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The Effect of Fast Neutron Irradiation on the Recombination of Electrons and Holes in Germanium Crystals

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It is found that irradiation of germanium crystals with fast neutrons leads to an increase of the rate of volume recombination. The probability of recombination trapping of charge carriers by defects which appear as a result of irradiation is estimated. The strong effect of neutron irradiation on the lifetime of carriers can be used to record and measure integral fluxes of fast neutrons.

1. STRUCTURAL DEFECTS OCCUR in crystals under the influence of fast neutrons. The disturbance of the periodic structure changes the mechanical, electrical, and optical properties of the crystals. The changes of the electrical conductivity of germanium and of silicon subjected to the action of fast neutrons have been studied by many investigators, in particular Lark-Horowitz[1] and Fan [2], and have been utilized in a dosimeter proposed by Cassen[3].

Structural defects in crystals of semiconductors serve as recombination trapping centers for electrons and holes. The effective capture cross-section for holes by defects formed in the bombardment of germanium by electrons with energy above 0.5 Mev was estimated in our work[4] and came to $0.7 \cdot 10^{-16}$ cm^2, *i.e.*, close to the capture cross-section of thermoacceptors, according to the data of Kalishnikov and Ostroborodova[5].

The purpose of the present work is to estimate the effect of germanium-crystal neutron-produced lattice defects on the recombination of electrons and holes.

The number of germanium nuclei displaced owing to scattering of fast neutrons by the lattice sites as a result can be calculated on the basis of data on the transverse cross-sections for the interaction of fast neutrons with Ge nuclei[6]. According to Ref. 6, the transverse cross-sections for the scattering of germanium nuclei by fast neutrons with energy E_n in the range 0.4 – 3.5 Mev are respectively

E_n, Mev	0.4	1.0	1.5	2	3.5	14
T, barns	5.5	5.0	3.5	3.3	3.5	2*

As a consequence of the fact that the energy transferred to a germanium nucleus by fast neutron can amount to a significant figure ($0.054\ E_n$), secondary and higher atomic displacements can occur. Ref. 7, gives a method of calculating the total number $\bar{N}_d$ of Ge atoms displaced as a result of primary energy transfer. Allowing for the possibility that an

*The atlas of transverse cross-sections contains no data on σ_t for E_n = 14 Mev. The value 2×10^{-27} cm^2 is obtained by extrapolation. The accuracy of the estimate is not lower than ± 50%.

incident atom takes up the position of a displaced atom[2], $\overline{N}_d$ is expressed as

$$\overline{N}_d = [E_m / (E_m - E_d)] \times [0.766 + 0.352 \ln (E_m / 4E_L)],$$

where E_m is the maximum energy which a fast neutron transfers to a nucleus; $E_m = E_n\, 4mM/(m + M)^2$, where m is the mass of the neutron and M is the mass of the germanium neucleus; E_d is the minimum energy which must be transferred to a Ge atom in order to displace it from a lattice site. According to data obtained in experiments on bombarding germanium with fast electrons, the energy E_d is 22.5 ev[8], where only defects which are stable at room temperature are taken into account. In the following it is assumed that the effect of self recovery of defects during the time of irradiation can be disregarded.

For neutrons with energies E_n from 0.01 to 14 Mev, $\overline{N}_d$ in a germanium crystal comes to

E_n, Mev	0.01	0.05	0.1	0.5	1	5	10	14
N_d	1.46	1.97	2.22	2.78	3.03	3.59	3.83	3.95

The range of the germanium atoms in the crystal is small. On account of this, groups of vacant lattice sites and interstitial atoms situated close to one another arise during neutron bombardment along with the usual isolated Frenkel defects.[9]

2. We carried out experiments on fast neutron bombardment of single crystals of *n*-type germanium with specific resistances of 24 and 35 Ω cm. and initial bulk lifetimes at room temperature equal to 650 ± 50 and 1400 ± 200 microseconds. Crystals were obtained in our laboratory by a drawing technique. Both crystals were irradiated simultaneously. They were placed at equal distances (2.0 ± 0.4 cm.) from the tritium target which served as the source of neutrons.

The temperature of the crystals during the time of the experiment did not exceed room temperature by more than 10°C. In one of the specimens studied, the lifetime of the charge carriers was measured immediately before and after irradiation. A bridge method[10,11] was used for the measurement. The lifetime τ_0 of the carriers before the beginning of irradiation was 1400 ± 200 μ sec; after irradiation it fell to 420 ± 10 μ sec.

In the second specimen a p–n junction was obtained by fusing on some indium. The measured quantity, from which it was possible to judge the change in recombination rate, was in this case the short-circuit current between the p and n regions, flowing upon illumination of the opposite face by a light flux of constant intensity (see Fig. 1). The results of the measurements are given in the table.

Dark current, which could have been due to ionization in the germanium on account of the γ background and of the rearrangement of the electron shells of the displaced atoms, was not observed

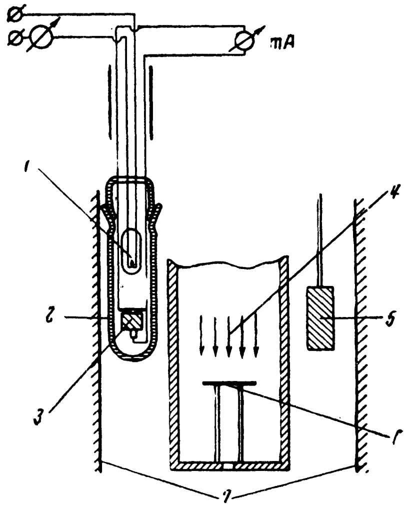

FIG. 1. 1—lamp, 2—glass ampoule, 3—germanium photocell, 4—deuteron beam,, 5—germanium crystal, 6—tritium target, 7—lead.

Number of neutrons per cm^2, $n_n \times 10^{11}$	Number of defects per cm^3.	Short circuit current I_{sc} ma.
0	0	0.87
0.45	$0.15 \cdot 10^{10}$	0.80
0.95	$0.34 \cdot 10^{10}$	0.735
1.41	$0.50 \cdot 10^{10}$	0.708
1.95	$0.69 \cdot 10^{10}$	0.649

Number of neutrons per cm^2, $n_n \times 10^{11}$	Number of defects per cm^3.	Short circuit current I_{sc} ma.
2.40	$0.85 \cdot 10^{10}$	0.615
3.23	$1.15 \cdot 10^{10}$	0.578
3.80	$1.35 \cdot 10^{11}$	0.540
4.37	$1.55 \cdot 10^{10}$	0.510
5.0	$1.78 \cdot 10^{10}$	0.481

with apparatus having a sensitivity of 10^{-7} amp. The mean intensity of the 14-Mev neutron flux amounted to ~ 1.10^{7}.neutrons/sec. per square cm. of surface of the specimen. Experiments were carried out with a set-up used neutron spectrometry[12]. The additional flux of the neutrons scattered and slowed down by the lead surrounding the tritium target was taken into account in the calculation of the total number of defects formed in the crystals.

Owing to the fact that with the comparatively small integral neutron fluxes used in our experiments, the concentration of carriers could be considered constant, the initial lifetime τ_0, the lifetime after irradiation τ, and the concentration of formed defects n are connected by a simple relation[4]:

$$(1/\tau)-(1/\tau_0) \doteq n_d v_p \theta.$$

Considering that the defects formed trap carriers separately, i.e. act on the recombination independently of one another, then taking the thermal speed of the holes as $v_p = 1.1 \times 10^{7}$ cm/sec, we obtain the value of the cross-section for recombination trapping θ.

$$\theta = (1 \pm 0.5) \times 10^{-15} \text{ cm}^2.$$

For an estimate of the change of the recombination rate from the drop of the short circuit current, the following considerations were used. Let us examine the scheme shown in Fig. 2, the crystal with the fused-on p–n junction having a thickness d. The

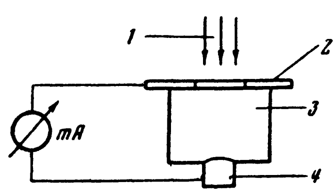

FIG. 2. 1—light, 2—nickel collar, 3—n-type germanium, 4—indium.

generation of surplus carriers by the light proceeds in a layer close to the surface, thin in comparison with d. Let the total number of holes generated by the light in unit time be G. The short circuit current I_{sc} can be expressed as $I_{sc} = qaG$, where q is the electron charge, and a the effective quantum yield or collection coefficient of the carriers[14]. In the one-dimensional case[15], under the condition that the reciprocal value of the linear absorption coefficient of light $1/k \gg 1/L$; $1/k \gg s/D_p$, where L is the diffusion length of the holes, s is the rate of surface recombination, and P_p is the diffusion coefficient, we have

$$a = \frac{2}{(1-sL/D_p)e^{-d/L}+(1+sL/D_p)e^{d/L}}$$

The formula for a can be reduced to the simple expression $a = Ae^{d/L}$, where A = const., under the following conditions: $d/L \gtrsim 2$, $L \lesssim 5 \times 10^{-2}$cm, and and with surface recombination rates such as are obtained on etching germanium in hydrogen peroxide. For constant G, the ratio of I_{sc} after irradiation to the original value $I^0_{sc} = qa_0G$,

$$I_{sc}/I^0_{sc} = a/a_0.$$

Calculating a_0 with a reasonable assumption about the value of s established by means of a surface treatment, on the basis of known data on the original diffusion length L_0 in the non-irradiated material, one can determine a, and consequently L and τ, knowing the measured ratio I_{sc} to I^0_{sc}. With the lower limit of possible values for s equal to 150 cm /sec, θ turns out equal to 1.05×10^{-15} cm^2; for s = 600 cm/sec. $\theta = 1.29 \times 10^{-15}$ cm^2.

The dependence of the reciprocal value of the short circuit current on the integral radiation dose is presented in Fig. 3, calculated on the basis of the last formula and experimental values for L_0 and I^0_{sc}.

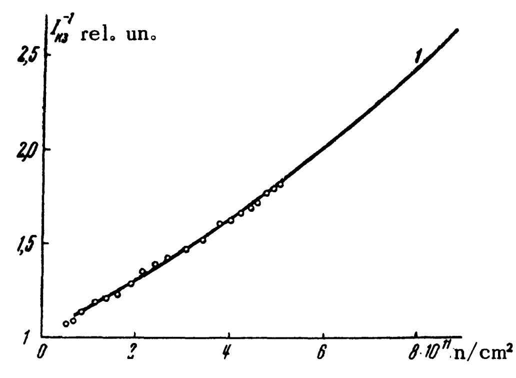

FIG. 3. 1—s = 300 cm/sec; $\theta = 1.1 \times 10^{-15}$ cm^2; ○—experimental points. The ordinate is labeled I^{-1}_{sc} (relative units) and the abscissa in labeled neutrons/cm^2.

The relation between $1/I$ and the integral radiation dose can be utilized for the determination of dosage of fast neutrons starting with neutron fluxes of the order of 5×10^{6} neutrons/cm^2 sec. Dosimeteric apparatus, based on the change in lifetime of carriers in germanium crystals can have a sensitivity of Cassen's dosimeter[3], based on the measurement of electric conductivity of crystals. The sharp difference in recombination trapping cross-sections for the cases of defect formation by fast neutrons and β-particles found in our experiments is explained, apparently, by the high hole-trapping efficiency of an agglomeration of defects.

On the basis of available data one can not also exclude the possibility of local melting of the germanium upon displacement of a germanium nucleus, to which a neutron transfers an energy of several hundred kev, inside the crystal. Rapid cooling of a small region[13] can lead to the appearance of additional defects of the crystal lattice which are not taken into account in the Snyder-Neufeld theory[7] which we used to calculate the number of displaced atoms.

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