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Low-frequency edge excitations in an electrostatically confined GaAs–AlGaAs two-dimensional electron gas

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Abstract. We report an experimental study of the propagation of low-frequency (1–30 MHz) edge excitations in a two-dimensional electron gas confined electrostatically by means of gate induced depletion. This technique allows control of edge channel structure without change of the bulk properties of the electron gas. We have observed a strong dependence of the velocity of the edge excitations on gate voltage and demonstrate that such spectroscopy is a sensitive probe of the two-dimensional edge electronic structure.

Experiments on high-mobility two-dimensional electron gases (2DEGs) have revealed many phenomena in the areas of non-local and non-equilibrium magnetotransport. These effects are a consequence of a lateral confining potential that is smooth on the scale of the magnetic length and results in spatially separated edge channels (ECs) [1]. The conventional method of investigating the edge structure of a 2DEG employs Schottky gates and ohmic contacts to control and monitor current in a given EC. Spatially separated ECs form a complex vibrational system and therefore can be investigated by contactless methods, a factor which has not been widely explored although the edge excitation (EE) spectrum contains comprehensive information about EC spatial structure and interchannel interaction. The more general properties of EEs unrelated to detailed EC structure have been discussed in the literature [2, 3]. In [4] the propagation of interacting charge density waves along ECs was considered in a simple phenomenological model and the EE spectrum was calculated. One branch of the EE spectrum corresponds to in phase vibrations of charge in different ECs. This simplest type of EE was identified in [4] as an edge magneto-plasmon (EMP). Other branches of the EE spectrum correspond to out of phase vibrations of charge in ECs. We shall refer to these vibrations as non-equilibrium EEs. The velocity of non-equilibrium EEs is smaller than EMP velocity and their damping is larger due to interchannel scattering [4].

The purpose of this paper is to demonstrate experimentally that low-frequency ($\omega\tau \ll 1, \tau$ being the momentum relaxation time at zero magnetic field) EMPs can probe the 2DEG edge electronic structure.

In practice, EMPs are rather simple to observe. The first observation of high-frequency ($\sim 5 \times 10^{11}$ Hz) EMPs was reported in [5], and that of low-frequency EMPs ($\sim 10^{8}$ Hz) in

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[6]. A recent discussion of low-frequency EMPs can be found in [4] and [7–9]. The EMP study in 2DEGs on liquid helium surfaces is presented in [10–12].

It is not simple, however, to demonstrate the connection between the EMP spectra and the 2DEG edge electronic structure. While EMP charge is concentrated at the edge the potential drop created by this charge takes place in the 'bulk' of the 2DEG. This has been shown in [13] where EMPs were measured in a 2DEG placed near a parallel metal plate. The EMP frequency was shown to depend on the distance between the 2DEG and the metal plate even for large distances ($> 100\ \mu$m); this showed that the EMP electric field is indeed distributed far from the 2DEG edges. Away from the quantum Hall effect (QHE) regime, the conductivity σ_{xx} is sufficiently large that the bulk properties can influence the edge charge distribution as well [14]. Thus the EMP spectra may incorporate both edge and bulk properties of the 2DEG. The non-equilibrium EEs are more closely related to the edge states but these EEs are difficult to observe [4]. In this paper we describe a new experimental technique that allows one to directly observe the influence of edge state structure on the EMP spectrum.

We have examined the EEs in a 2DEG confined electrostatically by means of a gate, which encircles an electron gas 4 mm in diameter (figure 1). By applying a gate voltage the edge potential can be controlled without changing the bulk properties of the 2DEG. As the EMP field in the 2DEG outside the circle is screened by the gate, changes in the EMP spectra caused by the gate voltage have to be attributed to the influence of the edge electronic structure on the EMP modes. We note that this method is only applicable to the low-frequency EMPs that exist in macroscopic samples as conventional infrared studies of 2DEG plasma vibrations employ small ($\sim 1\ \mu$m) dots or strips. In this case the gate would influence the whole dot and the very separation of the edge and bulk regions is questionable. Another advantage of low-frequency EMPs is that they allow study of the QHE regime if this still exists at low enough frequencies.

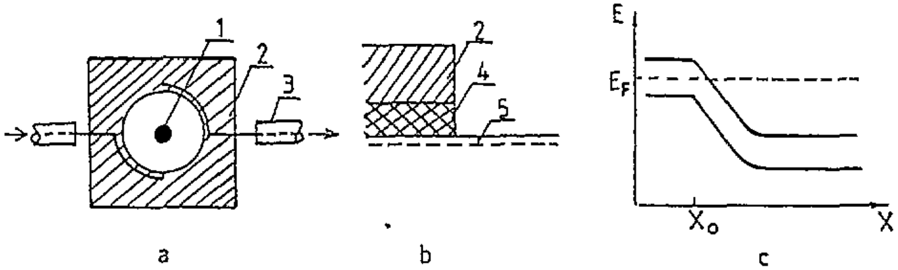

Figure 1. (*a*) Schematic view of the sample with coaxial connections; (*b*) cross section of the sample near the gate edge. 1, ohmic contact to 2DEG; 2, gate metallization; 3, cable; 4, GeO_x film; 5, 2DEG. (*c*) Landau levels following the edge potential; x_0 denotes the position of the gate edge.

Our experiments utilized a 2DEG formation in a GaAs–AlGaAs heterostructure with carrier concentration $\sim 1.2\times10^{11}$ cm^{-2} and $\mu \simeq 1\times10^{6}$ cm^{2} V^{-1} s^{-1}. The geometry of the gate is shown in figure 1(*a*) and (*b*). The 50 nm thick GeO_x film prevents leakage between the large 100 nm thick NiCr–Au gate and the 2DEG. The electrostatically defined 2DEG area (a circle of diameter 4 mm), may be considered as a transient resonator. When the external generator frequency coincides with the frequency of a particular EE, a signal appeared in the coaxial cable leading to the receiver and was detected by a spectrum analyser preceded by a low-noise radio frequency (RF) amplifier. The tracking generator of the spectrum analyser was utilized as an RF source. All the data were taken at 300 mK. Figure 2 shows the experimental curves for small gate voltages ($V_g < 1$ V) with the 2DEG in the QHE regime at filling factors $\nu = 1, 2$. At $V_g = 0$, the signal is due to capacitive coupling between the cables and the 2DEG. For negative V_g (in practice we apply a positive bias to the 2DEG, and the gate is grounded), the resonant signal appears with a frequency dependent on V_g. The noise seen in figure 2 is mainly due to electromagnetic interference. To avoid non-linear effects we used a low incident RF power level and a sensitive RF receiver allowing us to detect RF signals less than 10^{-8} V in magnitude. We were able to significantly reduce the noise by averaging up to 32 frequency sweeps. This procedure took a long time but did not change the EE's resonant frequencies, which is why we present the data taken without averaging.

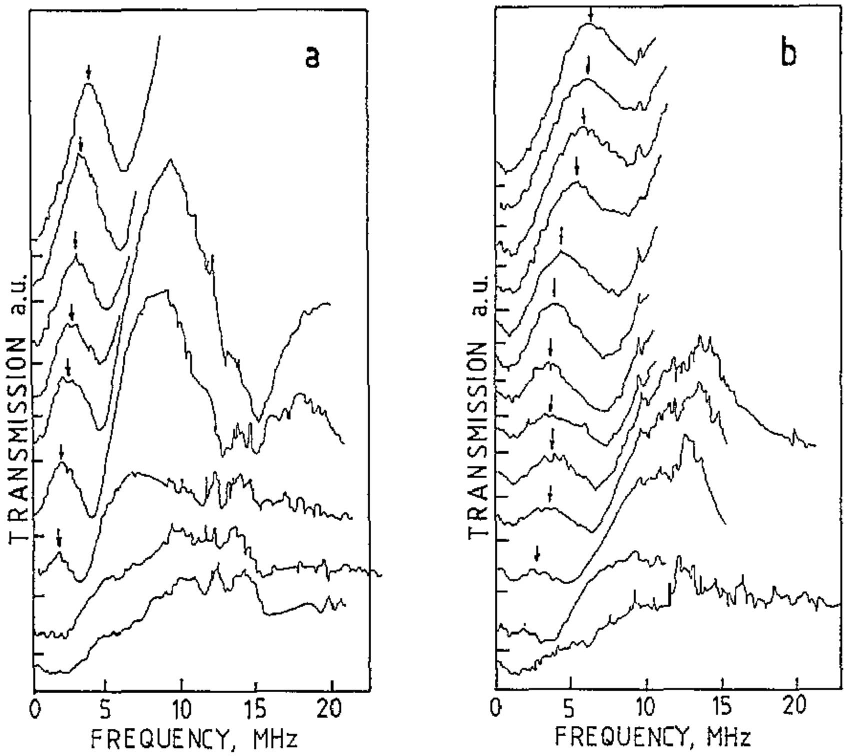

Figure 2. (*a*) Transmission as a function of frequency for $\nu = 1$. Voltage V_g (from bottom to top) = 0, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.4 and 1.7 V. (*b*) $\nu = 2$; $V_g = 0$, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75 and 0.8 V.

The resonance curves for $V_g = 4$ V and $\nu = 1, 2, 3$ and 4 are shown in figure 3. The resonances shown in figures 2 and 3 are due to the EMP excitations; figure 3 also demonstrates the spatial EMP harmonics for $\nu = 1$ and 2. The resonant frequency as a function of V_g is shown in figure 4 where the dependence for $\nu = 3$ is presented for the case $V_g > 3$ V; for 1 V< $V_g < 3$ V the resonance curves have a complex form that makes it difficult to determine the resonant frequencies. The experimental error in resonant frequency value is dependent on the EMP linewidth and is less than ±0.4, ±0.6 and ±1.2 MHz for $\nu = 1, 2$ and 4 respectively.

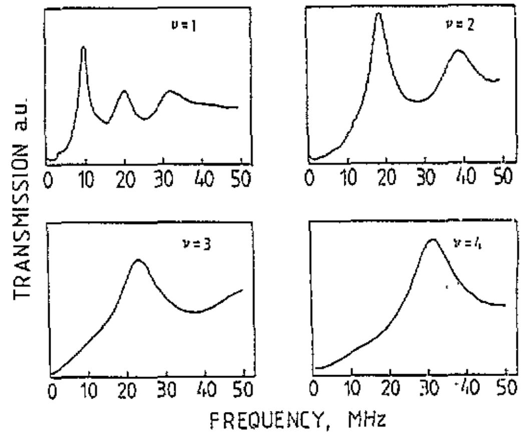

Figure 3. Experimental spectra at $V_g = 4$ V for $\nu = 1, 2, 3$ and 4.

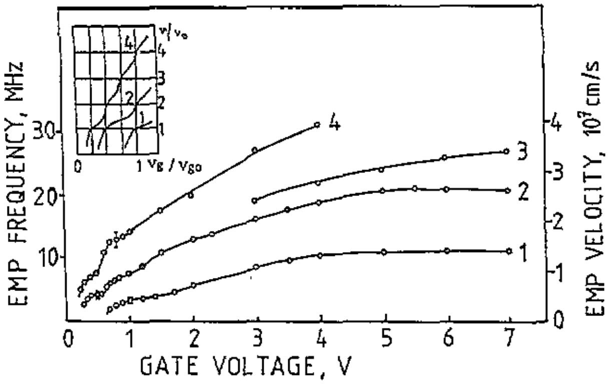

Figure 4. Resonant frequency (velocity) of EMP versus V_g for $\nu = 1, 2, 3$ and 4. Inset: the schematic representation of $v(V_g)$ dependences expected to follow from the multichannel structure of the edge states (see text).

The resonant frequency value is determined by the EE's velocity v, and by the perimeter of the confined 2DEG; this is almost constant because the maximum change in radius of the 2DEG is a few microns, negligible compared to the 2 mm radius of the confining gate. Therefore, the resonant frequencies of figures 2 and 4 are a measure of the EE velocity along the boundary of the 2DEG.

For a qualitative explanation of the experimental data we will use the phenomenological model described in [4]. If there are n ECs then the EMP velocity is given by

$$v = nae^2/h \tag{1}$$

where a^{-1} can be considered to be the capacitance per unit length of the EC and n indicates the electrostatic interchannel interaction. The coefficient a depends on the spatial structure of the EC and the dielectric environment, being dependent on the distance between the EC and the gate. We have assumed in (1) that all the ECs are identical and have neglected the distance between them [4].

We now consider the type of $v(V_g)$ dependence expected from (1). Let V_{g0} be a depletion gate voltage sufficient to bring delocalized states belonging to the first Landau level (LL) to the Fermi level when $\nu = 1$. This results in resonant transmission (figure 2(*a*)) and a steep increase of the EMP velocity. Let $v(V_{g0}) \equiv v_0$ be the EMP velocity when the EC has just been created. Further increase of V_g moves the EC away from the gate, the capacitance a^{-1} becomes smaller and v increases. At filling factor $\nu = 2$ the first EC appears at $V_g \simeq \frac{1}{2}V_{g0}$. Now (figure 1(*c*)) the number of ECs ($n = 1$) does not coincide with the number of LLs ($\nu = 2$). (1) assumes that EMP velocity depends on edge electronic structure so we can expect $v(\frac{1}{2}V_{g0}) = v_0$ (neglecting the possible dependence of coefficient a in (1) on magnetic field). So the EMP signal is expected to appear at half the value of V_g required for the EMP signal when $\nu = 1$. At $V_g = V_{g0}$ the second EC appears and should be accompanied by a steplike increase of v up to $v(V_{g0}) = 2v_0$. When V_g is larger than V_{g0} the $v(V_g)$ dependence is controlled by the movement of both ECs away from the gate.

For $\nu > 1$ the appearance of a new EC is accompanied by change and movement of the ECs already apparent. This seems to result in washing out of the steps, especially for large ν when the gate voltage separation V_{g0}/ν between subsequent steps is small. The expected $v(V_g)$ dependences for $\nu = 1, 2$ and 4 are shown in an inset in figure 4.

The experimental data are in good qualitative agreement with this picture. The EMP at $\nu = 2$ appears at smaller V_g (0.3 V, figure 2(*b*)) than the EMP at $\nu = 1$ (0.7 V, figure 2(*a*)). For $\nu = 4$ the EMP resonant frequency is difficult to measure at $V_g < 0.3$ V because of the large linewidth. For $\nu = 1$ and 2 we indeed observed steplike features in $v(V_g)$ dependences (figure 4), which are in qualitative agreement with the expected picture, assuming $V_{g0} \simeq 1$ V and $v_0 \simeq 5 \times 10^6$ cm s^{-1}. This means that the contribution of a new EC to the EMP frequency is about 3.5 MHz. For $\nu = 4$ the experimental error (±1.2 MHz) becomes comparable with this contribution. This is probably the reason why we have not resolved the fine structure in the $v(V_g)$ dependence for $\nu = 4$ in figure 4.

In the range $1\ \text{V} < V_g < 4$ V the EMP velocity increases for all ν (figure 4). This was explained by the increase of the distance between the gate and the ECs. However, at $V_g > 4$ V, $v(V_g)$ dependences for $\nu = 1$ and 2 show saturation and even weak decrease. At present we cannot suggest an explanation of such behaviour. Perhaps one has to take into account a dependence of the EC width w on V_g. A sufficiently strong increase of w (and therefore increase in capacitance a^{-1}) could result in a saturation of the $v(V_g)$ dependence.

We have seen that EMPs can probe the EC structure and interchannel interaction. We can also estimate the spatial resolution of our method, as from [15] it follows that a 1 V change in V_g results in ~ 2000 Å shift in the positions of ECs for the carrier density $\sim 10^{11}$ cm^{-2}. On the other hand a 1 V change in V_g corresponds to ~ 3 MHz change in EMP resonant frequency for $\nu = 1$ and $1\ \text{V} < V_g < 4$ V (figure 4). As we can distinguish ~ 0.4 MHz shift in EMP frequency for $\nu = 1$ we conclude that EMP resonances in a macroscopic (4 mm diameter) sample allow one to probe the EC structure with resolution $\leqslant 300$ Å.

So we can conclude that in the gate voltage domain up to 4 V the experimental data can be qualitatively explained in terms of interacting charge density waves propagating along the ECs, the picture that results in (1). The quantitative explanation of the experimental data can be given by the microscopic theory of EEs based on a realistic model of edge states. A reasonable basis for the theory was presented in [15]; however, in our opinion the main problem is to quantitatively account for the disorder.

In summary, we have observed for the first time low-frequency EMPs propagating along the electrostatically defined edge of a 2DEG. This observation gives us a new experimental technique for the study of 2DEG edge electronic structure. The technique takes advantage of the dependence of the low-frequency EMP spectrum on edge potential. As the edge potential was changed the EMP velocity reflected the appearance of ECs and the interaction between them. Combined with the microscopic theory of EEs the method can give quantitative information about the EC spatial structure and the electrostatic potential in gated 2DEG structures, which are widely used for many applications [16].

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