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Importance of symmetry breaking in two-dimensional lateral-surface superlattices

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We have investigated commensurability oscillations in the magnetoresistances of two-dimensional lateral surface superlattices with square patterns and periods of 100 nm. In some of our samples the symmetry of the potential was broken by the presence of stress and strong piezoelectric effects. Oscillations were weak in symmetric samples, but became much stronger for transport along the $[01\overline{1}]$ direction [on a (100) wafer] when the symmetry was broken. For transport along the [010] and [001] directions in the asymmetric samples, the dominant Fourier component in the potential was at an angle of 45° to the transport direction, and the commensurability oscillations had an effective period of $100/\sqrt{2}$ nm. All of these observations are fully in accord with a recent semi-classical theory based on the guiding center drift concept.

The lateral surface superlattice (LSSL), in which a periodic potential is superimposed upon a two-dimensional electron gas (2DEG), provides a convenient means for investigating the transport of high mobility electrons in such a potential. The dominant effect seen in one-dimensional (1D) LSSLs (in which potential modulation is unidirectional) is commensurability oscillations (COs) in the magnetoresistance.[1] These can be explained semiclassically[2] from interference between cyclotron motion and the superlattice. For a simple periodic potential, $V(x)$, the interference causes a drift along the equipotentials parallel to the y axis, which contributes to the conductivity σ_{yy} and the resistivity ρ_{xx}. No effect on ρ_{yy} is expected in this approach.[2] Quantum-mechanical analysis[3,4] yields a similar result but with small contributions to ρ_{yy}. Overall agreement between theory and experiments on 1D LSSLs is excellent, even for the strong piezoelectric potentials in strained LSSLs.[5–7]

In comparison with the 1D case, the experimental situation concerning 2D LSSLs (in which the potential modulation varies with both x and y) is less certain. If strong modulation is applied by punching through the 2DEG to produce arrays of antidots, then magnetoresistance features are observed which can be associated with particular orbits (enclosing defined numbers of antidots for example). When the modulation is weaker, COs are observed, though they are generally of low amplitude and may have the opposite phase to that observed in 1D.[8] The presence of COs in 2D LSSLs has been explained by a semi-classical calculation,[9] which predicts that each Fourier component in the 2D potential leads to its own series of COs of amplitude equivalent to that predicted for 1D modulation. However this calculation was unable to account fully for the data available at the time, and quantum mechanical arguments[10] were frequently invoked.

In a recent paper Grant, Long, and Davies[11] re-examined the semiclassical guiding center concept[2] as applied to 2D LSSLs. They found that the guiding center drifts along contours of an effective potential, derived from the actual potential but with each Fourier component modulated by an interference term $J_0(qR_c)$, where q is the wave vector of the Fourier component, R_c is the cyclotron radius and J_0 is a Bessel function of the first kind. Realistic potentials led to both closed and open guiding center orbits. The former correspond to pinned trajectories and are expected to produce negligibly small contributions to the conductivity (in the limit $\omega_c\tau \gg 1$, where ω_c is the cyclotron frequency and τ is the scattering time), while the latter are directly analogous to the drifting orbits in the 1D theory and produce similar resistivity structure. For a potential symmetric between the x and y-axes, only closed orbits are found, and the COs are predicted to be absent. For an asymmetric potential, however, significant COs are expected. Grant *et al.* also showed that only one direction of drift is dominant at any field, and that the drift may switch from one direction to another if the dominating Fourier component changes.

The aim of this paper is to report some recent transport experiments on 2D LSSLs, some of which were designed to exploit the piezoelectric effect and generate an asymmetric potential modulation. These experiments confirm the model of Grant *et al.*; the main features of the observations can be explained within the semi-classical guiding center drift concept, without the need to invoke quantum mechanics. In these experiments the samples were fabricated from two different MBE layers grown on (100) GaAs wafers. The first layer was a standard $GaAs/Al_xGa_{1-x}As$ δ-doped heterostructure, with a spacer thickness of 20 nm, and the 2DEG lying 53 nm below the surface. The LSSL modulation was generated by a shallow surface etch to a depth of 18 nm. The second layer was identical except that a pseudomorphic strained layer of $In_{0.2}Ga_{0.8}As$, 6-nm thick, was introduced 10 nm from the surface. When the surface of this second layer was etched in the same way as the first, the strained layer was patterned and a stress modulation produced. This coupled to the 2DEG by means of the piezoelectric effect[6] producing an anisotropic potential modulation and hence breaking the symmetry of the sample. This technique has previously been used[6] to produce strong modulation of the 2DEG in 1D LSSLs with short periods. In this earlier work, two main sources of potential modulation were identified, the

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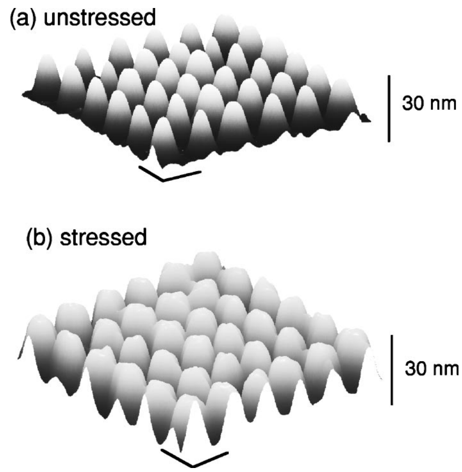

FIG. 1. AFM images of two representative superlattices without gates. The inclined bars give the principal lattice vectors (100 nm in each case). (a) Unstressed sample. (b) Stressed samples.

anisotropic *piezoelectric* effect, and the modulation due to the removal of material in the patterning process, which brings the surface states closer to the 2DEG. We call this the *surface* effect. In accord with expectations, the surface effect was found to be isotropic, whereas the results obtained for the piezoelectric component were in reasonable agreement both with the sign of the anisotropy and the magnitude of the modulation predicted theoretically.[12] In our 2D work, we expect that the *unstressed* samples will show isotropic modulation from a symmetric etch pattern, whereas the *stressed* samples will generally show different modulation amplitudes in different directions, as for the 1D stressed samples.

When unpatterned, both stressed and unstressed wafers contained typically 3.7×10^{15} m^{-2} carriers with a transport mobility of around 90 $m^2\,V^{-1}\,s^{-1}$. Groups of 4 Hall bars of width 10 μm and with voltage contacts 30 μm apart were fabricated, aligned in the [010], [011], [001], and $[01\bar{1}]$ directions. Electron beam lithography was used to define a pattern of dots of resist of diameter 50 nm on a square grid of period 100 nm, aligned to the edges of the Hall bar and covering all the region between the voltage contacts. The grid between the dots was wet etched to leave a regular square array of pillars, and the resist mask was then removed. The depths of the valleys between neighboring pillars were measured using an AFM and found to be 18 ± 2 nm for both sets of samples. Representative images are shown in Fig. 1.

Because the etch depths were the same in both stressed and unstressed samples, we assume that the surface modulation was approximately the same in both, as in the 1D experiments.[6] Fabrication was completed by blanketing the etched area with a thick Ti/Au Schottky gate, which was used to vary the mean carrier concentration and also the surface component of the potential. Note that, with the gate biased strongly negative so that the total surface potential dominates the piezoelectric effect, our system results in coupled *dots* rather than antidots. Hence features associated with cyclotron motion round one or more cells are not observed in our data. The magnetoresistances of the samples were measured using orthodox lock-in techniques with measuring currents of typically 100 nA. Measurements were made at 4 or 5 K to suppress the low field Shubnikov–de Haas (SdH) oscillations and reveal the COs more clearly.

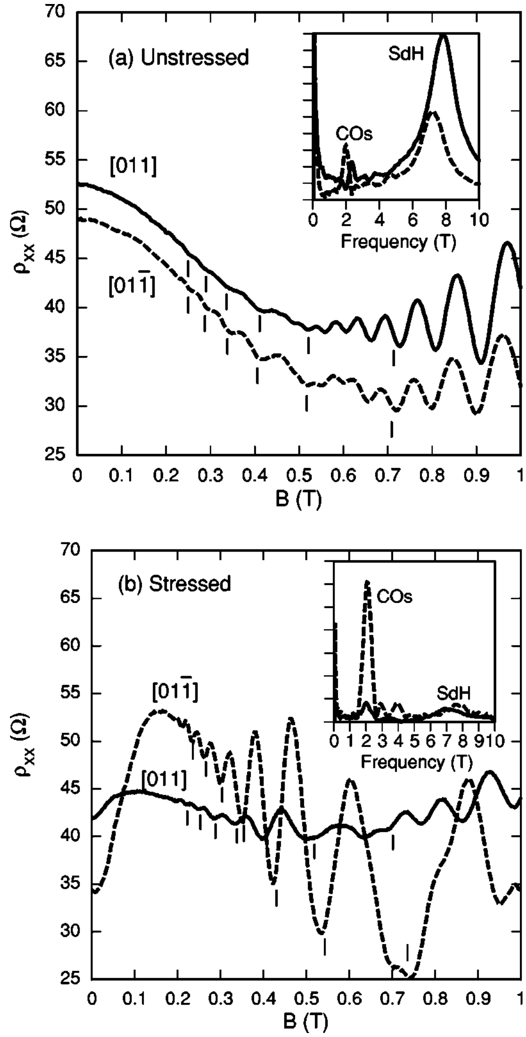

FIG. 2. Magnetoresistance traces for samples aligned to the cleavage planes. Full lines current flow in [011] direction, hatched lines $[01\bar{1}]$ direction. Vertical lines are predicted minima for COs, for a lattice period of 100 nm (see text). Inset : FFT spectra for these data sets. Peaks at around 8 T are from Shubnikov-de Haas oscillations. Peaks at around 2.0 T are from COs. (a) Unstressed samples. (b) Stressed samples.

In Fig. 2(a) we plot magnetoresistance traces for two unstressed samples aligned with [011] and $[01\bar{1}]$ and measured without gate bias, and in Fig. 2(b) we give the equivalent data for the stressed samples. Insets to the figures show Fast Fourier Transforms (FFTs) of the data in reciprocal field. All four samples have zero field resistivities about two or three times the unpatterned value. The carrier concentrations deduced from the high field SdH oscillations are reduced by less than 10% by the etching process, and most of the change in resistivity comes from a decrease in mobility. We believe that this reflects the greater random scattering in the patterned wafer. COs are observed in all traces with minima in the positions expected for the fundamental (1,0) wave vector in a 100 nm period 2D LSSL, evaluated according to the semiclassical theory.[2] [The notation used here is (n_x, n_y) where x is the local coordinate along the Hall bar axis, n_x is the index of the reciprocal lattice point of the LSSL in the x direction and n_y in the perpendicular direction.] The differences between the *strengths* of the COs in the two pairs of traces are striking. In the unstressed samples, the COs in the two directions are both very weak. We quantify their strengths by evaluating their peak to peak amplitudes at the fourth CO peak and normalizing these to the zero field resistivity. The two unstressed samples have normalized amplitudes computed by this method of 0.013 (for [011]) and 0.033 ($[01\bar{1}]$). On the other hand both the stressed samples in Fig. 2(b) show stronger oscillations. The normalized amplitude for [011], 0.074, is a little larger than that for the unstressed samples and that for $[01\bar{1}]$, 0.26, is much stronger still. This general pattern conforms to the predictions of Grant *et al.*[11] The unstressed samples are dominated by the surface effect, which we expect will be similar in the two orthogonal directions, leading to a nearly symmetric modulation with few open guiding center orbits. Our expectation is therefore for small CO amplitudes, as is observed. In the stressed samples, there is piezoelectric modulation in both the [011] and $[01\bar{1}]$ directions but the potential is of opposite sign. When one adds in the surface effect, which is of the same sign for the two directions, one direction has an enhanced potential magnitude and in the other direction it is reduced. For 100 nm period devices, theory predicts[12,13] and 1D experiments confirm[14] that $[01\bar{1}]$ is the direction of reinforcement, and will have the larger potential. For a 2D superlattice with a dominating (1,0) component in the potential, Grant *et al.* predict that open drifting orbits will develop along the y direction, and the resistivity component ρ_{xx} will contain the strong CO structure. This is exactly in accord with the data of Fig. 2(b).

The data from the [010] and [001] Hall bars also exhibit a striking confirmation of the 2D guiding center model. The unstressed samples show only extremely weak CO structures, which cannot be accurately quantified (normalized amplitude less than 0.01). However when the stressor is present, significant COs are observed. Data are presented in Fig. 3 for both directions, with the gates forward biased at 0.3 V. The characteristics are almost identical, and remarkably the period of the modulation which gives rise to the COs is not 100 nm, but 72 nm, as revealed by the bars marking the minima and the FFT in the inset to Fig. 3. The explanation of this effect is as follows. For these Hall bar directions, the (1,0) and (0,1) Fourier components contain no piezoelectric potential.[13] Biasing the gate forward reduces the surface potential at these reciprocal lattice points to small values. However the (1,1) and $(1,-1)$ Fourier components contain significant piezoelectric contributions. The guiding center model[11] predicts that, if one of these components is large enough, the drift will switch to this direction, at 45° to the axes of the Hall bars. This drift will contribute equally to ρ_{xx} and ρ_{yy}, with a period equivalent to $100/\sqrt{2}$ nm, just as we have observed. We therefore have another powerful confirmation of the guiding center model of Grant *et al.* At more negative gate biases, the (1,0) and (0,1) components in the potential for these samples increase, and the magnetoresistance characteristics become more complex. We will discuss them in a future paper.

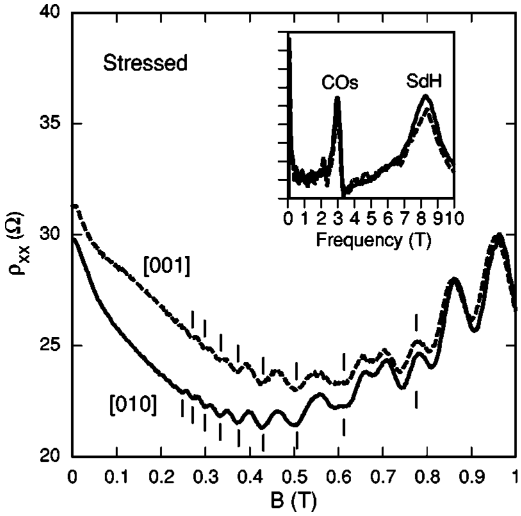

FIG. 3. Magnetoresistance traces for stressed samples aligned to the crystal axes. Full line [010], hatched line [001]. Vertical lines are predicted minima for a lattice period of $100/\sqrt{2}$ nm. Inset: FFT spectra for these data sets. Peaks at 2.8 T are for the COs.

Although qualitatively the guiding center model provides an excellent description of this data, there are some details which remain to be fully understood. In particular the model predicts that, in cases of strongly broken symmetry, where the dominating potential component is (1,0), drift will occur in the y direction and the oscillatory contribution to the resistivity will be large. However for the orthogonal Hall bar, where the (0,1) component is dominant, a longitudinal resistivity trace free of COs is predicted. Figure 2(b) shows however that in this direction the COs are not completely suppressed. There are a number of possible reasons for this. First the model assumes that all pinned guiding center orbits give a negligible contribution to the COs. As discussed by Grant *et al.* this is only true for large scattering times ($\omega_c \tau \gg 1$). Second the model ignores quantum mechanical effects, which are known to involve the CO periodicity[10] (associated in the quantum mechanical models with flat Landau bands) and are still expected to be present for asymmetric potentials. Thirdly, the FFT of the CO data of Fig. 2(b) shows the presence of a small but significant second harmonic. Harmonics are known to affect the zeroes in the effective potential,[15] and hence for some fields switching of the drift direction between [011] and $[01\bar{1}]$ may occur, with resultant contributions to the resistivity in both directions. Further work will be necessary to distinguish between these possible mechanisms.

In 1D LSSLs positive magnetoresistance (PMR) is usually observed at low fields, with the field at the peak related to the amplitude of the potential.[16,17] Our data shows PMR structure for the strongly asymmetric [011] and $[01\bar{1}]$ directions of Fig. 2(b), but not for the data of Figs. 2(a) and 3, where the COs are weaker. The simulations[11] suggest however that a PMR peak should be seen even for symmetrically modulated LSSLs. At present we do not understand why we see PMR structures only in the asymmetric cases. It is possible that random potential fluctuations in the sample may disturb the streaming orbits responsible for the PMR when the potential components in different directions are similar to one another.

Other recent investigations of short period, nominally symmetric 2D LSSLs have both reported significant COs.[18,19] Both these experiments employed the technique of forming a 2D lattice of holes in a PMMA resist film and metallising over the top to produce a patterned gate. This method may well introduce significant strain into the system and hence generate piezoelectric modulation, which will break the symmetry and, according to our model, generate COs. Steffens *et al.*[18] ascribe the CO structure they observe to quantum mechanical effects, but in the light of this study, it is plausible to suggest that asymmetries in the sample may be involved. In the work of Albrecht *et al.*[19] significant novel band structure effects are described and explained. The authors also observe CO structure but do not discuss its origin.

We have reported measurements of the COs in both symmetric and asymmetric 2D superlattice potentials. An asymmetric potential was found to be essential for the observation of strong COs. This is in agreement with a recent semiclassical theory[11] based on the guiding center of cyclotron motion, without the need to invoke quantum mechanics. Further confirmation of this theory was found by measuring samples whose patterns were aligned to the crystal axes. For these, the wave vector of the dominant piezoelectric component in the potential is at an angle to the pattern and the COs showed the appropriate reduced spatial period. We have therefore a coherent semiclassical picture that explains the main features of our experiments.

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