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METASTABLE SHALLOW DONOR STATES OF n-GaAs IN A MAGNETIC FIELD

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The photothermal spectrum of shallow donors in n-GaAs has been investigated at various magnetic field strengths up to $4T$ at different temperatures between 1.4 and $12K$. Weak spectral structures observed at frequencies above the dominant $1s \rightarrow 2p_{+1}$ line are attributed to optical excitations into metastable states which arise in a magnetic field. The final states of these transitions can be unambiguously assigned by using high field quantum numbers.

The optical excitation spectra of hydrogen-like shallow donors in high purity GaAs epitaxial layers have been studied extensively in the past by photothermal ionisation spectroscopy. The techniques of high resolution far-infrared Fourier spectroscopy [1,2,3] as well as far-infrared laser magnetospectroscopy [4] have been applied yielding detailed knowledge of donor levels in a wide range of magnetic field strengths. Since the early work of Larsen [5] many variational calculations based on the effective mass approximation have been performed reproducing the bound donor levels in excellent agreement with experimental results [6].

The most prominent lines observed in photoconductivity spectra at low temperatures correspond to transitions from the $1s$ donor ground state to $2p_{\pm 1}$ states where nl_m is the low field hydrogen atom energy level notation. Besides these strong lines, weak transitions like $1s \rightarrow 2s$ are observed violating the electric dipole selection rules. This effect is attributed to admixing of p-states due to the Stark effect caused by the strong electric fields of ionized impurities in the partially compensated material. The photoconductivity spectra of n-GaAs in a magnetic field contain, however, additional weak structures which have not yet been identified. In the present study we show that most of these lines, being observed in Faraday configuration, may be grouped in pairs with frequency separation ω_c, where $\omega_c = eB/m^*$ is the conduction band cyclotron frequency. Taking into account electric dipole selection rules $\Delta m = \pm 1$ and $\pi_i \pi_f = -1$, where $\pi_{i,f}$ are the parities of the initial and final states respectively, we conclude that most of the observed structures are due to excitation of metastable states from the donor ground state. Metastable states arise in a magnetic field out of the donor continuum and do not lead to donor bound states in the zero field limit. The final states may be assigned by high field quantum numbers (N, m, κ) where N and m denote the Landau levels and the angular momentum respectively and κ counts the donor states below each (N, m) Landau subband. The parity of a state in the high field notation is given by $\pi = (-1)^{m+\kappa}$.

The measurements were carried out on an n-GaAs epitaxial layer of $41 \mu m$ thickness predominantly containing silicon shallow donors with an effective concentration $N_D - N_A = 9.2 \cdot 10^{13}$ cm^{-3}. The mobility at liquid nitrogen temperature was $\mu = 9.4 \cdot 10^4$ cm^2/Vs. Ohmic point contacts were alloyed at opposite edges of the layer and a wedged piece of polished semiinsulating GaAs was glued with paraffin oil onto the substrate face in order to avoid optical interference effects. The sample was mounted at the end of a metallic light pipe fitted in a variable temperature cryostat at the center of a superconducting magnet. The photoconductivity spectra were measured in Faraday configuration by a commercial far-infrared Fourier-spectrometer in the frequency range between $25\ cm^{-1}$ and $180\ cm^{-1}$. A standard load resistor circuit was used to keep the bias voltage well below the impact ionization threshold of shallow donors in order to minimize current noise and to avoid impact ionization nonlinearities [7].

Alltogether about 100 spectra measured at various temperatures between $T = 2K$ and $10K$ for different magnetic field strengths up to $B = 4T$ were evaluated yielding reasonable confidence in the spectral positions of even weak photoconductivity structures. A typical spectrum obtained at $B = 1T$ is plotted in Fig.1 for frequencies higher than that of the $1s \rightarrow 2p_{+1}$ transition. The grouping of lines in pairs separated by the frequency difference ω_c is indicated by double arrows. Identified lines due to optical excitations from the donor ground state are labelled with the quantum numbers of the corresponding final states. Zero field hydrogen atom notation nl_m and high field quantum numbers (N, m, κ) are used to distinguish between bound and metastable final states respectively. With the exception of the forbidden transitions $1s \rightarrow 3d_{+1}$ and, not shown in Fig. 1, $1s \rightarrow 2s$ and $1s \rightarrow 2p_0$, all observed lines may be assigned without any constraint taking into account the electric dipole selection rules. Transitions are allowed to final states with $m = \pm 1$ and $\pi = (-1)^{m+\kappa} = -1$, i.e. κ even.

In Fig. 2 a transition energy level scheme is plotted showing the magnetic field dependence of all experimentally observed lines. Final bound states are denoted by both high field and hydrogen atom quantum numbers. Transitions labelled by an asterisk have been identified for the first time in the present investigation. The broken lines represent the energy seperation between Landau levels and the donor ground state obtained from [6].

The interpretation of the observed spectral structures is based on the work of Simola and Virtamo [8]. The correspondence of zero field hydrogenic states and high field states has been controversal yielding erroneous assignments in the early work on n-GaAs. This occurred in spite of the fact that the theoretical background was established at the latest in [9] by Boyle and Howard on investigations of the Zeeman spectra of germanium donors. In [8] it was shown that a compatibility relation between zero field and high field states may be uniquely established by applying the quantum mechanical non-crossing rule based on the conservation of the angular momentum component parallel to the magnetic field and parity conservation. Donor states

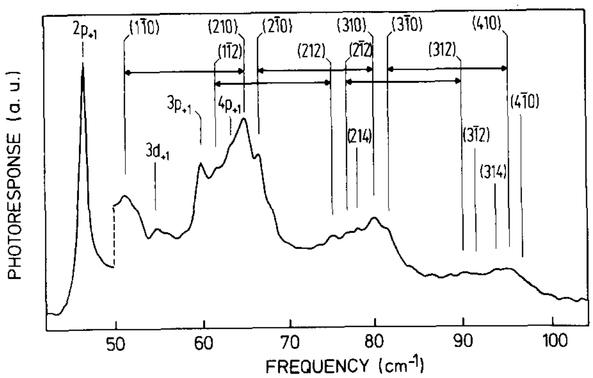

Fig. 1: Photoconductivity spectrum measured at $B = 1T$ and $T = 1.5K$. Double arrows indicate the energy separation $\hbar\omega_c$. (N, m, κ) and nl_m label final metastable and bound states, respectively.

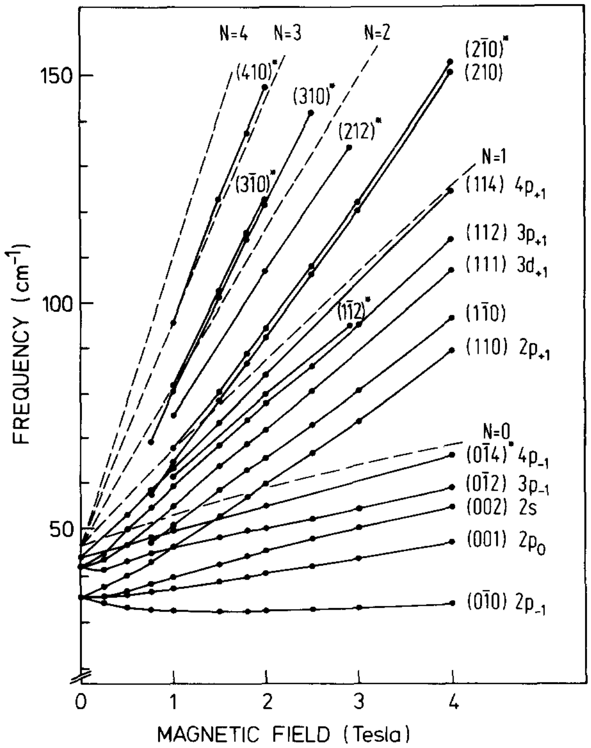

Fig. 2: Magnetic Field dependence of all lines observed in the present study. Final bound states are labelled by both zero field and high field notation, new identifications are indicated by an asterisk. Broken lines show Landau level transition frequencies.

that are bound in the zero field limit remain bound in magnetic fields of any strength. Thus hydrogenic nl_m with $m \leq 0$ states progress into $(N, m, \kappa) = (0, m, \kappa)$ lying below the $N = 0$ Landau level, i.e. below the band edge. In the case of $m > 0$, they cross the band edge and constitute an infinite series of bound states below each $N = m$ Landau level. States of the latter class are degenerate with the $N = m - 1$ Landau level continuum. However, because free electrons in a Landau subband may have angular momenta $m \leq N$ only, these states are bound due to angular momentum conservation.

In addition to the states derived from and exhausting all zero field bound states, the hydrogenic continuum (structureless in the field free situation) also exhibits structure in a magnetic field. For any (N, m) with $m < N$ an infinite series of electron resonance states arises below each Landau level. These states are coupled through the Coulomb potential with free states of the same m and smaller N. In the limit of $B \rightarrow \infty$, the coupling vanishes yielding true bound states. For finite magnetic field strength, however, these states are metastable and autoionization transitions may occur into the continuum without energy exchange [8,10]. Satisfying selection rules in Faraday configuration $(N, \pm 1, \kappa)$ states with κ even are accessible from the $1s = (0,0,0)$ ground state by electrical dipole transitions. All $m = -1$ states in the conduction band and all $m = +1$ states with $N > 1$ are metastable. Since the energy difference $E_{N,m,\kappa} - E_{N-m,-m,\kappa} = m\hbar\omega_c$ follows from time inversion, optical $\Delta m = \pm 1$ transitions yield pairs of lines separated by ω_c in frequency.

In summary, a series of weak lines in the photothermal spectrum of n-GaAs in a magnetic field have been identified. Most of the lines lying spectrally above the dominant $1s \rightarrow 2p_{+1}$ transition can be attributed to optical excitations of metastable shallow donor states. In a recent work Labrujere et al. have reported similar investigations carried out by FIR laser magnetospectroscopy [10]. Due to the inherent higher intensity of laser excitation a greater number of high frequency lines were obtained. They attributed all observed spectral structures to transitions between bound donor states, some transitions violating selection rules. We believe that these lines, at least in part, are of the same type as discussed above being caused by transitions to metastable states which cannot be assigned by zero field hydrogen atom quantum numbers.

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References

[1] R. Kaplan, M. A. Kinch and W. C. Scott, Solid State Commun. **7**, 883 (1968)

[2] G. E. Stillman, C. M. Wolfe and J. O. Dimmock, Solid State Commun. **7**, 991 (1969)

[3] S. Narita and M. Miyao, Solid State Commun. **9**, 2161 (1971)

[4] C. J. Armistead, P.Knowles, S. P. Naida and R.A. Stradling, J. Phys. C **17**, 6415 (1984)

[5] D. M. Larsen, Phys. Rev. B **8**, 535 (1973)

[6] P. C. Macado and N.C. McGill, J. Phys. C **19**, 873 (1986) and references therein

[7] E. Schöll, W. Heisel and W. Prettl, J. Phys. B **47**, 285 (1982)

[8] J. Simola and J. Virtamo, J. Phys. B **11**, 3309 (1978)

[9] W. S. Boyle and R.E. Howard, J.Phys. Chem. Solids **19**, 181 (1961)

[10] A.C. Labrujere, T. O. Klaassen, and W.Th. Wenckebach, 12th Int. Conf. on Infrared and Millimeter Waves, Orlando, 1987.