

DEFECTS IN NEUTRON IRRADIATED QUENCHED p-Ge

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Abstract: The results of the study of lattice defects in quenched and irradiated p-type Ge crystals are reported. Specimens have been irradiated at 60°C by reactor neutrons. Some of the specimens were quenched previously, from 800 °C down to the liquid nitrogen temperature. Both quenching and fast neutron irradiation induced acceptor-like defects.

Isochronal annealing revealed three annealing stages in neutron irradiated and four stages in quenched and irradiated specimens. The dose dependence of these stages and interaction of radiation defects with quenched-in defects have been investigated and discussed.

1. Introduction

Thermal defects in Ge, induced by quenching, have been the subject of many investigations¹⁻⁸⁾. It was found that thermal defects behave as acceptors stable up to 300°C. Recent experiments showed some differences in annealing of quenched n- and p-type Ge⁹⁻¹⁰⁾. The nature of thermal defects, regardless of many experimental facts, is still in question.

Radiation defects in Ge induced by γ -rays¹¹⁾, electrons¹²⁾ and neutrons¹³⁾ have been studied more extensively. The results of these investigations, which confirm the low migration energy of vacancies and interstitials, caused the rejection of some defect configurations previously considered as appropriate for explanation of thermal defects. Quenched defects most likely can be regarded as complexes of vacancies with themselves or with other lattice defects such as impurities. These complexes could influence the process of radiation defects formation, the fact supported by the results of Khansevarov et al.¹⁴⁾. They established the decrease of the radiation damage rate in the quenched specimens.

The aim of the present work is to investigate what happens when interstitials and vacancies are introduced by irradiation in the specimens which already contain thermal defects. Particular emphasis was placed on the annealing behaviour after simultaneous irradiation of two specimens, one of which has been previously quenched. The results could be used in getting some new information on the damage by reactor irradiation.

2. Experimental procedure

Germanium single crystals of rectangular shape ($20 \times 2 \times 1 \text{ mm}^3$) gallium doped ($8 \cdot 10^{13} \text{ cm}^{-3}$) were used. Relatively resistant to irradiation, p-type Ge was chosen to escape dealing with many different kinds of defects which could be formed in n-Ge¹¹). Specimens were prepared by mechanical polishing, cleaning and etching in CP-4A solution.

The irradiation of specimens has been performed at 60 °C in the nuclear reactor. The time of irradiation varied from 5 to 10 minutes, which corresponds to thermal neutron dose from 1 to $20 \cdot 10^{16} \text{ n/cm}^2$ respectively. The equivalent fast neutron dose was one order of magnitude smaller. Some of the specimens have been previously quenched from 800–850°C down to the liquid nitrogen temperature by original technique and experimental procedure⁷⁾.

After irradiation, specimens were held at room temperature for period of one month in order to allow the decay of radioactive Ge⁷¹ into the stable Ga^{71 15}).

Twenty minutes isochronal annealing in helium atmosphere up to 500 °C has been performed. To avoid introduction of additional defects by annealing at temperature above 350 °C¹⁶⁾, the cooling of specimens after 20 minutes of annealing was done slowly with cooling rate of 0.1 °C/s. During the course of annealing the carrier concentration at room temperature, as determined by Hall coefficient measurement, has been followed.

3. Results and discussion

Fig. 1 shows the influence of irradiation and isochronal annealing on the carrier concentration at room temperature for two specimens (A and A'). One of them (A') was previously quenched. Quenching resulted in the increase of hole concentration due to acceptor behaviour of induced thermal defects. After neutron irradiation, a substantial increase of hole concentration was established in both specimens, which means that new acceptor-like defects were formed. Neutrons are generally more effective in creation of defects than γ -rays. For instance, in p-type germanium irradiated by γ -rays hole concentration remains practically unaltered¹¹⁾. This difference can be explained by different defect formation mechanisms. In case of γ -rays irradiation isolated vacancies and interstitials, very mobile at room temperature, are formed uniformly throughout the specimen and since there is no way in p-type germanium to stabilize damage, these primary

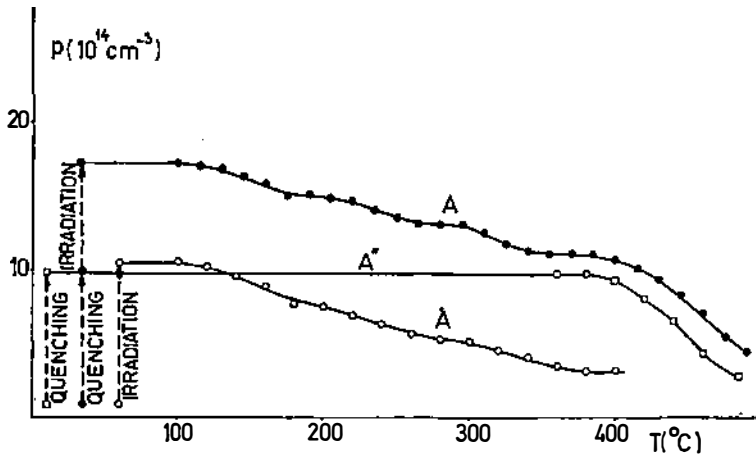


Fig. 1. Isochronal annealing of carrier concentration for: sample A exposed to thermal neutron dose of $1 \cdot 10^{16}$ n/cm ; sample A' quenched from 800 °C and irradiated simultaneously with sample A; sample A'' only quenched from 800°C.

defects disappear. In case of reactor irradiation, the defect distribution is quite inhomogeneous, since nearly every primary collision initiates a displacement cascade, each containing a number of secondary and higher order defects which are stable at room temperature¹³⁾.

Isochronal annealing reveals three annealing stages in specimen A and an additional one, fourth stage, in specimen A'. This stage takes place in the same temperature range (above 400 °C) in which the defects induced only by quenching disappear (specimen A''). Thus it corresponds to the annealing of thermal defects which were present in specimen A' before irradiation. The magnitude of this stage is about 10% smaller than the increase of hole concentration due to quenching before irradiation.

Other three annealing stages, stage I (100—180 °C), stage II (200—270 °C) and stage III (280—370 °C) seem to be almost equally pronounced in both specimens A and A' although it is difficult to resolve them quantitatively since they appear very close.

As it can be seen from the curve A, the hole concentration after annealing is higher than that before irradiation. Some fraction of acceptors also remains after finishing the annealing procedure. We attribute this effect to the increase of concentration of doping impurity since the remaining fraction is quantitatively comparable with the concentration of gallium atoms formed by decay of the radioactive Ge⁷¹¹⁵⁾.

Figure 2 presents the effect of quenching, irradiation and isochronal annealing on the hole concentration at room temperature for the next two p-type Ge specimens B and B' which were exposed to neutron dose twice as high as that used for

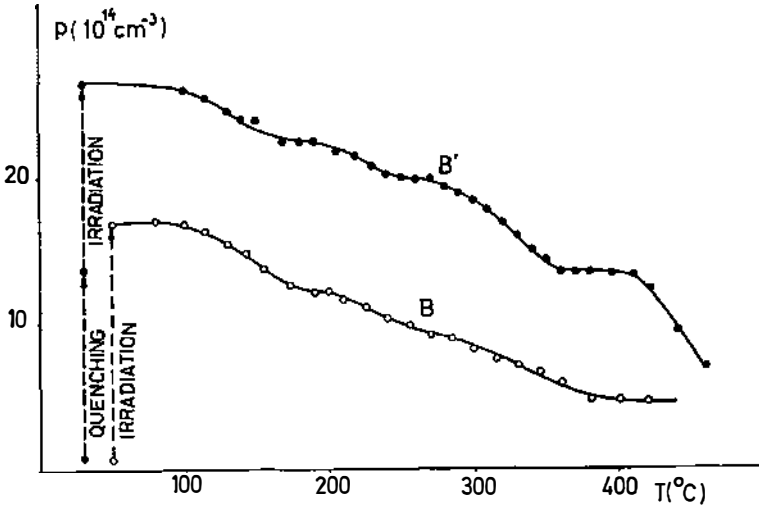


Fig. 2. Isochronal annealing of carrier concentration for: sample B exposed to thermal neutron dose of $2 \cdot 10^{16}$ n/cm²; sample B' quenched from 860°C and irradiated simultaneously with sample B.

specimens A and A'. The analysis of Figure 2 leads to similar conclusions concerning the annealing stages I to IV as in case of specimens A and A':

- the magnitude of stage IV, which presents the remaining concentration of thermal defects after irradiation and annealing, is about 30% smaller than the concentration of thermal defects after quenching;
- the magnitudes of stages I and II in quenched (B') and unquenched (B) specimen are comparable within the uncertainties coming from poorly resolved annealing stages. However, the magnitude of stage III is about 20% greater in quenched specimen (B').

Defects induced by irradiation do not anneal out completely (curve B). The remaining fraction of acceptors is almost twice as high as in the case of specimen exposed to lower irradiation dose (curve A in Fig. 1), the fact which supports explanation of this effect by radioactive transformation of Ge⁷¹ into Ga.

The comparison of Figs. 1 and 2 offers the dose dependence of annealing stages I—IV. The amount of recovery for stage I and stage III increases with increasing of irradiation dose. However, stage II seems to have already reached its saturation in case of lower irradiation dose. Concerning stage IV, its relative amount decreases with increasing irradiation dose.

In order to propose a reasonable explanation of the observed annealing stages, one should consider which kind of defects might arise after a displacement cascade was produced by fast neutron. One can expect a number of stable secondary and higher order defects per cascade to be formed inside the disordered region of the lattice. The concentration of such defects should increase with increasing irradiation dose, since the number of cascades increases. Strong dependence of stage I

and stage III on irradiation dose indicates that defects responsible for these stages are most probably intrinsic defects such as divacancies and vacancy clusters formed inside a cascade. The stage I could be assigned to migration of divacancies since it was found that divacancies anneal near 130°C¹²⁾. On the other hand, the saturation with dose of stage II shows that the defects are formed in the hole specimen. Namely, a certain number of free vacancies and even a greater number of free interstitials, which have escaped the recombination, migrate in the lattice and form complexes with impurities present in the specimen. We assign tentatively stage II to the complex of vacancies or interstitials with some impurity atoms. The concentration of that impurity represents the upper value for the magnitude of stage II. One can only speculate upon which impurity is in question. Since the concentration of gallium, as doping impurity, as well as concentration of compensating donors are smaller than the concentration of stage II defects, the most probable partners to trap vacancies or interstitials are electrically neutral impurities such as oxygen or silicon¹¹⁾.

The fact that stage IV appears only in those specimens which were quenched before irradiation, indicates that fast neutrons do not produce thermal defects in detectable amount. On the contrary, the concentration of thermal defects introduced into the lattice by quenching decreases as the result of neutron irradiation. The decreasing means that free interstitials and/or free vacancies, which escaped recombination or trapping, have reacted with thermal defects changing their nature. The greater concentration of stage III defects in quenched and irradiated specimen than that in only irradiated specimen can be, for instance, explained by the transformation of thermal defects into stage III defects.

4. Conclusion

Many problems remain to be solved in respect to behaviour of lattice defects in fast neutron irradiated and quenched p-type Ge. The results of this work could be summarized as following:

- reactor neutrons produce at least three kinds of defects stable at irradiation stages are strongly dose-dependent and may be related to intrinsic defects stabilized inside a displacement cascade. The third annealing stage saturates with increasing irradiation dose and can be related to a complex of some impurity with either a vacancy or an interstitial;
- defects introduced into lattice by quenching of p-Ge are not produced by reactor neutrons. On the contrary, concentration of thermal defects decreases when a quenched specimen is exposed to reactor neutrons. This indicates that free vacancies react with thermal defects changing their nature. It is difficult to identify the products of these reactions because the reactor neutron damage is generally very complex.

Therefore, for the study of interaction of thermal defects and free interstitials (free vacancies) reactor neutrons are not appropriate.

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DEFEKTI U KALJENOM p-Ge KOJI JE OZRAČEN NEUTRONIMA

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Sadržaj

Proučavani su defekti rešetke u zakaljenom i ozračenom p-Ge. Uzorci su ozračivani na 60°C reaktorskim neutronima. Neki uzorci bili su prethodno kaljeni na 800 °C do temperature tečnog azota. Kaljenjem kao i ozračivanjem brzim neutronima izazvani su defekti akceptorskog tipa.

Izohronim odgrevanjem otkrivena su tri stanja odgrevanja u označenim uzorcima i četiri stanja u uzorcima koji su kaljeni i ozračivani. Ispitana je i diskutovana zavisnost ovih stanja od doze ozračivanja, kao i interakcija radijacionih i termalnih defekata.