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Observation of giant magnetoresistance due to open orbits in hybrid semiconductor/ferromagnet devices

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We have investigated the magnetoresistance of a heterostructure containing a near surface two-dimensional electron gas subject to a periodic magnetic field that alternates in sign. The field is produced by an array of submicrometer ferromagnets fabricated on the surface of the heterostructure. We observe a giant low-field magnetoresistance due to electrons propagating in open orbits along lines of zero magnetic field. We are able to account for the observed form and magnitude of this magnetoresistance in a semiclassical model. [S0163-1829(97)51424-X]

The nature of the electron states of two-dimensional systems (2DES's) in a nonuniform magnetic field has attracted considerable interest recently. The existence of extended states in a random magnetic field is still a matter of controversy.[1–4] In a magnetic field that varies spatially about a mean of zero, the existence of delocalized 1D states propagating along the contours of zero magnetic field has been predicted theoretically.[5–7] Magnetoresistance commensurability oscillations have recently been observed in experimental studies of 2DES's in periodically modulated magnetic fields[8–10] and it has been suggested that an additional low-field magnetoresistance might be associated with such 1D states.[9] Large-period, sign-alternating magnetic modulations have been studied for nonplanar 2DES's in the quantum regime.[11,12]

In this paper, we report the observation of a very large, low-field magnetoresistance (MR) that provides clear evidence for the channeling of 2D electrons in open orbits[5–7] along lines of zero magnetic field. A periodic, sign-alternating magnetic modulation is produced by a submicrometer ferromagnetic grating fabricated above a near-surface 2DES. By tilting the applied external magnetic field with respect to the plane of the 2DES, we are able to study systematically the dependence of the MR on the amplitude of the magnetic modulation. Our experimental results are shown to be in good quantitative agreement with a semiclassical model. The semiclassical origin of the MR is confirmed by the fact that it is still observable above 200 K.

The device used is illustrated schematically in Fig. 1. The 2DES 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. After infrared illumination, the electron density saturates at 4.8×10^{15} m^{-2}, while the electron mobility of 70 $m^2\,V^{-1}\,s^{-1}$ corresponds to an electron mean free path of $1_e=7.7$ μm. An array of nickel stripes with period $a=500$ nm has been fabricated by electron-beam lithography directly on the surface of the heterostructure. The stripes are taken to be along the y direction. The stripes have nominal width $d=200$ nm and height $h=100$ nm. In order to avoid any strain-induced electric modulation at the 2DES (Refs. 8–10) due to the differential thermal contraction of Ni and GaAs, the stripes are oriented normal to the [100] direction which is nonpiezoelectric.[13] The grating covers the entire active area of the Hall bar devices, which are 50 μm wide and which have voltage probes separated by 130 μm. The current direction is perpendicular to the direction of the stripes.

Figure 2 shows the longitudinal MR of the device measured with the external magnetic field perpendicular to the plane of the 2DES (θ=0). The ''sweep up'' trace is for B swept continuously from -0.5 to $+0.5$ T and the ''sweep down'' trace is for $+0.5$ to -0.5 T. The observed MR oscil-

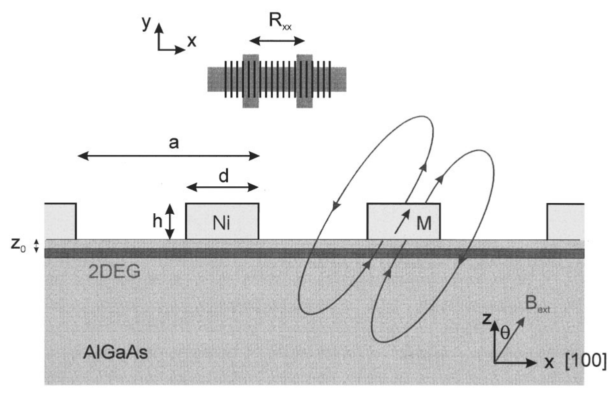

FIG. 1. The device structure: $a=500$ nm; $d=200$ nm; $h=100$ nm; $z_0=35$ nm.

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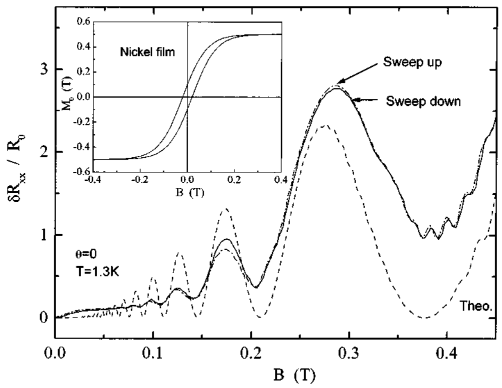

FIG. 2. Commensurability oscillations in the longitudinal MR, measured at 1.3 K ant $\theta=0$ for ''up'' (dot-dashed line) and ''down'' (solid line) field sweeps compared with the calculated behavior (dashed line) for a pure magnetic modulation ($\delta R_{xx} = [R_{xx}(B) - R_0]$; $R_0 = 52\ \Omega$. Inset: The form of the magnetization used in the calculation.

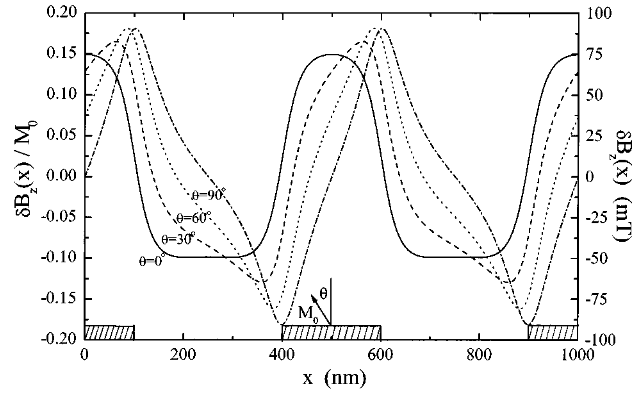

FIG. 4. The calculated z-component of the magnetic field $\delta B_z(x)$ at the 2DES for different orientations of the magnetization of the stripes. The left-hand axis is in units of the magnetization. The right-hand axis gives the absolute magnitude of the modulation for $B_{ext} > 0.2$ T.

lations result from commensurability effects between the diameter of the cyclotron orbit at the Fermi level $2R_c$ and the period of the magnetic modulation. For applied magnetic fields of less than 0.2 T the MR is hysteretic. We associate this with the hysteresis of the magnetization of the Ni stripes.

Figure 3 shows the measured MR for different angles θ between the external magnetic field B_{ext} and the z-y plane [see Fig. 1(a)], i.e., with the in-plane component perpendicular to the stripes. The results are plotted versus the z component of the applied field B_z, which is the component which affects the motion of the electrons in the 2DES. The most striking feature is the appearance of a low-field MR which becomes much stronger and extends to larger B_z as θ increases. R_{xx} increases by a factor of up to ~2 on application of a B_z of only 50 mT. We observe a strongly hysteretic behavior of this MR for $B_{ext} < 0.2$ T independent of θ. This shows that the MR is due to the magnetization M_0 of the nickel stripes and suggests that M_0 is saturated and nonhysteretic for $B_{ext} > 0.2$ T. The low-field MR decreases in magnitude with increasing temperature but is still observable and hysteretic at temperatures well above 200 K, which attests to its semiclassical origin. When the applied field is tilted so that the in-plane component of the magnetization is along the stripes, the MR is found to depend only upon B_z since the magnetization component along the stripes produces no stray field at the 2DEG.

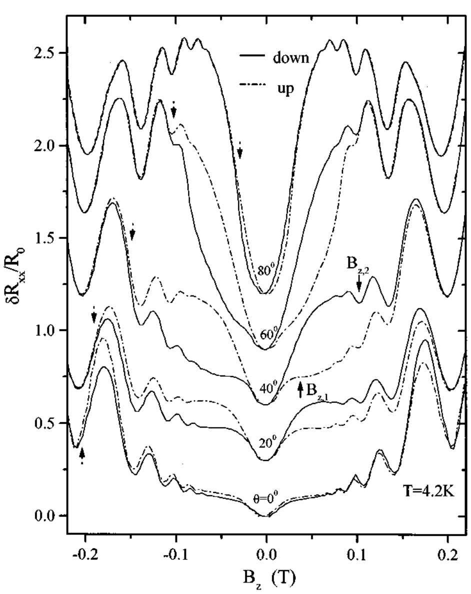

FIG. 3. The low-field MR measured at 4 K as a function of the component of the magnetic field normal to the 2DES, B_z, for different tilt angles θ. The 20°, 40°, 60°, and 80° traces are vertically offset by 0.3, 0.6, 0.9, and 1.2, respectively. Results for up sweeps (dash-dotted lines) and down sweeps (full lines) are shown. The arrows indicate the values of B_z for which $B_{ext} = 0.27$. $B_{z,1}$ and $B_{z,2}$ are explained in the text and are the same as the field components in the inset to Fig. 5(b).

The magnetization of the ferromagnetic grating produces a magnetic field at the 2DES with a z component δB_z. It is this component which influences the electron dynamics. We have calculated δB_z as a function of θ assuming that the stripes have a uniform magnetization that is parallel to the external magnetic field. The results, shown in Fig. 4, were obtained from both a Fourier analysis of Maxwell's equations[14] and, as a check, by integration over the equivalent magnetic pole densities at the boundary faces of the stripes.[15] The amplitude of the modulation is quite large due to the shallowness of the 2DES and the reasonably small demagnetizing factors in our geometry.[15] The form of δB_z changes from being square-wave-like for $\theta=0$ (perpendicular field) to almost triangular for $\theta=90°$ (in-plane field). The amplitude of the modulation is a weak function of θ but is largest for *in-plane* magnetization. The $\theta=0$ modulation is asymmetric about zero field because the width of the stripes is not equal to one-half the period of the modulation. Our calculated results will be accurate when the external field is sufficiently large to saturate the magnetization and enforce near uniform magnetization. For smaller external fields the demagnetizing field will lead to nonuniform magnetization and a small reduction of the modulation amplitude.

The magnetization M_0 of the nickel grating will be a function of B_{ext} and will be hysteretic. Pure continuous Ni films of similar thickness to those used here reach the saturation magnetization of 0.51 T (Ref. 16) on application of external fields of about 20 mT.[17] Our patterned wires will, however, be highly disordered and, as discussed above, we observe hysteretic behavior suggesting saturation for external fields of about 0.2 T. To model the dependence of the magnetization on the external field, we use the form shown in the inset to Fig. 2, which we will show below is consistent with the measured MR.

In a uniform magnetic field, electrons move in closed cyclotron orbits whose guiding centers are fixed in space. In the presence of a small 1D magnetic modulation, the guiding center drift velocity of the cyclotronlike states has maxima whenever the cyclotron diameter is commensurate with the modulation period, within a phase factor. The predicted MR for a purely sinusoidal magnetic modulation with a z component at the 2DES of amplitude B_0, without an electrostatic contribution,[18] is

$$\frac{\delta R_{xx}}{R_0}=\left[\frac{ak_F}{4\pi^2}\left(\frac{\hbar\omega_0}{E_F}\right)^2\left(\frac{l_e}{l_m}\right)^2\right]\times\left\{1-A\left(\frac{T}{T_a}\right)+A\left(\frac{T}{T_a}\right)\sin^2\left(\frac{2\pi R_c}{a}-\frac{\pi}{4}\right)\right\}, \quad (1)$$

where a is the period of the modulation, k_F and E_F are the Fermi wave vector and energy, respectively, l_e and $l_m=(\hbar/eB)^{1/2}$ are the electron mean free path and the magnetic length, respectively, $A(x)=x/\sinh(x)$, $4\pi^2k_BT_a=\hbar\omega_c ak_F$, with $\omega_c=eB/m^*$ where m^* is the electron effective mass, and $\omega_0=eB_0/m^*$. We have used Eq. (1) to calculate the magnetoresistance taking the first harmonic of the calculated modulation of Fig. 4 as B_0, with M_0 given by the model hysteresis curve of Fig. 2.

As Fig. 2 shows, the calculated peak positions agree well with the experimental results. This indicates that the oscillations arise from a predominantly magnetic modulation. There is also good agreement between the theory and experiment for the magnitude of the last commensurability peak at ~0.27 T. Above ~0.2 T the theoretical prediction involves no free parameters so this agreement confirms the accuracy of the calculated saturation modulation amplitude. Below 0.2 T the decrease in amplitude will depend upon the exact form of the $M_0(B_{ext})$ and damping due to scattering, which is not included in Eq. (1).

The observed low-field MR (Fig. 3) can be understood in terms of channeling[19] of electrons along lines of zero magnetic field within the sample. Consider first the case of zero external field but finite modulation field δB_z. In this situation, two kinds of electron states coexist. Electrons which have a sufficiently large initial velocity component perpendicular to the magnetic stripes will propagate across the sample in the same direction they would have in the absence of the modulation. Electrons with smaller initial velocity components cannot pass through the magnetic barriers and will be channeled in the y direction along snakelike orbits centered on the lines of zero B. All electrons close to the Fermi circle crossing a $B=0$ line at an angle ϕ less than a maximum angle ϕ_{max}, determined by δB_z, will therefore be in these ''open'' orbits.

For $0<|B_z|<|\delta B_z|$ there are still two types of states, as is illustrated in Fig. 5(a). Open orbits which propagate with drift velocities close to the Fermi velocity v_F, and almost

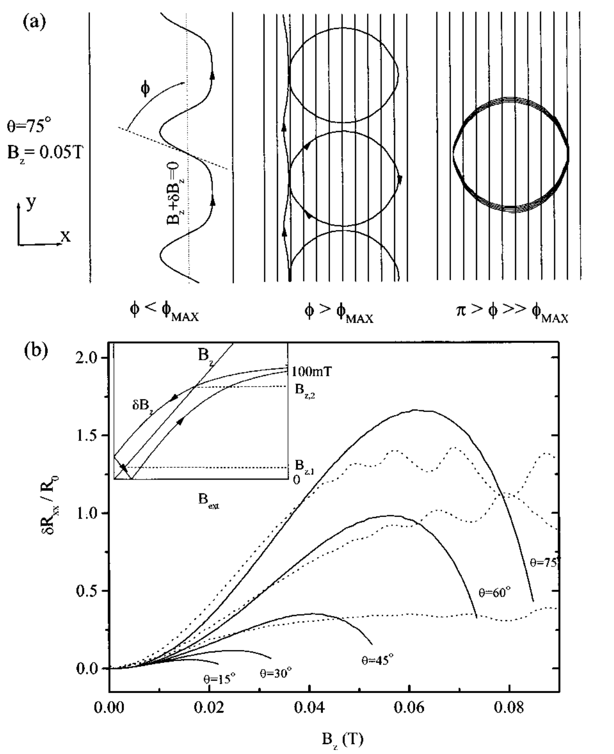

FIG. 5. (a) The three types of electron orbits, from left to right: open, intermediate, and closed. The vertical solid lines indicate the positions of the center of the stripes. The vertical dashed line indicates the $B_z+\delta B_z=0$ contour. (b) The calculated contribution to the MR of the orbits (solid lines) compared with the experimental results (dashed lines). Inset: illustration of the origin of the MR hysteresis drawn for $\theta=60°$ (see text).

closed cyclotronlike orbits with guiding center drift velocities very much less than v_F. To a good approximation one can therefore consider the electrons' guiding centers to be stationary apart from a fraction ϕ_{max}/π which are drifting with velocity $\simeq v_F$, where ϕ_{max} now depends upon both δB_z and B_z. For $|B_z|>|\delta B_z|$ the magnetic field at the 2DES no longer alternates in sign and there will be no such open orbits.

The guiding center drift correction to the D_{yy} diffusion coefficient leads to a MR:[20]

$$\Delta R_{xx}/R_0=2(\omega_c\tau)^2\langle\nu_d^2\rangle/\nu_F^2, \quad (2)$$

where τ is the elastic scattering time, and $\langle\nu_d^2\rangle$ is the appropriate average[20] of the square drift velocity. Approximating $\langle\nu_d^2\rangle\approx\nu_F^2(\phi_{max}/\pi)$ therefore gives

$$\Delta R_{xx}/R_0=(2\phi_{max}/\pi)(\omega_c\tau)^2. \quad (3)$$

We have calculated ϕ_{max} by numerically integrating the classical equation of motion for electrons traveling through the magnetic profiles of Fig. 4. In this calculation we again use the hysteresis curve of Fig. 2.

Figure 5(b) shows that the magnitude of the calculated MR and its dependence on tilt angle are in good agreement with our experimental results. The predicted rapid falloff of the MR as the magnitude of B_z approaches that of δB_z is not observed experimentally. This is because our approximation of zero guiding center drift for the ''closed'' orbits is no longer valid at larger fields.[19] Increasing θ increases the amplitude of the modulation through (i) the increase of M_0 for a given B_z and (ii) the increase of $\delta B_z/M_0$ (Fig. 4). The increase in the amplitude of the magnetic modulation increases the size of the MR and the width of the MR region in Fig. 3. We find that the calculated MR is not very sensitive to the *shape* of the magnetic modulation.

The hysteretic region extends to $B_{ext} \simeq 0.2$, independent of θ. The width of this region in B_z therefore decreases with increasing θ. The orbits, and therefore the low-field MR, only exist when B_z oscillates about zero, i.e. when $|B_z| < |\delta B_z|$. As the inset to Fig. 5 shows, this leads to a large hysteresis in the MR at intermediate angles. For the case of $\theta = 60°$ illustrated, one has an MR up to only $B_{z,1}$ on the ''up sweep'' but from $B_{z,2}$ on the ''down sweep''. The observed form of the MR hysteresis is well reproduced using Eq. (3) and the hysteretic magnetization of Fig. 2, as we will show in a later paper.

In summary, we have observes a strong low-field MR which is well accounted for by a simple semiclassical theory. The effect arises directly from the sign alternation of the magnetic field at the 2DES and provides experimental proof of the existence of 1D electron states propagating along lines of zero magnetic field.

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