Scattering of ballistic electrons at a mesoscopic spot of strong magnetic field

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We report quenching of the Hall effect with increasing magnetic field confined in a micron-sized spot. Such fields were created by placing tall ferromagnetic pillars on top of a two-dimensional electron gas, which allowed us to achieve the field strength up to 0.4 T under the pillars in the absence of external field. The quenching is accompanied by an anomalous increase in resistance and occurs when the cyclotron diameter matches the size of the magnetic spot. The results are explained by a rapid increase in the number of electrons that are scattered or quasilocalized by the magnetic region.

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During the last decade, transport phenomena in microinhomogeneous magnetic fields have been a subject of intense interest and significant experimental efforts.[1–13] Using microfabricated ferromagnetic and superconducting structures deposited on top of a two-dimensional electron gas (2DEG), various configurations of mesoscopic magnetic fields have been created and studied, including 1D and 2D periodic modulation,[1–4,14,15] individual magnetic barriers,[5–10,16–18] and a random distribution of magnetic field.[11–13,19–21] Several new phenomena have been found, with most attention being attracted by commensurability oscillations[1–4] and anomalous transport along special (e.g., snakelike) trajectories.[6,9,17,18]

In this paper, we report a different experimental geometry, where ballistic electrons at zero magnetic field are injected into a micron-sized region with a strong field inside. Their scattering as a function of the strength of the local field has been studied. Such a scheme is conceptually most simple and has often been considered in a theory of effects induced by magnetic barriers. In experiment, however, it has so far proved impossible to avoid additional (also interesting) effects caused by the presence of either external field or submicron spikes of strong magnetic field near the edges of magnetic microstructures.[6–9] We have implemented the idealized geometry by microfabricating dysprosium pillars with both height and diameter of the order of 1 μm on top of a 2DEG and magnetizing these pillars by an external field, which was subsequently removed, leaving a micron-sized spot of magnetic field in the 2DEG. The 2DEG's conductivity in zero external field was measured for different values of the magnetization of pillars' and, thus, for different fields underneath. The most unexpected finding of this work is that the Hall effect very rapidly becomes strongly suppressed while the resistivity increases significantly (by 100%), if the cyclotron diameter becomes smaller than the diameter of the magnetic spot. Monte Carlo simulations of ballistic transport through such field inhomogeneities show that the observed phenomena are associated with back scattering and trapping of electron orbits by the field region.

Our experimental devices are shown in Fig. 1 and consist of a set of Hall crosses having the lithographic width of about $w = 2$ μm etched in a GaAs/Al_xGa_{1-x}As heterostructure with a 2DEG embedded 70 nm below the surface. The 2DEG has the electron density of $n \approx 3.45\times10^{15}$ m^{-2} (increasing to 4.85×10^{15} m^{-2} after illumination) and mobility ≈ 100 $m^2/(V\,s)$. Dysprosium structures of different diameters $2r \approx 1$, 1.5, and 3 μm and of thickness $h \approx 1.5$ μm were placed in the center of the Hall crosses by electron-beam lithography using a special double-layer technique, which allowed lift-off procedures even for such an exceptionally thick Dy layer. Dy is a material with the highest known saturation magnetization (≈ 3.7 T at low temperatures) which, along with the fact that Dy films are known to produce negligibly small electrostatic and strain effects in a 2DEG, makes it most suitable for our studies. The inset in Fig. 2 shows the field profile in the plane of the 2DEG calculated for a uniformly magnetized pillar ($h \approx 1.5$ μm) and a disk ($h \approx 0.15$ μm) of the same diameter $2r \approx 1$ μm. It is seen clearly that, for the pillar geometry, the stray field outside the central area is at least one order of magnitude less than the magnetic field below the pillar. In contrast, for the case of a typical disk, the situation is quite opposite: the field profile exhibits a large sign-reversing spike near the edge and

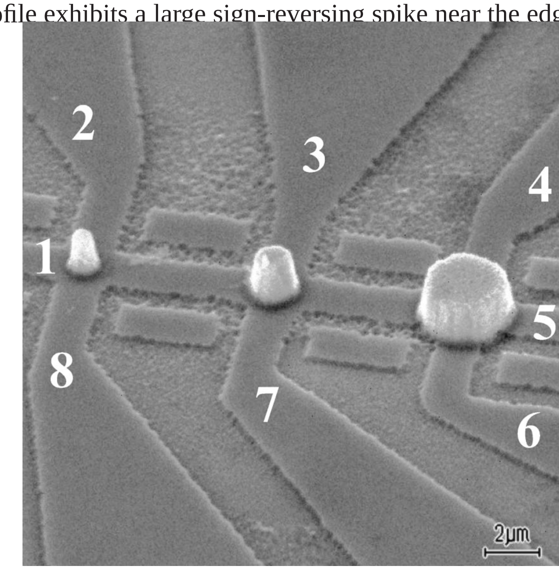

FIG. 1. Scanning electron micrograph of one of the studied devices with Dy pillars placed in the centers of three Hall crosses.

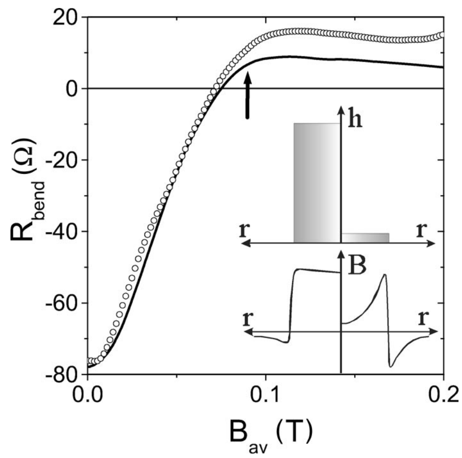

FIG. 2. Bend resistance R_{bend} measured for a Hall cross with 1.5-μm Dy pillar. Symbols: strongly inhomogeneous magnetic field is created by the magnetized pillar in the absence of any external field; solid line, R_{bend} in uniform magnetic field (the Dy pillar is demagnetized). The arrow marks the field where the two curves break apart. Inset: profiles of the magnetic field in the 2DEG below a uniformly magnetized pillar $[h/(2r)=1.5$; left] and a disk $[h/(2r)=0.15$; right].

a rather low field in the center (the spike has a width $\sim h$). The behavior reported in this work is essentially related to the presence of a finite-size spot of magnetic field with the steplike profile rather than a narrow spike in a 2DEG.

In order to vary the strength of the local field underneath the pillars, we used the following procedure. By cooling down our devices in zero field from temperatures above 120 K (above the ferromagnetic transition in Dy) to 0.3 K (where most experiments were performed), we ensured that the Dy pillars were in a demagnetized state (e.g., no magnetic field was detected in any 2DEG property). After that, we applied an external field along the axis, of pillars', sweeping it to a value B_{ex} and back to zero again. This procedure leaves remnant magnetization in Dy, which can be varied by sweeping each time to a different value of B_{ex}. By gradually increasing B_{ex} (from 0 up to 4 T in increments of 0.05 T), we have managed to increase magnetization of Dy in a gradual and highly reproducible manner, creating magnetic fields ranging from 0 to 0.4 T underneath the pillars.

As seen in Fig. 1, our devices contain a Hall cross that is totally covered by a large Dy tablet that generates a practically uniform field in the sensitive area of the cross (details to be published elsewhere). This cross was used only to measure remnant magnetization of Dy and calibrate remnant magnetic fields created by the other, smaller pillars.[22] It has previously been shown that ballistic transport through a Hall cross does not depend on a distribution of weak magnetic field inside and is determined just by its average over the central part of the cross (square $w\times w$).[5,16] Accordingly, it is convenient to present our experimental data in terms of the average magnetic field B_{av}, which—in the case of an inhomogeneous field—can be found from the measured magnetization of Dy and the calculated field profiles under different pillars as shown in the inset to Fig. 2.

Figure 2 plots the behavior of bend resistance R_{bend} found in uniform magnetic field and in the field with the steplike profile induced by a magnetized pillar. The bend resistance is defined as the ratio between the voltage measured between two adjacent contacts (e.g., leads 7 and 5 in Fig. 1) and the current put through the opposite pair of contacts (leads 1 and 3). For diffusive electrons, R_{bend} would be simply proportional to the resistivity of a 2DEG. Ballistic electrons, however, can overshoot the central region and enter the opposite (voltage) contact. This leads to negative values of R_{bend} as indeed seen in Fig. 2 in low fields. Stronger fields turn ballistic electrons away from entering the opposite lead, so that the bend resistance increases, becomes positive, and eventually saturates to a finite value, which is determined by scattering of curved electron orbits at boundaries and background impurities in the Hall cross. This saturation value of R_{bend} corresponds to the effective resistance of the cross as would be measured for diffusive electrons and the saturation is reached when the cyclotron diameter becomes less than the Hall cross dimensions.

In weak magnetic fields, we have observed no notable difference in the behavior of R_{bend} for the cases of uniform and strongly inhomogeneous magnetic fields (see Fig. 2). This shows that the ballistic transport in this regime is determined entirely by the average field, as expected.[5,16] However, in higher fields, where the bend resistance becomes positive, the two curves in Fig. 2 break apart, indicating that the approximation of the average field is no longer valid. The curve for the uniform field saturates at a value of 8 Ω, which is of the order of the 2DEG's longitudinal resistivity ρ_{xx}. The major effect induced by the field inhomogeneity is that R_{bend} exhibits saturation to a twice-higher value. This clearly shows that the local field created by the strongly magnetized Dy pillar introduces a significant amount of extra scattering in the cross.[23]

The behavior of the Hall effect with the increase of the field strength in the magnetic spot is shown in Fig. 3, where we plot measurements on the same cross for two different electron concentrations (in the dark and after illumination[24]). In weak fields, the Hall resistance R_H depends linearly on B_{av} and, as expected, practically coincided with the dependencies found in uniform field (for clarity of presentation, we avoid plotting the additional curves, which are almost straight lines over the whole range of Fig. 3). Above a certain magnetic field, however, the Hall effect in the inhomogeneous field no longer depends on B_{av} linearly. In this regime, R_H is strongly suppressed and, moreover, its slope dR_H/dB becomes nearly zero (high-concentration curve in Fig. 3). The latter behavior indicates most clearly that the average-field approximation[5,16] fails in the case of a strong magnetic inhomogeneity and the Hall response becomes dependent on details of a field distribution, in agreement with our conclusion for the case of R_{bend}.

To corroborate our experimental results, we have calculated the resistivity tensor using a billiard-ball model of ballistic transport.[25] As the magnetic-field distribution we used calculated magnetic-field profile for 1.5-μm Dy pillar presented on inset in Fig. 2. No fitting parameter was used in the model. The results of the numerical analysis are shown in Fig. 3 by dashed lines. In low fields, the theoretical and experimental curves follow each other almost exactly. Furthermore, if the strength of magnetic inhomogeneity in-

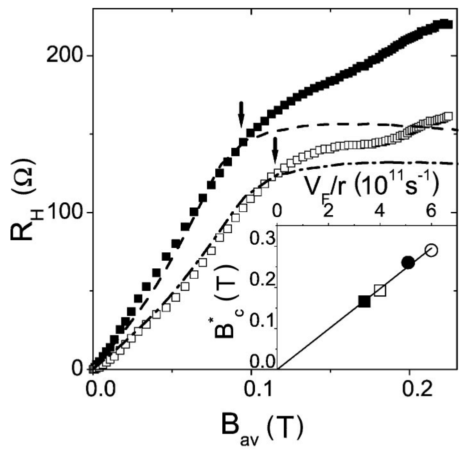

FIG. 3. Hall resistance measurements on the cross with 1.5-μm Dy pillar. Symbols are experimental data; curves, theoretical calculations. Solid symbols, and the dashed curve correspond to the low electron concentration, open symbols, and the dash-dotted line-high electron concentration. The arrows mark the critical fields B^*_{av}. Inset: dependence of the critical magnetic field B^*_c on electron concentration and radius of the pillars. Squares and circles are for the 1.5- and 1-μm Dy pillars, respectively.

creases above a critical value, the theory also yields a very rapid suppression of the Hall effect. This occurs above the same fields as those found experimentally. The only difference is that the theory predicts a stronger suppression than that observed in the experiment. This difference can be attributed to the fact that our devices have slightly rounded corners rather than the straight corners assumed in the numerical analysis.[16,26–28]

One can notice in Fig. 3 that the high-concentration curve bends at a slightly higher ($\sim$20%) field than the one for the low electron concentration. Our measurements on the smaller (1 μm) Dy pillars have shown a behavior very similar to that in Fig. 3, except that the bending occurs in magnetic fields of about 50% higher than those found for the 1.5-μm Dy pillar. We can quantify this rapid bending on the Hall curves by defining a critical magnetic field B^*, at which the slope changes noticeably with respect to the linear dependence found in uniform field. We have chosen, somewhat arbitrarily, a value of 25% for the critical slope change, and the arrows in Fig. 3 mark the critical fields determined in this way. These fields roughly coincide with the fields corresponding to splitting of the R_{bend} curves as shown in Fig. 2.

One may expect (and our theoretical analysis shows this as well) that the important parameter describing the breakdown of the average-field approximation is not the value of the average field, B_{av}, but the field strength underneath the pillar in the center of a Hall cross, B_c. Indeed, B_{av} takes into account stray fields and its value depends on the size of the cross, while B_c is a characteristic of the magnetic spot itself and defines the curvature of resulting electron trajectories. For each particular pillar the relation between B_{av} and B_c is determined only by the geometry, and we have found $B_c = 1.73B_{av}$ for the 1.5-μm pillar and $B_c = 3.87B_{av}$ for the 1-μm pillar. This yields the critical fields B^*_c under the 1.5-μm pillar to be $\approx$0.165 T in the dark and $\approx$0.195 T after illumination and, for the 1-μm pillar, $B^*_c \approx 0.26$ T and $\approx$0.29 T, respectively.

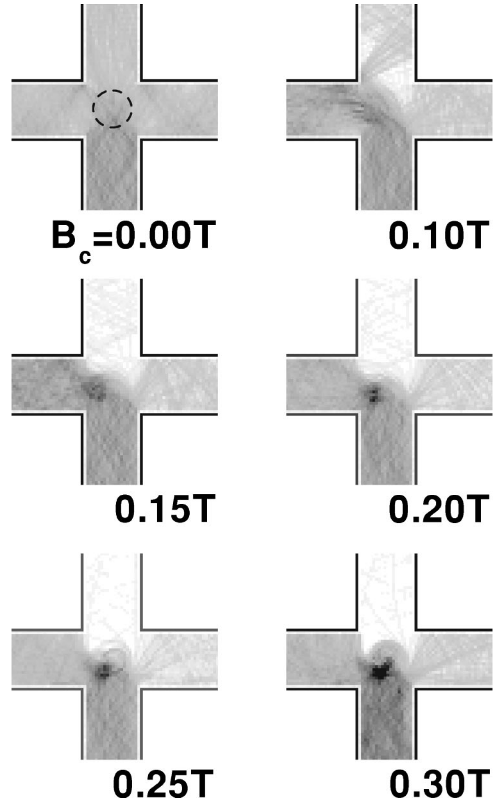

FIG. 4. Spatial distribution of the probability of finding injected electrons at different positions inside a Hall cross in the presence of a local spot of magnetic field with strength B_c. The magnetic spot used in our numerical simulations is shown by a circle in the top figure.

The above values are plotted in the inset of Fig. 3 as a function of V_F/r, where V_F is the Fermi velocity. This description conveniently allows us to present the data for different r and different concentrations (different V_F) on the same graph. The experimental data points in the inset fall on a straight line through the origin, which is described by the equation $B^*_c = \alpha(m^*/e)\times(V_F/r)$ or, alternatively, $r = \alpha\rho_c$, where m^* is the effective electron mass, e the electron charge, ρ_c the cyclotron radius, and α is a fitting parameter close to 1. The best-fitting parameter α is found to be 0.79, i.e., indeed close to unity (note that the exact value of α is sensitive to our chosen definition of B^*). In other words, the breakdown of the average-field approximation, which is seen as the rapid quenching of R_H and the strong increase in R_{bend}, occurs when the cyclotron diameter for ballistic electrons becomes equal to the size of the magnetic spots. Our calculations yield the same linear dependence with $\alpha = 0.80$ (for the same definition of B^*) and are shown by the solid line in the inset.

To gain a better physical insight, in Fig. 4 we have calculated the probability of finding ballistic electrons at different positions in a Hall cross, which has a spot of magnetic field in its center. Parameters for this numerical experiment are chosen to be the same as for our Hall crosses with the 1.5-μm Dy pillar. Ballistic electrons are injected from the bottom lead and the images in Fig. 4 show accumulated and superimposed snapshots of the generated electron trajectories. If no magnetic field is present ($B_c=0$) the probabilities for an electron to go left or right are equal (the same gray-scale densities), which means that no Hall effect is induced. At moderate fields inside the magnetic spot ($B_c=0.10$ and 0.15 T) electrons preferably turn left, which results in the appearance of Hall response. As the strength of the central field increases further and exceeds B_c^*, the probability for electrons to turn left diminishes and, at the same time, the probability of back-scattering increases dramatically (see images for 0.2, 0.25, and 0.3 T). Moreover, one can clearly see a sharp increase in the probability density, which appears at the center of the cross for $B>B_c^*$. A closer inspection shows that this effect is due to trajectories, which stay inside the magnetic spot for an extended period of time, i.e., the trajectories correspond to electrons that become virtually localized within the region. These electrons eventually have to leave the magnetic spot but they stay inside long enough to experience one or another sort of scattering and, for all practical purposes, can be considered as trapped. Neither the backscattered nor quasitrapped trajectories contribute to the Hall signal (in the latter case, electrons leave the magnetic spot in random directions), which qualitatively explains the diminished Hall response above B^*. At the same time, the increase in the number of backscattered and trapped electrons indicates that the magnetic spot becomes virtually nontransparent for injected electrons and scatters them randomly, which explains the observed increase in the bend resistance.

In conclusion, we have created a strong magnetic inhomogeneity in a 2DEG and observed a very rapid suppression of the Hall effect and a 100% increase in the bend resistance when the cyclotron radius becomes smaller than the size of the magnetic region. The results are in quantitative agreement with the billiard model of ballistic transport through a magnetic spot and can be interpreted as a decreased transparency of the magnetic-field region which starts to trap and scatter electrons. Our results demonstrate that, using tall ferromagnetic microstructures, it is possible to create efficient magnetic barriers in a 2DEG and, probably, even barriers with quantizing magnetic fields.

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[22] Remnant Hall signal measured on the cross with the large Dy pillar yields a value of remnant magnetic field under the tablet in the plane of the 2DEG. Using the known dimensions of this and other Dy pillars, we calculated their demagnetization factors, which then allowed us to calculate remnant magnetic fields under different tablets, for a given value of B_{ex}. The accuracy of the above procedure was proven directly by measuring magnetic fields under different pillars in low fields, where the Hall response is given by B_{ex} (Refs. 5,16) and at nitrogen temperatures, where the transport becomes diffusive and the Hall response is again given by the average field.

[23] Seemingly identical empty Hall crosses can sometimes exhibit R_{bend} saturating to somewhat different values. Therefore, to avoid any ambiguity, in Fig. 2 we plot measurements for the same Hall cross. In order to measure in a uniform field in the presence of a Dy pillar, we first demagnetized the pillar and then applied fields not exceeding 0.2 T. Because of the high coercitivity of Dy, such small external fields have appeared not to magnetize our pillars and disturb the uniform field distribution.

[24] To avoid any shadows in the 2DEG from the pillars, we illuminated our heterostructures from the back through the substrate.

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