Interaction of impurities and dislocations in a doped, plasticly-deformed n-type germanium

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Discrete impurity conductivity in doped n-type Ge becomes anisotropic and vanishes in proportion to plastic deformation. This effect is interpreted as a manifestation of "congregation" of impurities at a dislocation in the process of deformation and "purging" of impurities from the basic crystal volume at a high dislocation density.

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This work was undertaken to study low-temperature conductivity in doped n-type Ge subjected to plastic deformation. Specimens were prepared using methods similar to those in Ref. 1 except that the original material was GES-01 germanium with $N_{\mathrm{Sb}} = 2.5\times 10^{16}$ cm^{-3}.

Figure 1 shows the relationship between the degree of deformation of samples D and the free carrier concentration n, and also the mobility $\mu = R_x \sigma$ at 300 and 77 K (R_x is Hall coefficient, σ is conductivity). Evidently, as D increases both n and μ

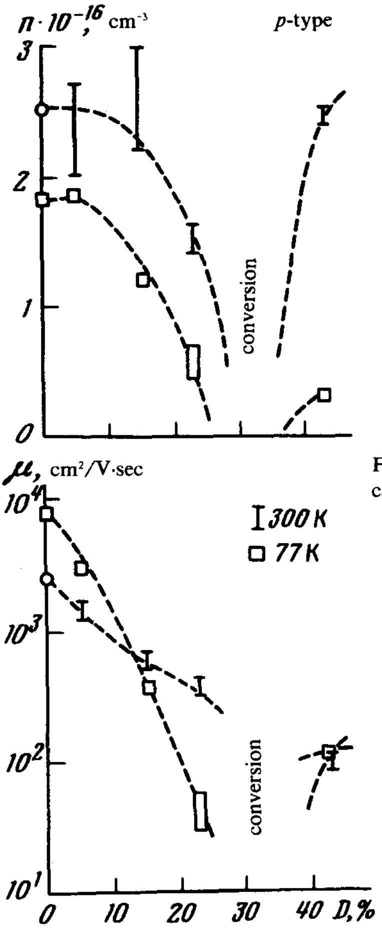

FIG. 1. Effect of plastic deformation on concentration of free carriers in n-type germanium and their mobility at 300 and 77 K.

decrease and the conductivity changes to p-type. These results are seemingly in qualitative agreement with the notion that the dislocation levels in Ge are, basically, acceptor in nature and their introduction into a n-type crystal leads to compensation and occurrence of an additional scattering mechanism.[2] However, we shall see from the data below on low-temperature conductivity that the basic effect associated with introduction of dislocations into doped germanium is spatial redistribution of impurities. We should note that the authors of Ref. 3, having studied doped silicon subjected to plastic deformation, have not observed this phenomenon and were led to the conclusion that impurities and dislocations both additively contribute to low-temperature conductivity.

Figure 2 shows curves of low-temperature conductivity of a number of specimen under observation. Curve 0 corresponds to the control specimen which has undergone the same thermal processing as other specimen but not deformation. Clearly, discrete conductivity (DC) is observed in this specimen in the low-temperature region from the impurity antimony atoms with constant activation energy $\epsilon_3;\rho(T)=\rho_3\exp(\epsilon_3/kT)$.

This type of temperature dependence is associated with so called "nearest neighbor" DC for which the selection of "flow" paths takes place over all the impurity states independent of their energy position.[14] Parameter ρ_3 is determined by the overlap integral and is a strong exponential function of the mean distance between impurities $R \sim N^{1/3}$. ϵ_3 equals the distance between the Fermi level and the maximum of the density of states spectrum and it represents the width of the impurity band.

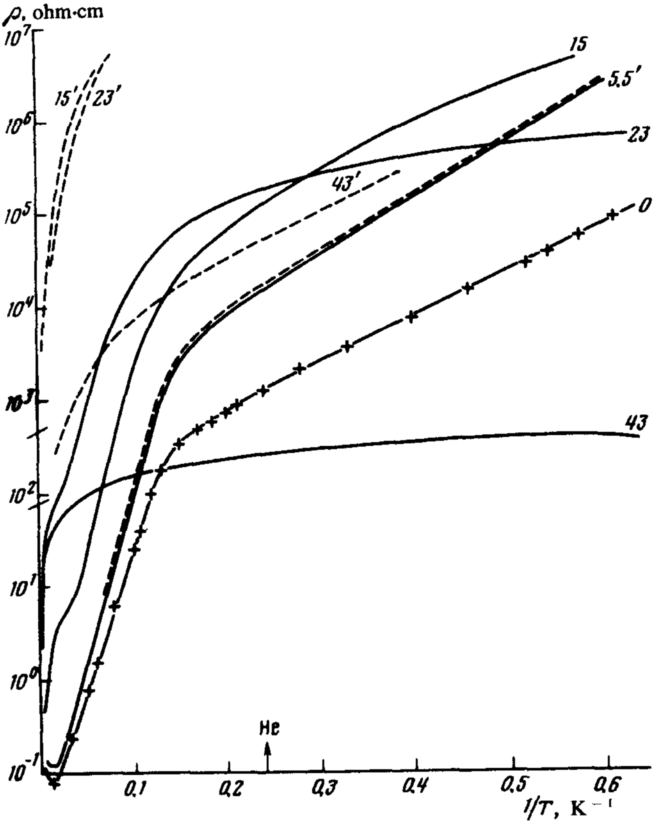

FIG. 2. Low-temperature conductivity of doped n-type germanium specimen subjected to plastic deformation. Crosses—control specimen $D = 0$; dashed lines—conductivity along direction of deformation; solid lines—in the plane perpendicular to that direction. Numbers at curves—degrees of deformation, in %.

Figure 2 shows that prior to conversion DC decreases as D increases while both ρ_3 and ϵ_3 increase. This attests against the idea of conventional compensation. Actually, in this case, as is known, as the degree of compensation K increases the value of DC increases due to decreasing ϵ_3, attains a maximum at $K = 0.5$, and only then begins to decrease. In practice, however, we see that for specimen with $D = 5$ and 15%, for which $K < 0.5$ judging by the Hall measurements, the DC the decreased significantly. The increase in ϵ_3 may attest to broadening of the impurity band due to inhomogeneous deformation of the lattice as a large number of dislocations is introduced. However, the basic result is an increase in the parameter ρ_3, shown by slashes along the ordinate axis (Fig. 2). As stated above, ρ_3 depends on the value of parameter R/a, where a is Bohr's radius of the donor electron.

The increase in ρ_3 and the observed DC anisotropy in specimen with $D = 15$ and 23% may be explained in terms of internal elastic stresses occurring in plasticly-deformed germanium. As is known, for example, in the case of the most effective elastic uniaxial deformation along $\langle 111 \rangle$ the donor wave function in n-type Ge becomes anisotropic and, in the case of doping with antimony, wave function overlap is diminished.[5] However, even in the case of "critical" elastic stresses, the value of ρ_3 for a specimen with the same concentration of antimony does not exceed 10^4 Ohm cm which is less than the resistivity of deformed specimen, especially along the deformation axis.[5] In addition to this, DC anisotropy should not exceed the anisotropy of the wave function[6] which for Ge is ~4–5, a fact that also contradicts experiment; in Fig. 2 the observed conductivity anisotropy exceeds it by two–three orders of magnitude.

Under the foregoing conditions we conclude that R increases as a result of plastic deformation, i.e., a decrease occurs in the concentration of impurities that take part in discrete conductivity, a decrease occurring nonuniformly in different directions which, consequently, explains the anisotropy effect. We assume the effect is caused by an "congregation" of impurities by dislocations at the time of plastic deformation. It could be assumed, of course, that the spatial distribution of impurities remains unchanged and, owing to direct proximity of dislocations, microcracks and other defects that occur in the course of plastic deformation, the energy level of some impurities undergoes sufficiently drastic changes (for example, it is forced out into the conduction band) such that these impurities cease to sustain the localized state for the electron. This would contribute to an effective reduction of concentration of impurities taking part in DC. However, in such a case the corresponding decrease in the concentration of free electrons would have to be observed at temperatures when the electrons transfer from impurities to the conduction band. This is not the case, however, in practice; for example, in a specimen with $D = 5\%$ an increase in ρ_3 corresponds to the 1.8-fold decrease in N while n remained practically unchanged (see Fig. 1). We are left to assume that a spatial redistribution takes place—"congregation" of impurities around dislocations"—as a result of which n changes little, and since the discrete resistance depends on purged regions around dislocations, the value of ρ_3 should sharply increase.

The phenomenon of formation of impurity "atmospheres" around dislocations is well known.[7] The effect of "purging" impurities from the basic volume of a crystal—which we observed—may be explained in terms of a high density of dislocations (calculated to be of the order of $\sim 10^{10}$ cm^{-2}) when the mean distance between them is small ($l_0 \sim 10^{-5}$ cm). Under these conditions, all impurities may succeed in being drawn toward the dislocations during the period of high-temperature plastic deformation, and this requires that the condition $l_D > l_0$ be satisfied. Here l_D is the diffusion path length of impurities [$(l_D = (D_p t)^{1/2}$, where D_p is diffusivity at a temperature corresponding to plastic deformation and t is time of deformation]. Numerical calculation show this relationship is satisfied in our case.

The study of low-temperature conductivity in a plasticly-deformed, "pure"—impurities free—germanium revealed DC anisotropy "with respect to dislocations"—

conductivity in the [111] plane perpendicular to the deformation axis was much better than along the axis.[1] This attests to the fact that the [111] plane, which in Ge constitutes the sliding surface, contains accumulated dislocations and other defects. Figure 2 shows that the impurity DC anisotropy in specimen with $D = 15$ and 23% is similar in nature. This case, taking into account, that the geometry and other conditions of plastic deformation are the same in Ref. 1 and our work, may be regarded as yet another indication of "drawing" of impurities toward dislocations.

The temperature dependence of conductivity of the most deformed specimen with $D = 43\%$ that has been converted into p-type, agrees with similar data,[1] the result pertaining to both measurement directions. This provides a basis for concluding that in the material in question the charge transfer occurs by means of a conductivity mechanism involving dislocations; moreover, the presence of impurity "atmospheres" around dislocations fails to exert a significant effect on the conductivity.

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