*Semiconductor Physics, Quantum Electronics & Optoelectronics, 2006. V. 9, N 3. P. 22-24.*

PACS 42.25.Bs, 61.82.Fk

# Study of the absorption band in the range 0.3-0.9 eV inherent to solid solutions *p*-$Ge_{1-x}Si_x$ irradiated by fast electrons at the temperature 77 K

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**Abstract.** $Ge_{1-x}Si_x$ solid solutions are one of promissing materials for semiconductor technique. However, their electrical and optical properties, especially with silicon content more than 5 at. % have been little studied. In particular, in the number of works [1-3] there have been presented the experimental results of study in the region 0.52 eV in germanium irradiated by fast electrons, gamma-rays and protons at the temperature of liquid nitrogen. In the literature, however, there are no data on studying the absorption band in the range 0.52 eV in $Ge_{1-x}Si_x$ solid solution irradiated by fast electrons.

**Keywords:** germanium-silicon alloy, optical absorption, energy of electrons, divacancy.

Manuscript received 08.02.06; accepted for publication 23.10.06.

## 1. Introduction

In a series of works [1, 4], there have been presented the experimental results of studying the absorption band of germanium and *n*-$Ge_{1-x}Si_x$ solid solutions irradiated by fast electrons, gamma rays and protons at the temperature of liquid nitrogen in the range of 0.3 to 0.9 eV. However, in the literature, there are no data on study of the absorption band in the same range for *p*-$Ge_{1-x}Si_x$ solid solutions irradiated by fast electrons.

## 2. Experimental

This work presents the results of measurements of IR absorption spectra, impurity photoconductivity and Hall effect in the samples of *p*-type $Ge_{1-x}Si_x$ solid solution, alloyed by gallium with the specific resistances of 0.3 to 1.0 Ohm·cm irradiated at 77 K by electrons with the energy 4.5 MeV up to the integral fluxes $2\cdot10^{17}\,cm^2$. Irradiation was effected by the procedure described in [2].

The samples of germanium and $Ge_{1-x}Si_x$ solid solution of *n*-type with 5, 10, and 15 at. % Si were grown by the Czochralski method with additional feeding.

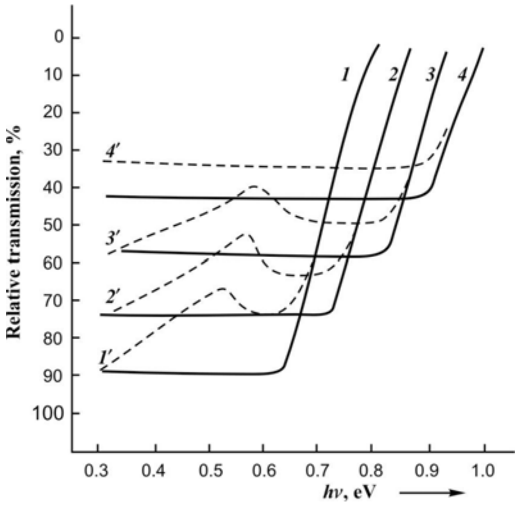
The thickness of samples was 0.8…1.0 mm, which allowed to obtain the uniform by depth distribution of radiation defects by using electrons with the energy mentioned above.

## 3. Results and discussion

There were studied the radiation defects responsible for absorption in the region 0.3…0.9 eV in *p*-$Ge_{1-x}Si_x$ and Ge solid solutions alloyed Ga irradiated by fast electrons with the energy 4.5 MeV at the temperature of liquid nitrogen. The irradiation was performed by electrons to the integral fluxes $\Phi = 2.5\cdot10^{17}\,cm^{-2}$.

The results of the IR-absorption and Hall coefficient measurements on the samples with the concentration $2.5\cdot10^{17}\,cm^{-3}$ showed that absorption in the range 0.3-0.9 eV is detected independently of the initial impurity concentration (though the basic carrier concentration at such irradiation slightly changes). But it should be noted that at given dosage and energy of electrons, the increase of the initial carrier concentration results in the increase of the absorption band intensity.

Shown in the figure is the change of the absorption band before and after irradiation by electrons. In the germanium samples, the change is displayed for the flux $\Phi = 3.5\cdot10^{16}\,cm^{-2}$ and in the *p*-$Ge_{1-x}Si_x$ samples with 5, 10 at.% Si – at the flux $2.5\cdot10^{16}\,cm^{-2}$. In samples with $x = 0.15$, the band was not observed though with increasing Si content the irradiation dosage increases necessary for appearance of absorption band. With increasing the silicon content in solid solution, a band shifts toward shorter waves.




Spectra of absorption of $p$-$Ge_{1-x}Si_x$ samples before (1-4) and after (1´-4´) irradiation by electrons with the energy 4.5 MeV. $\Phi = 5{\cdot}10^{16}\,cm^{-2}$ (1) and $2{\cdot}10^{17}\,cm^{-2}$ (2-4), when $x = 0$ (1); 0.05 (2); 0.10 (3) and 0.15 (4).

Studies of the Hall effect on Ge and $p$-$Ge_{1-x}Si_x$ samples with the concentration up to $5{\cdot}10^{16}\,cm^{-3}$ showed that after irradiation in the germanium sample there is a level with the energy state $E_v$+0.16 eV and, in the $p$-$Ge_{1-x}Si_x$ sample with $x = 0.05$, we have $E_v$+0.18 eV, with $x = 0.10$ – $E_v$+0.22 eV, with $x = 0.15$ no levels appear.

The obtained results show that the energy levels of radiation defects in the samples of $p$-type $Ge_{1-x}Si_x$ solid solution differ from these in the samples of $n$-type. These energy levels in spectra of IR-absorption give bands with the peaks 0.52, 0.55, and 0.59 eV, respectively.

From these results one can conclude that the spectrum of radiation defects strongly depends on the silicon content and the type of conductivity of $Ge_{1-x}Si_x$ solid solution.

Before and after irradiation as well as after each annealing within the temperature range of 77 to 420 K, the concentrations of current carriers and specific conductivity were measured at the temperature of liquid nitrogen in darkness.

The decrease in the concentration of current carriers within the temperature range of 8 to 160 K is difficult to be explained by electron adherence. In this case, the adherence centre should be attributed the extremely small cross-sections for capture of holes. At this stage, crystal properties change under action of illumination. As a result of irradiation, the metastable formations seem to arise capable to be rebuilt when heating and illuminating. Possibility for defect rebuilding when heating was mentioned previously [1, 3].

In $n$-type germanium, the vacancy motion was observed at the temperature 70 K. If the analogy with silicon is true then, in germanium of $p$-type, vacancies will be mobile at the temperatures substantially above 77 K. Therefore, one can assume that, as a result of metastable formation decay, free vacancies appear, which take part in creation of more stable complexes. If it is the case, then the activation energy (0.65 eV) at 160…260 K is due to the motion of free vacancies in $p$-type germanium.

The order of-reaction at this stage and partial reduction of hole concentration on exposing to white light don’t contradict it. At 360…420 K practically the full reduction of hole concentration occurs. The large value of the activation energy (2.5 eV) and complex mode of reaction show that, at this stage of annealing process, the gallium impurity plays a significant role. In [3, 4], there has been indicated that the activation energy within the temperature range of 360 to 420 K depends on the kind of alloying components, which indirectly confirms the correctness of the assumption made.

In the samples of $p$-type as in those of $n$-type after irradiation at the temperature of liquid nitrogen a light sensitivity effect is observed.

Annealing of $Ge_{1-x}Si_x$ samples showed that with increasing Si and the initial alloying component content the temperature when annealing defects occurred decreased.

In germanium samples after heating at the temperature 235 K, the absorption band in the range 0.3…0.9 eV fully disappears at 175 K.

As it was already mentioned, there was no common opinion concerning the structure of complex of radiation holes responsible for absorption bands in the range 0.3…0.9 eV. In [5], radiation defects that give the beginning of the absorption band have been identified with a divacancy. In this work, the results are based on the analogy between Ge and Si, in which divacancy have been studied by EPR method. In [6], this assumption is rejected showing that the defect is not an isolated vacancy but is rather simple complex capturing the Frenkel pairs.

In [2], it was assumed that the defect under study is a complex without donor atoms comprised, at least, two components including more than one vacancy and absorbed light only at certain charge states.

It is clear that the presented experimental data don’t allow to elucidate the nature of given complex. Considering the analogy between silicon and germanium and eventually bearing in mind the coincidence of basic properties of Ge and $Ge_{1-x}Si_x$ with $x = 0.05…0.15$ we made an attempts to explain the structure of this defect.

In [7, 8], there have been carried out various investigations of irradiated Si including the methods of EPR, photoconductivity and IR-absorption, on the basis of which there has been created a model of radiation defect responsible for absorption bands 1.8, 3.3, and 3.9 μm in the spectrum of IR-absorption of Si. These bands appear as a result of absorption in divacancy that may be in various charge states. It has been shown in these works that the absorption zone at 1.8 μm is due to electron transition that is possible only in divacancy at neutral or single-charge negative state whereas the absorption zone 3.9 μm appears only at single-charge negative state. Considering all above mentioned facts and the results of the previous electrophysical and optical investigations of defects at various charge states (1, 4) and assuming that many crystallographic and electrophysical parameters of Ge and $Ge_{1-x}Si_x$ with $x$ = 0.05…0.15 are similar, we suppose that it is divacancies that are responsible for the absorption band in the range of 0.3 to 0.9 eV. As a zone was observed in $n$-$Ge_{1-x}Si_x$ samples only after $n \to p$ conversion as a result of irradiation [10] the most likely that divacancy might be only at two charge states: neutral or single-charge negative. As is shown above similarly to silicon in $p$-$Ge_{1-x}Si_x$ when divacancy is at neutral state the absorption band appears in the range 0.3…0.9 eV.

## 4. Conclusions

Following the authors of [2, 4], we draw conclusion that the absorption band in the irradiated $Ge_{1-x}Si_x$ samples in appropriate spectral region is related not with photoelectrical active transitions but with vibration levels of complex radiation defect, in this case the adsorption displays when defect is at charge state which is determined by Fermi level location. The defect responsible for absorption either is not created as long as the Fermi level is in the forbidden band, or it is created and accumulated from the very beginning of irradiation but displays only at the certain charge state.

In conclusion the authors consider it as their pleasant duty to express sincere gratitude to D.B. Gerasimov for his help in performing experiments.

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