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Novel structures near $\nu = 9/2$ in short-period unidirectional lateral superlattices

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Abstract

Unidirectional lateral superlattices with a period $a = 92$ nm fabricated from two-dimensional electron gas (2DEG) with mobility $\mu = 76$ m^2/V s show novel structures around $\nu = 9/2$ at low temperatures (50 mK $\leq T \leq$ 350 mK). A shallow and broad dent with peaks on both sides appears when the direction of current is parallel to the direction of potential modulation, while a small peak emerges for the current direction parallel to the stripes of the grating. The observed phenomena resemble, albeit much smaller in magnitude, the anisotropic resistivity at half-filling of higher Landau levels recently observed in the plain 2DEGs with ultrahigh mobility and may be associated with the formation of charge density wave (CDW). © 2001 Elsevier Science Ltd. All rights reserved.

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Interplay between an artificial periodicity a of lateral superlattice (LSL) introduced into two-dimensional electron gas (2DEG), and the cyclotron diameter $2R_c$ is well known to give rise to commensurability magnetoresistance oscillation (Weiss oscillation) [1]. Since experimental studies of Weiss oscillation usually employ a of several hundred nanometers (see, e.g. [1]), the magnetic field B that makes $2R_c$ comparable to a is typically less than ~0.5 T. At those fields, Landau level quantization does not play a major role, and therefore the interpretation in terms of semiclassical trajectory [2] is valid. Since R_c is inversely proportional to B ($R_c = \hbar k_F/eB$ with $k_F = \sqrt{2\pi n_e}$ the Fermi wave number, n_e the electron areal density), the field range of interest shifts to higher-field side with the decrease of a. For small enough a, the field B giving $2R_c \sim a$ enters the "quantum Hall regime", where the extended states in the disorder-broadened Landau levels are energetically well separated from each other by the localized states inbetween, and where novel effects beyond semiclassical pictures may be expected. One of the motivations for us to introduce into 2DEG as small a as possible has been to pursue phenomena brought about by the interplay of a and R_c in the quantum Hall regime. Recently, several Hatree–Fock calculations [3–6] predicted unidirectional charge density wave (CDW) formation in a (plain) 2DEG in a moderately large magnetic field where higher Landau levels (index $N \geq 2$) is nearly half filled, i.e. near $\nu \equiv n_e h/eB = 9/2, 11/2, 13/2, \ldots$. The predicted periods of the CDW show slight variation among calculations [3–5,7,8], but fall in the range of 2.5–3 times R_c (or 5.8–6.7 times $l = \sqrt{\hbar/eB}$, the magnetic length) for $\nu = 9/2$. The CDW is expected to show strong response to the external periodic potential modulation having the same period. In fact, numerical studies of finite-size systems [9] showed sharp and strong peaks in the response functions to a certain wave vector, which was taken to provide another support for the CDW instability of the 2DEG. In the present paper, we report magnetotransport measurements of LSL with a near the theoretically predicted period of CDW, in search of experimental evidence for the CDW formation. We focus on $\nu = 9/2$, the half-filling state of $N = 2$ down-spin Landau level, since the calculation [7] predicts the highest melting temperature, hence maximum robustness of CDW against disorder for this highest-field state.

Our LSLs are prepared simply by placing a grating of

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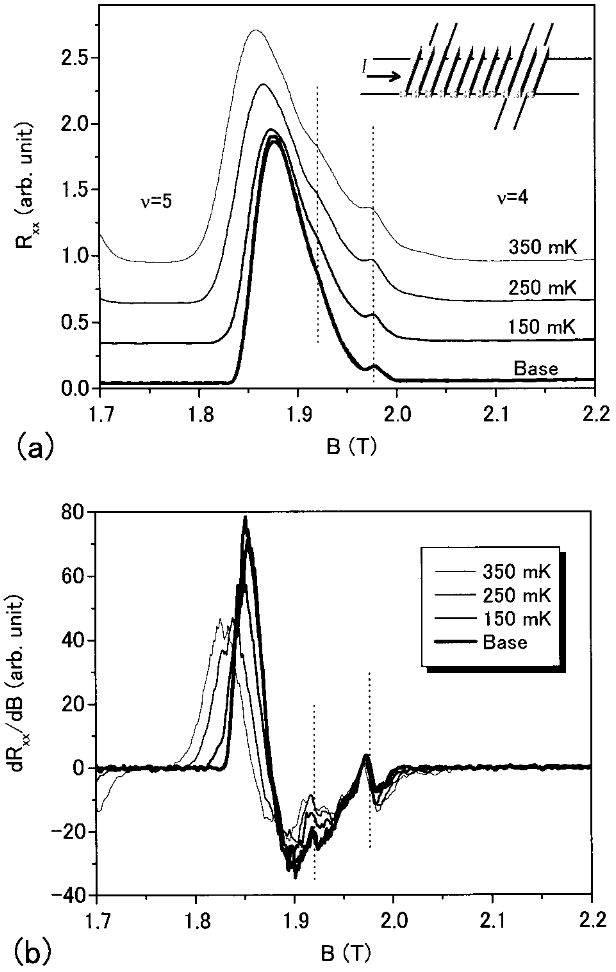

Fig. 1. (a) Magnetoresistance traces around $\nu = 9/2$ of the perpendicular LSL ($a = 92$ nm) at four different (bath) temperatures ($I = 100$ nA). Traces for higher temperatures are vertically shifted (0.3 units each) for clarity. Vertical dotted lines mark the positions of peaks (or shoulders) which flank the both ends of a shallow and broad dent. (b) Derivative with B of traces in (a).

high-resolution negative electron-beam resist [10,11] on top of 2DEG wafers. The grating introduces strain to the wafer on cooling down to cryogenic temperature and the strain, in turn, induces potential modulation mainly through the piezoelectric effect [12,13]. Conventional GaAs/AlGaAs 2DEG with mobility $\mu = 76$ m^2/(V s) (at 4.2 K) and $n_e = 2.1 \times 10^{15}$ m^{-2} is fabricated into two sequential Hall bars with channel width of 37 μm; one of the Hall bars is further processed into LSL and the other is used as a reference. LSLs with two different directions of the grating with respect to the direction of current are prepared; the *perpendicular LSLs* have a grating whose stripes are perpendicular to the current direction (therefore the direction of potential modulation is along the current) and for the *parallel LSLs* the grating stripes are parallel to the current (see the insets to Figs. 1a and 4). In both types of samples, the current axis of the Hall bars is set parallel to the $\langle 110 \rangle$ direction to maximize the strain-induced piezoelectric effect. (Note that the $\langle 110 \rangle$ and the $\langle 1\bar{1}0 \rangle$ directions are equivalent for the piezoelectric effect [12]. No direct effect on the resistivity of the crystallographic directions is expected for our 2DEG with modest mobility.) In what follows, we mainly discuss the results for LSLs with a period $a = 92$ nm, which is about 2.3 times R_c at $\nu = 9/2$. The period a is almost the same as the depth $d = 90$ nm of the heterointerface from the surface, resulting in a small amplitude V_0 of the potential modulation. From the amplitude of Weiss oscillation for the perpendicular LSL, we evaluate [13] $V_0 = 0.015$ meV or 0.2% of the Fermi energy E_F. For the parallel LSL, V_0 is assumed to be the same as that for the perpendicular LSL with the same period. The perpendicular LSL also shows positive magnetoresistance and commensurability oscillation of the $\nu = 3/2$ composite fermion, which is the subject of a separate paper [14]. The measurements are performed in a top-loading ^{3}He–^{4}He dilution refrigerator equipped with a sample rotation stage

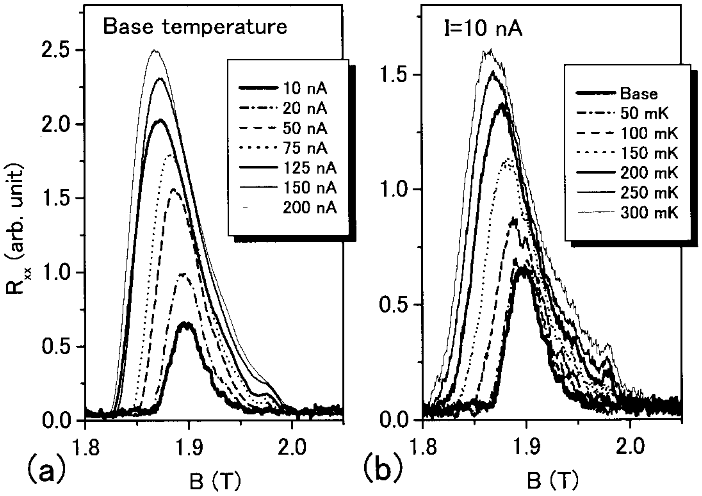

Fig. 2. (a) Traces taken with different excitation currents I at the base temperature. (b) Traces taken at different temperatures with $I = 10$ nA.

operated in a 17 T superconducting magnet. A standard ac lock-in technique (16 Hz) is employed for magnetoresistance measurements.

Fig. 1a shows magnetoresistance traces of the perpendicular LSL around $\nu = 9/2$ taken at four different (bath) temperatures, ranging from the base temperature (~20 mK) to 350 mK. The field for the exact $\nu = 9/2$ filling is 1.93 ± 0.03 T estimated either by the low field Shubnikov–de Haas (SdH) oscillation or by the quantum Hall R_{xx} minima or R_{xy} plateaus in the medium to high-field range.[1] A shallow and rather wide dent with peaks (or shoulders), marked by vertical dotted lines, on both sides is observed. The peak on the lower field side is less evident, but is clearly identified in the field derivative traces shown in Fig. 1b. The peaks become broader or, probably equivalently, the dent becomes shallower with temperature. Two traces taken on two different days are actually shown for the base temperature. They overlap with each other almost perfectly, demonstrating very good reproducibility of the structures in issue. These structures are absent in the traces taken simultaneously on the plain 2DEG of the reference Hall bar located adjacent to the LSL (see Fig. 3b). Since we are looking at very small structures, rather high excitation current, $I = 100$ nA, is employed for these measurements. As a result, the electron temperature is considerably higher than the bath temperature. The difference is roughly estimated, either by the maximum slope of the Hall resistance [15] or by the input power per electron [16], to be up to 50 mK for the base temperature and less serious for higher bath temperatures.

To see that the observed structures are not artifacts due to the high excitation current, traces taken with different currents ($I = 10$–200 nA) at the base temperature (Fig. 2a), and those taken at different temperatures up to 300 mK with $I = 10$ nA (Fig. 2b) are shown. Although the signal-to-noise ratio is poor for lower current traces, at least the peak on the higher-field side is still visible.

Samples are tilted with respect to the field to see the effect of in-plane magnetic field $B_{\|}$ on the observed new structures. Sample tilt is done in a way that the field is within the plane spanned by the sample-normal and the current direction; therefore, $B_{\|}$ is applied parallel to the current (see the inset of Fig. 3b). The traces are shown in Fig. 3. As demonstrated in Fig. 3b, $B_{\|}$ has no noticeable effect on the plain 2DEG. For the perpendicular LSL, on the other hand, $B_{\|}$ slightly pushes down the shallow dent, as is evident in the blow-up shown in Fig. 3a of the part near the higher-field peak.

We have also carried out similar measurements on another perpendicular LSL with a slightly larger period $a = 115$ nm ($a \simeq 2.9R_c$). Magnetoresistance traces around $\nu = 9/2$ are almost structureless, except for very small and broad humps at the positions near those of the peaks in Fig. 1, which may possibly be the sign of remnant structures.

Next we turn on to the parallel LSL. Magnetoresistance traces shown in Fig. 4 display a small peak at ~1.97 T, the position corresponding to that of a shallow dent for the perpendicular LSL. The dotted vertical lines in the figure indicate the fields for the flanking peaks in the perpendicular LSL shown in Figs. 1 and 3 multiplied by a correction factor 1.007 which takes account of a slight difference in the carrier concentrations. After correction by this factor, the positions of peaks and dips of SdH oscillation for the two LSLs perfectly match with each other. There are also many other unidentified structures especially in the low temperature trace around the transition peak of R_{xx}. These structures are reproducible among different sweeps and therefore

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[1] The error of ~2% for the $\nu = 9/2$ field was inevitable mainly due to hysteresis of superconducting magnet at low fields for SdH density measurement, and to the difficulty in exact positioning of just filling for the quantum Hall minima and plateaus.

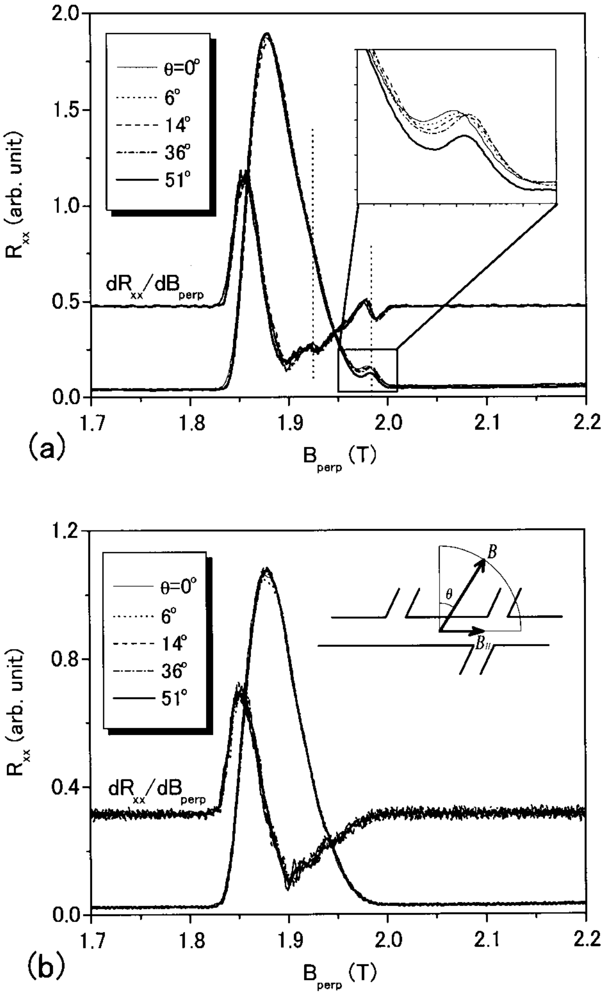

Fig. 3. (a) Traces of the perpendicular LSL with different tilt angles θ plotted against the component of the magnetic field normal to the 2DEG plane B_{perp}. Derivatives of the traces by B_{perp} are also shown. (b) Similar to (a) for the plain 2DEG. The field is tilted within the plane of the sample-normal and the current direction as shown in the inset.

cannot be dismissed as noises. However, similar structures are sometimes observed also in the plain 2DEG, suggesting that their origin is not directly linked with the LSL. We defer the scrutiny of these unidentified structures for the future study. The unidentified structures are soon washed out by raising the temperature as can be seen in Fig. 4. A small peak at ~1.97 T is more robust and survives up to higher temperature. This, along with its complete absence in plain 2DEG, brought us to the conclusion that the small peak is resulting from LSL, although it is less confirming compared with the case for perpendicular LSL. In all cases both for perpendicular and parallel LSLs, no noticeable structures are observed in R_{xy} apart from ordinary quantum Hall plateaus.

The observed structures around $\nu = 9/2$ are reminiscent of strongly anisotropic resistivity reported for plain 2DEG with ultrahigh mobility [17,18]. In those papers, it is reported that transport near $\nu = 9/2, 11/2, 13/2, \ldots$ critically depends on the direction of current with respect to the crystallographic axis of GaAs/AlGaAs wafers: for current flowing along the $\langle 1\bar{1}0 \rangle$ direction, resistivity shows sharp maxima at those half filling, while it turns into minima, often leaving peaks on both sides, when the current flow is in the $\langle 110 \rangle$ direction. The anisotropy manifests itself only at $T \leq 150$ mK for 2DEG with $\mu \sim 1000\ \mathrm{m^2/(V\ s)}$. Later on, acute sensitivity of the anisotropy to $B_{\|}$ is reported [19,20]: for strong enough $B_{\|}$ (roughly >0.5 T), the current direction along $B_{\|}$ gives maxima while current flowing vertically brings about minima, overwriting the original crystallographically defined preferred orientation. The origin of these anisotropies has still not been firmly established yet. The most widely accepted explanation at present is that it is associated with the formation of unidirectional CDW. The transport anisotropy in the absence of $B_{\|}$

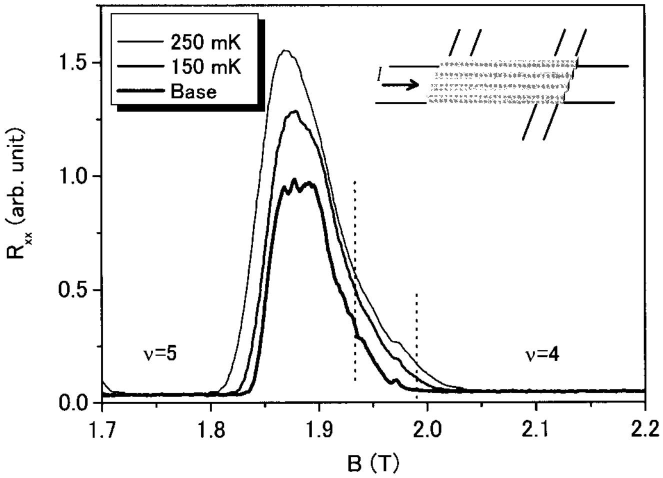

Fig. 4. Traces for the parallel LSL ($a = 92$ nm) at three different (bath) temperatures. ($I = 100$ nA.) Vertical dotted lines indicate the position of flanking peaks in the perpendicular LSL (Figs. 1 and 3), multiplied by a factor 1.007 to correct for slight difference in the electron densities.

demands some sort of built-in anisotropy in the 2DEG crystal. Growthfront of molecular beam epitaxy (MBE)-grown GaAs are known to show inequivalence between $\langle 1\bar{1}0\rangle$ and $\langle 110\rangle$ directions. Many aspects of the surface show structures elongated to the $\langle 1\bar{1}0\rangle$ direction: rows of atomic-scale arsenic dimers [21]; monolayer islands, typically 10–100 nm in size, formed in the course of 2D nucleation growth on the terrace [22]; bunched steps [23] or large (~μm in size and ~10 nm in height) mounds [24] formed on growth interruption and annealing. Also it is well known that monolayer steps running along the $\langle 1\bar{1}0\rangle$ direction (A-type steps) are relatively straight and smooth while those running parallel to $\langle 110\rangle$ (B-type steps) are ragged [23,25]. Tokura et al. [26] reported that 2DEGs with μ ranging from 500 to 1100 $\mathrm{m^2/(V\,s)}$ show anisotropic Hall mobility (at zero magnetic field); they showed that μ in the $\langle 1\bar{1}0\rangle$ direction is 1.05–1.6 times larger than μ in the $\langle 110\rangle$ direction. Later the same authors demonstrated [27] that the anisotropic μ results from A-type steps by using 2DEGs grown on vicinal substrate. They showed that local dipole induced via piezoelectric effect by small lattice strain due to the steps explains the dependence of μ on n_e. If the same mechanism is operative for the 2DEGs in Refs. [17,18], it follows that the current along the $\langle 110\rangle$ direction experiences modulated potential while the current flowing in the $\langle 1\bar{1}0\rangle$ direction does not. The situation is similar to our perpendicular LSL for the former current direction and to the parallel LSL for the latter. The observed structures in our magnetoresistance bolster this correspondence: a dent in the perpendicular LSL are consistent with the minimum for the $\langle 110\rangle$ current direction, and a peak appears both for our parallel LSL and for the current along the $\langle 1\bar{1}0\rangle$ direction. This suggests that the structures observed in our LSLs might also be related to the CDW formation. Our structures are observed up to much higher temperature for 2DEG with mobility more than an order of magnitude lower than those used in Refs. [17,18]. However, these do not necessarily invalidate the CDW picture. Calculated melting temperatures T_c for CDW [7] are rather high: for $\nu = 9/2$, $T_c \simeq 3.5$ K for an ideal 2DEG without any disorder, and still over 2 K for our disorder broadening $\Gamma_0 = 3.6\ \mathrm{K/T^{1/2}}$ estimated from the field 0.13 T of the commencement of SdH oscillation or even for $\Gamma_0 = 5.7\ \mathrm{K/T^{1/2}}$ calculated by the formula from Self-consistent Born approximation [28] using the scattering time deduced from the damping of SdH oscillation. We believe that lower temperatures and extremely high mobility are required for plain 2DEGs so as not to smear out, by temperature or impurity broadening, the tiny anisotropic potential modulation resulting from step-induced strain or from other anisotropy in the 2DEG crystal including aforementioned possible candidates. Our potential modulation is, although quite small compared with those usually used in experiments of Weiss oscillations, expected to be much larger than the built-in anisotropy in 2DEG, thereby making the requisition for temperature and mobility much less stringent.

As for the dependence on $B_{\|}$, our results are not in straightforward correspondence with the behavior of the plain 2DEG [19,20]. A dent in our perpendicular LSL becomes slightly deeper with $B_{\|}$ parallel to the current, as shown in Fig. 3a, while the same in-plane field turns minima into maxima for the plain 2DEGs. Theoretical calculations [7,8] show that it is energetically favorable for unidirectional CDW to be aligned with its stripes perpendicular to $B_{\|}$, to which the experimentally observed sensitivity of the anisotropic resistivity to $B_{\|}$ is attributed. The calculated energy difference, however, is quite small. Therefore even if it is capable of overwriting the very small native anisotropy of the crystal, it is probably beyond its competence to overturn a CDW whose direction is governed by a much larger modulation imposed by the grating. In these theoretical papers [7,8], it is implicitly assumed that the current direction giving resistivity minima is parallel to the stripes of CDW. However, the crystallographic direction of built-in potential modulation of plain 2DEG deduced from the anisotropic mobility [26,27] and our present result suggest that it is the other way around. Setting aside this incongruence, our result seems to be consistent with the theories in that $B_{\|}$ stabilizes the CDW that has the stripes perpendicular to the field, thereby corroborating the resultant minima.

So far we have shown that the observed structures in the magnetoresistance of our LSLs are consistent with the formation of CDW. However, we still have not obtained direct and compelling evidence of its formation. To gain more insight into the nature of the observed structures, more detailed and quantitative measurements with respect to the temperature, current, direction and magnitude of $B_{\|}$, or to n_e which controls both the field to achieve $\nu = 9/2$ and the corresponding R_c, will be necessary. For such detailed measurements, the magnitude of the observed structures seems to be a little too small. Probably 2DEG with higher mobility and LSL with larger potential modulation (without making the period larger) will be of much help. These two seem to be quite difficult to achieve at the same time since higher mobility usually requires deeper heterointerface from the surface and therefore incompatible with the large modulation amplitude as long as the modulation is introduced by a surface grating with a small period. The improvement of samples for more detailed studies belongs to our future challenge.

To summarize, we have observed novel structures near $\nu = 9/2$ in the magnetoresistance of unidirectional LSL with a period $a \simeq 2.3\,R_c$: a dent with flanking peaks on both sides when the current is perpendicular to LSL; and a small peak for the current parallel to LSL. The direction between the current and the potential modulation is consistent with that of the anisotropic resistivity observed in ultrahigh mobility plain 2DEGs [17,18], if the crystallographic direction of built-in potential inferred from anisotropic μ [26,27] is taken into account. The structures may be a manifestation of the response to the external periodic potential modulation of the theoretically predicted [3–6] CDW.

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