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Phenomena Induced by Sequential Proton and Electron Irradiation in Silicon Monocrystal

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Introduction

Study of effects in materials and electronic equipment under the influence of ionizing radiation is of great importance for the creation of radiation-resistant elements and devices for space, military and other special applications.

At present, when space and Moon exploration moved to a stage of intensive development, these tasks become relevant. Spacecrafts, during the period of their existence in space, are exposed simultaneous to various factors of space.

According to modern concepts, the main factors capable of damaging the electronic equipment of spacecraft are followings:

- ionizing radiation (electrons with energies of 0.1-10 MeV),
- protons with energies of 1-10^4 MeV;

Aim

Study of the phenomena induced by sequential irradiation with MeV energy protons and electrons in silicon monocrystal

- For this purpose were used.

  1. Protons with an energy of 15.5 MeV at the C-18 cyclotron
  2. Electrons with an energy of 3.7 MeV at the CANDLE Institute for Synchrotron Research

The nature and extent of the radiation effect on the physical parameters of materials strongly depends on the:

- type and energy of irradiation particles
- irradiation intensity
- irradiation conditions

Time diagram of radiation defect formation in semiconductors

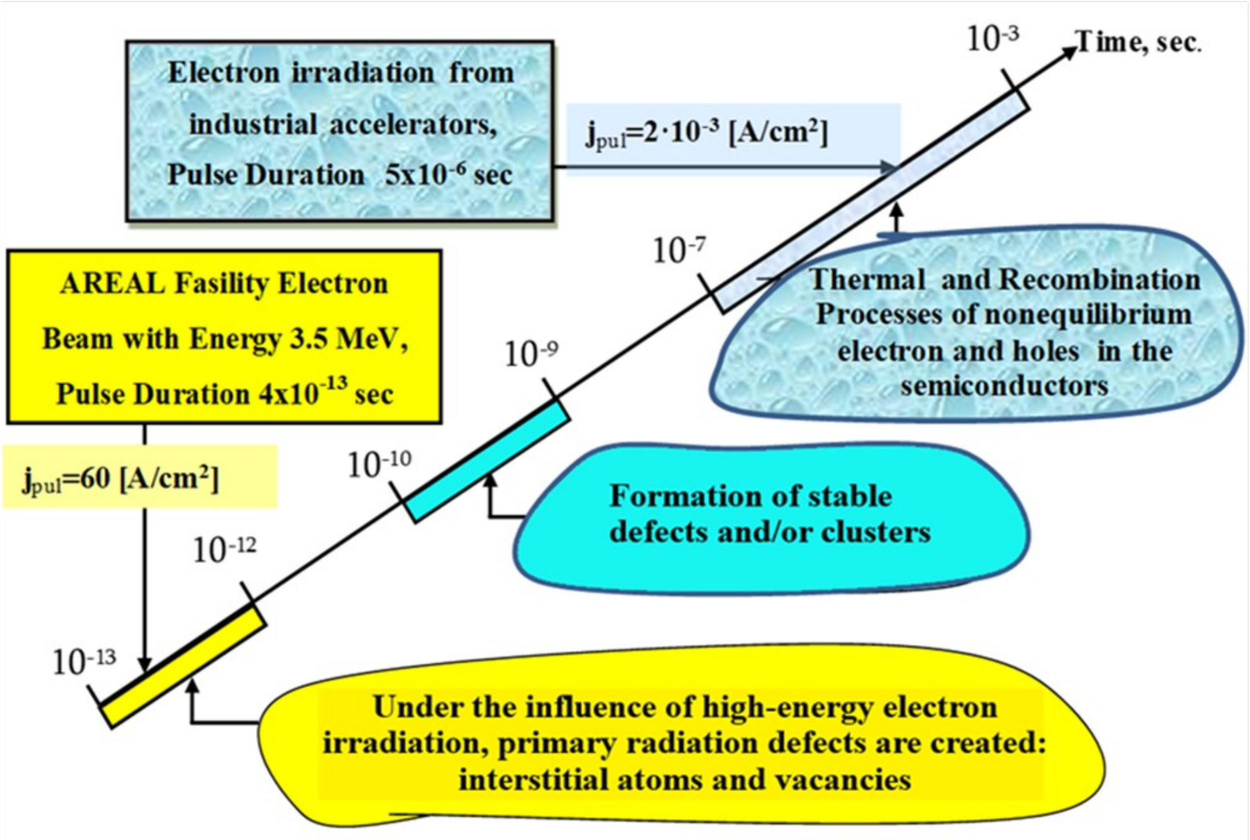


Fig. 1. Schematic presentation of the processes occurring in a semiconductor crystal after the irradiation by high-energy electrons.

- In radiation environment materials are simultaneously exposed to irradiation of different types high energy particles. However, it is impossible to create such conditions in laboratories.
- Protons with an energy of 15.5 MeV in silicon create radiation defects in the volume of the sample with dimensions of 50–100 nm, mainly of the cluster type.
- Electrons with an energy of 3.5 MeV in silicon create mainly point radiation defects in the volume of the sample. When previously proton-irradiated materials are irradiated with electrons, the structure of radiation defects changes, and their redistribution occurs too.
- From a scientific and practical point of view, it is interesting to study the sequential irradiation of materials with various types of particles.

Silicon sample parameters and maximum proton and electron irradiation doses

The behavior of concentration and mobility of samples with specific resistance of 20, 100, 700 Ohm·cm n-type silicon and 20, 45 Ohm·cm p-type was studied depending on irradiation doses in the temperature range of 200-300K.

Some of the samples were pre-irradiated with 15.5 MeV protons up to 10^{14} pr/cm^2, then sequential irradiation with 3.5 MeV electrons with fluxes up to 2.7*10^{14} el/cm^2.

Scheme of the Hall Effect experiment and general view of the sample

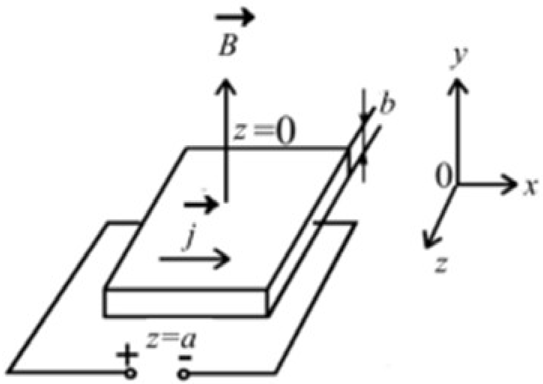


Fig. 2. Scheme for measuring Hall effect

$$n = \frac{IB}{U_H de},$$

$$\rho = \frac{U_\rho hd}{IL},$$

$$\mu = \frac{U_H L}{U_\rho Bd}:$$

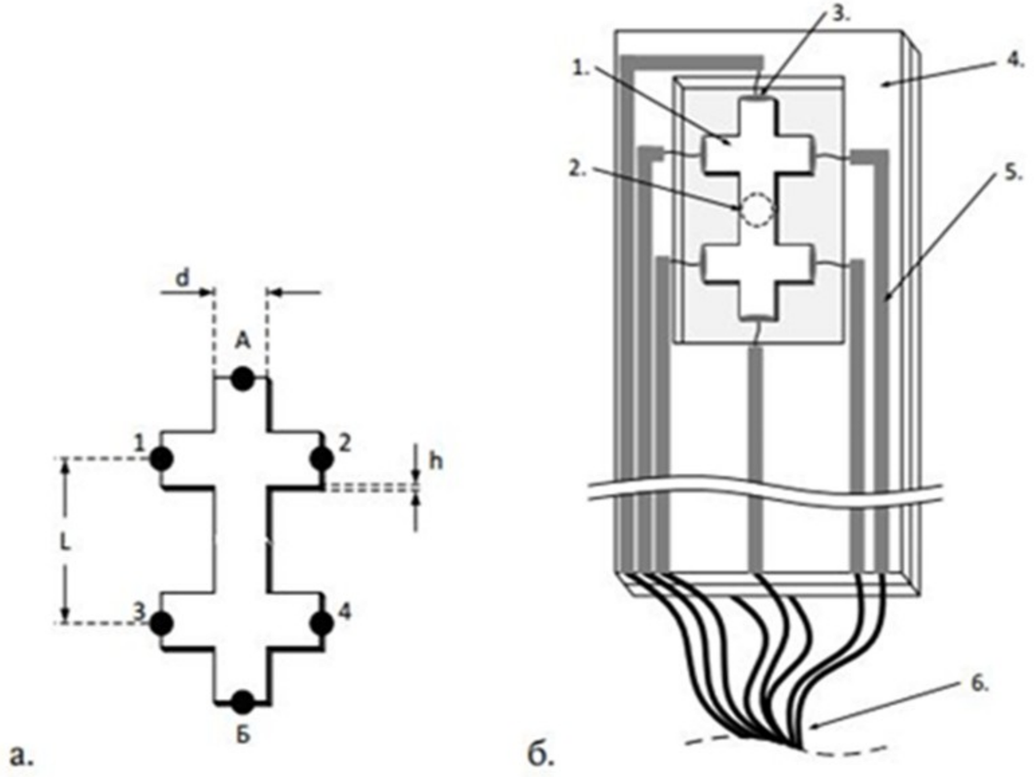
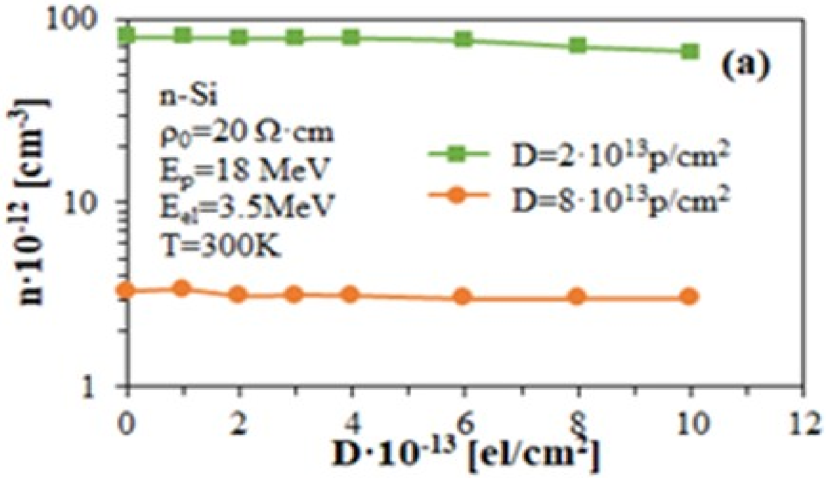


Fig. 3. a - type of sample. A, B, 1, 2, 3 and 4 points for contacts. d - width (3 mm), L - distance between (5 mm) contacts 1, 3 and 2, 4, h - thickness (0.5 mm), AB - total length (10 mm). b - substrate with a sample. 1. sample, 2. temperature sensor under the sample, 3. soldering points, 4. backing body (two-layer textolite), 5. metal tracks, 6. flexible wires going to the connector.



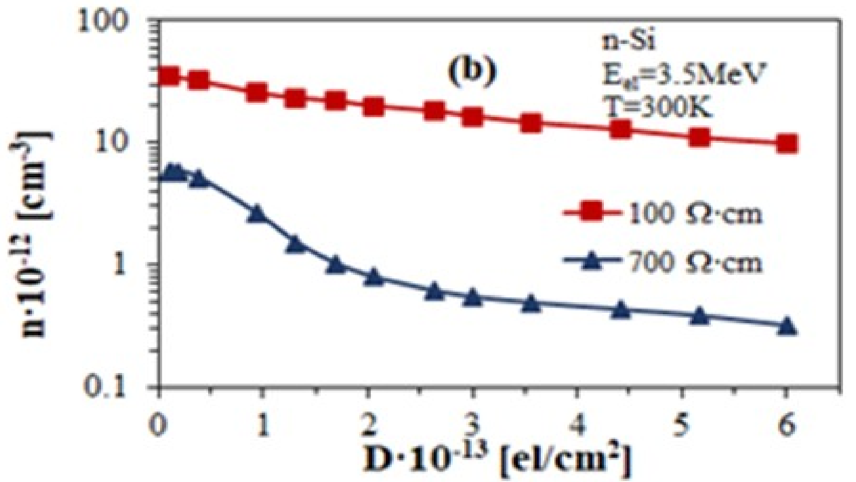
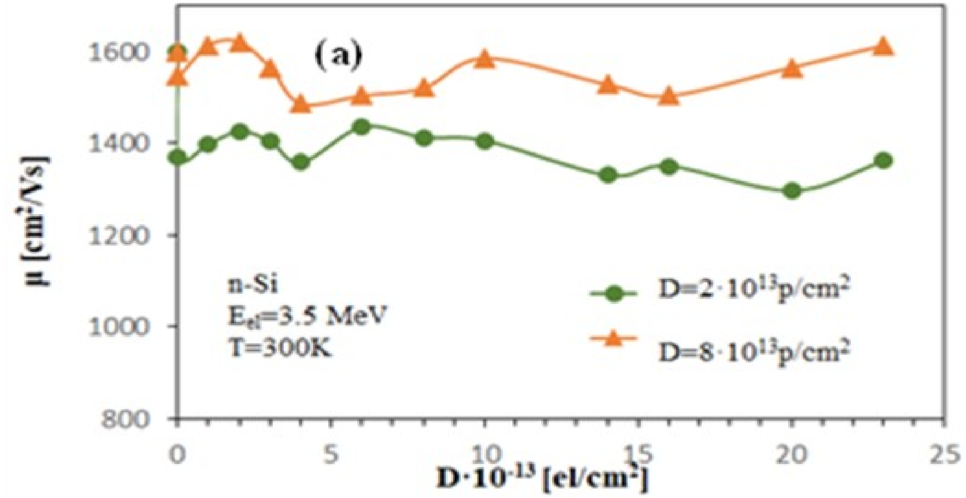


Fig. 4. Charge carrier concentrations depending on 3.5 MeV energy electron irradiation dose for silicon monocrystals, (a) previously irradiated by protons, (b) no previously irradiated samples.



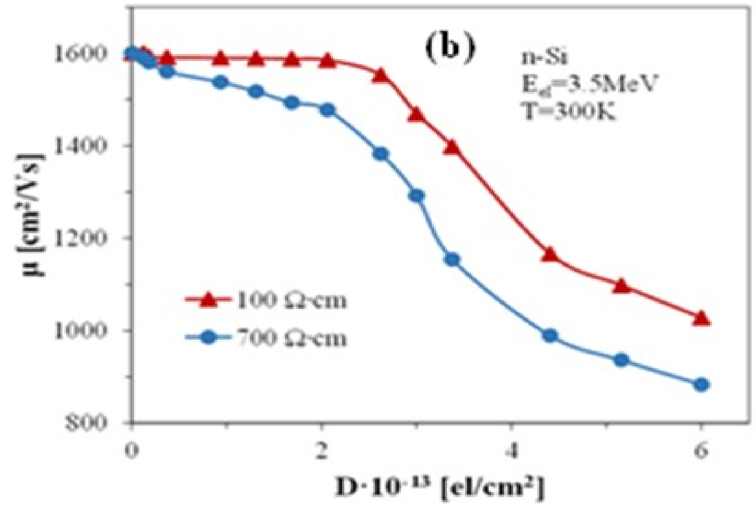


Fig.5 . Charge mobility depending on 3.5 MeV energy electron irradiation dose for silicon monocrystals, (a) previously irradiated by protons, (b) no previously irradiated samples.

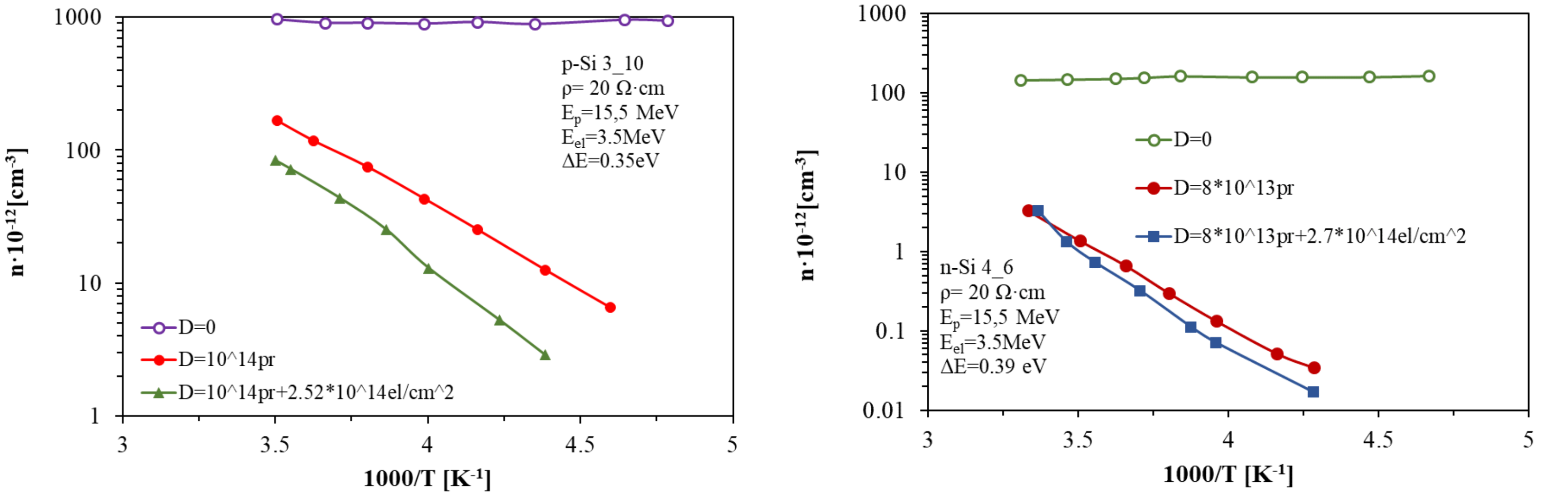


Fig. 6. Temperature dependence of charge carrier concentrations depending on electron irradiation dose for p and n types silicon monocrystals, previously irradiated by protons

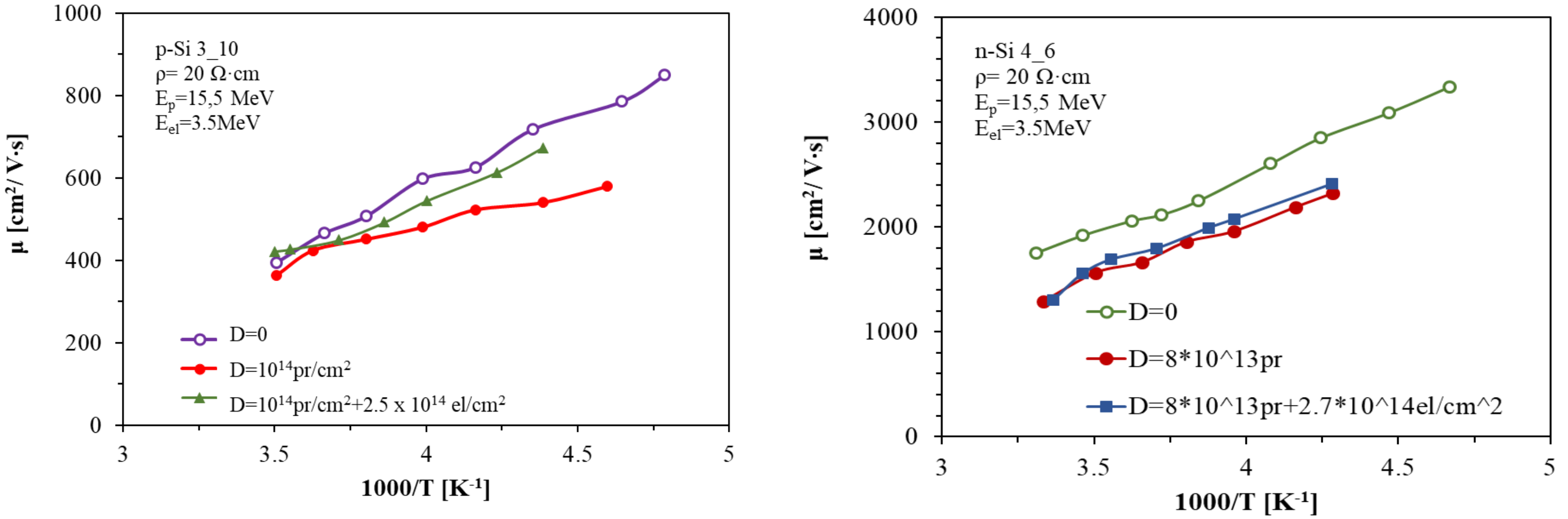


Fig. 7. Temperature dependence of charge carrier mobility depending on electron irradiation dose for p and n types silicon monocrystals, previously irradiated by protons

Introduction Rates of Electrically Active Radiation Defects in Electron Irradiated of n-Si Monocrystals

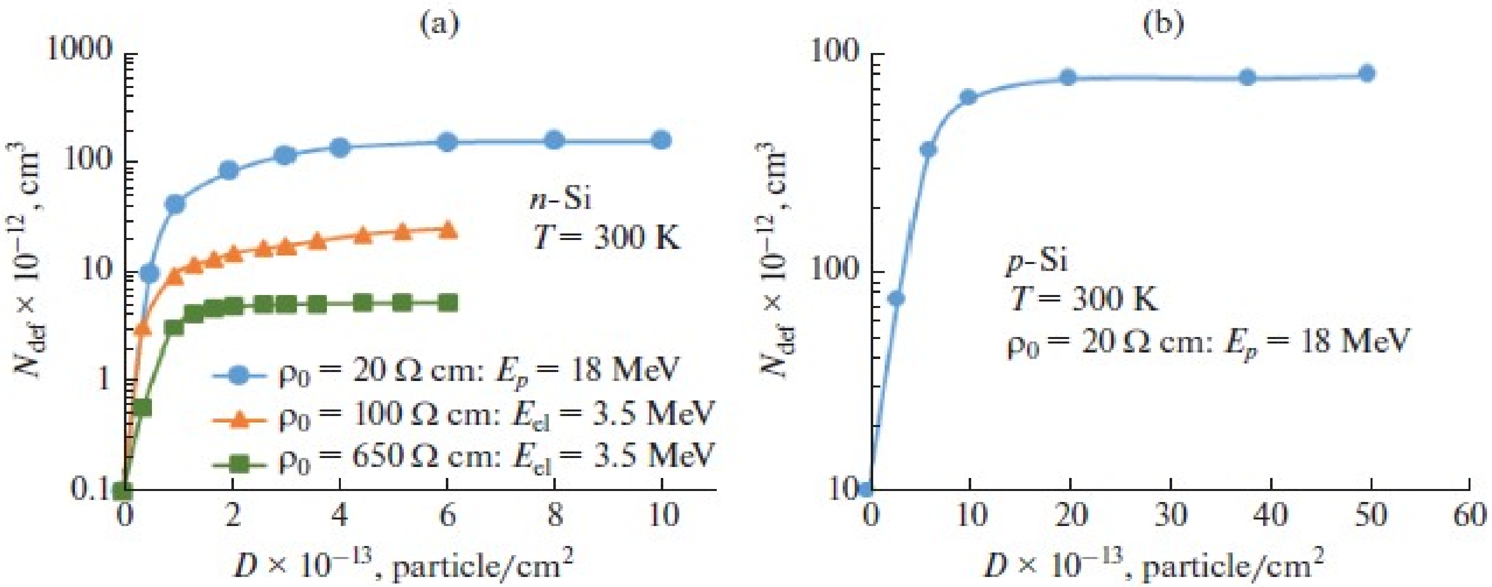


Fig. 8. Electrically active radiation defect concentration vs. irradiation dose in (a) *n*-type and (b) *p*-type silicon crystals. 20 Ohm cm *n*-type and *p*-type Si samples are irradiated by 18 MeV protons; 100 and 650 Ohm·cm *n*-type Si samples are irradiated by 3.5 MeV electrons.

$$N_{def} = n_0 - n(D) = n_0 ¿$$

Introduction Rates of Electrically Active Radiation Defects in Proton Irradiated *n*-type and *p*-type Si Monocrystals

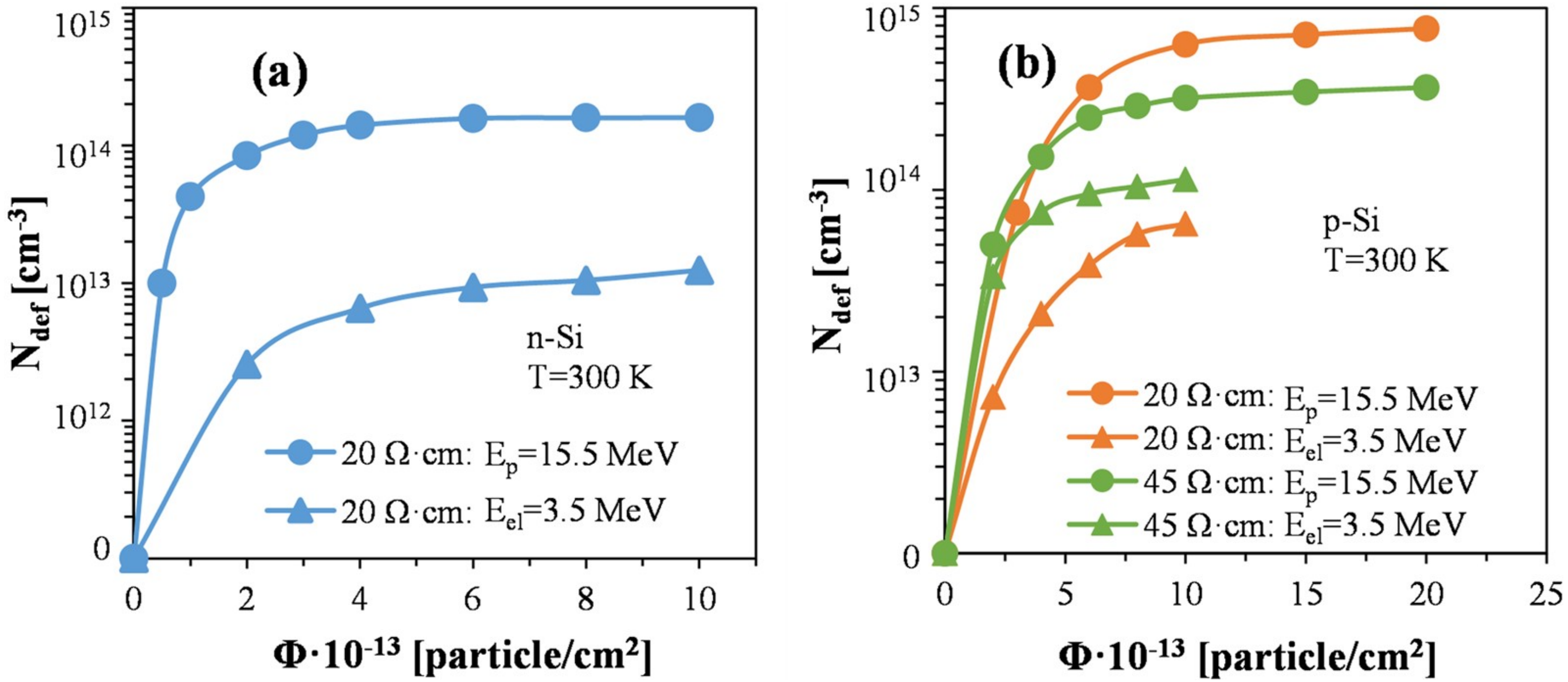


Fig. 9. Electrically active radiation defect concentration versus fluence for *n*-type (a) and *p*-type (b) silicon crystals irradiated by 15.5 MeV protons and 3.5 MeV electrons.

Conclusions

1. The results obtained during proton+electron sequential irradiation is showed that in the case of n-Si the effect is not noticeable, while in the case of p-Si the change is significant. It can be concluded that p-Si samples pre-irradiated with 15.5 MeV protons are more sensitive to electron irradiation than n-Si crystals.
2. We found that the behavior of the electrophysical parameters (charge carrier concentration, mobility, resistivity) of an n- and p-type silicon single crystal under irradiation with protons with an energy of 15.5 MeV and sequential irradiation with picosecond pulsed electrons with an energy of 3.5 MeV the introduction rate of concentration of electrically active radiation defects decreases exponentially and is described by the following empirical expression.

where n_0 is the concentration of free charges before irradiation, D is the irradiation dose, D_0 is the dose when

the number of defectors increases by e times.

Published works

1. Hrant N.Yeritsyan, Aram A.Sahakyan, Norair E.Grigoryan, Vachagan V.Harutyunyan, Vika V.Arzumanyan, Vasili M.Tsakanov, Bagrat A.Grigoryan, Gayane A.Amatuni, Christopher J.Rhodes, *Introduction rates of radiation defects in electron irradiated semiconductor crystals of n-Si and n-GaP,* Radiation Physics and Chemistry, 2020, v.176. https://doi.org/10.1016/j.radphyschem.2020.109056
2. Vachagan Harutyunyan, Aram Sahakyan, Andranik Manukyan, Bagrat Grigoryan, Hakob Davtyan, Ashot Vardanyan, Christopher J. Rhodes, Vika Arzumanyan, *Introduction Rates of Electrically Active Radiation Defects in Proton Irradiated n-Type and p-Type Si Monocrystals*, Journal of Electronic Materials, 2023. https://doi.org/10.1007/s11664-023-10700-7.
3. V. V. Harutyunyan, A. A. Sahakyan, V. V. Arzumanyan, *, N. Grigoryan, and A. Martirosyan *New Energy Electron and Proton Irradiation Effects in Semiconductor Materials for Space Applications*, *Physics of Particles and Nuclei Letters, 2023, Vol. 20, No. 5, pp. 1236–1239.* **DOI:** 10.1134/S1547477123050369

Thank you