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Abstract

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EXCITATION OF ELECTRONS IN GERMANIUM BY POTASSIUM IONS

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Fast heavy particles, moving in a substance, lose their energy in elastic collisions with lattice atoms and in the excitation of bound electrons into the conduction band. It is usually assumed that, when the velocity of the primary particle is less than the velocity of the electron in the hydrogen atom, $v_0 = 2.2 \cdot 10^8$ cm/sec, the probability of ionization rapidly decreases as the particle slows down and at $v \sim {}^1/_{20} v_0$ becomes practically equal to zero [(1)]. On this basis it is often supposed that ions (or atoms) with velocities $v < v_0$, in passing through a substance, lose their energy only in elastic collisions with lattice atoms, as a result of which the latter are displaced from their equilibrium positions into interstitial sites. Such an assumption is made, in particular, in the theoretical treatment of ion implantation and cathode sputtering in works [(2–4)]. At the same time, a study of the kinetic ejection of electrons by ions shows that for potassium ions, for example [(5,6)], appreciable emission of excited secondary electrons begins for refractory metals at $E = 1.5 \div 1.7$ keV, and for germanium already at $E \simeq 0.5$ keV, i.e., at $v \sim {}^1/_{25} v_0$ and $v \sim {}^1/_{44} v_0$, respectively. It is obvious that appreciable excitation of electrons into the conduction band can be observed at still lower ion velocities, and the lower, the narrower the forbidden-energy interval ΔE, equal for germanium to 0.75 eV. A study of the additional conductivity excited in a solid by fast ions will, it seems to us, help to investigate in more detail the mechanisms of slowing down particles with velocities $v < v_0$.

We investigated the change in the conductivity of a germanium single crystal under bombardment by potassium ions with energies from 400 to 10,000 eV ($v_{\max} \sim 0.1 v_0$), caused by excitation of electrons of the valence band. As targets we used plates measuring $19 \times 13 \times 0.3 \div 0.8$ mm, cut from an n-type germanium single crystal ($\rho = 35$ ohm $\cdot$ cm; $L = 2.5$ mm). Before being mounted in the apparatus, the targets were etched first in CP-4, then in 30% H_2O_2, and washed in boiling distilled water. To create nonrectifying contacts, aquadag was applied to the end surfaces of the specimens, after which the targets were fastened in special tantalum clamps that made it possible to pass currents through the specimen up to 50 A. Owing to this it was possible to heat the targets to temperatures close to the melting point of germanium. After such high-temperature treatment, the conductivity of the germanium became hole-type, and the aquadag-

Fig. 1 and Fig. 2 graphs

Figure 1: Fig. 1 and Fig. 2 graphs

germanium contacts nonrectifying. Probe measurements established that the resistance of the contacts did not exceed $1 \div 2\%$ of the total resistance of the specimen. The change in the type of conductivity could evidently be caused both by the removal from, or introduction into, the specimen of new impurity atoms, and by the formation of thermoacceptors during rapid cooling. In our experiments the cooling time of the targets to room temperature was usually chosen to be $1 \div 1.5$ h.

The investigation of the conductivity excited by potassium ions was carried out as follows. In the germanium plate, connected in series with the input resistance of a wide-band amplifier, there was created

a constant electric field from an external voltage source. After this, a beam of potassium ions, modulated by rectangular pulses of duration from 10 to 50 μsec, was directed onto the germanium surface. The nonequilibrium carriers produced by the potassium ions, moving in the electric field of the sample, create an additional current through the input resistance of the amplifier. After amplification the signal is fed to an S1-8 oscilloscope. In this way it is possible not only to record the total change in the conduction current through the sample, but also to determine

Fig. 1. $I_1^- = 0.5$ μa; $\varepsilon = 1.39$ V/cm;
$\tau \simeq 18$ μsec; $R_{\text{sample}} = 800$ Ω

Fig. 2. $I_1^+ = 0.15$ μa; $\varepsilon = 3.32$ V/cm.
1 –$\tau \simeq 4.5$ μsec, $R_{\text{sample}} = 420$ Ω;
2 –$\tau \simeq 16$ μsec, $R_{\text{sample}} = 800$ Ω;
3 –dependence γ

the law of its variation with time. The repetition frequency of the pulses was usually chosen within the range $2 \div 50$ sec^{-1}, and the intensity of the ion current was $\sim 0.1 \div 50$ μa. All measurements were carried out at a residual-gas pressure in the apparatus of $1 \cdot 10^{-6}$ mm Hg.

We first performed preliminary experiments to study the conductivity excited in germanium by electrons with energies from 400 to 10,000 eV. As was to be expected, directing an electron beam onto the germanium surface is accompanied by an increase in the electric current through the sample, and the rise and decay fronts of the induced-conductivity current are exponentials. It turned out that the time constants τ of the rise and decay of the pulses for samples not subjected to preliminary heat treatment are $3 \div 5$ μsec. Heating the targets in vacuum to a temperature of 800° increases τ to $10 \div 20$ μsec. The slower the cooling of the samples, the larger are the values of τ, which evidently may be identified with the mean lifetime of nonequilibrium carriers in the semiconduc-

Fig. 3

Figure 2: Fig. 3

tor. All the results given below were obtained by us for preheated targets that were at room temperature at the time of measurement.

Figure 1 shows the dependence of the ratio of the steady-state current of excited conductivity ΔI_0 to the primary-electron current I_1^- as a function of their energy. The curve in Fig. 1 is well extrapolated to the origin (this becomes clear if one takes into account that only 3.7 eV on average is expended in the formation of an electron–hole pair ([7])).

When germanium was bombarded with potassium ions, an increase in the conductivity of the samples was likewise observed, and it turned out that the time constants τ are approximately the same for both kinds of primary particles. Typical dependences of $\Delta I_0/I_1^+$ on the ion energy are presented in Fig. 2.

Curve 1 was obtained for a target which, after a 5-minute anneal at $t = 800°$, was cooled within several minutes to room temperature. The specimen was then heated again and slowly cooled by gradually reducing the filament current from 17 A to zero over 1.5 h. The results obtained after this are shown by curve 2. The smaller values of $\Delta I_0/I_1^+$ for t can be explained by the fact that, under rapid cooling, the concentration of thermoacceptors proves to be larger, which leads to a decrease in the mobility and lifetime of nonequilibrium carriers. Figure 2 also shows the dependence of the ion–electron emission coefficients γ on the energy of potassium ions (curve 3), obtained simultaneously with data 2.

The dependence $\Delta I_0/I_1^- = f(E)$ in Fig. 1 was measured for this same target after all the data presented in Fig. 2 had been obtained. The magnitude of the induced-conductivity current under bombardment both by electrons and by ions depends linearly on the electric-field strength ε in the specimen (see Fig. 3). Therefore, in order to compare the excitation of electrons into the conduction band under the action of K^+ ions and electrons, one should compare the quantities $\Delta I_0/I_1\varepsilon$. From the graphs presented it is easy to establish that

$$\left(\frac{\Delta I_0}{I_1^+\varepsilon}\right)_{K^+} = \beta\left(\frac{\Delta I_0}{I_1^-\varepsilon}\right)_{e^-},$$

where $\beta = f(E)$ and is, in particular, equal to 0.135, 0.114, 0.071, and 0.032 for energies of 8, 3, 1, and 0.5 keV, respectively. It should be noted that prolonged exposure of the targets in the forevacuum did not significantly affect the values of $\Delta I_0/I_1$, and therefore, apparently, one may assume that the data of Figs. 1 and 2, 2 refer to one and the same state of the specimen.

Fig. 3. $I_1^+ = 0.15$ μA; $E = 5$ keV; $\tau = 10$ μs; $R_{\text{sample}} = 250$ Ω

Fig. 4

Figure 3: Fig. 4

Figure 4 shows the dependence of $\Delta I_0/I_1^+$ and γ on the number of potassium ions N incident on the target surface. As N increases, a noticeable decrease in $\Delta I_0/I_1^+$ occurs (with τ simultaneously decreasing from 10 μs at $N = 10^{11}$ to 5 μs at $N = 4 \cdot 10^{12}$). When N reaches $\sim 10^{13}$ (the cross-sectional area of the ion beam is ~ 0.6 cm^2), $\Delta I_0/I_1^+$ becomes close to zero, while the values of γ begin to increase, reaching at $N \sim 5 \cdot 10^{13}$ a new stationary value.

Fig. 4. $I_1^+ = 0.3\,\mu$A; $E = 5$ keV; $R_{\text{sample}} = 250\,\Omega$; $\varepsilon = 5$ V/cm; 1—$\Delta I_0/I_1^+$; 2—γ

It should be noted that the results presented in Figs. 2 and 3 were obtained for targets that had not been subjected to preliminary irradiation. The number of particles incident on the specimen during the measurements did not exceed 10^{11}.

It may be hoped that a detailed study of the conductivity excited by relatively slow atomic particles in semiconductors and dielectrics will make it possible to clarify more precisely the question of the relation between the ionization cross section and the cross section for elastic collisions with lattice atoms in the range of velocities below v_0. On the other hand, comparison of the values of γ and of the total number of electrons excited into the conduction band will make it possible to judge the probability of secondary particles escaping into vacuum.

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References

1. N. Bohr, *The Passage of Atomic Particles Through Matter*, IL, 1950.

2. K. O. Nielsen, *Electromagnetically Enriched Isotopes and Mass-Spectrometry*, London, 1956.

3. J. A. Davies, G. A. Sims, *Canad. J. Chem.*, **39**, No. 3, 601 (1961).

4. F. Keywell, *Phys. Rev.*, **97**, No. 6, 1611 (1955).

5. N. N. Petrov, *Fiz. tverd. tela*, **2**, issue 5, 949 (1960).

6. I. A. Abronin, *Fiz. tverd. tela*, **3**, issue 2, 588 (1961).

7. V. S. Vavilov, *Usp. fiz. nauk*, **75**, issue 2, 263 (1961).

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