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Electrostatic tuning of charge velocity in a quantum Hall edge channel defined along the perimeter of a gate metal

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1. Introduction

Quantum Hall edge channels (ECs), which are formed along the edge of a two-dimensional electron system (2DES) in high magnetic field, show unique transport characteristics, such as chiral charge transport [1], coherent electron transport [2], and interacting electrons described by edge magnetoplasmon (EMP) modes [3] or the Tomonaga-Luttinger (TL) liquid theory [4]. Radio-frequency (RF) charge transport measurements allow us to study dynamical characteristics that cannot be investigated by conventional dc transport characteristics. One of the most fundamental characteristics is the velocity of charge density wave travelling in the EMP mode [3,5]. The variation of the charge velocity can be understood by considering electrostatic environment around the channel. When the channel is formed along a bare etching step of a sample (bare EC), Coulomb interaction of the travelling charge accelerates the charge transport, giving a typical velocity of about 1.5x10^6 m/s at the bulk filling factor ν = 2 in a typical AlGaAs/GaAs heterostructure [6]. In contrast, when the EC is covered with a uniform surface metal (metallized EC), partially screened Coulomb interaction gives much lower velocity of about 1.5x10^5 m/s at the same condition [6]. Moreover, when the EC is formed along the perimeter of a gate metal pattern (gate-defined EC), one can tune the velocity by changing the voltage applied to the gate in a typical range of 2 – 5 x10^5 m/s [7]. It should be noted that these charge velocities are significantly larger than the Fermi velocity of 1.6x10^4 m/s obtained from electron wave interference experiments [2]. In this way, the Coulomb interaction plays a significant role in charge velocity. Especially in the view of plasmonics applications, tunable velocity with external voltages will be useful for designing plasmonic circuits with ECs.

In this work, we investigate how the charge velocity changes with the electrostatic environment involving nominally-insulating bulk region and the gate metal. The charge velocity is investigated by measuring the phase shift of RF signal travelling through a gate-defined EC in a quantum Hall device. We find that the charge velocity depends on both the dc source voltage and the gate voltage, but the source voltage has stronger dependence. The velocity can be understood in terms of the channel capacitance describing the interaction to the bulk region and the gate metal. Our finding will be useful in tuning the charge velocity in a wider range, as well as in probing electronic states in the bulk region.

2. Tunable charge velocity with external voltages

Figure 1 (a) shows a schematic RF measurement setup for a quantum Hall device fabricated in an AlGaAs/GaAs heterostructure. The 2DES with electron density of 2.4x10^{11} cm^{-2} and low-temperature mobility of 2.1x10^6 cm^2/Vs shows clear quantized Hall conductance and zero longitudinal resistance R_{xx} ~ 0 in the vicinity of integer filling factors ν = 2 and 4 at 1.5 K. Following experiments were performed at ν = 2.1 (magnetic field of B = 4.7 T and corresponding cyclotron energy of $\hbar\omega_C$ = 7.8 meV), where R_{xx} is nominally zero within our experimental limit. We measure RF transport from the source through the EC to the drain. The EC consists of bare ECs on the source and drain sides, and the gate-defined EC of the interest in the central region. The gate-defined EC is formed when the gate voltage V_G is sufficiently negative (V_G < -0.3 V), but the EC is shortcut under the gate (indicated by the dashed line) when V_G = 0.

A vector network analyzer together with a preamplifier is used to measure the phase acquired from the input to the output. The phase acquired only in the gate-defined EC, $\Delta\theta$,

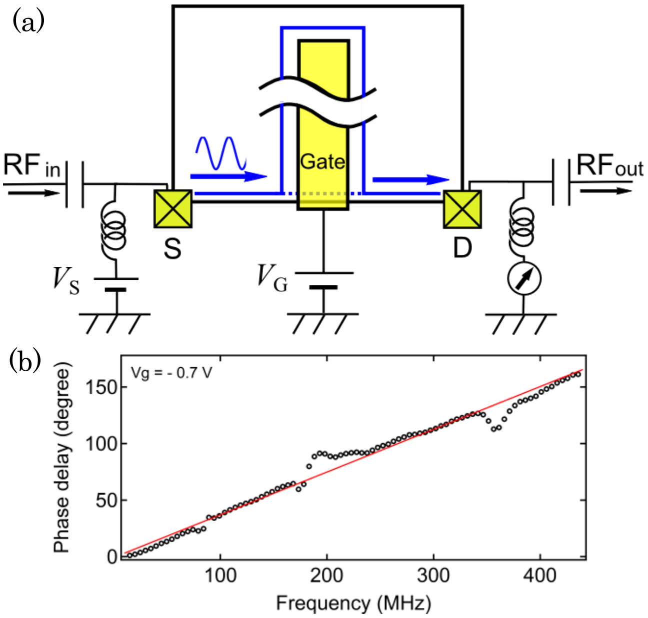

Fig. 1 (a) Schematic of a quantum Hall device with a RF transport measurement setup. A gate defined EC is formed along the perimeter of the gate pattern. (b) Frequency dependence of the phase acquired in the gate defined EC.

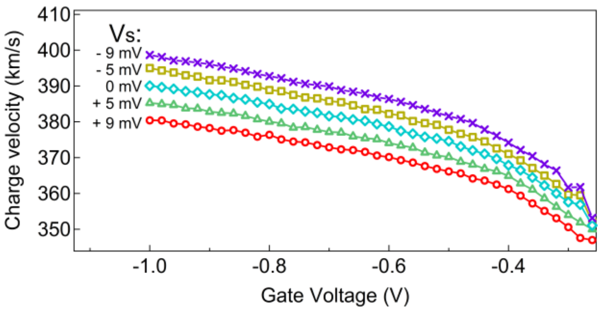

Fig. 2 Charge velocity in the gate-defined EC as a function of V_G for various V_S. Although V_S was swept in the narrow range (± 9 mV), V_S has stronger dependence as compared to V_G.

is obtained by subtracting the phase measured at $V_G = 0$ (shortcut). Figure 1(b) shows a typical frequency depend ence of $\Delta\theta$. The linear dependence implies a linear dispersion relation expected for screened ECs [8]. Some peak structures in Fig. 1(b), which might come from unwanted RF resonances, are disregarded. The velocity, v, is obtained from the relation $v = 2\pi fL/\Delta\theta$, where $L = 400$ μm is the length of the gate defined EC.

Figure 2 summarizes the dependence of the velocity for various source voltage, V_S, and gate voltage, V_G. The V_G dependence is consistent with previous studies [7]. Namely, as V_G is made more negative, the EC is more separated from the gate metal (less screening effect), giving higher velocity as observed. If the EC with the potential V_S and the gate metal with the potential V_G are all the ingredients that describe the velocity, V_S should have the same dependence on v. The V_S dependence, however, has 5- to 20-times larger effect for the same voltage swing. Such asymmetric dependence requires another ingredient, the bulk region, to describe the charge velocity [9].

Figure 3(a) shows a schematic cross section around the EC separated from the bulk region by an incompressible stripe of the width a. The bulk region does not contribute to the dc transport as confirmed by vanished longitudinal resistance. However, local charge transfer within disordered potential contours is allowed, and thus charge density wave (plasmon) can be excited. When the bulk charge is interacted with the edge charge, the velocity can be affected. The interaction can be described with coupling capacitances, C_B to the bulk region as well as C_G to the gate, by assuming that the bulk region is conductive for RFs. The charge velocity can be written as $v = \sigma_{xy}/C_{ch}$ with the Hall conductance σ_{xy} and the channel capacitance $C_{ch} = C_G + C_B$ in the simplified EMP model. Since the edge and bulk region is separated by a narrow incompressible stripe, C_B can be significant especially when C_G becomes smaller at large negative V_G. The observed large V_S dependence can be explained with the potential profiles for the first and second Landau levels schematically shown in Fig. 3(b). When finite V_S is applied with other Ohmic contacts grounded, the potential difference between edge and bulk region, V_{SB}, can take between 0 and V_S depending on the charge balance in the bulk region. The previous report for metallized ECs

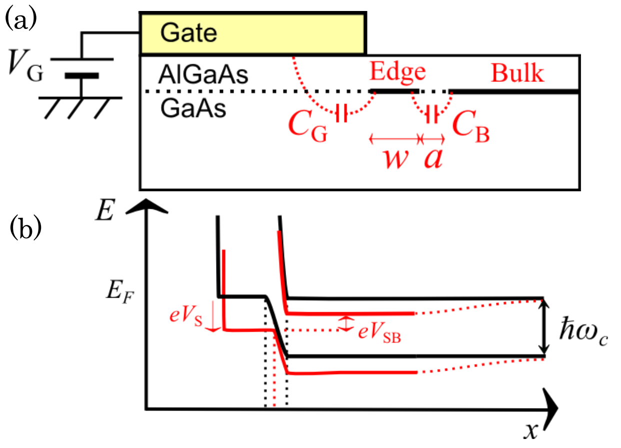

Fig. 3 (a) Schematic cross section around the edge channel (b) Schematic energy diagram of the edge and bulk region separated by an incompressible stripe.

indicates that V_{SB} varies depending on ν [9]. Since the width of the incompressible stripe, a, is given by

$$a = a_0\sqrt{1 - eV_{SB}/\hbar\omega_C}\ , \qquad (1)$$

where a_0 is the width at $V_S = 0$ [1], C_B should be sensitive to V_S. This crude model qualitatively explains the strong V_S dependence through C_B and weak V_G dependence through C_G.

3. Summary

Charge velocity of EMP mode in a gate-defined EC in quantum Hall regime is investigated by phase sensitive measurement of RF transport. We find strong source-voltage dependence and weak gate-voltage dependence on the velocity, which can be understood by considering conductive bulk region for high frequencies. Such electrical tuning of charge velocity will be useful for plasmonics applications.

Acknowledgments

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