Spectrum of low-frequency edge magnetoplasma waves under conditions of quantum Hall effect

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The spectrum of edge magnetoplasma waves in GaAs–AlGaAs heterostructures has been studied under conditions corresponding to the quantum Hall effect for filling factors $\nu = 1,2,4$ at temperatures of 0.4–4.2 K. The spectrum of the edge magnetoplasma waves is not equidistant. The resonant frequencies of these waves are proportional to ν (for integer values of ν).

Govorkov *et al.*[1] have observed low-frequency ($\omega \ll \tau^{-1}$, where τ is the momentum relaxation time) edge magnetoplasma waves in a $2D$ channel in a GaAs–AlGaAs heterostructure. Theoretical work on these waves has been carried out in several places.[2–6] According to the theoretical ideas, the spectrum and damping of these waves are determined by the conductivities σ_{xx} and σ_{xy} of the $2D$ channel and by a certain distance l, which has the meaning of the width of the distribution of the edge charge of the waves. The following expression was derived in Refs. 4 and 6 in a model with a $2D$ channel with a sharp boundary with the help of a local Ohm's law:

$$l = 2\pi \, | \sigma_{xx} (\omega) | / \omega \; . \tag{1}$$

Shikin[5] has asserted that in sufficiently strong magnetic fields ($B > 1$ T) the local nature of the Ohm's laws near the boundary of a $2D$ channel may be violated and that the role of l might be played by the Larmor radius: $l \sim r_L \sim B^{-1}$. In our opinion, it is reasonable at this point to regard l as a phenomenological parameter, to be determined empirically. If l is introduced *a priori*, then it is a simple matter to estimate the frequency (ω_p) and damping (Γ_p) of the fundamental mode of edge magnetoplasma waves (Ref. 6, for example):

$$\omega_p = \epsilon_1 \sigma_{xy} R^{-1} \ln{}^{R}/_{l} \; , \tag{2}$$

$$\Gamma_p = \epsilon_2 \sigma'_{xx} (\omega) l^{-1} \, [\ln{}^{R}/_{l}\,]^{-1} \; . \tag{3}$$

Here ε_1 and ε_2 are coefficients which reflect the influence of the insulating substrate and the shape of the sample, R is a characteristic dimension of the $2D$ channel, and $\sigma'_{xx}(\omega) \equiv \mathrm{Re}\,\sigma_{xx}(\omega)$. In this letter we are reporting a study of edge magnetoplasma waves for various integer values of ν. We compare the results with theoretical predictions.[4–6]

The waves were excited and detected by two miniature coaxial cables which linked the sample with the microwave source and detector (Fig. 1). The open-circuit

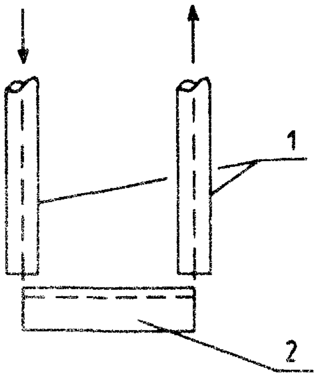

FIG. 1. Schematic diagram of the experimental method.

ends of the cables lay near the boundary of the 2*D* channel (there was no voltaic contact with the channel). From the circuit-theory standpoint, the arrangement which we used is a circuit with a reentrant resonator; the microwave resonator is the 2*D* channel itself. We studied heterostructures with typical dimensions of 3–5 mm and a substrate thickness of 0.4 mm. In the present letter we are reporting results for samples with narrow lines of edge magnetoplasma waves ($\omega_p/\Gamma_p \gtrsim 30$ under conditions corresponding to the quantum Hall effect at 0.4 K). Figure 2 shows the wave spectrum for the sample which had the highest mobility [among the samples which we used;

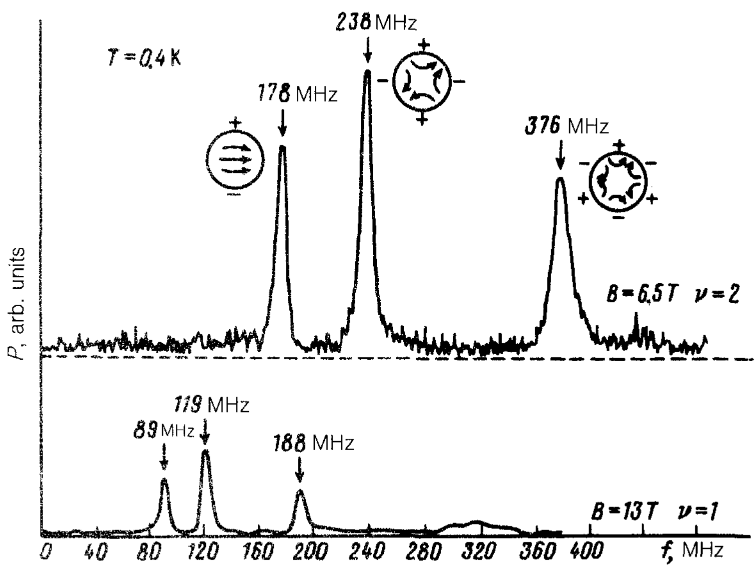

FIG. 2. Spectrum of edge magnetoplasma waves for $\nu = 1$ and 2. The sample had dimensions of 3.5×5 mm; the mobility was 500 000 cm^2 (V·s) at 4.2 K. The current distributions in the various wave modes are shown schematically beside the resonance curves.

$\mu = 500\,000 \text{ cm}^2/(\text{V}\cdot\text{s})$ at $T = 4.2$ K]. The first three wave modes can be seen clearly. The fact that the spectrum is not equidistant is evidence that the first few wave modes are of a distributed nature. We see that the relation $\omega_p(\nu) \sim \nu$ holds for all modes. We observed a slight ($\sim 3\%$) deviation from the behavior $\omega_p(\nu) \sim \nu$ for $\nu = 4$. For a sample with dimensions of 3×3 mm and a mobility $\mu \sim 10^5 \text{ cm}^2/(\text{V}\cdot\text{s})$, for example, the frequency of the fundamental mode took on the values 109.5, 218, and 422 MHz for $\nu = 1$, 2, and 4, respectively ($T = 0.42$ K). It is important to note that the quality factor for the waves at $\nu = 4$ was $Q \sim 20$, or half that at $\nu = 1$ and 2. Furthermore, an increase in the temperature resulted in an increase in the deviation of $\omega_p(\nu)$ from linearity. This deviation would thus logically be linked with an effect of damping on the frequency of the waves. We will discuss this question in more detail below.

When there is a deviation of ν from an integer value, the wave damping increases, and the plot of $\omega_p(B)$ acquires a flat region (Fig. 3a), which reflects the presence of a plateau on the $\sigma_{xy}(B)$ curve [see (2)]. A lowering of the temperature from 4 K to 0.4 K causes the line to narrow by a factor of about two; the value of ω_p increases slightly ($\sim 3\%$) in the process (Fig. 3b).

These results can be explained on the basis of expressions (2) and (3), if one makes the further assumption that l is of the form

$$l = l_0 + f(\sigma'_{xx}(\omega)), \tag{4}$$

where l_0 is independent of B, and f is an increasing function of $\sigma'_{xx}(\omega)$. We make the further assumption that for the narrow lines in Fig. 2 the value of $\sigma'_{xx}(\omega)$ is so small

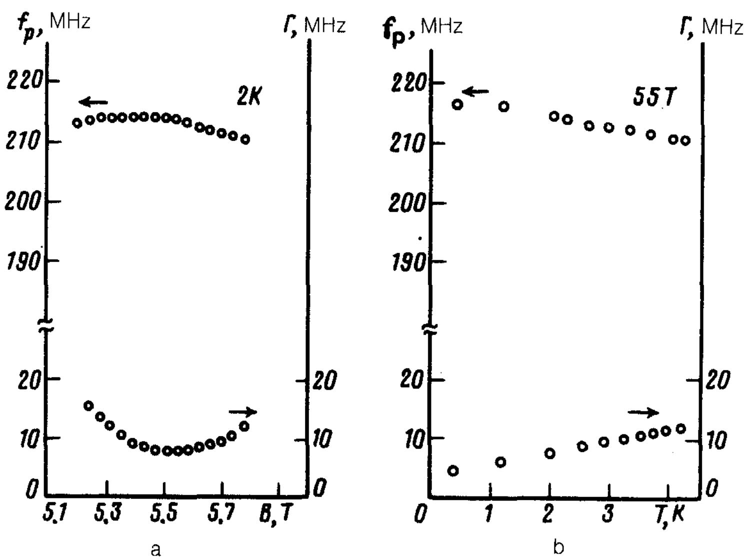

FIG. 3. Frequency and damping of the fundamental mode of edge magnetoplasma waves. a—Versus the magnetic field; b—versus the temperature. The dimensions of the sample were 3×3 mm, and the mobility was $\mu \sim 100\,000 \text{ cm}^2/(\text{V}\cdot\text{s})$ at 4.2 K.

that the condition $f \ll l_0$ holds. In this case we have $l \approx l_0$ and $\omega_p \sim \sigma_{xy} \sim \nu$ [see (2)]. When $\sigma'_{xx}(\omega)$ is sufficiently large, the decrease in ω_p due to the second term in (4) can become greater than the experimental error ($\sim 1\%$). We use this effect to explain the decrease (by 3%) in ω_p as T is increased from 0.4 K to 4.2 K (Fig. 3b) and also the deviation of $\omega_p(\nu)$ from linearity in the case $\nu = 4$.

Let us compare these results with the theoretical conclusions of Refs. 4–6. It can be asserted that l_0 is not determined by the Larmor radius,[5] since if it were we would have $l_0 \sim B^{-1}$, in disagreement with the data in Fig. 2. The calculations of Refs. 4 and 6 can be reconciled with the experimental results only under the condition that in the regime of the quantum Hall effect we have $\sigma''_{xx}(\omega) \gg \sigma'_{xx}(\omega)$ $(\sigma'' \equiv \mathrm{Im}\sigma)$ and $\sigma''_{xx}(\omega)/\omega$ [see (1)] does not depend on ν.

There are other mechanisms which could possibly determine l_0: the presence of a transition layer (of width $\sim l_0$) near the edge of the $2D$ channel, in which the carrier density changes, or the existence of fluctuations in an impurity potential with a correlation length $\sim l_0$. Clearly, direct measuremnts of $\sigma'_{xx}(\omega)$ and $\sigma''_{xx}(\omega)$ combined with the experimental data, not only would make it possible to test the validity of expression (1) but would also provide information about the edge currents under conditions corresponding to the quantum Hall effect.

The spectrum of edge magnetoplasma waves has been studied experimentally by Andrei *et al.*[7] They asserted[7] that the spectrum of edge magnetoplasma waves is equidistant, $\omega_p(\nu) \sim \nu \ln(\alpha/\nu)$, for integer values of ν and that the waves disappear at $T > 2$ K. The difference in the spectra of the waves can be explained on the basis of the presence of a metal gate near the $2D$ channel in Ref. 7; that gate could alter the wave spectrum. The other discrepancies, however, are difficult to explain. The carrier density in the $2D$ channel was modulated in order to improve the sensitivity in Ref. 7. For integer values of $\nu[\sigma_{xx}(\omega)$ is at a minimum, $\sigma_{xy} = \mathrm{const}]$, that approach may not be the best choice. Another possibility is that the discrepancies stem from differences in the test samples.

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