

18 MeV Proton Irradiation Effects on Electro-Physical Parameters of Silicon Crystals

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Abstract. A study was made of the concentration and mobility of charge carriers and the specific resistivity of n-type silicon monocrystals irradiated by 18 MeV protons. For irradiation doses of 10^{13} - 10^{14} pr/cm², the charge carriers' concentration and specific resistivity changed exponentially by more than two orders of magnitude, depending upon the actual dose received. The mobility of the charge carriers showed a non-monotonic dependence as a function of irradiation dose, which initially decreased, but then increased. These phenomena can be explained in terms of the formation of predominantly cluster-type radiation defects in the samples.

Keywords: Silicon crystal, 18 MeV proton irradiation, radiation defects and clusters, charge carriers' concentration and mobility, specific resistivity

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1. Introduction

Semiconductor silicon is widely used in the modern electronics industry as one of the fundamental components of various electronic devices. A significant number of these devices operate in high-energy particle radiation environments, such as space stations, satellites, nuclear reactors, etc., where the most intense particles are protons and electrons with energies of several MeV. To determine the effects of radiation damage on silicon crystals and devices has been the aim of many previous investigations and the topic remains of considerable scientific interest [1-5].

When materials are exposed to various high energy radiations (protons, electrons, neutrons, γ -rays, etc.), different types of structural radiation defects are generated, some of which are stable at room temperatures. The formation of radiation defects in materials depends essentially on the particular type of radiation employed, the energy, intensity and irradiation conditions, and also the concentration of uncontrolled chemical impurity atoms in the crystal [6-8]. When semiconductors are irradiated, the concentration of radiation defects increases while the concentration of charge carriers and their mobility both decrease. The radiation defects form new energy levels within the band gap of the semiconductor, and beginning from a particular critical concentration, affect the electro-physical parameters of semiconductor devices on up to their complete degradation [9-13].

In the case of irradiation using protons with energies higher than 10 MeV, nuclear scattering is significant. In silicon, for protons with energies in the range 10-50 MeV, elastic scattering dominates. During this elastic interaction, the atoms of the irradiated silicon receive kinetic energy and when this is sufficiently high, become sources of secondary defects for the displacement and ionization of atoms in the material [14].

Studying the kinetics of defect formation induced by high-energy proton irradiation in silicon crystals is of special interest for semiconductor radiation physics, since it is highly relevant for the creation of radiation resistant electronic devices that operate in extreme radiation environments.

The aim of this work is to study the effects of irradiation with 18 MeV protons on the concentration and mobility of charge carriers, and the electrical conductivity of silicon crystals.

2. Experimental methods

The samples investigated consisted of n-type silicon crystals with a specific resistivity of 20 $\Omega\cdot\text{cm}$, which were prepared in the form of a double cross with characteristic dimensions of 0.5x2x12 mm, as shown in Fig. 1(a) and the sample holder general view is shown in Fig. 1(b).

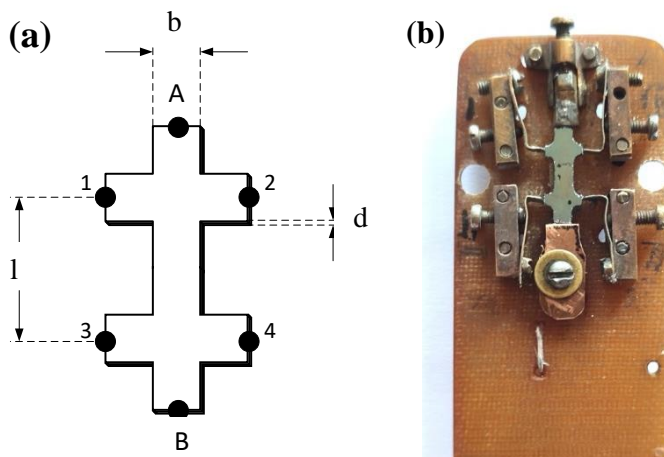


Fig. 1. (a) View of the silicon sample. A, B, 1, 2, 3 and 4 are points for contacts. b - width (2 mm), l - distance between (6 mm) contacts 1, 3 and 2, 4, d - thickness (0.5 mm), AB - total length (12 mm); (b) The sample holder general view.

Using the DC Hall effect measurement method, the silicon crystals' specific resistivity, mobility and concentration of charge carriers were determined for different irradiation doses and at temperatures in the range 150-300K.

The above parameters for the samples were calculated using the following expressions:

$$n = \frac{I}{U_H} \frac{B}{d \cdot e}, \mu = \frac{U_H}{U_\rho} \frac{l}{b \cdot B}, \rho = \frac{U_\rho}{I} \frac{d \cdot b}{l}, \quad (1)$$

where n is the concentration of charge carriers; μ is the mobility of charge carriers; ρ is the specific resistivity of the sample, I is the current flowing through the sample; $B = 0.5$ T is the magnetic field; U_H is the Hall effect voltage across the 1,2 and 3,4 contacts; U_ρ is the voltage between the 1,3 and 2,4 contacts; $e = 1.6 \cdot 10^{-19}$ C is the electron charge, d , l and b are the sample dimensions.

Proton irradiation was carried out using the C-18 cyclotron, in the Radioisotope Production Center located at AANL, Yerevan, Armenia. Irradiation was performed at a constant intensity of 10^{12} pr/cm²·s and the irradiation doses were in the range of 10^{13} - 10^{14} pr/cm² delivered by changing the irradiation exposure time. The irradiation was performed at room temperature. The proton beam was directed vertically onto the sample surface, because the sample thickness is 0.5mm and protons with an energy of 18 MeV have a free path length of about 2 mm in silicon crystals; thus, it can be assumed that the irradiation defects generated in the bulk of the sample are uniformly distributed. The average accuracy of experimental measurements is $\pm 5\%$.

3. Results and discussions

Experimental results are presented in the Figures 2-4. The dependence of the concentration of charge carriers on the 18 MeV energy proton irradiation dose for a silicon crystal with an initial specific resistivity of 20 $\Omega\cdot\text{cm}$ is illustrated in Fig. 2. As can be seen, the concentration of charge carriers as a result of proton irradiation doses in the range of 10^{13} p/cm² - 10^{14} p/cm², decreases by more than two orders of magnitude and can be described by an exponential function:

$$n(D) = n_0 \exp\left(-\frac{D}{D_0}\right), \quad (2)$$

where n_0 is the initial concentration of charge carriers, and $n(D)$ is their concentration at a given irradiation dose D , at room temperature; and 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 in the irradiated semiconductor samples. The $D_0 = 1.81 \cdot 10^{13}$ pr/cm² parameter also represents the efficiency of generation of the irradiation defects. In [8] it was shown that, in the case of electron irradiation, D_0 depends on the initial concentration of charge carriers, the presence of non-active impurity atoms in the sample, and energy of the electrons.

A similar exponential decrease in the concentration of charge carriers was observed for irradiation by electrons with energies of 1.1 and 3.5 MeV [8]. Therefore, it can be assumed that although the two kinds of radiation are completely different, when protons are used, it is mainly cluster type defects that are generated, while electrons create mainly point defects; nonetheless, the behavior of the concentration of charge carriers can be described by an identical exponential law in both cases.

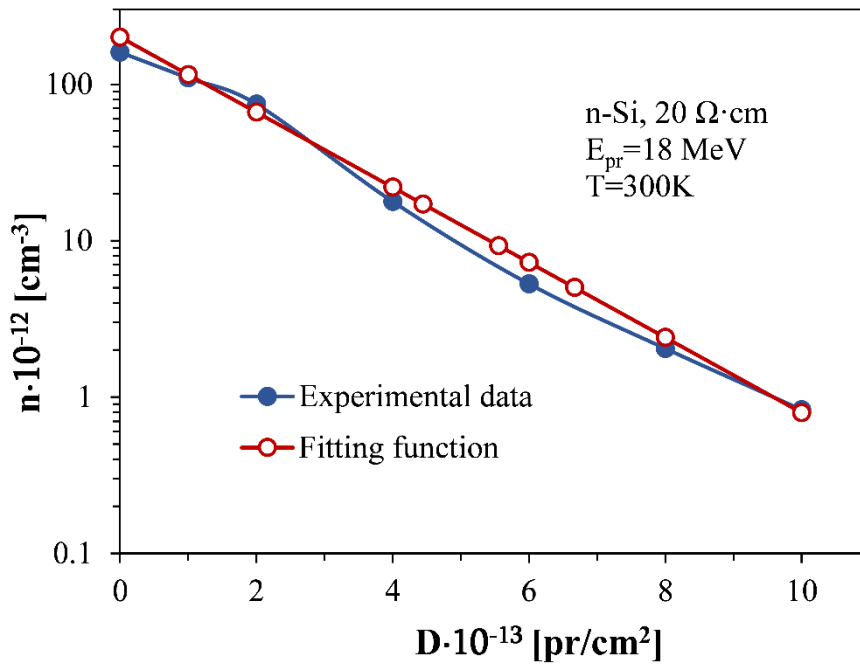


Fig. 2. Charge carriers' concentration versus 18 MeV energy proton irradiation dose at room temperature.

Fig. 3 shows the dependence of the specific resistivity of the silicon crystal on the irradiation dose delivered by 18 MeV energy protons, and which increases by more than two orders of magnitude according to the exponential function

$$\rho = \rho_0 \exp\left(\frac{D}{D_1}\right), \quad (3)$$

where $\rho_0 = 20 \Omega \cdot \text{cm}$ is the initial resistivity of silicon sample, and $D_1 = 1.83 \cdot 10^{13}$ pr/cm² is the irradiation dose at which the sample specific resistivity increases by a factor of e . When the values of the parameters D_0 and D_1 are compared, it can be noted that the changing rate of the specific resistivity of the sample is almost equal to the changing rate of the charge carriers. And considering a noticeable deviation from the fitting function (3) of the curve in Fig. 3, it can be assumed that this phenomenon is related with a non-monotonic behavior of the mobility of charge carriers as a function of irradiation dose (Fig. 4).

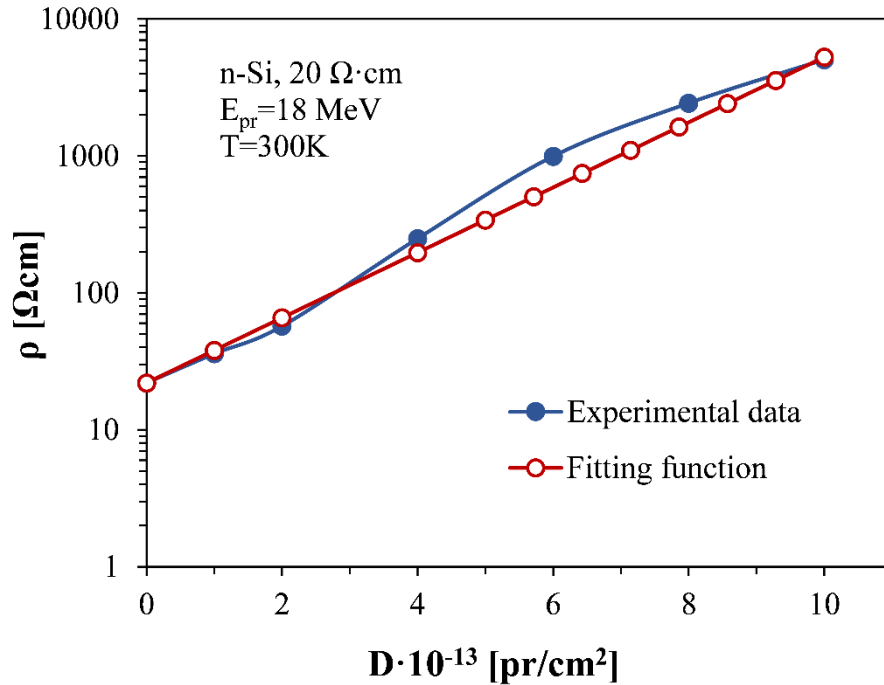


Fig. 3. The specific resistivity of the silicon crystal versus the 18 MeV energy proton irradiation dose at room temperature.

The change in mobility of the charge carriers, as a function of the irradiation dose from 18 MeV protons, is presented in Fig. 4, and clearly this behavior is non-monotonic. The mobility of the charge carriers first decreases up to an irradiation dose of $6 \cdot 10^{13}$ pr/cm² and then begins to increase significantly. From the radiation physics of semiconductors, it is known that during high-energy particle irradiations, radiation defects are generated in materials, which leads to a decrease in the concentration of charge carriers and to an increase in the scattering efficiency on generated radiation defects. As a result, the specific resistivity of semiconductors increases while the mobility of their charge carriers decreases monotonically [15, 16]. In particular, it was obtained that for 3.5 MeV electron irradiation the mobility of charge carriers decreases monotonically with increasing irradiation dose as can be seen in the insertion of Fig. 4 [8]. Although, the concentration of charge carriers in the given proton irradiation dose range 10^{13} - 10^{14} pr/cm² decreases by more than two orders of magnitude, the mobility, being related to the scattering of the charge carriers on the radiation defects, is found to increase above a certain the irradiation dose level. The latter is hard to explain from the perspective of normal semiconductor radiation physics, perspective and additional investigations are necessary to ascertain this unexpected increase in the mobility of the charge carriers.

It is probable that this phenomenon is related to the exact nature of the proton generated radiation defects, which are typically mainly cluster-type, and spatially distributed in a certain limited volume of the sample, meaning that the density of point type radiation defects in the remaining free volume of the sample is fairly low. Accordingly, the efficiency of scattering by the point radiation defects is small, and so the mobility of those free charge carriers not trapped by defects will not be significantly decreased. Further investigation is necessary to understand the surprising increase in the mobility of the charge carriers observed to occur above particular critical radiation doses.

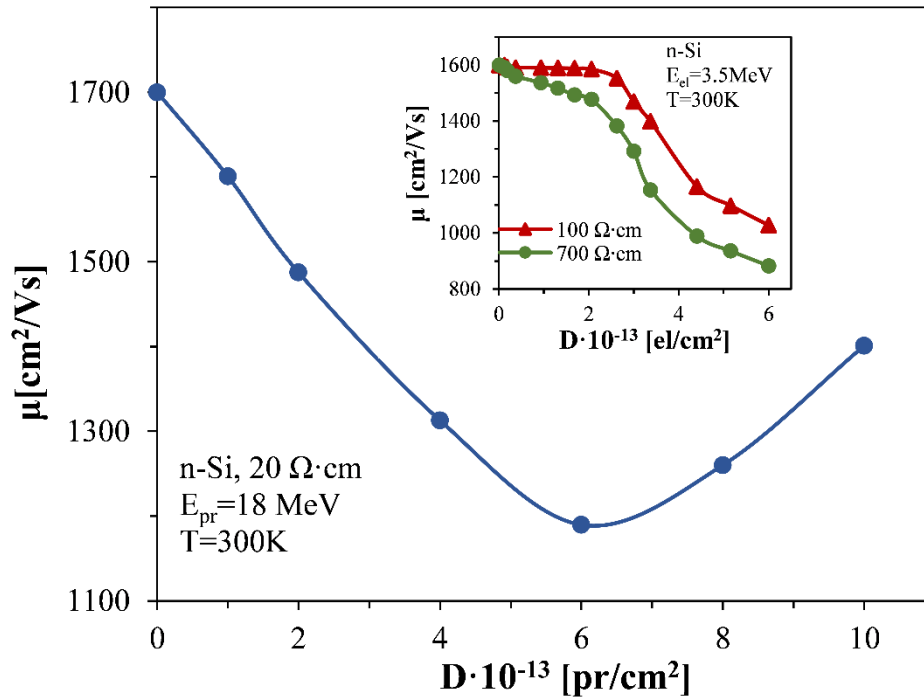


Fig. 4. The charge carriers' mobility of the silicon crystal versus 18 MeV energy proton irradiation dose at room temperatures. The insertion shows the charge carriers' mobility of the silicon crystal depending on 3.5 MeV energy electron irradiation dose at room temperatures [8].

4. Conclusions

The present investigations of the influence of 18 MeV proton irradiation on the behavior of the mobility and concentration of charge carriers, and the specific resistivity of 20 $\Omega\cdot\text{cm}$ n-type silicon monocrystals has shown that:

1. The impact of radiation defects on silicon crystal parameters formed by proton irradiation is partly similar to that produced by electron irradiation, despite the fact that protons generate mainly cluster type defects, while electrons create mainly point defects.
2. The charge carriers' concentration and specific resistivity were found to depend on the proton irradiation dose in the range 10^{13} - 10^{14} pr/cm² range, varying over more than two orders of magnitude, both of which can be described by exponential functions.
3. The dependence of the charge carrier mobility on the proton irradiation dose shows non-monotonic behavior, at first decreasing with increasing radiation dose and then at $6 \cdot 10^{13}$ pr/cm² dose this markedly increases. The latter effect is probably related to the cluster-type defects produced, which are sparsely distributed within the volume of the sample; however, additional work is required to understand this phenomenon more fully.

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References

- [1] M.L. Bourqui, L. Béchou, O. Gilard, Y. Deshayes, P.D. Vecchio, L.S. How, A. Touboul, *Microelectronics Reliability* **48** (2008) 1202.
- [2] S. Albergo, M. Chiorboli, C. Civinini, R. D'Alessandro, A. Macchiolo, C. Marchettini, M. Meschini, R. Potenza, A. Rovelli, A. Tricomi, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **583** (2007) 27–32.
- [3] C. Bebek, D. Groom, S. Holland, A. Karcher, W. Kolbe, J. Lee, M. Levi, N. Palaio, B. Turko, M. Uslenghi, M. Wagner, G. Wang, *IEEE Nuclear Science Symp. Conf. Record (Cat. No.01CH37310)* (2001).
- [4] C. Leroy, P.-G. Rancoita, *Reports on Progress in Physics* **70** (2007) 493.
- [5] C. Weiss, S. Park, J. Lefèvre, B. Boizot, C. Mohr, O. Cavani, S. Picard, R. Kurstjens, T. Niewelt, S. Janz, *Solar Energy Materials and Solar Cells* **209** (2020) 110430.
- [6] A. N. Larsen, A. Mesli, *Defects in Semiconductors* **91** (2015) 47.
- [7] H.N. Yeritsyan, A.A. Sahakyan, N.E. Grigoryan, V.V. Harutyunyan, B.A. Grigoryan, G.A. Amatuni, V.H. Petrosyan, A.A. Khachatryan, C. J. Rhodes, *Journal of Electronic Materials* **47** (2018) 4010.
- [8] H.N. Yeritsyan, A.A. Sahakyan, N.E. Grigoryan, V.V. Harutyunyan, V.V. Arzumanyan, V.M. Tsakanov, B.A. Grigoryan, G.A. Amatuni, C.J. Rhodes, *Radiation Physics and Chemistry* **176** (2020) 109056.
- [9] Z. Li, *Journal of Instrumentation* **4** (2009) P03011.
- [10] M. Siad, A. Keffous, Y. Belkacem, H. Menari, S. Mamma, C. L. Chaouch, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **512** (2003) 106.
- [11] E. Simoen, J. Vanhellemont, A. Alaerts, C. Claeys, E. Gaubas, A. Kaniava, H. Ohyama, H. Sunaqa, I. Nahsiyama, W. Skorupa, *Radiation Physics and Chemistry*, **50** (1997) 417.
- [12] J. Krupka, W. Karcz, P. Kamiński, L. Jensen, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **380** (2016) 76.
- [13] R. Brüggemann, S. Brehme, J. P. Kleider, M. E. Gueunier, W. Bronner, *Journal of Non-Crystalline Solids* **338-340** (2004) 477.
- [14] E.M. Donegani, *Energy-Dependent Proton Damage in Silicon* (Universität Hamburg, Hamburg, 2017).
- [15] V.S. Vavilov, *Radiation Influence on the Semiconductors* (Phys.-Mat. Edition, Moscow, (1963).
- [16] V.L. Vinetskij, G. A. Kholodar, *Radiation Physics of Semiconductors* (“Naukova Dumka” Edition, Kiev, 1979).