Spin resonance in $In_{0.53}Ga_{0.47}As$ under hydrostatic pressure

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Using a far-infrared photoconductivity technique, we made direct spin-resonance measurements on bulk $In_{0.53}Ga_{0.47}As$ under hydrostatic pressure up to 10 kbar. Results are analyzed through an eight-band $\mathbf{k}\cdot\mathbf{p}$ formalism to extract the effective electronic g factor g_c^* and the Kane interband matrix element E_p as a function of pressure. These are found to be given by the following best-fit relations: $E_p=24.13+0.069P$ (eV) and $g_c^*=-4.089+0.102P-1.2\times10^{-3}P^2$, where P is expressed in kbar. [S0163-1829(96)01040-5]

Owing to its high electron mobility and its relatively narrow gap, the $In_{1-x}Ga_xAs$ family of ternary alloys is of great interest for optoelectronic applications. A precise knowledge of the band structure of these compounds is therefore most relevant for device designing and optimization purposes. Furthermore, the use of strained-layer heterostructures in device fabrication brings the need for the study of the pressure dependence of the band structure. For these application-related reasons, as well as from a fundamental point of view, the Kane interband matrix element (E_p) is a band structure parameter of particular importance, since it plays a central role in the description of interband optical processes. This parameter can be obtained with a high degree of precision from a knowledge of the electronic effective g-factor value,[1] which can be determined directly from the observation of spin resonance (or the spin-flip transition). In bulk $In_{0.53}Ga_{0.47}As$, the observation of the spin-flip transition through far-infrared photoconductivity (PC) measurements was reported recently.[2] A brief review of previous studies is also given in Ref. 2.

In this paper, we report a study of the electron-spin resonance and cyclotron resonance in bulk $In_{0.53}Ga_{0.47}As$ under hydrostatic pressure up to 10 kbar, based on a far-infrared photoconductivity technique. Our experimental results allowed us to make a determination of the conduction-electron effective g factor g_c^* and of the Kane interband matrix element E_p as a function of pressure. The analysis of the experimental results was made following the same lines as in Ref. 2. Both cyclotron and spin resonance data were simultaneously fitted within the same theoretical framework, which is based on a model developed by Weiler, Aggarwal, and Lax.[3] In this approach, the interaction between the s-like conduction band (Γ_6^c) and the p–bonding-like valence bands (Γ_7^v and Γ_8^v) for both spin configurations are explicitly taken into account in a $\mathbf{k}\cdot\mathbf{p}$ formalism, and the influence of remote conduction bands (p antibonding, Γ_7^c and Γ_8^c) is treated as a perturbation. The theoretical model uses six valence band parameters, which were taken to have the following values:[4] $\Delta=0.36$ eV, $\gamma_1=0.62$, $\gamma_2=-1.02$, $\gamma_3=-0.36$, $\kappa=-1.91$, and $q=0$.

In principle, one can expect that an experimental study of g^* as a function of energy (or equivalently, as a function of magnetic field) can lead to a determination of the pair of parameters E_p and N_1 through a best-fit comparison with the model. However, because of the experimental uncertainty and the limited magnetic field range where the spin resonance could be observed, this procedure does not provide unique values for this pair of parameters.[2] One way to circumvent this problem consists in taking into account *both* g^* and m^* dependence on energy in the fitting procedure, a method that leads to an unambiguous determination of the three parameters E_p, F, and N_1. Experimentally, this brings need to conduct both cyclotron- and spin-resonance experiments on the same sample and under the same pressure conditions.

The measurements were made on a square shape (4×4 mm^2) 5-μm-thick $In_{0.53}Ga_{0.47}As$ epitaxial layer, not intentionally doped, grown on a InP substrate by a low-pressure metal organic chemical-vapor deposition technique. Far-infrared radiation generated by a CO_2-pumped molecular laser was used to observe the spin-resonance photoconductivity signal using a lock-in detection technique. Other details concerning the sample or the experimental technique can be found in Ref. 2.

The hydrostatic pressure was produced using a liquid clamp cell technique. An *in situ* calibrated InSb pressure gauge was used to measure the pressure when at low temperature. Optical access to the sample was provided by a sapphire window. At each pressure, we obtained a complete set of measurements including cyclotron resonance and spin resonance on the sample. Interband magnetophotoconductivity spectra were also obtained under the same experimental conditions, providing the value of the band-gap energy, but will not be discussed in this paper. All measurements were made at liquid-helium temperatures.

Figure 1(a) shows a typical photoconductivity spectrum exhibiting both spin and cyclotron resonances at a wavelength of 570.6 μm. The behavior of the spin-resonance peak position as a function of pressure is illustrated in Fig. 1(b). Variations in the general shape and amplitude of the different peaks seen in Fig. 1(b) can be attributed to changes in the

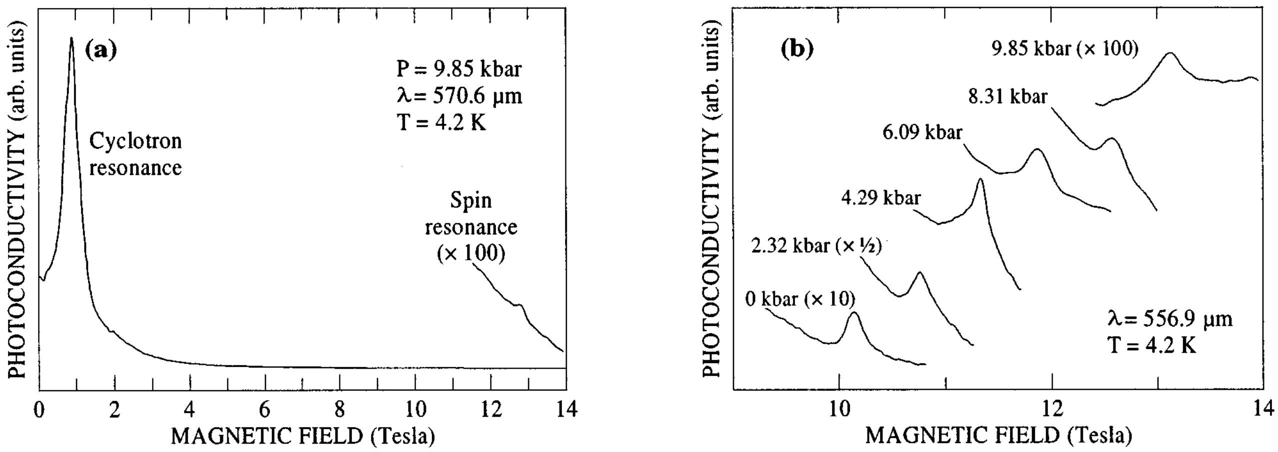

FIG. 1. (a) Typical photoconductivity spectrum obtained at 4.2 K with a wavelength of 570.6 μm. The pressure was 9.85 kbar. The peak at 12.8 T is the spin resonance, while the larger structure at low magnetic field is associated with cyclotron resonance and impurity-related transitions. (b) Spin resonance peak at several hydrostatic pressures, for a wavelength of 556.9 μm.

intensity and uniformity of the incident light from one pressure condition to the other. As conduction processes are involved in the photoconductivity, the pressure dependence of the carrier concentration and of the magnetoresistance could also modify the background shape of the signal. In our experiments, we have not observed impurity-related spin resonance peaks such as those observed in InSb.[5,6] This is presumably due to the lower electron mobility in our sample, that prevents such small structures from being detected.

In Fig. 2, the energy of the resonances is plotted as a function of their magnetic field position, for representative values of hydrostatic pressure. Since the pressure causes the gap to increase, one can think, in a qualitative manner, of the effect of hydrostatic pressure as bringing the band structure of $In_{0.53}Ga_{0.47}As$ closer to that of GaAs, which has a larger gap, a larger effective mass and a smaller magnitude of electronic g factor than $In_{0.53}Ga_{0.47}As$. Since the gap of GaAs and InAs differ by about 1 eV, and since a pressure of 1 kbar increases the gap by approximately 10 meV, we can say, in a rough but useful analogy, that the application of 1 kbar of pressure is similar, as far as the band structure near the Γ point is concerned, to an increase of about 1% in the gallium content of the alloy. The spin- and cyclotron-resonance magnetic fields are therefore both expected to rise under pressure, as confirmed by the data shown in Fig. 2.

At each pressure, we performed a fit of the cyclotron- and spin-resonance data with the theoretical model to extract the values of N_1, F, and E_p. The band-gap value was taken from a relation, given in Table I, which was established from interband photoconductivity measurements (not shown) on our sample. Theoretical curves are illustrated in Fig. 2 together with the experimental data, while Fig. 3 shows the variation of the fitting parameters with pressure. Best fits were obtained with values of N_1 close to zero, on the positive side ($N_1 \lesssim 0.02$). Such positive values being unacceptable from a theoretical basis, we chose to force N_1 to zero in the analysis, which caused only an insignificant reduction on the overall quality of the fit. Within experimental accuracy, N_1 was found to remain equal to zero throughout the pressure range used. The effective-mass m_c^*, E_p, and F param-

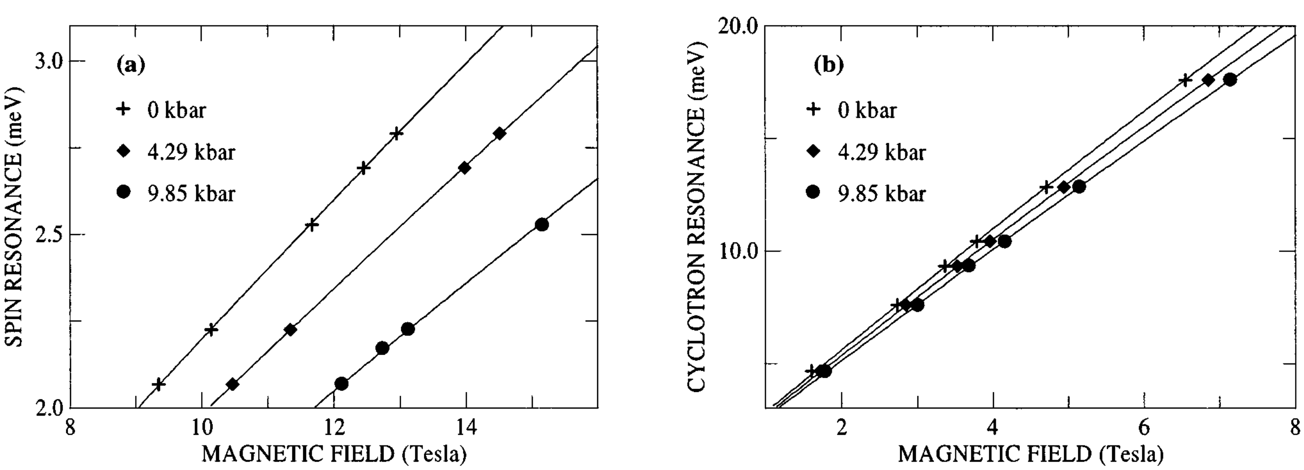

FIG. 2. (a) Spin-resonance energy as a function of magnetic field for several hydrostatic pressure conditions. Symbols correspond to measured values. Curves are obtained with the theoretical model described in the text. (b) The analog of (a) for cyclotron resonance.

TABLE I. Band parameters of $In_{0.53}Ga_{0.47}As$ and their pressure dependence. E_g was determined from interband photoconductivity measurements. m_c^*, g_c^* E_p, and F were obtained through the fitting procedure described in the text. The indicated error ranges are related to the mathematical fit on data that were all obtained on the same sample. Fluctuations in the alloy composition from one sample to another were not considered in these error estimates.

E_g	$0.8117+9.45\times10^{-3}P\pm0.0005$	(eV)
m_c^*	$0.0410+4.0\times10^{-4}P\pm0.0002$	(m_e)
g_c^*	$-4.089+0.102P-1.2\times10^{-3}P^2\pm0.01$	
E_p	$24.13+0.069P\pm0.04$	(eV)
F	$-1.64-0.014P\pm0.03$	
N_1	0 ± 0.02	

eters are found to vary linearly with pressure, while the g factor varies quadratically with P. The polynomial expressions describing these results are listed in Table I.

The effective-mass was deduced from the cyclotron-resonance data by considering the transition between Landau levels $n=0$ and 1, and taking into account the magnetopolaron effect within the theoretical framework of Lindemann *et al.*[7] and Beevens *et al.*[8] The contribution of both LO-phonon modes present in $In_{0.53}Ga_{0.47}As$, with their proper coupling parameter (or Fröhlich constant),[9] were included in the calculation of the corrections due to the magnetopolaron effect. The obtained variation of m^* is in agreement with previous results;[8] the small differences between the two sets of results are attributable to the fact that in Ref. 8, the influence of the InAs-like LO-phonon mode was neglected in the magneto-polaron corrections.

The Kane interband matrix element is found to increase with pressure, which is consistent with the fact that E_p is larger in GaAs than in InAs (28.9 eV compared to 22.2 eV, respectively[1]). Using the simple analogy mentioned above, a pressure of 10 kbar would correspond to a 10% increase in the gallium content of the sample. Assuming a linear variation of E_p between InAs and GaAs, this would translate into a 3% increase in the Kane matrix element, a value very close to what is actually obtained experimentally (a 2.9% increase in E_p at 9.85 kbar). Such reasoning can be used to grasp the magnitude of the variation of all other conduction-band parameters with pressure.

Concerning F, we can first note that the best-fit value we obtained at ambient pressure ($F=-1.64$) compares with a simple estimation based on a linear interpolation between known values for GaAs and InAs ($F=-1.97$ and -1.02, respectively[1]), which gives $F=-1.47$ for $In_{0.53}Ga_{0.47}As$. The increasing magnitude of F with pressure indicates an increasing contribution to the nonparabolicity from higher conduction bands, which is due to a decreasing gap between the Γ_6^c band and the remote Γ_7^c and Γ_8^c conduction bands, and from an increasing coupling between these bands. The decrease in this gap is expected from the fact that the deformation potential of the remote Γ_7^c and Γ_8^c bands is smaller than that of the Γ_6^c band, as shown by pseudopotential theory.[10]

In our conditions, magnetopolaron interaction was found to bring a correction of less than 2% to the cyclotron resonance energy. However, this represents a contribution of up to 20% to the nonparabolic terms of the effective mass. The

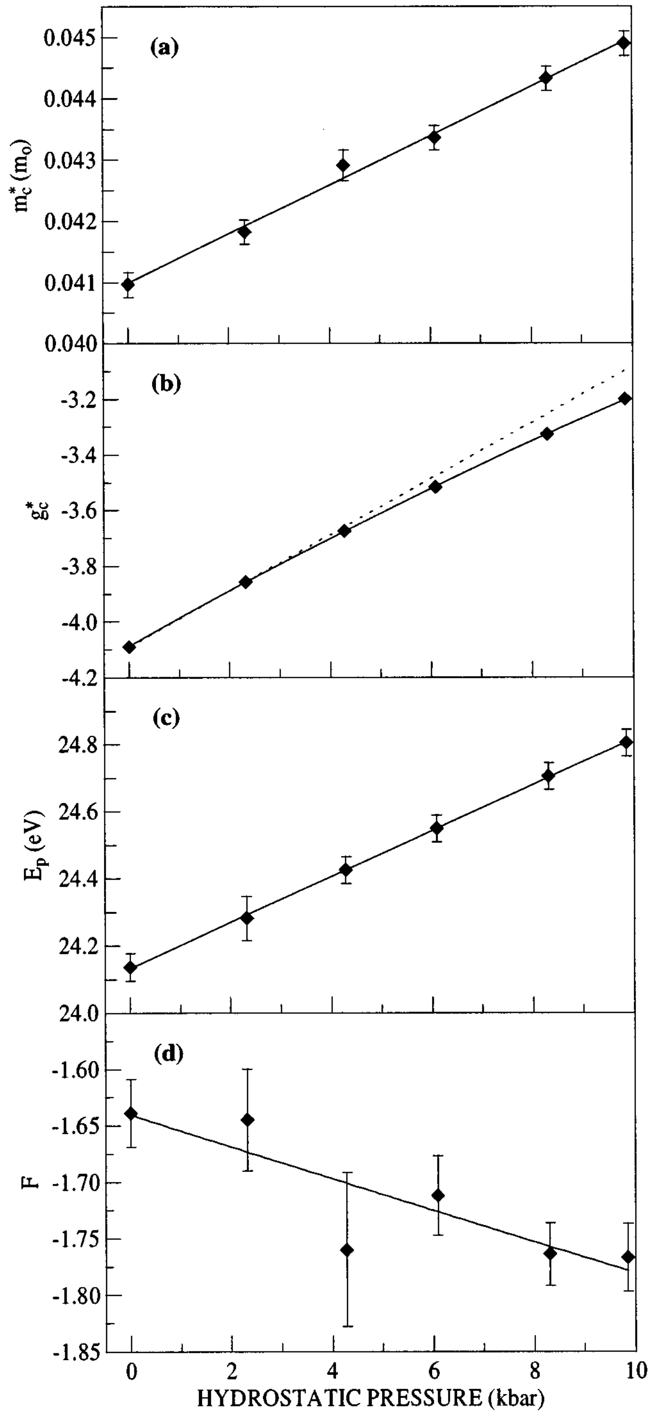

FIG. 3. Behavior of band parameters m_c^*, g_c^* E_p, and F as a function of pressure. The curves are obtained through a least square fit method; their mathematical expressions are given in Table I.

resonant magnetopolaron effect therefore had a non-negligible influence in the analysis of our cyclotron resonance data. On the other hand, we have neglected the variation with pressure of valence-band parameters γ_1, γ_2, γ_3, κ, and q. We checked that a change of 25% in any one of these parameters would not change our results significantly. This insensitivity is due to the fact that the transitions we observe occur between states lying close to the bottom of the conduction band, where nonparabolic corrections depend only very weakly on the details of the valence band structure. The validity of this approximation would have to be reexamined when interpreting data obtained in interband photoconductivity, where states lying far above the conduction-band edge can be probed.

Using a far-infrared photoconductivity technique, we were able to observe the electronic spin-resonance transition in *bulk* $In_{0.53}Ga_{0.47}As$ under hydrostatic pressure up to 10 kbar. The analysis of our spin and cyclotron resonance data, using an eight-band $\mathbf{k}\cdot\mathbf{p}$ model, led to the determination of the electronic g factor and Kane interband matrix element E_p in $In_{0.53}Ga_{0.47}As$ as a function of hydrostatic pressure.

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