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Coupling between quantum Hall edge channels on opposite sides of a Hall bar

Ngoc Han Tu[a], Masayuki Hashisaka[a,b], Takeshi Ota[a], Yoshiaki Sekine[a], Koji Muraki[a], Toshimasa Fujisawa[b], Norio Kumada[a,*]

[a] NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi 243-0198, Japan
[b] Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8551, Japan

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ABSTRACT

We investigate the coupling between quantum Hall (QH) edge channels (ECs) located at opposite sides of a 50-μm-wide Hall bar by exciting a charged wavepacket in one EC and detecting time-dependent current in the other EC. In a QH state, the current shows a peak followed by a dip, demonstrating the existence of capacitive coupling across the incompressible two-dimensional electron system (2DES). The observed magnetic field dependence of the amplitude and time delay of the current suggests that the capacitance is affected by the presence of localized states. We also show that the dominant manner of the coupling changes gradually as the system changes between the QH and non-QH states.

1. Introduction

In a quantum Hall (QH) state, electrons immersed in a perpendicular magnetic field propagate in chiral channels along the periphery of the two-dimensional electron system (2DES). The chiral edge channels (ECs) are considered ideal one-dimensional (1D) channels and used to perform quantum transport experiments. Examples include electron interference experiments based on concepts derived from quantum optics [1–5]. An important difference from optics is the presence of the Coulomb interaction. It has been shown that interactions between co-propagating ECs located on one side of a sample and separated by a narrow incompressible strip induce decoherence [6,7] and energy relaxation [8,9]. ECs are also used to investigate properties of Tomonaga-Luttinger liquid [10–13]. In these experiments, interactions between two ECs close to each other were used to induce spin-charge separation [10,13] and charge fractionalization [11,12].

In contrast to these investigations of interaction effects between adjacent ECs, interactions between ECs on opposite sides of a standard Hall bar sample with a typical width of 10 μm are routinely ignored because of larger distance. However, high-frequency transmittance measurements have shown that interactions between ECs separated by ∼ 100 μm are not negligible [14]. Indeed, a recent experiment using a system composed of two ECs separated by etching has demonstrated that the strength of the interactions decreases slowly with the distance in logarithmic law, and it decreases only by a factor of three when the

distance increases by more than two orders of magnitude from 0.3 to 50 μm [12]. These results imply that the interaction across the bulk 2DES, which has been investigated for a narrow constriction [15,16], should be taken into account to better understand quantum transport even in a standard Hall bar sample.

In this work, we investigate how the electronic state of the bulk 2DES affects the interaction between ECs propagating on the opposite sides of a sample by time-resolved transport measurements. We used graphene sample with a width of 50 μm. We selectively injected a charged wavepacket into an EC on one side (EC1) and measured the current in ECs on both sides in the time domain through two ohmic contacts Det1 and Det2 connected to EC1 and the other EC (EC2), respectively. The existence of interactions is confirmed by the observation of finite current at Det2. In a QH state, the current at Det2 shows a peak followed by a dip as a function of time, while its time integration is zero. This indicates that the two ECs are capacitively coupled across the incompressible 2DES. The strength of the capacitive coupling varies with magnetic field even in the region with vanishing longitudinal resistance R_{xx}. We suggest that localized states inside the incompressible 2DES enlarge the coupling strength. In the non-QH state, on the other hand, the Det2 current becomes a single peak as expected for the conductive coupling through the compressible 2DES. For completeness, we carried out similar measurements using a 2DES formed in GaAs, which is often used in quantum transport experiments. In a GaAs sample, contributions of the capacitive and conductive couplings
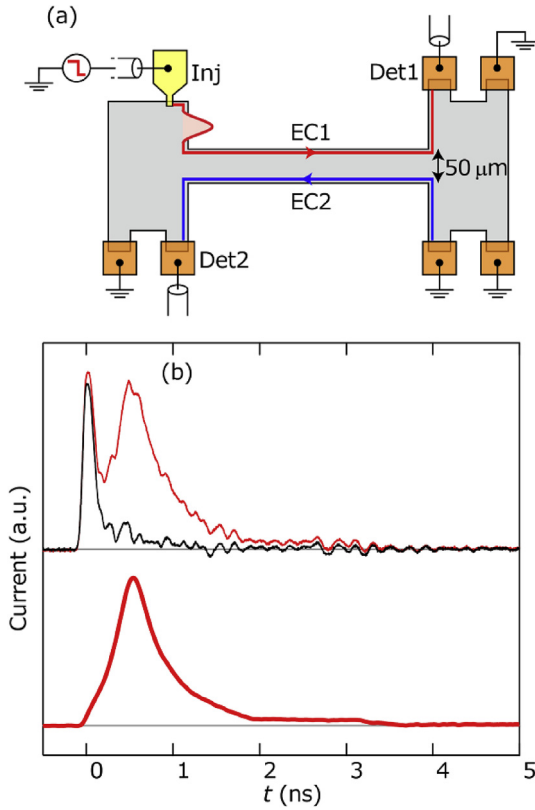

Fig. 1. (a) Schematic of a sample. An injection gate (yellow) and ohmic contacts (orange) are patterned on graphene (grey). High-frequency lines are connected to the injection gate and two ohmic contacts labeled Det1 and Det2. (b) Measured current as a function of t at Det1 at $B = 10$ T (red thin trace) and -10 T (black thin trace). By subtracting the current at $B = -10$ T from that at 10 T, crosstalk can be eliminated (red thick trace). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

oscillate following R_{xx}. These results indicate that presence of the inter-EC coupling is a common feature of QH systems.

2. Material and methods

Most of the data presented were obtained using graphene grown by thermal decomposition of a 6H-SiC(0001) substrate. Fig. 1(a) schematically shows the device structure and experimental setup. Graphene was etched to form a 50-μm-wide and 350-μm-long bar region. EC1 and 2 propagate along the top and bottom edges of the bar region, respectively. Six Cr/Au ohmic contacts were deposited on graphene. Two of them located at the downstream of EC1 and 2 from the bar region serve as Det1 and 2, respectively. After the formation of ohmic contacts, the surface of the graphene was covered with 100-nm-thick hydrogen silsesquioxane and 60-nm-thick SiO_2 insulating layers. An injection gate having a 10×10 μm^2 overlap with the patterned graphene was deposited on the insulating layer. The carriers are electrons, and the density is about 5×10^{11} cm^{-2}. The low-temperature mobility is about 12000 cm^2/V.

We also fabricated a similar device with 20-nm-thick GaAs/$Al_{0.3}Ga_{0.7}As$ quantum well. A 15-μm-wide and 350-μm-long bar region is formed by wet etching, and ohmic contacts were made by alloying with AuGeNi. The geometry other than the bar region is the same as that of the graphene sample. The electron density is 1.2×10^{11} cm^{-2}, and the low-temperature mobility is 2.1×10^6 cm^2/Vs.

Measurements were performed at 1.5 K for the graphene sample and about 100 mK for the GaAs sample. R_{xx} across the bar region was measured using a standard low-frequency lock-in technique. Magnetic

field B up to 10 T was applied from the back of the sample so that the chirality of ECs is clockwise at $B > 0$ T as shown in Fig. 1(a). A charged wavepacket excited by a voltage step with the rise time of about 100 ps applied to the injection gate propagates as 2D plasmons at $B = 0$ T or edge magnetoplasmons (EMPs) [17–22] at high B. From the rise time of the injection pulse, geometry of the injection gate, and the measured plasmon velocity, the width of the plasmon pulse is estimated to be a few hundred micrometers at Landau level filling factor $\nu = 2$ [12] and wider for larger ν. Plasmons reaching Det1 and Det2 are detected as time-dependent current using a sampling oscilloscope through an amplifier with 13.5 GHz bandwidth (model: Picosecond Pulse Labs 5840B). The red thin trace in Fig. 1(b) shows the measured current at Det1, which comprises the plasmon signal and unwanted crosstalk. We set the time origin $t = 0$ at the first peak of the crosstalk because it propagates with the speed of light and its time delay is negligible. The crosstalk component (black trace) can be obtained by measuring the current at inverted magnetic field $B = -10$ T, where the chirality of the ECs is reversed and excited charges do not arrive at Det1 and 2. Then, by subtracting the measured current at $B = -10$ T from those for $B \geq 0$, the crosstalk can be eliminated (red thick trace) [23]. The crosstalk is subtracted for all the current data plotted hereafter.

3. Results and discussion

Fig. 2(a) and (b) show color-scale plots of the current at Det1 and 2 (I_{Det1} and I_{Det2}), respectively, as a function of t and B. In the $\nu = 2$ QH state for $B \gtrsim 2$ T, where R_{xx} is vanishingly small [Fig. 2(c)], I_{Det2} shows a peak followed by a dip. We also plotted the integrated current in Fig. 2(d). Net current on Det2 obtained by $\int_0^{10 \, ns} I_{Det2} dt$ is almost zero, consistent with the vanishing R_{xx}. As discussed below, this behavior can be explained by a capacitive coupling across the incompressible bulk 2DES. Strength of the capacitive coupling can be evaluated by the area of the current dip obtained by $\frac{1}{2} \int_0^{10 \, ns} (|I_{Det2}| - I_{Det2}) dt$, which becomes a maximum at B close to the boundary to the non-QH state. In the non-QH state for smaller B, both I_{Det1} and I_{Det2} show a single peak. In this regime, $\int_0^{10 \, ns} I_{Det2} dt$ is finite, indicating that electrons are transmitted to EC2 as expected for the conductive coupling across the compressible bulk with finite R_{xx}.

We now focus on the results inside the QH effect regime ($B \gtrsim 2$ T). For epitaxial graphene grown on SiC substrate, charge transfer from the underlying substrate to graphene tends to pin the filling factor to $\nu = 2$, leading to exceptionally wide QH plateau [24,25]. This allows us to investigate the behavior inside the QH state in detail.

The appearance of a peak in I_{Det1} and a peak followed by a dip in I_{Det2} can be explained by the capacitive coupling between counter-propagating ECs in the bar region [11,12,26]. An EMP wavepacket with charge Q in EC1 induces charge $-rQ$ in EC2, and this forms a coupled EMP wavepacket in the bar region propagating to the downstream of EC1 [inset of Fig. 3(d)]. Simultaneously, because of the charge conservation, charge rQ is excited in EC2, which propagates to the downstream of EC2 and is detected by Det2 as a current peak. When the coupled EMP wavepacket arrives at the right end of the bar region, charge $-rQ$ in EC2 is reflected with induced charge r^2Q in EC1, while charge $(1 - r^2)Q$ is transmitted and appears as a current peak at Det1. The subsequent process at the left end leads to negative current with charge $-r(1 - r^2)Q$ at Det2. The value of r ($0 < r < 1$) approaches unity in the strong inter-EC coupling limit. Note that after similar multiple processes, the total charge arriving at Det1 and 2 should eventually become Q and zero, respectively.

In Fig. 3(a) and (b), I_{Det1} and I_{Det2} for several values of B are plotted, respectively. At $B \gtrsim 4$ T, where the system is deep in the QH regime, the current profile does not show significant B dependence. For smaller B, the amplitude and time position of the current peaks and dip vary with