Magnetocapacitance and the Edge State of a Two-Dimensional Electron System in the Quantum Hall Regime

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The magnetic field dependence of the capacitance of a GaAs/AlGaAs heterostructure through a two-dimensional electron system (2DES) is measured in the quantum Hall regime. The capacitance minima at the Hall plateaus are determined not by the 2DES area under the gate but by the edge length of the 2DES, which cannot be explained by an existing interpretation of the magnetocapacitance, where the capacitance is directly related to the 2DES density of states. We suggest an alternative model: the bottom values are essentially determined by the edge current carrying area. The widths of the current channels are estimated and compared with recent theoretical and experimental estimates.

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Magnetocapacitance investigations of a two-dimensional electron system (2DES) have been made by many researchers [1-5]. The capacitance shows quantum oscillations and minima at the quantum Hall plateaus. There have been mainly two interpretations about the quantum oscillations, that is, a density of states (DOS) model and a resistive plate model. In the DOS model [3,4], the measured capacitance consists of series capacitance of the barrier layer capacitance between the 2DES and the metal gate (C_b), and the channel capacitance, which is proportional to the DOS of the 2DES at the Fermi level E_F. When E_F is in the localized state between the Landau levels, the DOS becomes small and the minima of the measured capacitance are observed. In the resistive plate model [2], the total capacitance is determined by the distributed system of C_b and the resistive plate with σ_{xx}. The minima of the capacitance are due to the minima of σ_{xx}, when E_F is between the Landau levels. Since the samples with the Corbino geometry, where there are no edge states, are used in the resistive plate model, there is no influence of the edge state [6,7].

The concept of the edge state has attracted significant attention recently. It can explain a lot of curious magnetotransport properties in a 2DES such as the nonscaling four-terminal resistance with sample size [8], the nonlocal resistance [9,10], and the influence of extra probes on the magnetoresistance [11,12]. We have measured the magnetocapacitance of a GaAs/AlGaAs heterostructure with various shapes of the 2DES in order to investigate especially the roles of the edge state on the magnetocapacitance.

The samples used in this study were made from the GaAs/AlGaAs heterostructure wafers. The thicknesses of nondoped AlGaAs, doped AlGaAs, and the GaAs cap layer were 200, 600, and 200 Å, respectively. The electron carrier concentration and mobility of the wafers were $N_s = 2.8\times10^{11}$ cm^{-2} and $\mu = 3.7\times10^5$ cm^2/V s at 0.5 K, respectively. The sample used in the magnetocapacitance measurement was fabricated by the wet chemical etching and uv lithography techniques. The Schottky gate was formed by evaporating Au on the GaAs cap layer and the electrode was made by alloying the AuGe/Ni/Au layer. A schematic view of the sample is shown in Fig. 1(a). The differential capacitance with

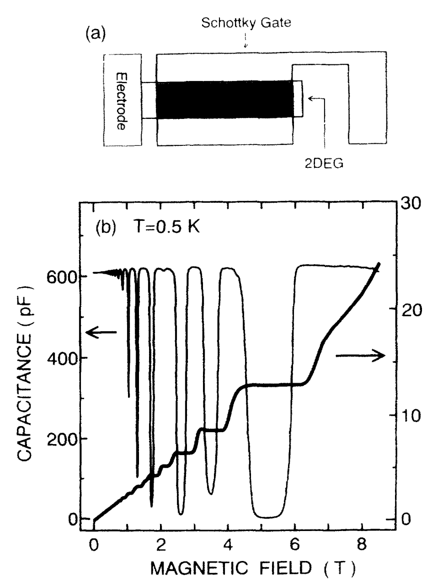

FIG. 1. (a) Schematic view of samples used in magnetocapacitance measurement. (b) Magnetocapacitance and Hall resistance measured in the same wafer. The gated area is 0.4×1.4 mm^2.

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respect to the gate voltage between the electrode and the gate was measured by a capacitance bridge (Andeen-Hagerling 2500 A) with a modulation frequency of 1 kHz at 0.5 K. The differential capacitance is abbreviated to capacitance. The gated area (S) is defined as the area of the 2DES which is covered with the Schottky gate as shown by the hatched region in Fig. 1(a). The modulation voltage amplitude (1 mV) was small enough to have no influence on the signal. Magnetic fields up to 8 T were applied perpendicularly to the plane of 2DES. In Fig. 1(b), a typical magnetocapacitance (real part) is shown together with the Hall resistance, which was measured in a Hall bar sample made from the same wafer. The capacitance shows minima at the Hall plateaus. The measured capacitance at zero magnetic field agrees very well with that expected for a two-plate capacitor (C_b) in the measured geometry. The capacitance shown is the corrected one, after the stray capacitance is subtracted from the measured one. The stray capacitance (2-3 pF) was estimated from the capacitance at the negative gate voltage to be enough to deplete the two-dimensional electron gas beneath the gate. It was confirmed that the stray capacitance is independent of magnetic field up to 8 T. The imaginary part of the capacitance was measured simultaneously; it becomes negligibly small at the minima of real capacitance of $\nu=2$ and 4 as reported in other papers [2,5]. The temperature dependence of the capacitance minima was also measured between 80 mK and 10 K [13]. The capacitance practically levels off below 0.5 K and tends to drastically increase above 0.5 K, probably because of an increase of σ_{xx}.

In order to examine whether the magnetocapacitance is related to the DOS of the 2DES as predicted from the DOS model, we measured the capacitance of the samples with different gated areas and with the same longitudinal edge length of the gated area as shown in Fig. 2(a). The capacitance at zero magnetic field is proportional to the gated area; however, the bottom values of the capacitances are almost the same. In Fig. 2(b), we plot the bottom values at various filling factors of Landau levels ν with respect to the gated area. This result cannot be explained by the DOS model, where the minima of the capacitance must be proportional to the gated area. Next, we measured the capacitance with different edge lengths [$L_e=2N(2a+2b)=2nL$ with $n=1$, 2, 4, and 8] due to fins and with the same sample length ($L=1400\ \mu$m) and width ($D=400\ \mu$m) as shown in Fig. 3(a), where $N=L/2b=35$ is the number of fins. The bottom capacitance values become larger by more than several times with the edge length, although the capacitance at zero magnetic field differs by at most 35%. The capacitance difference at zero field is due to the increment of gated areas by the extra fins. In Fig. 3(b), the bottom values at various ν are plotted with the edge lengths. The bottom values at $\nu=2$ and 4 are found to be nearly proportional to the edge lengths. It is clearly evidenced that the capacitance at the Hall plateaus is governed by the "edge."

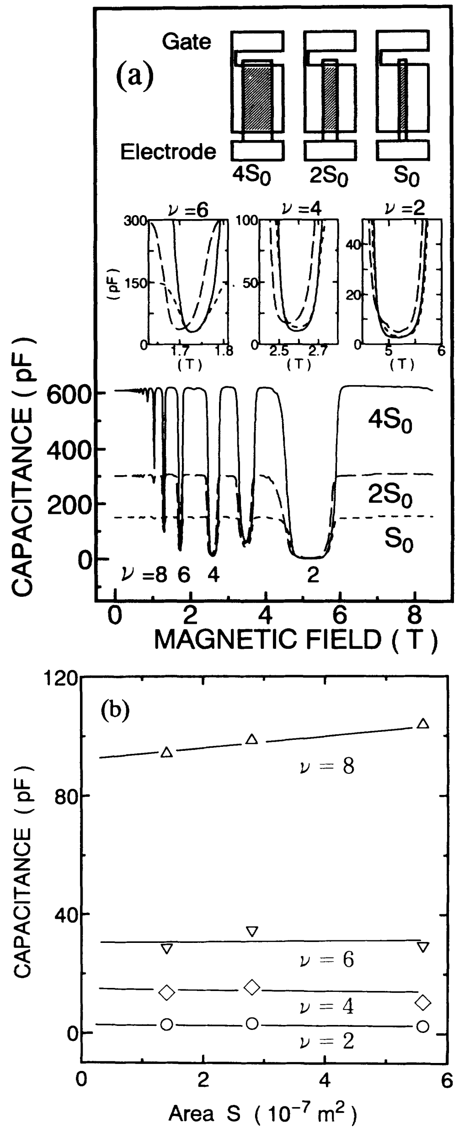

FIG. 2. (a) Magnetocapacitance of the samples with various gated areas and the same edge length of the gate as shown schematically in upper inset. The area S_0 is 0.1×1.4 mm^2. Lower insets are closeups near the capacitance minima at $\nu=2$, 4, and 6. (b) Bottom values of magnetocapacitance at various filling factors (ν) are plotted with respect to the gated area. Bottom values are nearly independent of the gate area. Solid lines are provided to guide the eye.

A solution of the Poisson equation in a GaAs/AlGaAs heterostructure yields [4]

$$e\phi_g=(e^2d_b/\varepsilon_b)N_s+E_F+K\ , \qquad (1)$$

where ϕ_g is an electric potential of the gate, d_b the thickness of the barrier layer (1000 Å), the ε_b the effective dielectric constant of the barrier layer ($\varepsilon_b=12.3\varepsilon_0$ in this study), and K comes from a term due to fixed charges in the barrier layer and barrier heights at interfaces. At low temperatures, carriers in the barrier layer are frozen out,

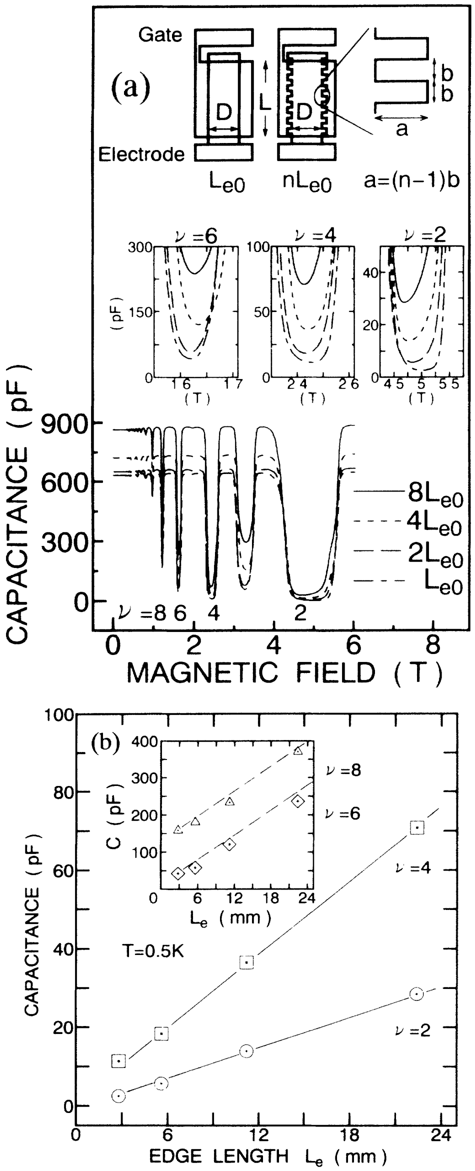

FIG. 3. (a) Magnetocapacitance of the samples with various edge lengths ($L_e = 2nL$) due to fins as shown schematically in upper inset. Main sample length L, width D, and fin width b are 1400, 400, and 20 μm, respectively. Fin length a is $(n-1)b$ with $n = 2,4,8$. Lower insets are close-ups near the capacitance minima at $\nu = 2$, 4, and 6. (b) Bottom values of magnetocapacitance at various ν are plotted with the edge lengths. Bottom values at $\nu = 2$ and 4 are proportional to the edge length. Solid lines are provided to guide the eye. The broken line in the inset is the calculated one (see text).

and K is regarded as a constant. The (differential) capacitance (C) is given as

$$1/C = dV_g/dQ = d(\phi_g - E_F/e)/d(SeN_s) = d_b/S\varepsilon_b\,, \quad (2)$$

where V_g is the gate voltage, Q the total charge in 2DES, and S the gated area. It should be noted that V_g is not ϕ_g but $\phi_g - E_F/e$. If one would set $V_g = \phi_g$, $1/C$ might be proportional to $dE_F/dN_s = 1/D(E_F)$, where $D(E_F)$ is the DOS of the 2DES at E_F. As seen from Eq. (2), the capacitance is determined by the geometry of the capacitor (d_b and S) and it seems that the capacitance is independent of magnetic fields.

At the ideal quantum Hall plateau ($\sigma_{xx} = 0$), the bulk state is fully localized and the electron conduction occurs only through the edge states at E_F. The induced charge caused by a change of V_g in the 2DES is not supplied to the bulk area but to the edge state region from the electrode. At the quantum Hall plateaus, the effective area of the capacitor [S in Eq. (2)] should be reduced from the total gated area to the conductive (edge) region and then the capacitance shows minima. By this model, we could estimate in principle the widths of edge channels from the bottom values of the capacitance.

The capacitance between a strip metal plate (whose area is S^*) and a metal plate is given approximately as

$$C^* = \varepsilon_b S^*/d_{b^*}\,. \quad (3)$$

By substituting the observed bottom values for C^* in Eq. (3), we estimated the width of the conductive region [$W(\nu)$] along the edge by assuming that $S^* = W(\nu)L_e$, where L_e is the edge length. In Table I, the estimated $W(\nu)$ with various filling factors (ν) from the sample without fins in Fig. 3(a) is listed. As seen in Table I, $W(\nu)$ becomes increasingly larger with ν. The estimated $W(\nu)$ at $\nu = 6$ and 8 is larger than a half-width of the fin ($b/2 = 10\ \mu$m) in the samples in Fig. 3(a); the edge region fills in the fins completely. The broken lines in the inset of Fig. 3(b) are calculated by assuming that the fins are filled with the conductive region, where the slope of the line is uniquely determined by the fin area.

TABLE I. Estimated effective width [$W(\nu)$] of conductive region along the edge channel with various filling factors (ν).

	Filling factor (ν) 2	4	6	8
$W(\nu)$(μm)	0.7[a]	3.0[a]	10.7	41.9

[a]At $\nu = 2$ and 4, $W(\nu)$ is regarded as the total width of edge channels in the text.

At $\nu = 2$ and 4, $W(\nu)$ is regarded as the total width of the edge channels, since σ_{xx} estimated from the imaginary part of capacitance is negligible. On the other hand, the effect of finite σ_{xx} cannot be neglected at $\nu = 6$ and 8 and $W(\nu)$ may be much larger than the width of the edge channels. However, the estimated $W(\nu)$ even at $\nu = 2$ and 4 is much larger than the order of the magnetic length [$\lambda = (\hbar/eB)^{1/2}$] and the cyclotron radius [$r_c = \hbar \times (2\pi N_s)^{1/2}/eB$] conjectured from the single electron Landau level picture. For example, $\lambda = 110$ Å and $r_c = 160$ Å at $\nu = 2$ in this sample. In a qualitative picture of the edge states taking into account the screening effect

[14], it has been pointed out that the edge channel is expressed as the compressible liquid in 2DES and the electrostatic potential and the Landau levels become flat in the compressible liquid (the edge state) and the width of the edge state broadens. Self-consistent calculations about the energy dispersion of edge states have been made [15,16]. Chklovskii, Shklovskii, and Glazman calculated the total width of the edge states $[W(\nu)]$ analytically and $W(\nu)$ was given approximately as $L_d\{4\nu^2/(2\nu+0.5)\}$, where L_d is the width of the depletion layer at the sample boundary [17]. Since L_d is estimated as 0.2–0.5 μm [18,19], the calculated $W(\nu)$ at $\nu=2$ is of order microns and comparable to the measured $W(\nu)$ in Table I. In this calculation the spin degeneracy effect is not considered and the quantum effect is only taken into account semiclassically. Recently Hwang, Tsui, and Shayegan estimated that the width of the edge state is 0.4 μm at $\nu=1$ from the narrow channel magnetotransport measurement [20]. This value is also comparable to our results. It should be pointed out that a qualitatively new feature is presented at the present stage.

In summary, the magnetocapacitance of a GaAs/AlGaAs heterostruture through 2DES is investigated with various gated areas and edge lengths. The bottom values of the magnetocapacitance at the quantum Hall plateaus are not proportional to the gated area but the edge length. We propose a model in which the bottom values are decided by the effective area of edge channels to which the carrier can be supplied from the electrode. From this model, the total width of the edge current channels is estimated, which is much larger than the magnetic length and the cyclotron radius. The estimated value is compared with the calculated one based on an electrostatic theory taking into account the screening effect and the recent experiment.

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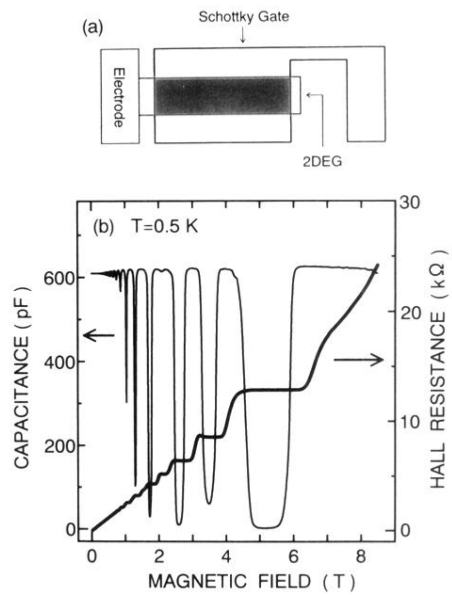

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