Field and Density Dependence of Edge Magnetoplasmon Transport in a Quantum Hall System

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Abstract. We investigate edge channel properties in integer quantum Hall regime through time-of-flight measurements of edge magnetoplasmons (EMPs). EMPs are injected by applying a voltage pulse to an Ohmic contact and detected by applying another voltage pulse to a quantum point contact. By controlling the time interval between the injection and detection pulses, the velocity of EMPs is determined. The width of edge channels calculated from the velocity of EMPs oscillates with filling factor: as the filling factor is decreased to an integer, the width increases almost by one order of magnitude from ∼0.3 to ∼3 µm. Furthermore, we find that the width at a fixed filling factor increases with decreasing electron density in the bulk two-dimensional system.

1. Introduction

In a quantum Hall (QH) system, the interior of the two-dimensional electron system (2DES) is incompressible and the current flows in one-dimensional edge channels. Collective charge density excitations in edge channels are called edge magnetoplasmons (EMPs) [1]. EMPs have been investigated extensively both theoretically [1–3] and experimentally [4–7]. In a sample with a front gate, oscillations of the width l of edge channels as a function of the filling factor ν has been detected as the oscillations of the velocity of EMPs [5, 7]. Recently, the velocity control of EMPs has been demonstrated by changing the degree of screening by a front gate [8].

In this work, we investigate effects of electron density on the velocity of EMPs in a sample with a front gate. We carried out time-of-flight measurements of EMPs for three values of the density. For all the densities, the velocity takes minima at integer ν. At a fixed ν, the velocity decreases with decreasing density. These results show that l depends not only on ν but also on the density.

2. Experiments

The sample used contains a 20-nm-wide GaAs quantum well. The 2DES is 160 nm below the surface. The low-temperature mobility is 2.1 × 10^6 cm^2/Vs at an as grown density of 1.27 × 10^{11} cm^{-2}. A schematic view of the sample structure and the experimental setup are shown in the inset of Fig. 1. A quantum point contact (QPC) was fabricated close to the drain contact D1. A front gate crosses the sample between the source contact S and the D1 contact.
For the time-of-flight measurement, the DC bias for the source and drain contacts is 0 V and the QPC is set close to the pinch-off condition. An EMP pulse is injected by applying a square voltage pulse to the S contact; the time width and the amplitude of the pulse is 5 ns and 5 mV, respectively. To detect the EMP pulse, another voltage pulse with 1 ns in time width and 100 mV in amplitude is applied to the QPC. If the QPC is open when the EMP pulse is arrived, EMPs are detected as a current through the D1 contact; otherwise they are reflected by the split gates and collected by the drain contact D2 [8]. By controlling the time interval \( t \) between the injection and detection pulses, a profile of the EMP pulse is obtained. The rising time of the pulses is 20 ps at the output of the pulse generator and increases to 50 ps at the sample; in the sample, the rising time is further increased by various mechanisms including high Ohmic resistance, capacitive coupling between EMPs and the front gate, and nonlinear dispersion of EMPs. The repetition time is 60 ns. All measurements are performed at 1.5 K.

3. Results and discussions
First, we show results of three-terminal DC measurements, demonstrating the chirality of the edge current. Figure 1 shows the current through the D1 contact as a function of the magnetic field \( B \) for the front gate bias \( V_{fg} = 0 \) V, where the electron density in the gated region is \( n = 1.08 \times 10^{11} \text{cm}^{-2} \). Constant biases of 1.0 mV and −0.2 mV are applied to the S and D2 contacts, respectively. When a perpendicular field is applied in the direction pointing into the page, the current shows peaks in the QH effect regime. In this case, the chirality of the edge channel is anticlockwise, where the current flows in the direction S → D1 → D2 → S. On the other hand, when the perpendicular field is in the opposite direction, the current flows clockwise and shows minima in the QH effect regime.

For the time-of-flight measurements, the chirality is fixed to be anticlockwise, so that EMPs injected from the S contact propagate along the lower boundary to the contact D1. The length of the edge channel between the S contact and the QPC in the regions with and without the front gate is 480 \( \mu \)m and 937 \( \mu \)m, respectively. Figure 2 presents results of time-of-flight measurements for \( B = 0.2 \) T and several magnetic fields around \( \nu = 1 \) at \( V_{fg} = 0 \) V. For \( B = 0.2 \) T, where injected electrons propagate as two-dimensional bulk plasmons in the 2DES rather than EMPs, the current start to rise at \( t \sim 0 \). For larger fields, where the edge channels are well developed, current rises with a time delay, which corresponds to the traveling time of EMPs from the S contact to the QPC along the edge channel. Around \( \nu = 1 \), the delay time increases as \( \nu = 1 \) is approached from lower field. At the same time, the EMP pulse becomes broad; for the field slightly larger than that for \( \nu = 1 \), the EMP pulse becomes broader than the repetition time 60 ns.
Figure 2. Current as a function of the time interval \( t \) between the injection and detection pulses for a low field \( B = 0.2 \) T and around \( \nu = 1 \) at \( n = 1.08 \times 10^{11} \) cm\(^{-2}\). Data for \( B = 0.2 \) T is reduced by a factor of three. Arrows represent the delay time \( t_d \). Traces are vertically offset for clarity.

Figure 3. (a) Delay time \( t_d \) of EMPs as a function of the magnetic field for three values of the electron density in the gated region. Arrows represent the field for \( \nu = 1 \). (b) Velocity of EMPs as a function of filling factor. Inset shows the velocity at \( \nu = 2.63 \) as a function of \( n \).

We carried out similar measurements over a wide range of the magnetic field and for three values of \( V_{fg} \). Figure 3(a) shows the delay time \( t_d \) of the EMP pulse for three values of \( n \) as a function of the magnetic field; \( t_d \) is defined as the maximum of the derivative of the EMP pulse (arrows in Fig. 2). For all \( n \), \( t_d \) increases as the field is increased to the value for even integer \( \nu \) or \( \nu = 1 \). For slightly larger field, \( t_d \) can not be determined because the EMP pulse is too broad. Note that \( t_d \) contains contributions both from the gated and ungated regions; by a similar time-of-flight measurement using an ungated sample, we confirmed that the velocity of EMPs in the ungated region is 10 times faster and depends monotonically on the magnetic field (not shown here) as shown in Ref. [4]. Accordingly, \( t_d \) mainly reflects the contribution from the gated region.

We subtracted the contribution of the ungated region from \( t_d \) and calculated the velocity of EMPs in the gated region. Figure 3(b) shows the velocity as a function of \( \nu \). The velocity
Figure 4. Width of the edge channel calculated by using Eq.(1) as a function of the filling factor.

shows, in addition to the asymmetric oscillations as a function of \( \nu \), a monotonic increase with increasing \( n \) [an example is shown in the inset of Fig. 3(b)].

Now, we calculate the width of the edge channels \( l \) using the equation [3, 6],

\[
v = \frac{e^2 \nu_{in} d}{\hbar \epsilon_0 \epsilon_l},
\]

where \( v \) is the velocity of EMPs, \( d = 160 \text{ nm} \) is the distance between the 2DES and the front gate, \( \epsilon_0 \epsilon \) is the dielectric constant of GaAs. \( \nu_{in} \) is the filling factor of the innermost incompressible strip, e.g., \( \nu_{in} = 1 \) for \( 1 \leq \nu < 2 \). Figure 4 shows the calculated \( l \) as a function of \( \nu \). \( l \) varies over a wide range between 0.3 and 3.5 \( \mu \text{m} \). The asymmetric oscillations of \( l \) as a function of \( \nu \) has been observed [5] and explained as due to a periodic change in the position of the innermost incompressible stripe, which separates edge channels from the bulk 2DES. For instance, as \( \nu \) is decreased from 2.5, the innermost incompressible stripe with \( \nu_{in} = 2 \) moves toward the interior of the 2DES, leading to the increase in \( l \). When \( \nu \) becomes smaller than 2, the \( \nu_{in} = 2 \) incompressible stripe vanishes and then the \( \nu_{in} = 1 \) incompressible stripe becomes the boundary between the edge channel and the 2DES, resulting in the abrupt decrease in \( l \) [9]. On the other hand, at a fixed \( \nu \), \( l \) increases with decreasing \( n \). This indicates that the slope of the edge potential is slower for smaller \( n \). This is consistent with an electrostatic calculation [10] of edge states.

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References
[1] Volkov V A and Mikhilov S A 1988 Zh. Eksp. Theor. Fiz. 94 217
[2] Aleiner I L and Glazman L I 1994 Phys. Rev. Lett. 72 2935
[3] Johnson M D and Vignale G 2003 Phys. Rev. B 67 205332
[4] Ashoori R C, Stormer H L, Pfeiffer L N, Baldwin K W and West K 1992 Phys. Rev. B 45 3894
[5] Zhitenev N B, Haug R J, v Klitzing K and Eberl K 1994 Phys. Rev. B 49 7809
[6] Zhitenev N B, Haug R J, v Klitzing K and Eberl K 1995 Phys. Rev. B 52 11277
[7] Ernst G, Zhitenev N B, Haug R J and von Klitzing K 1997 Phys. Rev. Lett. 79 3748
[8] Kamata H, Ota T, Muraki K and Fujisawa T 2010 Phys. Rev. B 81 085329
[9] Ahlswede E, Weitz P, Weis J, von Klitzing K and Eberl K 2001 Physica B 298 562
[10] Chkovskii D B, Shklovskii B I and Glazman L I 1992 Phys. Rev. B 46 4026