Magnetoresistance in a back-gated surface superlattice

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We study a surface superlattice structure, consisting of a two dimensional electron gas (2DEG) with a periodic array of Schottky gates on the surface *and* an additional back gate, which independently controls the 2DEG density. We use several independent features in the magnetoresistance to determine the magnitude V of the periodic potential induced in the 2DEG, and its dependence on the gate voltages. We obtain a systematic quantitative picture of V, which is generally in good agreement with theoretical expectations. However our density dependence cannot be accounted for within the usual picture of static screening in a 2DEG. [S0163-1829(96)08944-8]

A periodic potential can be imposed on a two-dimensional electron gas (2DEG) by an array of surface electrodes, or gates. When a voltage V_g is applied to the gates, a periodic potential is induced in the 2DEG, whose magnitude depends on V_g. Such a structure is referred to as a surface superlattice (SSL).[1–7] In this paper we will concern ourselves with grating SSL's, namely, the case where the gate array consists of wires, imposing a potential which is periodic in the x direction but uniform in the y direction of the 2DEG plane.

Transport in SSL's has been studied extensively in recent years. The quantity measured is the resistivity ρ_{xx}, or the resistance R_{xx}, for current flowing in the direction of the periodic modulation. One of the most celebrated and widely studied effects is the oscillations in the magnetoresistance (MR) at moderate magnetic fields, B.[8–10] These oscillations are understood as a semiclassical effect associated with recurring commensurability between the cyclotron orbit and the periodic potential. Such commensurability leads to a drift, in the y direction, of the guiding center of the cyclotron orbit, which in turn increases ρ_{xx}. Using classical arguments, Beenakker[11] showed that the MR is then given by

$$\frac{\Delta\rho_{xx}}{\rho_{xx}}=\left(\frac{eV}{E_F}\right)^2\left(\frac{l^2}{aR_c}\right)\cos^2\left(\frac{2\pi R_c}{a}-\frac{\pi}{4}\right), \qquad (1)$$

where E_F is the Fermi energy, V is the amplitude of the periodic potential, a is the period of SSL, l is the electron mean free path, and R_c is the cyclotron radius. At very low fields one observes positive MR rather than oscillations. This positive MR, which is approximately quadratic at low B, extends from zero up to a ''critical'' magnetic field B_c. Beton *et al.*[12] derived an expression for the value of this field,

$$B_c=\frac{2\pi V}{au_F}, \qquad (2)$$

where u_F is the Fermi velocity. This result was obtained by considering the classical trajectories of electrons in a periodic potential in a weak field. The MR is not quadratic through the entire range, and the *maximum* of the MR occurs not at the above value, but at a slightly smaller field,

$$B_c\approx\frac{5V}{au_F}. \qquad (2a)$$

This, rather than Eq. (2), is the value that is determined experimentally.

A somewhat different analysis of this positive MR was proposed by Streda and MacDonald,[13] who described this effect as being due to magnetic breakdown between open and closed orbits in momentum space. They obtained the expression

$$B_c=\left(\frac{me}{4\hbar^2}\right)\left(\frac{aV^2}{u_F}\right) \qquad (3)$$

for the critical field.

Thus both the MR oscillations and the low-field positive MR can be used to determine V, giving two seemingly independent measures of the same quantity. This quantity is of considerable practical and theoretical interest. The different mechanisms that influence the value of V in such structures have recently been studied, with particular focus on the piezoelectric contribution of strain produced by the gate metal.[14,15]

In previous work on SSL's, there was no possibility to separately control n, the density of the 2DEG, and the strength of periodic potential V. Increasing V_g in the negative sense not only increases V but also reduces n. In the present study we overcome this problem by using a doubly gated structure, where the density is independently controlled by a back gate, while a gate array on the surface is used to induce a periodic potential in the underlying 2DEG.

The samples were made using an ISIS (Inverted Semiconductor-Insulator-Semiconductor) heterostructure[16,17] grown by molecular beam epitaxy on conductive GaAs. A profile of the structure is schematically presented in Fig. 1. Mesas with Hall bar geometry, 5 μm wide and 35 μm long (between voltage probes) were patterned on the surface using wet etching. Shallow $Ni_xGe_{1-x}Au$ Ohmic contacts were deposited and alloyed, taking special care to avoid punch through to the conductive substrate. A positive ''backgate'' voltage V_b applied to the substrate, with respect to the Ohmic contacts, induces a 2DEG as shown in Fig. 1, whose density n varies with V_b. Note that unlike the case of con-

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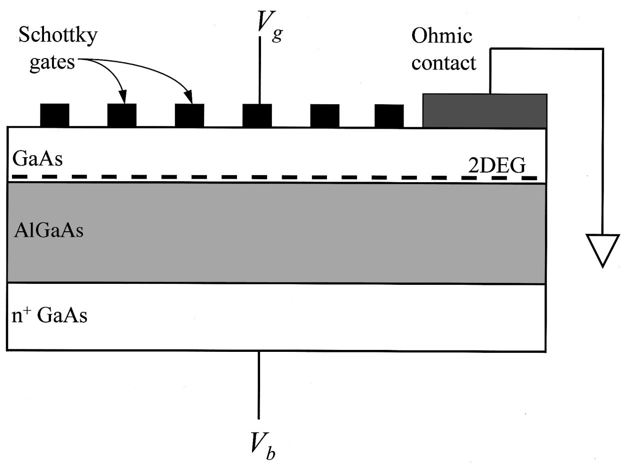

FIG. 1. A schematic profile of the samples studied. The heterostructure layer sequence, known as ISIS (Ref. 16), forms a high-mobility 2DEG in the GaAs layer on top of the (undoped) $Al_xGa_{1-x}As$ barrier. The 2DEG density n is controlled by the back-gate voltage V_b, which is applied to the conductive substrate. An array of Schottky electrodes on the surface, in a grating configuration, induces a periodic potential in the 2DEG, whose strength V is separately controlled by the voltage V_g on these gates. The period of the grating is 0.2 μm.

ventional heterostructures, here the 2DEG is located *above* the heterojunction interface, which is why ISIS structures are referred to as ''inverted.'' An array of narrow Schottky gates, each approximately 25 nm wide, with period $a=200$ nm is formed on the surface of the Hall bar using electron beam lithography. The voltage on these Schottky gates is denoted by V_g. Resistance measurements are performed using standard lock-in techniques at $T=1.5$ K.

Figure 2 shows several measurements for $V_g=-0.15$ V.

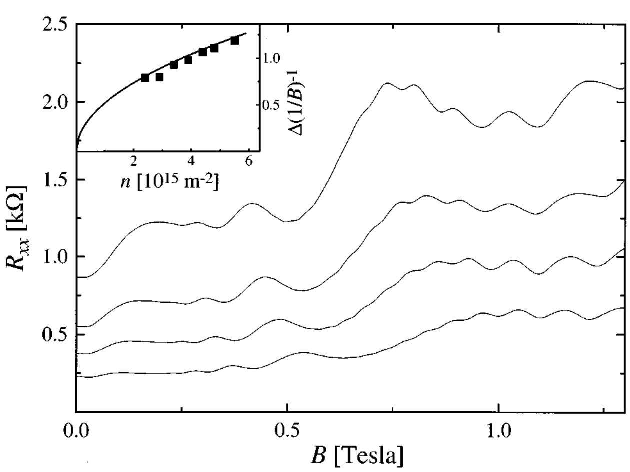

FIG. 2. Resistance R_{xx} vs magnetic field for $V_g=-0.15$ V, where different curves correspond to different backgate voltages. The density n decreases from the lower curve to the upper curve ($n=5.5$, 4.4, 3.9, 3.4×10^{15} m^{-2}, respectively). The oscillations at intermediate fields are the SSL commensurability oscillations described in the text, which are periodic in $1/B$. The measurements are at $T=1.5$ K. Inset: The inverse period of the oscillations plotted vs density n. The solid line is a theoretical prediction, Eq. (4). There are no fitting parameters.

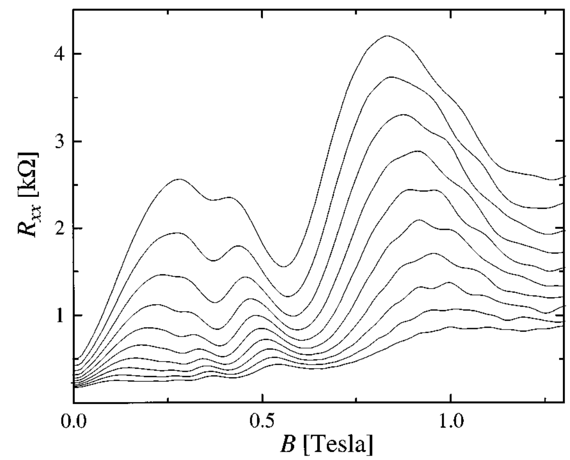

FIG. 3. Resistance R_{xx} vs magnetic field for $V_b=2.2$ V, with $V_g=-0.1$ to -0.6 V in equal steps of 0.1 V. The measurements are at $T=1.5$ K. The amplitude of oscillations and the low-field positive magnetoresistance depend on the strength of the periodic potential induced by V_g.

The different curves correspond to different values of V_b, i.e., for different 2DEG densities. At very low fields we find positive MR, which extends up to a field of about 0.1–0.2 T. The rapid oscillations seen at $B\sim1$ T are the Shubnikov–de Haas oscillations, which are used to determine n. The oscillations at intermediate fields are those resulting from the commensurability of the cyclotron radius and the SSL periodic potential, as discussed above. This plot demonstrates the power of the back-gated ISIS heterostructure in establishing the origin of these effects, as follows: The commensurability oscillations, which are periodic in $1/B$, have a period which can be shown, from Eq. (1), to be given by

$$\left(\Delta\,\frac{1}{B}\right)^{-1}=\frac{2\hbar\sqrt{2\pi n}}{ea}. \tag{4}$$

We plot the measured inverse-period of these oscillations versus density, in the inset of Fig. 2, along with the solid line corresponding to Eq. (4). The agreement is very good.

In Fig. 3 we show results of measurements with the same V_b, but for different V_g ranging from -0.1 V for the lowest curve to -0.6 V for the upper curve. It is clearly seen that the size of the oscillations and of the positive MR are strongly dependent on V_g, increasing as the latter is made more negative. Although changing V_g entails a certain change in n as well, this effect is much smaller than for the case where V_b was tuned.

Using these data we can calculate V, both from the positive MR and from the MR oscillations. In Fig. 4 we plot these values of V versus V_g. The different symbols correspond to three different analyses, which we now discuss.

The square symbols in Fig. 4 are values derived from the low-field positive MR. From Eqs. (2)–(3) we see that the product $B_c\times u_F$ is a quantity that scales with the amplitude of the periodic potential in both theoretical models.[12,13] We find that this product has a remarkably linear dependence on V_g. V itself is also expected to be approximately linear in V_g, from theoretical considerations[14] and also from the other

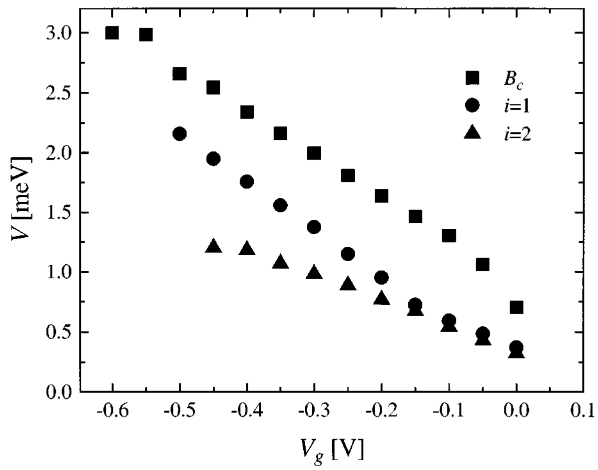

FIG. 4. The magnitude V of the periodic potential, plotted vs the gate voltage V_g. The different symbols correspond to different methods of extracting V from the magnetoresistance, as explained in the text: from the maximum field B_c of the low-field positive MR (squares), from the size of the $i=1$ commensurability peak (circles), and from the $i=2$ peak (triangles).

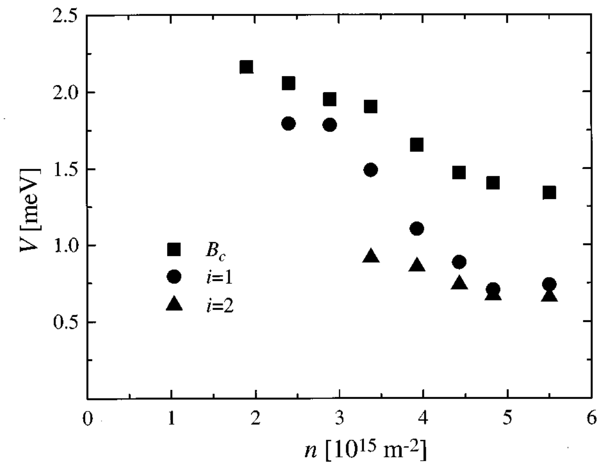

FIG. 5. The value of V plotted vs the density n. In these measurements V_g was fixed, while n was tuned by the substrate voltage V_b. The different symbols correspond to different methods of determining V from the magnetoresistance, as in the previous figure. The dependence of V on n at fixed V_g is not accounted for by screening.

MR data shown below. Therefore, a consistent picture favors Eq. (2a), and so we use the latter to calculate V from B_c. The results are shown in Fig. 4.

The circles and triangles in Fig. 4 correspond to values of V extracted from the oscillatory part of the MR. The amplitude of each oscillation was determined by taking the difference between the peak resistance and the interpolated resistance between the neighboring minima (both linear and quadratic spline interpolations were checked). This is a necessary step since the minima are not all at the same value. We thus obtain a value $\Delta\rho_i$ of the MR at the highest-field peak ($i=1$) and second-highest peak ($i=2$), respectively. From Eq. (1) we then obtain

$$\frac{\Delta\rho_i}{\rho_0}=\left(\frac{eV}{E_F}\right)^2\left(\frac{l^2}{aR_c^i}\right), \tag{5}$$

where R_c^i is the cyclotron radius at the ith peak. Thus the circles (triangles) in Fig. 4 correspond to V extracted from Eq. (5) for $i=1$ ($i=2$).

The values of V calculated from B_c are larger than the values calculated from the oscillations, but all show the same trend and similar magnitude. The values extracted from $i=1$ and 2 are equal when the periodic potential is weak, but they start to differ as the potential becomes stronger. We speculate that this is a suppression of the measured oscillation amplitude, relative to the ''naive'' theoretical value, due to the distortion of the circular cyclotron motion by the presence of the periodic potential.[12] This effect becomes more significant as V increases or as B decreases, which is why this suppression is much stronger in the case of the $i=2$ peak. In particular we propose that in this range the triangles present an underestimate of V. It is also likely that the circles ($i=1$) involve an underestimate, although a less severe one.

In any case, Fig. 4 portrays a consistent picture where V depends linearly on V_g. This is not surprising, of course, but it implies that the primary mechanism of periodic modulation inside the 2DEG in these samples is electrostatic in nature, rather than, e.g., strain.[14,15] The potential modulation at zero gate voltage corresponds to the built-in potential of the Schottky barrier.[18] In fact we can estimate its value from the data, by extrapolation to the V_g-axis intercept, which is ~ -0.2 V. From the slope we obtain the ratio between V and the gate voltage, which turns out to be $dV/dV_g \approx 3.7\times10^{-3}$. Using the model of Davies and Larkin[14] for the case of screened electrostatic modulation, we can calculate the expected theoretical value for this ratio in our structure. Taking the superlattice period $a=200$ nm, the depth of the 2DEG $d=70$ nm, and the width of the metallic gate wires ≈ 25 nm, we obtain $dV/dV_g \approx 3.6\times10^{-3}$, which agrees well with the measured results.

The amplitude V as a function of n, with constant V_g, is shown in Fig. 5. This is obtained by changing the back gate bias, V_b, with n determined from the Shubnikov–de Haas oscillations at higher B. The different symbols correspond to the different modes of extracting V from the MR, as discussed above. We clearly see that changing n causes a change in V. The effect is weak at high n, but becomes more pronounced as the density decreases. This result is not entirely obvious because V is expected to depend only on V_g and on the structure of the device, but not on n. We note that there is some dependence of d, the vertical position of the 2DEG, on V_b; however, it is too small to account for the observed change in V. The theoretical *in*dependence of V on n results from the fact that screening in two dimensions does not depend on n.[19]

Figure 5 implies that standard 2DEG screening is not necessarily accurate in estimating V. Usually, screening is introduced when the external potential is small with respect to the Fermi energy and one can neglect the influence of this potential on the electronic density of states. But in our experiments the potential can be substantial. Such a periodic potential changes the wave functions and the density of states of the 2DEG. In particular, part of the electrons become bound in the x direction, and screening is therefore reduced. Thus for fixed V_g and decreasing n, this effect becomes gradually more significant and causes the enhancement of the periodic potential inside the 2DEG.

In conclusion, we have used various aspects of the magnetoresistance to study the amplitude of the periodic potential in a grating-type surface superlattice. Our measurements were facilitated by samples with the combination of a back gate and surface Schottky gates, allowing separate control of the electron density and of the strength of the periodic potential V. We generally find good agreement between experimental and theoretical values, although the values of V suggested by the positive magnetoresistance are somewhat larger than those suggested by the commensurability oscillations. We also find that for fixed gate voltage, V depends directly on the density; this fact is not accounted for within the usual theoretical treatment of this system.

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