THE IMPACT OF RADIATION ON SEMICONDUCTING CHARACTERISTICS OF MONOCRYSTALLINE SILICON AND GERMANIUM

by

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The paper examines the effects of radiation on the electrical characteristics of monocrystalline silicon and germanium. Samples of monocrystalline silicon and germanium are irradiated under controlled laboratory conditions in the field of neutron, X- and γ-radiation. Change of the samples' specific resistance was measured dependent on the radiation dose with the type of radiation as a parameter. Next, the dependence of the samples resistance on temperature was recorded (in the impurities region and in intrinsic region) with the previously absorbed dose as a parameter. The results were statistically analyzed and explained on the basis of radiation effects in solids. The results are compared with those obtained by using Monte Carlo method. A good agreement was confirmed by the mentioned experimental investigation.

Key words: neutron radiation, X-radiation, gamma radiation, silicon, germanium, radiation effects, Monte-Carlo method

INTRODUCTION

An increasing degree of the semiconductor components' miniaturization as well as higher electromagnetic contamination of the environment brings into question the reliability of modern electronic devices. This is particularly emphasized in the operating conditions of electronic devices related to: nuclear power facilities, biomedical devices based on ionizing radiation applications and the pulse power devices [1-4].

Under those operating conditions and an exceptional reliability of the electronic devices required, the issue of their radiation resistance is of great importance.

Tests of the electronic components in the field of radiation with defined parameters are, objectively, the most reliable method for the determination of their radiation resistance. However, such tests are extremely complex and require complex experiments involving a variation of the radiation field parameters.

This is necessary because effective cross-sections for the radiation interactions with the materials from which the semiconductor components are made have a complex dependence on the type and energy of radiation. Undoubtedly, even if testing in laboratory conditions is unquestionably efficient, they are often technically and/or economically difficult to implement.

Of particular interest in the practice is a combined dependence of semiconductor parameters both on effects of radiation and temperature. In order to assess the impact of radiation and temperature on the functioning of semiconductor components, it is necessary, first, to determine their impact on material of which the semiconductor is made.

The aim of this paper was to determine the dependence of the specific resistance of mono crystalline Si and Ge both on radiation dose (neutron, X- and γ-radiation) and temperature.

EXPERIMENT

The idea of the experiment was to determine the impact of radiation and changes in temperature on semiconductor materials. For this purpose, the samples used were of mono crystalline Si and Ge grown by the method of Czochralski. These samples were ex-

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posed to neutron, X- and γ-radiation fields with precisely defined parameters. Then, semiconductor parameters such as specific electrical resistance and the concentration of majority carriers were determined.

In addition, the influence of radiation on semiconductor materials at elevated temperatures has been investigated. For this purpose, the samples of monocrystalline Si and Ge, irradiated with a defined radiation dose (a parameter of the experiment), were heated and the changes of the resistance were recorded both in their intrinsic range and saturation range. The obtained results are represented by a dependency of logarithmic value of the sample resistance on the reciprocal value of the absolute temperature.

As a source of neutron radiation the Am-Be source was used. Fast and thermal neutrons were obtained from the same source surrounded by30 cm of water. Thermal neutrons were of energies that corresponded to an ambient temperature (20 ºC). The intensity of neutron emission from this source was 2.7 10^6 neutron/s, with the mean energy of 5.5 MeV. The quality of n-field for this neutron spectrum was $Q_n = 7$.The dose of neutron radiation is expressed in a time of exposure to Am-Be source of a tested sample.In order to test the radiation resistance in X-radiation field, the X-ray tube was used. Radiation quality of X-field was N-300 with the mean energy of 208 keV. For testing the resistance in γ-radiation field, the ^{60}Co source was used. Unit radiation field is determined by the value of the absorbed dose in the air at different distances from the radiation source. The absorbed dose of samples was determined by changing the position of the sample in the field during radiation. The absorbed dose in silicon is calculated from the absorbed dose in the air, by using the energy absorption coefficient which corresponds to the mean energy of ^{60}Co that is 1.25 MeV. All measurements were carried out at room temperature of 20 °C (except in the case of measuring dependence of the resistance on the reciprocal of the absolute temperature).

Five samples were used, four of which were made of mono crystalline silicon and one germanium. The absorbed dose varied in the range of 0.05 kGy to 12 kGy. The results presented were obtained by averaging all the experimental results for all five samples in 10 series of irradiation.Uncertainty of measurement results was about 10 % for all five of samples [5, 6].

The parameters of the experiment were radiation energy and dose. Electrical characteristics of monocrystalline silicon and germanium were determined by four-point probe method.

The measurement process was conducted in the following steps:
- preparation of the samples,
- loading of samples into the field of radiation,
- the irradiation within the calculated time duration in order to obtain the specified dose; the absorbed doses were determined for each sample according to the valid international standards,
- determining parameters of the semiconductor, and
- determining dependency of logarithmic value of the sample resistance on the reciprocal value of the absolute temperature in their intrinsic range and saturation range.

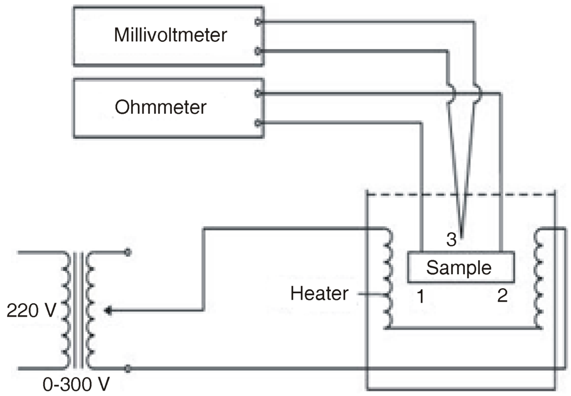

Figure 1. The scheme of the measuring system for recording the temperature dependence of the irradiated semiconductor samples (1 and 2 – points among which the sample resistance is measured, 3 – thermocouple)

Testing of thermal characteristics of semiconductor materials was completed by heating the sample. During this process the measurements of temperature and resistance were recorded.

Figure 1 shows the scheme of the measuring system for recording the temperature dependence of the irradiated semiconductor samples.

RESULTS AND DISCUSSION

Figure 2 shows the dependence of the specific electrical resistance ρ on X-rays doses D for Si and Ge samples. Based on the results shown in fig. 2 it can be seen that the specific resistance increases with the irradiation dose. This result can be explained by the interaction of the X-radiation with the Si (or Ge) atoms in the crystal lattice.

That occasion could cause ejection of atoms of Si from the crystal lattice and formation of vacancies.

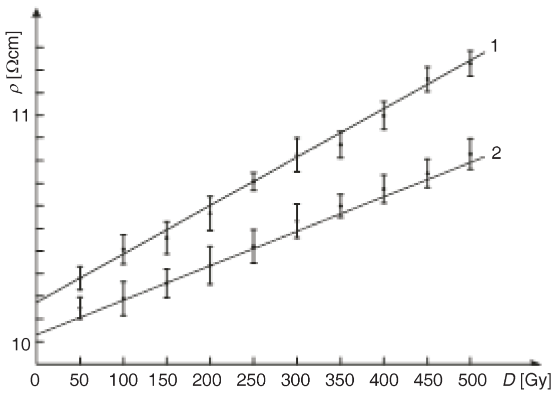

Figure 2. The dependence of the mean values of the specific electrical resistance on the absorbed dose of X-rays (1 – Si sample; 2 – Ge sample)

Such a vacancy is a "trap" for the free charge carriers (electrons) and they, after falling into it, cease to participate in the current transmission. As the specific conductivity of semiconductor material is linearly proportional to the concentration of the majority of charge carriers, the obtained result has been expected. This conclusion was confirmed by the results obtained with Ge sample which showed that the established linearity is lost with increasing temperature above its intrinsic region. This can be explained by thermal generation of new electron-hole pairs, as well as by the release of a part of electrons from the vacancies created due to the exposure to X-radiation [7-9].

Figure 3 shows the dependence of the specific resistance on γ-radiation for Si and Ge samples. The dependence is very similar to dependence shown in fig. 2. The difference in respect to X-radiation is a significantly greater dose of γ-radiation needed for the same change of the specific resistance of silicon. This finding can be explained by the fact that the effective cross-section for the interaction of X-radiation with the Si atom is much larger than the corresponding effective cross section for γ-radiation.

As a result, it confirmed that the X-rays (having much lower energy than γ-radiation) create vacancies more efficiently in monocrystalline silicon. In case of elevated temperatures to the upper limit of their intrinsic region the observed effect of γ-radiation is opposite.

Figure 4 shows the dependence of the specific resistance of the Si sample on exposure time n to neutron radiation (similar result was obtained for the germanium sample).

It is evident, from fig. 4, that the impact of neutron radiation on the samples specific resistance is quantitatively similar to those of X- and γ-radiation but it is qualitatively distinctive. This is explained by greater mass of neutrons and more effective cross-sections for the ejection of Si atoms from the lattice nodes and creation of a vacancy. In the case of neutrons, this effect is more pronounced for fast neutrons than for the thermal ones. This effect, which is the opposite to that of X-rays, is a consequence of the greater penetrating power of fast neutrons and a greater probability for production of vacancies.

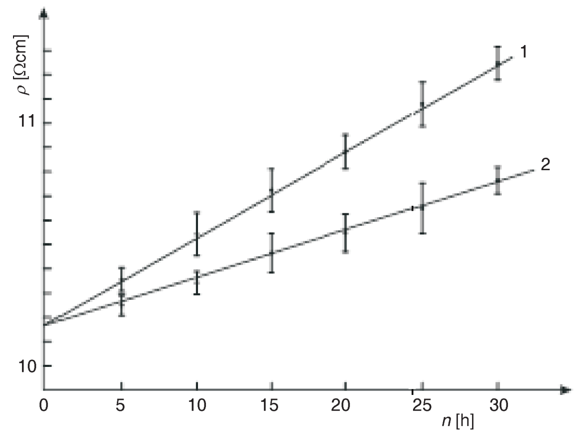

Figure 4. Dependence of the specific resistance of the Si on the exposure time to neutron radiation (1 – fast neutrons, 2 – thermal neutrons)

Such an interpretation is confirmed by comparing the effect of fast and thermal neutrons on the specific resistance, with incident beam being perpendicular and parallel to the sample, fig. 5.

The results of Monte Carlo simulations [10]of the interaction of neutron, X- and γ-radiation with silicon obtained under the conditions of the experiment are shown in fig. 6. The fig. 6 clearly shows that neutron and X-radiation create a significantly larger number of vacancies N in silicon than γ-radiation (a similar result was obtained for germanium).

Figures 7, 8 and 9 show the dependence of logarithmic value of the germanium sample resistance R on the reciprocal value of the absolute temperature T both in the impurities region and intrinsic region. Figure 7 shows this particular dependence with a dose of neutron radiation as a parameter. Figure 8 shows above

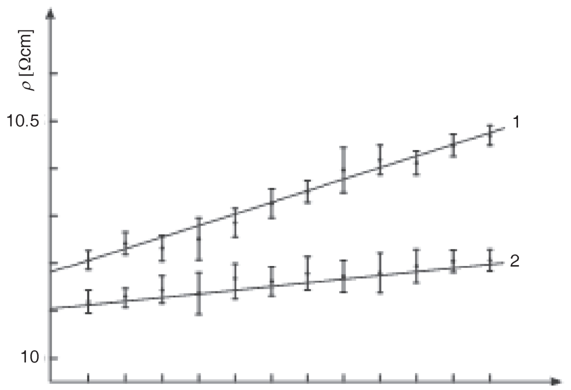

Figure 3. Dependence of the mean values of the specific electrical resistance on the gamma radiation dose (1 – Si sample; 2 – Ge sample)

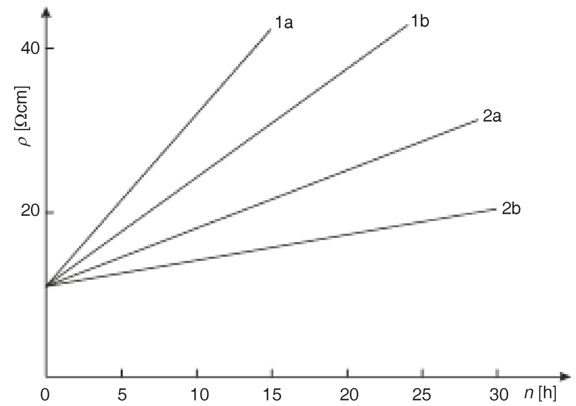

Figure 5. Dependence of the specific resistance on the exposure time to neutron radiation (1 – fast neutrons, 2 – thermal neutrons, a – perpendicular beam, b – parallel beam)

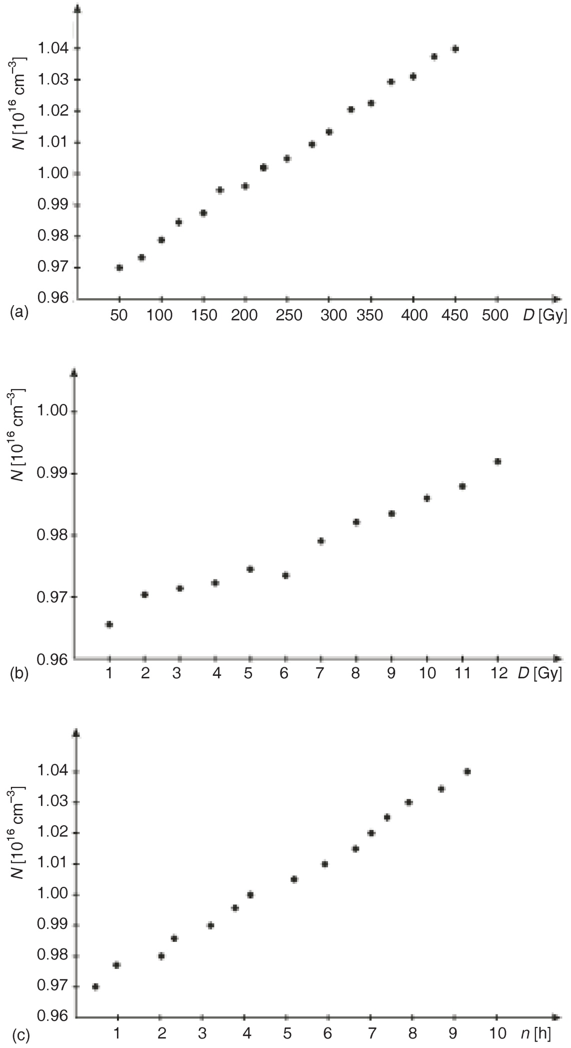

Figure 6. Dependence of the number of resulting vacancies on the exposure time obtained by Monte Carlo simulation; (a) X-radiation. (b) γ-radiation, and (c) neutron radiation

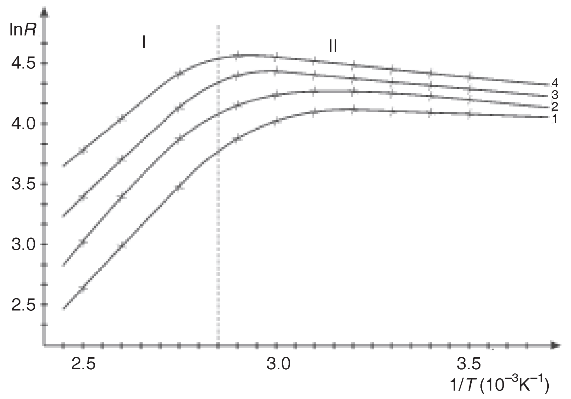

Figure 7. The dependence of the logarithmic value of the germanium sample resistance on the reciprocal value of the absolute temperature in the impurities region (I) and intrinsic region (II); dose of neutron radiation as a parameter: 1– 0 h, 2 – 10 h, 3 – 15 h, and 4 – 20 h

mentioned dependence with a dose of X-radiation as a parameter. Figure 9 shows the dependency with a dose of γ-radiation as a parameter.

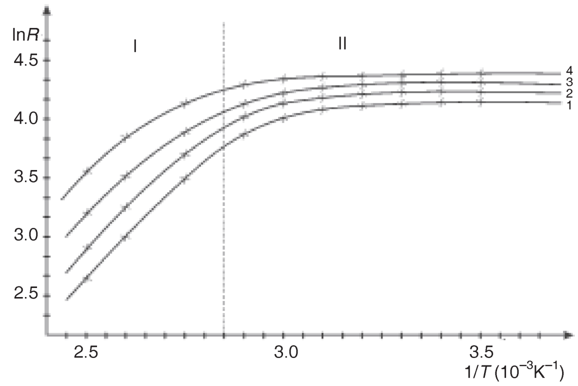

Figure 8. The dependence of the logarithmic value of the germanium sample resistance on the reciprocal value of the absolute temperature in the impurities region (I) and intrinsic region (II); dose of X-radiation as a parameter: 1 – 0 Gy, 2 – 200 Gy, 3 – 300 Gy, and 4 – 400 Gy

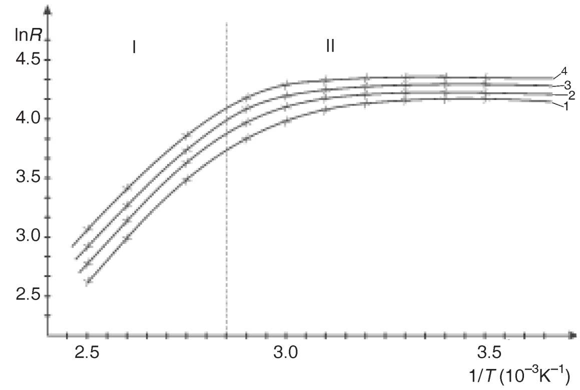

Figure 9. The dependence of the logarithmic value of the germanium sample resistance on the reciprocal value of the absolute temperature in the impurities region (I) and intrinsic region (II); dose of γ-radiation as a parameter: 1 – 0 kGy, 2 – 6 kGy, 3 – 9 kGy, and 4 – 12 kGy

In figs. 7, 8, and 9 it can be seen that the radiation affects the resistance of the germanium sample significantly more in the impurities region than in intrinsic region. This effect can be explained by a low concentration of free carriers in the latter region (samples were with a minimum concentration of free carriers). Otherwise, the mechanism of this influence is the same as it was described above (creating of vacancies – which absorb the free carriers). The temperature elevation does not affect this mechanism in the impurities region and intrinsic region. It can be concluded that the binding energy of captured free carriers is higher than the characteristic energies of these regions.

CONCLUSIONS

Observing the impact of neutron, X- and γ-radiation on the fundamental semiconductor materials, silicon and germanium, it is concluded that the effect of the radiation reduces the concentration of free carriers.

This impact is explained with the effect of destruction of mono crystalline structure and forming of vacancies. The resulting vacancies absorb the free charge carriers, thereby, preventing them from participating in the transmission of electricity. The binding energy of such absorbed electrons is higher than the width of the energy gap, determined by observing the dependence of samples resistance on the temperature in the impurities region and intrinsic region (with the radiation type and dose as parameters). These investigations have shown that the effect of radiation is more expressed in the impurities region and less noticeable in intrinsic region.

The Monte Carlo simulation of corresponding effects of radiation interaction with mono crystalline silicon and germanium showed that the conclusion on the mechanism by which the radiation affects the concentration of free carriers is correct.

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AUTHORS' CONTRIBUTIONS

Theoretical analysis carried out by M. D. Obrenović. The manuscript was written, and the figures were prepared by M. D. Obrenović. All authors analyzed and discussed the results.

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УТИЦАЈ ЗРАЧЕЊА НА ПОЛУПРОВОДНИЧКЕ КАРАКТЕРИСТИКЕ МОНОКРИСТАЛНОГ СИЛИЦИЈУМА И ГЕРМАНИЈУМА

У раду се разматра дејство нуклеарног зрачења на електричне карактеристике монокристалног силицијума и германијума. Узорци монокристалног силицијума и германијума озрачивани су, под контролисаним лабораторијским условима, у пољу неутронског, X- и γ-зрачења. Мерена је промена специфичне отпорности узорака од доза зрачења уз врсту зрачења као параметар. Потом је снимана зависност отпорности полупроводничких узорака од температура (у примесној и сопственој области) уз претходно апсорбовану дозу као параметар. Добијени резултати обрађени су статистички и објашњени на основу радијационих ефеката у чврстим материјалима. Добијени закључци упоређени су са резултатима одговарајућих симулација Монте Карло методом. Добијено је добро слагање које је потврдило претходно дата тумачење.

Кључне речи: неутронско зрачење, X-зрачење, γ-зрачење, силицијум, германијум, радијациони ефект, Монте-Карло симулација