ENERGY OF IONIZATION BY ELECTRONS IN SILICON CRYSTALS

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THE mean ionization energy ϵ is one of the fundamental parameters which determines the efficiency with which the energy of nuclear radiation is transformed to electrical energy by semiconducting p-n junctions,[1] as well as the counting efficiency of crystal counters.

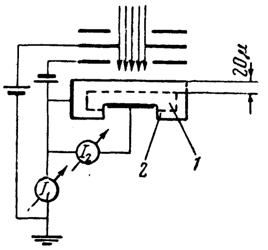

FIG. 1. Diagram of the experiment for finding ϵ in silicon. 1 — p-type silicon; 2 — n-type silicon (doped with phosphorous).

A determination of ϵ in silicon single crystals for ionization by electrons with energies between 10 and 30 kev has been performed in the same way as previously in germanium single crystals, by measuring the "multiplication" factor for current carriers.[2] We measured the ratio of the excess carrier current through the p-n junction, due to generation of electron-hole pairs by high (primary) electrons, to the primary electron current. The recombination losses were evaluated by an independent determination of the collector coefficient α, which depends on the geometry of the irradiated crystal, on the surface recombination rate of nonequilibrium carriers, and on their diffusion length.[3]

In these experiments we used p-type silicon single crystals with p-n junctions obtained by thermal diffusion of gaseous phosphorous.[4] The irradiation was performed from the direction of the n-type material, perpendicular to the crystal surface and parallel to the p-n junction (see Fig. 1).

Because of the low carrier diffusion lengths occurring in silicon after thermal diffusion of impurities to obtain a p-n junction, we used a crystal whose junction is located about 20 μ from the irradiated surface. We found that when the excess carriers are excited in these samples by monochromatic light incident on the same surface as struck by the electrons, α depends strongly on λ, and therefore also on the depth at which electron-hole pairs are produced.[4]

It was established that in contradistinction with germanium, α does not change during evacuation of the system (from atmospheric pressure to 10^{-7} mm Hg) or during electron bombardment. This is due to the occurrence of a thin, but quite firm film of quartz on the silicon surface. The thickness of this film, which lowers the initial energy of the electrons entering the silicon, was evaluated from its breakdown potential and was found to be between 0.5 and 0.7 μ. Ion bombardment led to diminution of α due to an increase in the surface recombination rate.

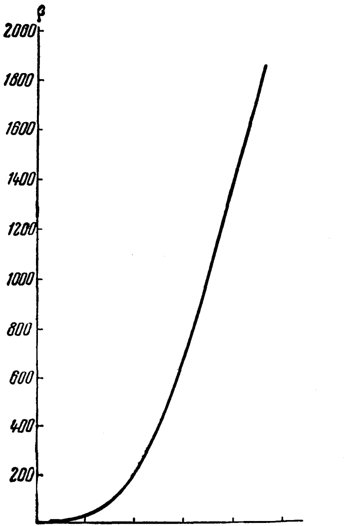

FIG. 2. The "multiplication" factor of electrons in a silicon as a function of the primary electron energy.

Figure 2 gives the experimental dependence of the "multiplication" factor β for electrons in silicon (without accounting for recombination losses) on the primary electron energy V from 1.5 to 30 kev. The shape of the curve indicates the existence of a "dead layer" on the surface. The electrons lose part of their energy in this layer, but it is transparent to light. We evaluated the distribution of ionization losses through the depth into the crystal, accounting for scattering of the primary electrons in the crystal, from the data calculated by Iurkov[5] using Spencer's method.

We evaluated ϵ for each value of V by comparing β for this energy with the value of α for light whose wavelength is such that the inverse of the linear absorption coefficient is equal to the mean free path of the electrons of given energy. The ratio α/β, which is proportional to ϵ, should not depend on the depth at which the ionization takes place in a silicon crystal. On this basis, the $\beta(V)$ curve was used to evaluate the thickness of the quartz layer. This was found to be 0.6 μ, which agrees with the data obtained from the breakdown potential.

The value of ϵ we have obtained is 4.2 ± 0.6 ev.

The authors express their gratitude to Professor B. M. Vul for many valuable remarks.

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FINE STRUCTURE OF ELECTRON PARAMAGNETIC RESONANCE OF THE Fe^{3+} IONS IN THE Al_2O_3 LATTICE

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THE electron paramagnetic resonance spectrum of Fe^{3+} ions, introduced isomorphically into the Al_2O_3 lattice to an iron concentration of 10^{-3}, has been investigated at room temperature at three frequencies in the range from 2.5×10^{10} to 4×10^{10} cps and for magnetic fields up to 16.2 kilo-oersteds. It was found that the Fe^{3+} ions form two nonequivalent systems each of which gives a spectrum of five resonance lines. When the external magnetic field is applied parallel or perpendicular to the crystal axis, both spectra overlap. This indicates that the crystal axis fields lie in the same direction for both ion systems. The nonequivalence is due to the difference in the directions of the cubic field axes. For orientations far from the "parallel" and "perpendicular" ones, the lines of each system broaden and a weak splitting into two components is observed. This indicates that each nonequivalent ion system consists of two subsystems with somewhat differently directed cubic crystal field axes.

In order to interpret the spectrum observed, we used a Hamiltonian of the form[1]

$$\hat{H} = g\beta (H_z\hat{S}_z + H_x\hat{S}_x + H_y\hat{S}_y) + \frac{1}{6} a [\hat{S}_\xi^4 + \hat{S}_\eta^4 + \hat{S}_\zeta^4 - \frac{1}{5} S(S+1)(3S^2+3S-1)]$$
$$+ D\left[\hat{S}_z^2 - \frac{1}{3} S(S+1)\right] + \frac{1}{180} F [35\hat{S}_z^4 - 30S(S+1)\hat{S}_z^2 + 25\hat{S}_z^2 - 6S(S+1) + 3S^2(S+1)^2],$$

where g is the spectroscopic splitting factor, β is the Bohr magneton, S is the electron spin and is equal to $5/2$ for Fe^{3+}, $\hat{\mathbf{S}}$ is the spin operator, **H** is the magnetic field strength, a is the cubic lattice constant, and D and F are the second and fourth degree trigonal field constants. The $\xi\eta\zeta$ coordinate system is constructed of the cubic crystal field axes, and the Z axis lies along the direction of the trigonal axis which is also the (111) axis of the $\xi\eta\zeta$ coordinate system.

The formulas for the fields of the observed lines given by Bleaney and Trenam[1] (which are valid for strong fields when $g\beta H \gg a$, D, and F) are inapplicable because of the relatively high value of D. Therefore the energy levels were evaluated by perturbation theory, to second order in the case of the "parallel" orientation, and to first order in the case of the "perpendicular" orientation. The unperturbed Hamiltonian was taken as

$$\hat{H}_0 = g\beta (H_z\hat{S}_z + H_x\hat{S}_x + H_y\hat{S}_y) + D\left[\hat{S}_z^2 - \frac{1}{3} S(S+1)\right].$$

For the "parallel" orientation the formulas for the $\Delta M = \pm 1$ transitions are