Measurement of Energy Relaxation in Quantum Hall Edge States Utilizing Quantum Point Contacts

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We demonstrated a method to probe local electronic states and energy relaxation in quantum Hall edge states utilizing quantum point contacts. We evaluated relaxation lengths in two cases; first, with electron tunneling, and second, only with energy exchange without tunneling between edge states. The results were consistent with previous experiments and validated our method with quantum point contacts. We applied this method to measure the energy relaxation length around a hotspot in quantum Hall regimes and revealed the possible short-distance relaxation process to be the relaxation due to energy exchange between edge states without electron tunneling.

KEYWORDS: quantum Hall effect, edge state, quantum point contact, local probe, energy relaxation, non-equilibrium distribution

1. Introduction

Edge states in the quantum Hall regime attract strong interests in basic science and applications to quantum electronics in semiconductor micro devices. Quantum Hall edge states have long coherence lengths in solids and well defined chirality. There is a good analogy between electrons propagating ballistically in edge states and photons propagating in optical media. By utilizing these properties, interesting electronic devices, e.g. electronic Fabry-Pérot interferometers, Mach-Zender interferometers and on-demand single electron sources, etc. have been demonstrated and used to explore the quantum nature of the electronic states in solids. Also, there are theoretical proposals to use quantum Hall edge states for quantum information processing applications by using the quantum states themselves or forming quantum networks connecting isolated quantum states like quantum dots.

In many of the applications, local electronic properties of the edge states and the spatial changes of the states induced by energy relaxation are important. Recently, experiments probing the local electronic states, non-equilibrium energy distribution and energy relaxation in quantum Hall edge states utilizing quantum dots as local probes have been reported. The electronic energy distribution can be accessed by using the discrete energy levels formed in quantum dots as energy filters. By measuring the spatial change of the electronic energy distribution, energy relaxation with a short relaxation length (3 μm), which originates from energy exchange between edge channels, was observed and the detail of the relaxation mechanism was discussed using a microscopic model. A similar approach has also been used to probe the electronic states in the fractional quantum Hall regime to reveal charge and heat transfer.

In this paper, we measured the local electronic states in quantum Hall edge states using a different kind of probe: quantum point contacts (QPCs). The QPC probes are easier to fabricate and can be applied to a wider range of experiments such as measurements in relatively high temperature conditions compared to the quantum dot probes. With QPC probes, we were able to access the local electrochemical potential and also maybe the local electron temperature as we will show in this paper. We used the QPC probes to investigate the spatial change of the local electronic states and evaluated the energy relaxation lengths.

In this paper first we applied the method to evaluate the relaxation length in the cases with electron tunneling and only with energy exchange without tunneling between edge states. By comparing these results with previous experiments, we checked the validity of our method. Next, we applied this method to probe energy relaxation around a specific energy dissipation point, called a “hotspot” in quantum Hall regimes, which is formed near a gate by applying a large source-drain bias across the gate to create hot electrons. We revealed the possible mechanism of the short-distance energy relaxation around the hotspot from the obtained relaxation length.

2. Device and Measurement Scheme

Figure 1(a) shows optical and scanning electron micrographs of the device. The device was fabricated from a GaAs/AlGaAs heterostructure wafer with sheet carrier density $3.9 \times 10^{15}$ m$^{-2}$ and mobility 52 m$^2$/Vs at 2 K. The two-dimensional electron gas is formed 60 nm beneath the surface. We patterned a mesa structure by wet-etching and formed Ti/Au Schottky surface gates to define QPCs by metal deposition. Five QPCs (QPC$^1$ - QPC$^5$) were formed by applying negative voltages on the gates and each QPC was connected to each corresponding Ohmic contact $O_1$ - $O_5$. The distance from QPC$^1$ to QPC$^2$ - QPC$^5$, $d$, is 1.0, 3.1, 9.7 and 30.0 μm, respectively.

We applied a magnetic field perpendicular to the wafer surface and created quantum Hall edge states in the mesa. With the magnetic field of 4.05 T, quantum Hall states with filling factor $\nu=4$ were formed in the bulk. At this magnetic field, the
spin splitting was not large enough to create fully spin split edge channels in our device at 2 K, so spin-degenerate two edge channels were formed in the device. The outer channel consists of ν=1 and 2, and the inner channel of ν=3 and 4. We injected electrons from the Ohmic contacts O₀ and O₁ to the device states, and created a non-equilibrium energy distribution by changing the transmission of QPC₁ and the voltages applied on O₀, V₀, and O₁, V₁, respectively (Fig. 1(b)). In the following experiments, we fixed V₀ = 0 V and changed only V₁. We monitored the change of the local electronic states by measuring voltages at the probe Ohmic contacts O₂ to O₅. By adjusting the conductance of one of the QPCs, QPCₙ(ν = 2, 3, 4, 5), to 2e²/h and the others to 0, the outermost edge channel can interact with only one Ohmic contact O₀. The voltage measured at O₅ using a voltage meter with high input impedance, V₅, reflects the local electronic states of the outermost edge channel at the position of QPCₙ. We can measure the change in the local electronic states as a function of d and get information about the energy relaxation by measuring V₅ for the different probes QPCₙ.

3. Energy Relaxation with Electron Tunneling

Energy relaxation in quantum Hall edge states can be classified mainly into two kinds of mechanisms. The first one is tunneling of electrons between edge states.¹⁸,¹⁹ Assume edge states which have different electrochemical potentials μ. If high-energy electrons in the edge states with higher μ tunnel to the edge states with lower μ, energy relaxation occurs to make μ of the edge states equivalent. The other is energy exchange between edge states (and probably also between edge states and bulk states) without tunneling of electrons.¹² There is always Coulomb interaction between the edge states and this enables energy exchange between them even without tunneling of electrons. For example, in the case of the edge states with different electron temperatures, the hot edge channel can radiate energy and then the energy relaxation, which equalizes electron temperature of the edge states, occurs by this process.

First, we measured the relaxation length of energy relaxation with the electron tunneling. To create a non-equilibrium energy distribution between the edge states with different μ, which causes the energy relaxation with electron tunneling, we connect the inner edge channel to contact O₀ and the outer edge channel to contact O₁ by adjusting the conductance through QPC₁ to 2e²/h and reflecting the inner edge channel at QPC₁. V₀ and V₁ determine the conductance of electrons supplied by O₀, μ₀, and by O₁, μ₁, respectively. We can create a difference in μ between the edge states and realize μ₀ < μ₁ by making V₀ > V₁ (Fig. 2(a)). In this case, electrons in the outer edge channel with higher energy can tunnel into the inner channel contacting O₀. This accompanies the energy relaxation with electron tunneling. We can measure the relaxation length of this process lᵣ by monitoring μ of the outer channel through the measurement of V₅ at QPC₂ - QPC₅.

Figure 2(b) shows the measured V₅ as a function of d. To normalize the value of V₅ as V₁, we plot the numerical derivative of V₅, dV₅/dV₁. In the low bias regime of V₁ (less than 100 μV), V₅ changes linearly with V₁ and dV₅/dV₁ can be defined uniquely. If there is energy relaxation in this range of d, V₅ will decrease with increasing d and we will observe the decrease of dV₅/dV₁. But in Fig. 2(b), the value of dV₅/dV₁ is always around 0.48 and we observe no such decrease of dV₅/dV₁ up to d = 30 μm. This result indicates lᵣ is much longer than 30 μm, the maximum length accessible in this device geometry.²⁰ This long lᵣ, induced by the tunneling of electrons between the edge states consisting of well separated Landau levels ν = 2 and 4, is consistent with the previous experiments using locally gated Hall bars with longer probe distances showing the long energy relaxation lengths (over 100 μm)¹⁸,¹⁹,²¹

![Fig. 1](image1.png)

![Fig. 2](image2.png)
4. Energy Relaxation Only with Energy Exchange

Next, we measured the energy relaxation without electron tunneling and only with energy exchange between edge channels. To induce such kind of relaxation, we set the conductance through QPC1 to $e^2/h$. The inner edge channel is connected to O0 and the outer edge channel is connected to both O0 and O1. The half of the electrons in the outer edge channel is supplied by O0 and the remaining half by O1. This results in the two-step non-equilibrium energy distribution with two Fermi levels $\mu_0$ and $\mu_1$ in the outer edge channel when we make a difference between $\mu_0$ and $\mu_1$ (Fig. 3(a)). In this case, the energy can be transferred from the outer to the inner edge channel because the outer channel can radiate energy in the process of the relaxation from the two-step non-equilibrium energy distribution to the conventional Fermi distribution. We will measure this energy relaxation length $l_e$ by monitoring $V_n$ of the outer channel at QPC2 - QPC3. Note that the energy relaxation with electron tunneling is negligible on this short scale as we observed in Fig. 2. We can get the pure relaxation length only by energy exchange between the edge states.

Figure 3(b) shows the measured $dV_n/dV_1$ as a function of $d$. In this measurement, we observe that $dV_n/dV_1$ abruptly decreases with increasing $d$. Therefore there is energy relaxation in this length scale. This result also shows that we can detect the change of the electronic energy distribution through the change of $V_n$ even in this case without change of the electrochemical potential, although the detail of the mechanism is not perfectly clear at present.  

To evaluate the relaxation length $l_e$, we fitted the data with a simple exponential decay. The solid line in Fig. 3(b) is the result of the fitting. The best fitting is obtained for $l_e$ of $3 \pm 1 \mu$m and this value is much smaller than $l$. This result is again consistent with the previous experiments utilizing quantum dots as the local probes, which show the short energy relaxation length $3 \mu$m. These two results of the energy relaxation lengths in the cases with electron tunneling and only with energy exchange without tunneling between edge states agree with the previous experiments. This agreement supports the validity of our measurement method with QPC probes, which can be applied to a wider range of experiments compared to the quantum dot probes.

The possible reason why $l_e$ is much smaller than $l$ is the following. In the case of relaxation only with energy exchange, the process needs only the interaction to mediate energy transfer between spatially separated edge channels like the long range Coulomb interaction and therefore requires a short relaxation length. On the other hand in the case of energy relaxation with electron tunneling, the process needs electron tunneling between spatially well separated distant edge channels, which happens rarely and requires a long relaxation distance. Thus, the energy relaxation with energy exchange will first occur and be followed by relaxation with tunneling of electrons on a longer scale.

5. Energy Relaxation around Hotspots

Finally, we applied the method with QPCs to measure the local electronic states and the energy relaxation around a hotspot. One kind of hotspot is known to be formed next to a QPC when we apply a high bias voltage across the QPC. If the applied bias exceeds the potential barrier formed by the voltages of the QPC gates, electrons with high energy pass through the QPC and form hot electrons in the drain. If we set the conductance of QPC1 to $2e^2/h$ and apply high bias across QPC1, the hot electrons are formed in the inner edge channel. The electron distribution in the inner channel will be the Fermi distribution originating from O0 plus hot electrons with higher energies supplied by O1 (Fig. 4(a)). We measured the energy relaxation length around this hotspot with our method.

Fig. 3. (color online) (a) Schematic of the experimental setup to probe the energy relaxation with energy exchange. The conductance of QPC1 is set to $e^2/h$. The inner edge channel is connected to O0 and the outer edge channel is connected to both O0 and O1. The half of electrons in the outer edge channel is supplied by O1 and the remaining half by O0. We can create the two-step non-equilibrium energy distribution with two Fermi energies $\mu_0$ and $\mu_1$ in the outer edge channel by controlling $V_0$ and $V_1$. (b) $dV_n/dV_1$ as a function of $d$. Decay of $dV_n/dV_1$ is observed with the increase of $d$. The solid line is the result of fitting and the evaluated relaxation length $l_e$ is $3 \pm 1 \mu$m.

Fig. 4. (color online) (a) Schematic of the experimental setup to probe energy relaxation around a hotspot. We set the conductance of QPC1 to $2e^2/h$ and applied high bias across QPC1 to form a hotspot next to QPC1. The inner edge channel has the non-equilibrium electronic energy distribution formed by the hot electrons supplied by O1 through QPC1. (b) $dV_n/dV_1$ as a function of $d$. Decay of $dV_n/dV_1$ is observed. The solid line is the result of fitting and the evaluated relaxation length $l_h$ is $2 \pm 1 \mu$m.
utilizing QPCs and discuss the possible mechanism of the energy relaxation from the information of the obtained relaxation length.

Figure 4(b) is the obtained results of \( dV_n/dV_1 \) as a function of \( d \). We applied a high bias up to 10 mV on \( O_1 \), which exceeds the potential barrier formed by the QPC of sub meV, to create a hotspot next to QPC1. The \( dV_n/dV_1 \) abruptly decreases with \( d \) in this measurement. This reflects the increase of the electron temperature in the outer edge channel and there is energy relaxation on this length scale. The solid line in Fig. 4(b) is the best fit to the data with the relaxation length \( l_h \) of 2 ± 1\( \mu \)m. This value is comparable with \( l_c \) obtained in the case of the energy relaxation only with energy exchange between the edge states (Fig. 3). From this result, we can conclude that the possible mechanism of the energy relaxation on this length scale around the hotspot is the exchange of energy between edge states without electron tunneling.\(^{23}\)

6. Conclusions

In conclusion, we have measured the local electronic states and evaluated the energy relaxation length of the quantum Hall edge channels utilizing QPC probes. We confirmed the relaxation length with electron tunneling as > 30\( \mu \)m and the relaxation length with energy exchange as \( 3 ± 1 \mu \)m. By comparing these results with the previous experiments, we have checked the validity of our detection method with QPCs. We applied this method to measure energy relaxation around a hotspot and obtained the value of 2 ± 1\( \mu \)m. This revealed that the possible relaxation mechanism on this length scale around the hotspot is the energy exchange between edge channels.

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23) The relaxation length by electron tunneling will also decrease with application of the bias voltage exceeding the Landau level spacing\(^{24}\) at 4 T. But in our measurement, we observed short relaxation length even when the bias is smaller than 7 mV. So, we think the possible relaxation mechanisms will be the energy exchange between the edge states.
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