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Far-infrared Laser Magnetospectroscopy of Donors and Acceptors in Ge

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Far-infrared Laser Magnetospectroscopy of Donors and Acceptors in Ge

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The energy levels of the donor impurity phosphorous and the acceptor impurity gallium in the elemental semiconductor host germanium have been investigated by measuring the absorption of radiation from a far-infrared laser as magnetic field intensity is varied.

1. Introduction

The energies of many phenomena of fundamental interest in semiconductor physics, for example electron kinetic energies, Fermi energies, cyclotron energies, phonon energies, and, the particular focus of this paper, the energies of impurity states, often fall in the far-infrared (FIR) or terahertz (THz) region of the electromagnetic spectrum. The study of these fundamental phenomena has been enhanced in recent decades by the development of new sources and techniques for THz spectroscopy such as the p-Ge laser, the free-electron laser (FEL), the generation of THz pulses ("T-rays") in non-linear optical media by ultra-short optical pulses and, relevant to this paper, the optically-pumped far-infrared laser (FIRL). Conventional FIR magnetospectroscopy of impurities in semiconductors involves holding the magnetic field constant while changing the photon frequency (using a spectrometer). In contrast, we hold the photon frequency constant (using a FIRL) while sweeping the magnetic field. Up until now this technique appears to have been restricted to III-V materials and usually associated with photoconductivity detection; in contrast, we here apply it to a group IV elemental semiconductor and detect impurity transitions by absorption spectroscopy. One advantage of laser spectroscopy is the availability of much higher powers, for which effects have been predicted theoretically [1] and for which initial results are available experimentally using a FEL [2]. Another advantage is the possibility of selective excitation of luminescence. In this paper we report magnetospectroscopy of both the acceptor impurity Ga and the donor impurity P in Ge under FIRL irradiation.

2. Zeeman Effect for Substitutional Impurities P and Ga in Ge

2.1 Theory

2.1.1 Phosphorous donor

Within the effective-mass approximation donor energy levels are atomic-like in the absence of magnetic field **B** and Landau-level–like in strong fields. To the extent that the conduction band is isotropic and parabolic the hydrogenic energy levels can simply be scaled by the electron effective mass and host dielectric constant; this approximation proves useful for such materials as GaAs, InSb and InP. The situation is complicated in Ge by the conduction band comprising four valleys. The Zeeman splitting now depends strongly on the angle that **B** makes with the crystal axes [3]. Moreover, for different impurities, in addition to the central-cell correction (which offsets the lowest energy level) a small species dependence on the field-induced levels has been found by calculation [4]. The effect of the magnetic field has been calculated for As and Sb donor impurities in Ge for $\mathbf{E}\perp\mathbf{B}\|[111]$ [4]; to our knowledge no calculations exist for P impurity for any orientation of **B** relative to the electric field vector **E** of the radiation and to the Ge crystal.

2.1.2 Gallium acceptor

A detailed theory of the magnetic-field dependence of shallow acceptor states in cubic semiconductors has been developed by Schmitt *et al.* [5] and extensive data given for generic acceptors in Ge and GaAs. Transitions deduced from this data [6] are shown in Fig. 1 (a).

2.2 Experiment

2.2.1 Phosphorous donor

The effect of the magnetic field has been measured for As and Sb donor impurities in Ge for **E**⊥**B**||[111] [7]. To our knowledge the Zeeman effect for P in Ge has not been measured systematically but only incidentally. For example, Navarro *et al.* [8] discuss the P impurity for **B**||[111] as part of a photothermal-ionisation study concentrating on the D(H,O) donor complex in Ge. Likewise, Warner *et al.* [9] have obtained data on Ge(P) in a spectrometer study whose main concern was Ge(Ga). Positions of transitions ascribed to P impurity extracted from such spectra [10] are given in Fig. 1(b).

2.2.2 Gallium acceptor

The lower-energy transitions of the Ga acceptor, namely the D and G lines, have been studied in detail by Warner *et al.* [9]. Transitions in the higher energy range extracted from this data are also given in Fig. 1(b).

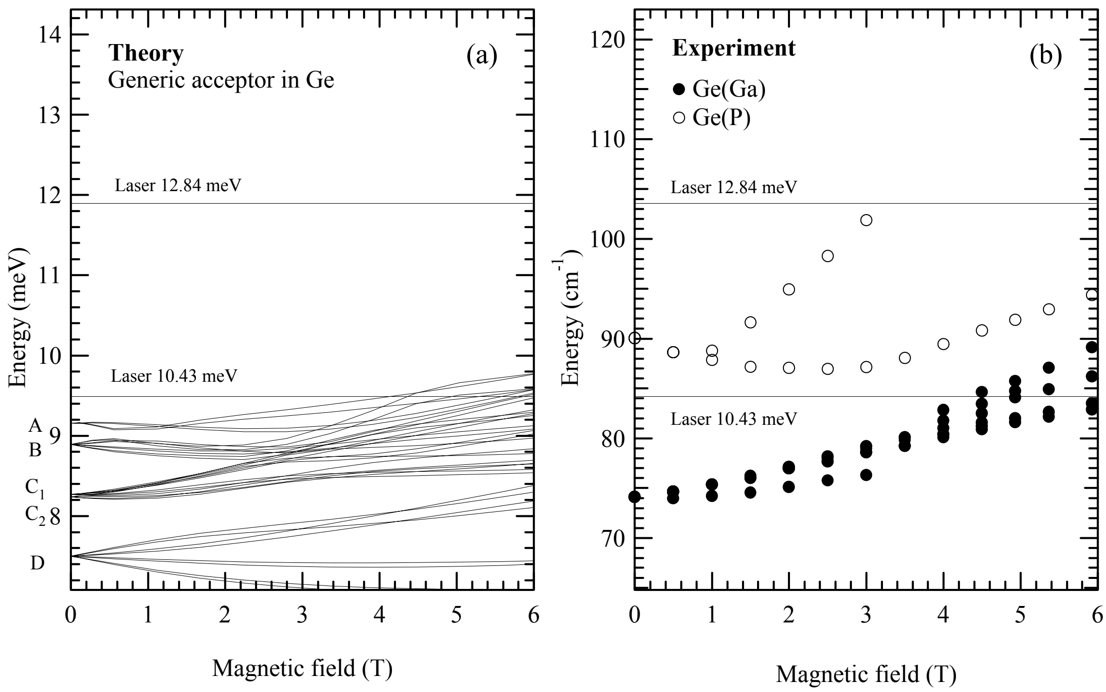

Fig. 1. Transitions of impurities in Ge for **E**⊥**B**||[001] from (a) theory [5] (generic acceptor) and (b) experiment [10] (Ga acceptor and P donor). The horizontal lines are laser energies used to obtain the spectra in Fig. 2; in (a) these are adjusted by the central-cell correction.

3. Experiment

3.1 Experimental details

An Edinburgh Instruments FIRL 100 optically-pumped molecular-gas laser was coupled in the Faraday geometry via light-pipe to the sample in the field centre of a 7 T split-coil Oxford Instruments superconducting magnet. The detector was a cooled (4 K) Si bolometer.

3.2 Experimental results

The experimental absorption data are given in Fig. 2 for two laser excitation energies.

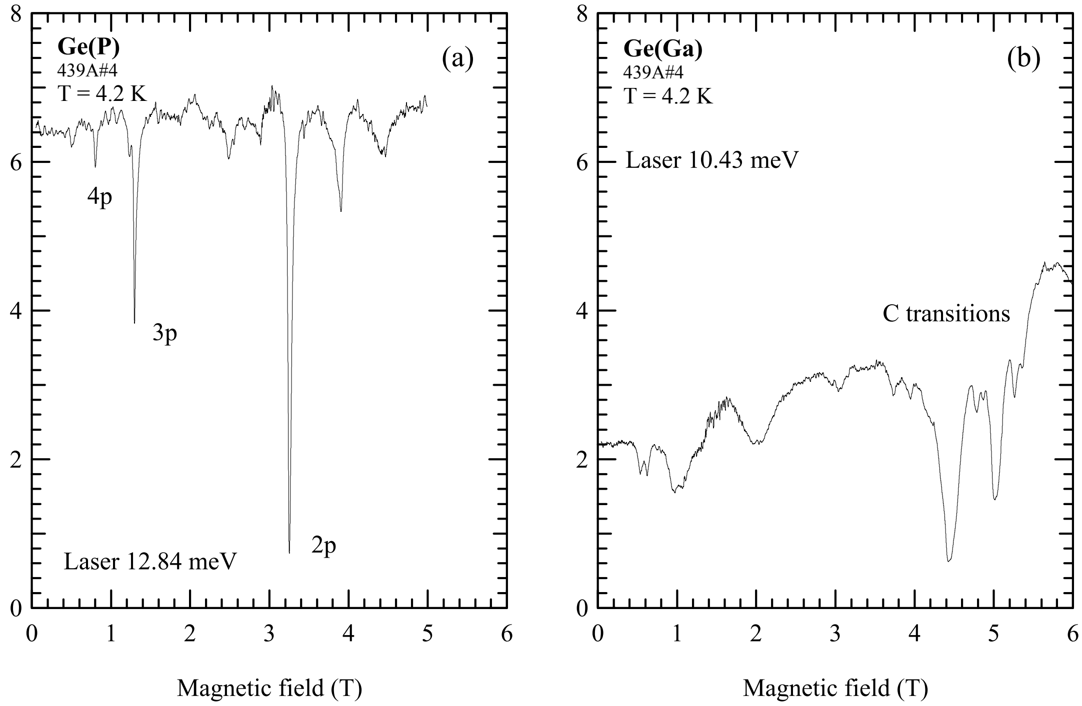

Fig. 2. Transitions of impurities in Ge for **E**⊥**B**||[001] determined by FIRL absorption. (a) Laser energy 12.84 meV, detecting Ge(P) transitions. (b) Laser energy 10.43 meV, detecting Ge(Ga) transitions. Vertical axis is absorption (au).

3.3 Discussion and conclusion

The principal lines arising for Ge(P) appear to be the high-energy components of the split $2p_{\pm}$, $3p_{\pm}$, $4p_{\pm}$ series. The low-energy components would be inaccessible to this experiment. Interestingly, there are other clear lines (e.g. at 4 T) that do not have this origin; these will be further investigated. Likewise the strongest lines for Ge(Ga) can be readily identified (~4-5 T) as arising from the C manifold. Other clear lines, 1-2 T cannot be associated with either A, B or C transitions (cf. Fig. 1). These warrant further investigation.

Acknowledgments

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References

[1] C. Zhang and W. Xu, *Physica B* **298**, 333 (2001).
[2] R.A. Lewis, I.V. Bradley and M. Henini, *Solid State Commun*. **122**, 223 (2002).
[3] R.R. Haering, *Can. J. Phys*. **36**, 1161 (1958).
[4] Y. Nisida and K. Horii, *J. Phys. Soc. Jpn.* **31**, 776 (1971).
[5] W.O.G. Schmitt, E. Bangert and G. Landwehr, *J. Phys.: Condens. Matter* **3**, 6789 (1991).
[6] P. Fisher, *priv. comm.* (2003).
[7] K. Horii and Y. Nishida, *J. Phys. Soc. Jpn.* **31**, 783 (1971).
[8] H. Navarro, J. Griffin and E.E. Haller, *J. Phys. C: Solid State Phys.* **21**, 1511 (1988).
[9] A.D. Warner *et al.*, Materials Science Forum **117&118**, 129 (1993).