Strongly Anisotropic Transport in Higher Two-Dimensional Landau Levels

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Abstract

Low-temperature, electronic transport in Landau levels $N > 1$ of a two-dimensional electron system is strongly anisotropic. At half-filling of either spin level of each such Landau level the magnetoresistance either collapses to form a deep minimum or is peaked in a sharp maximum, depending on the in-plane current direction. Such anisotropies are absent in the $N = 0$ and $N = 1$ Landau level, which are dominated by the states of the fractional quantum Hall effect. The transport anisotropies may be indicative of a new many particle state, which forms exclusively in higher Landau levels.

Two-dimensional electrons in high magnetic field exhibit a multitude of novel electronic phases[1,2]. The electronic states of the fractional quantum Hall effect (FQHE) are the most abundant and probably also the best known. Most of the transport studies have been performed on the lowest Landau level, $N = 0$. Magnetotransport on higher Landau levels has been limited to the still enigmatic even-denominator state at filling factor $\nu = 5/2$ and features in its immediate vicinity in the $N = 1$ Landau level[3–6]. Still higher Landau levels ($N > 1$) are largely uncharted from the point of view of novel electronic phases.

With our high-mobility ($\mu = 1.2 \times 10^7 cm^2/V \cdot sec$) sample of density $n = 2.3 \times 10^{11} cm^{-2}$ we were able to pursue transport features at partial fillings of higher Landau levels at magnetic fields as low as $1.5T$. Beyond the previously observed minima in the magnetoresistance R_{xx} at $\nu = 5/2$ and $7/2$[3–6] we find strong minima at half-filling in higher Landau levels, such as $\nu = 9/2, 11/2, 13/2, 15/2$ and $17/2$. These new features are flanked by other minima, whose positions do not seem to follow the sequence observed in the lower Landau levels. Most remarkably, the magnetoresistances at exactly half-filling from $\nu = 9/2$ through $\nu = 17/2$ are strongly dependent on the current-voltage contact configuration. Minima at these positions turn into steep maxima after rotating the current direction by 90°. This puzzling observation has been reported earlier in a preliminary communication[7] and has recently also been observed by Lilly *et al*[8]. The origin of these transport features in higher Landau levels and the reason for their extreme anisotropy remain unresolved but may be the result of the formation of electronic phases different from the well-known FQHE states.

Our square specimen of $5mm \times 5mm$ was cleaved along the $[\bar{1}10]$ and $[1\bar{1}0]$ directions from an MBE grown wafer. Eight indium contacts were diffused symmetrically around the edges of the sample. Experiments were performed in a dilution refrigerator immersed into a superconducting solenoid. Magnetoresistance, R_{xx}, and Hall resistance, R_{xy}, traces were recorded using a standard low-frequency lock-in technique with a $1 - 2nA$ excitation current. The magnetic field direction was always kept perpendicular to the 2D-electron system.

Fig.1 shows two magnetoresistance traces recorded at $T = 60mK$ between Landau level filling factor $\nu = 2$ and $\nu = 12$, *i.e.* for $N = 1$ through 6. In the $N = 1$ Landau level,

between $\nu = 2$ and 4, the previously observed characteristic features of the FQHE are well developed. In particular, the minima of the even-denominator FQHE states at $\nu = 5/2$ and $\nu = 7/2$ are clearly visible. Quite remarkably, however, in this high-mobility specimen features in R_{xx} , not unlike FQHE features, are discernible up to $\nu \sim 9$, which corresponds to the $N = 4$ Landau level. In particular, as seen in the lower trace (B), minima at half-filling are unexpectedly strong and visible up to $\nu = 17/2$. In the $N = 2$ Landau level their strengths even exceeds those of the $\nu = 5/2$ and $7/2$ minima. This is a surprising result, since the latter reside at higher magnetic field, where FQHE features are generally better developed. In fact, while there is a clear, progressive increase in strength from $\nu = 17/2$ to $9/2$, the $\nu = 7/2$ and $5/2$ minima, much weaker than the $9/2$ minimum, seem to interrupt this trend.

Beyond the strong minima at half-filling, additional satellite minima are visible in the $N = 2$ Landau level. It is difficult to associate these structures with a particular rational filling factor, but they are located in the vicinity of $1/4$ and $3/4$ filling. Similar to the situation at half-filling, these satellites appear much more dominant in the $N = 2$ Landau level than the satellites around $\nu = 7/2$ and $5/2$, which are most likely associated with $1/3$ and $2/3$ fillings of the $N = 1$ Landau level. Already at this stage one wonders whether the new features for $N > 1$ are at all related to the minima in the $N = 1$ and $N = 0$ Landau level, which are of FQHE origin.

The most striking discrepancy between the $N > 1$ and $N \leq 1$ data lies in their extraordinary dependence on the in-plane current direction. The top trace (A) of Fig.1 shows data from the same specimen at the same temperature as the bottom trace (B). The only difference is the configuration of the current and voltage probes, which have been rotated by 90° from B (see inserts to Fig.1). While the $N = 1$ FQHE structures are essentially independent of the in-plane current direction, the *minima* at half-filling in higher Landau levels turn into a set of sharp *peaks*. In particular the spike at $\nu = 9/2$ exceeds all other features of the spectrum by almost a factor of two. Towards higher filling factors (smaller B-fields) the strength of the peaks decreases. An alternating strong-weak-strong pattern

seems to be superimposed, possibly being associated with the alternating spin polarization of the electron system. Further inspection reveals that the data in trace A of Fig.1 seem to be a superposition of trace B and these sharp spikes at half-filling for $N > 1$. This becomes particularly apparent around $\nu = 9/2$ and $11/2$, where the satellite minima of the lower trace are preserved and new, inner satellites have been created by the addition of the peaks to the previous minima at half-filling. This notion is supported by data taken at $25mK$ in the configuration A where only the peaks remain and all other features have totally disappeared for $N > 1$ (see insert trace C).

The data of Fig.1 are very puzzling. Such extreme anisotropies are absent at filling factors $\nu < 4$, *i.e.* $N < 2$, in any two-dimensional specimen we have ever studied. On the other hand, we have now observed the anisotropy seen in Fig.1 for $\nu \geq 4$ in several other samples of electron densities 1.1 to 2.9×10^{11} cm^{-2} and mobilities 6.8 to $12.8 \times 10^6 cm^2 / V \cdot sec$. From this we conclude, that anisotropic transport is a pervasive feature around half-filling in Landau levels $N > 1$.

To further investigate the phenomenon we measured the temperature dependence of R_{xx} around $\nu = 9/2$ and $11/2$, where in Fig.1 the most pronounced anisotropies occur, and contrast it with the pattern around $\nu = 7/2$. As seen in the bottom trace of Fig.2, R_{xx} is essentially isotropic at $115mK$ from $\nu = 3$ to $\nu = 6$. This isotropy largely persists over most of the filling factor range down to the lowest temperatures. However, at $\nu = 9/2$ and $\nu = 11/2$ the traces bifurcate into a rapid rise and rapid drop, depending on the in-plane current direction. Fig.3 quantifies this behavior, showing the T-dependence at $\nu = 9/2$ for both current directions on an Arrhenius plot. After similar high-temperature values the peak shows a very rapid, approximately exponential rise over more than one order of magnitude while the minimum experiences an equivalent exponential drop. The characteristic energies, E, for the exponential part of the T-dependencies, are very similar $E \sim 0.55K$, where $R_{xx} \propto exp(\pm E/kT)$. Both traces saturate at temperatures $T < \sim 60mK$. In fact, the T-dependencies for the maximum and minimum are almost mirror symmetric, suggesting the same phenomenon to be responsible for the appearance of either transport behavior. The

saturation value of the maximum of $R_{xx} \sim 1.5k\Omega$ is close to the resistance step between the neighboring $\nu = 5$ to $\nu = 4$ Hall plateaus of $\Delta R_{xy} = (1/4 - 1/5)h/e^2 \sim 1.3k\Omega$. Inspection of our lowest temperature data at $25mK$, shown in the inset to Fig.1, reveals that such a relation between low-temperature R_{xx} peak value and step between neighboring R_{xy} plateaus holds, to within 25%, for all the spikes observed in R_{xx}.

The large anisotropies in R_{xx} are limited to $N > 1$ and absent in the $N = 1$ Landau level. This is clearly seen in the field range around $\nu = 7/2$ in Fig.2. Some discrepancies, particularly in the height of the flanks close to $\nu = 3$ and 4, are discernible and are found in most other 2D transport experiments. While their specific origin is also unclear, they never have the strong attribute of turning a minimum into a maximum or vice versa as it is observed around half-filling for $N > 1$. In fact, the strongly anisotropic behavior seems to be limited to the immediate vicinity of half-filling. This can be seen in Fig.2, where the flanks of each band around $\nu = 9/2$ and $11/2$ show little angular dependence. In particular, the minima flanking the features at half-filling, indicated by vertical, dashed lines, show isotropic transport behavior. As an example for this lack of anisotropy the right panel of Fig.3 quantifies the temperature dependence of the minimum at $\sim 2.22T$ in Fig.2 in a standard Arrhenius plot for both contact configurations. Both show the same exponential *drop* in R_{xx} with an activation energy of $\Delta = 1.7 \pm 0.2K$, where $R_{xx} \propto exp(-\Delta/2kT)$. This obviously isotropic behavior is in stark contrast to the strongly anisotropic T-dependence at $\nu = 9/2$ in the left panel of the same figure.

Compared to R_{xx}, the Hall resistance, R_{xy}, is only slightly anisotropic as seen in the top traces of Fig.2. At the highest temperature of $115mK$ (dashed trace) the Hall resistance from both current directions practically coincide (only one is shown). At the lowest temperature of $60mK$ the Hall resistance remains isotropic over most of the field range (solid and dotted line) with a noticeable stretch of anisotropy around $\nu = 9/2$ and $11/2$. We have not further investigated this anisotropy in the Hall resistance, since it could well arise from a small admixture of the strongly anisotropic R_{xx} into R_{xy}. While most of the Hall resistance is well behaved, an unusual observation is made in R_{xy} at the position of

the satellite minima, indicated by the vertical, dashed lines in Fig.2. They are located at $\nu = 5.76, 5.26, 4.73$ and 4.28, close to quarter-filling by either electrons or holes, although it is unclear whether they can be labeled with such rational fractions. Features around such even-denominator filling factors, observed earlier in the lowest Landau level, eventually developed into nearby odd-denominator FQHE states[9,10]. The R_{xy} values of such earlier states initially were intermittent, but eventually approached the correct, quantized value of the nearby odd-denominator state. The satellite minima highlighted in Fig.2 show quite a different R_{xy} development. While deep minima are developing in R_{xx} at these filling factors, the concomitant R_{xy} values do not tend towards the usual fractional Hall plateaus which are cutting through the classical Hall line. Instead, in spite of FQHE-like minima in R_{xx} , their R_{xy} values converge towards the nearest *integer* quantum Hall plateau. This behavior is particularly well developed at $\nu \sim 4 + 1/4$ ($B \sim 2.22T$) but is also apparent at the other "quarter-filling" factors for $N > 1$ (vertical, dashed lines).

Our central experimental finding can be summarized as follows: Electronic transport in the higher Landau levels, $N > 1$, differs in several ways from the usual electronic transport in Landau levels $N \leq 1$. Whereas in the lowest Landau levels the standard features of the FQHE dominate, transport around half-filling in higher Landau levels is extremely anisotropic, developing large maxima or deep minima depending on the in-plane current direction. Satellite minima in the vicinity of quarter-filling do not show this anisotropy, but forgo FQHE plateau formation in R_{xy}, approaching instead IQHE values for their concomitant plateaus.

The observed anisotropy can be of intrinsic or extrinsic origin. Two possible extrinsic sources come to mind: misalignment of the interface from the desired [001] direction or an in-plane electron density gradient. We have carefully measured the orientation of the wafer by X-ray diffraction and found the surface normal to deviate from the [001] direction by less than $0.05°$. Such a small deviation from [001] in a cubic material is unlikely to be responsible for the observed anisotropies. Density gradients, on the other hand, are often present in modulation-doped samples, such as ours. It is a by-product of the MBE growth

procedure with off-axis doping sources. This applies particularly to substrates that are not rotated, as is often the case for ultra-high mobility specimens. From sequential low B-field transport measurements around the perimeter of our sample we find, indeed, a small density gradient with a density variation of $< 1\%$ across the sample. The direction of the gradient is roughly along the current direction of the contact configuration that shows maxima in R_{xx}. Such a gradient can in principle account for an anisotropy.

At any given magnetic field, the high-density end of the sample is always at a slightly higher filling factor than the low-density end. In particular, the high-density part may reside at $\nu = 5$, whereas the low-density end may reside at $\nu = 4$, both being separated by a narrow stripe, in which the Fermi energy resides within a few delocalized states between these two filling factors. When the current direction is along the gradient, the two voltage probes along the edge of the specimen may reside at two different filling factors: one at $\nu = 5$ the other at $\nu = 4$. Instead of the usual zero-resistance of the IQHE minimum one would measure a resistance of $\Delta R_{xy} = (1/4 - 1/5)h/e^2 \approx 1.3k\Omega$, which is close to the resistance of $R_{xx} \approx 1.5k\Omega$, observed in the 9/2 peak. As the B-field is slightly raised or lowered, the separating stripe of delocalized states moves quickly towards the high-density or low-density end of the sample, subjecting both voltage probes to the same IQHE filling factor, and therefore showing the usual zero-resistance state in R_{xx}. As the B-field is swept and subsequent filling factors move through, one would observe a sequence of spikes and zero-resistance states, in which the spikes have a resistance of $R_{xx} = (1/\nu_{low} - 1/\nu_{high})h/e^2$, not unlike what is observed in the lowest temperature trace of Fig.1. In the other current direction, normal to the gradient, the separating stripe cannot fall between voltage probes, the spikes having the above resistance values are absent and the normal IQHE/FQHE pattern emerges. This is an attractive scenario to explain much of our observations. However, it has several severe short comings.

First, with a density variation of only 1% across the specimen, a 1% field change is sufficient to move the separating stripe across the sample. Therefore, the width of the spikes should be $< 1\%$, but are found to be $\sim 5\%$. Second, on reversing the B-field direction,

according to our simple model, the peaks should reverse sign, whereas the experiment (not shown) shows, that the sign of the spikes is maintained. Finally, the spikes and associated anisotropies are only observed for $N > 2$ and are not observed for $N \leq 2$, whereas our model would not discriminate between different Landau levels. For these reasons we have severe doubts that a density gradient can be origin of the observed spikes and their extreme anisotropies.

As to intrinsic origins for the phenomena, a novel many-particle states may be responsible for the observations. Koulakov *et al*[11] and Moessner and Chalker[12] have proposed new ground states for a clean electron system in weak magnetic fields in which $N >> 1$ Landau levels are totally occupied and the next Landau level is only partially filled. Their work suggests that new electronic states, such as charge-density-waves (CDW) or domain structures may be created, which could be the origin of the stark anisotropies. In particular, Koulakov *et al*[11] propose the existence of a "stripe phase" around half-filling of higher Landau levels, whereas a "bubble phase" of electron puddles on a triangular grid would exist in the flanks of the Landau levels. In the stripe phase the occupation of the highest level alternates spatially between totally full and totally empty on the length scale of a classical cyclotron orbit $r_c \sim (\hbar N / eB)^{1/2}$. Electrical current runs along the edge of the stripes. Such a phase could be responsible for the anisotropy of the transport properties that we observe. However, to be detectable in our experiment, the spatial symmetry of the sample needs to be broken and the stripes need to be preferentially aligned in one direction. The slight density gradient across the specimen may be sufficient to break the symmetry and pin the stripes, leading to a macroscopic anisotropy of the transport properties around half-filling. The triangular phase, on the other hand, may be related to the observation of the features in the vicinity of quarter filling. A recently modeled liquid crystal-like phase, proposed by Fradkin and Kivelson[13] may also be related to our observations. However, we are far from being able to make a positive experimental identification of any such novel electronic state.

In conclusion, we have observed stark anisotropies in the magnetotransport of two-dimensional electrons in higher Landau levels. Several of the experimentally observed fea-

tures resemble FQHE features known from transport in lower Landau levels, although, at closer inspection, they appear inconsistent with an interpretation in such term.

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FIGURES

FIG. 1. Magnetoresistance along two perpendicular in-plane directions of a two-dimensional electron system at $60mK$. The schematics next to the traces A and B indicate the position of the voltage probes in the magnetoresistance, V_{xx}, and Hall resistance , V_{xy} (Fig.2) configuration. I_0 identifies the current direction and the gray arrow on the sample indicates the direction of a slight density gradient (see main text). Strong anisotropies in the magnetoresistance are observed around half-filling in higher Landau levels ($\nu = 9/2$ through $\nu = 17/2$). Trace C of the insert shows $25mK$ data for the same contact configuration as trace A.

FIG. 2. Temperature dependence of a segment of data of Fig.1 The full lines are from configuration A , the dotted line from configuration B of Fig.1. The top traces are Hall resistances, R_{xy}, and their temperature dependence. Around quarter-filling (dashed vertical lines), the magnetoresistance develops minima not unlike FQHE minima, but the concomitant R_{xy} values approach IQHE plateaus.

FIG. 3. Left side: Temperature dependence of the 9/2 resistance maximum (filled circles) and 9/2 resistance minimum (open circles) at $\nu = 9/2$ versus inverse temperature. Although the behavior does not appear to be thermally activated we indicate some characteristic energy scale of $E \sim 0.55K$ by two straight line segments. Right side: Temperature dependence of the magnetoresistance around $\nu \sim 4 + 1/4$ ($B \sim 2.22T$) for both contact configurations of Fig.1. The behavior is isotropic and thermally activated over two orders of magnitude with an activation energy of $\Delta \sim 1.7K$ (solid line).
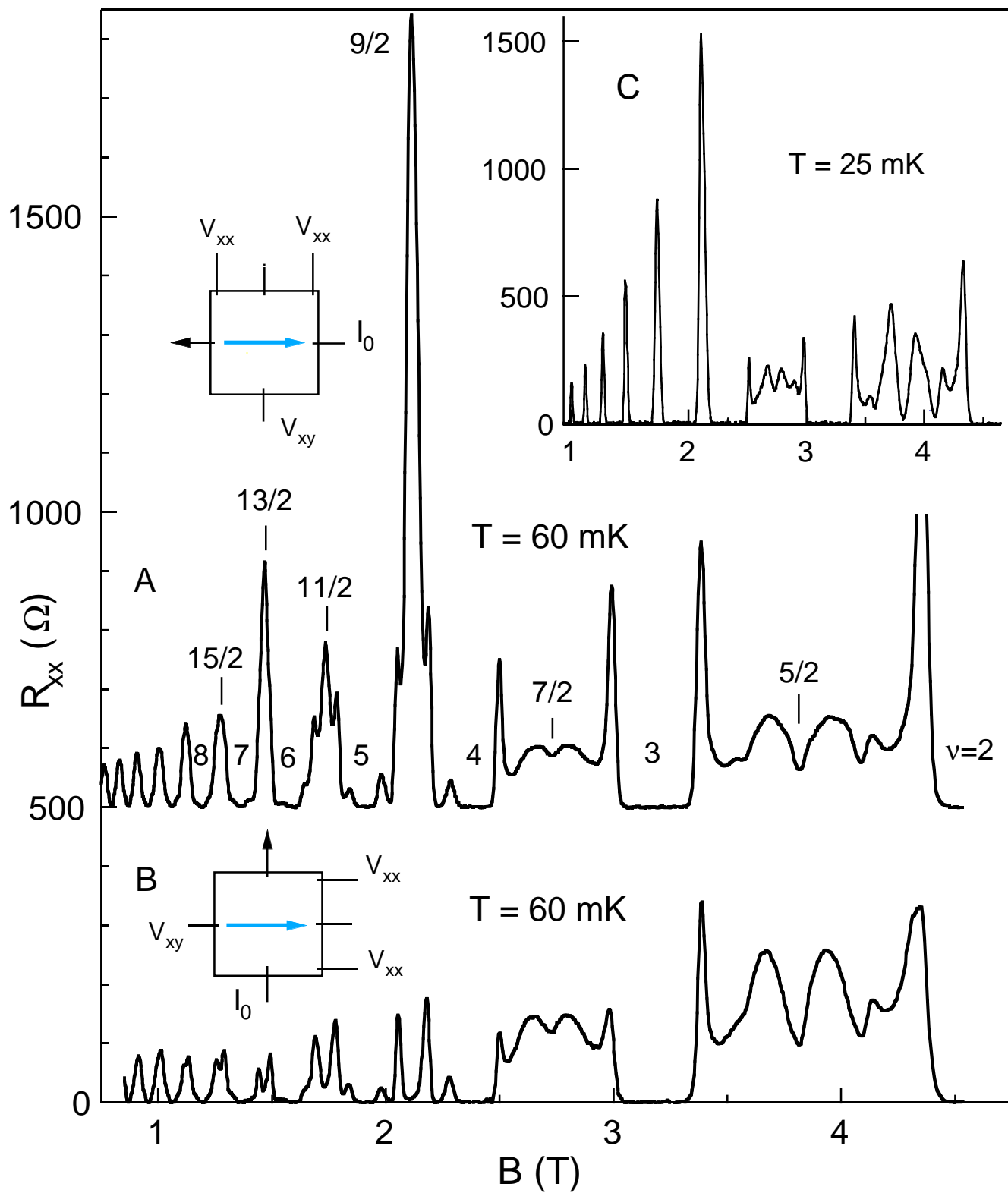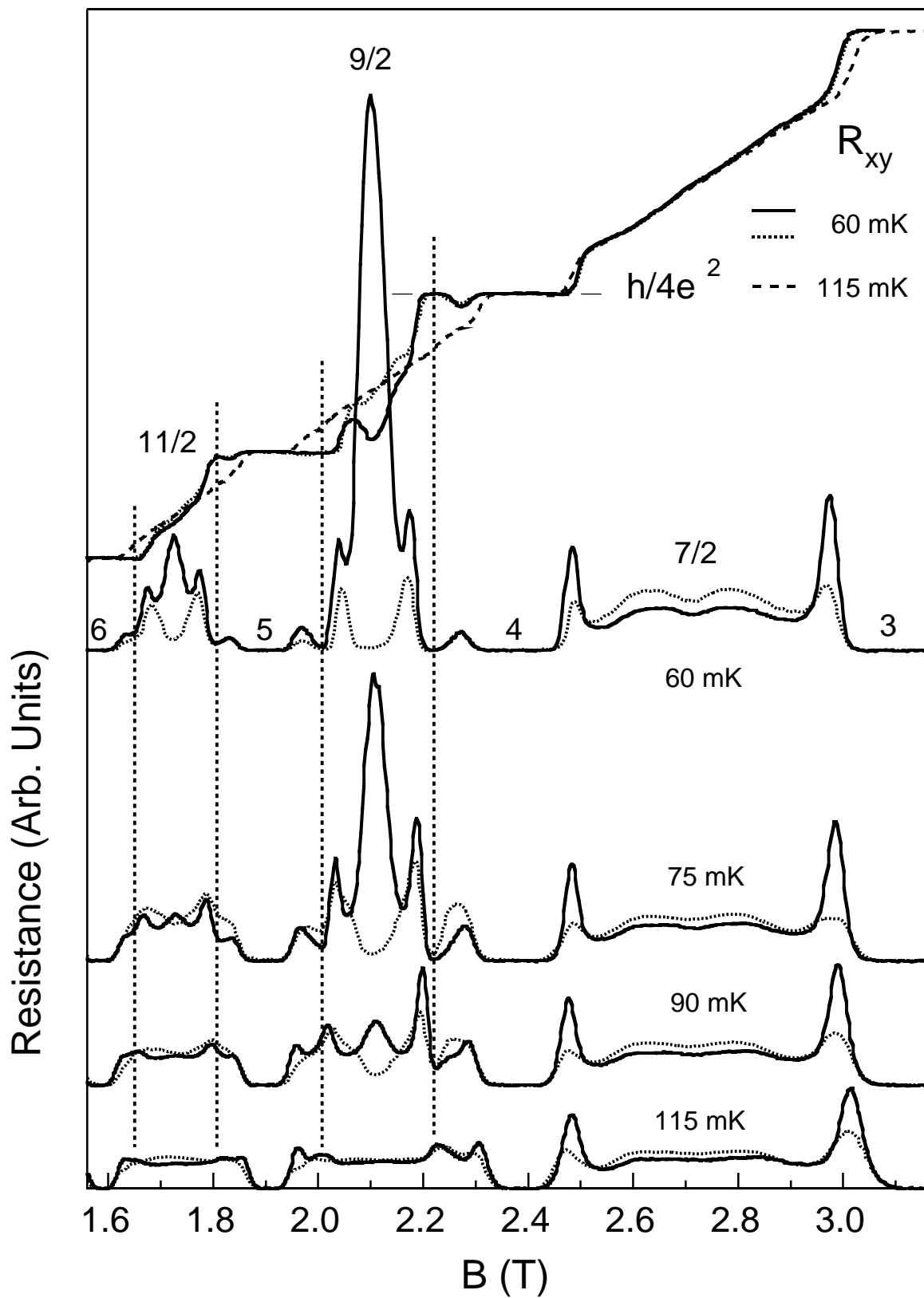
FIG. 1

FIG. 2

FIG. 3