Investigation of conductance fluctuations in quantum wires fabricated by cleaved edge overgrowth

F. Ertl[1], **M. Rother**[1], **W. Wegscheider**[1,2], **R.A. Deutschmann**[1], **M. Bichler**[1], **G. Abstreiter**[1]

[1] Walter Schottky Institut, Technische Universität München, Am Coulombwall, D-85748 Garching, Germany
[2] Institut für Angewandte und Experimentelle Physik, Universität Regensburg, D-93040 Regensburg, Germany

Abstract In this letter we present a study of conductance fluctuations appearing in the transport of single mode quantum wires fabricated by cleaved edge overgrowth. The temperature behavior of the variance is discussed in the framework of the Luttinger liquid theory for a set of different quantum wire lengths. We observe an unexpected quenching of the Luttinger liquid behavior with increasing wire length.

1 Introduction

With the realization of the quantum point contact, the 1D transport regime became experimentally accessible. These small and short constrictions defined by gates on semiconductor heterostructures already showed special features like the prominent conductance quantization in multiples of $2e^2/h$ at low-temperatures. For further exploration of 1D behavior, gated quantum wires (QWR) patterned by electron beam lithography became longer, but nevertheless these QWRs operated barely in the ballistic transport regime due to scattering on the rough boundaries. A real breakthrough was achieved by Yacoby and coworkers, who introduced QWRs fabricated by cleaved edge overgrowth (CEO) [1]. With their ballistic QWRs they observed a suppression of the conductance below the quantum value, which was attributed to a possible formation of a Luttinger liquid (LL) within the wire. Up to now the CEO QWRs attract considerable interest, because the question of whether there is a LL or not is not finally solved. We will present our latest results of conductance fluctuations (CF), which fit well to the predictions of LL theory (for a review see [3]).

2 Experimental

We also employ the CEO technique to create QWRs of high quality in the GaAs/AlGaAs material system. For details of the manufactoring process or the unique contacting scheme see [2]. We start with growing a 250 Å wide modulation doped quantum well, which sets the width of the QWR, on the [001]-surface by molecular beam epitaxy (MBE). Afterwards a tantalum gate is processed by conventional lithography on the specimen defining the QWR length (from 5 μm to nearly 50 μm) by the gate width. This sample then is cleaved in the ultrahigh vaccum of the MBE chamber and immediately a modulation doping sequence is grown on the fresh atomically smooth [110]-surface. The twofold confinement of the square (quantum well) and the triangular (modulation doping) potential creates one-dimensional states extending along the cleavage plane. Beneath the negatively biased gate the two-dimensional system of the well is depleted and a 1D system survives with two 2D system attached to the left and right. By changing the gate voltage the Fermi energy or correspondingly the electron density in the 1D system can be varied.

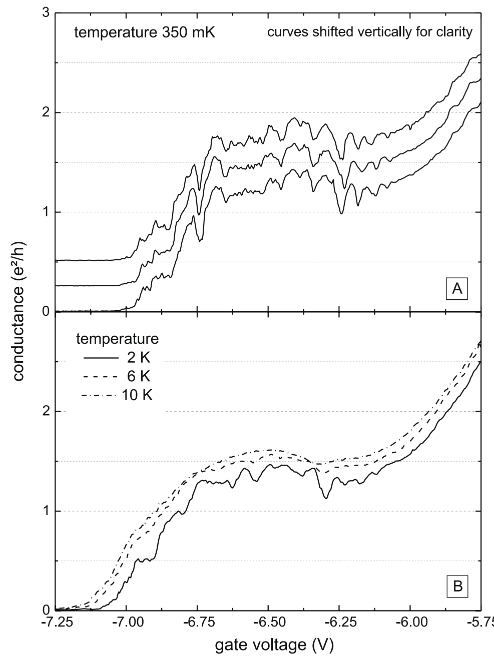

Fig. 1 Differential conductance of a 250 Å wide and 5 μm long QWR as a function of gate voltage, i. e. the Fermi energy. In graph A the reproducibility of the CFs is demonstrated, whereas graph B shows the temperature behavior of the fluctuations.

We characterize the QWRs by measuring the dependence of the differential conductance on the gate voltage or the Fermi energy. The measurements are carried out in four-terminal geometry using lock-in technique at 17 Hz with an excitation voltage of 10 μV. The sample is located in a pumped ^{3}He-cyrostat with an accessible temperature range of 300 mK to 10 K. Considerable experimental attention is paid to reduce the noise background and lock-in integration times of 3 s are used.

3 Results

Fig. 1A shows typical measurements of a 250 Å wide and 5 μm long QWR for the lowest subband. Three successive measurements are visible, which are shifted verti-

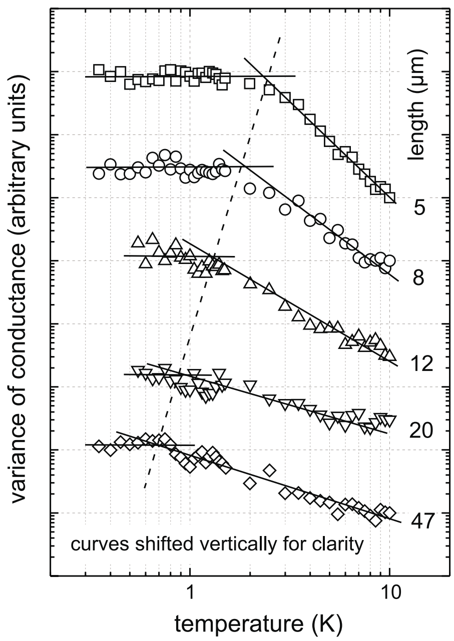

Fig. 2 Measured variance of the CFs versus temperature. Each of the curves, which are shifted vertically for clarity, represents the result for a different QWR length at fixed width of 250 Å. The data is plotted on a double logarithmic scale.

cally for clarity. The conductance exhibits a quantized plateau onto which several reproducible fluctuations are superimposed. The value of the quantized conductance plateau is suppressed below the conductance quantum of $2e^2/h$. The fluctuations indicate the presence of slight disorder. They emerge when parts of the electron wave packets are multiply reflected by the disorder and interfere with each other. Fig. 1B demonstrates the temperature behavior of the conductance measurements. When the temperature is raised the quantized plateau also rises and the CFs smear out. At 10 K the average conductance value is still different from the quantum and the fluctuations are no longer visible.

For a more extensive analysis we calculate the variance of the fluctuations $var(G) = \langle (G - \langle G \rangle)^2 \rangle$ in the region, where the lowest plateau is clearly defined. We obtain the mean conductance $\langle G \rangle$ from the pure conductance G by smoothing with adjacent averaging. This calculation is applied to a set of QWRs with different lengths of 5, 8, 12, 20 and 47 μm of which the results are plotted in Fig. 2 as a function of temperature T. The presentation of the data is on double logarithmic scale and the curves belonging to different QWR length are shifted vertically for clarity. The variance exhibits two regimes separated by a crossover temperature T_L. Below this temperature $T < T_L$ the variance remains at an almost constant value $var(G)$ = const. In the other regime for $T > T_L$ the variance clearly follows a power-law behavior $var(G) \propto T^{-\alpha}$. Furthermore the crossover temperature T_L shifts to lower temperatures with increasing wire length. Comparing these observations with the predictions of LL theory regarding to

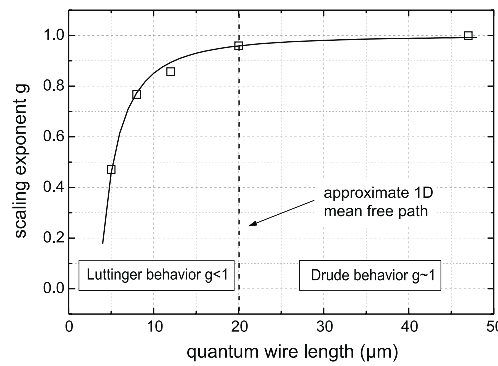

Fig. 3 LL scaling exponent g, which is a measure of the mutual electron- electron interaction, versus the QWR length. The scaling exponent is derived from the power-laws of the fluctuations variance.

CFs [4,5] shows clear agreement. These papers report of a temperature dependent power-law for the fluctuations variance $var(G) \propto T^{4g-5}$, which is cut off below a crossover temperature. The parameter g is the fundamental LL scaling exponent and gives a measure of the mutual electron-electron interaction.

Finally we derive the LL scaling exponent g from the power-laws of the variance for all QWR lengths (see Fig. 3). The scaling exponent posseses a strong length dependence, which reveals a change in the interaction behavior of the electrons. Short wires show Luttinger behavior (repulsive interacting electrons $g < 1$) and long wires tend to Drude behavior (non-interacting electrons $g \approx 1$). This unexpected quenching of the LL behavior takes place for lengths larger than 20 μm, which is approximately the 1D mean free path [1]. We suggest that the quenching can be described by a new length L dependent power-law $(1 - g) \propto L^{-\beta}$ with a parameter of $\beta = 1.9 \pm 0.5$ from a least square curve fit.

4 Summary

In summary we have shown that the temperature behavior of conductance fluctuations in single mode quantum wires can be explained in terms of the Luttinger liquid theory. Also an unexpected quenching of the Luttinger liquid with increasing wire length was observed.

Acknowledgements This work is supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie within project III-V Quantenstruktursysteme and the Deutsche Forschungsgemeinschaft in framework of SFB 348.

References

1. A. Yacoby, H.L. Stormer, N.S. Windgreen, L.N. Pfeiffer, K.W. Baldwin, and K.W. West, Phys. Rev. Lett. **77**, (1996) 4612.
2. M. Rother, W. Wegscheider, R.A. Deutschmann, M. Bichler, and G. Abstreiter, Physica E **6**, (2000) 551.
3. J. Voit, Rep. Prog. Phys. **57**, (1995) 977.
4. S.R. Renn, and D.P. Arovas, Phys. Rev. Lett. **78**, (1997) 4091.
5. I. Safi, and H.J. Schulz, Phys. Rev. B **59**, (1999) 3040.