# Anisotropic transport of unidirectional lateral superlattice around half filling of $N \geq 1$ Landau levels

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**Abstract.** We report anisotropic transport features appearing around half filling of $N \geq 1$ Landau levels, prompted by very small but well-defined periodic external modulation. In most cases, a peak (a dip) appears for current along (across) the grating that introduces the modulation. We interpret the observed transport anisotropy as a manifestation, assisted by the external modulation, of the unidirectional charge density wave or stripe state, which is theoretically predicted to be the ground state of half-filled high Landau levels.

## 1. Introduction

In a lateral superlattice (LSL), an artificially introduced new length scale, the period $a$, can have a certain impact on the properties of a two-dimensional electron gas (2DEG), when $a$ coincides with or is close to a characteristic length scale of the 2DEG itself. A well-known example is the magnetoresistance oscillation resulting from the commensurability between $a$ and the cyclotron radius [1]. It has been predicted by Hartree-Fock calculations [2–4], and confirmed by a number of recent theories [5–7], that the ground state of high ($N \geq 2$) Landau levels is a unidirectional charge density wave (CDW) or stripe state. The period $a_{\mathrm{CDW}}$ of the stripe, another characteristic length scale of the 2DEG, is calculated to be ~4–8 times the magnetic length $l = \sqrt{\hbar/eB_\perp}$ [8, 9] with $B_\perp$ a magnetic field perpendicular to the 2DEG plane. For ordinary GaAs/AlGaAs 2DEG wafers, $a_{\mathrm{CDW}}$ will be in the range of 30–150 nm, the length readily accessible with modern fabrication technology. If 2DEG is inclined to spontaneously form CDW with period $a_{\mathrm{CDW}}$, it is natural to expect that an external modulation with period $a$ close to $a_{\mathrm{CDW}}$ will further promote the instability. In the present paper, we report anisotropic resistivity observed around half filling of $N \geq 1$ LLs in unidirectional LSLs with $a$=92 nm. The observed anisotropy is interpreted as resulting from stripe formation manifesting itself in the transport properties.

## 2. Experimental

The LSL devices for the present study were prepared from a conventional GaAs/AlGaAs 2DEG wafer with mobility $\mu$=75 $\mathrm{m^2/Vs}$ and electron areal density $n_e = 1.97\times10^{15}$ $\mathrm{m^{-2}}$. The wafer was mesa-etched into a $40\times40$ $\mu\mathrm{m}^2$ square with eight arms (~4 $\mu$m wide) for electric contact. A grating of negative electron-beam resist with period $a$=92 nm was placed on the surface to introduce strain-induced potential modulation into the 2DEG plane [10, 11]. The grating was placed with their lines parallel either to <110> or <1$\bar{1}$0> axis to maximize the strain-induced piezoelectric effect [12]. We mainly discuss the former configuration in the present paper, but we will show below that the two crystallographic axes do not make essential difference. From the amplitude of the low-field commensurability magnetoresistance oscillation, the amplitude of the potential modulation was estimated to be $V_0 \simeq 0.015$ meV or

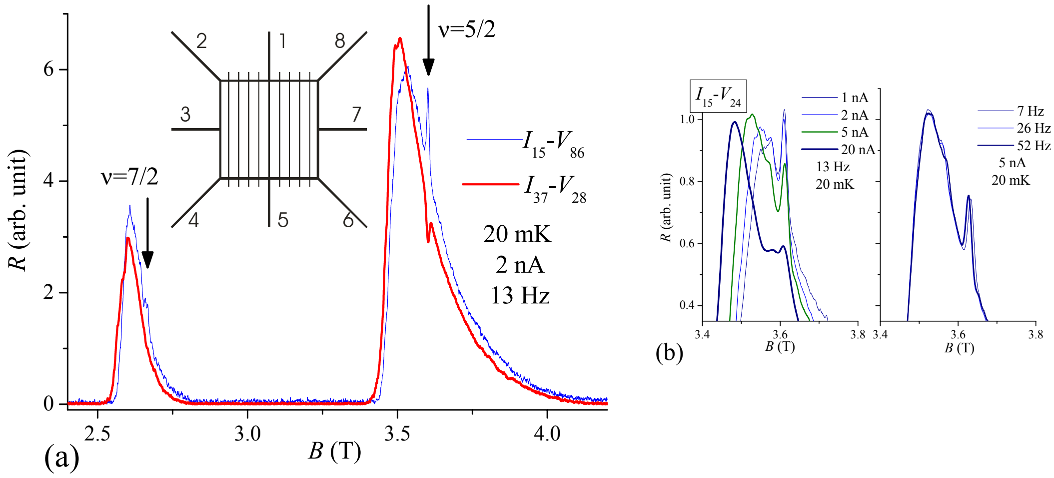


**Figure 1.** (a) Magnetoresistance traces for $N$=1 LL for current along ($I_{15}$-$V_{86}$) or across ($I_{37}$-$V_{28}$) the grating, showing sharp anisotropic features around $\nu$=5/2 and 7/2 as marked by arrows. The traces are taken after slight LED illumination and $\mu$=82 m$^2$/Vs and $n_e$=2.20$\times 10^{15}$ m$^{-2}$. Inset: schematic drawing of the sample. (b) Close up of the peak for current along the grating ($I_{15}$-$V_{24}$) showing the dependence on measurement current (left) and frequency (right).

0.2 % of the Fermi energy [11]. The square device allows measurement of anisotropy within a *single* sample, in contrast to Hall bar devices which require at least two distinct samples to measure anisotropy [10] and therefore makes stringent comparison difficult. Furthermore, resistance measurement with square geometry is reported to magnify the underlining intrinsic anisotropy of the resistivity tensor components [13, 14], which is, although not suitable for quantification of the anisotropy, advantageous in detecting small anisotropies. The inset of figure 1(a) depicts the schematic of the device. $I_{15}$-$V_{24}$ or $I_{15}$-$V_{86}$ mainly measures the resistivity component along the grating, while $I_{37}$-$V_{28}$ or $I_{37}$-$V_{46}$ mainly picks up the component across the grating, where the notation $I_{ij}$-$V_{kl}$ stands for a measurement using arms $i$ and $j$ as source/drain and $k$ and $l$ as voltage probes. The measurement is done in a dilution refrigerator with a sample rotation probe. Standard ac lock-in technique is used for the resistance measurements with measurement current $I$=2 nA or 5 nA and frequency 13 Hz unless otherwise stated.

## 3. $N$=1 Landau level

Figure 1(a) shows magnetoresistance traces for two current configurations for magnetic field range where Fermi energy resides in the $N$=1 LL, taken at the base temperature of our dilution refrigerator (∼20 mK). For current along the grating ($I_{15}$-$V_{86}$), a sharp peak appears around filling factors $\nu$=5/2 and 7/2, which is taken place by a dip for current across the grating ($I_{37}$-$V_{28}$). The anisotropic features are observed to be robust against a number of experimental parameters. The height (depth) of the peak (dip) remains almost unchanged up to 250 mK although the width slightly broadens with temperature [15]. The left panel of figure 1(b) shows that the peak is also not very sensitive to the amplitude of the ac measurement current; the broadening at $I$=20 nA is attributable to the heating effect. The right panel of figure 1(b) demonstrates the insensitivity to the frequency of the ac current for low enough frequencies.

The emergence of anisotropic state at $N$=1 LL was quite unexpected since the ground state of half-filled $N$=1 LL ($\nu$=5/2, 7/2) is known to be *isotropic* even-denominator fractional

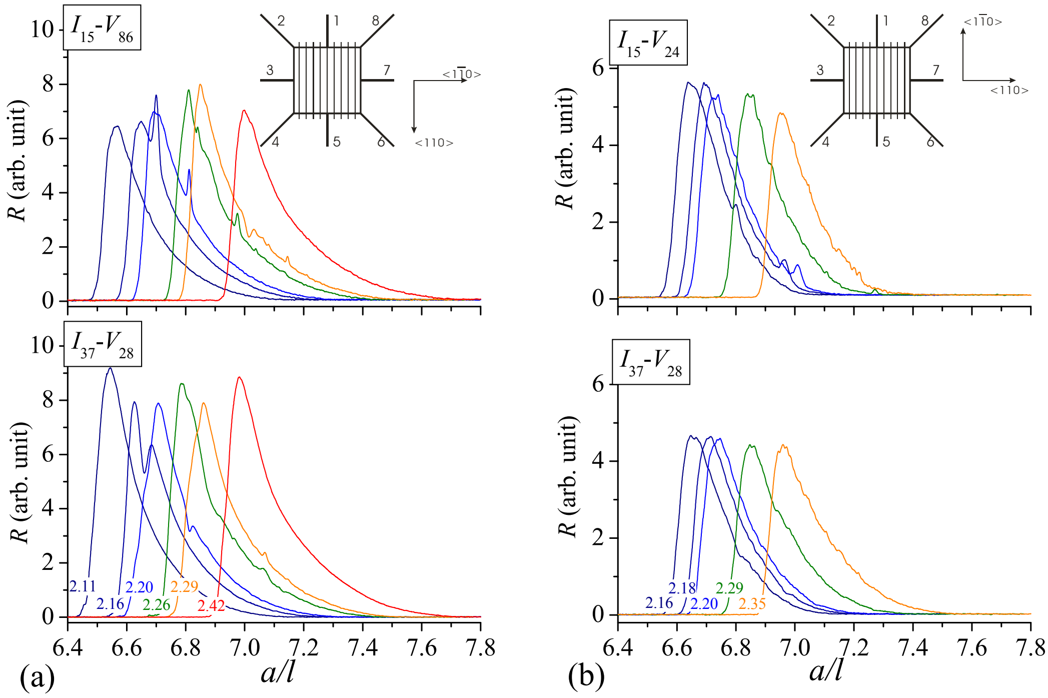


**Figure 2.** Resistance traces around $\nu$=5/2 plotted against $a/l$=$a\sqrt{eB_{\perp}/\hbar}$ with various $n_e$ successively increased by LED illumination. $n_e$'s in $10^{15}$ m$^{-2}$ are noted in the figure. (a) A device mainly discussed throughout the present paper with the lines of the grating parallel to <110> axis. (b) Another device with the grating lines parallel to <1$\bar{1}$0> axis.

quantum Hall state [16]. However, a numerical calculation [17] showed that slight modification in inter-electron interaction can cause transition of $N$=1 ground state from fractional quantum Hall state to the anisotropic stripe state. We interpret that the appearance of anisotropic state is a consequence of the external modulation playing two-fold role: to make the anisotropic state energetically favorable than the isotropic state and to assist the anisotropic state to be revealed in the transport which would otherwise be hindered by impurities in modest mobility 2DEGs.

To gain more insight to the observed anisotropic features, it is desirable to alter the ratio of the period $a$ to $l$, the fundamental characteristic length scale of the 2DEG in a magnetic field. Since $a$ is fixed once a device is prepared, we varied $a/l$=$a\sqrt{2\pi n_e/\nu}$ for fixed $\nu$ by changing $n_e$ via infrared LED illumination. This amounts to varying the ratio $a/a_{\mathrm{CDW}}$ since $a_{\mathrm{CDW}}$ is theoretically predicted to scale with $l$. Figure 2(a) displays evolution of the features with $n_e$. The first ($n_e$=2.11$\times$10$^{15}$ m$^{-2}$) and the last ($n_e$=2.42$\times$10$^{15}$ m$^{-2}$) traces are almost featureless and the peak/dip appears only for $n_e$ in between. The most pronounced features appears at $a/l \simeq 6.7$ with $n_e$=2.16$\times$10$^{15}$ m$^{-2}$. This implies 6.7$l$ represents a certain characteristic length scale for our present 2DEG. The simplest idea is to identify 6.7$l$ with $a_{\mathrm{CDW}}$. However a theory predicted much smaller value $a_{\mathrm{CDW}} \simeq$4.4–5.2$l$ for $N$=1 LL [8]. Finite thickness of the 2DEG, which is not taken into account in the theory, can in principle make $a_{\mathrm{CDW}}$ larger by softening the short-range repulsive part of the inter-electron interaction. A recent calculation [18] showed, however, that $a_{\mathrm{CDW}}$ increases only from 5.06$l$ to 5.07$l$ by the finite thickness comparable to our 2DEG (rms thickness estimated to be 4.8 nm). Apparently more works remain to be done to clarify the meaning of 6.7$l$.

For the interpretation of the observed transport anisotropy by the stripe phase, it is

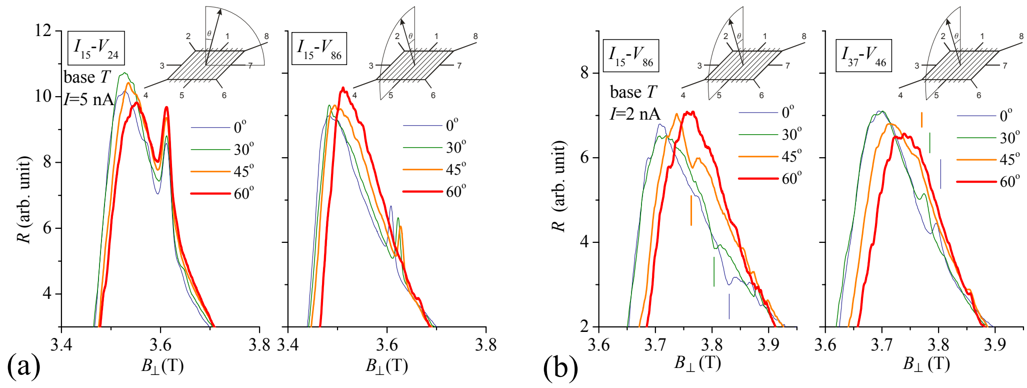


**Figure 3.** Resistance traces around $\nu$=5/2 in a tilted magnetic field plotted against $B_\perp$. (a) $n_e$=2.20$\times$10$^{15}$ m$^{-2}$ corresponding to the third trace in figure 2(a). Current is along the grating for both figures. In-plane field $B_{||}$ is introduced either perpendicular (left) or parallel (right) to the grating. The peak is observed to be destroyed by $B_{||}$ in the latter configuration. (b) $n_e$=2.29$\times$10$^{15}$ m$^{-2}$ corresponding to the fifth trace in figure 2(a). Current is either along (left) or across (right) the grating. $B_{||}$ is parallel to the grating for both figures. Vertical lines mark the positions of the peak/dip with their length roughly representing the magnitude of the features.

necessary to determine the direction of the stripe with respect to the external modulation. Although it seems intuitively obvious that the stripe aligns parallel to the external modulation, several calculations predict [19–21], in the situation the period $a$ of external modulation is much larger than $a_{\rm CDW}$, that it is lower in energy for the stripes to be oriented orthogonal to the external modulation. In our case, however, we believe $a$ does not differ very much from $a_{\rm CDW}$ and therefore the stripe is likely to align with the external modulation. This is more or less supported by the dependence of the anisotropic features to the in-plane magnetic field $B_{||}$ [15] [see figure 3(a)], combined with the theoretical calculations [8, 9] showing that the stripe prefers to be perpendicular to $B_{||}$ for thin ($\leq$6 nm) 2DEG. Parallel alignment of the stripe to the grating poses difficulty in the interpretation of the resistance: it signifies that the current direction along (across) the stripe results in resistance maxima (minima), which somewhat contradicts our intuition. However, this might not be impossible if the stripe is not pinned by impurities or locked to the external modulation. The sliding-motion picture is supported by the insensitivity of the peak to $I$ [figure 1(b)], which suggests the lack of non-linear $I-V$ characteristics (although our measurement varying the amplitude of ac current may not be best suited to showing this). Of course, more work is required to confirm this picture.

An interesting observation in figure 2(a) is that at $n_e$=2.29 $\times$10$^{15}$ m$^{-2}$ (the fifth trace), the peak and dip interchange their positions: a dip (peak) appears for current along (across) the grating at $a/l \simeq$7.0. Assuming that the appearance of the peak/dip is determined by the orientation of the stripe, this means that the stripe turns its direction by 90° at this $n_e$ (or $a/l$). The possibility of such turnaround is actually pointed out by a recent theory [21]. The direction of the stripe is expected to be reflected in the behavior under the in-plane field. As shown in figure 3(b), the interchanged dip/peak under $B_{||}$ parallel to the grating seems to survive slightly better than before the interchange [the right panel of figure 3(a)], consistent with the turnaround. Also it is noted that features move in the opposite direction: the dip/peak moves in lower $B_\perp$ side in figure 3(b) with the tilt angle $\theta$, in contrast to the situation in the right panel of figure 3(a). This also suggests some qualitative change takes place during

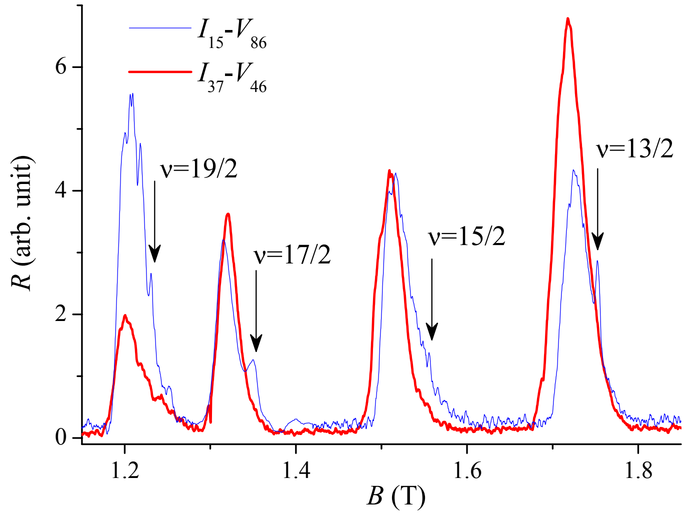


**Figure 4.** Magnetoresistance traces for higher LLs ($N$=3 and 4) showing peaks around half filling for current along the grating.

the interchange. However, the dip/peak after the interchange seems to be rather too small to conclude that the turnaround actually takes place.

In order to confirm that the observed phenomena are ruled by external modulation, not by crystallographic axis, another device with the grating lines parallel to the $<1\bar{1}0>$ axis is prepared. The $<110>$ and $<1\bar{1}0>$ axes are reported to be equivalent for the strain-induced piezoelectric effect [12], but are the source of strongly anisotropic transport in a ultrahigh mobility ($\mu \geq 1000$ m$^2$/Vs) plain 2DEGs [22, 23]. As shown in figure 2, the appearing anisotropic features are essentially the same for the two crystallographic configurations (including the interchange of the peak/dip). The peak/dip in figure 2(b) appears to be less clear, but we attribute this to the slightly worse quality of the lithographically defined grating.

## 4. Higher Landau levels

The anisotropic features are also observed in higher ($N \geq 2$) LLs, where the ground state is theoretically predict to be the anisotropic stripe state. Figure 4 displays a typical example showing peaks around $\nu$=13/2, 15/2, 17/2 and 19/2 for current along the grating. The dips for current across the grating is not necessarily well resolved in this case (but can occasionally be seen with closer look, see, e.g., $\nu$=19/2). The peaks are observed up to filling factor $\nu$=25/2 [24]. The peaks tend to display alternating intensity, with higher-magnetic-field spin sublevels of each LL showing more distinct peak. [This is also the case for $N$=1 LL as is obvious comparing $\nu$=5/2 and 7/2 in figure 1(a).]

Apart from these sharp anisotropic features, we have noticed anisotropic and also alternating behaviors of inter-LL transition peaks (the maximum of resistance between two successive integer quantum Hall states). As shown in figure 5, transition peak height is enhanced at $n_e$=2.1–2.3×10$^{15}$ m$^{-2}$ (the $n_e$ range where a sharp peak/dip is observed around $\nu$=5/2) for current along the grating, which does not happen for current across the grating. In a tilted magnetic field, although $B_{||}$ perpendicular to the grating does not change the peak heights (smaller symbols with dotted lines in figure 6), $B_{||}$ parallel to the grating (larger

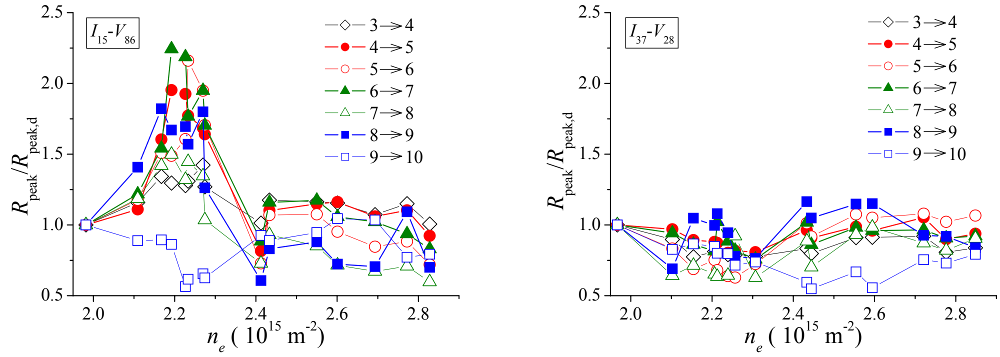


**Figure 5.** Evolution with $n_e$ of inter-LL transition peak height normalized by the peak height before illumination ($n_e$=1.97×$10^{15}$ $m^{-2}$). $p \rightarrow q$ denotes the transition from filling factor $\nu = p$ to $q$. Solid and open symbols represent higher and lower-field spin sublevels of each LL, respectively. Left: current along the grating. Right: current across the grating.

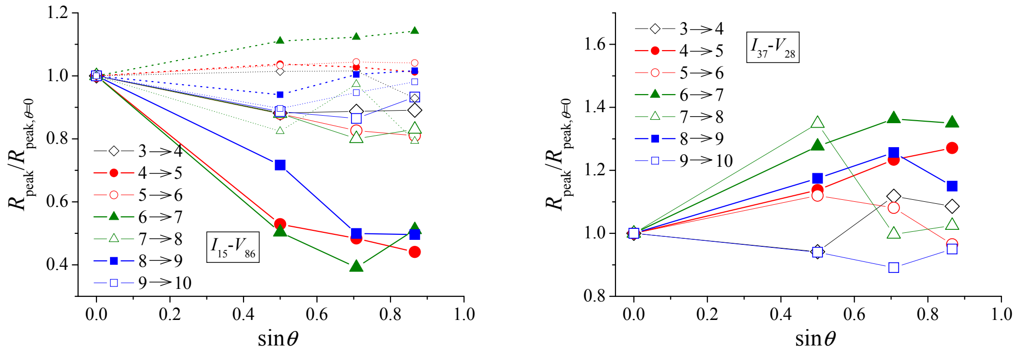


**Figure 6.** Inter-LL transition peak height in a tilted magnetic field (tilt angle $\theta$), normalized by the peak height at $\theta$=0°, plotted against sin$\theta$. For larger symbols with solid lines, $B_{||}$ introduced by the tilt is parallel to the grating, while for smaller symbols with dotted lines, $B_{||}$ is perpendicular to the grating. $p \rightarrow q$ denotes the transition from filling factor $\nu = p$ to $q$. Solid and open symbols represent higher and lower-field spin sublevel of each LL, respectively. Left: current along the grating. Right: current across the grating.

symbols with solid lines in figure 6) suppresses or enhances the peak height for current along or across the grating, respectively, for higher-field spin sublevels (solid symbols), while lower-field spin sublevels (open symbols) remain largely unchanged. At present, we do not know whether the behavior of the inter-LL peaks is related to the sharp anisotropic features described throughout the present paper.

## 5. Discussions

In plain 2DEGs with exceptionally high mobility ($\mu \geq 1000$ $m^2$/Vs), strongly anisotropic resistivity is observed around half filling of high ($N \geq 2$) LLs [22, 23]. The anisotropy is fixed to the crystallographic axes of the host GaAs crystal, with current along <1$\bar{1}$0> axis (<110> axis) resulting in resistivity maxima (minima). Although the origin of anisotropy for plain 2DEGs with no intentionally introduced source of anisotropy is still not well understood, the transport anisotropy is now widely believed to be resulting from the anisotropic stripe ground state. By tilting the magnetic field, the crystallographic anisotropy is overwritten by the in-plane field, with current along (across) $B_{||}$ giving rise to the resistivity maxima (minima). In addition, the in-plane field serves to transform isotropic even-denominator ($\nu$=5/2, 7/2) fractional quantum Hall state into the anisotropic state for $N$=1 LL [25, 26]. Very recently, interchange of anisotropy axes by increasing $n_e$ is reported [27].

Although the anisotropy in ultrahigh mobility plain 2DEG and that in our unidirectional LSL have an overall resemblance, we discuss here major differences. First, robustness of the anisotropy against impurities, temperatures, etc., is quite different. For plain 2DEG, extremely low concentration of impurities (high mobility) and low temperature ($\leq$150 mK) is required. Our mobility is about an order of magnitude lower and the anisotropy survives up to at least 250 mK. We attribute the difference to the magnitude of the anisotropy energy. For plain 2DEGs, experimentally estimated anisotropy energy of unknown origin is only $\sim$1 mK per electron [28]. By comparison, our modulation amplitude $\sim$0.015 meV is much larger, although quite small as an LSL. In the plain 2DEGs, even if the stripe phase develop at relatively low mobility or high temperature, the stripe phase may fall into domains since the force trying to align them is so weak, and therefore, it will not manifest itself in macroscopic quantities such as resistivity. In fact, theoretical calculations predict rather high tolerance against impurities [9], and also rather high ($\geq$ 1K) onset temperature in the presence of strong enough anisotropy energy [8].

Second, the magnetic field range in which anisotropy is observed is quite different. For ultrahigh mobility plain 2DEGs, maxima/minima covers major part of the inter-LL transition region ($\Delta\nu_{\mathrm{FWHM}}\simeq$0.3–0.4), while our peak/dip is much sharper ($\Delta\nu_{\mathrm{FWHM}}\simeq$0.007). Our anisotropy takes place only when much severer condition for $\nu$ or $a/l$ is met (but once it occurs, it is much more robust).

Third, high (low) resistivity axis in ultrahigh mobility plain 2DEG is interpreted as current flowing across (along) the stripes. In the present interpretation for our LSL, it is the other way around. It is not known at present whether this represents fundamental difference between the two systems, or either of the interpretation is incorrect.

## 6. Conclusion

We have reported sharp anisotropic features observed around half filling of $N\geq$1 LLs in $a$=92 nm unidirectional LSL. We interpret them to be resulting from theoretically predicted unidirectional CDW or stripe state, but there remain a number of open questions to be solved in order to confirm the interpretation. We have also reported anisotropic and alternating-in-$B_{\perp}$ behavior of inter-LL transition peaks, which may also be related to the anisotropic stripe state.

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