The Hall effect and magnetoresistance of 2D electron gas in the scattering by flux quanta

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The conductivity of a degenerate 2D electron gas with a large mean-free path in a microscopically nonuniform magnetic field of Abrikosov vortices has been studied. A classical nonvanishing magnetoresistance has been observed. The Hall conductivity is set by the average value of the magnetic field.

In the present letter we report the results of an experimental study of galvanomagnetic properties of 2D electrons in GaAs/GaAlAs heterojunctions placed in a nonuniform microscopic magnetic field. The field nonuniformity was produced by depositing on the surface of a heterojunction of type-II superconducting film.[1] The uniform external magnetic field B applied at right angles to the heterojunction is

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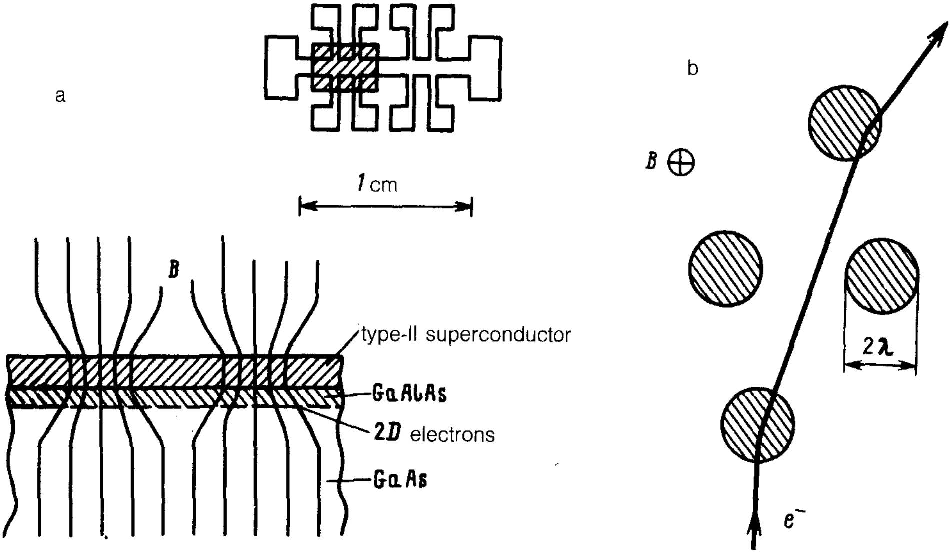

FIG. 1.

partitioned in the superconductor and in the immediate vicinity of its surface into single flux quanta Φ_0 (Abrikosov vortices) which have a characteristic size $\approx 2\lambda$, where $\lambda \approx 0.1$ μm is the screening length (Fig. 1a). The flux density increases linearly with increasing B and the characteristic distance between the vortices is $d \approx (\Phi_0/B)^{1/2} \approx 5[B(\mathrm{G})]^{-1/2}$ μm. At the same time, the mean-free path L of electrons in GaAlAs heterojunctions may be as high as several microns. A case can thus occur in the system we are studying, in which an electron will be affected by the field only along a small part of its path, while the Abrikosov vortices will be the electron scatterers[1)] (see Fig. 1b). The vortex in this case is an essentially quantum scatterer, since the classical angle of deflection of an electron which passes through the field of the flux quantum is always of the same order of magnitude as the angle of the quantum-mechanical diffraction (even when $\lambda_F \ll \lambda$, where λ_F is the electron wavelength). Furthermore, because of the presence of the vector potential, the scattering of electrons occurs outside the vortex region. The scattering by vortices is expected to lead to a peculiar behavior of the magnetoresistance of heterojunctions as a function of B. A question which naturally also arises is whether such a system exhibits a Hall effect and, if so, what is its magnitude?

The samples were synthesized from $GaAs/Ga_{0.7}Al_{0.3}As$ heterojunctions with an electron density 5–6×10^{11} cm^{-2} and mobilities 2.3×10^5 cm^2/(V·s) ($L = 2\mu$m) and 3×10^4 cm^2/(V·s) ($L \approx 0.3$ μm). The distance between the surface of the crystals and the 2D layer is about 400 Å. The mesa structure on the surface was etched in such a way that a single crystal concurrently had two identical samples with the Hall geometry (see the inset in fig. 1a). A superconducting film was deposited on one of the samples, while the other was the test sample used to compare the results with the case in which the field was distributed uniformly. As a type-II superconductor we used lead

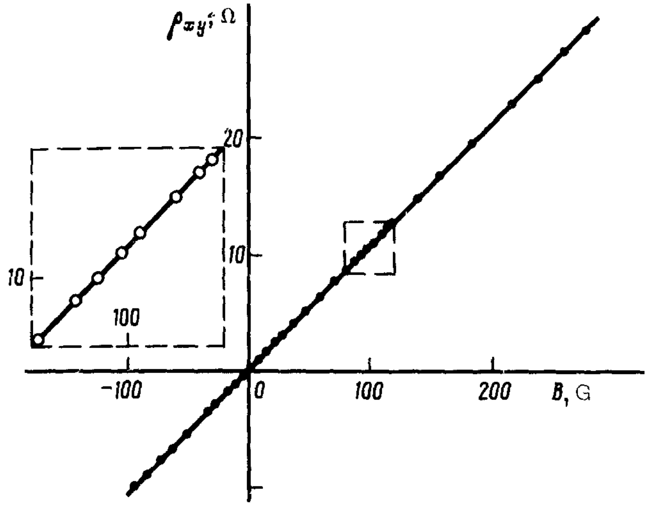

FIG. 2. The Hall resistivity of 2D electrons in a heterojunction in a uniform magnetic field (solid line) and in an Abrikosov vortex field (points). In the inset the scale is increased by a factor of four.

films of thickness 0.2 μm with $\lambda \approx 0.1$ μm, which was estimated from $H_{c2} \approx 1.0$ kg, taking into account that the superconducting transition temperature of the films was the same as the T_c of pure lead: $T_c = 7.2$ K. The resistance in the vortex field was measured when the samples were cooled in the magnetic field from $T > T_c$ to the temperature of the experiment: 4.2 K (Ref. 1).

Figure 2 shows the experimental curves of the Hall resistivity ρ_{xy} in a uniform field (the tested part of the structure) and in a vortex field. The curves for both samples agree within experimental error ($<1\%$), and ρ_{xy} depends linearly on B. We wish to note, in particular, that with an increase in B upon satisfaction of the condition $d < 2\lambda$, the fields of single vortices begin to overlap themselves and at $B = 200$ G the field modulation is no greater than several percent. Consequently, a sample with a superconductor in fields higher than 200 G can have a uniform field. An absence of any deviations from linearity on the ρ_{xy} curve in this sample in the region where a nonuniform field distribution becomes a uniform distribution is the most direct proof that the Hall effect in a vortex field obeys the same law as that in a uniform field: $\rho_{xy} = B/\text{nec}$.

Figure 3 shows the experimental curves of the additional resistance $\Delta R(B)$ which occurs in a vortex field and which is calculated as the difference between the resistances $\rho_{xx}(B)$ of the samples with a superconducting layer and those without it. In the case of a heterojunction with $L \approx 2$ μm in low fields we see a linear dependence $\Delta R(B)$ which corresponds to a linear increase in the concentration with B, $N = B/\Phi_0$, of the vortex scatterers. A further increase in B leads to a nearly uniform field distribution in the superconductor, and the difference between the samples under investigation and the test sample should vanish, as was observed experimentally. In the case of a heterojunction with $L \approx 0.3$ μm no difference has been observed between the samples in

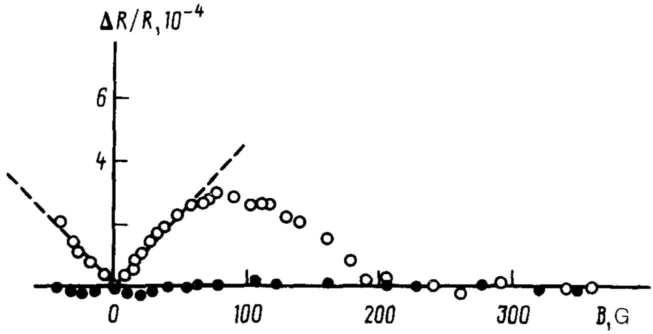

FIG. 3. Additional magnetoresistance in a vortex field. Open circles—for a sample with an electron mean-free path of 2 μm; filled circles—$L \approx 0.3$ μm.

question within the same experimental measurement error limits $\Delta R/R$ (Fig. 3). It should be emphasized that the positive value of ΔR which was observed is not related to the change in the slightly localized negative magnetoresistance in a vortex field. The weak localization in a vortex field was studied in Refs. 1 and 2. This localization accounts for the qualitatively different behavior of the additional resistance ΔR, which is seen only in fields $B \leqslant \Phi_0/L_\varphi^2 \approx 1$ G (L_φ is the length of the phase-coherence disruption of 2D electrons).

To explain the behavior of ρ_{xy} and ρ_{xx} in a vortex field, let us consider a simple model in which the field inside the vortex, B_0, does not depend on the coordinates: $B_0 = \Phi_0/\pi\lambda^2$ (Fig. 1b). The mean-free path and the vortex spacing are assumed to be large in comparison with λ. Upon passing through a vortex an electron is typically deflected through an angle $\theta_m = \omega_c^0 \tau_{\rm tr} = \lambda_F/\pi\lambda \ll 1$, where ω_c^0 is the cyclotron frequency in a field B_0, and $\tau_{\rm tr} = 2\lambda/v_F$ is the transit time. The value of θ_m is approximately equal to 0.07 under our experimental conditions. A deflection of the electron in the same direction after sequential passages through several vortices suggests that the average force of the vortices acts in the direction perpendicular to the electron motion. Let us estimate this force F in the field term of the kinetic equation: $\mathbf{F} \times \partial f/\partial \mathbf{p}$. Clearly, $F \approx \Delta p/\tau^*$, where $1/\tau^* = 2\lambda N v_F$ is the frequency of collisions with the vortices, and $\Delta p \approx p_F \theta_m$ is the variation of the transverse component of the momentum of the electron upon passage through a single vortex. We thus find $F \approx (e/c) v_F B$, consistent with the Lorentz force in a uniform external field. An exact quantum-mechanical calculation[2] (for $\lambda \gg \lambda_F$) gives a value of unity to the numerical coefficient in this formula. For the Hall resistivity we therefore obtain the standard formula: $\rho_{xy} = B/\text{nec}$. A random vortex distribution in space leads, even in the absence of any other scattering, to a finite resistivity, $\rho_{xx} = m/ne^2\tau_{\rm tr}$, where $1/\tau_{\rm tr} \approx (1/\tau^*)\,\theta_m^2 \propto B$. A classic nonvanishing magnetoresistance thus appears in a degenerate electronic system with an isotropic spectrum. This magnetoresistance, which is linear in B, occurs as a result of an increase in the vortex concentration due to an increase in the external field. Such a behavior of the magnetoresistance is in good agreement with that observed experimentally. For a sample with $L = 2$ μm in a 25-G field the theoretical value $\Delta R/R = L/v_F \tau_{tr}$ corresponds, however, to $\approx 10^{-3}$, which is approximately an order of magnitude larger than the value obtained experimentally.

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[1)] The idea that at $L \gg \lambda$ vortices can be viewed as auxiliary scatterers was advanced by I. B. Levinson.
[2)] The theory will be published elsewhere.

[1]A. K. Geĭm, Pis'ma Zh. Eksp. Teor. Fiz. **50**, 359 (1989) [JETP Lett. **50**, 389 (1989)].
[2]J. Rammer and A. L. Shelankov, Phys. Ref. B **36**, 3135 (1987).

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