High Field Zeeman Spectroscopy of Beryllium in Germanium

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The ground states of group II impurities in Ge are complex. For $Zn^{(0)}$ only the lowest is occupied at 4.2 K which is not the case for $Be^{(0)}$. The unperturbed spectrum of $Be^{(0)}$ is more complex than that of $Zn^{(0)}$, the G line being simplest. Reported here is a Zeeman study of the G line of $Be^{(0)}$ at fields up to 6 T.

1.   Introduction

Group II impurities in Ge bind two holes at low temperatures to give a solid state analogue of the He atom. The ground state of a H-like group III impurity in Ge reflects the complexity of the valence band. For a neutral double acceptor (NDA), this state is expected to be more complex due to interactions between its bound holes. Experiment shows that energy spacings and relative intensities of transitions of group II impurities are close to those of group III impurities [1,2]. The states of an NDA in which a single hole is excited is represented as a product of two single-hole states. For single acceptors, the ground state wave functions generate the irrep. $1\Gamma_8^+$ of $\overline{O}_h$ symmetry [1,2], and its excited states wavefunctions generate Γ_6^-, Γ_7^-, and Γ_8^- irreps. Here the notation of [3] are used. The symmetry of the ground state of an NDA is $\{1\Gamma_8^+ \times 1\Gamma_8^+\} = 1\Gamma_1^+ + 1\Gamma_3^+ + 1\Gamma_5^+$. For neutral zinc, $Zn^{(0)}$, it has been shown [4-6] that the $1\Gamma_1^+$ state is the lowest. Excitation of one hole to a p-like state gives excited states of symmetry $1\Gamma_8^+ \times n\Gamma_e^-$, where n = 1, 2, … and e = 6, 7, 8, *e.g.*, with e = 8, the excited states are $\Gamma_8^+ \times \Gamma_8^- = \Gamma_1^- + \Gamma_2^- + \Gamma_3^- + 2\Gamma_4^- + 2\Gamma_5^-$. The degeneracy of the ground state is lifted because of hole-hole interaction [7], however, for the excited states with one hole in a p-like orbital and the other still with an s-like orbital, these effects are insignificant. Zeeman studies have been made to determine the nature of $Be^{(0)}$ in Ge using the above model and are presented here.

2.   Unperturbed spectrum

The sample used to obtain the spectra of Be in Ge was cut from a disc of material ~28 mm in diameter and ~3 mm thick. The <113> growth axis of the boule was taken as [113] and the sample cut so that **B** could be applied along the [010] direction while retaining approximately the full thickness (t) of the slab. After mounting the sample on its holder and inserting this into the S.C. magnet, the holder was rotated about its vertical axis through ~17.5° to give **B**‖[010] since this direction is tilted out of the (113) plane by 17.55°.

The unperturbed spectrum of the G line of $Be^{(0)}$ in Ge is shown in Fig. 1 using an unapodized resolution of 0.15 cm^{-1} and an FTIR spectrometer; this is the same result as obtained elsewhere [8]; this line has been studied since it is well isolated from others in the spectrum. The sample contained some Al. The energies of the G lines were determined by fitting seven Lorentzians to the combined set. For t = 3.1 mm, the transmission was too low to show any of the structure reported by others [9] for the D, C, B and A lines.

It has been established [9] that, unlike $Zn^{(0)}$ and $Mg^{(0)}$, for $Be^{(0)}$ the ground state multiplet, $1\Gamma_1^+ + 1\Gamma_3^+ + 1\Gamma_5^+$, is closely spaced, with all three states contributing to the Lyman spectrum even at liquid He temperatures, although the $1\Gamma_1^+$ state is still the deepest. The energies of these states relative to the latter are 0.055 and 0.15 meV, *i.e.*, 0.44 and 1.21 cm^{-1}. However, even with three 'ground states', this cannot account for five or more G lines. It is known that the D line possesses at least six components and thus its excited state, of

symmetry $\Gamma_1^- + \Gamma_2^- + \Gamma_3^- + 2\left(\Gamma_4^- + \Gamma_5^-\right)$, must also be split [9]. The excited state of the G line is of the same symmetry; the lower lying the state the larger is its splitting [9], thus the lowest
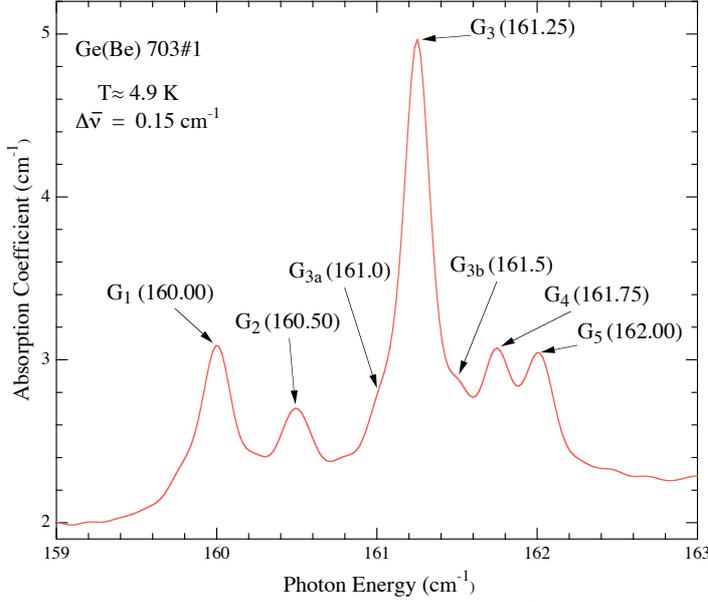

Fig. 1. Spectrum of the G line of Be$^{(0)}$ in Ge.

lying excited state, that of the G line, should have the largest splitting. For Zn$^{(0)}$ in Ge, with Γ_1^+ as ground state, the observation of two G lines is deduced to be due to the splitting of the two Γ_4^- states; the value of this splitting is 0.24 cm^{-1} [5]. This is based on the electric dipole selection rules for double acceptors; in O$_h$ notation these are as follows: $\Gamma_1^+ \Rightarrow \Gamma_4^-$, $\quad \Gamma_3^+ \Rightarrow \Gamma_4^-, \Gamma_5^-$, $\Gamma_5^+ \Rightarrow \Gamma_2^-, \Gamma_3^-, \Gamma_4^-, \Gamma_5^-$, permitting a total of 12 transitions. Since the binding energy of Be$^{(0)}$ is less than that of Zn$^{(0)}$, the splitting of the two Γ_4^- states of the G line of Be$^{(0)}$ should be larger than 0.24 cm^{-1}.

2. Zeeman Spectra of the G line of Be$^{(0)}$: B‖[010]

Zeeman studies were made in the Voigt configuration with radiation polarized either parallel ($E_{\parallel}$) or perpendicular ($E_{\perp}$) to B. With radiation incidence on the sample at ~17°, E inside the sample for $E_{\parallel}$ is no longer parallel to B. From the refractive index of Ge $E_{\parallel}$ is at 13.14^o to B. Thus, there is a component of $E_{\perp}$ present for the "$E_{\parallel}$" polarization; this is estimated to be ~5.2% of the total intensity for $E_{\parallel}$. The problem does not arise for $E_{\perp}$.

Figure 2. shows the Zeeman spectrum of the G line of Be$^{(0)}$ for B‖<100>, B = |B| = 4 T,; here t = 3.1 mm. Fig. 3 gives the dependence of the energies of the Zeeman components of this line on B; Subsequently, the sample was thinned, successively, to 1.8 mm, 1.18 mm, 0.50 mm and 0.31 mm. The data obtained for all thicknesses are included in Fig. 3. Note that the energies of the Zeeman D components of Al for $E_{\parallel}$ with B‖<100> agree to within 0.01 cm^{-1} of the known values at 6 T [10], thus confirming the orientation of B.

The complex Zeeman spectra consist of sharp components. It has not been possible to
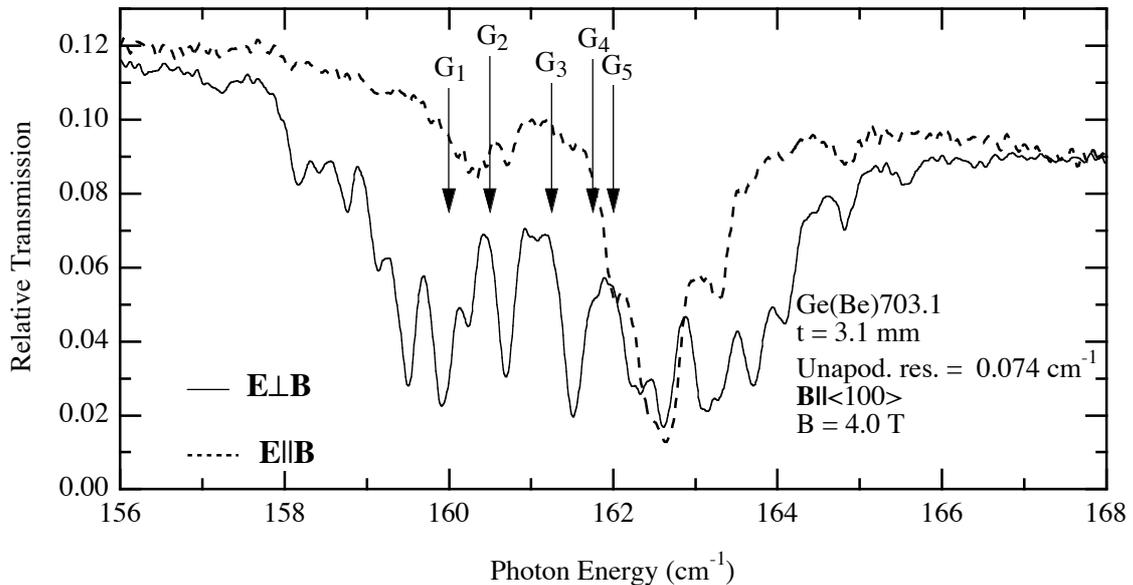

Fig. 2. Zeeman spectrum of the G line of Be in Ge at 4 T.

determine which of the five main G lines gives rise to which components. Part of this problem is presumably due to the degree of mixing between adjacent ground state Zeeman levels of the same symmetry as well as within the excited Zeeman states of the G lines. Under this direction of **B**, the site symmetry is C_{4h} and the three ground states reduce as follows: $\Gamma_1^+ \rightarrow \Gamma_1^+$; $\Gamma_3^+ \rightarrow \Gamma_1^+, \Gamma_2^+$ and $\Gamma_5^+ \rightarrow \Gamma_2^+, \Gamma_3^+, \Gamma_4^+$, while, for example, $\Gamma_4^- \rightarrow \Gamma_1^- + \Gamma_3^- + \Gamma_4^-$ and $\Gamma_5^- \rightarrow \Gamma_2^- + \Gamma_3^- + \Gamma_4^-$. Thus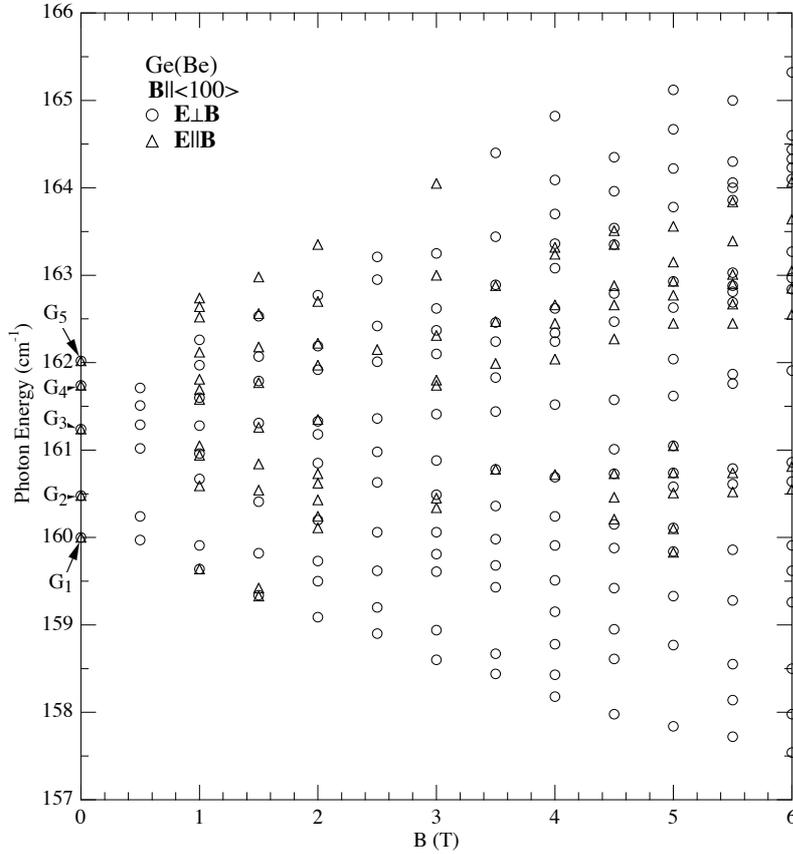, a significant amount of mixing between Zeeman states could take place at small fields which would make it difficult to follow the intensities of the Zeeman components as a guide to identifying their parent lines. It has been thought that a comparison of the Zeeman spectra of $Zn^{(0)}$ with those of $Be^{(0)}$ might have provided a way to separate out the transitions from the Γ_1^+ ground state from those of the other two ground states but this also seems to be thwarted by the mixing between Zeeman states of the same symmetry. Further Zeeman studies at different, lower temperatures, could help to identify the ground states involved in the Zeeman transitions; this has yet to be done.

Fig. 3. Dependence of the Zeeman components of the G-line of Be in Ge on B

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