Anomalous magnetoresistance in a two-dimensional hole gas

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The anomalous magnetoresistance of a two-dimensional hole gas in inversion channels on a silicon surface has been studied experimentally for the first time. The results show that this anomalous magnetoresistance can be described completely by the theory based on scattering by superconducting fluctuations. The energy relaxation time of the holes is determined. It is concluded that the spin–orbit scattering of holes plays an important role.

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A new explanation for the anomalous magnetoresistance has recently been proposed.[1–4] This explanation is based on an effect of the magnetic field on the quantum corrections to the kinetic coefficients. This approach has been successful, in particular, in explaining the behavior of the negative anomalous magnetoresistance in a two-dimensional electron gas.[5,6] Study of the anomalous magnetoresistance in two-dimensional systems is also proving an effective tool for studying the interaction between electrons and their energy relaxation time.[7,8]

In this letter we are reporting the first experimental study of the anomalous magnetoresistance in a two-dimensional hole gas in inversion channels on a silicon (111) surface. The results show that this magnetoresistance differs in nature from that in a two-dimensional gas of electrons (the sign of the anomalous magnetoresistance, for example, is positive).

The test samples were *p*-channel metal–oxide–semiconductor (MOS) transistors fabricated on a silicon (111) surface. The fabrication procedure and the basic characteristics of these transistors have been described elsewhere.[9] We measured the magnetoresistance $\Delta R = R(H) - R_0$ or the magnetoconductance $\Delta G = G(H) - G_0$ of the samples; here $R(H)$ and $G(H)$ are the resistance and conductance of the channel per unit area when the magnetic field H is oriented normal to the surface of the sample, and R_0 and G_0 are the same, but for $H = 0$. The excess of holes near the surface, Γ_p, was determined from the expression $\Gamma_p = C_d |V_g - V_T|/e$, where C_d is the capacitance of the dielectric, V_g is the voltage on the gate, and V_T is the threshold voltage of the transistor at 77.3 K. The measurements were carried out over the temperature range 4.2-20 K and over the range $\Gamma_p = (2–6) \times 10^{12}$ cm^{-2}. Under these conditions the hole gas at the Si (111) surface is two-dimensional.[9,10]

Figure 1a shows experimental curves of $\Delta R/R_0$ against the magnetic field H. The sign of the magnetoresistance is positive; its H dependence is initially quadratic, but with increasing H the increase in the magnetoresistance slows down. The classi-

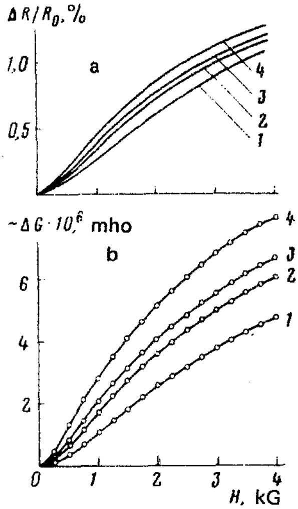

FIG. 1. a–Relative magnetoresistance; b–magnetoconductance of a hole channel vs the magnetic field at 4.2 K. Γ_p, 10^{12} cm^{-2}: 1–1.8; 2–2.8; 3–3.2; 4–5.85. In part b the points are experimental, while the curves are theoretical for the following parameters. 1-4–α = 0.28, 0.37, 0.39, and 0.41, respectively; τ_ϕ (in units of 10^{-12} s) = 4.4, 4.9, 5.6, and 7.2, respectively.

cal magnetoresistance is negligibly small in comparison with the observed magnetoresistance in this range of magnetic fields. Accordingly, a positive anomalous magnetoresistance is observed experimentally. Holyavko *et al.*[11] have reported a similar behavior of the magnetoresistance in a hole inversion channel, but they offered no explanation for it.

For a simple band structure, the theory of Al'tshuler *et al.*[4] yields the following expression for the anomalous magnetoresistance of a two-dimensional system:

$$\Delta G(H) = \frac{e^2}{2\pi^2 \hbar}\left[\alpha f(x) - g(T)\,\phi(y)\right], \tag{1}$$

where $f(x) = \ln x + \Psi(1/2 + 1/x)$, and $\Psi(z)$ is the logarithmic derivative of the γ function, the function $\phi(y)$ is tabulated in Ref. 4, $x = (4DeH/\hbar c)\tau_\phi$, $y = 2DeH/\pi cT$, D is the hole diffusion coefficient, τ_ϕ is the characteristic time for the phase relaxation of the wave function caused by inelastic collisions, and $g(T)$ is the constant of the interparticle interaction. The first term in (1) is the part of the anomalous magnetoresistance which is caused by Anderson localization and by scattering by superconducting fluctuations. Here $\alpha = -\beta(T)$ if there are no localization effects, and $\alpha = 1 - \beta(T)$ if there are localization effects [the function $\beta(T)$ is a function of $g(T)$ and is tabulated in Ref. 2]. The second term in (1) results from the H-dependent corrections to the state density for the interaction between particles.

Expression (1) was used for a comparison with experiment; the second term was ignored, since it is small in comparison with the first in this range of magnetic fields. The results of the comparison are shown in Fig. 1b. We see that the first term in (1) describes the experimental results well at the corresponding values α and τ_ϕ (given in the figure caption).

At low temperatures, the energy relaxation of the particles results primarily from collisions between particles, and in this case we have $\tau_\phi = \tau_E \sim E_F T^{-2}$, where E_F is the hole Fermi energy. Figure 2a shows the function $\tau_\phi(E_F)$ determined from

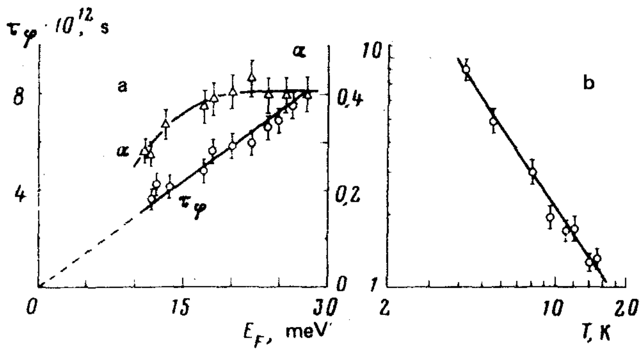

FIG. 2. a–Dependence of τ_ϕ and $-\alpha$ on E_F at 4.2 K; b–dependence of τ_ϕ on the temperature at $E_F = 25$ meV.

the measurements of the anomalous magnetoresistance at 4.2 K; within the experimental errors, this behavior is indeed linear. Figure 2b shows $\tau_\phi(T)$; this behavior is not quadratic and is described instead by $\tau_\phi \sim T^{-n}$, where $n = 1.5 \pm 0.1$. The results of Ref. 12 show that the function $\tau_\phi \sim T^{-2}$ is applicable only if there is no scattering by static defects. If this scattering is taken into account, a linear term appears in the T dependence of τ_ϕ, and the result of the joint effects of the quadratic and linear terms may be a nonquadratic dependence $\tau_\phi(T)$. A similar $\tau_\phi(T)$ dependence was observed by Kawaguchi and Kawaji[8] for electrons under conditions similar to those of the present experiments.

According to our experiments, the coefficient α lies between -0.3 and -0.4 (Fig. 2a) and is independent of the temperature, within the experimental errors. The corresponding values of the constant $\beta(T)$ are from 0.3 to 0.4 if there is no anomalous magnetoresistance resulting from the localization, or from 1.3 to 1.4 in the opposite case. The large values of $\beta(T)$ corresponding to the latter case, however, are possible only under conditions such that a superconducting transition occurs at $T \gtrsim 2$ K. Since superconductivity is not observed in a two-dimensional hole gas even at lower temperatures, we conclude that we have $\alpha = -\beta(T)$ in this particular case and that localization effects are not occurring. The anomalous magnetoresistance in the system studied in these experiments is therefore governed completely by the effect of the magnetic field on the scattering of holes by superconducting fluctuations.[2] The reason that there are no localization effects may be that the spin–orbit scattering of holes is playing an important role; as Al'tshuler *et al.* have shown,[4] this scattering suppresses the anomalous magnetoresistance due to Anderson localization.

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