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Irradiation and Annealing Behavior of *n*-Type Germanium and *n*-Type Silicon*

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Studies have been made on the irradiation induced changes in the conductivity and Hall coefficient of *n*-type germanium and *n*-type silicon. The irradiations were performed at 80°K using 5-Mev, 15-Mev and 45-Mev electrons. The number of defects formed, as measured by the observed carrier removal rates, depend logarithmically on the irradiation energy as predicted by the Seitz-Koehler model. Strong annealing processes were found to occur between 80°K and 350°K. These processes were distinct from annealing occurring after lower energy irradiations. The annealing processes also depended on the amount of irradiation the sample receives. Studies were also made on the effects of the electron bombardment rate at 30 Mev. None was observed initially although longer irradiations exhibited some differences.

1. Introduction

The energy dependence of the cross section for producing a displaced atom by relativistic electrons and the average energy imparted to this displaced atom are of interest. For charged particle irradiations the cross section for a Coulomb scattering, in which sufficient energy is imparted to displace the target atom, is considerably greater than the nuclear area and approaches a constant value at relativistic velocities. The distribution of the energy, E, imparted to the displaced atom is approximately proportional to $1/E^2$, and the average energy imparted to the displaced atoms increases logarithmically with the energy, E_0, of the incident irradiation. If the defects formed are simple non-interacting interstitial vacancy pairs (that is, the Seitz-Koehler model)[1] then the influence of the radiation on the properties of the material will also only depend logarithmically on E_0. Experiments have been performed at incident electron energies of 5, 15 and 45 Mev. Electrons in this energy range are expected to impart enough energy to the primary recoil so that the primary will be able to produce secondary displacements as well. Since the cross section for a moving atom to impart energy to other atoms of the lattice is equal to a large fraction of the atomic size, the secondary displacements will be produced within a fairly short distance of each other and some type of association or clustering is expected.

Studies were made on the irradiation response, and subsequent annealing, of the conductivity and Hall coefficient of *n*-type germanium and *n*-type silicon at 80°K. It is assumed that the carrier removal rate is proportional to the rate of defect formation, including both primaries and secondaries. A direct comparison can then be made with the predictions of the Seitz-Koehler theory. An experiment to determine the effect of high defect production rates in Ge will also be described.

2. Theoretical Background

It is useful to compare the amount of energy transferred to the germanium and silicon nuclei by electrons of various energies. The calculations are based on the Seitz-Koehler theory[1] which assumes non-interacting interstitial vacancy pairs. In their formulation, the expression for the maximum energy transfer, T_m, for a relativistic electron of energy E is $T_m(\text{ev})=560.8\ x(x+2)/A$ where A is the mass of the struck atom and $x=E/m_ec^2$ with $m_ec^2=0.511$ Mev. The average energy transfer is given by

$$\bar{E}=E_d(\log T_m/E_d-1+\pi\alpha)\ , \tag{1}$$

where $\alpha=Z_2/137$ and Z_2 is equal to the atomic number of the recoiling atom. The displacement energy E_d is chosen to be 30 ev for germanium and 25 ev for silicon. The resulting total number of displaced atoms is

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Table I. Energy transfer for electrons on silicon and germanium

Energy of Irradiation (Mev)		1	2	5	15	45
Maximum Energy Transfer (kev)	Si	0.15	0.46	2.3	18.5	158.0
	Ge	0.06	0.18	0.9	7.2	61.0
Average Energy Transfer (ev)	Si	30.0	56.0	96.0	148.0	200.0
	Ge	13.0	45.0	94.0	156.0	220.0
Total Number of Displaced Atoms per T_m	Si	1.9	2.1	2.8	3.8	5.0
	Ge	1.7	1.9	2.2	3.2	4.4

given by

$$N=\left(0.885+0.561\log\frac{x_m+1}{4}\right)\frac{x_m+1}{x_m} \qquad (2)$$

in which $x_m+1=T_m/E_d$. The results are summarized in Table I.

3. Experimental Results

For n-type germanium and silicon, the conductivity, carrier concentration and carrier mobility all decrease with irradiation. Evidently the defects formed are of the acceptor type which remove electrons from the conduction band leading to a decrease in the conductivity and carrier concentration. Also the defects must form new scattering centers, which cause a decrease in the carrier mobility.

For both As-doped and Sb-doped Ge (5×10^{15} donors/cm^3), carrier removal rates obtained from the Hall coefficient data are 2.4, 3.6 and 4.8 cm^{-1} for 5, 15 and 45 Mev electrons respectively. The theoretical ratio of the defect production rate between 5 and 15 Mev electrons is 1.45 and 2.0 respectively (refer to Table I). Our experimental results yield ratios of 1.5 and 2.0. For P-doped Si (3×10^{14} donors/cm^3), the theoretical ratio for 5 and 45 Mev electrons is 1.8 (refer to Table I) and our results yield 1.9 (0.85/0.45). This excellent agreement between theory and experiment implies that electrons in this energy region form the same type of defect.

Annealing studies can also be used to determine the type of defect formed. The simpler damage will anneal out at lower temperatures than the associated defect, if defect migration is important in the annealing, since it is improbable that the associated defects will be mobile until high temperatures. On As-doped and Sb-doped Ge and floating zone-refined P-doped Si, pulse annealing studies to 350°K have revealed that there are only minor differences between the effects of various energy electrons. It is of interest to note that all the annealing reported here takes place between 80°K and 350°K whereas, for lower energy irradiations[2], most annealing occurs above room temperature. This may occur because the interstitial-vacancy pairs formed by 5-Mev electrons at 80°K have a wider separation than those formed by 1-Mev electrons and are therefore stable at these temperatures.

For As-doped Ge at temperatures between 80°K and about 200°K, the carrier concentration and mobility anneal along the irradiation curve; this could be interpreted as simple interstitial-vacancy annealing. Above this temperature range the mobility anneals at a much faster rate than the carrier concentration. These data, along with the irradiation behavior, are summarized in Fig. 1

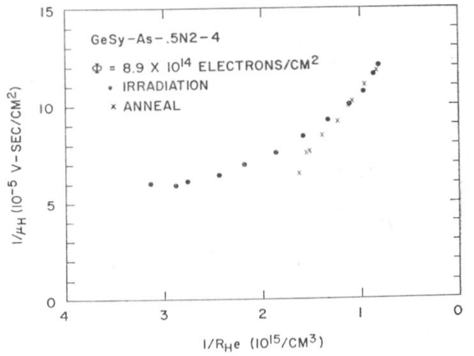

Fig. 1. Reciprocal Hall mobility *vs* carrier concentration for a 5-Mev irradiation and subsequent anneal for a heavily irradiated sample.

where the reciprocal Hall mobility is plotted *vs* the carrier concentration, after the manner of Brown, *et al.*[2] Although the data shown are for a 5-Mev irradiation, they are representative for all energies. The suggested interpretation[2),3)] of the behavior is that an acceptor defect associates with the original donor impurity causing a mobility anneal without a corresponding carrier anneal.

The initial part of the irradiation $1/\mu$ *vs* n curve can be interpreted on the basis of a singly-charged acceptor state. For longer irradiations (small n, large $1/\mu_H$), this is no longer the case nor can it be explained on the basis of a doubly charged acceptor. Experimentally, large trapping effects are observed in our samples in this region. It would appear that the traps, either initially present or radiation induced, play a predominant role here. These traps must also be charged, because the mobility is influenced to a much larger extent than the carrier concentration. A strange annealing phenomenon is observed if the radiation is stopped before the trapping region is reached. In Fig. 2 the results for a 5-Mev radiation are shown. The annealing behavior is significantly different although, after the final anneal, about the same amount of the

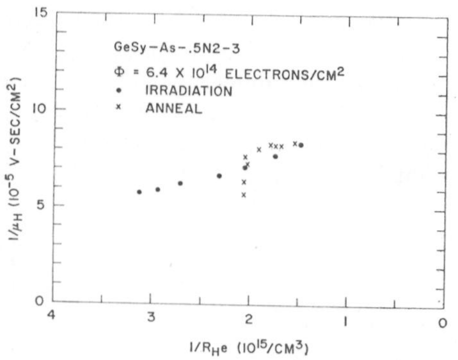

Fig. 2. Reciprocal Hall mobility *vs* carrier concentration for a 5-Mev irradiation and subsequent anneal for a lightly irradiated sample.

mobility and carrier concentrations have annealed as for the more heavily irradiated samples. There is also a certain amount of non-reproducibility among the annealing results of these lightly irradiated samples. The same type of behavior has been observed for Sb-doped Ge and P-doped Si.

Annealing studies have been performed on P-doped and As-doped Si and no significant differences are observed. The general annealing is similar to that occurring for As-doped Ge. Up to 150°K the irradiation and annealing curves coincide; however, above this point the mobility anneals at a more rapid rate than the carrier concentration. The interpretation is different, however, in that there is other evidence that the vacancy in floating zone-refined silicon associates with the original donor[4]. This indication is borne out by our results because, if the interstitial were moving, it would be difficult for it to associate with the larger arsenic donors.

An experiment to determine the effect of high defect production rate in Ge was also performed. Three samples with initial donor concentration of 10^{16} As/cm^3, were irradiated by 30-Mev electrons at 80°K with average currents during the 4.5-μ sec irradiation pulses of 2, 30 and 105 ma/cm^2. The result are shown in Fig. 3. The initial carrier removal rates are the same, but a difference is seen when the trapping region is reached.

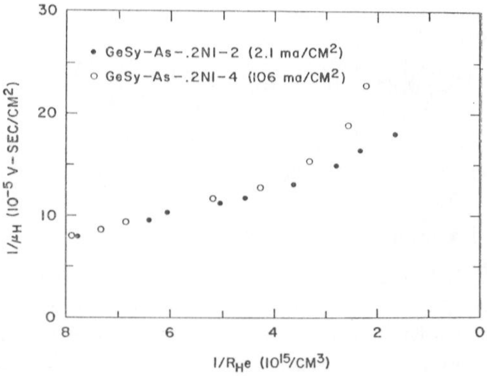

Fig. 3. Reciprocal Hall mobility *vs* carrier concentration for samples irradiated with 2.1, 30, and 106 ma/cm² (The circles (○) refer to 106 ma/cm² irradiations and the dots (●) refer to the 2.1 and 30 ma/cm² irradiations.)

Perhaps at 30 Mev the defect responsible for the rate effects observed with lower irradiation energies[5),6)] (0.5 to 1 Mev) is not formed. It is interesting, however, that in the trapping region there is a charge effect associated with the amount of current with which the sample is irradiated.

Conclusions

The interpretation of the irradiation response and subsequent annealing of the defects produced at 80°K in n-type germanium and n-type silicon by relativistic electrons with energies between 5 Mev and 45 Mev indicate that the same type of defect is being formed in this range. Furthermore, these defects cannot be very complex in nature because a large amount of annealing occurs below room temperature and some of this annealing clearly depends on defect migration. The temperature range in which the annealing takes place also is much lower than that observed by other investigators using 1 Mev electrons. Neither was the initial defect production rate found to depend on the number of electrons the sample received per pulse, as in the 1 Mev experiments performed by others. If different types of defects are being formed by 1 Mev and 5 Mev electrons, as our results would indicate, this region should be more carefully explored, especially with the use of techniques and equipment sensitive to the microscopic properties of solids, such as electron spin resonance equipment.

The difference in annealing characteristics which depend on the amount of irradiation the samples receive is difficult to explain. It is not at all clear either whether the charge trapping processes observed have any influence on the annealing.

References

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DISCUSSION

Vook, E. L.: It is interesting that your effective threshold displacement energy seems to be 25 ev which is much higher than the incipient threshold previously reported. This agrees with our results for InSb and GaAs. My second comment is that the annealing of length change in deuteron irradiated germanium together with the results of electron irradiation show that interstitial clusters break up at 200°K which would produce an annealing in mobility not accompanied by an annealing in carrier concentration in agreement with your results.

Crawford, J. H., Jr.: Curtis has observed a minority trap at 0.17 ev in *n*-type Ge irradiated with Co^{60} γ-rays near room temperature. It was not clear from your paper whether the traps you observed annealed well below room temperature or not. If such annealing of traps does occur, it would indicate that an additional trap or set of traps is produced in your irradiation, which are less stable than those observed by Curtis. Did such annealing occur?

Wikner, E. G.: Trapping is still observed after a room temperature anneal. Since no studies have been made on the energy level of the traps, it cannot de said whether the traps formed by our irradiations are the same as your observations or whether the trapping state is affected by the anneal.