Magneto Infrared Absorption in High Electron Density GaAs Quantum Wells

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Magneto infrared absorption measurements have been performed in a highly doped GaAs quantum well which has been lifted off and bonded to a silicon substrate, in order to study the resonant polaron interaction. It is found that the pinning of the cyclotron energy occurs at an energy close to that of the transverse optical phonon of GaAs. This unexpected result is explained by a model taking into account the full dielectric constant of the quantum well.

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The Fröhlich interaction is one of the main electron-phonon intrinsic interactions in polar materials and has attracted much attention both in three-dimensional (3D) [1] and two-dimensional (2D) [2,3] structures. The most spectacular manifestation of this interaction is the effect of resonant magnetopolaron coupling (RMPC), i.e., an anticipated anticrossing behavior between the $|n = 0 + 1\ \mathrm{LO\ phonon}\rangle$ state and the $|n = 1\rangle$ state, n being the Landau level (LL) index, when the cyclotron frequency $\omega_c = eB/m^*$ equals the longitudinal optical (LO) phonon frequency ω_{LO} (B is the applied magnetic field and m^* is the carrier effective mass). This has been studied theoretically using both perturbation theories [1,2] and the memory function approach [3]. Whereas the former method restricted the analysis to vanishing doping levels, the latter has been extended to include the electron-electron interaction, predicting a disappearance of the coupling with increasing electron density. However, in doped systems ω_{LO} is no longer a normal mode of the system and couples to the plasma mode ω_p in 3D [4] or to intersubband plasmon modes in 2D [5,6], thus giving rise to new longitudinal modes with frequencies ω_L^- and ω_L^+. We argue here that these new coupled modes are the only excitations which can couple to electrons via their associated macrosopic electric field. Therefore the theoretical treatment of doped systems assuming the existence of uncoupled pure LO phonons is obviously not consistent.

Experimentally there have been numerous investigations into resonant polaronic coupling [7–11], but the results are often obscured by the presence of the reststrahlen band, and the strong dielectric effects in this region make the comparison between experiment and theory unreliable. This is a major obstacle that we have been able to overcome in the present investigation. In this Letter we report on polaronic effects in a high carrier density GaAs quantum well. The experiment shows no polaron coupling involving the undressed LO phonon mode; instead the pinning of the cyclotron resonance at a frequency close to ω_{TO} is clearly observed. The pinning energy is explained in terms of coupling of the cyclotron resonance excitation with the magneto-plasmon-LO-phonon mode ω_L^- which occurs in this structure around the frequency of the transverse optical (TO) phonon ω_{TO}.

The samples studied were grown by molecular-beam epitaxy on semi-insulating GaAs substrates as described in Ref. [12]. A quantum well (QW), of width $L = 10$ nm, is sandwiched between two 60 period AlAs/GaAs superlattices which are δ-doped by silicon in the third GaAs well on either side of the QW. This results in high mobility electrons in the QW, with additional electrons being trapped by AlAs X-band-like states in the barrier layer adjacent to the doped GaAs well. This configuration provides high electron densities, high electron mobilities, and also maintains a symmetric band structure. A number of such samples have been studied demonstrating all nonlinear effects in the RMPC region, but the data at higher fields are obscured by the reststrahlen band absorption. In order to overcome this problem we have, for one of the samples, lifted off the epilayer from the substrate by selective etching and deposited it on a wedged silicon substrate. The sample area is of the order of 5 mm^2 and Hall measurements on a parent sample provided a value for the carrier concentration $n_s = 1.28 \times 10^{12}$ cm^{-2} and a mobility of 114 m^2/V s. Band structure calculations show that the splitting E_{01} of the two lowest electric subbands E_0 and E_1 equals 120 meV and the 2D electron gas (2DEG) occupies only the E_0 level. Transmission measurements on this sample were performed with a Bruker IFS-113 Fourier transform spectrometer, at a temperature of 1.7 K, in magnetic fields B up to 28 T applied perpendicularly to the 2DEG plane. The infrared radiation was detected by a silicon bolometer placed *in situ* behind the sample which was mounted on a rotating sample holder. For each value of B a reference and sample spectra are recorded and ratioed, the reference spectrum being that of a piece of the wedged silicon substrate. Therefore the results displayed in Fig. 1 are the absolute transmission spectra eliminating the response of the experimental setup.

The spectra (Fig. 1) exhibit two well defined TO absorption lines at $\hbar\omega_{\mathrm{TO}}(\mathrm{GaAs}) = 33.6$ meV and

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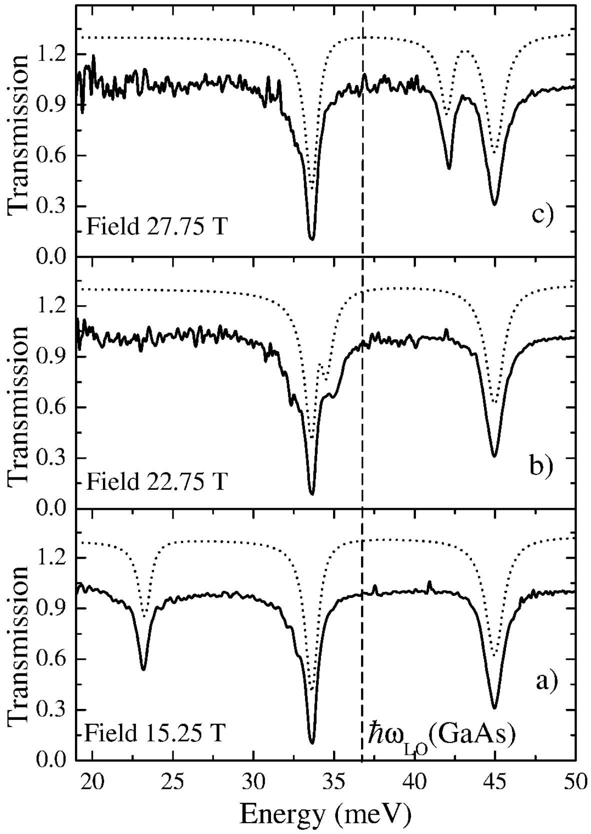

FIG. 1. Examples of the spectra obtained at (a) 15.25 T, (b) 22.75 T, and (c) 27.75 T. The dotted lines show the theoretical results (shifted vertically for clarity) of the multilayer transmission response of the structure as described in the text.

$\hbar\omega_{TO}$(AlAs) = 44.9 meV together with a characteristic B dependent cyclotron resonance (CR) absorption line which appears as a single line at low and high fields but splits into two components below and nearby ω_{TO}(GaAs) (see below). It is important to note (Fig. 1b) that the observation of the CR structure is obscured only in a narrow energy range around ω_{TO}(GaAs) but not in the region where the CR line coincides with ω_{LO}(GaAs). To understand the data we have calculated the optical transmission of the whole structure using the multilayer dielectric model [13] and the exact layer sequence of the samples. As evidenced in Fig. 1, we obtain a very reasonable fit for both TO absorption lines with the following high frequency dielectric constant, energies, and damping parameters $\varepsilon_\infty = 10.6$ (8.4), $\hbar\omega_{LO} = 36.3$ (49.1), and $\gamma_{TO} = 0.25$ (0.56) meV for GaAs (AlAs), respectively. The CR absorption is mimicked neglecting occupation effects and polaronic coupling, with a single oscillator corresponding to the reduced effective mass $m^*/m_0 = 0.077$ (where m_0 is the free electron mass) and a damping parameter $\gamma_e = 0.1$ meV.

Although we have been able to closely reproduce the experimental results, the small low energy asymmetry of the GaAs TO line (observed at any fields and possibly resulting from the confined phonon models) is not accounted for by the model. In order to be more accurate we ratioed the transmission spectra at finite B by the absolute transmission spectra recorded at $B = 0$. The resulting curves are shown in Fig. 2. The ω_{TO} absorption is now also absent and we can more clearly follow the evolution of the CR absorption structure. Nevertheless, we prefer to be rather conservative with respect to our data treatment and have ignored structures appearing in the frequency range around $\hbar\omega_{TO}$ when fitting the resonances with Lorentzians and plotting, in Fig. 3, the obtained transition energies versus B. Beyond 17 T when the filling factor $\nu < 3$ ($\nu = n_s/G_B$, $G_B = eB/h$ is the LL degeneracy) the CR line clearly splits into two components A and B (Figs. 2 and 3a), whereas a single CR line denoted C is observed above 23 T.

Let us first concentrate on the two, A and B, CR components. Line B is clearly observed for $\nu < 3$ (Fig. 3) and progressively disappears from the spectrum. It is not observed in high magnetic fields when ν approaches 2 because the $n = 1$ LL gets depopulated. The splitting of the CR into A and B components is attributed to two possible different CR transitions involving the $n = 0$ (line A) and the second $n = 1$ (line B) Landau level in the initial state (see Fig. 3 inset). These two transitions involve opposite

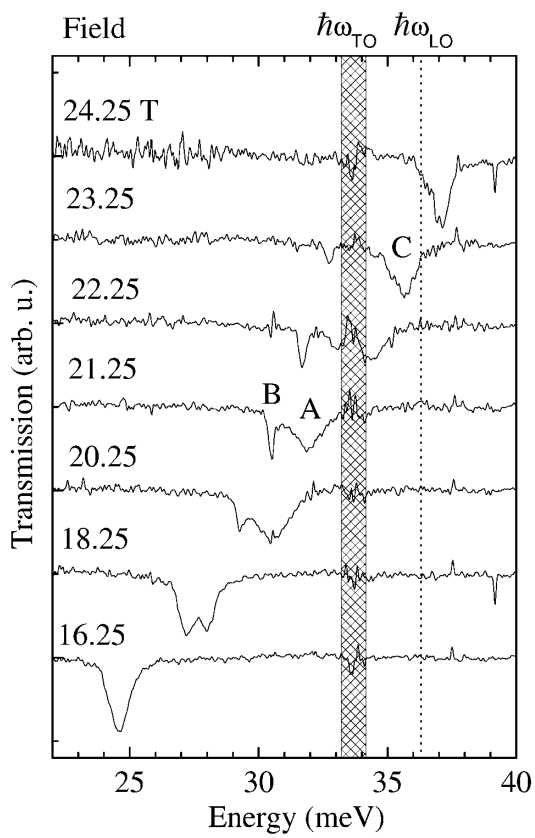

FIG. 2. Characteristic spectra at various magnetic fields. The splitting of the CR line into A and B components appears clearly below $\hbar\omega_{TO}$. The hatched area corresponds to the width of the TO absorption line.

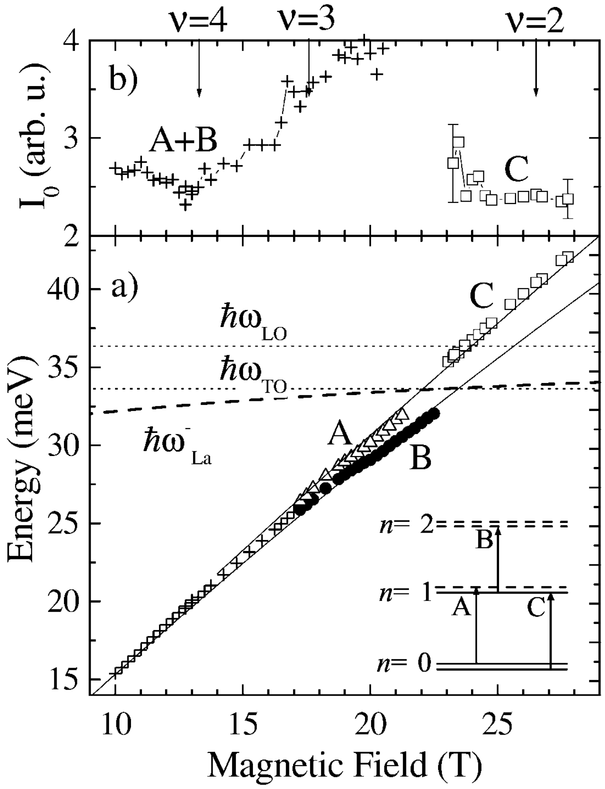

FIG. 3. (a) Magnetic field variation of the different CR line energies, determined by fitting the zero field ratioed data using Lorentzians. The thin solid lines correspond to the calculated CR transitions including NP effects. (b) The corresponding total integrated absorption intensity I_0 in arbitrary units for the CR lines.

spin electrons and can differ in energy due to the band nonparabolicity (NP). Indeed, due to combined effects of confinement, high doping levels, and high magnetic fields one spans an energy range where NP effects are important. In such a case, one can write within the random phase approximation [5,13], the generalized cyclotron active dielectric function ε_a of the GaAs in the Faraday configuration, neglecting damping and polaronic effects, as

$$\varepsilon_a(\omega) = \varepsilon_\infty \frac{\omega_{LO}^2 - \omega^2}{\omega_{TO}^2 - \omega^2} - \frac{4\pi e^2 G_B}{L\omega} \times \sum_{n=0}^{\infty} \sum_{\sigma} \frac{(f_{n,\sigma} - f_{n+1,\sigma})(n+1)}{[\omega - (E_{n+1,\sigma} - E_{n,\sigma})/\hbar] m^*_{n,\sigma}}, \tag{1}$$

where $f_{n,\sigma}$ is the distribution function of electrons in the nth LL, with spin σ, energy $E_{n,\sigma}$, and effective masses $m^*_{n,\sigma}$ and $\sum_{n,\sigma} G_B(f_{n,\sigma} - f_{n+1,\sigma})(n+1) = n_s$. Equation (1) is the 3D dielectric constant which is used for the QW layer in the multilayer dielectric model, the quasi-2D character being introduced through the boundary conditions [13] imposed on the electric and magnetic components of the radiation field at each interface. Calculations performed with a ten-band $\mathbf{k} \cdot \mathbf{p}$ model [14] reveal that the splitting between peaks A and B is due to the NP effects with transitions originating from the $n = 0$ and $n = 1$ LL, respectively, in accordance with the previous discussion (Fig. 3a, thin lines).

It is natural to assume that lines A and C represent the same transition observed on either side of $\hbar\omega_{TO}$. We argue here that this transition suffers an interaction in the vicinity of $\hbar\omega_{TO}$. The interaction is clearly inferred from the fact that peaks A and C have a width increasing significantly on both sides of $\hbar\omega_{TO}$ (Fig. 2). What convinces us more is the weak change in the slopes of the energy variation of lines A and C below and above $\hbar\omega_{TO}$ and the increase of the *total* integrated CR intensity I_0 around $\hbar\omega_{TO}$ (Fig. 3b) whereas, as expected for a noninteracting system, I_0 remains constant at high and low fields. The amplitude of an eventual anticrossing between lines A and C is, however, hard to ascertain accurately due to possible experimental errors in estimating the peak position in the closed vicinity of $\hbar\omega_{TO}$. The interaction with phononlike modes occurs around $\hbar\omega_{TO}$ whereas no singularity is observed around $\hbar\omega_{LO}$. The absence of this singularity has already been reported [7,8] on samples with lower doping levels ($\nu < 2$) but not explained.

An experiment that can also probe the electron-phonon-like modes is the magnetophonon resonance (MPR) effect which manifests itself as an oscillatory component, in reciprocal magnetic field, of the resistivity. This component is proportional to $\cos(2\pi\omega_0/\omega_c)$ [15], where ω_0 has been up till now assumed to be equal to ω_{LO}. We have performed magnetoresistivity measurements on the parent sample and observed the MPR oscillations between 5 and 15 T for temperatures ranging from 90 to 140 K (Fig. 4). These experiments provide the mean value $\hbar\omega_0(\text{meV})m^*(m_0) = 2.60 \pm 0.05$ when interpreted with standard theory [15]. Taking for m^* the value of 0.078 measured by cyclotron resonance at this temperature, we deduce a value $\hbar\omega_0 = 33.3 \pm 0.7$ meV which is close to $\hbar\omega_{TO}$ and definitively lower than $\hbar\omega_{LO}$. We therefore confirm that there exist longitudinal modes with energies close to $\hbar\omega_{TO}$ which interact with the CR mode.

In order to identify the nature of these modes, one can use a simplified version of Eq. (1) neglecting the NP effects:

$$\varepsilon_a(\omega) = \varepsilon_\infty \frac{\omega_{LO}^2 - \omega^2}{\omega_{TO}^2 - \omega^2} - \frac{\omega_p^2}{\omega(\omega - \omega_c)} \tag{2}$$

with $\omega_p^2 = 4\pi N e^2/m^*$, where $N = n_s/L$ is the corresponding 3D electronic density. The longitudinal solution of Eq. (2) ($\rightarrow \varepsilon_a = 0$) is composed of two modes ω_{La}^- and ω_{La}^+ [16] starting from ω_L^- and ω_L^+ at $B = 0$ and pinned to $\omega = \omega_{LO}$ and $\omega = \omega_c$, respectively, for extreme values of B. It is clear from Eq. (2) that $\varepsilon_a(\omega)$ has two poles at $\omega = \omega_c$ and $\omega = \omega_{TO}$ and therefore a zero (corresponding to ω_{La}^-) in between. When $\omega = \omega_c = \omega_{TO}$, ω_{La}^- coincides with the common pole. This property is independent on ω_p^2 (and therefore on N); the $\omega_{La}^-(N, B)$ curves display

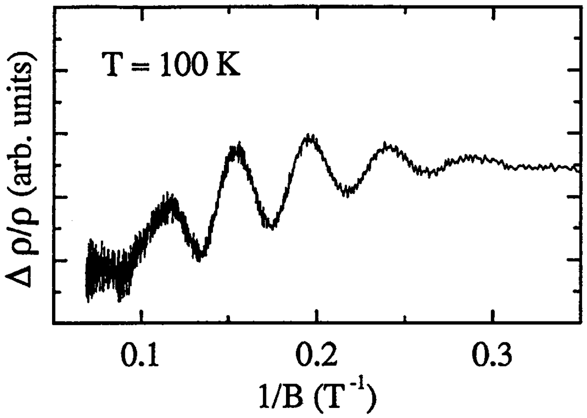

FIG. 4. Oscillatory component of the resistivity versus the inverse of B.

a fixed point at $\omega = \omega_{\mathrm{TO}}$. The resulting curve $\omega_{La}^{-}(B)$ is displayed in Fig. 3a for the present case: it is clear that the resonant interaction should occur between *this mode* and the CR mode always at $\omega = \omega_{\mathrm{TO}}$. The calculated mean frequency is in reasonable agreement with our experimental findings. Though the resonant interaction occurs at $\omega = \omega_{\mathrm{TO}}$ this does not imply that the maximum interaction occurs at this energy: the reason is that the macroscopic electric field associated with ω_{La}^{-} and which governs the strength of the interaction goes to zero, in the absence of damping, when $\omega_{La}^{-} = \omega_{\mathrm{TO}}$. One can note, for instance, that the amplitude of the MPR oscillations decreases at high fields which could also be the signature of the vanishing interaction.

This interpretation is based on a 3D-like model for the dielectric constant. In a 2D model [5,6], intersubband plasmon modes also exist. They can be measured by resonant Raman scattering measurements [17] which in this sample give a longitudinal transition at 35.5 ± 0.05 meV. This mode which propagates in a 2D plane, is in the infrared range essentially independent of B [6]. It does not seem that the observed coupling occurs with this mode. A more quantitative analysis requires theoretical efforts for a complete treatment of polaronic coupling with magneto-plasmon-phonon modes.

In conclusion, we have performed magnetoabsorption measurements on a highly doped epilayer lifted off the substrate and bonded to a silicon substrate. We have demonstrated that near the ω_{TO} frequency the CR line splits into two components due to occupation and nonparabolicity effects. The CR transition originating from the $n = 0$ LL has been investigated through the reststrahlen band and no coupling with undressed LO phonon modes has been observed. The CR mode has been found to interact with a longitudinal mode which has been identified by magnetophonon resonance experiment and which, for our sample, has an energy close to $\hbar\omega_{\mathrm{TO}}$. We have assigned this mode to the low energy coupled magneto-plasmon-phonon mode of the GaAs QW. We hope that this Letter will stimulate theoretical work to identify the nature of the interaction between electrons and this type of mode.

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