Quantum Hall Edge States Probed by Plasmon Excitations

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ABSTRACT

Microwave transmission through a coplanar waveguide placed on the surface of a wafer containing a two-dimensional electron gas has been employed to investigate the excitations of edge-magnetoplasmons at the integer quantum Hall edge states. The edges are electrostatically introduced by applying a negative bias to a metallic gate. The excitation frequency is found to vary with the gate bias, reflecting the variation in the distance of the edges from the gate and in the spatial distribution of electrons within the edge states. The measurement of the microwave transmission, or equivalently of the concomitant thermoelectric voltages due to microwave heating, has thus been shown to be a powerful tool to examine the edge states in the quantum Hall effect.

INTRODUCTION

Edge states in the quantum Hall effect

The quantum Hall effect is arguably the most remarkable phenomenon that takes place in a two-dimensional electron gas (2DEG) subjected to a strong magnetic field. The integer quantum Hall effect manifests itself as a series of plateaus in the Hall resistance R_{xy}, accompanied by a vanishing diagonal resistance ($R_{xx} = 0$). The value of R_{xy} at a plateau is quantized, with extremely high precision, to a value determined solely by fundamental physical constants ($R_{xy} = R_K/p$, $p = 1,2,3,\ldots$, with $R_K = h/e^2 = 25812.807\ \Omega$ representing the von Klitzing constant), and thus is employed as the standard for electrical resistance in metrology. The quantized R_{xy} and the vanishing R_{xx} are basically attributable to the formation of dissipationless one-dimensional chiral channels at the edge of the sample, dubbed the quantum Hall edge states, while leaving the interior of the sample insulating (bulk localized state). The edge states have been a subject of longstanding interest, not only for their crucial role in the quantum Hall effect but also for their potential application as channels capable of carrying charges and spins without backscattering. As suggested by the co-presence of the (topologically protected) chiral edge states and the bulk insulating states, the quantum Hall effect can be categorized as a class of the topological insulators, the earliest-known species among the topological insulators constituting a group of materials currently attracting a surge of interest.

Coplanar waveguide

A coplanar waveguide (CPW) is a type of planar transmission line, composed of a central electrode flanked by side electrodes, corresponding to the center core and the metallic shield in a coaxial cable, respectively. A CPW placed on the surface of a GaAs/AlGaAs 2DEG wafer (Fig. 1a) has been widely employed to experimentally study various high-frequency phenomena that take place in the 2DEG. The microwave propagating through the CPW interacts with the 2DEG buried in the wafer. The interaction enables us to elicit a wealth of information on the properties of the 2DEG. This experimental technique has been applied thus far to studies of high-frequency conductivity and of the excitation of varieties of many-body states. Typical examples of the latter are the pinning modes of various magnetic-field-induced electron-solid-like states, including the Wigner crystal, bubble and stripe phases.

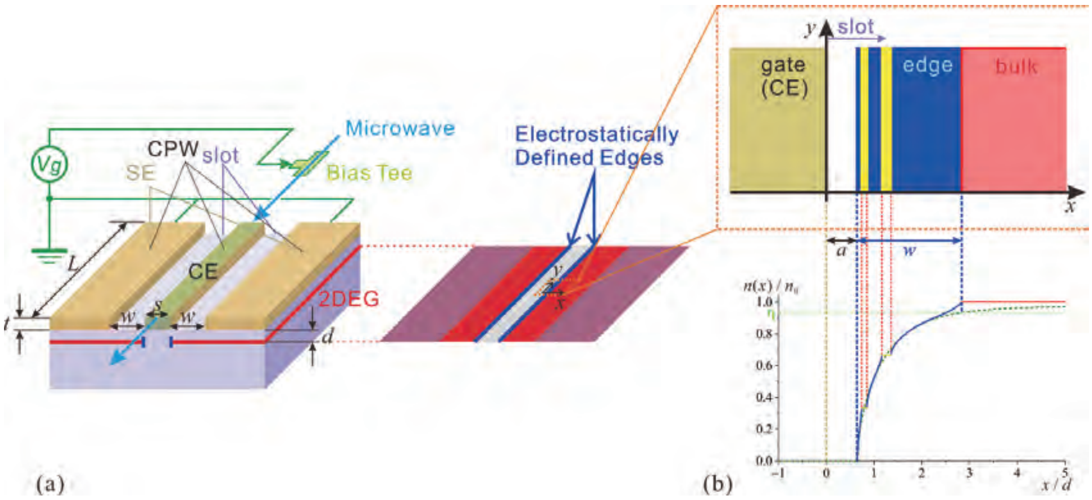

Fig. 1: (a) Schematic drawing of the device used in the measurement. 2DEG: two-dimensional electron gas. CPW: coplanar waveguide. CE: central electrode of the CPW. SE: side electrodes of the CPW. Edges are introduced into the slot regions of the CPW by applying a negative bias V_g to the CE and thereby depleting the underlying electrons. The microwave transmission through the CPW and the thermoelectric voltages between the Ohmic contacts (not shown) generated by microwave heating are measured with this device. (b) Closer view around the edge. (Top) Top view. (Bottom) Electron density profile $n(x)$. a and w represent the depletion width (the distance between the CE and the edge state) and the width of the edge state, respectively.

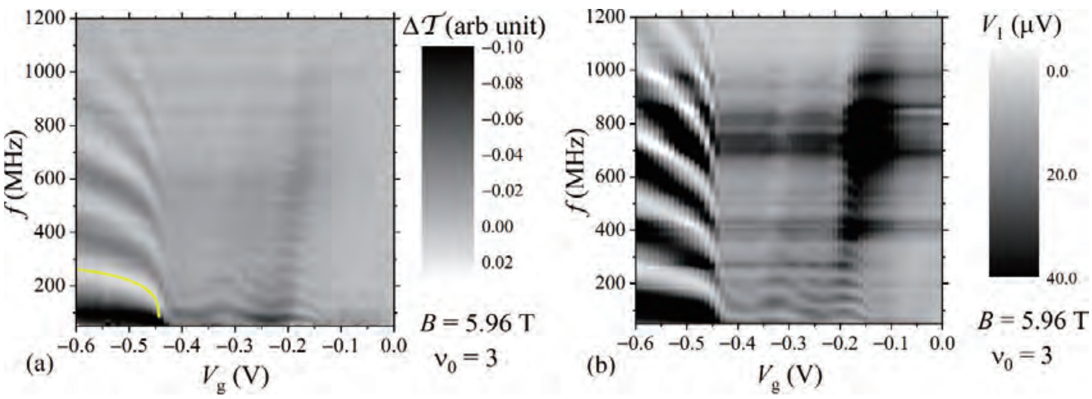

Fig. 2: Grayscale plot of the bias V_g and frequency f dependence of the microwave transmission $\Delta\mathcal{T}$ (a) and thermoelectric voltage V_1 (b), at $\nu_0 = 3$ integer quantum Hall state. (The magnetic field is adjusted for the electrons to fill exactly three Landau levels.) Excitations of the edge-magnetoplasmons are observed as peaks (lighter tone) in both (a) and (b). The fundamental mode and the higher harmonics are observed. The thick yellow curve in (a) depicts calculated excitation frequency of the edge-magnetoplasmons vs. V_g for the fundamental mode.

PROBING EDGE STATES BY EDGE-MAGNETOPLASMONS

Detection of edge-magnetoplasmons

In the present study, the CPW measurement technique is applied in the exploration of the quantum Hall edge state, making use of the excitation of the plasmons at the edges. Noting that the method possesses high sensitivity to the 2DEG located beneath the slot of the CPW, edges are introduced to this region by applying a negative bias to the central electrode of the CPW (Fig. 1). Owing to the high sensitivity of this measurement setup, edge-magnetoplasmons, the plasmons excited at the edge states subjected to a magnetic field and having a much lower excitation frequency compared to the bulk counterparts, are clearly observed with the microwave transmission and also with the thermoelectric voltage generated by the accompanying microwave heating (Fig.2). The frequency of the excitation provides us with information on the location of the edge state (relative to the central electrode) and the width of the edge states (Fig. 1b).

Gate voltage dependence of the excitation frequency

By decreasing the bias V_g (< 0) applied to the central electrode, the electron density beneath the central electrode gradually decreases. At a threshold value V_{dpl} specific to the 2DEG wafer, the electrons are completely depleted and the edge of the 2DEG is formed at the brink of the slot region close to the central electrode. By further reducing the bias V_g ($V_g < V_{dpl}$), the edge state is repelled farther away from the central electrode. The bias V_g also alters the spatial distribution of the electron density near the edge of the 2DEG ($n(x)$ in Fig. 1b). The present study reveals that the excitation frequency of the edge-magnetoplasmons also varies with V_g. The distance between the central electrode and the edge state a and the electron density profile $n(x)$, hence the width of the edge state w, can be calculated using electrostatics. With the values of a and w thus obtained, one can, in turn, calculate the excitation frequency of the edge-magnetoplasmons. The experimentally observed excitation frequencies are found to be in excellent agreement with the calculated ones. The measurement of the excitation frequencies of the edge-magnetoplasmons has thus been proven to be a tool capable of probing the real-space distribution of the quantum Hall edge states. The change of the excitation frequency observed in the present study results from the variation in the plasmon propagation velocity owing to the changes in a and w. These changes, however, do not affect R_{xx} and R_{xy} in the quantum Hall effect mentioned above. The present measurement thus allows us to investigate fundamental properties of the quantum Hall edge states inaccessible by the ordinary resistance measurements. The knowledge regarding plasmon excitations obtained in the present study will be of value in attempts to control plasmons, of which applications in optical devices are considered under the terminology of "plasmonics".

Acknowledgements: This work was supported by JSPS KAKENHI Grant Numbers JP26400311 and JP17K05491.

References

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Published in the June 2018 issue of the *Journal of the Physical Society of Japan* as an Editor's Choice article.

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