ROLE OF IMPURITIES OF GROUPS III AND V IN THE FORMATION OF DEFECTS FOLLOWING γ IRRADIATION OF GERMANIUM

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In earlier studies of the action of nuclear radiations on semiconductors [1] it was assumed that the process of defect formation reduces to the occurrence of Frenkel pairs or Schottky defects. Recent investigations of EPR in silicon bombarded with electrons at room temperature have shown that the change of the parameters of the material is due not to the appearance of free vacancies or interstitial atoms, but to the formation of complexes of vacancies with impurities. The studies were made, in particular, for vacancy-donor (VD) complexes of group V [2, 3], and vacancy-acceptor (VA) complexes of group III [4]. At the present time there are no corresponding data for germanium.

The purpose of the present investigation was to elucidate the role of impurities of groups III and V in the formation of defects in germanium. The main investigated parameters were chosen to be the concentrations N_D^V of the donor states of the group-V atoms and N_A^{III} of the acceptor states of the group-III atoms. For a separate determination of these quantities [5, 6] measurements were made of the temperature dependences of the Hall coefficient R in the temperature interval 4.2 - 300°K and of the photoconductivity in the submillimeter region of the spectrum [7] at 7°K. From the R(T) dependences, in addition, we could find [8, 9] the concentrations of the individual acceptor levels resulting from irradiation and their sum N_A^{rad}. The Hall measurements make it possible to assess the value of N_D^V only in n-type material (prior to n-p conversion). It is important, however, to have information concerning this concentration in the entire irradiation-dose interval. Such data were obtained for samples in the limiting state (p-type, which remains unchanged no matter how large the increase of the irradiation dose Φ) in investigations of the photoconductivity spectrum in the submillimeter band. This band contains the lines of transitions between excited states of shallow impurities, and at the attainable resolution of the instrument [7] the spectra of the excited states of the group-V donors and group-III acceptors can be readily identified. The donor and acceptor spectral-line intensity was determined under conditions of complete neutralization by interband excitation. Under these conditions, the line intensity is proportional to the number of impurity states.

We investigated samples of Ge doped with P, As, Sb, and Bi[1)] with different concentrations (5×10^{13} - 2×10^{15} cm^{-3}) of each of the impurities, irradiated at room temperature with the γ rays from ^{60}Co (flux 1×10^{12} quanta/cm^{2}sec). Typical measurement results are given in the table.

We see that the concentration N_D^V of the donor states of all the impurities of group V decreases upon irradiation. It is most probable that this is the consequence of the binding of the donors into complexes [2, 3, 10].

[1)]For germanium doped with phosphorus, results of Hall measurements were published earlier [8].

Impurity	State of sample	Dose Φ $\times 10^{-16}$, cm^{-2}	N_D^V $\times 10^{-13}$, cm^{-3}	N_A^{III} $\times 10^{-13}$, cm^{-3}
P	initial	–	17.0	~1.7
	irradiated n-type	5.4	10.4	~1.9
	irradiated limiting p-type	198	⩽ 0.1	2.0
As	initial	–	12.0	~0.3
	irradiated n-type	5.7	7.0	~0.3
Sb	initial	–	104	~2.4
	irradiated n-type	34	57	~2.5
	initial	–	12.9	~2.7
	irradiated limiting p-type	311	⩽ 0.1	2.7
Bi	initial	–	203	~2.0
	irradiated n-type	68	116	~2.0

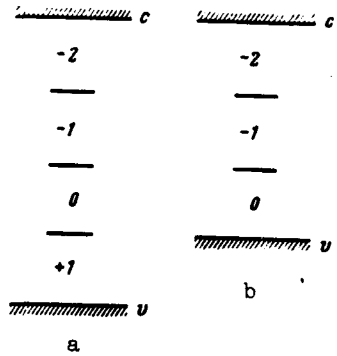
The concentration N_A^{III} of the shallow acceptor states is the same in the initial, irradiated (n-type) and the limiting states[2]. One can therefore assume that the group-III atoms interact neither with the vacancies nor with the interstitial atoms.

It should be noted, in addition, that the decrease in the number of the donor states exceeds the total concentration of the deep compensating acceptors, $\Delta N_D^V > N_A^{rad}$, i.e., the produced acceptor levels cannot belong to the VD complexes. It follows therefore that the electronic states of the complexes lie in the valence band. The initial rates of change of the concentrations of all four types of donor are approximatley equal and lie in the range (1.0 - 1.3) $\times 10^{-3}$ cm^{-1}quantum^{-1}. This means that under the conditions in question the rate of VD complex formation is determined exclusively by the rate of generation of the free vacancies [10].

The results of our measurements allow us to draw the following conclusions: 1) The process of formation of VD complexes in germanium is shown to be quite universal, equally effective with respect to different elements of group V, and capable of producing the usually observed decrease of electron density under conditions when Frenkel or Schottky defects are generated at room temperature. The electronic states of the complexes lie in the valence band. 2) The high radiation stability of p-type germanium [12] (compared with n-Ge) is obviously a consequence of the fact that the acceptors of group III in Ge do not interact with the interstitial atoms or vacancies. 3) It is known that the Fermi level tends upon irradiation towards the valence band in germanium and towards the center of the forbidden band in silicon. The fact that acceptors of group III form VA complexes in silicon and do not take part in the defect formation in germanium can explain this difference. 4) Certain considerations can be advanced concerning the energy spectrum of a free vacancy. As shown in [13], a free vacancy in silicon can have four different charge

[2] The assumption that N_A^{III} is constant during the irradiation process was advanced earlier in [11] for Ge doped with Sb.

states: V^{-2}, V^{-1}, V^{0}, and V^{+1} (see Fig. a). Owing to the Coulomb interaction, the negatively charged vacancies in n-Si are apparently captured by ionized D^{+1} donors, and V^{+1} in p-type material are captured by ionized acceptors A^{-1}, in which case the Fermi level in n- and p-type silicon should tend to the center of the forbidden band. Since the donors in germanium make up VD complexes, and the acceptors of group III do not take part in defect formation, it can be assumed that a vacancy in Ge has only three charge states: V^{-2}, V^{-1}, and V^{0} (see Fig. b).



a - Energy spectrum of free vacancy in silicon in accordance with [13], b - proposed energy spectrum of free vacancy in germanium.

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SEARCH FOR BARYON RESONANCES IN THE pγ SYSTEM

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We present in this article the result of a search for baryon resonances in the mass interval $M_n < M_{N'} < M_n + M_\pi$, decaying in accordance with the scheme $N' \to p + \gamma$.

The possible existence of a new nucleon state in this mass region was considered in [1, 2]. The prediction in [1] was based on the choice of a unitary multiplet for the resonance Σ(1475). Under the condition that it is a member of a unitary octet containing the resonances Ξ(1630), Λ(1330), and N', the Gell-Mann-Okubo formula was used to determine the mass of N'. The value of the mass of N' was refined with the aid of experimental data on πN scattering. It was shown that the most probable value of the mass of N' lies below the πN threshold. In [2] the prediction was based on the nucleon-meson model of the shell