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Bragg peak effect on the electrical characteristics of Si detectors irradiated with medium energy ^{40}Ar ions

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Abstract. The investigation is focused on the simulation of the I-V characteristics of Si p^+-n-n^+ diodes irradiated with medium-energy ^{40}Ar ions whose range is less than the detector thickness. The characteristics were simulated by considering the distribution of the current generating defects related to the profile of primary vacancies with a sharply rising density at the end of the ion track, which was defined by using the TRIM software. The defects involved in the simulation were two radiation-induced acceptors, the one positioned at $E_C - 0.42$ eV and the other in the lower half of the bandgap at $E_C - 0.65$ eV, responsible for the bulk current generation and the electric field distribution, respectively. With the adjusted characteristics of the defects, I-V characteristics in the fluence range $(1–4)\times10^9$ cm^{-2} demonstrated a quantitative agreement with the experimental curves and a strict proportionality of the maximum current to the fluence. The electric field evolution with ion fluence was calculated and discussed as information complementary to the I-V data.

Keywords: defects, silicon detectors, ion irradiation, radiation hardness, current simulation

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Влияние пика Брэгга на электрические характеристики кремниевых детекторов, облученных ионами ^{40}Ar средней энергии

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Аннотация. Работа посвящена моделированию генерационного тока кремниевых детекторов, облученных ионами ^{40}Ar средней энергией, формирующих в структуре пик Брэгга. Продемонстрированы моделирование распределения первичных дефектов в среде TRIM, распределения электрического поля при различных дозах облучения, а также сравнение экспериментальных вольт-амперных характеристик и построенных на основе моделирования. В качестве основы для расчетов принята двухуровневая модель генерации

Ключевые слова: дефекты, кремниевые детекторы, облучение ионами, радиационная стойкость, симуляция тока

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Introduction

Silicon detectors are currently a central element of the largest detection systems in accelerator complexes such as Large Hadron Collider, CERN, and GSI, Darmstadt. One of the main features of such facilities is the huge energy of accelerated particles, reaching hundreds of GeV. Under these conditions, particles traverse the total detector depth and create a uniform defect distribution throughout the device, and the detector properties in the entire bulk degrade uniformly. The model of Si detector degradation with uniformly damaged volume was developed in many studies and successfully applied for an explanation of the detector radiation degradation under the influence of light particles of high energies [1].

Nuclear physics where the study of exotic ions is one of the focuses of interest, is also exploiting the beams of larger and larger intensity. A specific feature of such experiments is that the ranges of the ion mass and the energy are wide enough, and thus detected ions can pass through the detectors creating an almost uniformly distributed damage in the detector bulk or stop inside it. The results of recent study on the comparison of radiation effects of high-energy protons and ^{40}Ar ions on Si detectors [2] demonstrated the applicability of the parameterization of the irradiated silicon properties, namely, the introduction rates of radiation-induced defects, by using scaling coefficients, and thus extend them for the modeling of heavy ion effects on Si detectors.

In the case of short-range ions (the range is less than the detector thickness), another important issue arises. The rate of energy loss increases with the energy reduction, and thus at the ion stopping point the primary defect density might be up to several orders of magnitude larger than at the beginning of the ion range, thus forming the Bragg peak. This adds to the detector degradation a new factor, a vastly non-uniform distribution of radiation defects along the ion paths.

The impact of the Bragg peak region (BPR) on the electrical characteristics has already been observed in the recent study of Si diodes irradiated with short-range ions [3]. In the current work, this line of investigation is continued and focused on the practical issue, the analysis of I-V characteristics of p^+-n-n^+ diodes irradiated with medium energy ^{40}Ar ions forming the BPR in the silicon bulk. The goal of the work is to propose parameterization of the silicon properties, which allows calculating I-V characteristics of irradiated diodes. For this, simulations of the I-V characteristics and the distribution of the electric field across the diode depth x, $E(x)$, were carried out. The obtained results can be considered as a first step in the physics of radiation degradation of Si detector exposed to short-range ion irradiation.

Experimental

The samples were processed on the n-type Czochralski silicon wafer with a resistivity of 60 Ωcm, which allows precise profiling the effective space charge concentration N_{eff} in the damaged region by increasing the range of bias voltage needed for its depletion. The diode thickness and the p^+-n junction area were 300 μm and 23 mm^2, respectively. All samples contained a guard rings structure surrounding the p^+ contact and stabilizing I-V characteristics of the diodes. Three samples were irradiated with 53.4 MeV ^{40}Ar ions to the fluences $\Phi1 = 1\times10^9$, $\Phi2 = 2\times10^9$ and $\Phi3 = 4\times10^9$ cm^{-2}.

The I-V measurements were carried out at room temperature (RT) in the voltage range 0–100 V using Keithley 487 picoammeter with the diode guard ring grounded. The dependences of the bulk current on voltage after irradiation and beneficial annealing of the samples are shown in Fig. 1, *a*. The shapes of the characteristics are similar for all fluences.

Simulations of primary defect distribution using TRIM

The distribution of primary defects in silicon irradiated with 53.4 MeV ^{40}Ar ions was calculated by using Transport of Ions in Matter (TRIM) software [4]. Fig. 1, *b* shows the amount of primary vacancies $N_v(x)$ defined as their number generated in the layer at the depth x over a length of 1 Å per 1 ion and distributed across the ion range r_p of about 15 μm.

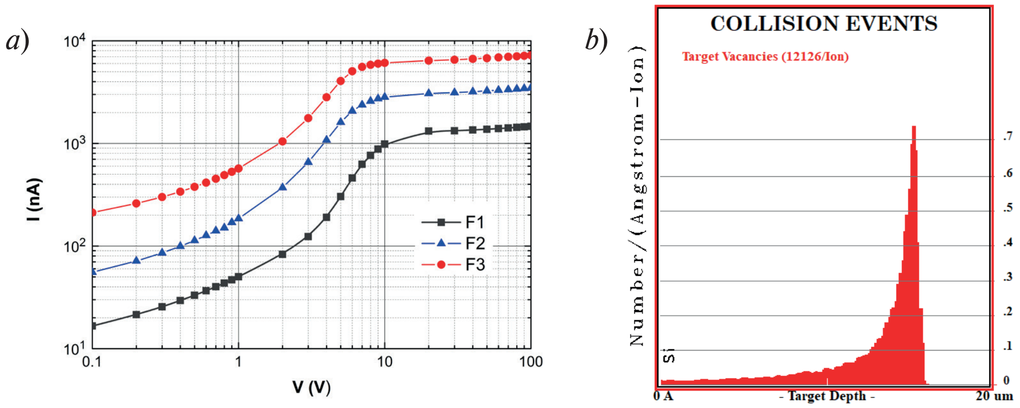

Fig. 1. Experimental I-V characteristics of Si diode irradiated with 53.4 MeV ^{40}Ar ions vs (*a*) primary defect distribution in silicon irradiated with 53.4 MeV ^{40}Ar ions calculated by using TRIM (*b*)

Obviously, subsequent interactions of the vacancies with the target atoms, the contaminations and with each other cannot be determined using simulations in TRIM, but it can be assumed that some fraction of the vacancies will contribute to the formation of electrically active defects with deep energy levels acting as the current generation centers and/or the levels responsible for the electric field distribution in the depleted region in the reverse biased diode.

Simulation of I-V characteristics and $E(x)$ profiles along the track of short-range ^{40}Ar ions

In the I-V characteristics the current shows a gradual and then a sharp rise (the latter identified with the BPR), and the following tendency to the current saturation at V about 10 V. This value is related to the depletion of the damaged region: the higher the fluence, the higher the saturated current.

Given the capabilities of the program used for simulating the electrical characteristics of p+-n-n^+ Si diodes described in [5], the N_v dependence on the coordinate x normal to the diode surface was tabulated within the ion range. Accordingly, the concentration of electrically active defects affecting the diode I-V characteristics was assumed to be proportional to the concentration N_v. The proportionality coefficient K was an adjustable parameter, the same along the entire ion tracks, but individual for a particular type of defects.

An approach to describing the characteristics of radiation-induced defects was similar to that previously used to analyze the degradation processes in Si detectors irradiated with high- energy protons, in which the set of numerous electrically active radiation defects was replaced by a minimal number of effective defects with adjustable parameters [6]. Each of them is associated with a certain process, which enables an independent fit to the diode characteristics.

In the modeling the I-V characteristics of diodes irradiated with short-range particles, the parametrization of radiation effects should take into account the following factors:

- the rate of thermal generation of electrons and holes in the depleted region and its nonuniformity over the thickness of the diode in accordance with a vacancy profile taken from the TRIM data,
- compensation of positive charge of shallow impurities (phosphorus shallow donors in the n-type silicon) by negatively charged acceptors induced by ions, which determines the distribution of the electric field in the diode.

In the study, these processes were described by introducing into the model two effective acceptor energy levels, one of which, DA1, determined the rate of the current generation in the depleted region of the structure, while the second, DA2, compensated shallow donors, thus forming the distribution of the electric field.

The DA1 was considered as the acceptor acting as an electron trap positioned at $E_C - 0.42$ eV. This energy level does not affect the space charge concentration since it is located in the upper half of the bandgap and remains electrically neutral in the electric field region. The rate of the current generation via this energy level is determined by the activation energy $E_g - 0.42 = 0.7$ eV (where E_g is the silicon bandgap equal to 1.12 eV at RT). The second acceptor DA2 is the effective energy level located in the lower half of the bandgap at $E_C - 0.65$ eV and capable of compensating the charge of shallow donors; thereby it determines the electric field distribution in the diode. It should be noted that both levels, DA1 and DA2, are current generation centers since they have close activation energies of 0.7 and 0.65 eV, respectively; however, their concentrations are rather different. The parameters of the levels are the electron and hole capture cross-sections set to be the same and equal to 1×10^{-13} cm^2.

The experimental I-V characteristics and simulated curves are compared in Fig. 2. Qualitative agreement is observed for all fluences. It should be noted that the common feature of the current rise shape is the decrease in voltage at which the rate of the rise with the bias is maximal. This indicates that the material in the LDR becomes more compensated with increasing dose, which results in a lower depletion voltage of the whole damaged region. The maximum agreement between the calculated and the experimental curves is observed for the diode irradiated to Φ3. Therefore, the deviations of the current rise profile with voltage for lower fluences should be attributed to the impact of the p$^+$-n junction periphery on the current rather than to the factors related to the mechanisms of the silicon bulk deterioration under irradiation. The same applies to the slow increase in current observed in all I-V characteristics after depletion of the entire damaged region, which can be related to the surface properties of the structure. All simulated I-V characteristics show a smoother transition from the current rise to its saturation than the experimental ones. The reason may be the channeling of some fraction of impinging ions, which blurs the border of the damaged region and increases the width of the BPR, creating a damaged layer at a depth greater than r_p.

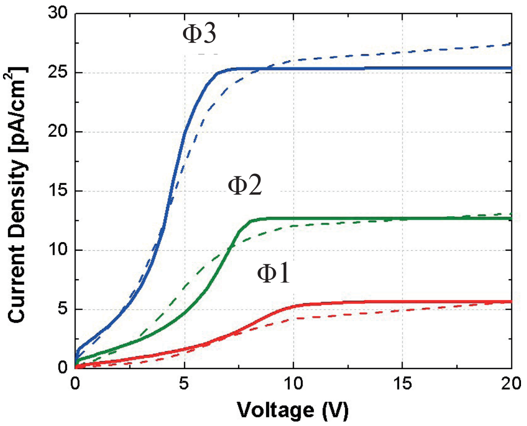

Fig.2. Comparison of the simulated and experimental I-V characteristics of irradiated

Figures 3, *a* and *b* show the simulated distributions of the effective acceptor concentrations over the depth of the damaged layer, along with the concentration of shallow donors $N_{SD} = 7\times10^{13}$ cm^{-3}. The DA1 and DA2 distributions correspond to the introduction coefficients $K_{DA1} = 0.4$ and $K_{DA2} = 0.007$ per vacancy obtained from the fitting and are presented for the minimum and maximum fluences. At $\Phi = 4\times10^9$ cm^{-2}, the concentration of DA2 exceeds the concentration of shallow donors in the most of the Bragg peak region (13–15 μm), i.e., this bulk is overcompensated.

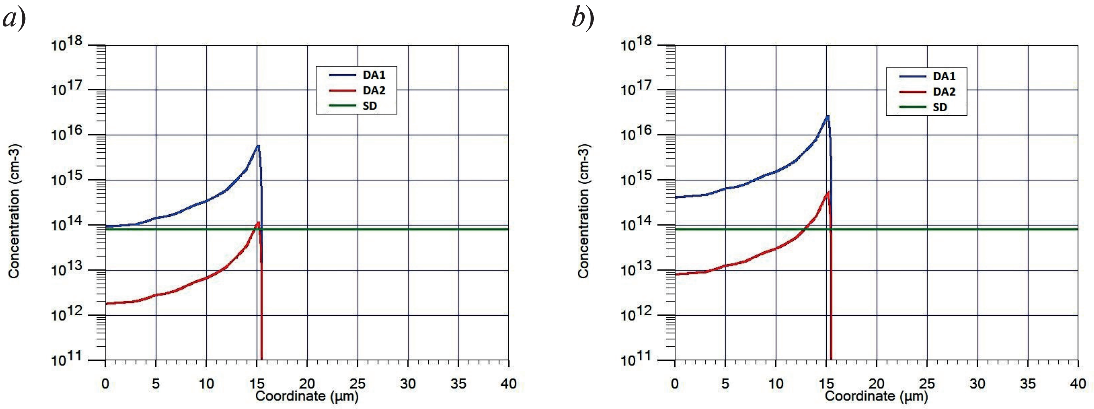

Fig. 3. Simulated distributions of the DA1 and DA2 concentrations in irradiated diodes. Φ (cm^{-2}): 1×10^9 (*a*) and 4×10^9 (*b*). For comparison, concentration of shallow donors is shown

The important data obtained as a result of the I-V characteristics simulation are shown in Fig. 4, which presents the distribution of the electric field $E(x)$ in the diodes at various bias voltages. The $E(x)$ profiles in Fig. 4, *a* correspond to the minimum Φ. In this case, according to Fig. 3, *a*, the DA2 concentration is below the concentration of shallow donors even at the Bragg peak maximum, and the arising structure can be considered as a p$^+$-n junction in silicon with a nonuniform negative concentration $N_{eff} = \text{abs}(N_{SD} - N_{DA2})$. Accordingly, the width of the depleted region increases gradually when propagating into the damaged region. A feature of the $E(x)$ profile in the region of the Bragg peak is that after its depletion, the electric field gradient increases (Fig. 4, *a*) and corresponds to the concentration of donors in the nonirradiated silicon.

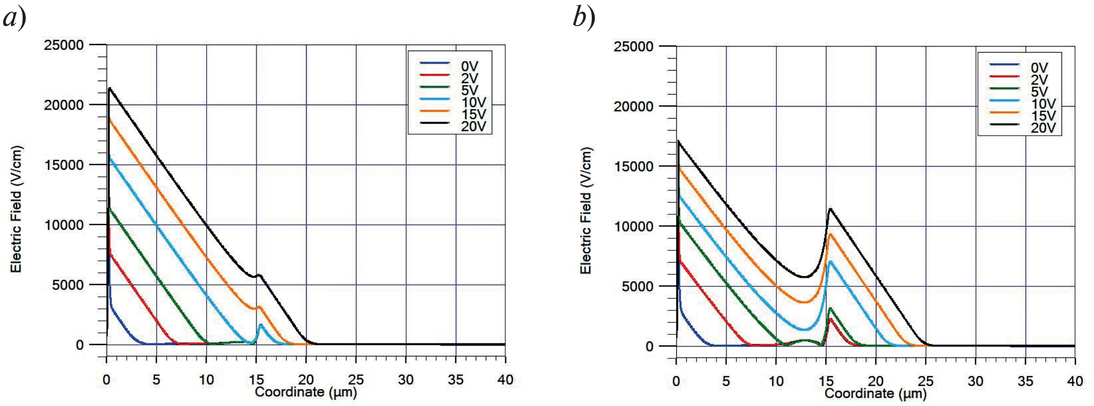

Fig.4. Distribution of the electric field across the diode thickness. Φ (cm^{-2}): *a*) 1×10^9, and *b*) 4×10^9

At the maximum fluence, the appearance of a built-in field in the range 0–5 V is clearly visible at both sides of the border between the BPR and a nondamaged region (Fig. 4, *b*). At higher bias, the electric field region is propagating outside the BPR, starting from a depth $x = 15$ μm, and at $V = 10$ V the BPR is fully depleted. Such a change in the electric field with increasing voltage is a direct consequence of the silicon overcompensation by the DA2 acceptors inside a part of the damaged region and the appearance of a narrow region of the p-type silicon forming an internal p-n junction at the BPR border with a nonirradiated silicon bulk. However, since this feature is associated with the DA2 defect, whose concentration is less than that of the DA1, it does not affect the linear rise of the bulk current vs. fluence.

Calculations show that further increase in fluence leads to the qualitative changes in the shapes of I-V characteristics, which requires separate experiments and is beyond the scope of the present study.

Conclusion

The performed simulation of I-V characteristics of the diodes irradiated with short-range 40Ar ions showed that they can be described by two acceptors: an acceptor in the upper half of the bandgap E_C – 0.42 eV and an acceptor in the lower half at E_C – 0.65 eV responsible for the bulk current generation and the electric field distribution, respectively. The proposed system of defects allows proportional scaling of the current in Si diodes irradiated with ions in the range $\Phi \leq 4\times10^9$ cm^{-2}, which does not yield a significant excess of the induced acceptor concentration over the concentration of initial shallow donors in the raw n-type Si. This value is apparently the threshold fluence above which the current vs. fluence proportionality might be disturbed. The developed approach and the proposed parameterization of the concentration of acceptors induced by radiation allows their application to predict the impact of any short-range ions basing on the primary defect profile obtained via a program like TRIM.

REFERENCES

1. **Moll M.,** Displacement Damage in Silicon Detectors for High Energy Physics, IEEE Transactions on Nuclear Science. 8 (65) (2018) 1561–1582.

2. **Eremin V., Mitina D., Fomichev A., Kiselev O., Egorov N., Eremin I., Shepelev A., Verbitskaya E.,** A comparative study of silicon detector degradation under irradiation by heavy ions and relativistic protons, Journal of Instrumentation, 13 (2018) P01019.

3. **Mitina D., Eremin V., Verbitskaya E., Eremin I.,** DLTS spectra of radiation-induced defects in silicon detectors with heavily damaged Bragg peak region, Journal of Physics: Conference Series, 1 (1697) (2020) 012071.

4. **Mitina D., Verbitskaya E., Eremin V.,** Issues of TRIM program as a tool for developing a silicon detectors radiation degradation scenario, Journal of Physics: Conference Series, 4 (1400) (2019) 044014.

5. **Eremin V., Fadeeva N., Verbitskaya E.,** The impact of active base on the bulk current in silicon heavily irradiated detectors, Journal of Instrumentation, 12 (2018) P09005.

6. **Verbitskaya E., Eremin V., Ilyashenko I., Li Z.,** Carrier generation in irradiated Si detectors and its impact on the electric field profile, Nuclear Instruments and Methods in Physics Research A, 754 (2014) 63–70.

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