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Electrophysical Properties of Monocrystalline n-Si+0.4at%Ge:P Alloy irradiated by ^{60}Co Gamma Photons

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Abstract

In the monocrystal n-Si+0.4at.%Ge:P alloy irradiated with ^{60}Co gamma photons non-monotonic changes in electrical resistance, current carrier concentration and mobility were detected by isochronal annealing at a temperature range of 20-400°C. The contribution of current transformations in the structure of radiation defects (PV, VO, VO_2, C_iC_s, C_iO_i) to the temperature changes of electrical characteristics is analyzed. n-p conversion was detected at the critical temperature (˜100°C) of isochronal annealing. Dissociation of PV centers and formation of electrically active VO centers were detected in the 120-150°C range. As a result, the concentration of current carriers increases. At elevated temperatures (> 150°C) non-monotonic changes in electrical characteristics are observed.The paper analyzes the contribution of Ge to the anomalous temperature changes of the electrophysical characteristics of the n-SiGe alloy.

Keywords: *Monocrystalline SiGe, γ-radiation, n-p conversion, radiation defect, isochronal annealing.*

Introduction. Monocrystalline Si-Ge system alloys are the basic materials for heterostructures of bipolar and field-effect transistors. Based on them, effective nuclear radiation detectors [1, 2], thermal neutron monochromators and X-ray diffractometry devices [3, 4], pressure sensors, thermoresistors have been developed. The prospects for using them in integrated circuits, devices in microelectromechanical and nanoelectromechanical systems are quite high.

Over the last two decades complex research studies have been carried out on the mechanisms of changes in the structure and physical properties (Electrophysical, optical, thermal, mechanical,...)of Si-Ge alloys generated by thermal, mechanical and radiation influence. Today significant results are obtained in the field of research of thermomechanical and radiation defects. From the analysis of modern scientific sources, it is clear that under isothermal and isochronal annealing conditions the regularities of changes in electrophysical properties under the influence of types of structural defects, thermal stability and transformations in Si-Ge system alloys are clearly insufficiently studied.

The paper presents the results of a study of the electrical properties of a monocrystalline n-Si+0.4at%Ge:P alloy. The test crystal was obtained by the Czochralski method [111] in the crystallographic direction. Experimental measurements were performed on the double sided polished plates orientated along (111). Electrophysical characteristics were determined by measuring the Hall effect at room temperature using the van der Pauw Method 0.5 Tesla in a constant magnetic field of 0,5 Tesla induction on a standard device: Ecopia HMS-3000. Irradiation with high-energy gamma-photons was performed using a ^{60}Co source. The irradiation fluence was $2\cdot10^{16}$cm^{-2}. The specimens are characterized by dislocation density of ˜ 1.10^{4}cm^{2} on the (111) plane.

It has been experimentally shown that the electrical resistivity of a samples irradiated with ^{60}Co gamma photons increases by ˜ 2.5 times. This is to be expected as E-centers (phosphorus + vacancy) are formed during the irradiation process. It is known, that E-centers introduce a deep acceptor energy level (E_C - 0.43 eV) in the forbidden zone of the SiGe alloy.The vacancy formed during the irradiation process by interaction with the phosphorus atom produces a negatively charged E-center in the Si (and also SiGe) crystal lattice.During the irradiation process, two electrons move from the conduction zone to the forbidden zone and are localized to the E-center (Figure 1.).

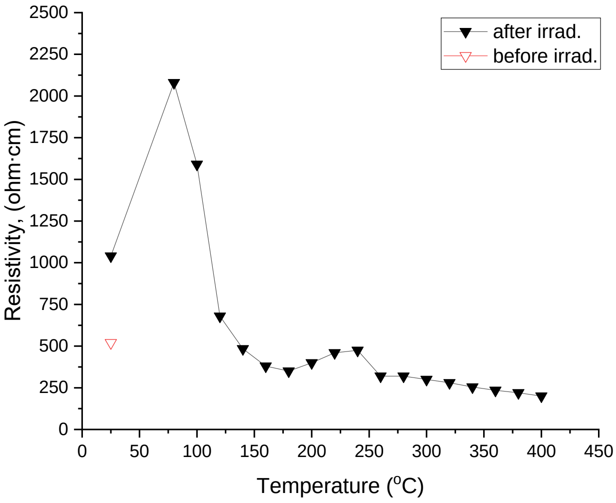

Figure 1.Change in the electrical resistivity of the ^{60}Co gamma photon irradiated n-Si+0.4 at% Ge:P alloy by isochronal annealing at a temperature range of 20-400°C

By increasing of the annealing temperature, additional vacancy-phosphorus pairs are formed (E-centers), which continues to reduce the concentration of electrons in the conduction zone and therefore, increase the electrical resistivity. The process is continued at a temperature of 120 °C; It reaches a peak at 80°C temperature. Such changes in electrical resistivity are due to changes in electronic states in the deformed areas of the single crystal and in the vicinity core of the dislocation.

With further increase of temperature, the electrical resistivity decreases, which lasts up to a maximum temperature of 400 °C.

A slight increase in electrical resistivity in the temperature range of 200-250°C has been detected. At temperatures above ~100°C the E-centers are annealed faster and the A-centers (O + V) multiply simultaneously. These two processes are taking place with the zigzag changes in the current carriers concentration. Weak peak shape increase of the electrical resistivity at 300°C might be stipulated by reducing the concentration of electrically active A-centers and vacancies in the annealing process.

Non-monotonic changes in electron concentration were detected in the range of 20-400°C of isochronal annealing. The concentration of current-carrying electrons decreases by 3.5 times compared to the initial state under the influence of radiation, which correlates well with the increase of electrical resistivity. Such changes are mainly due to the compensative action of E-centers. This is followed by the reverse process of dissociation of E-centers. The electrically active A-centers (VOs) are generated intensively and the concentration of current-carrying holes are a. They are revealed by n-p conversion near a critical temperature of 120°C. Following temperature changes of the electrophysical properties up to the temperature of 400°C are carried out under the p-type conductivity of the sample.

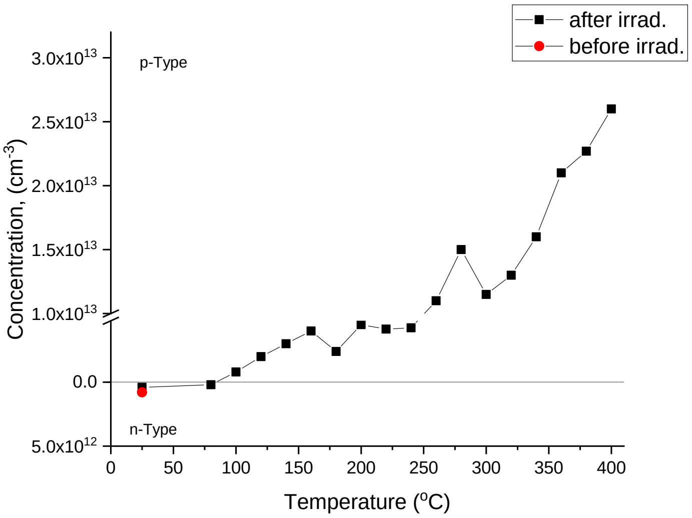

Figure 2.Changes of current carriers concentration in the temperature range of 20-400°C of **n-Si+0.4at%Ge:P alloy irradiated by ^{60}Co gamma-photons**

Intense dissociation of E-centers at the range of 120-150°C is followed by the release of vacancies from them. Some of them are associated with O_i- atoms, which at a concentration of 10^{17}–10^{18}cm^{-3} are constantly present in the Si and SiGe crystals obtained by the Czochralski method. The second part of the vacancies creates divacancies.

Divacancies in turn are associated with Oi atoms and V2O complexes are formed. This type of transformations in the structure of defects lead to the realization of opposite processes of bonding and release of current-carrying electrons and holes. C_i atoms displaced by gamma radiation in the carbon intenstitial position are also involved in changes in electronic states. They are intensively annealed to temperature of 110°C, thereby significantly increasing the concentration of current-carrying holes. In this case, the inverse proportions of the electrical resistivity and the current carriers concentration are not clearly observed. This is due to the fact that according to the literature data [5] in the temperature range of 100-200°C the processes of association and dissociation of other types of defects under thermal influence in the conditions of variability of their electrical activity.

Intensive annealing of Ev + 0.28 eV center is expected in the temperature range of 200-300°C. Consequently, the concentration of divacancies is significantly reduced. The process is accompanied by a decrease in the electrical resistivity and an increase in the concentration of the current-carrying holes in the form of a peak near temperature of 280°C. Significant changes in the rate of increase of concentration of current carriers are observed in the range of 300-400 °C. This can be explained as follows: In the process of dissociation of divacancies, it is possible to multiply new types of defects containing vacancies with energy level Ev + 0.22 eV, which are annealed in two stages at temperature range of 300-330°C and 360-400°C. The nature of these defects has not yet been determined. Their features are clearly influenced by other defects. In particular, localized areas in the crystal lattice with a high density of dislocations.

Annealing processes of radiation defects in Si and SiGe alloys also take place at elevated temperatures (T> 300 ° C). This especially refers to crystals obtained by the Chokhralski method, in which the concentration of Oi and Cs impurities is relatively high. Gradual annealing of thermally steady complexes containing them leads to a sharp increase in the current carriers concentration.

The temperature changes in current carriers mobility under isochronal annealing conditions are significantly dependent on the real structure, which is characterized by a very peculiar dislocation structure under relatively low concentrations of phosphorus and germanium. Dislocational deformed areas with high density of dislocations are energetically favorable positions for the replacement of technological impurities (O, C, ...) and their clusters. According to well-known experimental and theoretical studies, it is the deformed areas associated with dislocations that create the potential for anomalous changes in electrophysical characteristics (primarily mobility and lifetime). Indeed, in the present case the mobility undergoes the following anomalous changes.

The electrons mobility of the initial nonirradiated sample is high. Its reduction is observed after irradiation by ^{60}Co gamma photons (Fig. 3). The gradual decrease in mobility with predominant scattering on radiation defects (E-centers) continues until the temperature of isochronal annealing of 100°C. C_i-C_s complexes experience accelerated dissociation from temperatures of 120-130°C, E-centers dissociation is practically completed and by migration of a significant number of vacancies released from it to oxygen Oi, A-centers (VO) are formed.All of the above stimulates the formation of current-carrying holes and enhances their scattering by radiation defects. This circumstance causes a significant decrease of mobility in the temperature range of 100-250°C.

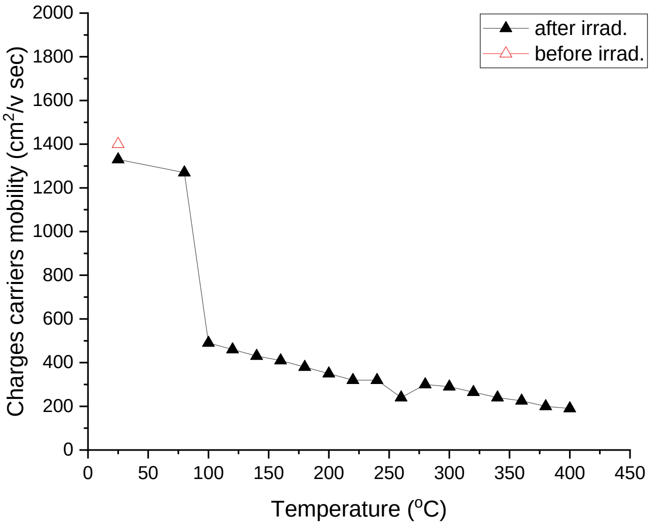

Figure 3. Temperature changes of current carriers mobility in the isochronal annealing process of n-Si + 0.4 at% Ge: P irradiated by ^{60}Co gamma-photons

In the test sample, which is a solid solution of low-content germanium SiGe, peculiar changes in the mobility of electrons and holes are expected, which may be one of the main reasons for the n-p conversion. In particular, in the alloys of Si1-xGex structure with increasing concentrations from $x \simeq 0.02$, the mobility decreases slowly and when of $x \leq 0.02$ the holes mobility significantly exceeds the mobility of the electrons. These germanium-depleted areas may exist in experimental specimens structure. According to the atomic theory of alloy scattering, it is expected that electrons will be more dispersed in dilute SiGe solid solutions under bond variation conditions than holes, with variation of local atomic composition. It is also noteworthy that the effect of electron dispersion in SiGe solid solutions with high germanium content is strongly represented. Because of this, even under conditions of unequal distribution of germanium, the changes of holes and electrons mobility are limited and, consequently, it is more difficult to detect n-p conversion in the irradiated state. This is experimentally confirmed by specific changes in the electrophysical properties of n-Si +0.4at%Ge:P alloy under isochronous annealing conditions in the temperature range of 20-400 °C. In the range of 270-280°C, a slight increase of the holes mobility is observed, which corresponds to the temperature range of peak shape increase of their concentrations. Here it is possible to detect the influence of dispersion phase inclusions. They may have existed in dislocation groups or in a set of deformation origin defects. Annealing of multicomponent complexes begins from 300 °C. Some of them are current carriers scattering centers, for example, $V_3 + O_3$ and $V_3 + O_2$ complexes. In contrast, the C_i, V_4, V_3+O_3 and V_2+O_2 complexes are not recombination centers and practically do not participate in mobility changes at elevated temperatures.

Based on the abovementioned, gradually reduce of the mobility of the holes in the interval 300-400°C might be related to the intensive dissociation of electrically active complexes and, consequently, a significant increase of current carriers concentration, thereby enhancing scattering and reducing mobility.

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^{60}Co გამა-ფოტონებით დასხივებული მონოკრისტალური n-Si+0.4 ატ%Ge:P შენადნობის ელექტროფიზიკური თვისებები

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აბსტრაქტი. შესწავლილია ^{60}Co გამა-ფოტონებით დასხივებული მონოკრისტალური n-Si+0.4ატ%Ge:P შენადნობში ელექტროფიზიკური თვისებები. იზოქრონული მოწვების 20-400°C ტემპერატურულ ინტერვალში გამოვლენილია კუთრი ელექტრული წინაღობის, დენის მატარებლების კონცენტრაციისა და ძვრადობის არამონოტონური ცვლილებები. გაანალიზებულია რადიაციული დეფექტების (PV, VO, VO_2, C_iC_s და C_iO_i) სტრუქტურაში მიმდინარე გარდაქმნების წვლილი ელექტრული მახასიათებლების ტემპერატურულ ცვლილებებში. იზოქრონული მოწვის კრიტიკული ტემპერატურის (~100°C) არეში გამოვლენილია n-p კონვერსია. 120-150°C ინტერვალში გამოვლინდა PV ცენტრების დისოციაცია და ელექტრულად აქტიური VO ცენტრების ფორმირება. აღნიშნულის შედეგად იზრდება დენის მატარებლების კონცენტრაცია. ამაღლებულ ტემპერატურებზე ($T \geq 150°C$) ელექტრული მახასიათებლები განიცდიან არამონოტონურ ცვლილებებს. გაანალიზებულია გერმანიუმის წვლილი n-SiGe შენადნობის ელექტროფიზიკური მახასიათებლების ანომალურ ტემპერატურულ ცვლილებებში.

საკვანძო სიტყვები: მონოკრისტალური SiGe შენადნობი, γ-რადიაცია, n-p კონვერსია, რადიაციული დეფექტი, იზოქრონული მოწვა.