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Strong three-level resonant magnetopolaron effect due to the intersubband coupling in heavily modulation-doped GaAs/Al_xGa_{1-x}As single quantum wells at high magnetic fields

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Electron cyclotron resonance (CR) measurements have been carried out in magnetic fields up to 32 T to study electron-phonon interaction in two heavily modulation-δ-doped GaAs/$Al_{0.3}Ga_{0.7}$As single-quantum-well samples. No measurable resonant magnetopolaron effects were observed in either sample in the region of the GaAs longitudinal optical (LO) phonons. However, when the CR frequency is above LO phonon frequency, $\omega_{LO}=E_{LO}/\hbar$, at high magnetic fields ($B>27$ T), electron CR exhibits a strong avoided-level-crossing splitting for both samples at frequencies close to $\omega_{LO}+(E_2-E_1)/\hbar$, where E_2, and E_1 are the energies of the bottoms of the second and the first subbands, respectively. The energy separation between the two branches is large with the minimum separation of 40 cm^{-1} occurring at around 30.5 T. A detailed theoretical analysis, which includes a self-consistent calculation of the band structure and the effects of electron-phonon interaction on the CR, shows that this type of splitting is due to a three-level resonance between the second Landau level of the first electron subband and the lowest Landau level of the second subband plus one GaAs LO phonon. The absence of occupation effects in the final states and weak screening for this three-level process yields large energy separation even in the presence of high electron densities. Excellent agreement between the theory and the experimental results is obtained.

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Understanding the strength of the interaction of electrons with optical phonons in quasi-two dimensional (Q2D) systems and its dependence on carrier density is important in device application of such structures, the study of this interaction also reveals fundamental physics of these systems. Extensive investigations have been carried out on this subject for many years both theoretically[1–6] and experimentally.[7–13] Recently, due to the availability of sufficient steady high magnetic fields, phenomena associated with electron-phonon (e-ph) interaction have been observed.[14] Thanks to the detailed and careful theoretical calculation, which incorporated all the important aspects of band nonparabolicity and of the e-ph interaction in a Q2D system, it has been possible: (1) to understand the important role played by slab and interface phonons;[15] and (2) to discover a very interesting reversal of spin split CR lines due to blocking of the polaron effect.[16]

An important tool in the study of the e-ph interaction is the resonant magnetopolaron effect.[17] For a Q2D system in a magnetic field, both free electron cyclotron resonance (CR) and intraband impurity transition can yield such magnetopolaron resonances. When the energy separation of a pair of unperturbed electron energy levels, e.g., $N=0$ and $N=1$ free electron Landau levels (LL's), or $1s$ and $2p+$ impurity levels, is close to the longitudinal optical (LO) phonon energy, E_{LO}, a so-called two-level resonant magnetopolaron effect occurs. It has also been shown[18] that a three-level impurity-bound magnetopolaron effect can occur in a Q2D system; in this case the energy separation of the 2_p^+ and 2_p^- states is close to E_{LO}. When an electron is excited from the ground ($1s$) state to the 2_p^+ state, it will be resonantly coupled to the 2_p^- state via emission of a LO phonon.

The two-level magnetopolaron effect in electron CR measurements has been used extensively to study the e-ph interaction, but the three-level effect in free electron CR measurements has not been reported to date. It is not surprising that the three-level effect in CR measurement has never been observed in a bulk system, since there are simply no suitable

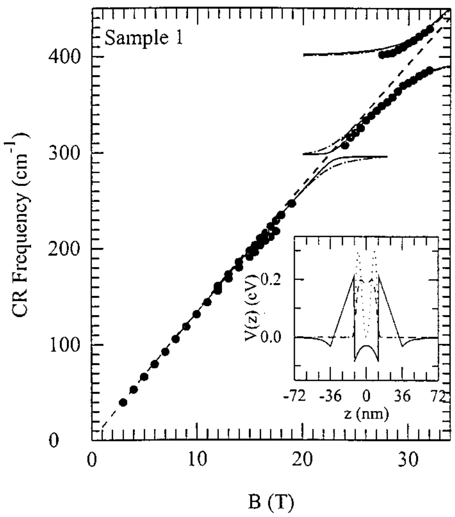

FIG. 1. The symbols are the CR transition energy vs field for sample 1. The curves are calculated polaron CR which incorporates the influence of LL occupancy and screening effects to the e-ph interaction, and conduction-band nonparabolicity. The solid curve is for spin down and the dash-dotted curve for spin up transitions. The inset shows the self-consistent potential profile with the electron density in the first two lowest subband levels.

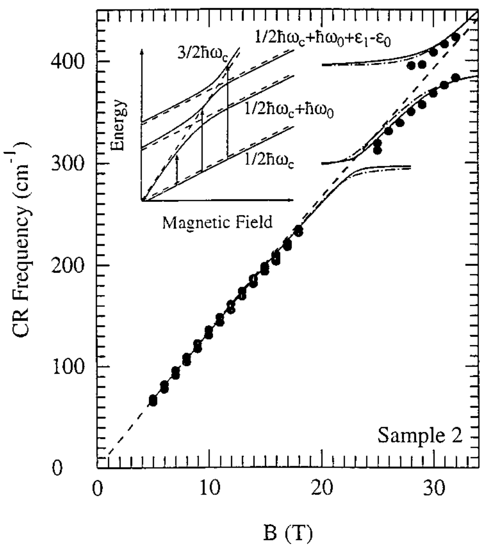

FIG. 2. The same as Fig. 1 but now for sample 2. The inset is a schematic diagram of the three-level polaron effect (dashed curves are the results without polaron effect).

energy levels available. However, in a Q2D system, there is a set of LL's associated with each subband level. Therefore, in principle, a three-level resonant magnetopolaron effect can occur due to the coupling between two LL's in different subbands. Our recent theoretical calculations[19] predicted that screening (due to the large electron density needed) will not kill this three-level resonant effect and that it should occur in a Q2D system at energies higher than LO phonon energy. Thus splitting will greatly affect the electron CR excitation spectra at high magnetic fields. Similar to the impurity system, a three-level resonance in CR measurement should occur when the magnetic field is such that the energy difference between a higher LL of the first subband and a lower LL of the second subband is equal to the phonon energy. In this case, a free electron is excited from the $N=0$ LL in the lowest subband (E_1) to the $N=1$ LL in the same subband via the electric dipole interaction; the final state of this transition is coupled resonantly via the emission of a LO phonon to the $N=0$ LL of the second subband (E_2) (see the inset of Fig. 2).

To study this three-level resonant magnetopolaron effect and the effects of a larger density of free electrons in the presence of high magnetic fields we have measured electron CR in two heavily modulation-δ-doped GaAs/$Al_{0.3}Ga_{0.7}As$ 240 Å single-quantum-well samples in magnetic fields up to 32 T. The electron CR measurements were carried out with the infrared transmission facility at the National High Magnetic Field Laboratory at Florida State University. The setup consists of a Bruker 113v Fourier transform interferometer in conjunction with a metal light-pipe condensing-cone system (details are given elsewhere[20]); the detector used in the measurements is a 4.2 K silicon bolometer. The temperature of the sample is maintained at 4.2 K, and the applied magnetic field is varied up to 32 T. The two GaAs/$Al_{0.3}Ga_{0.7}As$ single quantum-well samples were grown by molecular-beam epitaxy at Sandia National Laboratories. Both samples are symmetrically δ-doped with silicon in the barrier with 240 Å setoff distance. The electron densities measured from the quantum Hall effect and longitudinal resistivity are 8.0 $\times 10^{11}\,cm^{-2}$, and $8.9\times 10^{11}\,cm^{-2}$, and the electron mobilities measured at 4.2 K are 160 000 cm^2/Vs and 86 000 cm^2/Vs, respectively for samples 1 and 2.

In the two-level resonant magnetopolaron region ($E_{CR}=E_{LO}$) there is no noticeable polaron effect on the electron CR in either sample within our experimental error as shown in Figs. 1 and 2. This is not surprising since the combination of the LL occupation effects due to the Pauli principle and the strong screening of the e-ph interaction for noninteger filling factors reduces greatly the effective interaction for these two heavily doped samples.[21] However, above the GaAs LO phonon frequency at high fields ($B>27$ T), electron CR exhibits a very strong avoided-level-crossing splitting for both samples (see Figs. 1 and 2) at energies E. For both samples the energy differences $E-E_{LO}$ agree very well with the subband separations E_2-E_1, which were measured with magneto-photoluminescence. Since the second subband is populated for both samples up to 15 T, the separation between the two subbands can be measured very accurately. The splitting of electron CR between the two branches is fairly large, with a minimum energy separation of about 40 cm^{-1} near 30.5 T for both samples. We attribute this splitting to the three-level resonance discussed above.

Figure 3 is a plot of the raw spectra taken at different magnetic fields for sample 2. The spectra for sample 1 show essentially the same behavior. These spectra are normalized magnetotransmission, i.e., the ratios of a spectrum taken at a particular magnetic field to a spectrum taken at zero field. At low magnetic fields, there are two electron CR that are very close together, as shown in the top panel of Fig. 3 for the transmission spectra at 12 and 14 T, respectively. These two resonances are well understood. The splitting results from a

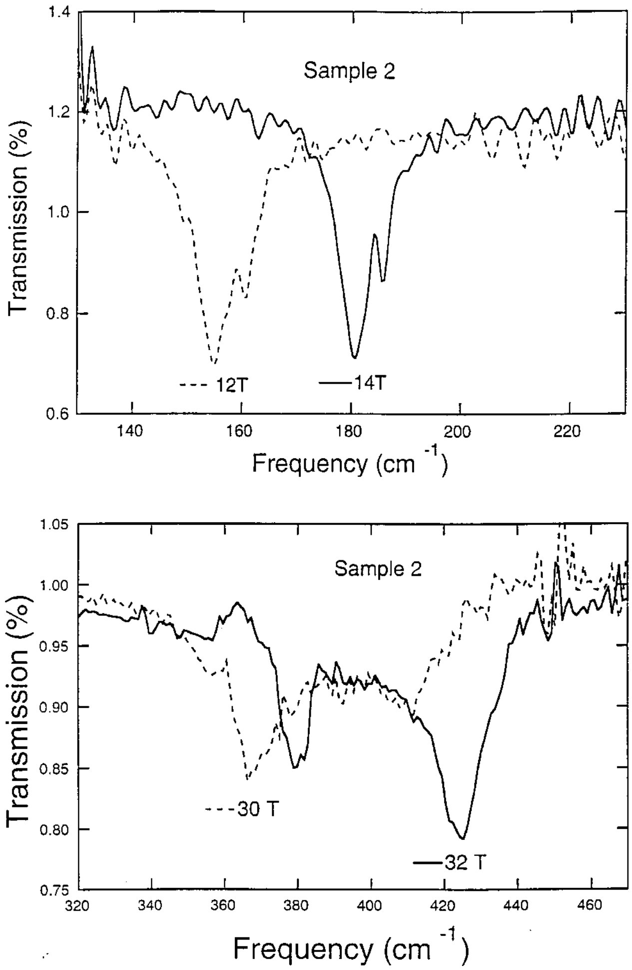

FIG. 3. Normalized transmission spectra at 12 and 14 T for the top panel and 30 and 32 T for the bottom panel for sample 2, respectively.

combination of nonparabolicity, self-consistent band bending, and, in this magnetic-field region, occupancy of LL's in the second subband.[22] As discussed in Ref. 22, in this field region the CR of the second LL to the third LL for the first subband has a higher transition energy than the CR of the first LL to the second LL for the second subband due to the combination of nonparabolicity and energy band bending. This gives rise the slightly separated two CR. The bottom panel of Fig. 3 shows the spectra taken at 30 and 32 T, respectively for the sample 2. It is obvious that the two resonances at the bottom panel are much further apart. The lower energy resonance is definitely dominant when the two resonances are first observable. Above the resonant field (about 30.5 T) or energy, the upper resonance dominants. The lower energy resonance gradually loses intensity as the field is increased, while the higher energy resonance gains intensity over the same region. This is typical behavior for the resonant magnetopolaron effect.

Figures 1 and 2 show the measured electron CR frequency vs magnetic field for the two samples. Apart from the small splitting discussed above there is no measurable deviation in either sample from an almost straight-line extrapolation of the low-field CR data (the dashed curve is the theoretical CR if only band non-parabolicity is incorporated). Even in the region of resonance with the GaAs LO phonons ($E_{\rm CR}=E_{\rm LO}$) there is no measurable resonant polaron effect. However, above the GaAs LO phonon frequency at high fields ($B>27$ T), electron CR exhibits a very strong avoided-level-crossing splitting for both samples. The pinning frequency is slightly different for the two samples, about 400 cm^{-1} for sample 1, and 395 cm^{-1} for sample 2.

To explain the experimental results quantitatively, detailed calculations specific for our two samples have been carried out. First, the subband structure was calculated self-consistently with all donors assumed to be fully ionized. The solution of the coupled Schrödinger and Poisson equations is shown in the inset of Fig. 2. Then, the correction to the CR frequency due to the electron bulk LO-phonon coupling is evaluated by using the well-established memory function approach (see Ref. 21 and references therein).

By introducing a memory function $M_s(\omega)$, the dynamical conductivity of Q2D electrons can be written as $\sigma(\omega)=\Sigma_s(in_se^2/m_b)/[\omega-\omega_c-M_s(\omega)]$, with s being the electron spin index, n_s is the averaged electron density of spin s, m_b is the electron bare band mass, and $\omega_c=eB/m_bc$ is the bare CR frequency. $M_s(\omega)$ can be written as $M_s(\omega)=(1/\omega)\int_0^\infty(1-e^{i\omega t})\mathrm{Im}\,F_s(t)dt$, with

$$F_s(t)=-\sum_k \frac{k_\parallel^2}{n_s m_b \hbar}|V_k|^2\exp(-i\omega_{\rm LO}t) \times[iD_s(k,t)+n_B(\omega_{\rm LO})iD_S^R(k,T)],$$

where V_k is the electron-phonon interaction matrix element and $n_B(\omega_{\rm LO})$ is the number of phonons. $D_s(\mathbf{k},t)(D_s^R(\mathbf{k},t))$ is the (retarded) density-density correlation function of electrons with spin s, which contains the Pauli-blocking effect and the screening of the electron-phonon interaction. The interaction corrected CR frequency is obtained by solving $\omega-\omega_c-M_s(\omega)=0$, and the influence of nonparabolic conduction band is included within a local parabolic band approximation using the two-band Kane model. No fitting parameters are introduced in our calculation and well-accepted values are used for the electron bare mass ($m_b/m_e=0.0665$) and the electron-phonon coupling strength ($\alpha=0.068$).

Our theoretical results are shown by the solid curves (spin down) and dash-dotted (spin up) curves in Figs. 1 and 2. The agreement between the experimental results and our theoretical calculations is very reasonable over the field range for which a comparison is possible. In particular, the large splitting around $h\omega_{\rm LO}+(E_2-E_1)$ is explained nicely within the experimental error (approximately the size of the symbols) by our calculation with no adjustable parameters.

The above theory confirms that the observed splitting is due to the three-level resonance through the subband coupling. Nevertheless, other possible origins for this splitting can also be considered. Since the resonance region is very close to the LO-phonon frequency of AlAs it may be possible that this splitting is caused by the interaction between the electron and some kind of AlAs LO-phonon mode. This is easily excluded based on the arguments similar to those presented in Ref. 15. Since both samples have only one relatively wider single quantum well, and the electron densities are very high, the two possible schemes for electrons interacting with AlAs-like phonons can not be realized. First, electron wave-function penetration into such wider AlGaAs barrier is negligible, and second, the interaction between electrons and interface AlAs phonon modes is completely blocked for such high electron densities.

The inset of Fig. 2 shows the energy diagram (for 30 T) which illustrates our explanation. Here the dashed lines are the results without inclusion of the e-ph interaction and the solid curves include the e-ph interaction resulting in the anticrossing of the different levels. Notice that there are two anticrossings, the first one is the well-known two-level magnetopolaron effect. The second anticrossing is a new result and has not been observed before. It occurs when the energy separation between the 0 and 1st LL of the first subband equals $(E_2 - E_1) + E_{\mathrm{LO}}$. Notice from Figs. 1 and 2 that the two-level resonance results in a very weak splitting as compared to the three-level one. This interesting behavior is understood based on the fact that electron screening and occupancy effects are very strong in the two-level system, and very weak in the three-level system. This is the reason for the absence of an observable direct resonant interaction (two-level system) between the electrons and GaAs LO phonons at lower fields. For a three-level resonance, however, the Pauli principle (occupation effect) plays no role, because the final state is essentially unoccupied—it lies in the next (unoccupied at high fields) subband. In addition, screening is also weak, because the single-particle wave functions in the z direction are orthogonal for the first and second subbands. Therefore, the screening of states in the second subband due to electrons in the lowest subband is expected to be weak. This basic physics accounts for the large splitting observed for the three-level system and the absence of an observable effect for the two-level system.

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