Zeeman spectroscopy of the Be acceptor in GaAs to intermediate fields

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Abstract
Magneto-spectroscopy to 17.5 T of the Be acceptor impurity in GaAs in the Faraday configuration using unpolarised radiation is reported. One strong component of the G-line is observed. This moves slowly with field at ~0.24 cm−2 T. All eight transitions expected for the D-line are observed, allowing some of the splittings of the field-induced components of the ground and the second excited states to be determined.

Keywords: A. Semiconductors; B. Epitaxy; C. Impurities in semiconductors; D. Electronic states (localised); E. Light absorption and reflection

1. Introduction

Compared to the extensive literature on the magneto-spectroscopy of donors in GaAs, and of acceptors in Si and Ge, relatively little has been published on acceptors in GaAs. Kirkman et al. [1] first observed acceptor spectra in GaAs. The impurities involved were C and Zn. Absorption measurements proving difficult, these authors resorted to photo-thermal ionisation spectroscopy (PTIS). This method requires a rather high temperature and thus broad lines result. Magnetospectra were recorded to 9 T, but low resolution and ambiguity concerning the polarisation of the incident radiation limited the usefulness of the results. Atzmüller et al. [2] give a very complete set of Zeeman data in the Voigt configuration for the same impurities, for the electric field of the radiation E both parallel and perpendicular to the magnetic field B, for B parallel to each of the three high-symmetry directions (100), (110), and (111). This work extends that of Schubert et al. [3] for C in GaAs. Reeder et al. [4–7] report on Be in GaAs to 9 T, but few lines are observed and these are quite broad.

We have recently reported on the far-infrared spectroscopy of Be in GaAs [8] and also on PTIS and photoluminescence for this impurity system [9]. We have made Zeeman measurements in the Voigt configuration with B || [001] and E || B and E ⊥ B for the strongest line of the Lyman series, allowing the g-factors of the ground and the second excited state to be estimated [10]; these compare well with the previous experimental [2] and theoretical [11] estimates for these quantities for acceptors in GaAs.

A dimensionless measure of the strength of the magnetic field applied to a hydrogenic impurity system is \( \beta_0 \), where \( \beta_0 = \frac{R_0}{\gamma_1 \mu_B} \), with \( R_0 \) the effective Rydberg, \( \gamma_1 \) a Luttinger parameter, and \( \mu_B \) the Bohr magneton. For acceptors in GaAs, \( \beta_0 \approx 34 \) T. The present work extends the range for which detailed Zeeman data are available for an acceptor in GaAs from ~ \( \beta_0/5 \) (low-field regime) to ~ \( \beta_0/2 \) (intermediate-field regime).

2. Experimental

The sample, denoted by NU652, used in these experiments consisted of a 3-μm thick layer doped with Be at density \( 2.3 \times 10^{16} \) atoms cm−3. It was grown by molecular beam epitaxy on a 450-μm-thick (100) GaAs substrate. The sample was wedged to suppress optical interference between the front and back faces. Far-infrared absorption spectra of this and similar samples are given in detail in Ref. [8].

The measurements were made at the National High Magnetic Field Laboratory, Tallahassee, USA, in a...
superconducting magnet. The data were collected using a Bruker Model IFS 113v Fourier-transform infrared spectrometer. The light was conducted to the sample at the field centre via a metal light pipe and condenser cone. A liquid-helium-cooled Si bolometer detector was employed. Measurements were made with the magnetic field and direction of light propagation parallel (Faraday configuration) and these parallel to the growth direction of the sample, using nominally unpolarised radiation. Appropriate beam splitters were employed to optimise the signal for the various spectral features examined.

3. Results and discussion

Fig. 1 shows the spectra for the G-line in magnetic fields from 5 to 17.5 T ratioed with the unperturbed spectrum. Two distinct components are observed when the magnetic field is applied. The stronger component moves to 138.5 cm\(^{-1}\) and the weaker component to 135.7 cm\(^{-1}\), respectively, at 17.5 T.

Fig. 2 is a fan chart showing the energies of the two components of the G-line seen in Fig. 1 as a function of magnetic field. Data for the stronger component are given from 5 to 17.5 T, although the datum at 6.25 T is less reliable than the others. Data are shown for the weaker line at and above 13.75 T. Also shown in Fig. 2 are the straight lines obtained from the \(g\)-factors in Table 5 of Atzmüller et al. [2] (dot-dash line), the \(g\)-factors in Table 9 of Schmitt et al. [11] (dotted line), the quadratic fit to the data of Atzmüller et al. [2] from their Table 2 (dashed line), and the theoretical results from Fig. 4 of Schmitt et al. [11] (full line). (The experimental data of Atzmüller et al. [2] and the theory of Schmitt et al. [11] are given in Fig. 10 of Schmitt et al. [11] for \(B\) up to 7 T.)

From the upper part of Fig. 2, it may be seen that our data for the strongest transition correspond closely to the straight lines given by the two sets of \(g\)-factors for transitions between the \(M = -3/2\) ground state and the \(M = -1/2\) excited state, and also to the quadratic fit to the earlier
experimental data. On this basis, we identify the strong transition as being the component (8,5). Here we use the notation of Baker et al. [12], where the first number denotes the subscript \( n \) in the representation \( G_n \) of the ground state of \( \text{O}_h \) and likewise the second number refers to the excited state. The same transition is denoted \( \text{X} \) by Atzmüller et al. [2] and \( 5 \rightarrow 8 \) by Schmitt et al. [11].

The only possibility for the weaker line appears to be (5,6), that is, \( \text{W} \) in the notation of Atzmüller et al. [2] and \( 6 \rightarrow 5 \) in the notation of Schmitt et al. [11]. The agreement between our data and the curves shown in Fig. 2 is not as good for this line as for the transition (8,5). However, the following considerations should be borne in mind: (a) \( g \)-factors are strictly defined in the limit \( B \rightarrow 0 \). Schmitt et al. [11] point out that the Zeeman splitting calculated from \( g \)-factors is useful only to about \( \beta_0 / 5 \), which in the present case corresponds to \( \sim 7 \text{T} \). (b) The fits given by Atzmüller et al. [2] were made to the data in the range \( 0 \leq B \leq 7 \text{T} \). Extrapolating this data to 17.5 T may not be justified. (c) The results of the calculations of Schmitt et al. [11] are only given to 10 T, whereas our data extend to 17.5 T. (d) The size of the observed splitting is rather small, amounting, for the stronger line, to only \( \sim 4 \text{cm}^{-1} \) at the highest field.

The field-induced components of the D-line are shown in Fig. 3 (crosses). Also shown in this figure are our earlier data [10] to 6 T (circles). The earlier data were collected in the Voigt configuration, but are directly comparable to the data we have collected now in the Faraday configuration, as in both cases \( \mathbf{E} \perp \mathbf{B} \parallel [001] \). The four lines observed earlier correspond to the four lines reported by Atzmüller et al. [2] and labelled in that reference in descending order of energy as \( \text{e, d, b, and a} \). These are identified as the transitions (8,7), (6,5), (5,6) and (7,8), respectively. Also shown in Fig. 3 are curves deduced from the calculation of Schmitt et al. [11] to 10 T.

Concerning the transitions observed here at higher fields, there seems little ambiguity in the identification of the four of lowest energy as being, in order of increasing energy \( (7,8), (7,6), (5,8) \) and \( (5,6) \). The higher energy transitions have been identified as indicated in Fig. 3. It might be noted that the theoretical curves show (8,5) and (8,7) (and (6,5) and (6,7) approaching, and possibly crossing at the experimental fields we have accessed.
Having identified the various transitions, it is now possible to determine some splittings of the ground and excited states. The transitions observed for the G-line (Figs. 1 and 2), and also our earlier results for the D-line (circles in Fig. 3) have no initial or final states in common, so the data are of limited usefulness in this respect. For the D-line in high field, however, all expected transitions are observed. Taken in pairs these allow us to determine, each in two ways, the splitting between the $G_8/G_6$ states, and the $G_7/G_5$ states, for both ground and excited states manifolds. These are plotted in Fig. 4. These data should prove valuable in testing models of shallow impurity levels beyond the low field and into the intermediate-field magnetic range.

4. Conclusion

The scope of the present work may be compared with that of the most thorough study until now of shallow acceptors in GaAs, that of Atzmüller et al. [2]. In contrast to the earlier authors we have employed the Faraday geometry rather than the Voigt, and unpolarised light rather than polarised; but we have only one principal impurity species, avoiding, e.g. the confusion of the zinc D-line with the carbon C-line and, most importantly, we have extended the field range of data from 7 to 17.5 T. The data presented here to the intermediate field provide a more severe test of theoretical calculations than does data presented in the literature to date and so may lead to a more reliable set of Luttinger parameters for GaAs.

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Fig. 4. Energy splittings of components of the ground state and the excited state for the D-line in GaAs:Be.

References