A magnetic barrier in confined two-dimensional electron gases: Nanomagnetometers and magnetic switches

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We investigate the conductance properties of a hybrid ferromagnet-semiconductor structure consisting of a confined two-dimensional electron gas and a transverse ferromagnetic strip on top. Within the framework of the Landauer-Büttiker model, we develop an alternative way to consider magnetic fields. Our method describes devices ranging from a recently realized nanomagnetometer down to quasi one-dimensional quantum wires. We provide a rigorous way to relate the measured resistance to the actual magnetization of the strip. Regarding the quasi one-dimensional wires we propose a new device application, a tunable magnetic switch.

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Hybrid ferromagnet-semiconductor structures recently have attracted much attention. Such a combination for instance would allow to probe magnetic properties on a nanometer scale, or to build devices such as spin-valves or nanomagnetometers. In this letter we are interested in the latter class of structures, where the spin of the electron plays a minor role. After a brief review of the experimental situation we present the model and the method used to describe the full quantum mechanical problem. We then discuss the results obtained and compare them with the experiment. A possible device application is discussed at the end.

A device that has been experimentally realized consists of a two-dimensional electron gas (2DEG) which flows through a lateral constriction, i.e. a quantum wire, with a ferromagnetic strip placed on top of it (see Fig. 1). The linear conductance along the longitudinal direction acts as a probe for magnetic fields. As the g-factor for the 2DEG is relatively small the spin degree of freedom enters only as a factor of 2 in the conductance. Only the perpendicular component of the magnetic field \( B_z \) can affect the transport properties of the system. However an external magnetic field \( H_{\text{ext}} \) in the longitudinal direction can be applied in order to rotate the strip’s magnetization \( \mathbf{M} \). For \( H_{\text{ext}} = 0 \), \( \mathbf{M} \) is assumed to point into the transverse direction, due to symmetry this results in zero perpendicular magnetic field \( B_z \). As soon as \( \mathbf{M} \) acquires a non-zero \( x \)-component, a finite \( B_z \) appears which acts as a magnetic barrier in the wire. A typical profile of \( B_z \) is shown in Fig. 2. It is obvious that the presence of such a barrier strongly alters the conductance properties. Kubrak et al. measured the change in the longitudinal conductance as a function of \( H_{\text{ext}} \). They observed a decrease in the conductance with increasing \( |H_{\text{ext}}| \) until it saturates at a finite value. Moreover they could measure a hysteresis, from which one can conclude that the saturation is reached when \( \mathbf{M} \) points entirely into the longitudinal direction.

In order to explain their experimental findings Kubrak et al. applied a semi-classical theory developed for periodic structures. Although some comparison could be done, we think a more rigorous calculation should be performed. Moreover in our model we take into account the transverse confinement and this allows us to go from a quasi 1D quantum wire (few propagating channels) to the Hall-bar situation of the experiment (many propagating channels). The work presented in this letter is therefore more applicable than full 2D theories and describes more realistic electro-magnetic fields than previous quantum wire model calculations.

Our approach is based on the Landauer-Büttiker model which is appropriate if electron-electron interactions are negligible. The conductance is given by the sum over the transmission probabilities of all propagating channels:

\[ G = \frac{2e^2}{h} \sum_{n,m=1}^{N} T_{nm}. \]

(1)

Usually the magnetic field is introduced by choosing a gauge in which the vector potential has only a non-vanishing component along the direction of current flow. This leads to a dependence of the transverse wave function on the longitudinal \( k \)-vectors, which in addition are complex. On the contrary we choose a gauge where the vector potential is all along the transverse direction:

\[ \mathbf{A}(x,y) = \mathbf{A}(x) = \int dx B_z(x) \hat{y}. \]

(2)

We now introduce a discretization grid \( \{ x_i \} \) for the longitudinal direction. Thus we cut the wire into thin slices bounded by the grid points and assign a constant vector potential to each slice. In every slice the Hamiltonian...
can be decomposed in a longitudinal (free motion) and a transverse part, that contains all the information on the magnetic field:

\[ H_{\text{long}}^{\text{trans}} = \frac{\hbar^2}{2m} \partial_y^2 \]

\[ H_{\text{trans}}^{\text{trans}} = \frac{1}{2m} (-i\hbar \partial_y + eA_{x_i})^2 + V_{x_i}(y), \] (3)

where \( A_{x_i} = A(x_i) \) and \( V_{x_i}(y) \) is the transverse confining potential in the \( i \)-th slice. The presence of the gauge field changes the transverse solution in every slice like

\[ \chi_{n,x_i}(y) = \chi^0_n(y) e^{-i e/\hbar A_{x_i} y} \]
\[ E_{n,x_i} = E^0_{n,x_i}, \] (4)

where quantities with a 0 superscript refer to zero magnetic field. Hence the vector potential leaves the transverse eigenenergies unchanged and manifests itself only in a local phase of the wave function. Finally we use a scattering matrix method to compute the transmission through the entire structure \[ ] One big advantage of our method is that an increase in complexity of the device’ or barrier’s structure does not affect the simulation setup, due to its modular architecture.

In the present work we consider a hard wall confining potential of width \( W \). The transport problem is fully described by the transverse eigenenergies in each slice \( E_{n,x_i} \), and the overlap integrals between transverse wave functions belonging to neighboring slices \( S_{nm} = \langle \chi_{n,x_i} | \chi_{m,x_{i+1}} \rangle \). The vector potential appears in the expressions for the overlap integrals only as \( eW/\hbar (A_{x_{i+1}} - A_{x_{i}}) = eW/\hbar \int_{x_{i+1}}^{x_{i+1}} dx' B(x') = \Phi_{x_{i+1}}/\Phi' \), where \( \Phi_{x_i} \) is the magnetic flux in the slice that goes from \( x_i \) to \( x_{i+1} \), and \( \Phi' \) is the flux quantum. The previous remark assures us that the method is not affected by the problems that may arise in discretizing a gauge field, as the results manifestly depend only on the spatial distribution of magnetic flux. The overlap integrals also contain the information of how much mode-mixing occurs at the interfaces between the slices; we use this property to obtain a criterion for selecting the longitudinal discretization mesh. In particular, we require magnetic induced mode-mixing to be small, and this condition translates into \( \Phi_{x_i}/\Phi' < 1 \). Thus the discretization grid has to be chosen so that each transverse slice contains less than a flux quantum. In our numerical calculation this is assured by an adaptive procedure for selecting the longitudinal mesh. \[ ] The magnetic field used for the calculations is computed from the equivalent surface pole densities of \( M_s \) with the approximation that the height of the strip \( h_z \) is much smaller than the distance of the 2DEG from the strip’s center \( z_0 \). The width of the strip shall be denoted as \( d \). In Fig. we show the magnetic field profile, computed making use of the afore mentioned approximation and without it. Although there is a small deviation for the peak values, the approximation is a good one even for strip heights that are of the same order of \( z_0 \).

The first results we show regard a wide wire and its potential application as a nanomagnetometer. In Fig. we show the longitudinal resistance change \( \Delta R \) of a two-point measurement as a function of the longitudinal magnetization. This plot allows to extract \( M_x \) from the measured \( \Delta R \), which then can be used to derive the \( M_x \) vs \( H_{\text{ext}} \) characteristics (hysteresis curve) for the real experimental situation. \[ ] The solid line corresponds to the experimental setup. \[ ] The inset shows the sensitivity of the resistance to the magnetic field. Decreasing the width of the wire leads to lower values of the sensitivity, due to the fact that the wire picks up less magnetic flux. In addition little bumps appear, caused by the increasing influence of the lateral confinement. The computed \( \Delta R-M_x \) relation is in good agreement with the experimental findings.

From now on we will present results for the case of narrow wires, where the quantization along the transverse direction becomes crucial. In Fig. we show the linear conductance vs the Fermi Energy. For small \( M_x \) the conductance resembles the zero field case, but it shows little oscillations around channel openings. These oscillations develop into well-defined resonances, that only manifest themselves in the highest propagating mode. For large magnetization values one clearly can identify the shift of the conductance plateau towards higher energies. This depletion of the conducting channels by the magnetic field becomes more obvious in Fig. where we plot the conductance as a function of the magnetization for three different Fermi energies (indicated by arrows in Fig. ). Although we have increased the magnetization to values that are higher than experimentally achievable with ferromagnetic materials (e.g. the saturation value for cobalt is \( \mu_0 M_s \approx 1.8T \)), this is interesting not only for theoretical reasons, but also because high-field situations could be realized by different experimental setups. However we wish to point out that the abrupt drop of the conductance for the one mode case occurs when the magnetization exceeds an experimentally accessible threshold value.

In virtue of the previous remark we propose that this device, in the few conducting channel regime, can be used as a tunable magnetic switch. The switch is open if the component of the external magnetic field along the longitudinal direction is large enough to rotate the magnetization \( M \) such that it magnetically depletes the wire. The field value at which the switching occurs can be tuned by varying the Fermi Energy (or the width) of the wire, or the geometrical parameters of the ferromagnetic strip. We would like to remark that all the key building blocks for such a device (shallow 2DEG, few modes quantum wire and ferromagnetic strip deposition) have been experimentally realized.

In conclusion we developed a method to describe transport through a confined 2DEG with a magnetic barrier. We performed calculations which will allow to relate the experimentally measured resistance to the properties of the ferromagnetic strip (hysteresis curve). We also inves-
tigated much smaller systems. Based on our findings we propose to use these quantum wires-ferromagnet hybrid structure as tunable magnetic switches.

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FIG. 4. Conductance vs Fermi Energy (in units of the first subband energy $E_1$) in a narrow wire $W = 200\text{nm}$ for different magnetization $\mu_0 M_x = 0.1\text{T}$ (solid), $\mu_0 M_x = 0.5\text{T}$ (dashed), $\mu_0 M_x = 1.0\text{T}$ (dotted), $\mu_0 M_x = 2.0\text{T}$ (long dashed) and $\mu M_0 = 5.0\text{T}$ (dot-dashed). Barrier parameters: $d = 400\text{nm}$, $h_z = 120\text{nm}$, $z_0 = 95\text{nm}$.

FIG. 5. Conductance vs longitudinal magnetization in a narrow wire ($W = 200\text{nm}$ for different Fermi Energies $E_F = 1.5E_1$ (solid), $E_F = 6.5E_1$ (dotted) and $E_F = 12.5E_1$ (dashed). Barrier parameters: $d = 400\text{nm}$, $h_z = 120\text{nm}$, $z_0 = 95\text{nm}$.