Short Notes

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Transverse Magnetoresistance of Uniaxially Stressed p-Ge

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Up to now piezogalvanomagnetic effects in p-Ge are insufficiently studied, both theoretical and experimental investigations were carried out in the range of weak deformations (1 to 4). However, the galvanomagnetic effects have been shown, by the calculation made in (5), to change essentially when passing from weak deformations to strong ones (the corresponding criteria will be given later).

In the present note the transverse magnetoresistance (TMR) ϱ_H/ϱ_o was investigated in p-Ge ($\varrho_{300\,^oK} \approx 16$ Ωcm, $n_p \approx 1.2\times10^{14}$ cm^{-3}) in a wide range of mechanical loads X ($0 \leqq X \leqq 9000$ kp/cm^2) and in the range of magnetic fields $0 \leqq H \leqq 20$ kOe. In Fig. 1 and 2 the magnetic field dependences of TMR for different X are presented for the cases $\vec{j} \parallel \vec{X} \parallel [111]$ and of $\vec{j} \parallel \vec{X} \parallel [001]$ obtained at 77 ^oK and $\vec{H} \parallel [1\bar{1}0]$ ($\vec{j}$ is the current density). The dependences $\varrho_H/\varrho_o = f(X)$ at two values of the magnetic field (H = 0.9 and H = 5 kOe) for the same cases are shown in Fig. 3.

The characteristic feature of Fig. 1, 2, and 3 is the identical form of the dependences obtained for $\vec{j} \parallel \vec{X} \parallel [111]$ and $\vec{j} \parallel \vec{X} \parallel [100]$. In both cases ϱ_H^x/ϱ_o^x originally diminishes as X is increases (as compared to the TMR for X = 0) and above some pressure rises in the range of greater pressures, $\varrho_H^x/\varrho_o^x > \varrho_H/\varrho_o\big|_{X=0}$ (Fig. 3). However, while in weak magnetic fields (H = 0.9 kOe) the rise of ϱ_H^x/ϱ_o^x took place up to the highest X (Fig. 3, curves 1 and 1'), in stronger magnetic fields (H = 5 kOe) ϱ_H^x/ϱ_o^x began to diminish somewhat in the range of high pressures (curves 2 and 2'). At magnetic fields $H \geqq 10$ kOe the TMR ϱ_H^x/ϱ_o^x increased over the whole range of X.

The qualitative likeness of the dependences $\varrho_H/\varrho_o = f(H, X)$ for two different orientations of the current permits to conclude that their features to be discussed

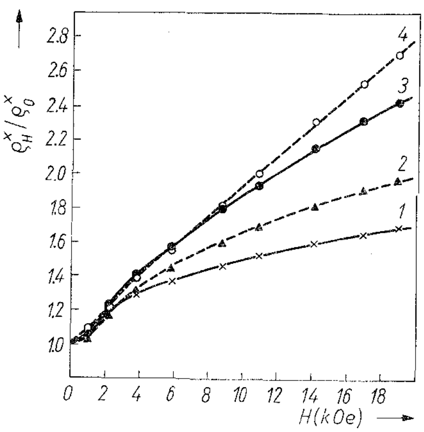


Fig. 1

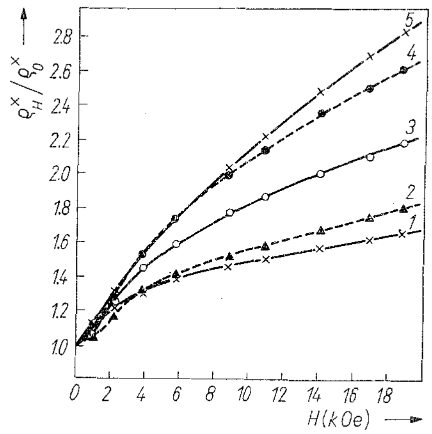


Fig. 2

Fig. 1. The magnetic field dependences of the transverse magnetoresistance for different values of mechanical loads X in the cases $\vec{j} \parallel \vec{X} \parallel [111]$ and $\vec{H} \parallel [1\bar{1}0]$; (1) X = 0, (2) X = 2000, (3) X = 4500, (4) X = 9000 kp/cm^2

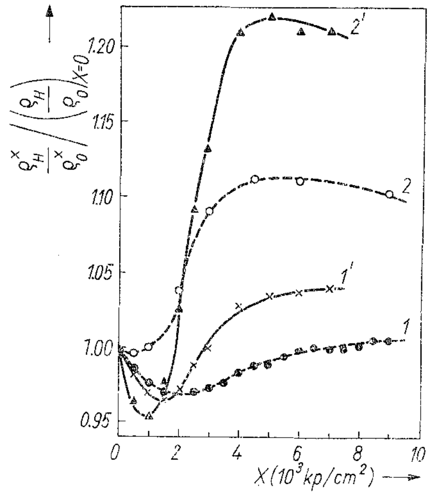
Fig. 2. The magnetic field dependences of the transverse magnetoresistance for different values of mechanical loads X in the case $\vec{j} \parallel \vec{X} \parallel [100]$ and $\vec{H} \parallel [1\bar{1}0]$; (1) X = 0, (2) X = 2000, (3) X = 3000, (4) X = 4500, (5) X = = 7000 kp/cm^2

are determined basically by the variation of the band structure with pressure (1, 2, 5, 6) and to a lesser extent by the anisotropy of the dispersion law in unstressed p-Ge. Hence, the attempt can be made to understand qualitatively the physical meaning of the obtained dependences suggesting the isotropy of the properties of p-Ge in absence of deformation and to introduce similarly to (7) an average deformation potential constant $\bar{b} = \bar{d}/\sqrt{3}$, an average band parameter $B = D/\sqrt{3}$, and average values of the elastic constants $\frac{1}{2}(\bar{c}_{11} - \bar{c}_{12}) = \bar{c}_{44}$. Then the dispersion law for each band of a stressed semiconductor ((2) §30, (6)) may be written as follows:

$$E_l(\vec{k}) = A k^2 - (-1)^l \sqrt{\bar{B}^2 k^4 + |\bar{B}|\eta(k^2 - 3k_z^2) + \eta^2}\,, \qquad (1)$$

where E_l is the energy in the band l; l = 1, 2 is the band number (at $\eta = 0$ l = 1 and l = 2 correspond to the bands of light and heavy holes); $\vec{k}$ is the wave vector; $\eta = \frac{\bar{b}\,\bar{B}}{|\bar{B}|}(\varepsilon_{xx} - \varepsilon_{zz})$, $\varepsilon_{xx} = \varepsilon_{yy} \neq \varepsilon_{zz}$, $\varepsilon_{xz} = \varepsilon_{yz} = \varepsilon_{xy} = 0$ are the components

Fig. 3. The mechanical load dependences of the transverse magnetoresistance for two values of the magnetic field strength H;
(1) $\vec{j} \parallel \vec{X} \parallel [111]$; $\vec{H} \parallel [1\bar{1}0]$ and $|H| = 0.9$ kOe,
(2) $\vec{j} \parallel \vec{X} \parallel [111]$; $\vec{H} \parallel [1\bar{1}0]$ and $|H| = 5$ kOe,
(1') $\vec{j} \parallel \vec{X} \parallel [100]$; $\vec{H} \parallel [1\bar{1}0]$ and $|H| = 0.9$ kOe,
(2') $\vec{j} \parallel \vec{X} \parallel [100]$; $\vec{H} \parallel [1\bar{1}0]$ and $|H| = 5$ kOe



of the deformation tensor, current and pressure are directed along the Z-axis; A, $\bar{B}$, and $\bar{b}$ were given in reference (2). Since $\bar{b}\,\bar{B} > 0$, then $\eta > 0$ for compression along the Z-axis.

As the calculation of ϱ_H/ϱ_o will not be especially difficult in the approximations accepted above, we shall present the final results for the case of acoustic phonon scattering and for the following limits in deformation and magnetic field: a) weak deformation at weak and strong magnetic fields H, b) strong deformation at weak and classically strong H. The calculation are carried out as in (5, 7, 10) and the relaxation times necessary for the calculation in the case of weak deformation ($\eta \ll \varkappa T$) are obtained just as for X = 0 in (7, 8) ($\varkappa$ is the Boltzmann constant and T is the temperature). At strong deformation ($\eta \gg \varkappa T$, for p-Ge at 77 $^{\circ}$K $\eta \approx \varkappa T$ when X = 2300 kp/cm^2) all holes are in the second band and the isoenergetic surfaces turn into ellipsoids (1). In this case the anisotropy scattering theory can be used (9).

Consider the case of weak magnetic fields ($\varrho_H/\varrho_o - 1 \ll 1$), when the TMR at X = 0 is determined basically by the light holes (7). Their effective mass (l = 1) increases with pressure (equation (1)) and the cyclotron frequency ($\omega_1 = eH/c\,m_1$) and the TMR $\sim \omega^2$ decrease (Fig. 3, curves a and 1', X < 1500 kp/cm^2). With the rise of pressure the filling of the light hole band decreases and the fall of the TMR ϱ_H^X/ϱ_o^X passes into a rise (Fig. 3, curves 1 and 1', X > 1500 kp/cm^2) due to the increase of the cyclotron frequency of the heavy holes $\omega_2 = eH/c\,m_2$ (m_2 decreases with pressure (equation (1)). Such dependence of the TMR on pressure at weak H is confirmed by the expression obtained on the assumptions discussed above:

$$\frac{\varrho_H^x}{\varrho_o^x} = \frac{\varrho_H}{\varrho_o}(0)\left[1 - 1.54\,\frac{\eta}{\varkappa T}\ln\frac{\varkappa T}{\eta}\left(\frac{\varrho_H}{\varrho_o}(0) - 1\right)\right], \quad 0 < \eta \ll \varkappa T; \qquad (2)$$

$$\frac{\varrho_H^x}{\varrho_o^x} = \frac{\varrho_H}{\varrho_o}(0)\left[1 + 5.2\left(\frac{\varrho_H}{\varrho_o}(0) - 1\right)\right], \qquad \eta \gg \varkappa T\,. \qquad (3)$$

It follows from equation (3) that ϱ_H^x/ϱ_o^x with $\eta \gg \varkappa T$ tends to a value greater than the corresponding one at X = 0, which is observed experimentally at great X.

While passing to the range of higher H the situation is somewhat complicated. In fact, the condition of classically strong magnetic fields is not fulfilled in the investigated crystals in absence of deformation, since the quantization of light holes ($\hbar\omega_1/\varkappa T \approx 1$ at H ≈ 24 kOe) begins before the criterion of classically strong magnetic fields for heavy holes is fulfilled ($\omega_2\tau_2^o \gg 1$ at H ≫ 3 kOe, where τ_2^o is the relaxation time of heavy holes at $E_2 = \varkappa T$), i.e. the conditions $\hbar\omega_1/\varkappa T \ll 1$ and $\omega_2\tau_2^o \gg 1$ are not combined in the interval $3 \leqq H \leqq 24$ kOe.

In strong magnetic fields at X = 0 the TMR is determined basically by heavy holes. The weak deformation increasing the cyclotron frequency should result in a rise of the TMR:

$$\frac{\varrho_H^x}{\varrho_o^x} = \frac{32}{9\pi}\cdot 1.3\left[1 - \frac{5.4}{(\omega_2\varepsilon_2^o)^2} + \frac{\eta}{\varkappa T}\,0.06\left(\frac{37.8}{(\omega_2\varepsilon_2^o)^2} - 1\right)\right]; \quad \omega_2\tau_2^o > 1\,. \qquad (4)$$

This dependence is confirmed experimentally (transition from curve 1 to curve 2, H ≳ 10 kOe, Fig. 1, 2).

The increase of pressure was found to cause a hole transfer from the first band to the second one (2, 6). The change of the dispersion law has the effect that the quantization of light holes begins at higher magnetic fields than at X = 0 and the criterion of strong magnetic fields for heavy holes is displaced to the range of lower H. For the maximum pressure used in the experiment $\hbar\omega_1/\varkappa T\big|_{\eta\gg\varkappa T} \approx 1$ at H ≈ ≈ 43 kOe and $\omega_2\tau_2^o\big|_{\eta\gg\varkappa T} \gg 1$ at H ≫ 0.4 kOe. Hence the conditions $\hbar\omega_1/\varkappa T\big|_{\eta\gg\varkappa T} \ll 1$ and $\omega_2\tau_2^o\big|_{\eta\gg\varkappa T} \gg 1$ are combined in a sufficiently wide range of magnetic fields.

As a result, a certain interval of H appears where the condition of classically strong magnetic fields is fulfilled and, according to calculations:

$$\frac{\varrho_H^x}{\varrho_o^x} = \frac{32}{\pi}\left(1 + \frac{1.33\,\varkappa T}{\eta}\right) , \qquad \omega_2 \tau_2^o \Big|_{\eta \gg \varkappa T} \gg 1 \tag{5}$$

a decrease of ϱ_H^x/ϱ_o^x should be observed, which takes place in the experiment (Fig. 3, curves 2 and 2', X $\gtrsim$ 4000 kp/cm^2).

Thus the variation of the TMR with pressure in p-Ge is qualitatively explained by the expressions (2 to 5) in the range magnetic fields where the quantization is not essential. In the cases where quantization takes place the dependences $\varrho_H^x/\varrho_o^x = f(H, X)$ are not discussed.

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