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Introduction rates of radiation defects in electron irradiated semiconductor crystals of n-Si and n-GaP

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ABSTRACT

A study was made of the introduction rate of radiation defects $\Delta N_{def}/\Delta D$ versus the fast electron irradiation dose (D) in semiconductor crystals of n-Si and n-GaP. We take the concentration of radiation defects concentration N_{def} to be the difference between the carrier concentration of semiconductors before n_0 and after irradiation $n(D)$ at the dose D, delivered at room temperature. By application of an appropriate fitting function to the dose dependent curves of the $N_{def}(D)$, it was demonstrated that the empiric exponential law of the form $N_{def} = n_0(1 - \exp(-D/D_0))$ gives the best agreement with the experimental data, irrespective of the electron energy and irradiation dose. D_0 is the irradiation dose, at which the carrier concentration $n(D)$ at a temperature $T = 300$K decreases by a factor of e. The results showed that the formation of radiation defects in the samples studied is not a linear process and $\Delta N_{def}/\Delta D$ are found to decrease exponentially with increasing irradiation dose, according to their particular character. Using the same fitting method, it was found that for certain samples, beyond a particular radiation dose level, the rate of carrier mobility versus radiation dose also decreased exponentially.

1. Introduction

A substantial body of experimental and theoretical data has been accumulated concerning the determination of the modification of the properties of semiconductor materials and devices, that have been irradiated with high energy particles (monographs Kozlovski and Abrosimova, 2005, Smirnov, 1977, reviews Emtsev et al., 2012, Leroy and Rancoita, 2007, Duzellier, 2005, Aurangzeb Khan et al., 2000, articles Panki et al., 2004, Murin et al., 2006, Alkauskas et al., 2016, Kinchin and Pease, 1955, 1956, Freysoldt et al., 2014). However, the induction rate of radiation defects in semiconductors and the differences between them have only seldom been investigated (Dvurechenski et al., 1979; Akhmetov and Bolotov, 1979). The current paper addresses this gap and systematizes available data in order to provide an improved explanation of the physical nature of the influence of the irradiation on the semiconductor parameters.

From an applied perspective, the changes induced by high energy irradiations in semiconductors and devices are characterized by modifications in their electro-physical properties: specifically, the concentration, mobility and lifetime of the charge carriers. Hence, the changes in the properties of irradiated materials are found to vary with irradiation dose, and this causes differences in the radiation stabilities of particular materials and devices made from them. It is known that substantial differences occur in the introduction rate of radiation defects in irradiated samples, which depend both on the irradiation dose itself, and the impurity content of the irradiated samples. The principal mechanism involved in such radiation induced modifications is the displacement of host atoms and the creation of vacancy-interstitials (V-I) which interact with impurities and induce energy levels in the forbidden gap of the semiconductor zone structure, so compensating the electro-conductivity.

In the present work, the introduction rate of radiation induced defects was studied, as a function of irradiation dose, and analyzed in view of the fact that the radiation induced processes, mentioned above, are complicated and often occur in a non-linear fashion according to the irradiation dose. Hence, the radiation induced changes in the material properties can vary unpredictably with irradiation dose, which leads to differing radiation stabilities of irradiated materials and devices made

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from them.

This circumstance is of particular importance for applications involving materials and devices that are located on the external surfaces of satellites or used as solar cells, and which operate in the space radiation environment over periods of years, during which time they may accumulate large radiation doses (Babaee and Ghozati, 2017; Bhat et al., 2015). It was shown that there is a substantial difference in the introduction rate of radiation defects in Si and GaP samples that contain different types, and concentrations, of impurities, and also when ultrafast electron irradiation is used. The particular novelty of the present work is that it provides the first analysis of the energy and dose dependences of the introduction rate of radiation defects, as a result of electron irradiation, in particular using pico-second duration pulses, in crystalline silicon.

2. Physical concept of the methods for estimation of introduction rates of radiation defects

The aim is to identify an effective property of the irradiated sample in order to express changes in the structures and physical properties of semiconductors so that materials with specific predictable parameters can be created. To achieve this, requires an elucidation of complex inter-dependences between structural defects and electronic effects. The problem involves a wide range of activities to be undertaken to evaluate the non-linear response of the properties of materials to non-equilibrium processes, such as irradiation and to create a relationship between the structure, impurity content and electrical properties of the material (Yunusov et al., 1978).

Two approaches aimed to describe the introduction rate of radiation defects may be applied: (1) a comparison of theoretical models with experimental data, and (2) derivation of analytic expressions by fitting empirical functions to curves obtained from experimental measurements. In this work, we chose the latter approach, from which results were obtained that are in good agreement with literature data. Results from direct current Hall effect measurements were used to give charge carrier concentration and mobility as a function of electron irradiation dose (Yeritsyan et al., 2016). From optical absorption spectra, and deep level transient spectroscopy (DLTS) measurements, as were used in refs. (Akhmetov and Bolotov, 1979; Schvartz and Antony, 1984; Brudnyi et al., 1980), the same behavior was observed regarding the introduction rates of the radiation defects, even when the samples were irradiated with protons, rather than electrons (Emtsev et al., 2012).

Irradiation of the samples was carried out at room temperatures, using a linear accelerator at the CANDLE Synchrotron Radiation Institute (Armenia), which delivered electrons with the following characteristics: 3.5 MeV energy, 4×10^{-13} s pulse duration, 12 Hz frequency, and an impulse charge of 60 pico-Coulomb. Other samples were irradiated by electrons with energies of 7.5 MeV and 50 MeV pulse duration on the micro-second range at Yerevan Physics Institute linacs. The samples were cut out in a double-cross shape with 6 Ohmic contacts for electrical measurements, a thickness of at 0.8–1.0 mm, and dimensions of 3×10 mm^2.

The irradiation dose was defined as in Eq (1):

$$D = 6.25 \times 10^{12}\frac{It}{S}, \tag{1}$$

where I is the mean current in μA, t is the exposition time in seconds and S is the cross-section of the beam in cm^2.

The beam current was measured from an accumulated charge in a Faraday cup. The electrical conductivity and the mobility of the charge carriers were measured using a known Hall effect method, at different temperatures. The electrical conductivity was calculated from the identity $\sigma = \mu ne$, where μ is the (Hall) mobility of the charge carriers, n is the concentration of the main charge carriers, and e is the electron charge. The charge carriers' mobility was defined as in Eq. (2), in relation to Hall effect measurements:

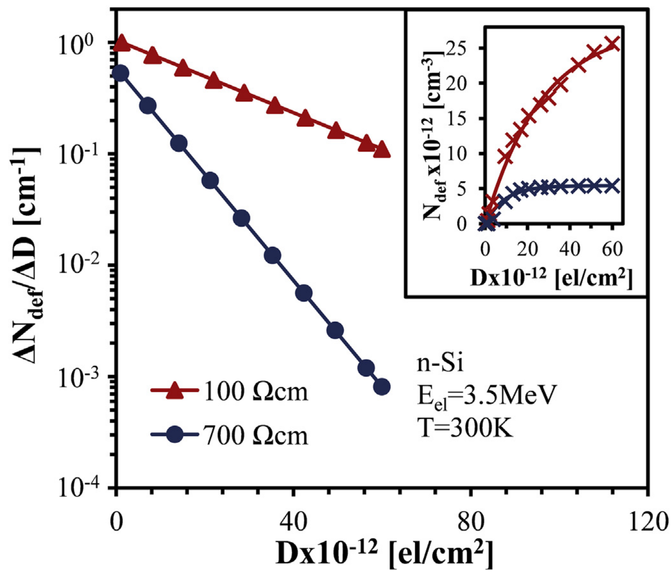

Fig. 1. Radiation defects introduction rate vs. irradiation dose for silicon samples with initial specific resistivity of 100 Ωcm and 700 Ωcm. The values for the induced radiation defects for each applied dose are presented in the insert. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$\mu = \frac{U_H l}{U_\rho bB}, \tag{2}$$

where U_H is the potential difference between the Hall contacts, U_ρ is the potential difference between the conductivity contacts, B - is the magnetic field induction, and l and b are the length and width of the sample, respectively.

3. Results and discussions

The results for the current measurements are presented in Figs. 1–5. We define the rate of introduction of radiation induced defects, to be

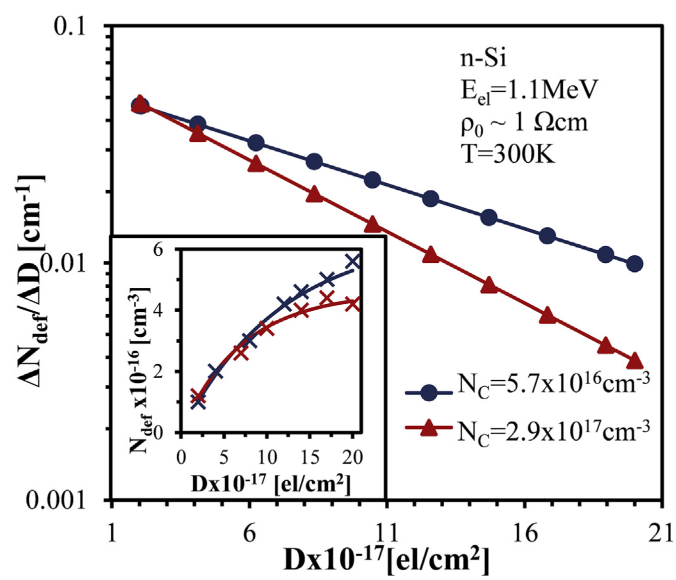

Fig. 2. Introduction rate of radiation defects vs. irradiation dose for n -type silicon doped with different concentrations of carbon atoms and $N_C = 2.9 \times 10^{17}$cm^{-3} (Akhmetov and Bolotov, 1979). The induced radiation defects values for each applied dose are presented in the insert. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

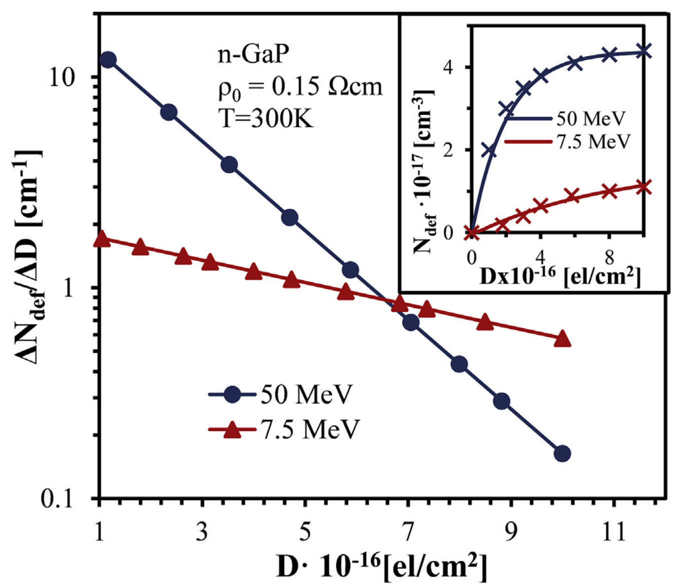

Fig. 3. Introduction rate of radiation defects vs. irradiation dose for n-GaP samples with an initial specific resistivity of 0.15 Ω cm, irradiated by electrons with energies of 50 MeV and 7.5 MeV. In the insert is shown the induced radiation defects values for each applied dose.

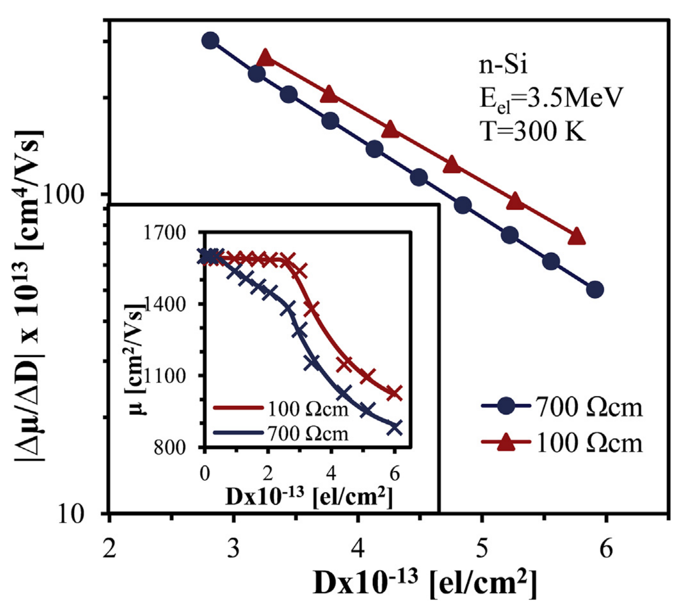

Fig. 4. Absolute value of charge carriers' mobility change rate as a function of electron irradiation dose (using 3.5 MeV electrons delivered with a pulse duration of picoseconds) for n-Si samples with specific resistivity of 100 Ωcm and 700 Ωcm. The charge carriers' mobility values for each applied dose are presented in the insert.

the change in charge carrier concentration as a function of the irradiation dose at room temperatures; in other words, its removal per irradiation dose, i. e. the derivative, $\Delta N_{def}/\Delta D$. By application of the fitting method to the dose-dependence curves, shown as insertions in the $N_{def}(D)$ (Figs. 1–3), it was found that the empiric exponential function provided the best agreement with the experimental data, independent of the electron energy and radiation dose. The exponential function used is represented in Eq. (3):

$$N_{def} = n_0 - n(D) = n_0(1 - \exp(-D/D_0)) \tag{3}$$

where n_0 is the initial concentration of charge carriers, and $n(D)$ is their concentration at a given irradiation dose D, at room temperatures; and

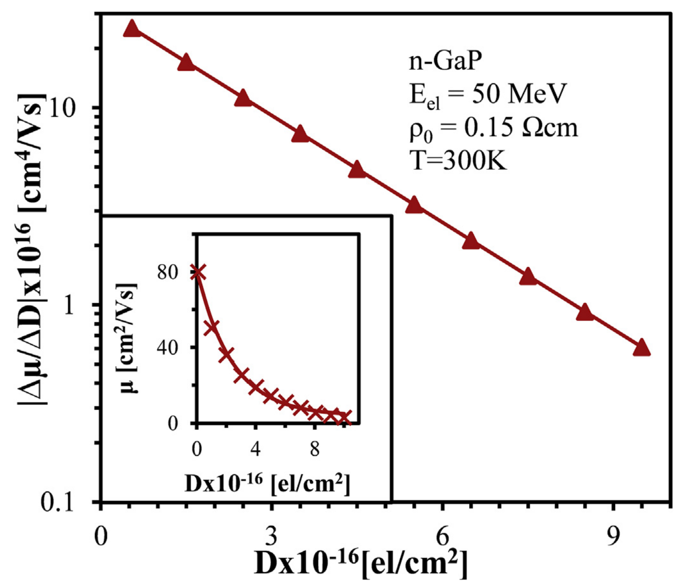

Fig. 5. Absolute value of charge carriers' mobility change rate depending on 50 MeV energy microseconds duration pulse electron irradiation dose for n-GaP samples with initial specific resistivity of 0.15 Ωcm. In the insertion the mobility values for applied doses are presented.

D_0 is the irradiation dose at which the carrier concentration $n(D)$ at a temperature T = 300K decreases by a factor of e in the irradiated semiconductor samples. D_0 depends on the initial concentration of the charge carriers' n_0, the energy of the irradiation electrons E_{el} and the irradiation intensity. From the expression given in Eqn. (3) it is straightforward to evaluate the introduction rate of radiation defects $\Delta N_{def}/\Delta D$ versus the irradiation dose from fast electrons D, in the semiconductor crystals n-Si and n-GaP, according to Eq. (4):

$$\frac{\Delta N_{def}}{\Delta D} = \frac{n_0}{D_0}\exp(-D/D_0) \tag{4}$$

Thus, the use of the fitting method for the dose-dependence curves in the $N_{def}(D)$ showed that the introduction rate of radiation defects can be described in terms of a decreasing empirical exponential function.

Table 1 shows the types of samples studied, along with their electrical characteristics, as well as the parameters for the fast electron irradiation. Semiconductor samples were specifically chosen whose electrical parameters varied by more than three orders of magnitude and fast electrons were used with energies in the range 1–50 MeV. Semiconductors with great difference of parameters were chosen for good observation of parameters' change and to demonstrate the usefulness of current investigation for large range of change of material properties. The electron beams have different pulse durations and respective irradiation intensities that vary by more than four orders of magnitude. It is known that the types and parameters of radiation-induced defects in semiconductors are acutely dependent on the intensity of the bombarding particles. From this point of view, the use of ultra short electron pulses with pico-second duration significantly broadens the range of current density in the pulse. Table 1 presents the characteristic parameter D_0 for the samples studied, which indicates the electron irradiation dose at which the carrier concentration in semiconductors decreases by a factor of e, and which is highly dependent on the initial parameters of the semiconductors, the energy of the irradiating electrons, and the pulse duration, as well as the presence of non-active impurities present in the samples.

Fig. 1 shows that the introduction rate strongly depends on the concentration of the initial charge carriers in crystalline silicon samples. Irradiation was performed using pulses of electrons of pico-second duration, and an energy of 3.5 MeV. For the sample with an initial resistivity of 100 Ωcm, the introduction rate was found to change by

Table 1
Characteristics of the samples investigated and the electron beam parameters. ρ_0 is the specific resistance of semiconductors, N_C is the carbon impurity concentration in Si, and D_0 is the characteristic irradiation dose at which the carrier concentration in semiconductors decreases by a factor of e.

Sample name	ρ_0 [Ωcm]	D_0 [el/cm^2]	Electron Energy [MeV]	Irradiation pulse duration [sec.]	Current in pulse [A/cm^2]
n-Si	700	9.11×10^{12}	3.5	4×10^{-13}	60
n-Si	100	2.67×10^{13}	3.5	4×10^{-13}	60
n-Si ($N_C = 5.7 \times 10^{16}$ cm^{-3})	1	1.17×10^{18}	1.1	5×10^{-6}	0.002
n-Si ($N_C = 2.9 \times 10^{17}$ cm^{-3})	1	7.22×10^{17}	1.1	5×10^{-6}	0.002
n-GaP	0.15	2.11×10^{16}	50	5×10^{-6}	0.002
n-GaP	0.15	8.17×10^{16}	7.5	5×10^{-6}	0.002

almost one order of magnitude, while for the sample with a resistivity of 700 Ωcm, it changed by almost three orders of magnitude, using the same irradiation dose. The data from Table 1 shows that the initial concentration of the charge carriers for these two samples changes by a factor of seven, while D_0, which characterizes the efficiency of the generation of radiation defects in semiconductors, changes by only a factor of three. Accordingly, we propose that radiation defects are formed in silicon crystals by a non linear process.

In ref. Akhmetov and Bolotov (1979), n-Si samples with an initial specific resistivity of 1Ωcm, and doped with different concentrations of carbon atoms, were irradiated at room temperatures using electrons of 1.1 MeV energy, and a pulse duration of microseconds, and studied using infrared absorption measurements. Using the fitting method, described above, we discovered that the difference between the formation rates of radiation induced defects in these two samples enlarged with increasing irradiation dose. Furthermore, the defect formation rate in the sample with high concentration of doped Carbon was found to decrease much more rapidly than in the sample whose doped carbon concentration was low. We conclude, therefore, that the presence of electrically non-active impurities can substantially influence the rate at which radiation defects are generated in a semiconductor silicon crystal.

The introduction rate for radiation defects in n-GaP crystals (Fig. 3) was determined after irradiation by electrons with different energies (7.5 MeV and 50 MeV). It is known that when semiconductors are irradiated with 50 MeV electrons, mostly cluster defects are produced, while 7.5 MeV electrons produce mainly simple defects (Brailovskii et al., 1980). Fig. 3 shows that the introduction rate of radiation defects in a sample, which was irradiated with 50 MeV electrons decreased more rapidly than when 7.5 MeV electrons were used. Thus, the introduction rate changed by almost two orders of magnitude for the 50 MeV electron irradiation, while for the sample irradiated by electrons with energy 7.5 MeV it changed by just about a factor of three. In probability, this difference in the introduction rate for the two samples is due to the different types of radiation defects (point defects and clusters) that are produced. For certain samples, we estimated the changes in the mobility rate of the charge carriers over the range of radiation doses where the changes were found to be significant. Relevant data for n-Si samples irradiated by electrons with energy of 3.5 MeV and n-GaP samples irradiated by electrons with energy 50 MeV, are presented in Figs. 4 and 5.

In Fig. 4 are presented changes in the charge carrier mobility rate as a function of different irradiation doses, for the interval where the decrease is acute. It is clear from this figure that the change is very sensitive, beginning from a particular value of irradiation dose and for both samples, an exponential decline was observed. Fig. 4 also shows that for the sample with an initial resistivity 700 Ωcm, the mobility change rate is significantly smaller than for the sample with an initial resistivity of 100 Ωcm. Since the charge carrier concentration in the sample with an initial resistivity of 100 Ωcm is almost seven times greater than in the 700 Ωcm resistivity sample, we suggest that the mobility change rate depends on the concentration of charge carriers. Thus, for those samples where the carrier concentration is highest, the mobility change rate is greatest.

An interesting feature was noted for the 100 Ωcm sample regarding changes in the mobility of the charge carriers, as a function of irradiation dose (Fig. 4), which may influence its resistivity (or electroconductivity) behavior. However, for the 700 Ωcm sample, only a classical (almost linear) increase of resistivity in the applied dose region was observed.

The mobility change rate versus irradiation dose after the n-GaP sample irradiation by 50 MeV electrons is presented in Fig. 5. Although GaP is a different type of semiconductor than Si, and the mobility of its charge carriers is essentially smaller than for crystalline silicon, an exponential decay of the charge carrier mobility rate was also observed. Comparing data presented in Figs. 4 and 5 over the dose ranges investigated we may conclude that rate change for the mobility of charge carriers in the n-GaP sample is smaller than in the n-Si samples by roughly one order of magnitude.

In all figures errors are lying within the experimental points. Hall effect measurements' uncertainties is less than 2%, and fitting method's errors are found to be ± 5%.

It is known that, as a result of irradiating semiconductors, the main effect is that their electrical conductivity decreases, so that they become highly-resistive. This behavior has been related to the formation of (preferably) acceptor or donor levels in the zone structure forbidden gap of the semiconductor (Emtsev and Mashovets, 1981) and a significant correlation exists between changes in the electrical conductivity of semiconductors and the energy levels that are introduced by radiation defects. This effect causes a tendency towards compensation of the electrical conductivity of a semiconductor, by radiation defects, and thus semiconductors tend to develop an intrinsic conductivity as a result of irradiation.

4. Conclusions

A study was made of the introduction rates of radiation defects $\Delta N_{def}/\Delta D$ measured as a function of electron irradiation dose in semiconductor materials n-type Si with specific resistances of 1 Ωcm, 100 Ωcm, 700 Ωcm and n-GaP with a specific resistance 0.15 Ωcm. For the dose dependence of the concentration of radiation defects, an empiric exponential function of the form $N_{def} = n_0(1 - \exp(-D/D_0))$ was derived, which is independent of the electron energy and irradiation dose for both semiconductors. It was found that the characteristic parameter for the radiation defects generation efficiency D_0 is strongly dependent on the initial carrier concentration n_0 of the semiconductors, the energy of the irradiating electrons, and the pulse duration, in addition to the presence of non-active impurities, such as carbon, in the samples. Comparison of the generation rate for radiation defects in samples with a resistivity of 100 Ωcm and 700 Ωcm showed that the formation of defects on irradiation is a non-linear process in silicon crystals. It was found that the introduction rate of radiation defects in the n-GaP sample, when 50 MeV electrons were used, which mainly creates cluster defects in the crystal, decreased more sharply than in case of irradiation with electrons of 7.5 MeV, which mainly forms point defects. Hence, the difference in the introduction rate of radiation defects depends on nature of the defects themselves. It is also clear that electrically non-active impurities in a silicon crystal can have a noticeable influence on the rate at which radiation defects are generated in this semiconductor material. The study of changes in the rate of the mobility of charge carriers as a function of irradiation dose shows an exponential decrease for both types of sample. The results showed that for samples with higher carrier concentrations, the mobility change rate is visibly greater than for samples with lower carrier concentrations.

Authors contribution

Hrant Yeritsyan: formulation of research goals and aims, draft of manuscript; Aram Sahakyan: methodology, experimental investigation, draft of manuscript; Norair Grigoryan: experimental investigation, data preparation; Vachagan Harutyunyan: project administration; Vika Arzumanyan: data collection, software, figures; Vasili Tsakanov: conceptualization, research activity planning: Gayane Amatuni: data curation; Bagrat Grigoryan: preparation of works and carry out experiments in accelerator; Christopher Rhodes: editing of manuscript for publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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