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Magnetotransport in Two Parallel 2DEG Formed by a Delta Doped Layer and a Heterojunction in GaAs

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We report magnetotransport measurements on a two-layer electron system with large spacing between the layers. Application of differential methods allows the investigation of each of the two conducting layers separately. At low magnetic fields we observe additional high-mobility carriers located between the two conducting layers forming an extended electronic state. With increasing magnetic field these electrons freeze out. The integer and fractional quantum Hall effect of the high-mobility electron gas has also been studied.

Introduction

High-mobility two-dimensional electron gases (2DEG) exhibit both the integer and the fractional quantum Hall effect. In the recent years considerable interest focusses on semiconductor structures with an additional degree of freedom associated with the third dimension. Magnetotransport investigations on double quantum wells with narrow layer spacing [1,2] showed the importance of Coulomb interaction and tunneling of carriers between the two 2DEG. At larger spacing between the layers these effects are considered to be unimportant. However, a small amount of electrons can transfer from one layer to the other via the three dimensional electronic states.

The purpose of our experiments is to investigate the quantum mechanical system consisting of two parallel electron channels by magnetotransport studies. One channel is a high mobility 2DEG (HM2DEG) formed at a GaAs/AlGaAs heterojunction, the other a low mobility 2DEG from a Si-delta-doped layer in GaAs. To study the mutual influence of the two channels in magnetotransport experiments we use samples with channel spacing of 200nm and 300nm.

Samples

The samples are grown by molecular beam epitaxy. The layer sequence is schematically shown in the inset of Fig. 1. The electron concentration of the Si-delta-doped layer and of the HM2DEG are $20*10^{15}\ m^{-2}$ and $3.3*10^{15}\ m^{-2}$ respectively. The electron concentration in the HM2DEG can be changed by a gate voltage. The samples have the shape of conventional Hall bar.

Experiments

The magnetotransport measurements were carried out at sample temperatures of 0.3 K. For conventional dc-magnetotransport experiments on a system with two parallel conducting layers, the resistance R_{xx} (see Fig.1) as well as the Hall voltage R_{xy} are mainly determined by the low mobility 2DEG, in our case the delta-doped layer. Only at very low magnetic field a considerable contribution of the HM2DEG to R_{xx} is obtained.

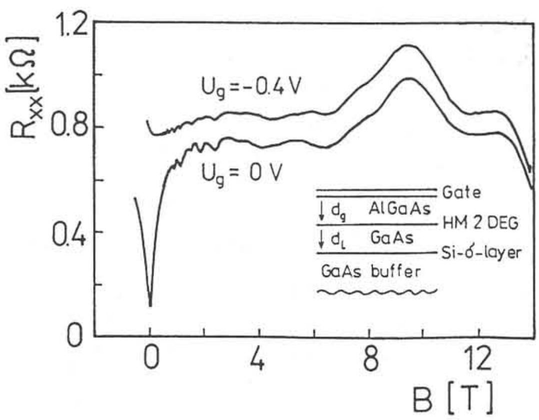

Fig.1 Longitudinal resistance $\mathbf{R_{xx}}$ vs. magnetic field **B** for the two parallel conducting layers (U_g=0 V) and for the delta layer only (U_g=-0.4 V), sample #1, d_l=300nm.

With increasing magnetic field the increasing Landau level split off. Therefore the transport in the HM2DEG becomes quantized and localized and a giant positive magnetoresistance arises in our system.

To investigate the two layers separately, we have performed differential magnetotransport measurements in which the Hall and the resistivity signals were modulated by an ac gate voltage.

Results at low magnetic fields

By decreasing the gate voltage first the electrons in the HM2DEG will be depleted. As long as the HM2DEG can sufficiently screen the delta doped layer from the gate field, the resistivity change is determined by the amount of these depleted electrons. In this manner, we can investigate the magneto-transport properties of each of the two 2DEG separately, especially of the HM2DEG. The gate-voltage dependent differential conductivity at various low magnetic fields is shown in Fig. 2.

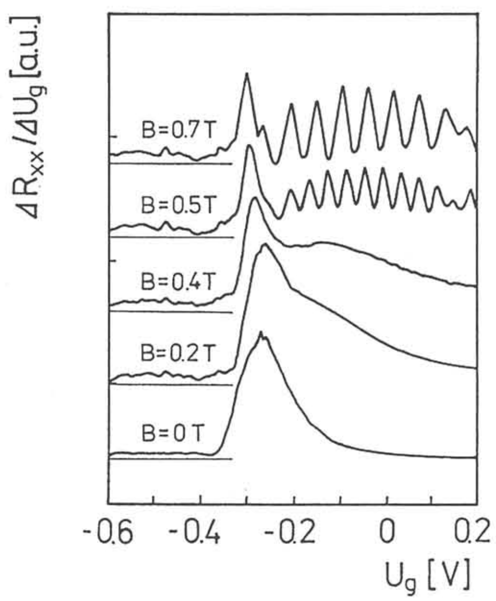

Fig. 2 Differential conductivity vs. gate voltage U_g at low magnetic fields. The lines indicate zero value for each curve.
sample #1 (d_l= 300nm).

In the voltage range from -0.25 to 0.2 V the Shubnikov de Haas oscillation arises from the HM2DEG and represents the gate-voltage dependent filling factor ν. Comparison of the measurements at different magnetic field yields the depletion voltage for the HM2DEG, U_{depl}, and the filling factor ν from the following relation:

$$\nu = \frac{U_g - U_{depl}}{d_g} \frac{\epsilon}{e} \frac{h}{e B} \qquad (1)$$

where d_g is the spacing between the gate and the HM2DEG.

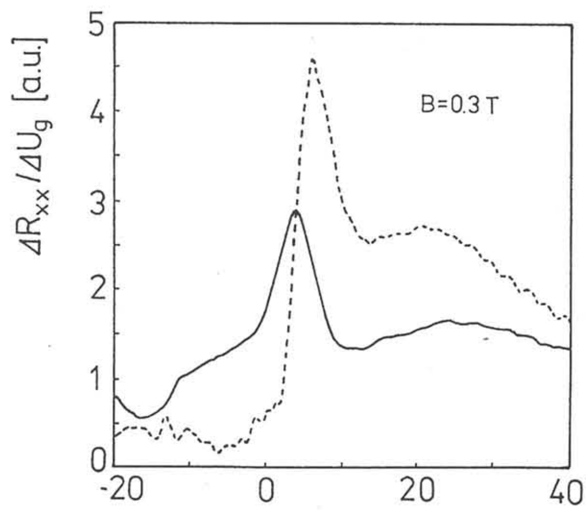

Fig.3 Differential conductivity vs. filling factor.
-- sample #1, (d_l=300nm), — sample #2, (d_l=200nm)

In Fig. 3 we show the dependence of the differential conductivity for two samples with different distance of the delta-doped layer to the HM2DEG at very low magnetic field. For filling factors $\nu > 10$ the differential conductivity is dramatically suppressed during the beginning Landau level separation in the HM2DEG. At low filling factors which represent a high degree of depletion of the HM2DEG, a maximum in the differential conductivity occurs but with no SdH oscillation. We assume that the origin of this maximum is due to the creation of electronic states much more extended toward the delta doped layer. This assumption is supported by the results of self-consistent calculations of the charge and potential distribution using Schrödinger and Poisson equations. The sublevel distance decreases dramatically at $\nu > 10$, thus, that SdH oscillations are effectively suppressed. The sample with smaller distance between the delta-doped layer and the HM2DEG exhibits an additional structure in the differential conductivity at zero and 'negative filling factors'. The so called 'negative filling factor' represents the situation that the HM2DEG is fully depleted and cannot anymore screen the delta doped layer from the gate field. Hence, this additional structure arises from the modulation of high-energy subbands of the delta doped layer. The occurrence of this structure indicates that electrons exist having a mobility comparable to that of the HM2DEG, and we believe that these high-mobility electrons are extended towards the HM2DEG. From the relevant gate voltage region $0.7*10^{15}$ m^{-2} such electrons are estimated. This agrees well with the results of self-consistent calculation.

Results at high magnetic fields

We have mentioned before that high-magnetic field effects which are associated with the HM2DEG cannot be studied by usual dc Hall experiments because the low-mobility 2DEG short-circuits the Hall voltage. Using differential magnetotransport measurements, however, the high field properties of the HM2DEG can be investigated, too.

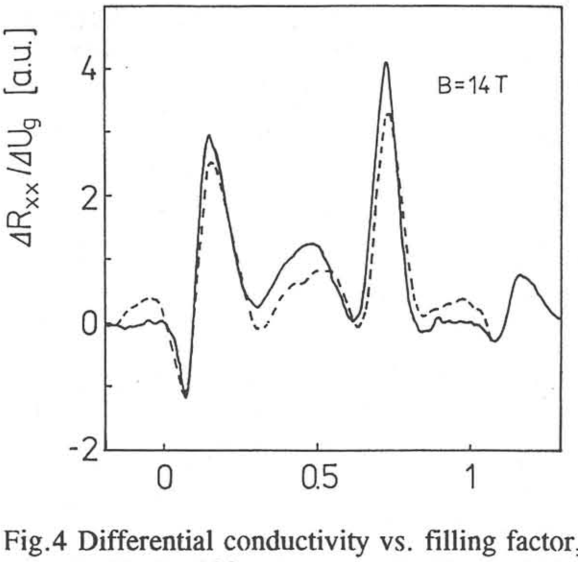

Fig.4 Differential conductivity vs. filling factor. -- sample #1 (d_i=300nm), — sample #2 (d_i=200nm)

In Fig. 4 we show the filling-factor dependent differential conductivity for both samples. It is seen that minima at filling factors of about 0.35 and 0.65 arise. It must be pointed out, however, that the determination of ν by means of eg.(1) depends on the knowledge of d_g, and so there is some uncertainty in scaling. Further it is assumed that U_{depl} does not depend on the magnetic field. Therefore the positions of the filling- factor minima of the differential magnetoconductivity are only a rough estimate for the filling factors 1/3 and 2/3. The origin of the minimum at ν of about 0.1 is yet unclear. From data of Fig. 4 it follows that there is no significant difference between the two samples at high magnetic fields. The structures at 'negative filling factors' which appear at low magnetic field vanish for magnetic fields higher than 8 T. This indicates a magnetic-field-induced freeze out of the high mobility electrons between the two layers.

Conclusions

Differential magnetotransport measurements in a two layer system the with large spacing between the electron channels allow the investigation of both layers, separately. At low magnetic fields additional high-mobility carriers are discovered which form an extended electronic state between the two layers. With increasing magnetic field these electrons are frozen out. The high mobility electrons show the integer and fractional quantum Hall effect.

References

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