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Influence of retardation effects on 2D magnetoplasmon spectrum

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Within dissipationless limit the magnetic field dependence of magnetoplasmon spectrum for unbounded 2DEG system found to intersect the cyclotron resonance line, and, then approaches the frequency given by light dispersion relation. Recent experiments done for macroscopic disc-shape 2DEG systems confirm theory expectations.

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Plasma oscillations in two-dimensional electron gas(2DEG) were first predicted in the middle 60th [1], and, then observed experimentally in liquid helium system [2] and silicon inversion layers [3, 4]. The recent observation [5] of magnetoplasmon(MP) spectrum reported to be affected by retardation effects, discussed more than tree decades ago, recommences the interest to the above problem. With retardation effects accounted we analyze 2D MP spectrum first derived in Ref. [6]. It will be argued that in large-mesa 2D systems [5] the role of edges becomes less significant, therefore the observed MP features can be accounted within conventional MP theory [6] for unbounded 2D system.

Let us assume unbounded 2D electron gas imbedded in a dielectric in the presence of the perpendicular magnetic field. Following Ref. [7], the Maxwell equations for in-plane components of the electrodynamic potentials $\mathbf{A}, \phi$ yield

$$\Box\phi = 4\pi\rho, \quad \Box\mathbf{A} = \frac{4\pi\mathbf{j}}{c},$$
$$\mathrm{div}\mathbf{A} + \frac{\epsilon}{c}\frac{\partial\phi}{\partial t} = 0, \tag{1}$$
$$\mathbf{j} = -\sigma^{*}\left(\nabla\phi + \frac{1}{c}\frac{\partial\mathbf{A}}{\partial t}\right),$$

where $\Box = (\epsilon/c^2)(\partial^2/\partial t^2) - \Delta$ is the d'Lambert operator, σ^{*} the conductivity tensor. Assuming the magnetoplasmon $e^{(i\mathbf{qr}-i\omega t)}$ propagated in 2DEG, and, then separating longitudinal and transverse in-plane components of the vector potential [7], 2D magnetoplasmon dispersion relation yields:

$$\left(\frac{\epsilon}{2\pi} + \frac{i\sigma_{xx}\kappa}{\omega}\right)\left(\frac{1}{2\pi} - \frac{i\omega\sigma_{xx}}{c^2\kappa}\right) + \frac{\sigma_{yx}^2}{c^2} = 0, \tag{2}$$

where $\kappa = \sqrt{q^2 - \epsilon w^2/c^2}$. This result is exactly that obtained by Chiu [6]. Within dissipationless limit the components of the conductivity tensor

$$\sigma_{xx} = \sigma_{yy} = \frac{i\omega ne^2}{m(\omega^2 - \omega_c^2)}, \quad \sigma_{yx} = -\sigma_{xy} = \frac{i\omega_c}{\omega}\sigma_{xx}$$

allow us to simplify Eq.(2) as follows

$$(Q^2 - \Omega^2)^{\frac{1}{2}} = \sqrt{\frac{(1+\Omega_c^2-\Omega^2)^2}{4} + \Omega^2} - \frac{1+\Omega_c^2-\Omega^2}{2}, \tag{3}$$

where we introduce the dimensionless wave vector $Q = qc/\omega_p\sqrt{\epsilon}$, frequency $\Omega = \omega/\omega_p$ and cyclotron frequency $\Omega_c = \omega_c/\omega_p$, the all are expressed in a certain frequency unit $\omega_p = 2\pi ne^2/mc\sqrt{\epsilon}$. We further clarify the physical sense of ω_p.

In absence of the magnetic field Eq.(3) reproduces the conventional [1, 7] zero-field longitudinal plasmon dispersion relation $\epsilon = 2\pi i\sigma_{xx}\kappa/\omega$ as follows

$$Q^2 = \Omega_0^2 + \Omega_0^4. \tag{4}$$

In the short-wavelength limit $Q \gg 1$ one obtains well-known square-root plasmon dispersion as $\omega_0 = \sqrt{(2\pi ne^2/m\epsilon)q}$. The opposite long-wavelength limit case $Q \ll 1$ corresponds to light dispersion relation $\omega_l = cq/\sqrt{\epsilon}$ shown in Fig.1 by the dotted line. In actual fact, ω_p denotes the frequency when the zero-field plasmon phase velocity deduced from square-root dispersion law approaches the light velocity. Note that the authors [5] demonstrate the excellent agreement between the zero-field 2D plasmon theory [1, 8] and experimental results. For different disc-geometry quantum well samples the wave vector reported to relate to 2DEG disc diameter via $q = \alpha/d, \alpha = 2.4$ in consistent with theory $\alpha = 3\pi/4$ [9].

The question we attempt to answer is whether retardation effects should modify 2D magnetoplasmon spectrum. In actual fact, Eq.(3) demonstrates that at fixed

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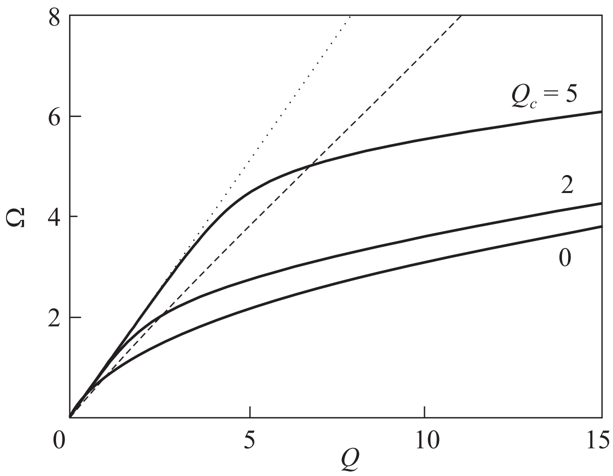

Fig.1. Magnetoplasmon dispersion at $\Omega_c = 0$ (zero-field plasmon); 2; 5. Asymptote: light dispersion (dotted line). Dashed line represents the dependence $\Omega_{cr}(Q)$ when the condition $\omega = \omega_c$ is satisfied

Q the plasma frequency grows with magnetic field, and, then intersects the CR line(see Figs.1, 2). This behavior is, however, unexpected within edge magnetoplasmon formalism [10, 11]. Substituting $\Omega = \Omega_c$ into Eq.(3) we derive the dependence(Fig.1, dashed line) of the MP-CR intersection frequency vs wave vector $\Omega_{cr}(Q)$. It is to be noted that low-field magnetoplasmon remains longitudinal at $\omega_c < \omega$, and, then becomes transverse one when $\omega_c > \omega$.

Further increase of the magnetic field results in saturation of the magnetoplasmon spectrum (Fig.2) at certain frequency given by the light dispersion relation.

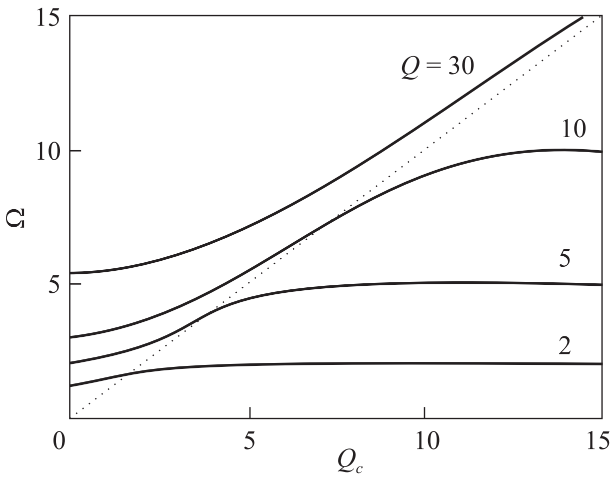

Fig.2. 2D magnetoplasmon spectra vs dimensionless cyclotron frequency Ω_c for different MP wave vector $Q = 2, 5, 10, 30$. Arrows represent the light frequency. Cyclotron resonance is represented by dotted line

Experimentally, irrespective to 2DEG density the macroscopic(d = 1mm) disc-mesa samples demonstrate [5] MP spectra(with the lowest radial and angular momenta numbers) cut-off at certain frequency 50 GHz. The latter is larger than that deduced from light dispersion relation $\omega_l/2\pi = 32$ GHz, where we use GaAs dielectric constant $\epsilon = 12.8$. However, for actual (GaAs + free space) system the average dielectric constant [9], i.e $\epsilon^* = (1+\epsilon)/2$, provides much better agreement(see Table), namely that $f_l = (1/2\pi)(qc/\sqrt{\epsilon^*}) = 44$ GHz. Note, in contrast to predicted MP spectrum saturation in strong fields, the experiments [5] demonstrate intriguing zigzag behavior remaining unexplained within our formalism.

It is instructive to compare the lowest angular momentum MP spectrum reported in [5] with that provided by the present theory. For example, for GaAs/AlGaAs heterostructure($n = 2.54 \cdot 10^{11}\mathrm{cm}^{-2}$, $m = 0.067 m_0$, $d = 1$ mm, $\epsilon = 12.8$) one obtains $\omega_p = 5.6 \cdot 10^{10}\,\mathrm{c}^{-1}$ and $Q = 3.6$. With the help of Eq.(4) and Eq.(3), the zero-field plasmon frequency $f_0 = \omega_0/2\pi = 16$ GHz and $f_{cr} = \omega_{cr}/2\pi = 25$ GHz found to be comparable with experimental values 20 GHz and 32 GHz respectively. The excellent agreement($f_0 = 21$ GHz $f_{cr} = 34$ GHz respectively) with experiment is provided using the average dielectric constant ϵ^*. Table represents the comparison between the present theory and available experimental data. Note, in [5] the experimental range of frequencies < 60 GHz is less than that expected to include MP-CR intersection and subsequent spectra saturation in low density, small disc-mesa 2DEG case.

Theory vs experiment [5]

d,mm	$n \cdot 10^{10}\mathrm{cm}^{-2}$	Q	f_0 *,GHz	f_{cr},GHz	f_l,GHz
1.0	66.0	1.4	**31**/27	**36**/37	**44**/50
1.0	25.4	3.6	**21**/20	**34**/32	**44**/50
0.2	4.2	108	**21**/20	**155**/-	**218**/-
0.1	4.2	359	**23**/29	**308**/-	**435**/-

(* f values are given as theory/experiment)

In conclusion, we demonstrate the strong influence of retardation effects on magnetoplasmon spectrum in unbounded 2DEG system. The magnetic field dependence of MP spectrum found to intersect the cyclotron resonance line, and, then approaches the frequency given by light dispersion relation. The recent MP experiments in large disc-shape 2DEG system confirm theory predictions.

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