Magnetophonon resonance under hydrostatic pressure in GaAs-$Al_{0.28}Ga_{0.72}As$ and $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ heterojunctions

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We report magnetophonon resonance measurements under hydrostatic pressure in GaAs-$Al_{0.28}Ga_{0.72}As$ and $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ heterojunctions. The effective mass and the amplitude of the oscillations are measured in the range 150–300 K under pressures up to 16 kbar. The observed enhancement of the effective mass above its band-edge value has a relative amplitude of the order of 10% and 30% in the GaAs- and $Ga_{0.47}In_{0.53}As$-based heterojunctions, respectively. In its major part, the mass enhancement can be explained by band nonparabolicity. We discuss the possible influence of magnetic-field-dependent screening of the electron-phonon interaction which brings changes in the polaron correction of the effective mass and in the amplitude of the magnetophonon oscillations.

I. INTRODUCTION

The magnetophonon resonance effect (MPR) has been used since the mid-1960s to investigate the band-structure parameters and transport processes in III-V compounds (see, e.g., Ref. 1 for an up-to-date review). The hydrostatic pressure technique has been advantageously associated with MPR measurements to study the behavior of the effective mass under pressure and compare it to the predictions of the $\mathbf{k}\cdot\mathbf{p}$ theory.[2–4]

Recently, several authors have reported MPR measurements in two-dimensional (2D) systems such as n-type GaAs-$Al_xGa_{1-x}As$ heterostructures,[5–7] or $Ga_{0.47}In_{0.53}As$-InP and $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ systems.[8–10] In this paper, we report the first observations of MPR under hydrostatic pressure in GaAs-$Al_{0.28}Ga_{0.72}As$ and $Ga_{0.47}In_{0.53}As$-$Al_{0.48}in_{0.52}As$ heterojunctions.

We show that MPR measurements under hydrostatic pressure can provide some additional information about the electron–LO-phonon coupling in two dimensions. We will first concentrate on the effective-mass measurements for both systems and we will then show how the oscillation amplitude (which is a measure of the electron-phonon interaction) is affected by the pressure-induced decrease of the carrier concentration. The results are discussed in terms of nonparabolicity and screening effects.

II. THE MAGNETOPHONON RESONANCE

A. Effective mass

The magnetophonon effect manifests itself as an oscillatory behavior of the resistivity as a function of the magnetic field B. These oscillations are due to electron–LO-phonon interactions which become resonant when

$$\omega_{LO}=NeB_N/m^* , \quad (1)$$

where N is the resonance index and B_N is the magnetic field at this resonance. From the measurement of B_N, the effective mass m^* or the phonon frequency ω_{LO} can be deduced, provided that one of the two is known. To observe the MPR effect, the temperature must be high enough to have a sufficient phonon population, but not too high, since the thermal broadening of the Landau levels reduces the oscillation amplitude. Optimal temperatures are usually in the range 100–250 K. In analyzing MPR results, one then has to consider the fact that the thermal distribution of the electrons will lead to the observation of an increased value of the effective mass compared to the band-edge mass m_0^* because of nonparabolicity effects. In 2D systems the electric quantization provides an additional amount of kinetic energy which must also be considered when one wants to deduce m_0^* from the measured mass. We will see below how this can be done in a simplified way in the case of our heterostructures.

The value of the effective mass is also affected by the electron–LO-phonon interaction (polaron effect). At low magnetic fields, the renormalization factor of m^* is $1+\alpha/6$ in 3D and $1+\pi\alpha/8$ in 2D, where α is the Fröhlich coupling constant, and this factor is expected to be strongly increased in large magnetic fields, especially in the ideal 2D case.[11–14] However, it has been shown that the finite extent of the wave function of the 2D gas and screening effects reduce the Fröhlich coupling.[11,13,15–17] Both reduced[16,18–20] and enhanced[21,22] polaron effects have been reported for different 2D systems in low-temperature cyclotron-resonance and photoluminescence experiments.

In our analysis, we use a known value of the phonon energy to calculate the effective mass. In heterostructures, the choice of the phonon which has to be considered is, however, by no means obvious. In the GaAs-$Al_xGa_{1-x}As$ system most of the time it has been assumed that the electrons interact with the bulk GaAs phonon mode[6,7] at a frequency of $\omega_{LO}=296$ cm^{-1} at low temperature.[23] But there is now growing evidence that the MPR is due to a different optical mode whose frequency is lower than that of the bulk GaAs LO phonon,[18] and a value of $\omega_{LO}=282$ cm^{-1} would be a better candidate.

In the $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ heterojunction, each side of the interface is made of a ternary alloy where two LO-phonon modes are present. But it is generally assumed that the 2D electron gas couples to a degenerate InAs-like mode (which has an energy close to the InAs modes of bulk $Ga_{0.47}In_{0.53}As$ and $Al_{0.48}In_{0.52}As$), in spite of the fact that the GaAs mode of $Ga_{0.47}In_{0.53}As$ presents a larger oscillator strength than the InAs mode.[9,10] But recently, a resonant coupling at the energy of the TO modes rather than the LO modes has been observed both in $Ga_{0.47}In_{0.53}As$-$Al_{0.48}in_{0.52}As$ and $Ga_{0.47}In_{0.53}As$-InP heterojunctions.[24,25] By contrast, discontinuity and enhancement of the cyclotron-resonance mass were observed at the LO energy in $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ and $Ga_{0.47}In_{0.53}As$-InP multiple-quantum well structures, respectively.[25] Such anomalous Fröhlich coupling of 2D electrons to optical phonons at unexpected low phonon frequencies in these heterojunctions is not well understood but either interface phonon modes[26] or plasmon-phonon modes[27] were suggested.

B. Amplitude of the oscillations

The amplitude of MPR oscillations can give valuable information about the magnitude of the electron-phonon interaction. Stradling and Wood[28] proposed the following empirical expression to describe the oscillatory part of the magnetoresistivity:

$$\Delta\rho_{xx} \sim \exp\left[\frac{-\bar{\gamma}\omega_{LO}}{\omega_c}\right]\cos\left[2\pi\frac{\omega_{LO}}{\omega_c}\right], \qquad (2)$$

where $\omega_c = eB/m^*$ is the cyclotron frequency and $\bar{\gamma}$ is the damping factor. In a theory including a Lorentzian broadening of the Landau levels, Barker[29] showed that this expression corresponds to the first term of a series giving the conductivity:

$$\Delta\sigma_{xx} = \sum_r \frac{1}{r}\exp(-2\pi r\gamma)\cos\left[2\pi r\frac{\omega_{LO}}{\omega_c}\right], \qquad (3)$$

with $\gamma=\Gamma/\hbar\omega_c=(\bar{\gamma}/2\pi)(\omega_{LO}/\omega_c)$ and Γ is the broadening parameter. $\bar{\gamma}$ has been widely studied as a function of temperature and magnetic field in n-type InSb (Ref. 30) and n-type GaAs.[31–33]

The amplitude of the oscillations has also been investigated as a function of pressure in n-type InP and n-type GaAs,[2] and was found to increase slightly with P. The results were interpreted in terms of changes in the relative strengths of the different scattering mechanisms.

The MPR effect has already been observed in many different 2D systems, as seen above,[5–10] but only Englert *et al.*[6] have reported measurements of the oscillation amplitude as a function of temperature in GaAs-$Al_xGa_{1-x}As$ heterostructures. They observe a broad maximum of $\Delta\rho/\rho(B)$ around 210 K. A qualitative study of MPR oscillations in $Ga_{0.47}In_{0.53}As$-InP (Ref. 10) heterojunctions shows a maximum of the second derivative of $\rho(B)$ at 160 K. Kido *et al.*[7] report a damping factor much larger in GaAs-$Al_{0.3}Ga_{0.7}As$ heterojunctions than in bulk GaAs and suggest that different scattering mechanisms might be dominant in each case. Very few theoretical investigations of MPR effects in 2D systems have been made:[34] the transvere conductivity was calculated using the Kubo formalism or starting from the momentum balance equation. But, up to now, there exists no theory that takes into account screening of the electron-phonon interactions and broadening effects self-consistently in large magnetic fields.

III. EXPERIMENTAL

The samples were n-type modulation doped heterojunctions with standard Hall-bridge shape, grown by molecular-beam epitaxy (MBE). The thicknesses and dopings of the different layers are summarized in Table I. Detailed studies of their transport properties under low magnetic fields as a function of pressure and temperature (see Table II), as well as a description of the pressure apparatus, have been reported elsewhere.[35,36] The oscillatory part of the $\rho_{xx}(B)$ curves were obtained from the resistivity signal by using a linear compensation of the nonoscillatory part of the magnetoresistance. Although less sensitive than the double-derivative technique for the observation of weak peaks, this method allows direct measurement of MPR amplitude to be made for the low values of the resonance index N.

TABLE I. The sample parameters.

	GaAs-$Al_{0.28}Ga_{0.72}As$	$Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$
Protecting layer	GaAs 50 Å Si-doped, 10^{18} cm^{-3}	
Barrier	$Al_{0.28}Ga_{0.72}As$ 500 Å Si-doped, 5.7×10^{17} cm^{-3}	$Al_{0.48}In_{0.52}As$ 1500 Å Si-doped, 2×10^{17} cm^{-2}
Spacer	$Al_{0.28}Ga_{0.72}As$ 300 Å undoped	$Al_{0.48}In_{0.52}As$ 80 Å undoped
Buffer	GaAs 1 μm undoped, *p* residual	$Ga_{0.47}In_{0.53}As$ 1.5 μm undoped, *n* residual
Substrate	Semi-insulating GaAs Cr-doped	Semi-insulating InP Fe-doped

IV. RESULTS AND DISCUSSION

A. Effective mass

1. Magnetophonon mass and nonparabolicity

Figure 1 shows MPR recordings at representative pressures for both types of heterojunctions. In each case the resonance peaks shift toward higher fields with increasing pressure due to the increase of the effective mass. We determine the resonance fields B_N as the values of magnetic field corresponding to the tangency points between the resistivity peaks and the envelope curve of the oscillations. This method corrects directly for the apparent shift of the maxima due to the damping of the oscillations.

The effective mass m^*, as determined from Eq. (1), is plotted in Figs. 2 and 3 as a function of pressure for two resonances. For GaAs-$Al_{0.28}Ga_{0.72}As$ and $Ga_{0.47}in_{0.53}As$-$Al_{0.48}In_{0.52}As$, we have used $\omega_{LO}=282$ and 222 cm^{-1}, as respectively suggested by the works of Brummell *et al.*[18] and Nicholas *et al.*[24] In GaAs-$Al_{0.28}Ga_{0.72}As$, we have assumed the same temperature and pressure dependence as found in bulk GaAs,[23,37] and for the InAs-like mode in $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ we have assumed a similar temperature dependence and we have taken the pressure dependence from the Gruneisen formula:[38]

$$\omega_{LO}(\mathrm{GaAs})=282(1-4\times10^{-5}T)(1+1.5\times10^{-3}P)\ , \quad (4)$$

$$\omega_{LO}(\mathrm{InAs})=222(1-4\times10^{-5}T)(1+1.8\times10^{-3}P)\ , \quad (5)$$

where T is in K, P in kbar, and ω_{LO} in cm^{-1}. Note that

TABLE II. Temperature and pressure dependence of the carrier concentration N_s and the mobility μ_s of the 2D electron gas in both systems.

	Ambient pressure		High pressure		
T (K)	N_s (10^{11} cm^{-2})	μ_s ($cm^2\,V^{-1}\,s^{-1}$)	P (kbar)	$N_s(P)$ (10^{11} cm^{-2})	$\mu_s(P)$ ($cm^2\,V^{-1}\,s^{-1}$)
		GaAs-$Al_{0.28}Ga_{0.72}As$[a]			
4.2	2.3	328 000	7.7	1.03	138 200
150	2	35 000	13.6	0.21	21 000
215	2.35	13 000	13.6	0.54	11 700
290	2.6	8 000	14.4	0.8	6 000
		$Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$[a,b]			
4.2	5.75	72 000	14.5	4.9	50 000
150	6.02	29 000	13.6	5.1	24 000
220		16 500	13.6		13 000
300		11 000	15		8 500

[a] The high-temperature data are estimated after correction for parallel conduction (Refs. 35 and 36).
[b] The high-temperature data come from a different sample of the same wafer. N_s was assumed to be temperature independent (Ref. 36).

these pressure and temperature shifts of ω_{LO} are small and could very well be neglected in a first approach.

The periodicity of the oscillations (NB_N) gives B_1 around $22.1T$ and $12.2T$, at ambient pressure, in GaAs-$Al_{0.28}Ga_{0.72}As$ and $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$, respectively. In GaAs-$Al_{0.28}Ga_{0.72}As$ the $N=2$ and 3 peaks give roughly the same effective mass, and the fundamental resonance $N=1$ could not be observed in this case, since it occurs above our field limit of $18T$.

We now compare the MPR mass m^* to the band-edge mass m_0^* measured in bulk GaAs and $Ga_{0.47}In_{0.53}As$.[3,4] If we neglect the polaron correction to the effective mass, the mass enhancement due to nonparabolicity is then given by the difference between m^* and m_0^* in Figs. 2 and 3, and has a relative magnitude of 10%, 10.5%, and 12% at 150, 215, and 290 K in GaAs-$Al_{0.28}Ga_{0.72}As$, and 28% and 34% at 150 and 220 K in $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ at ambient pressure.

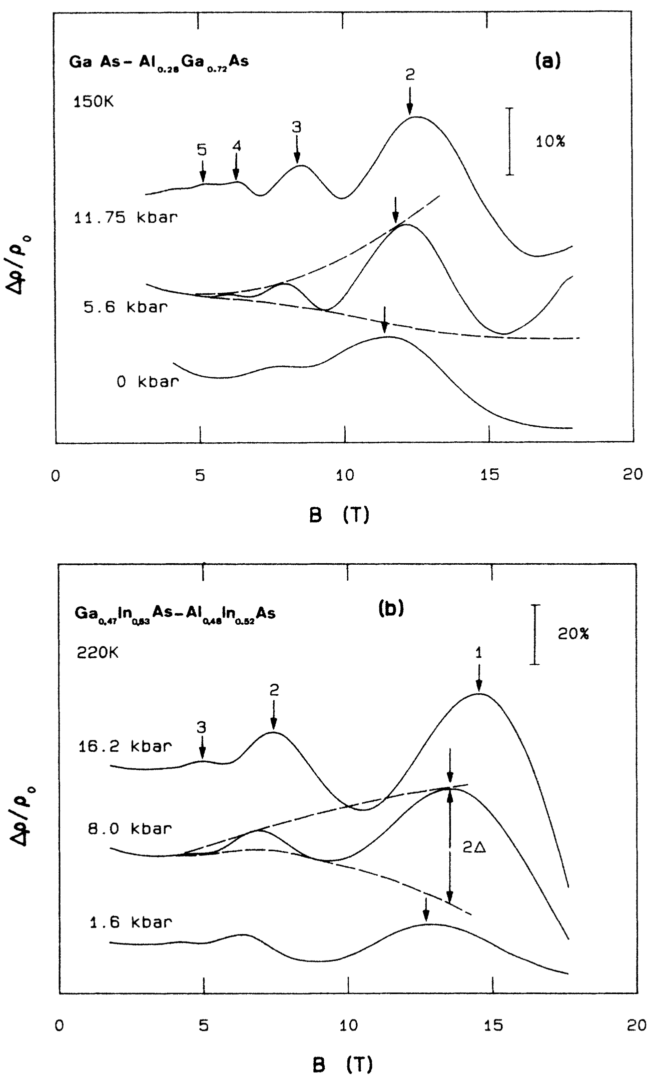

FIG. 1. Typical magnetophonon resonance oscillations for representative pressures: (a) in GaAs-$Al_{0.28}Ga_{0.72}As$ at 150 K, and (b) in $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ at 220 K. The dashed line shows the exponential damping of the oscillations, Δ is the relative amplitude, and arrows point to the resonances.

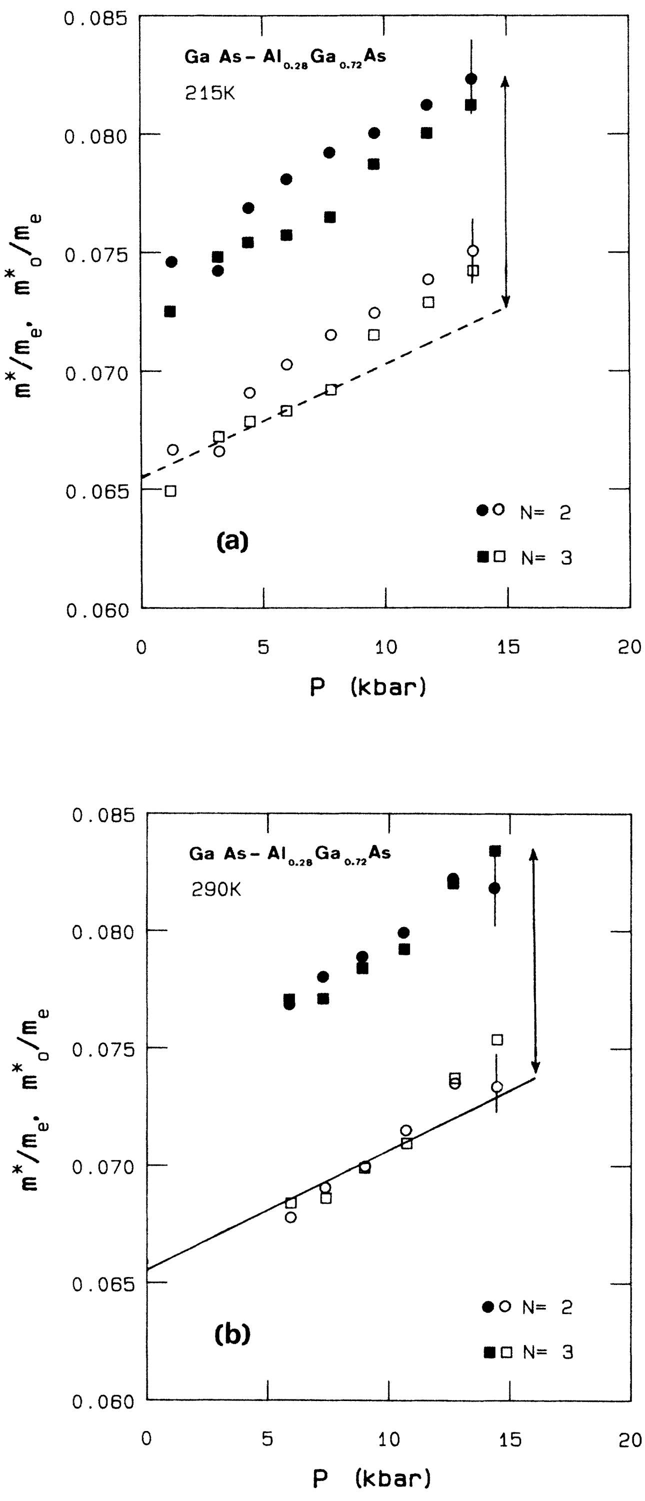

FIG. 2. Pressure dependence of the effective mass in GaAs-$Al_{0.28}Ga_{0.72}As$: (a) at 215 K, and (b) at 290 K. Solid symbols represent the MPR mass m^* and open symbols correspond to the band-edge mass m_0^*. The error bar shown is the same at any pressure. The arrows show the nonparabolic enhancement to the mass. The solid line gives bulk results after Shantharama *et al.* (Ref. 3) and the dashed lines are obtained from five-band $\mathbf{k}\cdot\mathbf{p}$ theory (Ref. 45), using the matrix elements of Ref. 3. Note that both lines coincide at 290 K. No bulk results were available at 215 K from Ref. 3.

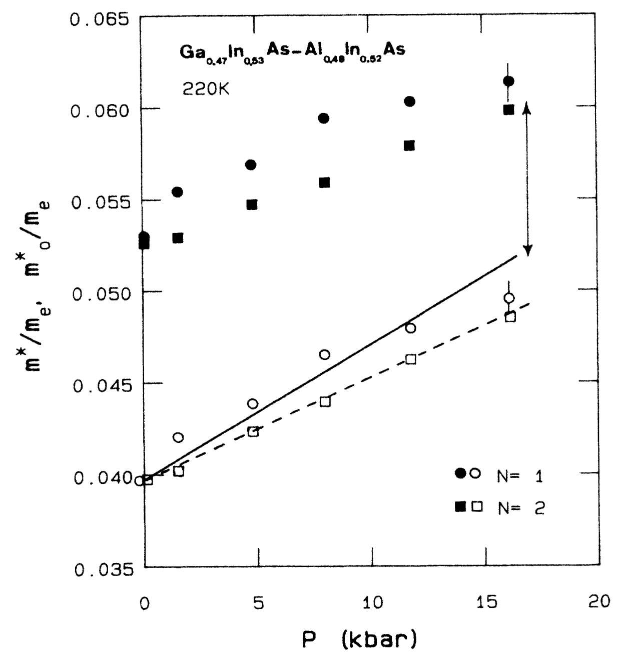

FIG. 3. Pressure dependence of the effective mass in $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ at 220 K. Same remarks as in Fig. 2 apply here for symbols and error bars. The solid line gives the slope in bulk $Ga_{0.47}In_{0.53}As$ at 210 K after Shantharama *et al.* (Ref. 4) and the dashed lines are from five-band $\mathbf{k}\cdot\mathbf{p}$ theory (Ref. 45) with $P^2=23.8$ eV, $(p')^2=2.9$ eV, and $C=-2$ for the matrix elements.

This is greater than what is reported for undoped bulk GaAs (2.8% and 4.6% at 65 and 300 K)[28] and $Ga_{0.47}In_{0.53}As$ (16–18 % at 210 K).[4] The mass enhancement is seen to decrease as the pressure is increased in $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ (18% at 15 kbar). This is an expected behavior since pressure brings a decrease in the electron concentration[35,36] (and, therefore, in the energy of the quantized levels) and an increase in the gap (i.e., a reduction in the nonparabolicity of the band). In

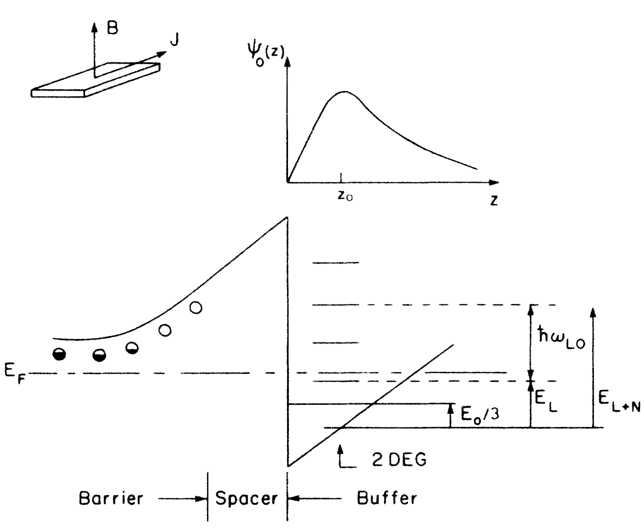

FIG. 4. Sketch of the energetic parameters for a resonant electron–LO-phonon coupling at a heterojunction interface.

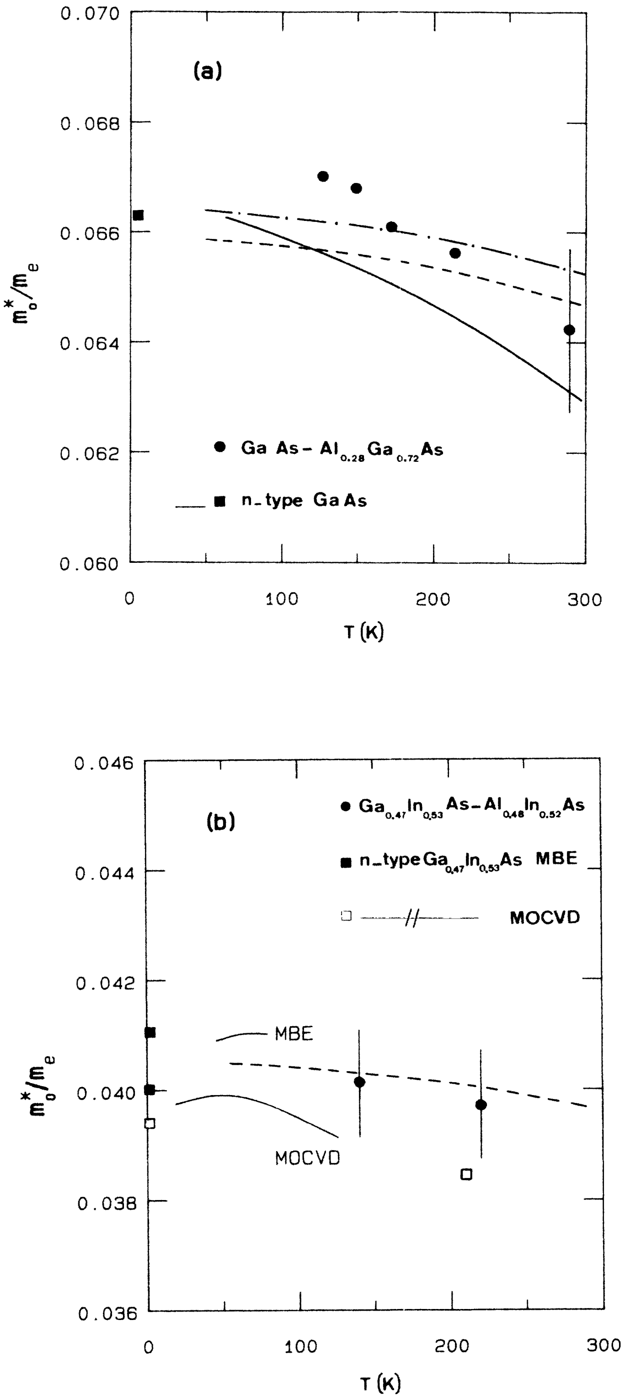

FIG. 5. Temperature dependence of the band-edge mass in the heterojunctions at ambient pressure compared to the related bulk layers. (a) GaAs. The solid line has been deduced from MPR data of Stradling and Wood (Ref. 28). The dashed line and the dash-dotted line are from five-band $\mathbf{k}\cdot\mathbf{p}$ theory with the matrix elements after Zawadzki and Pfeffer (Ref. 44) and Shantharama *et al.* (Ref. 3), respectively. The low-temperature point is taken from Ref. 43. (b) $Ga_{0.47}In_{0.53}As$. The dashed line is obtained from five-band $\mathbf{k}\cdot\mathbf{p}$ theory as in Fig. 3. The solid lines are deduced from cyclotron-resonance data of Sarkar *et al.* (Ref. 42) and the low-temperature point (210 K) comes from MPR measurements (Ref. 4).

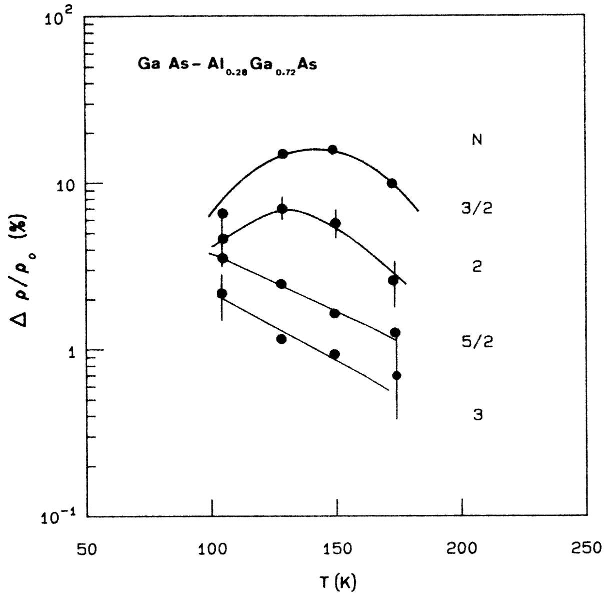

FIG. 6. Temperature dependence of the oscillation amplitude in GaAs-$Al_{0.28}Ga_{0.72}As$ at ambient pressure. Only representative error bars are shown for clarity.

GaAs-$Al_{0.28}Ga_{0.72}As$, however, a different behavior is observed, namely the mass enhancement increases slightly with pressure (10.6%, 14%, and 14.2% at 150 K, 215 K, 290 K, and 15 kbar). We show below that a significant increase in the polaron correction could be responsible for this.

2. *A model for MPR analysis in the heterojunctions*

We propose a simple model, based on $\mathbf{k}\cdot\mathbf{p}$ theory, to account for the observed mass enhancement in the heterojunctions. This model considers the transitions between all Landau levels separated by the energy of the LO phonon (Fig. 4). Each transition between one initial level L and a final level $L+N$ is weighted by the occupancy of level L and the nonoccupancy of level $L+N$. Neglecting spin effects at high temperature in the formalism of Palik *et al.*,[39] based on the three-band $\mathbf{k}\cdot\mathbf{p}$ model, we get, for the resonance N,

$$\frac{1}{m^*}=\frac{1}{m_0^*}\left[1+2K_2\sum_L W_{L,N}\frac{\langle E\rangle_{L,N}}{E_g}\right], \tag{6}$$

where $\langle E\rangle_{L,N}$ is the mean energy of the transition:

$$\langle E\rangle_{L,N}=\frac{(E_{L+N}+E_L)}{2}=\frac{E_0}{3}+\left[\frac{2L+N+1}{2N}\right]\hbar\omega_{LO}\,. \tag{7}$$

$W_{L,N}$ is the weight of the transition and is calculated using the Fermi distribution. The position of the Fermi level is estimated as a function of B, neglecting the broadening of the Landau levels.[40] The energy of the quantized level E_0 (relative to the bottom of the well) is calculated in the triangular well approximation (see Ref. 36). The factor $\frac{1}{3}$ in front of E_0 in Eq. (7) accounts for the fact that the mean position of the electron gas is not the same as the well's bottom position (Fig. 4). These estimations of E_0 have been made using the experimental values of the electron concentrations as the input data. Three-band $\mathbf{k}\cdot\mathbf{p}$ theory[39] gives -0.83 and -0.85 for the nonparabolicity coefficient K_2 in GaAs and $Ga_{0.47}In_{0.53}As$, respectively. However, there has been recent experimental evidence for larger values of K_2 in bulk GaAs (-1.75 ± 0.05) (Ref. 41) and GaInAs (-1.7 ± 0.3) (Ref. 42), and in GaAs-$Al_{0.3}Ga_{0.7}As$ (-1.4 ± 0.1) (Ref. 43), from low-temperature ($T<100$ K) cyclotron-resonance measurements at frequencies below ω_{LO}. A five-band $\mathbf{k}\cdot\mathbf{p}$ theory[44] also suggests such larger K_2. The smaller value of K_2 found in GaAs-$Al_{0.3}Ga_{0.7}As$ heterojunctions compared to bulk GaAs at low temperature was attributed to the screening of the polaron effect in heterojunctions. Above 100 K, the screening was found to disappear and a polaron enhancement of 2% was observed on m^* for heterojunctions with low electron concentration[18] (0.9 and 1.8×10^{11} cm^{-2}). In the present work, we have used $K_2=-1.5$ for both heterojunctions. For the GaAs-$Al_{0.28}Ga_{0.72}As$ heterojunction, we have considered only the first quantized level E_0. In the case of $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$, the E_1 level is much closer to E_0 (Ref. 36) and was therefore included in our analysis by using a straightforward extension of Eqs. (6) and (7).

3. *Results*

The band-edge mass calculated from our MPR measurements with Eqs. (6) and (7) is plotted in Figs. 2 and 3 as a function of pressure and compared to bulk results and five-band $\mathbf{k}\cdot\mathbf{p}$ theory.[44,45] The band-edge mass is shown as open symbols.

In both systems, we observe that the nonparabolicity-induced mass enhancement $(m^*-m_0^*)/m_0^*$, as calculated with Eq. (6), decreases with increasing pressure, as expected. However, the calculated pressure dependence of m_0^* differs from that measured in bulk layers. The slope is too large in GaAs-$Al_{0.28}Ga_{0.72}As$ (0.9% kbar^{-1} instead of 0.8% kbar^{-1}), while it is too small in $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ (1.3–1.5% kbar^{-1} instead of 2% kbar^{-1}), compared to bulk. In GaAs-$Al_{0.28}Ga_{0.72}As$, the difference between the band-edge mass in bulk and our result is about 2% at high pressure, and this could be well accounted for by the polaron corrections that have not been included in Eq. (6). Such interpretation is consistent with the fact that the electron-phonon coupling is increased at high pressure (see Sec. IV B). In $Ga_{0.47}In_{0.53}Al$-$Al_{0.48}In_{0.52}As$, the discrepancy is much more important and cannot be attributed only to the $1+\pi\alpha/8$ polaron correction. Note that our results can be described with a five-band $\mathbf{k}\cdot\mathbf{p}$ approach,[45] using a reduced value of the momentum matrix element to account for alloy disorder, as proposed by Pearsall[46] (see Fig. 3). Such alloy disorder effects, although they seem to play a significant role in the transport properties of $Ga_{0.48}In_{0.52}As$, are not well understood at this moment.[4]

The temperature dependence of the band-edge mass in bulk GaAs and bulk $Ga_{0.48}In_{0.52}As$ is reported in Fig. 5, together with our results for the respective heterojunctions. For GaAs, we have corrected the MPR data of Stradling and Wood[28] for nonparabolicity (using $K_2=-1.4\pm0.1$) between 60 and 290 K and for polaron effects using the factor $1+\alpha/4$ (Ref. 1) where $\alpha=0.06$, and for $Ga_{0.47}In_{0.53}As$ we have corrected the cyclotron-resonance data of Sarkar *et al.*[42] with $K_2=-1.7$ and $\alpha=0.02$ (Ref. 9) (details have been reported elsewhere[47]). The results of five-band **k**·**p** theory are also shown, where the dilational change in energy gap was used instead of the temperature dependence of the optical gap (see Refs. 3 and 28). It can be seen that the results for the heterojunctions agree fairly well with both bulk data and theory.

B. Amplitude of the oscillations

The temperature dependence of the oscillation amplitude is shown in Fig. 6 for $GaAs\text{-}Al_{0.28}Ga_{0.72}As$. A maximum of $\Delta\rho/\rho_0$ is observed at 130 K for $N=2$,

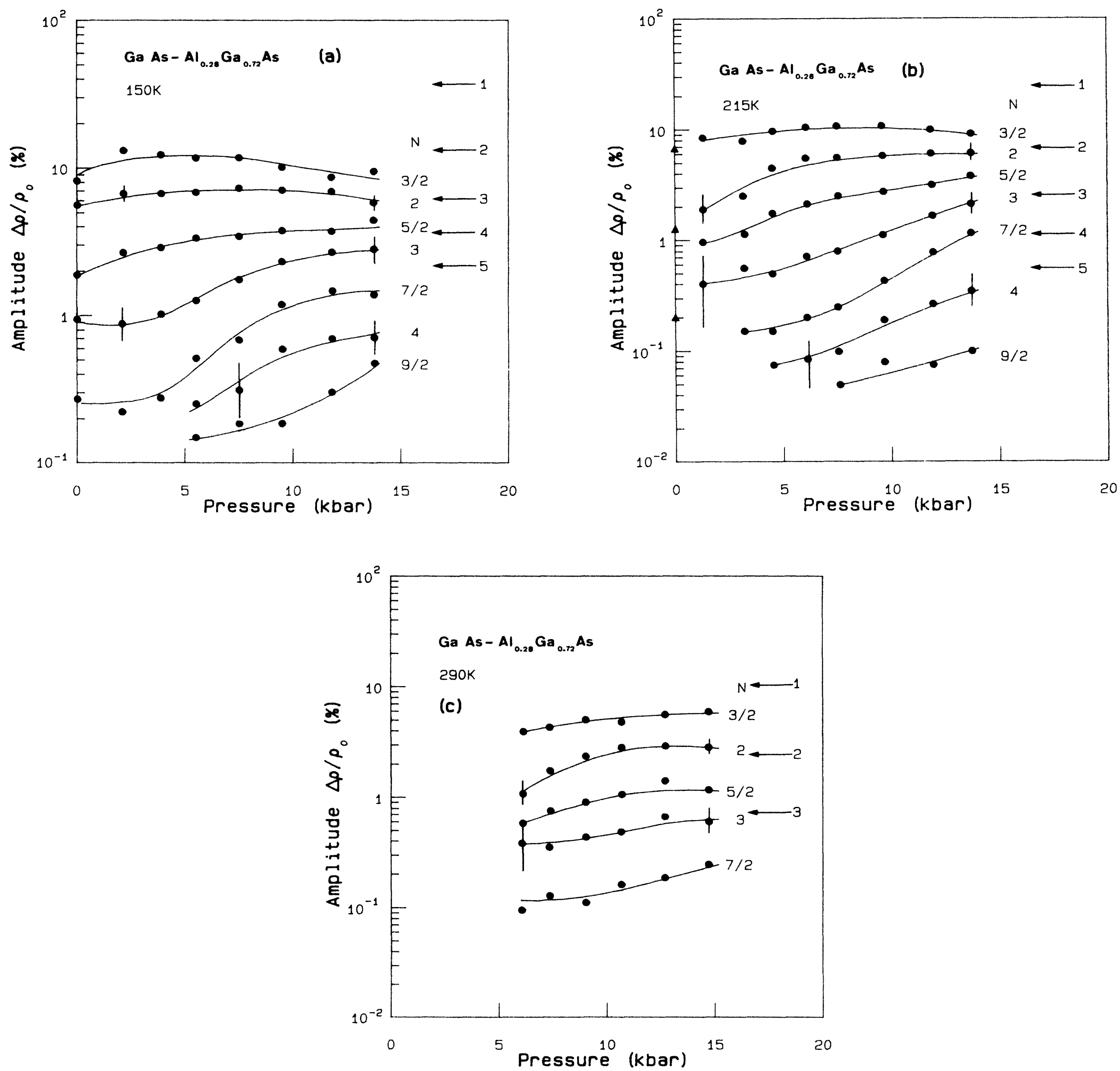

FIG. 7. Pressure dependence of the oscillation amplitude in $GaAs\text{-}Al_{0.28}Ga_{0.72}As$, (a) 150 K, (b) at 215 K, and (c) at 290 K. Arrows indicate bulk amplitudes at ambient pressure after Kido and Miura (Ref. 33) and triangles at 0 kbar and 215 K are 2D amplitudes for $N=1$, 2, and 3 in a higher concentration heterojunction ($N_s=3.4\times10^{11}$ cm^{-2}) after Englert *et al.* (Ref. 6). Same remarks as in Fig. 6 apply for error bars in Figs. 7–10.

which agrees with observations in bulk GaAs,[28,33] and with Barker's theory,[29] but no maximum was detected for larger quantum numbers N. In $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$, the amplitudes were larger at 150 than at 220 K, the ratio changing with pressure.

The relative amplitudes $\Delta\rho/\rho_0$ of all the resistivity peaks are plotted as a function of pressure in Figs. 7 and 8. The amplitude is defined as the half separation between the envelope curves of the oscillations at the positions of the maxima (Δ_N) and minima ($\Delta_{N+1/2}$) of the resistivity. The damping of the oscillations appears not to be exponential at low pressure, but it is useful to define the damping factor as

$$\bar{\gamma}_N = 2\ln\left[\frac{\Delta_N}{\Delta_{N+1/2}}\right], \tag{8}$$

nonetheless. Results are presented versus pressure in Figs. 9 and 10 for both heterojunctions.

In the $GaAs$-$Al_{0.28}Ga_{0.72}As$ heterostructures, the amplitude of all peaks increases with pressure and seems to reach a maximum value at pressures which are higher for larger values of N. Also shown in Fig. 7 are the amplitudes observed at ambient pressure on undoped n-type GaAs.[33] It appears that as the electron concentration in the heterojunctions becomes very low, the amplitude of the oscillations tends to reach a maximum value which is close to that of bulk GaAs. In this situation (high pressure) the damping parameter is about 1, as in bulk GaAs (Fig. 9). At lower pressure, we have situations where certain peaks have reached their maximum amplitude and others do not, and this results in a nonexponential decrease of the amplitude with B^{-1}, leading to unequal spacings between the curves giving the logarithm of the amplitudes in Fig. 7. In other words, the damping factor depends on magnetic field in that case (Fig. 9), and this dependence changes with pressure, i.e., with the electron concentration. In another sample, having a smaller spacer (200 Å) and an electron concentration of 3×10^{11} cm^{-2} at 0 kbar, we have observed an identical behavior, with, of course, different values for the damping factor and the amplitude of the oscillations.

These results indicate that the nonexponential increase in the amplitude is linked to the 2D character and to the degeneracy of the system. For very low values of N_s, the system tends to behave as in the 3D case, as can be expected, since the electron wave functions then have large spreadings.

In the $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$ system, the amplitude of the oscillations shows, at first sight, a quite different behavior: as the pressure is increased, only the fundamental resonance $N=1$ has a strongly increasing amplitude, while the other peaks show a very weak pressure dependence (Fig. 8). However, similarly to $GaAs$-$Ga_{0.72}Al_{0.28}As$ heterostructures, a nearly exponential decrease of the amplitude with B^{-1} is observed at high pressure, while it is not the case at 0 kbar. At 16 kbar, the damping factor is about twice as large as in bulk GaAs (Fig. 10). Since $Ga_{0.47}In_{0.53}As$ is a ternary alloy presenting a larger residual doping than GaAs, we can expect $\bar{\gamma}$ to be enhanced, but no quantitative measurements of MPR amplitude have ever been reported and therefore no comparison is possible.

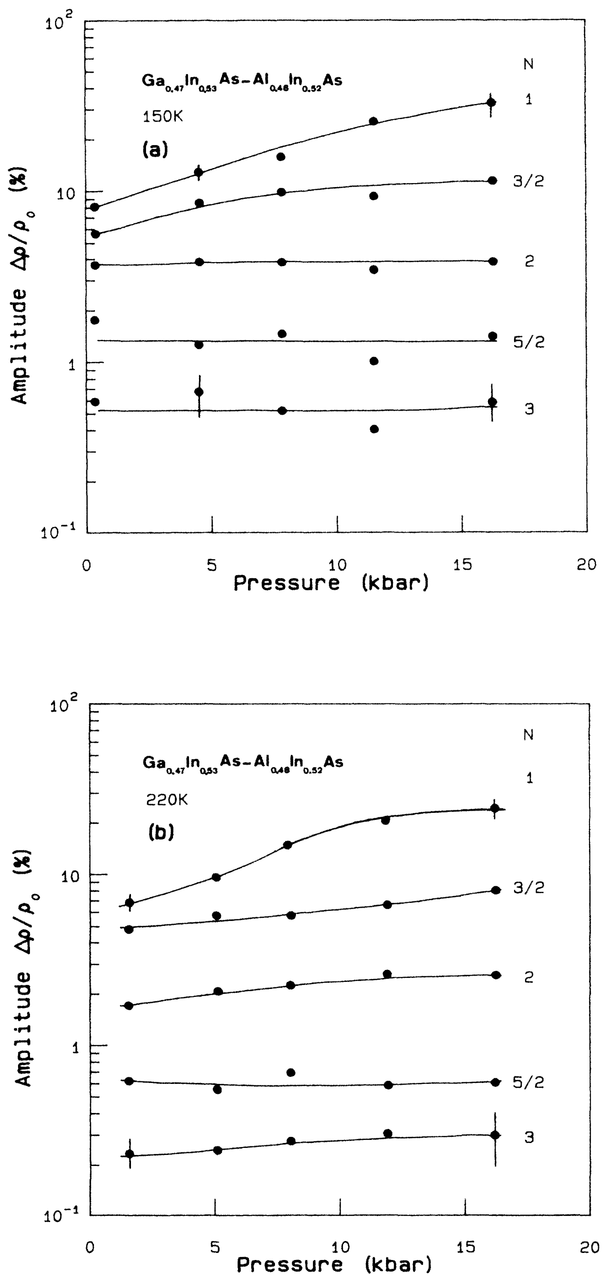

FIG. 8. Pressure dependence of the oscillation amplitude in $Ga_{0.47}In_{0.53}As$-$Al_{0.48}In_{0.52}As$, (a) at 150 K and (b) at 220 K.

V. CONCLUSION

The interpretation of such observations could presumably be found in the effect of screening of the electron-phonon interactions. Theoretical results (at $B=0$) of Ref. 17 show that, due to screening, the polaron correction to the effective mass decreases when N_s increases. This effect has a small magnitude but, as pointed out by Brummell et al.,[18] high magnetic fields can be expected to cause a substantial enlargement of it. At this moment, there is no theoretical estimation available with which we could compare our results.

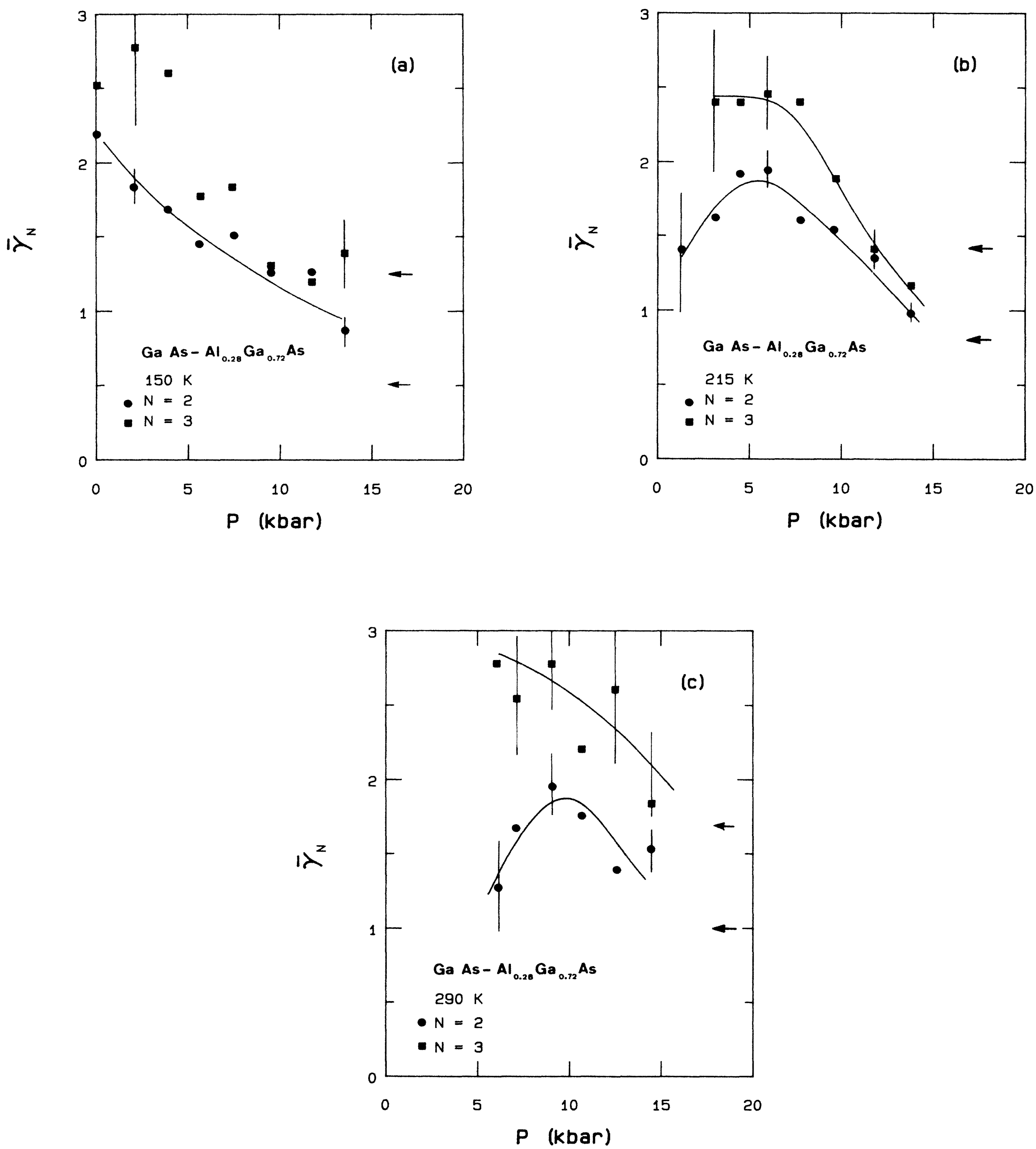

FIG. 9. Pressure dependence of the damping factor in GaAs-$Al_{0.28}Ga_{0.72}As$ for two resonances, (a) at 150 K, (b) at 215 K, and (c) at 300 K. Arrows indicate the extreme values reported in literature for bulk GaAs (Refs. 28, 32, and 33). Lines are just guides for the eyes.

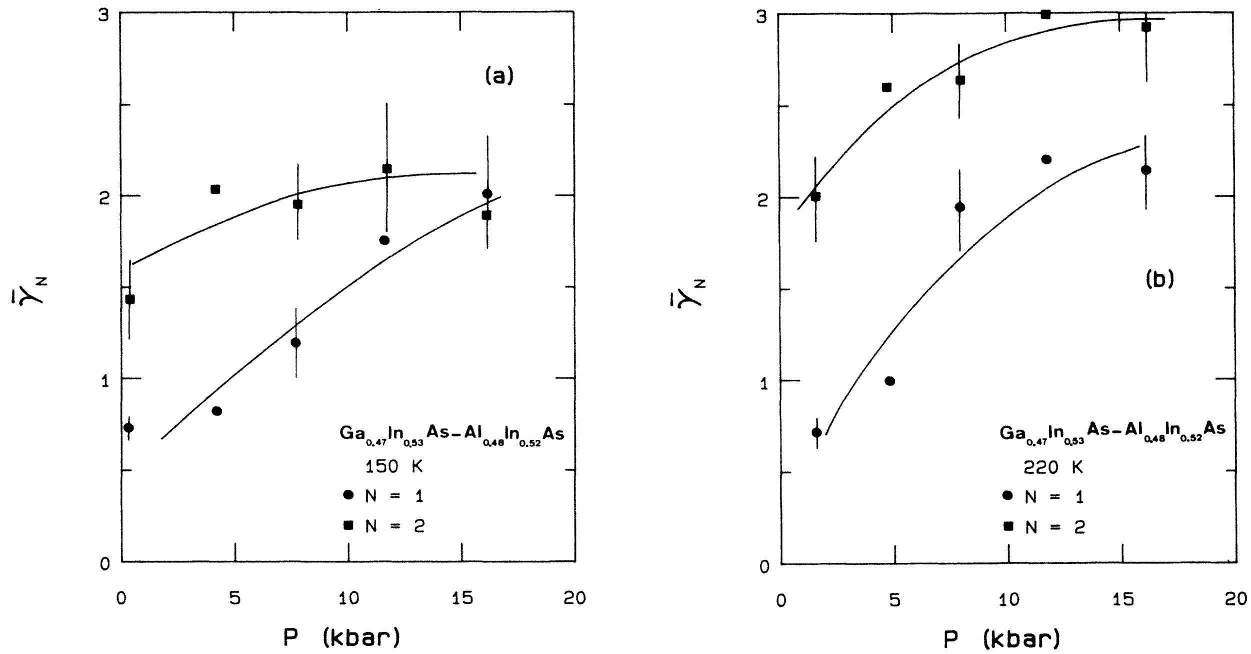

FIG. 10. Pressure dependence of the damping factor in $Ga_{0.47}In_{0.53}As-Al_{0.48}in_{0.52}As$ for two resonances, (a) at 150 K and (b) at 220 K. Lines are just guides for the eyes.

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