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Modification of the Electron-Phonon Interactions in GaAs-GaAlAs Heterojunctions

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We report cyclotron and magnetophonon resonance experiments on GaAs-GaAlAs heterojunctions as a function of temperature. The cyclotron mass shows an anomalous increase with temperature, which we attribute to strong screening of the electron–optic-phonon interaction at low temperatures suppressing the polaron mass enhancement. The magnetophonon resonance results yield phonon frequencies significantly below the bulk GaAs LO values, suggesting that the electrons are interacting with phonons associated with the interface.

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Electron-optic phonon interactions in semiconductor heterostructures have generated considerable interest in recent years. Theoretical work[1-4] predicts polaron effects in two-dimensional (2D) systems should be stronger than in the corresponding bulk materials, but the finite wave functions in the third dimension[4-6] and screening[5,7,8] should reduce the coupling. Experiments on various 2D systems have suggested both enhanced[9,10] and reduced[8,11,12] effects. Magnetophonon resonance[13,14] has shown that the material used to confine the electrons and the form of the confining potential significantly influence the interactions. A recent cyclotron resonance study of GaInAs-based heterostructures[15,16] showed resonant polaron coupling near the TO-phonon frequencies, in contrast to the expected interaction with LO modes. This result has been interpreted in terms of screening[15-17] and coupling to interface phonons.[18] This Letter reports cyclotron resonance measurements on GaAs-$Ga_{0.7}Al_{0.3}As$ heterojunctions which indicate that screening of the electron-phonon interaction is important, and magnetophonon resonance results which suggest that the dominant interaction is not with bulk GaAs LO phonons. This is particularly significant for GaAs-GaAlAs devices working at 300 or 77 K, where the scattering is dominated by LO phonons.

The samples used were grown by molecular-beam epitaxy (MBE) at Philips Research Laboratories, Redhill,[19] and had electron concentrations between 0.9×10^{11} and 1.8×10^{11} cm^2, with 4.2-K mobilities of order 500000 $cm^2\ V^{-1}\ s^{-1}$. Cyclotron resonances were observed as a function of temperature in the transmission of 118.83-μm radiation from a far-infrared laser. The high sample quality is reflected in the extremely narrow linewidths ($\Delta B/B \simeq \frac{1}{300}$) at low temperatures, but the resonances broaden rapidly with increasing temperature; above ~30 K the linewidths are limited by phonon scattering and vary as $T^{3/2}$. Assuming a resonant field uncertainty of 10% of the linewidth gives typical uncertainties in the mass of 0.04% and 0.3% at 4 and 100 K, respectively. In the three samples studied, only the lowest Landau level would be populated at $T=0$, and the mass measured would be that associated with the transition between the $n=0$ and $n=1$ levels m^*_{01}. However, at finite temperatures the thermal population of higher levels will increase the mass through nonparabolicity. At a given temperature, m^*_{01} is calculated under the assumption that transitions weighted by the population of the initial levels and with use of the nonparabolicity measured in the same samples.[20] This was deduced from the frequency dependence of the low-temperature cyclotron mass in the quantum limit, where only the $n=0$ to $n=1$ transition occurs at a mean energy of $\hbar\omega_c$, and from the variation of the mass with electron concentration at low fields, where transitions occur at a mean energy of E_F. The nonparabolicity is lower than that measured in bulk GaAs,[21] consistent with the changes in polaron coupling discussed here, and is well described by five-band $\mathbf{k}\cdot\mathbf{p}$ theory,[21,22] but underestimated by simpler three-band calculations.[23] The correction required to deduce m^*_{01} is 0.7% at 100 K.

The values of m^*_{01} deduced are plotted against temperature in Fig. 1 and show an unexpected decrease, of order 2%, as the temperature falls below ~100 K. Similar measurements on bulk GaAs show no such change in m^*_{01}. We believe this to be due to temperature-dependent screening of the mass enhancement caused by polaron coupling. In an ideal 2D system, a mass enhancement of 3.9% would be expected at this frequency.[2,3] However, the finite wave function in the third dimension will reduce the coupling,[4-6] and the calculations of Das Sarma[5] give enhancements of 1.4%, 1.5%, and 1.6% for samples G63, G29, and G71, respectively. The fall in m^*_{01} below ~100 K is attributed to a further reduction in the mass enhancement caused by screening. The screening should depend upon the density of states within ~kT of the Fermi energy[24] and at low tempera-

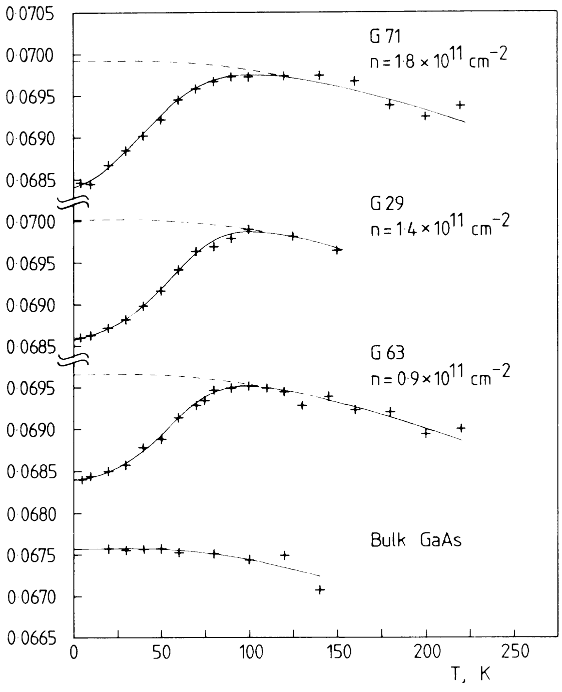

FIG. 1. The temperature dependence of m_{01}^* in three heterojunctions and bulk GaAs, showing the anomalous increase with temperature in the heterojunctions. The dashed lines are extrapolations using the bulk dependence.

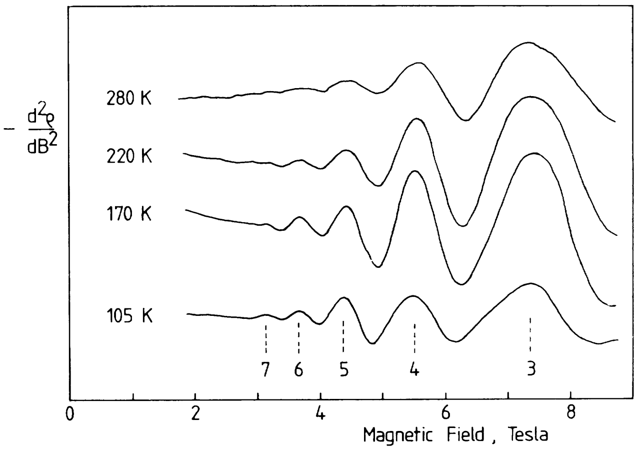

FIG. 2. Magnetophonon resonances in the second derivative of the magnetoresistance of sample G63.

tures the Landau levels, whose homogeneous width over ~100 Å is reflected in the cyclotron resonance linewidth, will be extremely sharp with a very high density of states. This leads to strong screening and the suppression of the polaron-mass enhancement, as well as oscillatory cyclotron resonance linewidths[25] attributed to filling-factor–dependent screening.[25,26] At higher temperatures, the increased level width and thermal energy will reduce the screening, so that the mass enhancement reappears. A similar argument has recently been used to explain changes in the resonant polaron coupling in GaAs-GaAlAs heterojunctions in hot-electron experiments.[27] No theoretical studies of screening of the electron-optic phonon coupling in high magnetic fields have been reported, but calculations for zero field[5,7,8] suggest that the coupling may be reduced by factors of 2–3. The effects in high fields may be expected to be much more extreme. Extrapolation of m_{01}^* at high temperatures to $T=0$ with the temperature dependence measured in bulk GaAs gives reductions in m_{01}^* of 1.8%, 2.1%, and 2.2% in samples G63, G29, and G71, respectively. These are slightly larger than the calculated values, with the same electron-concentration dependence, suggesting that most or all of the enhancement is screened out at low temperatures. This is supported by the nonparabolicities measured in bulk GaAs[21] and in GaAs-GaAlAs hererojunctions[20]; these differ by an amount approximately equal to the bulk polaron contribution. However, this comparison must be regarded as qualitative, as coupling to the LO phonons of bulk GaAs has been assumed, whereas the magnetophonon-resonance results described below suggest that interactions with other phonons are dominant.

When the LO-phonon energy is equal to the separation between two Landau levels, resonant absorption of a phonon can occur. This changes the scattering rate and gives rise to magnetophonon resonances,[28] which can be observed as oscillations in the magnetoresistance, periodic in $1/B$, at fields given by

$$\hbar\omega_{\mathrm{LO}} = N\hbar\omega_c = N\hbar eB/m^*, \quad N=1,2,3,\ldots . \tag{1}$$

The periodicity relates ω_{LO} and m^*, and so either can be deduced if the other is known. The resonances must be observed at temperatures high enough to ensure a sufficient LO-phonon population, but not so high as to cause excessive level broadening; optimum temperatures are typically 150 K. Magnetophonon resonances in GaAs-GaAlAs heterojunctions were first observed by Tsui *et al.*,[29] and two reports of more detailed measurements have since appeared.[30,31] However, none of these studies involved a comparison with a cyclotron mass measured at the same temperature, which leads to errors because of the unexpected temperature dependence of the mass. In addition, the measured nonparabolicity used in our analysis is greater than that predicted by three-band $\mathbf{k}\cdot\mathbf{p}$ theory.[22]

Because of the small oscillation amplitude ($\Delta\rho/\rho \simeq 1\%$) and the background magnetoresistance, the resonances were observed in the second derivative of the resistance with respect to field (Fig. 2). The fundamental fields NB_N deduced from the oscillation maxima lie in the range 22–22.5 T, slightly lower than reported by other workers[29–31] as a result of the lower electron concentrations in our samples and nonparabolicity. Before the phonon energies can be deduced from Eq. (1), several corrections must be applied. The oscillations form an exponentially damped sinusoidal series, periodic in $1/B$, and the actual resonance positions must be calculated from the oscillation maxima by use of the measured damping and tabulated correction factors.[28] The cyclotron masses were corrected for nonparabolicity with use of the parameters measured in the same samples.[20,28] In bulk semiconductors, resonant polaron effects introduce an additional enhancement of the magnetophonon mass by a factor of $1+\alpha/4$,[28] where α is the Fröhlich coupling constant, but the magnitude of this correction in 2D systems is unknown. However, low-temperature cyclotron-resonance measurements[8] suggest that the resonant polaron coupling in GaAs-GaAlAs heterojunctions is $\sim 75\%$ as strong as that in bulk GaAs. A resonant polaron correction of $1+0.75\alpha/4$ has therefore been used, but this may be an underestimate if the resonant polaron coupling increases with temperature because of reduced screening. In terms of the phonon frequencies, the damping, nonparabolicity, and resonant polaron corrections lower ω_{LO} by ~ 5, ~ 6, and $\sim 3\frac{1}{2}$ cm^{-1}, respectively. Above ~ 220 K, because the cyclotron resonances were too broad for accurate mass measurements, the phonon frequencies were calculated from an extrapolation of the lower-temperature masses.

The phonon frequencies deduced for samples G29 and G63 are shown in Fig. 3, together with interpolations between the 4- and 300-K LO and TO frequencies of bulk GaAs,[32] and it can be seen that they lie 12–15 cm^{-1} below the bulk LO frequency. For comparison, the raw data of Wood[33] for bulk GaAs was analyzed in the same manner, by use of the cyclotron masses and nonparabolicity measured in bulk GaAs.[21]. The resulting phonon frequencies lie close to the LO value as expected. In fact, the resonances in the heterojunctions occur at fields 3%–4% lower than in the bulk, despite the higher effective masses due to the confinement into electric subbands, so that significantly lower phonon frequencies will be deduced regardless of the exact magnitude of the corrections. The uncertainty over the resonant-polaron correction precludes a definitive determination of the phonon frequency, but the "best estimates" of Fig. 3 suggest a value of 282 cm^{-1} referred to $T=0$, compared with bulk LO and TO frequencies of 296.4 and 273.2 cm^{-1}, respectively. A larger resonant-polaron correction would reduce this value.

The measured phonon frequencies lie closer to the bulk TO value than the LO frequency, consistent with the resonant-polaron coupling near the TO frequencies seen in GaInAs-based heterojunctions.[15,16] One interpretation of these results invoked strong screening of the polarization field of the LO phonons, leading to a reduction in their frequency.[15-17] However, this seems unable to explain the present measurements because the screening should be strongly temperature dependent, as discussed above, causing the LO-phonon frequency to fall from the bulk LO value towards the TO frequency as the temperature is reduced. Although screening may be significant at the lowest temperatures, this suggests that the electrons are interacting with other phonon modes associated with the presence of the interface.

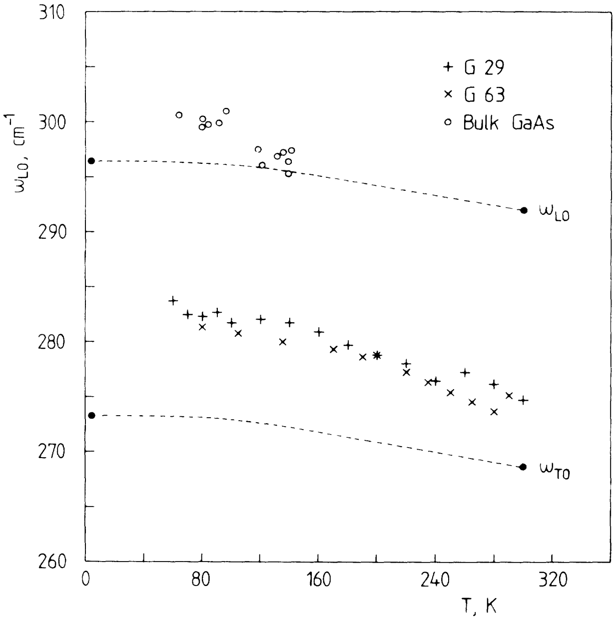

FIG. 3. The phonon frequencies deduced from the magnetophonon resonances in samples G29 and G63. The dashed lines are interpolations between Raman measurements on bulk GaAs, and the points lie well below the LO value, in contrast to bulk results analyzed in the same manner.

Reflectivity studies[34] show that $\mathrm{Ga}_{1-x}\mathrm{Al}_x\mathrm{As}$ exhibits two-mode behavior,[34] with "GaAs" LO and TO frequencies of 282 and 269 cm^{-1} and "AlAs" LO and TO values of 379 and 359 cm^{-1} at $x=0.3$, $T=0$. The measured phonon frequency thus corresponds closely with the "GaAs" LO mode of the GaAlAs, and interactions with this phonon have been observed in resonant Raman experiments on GaAs-GaAlAs superlattices.[35] However, the scattering by the confined modes of the GaAs was stronger, and it seems unlikely that interactions across the interface should dominate over coupling to the GaAs LO phonon. Alternatively, the resonances could be due to scattering by interface phonons, whose frequencies satisfy the condition $\varepsilon_1+\varepsilon_2=0$ for a single interface. This can be solved with use of suitable expressions for the dielectric constants.[13,14] In GaAs-GaAlAs heterojunctions the almost-degenerate "GaAs" modes in the two materials lead to two interface phonons in this region with frequencies of 290 and 270 cm^{-1}, the latter having a very weak oscillator strength. Microscopic calculations for GaSb-InAs superlattices[36] suggest that the continuous-media approximation may be inadequate for degenerate modes on both sides of the interface. The measured phonon frequency is near the top of the region where the LO-phonon bands of the two materials overlap, and modes continuous across the interface may exist at these frequencies. Transverse modes propagating through a superlattice have been predicted for a similar situation.[36] The magnetophonon oscillations could also consist of unresolved series due to scattering by two or more modes close in energy, such as the LO and TO phonons of bulk GaAs. However, it is clear that there must be significant coupling to a mode whose frequency is considerably lower than that of the bulk GaAs LO phonon.

In conclusion, we have demonstrated that polaron coupling in 2D systems is strongly modified by screening at low temperatures. At higher temperatures, where the screening is reduced, we find that the dominant electron-optic phonon interaction involves a phonon significantly lower in energy than the bulk LO phonon, but it has not been possible to identify its character.

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