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# INFLUENCE OF TWO-DIMENSIONAL COLLECTIVE MODES ON THE MAGNETO-INFRARED ABSORPTION IN DOUBLE LAYER GaAs QUANTUM WELLS WITH HIGH ELECTRONIC DENSITY

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## ABSTRACT

With the aid of the Green function formalism developed by the authors, we discuss the conditions allowing resonances between the cyclotron frequency $\omega_c$ and the *TO* and *LO* modes in the region of the spectra when retardation effects are taken into account in a quantum well with a double layer of two-dymensional (2D) electrons. It is shown that for cyclotron frequencies in the optical retarded region of spectra, the starting frequencies of in phase oscillations close to $\omega_c$ show a shift proportional to the density of carriers and to the applied field.

## RESUMEN

Con la ayuda del formalismo de funciones de Green desarrollado por los autores, se discuten las condiciones que permiten las resonancias entre la frecuencia ciclotrónica $\omega_c$ y los modos *TO* y *LO* en la región del espectro donde los efectos de retardo se toman en cuenta en un pozo cuántico con una capa doble de electrones bidimensionales (2D). Se muestra que para frecuencias ciclotrónicas en la región óptica retardada del espectro las frecuencias iniciales de las oscilaciones enfase cercanas a $\omega_c$ presentan un corrimiento proporcional a la densidad de portadores y al campo aplicado.

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**Key words**: magnetoplasmons, quantum well, cyclotron resonance, optical phonons.

## Introduction

Recently, retardation effects were observed in the spectrum of two-dimensional plasmons in high-electron-mobility GaAs=AlGaAs quantum wells [1]. This pioneering observation recommences the interest to the above problem [2]. 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. The hybrid cyclotron-plasmon modes which appear when retardation effects are accounted show unusual dependence of the frequency on B field. In the performed experiments the measured frequencies allowed to neglect the dispersion of the dielectric permittivity, i.e., were far from the reststrahlen where optical phonons play an important role.

The cyclotron resonances of high density and high mobility electron space-charge layers in thin GaAs quantum wells in Faraday geometry at frequencies covering the GaAs reststrahlen regime were considered experimentally by Poulter *et al.* [3,4]. It was observed that under resonant conditions, when the cyclotron resonance reaches energies close to the longitudinal optical phonon energy, there is no interaction between the cyclotron and phonon modes. Instead, an interaction is observed with a mode which has an energy close to the transverse optic (TO) phonon energy. The results were interpreted with reference to a model appropriate only for bulk systems as a coupling to a collective magneto-plasmon-phonon mode. This model was criticized by B. Zhang *et al.* [5], and some qualitative considerations on the character of the spectra in the long-wavelength limit were included, but without consideration of retardation effects. In the system considered in [3,4] it is possible to have two layers of two-dymensional (2D) electrons, which have a collective excitation spectrum with frequencies depending on a wave vector $\boldsymbol{k}$ parallel to the layer plane. Recently [6] a Green function formalism was proposed in order to calculate the components of the photon propagator in a double layer electron system in a single quantum well with high electronic densities in a transversal magnetic field. The power spectra and the dispersion of the sets of *nonretarded* collective modes which arise in such system were discussed for cyclotron frequencies lying in the reststrahlen region of the spectra.

In a double layer system it is possible the propagation of an acoustic plasmon [7], corresponding to out of phase oscillations between the 2D layers. It is the aim of this communication to discuss the character of the coupled magnetoplasmon-phonon modes when *retardation* effects are taken into account, with special emphasis on the out of phase oscillations. which can arise in the considered system.

## Model

As in [6], we consider a bilayer system of two-dimensional ($2D$) electron layers with carrier concentration $n_s$ located at the surfaces $z$=0, $d$. The dielectric function of such system is $\varepsilon(z)=\varepsilon_1[\theta(-z)+\theta(z-d)]+\varepsilon_2(\omega)[\theta(z)\theta(d-z)]$, with $\varepsilon_2(\omega)=\varepsilon_\infty(\omega^2-\omega_{LO}^2)/[\omega^2-\omega_{TO}^2]$, $\varepsilon_\infty$ being the high-frequency dielectric permittivity of the well at $0<z<d$; $\omega_{TO}$ and $\omega_{LO}$ are, respectively, the frequencies of the transversal ($TO$) and longitudinal ($LO$) optical modes. The dynamics of such electron system induces a $2D$ current density $j_i(\boldsymbol{r},t)=\sigma_{ij}[E_j(\boldsymbol{r}_{||},0,t)\delta(z)+E_j(\boldsymbol{r}_{||},d,t)\delta(z-d)]$, where $\boldsymbol{r}=(\boldsymbol{r}_{||},z)$, $\sigma_{ij}$ are the components of the magnetoconductivity tensor of the 2D electron gas and $E_j(\boldsymbol{r}_{||},z,t)$ is the dynamic electric field at $z$. The dispersion law of the collective modes arising in the considered sytem corresponds to the roots of the equation

$$\begin{vmatrix} f_1 & f_2 & f_H & f_H \\ f_2 s^{-1} & f_1 s & f_H s^{-1} & f_H s \\ g_H & g_H & g_1 & g_2 \\ g_H s^{-1} & g_H s & g_2 s^{-1} & g_1 s \end{vmatrix} = 0, \qquad (3)$$

where $f_\pm=\varepsilon_1/\kappa_1\pm\varepsilon_2/\kappa_2+4\pi i\sigma_{xx}/\omega$, $g_\pm=\kappa_1\pm\kappa_2-4\pi i\omega\sigma_{yy}/c^2$, $f_H=4\pi i\sigma_{xy}/\omega$, $g_H=4\pi i\omega\sigma_{yx}/c^2$, $s=\exp(\kappa_2 d)$, $\kappa_i=(k^2-\varepsilon_2\omega^2/c^2-)^{1/2}$, $i$=1,2. It can be shown that (3) reduces to

$$\left(\frac{4\pi\sigma_{xy}}{c}\right)^2+\left[\frac{\varepsilon_1}{\kappa_1}+\frac{\varepsilon_2}{\kappa_2}S\left(\frac{\kappa_2 d}{2}\right)+\frac{4\pi i\sigma_{xx}}{\omega}\right]\left[\kappa_1+\kappa_2 S\left(\frac{\kappa_2 d}{2}\right)-\frac{4\pi i\omega\sigma_{yy}}{c^2}\right]=0, \qquad (4)$$

where $S(x)$=tanh($x$) (respectively, $S(x)$=coth($x$)) for in phase (respectively, out of phase) oscillations at the electron layers. This dispersion relation contains as particular cases the dispersion relations of confined polariton modes in a slab of ionic crystal in the non-retarded region of spectra ($\sigma_{ij}$=0) [8] and the non-retarded collective modes of a double layer sheet [9].

**Diccussion**

Let us discuss our results in the reststrahlen region for magnetic fields corresponding to cyclotron frequencies obeying $\omega_{TO}\leq\omega_c\leq\omega_{LO}$. We use the following set of parameters [3]: $d$=10 nm, $n_s=1.28\times10^{12}$ cm$^{-2}$, $\hbar\omega_{TO}$=33.6 meV, $\omega_{LO}=1.08\omega_{TO}$, $\varepsilon_\infty$=10.6, $m=0.77m_0$ (where $m_0$ is the free electron mass). For frequencies in the considered region non-local effects on the magnetoconductivity tensor can be neglected and Drude like expressions for $\sigma_{ij}$ can be used.

For in phase oscillations there is a mode starting at the line $\kappa_1$=0 with frequency

$$\omega=\omega_c-2(\varepsilon_\infty-\varepsilon_1)^{-1}[(\omega_c^2-\omega_{TO}^2)/(\omega_O^2-\omega_c^2)](\omega_{pl}^2/2\omega_c), \quad (5)$$

which is below the ciclotron frequency $\omega_c$. Due to the fact that for the samples considered in [3] $\omega_{pl}<\omega_{TO}$, the shift $\delta\omega/\omega_{TO}$ of the starting frequency is relatively small. These results are ilustrated in Fig. 1a for different densities of carriers at the 2D layers. Note that for $\omega_c=\omega_{TO}$ the shift $\delta\omega/\omega_{TO}$ is zero, i.e., the frequency at which the collective mode starts is exactly $\omega_c$. This means that the magnotoplasmon is pinned by the transverse optical mode, as was observed in [3].

The frequency of the described mode rises with $k$, until it reaches $\omega_c$. These results are ilustrated in Fig. 1b for the special case of resonance between the cyclotron frequency and the longitudinal optical phonons.

Additionally, there is a second mode of in phase oscillations starting at $\kappa_1$=0 with a frequency

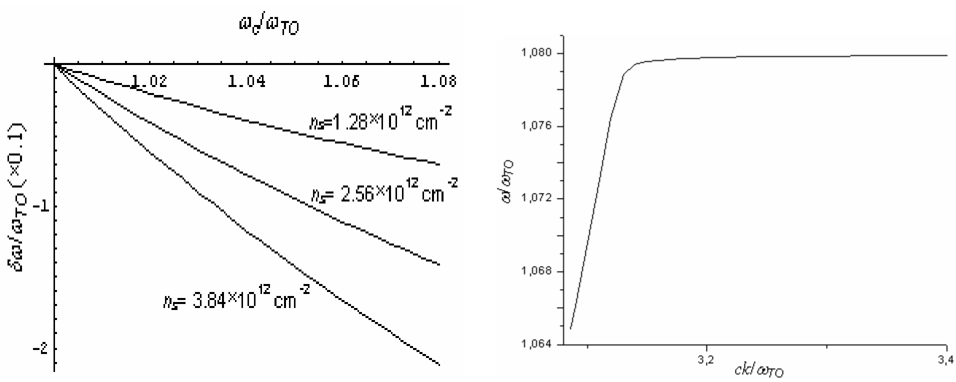
$$\omega=\omega_O+2(\varepsilon_\infty-\varepsilon_1)^{-1}[(\omega_O^2-\omega_{TO}^2)/(\omega_O^2-\omega_c^2)](\omega_{pl}^2/2\omega_O), \quad (6)$$

where $\omega_O^2=[(\varepsilon_0-\varepsilon_1)/(\varepsilon_\infty-\varepsilon_1)]\omega_{TO}^2$. With $k$ this mode increases linearly and its dispersion relation corresponds to that of a electromagnetic wave propagating in an unbounded medium with permitivity $\varepsilon_1$. This frequency is above the frequency of the longitudinal optical phonons.

For out of phase oscillations the starting frequency is given by

$$\omega=\omega_c[1-(\omega_{pl}d/c)^2]\approx\omega_c, \quad (7)$$

i.e., the shift of the cyclotron frequency of out of phase magnetoplasmons in the retarded region of the spectra is negligible.




*(a)* *(b)*

Figure 1

The behaviour of the modes in the nonretarded region of spectra, with special emphasis on the $kd$>>1 region is described in [6].

## Conclusion

In conclusion, for applied magnetic fields such that, the electron cyclotron frequency lies in the reststrahlen retarded region of spectra, the starting frequencies of in phase oscillations close to $\omega_c$ undergoe a shift of the order $(\omega_c^2-\omega_{TO}^2)\omega_{pl}^2/2\omega_c$, which gives account to the fact of pinning of the ciclotron frequency to the frequency of transversal optical phonons.

The results of this work can be extended to the more difficult case of coupled magnetoplasmon-phonon modes in parallel magnetic fields, where additional bands of undamped plasmons have been predicted for quantum wells with two-layer plasmon modes induced in a single quantum well by in-plane magnetic fields [7].

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