Effect of edge transmission and elastic scattering on the resistance of magnetic barriers

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I. INTRODUCTION

A two-dimensional electron gas (2DEG) reacts sensitively to perpendicular magnetic fields. Making the magnetic field inhomogeneous opens the door to a wide variety of fascinating effects and applications, ranging from magnetic superlattices[1] and magnetic waveguides[2] to Hall sensors for magnetic nanostructures.[3, 4] In a classical picture, magnetic barriers can be considered as selective transmitters that filter the electrons according to their angle of incidence.[5] In a ballistic sample without edges, one would therefore expect that above a critical barrier height the barrier closes, all electrons are reflected and the resistance approaches infinity. Recently, magnetic barriers have received renewed interest due to their potential applications as tunable spin filters and detectors, both of which are highly desirable spintronics devices.[6, 7] In a classical configuration strongly localized along one in-plane direction and homogeneous in the second one.[6] In a classical picture, magnetic barriers can be considered as selective transmitters that filter the electrons according to their angle of incidence.[5] In a ballistic sample without edges, one would therefore expect that above a critical barrier height the barrier closes, all electrons are reflected and the resistance approaches infinity. Recently, magnetic barriers have received renewed interest due to their potential applications as tunable spin filters and detectors, both of which are highly desirable spintronics devices.[6, 7] In such a setup, the magnetic barrier originates from the z-component of the stray field of the ferromagnet, see Fig. 1. This experimental implementation is also the basis for a significant fraction of the theoretical studies.[14, 15, 24, 25]

For an experimental implementation of the theoretical concepts, a detailed and quantitative understanding of the measured transmission properties of tunable magnetic barriers is needed. Previous studies have already shown that both edge transmission and scattering in the barrier region are relevant.[21, 23] Here, we build on these results and discuss in detail how the resistance of tunable magnetic barriers depends upon the $E \times B$ drift at the edges, on the elastic scattering and on thermal smearing. In order to magnify these influences, we have prepared our ferromagnetic films from dysprosium which has a particularly large bulk saturation magnetization of $\mu_0 M = 3.75$ T. This allows us to drive the barriers well into the closed regime, where the transport through the structure is exclusively determined by the effects of interest here. In addition, a top gate was used to tune the electron density.

These measurements are interpreted in a semi-classical picture based on the billiard model for ballistic conductors.[23, 24] We find that (i) the combination of both $E \times B$ type edge drifts and elastic scattering in the barrier determines the barrier resistance, (ii) reasonable assumptions regarding the distribution of scattering angles for the elastic electron scattering lead to excellent agreement of the experimental data with the model, and (iii) thermal smearing has a marginal influence at liquid helium temperatures.

The outline of the paper is as follows: in Section II, we describe the sample preparation, the experimental
setup and the measurement methodology. The experimental results are presented in Section III, while the semi-classical model and its application to our measurements is the topic of Section IV. The paper concludes with a summary and a discussion (Section V).

II. SAMPLE PREPARATION AND EXPERIMENTAL SETUP

A commercially available GaAs/AlₓGa₁₋ₓAs heterostructure with a 2DEG 65 nm below the surface was laterally patterned by using optical lithography and subsequent processing steps. A Hall bar geometry (Fig. 1) was defined by wet chemical etching. Au/Ge ohmic contacts were defined at source and drain contacts and at the voltage probes 1 to 8. A dysprosium (Dy) platelet with a thickness of \( h₀ = 300 \) nm was defined at the heterostructure surface by Dy thermal evaporation at a base pressure of \( 2 \times 10^{-6} \) mbar. A Cr/Au gate layer of 150 nm thickness was deposited on top to prevent the Dy from oxidizing under ambient conditions and to allow the carrier density to be tuned. Six samples were measured, and all showed qualitatively identical behavior. Here, we discuss data taken from one representative sample.

The samples were inserted in a liquid helium cryostat with a variable temperature insert that permits variation of the temperature between 2 K and room temperature. The sample stage is equipped with a rotatable sample holder, such that the magnetic field could be oriented within the x-z plane with an accuracy better than 0.1 degrees.

The carrier densities and the electron mobility were determined from conventional four-probe measurements of the components of the resistance tensor, \( R_{xx} \) and \( R_{xy} \) in perpendicular magnetic fields. The ungated electron density is \( 2.3 \times 10^{13} \) m\(^{-2} \), and the mobility at a temperature of 2 K is \( 29.0 \) m\(^2\)/Vs, corresponding to a Drude scattering time of \( \tau_D = 10.2 \) ps and an elastic mean free path of 2.2 \( \mu \)m. The quantum scattering time was determined from the envelope of the Shubnikov-de Haas oscillations as \( \tau_q = 1.05 \) ps. The vanishing of the Hall voltage was furthermore used to detect the parallel magnetic field configuration. At the maximum magnetic field \( B = 8 \) T used in our experiments, we estimate that the maximum external perpendicular magnetic field component is below 5 mT.

Strong parallel magnetic fields are well known to affect the transport properties of 2DEGs by modifying the density of states and the interactions. In addition, the electron effective mass becomes slightly anisotropic. These effects show up as a weak and approximately parabolic magnetoresistivity.

Increasing B also magnetizes the Dy film along the x-direction. The z-component of the fringe field at the 2DEG is strongly localized at the edge of the Dy in the x-direction and forms the magnetic barrier. The x- and z-components of the fringe field are shown in Fig. 1(c) for the literature value of the saturation magnetization of Dy. Assuming that the fringe field follows the corresponding analytic expressions, \( B_z(B, x) \) is given by

\[
B_z(B, x) = -\frac{\mu_0 M(B)}{4\pi} \ln \left( \frac{x^2 + z_0^2}{x^2 + (z_0 + h_0)^2} \right) \tag{1}
\]

where \( z_0 \) is the distance of the 2DEG from the surface and \( h_0 \) denotes the thickness of the Dy film, see Fig. 1(c). This relation neglects the second magnetic barrier residing at contacts 4 and 8, which is justified since it is sufficiently far away from the region probed between contacts 2 and 3. Edge roughness of the magnetic film may also lead to deviations from eq. (1). We characterized the Dy edge by atomic force microscope measurements and found an edge roughness (single standard deviation) of 35 nm, which is smeared out to a large extent at the 2DEG. We therefore neglect the edge roughness in the following. The magnetization in the x-direction as a function of \( B \) is denoted by \( M(B) \), which can be estimated from Hall measurements on a magnetic barrier as described below. The x-component of the fringe field has a much smaller effect on the 2DEG and is moreover small compared with the B field required to establish saturation (i.e. \( B_{sat} \approx 4.5 \) T, see the inset in Fig. 2). It is therefore neglected in the following.
A current of 100 nA at a frequency of 13.6 Hz is passed from source to drain. The barrier resistance is obtained from the voltage measured between contacts 2 and 3 (Fig. 1) with a lock-in amplifier. The Hall voltage measured between contacts 4 and 8 is used to determine $M(B)$. We assume in the discussion below that the magnetic barriers at both edges of the Dy platelet differ only by their sign.

### III. EXPERIMENTAL RESULTS

Figure 2 shows a typical magnetoresistance trace $R_{xx}(B)$ of our samples, measured on sample A. The traces are hysteretic, reflecting the magnetization characteristics of the Dy film (inset). At the coercive magnetic fields at $\pm 0.9 \, \text{T}$, $R_{xx}(B)$ has minima which equal to high accuracy the magnetoresistance outside the Dy film measured over an identical distance. This shows that the micromagnetic structure in the Dy film which becomes most relevant around the coercive magnetic field [20] has no noticeable effect in our experiments. $R_{xx}(B)$ increases as one goes away from the coercive field, but neither saturates nor approaches infinity, even well above the saturation magnetic field. The slope $dR_{xx}/dB$ above $B_{sat}$ is only partly due to the parabolic background. As discussed in more detail below, if our barrier were fully ballistic and without edges, it would close at $B_{sat}$ away from the minimum of $R_{xx}$. Thus, in 88% of the magnetic field interval scanned, the transmission is governed by the edge and scattering effects of interest. Note that the $R_{xx}(B)$ traces are slightly asymmetric around their minimum. We attribute this effect to the proximity of the voltage probes (17 $\mu$m) to the magnetic barrier, over which the electrons ejected from the barrier may not yet form a Fermi sphere, even though the probes are about 8 elastic mean free paths away from the barrier. Similar effects have been observed by Leadbeater et al. [16] and subsequently been explained in detail by Ibrahim et al. [17].

The Hall resistance of the magnetic barrier (inset in Fig. 1) measures $B_z(B,x)$, averaged over the spatial extension $L$ in the $x$-direction of the Hall probe contacts 4 and 8, i.e. over $8 \mu m$, according to

$$R_{xy}(B) = -\frac{\alpha}{Le} \int_{-L/2}^{L/2} B_z(B,x)dx$$  \hspace{1cm} (2)$$

Here, $\alpha$ represents a Hall factor which may deviate from 1, depending on the sample geometry and the mean free path. [35, 36, 37] For our structure, $\alpha \approx 1$ is expected [3], and we have no reason to assume otherwise, in contrast to the findings reported in Ref. [20]. Here, we have assumed that the magnetic barrier on top of our Hall cross is adequately described by the ballistic model, even though the mean free path is smaller than the width of the voltage probes. Since, however, the FWHM of our barrier in the closed regime is no larger than 300 nm and thus much smaller than the mean free path, and the maximum magnetic field multiplied by the electron mobility $B_{max} \times \mu \gg 1$ for our system in the closed regime, the diffusive model developed in Ref. [38] does not strictly apply as well. [36] while to the best of our knowledge, a model for the intermediate regime is not available. For $\alpha = 1$, we determine from the measured $R_{xy}(B)$ a saturation magnetization of $M_s = 1.9 \, \text{T}$ for our Dy films. This is significantly below the literature value for bulk dysprosium. We attribute this reduction to the embedding of oxygen into the Dy film during metallization, as well as to the granularity of the film. [27] This interpretation is supported by our observation of $\mu_0 M_s$ dropping over time in samples where the Dy films is not covered by a Cr/Au layer.

Figure 3 reproduces the behavior of the barrier magnetoresistance as the temperature is changed.

![Graph](image1.png)

**FIG. 2:** Resistance of the magnetic barrier as a function of the magnetic field (full lines), as measured between contacts 2 and 3. The dashed line shows the magnetoresistance of the 2DEG, measured between contacts 1 and 2. Inset: Hall resistance of the magnetic barrier (the voltage was collected between contacts 4 and 8). The arrows denote the scan directions.

![Graph](image2.png)

**FIG. 3:** Temperature dependence of the magnetic barrier magnetoresistance.
temperature is increased, the magnetic barrier resistance is reduced. At the same time, the shape of the barrier becomes more nearly triangular and the hysteresis decreases. Simultaneously, the resistance minima increase and are shifted to smaller absolute values of $B$. As will be explained in more detail below, this behavior can be understood in terms of a combination of increased scattering and a reduced coercivity of the Dy film as the temperature is increased, while the thermal smearing of the Fermi function plays a marginal role. A slight hysteresis is observed even above the literature value the barrier and reaches the $x$ position 10 $W$. Strong electric edge fields generate specular reflection. The magnetic barrier is incorporated as given by eq. (1) in the $x$-direction and homogeneous in the y-direction. We have introduced scattering in the 2DEG by assuming scattering after time of flights which obey a Poisson distribution with a time constant of $\tau_q$. The electrons in a 2DEG in a modulation-doped Ga[Al]As heterostructure are predominantly scattered at the ionized donors in the doping layer, and the corresponding screened Coulomb scattering is known to form an approximately Gaussian distribution of scattering angles. [20] We therefore assume a Gaussian distribution of scattering angles $\theta$ with a standard deviation of $0.1\pi$, centered at $\theta = 0$ and limited to $|\theta| \leq \pi$. Within our model, the times of flight between two subsequent scattering events form a Poisson distribution with an expectation value of $\tau$. At a scattering event, the angles between the initial and the final electron velocity vector direction are changed according to the distribution function described above. These two distributions reproduce the experimentally determined values for $\tau_q$ and $\tau_D$.

We remark that our simulation results are rather insensitive to the chosen distribution function of scattering angles. We have also used a rectangular distribution, namely a constant probability for scattering angles $\theta \leq 0.06\pi$ and a probability of zero for larger angles. Even though we find slightly higher values for the resistance (about 2.5 %) at small fields, the same values are found in the closed regime.

For each magnetic field, 40000 electrons of Fermi energy $E_F$ are injected. The transmission is determined by

$$T(E_F, B) = \frac{1}{2W} \int_{-W/2}^{W/2} dy \int_{-\pi}^{\pi} \cos(\alpha) t(E_F, \alpha, y, B) d\alpha$$

(3)

Here, $\alpha$ is the angle between the $x$-direction and the direction in which the electron is injected and $t(E_F, \alpha, y, B)$ is either 1 or 0 depending on whether the electron with the corresponding initial conditions is transmitted or not. We note that the carrier density under the Dy film may differ from that underneath the Cr/Au gate, as a consequence of different Schottky barriers. Hall measurements at voltage probes 1 and 5, as well as at 3 and 7, respectively, indicate that the electron density under the Dy is roughly 5% larger as compared with the density measured outside, but this value is ambiguous since the $z$-component of the Dy fringe field superimposes on the homogeneous magnetic field in the $z$-direction and we were unable to separate these two contributions to the modified Hall resistance. [20] We have neglected this density step in our simulations.

The conductance is given by

$$G(E_F, B) = N(E_F) \frac{2e^2}{h} \frac{T(E_F, B)}{1 - T(E_F, B)}$$

(4)

where $N = 2W/\lambda_F = 918$ is the number of modes in our Hall bar and $\lambda_F$ is the Fermi wavelength. We note that according to eq. (4) the contact resistance ($R_c = h/2e^2N = 14.1 \Omega$) between an infinitely extended 2DEG and the Hall bar does not contribute to $R_{xx}$. [20] From eq. (4), the longitudinal resistance $R_{xx}$ across the barrier for a given carrier density is readily obtained from $R_{xx}(B) \equiv 1/G(E_F, B)$. As a test simulation, we have turned off all scattering and set the electric field at the edges to zero, thereby simulating a ballistic magnetic barrier which extends to infinity in the $y$-direction. In this case, the numerical results closely match the corresponding analytical expression [21] and reproduce the critical angle of incidence for which the magnetic barrier closes to an accuracy of 1 degree.

For a comparison of the simulations with the experiments, the magnetization trace $M(B)$ shown in the
In our simulations, we have assumed an electric field of $|\vec{E}| = 10^6 \text{V/m}$. This value can be considered an upper limit, based upon measurements of the steepness of the confining walls and in agreement with the consideration that a potential change of the order of $E_F/e$ cannot occur over a length smaller than the screening length. We note that the simulated barrier resistance is only weakly dependent on the strength of the edge electric field.

For an infinitely extended closed magnetic barrier in a disordered system, the resistance is also kept finite by scattering events in the barrier region, see Fig. 4(a). This is again illustrated by the characteristic trajectories, see the inset in Fig. 4(a): a scattering event may redirect an electron which in the absence of scattering would be rejected by the barrier. For elastic mean free paths comparable to or below the spatial extension of the barrier, the barrier becomes unimportant (open squares in Fig. 4(a), where the simulated elastic mean free path was 440 nm).

In comparison with the experimental data in Fig. 2(a), we observe that the numerical trace for $R_{xx}(B)$ that takes only the scattering into account but disregards edge effects disagrees significantly with the experiment. Here, the measured background magnetoresistance (Fig. 2) has been replaced by its value at $B = 0$ T. The shape of the measurement trace is reproduced, but its absolute value differs by up to 30%. We point out that in this simulation, the only adjustable parameter is the distribution of scattering angles under the constraints set by the measured values for $\tau_D$ and $\tau_q$, which is determined by the details of the disorder potential landscape.

From this separate discussion of the two mechanisms, it emerges that a combination of both edge transmission and scattering-induced transmission determines $R_{xx}(B)$. In fact, inclusion of both elastic scattering in accordance with the measured scattering times, as well as an electrostatic edge field of $|\vec{E}| = 10^6 \text{V/m}$, gives a very good reproduction of the measured trace, see Fig. 4(a). We refrain from fitting the experimental data since further uncertainties may have an influence on this level of accuracy. First, there is a slight asymmetry of the measured traces, which we attribute to asymmetries in the voltage probe geometry. Second, the shape of the magnetic barrier may deviate from eq. (1), and it may be inhomogeneous in the y-direction. Furthermore, the electron density below the Dy deviates from that below the Cr. This effect could in principle be avoided by preparing a thin, homogeneous metal electrode between the semiconductor surface and the ferromagnet.

In order to investigate the influence of thermal smearing, we have calculated the energy dependent conductance $G(E, B)$ by varying the energy in eq. (4), from which the conductance at non-zero temperatures is obtained via

![Figure 4: (a) Comparison of model calculations for $R_{xx}(B)$ with the experimental trace of Fig. 2 (full line), corrected for the magnetoconductance of the 2DEG which is set to its constant value at $B = 0$ T. Full circles: $R_{xx}$ for a barrier with edges (edge electric field $|\vec{E}| = 10^6 \text{V/m}$) and no scattering; triangles: $R_{xx}$ for the barrier with no edges but scattering according to the experimentally determined scattering times; open circles: barrier resistance with both scattering and edge electric field; open squares: $R_{xx}$ for the structure with edges and a small quantum scattering time of $\tau_q = 0.2 \text{ps}$. Inset: typical calculated trajectories in the closed regime: scattering inside the magnetic barrier (trace 1) as well as $E \times B$ drifts by edge electric fields (trace 3) are responsible for a finite resistance. (b) Conductance of the magnetic barrier as a function of electron energy for several values of $\mu_0 M$ including edges and scattering. Large symbols in the figure correspond to the critical energy for which an infinitely extended barrier in a ballistic system will close (the corresponding energy dependent conductance for $\mu_0 M = 1.5 \text{T}$ is shown in the inset).]
where \( f \) denotes the Fermi-Dirac distribution function. Fig. 3(b) shows that the simulated \( G(E, B) \) is a nearly linear function of the electron energy. According to eq. (5), \( G(B, T) \) becomes independent of temperature for \( G(E, B) \propto E \). A similar relation is also approximately found within an analytic treatment of the infinitely extended, open magnetic barrier in a ballistic 2DEG \cite{21}, see the inset in Fig. 4(b). Hence, the inclusion of both edge effects and scattering does not change this insensitivity of the magnetic barrier resistance to thermal smearing. We conclude, therefore, that the changes of \( R_{xx}(B) \) with temperature are, besides the temperature dependence of \( \mu_0 \dot{M}(B) \), mainly due to the temperature dependence of the scattering times. In our experiments, we find that both scattering times are constant up to \( 6\) K, and in addition, we do not see significant changes in \( R_{xx}(B) \), see Fig. 3 while for larger temperatures, the observed Shubnikov-de Haas oscillations no longer allow a meaningful determination of \( \tau_q \). Hence, a reasonable approximation of the measurements at higher temperatures requires more detailed information regarding the scattering times and the distribution of scattering angles than available from our experiments.

We have furthermore studied numerically the effect of Zeeman splitting on \( R_{xx}(B) \) (using an effective g-factor of \(-0.44\)) due to which the two spin directions acquire different Fermi energies and therefore different partial conductances, resulting in a spin polarization of the current. Our simulations suggest that the influence of the spin splitting on \( R_{xx}(B) \) is marginal. Also, it is found numerically that the spin polarization of the current increases with increasing barrier height in the closed regime, but is below \( 10^{-3} \) for all magnetic fields. However, this value is about a factor of 5 larger than the simulated values for magnetic barriers without edges, and we conclude that edge transmission tends to increase the spin polarization. Even accounting for this increase, the effect for a 2DEG in Ga[Al]As remains very small. Finally, we have also incorporated magnetic mass effects induced by the strong parallel magnetic field \cite{33} and find that they are negligible in our parameter range.

V. SUMMARY AND CONCLUSION

We have studied the resistance of magnetic barriers defined in Ga[Al]As heterostructures in the quasi-ballistic regime as a function of in-plane magnetic fields. We have also described the system numerically within a semiclassical model, and we find that the finite resistance observed in the closed regime originates from both elastic scattering in the barrier region and from transmission via \( E \times B \) drifts at the edges of the Hall bar. By using the scattering times as extracted from the experiment, a very good agreement between measurement and simulation is obtained, especially given the uncertainties involved regarding the exact shape and homogeneity of the magnetic barrier. Furthermore, the barrier magnetoresistance is insensitive to thermal smearing, spin polarization and magnetic mass effects. The results also show how the resistance change induced by the magnetic barrier can be increased, which may be of importance if one wishes to observe quantum effects such as resonant tunneling \cite{6} or spin polarization. First of all, both larger mobilities and Hall bars of reduced width will reduce the scattering in the barrier region and thereby increase the barrier resistance. Also, defining soft edges reduces in principle the transmission via \( E \times B \) drift effects; our simulations however suggest that very soft edges with edge fields in the range of 100 V/m are required to obtain a noticeable effect. Finally, the deposition of clean ferromagnetic films under ultra high vacuum conditions should enhance the saturation magnetization almost up to a factor of two in our samples.

Our model can easily be extended to describe more complicated magnetic barrier structures, for example those suggested recently for use as tunable spin filters \cite{8, 11, 12, 13, 14, 15}.

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