Low-frequency dynamics of bounded 2D electron system in strong magnetic field

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The response of a 2D electron system in a magnetic field B has been found to depend on the frequency in a region well below the known characteristic frequencies. The effect arises when the size of the 2D system, L, becomes comparable to the length l_E, which determines the region in which the induced edge potential is localized. A method for contactless measurements of the conductivity σ_{xx} is proposed.

The dynamics of 2D electrons at low frequencies $f \ll eB/(2\pi m^* c)$ in a magnetic field is determined by edge magnetoplasma oscillations, which exist as a result of the presence of a boundary on the 2D system (Refs. 1 and 2 and the bibliographies there). In this letter we are reporting the observation and study of a response of a 2D system which arises at frequencies below the frequency of the fundamental mode of edge magnetoplasma oscillation, f_p, and which is also associated with the finite dimensions of the sample. The effect is attributed to the existence of a characteristic length $l_E(f,\sigma_{xx})$ of a 2D system. This length determines the spatial dispersion of the longitudinal dielectric constant of the 2D electrons and the region in which edge fluctuations of the charge are localized.[2] As a result, the dynamic response to an external electric field in the plane of the sample is determined primarily by an edge region, of width $\sim l_E$. The change in the response of the 2D system thus occurs when l_E is comparable to L. It is suggested that this effect be used for contactless measurements of σ_{xx} under conditions corresponding to the quantum Hall effect.

Experiments were carried out at $T = 4.2$ K on AlGaAs/GaAs heterojunctions, either square or rectangular, with a side $L = 1.5$–6 mm. The sample was inside a grounded metal screen between two electrodes, which were connected to an oscillator and to a receiver (Fig. 1; the screen is not shown.).[3] With a potential of constant amplitude on the excitation electrode, the field dependence of the normalized amplitude of the potential induced at the measurement electrode was measured: $A(f = \text{const}, B) = U(f = \text{const}, B)/U(f = \text{const}, B = 0)$. The results were then used to plot a frequency dependence $A(f, B = \text{const})$.

For a test cell in which the electrodes are positioned symmetrically with respect to the sample (Fig. 1), we have $A \geqslant 1$ for $f < f_p$ and $A < 1$ for $f > f_p$. This circumstance is attributed to the particular nature of the screening of the component of the external electric field in the plane of the sample by the field of the induced 2D charge, E_{ind} (Refs. 3 and 4). The screening increases toward resonance ($f < f_p$), since the amplitude E_{ind} increases, and its phase lag with respect to the external field increases.

The frequencies studied in the present experiments lay well below those in some

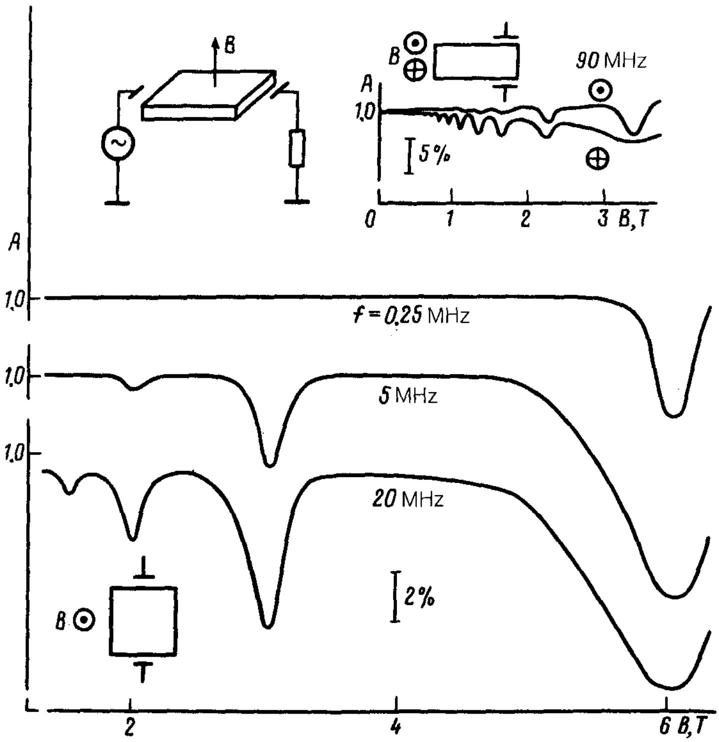

FIG. 1. $A(f=\text{const},B)$ for various frequencies (symmetric geometry) and $L=6$ mm. The electron mobility is $\mu=2\times10^5$ $cm^2/(V\cdot s)$, and the electron density is $n=2.9\times10^{11}$ cm^{-2}. The measurement layout is shown at the upper left. The inset shows curves of $A(f=\text{const},B)$ for various directions of B (asymmetric geometry). $L_1=2$ mm, $L_2=5$ mm, $\mu=2\times10^5$ $cm^2/(V\cdot s)$, $n=3.2\times10^{11}$ cm^{-2}.

previous experiments.[3] A more complex behavior was found for A; this behavior cannot be explained on the sole basis of the excitation of edge magnetoplasma oscillations. It follows from Fig. 1 that for certain fields B one observes $A<1$, instead of the expected $A\geqslant1$. This behavior indicates a weakening of the screening of the external field at frequencies far below f_p. The effect depends on the direction of B in the case of an asymmetric arrangement of the excitation and measurements electrodes with respect to the sample. This result, shown in the inset in Fig. 1, means that the gyration of the charges of the 2D system in the magnetic field is important for the observed effect. This result also makes it possible to eliminate from consideration instrumental effects, whose frequency dependence is determined by the properties of the test cell.

Important information is embodied in the frequency dependence $A(f,B=\text{const})$ (Fig. 2). It follows from these results that the effect can be characterized by the turn-on frequency f_0, which depends on B. At $f<f_0$ the external field is screened out completely by the charge of the 2D layer, while at $f\sim f_0$ it begins to penetrate into the sample. As the frequency is raised, the excitation of edge magnetoplasma oscillations becomes superimposed on this process, as can be seen from the inset in Fig. 2. The

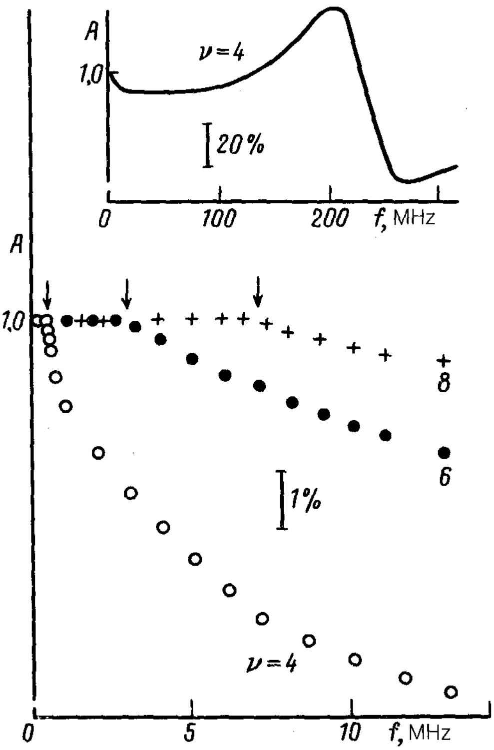

FIG. 2. $A(f,B=\text{const})$ for various filling factors ν. The inset shows the behavior of A in a frequency region which includes the resonance of edge magnetoplasma oscillations, $f_p = 240$ MHz. The arrows show the turn-on frequency f_0. $L = 5$ mm, $\mu = 1.5\times 10^5$ $\text{cm}^2/(\text{V}\cdot\text{s})$ $n = 2.4\times 10^{11}$ cm^{-2}.

dependence $A(f)$ near f_0 cannot be described in the form $\sim [f^2 + (1/2\pi\tau)^2]^{-0.5}$, which is characteristic of a relaxation process with a relaxation time τ.

It follows from Fig. 3 that f_0 is proportional to σ_{xx} and does not depend on the Hall conductivity σ_{xy}. The coefficient of the proportionality between σ_{xx} and f_0 does not depend on B; it has the dimensionality of a length. Measurements on samples with a Corbino-disk geometry show that σ_{xx} has no significant frequency dependence up to ~ 10 MHz. As the size of the sample is varied, f_0 also changes; specifically, it decreases with increasing L (the points in the inset in Fig. 3).

These results can be explained on the basis of the existence of a characteristic length $l_E = \sigma_{xx}/(4\pi\kappa_0\kappa f)$ of the 2D system, where κ is the effective dielectric constant of the surrounding medium, and κ_0 is the permittivity of free space. It was shown in Ref. 2 that this length, in particular, determines the size of the region in which the charge fluctuations forming the edge magnetoplasma oscillations are localized. Since l_E was introduced in Ref. 2 for an arbitrary frequency f, it might be suggested that l_E has the same meaning far from resonance, at $f<f_p$. Let us examine the dynamics of a bounded 2D system at $f<f_p$. Under the condition $l_E < L$, the density fluctuations of the 2D electrons are concentrated for the most part in a narrow region of width $\sim l_E$ near the edge. As f decreases, this region expands, screening the external electric field from the interior of the sample to a progressively greater extent, until l_E becomes

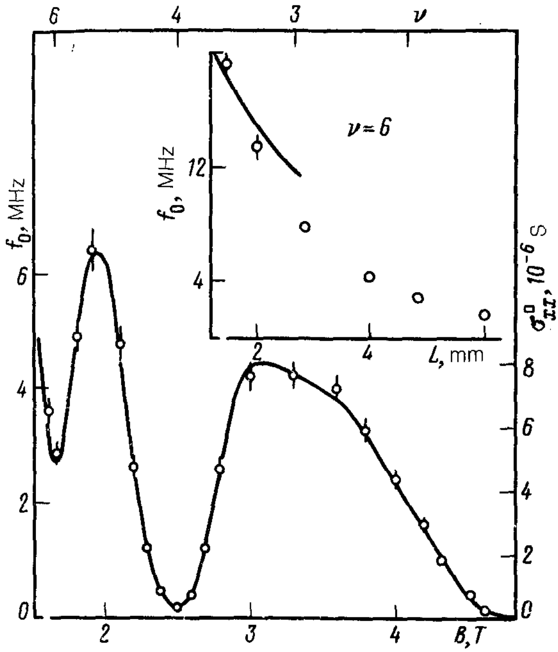

FIG. 3. Plots of f_0 (the points) and σ_{xx} ($f = 0$) (the line) versus B for $L = 5$ mm. The inset shows the measured (points) and theoretical (line) dependence of f_0 on L for a square sample. $\mu = 1.5\times10^5$ cm^2/(V·s), $n = 2.4\times10^{11}$ cm^{-2}.

comparable to $\sim L/2$. This event corresponds to the frequency f_0 on the frequency dependence of A. At all $f<f_0$ the dynamic response of the 2D system is a "bulk" response, by which we mean that the induced charge fluctuations are distributed over the entire 2D plane.

The expression for l_E given above remains valid as long as the distance (d) from the sample to the electrodes exceeds the size of the region in which the induced field is localized: $d > L/2$. Experimentally, this conditions corresponds to small values of L, for which there is a good agreement between the theoretical and experimental curves of $f_0(L)$ (see the inset in Fig. 3). In the calculations, the value $\kappa = 3$ was used; estimates indicate that this value is valid for samples 0.6 mm thick with $L = 2$–3 mm. For large $L(L/2 > d)$, l_E should also be independent of d. In this case, the calculations are complicated by the complex experimental geometry. The frequency dependence of A near f_0 also depends on the relation between d and L. The sharpest change in A is observed when the electrodes are near the edge of the sample, because of the pronounced spatial localization of the induced potential in this case.

A distinctive feature of this effect is that, although both dissipative and Hall currents flow through the sample, the region in which the edge charge and the potential are localized is determined exclusively by σ_{xx}. It thus becomes possible to carry out contactless measurements of $\sigma_{xx}(B)$ in a fairly simple way. We are of course most interested in determining σ_{xx} under conditions corresponding to the quantum Hall effect in samples with a high electron mobility, in which case σ_{xx} is very small. The following procedure is proposed for this purpose: The ratio f_0/σ_{xx} is first found for a sample with a known σ_{xx} and with a geometry and a plane thickness which are the same as that of the test sample. The result is then used to determine the unknown conductivity in the test sample. We have used this method to measure σ_{xx} in a 2D system with an electron density of 1.7×10^{11} cm^{-2} and a mobility $\sim10^6$ cm^2/(V·s). The sample was graciously furnished by G. Weimann. At $T=1.5$ K, for a filling factor $\nu=2$, the value of σ_{xx} was $\sim10^{-11}$ S ($f_0\approx30$ Hz and $L=2$ mm).

An interesting topic for further study would be high-quality samples, for which l_E may be comparable to other length scales of the 2D system, e.g., comparable to the magnetic length. For this case, the dynamics of the 2D electrons in a strong magnetic field would have to be analyzed at the microscopic level.

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