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Anomalous density dependence of anisotropic resistivity at half-filling of $N \geqslant 2$ Landau levels in short-period unidirectional lateral superlattice

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Abstract

A short-period (period $a = 92$ nm) unidirectional lateral superlattice with a uniform back gate has been used to investigate detailed dependence of anisotropic transport in $N \geqslant 2$ Landau levels on electron density n_e. Within rather narrow n_e range of 1.85–2.07×10^{15} m^{-2}, resistance peaks of quantum Hall transition regions are observed to grow (diminish) rapidly with n_e for the current across (along) the superlattice. The peak between filling factors 4 and 5 starts to split above $\sim 2.0 \times 10^{15}$ m^{-2} for the current across the superlattice, with the valley in between showing thermally activated temperature dependence with gap energy $\Delta \sim 140$ mK. The observed behavior of anisotropic transport suggests the relevance of the theoretically predicted charge density wave state.

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Keywords: Lateral superlattice; Magnetotransport; Anisotropy; CDW

Experimental findings of strongly anisotropic transport [1,2] and reentrant integer quantum Hall effect (RIQHE) [3] in ultrahigh mobility ($\mu \geqslant 1000$ m^2/Vs) two-dimensional electron gases (2DEGs) have aroused renewed interest in high ($N \geqslant 2$) Landau levels (LLs), which had been a less intensively studied subject compared with $N = 0$ and 1 LLs where the fractional quantum Hall effect (FQHE) takes place. It was theoretically suggested [4–6], prior to the experimental findings, that the ground state for 2DEG is a charge density wave (CDW) state with a period a_{CDW} several times the magnetic length $l = \sqrt{\hbar/eB}$, when the topmost LL is partially filled in addition to completely filled underlying LLs; around partial filling $\nu^* = \nu - [\nu] = \frac{1}{2}$, CDW favors a unidirectional "stripe" phase, while a "bubble" phase is preferred away from the half-filling. The stripe and the bubble phases were proposed to be the origin of anisotropic transport and RIQHE, respectively, which is basically supported by a number of later theoretical and experimental works (see e.g., [7]). However, the reason for the anisotropy being fixed to the crystallographic axes of the host GaAs/AlGaAs 2DEG wafer with no intentionally introduced source of anisotropy still remains unexplained. To gain more insight into the nature of anisotropy, we have been studying 2DEGs with artificially introduced anisotropy, namely, unidirectional lateral superlattices (LSLs), having a period a close to theoretically predicted a_{CDW} [8,9]. In the present

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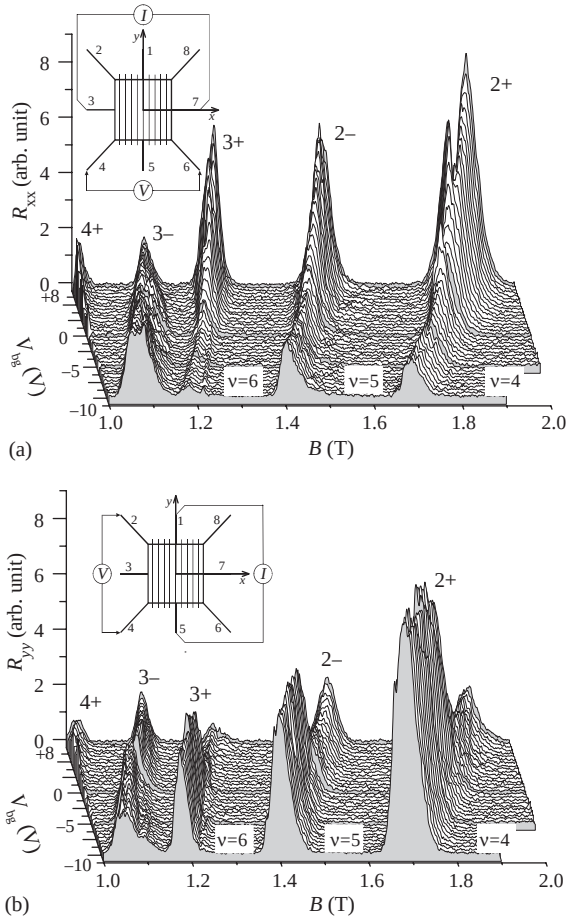

Fig. 1. Magnetoresistance traces for bg voltages V_{bg} from -10 to $+8$ V, corresponding to $n_e = 1.85$–2.07×10^{15} m^{-2}. $T \simeq 40$ mK. Resistance peaks are marked by the LL indices. Insets: current and voltage probe configuration.

paper, we report our experimental studies on the detailed dependence of anisotropy on electron density n_e.

The LSL device for the present study ($\mu \simeq 70$ m^2/Vs) is basically similar to those used in our previous works [9,10]—40×40 μm^2 mesa with eight arms and with a grating (a=92 nm) of electron beam resist placed on the front surface, which introduces periodic potential modulation with amplitude $\simeq 0.015$ meV (see insets to Fig. 1)—except that it contains a metallic back gate (bg). In the previous studies [9,10], we varied n_e by successive illumination employing persistent photoconductivity. However, the method is disadvantageous in obtaining high n_e resolution. More importantly, since the process is irreversible (n_e cannot be reduced), the method does not allow access to hysteretic behavior [11] that might take place when a collective phenomenon such as CDW is involved. In the present work, we circumvent these problems by using a bg. The bg was prepared by thinning the wafer from backside down to $\sim$ 100μm by wet etching and then depositing a gold film. Resistance measurements were done by a standard AC lock-in technique, 13 Hz and rms 5 nA, unless otherwise stated.

Fig. 1 shows magnetoresistance traces for the (a) current across or (b) along the grating, setting the bg voltage V_{bg} from -10 to $+8$ V by the increment of 0.5 V each. Correspondingly n_e varies from 1.85 to 2.07×10^{15} m^{-2}. In the magnetic field range shown, the Fermi energy E_F lies in $N = 2$ or 3 LL, (filling factor ν from 4 to 8). Resistance peaks between two adjacent quantum Hall states are marked by the quantum number $N\pm$ of the LL in which E_F lies, where $+$ ($-$) denotes the higher-(lower-)magnetic-field spin sublevel. In Fig. 1(a), the peaks 2+, 2−, and 3+ are observed to grow rapidly with n_e. The commencement of the sharp rise in the peak height takes place at smaller n_e for stronger magnetic fields, i.e. it first occurs in 2+, followed by 2− and then in 3+, when n_e is increased. The trend is reversed and the peak height decreases with n_e in Fig. 1(b). On the other hand, the height of the 3− peak (and lower magnetic field peaks not shown) does not change very much in the n_e range investigated. Another interesting finding is that the 2+ peak in Fig. 1(a) starts to split at $n_e \simeq 2.0 \times 10^{15}$ m^{-2}, and the valley in between becomes wider and deeper with n_e. This is more clearly represented in Fig. 2, which gives grayscale plots of R_{xx} and R_{yy} in the B-n_e plane for the positive V_{bg}. Development of a new minimum by increasing n_e is reminiscent of emergence of a new FQHE state, allowed to be resolved either by increase in the mobility or by shifting its filling factor to a higher magnetic field. However, FQHE has never been experimentally observed in $N \geqslant 2$ LLs, and the absence of FQHE is supported by theories (e.g. Refs. [4,5]). Moreover, Fig. 2(a) shows that the minimum follows constant-B ($\simeq 1.85$ T) line, and not governed by the filling factor, defying the explanation by FQHE. Rather it appears that the value of its magnetic length $l = 18.9$ nm or the ratio $a/l = 4.88$ is playing an important role. Hall

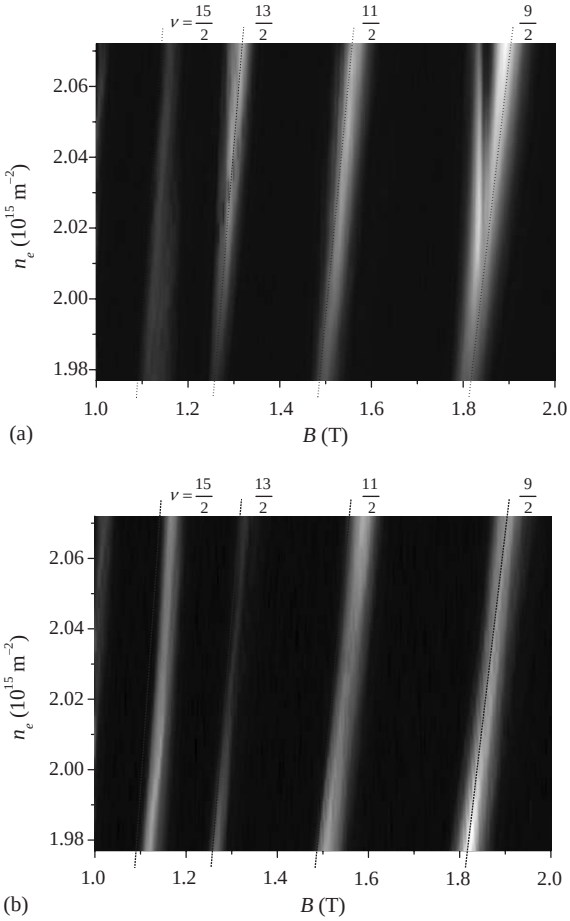

Fig. 2. Replots of Fig. 1 in grayscales for $V_{bg} > 0$, for the (a) current across or (b) along the grating. White (black) represents large (small) resistance. Thin dotted lines denote calculated positions of half-fillings.

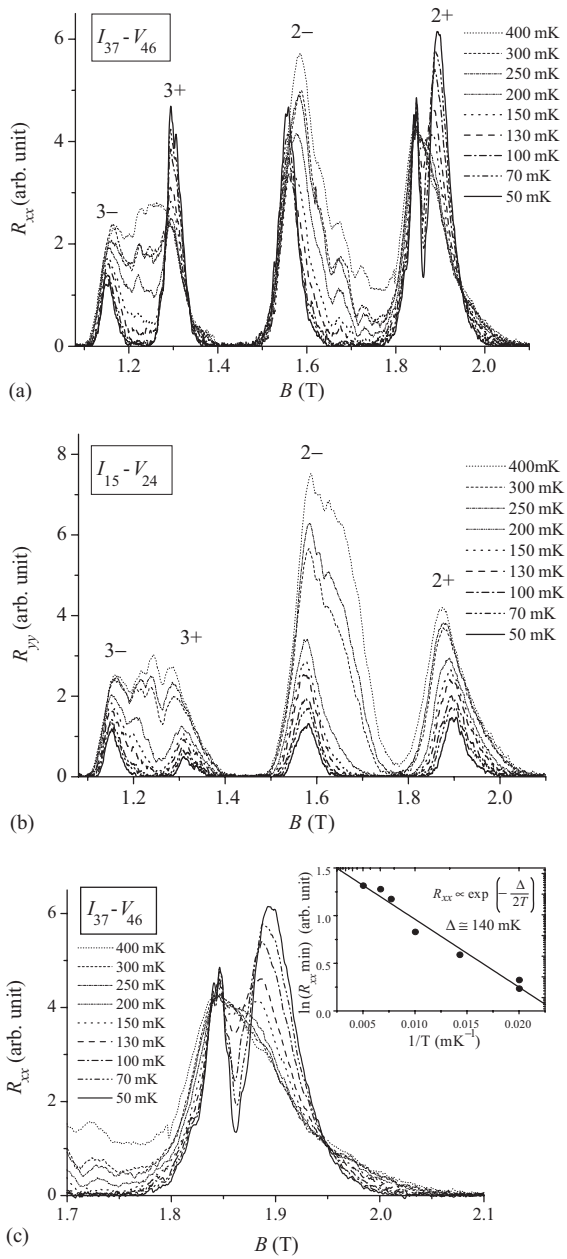

Fig. 3. Magnetoresistance traces for several temperatures for the (a) current across or (b) along the grating. (c) Close-up of the 2+ split peaks. Inset: Arrhenius plot of the resistance minimum. $n_e = 2.08 \times 10^{15}$ m^{-2}.

resistance also shows a drop at the position of the valley in the longitudinal resistance (see thick solid traces in Fig. 4). The drop may be viewed as the onset of RIQHE, not completed because the temperature is not low enough and/or the sample is not clean enough.

To further investigate the nature of the peak splitting and the valley observed, we took magnetoresistance traces at several temperatures (Fig. 3). For the current across the grating (Fig. 3(a)), the temperature dependence of the peak height shows alternating behavior with a magnetic field: peaks for lower-magnetic-field spin sublevels (2−, 3−) show "metallic" temperature dependence, i.e. the peak height increases with the temperature, while higher-magnetic-field branches (2+, 3+) are "insulating". On the other hand, all the peaks are "metallic" for the current along the grating

(Fig. 3(b)). Fig. 3(c) shows a close-up around the 2+ peak of Fig. 3(a). It can readily be seen that the valley is rather fragile and disappears (or equivalently peak splitting collapses) at a temperature as low as $\sim$ 150 mK. The minimum in the valley displays activated temperature dependence with a gap energy $\Delta \simeq 140$ mK, as shown in the inset.

So far we do not have consistent interpretation of our experimental results. Rapid growth of peaks by a slight change in n_e or by lowering the temperature (2+ and 3+ peaks) may be indicating the development of collective states, theoretically predicted CDW states being the most plausible candidate. A valley observed in the 2+ peak resembles RIQHE in the ultrahigh mobility plain 2DEGs, including the thermally activated temperature dependence. However, the latter is basically an isotropic effect, while the intriguing effect is observed only for the current across the grating in our case. Also, the relation between the present observation and our previous results is still unclear. We observed, using a similar device prepared from the same 2DEG wafer, a dip for the current across the grating, which is qualitatively similar to the present result, and a peak for the current along the grating, for $N = 1$ [10] and higher [9] LLs at larger n_e. The anisotropic features, however, were much more stable against the temperature. Obviously, more studies are necessary to establish the total picture.

In search for evidence of CDW being involved, we measured resistance with a DC current bias in addition to the AC excitation current, since depinning of the CDW will be reflected in non-linear I–V characteristics. As shown in Fig. 4, the valley in the 2+ peak becomes shallower and finally disappears with the increase of the DC bias from 0 to 30 nA. This, however, is probably mainly due to electron heating by the current, since the slope of the Hall resistance between adjacent plateaus, which is a measure of the effective temperature [12], becomes smaller with the DC current, to an extent similar to that of Hall resistance traces (not shown) at higher temperatures ($T \sim$ 100–150 mK). Nevertheless, it is interesting to point out that the [DC 0 nA, AC 25 nA] trace lies between the [DC 10 nA, AC 5 nA] and [DC 20 nA, AC 5 nA] traces, suggesting that a DC current is more effective in destroying the splitting than an AC current.

Finally, we would like to briefly describe a peculiar hysteretic behavior observed. We have done a number of bg sweeps up to the positive bias at which the peak splitting takes place ($V_{bg} \geqslant +5$ V). Most of the times, the splitting was actually observed. But in some sweeps, the valley was observed to be replaced by a

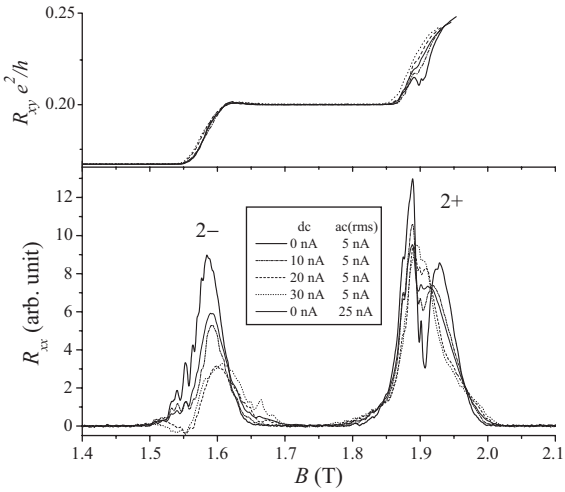

Fig. 4. Longitudinal (bottom) and Hall (top) resistance for $N = 2$ LL, for different measurement current conditions. In addition to the AC excitation current for lock-in measurement, a DC bias current is applied as noted in the figure. $T \simeq 20$ mK, n_e=2.10×10^{15} m^{-2}.

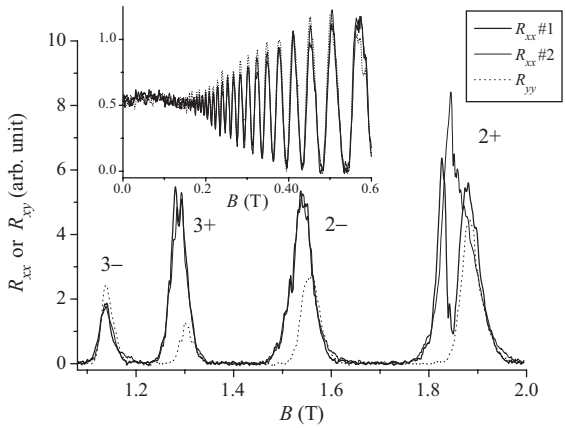

Fig. 5. Magnetoresistance traces for current across the grating with the same bg voltage $V_{bg} = +5$ V belonging to different run of the gate sweeps (thick and thin solid curves). A trace for current along the grating for the same V_{bg} is also shown (a thin dotted curve). Inset: low field part of the identical traces. $T \simeq 40$ mK, $n_e = 2.03 \times 10^{15}$ m^{-2}.

sharp peak, as shown in Fig. 5 (R_{xx} #2). As illustrated in the inset, Shubnikov–de Haas oscillation at low fields almost completely overlaps, demonstrating that the electron densities are almost the same. We have not yet sorted out the condition for appearance or disappearance of the splitting, but the splitting tends to appear when the gate sweep rate is slow enough (typically several hours to +5 V). Once it is accidentally gone, it is rather difficult to be recovered. We have found two ways to recover the splitting: (1) by first decreasing n_e (typically down to 1.7×10^{15} m^{-2}) by applying large negative bias and then slowly increasing n_e, and (2) by cooling down the sample again after warming up to room temperature. The hysteretic behavior is not inconsistent with the relevance of the collective phenomena such as CDW.

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