Modulation induced stripe phase at fractional fillings

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Abstract. We have experimentally examined the state of a two-dimensional electron gas subjected to unidirectional periodic potential modulation in the vicinity of the filling \(\nu=5/3\) (equivalent to \(\nu=1/3\) by the particle-hole symmetry). In addition to a peak in the longitudinal resistivity \(\rho_{xx}\), we find small amplitude oscillations roughly periodic in the magnetic field \(B\) in the Hall resistivity \(\rho_{yx}\). The oscillations appear in a narrow range of the electron density \(n_e\), and the period \(\Delta B\) of the oscillations increases with the slight increase in \(n_e\). The oscillations are interpreted as resulting from the commensurability between the high harmonics of the modulation potential and the stripe state, which is predicted by the density matrix renormalization group calculations to be the ground state in our system.

1. Introduction

In recent studies [1, 2], the present authors have investigated the effect of unidirectional periodic potential modulation \(V(x)\) on the fractional quantum Hall (FQH) states. We have experimentally found a peak that grows with decreasing temperature (see Fig. 3 (a)), instead of a minimum, in the resistivity \(\rho_{xx}\) in the vicinity of the filling \(\nu=5/3\) when the amplitude of the modulation is made sufficiently large [2]. In search of the origin of the peak, we performed calculations by the density matrix renormalization group (DMRG) method at \(\nu=1/3\) (equivalent to \(\nu=5/3\) by the particle-hole symmetry), which revealed phase transition from the FQH state to the stripe state having a period \(\sim 4l\) (with \(l=\sqrt{\hbar/eB}\) the magnetic length) [2] (see the next section) reminiscent of the stripe phase at higher Landau levels (LLs) [3, 4, 5]. The result strongly suggests that the observed peak is originating from the stripe phase, representing the first experimental indication for the stripe phase in the lowest Landau level (LLL). Note that experimental evidence for the stripe phase in the LLL, in spite of the theoretical prediction [6, 7], has been elusive thus far. In the present paper, we study the state at \(\nu\sim 5/3\) in more detail. The Hall resistivity \(\rho_{yx}\) is examined in addition to the longitudinal resistivity \(\rho_{xx}\). We explore the behavior of the resistivities under the application of the dc current bias \(I_{dc}\), which is expected to affect the pinning or sliding of the stripe state.

2. Result of DMRG calculations

In this section, we briefly review the result of the calculation by the DMRG method. We show the results for the rectangular as well as the sinusoidal modulation. Both types of the modulation exhibit qualitatively the same behavior. As shown in Fig. 1(a), the FQH gap \(\Delta_{1/3}\) decreases with increasing modulation amplitude \(V_0\), until it vanishes at the value of \(V_0\) close to \(\Delta_{1/3}\) at \(V_0=0\) for sinusoidal \(V(x)\), and at a smaller \(V_0\) for rectangular \(V(x)\). Charge density wave (CDW) with the
Figure 1. (a) Energy levels of the ground state (solid symbols) and the first excited state (open symbols) as a function of $V_0$. Triangles (squares) are for sinusoidal (rectangular) modulation. (b)(c) Charge density profile for various values of $V_0$; (b) sinusoidal modulation, (c) rectangular modulation. The profiles of the modulation potential $V(x)$ are plotted by dot-dashed lines. $\nu=1/3$ and calculated for $N_e=12$ electrons.

Figure 2. The pair correlation functions $g(x, y)$ at $\nu=1/3$ ($N_e=12$) for plain 2DEG (a), and for ULSL with sinusoidal modulation (b) and rectangular modulation (c).

The distance between adjacent peaks $\sim 4l$ develops after $\Delta_{1/3}$ vanishes; the emergence of the CDW is abrupt for the sinusoidal $V(x)$, whereas gradual development is already seen while the value of $\Delta_{1/3}$ is still finite for rectangular $V(x)$ (Fig. 1(b)(c)). The pair correlation functions displayed in Fig. 2 reveal the correlation at $4l$ not only in the $x$-direction but also in the $y$-direction (along the stripe), resembling the stripe-II phase in [7]. Despite the prominent stripe-like charge density profile in Fig. 1 (b), however, the correlation is rather unclear for sinusoidal $V(x)$ (Fig. 2(b)) (for the reason not known at present).

3. Experimental details

The device of the unidirectional lateral superlattice (ULSL) in the Hall-bar geometry was fabricated from a GaAs/AlGaAs two-dimensional electron gas (2DEG) wafer with the electron density $n_e=2.1\times10^{15}$ m$^{-2}$ and the mobility $\mu=77$ m$^2$/Vs. Unidirectional periodic modulation of the electrostatic potential $V(x)$ having the period $a=184$ nm was introduced via strain-induced piezoelectric effect [8] by placing a grating of electron-beam resist on the surface [9], with the direction $x$ parallel to the direction of the current (both $I_{ac}$ for the lock-in measurement and the dc bias $I_{dc}$) in the Hall bar. To maximize the piezoelectric effect and hence the modulation amplitude, the direction $x$ of the modulation was aligned to the [110] direction of the host crystal [8, 10]. The device also contains a section without the modulation (plain 2DEG) for reference adjacent to the ULSL section. The profile of the modulation $V(x)=\sum_n V_n \cos(2\pi n x/a + \phi_n)$ was determined by the analysis of the commensurability oscillations (CO) [11, 12]. Up to the
fourth harmonics were detected with $V_1=0.31$ meV, $V_2=0.1$ meV, $V_3=0.07$ meV, $V_4=0.05$ meV (CO have no sensitivity to the phases $\phi_n$). The profile is in between the two extreme cases, the sinusoidal and the rectangular modulation, but owing to the dominance of $V_1$, may be viewed as a sinusoidal modulation $V(x)=V_0 \cos(2\pi x/a)$ with $V_0=V_1$ in the roughest approximation. We will show below, however, that higher harmonics may be playing an important role in the oscillations observed in $\rho_{yx}$. The value of $V_1$ is larger than the $\nu=5/3$ FQH gap $\sim 0.1$ meV obtained by Lifshitz-Kosevich analysis [2, 13] in the plain 2DEG section, and therefore our sample is expected to be placed in the stripe phase according to Fig. 1(a). The measurement was performed in a dilution fridge at temperatures $T=15–480$ mK.

4. Experimental results and discussion

Traces of the longitudinal resistivity $\rho_{xx}$ measured by the standard ac lock-in technique using an ac current $I_{ac}=0.5$ nA ($f=13$ Hz) are shown in Fig. 3(a) for both the ULSL and the plain 2DEG sections. The ULSL section exhibits a peak that grows with decreasing temperature at $\nu \sim 5/3$ below $\sim 300$ mK, while the FQH state survives at $\nu=4/3$ albeit with rather complicated $T$- and $B$-dependences which may be signaling the possible competition between the FQH and the stripe states [2]. Assuming that the peak at $\nu \sim 5/3$ results from the pinning of the stripe phase, the depinning caused by the application of a dc bias current $I_{dc}$ is expected to reduce the peak height. In fact, the resistivity $\tilde{\rho}_{xx}$ measured by the ac lock-in technique with the current $I_{dc}$ (corresponding to the differential resistivity $\propto dV/dI$) displays decrease with the increase of $|I_{dc}|$ at smaller $|I_{dc}|$ (Fig. 3(b)). However, the decrease is rather gradual and not abrupt as expected from the pinning-depinning transition. The decrease can rather be explained by the increase in the electron temperature by $I_{dc}$ (due to the Joule heating), noting that the peak height reduces with increasing temperature at low temperatures. The electron-heating picture is consistent with the increase of $\rho_{xx}$ for larger $|I_{dc}|$ and also with the increase of $\tilde{\rho}_{xx}$ in the plain 2DEG. Interesting behavior to be noticed in Fig. 3(b) is the hysteresis between the up-sweeps and down-sweeps of $I_{dc}$, observed only in the ULSL section. Several traces, almost perfectly overlapping with each other, are plotted for both up- and down-sweeps (by thin blue and thick
(a)(d) Hall resistivity $\rho_{yx}$ for ULSL and the adjacent plain 2DEG at temperatures $T$ (mK) = 15 (bottom, blue), 25, 36, 49, 70, 90, 117, 170, 218, 275, 323, 475, 434, 480 (top, red). (b)(c)(e)(f) Hall resistivity $\tilde{\rho}_{yx}$ subjected to dc current bias $I_{dc}$, with down-sweeps (up-sweeps) of $I_{dc}$ plotted with thick red lines (thin blue lines), measured at $T=15$ mK; (b)(e) $B=5.41$ T (position of the peak in $\rho_{xx}$ of the ULSL) and (c)(f) $B=6.54$ T ($\nu=4/3$). ULSL (a–c) and plain 2DEG (d–f) are plotted by solid and dotted lines, respectively.

Slightly more complicated hysteretic behavior is observed also at $\nu=4/3$, possibly related to the co-presence of the two different phases, the FQH state and the stripe phase.

Similar plots for the Hall resistivity $\rho_{yx}$ are shown in Fig. 4 for ULSL (a–c) and plain 2DEG (d–f). Again, the ULSL section exhibits the hysteretic behavior. In the vicinity of $\nu=5/3$, the Hall resistivity in ULSL shows small amplitude oscillations roughly periodic in $B$, as highlighted in the inset of Fig. 4(a). The oscillations reduce their amplitude with increasing temperature, and vanish at $T\sim 300$ mK. The temperature range the oscillations are observed coincides with the range the peak develops in $\rho_{xx}$.

To further investigate the nature of the oscillations, we vary the electron density $n_e$ by illumination, employing the persistent-photoconductivity effect. The variation in $n_e$ leads to the shift in the magnetic field $B$ at which $\nu=5/3$ takes place, hence to the change in the magnetic length $l$ or the strength of the Coulomb interaction $e^2/\kappa l$. The evolution of the oscillations in the Hall resistivity $\tilde{\rho}_{yx}$ (with the dc bias current $I_{dc}$) is presented in Fig. 5. The period of the oscillations $\Delta B$ is seen to increase with increasing $n_e$, and the oscillations disappear for $n_e$ larger than $\sim 2.6 \times 10^{15}$ m$^{-2}$. Again, the role of $I_{dc}$ can be interpreted simply as heating of the electrons; the amplitude of the oscillations diminishes with increasing $I_{dc}$ but the period and phase of the red lines, respectively), certifying the reproducibility of the hysteresis. Although the origin of the hysteresis is not known at present, it is consistent with the presence of the collective phase.
Figure 5. Hall resistivity $\rho_{yx}$ in the vicinity of $\nu=5/3$ for different electron densities: $n_e$ (in $10^{15}$ m$^{-2}$) are (1) 2.1, (2) 2.2, (3) 2.5, (4) 2.7 and (5) 2.8. Traces with different colors represent different values of dc current bias $I_{dc}$ ranging from $I_{dc}=0$ nA (blue) down to either of $-5$ nA (1), (2) or $-4$ nA (3), (5) or $-3$ nA (4) (red).

oscillations remain unaltered. In the range of $n_e$ the oscillations are observed ((1)–(3) in Fig. 5), the expected period of the stripe state $\sim 4l$ is close to the fourth harmonic of the modulation $a/4=46$ nm. Furthermore, the change in the Coulomb energy during the oscillation period $\Delta B$ is also close to the amplitude of the fourth harmonic potential $V_4$. We therefore speculate that the oscillations result from some commensurability effect between the stripe state and the fourth harmonic potential. Our scenario is that the stripe phase in itself is basically brought about by the large fundamental component $V_1$, resulting in the peak in $\rho_{xx}$, but the oscillations require the high harmonics. Further studies are necessary, however, to elucidate the exact mechanism through which the commensurability affects the resistivities.

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