ELSEVIER

Physica B 249–251 (1998) 180–184

PHYSICA B

Temperature dependence of the "0.7" $2e^2/h$ quasi-plateau in strongly confined quantum point contacts

A. Kristensen[a,*], P.E. Lindelof[a], J. Bo Jensen[a], M. Zaffalon[a], J. Hollingbery[a], S.W. Pedersen[a], J. Nygård[a], H. Bruus[a], S.M. Reimann[a], C.B. Sørensen[a], M. Michel[b], A. Forchel[b]

[a] Niels Bohr Institute, Ørsted Laboratory, Universitetsparken 5, DK-2100 Copenhagen Ø, Denmark
[b] Technische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

Abstract

New results are presented of the "0.7" ($2e^2/h$) quasi-plateau of strongly confined point contacts. The strong confinement is obtained by combining shallow etching with metal gate deposition on GaAs/GaAlAs heterostructures. The resulting subband separations are up to 20 meV, and consequently, the quantized conductance is observed up to 30 K, an order of magnitude higher than in conventional split gate devices. Pronounced quasi-plateaus are observed at the lowest conductance steps from 1 to 30 K, where all structures are smeared out thermally. The deviation of the conductance from ideal integer quantization exhibits an activated behavior as a function of temperature with a density-dependent activation temperature around of 2 K. Our results are analyzed in terms of a model involving scattering against plasmons in the constriction.

Keywords: Quantum point contacts; Plasmon scattering; Quantized conductance

1. Introduction

The quantized conduction through a narrow point contact is one of the key effects in mesoscopic physics believed to demonstrate e.g. the validity of the single-particle Fermi-liquid picture in terms of the Landauer–Büttiker formalism, a central formalism in the field. However, the electron system in the narrow constriction forms a quasi-one-dimensional electron liquid, and such systems have long ago been predicted to exhibit significant deviations from the ordinary Fermi-liquid behavior. Thus, the quantum point contact (QPC) remains an important testing ground for the description of mesoscopic phenomena. Indeed recently, significant deviations from the Landauer–Büttiker theory have in fact been observed in quantum point contacts in the temperature dependence of the conductance quantization [1,2] and as a so-called "0.7" structure or quasi-plateau, appearing around 0.7 times the conductance quantum $2e^2/h$ [3]. Invoking a Luttinger-liquid approach [4] the deviations have been discussed in terms of interaction effects [5–7] and spin polarization of the one-dimensional electron liquid [8]. However, firm conclusions have been difficult to obtain partly due to the narrow temperature range (0.1–4 K) in which the effect can

* Corresponding author. Tel.: + 45 3532 0438; fax: + 45 3532 0460; e-mail: ak@fys.ku.dk.

0921-4526/98/$19.00
PII: S0921-4526(98)00094-5

be studied in conventional split gate quantum point contacts, where relatively close lying one-dimensional subbands are formed. One major point in this work is the fabrication of QPCs with large subband spacings which allow a more detailed study of the temperature dependence of the deviations from the standard single-particle picture.

2. The device

Our quantum point contacts were fabricated on conventional high electron mobility transistor (HEMT) structures by shallow wet-etching and gate metallization [9]. By molecular beam epitaxy (MBE), the following layer sequence was grown: 1 μm GaAs buffer, 20 nm $Ga_{0.7}Al_{0.3}As$ spacer, 40 nm $Ga_{0.7}Al_{0.3}$ As barrier layer with a Si concentration of $2 \times 10^{18}\,cm^{-3}$ and a 10 nm GaAs cap layer. The two-dimensional electron gas forms in the GaAs at the GaAs/$Ga_{0.7}Al_{0.3}As$ interface, buried 90 nm below the surface of the heterostructure. At 4.2 K, the carrier density was $2 \times 10^{15}\,m^{-2}$ and the mobility $104\,m^2/Vs$, measured in the dark. The sample was processed with a $20 \times 100\,\mu m^2$ mesa, etched 100 nm, and AuGeNi ohmic contacts to the 2DEG were formed by conventional UV-lithography and lift-off. The narrow QPC constriction was defined by shallow etching on the mesa. In order to perform the shallow etch with well-controlled edges, a 13 nm thick Al mask was formed by e-beam lithography and lift-off, using a field emission scanning electron microscope at an acceleration voltage of 2.5 kV. The sample was then shallow etched 55–60 nm in $H_2O:H_2O_2:NH_4OH$(75:0.5:0.5) at an etch rate of 4 nm/s. The etch-mask was removed, and a 80 nm thick, 5 μm wide Al gate electrode was deposited by UV-lithography and lift-off, covering the constriction and the surrounding 2DEG. The shape $y(x)$ of the etched constriction is parabolic, $y(x) = \pm (d/2 + ax^2)$. Hence, the geometry of the QPC is characterized by two numbers, the width of the constriction, d, and the curvature, a. We have studied values of d between 50 and 400 nm and of a between 0.00125 and $0.005\,nm^{-1}$. For channel widths $d < 300$ nm the channel is pinched-off at zero gate voltage, and a positive gate voltage is applied to open it. The conductance of the QPC was measured by conventional lock-in technique using an AC current bias of 1 nA at a frequency of 17 Hz. The gate leakage current was also monitored during low-temperature measurements, and it was found to be negligible (less than our measurement resolution of 10 pA) for $V_G < 1$ V. All samples showed well-defined conductance quantization well above 4 K. The most regular conductance steps at the highest temperatures were seen for the narrowest and longest constrictions $d = 50$ nm, $a = 0.00125\,nm^{-1}$.

We estimate subband separations in our QPCs up to 20 meV by comparing the measured temperature dependence to the theoretical model for conductance quantisation [10,11], and by applying a finite DC source drain voltage [3]. These are the highest values so far reported for lateral QPCs in GaAlAs/GaAs heterostructures [12]. They are much higher than the corresponding ones found in split gate devices [13,3] where subband energy spacings of $\simeq 2$ meV are found, and where the conductance quantisation disappears at about 4 K.

3. Experimental results

In this paper we focus on the results of a particular QPC with an etched center width $d = 205$ nm and wall curvature $a = 0.00125\,nm^{-1}$. The discussed temperature dependence is reproduced in four other samples investigated. Even though the quantization of conductance in the sample is visible up to 30 K, we present in Fig. 1 only measurements from 0.3 K to 8 K. In this temperature regime the deviations from Landauer–Büttiker theory is most clearly seen without having too much thermal smearing present. The main observation is that the deviation from perfect quantization seems to follow an activated behavior. This is demonstrated in the upper inset of the figure: a semi-logarithmic plot of the deviation $2 - G_{QPC}$ versus $1/T$ at a gate voltage of $V_G = 0.218$ V. In the temperature region from 1 to 8 K the data exhibit an activated behavior, from which we extract an activation temperature T_A. However, some caution is needed: our data only allow us to plot the activation behavior over one single order of magnitude. The lower inset of

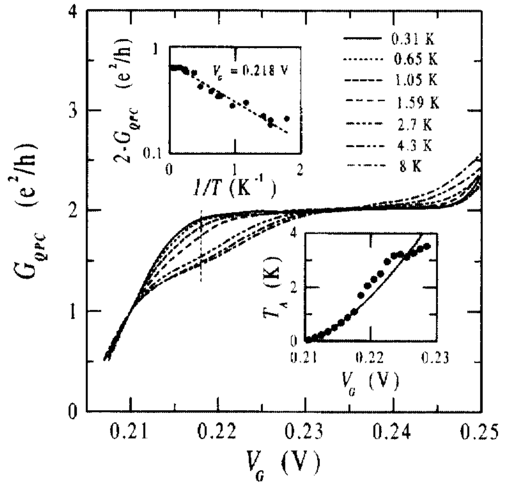

Fig. 1. Quantum point contact conductance G_{QPC} versus gate voltage V_G at the first conductance plateau measured at different temperatures. The QPC has a width $d = 205$ nm and a curvature $a = 0.00125\,\mathrm{nm}^{-1}$ (see text). Upper inset: Arrhenius plot of the deviation from ideal quantized conductance, $(2 - G_{QPC})$ versus $1/T$ at gate voltage $V_G = 0.218$ V (indicated by the vertical dashed line on the $G_{QPC} - V_G$ plot). The slope of dashed line on the Arrhenius plot gives an activation temperature T_a. Lower inset: T_a versus V_G for the first half of the first conductance plateau. The full-line is the result of the model calculation of Section 4.

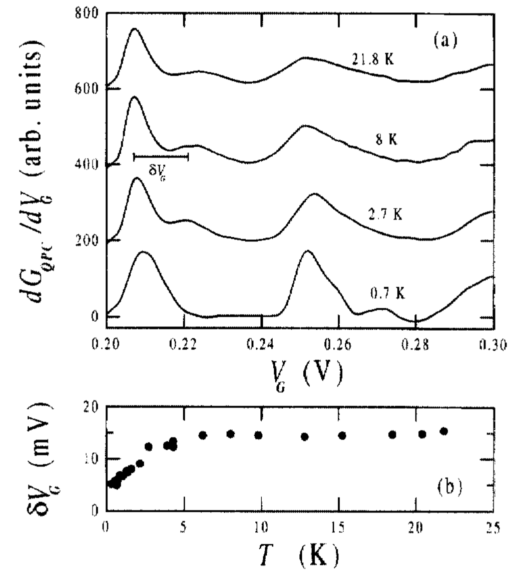

Fig. 2. (a) Transconductance dG_{QPC}/dV_G evaluated from the same data set as in Fig. 1. The "0.7" ($2ne^2$/h) structure emerges around 1 K as a satellite to the first transconductance peak ($n = 1$), and as shoulders on the peaks at higher n. The "0.7"-satellite can be followed to the highest temperatures where conductance quantization is still visible. (b) Separation δV_G between the $n = 1$ main peak and the "0.7"-satellite as a function of temperature.

Fig. 1 shows the extracted activation temperature as a function of gate voltage across the lower part of the first conductance plateau. We find that it rises from 0 to 4 K as the gate voltage is swept through the conductance step, i.e. as the electron density grows. This feature is discussed in Section 4.

In Fig. 2a we show the transconductance dG_{QPC}/dV_G measured at different temperatures. The first two conductance plateaus are seen as minima in transconductance at $V_G \sim 0.235$ and 0.28 V, separated by transconductance peaks. At temperatures above 1 K the "0.7" quasi-plateau appears at $V_G \sim 0.225$ V as a satellite to the first conductance peak, and as a shoulder to the higher peaks. From this behavior we can rule out thermal smearing as the mechanism behind the observed structure. Thermal smearing would broaden the transconductance peaks and make them more symmetric. The particular shape of the transconductance peaks could also simply be reflecting the energy dependence of the transmission probability for electrons traversing the constriction. However, such features would again be smeared out thermally rather than giving rise to additional structure appearing at high temperature. In Fig. 2b we have plotted the distance δV_G between the main peak and the satellite peak. The distance grows at the lowest temperatures, but above 5 K it saturates.

Our experimental results represent a confirmation and extension of the earlier results by Thomas et al. [14], who suggest that the "0.7"-structure may originate from spin polarization of the 1D-electron gas in zero magnetic field. We have also measured the low-temperature QPC conductance with a strong magnetic field, $B \leqslant 12$ T, applied in-plane with the 2DEG, and parallel with the current through the constriction. Like Thomas et al. we observe that the separation δV_G between the first main and satellite peak increases linearly with B, and we extract an enhanced g-factor of $g = 0.94$.

4. A theoretical model

The quasi-one-dimensionality of the electron liquid in the QPC has brought forward the possibility of Luttinger-liquid behavior [4]. The quasi-plateau has been discussed in the characteristic terms of separated charge and spin degrees of freedom of one-dimensional strongly coupled systems [5–8]. However, explanations invoking the Luttinger-liquid face at least one serious problem. The channel length of the typical QPC is very short, of the order of ten times the Fermi wavelength of the bulk 2DEG and only a few times the Fermi wavelength or less of the 1D channel itself. In contrast, the characteristic correlations of the Luttinger-liquid are established over long ranges. We are therefore seeking the explanation of the quasi-plateau in more simple terms. As mentioned, the evolution of the quasi-plateau as a function of temperature rules out single-particle effects like thermal smearing, asymmetrical barrier potential and resonances. It seems necessary to include electron–electron interaction effects to explain the phenomena. We propose a model, where the quasi-plateau is due to electron–electron interaction in the form of scattering of electrons against plasmons in the QPC.

We calculate the frequency ω_p^{1D} of the quasi-one-dimensional plasmons of the QPC in the long wave limit of the random phase approximation. The QPC is embedded in a dielectric of permittivity ε, and it is compensated by uniform background of the same density. The resulting dispersion relation is

$$\omega_p^{1D} = \sqrt{v_f^2 + \gamma e^2 n^{1D}/4\pi m^*}\, q, \qquad (1)$$

where $m*$ is the effective electron mass and $\gamma \approx 1$ is a numerical factor. Due to the presence of the 2DEG contacts the 1D plasmons are size quantized and acquire a finite gap. The lowest lying mode is a standing half wave with a wave number of the order of $q = \pi/L$, where L is the channel length. The electron density n^{1D} is controlled by the gate voltage V_G through $n^{1D} \propto C(V_G - V_0)$, where C is the capacitance and V_0 the pinch-off voltage, here defined by $G(V_0) = e^2/h$. As V_G is increased from V_0 the electron channel width increases from zero, and hence the capacitance is also an increasing function of V_G. Since n^{1D} is proportional to $\sqrt{\varepsilon_F}$, where ε_F is the Fermi energy in the channel, we end up with $\varepsilon_F = \alpha(V_G - V_0)^3$ to lowest order in V_G. The constants V_0 and α are found by combining the estimates of the 1D sublevel spacings with the two values of V_G where $G(V_G) = e^2/h$ and $G(V_G) = 3e^2/h$, respectively. Finally, we fit the resulting plasmon energy $\hbar\omega_p^{1D}$ to the activation data of Fig. 1 by adjusting L. In the inset of Fig. 1 we used $L = 0.1\ \mu m$.

The justification of our model is the following. The electron gas is divided into three regions, two 2DEG contact regions and one 1DEG QPC region. Scattering against plasmons of the bulk 2DEG is always present at all temperatures, and it is taken into account through the background resistance, which as usual is subtracted to obtain the correct values of the quantization plateaus. At temperatures well below $\hbar\omega_p^{1D}$ no further resistance is introduced by the 1D plasmons in the QPC. As temperature increases scattering against 1D plasmons becomes possible and results in an additional resistance leading to deviation from perfect conductance quantization of an activated form, with the activation energy given by the plasmon energy. As the gate voltage is increased the density of the 1DEG is also increased, and the gap in the plasmon spectrum grows, resulting in an enhanced activation energy. Finally, the plasmons of the 1DEG becomes more like the bulk 2DEG plasmons, and the additional resistance disappears into the background resistance. The position of the quasi-plateau is given by the voltage required to have a sufficient density of the 1DEG to have significant scattering against the plasmons. Of course, this crude model needs to be extended by taking into account, for example, possible spin polarization effects and the opening of the next conducting channel.

5. Concluding remarks

We have fabricated lateral QPCs in GaAs with an extraordinary strong confinement potential in the constriction raising by an order of magnitude the maximal temperature at which quantized conductance can be observed as compared to conventional split-gate devices. The enlarged temperature range enabled us to observe activated temperature dependence of the "0.7" quasi-plateaus, and we measured the activation temperature to rise from 0 to 4 K as the gate voltage is increased through the first half of the first conductance plateau. We have suggested a model to explain the observed effects based on scattering against 1D plasmons in the QPC. The model introduces a gap in the plasmon spectrum in a natural way. This gap is identified with the activation temperature, and the model can account for the gate voltage dependence of that temperature.

Acknowledgements

This research is part of the EU IT-LTR program Q-SWITCH (No. 20960). The III–V materials used in this investigation were made at the III–V NANOLAB, operated jointly by the Microelectronics Centre of the Danish Technical University and the Ørsted Laboratory, Niels Bohr Institute fAFG, University of Copenhagen. The research was partly supported by SNF grants 9502937 and 9601677. S.M.R. thanks the Studienstiftung des deutschen Volkes and the BASF AG for financial support. H.B. is supported by the Danish Natural Science Research Council through Ole Rømer Grant no. 9600548.

References

[1] S. Tarucha, T. Honda, T. Saku, Solid State Commun. 94 (1995) 413.
[2] A. Yacoby, H.L. Stormer, N.S. Wingreen, L.N. Pfeiffer, K.W. Baldwin, K.W. West, Phys. Rev. Lett. 77 (1996) 4612.
[3] K.J. Thomas, M.Y. Simmons, J.T. Nicholls, D.R. Mace, M. Pepper, D.A. Ritchie, Appl. Phys. Lett. 67 (1995) 109.
[4] C.L. Kane, M.P.A. Fisher, Phys. Rev. B 46 (1992) 15233.
[5] A. Kawabarta, J. Phys. Soc. Japan 65 (1996) 30.
[6] A. Shimizu, J. Phys. Soc. Japan 65 (1996) 1162.
[7] Y. Oreg, A.M. Finkelstein, Phys. Rev. B 54 (1996) 14265.
[8] D. Schmeltzer, E. Kogan, R. Berkovits, M. Kaveh, cond-mat/9704245 (1997).
[9] A. Kristensen, J. Bo Jensen, M. Zaffalon, C.B. Sørensen, S.M. Reimann, P.E. Lindelof, M. Michel, A. Forchel, J. Appl. Phys. 83 (1998) 607.
[10] H.A. Fertig, B.I. Halperin, Phys. Rev. B 36 (1987) 7969.
[11] M. Büttiker, Phys. Rev. B 41 (1990) 7906.
[12] The most sharply defined QPCs so far reported are in the articles: K. Ismail, S. Washburn, K.Y. Lee, Appl. Phys. Lett. 59 1998 (1991); H. Okada, T. Hashizume, K. Jinushi, T. Kudoh, H. Hasegawa, Proc. Int. Conf. Phys. Semiconductors, Berlin 1996, World Scientific, Singapore, 1996, pp. 1237–1240, but the authors of these articles do not attempt to extract the subband splitting.
[13] R. Taboryski, A. Kristensen, C.B. Sørensen, P.E. Lindelof, Phys. Rev. B 51 (1995) 2282.
[14] K.J. Thomas, J.T. Nicholls, M.Y. Simmons, M. Pepper, D.R. Mace, D.A. Ritchie, Phys. Rev. Lett. 77 (1996) 135.