Temperature dependence of large positive magnetoresistance in hybrid ferromagnetic/semiconductor devices

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We investigate a new type of magnetoresistance (MR) in which the resistivity of a near-surface two-dimensional electron gas is controlled by the magnetization of a submicron ferromagnetic grating defined on the surface of the device. We observe an increase in resistance of up to ~1500% at a temperature of 4 K and ~1% at 300 K. The magnitude and temperature dependence of the MR are well accounted for by a semiclassical theory. Optimization of device parameters is expected to increase considerably the magnitude of the room temperature MR.

Magnetic sensors based upon materials such as permalloy and magnetic multilayers have great promise principally because of the small magnetic fields required to change the magnetization state and hence the resistance of the devices. An attractive alternative approach is to try to use hybrid ferromagnetic/semiconductor devices in which the resistivities of the semiconductor element are controlled by the ferromagnetic element. This approach has been recently used to produce novel hybrid Hall sensors and micromagnetometers. We have recently demonstrated the existence of a new type of magnetoresistance (MR) at low temperatures by using a ferromagnetic grating deposited on the surface of a semiconductor device. In this letter we report very much larger magnetoresistances with values of ~1500% at low temperatures and ~1% at 300 K. Furthermore we show that while the large MR at low temperature arises from electrons moving in "snake orbits," the magnitude at room temperature is determined by a semiclassical effect which has previously been ignored. This in turn has important implications for the optimization of such devices.

The types of device used are illustrated schematically in Fig. 1. A two-dimensional electron gas (2DEG) is formed in a 22 nm wide GaAs/(AlGa)As quantum well, the center of which is only 35 nm beneath the surface of the heterostructure. The electron density is $4.5 \times 10^{15} \text{ m}^{-2}$. The electron mobility is $\mu = 70 (0.6) \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$ at 4(300) K, corresponding to electron mean free paths of $l_e = 7 (0.06) \mu\text{m}$. An array of nickel or cobalt stripes with period 500 nm is fabricated by electron beam lithography directly on the surface of the heterostructure. The stripes have nominal width of 200 nm and height of 100 or 120 nm and are taken to be along the $y$ direction. In order to avoid any strain-induced electric modulation at the 2DEG due to the differential thermal contraction of the ferromagnetic metal and the GaAs, the stripes are oriented normal to the [100] direction which is nonpiezoelectric. The grating covers the entire active area of the Hall bar devices, which are 50 $\mu\text{m}$ wide and which have

![Image](https://example.com/image.png)

FIG. 1. The device structure. The ferromagnetic grating has period 500 nm. The individual stripes have width 200 nm and heights of 100 or 120 nm. As the plan view shows, the current flows perpendicular to the stripes.

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oscillations are a result of a commensurability effect between the diameter of the cyclotron orbit at the Fermi level and the period of the magnetic modulation. As we have shown in Ref. 4, the very large low field magnetoresistance is due to electrons which are trapped in “snake orbits” centered on the lines of zero field due to the reversal in sign of the Lorentz force in crossing these lines. With the nickel stripes the MR is 140% at 1.3 K but with the cobalt stripes we now obtain values up to 1500%. This is due to the larger saturation magnetization which is 1.45 T for Co and 0.51 T for Ni. For \( \theta = 80° \) we calculated the maximum amplitude of the \( z \) component of the magnetic modulation at the 2DEG to be 87 mT for the Ni stripes and 320 mT for the Co stripes. The magnitude of the MR decreases rapidly with increasing temperature but is still appreciable at room temperature as shown in Figs. 3 and 4. The magnitude of the MR at room temperature is very much larger than expected from the mean square value of \( B_z \) and as we will show below it is 15 times larger than that predicted by the simple semiclassical theory of Ref. 4. The principal aim of this paper is to explain this relatively large value of the MR and to draw out the implication for room temperature devices which follow from this.

In the presence of the sign-alternating magnetic field, the dynamics of the electrons are considerably modified. In particular, electrons with initial \( x \) components of velocity below a critical value cannot traverse the magnetic barriers. These electrons are trapped in “snake orbits” propagating in the \( y \) direction along lines of zero magnetic field with drift velocities close to the Fermi velocity. Electrons which can traverse the magnetic barriers execute almost closed cyclotron-like orbits with guiding-centre drift velocities very much less than the Fermi velocity. The anisotropy of the electron dynamics leads to an anisotropic electron diffusivity. Electrons in the snake-like orbits have enhanced diffusivity in the \( y \) direction, \( D_{yy} \), while that in the \( x \) direction, \( D_{xx} \), is reduced. The diffusivity of the electrons in the cyclotron orbits falls as \( B_{z,ext} \) increases. At low temperatures, when the electron mobility is large and \( (\omega_c \tau)^2 \gg 1 \), where \( \omega_c \) is the cyclotron frequency corresponding to the average \( B_z \) and \( \tau \) is the scattering time, the measured resistivity, \( \rho_{xx} \), is proportional to \( D_{yy} \). As we showed in Ref. 4 this results in the very large positive magnetoresistance which increases as \( (\omega_c \tau)^2 = (\mu B_{z,ext})^2 \). Around room temperature \( (\omega_c \tau)^2 \ll 1 \) and \( \rho_{xx} \) is then proportional to \( D_{xx}^{-1} \). It is the therefore the reduction of \( D_{xx} \) due to the inability of a fraction of the electrons to surmount the magnetic barriers which gives rise to the measured MR at room temperature.

We have calculated the diffusivity tensor from the velocity-velocity correlation function for a periodic mag-

![FIG. 2. The relative change in the resistance, $\Delta R/R$, at 1.3 K and $\theta = 80°$. The solid lines are the measured results the dashed lines are the calculation. The smaller MR is for 100 nm Ni stripes the larger is for 120 nm high Co stripes.](image1)

![FIG. 3. The measured magnetoresistance for 120 nm high Co stripes at $\theta = 80°$ at a series of temperatures.](image2)

![FIG. 4. The temperature dependence of the magnitude of the MR for 120 nm high Co stripes at $\theta = 80°$ and $B_z = 0.1$ T. The open squares are the measurements. The solid line is the calculated MR; dashed line is the calculated contribution to the MR due to the modification of $D_{yy}$ [the first term in Eq. (1)]; the dotted line is that due to the modification of $D_{xx}$ [the second term in Eq. (1)].](image3)
magnetic field range of the MR in $B_z$ to calculate\(^4\) and from this one can use Eq. \(\Delta R = \frac{(\omega_s \tau)^2 2\Phi_m}{\pi - \Phi_m} + \frac{2\Phi_m - \sin 2\Phi_m}{\pi [1 + (\omega_s \tau)^2] / [(\omega_s \tau)^2 - (\omega_s \tau)^2] - 2\Phi_m + \sin 2\Phi_m} \). \hspace{1cm} \text{(1)}

The critical angle $\Phi_m$ is defined in Ref. 4. The individual snake orbits have a range of frequencies but these can be replaced by an average frequency $\omega_s$. The derivation of this expression will be presented elsewhere. The first term in this equation arises from the modification of $D_{xy}$. The second term, which we neglected in Ref. 4, arises from the modification of $D_{xx}$.

Provided the magnetization, $M$, of the stripes is known as a function of the externally applied field, the magnetic field profile in the plane of the 2D electrons is relatively easy to calculate\(^3\) and from this one can use Eq. (1) to calculate the MR. In our samples the Fermi temperature is \(\sim 200 \text{ K}\) and so at helium temperatures we can ignore departures from degeneracy. As Fig. 2 shows the agreement between the measured and calculated MR is quite good at low fields. At larger fields the calculation predicts that $\Delta R$ will fall back to zero while the measured values tend to saturate. In this region our model fails due to the inadequacy of the simplified description of the possible orbits.\(^4\) At helium temperatures the first term in Eq. (1) totally dominates. We then expect the magnitude of the MR to increase as approximately the square of the saturation magnetisation, $M_s$, as is observed, since the magnetic field range of the MR in $B_z$ is proportional to $M_s$ and the MR increases as approximately $B_z^2$.

To calculate the temperature dependence of the MR we take the appropriate thermal average over the energy dependent diffusivities. As Fig. 4 shows we find very good agreement with experiment. The effect of temperature on the electron distribution function has only a small effect on the calculated MR and the principal temperature dependence comes from that of the mobility. In practice, below 50 K the first term in Eq. (1) dominates since the mobility and hence $(\omega_s \tau)^2$ is large but this contribution decreases rapidly with increasing temperature as the mobility falls. Above 100 K it is the second term which is dominant. The magnitude of the magnetoresistance at room temperature is approximately proportional to $(\omega_s \tau)^2 = (\mu B_s)^2$, where $B_s$ is calculated to be approximately twice the amplitude of magnetic modulation for the Co stripes; up to 0.6 T. The persistence of the effect to room temperature is a consequence of the high frequency of the snake orbits.

At 300 K the mobility of the quantum well is only 0.6 m$^2$ V$^{-1}$ s$^{-1}$ so large improvements in the magnitude of the MR are expected for devices based upon InAs quantum wells which have much larger room temperature mobilities. The field scale of the room temperature MR is the external field needed to magnetize the stripes and to thus create the magnetic modulation. In the current experiment we need a total external magnetic field of \(~0.5 \text{ T}~\) to saturate the magnetization of the stripes perpendicular to their length. This value is due to the very large shape anisotropy of the long thin cobalt stripes. However, with an appropriate choice of ferromagnetic material and geometry it ought to be possible to make this field scale much smaller. The observed magnetoresistance is a consequence of the sign reversal of $B_z$ and does not arise from the periodicity of the ferromagnetic grating. As we will show elsewhere, it is also present for devices with single submicron magnetic stripes. Thus the prospects are promising for obtaining a MR with both a large total magnitude and large $dR_{xx}/dB$ in submicron devices.

In summary, we have observed a new type of MR which is well described by a semiclassical theory. The MR is due to a strong modification of the electron dynamics and is a generic effect which will be present for any combination of ferromagnet/semiconductor material. The resistance change is about 1% at room temperature in our current devices but optimization of the structures and materials used should lead to considerably larger room temperature values.

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