Giant magnetoresistance and hysteretic effects in hybrid semiconductor/ferromagnet devices

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Abstract

We have investigated ballistic magnetoresistance effects in a two dimensional electron gas subjected to a periodic magnetic field that alternates in sign. The magnetic field was produced by a submicron ferromagnetic grating, made of either nickel or cobalt stripes, which was fabricated at the surface of the heterostructure. We observe giant magnetoresistance effects due to the channeling of electrons along lines of zero magnetic field orientated perpendicular to the current. Our semiclassical model accounts in great detail for all features in the magnetoresistance.

Keywords: Giant magnetoresistance; Lateral superlattices; Two dimensional electron gas; Snake states

Recently there has been a lot of interest in the properties of electrons subjected to a nonhomogeneous magnetic field. A two-dimensional electron system (2DES) subjected to a periodic magnetic field with amplitude, $B_0$, much smaller than the external magnetic field, $B_{\text{ext}}$, exhibits magnetoresistance oscillations due to commensurability effects between the classical cyclotron radius and the period of the magnetic modulation [1–3]. When $B_0 > B_{\text{ext}}$, the resulting magnetic field alternates in sign. An electron travelling in the vicinity of a line of zero magnetic field follows a trajectory with curvature changing sign with the sign of the magnetic field [4–6]. These electron states are therefore confined to a 1D magnetic potential and propagate along open “snake” orbits. The existence of extended states in a random magnetic field is still a matter of controversy [7–10]. Nonhomogeneous magnetic fields obtained in nonplanar 2DEGs have also been investigated in the quantum regime [11,12].

In this work, we demonstrate that these snake orbits lead to a giant low magnetic field ($B$) magnetoresistance in a magnetic superlattice. The origin of this novel magnetoresistance effect lies in the fact that, at low $B$, the electrons are channelled by snake orbits along lines of zero magnetic field orientated perpendicular to the electric field. The amplitude of the magnetoresistance is enhanced by tilting $B_{\text{ext}}$ perpendicular to the magnetic stripes. This effect is due to an increase in the population of snake orbits when the amplitude of the magnetic modulation increases [13].
The hysteresis of the magnetoresistance also provides detailed information about the magnetic properties of our submicron ferromagnetic wires.

Our sample is illustrated schematically in Fig. 1. The 2DES was formed in the 22 nm wide quantum well of a GaAs/(AlGa)As double heterostructure the center of which is only 35 nm beneath the surface. The electron density is $4.5 \times 10^{15} \text{m}^{-2}$ and the electron mobility is $\mu = 70 \text{m}^2 \text{V}^{-1} \text{s}^{-1}$ giving a mean free path of $l_e = 7 \mu \text{m}$. Using electron beam lithography and lift-off techniques we have fabricated a periodic array of ferromagnetic stripes directly on top of the heterostructures. The ferromagnetic stripes have a nominal width of $d = 200 \text{nm}$ and a height $h = 120 \text{nm}$ (100 nm) for the Cobalt (respectively Nickel) grating. The stripes were orientated normal to both the electric field, as shown in the inset to Fig. 1, and the [1 0 0] crystallographic axis which is nonpiezoelectric [1–3]. Each grating covers the entirety of the 50 $\mu \text{m}$ wide high mobility electron channel which has voltage probes separated by 130 $\mu \text{m}$. Because the electrons are 2D their motion is only affected by the component of the magnetic field normal to the 2DES which we take as $B_z$. Tilting the external magnetic field by an angle $\theta$ with respect to the $z$-axis, as shown in Fig. 1, allows us to change magnetization of the stripes and subsequently to tune the magnetic modulation at the site of the 2DES.

Fig. 2 displays the magnetoresistance of both Cobalt and Nickel superlattices versus $B_z$ at different values of the tilt angle. At $\theta = 0$, the magnetoresistance exhibits a series of commensurability oscillations to the periodic magnetic potential [1], as shown in Fig. 2b. The striking feature of the data is a rapid increase of the low $B$ magnetoresistance when the tilt angle increases from $\theta = 0$ to 80°. At 80° the normalised magnetoresistance $\delta R_{xx}/R_0$ in Fig. 2a, was as large as $\sim 1700\%$ for the cobalt superlattices and $\sim 220\%$ for the nickel ones. Fig. 2a shows that the effect of the tilt angle is firstly to increase the range of magnetic field of the giant magnetoresistance up to $B_z = 100 \text{mT}$ and secondly to increase its slope at low $B$. The magnetoresistance also exhibits a hysteresis which when plotted against $B_z$ decreases in width with increasing $\theta$. The extent of the hysteresis is however independent of $\theta$ when plotted versus $B_{\text{ext}}$ rather than $B_z$. This observation suggests that the hysteresis is due to the ferromagnetic grating rather than to the electrons in the 2DES. Larger magnetoresistance effects for cobalt are expected in Fig. 2a due to the 3 times higher saturation magnetisation in cobalt compared to nickel; this together with the angular dependence of the magnetoresistance unambiguously rules out electrostatic effects as a possible explanation [1–3]. We can entirely explain the giant magnetoresistance effect as due to the formation of snake orbits: in particular, the width of the low-field magnetoresistance is the
magnetic field $B_z = B_0$ required to suppress the $B = 0$ lines in the sample. Secondly, we show the slope of the low-field magnetoresistance is proportional to the number of snake orbits on the Fermi surface.

Fourier transformation of Maxwell’s equations, allows us to derive the expression of the magnetic modulation at the site of the 2DES due to an infinite array of stripes with uniform magnetisation $M_0$:

$$\delta B_z(x, z_0) = M_0 \frac{hd}{a} \sum_{j=1}^{\infty} q_j F(q_j) \times \exp[-q_j(z_0 + h/2)] \cos(q_jx - \theta),$$  
(1)

where the form factor for rectangular stripes is

$$F(q_j) = \frac{\sin(q_j d/2) \sinh(q_j h/2)}{(q_j d/2) \sinh(q_j h/2)},$$  
(2)

$q_j = 2\pi j/a$; $a, d, h, z_0$ are the geometrical parameters defined in Fig. 1 and $\theta$ is the tilt angle of the external magnetic field with respect to the $z$-axis. Numerical simulations of electron trajectories show that, in such magnetic profile, only two types of classical electron orbits coexist. Electrons with a sufficiently large initial electron velocity component perpendicular to the magnetic stripes propagate across the sample in the same direction they would have in the absence of the modulation. Electrons with smaller initial velocity components are backscattered by the bands of opposite magnetic field and channelled along snake orbits centered on the lines of zero $B$. All electrons which are impinging on a $B = 0$ line with an angle $\varphi$ smaller than a given angle $\varphi_{\text{max}}$, are therefore trapped in such open snake orbits. A third possible type of cyclotron-like orbit confined to a single band of either positive or negative magnetic field [4–6] does not exist here due to the short period of our superlattice.

If a small magnetic field, $|B_z| < B_0$, is now applied to the superlattice, the free electron-like states form closed cyclotron orbits with guiding center almost frozen in space. Their drift velocity can be neglected compared to that of the open snake orbits which propagate along the $y$ direction with drift velocities, $v_{dy}$, close to the Fermi drift velocity $v_d \sim v_F \sin \varphi/\varphi$. The magnetic modulation induces a correction to the $D_{xy}$ diffusion coefficient which leads to a magnetoresistance [14]:

$$\frac{\Delta R_{xx}}{R_0} = 2(\mu B) \frac{v_{d}^2}{v_F^2},$$  
(3)
we find that to a very good approximation, \( \langle v^2 \rangle \approx v^2_0 (\phi_{\text{max}}/\pi) \) which gives:

\[
\frac{\Delta R_{xx}}{R_0} = (2\phi_{\text{max}}/\pi)(\mu B)^2
\]

The slope of the quadratic magnetoresistance, \( \phi_{\text{max}}/\pi \), is simply the ratio of the number of snake states to the total number of states on the Fermi circle. We now understand that any increase in \( B_0 \) increases the slope of the magnetoresistance by trapping more free-electron states into snake states. When \( |B_z| \) becomes larger than \( B_0 \) the snake orbits are destroyed because the total magnetic field does not alternate in sign anymore. Subsequently the giant magnetoresistance disappears at \( B_z = B_0 \).

Increasing \( \theta \) effectively increases \( B_0 \) through (i) the increase of \( \delta B_z/M_0 \), which is a geometrical effect in Eq. (1), and (ii) the increase of \( M_0 \) at a given \( B_z \). The latter effect is because \( M_0 \) depends on \( B_{\text{ext}} \) whereas the dynamics of the electrons in the 2DES is affected by \( B_z \). At \( \theta = 90^\circ \) for example, \( B_0 \) can be maximised by saturating the magnetisation of the stripes while the average magnetic field at the site of the 2DES remains \( B_z = 0 \).

Fig. 3a shows the hysteresis of the magnetoresistance of the nickel superlattice for \( \theta = 40^\circ \) and \( 60^\circ \). Magnetoresistance hysteresis is stronger in nickel superlattices because our procedure for metal deposition resulted in films of nickel with lower quality than the cobalt ones. As already noted in Fig. 2, the width of the hysteresis region shrinks as \( \cos \theta \). The shape of the hysteresis is a complicated function of the tilt angle which we now describe. The inset to Fig. 3b plots both \( B_z = B_{\text{ext}} \cos \theta \) and \( B_0 = k |M_0(B_{\text{ext}})| \) as a function of \( B_{\text{ext}} \). Rigorously, \( k \) has a small dependence on \( \theta \) given by Eq. (1) but we will neglect it here for the purpose of clarity. Since the existence of snake orbits requires \( B_z < B_0 \), the width of the positive magnetoresistance is simply given by the intercepts at \( B_z = B_0 \). At small tilt angles, represented by \( \theta_1 \) in Fig. 3b, there are two distinct intercepts between the sweep up and down curves at \( B_{z,1} \) and \( B_{z,2} \), respectively. \( B_{z,1} \) and \( B_{z,2} \) therefore define two different values for the falldown of the magnetoresistance which result in the hysteresis seen at \( \theta < 30^\circ \) in Fig. 2. As \( \theta \) increases, \( B_{z,2} - B_{z,1} \) increases by construction and the hysteresis widens.

![Fig. 3. (a) Hysteresis in the magnetoresistance of the nickel superlattice. (b) Calculated hysteresis at an angle \( \theta \sim 40-60^\circ \). The inset displays the amplitude of the magnetic modulation together with the normal component of the external magnetic field at two different values of the tilt angle.](image)
References