# Edge magnetoplasmons under conditions of the quantum Hall effect

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Edge magnetoplasmons in a bounded two-dimensional electron system at a GaAs–AlGaAs interface are studied under conditions of the quantum Hall effect. Theoretical and experimental results show that the frequency of the quantum Hall effect oscillates as a function of the magnetic field in the low-frequency limit. The damping of this effect is similar to that of the Hall conductivity.

A disruption of translational invariance in a bounded two-dimensional ($2D$) electron system in a magnetic field $H$ gives rise to plasma oscillations of a new type, which propagate along the edge of the system: edge magnetoplasmons. Their frequency falls off as $H^{-1}$ in strong fields $H$ (the classical regime). This mode has been observed in classical $2D$ systems (electrons on helium[1,2]) and degenerate $2D$ systems (electrons at a heterojunction[3,4]).

The damping of edge magnetoplasmons in strong fields $H$ may be slightly even in the low-frequency limit[5,6] $\omega\tau^* \ll 1$. On the other hand, at sufficiently low values of $\omega$ (at least up to [7,8] $f = \omega/2\pi \sim 35$ GHz) a quantum Hall effect should be manifested. There is the problem of how the quantum Hall effect affects the properties of edge magnetoplasmons.

In the present letter we report a study of edge magnetoplasmons under conditions of the integer quantum Hall effect. We predict and also report the observation of a quantum regime of edge magnetoplasmons: As $H$ is varied, the frequency of the edge magnetoplasmons $\omega_p'$, oscillates with the period of the Shubnikov–de Haas effect, and the damping $\omega_p''$ reproduces the behavior of the quantum Hall conductivity $\sigma_{xy}(H)$.

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*1. Theory.* We first consider a semi-infinite $2D$ layer $\{z=0,\ x\geqslant 0\}$ in a magnetic field $\mathbf{H}=(0,0,H)$. From the general dispersion relation[5] we find the following expression for the spectrum of edge magnetoplasmons in a $2D$ electron system at a heterojunction (without metal electrodes) in the low-frequency limit ($\omega\tau^*\ll 1$, $\omega\ll\omega_c$):

$$\omega_p(q) = \frac{2q\sigma_{yx}}{\epsilon}\ln\left[\frac{2e}{\pi}\,\frac{\sigma_{yx}}{\sigma_{xx}}\ln\left(\frac{2e}{\pi}\,\frac{\sigma_{yx}}{\sigma_{xx}}\right)\right]+\frac{i\pi q\sigma_{yx}}{\epsilon}, \tag{1}$$

where $\tau^*=\mathrm{Im}\,\sigma_{xx}/\omega\mathrm{Re}\,\sigma_{xx}$ (in the Drude model, $\tau^*$ is the same as the elastic relaxation time); $\omega_c$ is the cyclotron frequency, $q$ is the wave vector of the edge magnetoplasmons, parallel to the edge of the system; $e=2.72...$; $\epsilon$ is the average dielectric constant of the surrounding medium; and $\sigma_{xx}$ and $\sigma_{yx}$ are components of the conductivity tensor of an unbounded $2D$ layer at low values of $\omega$. We wish to stress the unusual nature of spectrum (1): 1) The edge magnetoplasmons, in contrast with ordinary plasmons, are well defined even in the low-frequency limit if $\sigma_{xx}\ll\sigma_{yx}$; 2) $\omega_p' = \mathrm{Re}\,\omega_p$ depends on the dissipative component of the conductivity, $\sigma_{xx}$, and oscillates as a function of $H$; 3) $\omega_p''=\mathrm{Im}\,\omega_p$ does not depend on $\sigma_{xx}$ and is quantized in the $\sigma_{yx}$ quantization regime.

It can be shown that a significant fraction of the charge of edge magnetoplasmons is concentrated near the edge of the sample in a band of width $l=|2\pi\sigma_{xx}/\omega_p\epsilon|$. If the condition $l\ll L_xL_y$ is satisfied in a sample of dimensions $L_x\times L_y$, the spectrum of edge magnetoplasmons remains of the same form as in (1) but with

$$q = q_n = 1 - \frac{\omega_p(q_n),}{\omega}, \tag{2}$$

where $P$ is the perimeter of the sample, and $n=1,2,...$ is the index of the edge-magnetoplasmon mode. Under these conditions, the edge-magnetoplasmon of the response of the system to an external electric field is described by the effective dielectric constant

$$\tilde{\epsilon}(\omega, q_n) = 1 - \frac{\omega_p(q_n)}{\omega}. \tag{3}$$

The constant in (3) determines the screening of the external electric field. For example, in a disk of radius $R$ this constant relates the values of the cylindrical Fourier harmonics of the external potential $\varphi_{\mathrm{ext}}$ and the total potential $\varphi_{\mathrm{tot}}$ at the edge of the sample ($q_n=n/R$):

$$\varphi_{tot}(\omega, q_n) = \varphi_{ext}(\omega, q_n)/\tilde{\epsilon}(\omega, q_n). \tag{4}$$

*2. Experimental.* We have studied GaAs–AlGaAs heterojunctions at liquid-helium temperature. The mobility and density of the $2D$ electrons lie in the ranges $\mu=(0.25\text{–}1.0)\times10^5\ \mathrm{cm^2/(V\cdot s)}$ and $n_s=(3\text{–}7)\times10^{11}\ \mathrm{cm^{-2}}$ for different samples. The conditions for the applicability of (1)–(3) hold by a wide margin. The samples, of thickness $d=0.4$ mm, are positioned on a foam plastic base between two rod electrodes, which are enclosed by a grounded cylindrical screen, as shown in the inset in Fig. 1. The amplitude of the potential on the electrode connected to the oscillator is held constant with respect to this screen. We measure the $H$ dependence of the voltage

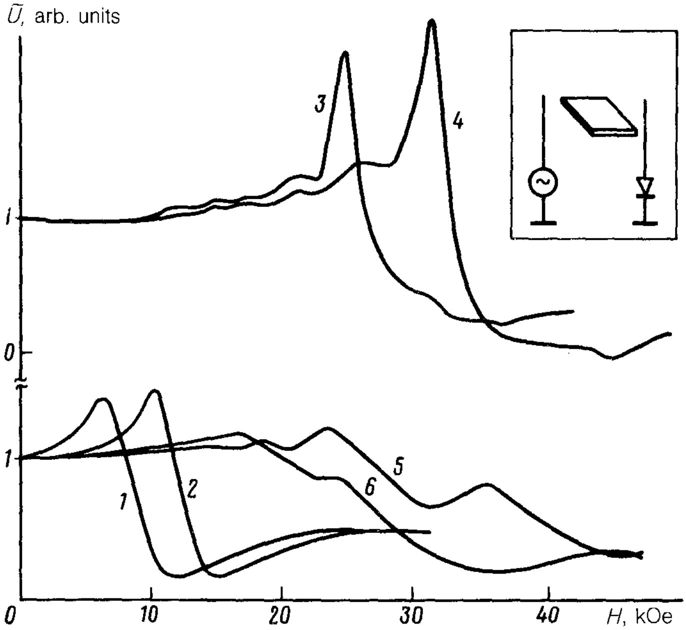


FIG. 1. The normalized detector $\widetilde{U}=U(H,f)/U(0,f)$ versus $H$ for various samples at $f=$ const. 1,2—$f=2$ and 1.5 GHz, $n_s=3.7\times10^{11}$ cm$^{-2}$, $P=1.2$ cm; 3,4—$n_s=3.7\times10^{11}$ cm$^{-2}$ and $4.3\times10^{11}$ cm$^{-2}$, $f=0.59$ GHz, $P=1.2$ cm; 5,6—$f=0.4$ and 0.55 GHz, $n_s=3.48\times10^{11}$ cm$^{-2}$ $P=1.0$ cm.

at a quadratic detector $U$, for various values of $f$ over the range 0.05–5 GHz. The current through the detector is equal to the time derivative of the charge induced at the measuring electrode and is therefore proportional to $f$ and to the electric field $E$ near this electrode. The field $E$ depends on the degree of screening of the field in the sample: Specifically, $E$ increases with increasing screening and vice versa. The degree of screening is determined by the quantity $\tilde{\epsilon}$, which should oscillate as a function of $H$ [see (1) and (3)].

The degree of screening of the electric field in the sample is indeed a nonmonotonic function of $H$ (Fig. 1). As $f$ is varied (curve 1, 2, 5, and 6), as $n_s$ is varied (curve 3 and 4), and also as the perimeter $P$ is varied, the positions of the sharpest structural features is $U(H)$ shift along the $H$ scale.

The shape of these structural features, the nature of their shift, and the magnitude of their shift suggest that near them the value of $\omega_p'/2\pi$ is close to $f$.

Information on the spectrum of edge magnetoplasmons can be extracted from curve of $\widetilde{U}(f)$ (Fig. 2). The curves which were found have an anomalous dispersion near a plasma resonance. It can be shown that if a sample has only a weak effect on $E$ at values of $f$ far from resonance [$\widetilde{U}(f=0)\approx\widetilde{U}(f=\infty)$], the following relations can be derived for the frequency and damping of the fundamental edge-magnetoplasmon mode: $\omega_p'=\pi(f_- + f_+)$, and $\omega_p''=\pi(f_- - f_+)$, where $f_-$ and $f_+$ are the positions of the minimum and maximum of $U(f)$.

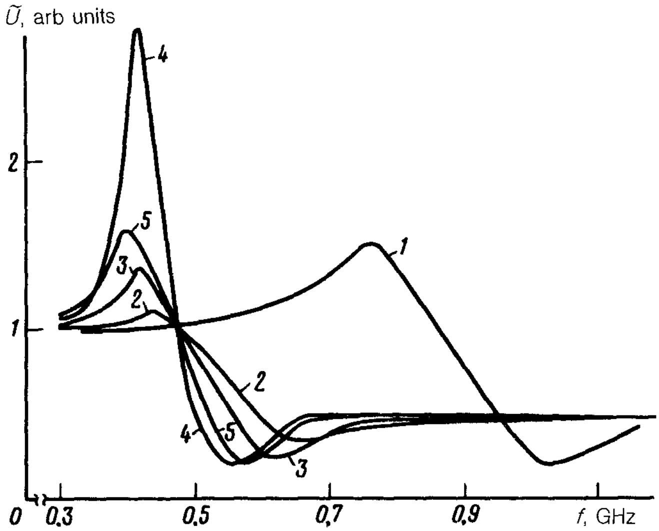


FIG. 2. $\tilde{U}$ versus $f$ at $H$ = const for a sample with $n_s = 3.86\times10^{11}$ cm$^{-2}$ and $P = 1.2$ cm. 1—$H = 22$ kOe; 2—$H = 34$ kOe; 3—$H = 38$ kOe; 4—$H = 40$ kOe; 5—$H = 42$ kOe.

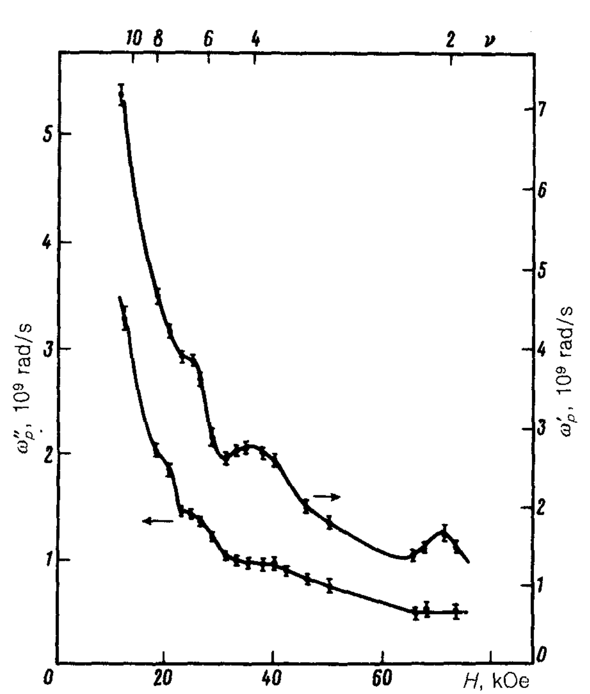


FIG. 3. The frequency $\omega_p'$ and the damping $\omega_p''$ and the damping $\omega_p''$ of the fundamental edge-magnetoplasmon mode versus $H$ and the filling factor $\nu$ for a sample with $n_s = 3.48\times10^{11}$ cm$^{-2}$ and $P = 1.0$ cm.

Figure 3 shows $\omega_p'$ and $\omega_p''$ as functions of $H$. Both of these curves agree qualitatively with the theory [expressions (1) and (2)]. A quantitative agreement—tested in the region of the $\sigma_{xy}(H)$ plateau—is reached when we set $n = 1$ and $\epsilon \approx 1.5$ in (1) and (2) and use for $\sigma_{yx}/\sigma_{xx}$ the values found from dc measurements. In the zeroth approximation in the parameter $qd \ll 1$, the electric field of an edge magnetoplasmon is in the volume around the sample, for the most part, and we have $\epsilon = 1$. For the sample in Fig. 3, this approximation is not very accurate ($qd \simeq 0.25$), and there is a component of $\epsilon$ which is a correction due to $\epsilon_{\mathrm{GaAs}} = 12.8$. The value $\epsilon \approx 1.5$ thus seems reasonable. The data in Figs. 2 and 3 also furnish a qualitative explanation for all the structural features on the experimental curves in Fig. 1 and the results of Ref. 4. The oscillations of $\widetilde{U}(H)$ and of the signal in Ref. 4 are attributed to the oscillatory dependence $\tilde{\epsilon}[\omega_p'(H)]$. Their amplitude increases toward the resonance. The inversion of the extrema of certain oscillations (curves 5 and 6 in Fig. 1 at $H \approx 35$ kOe), result from a change in the sign of $\partial \widetilde{U}/\partial\omega$, since we have sign $\partial \widetilde{U}/\partial\omega = -$ sign $\partial \widetilde{U}/\partial\omega_p'$ for $\tilde{\epsilon} = \tilde{\epsilon}(\omega/\omega_p)$.

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