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Interaction of optical phonons with electrons in an InAs quantum well

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The cyclotron resonance (CR) of electrons confined in a thin InAs quantum well sandwiched between thin GaSb layers has been studied experimentally. Since the transmission of radiation in thin polar layers is suppressed only near the TO frequency, we can tune the CR through the TO-LO frequency region of both materials. We find that there is a drastic influence of TO phonons on the CR line profile, resulting in split CR. This interaction is shown to be dominantly of optical origin; resonant polaron effects, both at TO or LO frequency, are, if present, very small.

Recently, resonantly enhanced magnetopolaron effects for quasi-two-dimensional electronic systems have been observed and investigated experimentally for different systems.[1-3] The effect occurs if the cyclotron resonance (CR) of frequency $\omega_c = eB/m_c$ is tuned with a magnetic field B through the LO frequency $\omega_{\rm LO}$ of the electronically active material. The enhancement of the polaron effect for 2D electronic systems, with respect to both the nonresonant 2D case ($\omega_c \ll \omega_{\rm LO}$) and the resonant ($\omega_c \approx \omega_{\rm LO}$) case in the bulk, has attracted much theoretical interest (e.g., Refs. 4–8). Recently, CR has been investigated in GaInAs heterojunctions where a resonant behavior of the CR mass m_c and CR half-width has been observed near the TO frequency and has been attributed to polaron effect due to the TO-phonon-electron coupling.[9] This is somewhat surprising, since so far the theoretical understanding of polaron effects has been considered to arise from LO-phonon coupling only.[10] We have investigated experimentally the CR in thin InAs quantum wells, which are sandwiched between two thin GaSb layers. In thin layers the transmission of radiation is suppressed only near the TO frequency, so that we can tune and study the CR throughout the entire TO-LO frequency region of both materials and investigate in detail its interaction with both TO and LO phonons.

The sample configuration is shown schematically in the inset of Fig. 1(c). The samples were prepared by molecular beam epitaxy on GaAs substrates (e.g., Ref. 11). On the substrate a buffer layer of GaAs and then a layer of GaSb (thickness about 500 nm) were first grown. This was followed by the InAs well of 20 nm and completed with a GaSb cap of 20 nm. All layers are nominally undoped. This system represents a type-II heterostructure where the GaSb valence band is about 150 meV above the InAs conduction band. In this system electrons are transferred from the GaSb into the InAs quantum well, creating, in an ideal case, an equal number of holes in GaSb and electrons in InAs. For the particular samples discussed here, due to extrinsic donors likely to be associated with the interfaces, the number of electrons is $N_S = 8.8 \times 10^{11}$ cm^{-2}, whereas the number of holes is much smaller and cannot be detected in the experiment. The dc mobility (van der Pauw) of the electrons at 4.2 K is 80.000 cm^2/V s. CR measurements were performed at 1.8 K in magnetic fields up to 12 T. The transmission of far-infrared (FIR) radiation through the sample was measured with a Fourier transform spectrometer which was connected via a waveguide system to the cryostat. Spectra were taken in the frequency domain at fixed magnetic fields B perpendicular to the surface.

The absolute transmission through the sample is shown in Fig. 1(a). Two resonances are observed in the spectra. Whereas in a thick layer the reststrahlen region between TO and LO frequency is nontransparent, here for the thin layers transmission is only partially suppressed near the TO frequencies of the materials. The decrease of the transmission above 250 cm^{-1} is caused by the onset of the reststrahlen band of the thick GaAs substrate. Using classical damped oscillator models for the dielectric functions of InAs, GaSb, and GaAs, we can accurately determine the TO frequencies and the phonon damping times $\tau_{\rm ph}$ of InAs and GaSb for our samples at 1.8 K from fits of the full Fresnel equations to the experimental transmission spectra [Fig. 1(a)]. Our values of $\omega_{\rm TO}$ are in excellent agreement with data measured at He temperature in Ref. 12. So we take the data from Ref. 12 for the static (ε_s) and high-frequency (ε_∞) dielectric functions and use throughout this paper the following values for InAs (GaSb): $\omega_{\rm TO} = 218.5$ (230.5) cm^{-1}, $\omega_{\rm LO} = 242.5$ (240) cm^{-1}, $\tau_{\rm ph} = 10^{-11}$ (10^{-11}) s, $\varepsilon_s = 15.15$ (15.69), $\varepsilon_\infty = 12.25$ (14.44).

The CR for $\omega_c < \omega_{\rm TO}$ in the same quantum-well structures used here have been investigated previously.[13] It has been found that these systems exhibit pronounced oscillations of CR amplitude and half-width which are related to the filling factor $\nu = N_S h/eB$ of the Landau levels. This behavior arises from the self-consistent interaction of screening and Landau level width, and is discussed in detail in Ref. 13. We will come back to this point below. However, we would like to note here that it was found that the CR mass m_c is within better than ±1% constant for the entire B region covered. Its value is $m_c = 0.0374 m_0$.

Original spectra of CR excitation in the phonon region are shown in Fig. 1(b). The transmission $T(B)$ through the sample, measured at fixed B, is normalized to the transmission $T(0)$ at $B=0$. Whereas for small B a CR is observed with a "normal" line shape [e.g., at $B=8.09$ T in Fig. 1(b)], structures appear in the profile if with increasing B the CR is tuned through the TO frequencies of both InAs and GaSb. The effect of the TO phonons from the InAs layer is significantly smaller as compared with GaSb-TO phonons. This is directly correlated with the small TO activity in the thin (20 nm) InAs layer in comparison with the thicker (500 nm) GaSb layer that is shown in Fig. 1(a). To compare the experimental spectra in the following with theory we take the positions for the minima in the normalized transmission. The positions are indicated by arrows in Fig. 1(b) and depicted in Fig. 2. Here we neglect the small minima structures for the InAs-TO-phonon interaction.

One has to be very careful in analyzing these spectra, in particular, if one wants to extract possible polaron effects on the CR mass. The optical response of the system is governed by two strongly resonant processes, the resonant dielectric function of the materials at the TO frequency and the resonant absorption of the 2D electronic system at ω_c, where the latter shifts with increasing magnetic field. To demonstrate this we assume for a moment a simple model with a two-dimensional electronic system at the

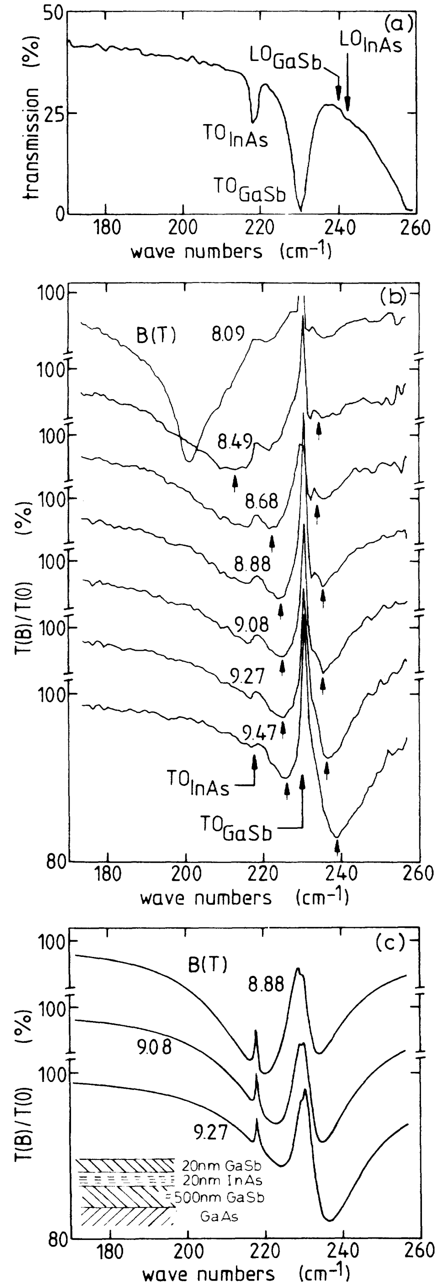

FIG. 1. (a) Absolute transmission of the sample. The transmission dips at the TO frequencies of InAs and GaSb and the positions of the LO frequencies from Ref. 12 are indicated. (b) Experimental transmission $T(B)$ at different magnetic fields B normalized to the transmission at $B=0$. (c) Calculated spectra $T(B)/T(0)$ for different B and for a fixed CR mass $m_c = 0.0374 m_0$. The spectral resolution in the experimental spectra [(a) and (b)] is 1 cm^{-1}.

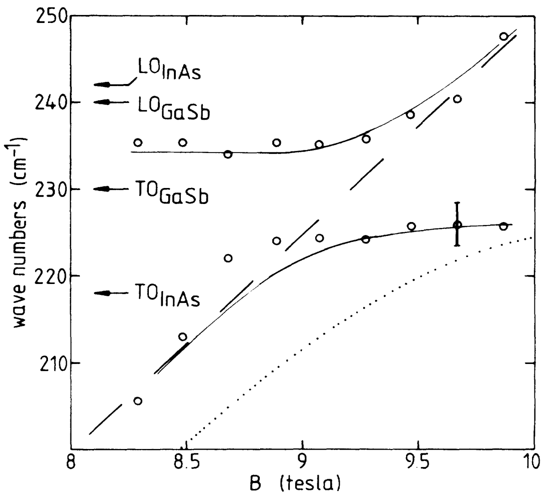

FIG. 2. Experimental positions for transmission minima from Fig. 1(b). (The small structures associated with InAs-TO coupling are not shown separately.) The dashed line depicts the CR positions extrapolated from values below the phonon frequencies, where it varies linearly in B. The full lines show the calculated positions of transmission minima using classical Fresnel equations and a fixed B-independent mass of $m_c = 0.0374 m_0$. The splitting of the CR profile arises from the optical response of two resonant processes, i.e., the TO resonance excitation and the CR excitation. The dotted line indicates the lower branch of the transmission minima assuming a varying B-dependent mass $m_c(B)$ according to a LO-polaron effect for InAs within the static screening model of Ref. 8.

boundary of vacuum and a polar semiconductor. Then the relative change of transmission is[14]

$$\frac{\Delta T}{T}=\frac{T(N_S)-T(0)}{T(0)}=-\frac{2(1+\sqrt{\varepsilon})s_r+s_r^2+s_i^2}{(1+\sqrt{\varepsilon}+s_r)^2+s_i^2} . \tag{1}$$

Here $T(N_S)$ and $T(0)$ are, respectively, the transmission of normally incident radiation with and without carriers, $\varepsilon(\omega)$ is the dielectric function (assumed to be real), and $s(\omega)=s_r+is_i=\sigma(\omega)/\varepsilon_0 c$ is the reduced dynamic conductivity. The dynamic conductivity will be described by a Drude-type dependence.

$$\sigma(\omega,B)=N_s e^2\tau_c/m_c[1-i(\omega-\omega_c)\tau_c] , \tag{2}$$

where m_c is the cyclotron mass, $\omega_c=eB/m_c$ is the CR frequency, and τ_c the scattering time. If ε in (1) does not depend on frequency and if $s\ll 1+\sqrt{\varepsilon}$, then the response $\Delta T/T$ is proportional to the real part $\mathrm{Re}\sigma(\omega)$ of the magnetoconductivity giving the well-known CR profile proportional to $[1-(\omega-\omega_c)^2\tau^2]^{-1}$. In our situation, in the regime of the phonon frequencies, $\varepsilon(\omega)$ depends strongly on frequency, thus the CR profile is strongly modified by the singularities of $\varepsilon(\omega)$ at ω_{TO}. In our multilayered system with different phonon frequencies the situation is even more complex. Thus, to compare experimental and theoretical spectra we have calculated the response from the complete Fresnel equations of the multilayered system, using complex dielectric functions according to a Lorentzian oscillator model for the InAs, GaSb, and GaAs layers. (ε_s, ω_{TO}, and ω_{LO} are given above.) In Fig. 1(c) we show calculated spectra where we use a dynamic conductivity according to Eq. (2) with $\tau_c=0.5\times10^{-12}$ s, which fits the half-width of the CR and a constant value of $m_c=0.0374m_0$. The calculated spectra in Fig. 1(c) show the same features as the experimental spectra with a split CR.

The transmission minimum positions of the calculated split CR, as obtained by the procedure described above, are shown in Fig. 2 in full lines. Within the experimental accuracy the experimental splitting is reproduced. The important point is that we can explain the experimental results using a constant CR mass of $m_c=0.0374m_0$. The analysis shows that within the experimental accuracy of ± 1% we do not detect any deviation in the CR position at the LO frequency of InAs, where one would expect polaron effects due to LO-phonon-electron coupling. Also there is no effect on the CR position at the TO frequency of the quantum-well material InAs. The apparent resonant coupling at the TO frequency of GaSb, the material where only tails of the electron wave functions are present, can be fully explained by the classical optical response.

Concerning possible effects on the half-width of the resonance we have stated above that for the InAs quantum well here a strong oscillatory behavior of the CR half-width and amplitude was observed.[13] Accidentally for the charge density $N_S=8.8\times10^{11}$ cm^{-2} of our samples we are in the situation that for the frequency range of interest here we are close to the situation where exactly two Landau levels are filled. Thus, screening is suppressed and τ_c is relatively low. To provide some examplary numbers, we find at $B=8.5$ T (8.7,10) with CR frequency $\omega_c=213$ cm^{-1} (217,250) and relative Landau occupation $n=\nu/2=2.14$ (2,1.82), $\tau_c\approx0.3\times10^{-12}$ s (0.2,0.4). This variation in τ_c is, however, fully within the oscillation of τ_c that we extrapolate from lower magnetic fields.[13] In other words we cannot extract any additional influence of polaron interaction on the CR linewidth. In particular, there is no extra variation in τ_c corresponding to LO or TO frequencies.

Resonant polaron interaction of 2D electrons with phonons is a complex problem, which so far has only been treated approximately.[3-8] For a strictly 2D electronic system the 2D polaron effect is enhanced with respect to both the nonresonant 2D polaron effect as well as to the resonant effect in the bulk. This situation has been observed experimentally for electron inversion layers in InSb.[1] If the resonant splitting is expressed in terms of a relative enhancement of the CR mass at ω_{LO}; $\gamma=\Delta m_c/m_c(B\rightarrow0)$, then for InSb, depending on the density, γ up to 10% was found. For GaAs heterostructures $\gamma\approx5\%$ (Ref. 3) to $\gamma\approx2.5\%$ (Ref. 2) has been observed which is smaller than the expected, strictly 2D value. It has been shown that the finite width of the wave functions, and in particular the effect of screening, is important in reducing the resonant enhancement.[3,8] For InAs with the Fröhlich polaron coupling constant $\alpha=0.055$ we expect for the strictly 2D case a splitting of $\gamma=15\%$. Taking into account effects of finite thickness and screening, within the static screening model of Ref. 8, we estimate a reduction of the polaron effect thus that γ is about 8%. The resonance positions assuming such a polaron effect for LO coupling with InAs is shown by the dotted line in Fig. 2. This is clearly *not* observed in the experiment.

Two effects shall be discussed which might possibly explain the absence of any pronounced polaron effects in our experiment. Firstly, it is known that the phonon spectrum in thin layers is changed with respect to the bulk. In particular when the phonon spectra of the two materials do not overlap in energy, confinement of phonons occurs.[15,16] Also, additional surface and interface modes are present. So far all theories on resonant 2D-electron-phonon coupling assume bulk phonons. Nonresonant polaron effects due to interface phonons in semi-infinite systems[17] or double heterostructures[18] have been considered. However, careful investigations on InSb-MOS structures[1] have shown no evidence for interface phonon coupling.

A second effect that might be important for our experiment are Landau-level occupation effects. A magnetic field of 9.7 T is necessary to match the CR frequency with ω_{LO} of InAs. This corresponds to a relative occupation of Landau levels $n=\nu/2=1.88$. Between $B=8$ and 10 T n varies from 2.3 to 1.8. So one is close to the situation that the highest Landau level is completely filled. In this case, at least in first order, the Pauli principle forbids resonant polaron interaction, i.e., interaction of electron states $|\text{Landau level } n+1, \text{ no phonon}\rangle$ with electron states $|\text{Landau level } n, \text{ one phonon}\rangle$.[19] This problem has been addressed in Refs. 6 and 20; however, no rigorous theory of occupation effects has been given. To demonstrate the complexity of this problem we would like to point out, that for this situation of fully occupied Landau levels we observe[13] broad CR which is a direct consequence of the reduced screening in this case. A reduction of screening due to fully occupied Landau levels, however, would favor resonant polaron effects in the limit of static screening theories. Also, from the experiments in Ref. 13 it can be deduced that there is density of states between the Landau levels, thus the interaction discussed above is not strictly forbidden. It seems necessary to have theories on resonant magnetopolaron coupling which, first, truly take into account the phonon spectrum of the thin layer, and second, consider Landau-level occupation effects including self-consistent and dynamic screening to explain details of magnetopolaron interaction in more complex situations.

In conclusion, we have investigated CR in thin InAs quantum wells. A strong interaction with TO phonons in the adjacent GaSb is observed. Our experiments show that a careful analysis and exact knowledge of the dielectric functions of the involved systems is necessary to extract possible polaron effects. We can show that the interaction of optical phonons with the CR for our samples is dominantly of optical dielectric origin and resonant polaron effects, both at TO and LO frequencies are, if present, small.

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