Magneto infra-red absorption in high electronic density GaAs quantum wells

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Magneto infra-red 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.

The Fröhlich interaction is one of the main electron-phonon intrinsic interactions in polar materials, and has attracted much attention both in 3-dimensional (3D) [1] and 2-dimensional (2D) [2, 3] structures. The most spectacular manifestation of this interaction is the effect of resonant magneto-polaron coupling (RMPC), i.e. an anticipated anticrossing behaviour between the $|n = 0 + 1\text{ LO phonon}|$ state and the $|n = 1\rangle$ state, $n$ being the Landau level (LL) index, when the cyclotron frequency $\omega_c = eB/m^* \omega_{\text{LO}}$ equals the longitudinal optical phonon frequency $\omega_{\text{LO}}$ ($B$ is the applied magnetic field and $m^*$ 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 $\omega_{\text{LO}}$ is no longer a normal mode of the system and couples to the plasma mode $\omega_p$ in 3D [4] or to intersubband plasmon modes in 2D [5, 6], thus giving rise to new longitudinal modes with frequencies $\omega_{L1}$ and $\omega_{L2}$. We argue here that these new coupled modes are the only excitations which can couple to electrons via their associated macroscopic 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 $\omega_{\text{TO}}$ is clearly observed. The pinning energy is explained in terms of coupling of the cyclotron resonance excitation with the magneto-plasmon-LO-phonon mode $\omega_{L}^+$ which occurs in this structure around the frequency of the transverse optical (TO) phonon $\omega_{\text{TO}}$.

The samples studied were grown by MBE on semi-insulating GaAs substrates as described in Ref. 12. A quantum well (QW), of width $L = 10\text{ nm}$, is sandwiched between two 60 period AlAs/GaAs superlattices which are $\delta$-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 epi-layer from the substrate by selective etching and deposited it on a wedged silicon substrate. The sample area is of the order of $5\text{ mm}^2$ and Hall measurements on a parent sample provided a value for the carrier concentration $n_s = 1.28 \times 10^{12}\text{ cm}^{-2}$ and a mobility of $114\text{ m}^2/\text{Vs}$. Band structure calculations show that the splitting $E_{01}$ of the two lowest electric subbands $E_0$ and $E_1$ equals $120\text{ meV}$ and the 2D electron gas (2DEG) occupy only the $E_0$ level. Transmission measurements on this sample were performed with a Bruker IFS–113 Fourier transform spectrometer, at a temperature of $1.7\text{ K}$, in magnetic fields $B$ up to $28\text{ T}$ 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 rotat-
which appears as a single line at low and high fields, but splits into two components below and nearby $\omega_{TO}(\text{GaAs})$ (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 $\omega_{TO}(\text{GaAs})$ but not in the region where the CR line coincides with $\omega_{LO}(\text{GaAs})$. To understand the data we have calculated the optical transmission of the whole structure using the multi-layer dielectric model \cite{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 $\gamma_{TO} = 0.25\; (0.56)\; \text{meV}$ 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 $\gamma_e = 0.1\; \text{meV}$.

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 $\omega_{TO}$ 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.

**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 multi-layer transmission response of the structure as described in the text.

Let us first concentrate on the two, A and B, CR components. The 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 $\nu$ approaches 2 because the $n = 1$ LL gets depopulated. The splitting of the CR into A and B components appears clearly below $\hbar \omega_{TO}$. The hatched area corresponds to the width of the TO absorption line.

**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.** Transitions $\nu = 0$ (line A) and the second $n = 1$ (line B) Landau level in the initial state (see insert in Fig. 3). These two transitions involve opposite 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 \(\varepsilon_a\) of the GaAs in the Faraday configuration, neglecting damping and polaronic effects as:

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

where \(f_{n,\sigma}\) is the distribution function of electrons in the \(n\)-th LL, with spin \(\sigma\), energy \(E_{n,\sigma}\) and effective masses \(m^*_{n,\sigma}\). Eq. 1 is the 3D dielectric constant which is used for the QW layer in the multi-layer dielectric model, the quasi 2D character being introduced through the boundary conditions \[13\] imposed to the electric and magnetic components of the radiation field at each interface. Calculations performed with a 10-bands \(k.p\) 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 the \(\hbar\omega_{TO}\). The interaction is clearly inferred from the fact that the 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 the 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 non interacting 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 phonon-like 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 magneto-phonon resonance (MPR) effect which manifests itself as an oscillatory component, in reciprocal magnetic field, of the resistivity. This component is proportional to \(\cos(2\pi\omega_\nu/\omega_c)\) \[15\] where \(\omega_\nu\) has been up till now assumed to be equal to \(\omega_{LO}\). We have performed magneto-resistivity measurements on the parent sample and observed the MPR oscillations between 5 and 15 T for temperatures ranging from 90 K to 140 K (Fig. 4). These experiments provide the mean value \(\hbar\omega_\nu(\text{meV})m^*(m_0) = 2.60 \pm 0.05\) 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 \(\hbar\omega_\nu = 33.3 \pm 0.7\) 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.

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.

FIG. 4. Oscillatory component of the resistivity versus the inverse of \(B\).

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

$$\varepsilon_a(\omega) = \varepsilon_\infty \left( \frac{\omega_{\text{LO}}^2 - \omega^2}{\omega_{\text{TO}}^2 - \omega^2} - \frac{\omega_p^2}{\omega(\omega - \omega_c)} \right)$$  \hspace{1cm} (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 ($\varepsilon_a = 0$) are composed of two modes $\omega_{\text{La}}^\pm$ and $\omega_{\text{La}}^\pm$ [16] starting from $\omega_{\text{La}}^L$ and $\omega_{\text{La}}^L$ at $B = 0$ and pinned to $\omega = \omega_{\text{LO}}$ 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 $\omega = \omega_{\text{TO}}$ and therefore a zero (corresponding to $\omega_{\text{La}}$) in between. When $\omega = \omega_c = \omega_{\text{TO}}$, $\omega_{\text{La}}$ coincides with the common pole. This property is independent on $\omega_p^2$ (and therefore on $N$); the $\omega_{\text{La}}(N, B)$ curves display fixed point at $\omega = \omega_{\text{TO}}$. The resulting curve $\omega_{\text{La}}(B)$ 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 $\omega = \omega_{\text{TO}}$. The calculated mean frequency is in reasonable agreement with our experimental findings. Though the resonant interaction occurs at $\omega = \omega_{\text{TO}}$ this does not imply that the maximum interaction occurs at this energy: the reason is that the macroscopic electric field associated with $\omega_{\text{La}}$ and which governs the strength of the interaction goes to zero, in the absence of damping, when $\omega_{\text{La}} = \omega_{\text{TO}}$. 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 $35.5 \pm 0.05$ meV. This mode which propagates in a 2D plane, is in the infra-red range essentially independent on $B$ [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 magneto-absorption measurements on a highly doped epi layer lifted off the substrate and bonded to a silicon substrate. We have demonstrated that near the $\omega_{\text{TO}}$ frequency the CR line splits into two components due to occupation and non-parabolicity 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 magneto-phonon resonance experiment and which, for our sample, has an energy close to $h\omega_{\text{TO}}$. We have assigned this mode to the low energy coupled magneto-plasmon-phonon mode of the GaAs QW. We hope that this report will stimulate theoretical work to identify the nature of the interaction between electrons and this type of modes.

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