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LATTICE DEFECTS IN γ-IRRADIATED p-TYPE Ge

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Abstract: Lattice defects in gallium-doped germanium irradiated by Co^{60} γ-rays at room temperature have been investigated. The hole concentration in the specimen with low amount of gallium ($8x10^{13}cm^{-3}$) was unaltered during irradiation but in the specimen with $8x10^{14}$ gallium/cm^3 a rapid initial decrease of carrier concentration with tendency of saturation was observed. Isochronal annealing after the irradiation revealed two annealing stages centred around 125°C and 310°C. It was concluded that the first stage is impurity dependent and the corresponding annealing model was proposed.

1. Introduction

Lattice defects in n-type Ge induced by γ-irradiation at room temperature have been extensively studied by Mashovets and co-workers[1]. They concluded that the mobility of primary defects at room temperature is extremely high and that the major portion of primary defects is lost by means of mutual recombination of vacancies (V) and interstitials (I). Only a few of the primary defects through interaction with group V impurity atoms (D) give rise to formation of lattice defects stable at irradiation temperature, such as V-D and I-D complexes[2].

There are very few information on lattice defects in p-type Ge induced by irradiation at room temperature. It was reported that the concentration of the acceptor states of group III impurity atoms remains practically conctant during γ-irradiation[2]. For the high radiation stability of p-type Ge two assumptions have been given: either secondary defects including group III impurity atoms are unstable at room temperature or group III atoms appear to be the recombination centres for the vacancies and self-interstitials[1].

The aim of this work is to investigate more extensively the radiation damage in p-type Ge induced by γ-rays at room temperature.

For this purpose we examined p-type Ge specimens with different concentration of gallium as doping impurity and low doped n-type Ge spe cimans converted into p-type by quenching.

2. Experimental procedure

Germanium single crystals of rectangular shape (20x2x1 mm^3) gallium doped ($8x10^{13}$ and $8x10^{14}$ cm^{-3}) and antimony doped ($6x10^{13}$ end $2x10^{14}$ cm^{-3}) were used. The irradiation of the specimens has been performed at about 30^oC in a Co^{60} source with intensity of $4x10^{12}$ photons/cm^2s.

Twenty minutes isochronal annealing in hellium atmosphere up to 500^oC has been performed after irradiation. During the irradiation and during the course of annealing the carrier concentration at room temperature, determined by Hall coefficient measurement, has been monitored

3. Results and discussion

Figure 1 shows the influence of irradiation and isochronal annealing on tne carrier concentration at room temperature for a set of Ge specimens with different initial characteristics. Specimens A, B and C were being irradiated for two months and for the specimen D irradiation time was five months.

The specimen A was converted from originally n- to p-type, due to irradiation. The most of induced defects anneal in the temperature range 100°-200^oC and after a small annealing stage around 400^oC the initial carrier concentration is restored. The observed behaviour of n-type Ge is in accordance with the model of defects formation and annealing proposed by Mashovets and co-workers[2].

The specimen B was not affected by irradiation but in the specimen C the carrier concentration was reduced. The complete amount of reduction was observed already after approximately 20 days of irradiation and during the prolonged irradiation the carrier concentration remains constant. Two annealing stages are found in the specimen C, the first one in the temperature range 100°-150^oC and the second one centred around 310^oC.

In order to examine whether gallium atoms are included into the lattice defects responsible for the two observed annealing stages, we investigated an originally low doped n-type specimen which was

converted to p-type by quenching using the experimental procedure already reported[3]. In this specimen (D) the 100°-150°C annealing stage was not observed but the stage around 310°C appeared again.

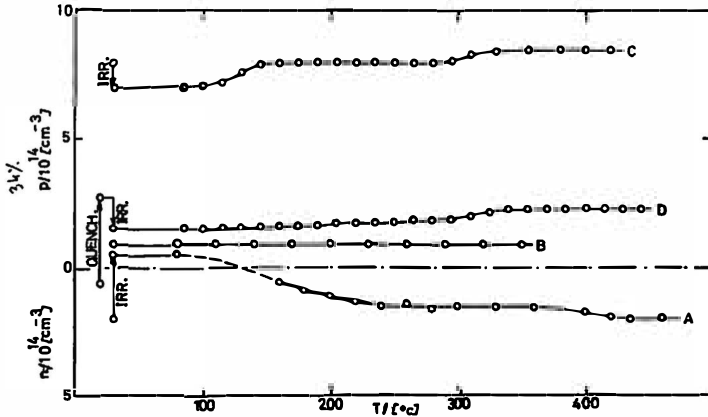

Fig. 1. The shange of carrier concentration due to -irradiation at room temperature and 20 minutes isochronal annealing

The comparison of annealing behaviour in specimens C and D indicates that the defect which anneals around 310°C does not contain gallium atom, contrary to the defect responsible for the annealing stage 100°-150°C which should include gallium atom as a member. This statement is in accordance with results of Saito et al[4] who studied lattice defects in p-type Ge after electron irradiation at liquid nitrogen temperature and found an annealing stage above 100°C with activation energy which is dependent on the kind of doping impurity.

In discussion on the higher radiation stability of p-type Ge in contrast to n-type we should first analyse the influence of the charge state of primary defects and impurity atoms on the possibility of forming secondary defects. According to the present experimental knowledge concerning primary defects, vacancy has two acceptor states in the forbidden gap, the position of the first state was estimated to be 0.25 eV above valence band and the position of the second state 0.2 eV[2] below conduction band, and exist in three different charge states: $V^{=}$, V^{-} and V^{0}. Most likely, the interstitial has one

donor state located at about 0.3 eV below the conduction band and can exist, depending on the Fermi level position, in two charge states, namely I^+ and I^o[1].

In n-type Ge, due to the location of the Fermi level near conduction band, self interstitials are neutral, vacancies negative and donors positive and in respect to the Coulomb interaction between primary defects and donors it is possible that donors trap both kinds of primary defects preventing in that way their mutual recombination.

In low doped p-type Ge (specimen B) the Fermi level is located above the lower acceptor level of vacancy. Interstitials are now positive and vacancies negative. The formation of a vacancy-gallium complex is difficult because of the Coulomb repulsion between a vacancy V^- and a gallium atom Ga^-. The charge states of an interstitial I^+ and a gallium atom Ga^- promote replacement of gallium atom and creation of interstitial gallium Ga_i, similarly to irradiated p-type Si. The fact that the hole concentration remains practically constant during irradiation can be however explained either by radiation anneal of gallium interstitials according to the reaction: $V^- + Ga_i^+ \rightarrow Ga^- + \text{hole}$ or by the instability of gallium interstitials at irradiation temperature. The last assumption is supported by the results of Saito et al. which indicate that gallium interstitials are movable below room temperature[4].

How to interpret now the fact that in p-type Ge doped with $8x10^{14}$ gallium/cm^3 (specimen C) irradiation produces an initial decrease of hole concentration with a tendency to saturation. A simple calculation shows that the Fermi level at room temperature in this case is located below the lower acceptor level of vacancy and vacancy is then neutral. The Coulomb repulsion between a vacancy and a gallium does not exist and the formation of a vacancy-gallium complex is possible. The observed decrease of hole concentration during irradiation indicated that vacancy-gallium complex is neutral or donor-like defect. Simultaneously with decreasing of hole concentration the Fermi level is lifted to the middle of energy gap and hole concentration does not change upon irradiation at the moment Fermi level reaches the lower acceptor level of vacancy because vacancies produced by irradiation are in negative

charge state and formation of vacancy-gallium complex is stopped.

For the completion of this model it is important to know what happens with self interstitials because if both members of a Frenkel pair are not trapped irradiation anneal takes place and there is no damage of the lattice. We propose that a self interstitial may be trapped by an unknown impurity which is always present in germanium such as oxygen or silicon. It was pointed out that silicon atoms act as effective traps for germanium interstitials[2]. It is now possible to explain the annealing behaviour of p-type Ge (specimen C) in a satisfactory way. The first stage (100°-$150^{o}C$) corresponds to the dissociation of a V-Ga pair and the second (around $310^{o}C$) to the dissociation of I-unknown impurity pair. This proposal takes into account that gallium is a member of the defect responsible for annealing stage I and that stage II defect does not include gallium.

References

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