Low-frequency edge magnetoplasmons in the quantum Hall regime under conditions of reduced Coulomb interaction

1992 J. Phys.: Condens. Matter 4 3955

(http://iopscience.iop.org/0953-8984/4/15/010)

J. Phys.: Condens. Matter 4 (1992) 3955–3960. Printed in the UK

Low-frequency edge magnetoplasmons in the quantum Hall regime under conditions of reduced Coulomb interaction

A V Polisskii†, V I Talyanskii†, N B Zhitenev†, J Cole‡, C G Smith‡, M Pepper‡, D A Ritchie‡, J E F Frost‡ and G A C Jones‡

† Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, Moscow, Russia

‡ Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

Received 3 December 1991, in final form 19 February 1992

Abstract. We have measured edge magnetoplasmon oscillations (EMP) in a high-mobility GaAs–GaAlAs heterostructure in the quantum Hall regime. By placing a ground plane close to the two-dimensional electron gas the electrostatic field far from the edge is screened. By varying the separation of the ground plane from the 2DEG the distance that the electrostatic fields penetrates from the edge can be varied. The relative importance of the edge and bulk contributions to the EMP are thus deduced and we are able to estimate the width of the EMP charge distribution in the QHE regime as 1 μm. We attribute this width as being due to the characteristic size of the random potential near the edge of the 2DEG.

Recently there has been a great deal of interest in the physics occuring at the edge of a two-dimensional electron gas system (2DEG) in the quantum Hall regime. Description of the integer quantum Hall effect (QHE) in terms of reflection and transmission of edge channels [1] and the first attempts to study gapless excitations under fractional QHE conditions [2–4] reveal the importance of further experimental investigation of processes near to the boundary of a 2DEG.

Edge magnetoplasmon oscillations (EMP) are eigen-oscillations of a 2DEG in a high transverse magnetic field and the frequencies of these oscillations are determined mainly by the perimeter length of the 2DEG. EMP were first observed experimentally by Allen *et al* [5] in GaAs–GaAlAs heterostructures. They observed this effect in a set of 2D disks with diameters of 3 μm in the presence of far-infrared radiation. Later EMPs were observed in a 2DEG confined at the surface of liquid helium [6, 7]. Low-frequency ($\omega\tau \ll 1$, where τ is the momentum relaxation time at zero magnetic field) EMP in GaAs–GaAlAs heterostructures were then observed [8] and since then have been studied by a number of investigators [9–14]. Quite recently low-frequency EMPs in a 2DEG on liquid helium were also observed [15]. The features of the propagation of the EMP that are connected with the electronic properties of the edge of the 2DEG are of special interest. One of these properties is discussed in [12] where it is pointed out that the frequency of an EMP is determined by two contributions. First a Coulomb part describes charge transfer from one part of the edge of the sample to another through the bulk of the 2DEG, while the second, a drift part, is determined by direct charge transfer along the edge of the sample under the influence of an effective electric field confining the 2DEG.

In this work an attempt was made to investigate some effects connected with the electronic properties of the boundary of the 2DEG in the QHE regime. EMPs were studied in the 2D channel of the GaAs–AlGaAs heterostructure placed near a metal plate. In such a system the electrostatic field of the EMP is highly screened far from the edge, and the influence of the electronic properties of the edge become more important.

We used GaAs–AlGaAs heterostructures of rectangular and square shape. A Teflon film was placed between the face of the heterostructure and a metal plate (copper and aluminium were used). The surface of this plate was milled until flat and was then polished with a 1 μm diamond paste. EMP resonances in this system were detected with the help of two coaxial lines connected to an RF generator and receiver respectively [11, 13]. The lineshape of the EMP resonances was determined by sweeping the frequency while keeping the magnetic field constant [11, 13], and a phase-sensitive technique, which is convenient for studying broad EMP lines, was used.

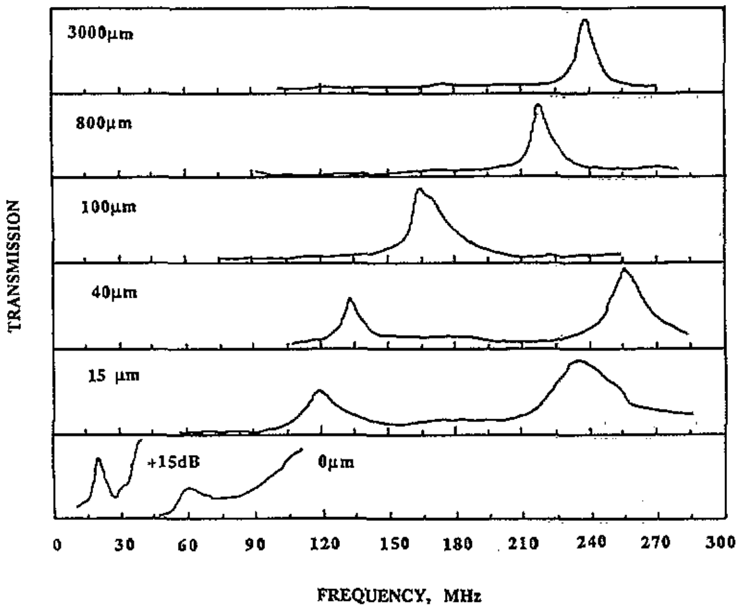

Figure 1. The EMP spectra under the quantum Hall effect regime (B = 5.5 T, ν = 2) at different insulator thicknesses. From top to bottom d = 3000, 800, 100, 40, 15 and 0 μm. The temperature T = 0.4 K.

Experimental curves corresponding to various distances d between the 2DEG and the metal plate are shown in figure 1. It is clear that the EMP frequency drops when d decreases. At d = 40 μm and 15 μm the high-frequency peaks correspond to the spatial harmonic of the fundamental mode. The lower curve was obtained for the sample pressed to the metal surface without an insulator. The distance between the 2DEG and the metal is determined by the roughness of the metal surface which we estimate to be d = 1 μm. In this case the resonance peak has a frequency of 20 MHz and a width of 5 MHz. At higher frequencies a continuous spectra is observed, and the transmission increases with frequency. The origin of this is not clear. One possible explanation is that it is composed of a spatial harmonic of the fundamental mode with a low quality factor. The increase in intensity is then due to an increase of coupling between the RF cables and the EMP. It is worth noting that we have not observed any EMP resonances with metal evaporated directly onto the GaAs–GaAlAs heterostructure.

The variation of the 20 MHz resonance with magnetic field near the $\nu = 2$ filling factor is shown in figure 2. It is seen that the EMP frequency remains nearly constant while the damping changes considerably. When ν deviates sufficiently from an integer value, the EMP frequency decreases and the quality factor becomes very low (figure 3). The interval of ν where the frequency exhibits plateau-like behaviour can vary from sample to sample (figure 3).

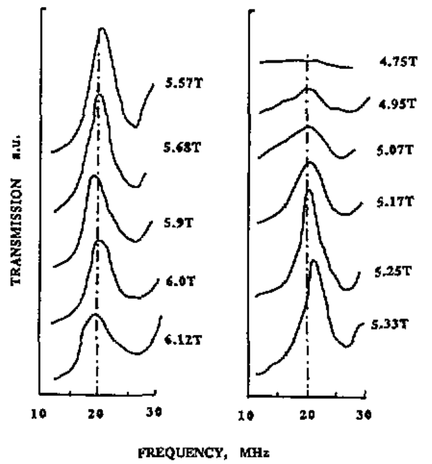

Figure 2. The EMP resonance at different magnetic field strengths, B, around a filling factor $\nu = 2$ ($B = 5.5$ T). The sample is placed directly on the metal surface. Temperature $T = 0.4$ K.

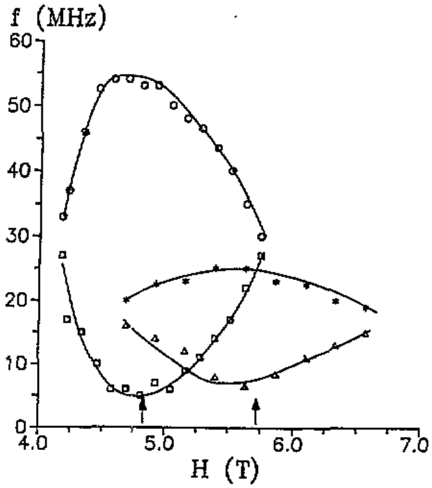

Figure 3. The resonance frequency (O, $*$) and damping (□, Δ) of the EMP for two samples with a mobility $\simeq 2 \times 10^5$ cm^2 V^{-1} s^{-1}. Arrows, indicate the magnetic field values corresponding to the integer filling factor $\nu = 2$. The lines are guides for the eye. The data were obtained with the help of a phase-sensitive technique. $T = 0.6$ K.

Let us consider the results obtained. Unfortunately a microscopic theory of EMP, taking into account the detailed electronic structure of the edge of a 2DEG has not been developed yet. We will use a qualitative picture to show how the structure of the boundary of the 2DEG is contained within the spectrum of the EMP. As is shown in [16], some length Δ has to be introduced for a qualitative description of an EMP. This length represents the width of a strip along the edge of the 2DEG, in which moving charge of the EMP is distributed. Using continuity and Poisson's equations (retardation effects can be neglected [16, 17, 18] and taking image charges in the metal into account, it is possible to obtain a dispersion law for the EMP:

$$\omega = (2\sigma_{xy}k/\epsilon)\ \ln\,(d/\Delta) + kI_{\rm D}/Q \qquad (d \gg \Delta) \tag{1}$$

where σ_{xy} is Hall conductivity, k the wavevector, ϵ the effective dielectric susceptibility, Q the charge per unit length along the edge, and $I_{\rm D}$ the current along the edge of the 2D channel determined by the drift of charge under the influence of forces restricting the edge of the 2D channel. The quantum derivation of (1) at the extreme limit $\Delta = l_m$ (l_m is the magnetic length) was developed in [12]. The EMP spectrum in a finite sample could be determined from the quantization equation $2\pi n/k = P$ where n is an integer, and P is the perimeter. It is clear from equation (1) that information about the electronic structure at the edge of a 2DEG will come from the measured value of Δ and from the drift term.

Let us compare the experimental value of the EMP frequency for the heterostructure placed directly on the metal (20 MHz) with the theoretical one derived from the formula (1). Using values $\sigma_{xy} \simeq 10^8$ cm s^{-1} ($\nu = 2$), $P \simeq 1.2$ cm, and $\epsilon \approx 4$ to 6, one can conclude $\ln(d/\Delta) \simeq 0.7$ to 1 and $\Delta \simeq 0.5$ μm. In this estimate we neglect the drift term in (1). This term will be discussed below in detail. So we find under the QHE regime $\Delta \gg l_m$ ($l_m \sim 100$ Å at $B \sim 5$ T).

On the other hand it is known [16, 17] that at sufficiently large $\sigma_{xx}(\omega)$, when the length

$$l_\sigma = 2\pi|\sigma_{xx}(\omega)|/\omega\epsilon \tag{2}$$

becomes greater than any microscopic length, one should use $\Delta = l_\sigma$. Such a situation could occur in GaAs–GaAlAs heterostructures at high enough temperatures [14] and in 2DEGs on liquid helium in a specific range of magnetic fields [15]. However, this is not the case in our experiment in the QHE regime. In reality, in some interval $\Delta\nu$ around $\nu = 2$ the frequency of the EMP is nearly constant, whereas the linewidth (and consequently σ_{xx}) varies (see figures 2 and 3). So in this interval some length greater than l_σ determines the EMP frequency. Only by further increasing $\Delta\nu$ (and l_σ) does Δ become determined by l_σ and the EMP frequency decrease due to the increasing of l_σ (figure 3). Equation (1) does not remain valid if $l_\sigma \simeq \Delta \gg d$; instead, a local capacitance approach should be used [16, 17, 19] for the first term in (1):

$$\omega = 2\sigma_{xy}k\sqrt{d}/\epsilon\sqrt{l_\sigma} \qquad (d \ll l_\sigma). \tag{3}$$

Thus the experimental data lead to the conclusion that in the QHE regime the width (Δ) of the edge charge distribution is larger than l_m and l_σ. The value of Δ in the QHE regime can only be properly calculated with the help of a microscopic understanding of the physical processes occurring at the edge. This is unknown, so the idea of an 'edge' to a 2DEG is not strictly defined. We can, by making some assumptions, ignore the detailed behaviour of the states at the edge of the sample and just define the edge as the region where the delocalized states are distributed. It is quite possible that the width of this strip is determined by the random potential near the 2DEG perimeter. In this case the EMP charge should be distributed in this strip. It is interesting to note in this context that in [12] it was assumed that away from the centre of the Hall plateaux the width of the EMP charge distribution is determined by the localization length. In that case if there are fluctuations in the 2DEG carrier density along the perimeter, the localization length will determine the edge charge distribution even at integer filling factor values.

We will now discuss the possible experimental detection of a drift term. If the case $\Delta = l_m$ were realized, the entire EMP charge would move with velocity $v_d = E/B$ (here $E \simeq E_F/l_m \approx \hbar\Omega_c/l_m$ is the restricting field, E_F the Fermi energy, and Ω_c is the cyclotron frequency), and the second term in (1) would become

$$kI_D/Q = kv_dQ/Q = kv_d \simeq 10 \text{ MHz}$$

(assumiing that $P = 2\pi/k = 1.2$ cm, $B = 5.5$ T). However, the electrostatic term in equation (1) would be about 100 MHz (for $d = 1\ \mu$m, $l_m = 10$ nm) and contributions from the drift term would reach 10%.

In our experiment the estimation of the drift term is not clear. It is reasonable to assume that $\Delta(\simeq 5\times10^2$ nm) is smaller than the width (r), the range of the restricting electric field E. r may be the width of the depletion region due to the surface states. In this case all the carriers are in the same restricting field $E \sim E_F/r = \hbar\Omega_c/r$. The second term in equation (1) can then be estimated as

$$kI_D/Q \simeq (2\pi/P)\hbar\Omega_c/rB < (2\pi/P)\hbar\Omega_c/B\Delta \simeq 0.3 \text{ MHz}.$$

We now consider the situation when the value of $\sigma_{xx}(\omega)$ is so large that the theory in [16, 17] is applicable and $\Delta = l_\sigma$. This means that l_σ is much larger than the width (r) of the strip over which the restricting field acts. For a sharp boundary to the 2DEG, r is likely to be the cyclotron radius. Taking into account that only carriers that are nearer to the boundary than a distance r possess a drift velocity, then

$$\frac{kI_D}{Q} = \frac{kv_d}{Q}\int_0^r n(x)\ \mathrm{d}x \approx \frac{2\pi}{P}\frac{\hbar\Omega_c}{BrQ}\int_0^r n(x)\ \mathrm{d}x \qquad (4)$$

where $n(x)$ is the density of the edge charge and x is the direction perpendicular to the boundary. The expression for $n(x)$ is taken from [17], equation (38b):

$$n(x) \simeq Q\sqrt{l_\sigma}/l_\sigma\sqrt{\pi x} \qquad x \ll l_\sigma/\pi$$

so the drift term can be written as

$$2\pi\hbar\Omega_c\sqrt{r}/PrB\sqrt{l_\sigma}$$

As an example, if $r = 10$ nm, $l_\sigma = 1000$ nm, and $P = 1$ cm, equation (4) gives 1 MHz.

In conclusion, we have investigated the EMP in a system consisting of a 2DEG in a GaAs–GaAlAs heterostructure with a metal plate above it which can be put at various distances away. Our data allow us to estimate the width of the EMP charge distribution in the QHE regime as 1 μm. We connect this width with the characteristic size of the random potential near the edge of the 2DEG.

Acknowledgments

We would like to thank V B Shikin, V T Dolgopolov and M I Reznikov for numerous helpful discussions.

References

[1] Buttiker M 1988 *Phys. Rev.* B **38** 9375
[2] Wen X G 1991 *Phys. Rev.* B **43** 11 025
[3] Beenakker C W J 1990 *Phys. Rev. Lett.* **64** 216
[4] MacDonald A H 1990 *Phys. Rev. Lett.* **64** 220
[5] Allen S J, Stormer H L and Hwang J C M 1983 *Phys. Rev.* B **28** 4875

[6] Mast D B, Dahm A J and Fetter A J *Phys. Rev. Lett.* **54** 1706
[7] Glattli D C, Andrei E Y, Deville G, Pointrenaud G and Williams F I B *Phys. Rev. Lett.* **54** 1710
[8] Govorkov S A, Reznikov M I, Senichkin A P and Talyanskii V I 1986 *Pis. Zh. Eksp. Teor. Fiz.* **44** 380 (Engl Transl. 1986 *JETP Lett.* **44** 487)
[9] Volkov V A, Galchenkov D V, Galchenkov L A, Grodnenskii I M, Matov O R and Mikhailov S A 1986 *Pis. Zh. Eksp. Teor. Fiz.* **44** 510 (Engl. Transl. 1986 *JETP Lett.* **44** 655)
[10] Andrey E Y, Glattli D C, Williams F I B and Heiblum M 1988 *Surf. Sci.* **196** 501
[11] Talyanskii V I, Wassermeier M, Wixforth A, Oshinovo J, Kotthaus J P, Batov I E, Nickel H and Schlapp W 1990 *Surf. Sci.* **229** 40
[12] Wassmeier M, Oshinovo J, Kotthaus J P, MacDonald A H, Foxon C T and Harris J J 1990 *Phys. Rev.* B **41** 10 287
[13] Talyanskii V I, Batov I E, Medvedev B K, Kotthaus J, Wassermeier M, Wixforth A, Weimann J, Schlapp W and Nikel H 1989 *Pis. Zh. Eksp. Teor. Fiz.* **50** 196 (Engl. Transl. 1989 *JETP Lett.* **50** 221)
[14] Grodnensky I, Heitmann D and von Klitzing K 1991 *Phys. Rev. Lett.* **67** 1019
[15] Peters P J M, Lea M J, Jansen A M, Stone A O, Jacobs W P N M, Fozooni P and van der Heijden R W 1991 *Phys. Rev. Lett.* **67** 2199
[16] Volkov V A and Mikhailov S A 1988 *Zh. Eksp. Teor. Fiz.* **94** 217 (Engl. Transl. 1988 *Sov. Phys.–JETP* **67** 1639
[17] Volkov V A and Mikhailov S A1991 *Modern Problems in Condensed Matter Sciences* vol 27.2, ed V M Agranovich and A A Maradudin (Amsterdam: North-Holland) ch 15, p 855
[18] Fetter A L 1985 *Phys. Rev.* B **32** 7676
[19] Nazin S S and Shikin V B 1988 *Zh. Eksp. Teor. Fiz.* **94** 133