Negative magnetoresistance in a two-dimensional electron gas

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It is shown that the experimental dependences of the negative magnetoresistance in an inversion channel in the range of electron densities $(1.7\text{–}10)\times 10^{12}$ cm^{-2} are described by a new theory of this effect, which is associated with the influence of magnetic field on quantum corrections to the conductivity.

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The negative magnetic resistance in quasi-two-dimensional systems, which is associated with the effect of magnetic field on quantum corrections to the conductivity, has been explained in recently published papers.[1–3] We report in this paper the results of an investigation of the conductivity of an inversion *n* channel of a silicon MDP transistor at 4.2 K in a magnetic field up to 6 kG normal to the surface of the structure. The fabrication of these samples and the measurement method were described in greater detail in Ref. 4. The results of an investigation of the conductivity oscillations in a quantizing magnetic field, which confirm that the electron system in the inversion

TABLE I.

	$V_g(B)$	$\sigma_0\,(mS)$	$n_s\times10^{-12}(\mathrm{cm}^{-2})$	$\mu\,\frac{\mathrm{cm}^2}{\mathrm{B\cdot sec}}$	a	$b\left(\mathrm{kG}^{-1}\right)$	$\tau_\phi\,10^{12}$ (sec)	$\frac{\epsilon_F}{kT}\tau_p\,10^{12}$ (sec)
1	10	0.802	1.71	3330	0.62	10	5.4	9.1
2	15	1.266	2.35	3730	0.63	23	7.9	14.4
3	22	1.808	3.24	3770	0.46	70	17	20.6
4	35	2.390	4.88	3210	0.50	125	22	27.2
5	40	2.490	5,52	3000	0.52	150	26	28.4
6	50	2.502	6.79	2380	0.53	160	28	28.5
7	60	2,386	8.06	1770	0.53	170	30	27.1

channel of these samples is two-dimensional, were also reported in Ref. 4. The dependence of the carrier density in the channel for different voltages (V_g) at the structure's gate was determined from the oscillaton period of the magnetic field (see Table I).

Figure 1 shows the dependence of the relative variation of conductivity $-\Delta\sigma(H)/\sigma_0$ on the magnetic field H for different carrier densities in the channel (σ_0 is the conductivity at $H=0$ and $\Delta\sigma=\sigma_0-\sigma_H$).

The dependence of the anomalous part of magnetic conductivity on the magnetic

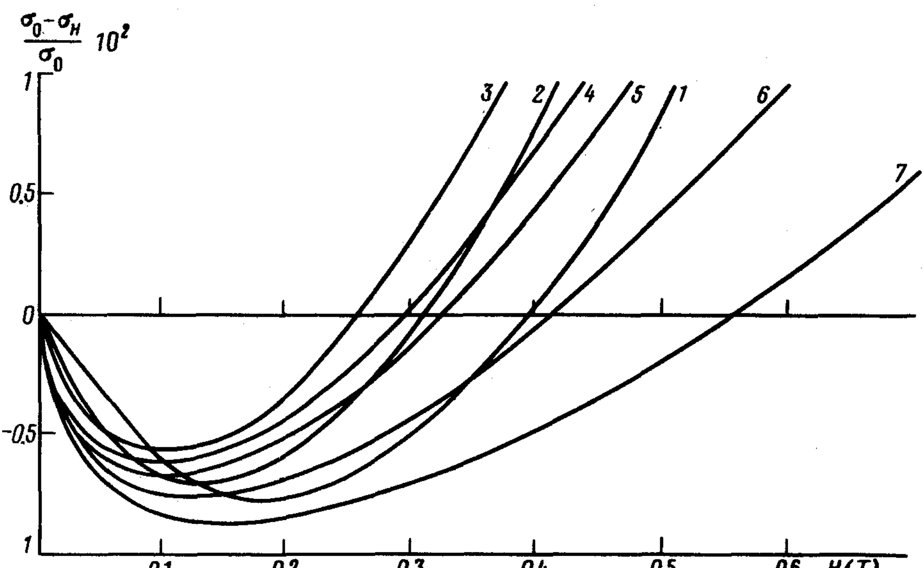

FIG. 1. Dependence of magnetic conductance $(\sigma_0-\sigma_H)/\sigma_0$ on the magnetic field H(kG) for different electron densities in the channel. (The numbers of the curves correspond to the numbers of the lines in Table I.)

field was obtained in the theoretical papers of Refs. 1 and 2 in the form

$$\Delta\sigma_a(H) = a\,\frac{e^2}{2\pi^2 h}\, f\left(\frac{4\,DeH}{\hbar c}\,\tau_\phi\right), \tag{1}$$

where $f(x) = \ln x + \psi(1/2 + 1/x)$, $\psi(x)$ is the digamma function, D is the diffusion coefficient, and τ_ϕ is the relaxation time of the phase of the wave function due to inelastic collisions. The value of the coefficient a, which is associated with the electron-impurity and interelectronic interactions, was discussed in Refs. 2 and 3.

The quantity $\left[\Delta\sigma(H) + \sigma_0\left(\frac{\mu H}{c}\right)^2\right]/\sigma_{00}$ as a function of the magnetic field for different voltages at the gate is represented by the open circles in Fig. 2, $\sigma_{00} \equiv \frac{e^2}{2\pi^2\hbar}$, and $-\sigma_0\left(\frac{\mu H}{c}\right)^2$ is the classical part of the magnetic conductivity, provided that $(\mu H/c)^2 < < 1$ (μ is the electron mobility). The solid curves represent the quantity $af(bH) = \Delta\sigma_a(H)/\sigma_{00}$ [see expression (1)], which was calculated for the values a and b

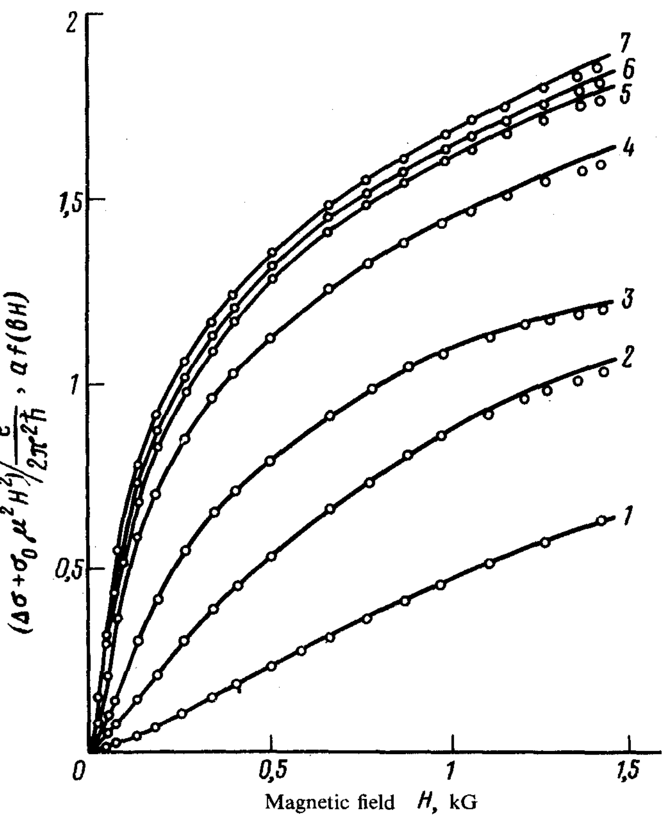

FIG. 2. Dependence of $[\Delta\sigma(H) + \sigma_0(\mu H/c)^2]/\sigma_{00}$ (open circles) and of $af(bH)$ (curves) on the magnetic field H (kG). (The numbers of the curves correspond to the numbers of the lines in Table I.)

given in Table I. The quantity

$$b = \frac{4De}{\hbar c}\tau_\phi = \frac{2}{\pi}\frac{\sigma}{\sigma_{00}}\frac{e\tau_\phi}{c\,m^*d} = 2{,}33\cdot 10^{15}\sigma_0\,\tau_\phi\ (\mathrm{kG}^{-1})$$

for $m_d^*/m_0 = 0.195\ n_v$ and $n_v = 2$(n_v is the number of valleys).

The experimental curves in Fig. 2 are in good agreement with the calculated curves. The slight divergence for fields $H > 1$kG is possibly attributable to a reduction of the mobility μ by 3–5% because of the error in determining the concentration using the method of Ref. 4. To verify this assumption, we analyzed the results of the measurements for $H > 1$kG, starting out from the fact that for $x > 70$

$$f(x) \approx \ln x + \psi\left(\frac{1}{2}\right) \equiv f_H(bH)\,.$$

Figure 3 shows the dependences of $\Delta\sigma(H)/\sigma_{00} f_H(bH)$ on $H^2/f_H(bH)$ with the b values listed in Table I. As we can see in Fig. 3, the experimental points are plotted on the curves and the quantity a, which is determined by the cutoff, turns out to be close to

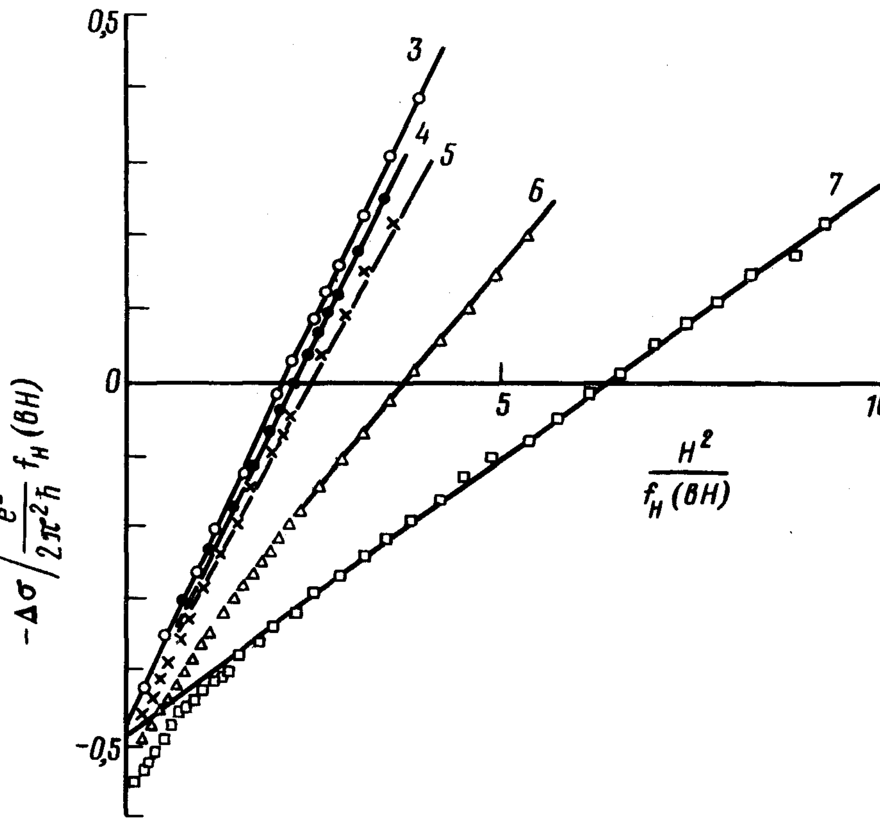

FIG. 3. Dependence of $\Delta\sigma(H/\sigma_{00} f_H(bH)$ on $H^2/f_H(bH)$(kG^2). (The numbers of the curves correspond to the numbers of the lines in Table I.)

those values which are given in Table I.

The values of τ_ϕ, which were calculated from the value of b, are also given in Table I. The value of τ_ϕ is of the order of magnitude of the value estimated by using the expression from Ref. 5

$$\tau_\phi' \approx \frac{\epsilon_F}{kT}\tau_p , \tag{2}$$

where ϵ_F is the Fermi energy, τ_p is the relaxation time of the pulse, which is determined from the mobility, and τ_ϕ is the relaxation time of the phase of a wave function in the presence of a large amount of impurity. The values of τ_ϕ, calculated according to Eq. (2), are given by Table I. The value of τ_ϵ, obtained in Ref. 6 for $T = 4.2\text{K}$ and $n_s = 5\times 10^{12}\ \text{cm}^{-2}$, is almost equal to our value of τ_ϕ under the same conditions.

It was shown in Ref. 3 that the coefficient a for a many-valley band structure is equal to $n_v - (2n_v^2 - n_v)\beta(T)$ provided that $4DeH\tau_v/\hbar c >> 1$ or $1 - (2 - 1/n_v)\beta(T)$ if the inequality has the opposite sign (τ_v is the inter-valley relaxation time). Assuming that $a = 0.5$ and $n_v = 2$, we can determine the coupling constant $-g(T)$ of electrons,[2] which is equal to 0.44 if $4DeH\tau_v/\hbar c >> 1$ and is equal to 0.5 if $4DeH\tau_v/\hbar c << 1$.

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