Magnetotransport of Unidirectional Lateral Superlattice Around Half-Odd Filling of Landau Levels

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We have studied magnetotransport of unidirectional lateral superlattice around half-odd filling of Landau levels. For small enough period a=92 nm, intriguing features are observed around two particular filling factors ν=3/2 and 9/2: positive magnetoresistance and commensurability oscillation of hole-based ν=3/2 composite fermions, and new unknown structures around ν=9/2 which might possibly be related to the theoretically-predicted charge density wave formation at higher Landau levels. With slightly larger period a=115 nm, only incomplete signs of these structures are observed.

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I. INTRODUCTION

Two-dimensional electron gas (2DEG) at half-odd filling is known to exhibit versatile nature depending on the index N of the Landau level (LL) to be half occupied. When the lowest LL (N=0) is half filled (filling factor ν=1/2, 3/2), 2DEG behaves as Fermi liquid of composite Fermions (CFs), while even-denominator fractional quantum Hall effect (FQHE) emerges for N=1 (ν=5/2, 7/2) [1]. For higher LLs ($N \geq 2$), Hartree-Fock calculations [2, 3] predict that the ground state is the charge density wave (CDW) state. Strongly anisotropic electronic transport recently uncovered for ultrahigh mobility 2DEGs [4, 5] is believed to be associated with the CDW. In the present work, we introduce an artificial length scale a, the period of unidirectional lateral superlattice (LSL), to see the phenomena brought about by the interplay between a and the characteristic length scales of 2DEG around half-odd filling factors. For small enough period a=92 nm, interesting features are observed at ν=3/2 and 9/2 (Fig. 1). In the present paper, we focus on the two filling factors. The features are obscured by a slight increase of the period to a=115 nm.

II. COMPOSITE FERMIONS AT ν=3/2

Behavior of 2DEG around ν=3/2 is well described by the Fermi sea of CFs, in much the same way as the case for more familiar ν=1/2 CFs. However, significant differences arise because a ν=3/2 CF is formed by attaching two flux quanta to a *hole* from the ν=2 state, the state at which both spin branches of the lowest LL is completely filled. Since the number of electrons the lowest LL can accommodate varies with $B_\perp$, the magnetic field perpendicular to the 2DEG plane, so does the density of holes hence density n_{CF} of ν=3/2 CFs as $n_{\mathrm{CF}} = 2B_\perp e/h - n_e$, with n_e the (fixed) density of electrons. As a consequence, effective magnetic field B_{eff} experienced by CFs slightly away from exact filling 3/2 reads, $B_{\mathrm{eff}} = B_\perp - 2n_{\mathrm{CF}}e/h = -3(B_\perp - B_{3/2})$, where $B_{3/2}$ denotes $B_\perp$ exactly at ν=3/2.

In LSL, periodic potential modulation entails periodic modulation of n_e, which works as periodic modulation of B_{eff} for CFs. Therefore behavior of CFs under potential modulation is expected to be analogous to that of electrons under magnetic-field modulation: minima of commensurability oscillation (CO) occurs at $2R_{\mathrm{c}}/a = n + 1/4$ instead of $2R_{\mathrm{c}}/a = n - 1/4$ (n=1,2,3,...), where $R_{\mathrm{c}} = \hbar k_{\mathrm{F}}/eB$ represents cyclotron radius with k_{F} the Fermi wavenumber [6]. This has recently been confirmed for ν=1/2 CFs [7, 8]. In Fig. 2, we present our results for ν=3/2 CFs. For a=92 nm LSL, two important elements in the transport properties of LSL, positive magnetoresistance (PMR) emanating from B_{eff}=0 and CO at larger $|B_{\mathrm{eff}}|$, are observed. We believe these observations are enabled by (1) making a much smaller than the mean free path L_{CF} of the ν=3/2 CF, which is estimated to be $\sim$ 1.1 μm for our present sample and (2) modulation amplitude was kept small enough so as not to obstacle the cyclotron motion [9]. In Refs. [7, 8], the observed PMR can be subdivided into two distinct contributions: low $|B_{\mathrm{eff}}|$ part attributable to the "snake orbit" and steep a rise with $|B_{\mathrm{eff}}|$ between (n=1) CO and the commencement of FQHE. In our case, since n=1 CO minima is already on the verge of ν=4/3 and 5/3 FQHE owing to the smallness of a, only the former contribution can be seen. The range of $|B_{\mathrm{eff}}|$ for the snake-orbit PMR can be used to evaluate the amplitude of B_{eff} modulation hence of the potential modulation, which for the present sample is $\sim$2 % of the Fermi energy. On the other hand, the modulation amplitude can also be estimated from ordinary CO of electrons at low fields [10], which gives much smaller value $\sim$0.2 %. The discrepancy may be representing worse efficiency of screening for CFs than for electrons [11]. The position of CF minima is a measure of $k_{\mathrm{F}} = \sqrt{4\pi n_{\mathrm{CF}} f}$, where f denotes the polarization of the CFs (f=1 and f=0.5 for fully spin-polarized and fully spin-unpolarized cases, respectively). As shown in the right panel of Fig. 2, most of the minima positions are consistent with fully spin-polarized k_{F} (solid downward triangles). It is important to point out that the dependence of k_{F} on B_{eff} via n_{CF} is taken into account here. If one uses instead the constant value $\sqrt{4\pi n_e/3}$, the value exactly at ν=3/2, agreement becomes noticeably worse. A few CO minima up to n=3 are observed in contrast to the case of previously reported ν=1/2

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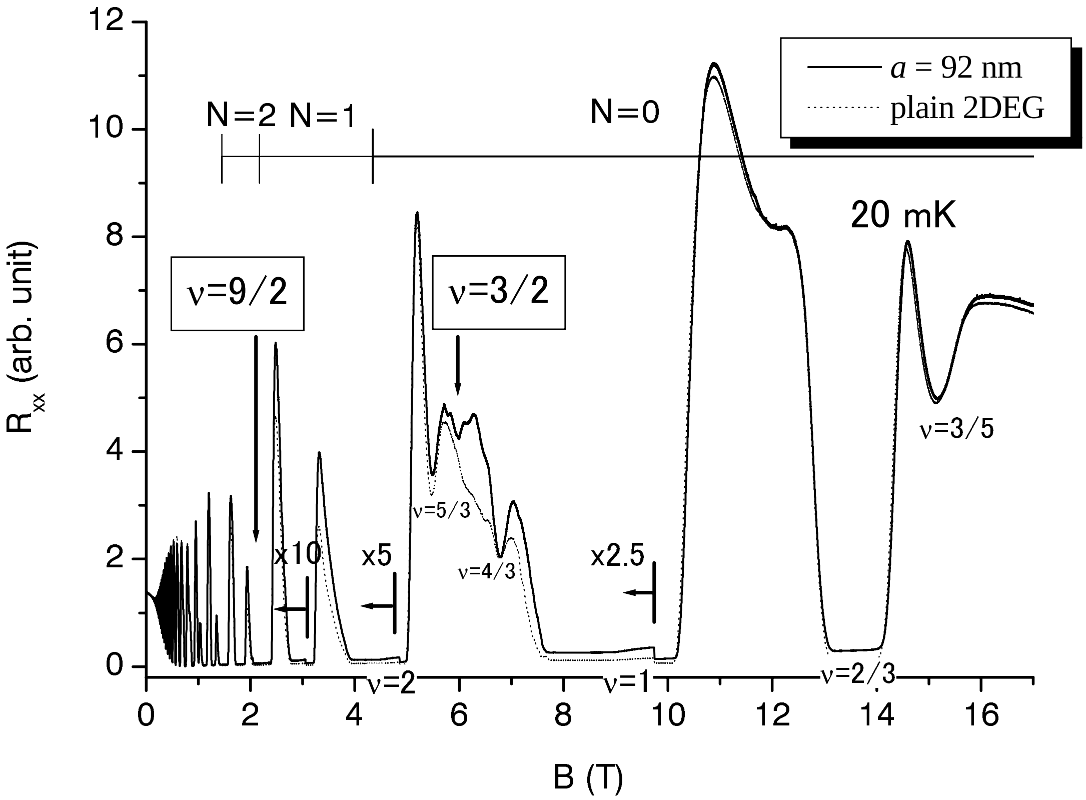

FIG. 1: Overview of resistance of a=92 nm LSL along with that of plain 2DEG measured simultaneously. Structures around ν=9/2 is not discernible at this scale.

CFs where only n=1 minima appeared. One dip at $B\sim$5.57 T can be explained by fully spin-unpolarized k_F. The origin of the apparent co-presence of the two extreme case of spin-polarization remains unexplained at present. With slight increase of a to 115 nm, only a small dent at ν=3/2 is observed, which is probably a trace of incompletely developed PMR. It is hard to identify CO. By increasing a, modulation amplitude is inevitably enhanced at the same time, making concomitantly the requirements (1) and (2) mentioned above difficult to be met. In the 2DEG wafer from which our present LSLs are fabricated, 2DEG plane resides at the depth d=90 nm from the surface. In general, it is difficult to make a smaller than d, which leaves us very small window in a for observing CO of CFs.

III. NEW STRUCTURES AROUND ν=9/2

As mentioned earlier, theoretical calculations predict CDW formation at the half-filling of higher ($N\geq$2) LLs [2, 3]. The period of CDW is predicted to be close to the cyclotron diameter 2R_c; the predicted period shows slight scattering among calculations but falls in the range of 2.5−3 times R_c [2, 3, 12, 13]. So far, no transport anomaly has been reported at the quantum Hall transition region for middling mobility 2DEGs ($\mu\sim$100 m^2/Vs) except probably for resistance fluctuations observed in mesoscopic samples [14]. Only with exceptionally high quality wafers with $\mu\sim$1000 m^2/Vs or better has the anisotropic resistivity been observed. Although not clearly identified yet, there ought to be some native anisotropy in the 2DEG crystal that ends up in the anisotropic transport. The native anisotropy will be extremely weak and will readily be washed away with the slightest disorder. However by enforcing anisotropy much stronger than native ones from outside, the possibility opens up for the anisotropic transport to survive the disorder. Especially if the electron system has a tendency toward voluntarily forming CDW with a specific period, periodic modulation with the same period will be of maximum efficiency. In fact, numerical calculation of finite size systems [15] indicated strong response of 2DEG with half-filled N=2 and 3 LLs to a periodic potential with a certain period. The idea made us take a closer look around ν=9/2 (the state with the highest field among a series of half-filled $N\geq$2 LLs, 9/2, 11/2, 13/2,...) of our a=92 nm and 115 nm LSLs, each period corresponding to 2.3 R_c and 2.9 R_c, respectively. As shown in Fig. 3, some unknown structures are observed around ν=9/2 for a=92 nm LSL (Fig. 3): rather broad hump and small peak (marked by vertical dotted lines) flanking lower and higher field sides, respectively, of a shallow broad dent at ν=9/2. The structures are easier to be identified in the derivative traces Fig. 3b. For the a=115 nm LSL, the structures are less apparent but seem not to be completely

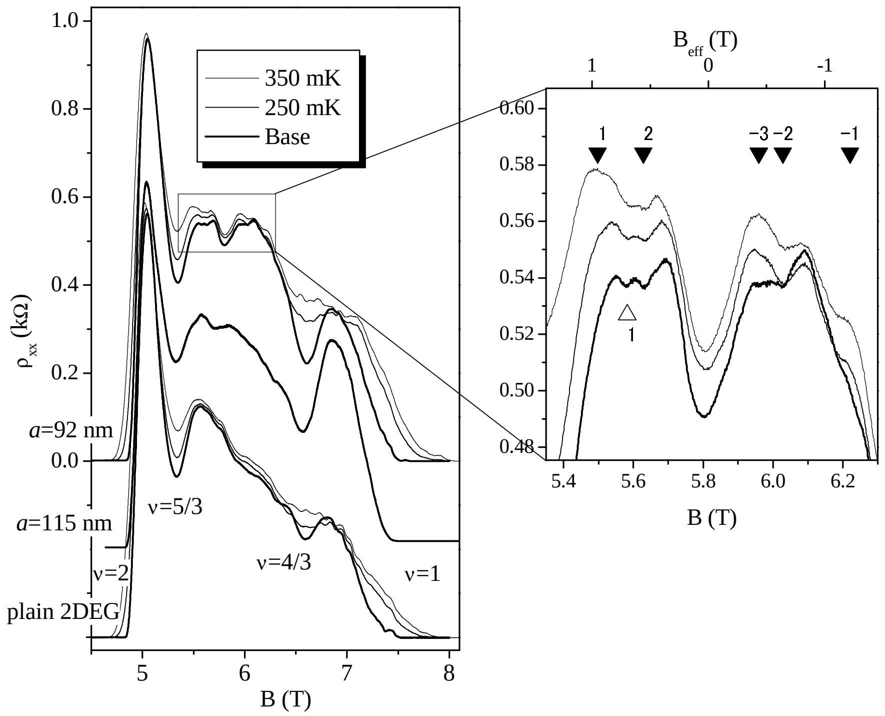

FIG. 2: Left panel: Resistivity between ν=1 and 2 for several temperatures. Only the base temperature (bath ∼20 mK) trace is shown for a=115 nm LSL. Traces for a=115 nm LSL and plain 2DEG are vertically shifted for clarity. Right panel: Close up of the vicinity of ν=3/2 for a=92 nm LSL. Positions of CO minima consistent with fully spin-polarized (fully spin-unpolarized) k_F are marked by solid downward (open upward) triangles.

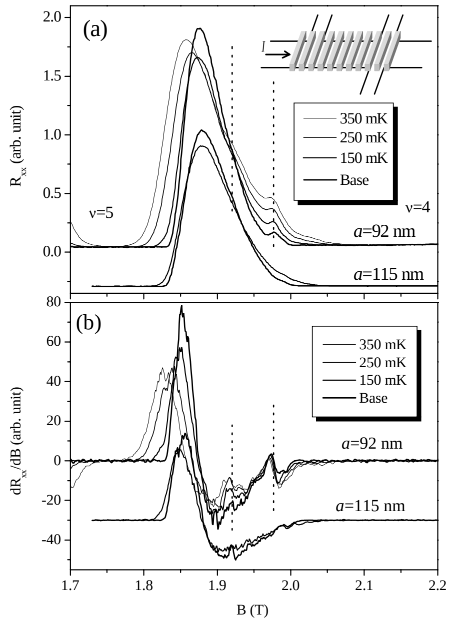

FIG. 3: (a) Magnetoresistance traces around ν=9/2 for several temperatures. Traces for a=115 nm LSL are vertically shifted for clarity. (b) Derivative with B of traces in (a).

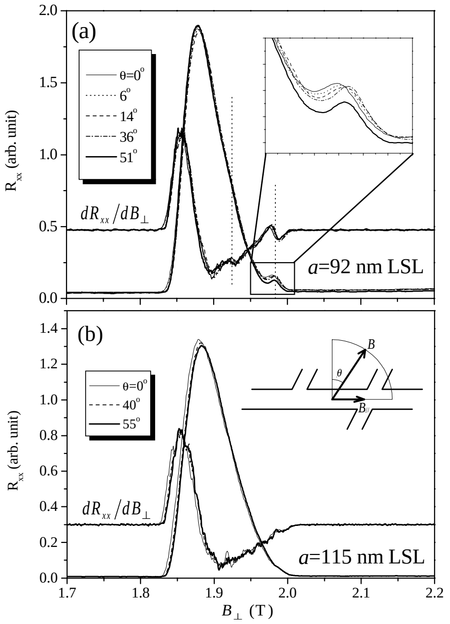

FIG. 4: Traces with several values of the angle θ (depicted in the inset of (b)) plotted against $B_\perp$. Derivative traces with $B_\perp$ are also shown. (a) a=92 nm LSL. (b) a=115 nm LSL.

absent. By contrast, structures are completely absent in plain 2DEG [16] as expected. Introducing a magnetic field component parallel to the current by tilting the field, the shallow dent are observed to become deeper for a=92 nm LSL (Fig. 4a). We have also made LSL with stripes parallel to the direction of the current, which shows a tiny peak instead of the shallow dent at ν=9/2 [16]. The structures resemble the anisotropic structures observed in ultrahigh mobility 2DEGS, although the magnitudes are far smaller, and may be capturing the manifestation of the CDW in the resistivity. In order to interpret the structures in our resistivity traces by the involvement of CDW, it is necessary to elucidate the direction of CDW stripes with respect to the potential modulation, and how the CDW manifests itself in the transport. It is tempting to assume that (i) CDW stripes align with potential modulation, and (ii) the current is more difficult to flow in the direction perpendicular to the CDW stripes. The assumptions (i) and (ii) lead to a maximum (a minimum) in resistivity for potential modulation perpendicular (parallel) to the direction of the current. This appears to be the opposite to our observation: a shallow dent (a tiny peak) is seen for perpendicular (parallel) LSL. Therefore either (i) or (ii) has to be incorrect. Recent calculations [17, 18] claims that energy becomes lower when the CDW stripes are *orthogonal* to the external potential modulation, in accordance with recent experiment [19] examining the correlation between surface morphology and electron transport of ultrahigh mobility 2DEGs. However, the calculations may not be directly applicable to our experiments since they assume the period of potential modulation a much larger than that of CDW, while in our samples a is expected to be close to (or maybe even smaller than) the CDW period. The assumption (ii) is widely taken for granted [20, 21], but we believe it is not so obvious since it assumes that the CDW is pinned, and no care is taken of the difference between the bulk and the edge of the sample, etc. Obviously more experimental works will be necessary to clear up this apparent inconsistency.

Acknowledgments

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