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Electron-phonon interactions in a single modulation-doped GaInAs quantum well

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Abstract – Precise absolute far-infra-red magneto-transmission experiments have been performed under magnetic fields up to 28 T on a series of single Ga_{0.24}In_{0.76}As quantum wells *n*-type modulation doped at different levels. The transmission spectra have been simulated with a multilayer dielectric model. This allows us to extract the imaginary part of the optical response function which reveals new singular features related to electron-phonon interactions. In addition to the expected polaronic effects due to the longitudinal (LO) phonons, one observes other interactions with the transverse optical (TO) phonons and a new kind of carrier concentration-dependent interaction with interface phonons. This system provides a unique opportunity to study multiple types of electron-phonon interactions in a single type of compound.

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In bulk zinc-blende semiconductors the electron-phonon interaction appears with the TO phonons through the deformation potential mechanism and/or with the LO phonons due mainly to the Fröhlich interaction. In addition, in the quasi-two-dimensional (Q2D) structures based on these semiconductors, interface phonons are developed and are also expected to interact with electrons. The purpose of our report is to quantify all these electron-phonon interactions in a specific system, a single Ga_{0.24}In_{0.76}As quantum well (QW) sandwiched between InP layers, where they are all observed. Free polaronic effects due to the Fröhlich interaction in polar semiconductors have been the object of many reports [1–4]. However these effects were not in general quantified experimentally. Theoretically they were first studied by Lee and Pines [5] and later by Feynman [6]. It was realized that this kind of interaction could not be properly handled by perturbation theory and requires a global treatment. Such an approach was proposed by Feynman *et al.*, [7], and referred to as the FHIP model. It has been invoked to explain the polaronic mass and later extended by Peeters and Devreese [8] to extract the conductivity of the Q2D electron gas in the presence of free polaronic effects. This provides a basic model to compare with experimental results provided one can obtain experimentally the information on the imaginary part of the corresponding interaction. Such an approach

has been recently applied to interpret the cyclotron resonance data on GaAs-based QW structures [9].

Far-infra-red magneto-optical transmission experiments were performed with a Bruker 113 Fourier-transform spectrometer in magnetic field strengths up to 28 T and at a fixed temperature of 1.8 K. For each fixed value of the magnetic field B , an *absolute* magneto infra-red transmission spectrum ($TA(B, \omega)$) is measured by using a rotating sample holder containing a hole to obtain a reference spectrum under the same conditions as for the sample. The Faraday configuration is used with the $\mathbf{k}$ vector of the incoming light parallel to $\mathbf{B}$ and also to the growth axis of the sample. These spectra $TA(B, \omega)$ are in turn divided by $TA(0, \omega)$ to obtain the *relative* transmission spectra $TR(B, \omega)$ which will be displayed in the present paper (see fig. 1). The analysis of these spectra is based on a multilayer dielectric model [10]. This is essential because, in the frequency range of interest, the spectra can be distorted by dielectric interference effects independent of the existence of any electron-phonon interactions.

A series of samples consisting of single modulation-doped Ga_{0.24}In_{0.76}As QW of width $dw = 10$ nm sandwiched between InP layers have been investigated. These samples, from a dielectric point of view, are therefore very simple. The structures were modulation doped with a 20 nm InP spacer. In fact the carrier density for a

Fig. 1: (Color online) Relative transmission curves as a function of the energy. They reflect the cyclotron resonance (CR) traces for different values of the magnetic field obtained on a given sample and for different experimental conditions of illumination: a) carrier concentration $Ns = 4.2 \times 10^{11} \text{ cm}^{-2}$, b) carrier concentration $Ns = 2.5 \times 10^{11} \text{ cm}^{-2}$. The inset in b) mimics the CR transition between the $n = 0$ and $n = 1$ Landau levels.

given sample varies significantly with the illumination conditions depending on the infra-red windows and type of beam-splitter of the Fourier-transform spectrometer. Different doping levels Ns were obtained ranging from 1.4 to $4.5 \times 10^{11} \text{ cm}^{-2}$ and mobility ranging from 1 to $3 \times 10^5 \text{ cm}^2/(\text{Vs})$ respectively. Due to the presence of the InP layers the samples are optically opaque in the corresponding Reststrahlen band (RB) energies between 37 to 43 meV .

$\text{Ga}_x\text{In}_{1-x}\text{As}$ is a ternary compound which is known to display a two-mode behavior with two TO modes, TO_1 and TO_2 which are “InAs-like” and “GaAs-like” respectively. Their energies vary linearly with the x content between those of InAs and GaAs. These properties are well documented [11,12]. Due to the macroscopic electric field the two LO modes (LO_1 and LO_2) interact (repel each other) in a way which is dependent on the x content. This is an important point because it will help to identify the different electron-phonon interactions occurring in the system. It is known also that the lattice constant of this compound is only matched to that of InP for $x = 0.47$. Therefore the choice made for $x = 0.24$ is not favorable in terms of strain (mainly leading to a broadening of the phonon transitions). The motivation to choose this x value was driven by the fact that the energy of the higher LO mode remains in the available range of energies below the RB of InP and also because the asymmetry of interaction with the two LO modes is optimal.

A collection of $\text{TR}(B, \omega)$ spectra, obtained on a given sample, are displayed in fig. 1 for different values of the magnetic field B and two different experimental conditions of illumination leading to different carrier concentrations Ns . For each value of B the trace observed is the cyclotron resonance signature which, in the present case for B larger than 7 T , corresponds the transition between the $n = 0$ and $n = 1$ Landau levels (see inset fig. 1b)). In the absence of interactions the width of this transition should remain constant. It is clearly apparent in fig. 1a) and b) that for both values of Ns there are interactions of different kinds

at energies below the RB on InP and that, for the lower Ns value, another interaction occurs at energies higher than the RB of InP.

The $\text{TR}(B, \omega)$ spectra are simulated with the multi-layer dielectric model [10] in which each layer is described by its appropriate dielectric function. For the doped QW, the corresponding function $\bar{\epsilon}$ is tensorial and the diagonal part, for instance, is written as

$$\epsilon_{xx} = \epsilon_{\text{ph}} - \frac{\omega_p^2}{\omega[\omega - (\omega_{\text{NP}} - \text{Re}(\Sigma(\omega))) + i(\eta + \text{Im}(\Sigma(\omega)))]} \quad (1)$$

in which the x -axis is assumed to lie in the plane of the QW, ϵ_{ph} is the contribution of the $\text{Ga}_x\text{In}_{1-x}\text{As}$ lattice [12], ω_{NP} is the contribution to the cyclotron resonance frequency of the non-parabolicity (NP) effects [13], η is the field-independent contribution of the background defects to the line width, while $\Sigma(\omega)$ represents the self-energy correction due to interactions between the electron gas and elementary excitations to be discussed further. Whatever the origin of these interactions, it is known that $\text{Im}(\Sigma(\omega))$ and $\text{Re}(\Sigma(\omega))$ should be related by the Kramers-Krönig (KK) transformation. The effective mass m^* entering the plasma frequency ω_p is calculated with the same NP model. In the fitting process, we *first* neglect the frequency dependence of Σ and are left with two independent fitting parameters $\omega_c = \omega_{\text{NP}} - \text{Re}(\Sigma)$ and $\delta_0 = \eta + \text{Im}(\Sigma)$ for each magnetic field. The resultant parameters ($\hbar\omega_c/B$ and δ_0) will be displayed and analyzed as a function of the energy $E = \hbar\omega_c$: this way of plotting the data is convenient because in the absence of interactions it should reduce to straight lines and therefore any departure from these linear variations reveals the presence of interactions.

In fig. 2a) are plotted the observed variations of $\text{Im}(\Sigma) = \delta_0 - \eta$ for a given sample with different values of the carrier concentration Ns as a function of the energy below the RB energies of InP. The shape of the interaction is strongly dependent on Ns . For the highest values of Ns the shape

Fig. 2: (Color online) a) variation of $\text{Im}(\Sigma)$ with the energy for three different carrier concentration N_s in units of 10^{11} cm^{-2} . b) Fit of $\text{Im}(\Sigma)$ for $N_s = 4.2 \times 10^{11} \text{ cm}^{-2}$ with the imaginary part of the phonon dielectric function; the dashed and dotted curves are the theoretical values [12] of the imaginary part of the phonon dielectric function and of its inverse, respectively. c) Polaronic contribution to $\text{Im}(\Sigma)$, namely $\text{Im}(\Sigma_{\text{Pol}})$, as a function of the energy for different values of N_s (see text). Arrows in a) and c) indicate the energies of the phonon modes [12].

can be fitted with two Lorentzian curves (continuous line in fig. 2b)) with a relative amplitude corresponding to that predicted for $\text{Im}(\epsilon_{\text{ph}})$ by the phonon model [12] displayed in the same figure as the dashed curve. Of course the broadening of the fitted curve is much larger and also a little bit shifted as compared to the theory but this is expected, due to strain effects, in these systems [14]. Such an interaction is typical of a standard electron-phonon interaction with TO phonons driven by the deformation potential mechanism. At that level we do not have any sign of the Fröhlich interaction. In a binary system this latter interaction is governed by the Fröhlich constant $\alpha^{\text{F}} \sim (\epsilon_{\infty}^{-1} - \epsilon_0^{-1}) \sim \text{Im}(-1/\epsilon_{\text{ph}}(\omega_{\text{LO}}))$ where ϵ_{∞} and ϵ_0 are the high- and low-frequency dielectric constants, respectively, of the polar material. In the present case the theoretical variation of $\text{Im}(-1/\epsilon_{\text{ph}})$ is also plotted in fig. 2b). It clearly shows that the Fröhlich interactions should be dominated in this kind of compound by the GaAs-type LO phonon. Indeed when lowering the carrier concentration some new contributions to the $\text{Im}(\Sigma)$ develop (see fig. 1a)) increasing when N_s decreases but still showing some contribution from the TO phonons. By subtracting the contribution of the TO phonons proportional to that shown in fig. 2b), one can obtain the contribution to $\text{Im}(\Sigma)$, called $\text{Im}(\Sigma_{\text{Pol}})$ due to polaronic interactions (see fig. 2c)). We observe that the relative strength of these interactions for both LO phonons are indeed compatible with the predictions of the phonon model as displayed in fig. 2b). We should, however, include some broadening due to strain effects. In order to quantify these interactions we need information at higher energies which means higher magnetic fields [9].

In fig. 3a) and c), the $\text{TR}(B, \omega)$ spectra are displayed (open dots) for different values of the magnetic field B , and for two characteristic samples and carrier concentration. The philosophy adopted [9] to treat the information is to fit the data obtained for δ_0 with different models of interaction to obtain a complete simulation of the whole δ_0 variation with the energy E (continuous curves in top panels of fig. 3b) and d). The KK transform of this curve is then compared with the data of $\hbar\omega_c/B$

displayed in the bottom panels of fig. 3b) and d). Doing so, we obtain two “universal” curves $\delta_0(E)$ and $\hbar\omega_c/B(E)$ which, when injected into the multilayer dielectric model, should reproduce, if the self-consistency is achieved, the experimental transmission curves for *any* value of the magnetic field B . In this process the relation between the energy E and B is given by the non-parabolicity curve displayed in the bottom panels of fig. 3b) and d). The procedure is only valid for filling factors lower than 2 which is always the case for the present results.

The first task is then to choose the models for the different contributions to $\delta_0(E)$. For the interactions with the TO phonons we use the model displayed in fig. 2b) always keeping the relative strength of interaction given by the phonon model [12]. The results are shown in fig. 3b) and d), in the top panels, as dotted lines. For the polaron interaction we restrict ourselves to the one-polaron model and, using the FHIP theory, write down $\text{Im}(\Sigma^{\text{Pol}})$ as [8]:

$$\text{Im}(\Sigma_i^{\text{Pol}}(\omega)) = \frac{\alpha_i(\omega_{\text{LO}_i})^2}{\omega} |A_0^i(\omega)|^{1/2} e^{-R_i|A_0^i(\omega)|} \Theta(A_0^i(\omega)), \quad (2)$$

where $A_0^i(\omega) = \omega/\omega_{\text{LO}_i} - 1$ for $i = 1, 2$ labelling the two LO modes, $\Theta(x) = 1$ for $x > 1$ or zero otherwise. The FHIP model, developed in a one-electron picture for 3D compounds, assumes that the electron-phonon interaction is harmonic instead of Coulombic as in the case of the Fröhlich interaction. The coefficient α_i in eq. (2) should therefore include different corrections. In fact α_i and R_i are not really independent. We will discuss below the way we can choose them but, in all samples, the choice was made in such a way that the relative weight of each phonon contribution is close to 2.4 as derived from the phonon model [11]. The resulting fits for this polaronic interaction are displayed in fig. 3b) and d), in the top panels, as dashed lines. We have added some broadening in the low-energy side of the LO threshold to take into account strain effects.

It turns out that with all previous interactions, the KK transform of $\delta_0(E)$ cannot reproduce the strong

Fig. 3: (Color online) a) and c) variation of the $\text{TR}(B, \omega)$ spectra, outside the Reststrahlen band energy of InP, as a function of the energy for different values of the magnetic field B (open dots) and different samples with carrier density $N_s = 1.4 \times 10^{11} \text{ cm}^{-2}$ (a)) and $N_s = 2.5 \times 10^{11} \text{ cm}^{-2}$ (c)). The continuous lines in a) and c) are a fit to the data with the self-consistent model explained in the text. b) Variation of the fitting parameters δ_0 (top panel) and $\hbar\omega_c/B$ (bottom panel) for $N_s = 1.4 \times 10^{11} \text{ cm}^{-2}$. The dotted, dashed and dot-dashed lines in the top panel are the different fitted contributions to $\text{Im}(\Sigma)$ (see text). The solid lines in both panels are the functions of energy used to fit the data in a). d) Same as b) for the sample with $N_s = 2.5 \times 10^{11} \text{ cm}^{-2}$ with the corresponding results used to fit the data in c). The dashed lines in the lower panels of b) and d) show the fitted NP variation of $\hbar\omega_c/B$ in the absence of electron-phonon interactions.

up-wards variation of $\hbar\omega_c/B(E)$ above the RB energies of InP. We are therefore led to assume the existence of another electron-phonon interaction in the high-energy range. This is reminiscent of the additional interaction observed in GaAs [9] which has been called the “XP” interaction and is very likely due to interaction with interface phonons. We have reproduced it with a Lorentzian shape displayed as dash-dotted lines in the top panels of fig. 3b) and d). Added to the previous contributions of the electron-phonon interactions the total variation of $\delta_0(E)$ as well as the corresponding KK transform of $\delta_0(E) - \eta$ are obtained. As already mentioned the final step is to compare the predictions of the two “universal” curves with experimental data: the results are displayed as continuous lines in fig. 3a) and c). The agreement is reasonable even when the scale of the transmission curves is noticeably enlarged. We then have a set of fitting electron-phonon interaction parameters which is consistent, within the different models of interaction, though it is not completely unique due to strain effects and the absence of precise data in the high-energy range of the Reststrahlen band of InP.

Before discussing these parameters, it is worth mentioning that high field experiments performed on sample with $N_s = 4.2 \times 10^{11} \text{ cm}^{-2}$ do not show any clear sign of interaction with the LO phonons or with interface phonons at energies higher than the Reststrahlen band of InP (see fig. 1b)).

The interaction with TO phonons is well reproduced by a model implying the deformation potential mechanism although, in principle, this mechanism is forbidden in the conduction band of *bulk* zinc-blende compounds. However, in Q2D systems, the conduction band wave function acquires some contribution from the valence band wave function due to NP effects which in the present case are quite important. Indeed, a simple four-band model predicts an admixture with the light and heavy hole wave function which amounts to 0.5 per cent. Knowing that the deformation potential of TO phonons for the valence bands is of the order of 40 eV for GaAs and InAs [15], this can explain our data.

We discuss now the fit of polaronic effects with the FHIP model. For each LO phonon, the model depends

Table 1: Parameters used to fit the different electron-phonon interactions in the $\text{Ga}_{0.24}\text{In}_{0.76}\text{As}$ samples. For all samples the phonon energies are the same: $\hbar\omega_{\text{TO}_1} = 28.5 \pm 0.1$ meV, $\hbar\omega_{\text{TO}_2} = 31.3 \pm 0.1$, $\hbar\omega_{\text{LO}_1} = 29.3 \pm 0.1$, $\hbar\omega_{\text{LO}_2} = 32.2 \pm 0.1$.

Sample N_s (10^{11} cm^{-2})	v_1	I_1^{Pol} (meV ²)	E^{XP} (meV)	I^{XP} (meV ²)
053a 2.5 ± 0.1	14 ± 1	0.064 ± 0.001	44.2 ± 0.1	0.76 ± 0.2
053a 3.0 ± 0.1	12 ± 1	0.043 ± 0.001	43.8 ± 0.1	0.74 ± 0.2
056a 1.4 ± 0.1	18 ± 2	0.234 ± 0.003	44.0 ± 0.1	0.77 ± 0.2
056a 3.0 ± 0.1	12 ± 1	0.039 ± 0.001	43.4 ± 0.1	0.77 ± 0.2

on two parameters: v and w in reduced units of ω_{LO} . One of them (w) is close to 1 while $v^2 - w^2$ represents the force constant of the harmonic interaction (playing the role of the Fröhlich constant α^{F}). Following the results of ref. [8] our fitting parameters are expressed in function of the FHIP parameters in the following way: $R_i = (v_i^2/w_i^2 - 1)/v_i$ and $\alpha_i = \alpha_{\text{S}} \times (2\alpha_i^{\text{F}}/3) \times (v_i/w_i)^3$. α_{S} has been introduced to take into account the effects of low dimensionality and at least in part screening effects which should be common to both LO interactions. The different Fröhlich constants α_i^{F} , calculated from ref. [11] are: $\alpha_2^{\text{F}} = 0.0415$ and $\alpha_1^{\text{F}} = 0.0172$ with a relative ratio of about 2.4.

In the fitting process, applied to our samples for concentrations N_s ranging between 1.4 to $3.5 \times 10^{11} \text{ cm}^{-2}$, we did not find, within the experimental errors, any significant variation of the LO energies with the doping. We will therefore set the corresponding values of w_i to 1 for each mode leading to values $R_i = (v_i^2 - 1)/v_i$ and $\alpha_i = \alpha_{\text{S}} \times (2\alpha_i^{\text{F}}/3) \times (v_i)^3$ which are only dependent, in addition to α_{S} , on a *single* parameter v_i which has to be scaled with the corresponding LO phonon. Within these simplifying assumptions, the global fit is found acceptable for different pairs of parameters (α_{S} and v_1) whereas the integrated strength of the interaction $I_i^{\text{Pol}} = \int \text{Im}(\Sigma_i^{\text{Pol}}(\omega))d\omega$ remains relatively constant. This is the quantity which, in our opinion, should be representative of the physics. We show in table 1 the different values of the parameters used to fit the polaronic interaction in our samples. The parameter v_1 is found to increase when N_s decreases which reflects the screening effects in this model. This corresponds to an increase of I_1^{Pol} . In all cases the ratio $I_2^{\text{Pol}}/I_1^{\text{Pol}} = 2.30 \pm 0.02$ which is close to 2.4. The results are therefore relatively consistent.

We now discuss the results obtained for the “XP” interaction. In the case of GaAs samples [9] sandwiched between two GaAs/AlAs superlattices, the “XP” interaction is observed with a maximum strength when polaronic effects are important, peaking at energies close, but below $\hbar\omega_{\text{LO}}(\text{AlAs})$. Here also this interaction appears when polaronic effects are important although we cannot exclude

that it also appears with a smaller strength, for higher doped samples in the RB energies of InP¹. As shown in table 1 this interaction, however peaks at an energy higher than $\hbar\omega_{\text{LO}}(\text{InP}) = 42.6$ meV. In addition it is clearly much stronger (with respect to the polaronic interaction) than in the case of GaAs. Such a dissipative interaction has to be related to modes of dielectric origin like the interface phonon modes. In the symmetric structure of the samples, these are the symmetric IP modes which are active in the infra-red. In the absence of magnetic field, the energy of these modes are solutions of the following equation [16]:

$$\varepsilon_{\text{InP}} = -\varepsilon_{\text{Ga}_{0.24}\text{In}_{0.76}\text{As}} \times \tanh(q_{//}dw/2), \quad (3)$$

where $q_{//}$ is the wave vector of the interface electromagnetic wave travelling parallel to the plane of the Q2D gas. Note that the wave function of these symmetric interface modes does not vanish at the center of the QW (unlike the anti-symmetric modes) and therefore have a significant overlap with the wave function of the Q2D gas [17]. Whereas in the absence of magnetic field the solution of eq. (3) lies between the RB energies of $\text{Ga}_{0.24}\text{In}_{0.76}\text{As}$ and InP, the magnetic field dependence of $\varepsilon_{\text{Ga}_{0.24}\text{In}_{0.76}\text{As}}$ leaves the possibility of solutions beyond the LO energy of InP. This has never been worked out on a theoretical basis to our knowledge. Following the approach of ref. [16] the interaction should be resonant, with a Lorentzian shape, at an energy of electrons which matches that of the interface phonon with the conservation of momentum. In magnetic field the momentum $q_{//}$ should be of the order of the inverse of the magnetic field length $l_B = (\hbar/eB)^{1/2}$. Indeed when using our model to solve eq. (3) we find, with such a value of l_B , a real solution in the corresponding range of B where it is observed. The existence of a possible solution depends noticeably on the damping of the different oscillators entering in the equation and this

¹When analyzing, for the highest doped sample, the variation of $\hbar\omega_c/B(E)$ below the RB energies of InP we did not observe, within the experimental errors, a real contribution of the “XP” interaction: if it exists it should be much weaker than that reported in table 1 which means that it is also screened though at a level weaker than for the polaronic interaction.

is the reason why it exists only in a restricted range of magnetic field. Therefore we think that the “XP” feature is due to the electron-phonon interaction with the magnetic field-dependent symmetric interface mode. This interaction is strong with respect to the polaronic interaction (see table 1) and also apparently not very screened. Its strength is explained with the results of ref. [16] where it is shown that the matrix element depends mainly on the Fröhlich constant of the barrier $\alpha_{\text{InP}}^{\text{F}} = 0.115$ which is much stronger than that of $\text{Ga}_{0.24}\text{In}_{0.76}\text{As}$. Its weak dependence on N_s can also be understood because the macroscopic electric field generated in the barrier InP is naturally less screened by the carriers located in the QW.

In the present work, as in ref. [9], we have used the FIHP model to fit the imaginary part of the polaronic interaction. Despite the fact that this model assumes a harmonic interaction instead of a Coulombic one, it reproduces in a reasonable way the main effect of the abrupt screening by free carriers. The standard way to deal with screening is to divide the interaction by the dielectric constant of the magneto-plasmon [18]. However this approach will never reproduce the observations as already mentioned by Das Sarma [19]. The reason why the FIHP model succeeds is that indeed the interaction occurs in the exponential function (eq. (2)). Of course the individual parameters of the FIHP model do not have a real physical significance but globally if a complete model with a Coulombic interaction is derived, the related imaginary part of the interaction has to reproduce this abrupt variation with the carrier concentration.

In conclusion, we have performed infra-red magneto-optical transmission measurements of a Q2D electron gas in a single modulation-doped $\text{Ga}_{0.24}\text{In}_{0.76}\text{As}$ QW with different carrier densities, for magnetic fields high enough to scan the cyclotron resonance frequency beyond the Reststrahlen band of InP. From the experimental spectra, we have extracted the imaginary part of the response function which reveals several singularities with a number and strength depending on the carrier density. These singularities have been attributed to electron-phonon interactions. For carrier densities N_s larger than about $3.8 \times 10^{11} \text{ cm}^{-2}$ the only observed interaction is with TO phonons. For lower densities this interaction remains finite but the dominant interaction, of polaronic character, implies the LO phonons with an intensity increasing abruptly when N_s decreases. Within the experimental errors we did not observe any significant screening of the energies of the respective LO phonons with N_s but the Fröhlich interaction itself is strongly screened. When this interaction is important, it is also accompanied by an additional interaction with the symmetric interface mode of the structure, which is strong and apparently less screened than the direct polaronic interaction. This latter interaction has been treated with a simplified version of the FIHP

polaronic model which may also be questioned especially concerning the way it reproduces the screening effects. We think that a more elaborate theory in Q2D structures which includes effects of screening and interaction with interface modes would be interesting to confront with the present data.

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