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1963

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Abstract

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LOW-TEMPERATURE BREAKDOWN IN p-GERMANIUM UNDER UNIAXIAL COMPRESSION

In studying low-temperature breakdown in thin layers of germanium, we, together with É. I. Zavaritskaya, found that in individual samples the breakdown voltage was less than the usual value of the ionization potential of impurity atoms ([1]). Since a possible cause of this phenomenon could be inhomogeneous deformations arising in some samples, we investigated the dependence of the breakdown voltages in germanium under uniaxial compression.

Uniaxial compression breaks the symmetry of the crystal lattice and, as Pikus and Bir showed, leads to the lifting of the degeneracy present in the valence band of germanium at the value of the wave vector $k = 0$ ([2]).

From the theory developed in ([2,4]) it follows that, for sufficiently large deformations and low temperatures, the splitting between the bands under compression along the [100] axis is

$$E_s = -2b(1+r)\varepsilon_{100},$$

and under compression along the [111] axis,

$$E_s = -2d(1+r')\varepsilon_{111}/\sqrt{3},$$

where the Poisson coefficients are

$$r = -\frac{S_{12}}{S_{11}},$$

$$r' = -\frac{S_{11}+2S_{12}-\frac{1}{2}S_{44}}{S_{11}+2S_{12}+S_{44}},$$

and b and d are deformation-potential coefficients.

Fig. 1. Dependence of the ionization potential of indium in germanium on pressure

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Figure 2

Figure 2: Figure 2

In paper ([3]), Price calculated the ground state of acceptor atoms, using Bloch functions of the split bands, and represented the dependence of the ionization potential W_i on the deformation ε in the form

$$W_i = W_\infty + \frac{W_1}{\varepsilon} + \dots, \tag{1}$$

where W_∞ is a constant equal to the ionization potential at infinite removal of the split bands; W_1 is a constant determined from the calculation.

As follows from (1), W_i decreases with increasing pressure; therefore, the study of low-temperature breakdown under these conditions represents a rare and still almost unused possibility of tracing, in one and the same material, the dependence of the breakdown field strength on the magnitude of the ionization potential ([5]).

The dependence of the ionization potential on deformation was studied by Hall by measuring the Hall effect at low temperatures ([4]). Similar measurements were carried out by us for our germanium samples. At room temperature the material had $\rho = 16$ ohm • cm. In a separate determination of the donor and acceptor concentrations, it was found that in our samples $N_a = 3.3 \cdot 10^{14}$ cm^{-3} and $N_d = 8 \cdot 10^{13}$cm^{-3}.

The results of calculating the ionization potential W_i as a function of pressure along the [111] axis from our measurements of the Hall effect at different

temperatures are shown in Fig. 1. The breakdown voltages were measured under compression along the axes [111] and [100].

From the current-voltage characteristics measured at different pressures, one can determine rather accurately the voltage at which a steep increase in current begins, equate it to the breakdown voltage, and calculate the breakdown field strength E. The dependence of E on pressure is shown in Fig. 2a for compression along the [111] axis and in Fig. 2b for compression along the [100] axis.

Fig. 2. Dependence of the breakdown field strength on compression: a—along the [111] axis, b—along the [100] axis. Temperature 5.2°K.

Figure 3

Figure 3: Figure 3

The constants W_∞ and W_1 of equation (1) can be determined from the curve $W_i = \varphi\left(\frac{1}{\varepsilon}\right)$ in the region of large ε, which gives the values $W_1 = 5 \cdot 10^{-6}$ V and, on extrapolation to $\frac{1}{\varepsilon} = 0$, the value $W_\infty = 6.1 \cdot 10^{-3}$ V.

According to the data of work ([4]), the coefficient of the deformation potential

$$d = -\sqrt{3}\, Z_0 / 2(1 + r') W_1, \tag{2}$$

where $Z_0 = 80.1 \cdot 10^{-6}$ V^2 and r'—the Poisson coefficient for compression along the [111] axis at low temperatures—is equal to 0.154 ([6]). Thus, according to the value of W_1 found, the deformation potential for pure shear in germanium is $d = -12$ V. The values of W_1 found by us and, correspondingly, d, differ somewhat from those given in Hall' s work, possibly because of the different quality of the samples.

Low-temperature breakdown, as is known, is caused by impact ionization of the excess impurity. It may be assumed that the breakdown field strength is reached at such a value of the field when the energy accumulated over a mean free path reaches a certain magnitude, of the order of the ionization energy of the impurity atoms. As Chuenkov showed ([7]), in low-temperature breakdown

$$E l_{ak} \sim W_i^{5/4}, \tag{3}$$

where l_{ak} is the electron mean free path in scattering by acoustic lattice vibrations.

Fig. 3. Dependence of the breakdown field strength on the ionization potential

Figure 3 shows the dependence of the breakdown field strength E on W_i, and Fig. 4 shows the same data in the form of the dependence of E on $W_i^{5/4}$, only in the region of high pressures.

At high pressures, according to Hall' s measurements, $\mu =$ const, and consequently $l =$ const. Under these same conditions the splitting of the zones is so large that degeneracy can be neglected, and therefore the conditions are realized under which relation (3) should hold. Indeed, the results of the measurements at large ε satisfy (3), and upon extrapolation the straight line in Fig. 4 passes through the origin.

At sufficiently high pressures, as is evident from the data of Fig. 4, one may assume that the breakdown field strength

Fig. 4. Dependence of the breakdown field strength E on $W_i^{5/4}$.

Figure 4: Fig. 4. Dependence of the breakdown field strength E on $W_i^{5/4}$.

$$E = aW_i^{5/4} = aW_\infty^{5/4}\left(1 + \frac{W_1}{W_\infty \varepsilon}\right)^{5/4};$$

for $W_1/W_\infty\varepsilon < 1$

$$E = E_\infty + \frac{E_1}{\varepsilon},$$

where

$$E_\infty = aW_\infty^{5/4}, \quad E_1 = \frac{5}{4}\frac{W_1 E_\infty}{W_\infty},$$

whence

$$W_1 = \frac{4}{5}\frac{E_1 W_\infty}{E_\infty}. \tag{4}$$

E_1 and E_∞ are readily determined from the curve $E = \varphi\left(\frac{1}{\varepsilon}\right)$ in the region of large ε. According to our measurements, $E_1 = 1.85 \cdot 10^{-3}$ V/cm and $E_\infty = 1.27$ V/cm.

Thus, knowing W_∞, one can determine solely from measurements of the breakdown voltages the constant W_1 introduced by Price. Substituting into (4) the experimentally determined values E_1, E_∞, and W_∞, we find $W_1 = 7.1 \cdot 10^{-6}$ eV and, correspondingly, $d = -8.6$ eV.

As follows from works ([2],[3]), theoretically the results of measurements at high pressures are most simply interpreted, but the relative changes in the breakdown field strength are greatest in the region of low pressures. In this case, as shown in work ([4]), for calculating the ionization energy a good approximation may be

$$W_i = \frac{1}{2}\left[W_\infty - E_s + \sqrt{(E_s + W_\infty)^2 + 4Z_0}\right], \tag{5}$$

which is also confirmed by our measurements.

Fig. 4. Dependence of the breakdown field strength E on $W_i^{5/4}$.

However, to calculate the breakdown voltages at low pressures, one must also take into account the influence of the mobility, which, unlike in the region of high pressures, does not remain constant as the deformation changes.

As follows from (5),

$$W_\infty = W_0 - \frac{Z_0}{W_0}; \tag{6}$$

the values W_0 are usually known, while the values Z_0 have been calculated theoretically in the effective-mass approximation. Substitution of these values into (6) gives $W_\infty = 4.5 \cdot 10^{-3}$ eV and, correspondingly, $d = -11.6$ eV.

The authors express their gratitude to V. A. Chuenkov for valuable discussions.

Received
19 VIII 1963

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Note: Figure translations are in progress. See original paper for figures.