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Physica E 13 (2002) 732–735

PHYSICA E

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Magnetoresistance of a modulated two-dimensional electron gas in a parallel magnetic field

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Abstract

We have measured the magnetoresistance of a trench-like modulated two-dimensional electron gas in a parallel magnetic field in comparison with an unstructured reference sample. We observe a step-like increase in the magnetoresistance of the trench sample that is not present in the reference. We attribute this to different numbers of edge channels being transported through the trench structure. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 73.43.Qt; 73.63.Hs

Keywords: Magnetotransport; Edge channels; Parallel magnetic field

1. Introduction

While two-dimensional electron gases (2DEG) in a uniform magnetic field represent an area of great interest in modern semiconductor physics, the more complex situation of a 2DEG in a spatially varying field has attracted attention only recently. One possibility to realize such a situation is the use of patterned layers made out of ferromagnetic or superconducting materials above the 2DEG [1–3]. With this technique, it is possible to produce weak variations of the magnetic field. Another way applies regrowth technology to vary the topography of the 2DEG [4].

A particularly interesting structure is a trench shaped 2DEG in a parallel magnetic field. In this case, regions which are only submitted to a parallel field component are in series with areas influenced by perpendicular components. This perpendicular magnetic field introduces a Landau-quantized density of states (DOS) in the side walls of the trench. The resulting coupling between a quantized and a continuous DOS promises interesting transport properties.

2. Experiment

A profile and a top view of our fabricated trench sample are shown in the insets of Fig. 1. The trench was defined by electron-beam lithography in combination with wet chemical etching on a GaAs-wafer before growing the 2DEG in a molecular beam epitaxy (MBE) system [5]. Note that the slope of the trench sides changes very smoothly over a range of more than 3 μ and the angle relative to the bottom of the trench does not exceed $\alpha = 8^\circ$.

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PII: S1386-9477(02)00270-9

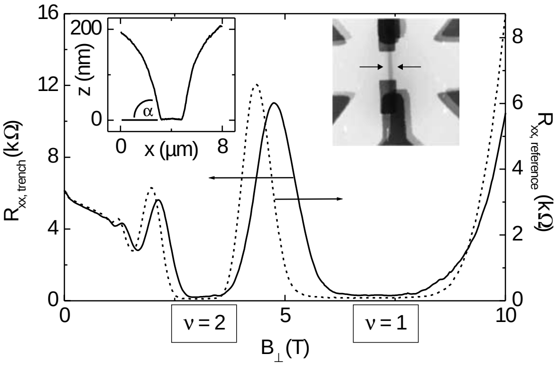

Fig. 1. Longitudinal magnetoresistance of both samples in a perpendicular field at $T = 400$ mK. Left inset: Depth profile of the trench measured with an AFM. Note the different axis scales—the maximum angle is $\alpha = 8^\circ$. Right inset: Topview of the sample. The trench is located between the arrows; the scanning area is 80×80 μm.

The heterostructure has the following layer sequence: On the GaAs substrate follows a spacer layer of 10 nm GaAs and 25 layers of a sandwich of 1.9 nm $Al_{0.33}Ga_{0.67}As$ and 3.8 nm GaAs. Then an additional spacer of 30 nm $Al_{0.33}Ga_{0.67}As$ was fabricated. Subsequently, the 20 nm GaAs quantum well and a further spacer (10 nm $Al_{0.33}Ga_{0.67}As$) were deposited. Then comes a 40 nm Si-doped $Al_{0.33}Ga_{0.67}As$ layer covered by 5 nm GaAs.

A second sample was fabricated on the same wafer without any etched groove to serve as a reference. Both samples are patterned in standard Hallbar geometry. R_{xx} and R_{xy} were measured for both samples simultaneously using standard lock-in technique at a temperature of $T = 400$ mK and magnetic fields up to 28 T.

We characterized both samples in a perpendicular field (Fig. 1). For the reference we find $n = 1.6 \times 10^{15}\ \mathrm{m}^{-2}$ and $\mu = 1.4\ \mathrm{m}^2/\mathrm{V\,s}$. The trench sample shows a carrier density $n = 1.8 \times 10^{15}\ \mathrm{m}^{-2}$ and mobility $\mu = 0.7\ \mathrm{m}^2/\mathrm{V\,s}$. For the R_{xx} measurement, the electrical contacts are situated on both sides of the trench, e.g. the mobility incorporates any influences of the groove on the electrical properties of the 2DEG. The smaller mobility of the trench compared to the reference stems from increased scattering as indicated by additional collision broadening of the Shubnikov-de Haas oscillations (Fig. 1).

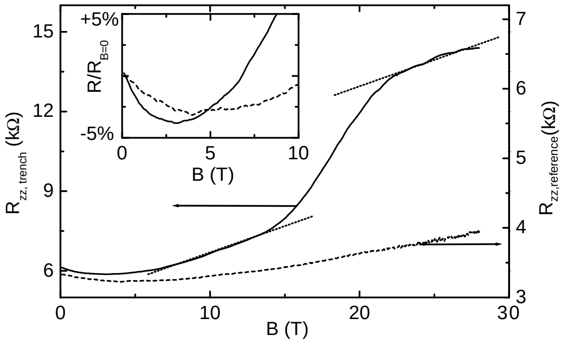

Fig. 2. Resistance for both samples at 400 mK vs. parallel magnetic field (solid line—trench, dashed line—reference). The dotted lines are to guide the eye. Inset: The magnetoresistance of both samples for small parallel magnetic fields normalized on the respective zero-field resistance.

3. Results and discussion

In a perpendicular magnetic field both samples show almost identical behaviour (Fig. 1). This changes dramatically for a parallel magnetic field. The corresponding experimental data are plotted in Fig. 2. The most dramatic effect of the parallel magnetic field is a strongly increasing magnetoresistance of the trench sample. It is about an order of magnitude bigger than any effects present in the reference. Before analysing this spectacular result, we will first consider effects at small magnetic fields and similar features of both samples.

The magnetoresistance of both samples is slightly asymmetric. The difference between both field polarities is linear with a slope $\approx 50\ \Omega/\mathrm{T}$ for the trench sample. We attribute it to slight differences of the Hall voltages at the potential probes: If two regions of a 2DEG are submitted to different polarities of a magnetic field, an additional linear voltage drop of two times the Hall voltage between the contacts on *one* side of the sample occurs [6]. This is the case for the trench walls. For the opposite field direction this voltage drop is located on the other side of the sample. In the case of a homogeneous sample any Hall voltages would cancel out because of their opposite signs. However, a difference of $\approx 0.2^\circ$ in the slopes or of $\approx 2\%$ in electron density can account for the observed linear voltage drop. For the reference this asymmetry is about an order of magnitude smaller

($\approx 5\,\Omega/\mathrm{T}$) and is possibly due to the roughness of the 2DEG.

A second common effect observed in both samples is a negative magnetoresistance resistance (NMR) in the small field range (Fig. 2, inset). Relative to the zero-field resistance it has the same amplitude for both samples, however, in the trench sample it already vanishes at comparably lower magnetic field B_c. Due to its total suppression above 10 K (data not shown) we identify it as a phase-coherence effect. This NMR can also be eliminated by increasing the carrier-density using persistent photolconductivity. A model [7] proposes a NMR in a parallel magnetic field with a critical field B_c enhanced by a factor of $l/\langle Z\rangle$, compared to weak localization in a perpendicular field, for which $B_c = \hbar/2el^2$ holds. Here l is the elastic scattering length and $\langle Z\rangle$ the average confining length of the electron. In case of our 2DEG this factor is of the order of ≈ 10. In the case of the trench structure we have a superposition of NDR due to parallel and perpendicular field components. This explains qualitatively the smaller B_c of the trench sample.

Now we will come to the magnetoresistance of the reference for high parallel magnetic fields. We observe an increase of the magnetoresistance of approximately 20% (see Fig. 2). Such a behaviour has been observed multiply in experiment, although the specific form differs between linear [8,9] and approximately parabolic B-field dependencies [10]. A theoretical model for the latter can be found in Ref. [11]. In our reference we observe a crossover from approximately quadratic behaviour at fields below 15 T to an approximately linear dependence above.

In the trench sample we find a dramatically increasing magnetoresistance. Two main features can be identified (Fig. 2): First, a steplike increase at 14 T and second, a linear part as can be deduced from the constant slope between 8 and 14 T, and above 22 T. The latter can be accounted for using a simple model: We calculated the resistance of the trench by dividing it into segments with each one of them with a different perpendicular field component. Just summing up the corresponding R_{xy} and R_{xx} values gives a linear magnetoresistance with only negligible modulation. However, this rough model can only give a qualitative description since the trench sides form quantum-Hall devices that are wide but short, so that only a fractional part of the Hall voltage can built up.

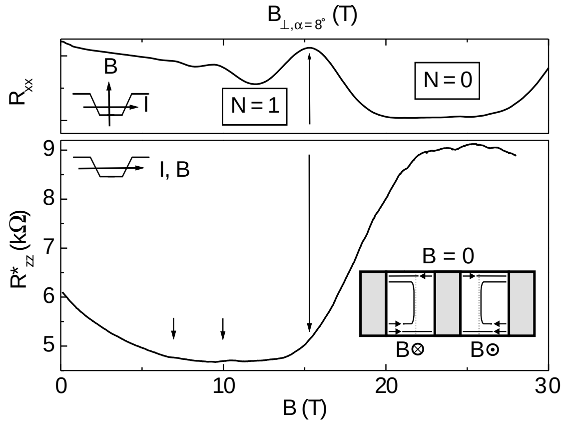

Fig. 3. Comparison between magnetoresistance of the trench sample in perpendicular (*upper graph*) and parallel (*lower graph*) field after subtracting the linear part. The effective B-field for the perpendicular case was computed using an angle of 8°. The arrows indicate the characteristic points of the magnetoresistance. Lower inset: The diagram depicts schematically the transport of edge channels. Above 20 T only one edge channel is transmitted through the sample.

If we subtract this linear part (see bottom panel of Fig. 3) we can identify two resistance plateaus between 8 and 14 T and above 22 T. We explain this feature with transport through different numbers of edge channels [12,13]: The density of states in the parallel regions of the trench sample is not influenced by the magnetic field. In the environment of the trench the angle between magnetic field and current vector—i.e. the effective perpendicular field—increases until it reaches its maximum at the bottom of the trench, thus leading to a Landau quantized DOS. The trench is about 2 μm wide while the phase-coherence length is of the order of 100 nm. So we assume the bottom of the trench to be acting effectively as a metallic contact connecting two Hall devices (e.g. the trench walls).

To continue this scenario we have computed the effective field in the trench walls using the maximum angle of 8° and plotted the corresponding perpendicular magnetoresistance in the top panel of Fig. 3. Indeed, the magnetic field $B = 14$ T where the step in the parallel magnetoresistance occurs coincides with the point where the extended states of Landau level $N = 1$ cross the Fermi edge ($E_F = 4.6$ eV). So above 14 T only one edge channel ($N = 0$) is available for transport through the sample, while the $N = 1$ channel is reflected. Since the $N = 1$ level is spin degenerated it contains the same DOS as the two spin split levels of $N = 0$, which leads to the increase of the resistance by a factor of roughly two. Strictly speaking this factor is somewhat smaller than two. Even this deviation can be understood qualitatively: The resistance reaches its higher plateau over a range of some 5 T. So while the extended states corresponding to $N = 1$ are moved across the Fermi edge, the DOS of the $N = 0$ levels increases with eB/h, which in turn raises the conductivity.

Below 14 T we find two structures at around 11 T and possibly 7 T that may be correlated to the depopulation of edge channels higher than $N = 1$. Since the Landau levels at higher filling factors are strongly collision broadened these features are smeared out. In fact, filling factor $\nu = 2$ is the first one with a fully developed plateau of the Hall resistance, thus at lower fields the Landau levels overlap and form an only slightly varying continuous DOS.

4. Summary

We have investigated the magnetoresistance of a trench-like formed 2DEG in a parallel magnetic field in comparison with an unstructured reference. We have observed a dramatically increasing resistance for the trench sample while the reference shows only slight changes. The magnetoresistance of the structured 2DEG consists mainly of two parts: one strong linear and a step like increase. The first one can be understood regarding the trench sides as a series of two-terminal Hall devices in different magnetic fields. The second can be attributed to the selective transport of single edge channels through the structure.

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