with Si only if the sample thickness is more than 10 mm. Simulation under this condition shows that the value of $\beta_{\text{prop}}^{\text{TRIM}}$ for protons has to be less than 0.1 cm$^{-1}$ which is $10^4$ lower than the value calculated from the proportion. This allows concluding that:

- proportionality between the vacancies generation rate and the irradiation effect on the $N_{\text{eff}}$ by protons and ions cannot be established;
- most of the vacancies of the dense track formed by $^{40}$Ar ion irradiation do not participate in the electrically active defect formation.

4. Features of Low Energy Ion Irradiation
Analysis Performed in the previous section is very simple in the interpretation; uniform irradiation causes uniform vacancy production over the sample. However, high energy irradiation requires the unique beams of heavy ions. It is much easier to perform the low energy ion irradiation since the acceleration instruments for it are more available. It has to be noticed, that the Bragg peak formation in the primary vacancy distribution is quite possible in these terms. The presence of such nonuniformity has to significantly affect the electrophysical properties of the irradiated structure. In

**Figure 2.** Comparison of the effective concentration dependences on fluence for 1.62 GeV $^{40}$Ar ions and 23 GeV protons [6]
order to make certain that the chosen irradiation will provide the Bragg peak, TRIM simulation was performed. The obtained collision plot and the energy loss to vacancy production dependence on depth are presented in figure 3a and 3b, respectively. Simulation was performed for silicon 300 µm thick sample, the energy of incident particles was 53.4 MeV and their number was $10^4$. Figure 3a demonstrates strongly disordered region around the ion stopping range where they release the main part of their initial energy. Therefore a primary number of vacancies is generated in the same region, which is displayed in figure 3b.

Figure 3. TRIM simulation of low energy ion irradiation. (a) Collision plot (b) Energy loss to vacancy production

In order to illustrate presented simulations and find out the features of the finally formed defect distribution, one should consider experimental characteristics of irradiated silicon detectors. Figure 4a illustrates the results of capacitance-voltage (CV) measurements. The dotted lines represent the experimental data for irradiated samples and the straight line shows CV before the irradiation. It can be seen, that with the fluence increase CV characteristics deviate more and more from a classic dependence. Furthermore, the capacitances of F2 and F3 samples increases in the certain voltage range of 4-7 V, which correlates to the possible Bragg peak region. Such dependencies cannot be described using well-known models and formulas. Usually, the effective concentration profiles can be extracted from CV measurements. However, in view of CV features, this procedure is relatively correct only for the lowest fluence of investigated samples. The $N_{eff}$ for F1 sample (dotted line) and calculated primary vacancy densities $N_v$ (dashed lines) are presented in figure 4b. The latter was extracted from the TRIM simulation of collision events data using the following relation: $N_v = \text{Vac}(x) \times F$, where $\text{Vac}(x)$ is the dependence of created target vacancy number on the target depth. It has to be noticed that the effective concentration profile has been rescaled by increasing $N_{eff}$ in 75 times.

Concentration profiles demonstrate two issues of the electrophysical properties of the low energy irradiated samples. Firstly, the $N_{eff}$ maximum, which can be associated with the Bragg peak maximum, is shifted from the simulated 15.2 µm position. Secondly, the left side of the experimental data peak is much sharpened while the theory predicts smooth growing as TRIM simulations indicate. Thus, several obstacles arise in the case of irradiation with low energy ions, making it difficult to analyze its influence on silicon detectors without a special physical model.
Figure 4. Comparison of the simulated and experimental data for low energy irradiation. (a) C-V characteristics (b) Profiles of the experimental effective concentration and simulated density of vacancies

5. Conclusion
TRIM simulations were performed both for low energy ion irradiation and high energy irradiation. The results display significant differences in radiation effects on the silicon structure, which can be clearly seen, e.g., in the simulated collision events plot. An attempt was made to find a correlation between the TRIM data and the results of the previous study on the heavy ions irradiation. The study demonstrates a clear proportion between the degradation of the detector properties under the ion and proton irradiation. It was assumed, that the rate of the vacancy generation calculated from the proportion for proton irradiation has to be similar to the TRIM simulated rate. Such an assumption was not verified. This indicates that only the experimental data allows building a reliable scenario for silicon detector degradation. As an option, one can fit the degradation parameters for ions with different masses and use the parametrization dependence. However, the special defect introduction by ions of different energies must be taken into account even in this case.

Experimental data for silicon detectors irradiated by low energy ions are only partially consistent with simulations. Analysis of the results for low energy irradiation revealed a requirement for a new physical model, taking into account the appearance of the Bragg peak in concentration profiles. Nevertheless, it has to be concluded that TRIM is a very useful instrument for the study of primary defect distribution; however, its application for estimation the radiation damage and the degradation scenario prediction calls for specific knowledge of defect formation processes.

References
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