Nonequilibrium galvanomagnetic effects of quasi-2D electrons in *p*-InSb/*i*-GaAs heteroepitaxial structures

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A negative photoconductivity which can be exploited to control the properties of the quasi-2D electron layer at an InSb/GaAs heterojunction has been discovered. Measurements carried out in electric fields at $T = 1.0$ K confirm the possibility of an energy relaxation of non-equilibrium electrons among 2D phonons.

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It has been predicted theoretically that localization and electron-electron interactions can cause the galvanomagnetic coefficients in degenerate semiconducting systems to behave anomalously as functions of the temperature and the field.[1,2] Measurements of the temperature dependence of the conductivity and of the Hall coefficient which have been carried out under equilibrium conditions for quasi-2D (quasi-two-dimensional) inversion electron layers in *p*-InSb/*i*-GaAs heteroepitaxial structures have presented an opportunity to experimentally study the predicted anomalies in the case of strong spin-orbit relaxation.[3] In the 2D case, in which electron-electron scattering determines the phase relaxation time τ_φ, we can write[4]

$$\tau_\varphi^{-1} = \frac{\pi kT}{\hbar}\,\frac{R^\square e^2}{2\pi^2\hbar}\ln\frac{\pi\hbar}{e^2 R^\square}, \tag{1}$$

where $R^\square$ is the surface resistivity of the film.

From (1) we find $\tau_\varphi \sim T^{-1}$, since $R^\square$ is a weaker, logarithmic function[2] of T; it also follows that by varying $R^\square$ at a fixed temperature we can change the ratio of τ_φ and the spin-orbit relaxation time τ_{so} over a broad range, so that we should be able to affect the behavior of the magnetoresistance.[2,5]

In the present measurements we varied $R^\square$ by making use of the negative photoconductivity which we have observed in *p*-InSb/*i*-GaAs. The sample was excited with a microminiature incandescent lamp mounted directly on the sample. The observed negative photo-conductivity exhibits a long-term relaxation (lasting for several tens of hours), so that the measurements can be taken after the exciting light is turned off.[6] The frozen conductivity can be disrupted by heating the sample to $T > 100$ K.

The transverse and longitudinal magnetoresistances are given by[2,7]

$$-\frac{\Delta R^\perp(H)}{R_0} = \frac{e^2}{2\pi^2\hbar}R^\square\left\{\frac{3}{2}f_2\left(\frac{4DeH}{\hbar c}\tau_\varphi^*\right) - \frac{1}{2}f_2\left(\frac{4DeH}{\hbar c}\tau_\varphi\right) - g_2(T)\varphi_2\left(\frac{2eH}{\pi c}\frac{D}{kT}\right) - \frac{1}{2}Fh_2\left(\frac{g\mu_B H}{kT}\right)\right\} \tag{2}$$

$$-\frac{\Delta R^\parallel(H)}{R_0} = \frac{e^2}{2\pi^2\hbar}R^\square\left\{\frac{3}{2}\ln\left(\frac{De^2H^2d^2}{3\hbar^2c^2}\tau_\varphi^* + 1\right) - \frac{1}{2}\ln\left(\frac{De^2H^2d^2}{3\hbar^2c^2}\tau_\varphi + 1\right) - g_2(T)\ln\left(1 + \frac{d^2e^2H^2}{3\hbar c^2}\frac{D}{kT}\right) - \frac{1}{2}Fh_2\left(\frac{g\mu_B H}{kT}\right)\right\}. \tag{3}$$

Working from the experimental data on the magnetoresistance (Fig. 1) and from Eqs. (2) and (3), we calculated the relaxation times for the scattering of electrons accompanied by a change in energy: the phase relaxation time τ_φ and the spin relaxation time, $\tau_{SO} = 3/4\{(\tau_\varphi^*)^{-1} - (\tau_\varphi)^{-1}\}$ (Fig. 2). We also calculated the parameters of the electron-electron interaction: $g_2 = 0.14$ and $F \lesssim 0.1$. In calculating τ_φ we used the diffusion coefficient $D = 50$ cm^2/s found from the generalized Einstein relation.[8]

Working from the expressions for the weak-field asymptotic behavior found from (2) and (3), we calculated the thickness of the quasi-2D electron layer: $d = (2.3 \pm 0.2)\times 10^{-6}$ cm. The dashed line in Fig. 2 is the theoretical temperature dependence of the electron-electron scattering time τ_{ee} (Ref. 4):

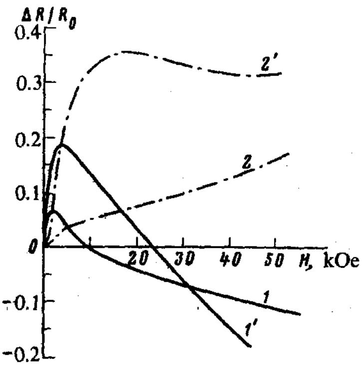

FIG. 1. 1',1—Transverse magnetoresistance; 2',2—longitudinal magnetoresistance of an InSb/GaAs heteroepitaxial structure. 1,2—$T = 4.2$ K; 1',2'—1.5 K.

$$\tau_{ee}^{-1} = \frac{3\pi kT \ln[(k_F l)(k_F d)]}{2\hbar (k_F l)(k_F d)}, \qquad (4)$$

where $l = V_F \tau = 5.1 \times 10^{-7}$ cm, and $V_F = p_F/ml = 10^8$ cm/s.

The points in Fig. 2 are experimental values of τ_φ found from the magnetoresistance at various temperatures. We see that these experimental points conform well to

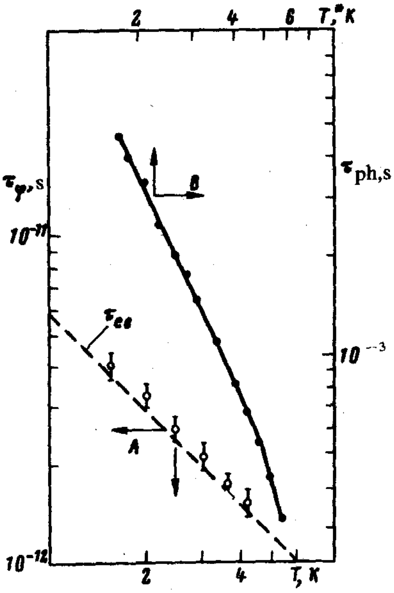

FIG. 2. A—Temperature dependence of the phase relaxation time τ_φ; B—temperature dependence of the electron-phonon relaxation time $\tau_{\rm ph}$ of quasi-2D electrons at an InSb/GaAs heterojunction. Here τ_{ee} is the phase relaxation time calculated for electron-electron relaxation in Ref. 4; the spin-orbit relaxation time is $\tau_{so} = 4.4 \times 10^{-13}$ s.

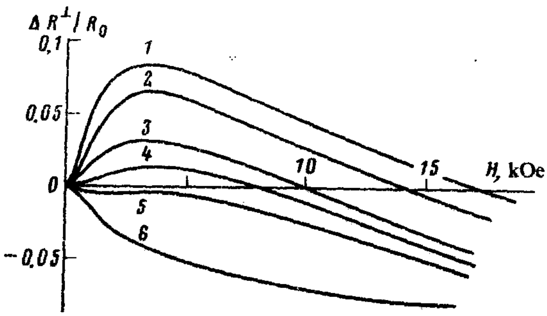

FIG. 3. Transverse magnetoresistance $\Delta R^{\perp}/R_0$ in the case of a frozen photoconductivity. The initial values of the surface resistivity $R^{\square}$ are: 1—36 kΩ; 2—46; 4—100; 5—137; 6—250.

the theoretical dependence $\tau_{ee}(T)$, furnishing evidence that electron-electron scattering plays a dominant role in the inelastic relaxation with a small momentum transfer, studied in Ref. 4. Our experimental dependence $\tau_{\varphi}(T)$ disagrees quantitatively and qualitatively with the theoretical conclusions reached in Ref. 9.

Figure 3 shows the transverse magnetoresistance of the sample at $T = 1.7$ K for various values of the initial surface resistivity, arranged by freezing the photoconductivity through a change in illumination level. We see that $R^{\square}$ strongly affects the nature of the magnetoresistance. The reason is that the illumination affects τ_{φ} (through the value of $R^{\square}$ at a fixed τ_{so}), disrupting the original ratio of τ_{φ} and τ_{so} and therefore changing the nature of the magnetoresistance. It has been shown elsewhere[2,5] that an alternating-sign magnetoresistance results from the two-parameter nature of dependence (2) with $\tau_{\varphi}^{*} \ll \tau_{\varphi}$; in contrast, when the arguments of the function $f_2(\tau_{\varphi}^{*})$ and $f_2(\tau_{\varphi})$ are the same, we have a negative magnetoresistance in all magnetic fields. During the illumination, $R^{\square}$ increases, and τ_{φ} decreases, according to (1), so that when τ_{φ} and τ_{so} become equal [the value calculated for τ_{so} from (2) is 4.4×10^{-13} s] the positive magnetoresistance is not observed.

From the voltage-current characteristics recorded under nonlinear conditions in terms of the electric field E we can determine the magnitude and temperature dependence of the electron-phonon relaxation time, $\tau_{\rm ph}$. An increase in E heats the electrons to some effective temperature $T^{*} = T + eEl_{\rm ph}$ [T is the lattice temperature, and $L_{\rm ph} = (D\tau_{\rm ph})^{1/2}$]. If the temperature rise is pronounced ($T^{*} \gg T$) we can write

$$\tau_{\rm ph}(T^{*}) = \frac{T^{*2}}{(eE)^2 D}\,. \tag{5}$$

If $\tau_{\rm ph} \sim T^{-\alpha}$, then $T^{*} \sim E^{2/(2+\alpha)}$. Which values of α are possible depends on the dimensionality of the phonons (2D or 3D) and on the temperature; these possible values are $\alpha = 2, 3, 4$. When electrons transfer energy to 2D phonons we have $\alpha = 2$, and according to (5) we should have the dependence $T^{*} \sim E^{1/2}$. The current-voltage characteristics of our samples at a zero magnetic field at $T = 1.0$ K turned out to be nonlinear at $E > 0.1$ V/cm, while at $0.2 \text{ V/cm} < E < 3.0$ V/cm we found

$T^* \sim E^{0.5 \pm 0.01}$, showing that the phonons interacting with the hot electrons are two-dimensional. From the condition for $2D$ phonons, $\lambda_{\text{ph}} \geqslant d$, we estimated the temperature T_2, below which the phonon system can be treated as two-dimensional at the thickness of the conducting layer, d. We found $T_2 = hs/kd = 6$ K for $d = 2.5 \times 10^{-6}$ cm, in good agreement with the temperature interval in Fig. 2, where $\tau_{\text{ph}} \sim T^{*-2}$. It can be seen from Fig. 2 that the inequality $\tau_{ee} \ll \tau_{\text{ph}}$ ($\tau_{ee} \equiv \tau_{\varphi}$) holds by a wide margin and justifies the introduction of an effective electron temperature for the test sample.

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