Journal of the Physical Society of Japan
Vol. 53, No. 10, October, 1984, pp. 3553–3559

Magnetophonon Resonance in Epitaxial n-InP in High Pulsed Magnetic Fields

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(Received June 11, 1984)

The transverse magnetophonon resonance in high purity epitaxial n-InP was investigated at temperatures between 123 and 270 K. High pulsed magnetic fields up to 40 T were applied to observe the fundamental resonance field. The temperature dependence of the magnetophonon effective mass m_0^* at the band-edge was precisely determined through the analysis of the resonant field positions including the peak for $N=1$. The determined value of m_0^* is $0.079m_0$ at 270 K and $0.084m_0$ at 143 K. The magnetic field dependence of the damping factor was found to be $\tilde{\gamma}\propto B^{2/3}$ in magnetic fields higher than 10 T. The temperature dependence of the damping factor was also obtained.

§1. Introduction

Recently, InP has attracted much attention as a material for the long wavelength semiconductor laser. The electron-phonon coupling constant α in n-InP for the polar optical phonon mode is 0.12 which is relatively large among various III–V compound semiconductors. Thus the electron transport is greatly influenced by the longitudinal optical (LO) phonon scattering. The magnetophonon resonance is a simple and useful means to investigate the effective mass in semiconductors in a wide temperature range. Since Gurevich and Firsov first predicted the possibility of the magnetophonon resonance,[1] it has been investigated in many substances. An oscillatory variation of the magnetoresistance is caused by resonant scattering of carriers between any two Landau levels close to $k_z=0$ by LO phonons. The resonance condition for such scattering is given by

$$\hbar\omega_l = N\hbar\omega_c \quad (N=1, 2, \cdots), \tag{1}$$

where $\hbar\omega_l$ is the energy of the LO phonons at the Γ point, ω_c is the cyclotron frequency, and N is the harmonic number. Stradling and Wood showed empirically that the oscillatory part of the magnetoresistance ρ_{osc} due to the magnetophonon resonance is represented by the following equation,[2]

$$\rho_{osc} \sim \exp\left(-\tilde{\gamma}\frac{B_0}{B}\right)\cos\left(2\pi\frac{B_0}{B}\right), \tag{2}$$

where B is the magnetic field, B_0 is the field for the fundamental resonance ($N=1$), and $\tilde{\gamma}$ is a quantity called damping factor. Barker gave a theoretical basis for the empirical formula (2), and derived theoretical expression of the damping factor $\tilde{\gamma}$ for various scattering mechanisms.[3] In experiments of magnetophonon resonance, the effective mass of carriers can be obtained from the period of the oscillation by use of (1), whereas from the damping of the oscillation, the carrier scattering mechanism can be studied.

The magnetophonon resonance in n-InP has been studied by Eaves *et al.*[4] and by Nakashima *et al.*[5] The recent development of pulsed high magnetic field technique has enabled us to measure the magnetophonon resonance very accurately in high field region up to about 40 T.[6] A new method to observe a small oscillatory part of the magnetoresistance superposed on the monotonic part has been developed for the magnetophonon resonance experiments in pulsed high fields.[7] A combination of this new technique with high mobility epitaxial samples much improved the accuracy of the available data from magnetophonon experiments in a high field range.

In this paper, we investigate the temperature dependence of the effective mass of carriers and the magnetic field- and the temperature-dependences of the damping factor in n-InP.

§2. Experimental Method

Transverse magnetophonon resonance measurements of high purity epitaxial n-InP were carried out between 123 and 270 K. Pulsed high magnetic fields up to 40 T were employed in order to observe the magnetophonon oscillations including the fundamental peak for $N=1$.

A high purity epitaxial n-InP crystal grown by the MOCVD method was used in the present experiment. The sample piece was cut into a rectangle of $5\times4\times0.5$ mm^3 with a 3.6 μm epitaxial layer grown on the semi-insulating InP substrate. Net impurity concentration N_D-N_A and electron mobility μ of the sample are N_D-N_A(300 K)$=2.1\times10^{15}$ cm^{-3}, N_D-N_A(77 K)$=1.4\times10^{15}$ cm^{-3}, μ(300 K)$=3900$ cm^{2}V^{-1}s^{-1}, μ(77 K)$=30400$ cm^{2}V^{-1}s^{-1}. Pulsed magnetic fields were produced by discharging a current from a condenser bank of 200 kJ (16 mF/5 kV) to a multi-turn solenoid coil which was cooled by liquid nitrogen. A half period of the field was about 23 ms. The strength of the magnetic field B was detected by the induction method with a pick up coil. The field intensity was calibrated by observing the Shubnikov-de Haas oscillation of a single crystal graphite below 4.2 K.

The four terminal method was employed to detect the magnetoresistance signal R. We cancelled the voltage induced by the pulsed magnetic fields by means of mixing appropriate magnitude of voltage which was picked up by a coil near the sample.

Since the amplitude of the magnetophonon oscillations which superposes on the magnetoresistance is much smaller than the monotonic part of the magnetoresistance, we employed the same technique as the one which we employed in our previous paper.[7] Namely, we observed the small magnetophonon oscillations ΔR in high magnetic fields by subtracting from the total magnetoresistance R the monotonic part of the magnetoresistance which was approximated by a smooth polynominal function of the field. This technique provides more accurate field values for the magnetophonon resonance peaks than the time-derivative method[2] and field modulation technique[8] in the high field range where the period of the oscillation becomes large. Typical experimental signals of R, ΔR and B are exhibited as a function of time in Fig. 1. The magnetophonon oscillation can be clearly seen in the ΔR signal, and can be observed twice in the rising and falling slopes of the magnetic field. We can obtain exactly the resonance peak positions and the amplitudes of the magnetophonon resonance from the ΔR curve as a function of B as shown in Fig. 2.

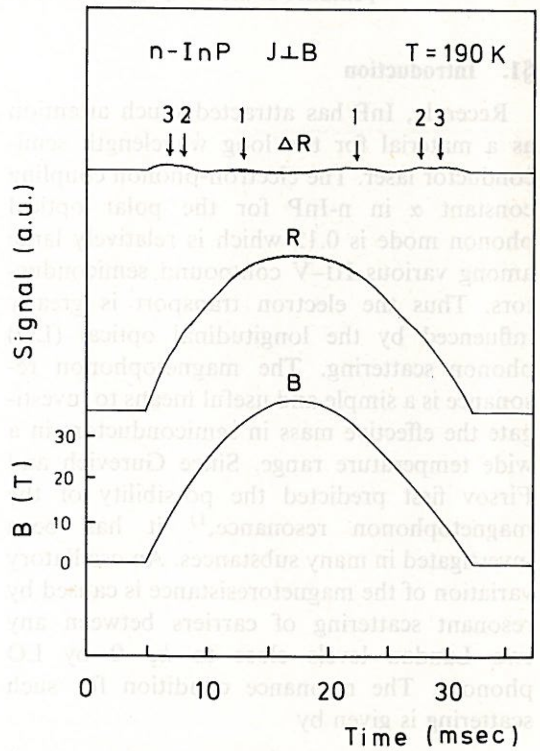

Fig. 1. Typical experimental recordings of the magnetophonon resonance in n-InP (R and ΔR) and magnetic field intensity (B) as a function of time. R is the total magnetoresistance and ΔR is the oscillatory part.

§3. Results and Discussion

Typical experimental recordings of the transverse magnetophonon resonance in n-InP are shown in Fig. 2 for various temperatures. The resonance peaks for the harmonic numbers from $N=1$ to $N=4$ are observed in the temperature range 123 K–270 K. Particularly, the resonance peak for the harmonic number of $N=1$ can be distinctly observed by virtue of the subtraction technique in our experiment. The resonance fields are assumed to be at the points where the oscillation curve contacts with its envelope curves as shown in Fig. 2. The observed fundamental field is 33.1 T at 143 K, 32.2 T at 200 K and 31.7 T at 270 K, and it decreases with increasing temperature. Such a temperature dependence is more clearly seen in Fig. 3 where the experimental peak positions multiplied by their harmonic number (NB_N) are plotted against temperature. It is expected that the same fundamental field is obtained for all values of N if resonant condition (1) is exactly obeyed. The peak positions were found to shift by about 4% to lower fields with increasing temperature from 143 K to 270 K. This magnitude of the shift is much larger than that of the LO phonon energy. The temperature dependence of the fundamental resonance is partly caused by the considerable deviation from parabolicity of the conduction band in InP.

We calculated the effective mass at the bottom of the band of InP from the data given in Fig. 3 taking account of a correction arising from the nonparabolicity of the conduction band as discussed by Stradling and Wood.[2] The experimentally observed magnetophonon peak position characterized by the harmonic number N is the average of the resonant field positions for all transitions satisfying (1) from each Landau level weighted by the carrier population. To estimate the contribution from each Landau level, the carrier population in each Landau level is assumed to be directly proportional to the Boltzmann factor. The energy of the L-th Landau level is approximately expressed as follows:

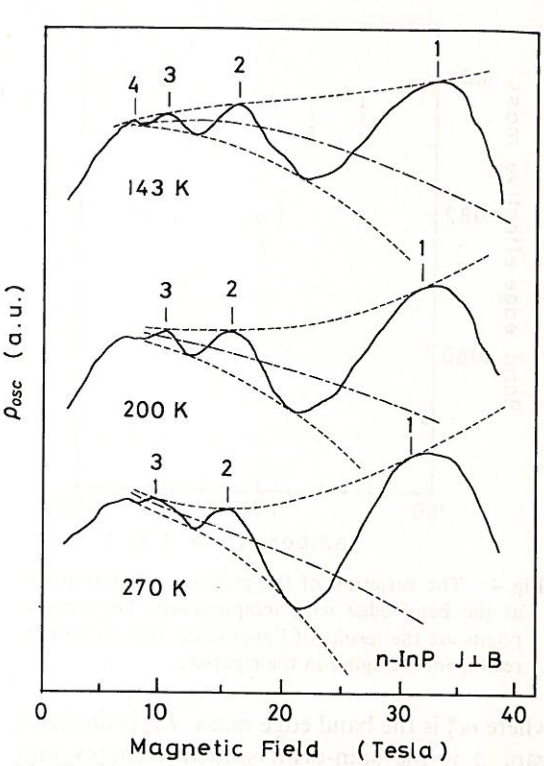

Fig. 2. Magnetophonon oscillations against magnetic field at various temperatures. The broken curves are the envelope of the oscillations and the dot-broken curve is the central line of the envelope.

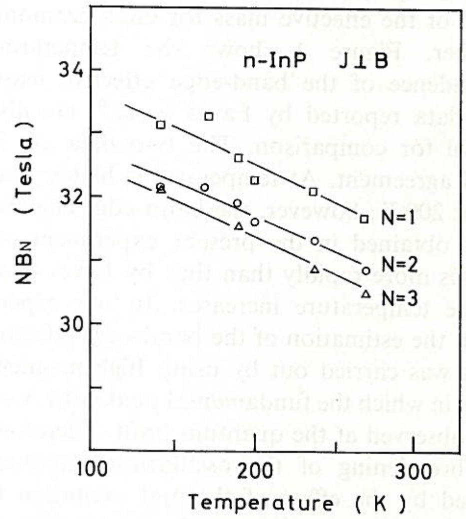

Fig. 3. The experimental peak positions multiplied by their respective harmonic number (NB_N) against temperature.

$$E_L=\left(L+\frac{1}{2}\right)\hbar\omega_c-\left(1-\frac{m_0^*}{m}\right)^2\frac{3E_G+4\Delta+2\Delta^2/E_G}{(E_G+\Delta)(3E_G+2\Delta)}\left(L+\frac{1}{2}\right)^2(\hbar\omega_c)^2, \quad (3)$$

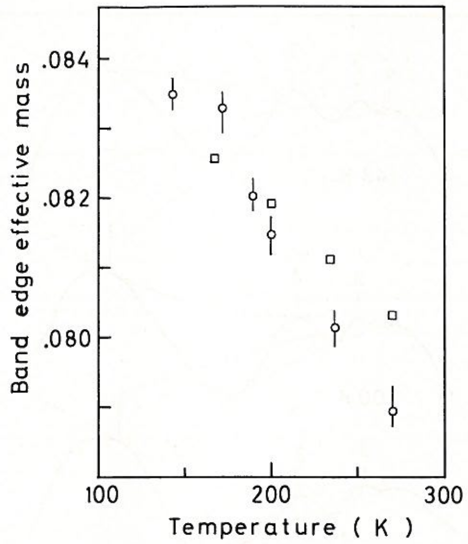

Fig. 4. The variation of the polaron effective mass at the band edge with temperature. The square points are the results of Eaves *et al.* (the data were read from the figure in their paper).

where m_0^* is the band edge mass, E_G is the band gap, Δ is the spin-orbit splitting energy and $\hbar\omega_c = \hbar eB/m_0^* c$. As for the LO phonon energy, the data given by Mooradian and Wright[9] was used. After applying the nonparabolicity correction, the band-edge effective mass at a given temperature is obtained as the average value of the effective mass for each harmonic number. Figure 4 shows the temperature dependence of the band-edge effective mass. The data reported by Eaves *et al.*[4] are also shown for comparison. The two data are in good agreement. At temperatures higher than about 200 K, however, the band-edge effective mass obtained in the present experiment decreases more rapidly than that by Eaves *et al.* as the temperature increases. In our experiment, the estimation of the band-edge effective mass was carried out by using high magnetic fields in which the fundamental peak with $N=1$ was observed at the quantum limit. Therefore, the broadening of the oscillation amplitude caused by the effect of thermal excitation to higher Landau levels is smaller in comparison to the experiments in the lower magnetic field range.

To obtain the bare electron mass from the magnetophonon mass thus determined, a further correction arising from the polaron effect must be applied. It has been shown by Palmer that the polaron correction which must be applied to the mass in the magnetophonon experiment to obtain the bare mass is $(1+\eta\alpha/2)$ where η is a numerical factor equal to 0.83, and α is the Fröhlich coupling constant.[4] The value of α is estimated to be 0.12[10] for InP. Applying this polaron correction, the following values of the bare effective mass m_b^* were found: $m_b^* = 0.075m_0$ at 270 K and $m_b^* = 0.080m_0$ at 143 K. These results are in reasonably good agreement with those reported by Nakashima *et al.*[5]

The large decrease of the band-edge mass with increasing temperature is primarily ascribed to the temperature dependence of the energy band gap E_G. However, calculating the effective mass based on Kane's model,[11] we found that the observed temperature dependence is slightly stronger than expected from the change in E_G. Nakashima *et al.* observed a temperature dependence of the effective mass larger than expected from the dilatational change of E_G.[5] The large temperature dependence of the magnetophonon mass was also reported by Stradling and Wood for GaAs, InAs and InSb in high temperature range.[2] The reason of the extraordinary large temperature dependence of the effective mass is not clear at the moment. It may be due to the change of the momentum matrix element P with increasing temperature.

Next, we discuss the magnetic field- and the temperature-dependences of the damping of the oscillation amplitude to elucidate the scattering mechanism in the higher magnetic field range. The temperature dependence of the oscillation amplitude for four harmonic numbers $N=1$, 2, 3 and 4 is shown in Fig. 5 where the ordinate is normalized by the zero-field resistivity. The maximum amplitude is obtained around 140 K for all the harmonic numbers. Similar temperature dependence of the amplitude has been seen for many other materials. The amplitude falls at high temperatures because of the decrease of the mobility, and decreases rapidly at low temperature because of the smaller excitation rate of the optical phonons. As is seen in Fig. 5, the spacing between the curves for harmonic number N and $N+1$ decreases with the increasing harmonic number. This

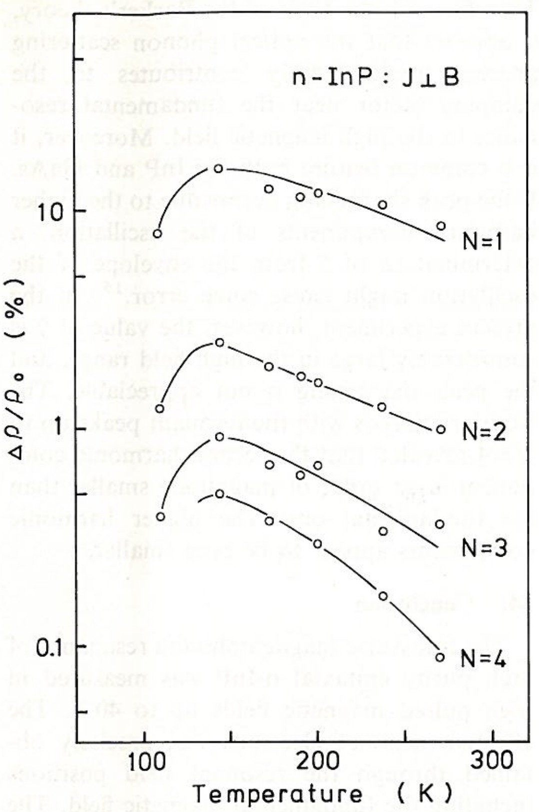

Fig. 5. The temperature dependence of the normalized amplitude of the magnetophonon oscillation for the harmonic number from 1 to 4.

means that the oscillation at higher magnetic fields is damped more strongly than in lower fields. It follows that in the high field region the damping factor increases as the magnetic field increases.

To estimate the damping factor $\tilde{\gamma}$ experimentally as a function of magnetic field, the following procedure was adopted.[6] The amplitude of the magnetophonon resonance ΔR at N=integer and N=half integer is given by $\Delta R_N \propto \exp(-\tilde{\gamma}N)$ and $\Delta R_{N+0.5} \propto \exp\{-\tilde{\gamma}(N+0.5)\}$, respectively, as seen from (2). Here the $\Delta R_{N+0.5}$ is the amplitude at the minimum between the N-th and the $(N+1)$-th maxima. Therefore, the damping factor $\tilde{\gamma}$ obeys the following relation

$$\tilde{\gamma}(N, N+0.5)=2\ln(\Delta R_N/\Delta R_{N+0.5}). \qquad (4)$$

By using this expression, the magnetic field dependence of the damping factor can be determined experimentally. The change of the

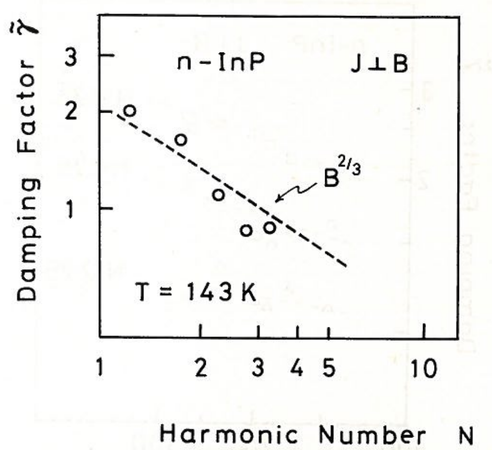

Fig. 6. The damping factor at 143 K as a function of harmonic number. The broken line indicates the dependence $B^{2/3}$.

damping factor $\tilde{\gamma}$ with the harmonic number N is shown in Fig. 6 for T=143 K. The damping factor is found to decrease in proportion to $N^{-2/3}$. Namely, the magnetic field dependence of $\tilde{\gamma}$ is given

$$\tilde{\gamma} \propto B^{2/3}. \qquad (5)$$

The same field dependence was also observed in GaAs in high magnetic field region for $N \geq 3$.[6] According to the Barker's theory,[3] the observed magnetic field dependence of the damping factor in magnetic fields higher than 10 T corresponds to the case of the phonon scattering. On the other hand, the scattering process related to the impurity gives the field independent damping factor.

In Fig. 7, plots of the damping factor versus temperature are shown for the harmonic number less than 2.25 (for the magnetic field higher than about 13 T). It is found that the damping factor increases slowly with increasing temperature in the range 143–270 K. The temperature dependence of the damping factor is slightly different for each harmonic number. The dotted lines in Fig. 7 express the temperature dependence of the damping factor obtained by the method of the least square fit. It is found that the temperature dependence of the damping factor becomes larger as the harmonic number decreases (as the magnetic field increases). The temperature dependence is approximately expressed as $\tilde{\gamma} \propto T^{0.37}$ for N=1.25, $\tilde{\gamma} \propto T^{0.30}$ for N=1.75 and $\tilde{\gamma} \propto T^{0.16}$ for N=

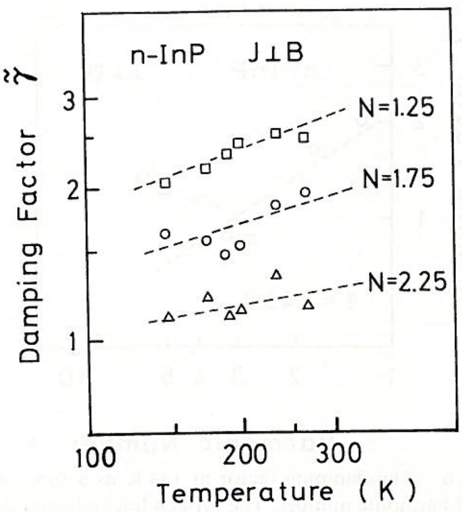

Fig. 7. The temperature dependence of the damping factor for various magnetic fields ($B \propto 1/N$). The broken lines were obtained by the method of least square fit.

2.25. Here the damping factor for (N-0.25) was obtained from the ratio of the oscillation amplitude at the N-th resonance peak (maximum of the resistance) to the preceding resistance minimum (the (N-0.5)-th peak). The temperature dependence of the damping factor obeying a relation $\tilde{\gamma} \propto T^{1/4}$ has been reported for InSb[13] and GaAs[14] in lower temperature and lower magnetic fields than our experiment and this dependence is explained by the band tailing effect. On the other hand, Senda *et al.*[14] and Kido and Miura[6] have reported the deviation of the temperature dependence from $\tilde{\gamma} \propto T^{1/4}$ in higher temperature range for GaAs. The reason of the deviation has not been explained theoretically.

The magnetic field dependence as expressed by (5) is suggestive of the contribution of the optical or acoustic phonon scattering as the dominant process to determine $\tilde{\gamma}$ in high magnetic field region on the basis of the Barker's theory. The contribution of the optical phonon scattering is considered to be larger than that of the acoustic phonon scattering. This theory also predicts a small temperature dependence close to $\tilde{\gamma} \propto T^{1/4}$ for the optical phonon scattering process in the case of InP through the change of the Bose-Einstein distribution of the optical phonons in the temperature range between 100 K and 200 K. Therefore, on the basis of the Barker's theory, it appears that the optical phonon scattering process predominantly contributes to the damping factor near the fundamental resonance in the high magnetic field. Moreover, it is a common feature both for InP and GaAs. If the peak sharpening occurs due to the higher harmonic components of the oscillation, a determination of $\tilde{\gamma}$ from the envelope of the oscillation might cause some error.[15] In the present experiment, however, the value of $\tilde{\gamma}$ is considerably large in the high field range, and the peak sharpening is not appreciable. The Fourier analysis with the resonant peaks up to $N=4$ revealed that the second harmonic component is an order of magnitude smaller than the fundamental one. The higher harmonic components appear to be even smaller.

§4. Conclusion

The transverse magnetophonon resonance of high purity epitaxial n-InP was measured in high pulsed magnetic fields up to 40 T. The effective mass of electrons was precisely obtained through the resonant field positions including the fundamental magnetic field. The masses at bottom of the conduction band are determined to be $0.079m_0$ at 270 K and $0.084m_0$ at 143 K. Applying a polaron correction, the band-edge effective masses are found to be $0.075m_0$ at 270 K and $0.080m_0$ at 143 K. The temperature dependence of the effective mass was found to be larger than expected from the change of the band gap. The magnetic field dependence of the damping factor was found experimentally as $\tilde{\gamma} \propto B^{2/3}$ in high magnetic field region. The temperature dependence of the damping factor was also obtained at high magnetic fields. It was found that the simple power law $\tilde{\gamma} \propto T^{1/4}$ as in the case of InSb and GaAs in low field region does not hold in the high field region.

Acknowledgement

The authors wish to thank Professor C. Hamaguchi and Professor R. A. Stradling for valuable discussion.

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