Non-equilibrium transport in a quantum wire in the quantum Hall regime

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Abstract. We investigate the equilibrium and non-equilibrium electron transport in a quantum wire (QW) in the quantum Hall regime. While the equilibrium conductance of the QW is quantized reflecting the dissipation-less quantum Hall edge transport, the quantization collapses when the QW is voltage-biased with the voltages larger than the critical ones. This phenomenon is accompanied by the dynamic nuclear polarization which causes the temporal variation of the QW conductance of the order of minutes.

1. Introduction

The quantum Hall effect (QHE) is the phenomenon peculiar to the two-dimensional electron gas (2DEG) systems, where the longitudinal resistance vanishes with a quantized Hall resistance \cite{1}. This behavior is well explained by the formation of the dissipation-less quantum Hall (QH) edge state \cite{2}. However, the dissipation-less state collapses in non-equilibrium \cite{3, 4}, which is called QHE breakdown. The mechanism of the breakdown still remains to be clarified in spite of intensive and extensive studies \cite{5, 6}. Many studies on this typical non-equilibrium phenomenon have been conducted in the bulk Hall-bar samples, for example, to determine where the breakdown takes place.

Recently, a similar collapse of the conductance quantization is known to occur in a mesoscopic scale in the non-equilibrium quantum Hall regime. Transport measurements in mesoscopic devices have been done by several groups \cite{7-12}, where the non-equilibrium state is addressed by probing the associated dynamic nuclear polarization (DNP). The mechanism of the DNP was explained as the flip-flop process between electron spin and nuclear spin due to the electron scattering between spin-resolved Landau levels \cite{7}.

As both the QHE breakdown and the DNP are non-equilibrium phenomena due to the collapse of the QH edge transport, it is natural to expect that they coexist in some situations. Indeed, the QHE breakdown is recently reported to serve as a method to create DNP in 2DEG \cite{13}. Moreover, Córcoles \textit{et al}. observed DNP in a quantum wire (QW) and discussed that it is due to the QHE breakdown \cite{11}.

Here we report the experimental observation of the collapse of the conductance quantization in the non-equilibrium QW. In the quantum Hall regime the differential conductance of QW at zero-bias is quantized, while the dissipation-less state collapses when the source-drain bias voltage applied to the QW \((V_{sd})\) exceeds a critical value.

We show that the collapse is induced by the electron tunneling from...
We also discuss the observation of the DNP accompanied by the electron tunneling between the Landau levels.

2. Experiments

Figure 1 shows the schematic measurement setup with the scanning electron microscope image of the sample fabricated on the GaAs/AlGaAs 2DEG. In the present experimental situation, the two channels are fully spin-polarized as schematically shown by the arrows. (b) Gate voltage dependence of the quantum wire conductance. At the conductance plateau at $e^2/h$, only the outer edge channel transmits electrons while the inner edge channel is reflected (see Fig. 1 (a)).

Figure 2 (a) shows the image plot of the differential conductance of the QW as a function of $V_{sd}$ and $B$ at $V_g = -1.4$ V. The upper panel shows the conductance at $B = 4.4$ T. Clear conductance plateau exists around zero bias voltage reflecting the dissipation-less QH edge transport. In Fig. 2(a), the white region corresponds to the conductance plateau. The plateau, however, collapses by applying the bias voltage exceeding $100$ µV. This critical value ($eV_{sd} = 100$ µV) falls in the same range as the Zeeman energy, while the Zeeman energy in the QW may be enhanced by the exchange interaction. As shown in the dotted line in the lower panel of Fig. 2 (a), the critical value of $V_{sd}$ to induce the collapse depends on the magnetic field. This suggests that the collapse is induced by the electron tunneling between the spin-resolved Landau levels; As the second Landau level in QW is empty in the present situation, the origin of the collapse can be explained as due to the electron tunneling from the lowest Landau level to the second one, which is localized inside or in the vicinity of the QW.

Figure 2 (b) shows the image plot of the differential conductance of the QW as a function of $V_{sd}$ and $V_g$. The conductance at $V_g = -1.6$ V is shown in the upper panel. As seen by the dotted curve in the image plot, the critical value is almost independent of $V_g$. By comparing between the results in Fig. 2(a) and 2(b), it is clear that the critical value is determined by the magnetic field, most probably by
the Zeeman splitting, being in agreement with the relevance of the electron tunneling between the spin-resolved Landau levels as discussed above.

The result shown in Figs. 2 (a) and 2 (b) is obtained when $V_{sd}$ is swept from the negative to the positive values. Figure 3 (a) shows dependence of the conductance on the sweep direction of $V_{sd}$. The hysteresis is observed around the critical value. As is often the case in the previous studies [9], such a hysteresis behavior strongly suggests the DNP generation via the hyperfine interaction between the electron spins and the nuclear spins. Actually, Fig. 3 (b) shows that the conductance obtained at $V_{sd}$

**Figure 2.** Differential conductance of the QW as a function of $V_{sd}$ measured at various (a) magnetic fields and (b) gate voltages. Upper panels are the cross-sections of the conductance at a fixed field or a gate voltage shown by the solid lines in the lower panels. The critical value to induce the collapse is shown in the lower panels by the dotted line.

**Figure 3.** (a) The QW conductance as a function of $V_{sd}$ showing the dependence on the sweep direction of $V_{sd}$. The arrows with "ON" and "OFF" indicate the source-drain bias voltage used in the measurement (b). (b) Observation of DNP development where the conductance varies in minutes. The relaxation time of DNP is also of the order of minutes.
around the critical value varies temporally with the scale of minutes, typical time scale of the phenomenon associated with DNP. The occurrence of the DNP supports that the origin of the collapse of the quantized conductance is the electron tunneling between the Landau levels, where the electron spins have to be flipped and some part of the spin degree of freedom is transferred to the nuclear spins. It was recently found that in bulk 2DEGs the skyrmions [17-19] and spin-textured edge states [20] affect the relaxation time of the DNP, although such a characteristic behavior of the relaxation time was not observed in the present study. The difference might be attributed to the difference between the bulk and the QW. To get further understandings, we have conducted the resistance-detected nuclear magnetic resonance and the shot noise measurement, which will be discussed elsewhere [21].

In conclusion, we have observed the collapse of the quantized conductance in the QW in the non-equilibrium QHE regime. The critical value of the bias voltage to induce this phenomenon depends on the Zeeman energy and the accompanying DNP is observed, which suggests the presence of the electron tunneling between the Landau levels in the QW.

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