Piezoresistance of uniaxially deformed p-type Ge

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The piezoresistance of p-type Ge has been investigated theoretically and experimentally but mainly in the weak deformation range.[1-4] The present paper reports the results of measurements of the longitudinal piezoresistance ρ_X/ρ_0 of p-type Ge, carried out in a wide range of mechanical loads ($0 < X < 10^4$ kg/cm²; j ∥ X ∥ [100] and j ∥ X ∥ [111], where j is the current density) at 77°K and it gives a semiquantitative explanation of the dependences obtained allowing for various scattering mechanisms in the range of weak and strong deformations.

A characteristic feature of the observed piezoresistance at low pressures is the inequality $\rho_X^{[100]} > \rho_X^{[111]}$, which is obeyed irrespective of the behavior of the resistivity of the sample (Fig. 1). This inequality follows, irrespective of the scattering mechanism, from an analysis of the expression for the piezoresistance,[2,4] which can be expressed in the form

$$\rho_X = \rho_0\left[1 - 0.6\frac{\eta}{\varkappa T}\left(\frac{\sigma_2}{\sigma_1+\sigma_2}\frac{\langle\tau_2\rangle}{\langle E\tau_2\rangle} - \frac{\sigma_1}{\sigma_1+\sigma_2}\frac{\langle\tau_1\rangle}{\langle E\tau_1\rangle}\right)\right], \quad \frac{\eta}{\varkappa T} \ll 1, \qquad (1)$$

where

$$\eta_{100} = \frac{bB}{B}\frac{1}{C_{11}-C_{12}} > 0, \quad \eta_{111} = \xi\eta_{100},$$

$$\xi = \frac{Dd}{3Bb}\frac{2(C_{11}-C_{12})}{C_{44}}, \quad B = \sqrt{B^2 + \frac{1}{5}C^2},$$

b and d are the deformation potential constants, B, D, and C are the band parameters,[2,4,5] $\varkappa$ is the Boltzmann constant, T is the temperature, C_{11}, C_{12}, and C_{44} are the elastic moduli; E is the energy, τ_i is the momentum dissipation time of holes in a band i (i = 1 and 2 represent the light- and heavy-hole bands); σ_i is the conductivity of holes of band i at x = 0, and

$$\langle E^n\tau_i\rangle = \frac{\int_0^\infty \tau_i(E)E^{n+3/2}e^{-\frac{E}{\varkappa T}}dE}{\int_0^\infty E^{3/2}e^{-\frac{E}{\varkappa T}}dE}.$$

If the scattering of holes in both bands is governed by the same mechanism with $\tau_i \propto E^n$, it follows that $(\rho_0-\rho_X)\cdot\rho_0^{-1} = 0.6(\eta/\varkappa T)[(\sigma_2-\sigma_1)/(\sigma_2+\sigma_1)][1/(n+3/2)]$ (refs. 2 and 4), and when the role of the impurity scattering increases, the piezoresistance should decrease, as found experimentally (note changes 1' → 3' and 1 → 3 in Fig. 1).

In the strong deformation region, i.e., when $\eta/\varkappa T \gg 1$ (at 77°K, we have $\eta = \varkappa T$ for $x \approx 2300$ kg/cm²), if the scattering by acoustic vibrations predominates, we have the opposite inequality: $\rho_X^{[100]} < \rho_X^{[111]}$ (curves 1-1', 2-2'). The same inequality is obtained as a result of calculations of the piezoresistance carried out by assuming that in the $\eta/\varkappa T \gg 1$ region the light-hole band is empty and the constant-energy surfaces of the heavy-hole band are nearly

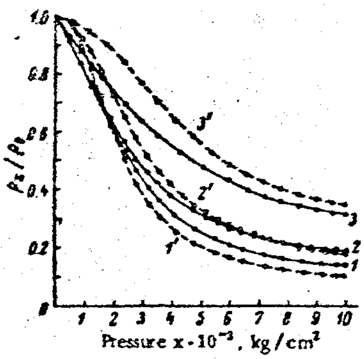

Fig. 1. Dependence of the resistivity ratio on the pressure applied at 77°K in the j ∥ x ∥ [111] (1-3) and j ∥ x ∥ [100] (1'-3') configurations. The resistivities of the samples were (Ω·cm): 1, 1') 2.1; 2, 2') 0.345; 3, 3') 0.0...

ellipsoids of revolution (the revolution is about the pressure axis) with $m_\perp > m_\parallel$ (refs. 4 and 5).

In this case we find that

$$\rho_X^{-1} = \frac{2}{3}\frac{e^2p}{\Gamma\left(\frac{3}{2}\right)}\int_0^\infty \xi^{3/2}\left(\frac{\tau}{m}\right)_\parallel e^{-\xi}d\xi, \qquad (2)$$

where p is the hole density, e is the hole charge, $\tau_\parallel$ and $m_\parallel^{-1}$ are the components of the relaxation time and reciprocal mass tensors and, as shown in refs. 4 and 5,

$$\frac{1}{m_\parallel}\Big|_{x\parallel[100]} = \frac{A+|B|}{m_0} \text{ and } \frac{1}{m_\parallel}\Big|_{x\parallel[111]} = \frac{A+\frac{1}{\sqrt{3}}|D|}{m_0},$$

where A is the band parameter used in refs. 4–6 and m_0 is the mass of a free electron.

The ratios $\rho_X^{[111]}/\rho_X^{[100]}$ can be found if we take the relaxation time tensor from ref. 7 for carriers scattered by the acoustic lattice vibrations, where for x ∥ [100] we take $\Xi_u^{[100]} = 3|b|/2$, $\Xi_d^{[100]} = a - |b|/2$, whereas for x ∥ [111], we use $\Xi_u^{[111]} = \sqrt{3}\,|d|/2$, $\Xi_d^{[111]} = a - |d|/2\sqrt{3}$. Therefore, when carriers are scattered by the acoustic vibrations, we obtain

$$\frac{\rho_X^{[111]}}{\rho_X^{[100]}} = \left(\frac{m_\parallel^{[111]}}{m_\parallel^{[100]}}\right)^{3/2}\frac{m_\perp^{[111]}}{m_\perp^{[100]}}\frac{\xi_\parallel^{[111]}(\Xi_d^{[111]})^2 + \eta_\parallel^{[111]}\Xi_u^{[111]}\Xi_d^{[111]} + \zeta_\parallel^{[111]}(\Xi_u^{[111]})^2}{\xi_\parallel^{[100]}(\Xi_d^{[100]})^2 + \eta_\parallel^{[100]}\Xi_u^{[100]}\Xi_d^{[100]} + \zeta_\parallel^{[100]}(\Xi_u^{[100]})^2}, \qquad (3)$$

where $\xi_\parallel$, $\eta_\parallel$, and $\zeta_\parallel$ are the functions of $m_\perp$ and $m_\parallel$ deduced in ref. 7, $1/m_\perp^{[100]} = (A - |B|/2)/m_0$ and $1/m_\perp^{[111]} = (A - |D|/2\sqrt{3})/m_0$. In the case of p-type Ge all the parameters (with the exception of a, b, and d) are well known.[6,8] Substituting these parameters into Eq. (3), we find that

$$\frac{\rho_X^{[111]}}{\rho_X^{[100]}} = 0.93\frac{1+0.133\frac{|d|}{a}+0.393\frac{d^2}{a^2}}{1+0.353\frac{|b|}{a}+1.25\frac{b^2}{a^2}}.$$

If we assume that $a = -2.5$, $b = -2.6$, and $d = -6.2$ eV (ref. 8), we obtain $(\rho_X^{[111]}/\rho_X^{[100]}) = 1.1$. However, if without altering b and d (they are close to the values of b and d in ref. 9), we increase a, we find that the ratio $\rho_X^{[111]}/\rho_X^{[100]}$ increases and for $a = -2.6$ eV (ref. 10), we obtain $\rho_X^{[111]} \cdot (\rho_X^{[100]})^{-1} = 1.53$. For the purest among the investigated p-type Ge crystals ($p \approx 10^{13}$ cm^{-3}) subjected to a pressure $x = 10^4$ kg/cm^2 (curves 1–1'), we obtain $(\rho_X^{[111]}/\rho_X^{[100]}) = 1.4$.

In the case of scattering by ionized impurities we can follow ref. 11, which deals with the case $m_\parallel > m_\perp$, and obtain expressions for the relaxation time of carriers with $m_\parallel < m_\perp$. In the lowest approximation with respect to γ^2, we obtain[11]

$$\frac{1}{\tau_\parallel} = \frac{3\pi e^4 \sqrt{2} N}{4\kappa^2 E^{3/2}} \frac{\sqrt{m_\parallel}}{m_\perp} \frac{1}{\alpha^3} \left(\frac{1}{2} \ln \frac{1-\alpha}{1+\alpha} + \frac{\alpha}{1-\alpha^2} \right) \ln \frac{1}{\gamma^2}, \qquad (4)$$

where $\alpha^2 = 1 - (m_\parallel / m_\perp)$, N is the impurity concentration, κ is the permittivity, $\gamma^2 = \hbar^2 (8 r m_\parallel E)^{-1}$, r is the screening radius, and $\hbar$ is Planck's constant.

It follows from Eqs. (2) and (4) that $(\rho_X^{[111]}/\rho_X^{[100]}) = 0.75 < 1$. The experimental value of $(\rho_X^{[111]}/\rho_X^{[100]})$ for $x = 10^4$ kg/cm^2 applied to a sample with $\rho_{0.77°K} = 0.086\ \Omega \cdot$cm is 0.91.

Thus, when the deformation is strong an increase in the importance of the impurity scattering reduces $(\rho_X^{[111]} \cdot (\rho_X^{[100]})^{-1}$, and when such scattering becomes predominant, we find that the inequality $\rho_X^{[100]} > \rho_X^{[111]}$ is satisfied at all pressures.

It should be noted that at 77°K the scattering by the optical lattice vibrations can be ignored.[12]

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