

Far-Infrared Magneto-Absorption of the Nonequilibrium Electron System in Indium Phosphide

Tyuzi OHYAMA, EIZO OTSUKA, Syoji YAMADA[†],
 Takashi FUKUI[†] and Naoki KOBAYASHI[†]

*Department of Physics, College of General Education, Osaka University,
 Toyonaka, Osaka 560*

[†]*Musashino Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation,
 Musashino-shi, Tokyo 180*

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Measurements of the far-infrared cyclotron resonance of conduction electrons and the Zeeman absorption of donors in a MOCVD grown InP have been carried out at 4.2 K under photo- and electric field-excitations. It is found that the effective mass of the electron and the donor binding energy are $m^* = (0.0817 \pm 0.0004)m_0$ and $E_b = 7.6$ meV, respectively. The electric field dependence of the resonance intensity can be explained in terms of impact ionization of the donor electrons. From time-resolved experiments, both the apparent lifetime and the scattering time of photoexcited electrons are also obtained.

Indium phosphide has been drawing attention for such device application as a solid state laser in view of its appropriate gap energy and high electron mobility. Though several features of electrons in metal-insulator-semiconductor (MIS) transistor and heterostructure devices are now clarified through capacitance, magnetoconductivity and optical measurements,¹⁻³⁾ the dynamic properties of the bulk InP, which govern the performance of devices, have so far been left intact except for a few FIR photoconductivity and photoluminescence properties.⁴⁻⁷⁾ The present work is concerned with the nature of the cyclotron resonance of conduction electrons and the Zeeman absorption of donor electrons in the presence of the photo- as well as the electric field-excitation.

An n-type InP crystal grown by the MOCVD method was used in the present experiment. The sample piece was a rectangular parallel-piped, having dimensions of $5 \times 5 \times 0.5$ mm³, in which a 3 μ m epitaxially grown layer was laid on the semi-insulating substrate. For the epilayer, we had the net impurity concentration $N_D - N_A = 2.1 \times 10^{15}$ cm⁻³ and the electron mobility $\mu_e(300$ K) = 3800 cm²/Vs. For the electrical pulse excitation experiment, two point probes were soldered on by tin. As the far-infrared source, wavelengths of 119 and 220 μ m were obtained from an H₂O laser and 84 and 172 μ m from a D₂O laser. The laser was operated in pulses at the repetition of 30 Hz in synchronized combination with a xenon flash lamp as well as with an electrical pulse generator, the repetition of which was held at 15 Hz. Pulse widths of the xenon flash lamp and the electric field were ~ 1 μ s and 50 μ s, respectively. The absorption spectra were obtained as $\ln(I_0/I_L)$, $\ln(I_0/I_E)$ and $\ln(I_0/I_{L+E})$ in accordance with the experimental purposes by means of two boxcars or a two-channel boxcar with the common aperture of 0.5 μ s. Here I_L , I_E and I_{L+E} are the intensities of the transmitted far-infrared laser beam with external photo- and/or electric field-excitation and I_0 is that without excitation. In time-resolved experiments, we employ a newly developed multi-channel system.⁸⁾ In this way we could directly detect the change in absorption coefficient induced by the photo- and electric field-excitations.

As the first step we consider the impact ionization of shallow donors. At high electric field, free carriers acquire enough kinetic energy to ionized neutral impurity atoms by impact, thus creating additional free carriers. Figure 1 shows typical traces of far-infrared magnetoabsorption obtained at 4.2 K by the above-mentioned modulation detection method and for the wavelength of 119 μ m at

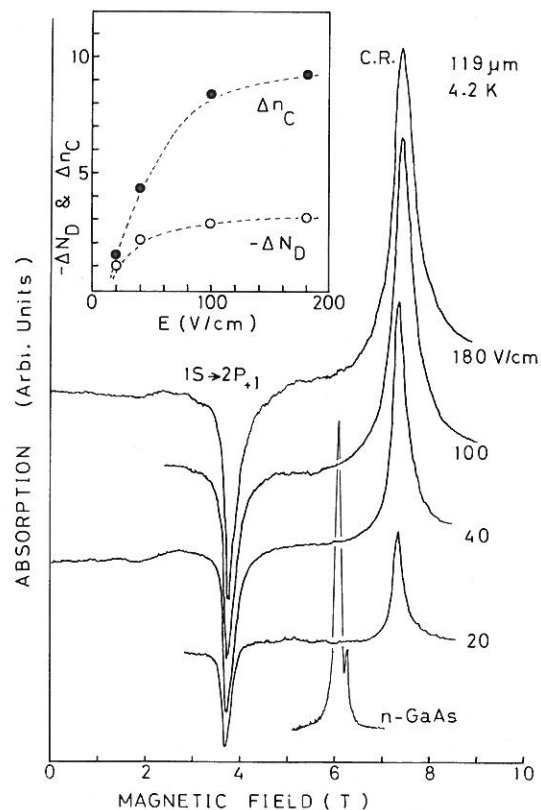


Fig. 1. Dependence of cyclotron resonance (C.R.) as well as Zeeman absorption ($1s \rightarrow 2p_{+1}$) signals on the electric field with the pulsed electric field modulation technique. The lowest trace is C.R. in GaAs shown for comparison to emphasize the appearance of the quantum line. The inset shows the relative change in absorption as a function of the electric field. Broken lines are simply to guide the experimental points.

various values of the electric field. The downward absorption signals, or the decreases in absorption on applying the electric field, arise from the $1s \rightarrow 2p_{+1}$ Zeeman transition of donor electrons. The cyclotron resonance of conduction electrons, on the other hand, obviously increases as the electric field is increased, especially above 20 V/cm, suggesting that the critical field for impact ionization is close to 20 V/cm. This value is somewhat higher than that for GaAs⁹⁾ because of the relatively low electron mobility and large binding energy of donors in InP. We plot the electric field dependence of the rise and fall in density of conduction electrons and donor electrons in the inset of Fig. 1. We note that they saturate above 100 V/cm. This means that the donor electrons are all excited into the conduction band through the impact ionization above 100 V/cm. On further increase of the electric field, one can expect the repopulation of electrons in the conduction band to occur. Then, in addition to the lowest Landau levels cyclotron transition, the quantum line signals originating from higher Landau level transitions may be observed for the material with a nonparabolic conduction band. In fact, two resonance lines are found in the spectra of GaAs,⁹⁾ which are taken at the same FIR wavelength and shown at the bottom of Fig. 1 for comparison. For InP, however, only a single line is observed even at the maximum electric field employed. It is very likely then that the conduction band of InP is well described by a parabolic energy surface.

Figure 2 shows the typical absorption spectra observed at 4.2 K for various wavelengths. The downward signals again arise from the $1s \rightarrow 2p_{+1}$ Zeeman absorption of donor electrons while the upward ones from the cyclotron re-

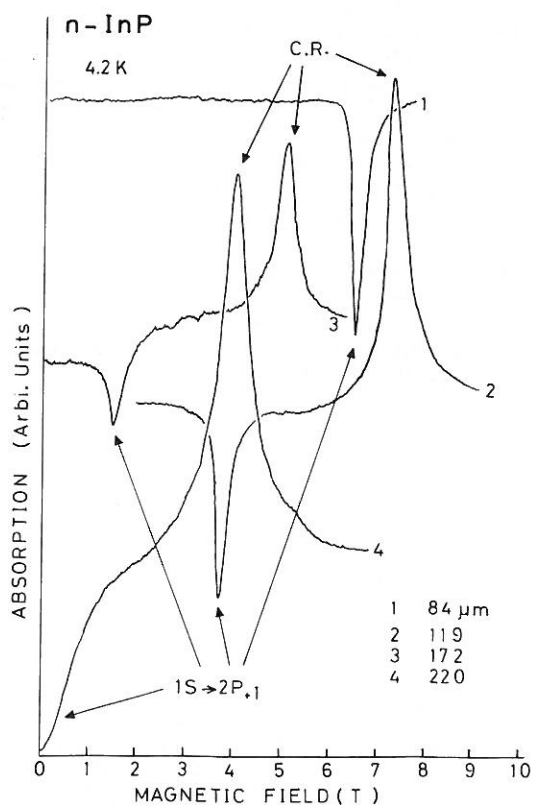


Fig. 2. Typical magneto-absorption traces with the pulsed electric field modulation technique for the FIR laser wavelengths of 84, 119, 172 and 220 μm .

sonance of conduction electrons. The effective mass values of the conduction electron determined at the wavelengths of 119, 172 and 220 μm agree within experimental error to yield $m^* = (0.0817 \pm 0.0004)m_0$. This value is compatible with $m^* = 0.0815m_0$ obtained at a lower magnetic field (2.6 T) and at relatively higher temperature (~ 10 K).⁴⁾ Any nonparabolic nature of the InP conduction band thus escapes recognition in the magnetic field range investigated. According to Kane's band theory,¹⁰⁾ the main factors characterizing the nonparabolicity are the gap energy E_g and the spin-orbit splitting Δ . So far as $E_g > \Delta$, the nonparabolicity is expected to decrease as E_g and the ratio $\eta = \Delta/E_g$ increase. As we have seen, however, the nonparabolicity of InP is smaller than that of GaAs,⁹⁾ in spite of the smaller E_g ($= 1.42$ eV) and η ($= 0.072$) of InP than those ($E_g = 1.53$ eV and $\eta = 0.22$) of GaAs. We should then recall another possible cause of nonparabolicity, namely, the polaron pinning effect¹¹⁾ that becomes more and more marked as the cyclotron energy approaches the optical phonon energy. In the case of GaAs, the ratio $\lambda = \omega_c/\omega_{LO}$ reaches 0.29 at the laser wavelength of 119 μm , whereas it remains $\lambda = 0.24$ for InP. The polaron pinning effect, accordingly, seems to be responsible for giving rise to the large nonparabolicity of the GaAs conduction band.⁹⁾

Taking note of our experimental results of the $1s \rightarrow 2p_{+1}$ Zeeman absorption with the variational calculation by Larsen,¹²⁾ we obtain the donor binding energy $E_b \sim 7.6$ meV, which agrees quite well with the theoretical estimation by the effective mass approximation, if one takes $m^* = 0.0817m_0$ and $\kappa = 12.1$ for the static dielectric constant.

Typical traces of the cyclotron resonance at 4.2 K are shown in Fig. 3 for the wavelength of 220 μm and at various delay-times after photoexcitation. We have no absorption signal for the cyclotron resonance experiment without photoexcitation, since very few electrons exist in the conduction band at 4.2 K. Through the time-dependence of the absorption intensity and the linewidth, we obtain the apparent lifetime and the scattering time of photoexcited electrons. The apparent lifetime is measured as 5.3 μs , which seems too large in view of the normal electron capture time by charged impurities or holes.¹³⁾ Such a slow decay of photoexcited electrons at low temperatures has been frequently observed in compensated materials of GaAs¹⁴⁾ and InSb.¹⁵⁾ It is understood to be a result of the joint action of the extremely slow donor-to-acceptor recombination and the screening of ionized impurities by photoexcited conduction electrons.

As the delay time is increased, both absorption intensity and linewidth decrease considerably. The intensity change is regarded simply as a change of the carrier-density. The line-width, on the other hand, is connected with the relaxation time τ through the relation

$$1/\tau = \omega \Delta B / B_r; \quad (1)$$

where ΔB is the half-width, B_r the resonance field and ω the angular frequency of the laser. For a period of time after the photoexcitation, when the carrier density is high, the line is broadened because of the carrier-carrier interaction,^{14,16)} and then tends to a fixed width. The quantity $1/\tau$ is found to be $4.1 \times 10^{11} \text{ s}^{-1}$ at the density-independent limit. This

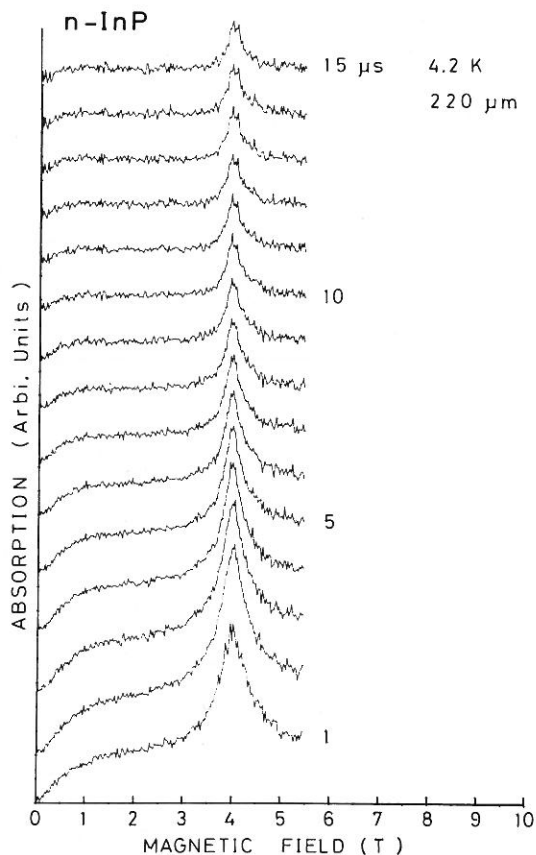


Fig. 3. Time-resolved cyclotron resonance of the photoexcited electrons obtained at 4.2 K and at the FIR laser wavelength of 220 μm . The sampling was made at every microsecond after the photoexcitation pulse.

value should be governed only by neutral impurity scattering under photoexcitation, since ionized impurities are completely photoneutralized.¹⁴⁾ The electron scattering rate by neutral donors is well accounted for by the Erginsoy formula¹⁷⁾ given by

$$1/\tau_{e-ND} = 20\hbar a_B N_D / m^* ; \quad (2)$$

where a_B is the effective Bohr radius. Substituting the numerical values appropriate to InP, i.e., $a_B = 79 \text{ \AA}$, $m^* = 0.0817m_0$ and in the present case $N_D = 3 \times 10^{15} \text{ cm}^{-3}$ which is derived by the same procedure as described elsewhere,¹⁸⁾ one obtains $1/\tau_{e-ND} = 6.7 \times 10^{11} \text{ s}^{-1}$. Taking account of the correction due to a high magnetic field,¹⁴⁾

our experimental value given above essentially agrees with this prediction by Erginsoy's formula. We thus obtain $\mu_e(B=4T) \approx 5.3 \times 10^4 \text{ cm}^2/\text{Vs}$ at 4.2 K.

In summary, various new and renewed features have been found for InP by time-resolved as well as by pulsed electric field-modulated far-infrared magneto-absorption measurements under photoexcitation: the critical field strength for impact ionization of donors, the donor binding energy, the effective mass of the conduction electron, the apparent lifetime of photoexcited electrons and the relaxation time by neutral impurity scatterings.

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