Two Dimensional Electrons in a Lateral Magnetic Superlattice

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We report, for the first time, ballistic magnetoresistance effects in a two-dimensional electron gas (2DEG) subjected to a spatially modulated periodic magnetic field. The periodic magnetic field is formed by the presence of superconducting stripes on the surface of the heterostructure with a 2DEG. We observe oscillatory magnetoresistance due to a commensurability effect between the classical cyclotron diameter and the period of magnetic modulation. The behavior is in agreement with existing theory with no adjustable parameters.

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High mobility, two-dimensional electron gases (2DEG), formed in GaAs/(AlGa)As heterostructures, allow ballistic electron motion over distances of the order of several microns. Using techniques such as electron beam lithography, one- and two-dimensional arrays of electrostatic gates with a feature size as small as 100 nm have been fabricated on the surface of the heterostructures, providing a periodic potential through which the electrons move. A variety of effects have been observed in the magnetoresistance of the 2DEG, depending of the nature of the externally applied electrostatic potential. The first effect of this type was seen with a one-dimensional periodic potential, where oscillations periodic in the inverse of the magnetic field B were observed in the magnetoresistance [1,2]. These were ascribed to a semiclassical commensurability effect [1–3]. The early experiments led to many subsequent studies including the observation of chaotic motion in a periodic potential [4]. Following and in parallel with this work there was significant interest in the behavior of *magnetically* modulated 2DEG [5,6]. Despite the theoretical work, the experimental observation of the motion of electrons in a periodic magnetic potential proved elusive.

In this Letter we report the first experimental measurements on a 2DEG in a periodically modulated magnetic field created by an array of superconducting stripes on the surface of a heterostructure. An electrostatic modulation is also unavoidably present due to the differential contraction between the metal and the substrate (see below). However, as described below, we have been able to isolate the effect of the magnetic potential and observe unambiguously the effect of the modulated magnetic field on the electron motion. There is an additional oscillatory magnetoresistance which corresponds to oscillations in the electron diffusion coefficients when the semiclassical cyclotron diameter is commensurate with the period of the magnetic modulation.

A schematic diagram of the sample design is shown in Fig. 1(a). A 2DEG, ungated electron density $\sim 1.5 \times 10^{15}$ m^{-2}, elastic mean free path ~ 10 μm, is formed in a standard GaAs/(AlGa)As heterostructure. A metallic gate (gold) of thickness 150 nm is deposited on the surface of the heterostructure followed by 200 nm of insulating germanium. Finally, stripes of a superconductor, of thickness between 100 and 200 nm, were fabricated on the surface of the insulating layer using electron beam lithography and standard lift-off techniques. We made standard Hall devices, width 50 μm, with both lead and niobium as the superconductors. The array of stripes had period a of 2 or 1 μm, and covered the whole area of the device for a length of 250 μm, 130 μm between voltage contacts. The relatively large period was chosen for a number of reasons. The mechanism which is responsible for the magnetic modulation in our case involves flux pinning on defects in a superconductor [7,8] and does not occur for stripes narrower than the vortex diameter (≈ 0.12 μm). Also, the amplitude of the magnetic field variation diminishes [9] as $\exp(-2\pi x/a)$, where x is the distance between the 2DEG and the stripes.

Figure 2(a) shows the magnetoresistance at 300 mK of a device with lead stripes of period 2 μm. Four-probe measurements were made with the current flowing perpendicular to the direction of the stripes and the magnetic field applied perpendicular to the plane of the 2DEG. The full line is produced when the magnetic field is swept from a relatively large negative value $B < -1$ T to a relatively large positive value $B > 1$ T, continuously through zero. The dashed curve corresponds to the opposite sweep, from positive to negative field. All experimental results are corrected for hysteresis due to the finite

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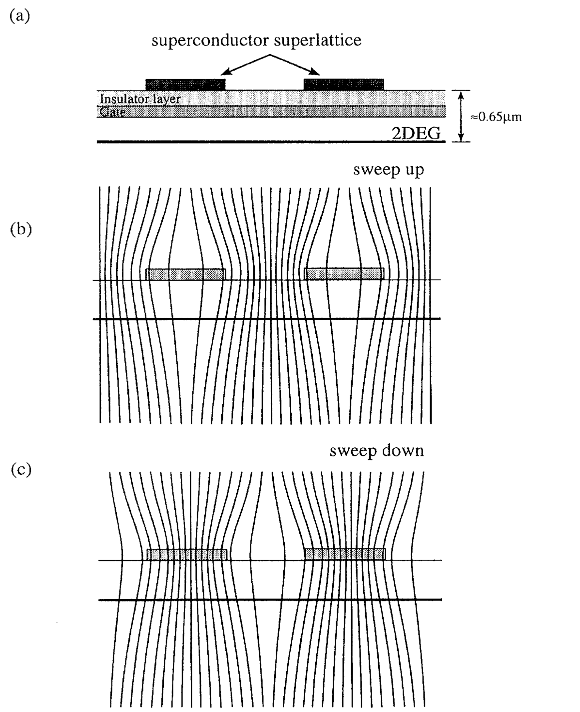

FIG. 1. (a) Schematic diagram of the devices. (b) Schematic representation of flux lines when the external field is being swept up. (c) Equivalent diagram to (b) with the field swept down.

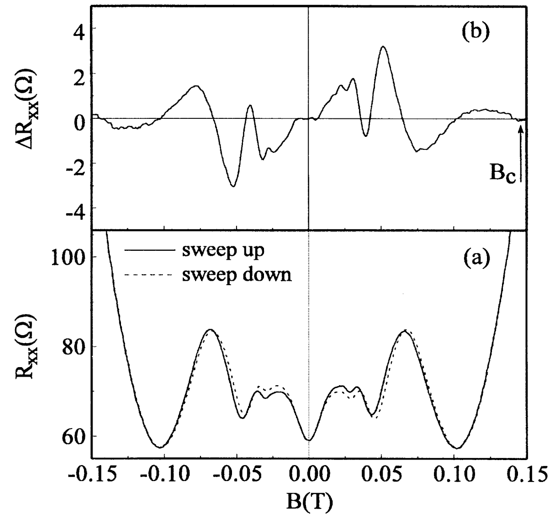

FIG. 2. (a) Magnetoresistance at 300 mK of a device with lead stripes of period 2 μm. The full line corresponds to the magnetic field swept from a negative to a positive value and the dashed line to a sweep in the opposite direction. (b) The difference ΔR_{xx} between the magnetoresistance curves shown in (a). B_c indicates the magnetic field where the two curves become identical.

sweep rate and the remanent field of the superconducting magnet. Following these corrections the sweep up and down R_{xx} curves are identical at low magnetic fields and at all fields above some critical value shown as B_c in Fig. 2(b). The Hall resistances are identical within experimental uncertainty over the entire field range, indicating that the observed difference between up and down R_{xx} curves is due to the effect of the superconductor pattern. More convincing proof can be produced by investigating the temperature dependence of the magnetoresistance. Figure 2(b) shows the difference between the magnetoresistance for up and down sweeps ΔR_{xx}, because the data of Fig. 2(a) and Fig. 3 shows ΔR_{xx} at various temperatures. Evidently B_c, the magnetic field where the difference disappears, decreases as the temperature T increases. B_c is plotted vs T in the inset to Fig. 3 together with the expected form for the superconducting critical field [8]. Above $T = 8$ K up and down sweeps are identical.

The results of Fig. 2(a) indicate that there is a relatively strong periodic *electrostatic* potential at the 2DEG, i.e., the magnetoresistance oscillations due to the electrostatic potential are stronger than those due to the magnetic modulation. We attribute this electrostatic modulation primarily to a piezoelectric effect caused by differential contraction at the interface [10]. The presence of the metallic gate between the stripes and the 2DEG screens effects due to surface charge. We turn now to the origin of the difference in the magnetoresistance for the different sweeps of magnetic field. It is known that thin films of lead are type II superconductors [7] with a low-temperature, upper critical field, $B_{c2} \sim 0.1$ T, which compares well with our observed cutoff field for the difference between up and down sweeps (see inset to Fig. 3). Consider the situation when the applied field B is decreasing from a value larger than B_{c2}. At $|B| > B_{c2}$ the superconductivity is destroyed and the field is homogeneous all over the 2DEG. As $|B|$ is swept below B_{c2}, the flux inside the superconducting stripes

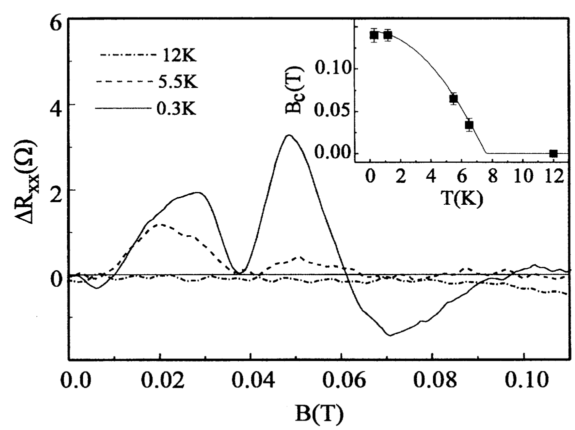

FIG. 3. ΔR_{xx} at three temperatures. Inset: B_c plotted vs temperature. The line is $B_C \propto [1 - (T/T_C)^2]$.

is segregated into a distribution of vortices which are trapped on random defects and hence cannot easily leave the superconductor. This leads to a *larger* value of the magnetic field in the stripes than it would if they were not superconducting or the pinning was absent. The field distribution for the decreasing field is shown schematically in Fig. 1(c). The same pinning mechanism leads to a different field distribution when $|B|$ is increasing [see Fig. 1(b)]. Vortices which are created by the external field and penetrate into a superconductor from the edges become trapped nearby and cannot move further into the central part of the stripes. This leads to a *smaller* value of the magnetic field in the center than near the edges, as is shown in Fig. 1(b). This changeover for the different sweep directions is equivalent to a change in sign (change in phase by π) of the magnetic modulation and explains the hysteretic behavior in Fig. 2(a). We note that this simple picture is not valid at very low fields for two reasons. First, vortices of both signs will be present inside the superconducting film: vortices trapped earlier and located in the center of the stripes and also "antivortices" which start penetrating the stripes from the edges. Second, the Meissner effect may also play a role in this regime and the flux distribution is expected to be rather complicated [7]. Fortunately, these complications persist only in a field range [7] $|B| < 0.01$ T, where the magnetoresistance is dominated by electrons channeled by the electrostatic potential [11].

Peeters and Vasilopoulos [6] explicitly considered the case where the 2DEG experiences both periodic electric and magnetic fields. In the case where the magnetic *field* modulation, amplitude B_0, is in phase with the electric *potential* modulation, amplitude V_0, they calculate the magnetoresistance R_{xx} relative to the zero field resistance R_0 at temperature T to be

$$\frac{(R_{xx} - R_0)}{R_0} = \left[\frac{ak_F}{4\pi^2} \left(\frac{\hbar\omega_0}{E_F} \right)^2 \left(\frac{\ell_e}{\ell_m} \right)^2 + \left(\frac{V_0}{E_F} \right)^2 \left(\frac{\ell_e^2}{aR_c} \right) \right] \left[1 - A\left(\frac{T}{T_a} \right) + A\left(\frac{T}{T_a} \right) \sin^2\left(\frac{2\pi R_c}{a} - \frac{\pi}{4} + \phi \right) \right], \tag{1}$$

where $\omega_0 = eB_0/2m^*$, with m^* the electron effective mass, k_F and E_F are the Fermi wave vector and energy, respectively, $R_c = \hbar k_F/eB$ and $\ell_m = (\hbar/eB)^{1/2}$. ℓ_e is the elastic mean free path $4\pi^2 k_B T_a = \hbar\omega_c a k_F$ with $\omega_c = eB/m^*$, and the function $A(x)$ is $x/\sinh(x)$. The phase angle ϕ is given by

$$\tan\phi = 2\pi V_0/(ak_F\hbar\omega_0). \tag{2}$$

Therefore, the effect of the periodic magnetic field is to introduce a phase shift to the magnetoresistance oscillations and also to alter their amplitude. These effects are rather subtle and would be difficult to observe were it not for the asymmetry between up and down field sweeps. As discussed above, this is due to a reversal of phase of the magnetic modulation which leads to the phase angle ϕ in Eq. (1) changing sign. If we then look at the difference ΔR_{xx} in the magnetoresistance traces for sweeping the field up and down we obtain

$$\left(\frac{\Delta R_{xx}}{R_0} \right) = -\left[\frac{ak_F}{4\pi^2} \left(\frac{\hbar\omega_0}{E_F} \right)^2 \left(\frac{\ell_e}{\ell_m} \right)^2 + \left(\frac{V_0}{E_F} \right)^2 \left(\frac{\ell_e^2}{aR_c} \right) \right] A(T/T_a) \sin 2\phi \cos(4\pi R_c/a). \tag{3}$$

Experimental values for this quantity are plotted in Fig. 2(b). In the case of relatively weak magnetic modulation, $\sin 2\phi \propto B_0/V_0$. It is possible to determine both V_0 and B_0 directly from the experimental data. To this end, we measured the phase difference 2ϕ between the oscillations when the field is swept in the two directions and used Eq. (2) to calculate values of B_0/V_0. Values of k_F are determined from Shubnikov-de Haas oscillations. By changing the applied bias on the metallic gate, we are able to vary k_F. V_0 may be estimated using the cutoff field for the positive magnetoresistance at low magnetic fields [11]. We find $V_0 \simeq 1$ meV independent of the bias on the gate. Values of B_0 as a function of field are plotted in Fig. 4(a) and are in qualitative agreement with the behavior expected from the flux-pinning mechanism. Assuming the modulation amplitude varies as the simple exponential [9] $\exp(-2\pi x/a)$, we find the modulation amplitude in the plane of the stripes to be $\sim$0.01 T at applied fields $\sim$0.03 T. In the devices with period 1 μm we also see strong oscillations periodic in $1/B$ as in the 2 μm devices, but we see no evidence for magnetoresistance hysteresis. In our structures, we expect a reduction by about an order of magnitude in B_0 for the 1 μm device relative to the 2 μm period but this should still have produced an observable effect. It is likely that the magnetic modulation decreases further when the width of the stripes becomes comparable with the vortex diameter and there is no longer any macroscopic gradient in the vortex concentration due to pinning. Similarly, we observed no modulation effect in samples with niobium stripes, despite looking at several samples with period of 1 and 2 μm. This might reflect the larger flux penetration length in niobium [12] (>0.12 μm) relative to lead ($\sim$ 0.06 μm).

Equation (3) now gives an expression for ΔR_{xx} in terms of measured parameters. Note that the oscillations are strictly periodic in $1/B$ with no phase shift. The inset to Fig. 4(a) shows plots of the observed periodicity of the oscillations for four different gate voltages. The lines are calculated from the measured electron densities.

Excellent quantitative agreement with theory is found. Figure 4(b) shows further comparison between theory, using Eq. (3), and the measured ΔR_{xx}. The measured values of B_0 are smoothed using the function shown in the inset to Fig. 4(a). Although the amplitudes are only in qualitative agreement, it should be remembered that there are no adjustable parameters in the theoretical line; we used the experimental values of V_0 and B_0 which have uncertainties $\sim \pm 50\%$. In the expression for ΔR_{xx} [Eq. (3)], for our experiment $\sin 2\phi \propto B_0/V_0$ and the first term in the bracket is negligible, relative to the second, so the amplitude is approximately proportional to $V_0 B_0$. Furthermore, the agreement is at least comparable to the quality of fits obtained for the oscillations due to the electrostatic potential alone (see, for example, Ref. [3]).

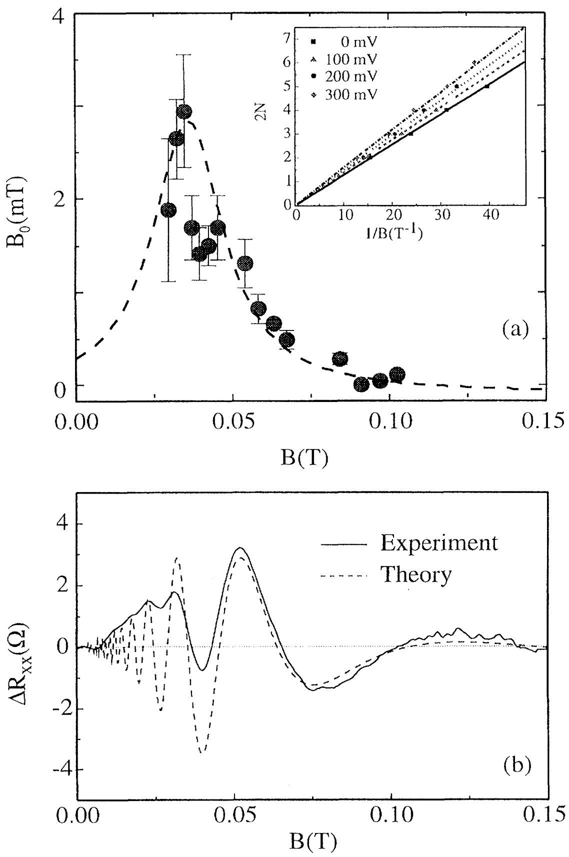

FIG. 4. (a) B_0 vs B determined from the phase of R_{xx}. The smoothed values are represented by the dashed curve. Inset: positions of maxima and minima of ΔR_{xx} plotted vs $1/B$ for various gate voltages. The lines have no adjustable parameters. (b) Comparison of experimental and theoretical behavior of ΔR_{xx}. There are no adjustable parameters.

In summary, we have observed, for the first time, magnetoresistance effects doe to the ballistic motion of electrons in a 2DEG subjected to a periodic magnetic field. We find good agreement with the existing theory. The magnetic potential is applied using stripes of superconducting material; the stripes produce the field variation by a flux mechanism which produced an asymmetry in the field variation depending on whether the external field is being swept up or down. It is the asymmetry which enables us to distinguish unambiguously between effects due to the magnetic and the electrostatic potentials. After the initial submission of the manuscript, we became aware of similar work at Max-Planck institute, Stuttgart where similar semiclassical effects have been observed.

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