Novel phenomena in one-dimensional non-linear transport in long quantum wires

T. Morimoto¹, M. Hemmi¹, R. Naito¹, K. Tsubaki¹, J. –S. Park¹, N. Aoki¹,², J. P. Bird³, and Y. Ochiai¹,²

1: Graduate School of Science and Technology, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

2: Department of Electronics and Mechanical Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

3. Department of Electrical Engineering, University at Buffalo, the State University of New York, Buffalo, NY 14260-1920

E-mail: t-morimoto@graduate.chiba-u.jp

Abstract. We have investigated the non-linear transport properties of split-gate quantum wires of various channel lengths. In this report, we present results on a resonant enhancement of the non-linear conductance that is observed near pinch-off under a finite source-drain bias voltage. The resonant phenomenon exhibits a strong dependence on temperature and in-plane magnetic field. We discuss the possible relationship of this phenomenon to the spin-polarized many-body state that has recently been suggested to occur in quasi-one dimensional systems.

1. Introduction

Quasi one-dimensional transport physics has been refocused by the discovery of novel many-body phenomena in quantum point contacts (QPC) and wires (QW). These phenomena are expected to reveal the fundamental properties of the electron-spin in confined systems, as well as potential applications to spin-electronics and quantum-computing. For nearly twenty years, transport in QWs and QPCs [1, 2] has been successfully explained in terms of single particle notions. More recently, however, there has been much interest in the possibility that the 0.7-structure that is observed in QPCs may be related to a novel spin phenomenon that arises in low dimensional systems at a low carrier density [3]. While many experimental [4-7] and theoretical studies [8, 9] have attempted to clarify this phenomenon, and have provided some insight into its likely origin, the microscopic origins of the apparent spontaneous spin polarization that occurs in these systems are still the subject of debate.

In this report, we present the results of measurements of the non-linear transport of QWs of various length, fabricated on the same substrate. At low temperatures (< 1 K), the non-linear conductance of these wires is found to show a peak-like enhancement as the source-drain bias is varied near pinch-off.
The enhancement grows increasingly pronounced in QWs of increasing length and shows a strong dependence on temperature and in-plane magnetic field. We discuss this phenomenon in terms of the possible formation of some novel many-body state close to pinch off.

2. Sample Preparation
Split-gate QWs with lengths of 150, 450, and 600 nm were fabricated on the same piece of a modulation-doped GaAs/AlGaAs single heterostructure as shown in Fig. 1(a). A two-dimensional electron gas (2DEG), with a carrier density of $2.1 \times 10^{11}$ cm$^{-2}$ and a mobility of $1.1 \times 10^6$ cm$^2$/Vs, was located 75 nm below the heterostructure surface. By fabricating the three different devices on the same wafer, we were able to obtain a consistent comparison of their length-dependent characteristics. Measurements of their electrical characteristics were performed using a 30 μV ac voltage excitation (for zero bias transport) and combined ac & dc excitation (for studies of non-linear transport). The sample was mounted in the mixing chamber of a $^3$He-$^4$He dilution refrigerator.

3. Experimental results
The quantized conductance measured at various temperatures is shown in Fig. 1(b). These results indicate quite standard behavior, namely a step-like variation of the conductance in integer increments of $2e^2/h$, indicative of linear transport via spin-degenerate one-dimensional subbands. The behavior of the linear conductance as a function of the gate voltage ($V_g$) provides only a limited understanding of transport in the QWs. Non-linear measurements, using a dc bias voltage, are important as an additional electrical probe of the intrinsic structure of the QW. Figure 1(c) shows the non-linear conductance of the 450-nm QW, measured by incrementing the $V_g$ in 2-mV steps at 4.2 K. Due to the thermal broadening of occupied states in the reservoirs, the usual integer and half-integer plateaus are not clearly observed in this measurement, with the exception of the first half-plateau at $0.5 \times 2e^2/h$. This result is consistent with the fact that the quantized conductance is not very clearly seen in the linear-conductance measurements at 4.2 K.

In previous work on non-linear transport in QPCs, a zero-bias peak has been reported in the non-linear conductance and has been suggested to be related to the occurrence of a Kondo phenomenon at low temperature [10]. In this study, however, we have observed a different kind of peak structure, which occurs at finite (i.e. non-zero) bias, and exhibits a strong dependence on temperature and magnetic field. Figure 2(a) shows a three-dimensional plot of the non-linear conductance, which was measured while incrementing the source-drain bias ($V_{SD}$) in 0.1-mV steps at 0.2 K. In the region near...
zero bias, the behavior of the conductance is almost the same as that found at zero bias shown in Fig. 1 (b). For a finite $V_{SD}$ however, a remarkable enhancement of the non-linear conductance is observed when $V_{SD}$ is increased beyond ~0.8 mV. Initially, this enhancement emerges as a shoulder-like feature that grows up from the pinch-off region. With further increase of $V_{SD}$, however, a clear peak emerges that separates the regions of pinch-off and finite conductance. As $V_{SD}$ is increased further, the peak amplitude grows dramatically and significantly exceeds $2e^2/h$. The form of this enhancement in the three different wires is shown in Fig. 2(b). Similar peaks are also found for negative $V_{SD}$, although their amplitude is a little smaller. Quickly after reaching the peak amplitude, the conductance then collapses at even higher $V_{SD}$, returning to a value close to the half-plateau at $e^2/h$. This basic resonance phenomenon, and its dependence on QW length, however, are not influenced by reversing the dc-bias polarity. These results therefore strongly suggest that this resonance has a clear dependence on channel length, becoming more pronounced in longer QWs.

Figure 3(a) shows the temperature dependence of the peak in the non-linear conductance of the 450-nm QW (with $V_{SD} = 2.2$ mV), measured in the temperature range from 0.2 K to 13 K. The peak height decreases dramatically with increasing temperature and the results of Fig. 3(b) show that the
dependence appears to be well described as a variation proportional to $T^{-2/3}$. In addition, although not shown here, application of an in-plane magnetic field (up to 6 T) is found to cause a marked decrease of the peak amplitude, behavior which is accompanied by a shift of the peak to less-negative gate voltages.

4. Summary
We have presented the results of measurements of the non-linear conductance of QWs of various length. At higher temperatures, above a degree Kelvin, we observed quite usual behavior in the QWs, in terms of their quantized linear conductance and their non-linear differential conductance. At low temperatures (~0.2 K), on the other hand, the corresponding behavior was found to be quite different, with the prominent observation being of a pronounced peak in the non-linear conductance at finite source-drain bias. The possibility that tunneling via single, or stochastic, impurity states is responsible for the observation of the peak seems unlikely, since such an effect should be suppressed in longer wires while the behavior that we observe becomes more pronounced with increasing wire length. Moreover, the influence of simple scattering and interference should produce only a small modulation of the conductance, less than $2e^2/h$. Instead, the large observed enhancement of the non-linear conductance appears to suggest the existence of a novel many-body state in these quasi-one dimensional systems, whose signature is a steep contribution to the $I-V$ characteristic in the transition region between pinch off and finite (normal) conduction. Our studies show that this many-body state is strongly suppressed by an increase of temperature, or by the application of an in-plane magnetic field which should modify the Zeeman energy of the state without affecting its cyclotron motion. This sensitivity to in-plane magnetic field, in particular, may suggest a spin-related interpretation of this phenomenon, although the detailed microscopic interpretation remains to be clarified.

5. Acknowledgement
This work was supported in part by Grant-in-Aids for Scientific Research of the Japan Society for the Promotion of Science (JPSJ) No.14750005 and 13450006, and also supported in part by Chiba University 21COE “Frontiers of Super-Functionality Organic Devices”. JPB gratefully acknowledges the support of the National Science Foundation (ECS-0224163), the Department of Energy (DE-FG03-01ER45920) and NYSTAR.

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