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Giant Magnetoresistance Induced by Magnetic Barriers

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***Abstract*—We present experimental results for hybrid ferromagnet/semiconductor devices in which 2D electrons propagate through sub-micron width magnet barriers. Magnetoresistances, MR, of $\sim$1000% are found at low temperatures and $\sim$1% at room temperature. We compared the measured behavior with numerical calculations and give the conditions needed to achieve large room temperature MR.**

***Index Terms*—Magnetoresistive devices, semiconductor devices.**

2D ELECTRONS in nonuniform magnetic fields are predicted to display a range of new semi-classical, and quantum effects [1]. Such nonuniform magnetic fields can be produced by patterned ferromagnetic structures above near-surface 2D electron systems. Micron or sub-micron sized ferromagnetic elements such as magnetic dots and stripes can be used to produce a range of field profiles at the 2DEG. Such hybrid devices have potential applications as magnetic field sensors, memory or logic elements and nanomagnetometers [2]–[5]. In this paper we consider the case of large amplitude, simple magnetic barriers. We show that the temperature dependence of the large MR observed in this system [2] provides important information on the conduction mechanisms and the prospects for useful devices operating at room temperature.

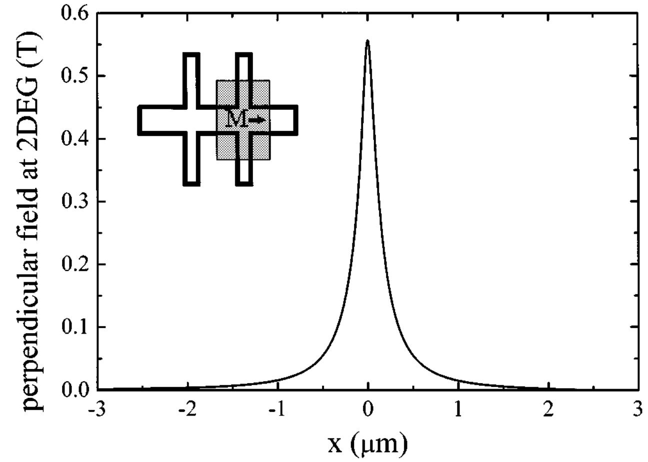

Fig. 1. Calculated magnetic field profile at the 2DEG for saturation M_x. Insert: device schematic.

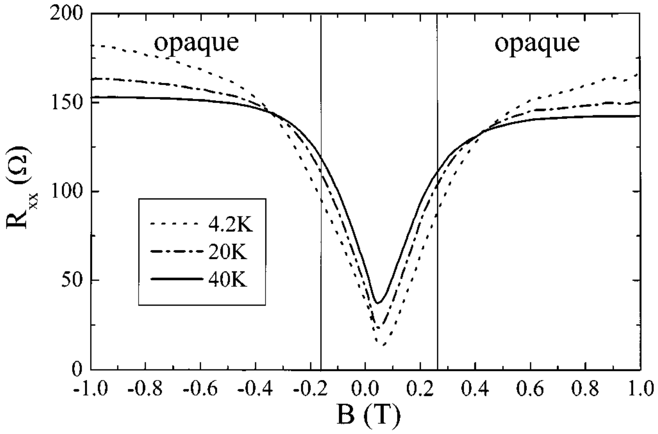

Fig. 2. Temperature dependence of $R_{xx}(B_{ext})$ due to a large amplitude simple magnetic barrier.

The devices are (AlGa)As/GaAs heterostructures in which the 2D electron gas, 2DEG, is formed at a hetero-interface only 50 nm beneath the surface. At 4 K, the electron density is 3.5×10^{15} m^{-2}, the mobility is $\sim$60 m^{2}V^{-1}s^{-1}, and the electron mean free path is $\sim$6 μm. We consider the 2DEG to lie in the x–y plane and the current to flow in the x-direction. Only the component of the magnetic field perpendicular to the plane of the 2DEG, B_z influences the electron dynamics. The magnetic barrier at the 2DEG is produced using the geometry shown in Fig. 1 [3]–[6]. The Co films which are 300 or 600 nm thick, and of length and width 100 to 200 μm, are fabricated on top of Hall bars that are 5 μm wide with voltage probes center to center separation 3 μm. In the absence of an external magnetic field the magnetization, M, of the ferromagnetic element will lie in the x–y plane due to the strong shape anisotropy. Application of an external magnetic field along the x-axis will orient M along this direction. At the plane of the 2DEG B_z is independent of y, has maximum amplitude beneath the edge of the element, $x = 0$, and decays rapidly on a length scale of a few hundred nanometers. The magnitude of B_z is proportional to the x-component of M. By sweeping an external magnetic field applied in the x direction, it is possible to change M_x continuously between positive and negative saturation magnetization, and thereby vary the amplitude and the sign of the inhomogeneous field profile at the 2DEG.

Figs. 2 and 3 show the measured R_{xx} as B_{ext} is swept from -0.4 T to $+0.4$ T. R_{xx} decreases from its maximum value (for

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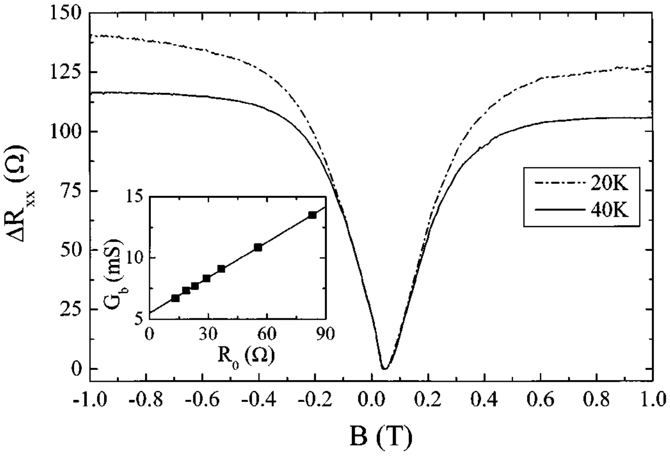

Fig. 3. Temperature dependence of ΔR_{xx}. Insert dependence of the barrier conductance on R_0.

$M_x = -M_{sat}$) to a minimum at the coercive field of the Co element ($M_x = 0$), rising back to the maximum value when M_x reaches $+M_{sat}$. For the same B_{ext} sweep R_{xy} changes from a negative to a positive value (see ref [3]). The use of R_{xy} in this geometry as a possible magnetic field sensor has already been considered in some detail [3]–[5]. We find that the measured R_{xy} at saturation is within 5% of that calculated using the average magnetic field in the Hall cross [4].

The width of the magnetic barrier in the current direction is very much smaller than the low temperature electron mean free path and so the resistance due to the barrier will be dependent on the ballistic transmission probability. This probability depends only upon the initial angle between the y-axis and the trajectory of an electron, entering the barrier region from the left-hand side. Above a critical angle, the electron is transmitted; below this angle, the electron is reflected due to the action of the Lorentz force. The critical angle, for an electron with velocity v, is given by

$$\cos\phi_c = 1 - e\Phi/mv; \qquad \Phi = \int B_z(x)\,dx$$

where Φ is the integrated z-component of the magnetic flux of the barrier. In our geometry the functional form $B_z(x)$ is particularly simple and the integral can be solved analytically to give $\Phi = d\mu_0 M_x/2$, where M_x is the x component of the magnetization of the ferromagnetic element and d is its thickness. If $\phi_c < \pi$, we are in the "transparent" regime and some ballistic transmission is allowed. The conductance of the barrier decreases with increasing barrier height as fewer and fewer electrons are transmitted. For $\phi_c = \pi$, all electrons are reflected and the semi-classical ballistic conductance equals zero, this we refer to as the "opaque" regime. Since we have found that R_{xy} is proportional to Φ we can obtain the functional form of $R_{xx}(\Phi)$ experimentally by plotting R_{xx} as a function of R_{xy} [3].

Fig. 2 shows that with increasing external field we are moving continuously from the "transparent" to the "opaque" regime in our samples. The measured conductance, however, remains finite.

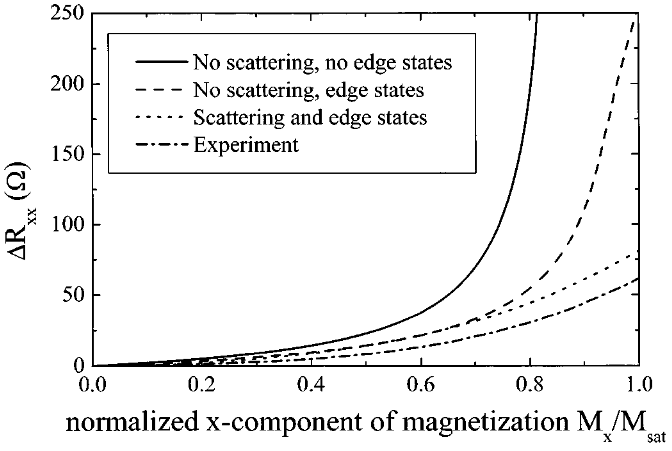

Fig. 4. Calculating the barrier resistance at 4 K.

In the standard semi-classical approach [7] ΔR_{xx} can be calculated directly from the appropriate average ballistic transmission probability to give

$$\Delta R_{xx} = (h/2e^2)(\pi/wk_F)(1 - \cos\phi_c)/(1 + \cos\phi_c),$$

where w is the width of the sample. This expression gives infinite ΔR_{xx} in the opaque regime. It also predicts that R_{xx} should increase linearly with the magnitude of M_x and thus with $\mathrm{mod}(R_{xy})$ for small barrier heights. However experimentally we observe an approximately quadratic dependence. Figs. 2 and 3 show clear evidence for a qualitative difference in the behavior of R_{xx} between the transparent and opaque regime. In the transparent regime, the additional resistance due to the presence of the magnetic barrier, ΔR_{xx} is temperature independent up to ~40 K although the total resistance, and thus the scattering rate, has increased by a factor of ~2. This behavior is consistent with ballistic transmission across the barrier. In the opaque regime, ΔR_{xx} is found to *decrease* with increasing temperature over the whole temperature range. For the case of Fig. 2 the negative temperature dependence of ΔR_{xx} is so large that the total resistance measured in the opaque regime has a negative temperature coefficient of resistance. This is what one would expect if the transmission were accomplished by scattering within the barrier region. The resistance at zero barrier magnetization, R_0, should be simply proportional to the scattering rate. The insert of Fig. 3 shows that the barrier conductance, $G = 1/\Delta R_{xx}$, increases linearly with R_0 and therefore with the scattering rate confirming the role of scattering-assisted conductance. However the intercept at zero R_0 indicates that the conductance would still be far from zero in the absence of scattering. The reason for this is that edge state transport is playing a significant role. The magnetic barrier has stationary bound states and corresponding edge states which can transmit electrons through the barrier. These states correspond to semi-classical skipping orbits at the physical edges of the conducting channel.

We have carried out a semi-classical Monte Carlo calculation of the barrier transmission coefficient including specular reflection of electrons at the sample edges and scattering. Details of this calculation will be presented elsewhere. Fig. 4 shows that

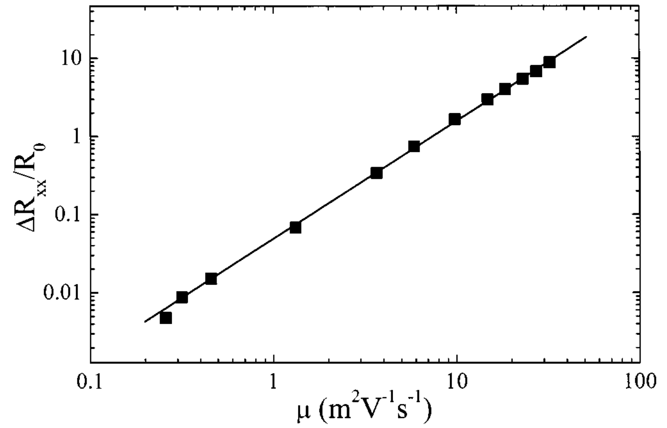

Fig. 5. Dependence of the magnitude of the induced MR on mobility. The lowest mobility corresponds to 300 K.

scattering and edge skipping are both playing significant roles. When they are included the divergence of ΔR_{xx} at large barrier amplitudes is removed and the dependence of ΔR_{xx} on barrier height becomes approximately quadratic, in agreement with our experimental results. These results contrast with those of reference [6] in which an additional MR mechanism is invoked to explain the observed barrier resistances.

At high temperatures the conduction will be diffusive. Fig. 5 shows that the observed MR falls from 1000% at 4 K to ~1% at 300 K. We find that $\Delta R_{xx}?/R_{xx}(0)$ varies as ~(mobility)$^{1.5}$ over a surprisingly large temperature range. Fig. 5 indicates that the MR values would be ~20% if InAs rather than GaAs based heterostructures were used since 300 K mobilities of ~3 $m^2V^{-1}s^{-1}$ can be achieved in the former system [8].

In summary, we find that large-amplitude magnetic barriers across hybrid Hall bar device can produce very large changes in R_{xx}. We find that both scattering and edge state conduction must be included to account for our measured results. We obtain MR values of ~1000% at 4 K, falling to ~1% at room temperature. Much larger values should be achieved in InAs based devices.

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