Quantum magnetotransport in periodic V-grooved heterojunctions

A. Tsukernik,[1] A. Palevski,[1] V. J. Goldman,[2] S. Luryi,[3] E. Kapon,[4] and A. Rudra[4]
[1]*School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*
[2]*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800*
[3]*Electrical and Computer Engineering Department, State University of New York, Stony Brook, New York 11794-2350*
[4]*Physics Department, Swiss Federal Institute of Technology, 1015 Lausanne, Switzerland*
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We report quantum magnetotransport experiments in novel 3-μm-period V-grooved GaAs/AlGaAs heterojunctions. In such structures a periodic spatial variation of the *normal* component of magnetic field is realized. We observe anomalous features in both weak and strong magnetic fields. The quantum Hall-effect steplike Hall resistance is replaced by an oscillatory variation when the current is applied parallel to the grooves. The longitudinal resistance peaks attain unusually high values $\gg h/e^2$ when the current is applied perpendicular to the grooves. We propose a model that explains certain features of the observed behavior, however, some puzzling anomalies remain.

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Quantum transport in two-dimensional electron gas (2DEG) has been widely investigated both theoretically and experimentally. It is well known that at sufficiently low temperatures a normal magnetic field B causes Landau quantization of electron sates and, as a result, the density of states at the Fermi energy varies periodically with $1/B$. At low B this leads to Shubnikov–de Haas oscillations of the longitudinal resistance, and at high fields it is the origin of the integer quantum Hall effect (IQHE).[1] In practice the quantum Hall effect (QHE) is realized at magnetic fields of a few tesla in 2DEG samples with linear dimensions ranging from a few microns to several millimeters. The magnetic field is usually produced by large superconducting coils and therefore it is fairly homogeneous on the scale of the sample's dimensions. For that reason most of the theoretical studies of the QHE have assumed the case of a uniform magnetic field.[2–4]

However, the IQHE is predominantly an orbital effect and it is sensitive to the magnetic-field component $B_\perp$ normal to the plane of 2DEG.[5] Spatial variation of the normal magnetic field can be realized by varying the orientation of the 2DEG plane over the sample area. 2DEG heterojunctions grown on V-grooved substrates provide such a system with a periodic variation in space of the normal magnetic-field component. This paper reports initial experimental studies of two-dimensional electron transport in the presence of such *non-uniform, periodic* magnetic field $B_\perp$. We observe anomalous features in both weak and strong magnetic fields described later in the paper. We propose a model that explains some features of the observed behavior, however puzzling anomalies remain.

Fabrication of V-grooved GaAs substrates and regrowth of GaAs/AlGaAs quantum wells by organometallic chemical vapor deposition (OMCVD) on such substrates has been known for some time. This technique has been successfully applied for the fabrication of quantum wires, which are formed at the bottom of the grooves.[6] Recently electron-transport experiments were performed on a modulation doped quantum well regrown on V-grooved substrates showing one-dimensional (1D) ballistic transport properties of quantum wires.[7] For the present experiments we have chosen to replace the quantum well by a single GaAs/AlGaAs heterojunction in order to avoid as much as possible the effect of 1D confinement at the bottom of the groove. The 2DEG structure was grown by low-pressure OMCVD on (100) GaAs substrates (aligned to $\pm 1°$) patterned with $d = 3$-μm period grating of V grooves in the [001] direction by wet chemical etching. The sequence of the regrown layers is shown schematically in Fig. 1(a), and the TEM cross section of GaAs/AlGaAs interface where 2DEG is confined is shown in Fig. 1(b).

The self-limiting kinetics of the growth develops a well-defined profile of the growing surface after a few hundred nanometers of deposition regardless of the initial details of the etched surface. At the bottom of the groove the GaAs-AlGaAs interface consists of a central (100) plane flanked by

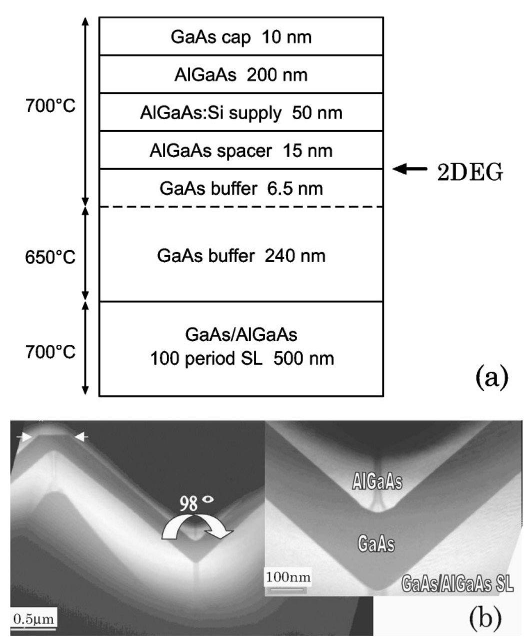

FIG. 1. (a) The schematic structure of the OMCVD grown layers. (b) A TEM cross section of the 3-μm-period V-grooved GaAs/AlGaAs heterojunction.

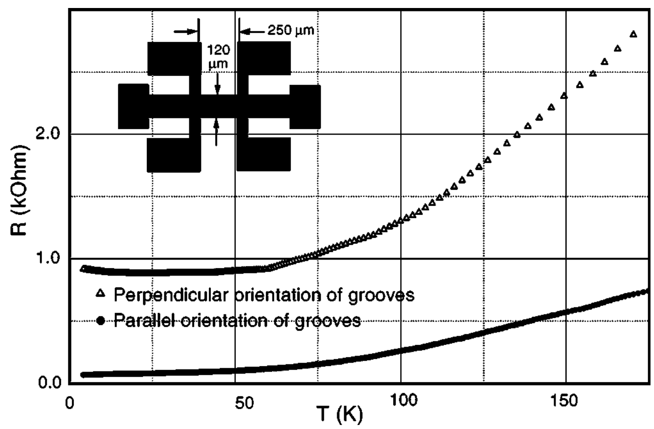

FIG. 2. The temperature variation of the resistance of the two samples with current direction parallel and perpendicular to the V grooves. Inset: the Hall bar geometry.

(311) and further out, (111) planes. The typical angle between the side walls consisting of a quasiperiodic variation of (111) and (211) planes ranges between 86° and 98° depending on the growth temperature. The top of the V groove is somewhat similar to the bottom as it consists of the same crystallographic plane, however the width of the (100) plane at the top, 0.32 μm wide in these samples, is typically much wider than at the bottom.

We have patterned Hall bar geometry samples (see inset of Fig. 2) using a standard photolithography procedure. The length of the mesa between the current pads is 750 μm, and the length and the width between voltage probes are 250 and 120 μm, correspondingly. We have fabricated samples with both orientations of the mask with respect to the V grooves, parallel (''parallel samples'') and perpendicular (''perpendicular samples'') to the direction of the channel between the current leads. The samples were measured by a standard four-probe lock-in amplifier technique in an Oxford TLM-400 dilution refrigerator.

At zero magnetic field, at room temperature the resistance is larger for the perpendicular samples than for the parallel samples. The resistance ratio is much larger than what can be accounted for by the geometrical factor (note that the actual length to width ratio of the 2DEG layer is about twice larger in perpendicular samples than in parallel ones). The anisotropy of the resistivity becomes more prominent as the temperature T is lowered. Figure 2 shows temperature dependence for samples of both orientations at zero magnetic field. Below 4.2 K the anisotropy ratio saturates at the value ≈ 12. Presumably, in these $B=0$ data resistance of the parallel samples is dominated by phonon scattering at higher T, and by impurity scattering at lower T. Clearly then, the data show that the elastic scattering at the side wall top and bottom boundaries dominates in perpendicular samples at low temperatures, when the phonon scattering is suppressed, and is significant even at room temperature.

In weak magnetic fields the Hall resistance R_{xy} is linear for the perpendicular samples, whereas strong deviation of R_{xy} from a linear dependence on B is observed for parallel samples, see Fig. 3. The difference in the behavior of R_{xy} becomes even more noticeable at higher fields, where the

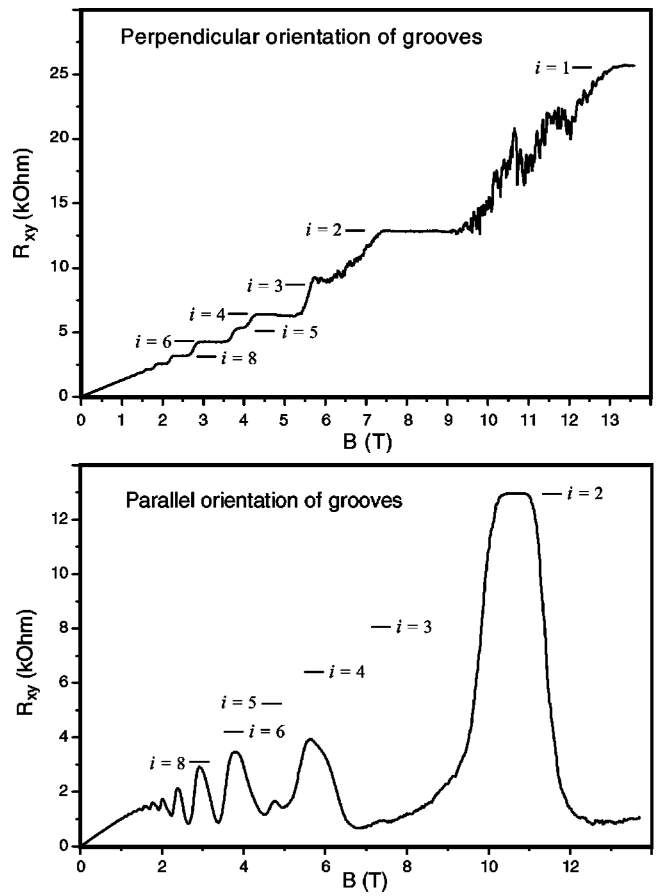

FIG. 3. The Hall resistance R_{xy} versus magnetic field for both sample orientations at $T=20$ mK. The horizontal dashes give the quantized values for the plateaus at $\nu = i$.

steplike variation of R_{xy}, typical for the QHE, occurs in perpendicular samples; it is replaced by an oscillatory variation of the Hall resistance in parallel samples. The longitudinal resistance R_{xx} also exhibits unusual features. The peak values of R_{xx} for a perpendicular sample are more than three orders of magnitude larger than those for a parallel one, see Fig. 4.

The magnetoresistance (MR) and Hall-effect data for low magnetic fields were analyzed to extract effective two-dimensional electron density n from the initial slope of R_{xy} vs B dependence, and from the Fourier analysis of Shubnikov–de Haas oscillations in R_{xx}, *assuming* that the applied magnetic field is normal to the 2DEG (that is taking $B=B_\perp$ throughout a sample). The analysis gives the following values: $n_\parallel^{(Hall)}=5.95\times 10^{11}$ cm^{-2}, $n_\parallel^{(MR)}=6.0\times 10^{11}$ cm^{-2} for parallel samples, and $n_\perp^{(Hall)}=4.8\times 10^{11}$ cm^{-2}, $n_\perp^{(MR)}=5.0\times 10^{11}$ cm^{-2} for perpendicular samples. For parallel samples it can be shown that the main contribution to R_{xy} and R_{xx} at low B comes from side walls of the grooves, and thus $B_\perp$ is smaller by a geometrical factor $a_\parallel = [\sin(98°/2)]^{-1} = 1.33$ [see Fig. 1(b)]. This gives the ''real'' electron densities at the side walls $n_w \approx 4.5\times 10^{11}$ cm^{-2}. By requiring the deduced n_w to match in both types of samples (the ''real'' 2DEG density is independent of the current direction), we obtain a different geometrical

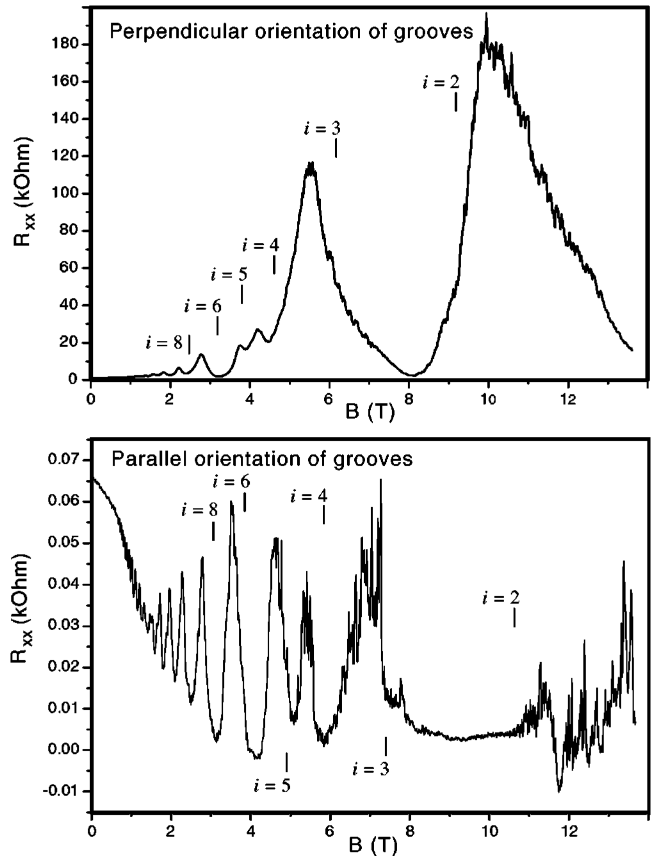

FIG. 4. The longitudinal resistance R_{xx} versus magnetic field for both sample orientations, $T = 20$ mK. The vertical dashes give positions in B of corresponding R_{xy} plateaus or maxima in Fig. 3.

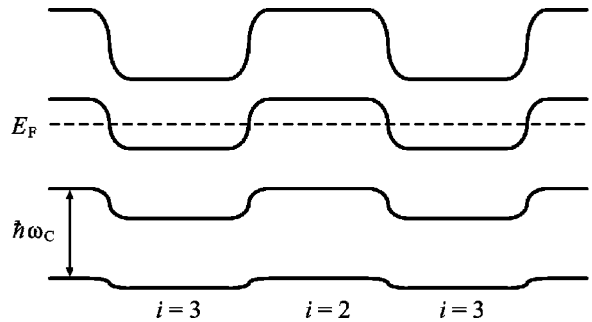

FIG. 5. A schematic diagram of Landau levels for a V-grooved sample. The filling factor is less for the flat regions at the top and bottom of a V groove perpendicular to B, and greater at the sidewalls, inclined to B at approximately 49°. Spin splitting is neglected here.

factor $a_\perp \approx 1.1$ for perpendicular samples. Indeed, for perpendicular samples the low-field contribution of the flat regions at the top of the grooves to R_{xy} and R_{xx} becomes significant since the current must flow through these regions. Thus, when the contribution of the grooves' top region dominates, $a_\perp$ is expected to be near 1.0, and $a_\perp$ is expected to be near 1.33 when it is negligible.

For higher magnetic fields our data of Figs. 3 and 4 show striking deviations from the standard IQHE in a uniform sample in uniform magnetic field.[1,8,9] First, most dramatically, the R_{xy} data for the parallel sample does not show quantum Hall (QH) plateaus except for $i=2$ nor does it follow the classical line $R_{xy}=B/en$, but rather R_{xy} approaches the classical values where plateaus should be and drops much in between. Second, also dramatically, the R_{xx} data for the perpendicular sample does not approach exponentially small values at B where R_{xy} is well quantized *in the same sample*. Third, R_{xx} for the perpendicular sample has peak values much greater than h/e^2 and R_{xx} for the parallel sample has peak values much less than h/e^2, both of which are impossible in edge-bulk transport models for an equilibrated QHE sample with an aspect ratio on the order of unity.[10,9] Fourth, less dramatically, certain *relative* irregularities are observed; for example, for both orientations there is no evidence for a QH plateau at $i=3$ although both $i=1$ and $i=5$ plateaus are seen in R_{xy} and R_{xx} data.

At this time we cannot explain all anomalous results, however some of the features of the observed magnetotransport can be understood within the following model. Our samples can be viewed as periodically varying in special macroscopic regions (stripes) with different filling factors $\nu = hn/eB_\perp$, due to periodic variation of $B_\perp$ across the V grooves. Connecting the same Landau index i of electron states between $\mathcal{N}$ such adjacent periods result in the Landau-level diagram shown schematically in Fig. 5. Each period of width $d=3$ μm consists of two sidewalls inclined by $\pm 49°$ to B, and a top region perpendicular to B. Thus the top regions have Landau levels at energies $\hbar\omega_C(i+\frac{1}{2})$ with $\omega_C \propto B$ and the sidewalls have Landau levels with $\omega_C \propto B_\perp = \sin(49°)B$. In the case when Fermi energy is located between consecutive Landau levels, the filling factor being near integer values in each stripe $\nu \approx i$ (but the filling factors in the neighboring stripes differing at least by unity), the Fermi energy will cross $2\mathcal{N}$ times each Landau level. In contrast, in a uniform density sample in homogeneous magnetic field and with the filling factor an integer, such crossing occurs only twice at the physical edges of the sample.[3,8] Thus V-grooved samples in a high B contain numerous counterpropagating internal edge channels.

Such internal edge channels have an immediate consequence for the Hall effect in the samples where the stripes with different filling factors are connecting one current pad to another (parallel samples). It was shown that for two such stripes the total R_{xy} is defined by the stripe with the higher filling factor, provided $\sigma_{xx}=\sigma_{yy}=0$ in each stripe.[11] It is easy to generalize this result for many stripes within an edge-network model;[8,9] we obtain the following expression for the Hall resistance in such parallel samples:

$$R_{xy}=(h/e^2)[i_w+\mathcal{N}(i_w-i_t)]^{-1}, \qquad (1)$$

where i_w and i_t are the exact fillings at the sidewalls and at the tops of the grooves ($i_w > i_t$), and $\mathcal{N}$ is the number of stripes with lower filling factors, surrounded on both sides by the stripes with higher filling factors. Thus for $\mathcal{N} \gg 1$, $\mathcal{N}$ equals the number of grooves. For $\mathcal{N} \gg 1$, R_{xy} of such samples is thus strongly suppressed ($\propto 1/\mathcal{N}$), relative to its classical value, when filling factors approach different integers in adjacent stripes. At half-integer filling in each stripe $\nu \approx i + \frac{1}{2}$, bulk conductivities σ_{xx}, $\sigma_{yy} \neq 0$, and within the same bulk-edge network models, the value of R_{xy} increases towards the classical value. The longitudinal R_{xx} can be thought of as $\mathcal{N}$ stripes of higher $\nu = \nu_w$, thus R_{xx} exhibits the usual Shubnikov–de Haas oscillations with the peak values reduced, however, to values $\propto (h/\mathcal{N}e^2)$. Indeed, the parallel sample of Figs. 3 and 4 has $\mathcal{N} \simeq 120/3 = 40$, so that experimental suppression levels of the R_{xy} dips and R_{xx} peaks are of the order predicted by the model.

The situation is quite different when the stripes are oriented perpendicular to the mesa (perpendicular samples). It has been shown in a number of experiments[12] that when different integer filling factor stripes are connected in a series, and bulk $\sigma_{xx} = \sigma_{yy} = 0$ in each stripe, the magnetotransport strongly depends on the equilibration length l_{eq} between the Landau levels in the same edge. For $l_{eq} \ll d$, where d is the width of the stripe, the longitudinal resistance of a sample containing $\mathcal{M}$ stripes with lower filling factors, each surrounded by stripes with higher filling factors on both sides, equals

$$R_{xx} = (h/e^2)\mathcal{M}(1/i_t - 1/i_w). \qquad (2)$$

In the opposite limit $l_{eq} \gg d$, the sample resistance

$$R_{xx} \approx (h/e^2)(d/l_{eq})\mathcal{M}(1/i_t - 1/i_w). \qquad (3)$$

Therefore, in our perpendicular samples R_{xx} measured on the scale comparable to or larger than the equilibration length should show high values $\propto \mathcal{M}(h/e^2)$ for such stripe orientation. For the perpendicular sample of Figs. 3 and 4, $\mathcal{M} \simeq 250/3 = 83$. On the other hand, R_{xy} measured by small-enough voltage probes (the width of the Hall probe d_p such that $d \ll d_p \ll l_{eq}$) should exhibit a standard IQHE behavior of a *single* stripe with the lower filling factor ν_t.

In general, there is a good qualitative agreement between the data and the proposed model. Indeed, we observe classical Hall-effect behavior at low fields, followed by standard IQHE plateaus at higher magnetic fields for perpendicular V-groove orientation, see Fig. 3. Moreover, the strong oscillations of R_{xy} between its classical values at the peaks and very low values in the valleys are natural outcomes of the model for parallel stripe orientation. There is a difficulty, however, to explain the strong shift of the $i = 2$ Hall plateau between the samples of two orientations. The comparison between the two curves in Fig. 3 clearly shows that there is no overlapping range of magnetic field for the $i = 2$ plateau. According to our model, the conditions for observation of a IQHE plateau are more robust for a perpendicular sample, and it can be expected to begin at lower magnetic fields, since R_{xy} is determined by the lower filling factor stripes. However, there is no obvious reason for this plateau to end before the range of the plateau of the parallel sample.

In conclusion, we report anomalous magnetoresistance and Hall-effect behavior of 2DEG in periodic V-grooved heterostructures, where $B_\perp$ varies periodically across the sample. We propose a model based on an internal edge network that qualitatively explains some features of the data, although puzzling anomalies remain. We hope that this work will motivate theoretical interest in the area of quantum electron transport in nonuniform, periodically varying magnetic fields.

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