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Peculiarities of the radiation defects generation and their isochronal annealing in monocrystalline n-Si+4at%Ge:P alloy

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Abstract

The effect of ^{60}Co gamma–photon irradiation on the radiation defects generation and their isochronal annealing in monocrystalline n-Si+4at%Ge:P alloy has been studied. Experimental bulk crystals were grown by Czochralski method in Ar atmosphere. Electrophysical characteristics were determined by the Hall effect measuring in a constant magnetic field at different stages of 20-minute isochronal annealing in 20-400°C temperature interval. It is established, that under the influence of compressive stresses localized near Ge atoms in the crystalline lattice of the experimental SiGe alloy decrease of the annealing temperature of radiation A-centers (VO) takes place. A change in dissociation temperature of radiation E-centers (PV) is revealed, stipulated by their directed migration in the stress field localized near dislocation.

Keywords: *SiGe alloy, radiation defect, gamma-photons, isochronal annealing.*

Introduction

Silicon-germanium system alloys are promising materials for use in modern semiconductor device technology. The interest in these materials is enhanced by the possibility of smooth variation of the crystal lattice parameter and the width of energy band gap under conditions of changing Si and Ge content in wide concentration ranges.

Currently, highly radiation-resistant high-speed devices based of SiGe system alloys are successfully used. In the world's leading scientific and technological centers, intensive work is being carried out to obtain Si-Ge alloys's bulk monocrystals and epitaxial structures of a perfect structure and controlled composition.

Complex research of technological origin and special processing defects in the real structure of Si-Ge alloys is an actual problem of semiconductor materials science. By gradually solving this problem, the possibilities of using semiconductor Si-Ge alloys in high-performance devices and systems will increase significantly.

Unlike Si and Ge semiconductors, the properties of radiation, deformation and thermal origin defects in bulk crystals of Si-Ge alloys have been less investigated. The study of the conditions of their generation, thermal stability and structural transformation has been mainly carried out by optical spectroscopy methods.

Despite numerous publications, there is practically no information in the scientific literature about the change in the electrophysical characteristics of radiation defects in bulk Si-Ge alloys in a wide range of isochronal annealing temperatures. This circumstance significantly hinders the study of electrical activity and thermal stability of radiation defects formed in the crystalline lattice of SiGe alloys.

It is known, that the covalent radius of the Ge atom is ≃4% larger than the covalent radius of the Si atom. Due to this, a localized stress field is formed near the Ge atoms in the crystalline lattice of Si-Ge alloys. It affects the conditions of generation and interaction of defects in the structure of Si-Ge alloys. The mechanisms of formation and interaction of different types of radiation defects in Ge-doped Si crystalline lattice, have been studied using optical spectroscopy methods in the infrared range of irradiation [1]. It is established, that at low concentrations, Ge atoms inhibit the annihilation of vacancy-interstitial (Si_i) atoms, while at high Ge concentrations, a tendency to clusters formation is revealed [2,3].

The aim of the present work is to study the formation and transformation processes of radiation defects in the n-type monocrystalline Si-Ge alloy with a relatively high Ge content (≃4at%) in the temperature range of 20-400°C isochronal annealing.

Research methodology

The bulk crystal of n-Si+4at.%Ge:P alloy was obtained by the Chokhralski method in an argon atmosphere in the [111] crystallographic direction. For irradiation and subsequent microstructural and electrophysical studies double-polished specimens were made from 0.8–1.0 mm thickness plates. Gamma-irradiation was performed from a ^{60}Co source with a fluence of $5\cdot10^{16}$ cm^{-2} at a temperature of ~50°C. Metallographic study was carried out on the optical microscope NMM-80RF/TRT. Electrophysical characteristics were determined in the constant magnetic field of 0.5 Tesla induction on the Ecopia HMS-3000 device by Hall effect measurements. Isochronal annealings in the temperature range of 20-400°C were performed in a vacuum of 10^{-4} torr. At each stage, the duration of isochronal annealing was 15 min, and the temperature step was 20°C.

Results and discussion

Changes in the specific electrical resistivity of the test sample in the temperature interval of isochronal annealing are non-monotonic and are characterized by the following properties (Fig. 1).

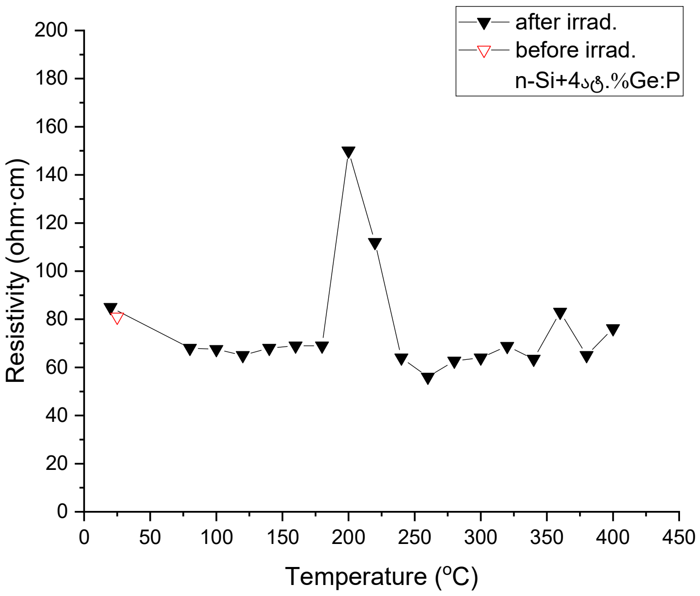

Fig.1. Temperature changes of electrical resistivity in the isochronal annealing range of 20-400°C in ^{60}Co gamma-photon irradiated n-Si+4at.%Ge:P alloy.

By gradually increasing the temperature of isochronal annealing, the electrical resistivity decreases to a temperature of 120°C. In the range of 120-175°C, its value increases slightly. In the given temperature range, the processes of dissociation of the E-center (PV) and association of the constituent components with other types of radiation defects takes place. In both cases, changes in electrical activity of radiation defects are expected. Concentration of germanium and technological impurities (O_i, C_S) are high in the test sample. This circumstance on the one hand complicates (the influence of Ge), and on the other hand (the influence of O_i) stimulates the formation of A-centers $(VO)^0$ with the participation of vacancies (V) released by the dissociation of E-centers. Due to the influence of dissociation-association processes, the change in electrical resistivity at temperatures of 100-175°C is relatively slow.
According to literature data, in the interval of 20-175°C, dissociation of one part of E-centers and distribution of constituent components in complexes of radiation defects takes place. The second part, as a whole, moves by diffusion in the crystalline lattice and forms complexes of various compositions with radiation defects (POV, PV_2, etc...). Near to 200°C change of peak shape of the specific electrical resistivity can be connected with the increase in the intensity of A-centers dissociation. The influence of high concentration of Ge is clearly revealed. In particular, the A-centers dissociation temperature decreases by 40-50°C compared to Si, in which the concentration of P is $\approx 10^{14}$ cm^{-3}. Strong overlap of stresses concentrated near Ge atoms (under conditions of high Ge concentration) stimulates the dissociation of VO centers and also association of part of them (~15%) with Oi atoms. This leads to the formation of optically active but electrically neutral VO_2 complexes. Above 200°C, the electrical resistivity decreases again significantly and is characterized by weakly visible zigzag changes. In these conditions, under the influence of Ge, the processes of dissosiation of divacancies and association with Oi are stimulated, as a result of which electrically

active vacancies and thermally unstable V_2O complexes are formed. All mentioned defects participate in the formation of more stable VmOn complexes under the influence of temperature and stresses concentrated near Ge atoms.

The compensating effect of radiation defects generated by gamma-photons led to a decrease in the electron concentration in the test sample(Fig. 2). Such defects are E-centers (PV), which are formed under irradiation exposure and absorb two electrons from the conduction band.Raising the isochronal annealing temperature up to 80°C leads to the dissociation process of E-centers and, accordingly, the release of electrons. This is shown on the graph by increasing the concentration of electrons. A gradual increase of the annealing temperature leads to decrease of the electron concentration into a temperature range of 120-200°C.

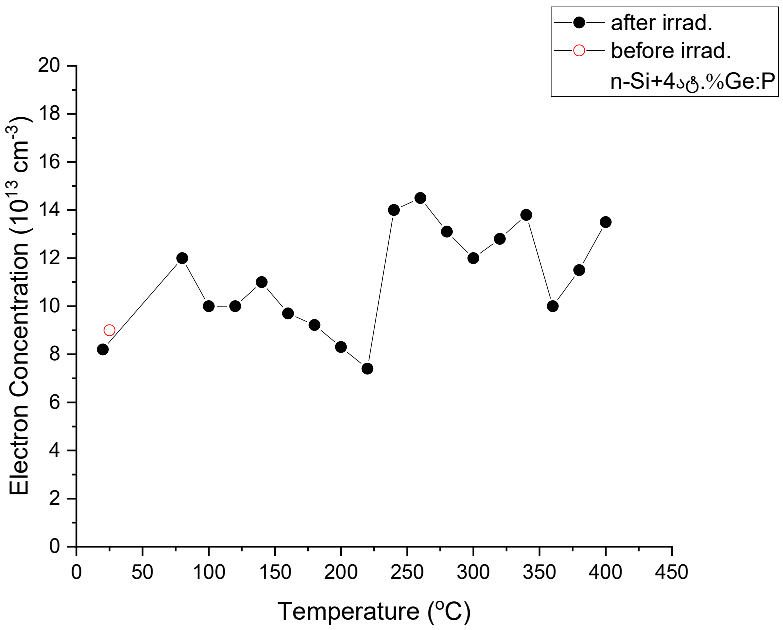

Fig. 2. Temperature changes of electron concentration in the isochronal annealing range of 20-400°C in ^{60}Co gamma-photon irradiated n-Si+4at.%Ge:P alloy.

In the mentioned temperature range, the participation of free electrons in the processes of recharging the dislocations cores and the filling of broken electronic bonds is expected. This circumstance leads to the decrease in the concentration of electrons in the interval 100-220°C.

At elevated temperatures (≥250°C), intense annealing of electrically active radiation defects and formation of multi-vacancy, electrically neutral defects take place, that means the weakening of compensating effect of radiation defects. This creates the conditions for increasing the concentration of electrons. It is possible that the processes of diffuse distribution of the dissociation products of radiation defects occur simultaneously in the cores of dislocations and in the surrounding atmospheres of impurities and defects. In such conditions, it is possible to release electrons from bonds and participate in new bonds in a certain number of them. For example, Si atom complexes near the vacancy-dislocation can be formed. Such transformations, which are practically difficult to control, cause a zigzag increase in the concentration of free electrons in the temperature interval of 250-400°C.

The temperature dependence of the mobility of the electrons in ^{60}Co gamma-photon irradiated n-Si+4at.%Ge:P alloy under the conditions of isochronal annealing is characterized by abundance of maxima and minima of different intensities in the temperature interval of 20-400°C (Fig. 3).

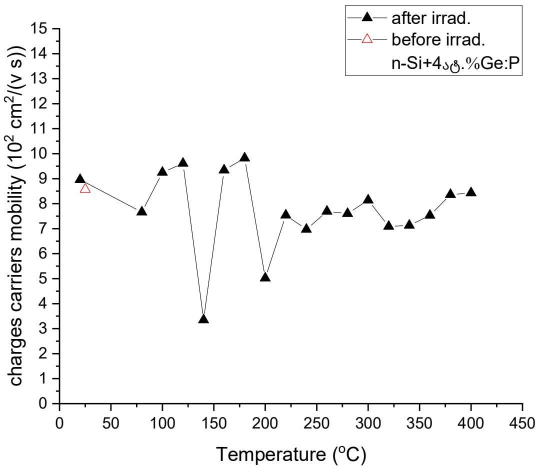

Fig. 3. Temperature changes of electron mobility in the isochronal annealing range of 20-400°C in ^{60}Co gamma-photon irradiated n-Si+4at.%Ge:P alloy.

At room temperature, the free electrons mobility in the gamma-irradiated samples is increased in comparison with the non-irradiated sample. Obviously, the compensating effect of radiation defects reduces the number of electrically active sputtering centers. Accordingly, opportunities to increase the mobility of electrons are created. Isochronal annealing at 80°C leads to a noticeable decrease in mobility, as the concentration of electrons in the conduction band increases due to the influence of electrons released by the dissociation of E-centers. The sharp increase and decrease of the mobility in the interval of 100-200°C is stipulated by many factors. First of all, it should be noted the areas created by strong inhomogeneous distribution of Ge atoms, with different lattice parameters and localized stress fields. Under such conditions, the lifetime of charge-carrying electrons varies over a wide range, even a small change in which significantly changes the magnitude of the mobility. On the other hand, in the deformed areas with a high content of Ge, new energetic states are realized for the transformation of radiation defects. In particular, it is possible to accelerate the formation and dissociation of A-centers, as well as changes in electronic states based on configurational changes of divacancies and E-centers related to P-V complexes. The formation of dielectric areas is not excluded, which is indicated by the increase in the shape of the peak of electrical resistivity near 200°C temperature.

In the areas of high Ge content, at elevated temperatures, the vacancy and internodal type dielectric and metallic dispersed inclusions intensively interact with each other. First of all, the vacancy origin inclusions are suppressed. Dissociation products are associated with components of internodal complexes. Such changes reduce the intensity of electron scattering and lead to the tendency to increase the mobility to the initial level. In the experimental n-SiGe alloy, the high concentration of Ge (~4 at.%Ge) and the increased concentration of phosphorus (10^{13}–$10^{14}cm^{-3}$) create additional opportunities for zigzagging changes of zone electron mobility. In particular, according to literature, in the vicinity of 150 and 300°C temperatures two-step annealing of CiCs complexes takes place, while at 350°C the A-centers are practically completely annealed. These processes are accompanied by zigzag changes in the concentration of zone electrons and, accordingly, their mobility.

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რადიაციული დეფექტების ჩასახვისა და მოწვის პროცესების თავისებურებანი მონოკრისტალურ n-Si+4ატ.%Ge:P შენადნობში

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აბსტრაქტი. შესწავლილია ^{60}Co გამა-ფოტონებით დასხივების გავლენა მაღალი კონცენტრაციით გერმანიუმის შემცველ მონოკრისტალურ n-Si+4ატ.%Ge:P შენადნობში რადიაციული დეფექტების ჩასახვისა და იზოქრონულად მოწვების პროცესებზე. საცდელი მოცულობითი კრისტალები მიღებულია ჩოხრალსკის მეთოდით არგონის ატმოსფეროში. ელექტროფიზიკური მახასიათებლები განსაზღვრული იქნა მუდმივ მაგნიტურ ველში ჰოლის კოეფიციენტის გაზომვებით 20-400°C ტემპერატურულ ინტერვალში 20-წუთიანი იზოქრონული მოწვების სხვადასხვა ეტაპზე. დადგენილია, რომ საცდელი SiGe შენადნობის კრისტალურ მესერში გერმანიუმის ატომებთან ლოკალიზებული შემკუმშავი ძაბვების გავლენით ადგილი აქვს რადიაციული A-ცენტრების (VO) მოწვის ტემპერატურის შემცირებას. გამოვლენილია რადიაციული E-ცენტრების (PV) დისოციაციის ტემპერატურის ცვლილება, განპირობებული მათი მიმართული მიგრაციით დისლოკაციებთან ლოკალიზებული ძაბვების ველში.

საკვანძო სიტყვები: SiGe შენადნობი, რადიაციული დეფექტი, გამა-ფოტონები, იზოქრონული მოწვა.