Resonant Magnetopolaron Effects due to Interface Phonons in GaAs/AlGaAs Multiple Quantum Well Structures

Y. J. Wang
National High Magnetic Field Laboratory at Florida State University, Tallahassee, Florida 32306

H. A. Nickel and B. D. McCombe
Department of Physics, State University of New York at Buffalo, Buffalo, New York 14260

F. M. Peeters and J. M. Shi
Department Natuurkunde, Universiteit Antwerpen (UIA), B-2610 Antwerpen, Belgium

G. Q. Hai
Departamento de Física, Universidade Federal de São Carlos, 13565-905 São Carlos, São Paulo, Brazil

X.-G. Wu
National Laboratory for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Science, Beijing, China

T. J. Eustis and W. Schaff
Department of Electrical Engineering, Cornell University, Ithaca, New York 14853
(Received 18 February 1997)

Polaron cyclotron resonance (CR) has been studied in three modulation-doped GaAs/$Al_{0.3}Ga_{0.7}As$ multiple quantum well structures in magnetic field up to 30 T. Large avoided-level-crossing splittings of the CR near the GaAs reststrahlen region, and smaller splittings in the region of the AlAs-like optical phonons of th AlGaAs barriers, are observed. Based on a comparison with a detailed theoretical calculation, the high frequency splitting, the magnitude of which increases with decreasing well width, is assigned to resonant polaron interactions with AlAs-like interface phonons. [S0031-9007(97)04404-9]

PACS numbers: 71.38.+i, 71.70.Di, 78.20.Ls

The interaction of charge carriers with optical phonons in quasi-two-dimensional (Q2D) systems has been of considerable interest both experimentally [1–6] and theoretically [7–12] for several years, since the electronic properties of semiconductors, particularly energy loss mechanisms for hot carriers, are strongly affected by this interaction. For bulk polar materials, the dominant interaction is between the charge carriers and longitudinal optical (LO) phonons [7]. Interface and confined phonons [11,12] and their interaction with charge carriers in quantum wells have received considerable attention recently, and it has been shown theoretically that these modes can play a significant role in narrow wells. However, a number of issues remain unresolved. In particular, a sum rule [13] makes it difficult to deconvolve the relative important of interactions with the various phonon modes of confined systems from measurements which are not phonon-frequency specific [14]. There has also been some controversy about the importance of interface and confined phonon modes in the region of resonant magnetopolaron interaction with GaAs phonons [6,11,12]. Raman scattering studies of short period GaAs/AlAs superlattices [15,16] have provided experimental evidence for both confined and interface modes, but there have been no experimental measurements of the strength of the interactions in either GaAs/AlAs or GaAs/AlGaAs quantum wells, there has been no experimental work showing the effects of interface phonons in quantum well structures with alloy barriers, and there has been no work demonstrating clearly the importance of this interaction in "normal" well width range (the order of greater than 100 Å) for practical devices (e.g., intersubband detectors).

The resonant magnetopolaron effect, which has been studied for a number of years in bulk [17,18] and Q2D [4–6] systems, provides a means of determining the strength of interactions with specific phonons. When the cyclotron resonance (CR) frequency, $\omega_c = eB/m^*c$, is tuned through the frequency of an appropriate optical phonon, a resonant avoid level crossing occurs. The magnitude of this avoided-level-crossing resonance is a direct measure of the strength of the effective interaction. Although such effects have been studied for some time, much remains unknown or poorly understood. Enhanced [1,19], comparable [20], and reduced [3,5,21] resonant polaron effects (relative to 3D) have been previously reported in Q2D systems. The detailed mechanisms leading to these observations have been obscured in some cases by inadequate theoretical models for the specific structures, and in other cases by incomplete experimental data due to an insufficient magnetic field. Nevertheless, appropriate

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experiments spanning the resonant region can reveal the existence of interactions with particular phonon modes, and, when combined with theoretical calculations, can be used to determine the strength of the interaction.

We have carried out an experimental study of electron CR vs magnetic field in three modulation-doped $GaAs/Al_{0.3}Ga_{0.7}As$ multiple-quantum-well samples in magnetic fields up to 30 T. Strong resonant avoided-level-crossing behavior was observed in the region of the GaAs optical phonons with a large splitting of the CR into upper and lower branches. In addition, and of paramount importance, a weaker splitting was observed at higher frequencies in the region of the AlAs-like optical phonons of the barriers. This splitting increases with decreasing well width from 240 to 120 Å, and is attributed to the resonant magnetopolaron interaction of electrons in the GaAs wells with barrier AlAs-like interface phonons. This permits the direct measurement of the importance of the interaction as a function of well width. The magnitude of the splitting is in good agreement with theoretical calculations carried out in the framework of the memory-function formalism [11] including effects of interface optical phonon modes, as well as screening and occupation effects. Our measurements, which are sensitive to specific phonons via the spectral specificity of the technique, demonstrate that, even for barriers containing only 30% Al and relatively wide GaAs wells, the AlAs-like interface phonon modes associated with the barriers interact significantly with electrons in the GaAs wells. A detailed comparison of theory and experiment for the upper and lower branches in the GaAs optical phonon region for two samples with different carrier densities suggests that screening and occupation effects are significant at the higher density and are of nearly equal importance.

The far infrared transmission measurements were carried out with a Bruker 113v Fourier transform interferometric spectrometer in conjunction with a metal light-pipe condensing-cone system and a 4.2 K silicon bolometer detector on samples maintained at 4.2 K in a 30 T resistive magnet. The three $GaAs/Al_{0.3}Ga_{0.7}As$ multiple-quantum-well (240 Å barrier) samples were grown by molecular beam epitaxy with fifteen and ten 240 Å wells, and eight 120 Å wells for samples *A*, *B*, and *C*, respectively. All samples are doped with silicon donors in the barriers, samples *A* and *B* over central $\frac{1}{3}$ and sample *C* in a planar sheet. The measured (from the quantum hall effect) electron densities per well for samples *A* and *B* are 1.5×10^{11} and 3.0×10^{11} cm^{-2}, respectively; the nominal doping for sample *C* is 1.5×10^{11} cm^{-2}. The maximum 30 T magnetic field permits CR measurements that span the entire GaAs and AlAs optical phonon regions.

Figure 1 is a plot of the measured CR frequency vs magnetic field for these samples; the solid lines are the calculated unperturbed single particle CR transition frequencies, which include the conduction band nonparabolicity. The data for all samples show clear, large CR splittings in the GaAs reststrahlen region. The frequencies of the lowest energy branch start to deviate from those of the unperturbed CR well below the GaAs-like optical phonon energies, and the intermediate branch approaches the GaAs-like LO phonon frequency from above as the field is decreased. The CR frequencies of samples *A* and *B* are indistinguishable at fields below 10 T. Larger differences are observed at higher fields, particularly for the intermediate branch in the region of resonance with the GaAs optical phonons.

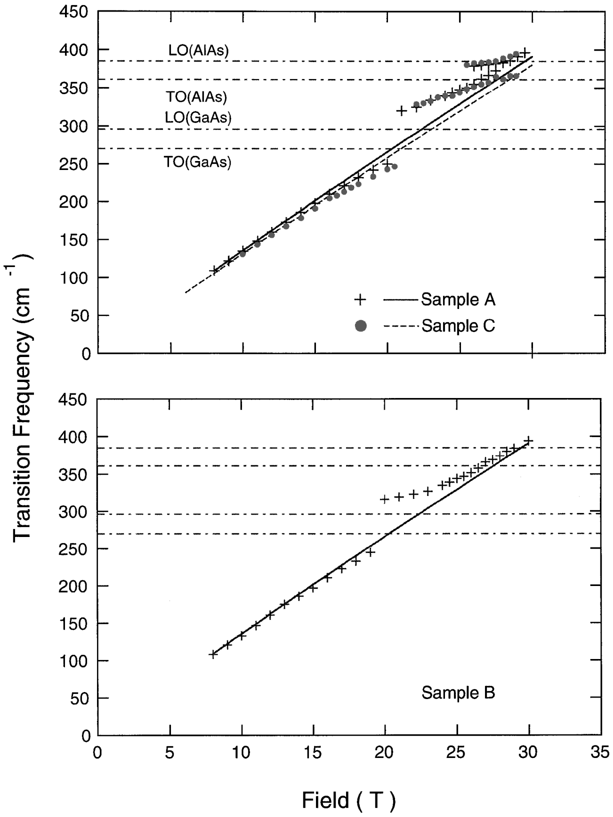

FIG. 1. Experimental data for all three samples. The tilted straight lines in the figures are the calculated CR transitions including nonparabolicity only.

At higher frequencies there are smaller splittings observed in the AlAs-like phonon region for samples *A* and *C*. Raw magnetotransmission spectra for these samples are shown in Fig. 2, at magnetic fields between 25 and 29 T. For sample *A* at 25 and 29 T, there is only one observable resonance minimum at 348 and 391 cm^{-1}, respectively. However, when the CR is tuned through the AlAs-like optical phonon region of the barriers (~26–28 T), the resonance is clearly split into two branches. The intermediate energy branch loses intensity gradually when the field is increased, while the highest energy branch gains intensity over this same region. Note that the pinning frequency (~370 cm^{-1}) lies *between* the AlAs-like LO and transverse optical (TO) frequencies. The minimum separation between the two branches at 27.5 T is approximately 8 cm^{-1}. A much clearer and larger splitting is observed in sample *C* with a minimum separation of 20 cm^{-1} at 27 T, and pinning frequency

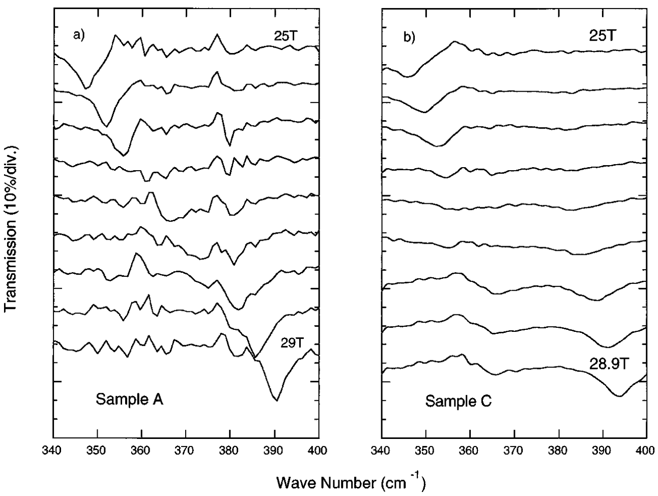

FIG. 2. Transmission spectra at several different fields divided by a zero-field reference spectrum for samples *A* and *C*. The traces are spaced every 0.5 T, except the lowest trace in (b). (a) sample *A*, (b) sample *C*.

close to 370 cm^{-1}. The interaction which causes the splitting clearly *increases* with decreasing well width.

There are two possible origins for this splitting: (1) electrons localized in the GaAs wells interacting with the AlAs-like slab LO phonons in the barriers due to electron wave-function penetration into the barriers, or (2) electrons in the GaAs wells interacting with AlAs-like *interface* phonons due to the tail of the interface modes in the GaAs wells. To estimate the importance of (1) we have calculated the fraction of the probability density of the ground confinement subband wave function penetrating into the $Al_{0.3}Ga_{0.7}As$ barrier for the structures of samples *A* and *C*. For a 240 Å $\times$ 240 Å structure this fraction is 3×10^{-4}; for a 120 Å $\times$ 240 Å structure it is 2×10^{-3}. Since the splitting of the CR at resonance with the GaAs LO modes is approximately 40 cm^{-1} (see Fig. 1), observed splittings (8 and 20 cm^{-1}) cannot be due to the interaction of the electrons in the wells with the AlAs-like LO phonons in the barriers, which should scale with the fraction of electron probability in the barriers because the Fröhlich electron-phonon coupling constant is approximately the same for GaAs ($\sim$0.068) and $Al_{0.3}Ga_{0.7}As$ ($\sim$0.073). Another strong argument against possibility (1) is the fact that for both well widths the pinning energies clearly lie *below* the AlAs-like LO phonon frequency for $Al_{0.3}Ga_{0.7}As$ at helium temperature [22].

The interaction between electrons and the symmetric pure AlAs interface optical (IO) phonon modes has been calculated [11]. In order to compare with the present experimental results, the contribution from the pure AlAs IO phonon modes is multiplied by 0.3. The modified theoretical calculation gives splittings of approximately 10 and 16 cm^{-1} near 371 cm^{-1} for the 240 and 120 Å wells, respectively, in reasonable agreement with the measured values. This is taken to be a confirmation of this assignment. For sample *B* the splitting into two branches is not resolved. It is likely that screening and Pauli principle effects reduce the effective interaction since the electron density for sample *B* is twice that of sample *A*.

Dielectric artifacts can also give rise to apparent splittings [5,23] in the reststrahlen region due to the resonant dielectric function of the material at the TO frequency. A computer simulation of the classical dielectric effects [24] in the reststrahlen region in the multilayer structure of our samples was performed to examine the possible effect of dielectric artifacts. For the present sample parameters, no measurable CR splitting in the GaAs reststrahlen region or in the region of the AlAs-like barrier phonons appears in the simulation.

To test the above conclusion, detailed theoretical calculations for the sample structures are compared with the experimental results in Fig. 3. The *difference* between the measured polaron CR frequency and the unperturbed CR frequency is plotted vs the measured frequency. The electron-phonon interaction Hamiltonian is given by the Fröhlich model, with the phonon modes modified due to confinement and the presence of the interfaces. Three types of optical phonon modes can interact with the electrons in the wells: (1) symmetric interface optical (IO) phonon modes, (2) antisymmetric IO phonon modes, and (3) confined GaAs slab LO phonon modes in the wells. The solid line in Fig. 3 was obtained by considering the effects of symmetric IO phonon and confined slab LO phonon modes in a single electron picture. This calculation agrees well with the experimental results over the entire resonant region. A calculation was also performed for coupling with only bulk GaAs 3D LO phonons (other lines in the figure). The results are nearly the same for the wider well samples (*A* and *B*), except near the AlAs-like phonon frequencies. This is to be expected for relatively wide quantum wells. But the agreement for sample *C* is clearly significantly worse. Confined and interface modes must be accounted for to get good agreement in this case. The GaAs-like interface phonon modes do not play an important role over the range of fields and frequencies for which the polaron CR is observable since their interaction with electrons is smaller than that of the GaAs confined phonon modes, and the experiments do not probe into the reststrahlen region where the resonance occurs. On the other hand, the AlAs-like IO modes do play an important role since there is no strong interaction with any slab modes, and the total AlGaAs thickness is small enough that the reststrahlen effect does not obscure the interaction. The symmetric AlAs-like IO modes are responsible for the splittings near 370 cm^{-1}, and inclusion of this interaction provides good agreement with experiment.

The doping concentrations of the samples lie in an intermediate regime for which both screening and occupation effects must be considered. The dashed lines in Fig. 3 are calculated results for coupling with only bulk GaAs LO phonons, and the dash-dotted lines are

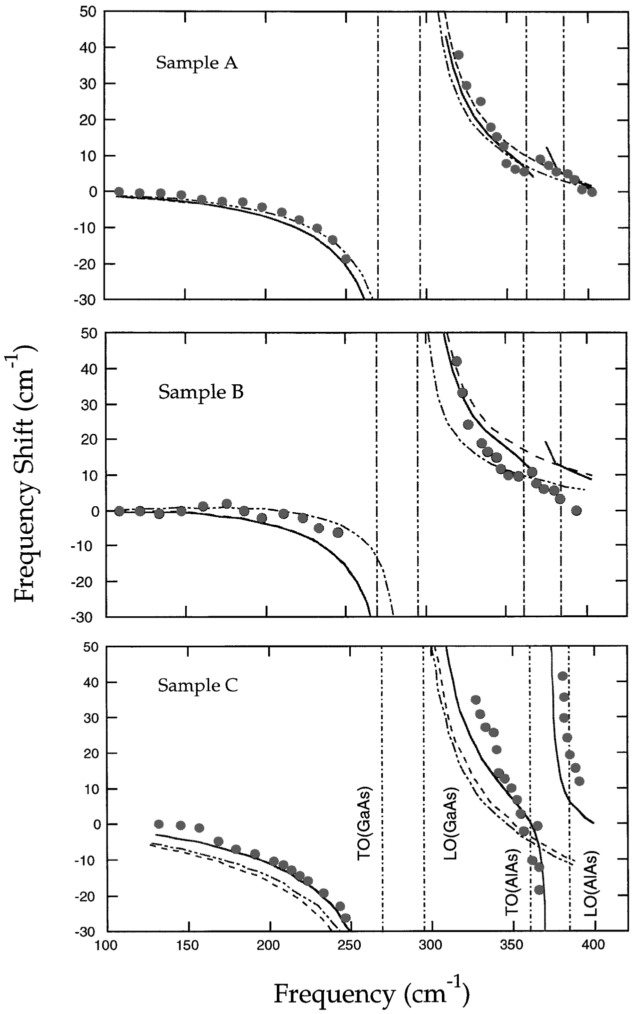

FIG. 3. Plot of frequency shift vs frequency for three samples. The dots are experimental data. The dashed curves are for coupling with only bulk GaAs optical phonons, the dash-dotted curves include screening effects within the RPA in addition to the coupling with the GaAs bulk phonons, and the solid curves consider the effects of IO phonon and slab LO optical phonon modes.

calculated results in which both screening (within the static random-phase approximation [10]) and occupation effects are taken into account in addition to the coupling with bulk GaAs optical phonons. It can be seen that, when occupation and screening effects are included, the agreement between the calculations and the experimental results are further improved in the GaAs region for sample *B*.

The importance of screening and Landau level occupation can also be seen from the region of AlAs-like phonons. Since the contribution to the interaction from screening and occupation effects are both important [25] in this region, the fact that a splitting in the AlAs-like phonon region is not observed in the higher doped sample *B* shows these effects play a strong role here.

Experimental work was performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-9016241 and by the State of Florida. B.D.M. and H.A.N. were supported in part by ONR Grant No. N00014-91-J-1939. F.M.P. is supported by the Belgian National Science Foundation.

[1] M. Horst, U. Merkt, and J.P. Kotthaus, Phys. Rev. Lett. **50**, 745 (1983).
[2] W. Seidenbusch, G. Lindemann, R. Lassnig, J. Edlinger, and G. Gornik, Surf. Sci. **142**, 375 (1984).
[3] H. Sigg, P. Wyder, and J.A.A.J. Perenboom, Phys. Rev. B **31**, 5253 (1985).
[4] Y.-H. Chang, B.D. McCombe, J.-M. Mercy, A.A. Reeder, J. Ralston, and G.A. Wicks, Phys. Rev. Lett. **61**, 1408 (1988).
[5] M. Ziesmann, D. Heitmann, and L.L. Chang, Phys. Rev. B **35**, 4541 (1987).
[6] J.P. Cheng, B.D. McCombe, and G. Brozak, Phys. Rev. B **43**, 9324 (1991).
[7] S. Das Sarma, Phys. Rev. B **27**, 2590 (1983).
[8] D.M. Larsen, Phys. Rev. B **30**, 4595 (1984).
[9] S. Das Sarma and B.A. Mason, Phys. Rev. B **31**, 5536 (1985).
[10] F.M. Peeters, X.-G. Wu, J.T. Devreese, C.J.G.M. Langerak, J. Singleton, D.J. Barnes, and R.J. Nicholas, Phys. Rev. B **45**, 4296 (1992).
[11] G.Q. Hai, F.M. Peeters, and J.T. Devreese, Phys. Rev. B **47**, 10 358 (1993).
[12] R. Chen, D.L. Lin, and T.F. George, Phys. Rev. B **41**, 1435 (1990).
[13] N. Mori and T. Ando, Phys. Rev. B **40**, 6175 (1989).
[14] According to the sum rule, the sum of all contributions of all phonon modes in confined systems to the form factors is exactly equal to that of the bulk phonon modes if the respective coupling constants are equal.
[15] A.K. Sood, J. Menendez, M. Cardona, and K. Ploog, Phys. Rev. Lett. **54**, 2115 (1985).
[16] C. Colvard, T.A. Gant, M.V. Klein, R. Merlin, R. Fischer, H. Morkoc, and A.C. Gossard, Phys. Rev. B **31**, 2080 (1985).
[17] D. Larsen, Phys. Rev. **135**, A419 (1964).
[18] B.D. McCombe and R. Kaplan, Phys. Rev. Lett. **21**, 756 (1968).
[19] J. Singleton, R.J. Nicholas, and F. Nasir, Solid State Commun. **58**, 833 (1986).
[20] J. Singleton, R.J. Nicholas, D.C. Rogers, and C.T.B. Foxon, Surf. Sci. **196**, 429 (1988).
[21] M.A. Hopkins, R.J. Nicholas, M.A. Brummell, J.J. Harris, and C.T. Foxon, Superlattices Microstruct. **2**, 319 (1986).
[22] From extrapolations of room temperature measurements quoted in S. Adachi, *GaAs and Related Materials* (World Scientific, Singapore, 1994), the helium temperature values are $\omega_{\rm TO}$ (AlAs-like) = 361 cm^{-1}; $\omega_{\rm TO}$ (AlAs-like) = 385 cm^{-1}.
[23] K. Karrai, S. Huant, G. Martinez, and L.C. Brunel, Solid State Commun. **66**, 355 (1988).
[24] J.P. Cheng and B.D. McCombe, Phys. Rev. Lett. **62**, 1925 (1989).
[25] X.-G. Wu, F.M. Peeters, and J.D. Devreese, Phys. Rev. B **36**, 9760 (1987).