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Galvanomagnetic effects in *p*-type germanium films

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An investigation was made of the electrical conductivity $\sigma = 1/\rho_0$, Hall coefficient R_H, and transverse magnetoresistance of single-crystal p-type Ge films with a fragmented structure (FS),[1)] which were evaporated in vacuum on Si substrates. Measurements of the magnetoresistance $\Delta\rho/\rho_0$ were carried out in weak magnetic fields H in the $H \perp n$ and $H \parallel \mathbf{n}$ configurations, where $\mathbf{n}$ is the normal to the film surface. Figure 1 gives typical temperature dependences of R_H, $\mu_H = R_H\sigma$, and the magnetoresistance. The effective Hall mobility μ_H was found to be an order of magnitude less than in bulk p-type Ge with the same value of R_H (Ref. 2) and the magnetoresistance was two orders of magnitude higher than $(\mu_H H/c)^2$. The temperature dependences of the magnetoresistance and μ_H were not correlated and the sign of the magnetoresistance anisotropy

$$K = \frac{\Delta\rho\,(H \perp n)}{\Delta\rho\,(H \parallel n)} - 1 \tag{1}$$

was a function of temperature.

We shall explain the experimental results by considering first a crystallite $(n_0; l_2/2)$ – intercrystallite boundary $[n(x) \ll n_0; l_1]$ – crystallite $(n_0; l_2/2)$ structure. The symbols in parentheses represent the carrier density and the size of the corresponding region in the direction of flow of the current (x axis). Films of p-type Ge on Si are in a deformed state (they are stretched) and are characterized by a tensor $(\tau/m)_{ii}$ which is diagonal in the coordinate system with the $\mathbf{z} \parallel \mathbf{n}$ axis, where $(\tau/m)_{yy} = (\tau/m)_{xx} \neq (\tau/m)_{zz}$ (Ref. 3). Here, $(1/m)_{ii}$ is the reciprocal effective mass tensor and τ_{ii} is the relaxation time tensor assumed to obey the relationship $\tau_{ii} = \tau_{ii}^0 \varepsilon^\alpha$, where $\varepsilon = E/kT$ is the dimensionless energy.

In the case of an intercrystallite (grain) boundary which is homogeneous along the y and z directions and in weak magnetic fields we find, on the assumption that $(\tau/m)_{ii}$ varies slowly with x compared with n, that the expressions for the transport coefficients are[4]

$$\sigma^{-1} = \frac{1}{e\mu_{xx}}\overline{n^{-1}}, \quad R_H = \frac{r_2}{r_1^2}\frac{1}{ec\bar{n}}, \quad \mu_H = \frac{\mu_{xx}}{\bar{n}\,\overline{n^{-1}}}\frac{r_2}{r_1^2}, \tag{2}$$

$$\frac{\Delta\rho}{\rho_0} = \frac{\mu_{xx}\mu_{ii}H^2}{c^2}\frac{r_3}{r_1^3}\left[1 - \frac{r_2^2}{r_1 r_3}\frac{1}{\bar{n}\,\overline{n^{-1}}}\right], \tag{3}$$

where

$$\mu_{kk}=e\left(\frac{\tau^0}{m}\right)_{kk}r_1,\quad r_p=\frac{\Gamma\left(\frac{5}{2}+p_2\right)}{\Gamma\left(\frac{5}{2}\right)},\quad \langle n^i\rangle=\frac{1}{l}\int_0^l n^i dx, \tag{4}$$

$i = y$ for $H = H_z$ and $i = z$ for $H = H_y$, and $l = l_1 + l_2$. The formulas (2) and (3) are valid if the transport lengths are short compared with l_1, and $l_1 \ll l_2$ (Ref. 4).

It is clear from Eqs. (2) and (4) that the Hall coefficient is governed by the average carrier density, i.e., the density in the crystallites, whereas the resistivity is determined by the average value of n^{-1}, i.e., by the intercrystallite boundaries and if $n(r) < n_0$, the inequality $\overline{n^{-1}} > \bar{n}^{-1}$ is satisfied. If, as in the case of polycrystalline films,[5,6] the reduction in the carrier density in intercrystallite boundaries of a fragmented structure is due to the presence of potential varriers $V(r)$ between the crystallites, we may assume that the greatest contribution to $\overline{n^{-1}}$ of an intercrystallite boundary is made by the region near the maximum of the barrier $V(r)$. Expanding $V(r) = V(x)$ as a series and locating the origin ($x = 0$) near the maximum $V = V_0$, we find that

$$n(x)=n_0\exp\left(-\frac{eV_0}{kT}\right)\exp(a_x x^2),\quad a_x=\frac{e}{kT}\left|\frac{\partial^2 V}{\partial x^2}\right| \tag{5}$$

and

$$\overline{n^{-1}}\simeq n_0^{-1}\left[1+\exp\left(\frac{eV_0}{kT}\right)\sqrt{\frac{\pi}{a_x}}\frac{1}{l}\right]. \tag{6}$$

Here, $\sqrt{\pi/a_x}$ is the thickness of an intercrystallite boundary. It follows from Eq. (6) that $\overline{n^{-1}} \gg \bar{n}_0^{-1}$ if $\exp(eV_0/kT)\cdot\sqrt{\pi/a_x}(1/l) \gg 1$. In this case the magnetoresistance is governed by the factor in front of the expression in brackets of Eq. (3), which is large for large values of μ_{kk}, whereas the Hall mobility μ_H is — according to Eq. (2) — $\overline{n^{-1}}/\bar{n}^{-1}$ times smaller than μ_{xx}. Thus, $\mu_H \ll \mu_H^0$, where $\mu_H^0 = (r_2/r_1^2)\mu_{xx}$ is the Hall mobility in a homogeneous sample with the same value of R_H.

In general, when an intercrystallite boundary is inhomogeneous in the y and z directions, the current crosses this boundary mainly in the region with the maximum carrier density ("saddle point"), where after expansion of $V(r)$ as a series the value of $n(r)$ can be represented by

$$n(r)=n_0\exp\left(-\frac{eV_0}{kT}\right)\exp(-a_z z^2-a_y y^2+a_x x^2),\quad a_i=\frac{e}{kT}\left|\frac{\partial^2 V}{\partial x_i^2}\right|,$$
$$x_i=x,\ y,\ z. \tag{7}$$

If $a_y = a_z = 0$, Eq. (7) reduces to Eq. (5), and we can apply the formulas (2) and (3).

The problem of the resistivity and magnetoresistance of a structure with "saddle" regions of this kind can be solved if $\overline{n^{-1}} \gg \bar{n}^{-1}$. Such a solution is given in Ref. 7 for the case when $a_x = a_y = a_z = 0$ and $(\tau/m)_{ii} = \tau/m$. If we generalize the results of Ref. 7 to the case of an asymmetric anisotropic "saddle" region of interest to us, we find that σ^{-1}, R_H, and μ_H are still given by the formulas of Eq. (2), where

$$\overline{n^{-1}}=n_0^{-1}\exp\left(\frac{eV_0}{kT}\right)\sqrt{\frac{a_y a_z}{\pi a_x}}\frac{d_y d_z}{l}\gg n_0^{-1}\simeq \bar{n}^{-1}, \tag{8}$$

and the magnetoresistance is governed by the factor in front of the brackets in Eq. (3). In Eq. (8), the quantities d_y and d_z are the dimensions of an intercrystallite boundary along the y and z axes, $\pi/\sqrt{a_y a_z}$ is the cross section of the current-conducting part of the "saddle" region, and $\pi/\sqrt{a_y a_z}d_y d_z \ll 1$. As a_y and a_z decrease without limit, Eq. (8) reduces to Eq. (6). The factor $1/\bar{n}\overline{n^{-1}}$ in Eqs. (2) and (3) is due to the shunting, by the crystallites, of the Hall emf in an intercrystallite boundary.

It follows from Refs. 7 and 8 that the expressions (2) and (3) give information on the characteristics of a sample if we substitute in Eq. (8) some typical parameters of intercrystallite boundaries governing the paths of flow of the current. Then, the magnetoresistance may be higher for higher values of μ_{kk}, and $\mu_H/\mu_{kk} \sim \bar{n}^{-1}/\overline{n^{-1}} \ll 1$. The determination of the mobility in films from their magnetoresistance on the basis of Eq. (3) gives, at 293°K for $\alpha = 1$, the value $\sim 850\ cm^2\cdot V^{-1}\cdot sec^{-1}$, which is close to the mobility in bulk p-type Ge with the same value of R_H (Ref. 2) and is an order of magnitude higher than μ_H (Fig. 1). In the $H \parallel n$ case we find that in all intercrystallite boundaries we have $H \perp x$ and the magnetoresistance $(\Delta\rho/\rho_0)$ $(H \parallel n)$ is found from Eq. (3) by replacing μ_{ii} with μ_{yy}. If $H \perp n$, the magnetic field makes various angles with the direction of the current across the boundaries so that $(\Delta\rho/\rho_0)$ $(H \perp n)$ is found from Eq. (3) by replacing μ_{ii} with $\beta\mu_{zz}$ (the coefficient $\beta < 1$ appears as a result of averaging over the various directions). In particular, in the case of a random distribution of the intercrystallite boundaries we have $\beta \approx 1/2$ and we should observe a longitudinal magnetoresistance of the same order as the transverse effect (see Ref. 7, where the three-dimensional case is considered, for which we have $\beta = 2/3$). In fact at 293°K the longitudinal magnetoresistance of our films is of the same order as the transverse effect, whereas in the case of uniaxially deformed[9] and undeformed[10] bulk p-type Ge it is at least an order of magnitude smalle than the transverse magnetoresistance.

If $\beta\mu_{zz} > \mu_{yy}$, then [see Eq. (1)] we find that $K = (\beta\mu_{zz}/\mu_{yy}) - 1 > 0$, whereas in the opposite case we obtain $K < 0$. When the temperature is varied in the interval 77-450°K, the relative band splitting η/kT changes and it follows from an estimate based on Ref. 11 that there is a room-temperature transition from strong deformations ($\eta/kT > 1$), characterized by $\mu_{zz} > \mu_{yy}$, to weak deformations ($\eta/kT < 1$), characterized by $\mu_{zz} < \mu_{yy}$ (Ref. 3). This explains the change in the sign of K with temperatur (Fig. 1).

Intercrystallite boundaries in polycrystalline films have been envoked earlier for the interpretation of the Hall effect and conductivity but not for the interpretation of the magnetoresistance. The value $V_0 \approx 15$ meV deduced by us from the dependence $\mu_H(T)$ is of the same or der as that reported for polycrystalline films in Ref. 6. It is clear from Eq. (6) that the small value of V_0 cannot

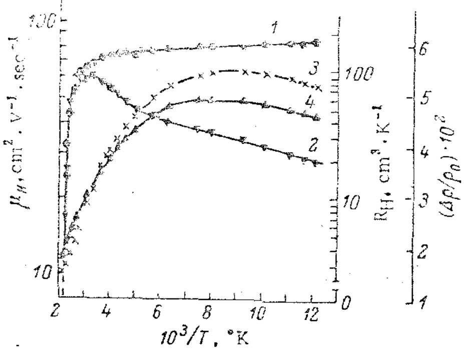

Fig. 1. Temperature dependences of R_H (1), μ_H (2), $(\Delta\rho/\rho_0)(H \perp n)$ (3), and $(\Delta\rho/\rho_0)(H \parallel n)$ (4) of a single-crystal germanium film, 9 μ thick, deposited at 850°C on a silicon substrate. The measurements were carried out in a field of H = 19.6 kOe.

explain the large discrepancy between μ_H and μ_H^0, whereas this discrepancy can be accounted for by using an inhomogeneous boundary model corresponding to Eq. (8). The applicability of the model employed here to polycrystalline films was tested by us by determining R_H, σ, and the magnetoresistance of p-type Ge polycrystalline films $\sim 5\ \mu$ thick prepared at T_0 = 623°K on GaAs and Si substrates. The mobilities deduced from the magnetoresistance were found to be four to five times higher than the effective values μ_H and were close to the mobilities in bulk p-type Ge with the same hole density.[2] We also observed a longitudinal magnetoresistance of the same order as the transverse effect and found no correlation between the temperature dependences of the magnetoresistance and μ_H, due to the temperature dependence of the ratio $\overline{n^{-1}}/\overline{n}^{-1}$.

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1) The fragmented structure is a specific defect structure which appears in heteroepitaxial systems as a result of relaxation of thermal stresses and represents an ordered network of microcracks and dislocation walls.[1]

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