Frequency-Shifted Polaron Coupling in $Ga_{0.47}In_{0.53}As$ Heterojunctions

R. J. Nicholas,[a] L. C. Brunel, S. Huant, K. Karrai, and J. C. Portal[b]
Service National des Champs Intenses, Centre National de la Recherche Scientifique, F-38042 Grenoble, France

and

M. A. Brummell
Clarendon Laboratory, Oxford OX1 3PU, United Kingdom

and

M. Razeghi
Laboratoire Central de Recherche, Thomson-CSF, F-91401 Orsay, France

and

K. Y. Cheng and A. Y. Cho
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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Frequency-dependent cyclotron-resonance measurements are reported on $Ga_{0.47}In_{0.53}As$-InP and $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ heterojunctions. Discontinuities in the effective mass occur at two frequencies as a result of resonant polaron coupling with both optic-phonon modes present in the $Ga_{0.47}In_{0.53}As$ alloy. The coupling occurs at the frequencies at the TO phonons, in contrast to measurements on bulk materials. Possible changes in the screening and polarization of the optic-phonon modes are considered.

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The interaction of electrons with optic phonons in two-dimensional systems is currently a subject of considerable debate. This Letter reports studies of magnetopolarons in $Ga_{0.47}In_{0.53}As$-based heterojunctions, which show that the dominant interaction occurs near the frequency of the transverse-optic (TO) phonons, in contrast to previous assumptions. Several other studies of polaron cyclotron resonance in two-dimensional (2D) systems have been reported, in which it has been found that polaronic effects are enhanced in some situations[1,2] and reduced in others.[3–5] Calculations suggest[6,7] that the expected interaction with LO phonons is enhanced by the relaxation of momentum conservation perpendicular to the interface and possible further contributions from interface optic phonons. However, the inclusion of screening and the surface potential[8–10] leads to a reduction in the coupling. Recent studies of magnetophonon oscillations in GaInAs 2D structures indicate that the interfaces and the confining potential play a significant role in determination of the dominant coupling.[11–13]

In this series of measurements we have studied cyclotron-resonance absorption in GaInAs-InP and GaInAs-AlInAs heterojunctions grown at Thomson-CSF by metal-organic chemical-vapor deposition[14] and at Bell Laboratories by molecular-beam epitaxy,[15] respectively. The samples have electron concentrations of 3×10^{11} and 8×10^{11} cm^{-2}, respectively, and have been described in earlier works.[16,17] The transmission of far-infrared radiation was studied as a function of magnetic field at 4.2 K, with a large number of wavelengths from an optically pumped far-infrared laser. Particular care was taken to study the region of 35–60 μm covering the *reststrahl* band of GaInAs. It was possible to work within the *Reststrahl,* since the samples were grown on InP substrates and the bulk GaInAs layers were only ~1 μm thick. It was found necessary to check the infrared wavelengths for each measurement with a Michelson interferometer to obtain accurate and reproducible results, as several of the frequently quoted lines in this region were found to be substantially in error when wavelength measurements were made to an accuracy of 0.1 μm, and often occur in closely spaced pairs. As a consequence, some of the resonance values reported in our earlier measurements[16] are substantially in error. The sample substrates were wedged to avoid interference.

Some typical experimental recordings are shown in Fig. 1. As the frequency approaches that of the optic phonons in GaInAs[16] the resonances are seen to broaden, and then to narrow very dramatically, becoming asymmetric at the same time. For the GaInAs-InP heterojunction, a second, unexplained resonance was also observed ~3 T above the normal cyclotron resonance for wavelengths in the region 50–60 μm. The resonance positions also show an anomalous dependence on frequency, as is shown in Fig. 2 for the two heterojunctions. The plot of resonant field against frequency shows two distinct breaks, at approximately

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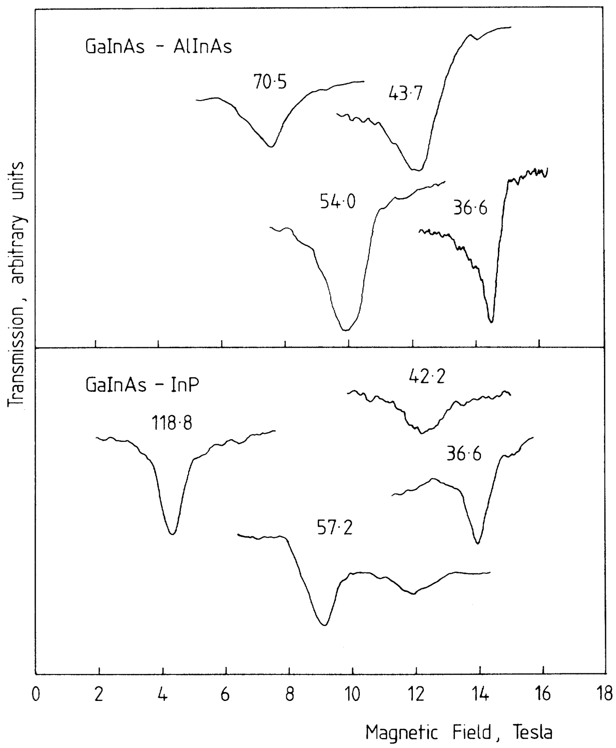

FIG. 1. Typical experimental recordings of the cyclotron resonance in 4.2 K in the two systems studied. The wavelength is shown in microns.

222 and 255 cm^{-1}, in the manner characteristic of polaron coupling. Such behavior has been observed in a number of bulk semiconductors,[18] with the break occurring at the frequency of the longitudinal-optic (LO) phonon. Coupling occurs primarily to the LO phonon because of its large polarization field. The coupling is demonstrated more clearly in the present case by a plot of the frequency dependence of the effective mass, as shown in Fig. 3. The typical error in these plots may be estimated by the assumption of an uncertainty in the resonant field of $\pm 10\%$ of the resonance halfwidth. In the region of the phonon energies, this gives $\Delta m^* \simeq \pm 0.0002 m_e$. This error increases at lower frequencies, as the resonance linewidth is only a weak function of magnetic field.

The optic-phonon properties of $Ga_{0.47}In_{0.53}As$ alloys have been measured both by reflectivity[19] and by Raman scattering.[20–22] These show that the optic modes have a "two-mode" character, corresponding to the two alloy constituents GaAs and InAs, with "GaAs" LO and TO frequencies of 272 and 256 cm^{-1} and "InAs" LO and TO frequencies of 233 and 226 cm^{-1} at 77 K. The Raman measurements were repeated on the present layers, giving the same values. The remarkable feature of the polaron cyclotron resonance is

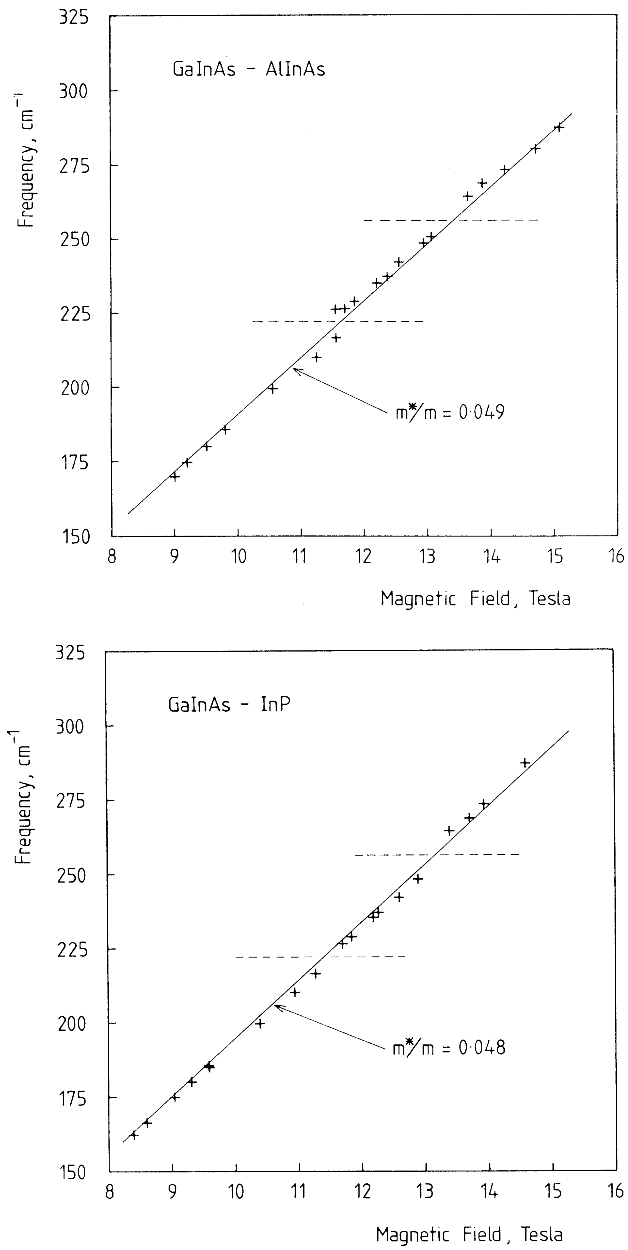

FIG. 2. The frequency dependence of the cyclotron resonant field in the region of the optic-phonon modes. The solid line shows the expected dependence for a constant effective mass, while the dashed lines indicate the apparent coupling frequencies of 222 and 255 cm^{-1}.

the coupling energies at which the discontinuities in the effective masses occur. These are at, or very slightly below, the energies of the TO phonons, and are well below the LO modes. There is also a very rapid narrowing and pronounced asymmetry of the resonances once the last coupling energy at 255 cm^{-1} has

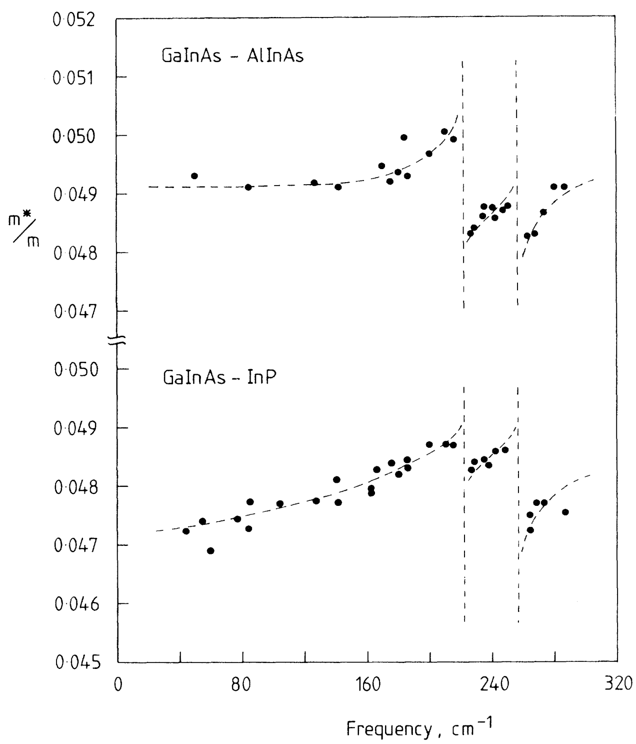

FIG. 3. The frequency dependence of the effective mass as deduced from the resonance positions shown in Fig. 2. The dashed lines are a guide to the eye, and also indicate the apparent coupling frequencies of 222 and 255 cm^{-1}.

been passed. By 287 cm^{-1}, there has been an approximately threefold fall in the linewidth. The rapid fall is a feature of both samples studied, and may itself account for the asymmetry of the line shape, which would narrow as the field increases, since the resonant coupling is a function of the field rather than the frequency. One possible cause of both asymmetric line shapes and peak shifts is the complex nature of the dielectric function in the *Reststrahl* region. Simulations of the complete dielectric function were used to determine the transmission,[23] and it was found that this did not cause any significant modifications to the resonance position or line shape for the layer thicknesses and frequencies studied. The narrowing thus seems to be further evidence for coupling at the TO frequency.

Two important points arise from the energy-dependent effective-mass plots shown in Fig. 3. Firstly, there is the shift of the resonant coupling down to the TO-phonon frequency for both optic-phonon modes. Secondly, the relative coupling strengths to the two modes are different in the two structures. The GaInAs-AlInAs heterojunction shows a much larger discontinuity at the lower, InAs mode, while the GaInAs-InP heterojunction has a larger discontinuity at the GaAs frequency. This behavior is entirely consistent with magnetophonon measurements, which show coupling to InAs modes in the GaInAs-AlInAs structures, and to GaAs modes in GaInAs-InP structures.[11-13] Well away from the resonant coupling, the difference in the high- and low-frequency masses should provide a direct measurement of the strength of the polaron coupling. This value could not be deduced from the present measurements, as it was not possible to extend the measurements to higher frequencies because of absorption in the *reststrahl* band of the InP substrates. Another complicating factor is the influence of nonparabolicity, which causes a linear rise in the effective mass with energy once the ultraquantum limit has been reached and the only transitions contributing to the resonance are those from the $N=0$ to the $N=1$ Landau level.[12,13] This occurs at ~ 6 and ~ 16 T for the two samples, respectively, which corresponds to frequencies of 110 and 300 cm^{-1}, and hence the data for the lower-concentration GaInAs-InP sample show a steady increase in mass in addition to the resonant effects. It has recently been demonstrated experimentally[24] that this nonparabolicity is approximately double that predicted by $\mathbf{k}\cdot\mathbf{p}$ theory, possibly as a result of alloy disorder. The occupation of a second electric subband in the higher-concentration sample may also be significant,[17] although no evidence was found for a separate transition with a significantly different effective mass.

Das Sarma[7] has calculated the magnitude of the effective-mass splitting for the resonant case $\omega_c \sim \omega_{LO}$. For a perfectly 2D system, this would give masses shifted by $\pm 10\%$ in GaInAs, around 5 times larger than the effect observed here. The inclusion of the finite wave function of the heterojunction in the third dimension will reduce this splitting by a factor of up to 3 for the 3D limit.[7,8] The full self-consistent inclusion of screening into the resonant polaron coupling is a problem which has not been fully studied; however, it is likely to be very important in high magnetic fields because of the extreme degeneracy of the Landau levels. Calculations without field indicate a significant reduction of the polaron mass enhancement by screening.[9] In contrast, recent measurements by Horst and Merkt[5] in the Voigt configuration suggest that screening and surface phonons do not contribute to the surface polaron.

It is well known from Raman measurements in heavily doped bulk GaAs[25] that the frequency of the coupled plasmon–optic-phonon system approaches that of the TO phonon for large q vectors. This behavior may be related to our results, where the dominant coupling is at the TO phonon frequency. An interchange of LO and TO phonon character has been observed recently in GaAs-GaAlAs superlattices by Zucker *et al.*,[26] in which selection rules for Raman scattering were found to be interchanged for the two phonons.

Coupling to TO modes is not observed in bulk material because their only polarization is at the surface, which is insignificant for the bulk case. For a thin ionic slab, a transverse vibration occurs at the bulk LO frequency and the longitudinal vibration occurs at the bulk TO frequency.[27] Because of the boundary conditions, the in-plane ionic vibrations all occur at the TO frequency,[26,27] and it is these that are most likely to couple to the electrons. The single boundary in the heterojunctions may be expected to exert a similar influence, although the analogy to slab modes is only approximate. It is clear that the presence of the interface is significant, since we have shown that the relative strengths of the couplings are different for the two different interfaces.

A detailed description of the coupled modes in the systems studied here is difficult because of the similarity of the q vectors and energies of the various excitations. The Thomas-Fermi wave vector, the phonon wave vectors, and the inverse of the electron wavelength for binding to the interface are all comparable ($\sim 10^8$ m^{-1}), which leads to a complicated dielectric function which must be determined self-consistently. Nevertheless, the experimental evidence shows a clear coupling to an optic-phonon mode at the frequency of the bulk TO phonon, with little or no coupling at the bulk LO frequency. The role of the interface has been clearly demonstrated by the different behavior shown by the two types of heterojunctions studied. This, and the presence of the two-dimensional electron gas, are thought to result in a modification of the polarization and screening associated with the optic-phonon modes, which produces very significant changes in the electron-phonon interaction at the heterojunction.

[(a)]Permanent address: Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom.

[(b)]Also at Laboratoire de Physique des Solides, Institut National des Sciences Appliquées, F-31077 Toulouse, France.

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