RESONANCE AND RELAXATION ATTENUATION BY NEUTRAL ACCEPTORS IN A MAGNETIC FIELD

HP. SCHAD, K. LAßMANN* and H. ZEILE*

Now at Institut für Angewandte Festkörperphysik, Freiburg, F.R.G., and
**Physikalisches Institut der Universität Stuttgart, Stuttgart, F.R.G.*

Abstract Fine structure, level splitting, and relaxation times of the acceptor ground state in cubic semiconductors can be deduced from ultrasonic attenuation. By the application of a magnetic field it is possible to vary the coupling strength and the number of acceptors on speaking terms with the ultrasonic wave. Making use of this possibility, we have determined directly effective coupling constants for relaxation attenuation and the temperature dependence of the critical intensity for saturation of the resonant interaction. Results obtained for p-type GaAs and Si are discussed in comparison with analogous results for glasses.

Introduction

The ground state of a hole bound to an acceptor in a cubic semiconductor is a fourfold degenerate Γ_8 state. This degeneracy is partly lifted into two twofold degenerate Kramers levels by the random internal elastic and electric fields due to strains and ions in the crystal. Thus, a p-type semiconductor (moderately doped) at low temperatures may be considered as a two level system with a distribution of splittings quite analogous to that of the presumed tunneling states in glasses, and the same problems arise as to the form and the width of this distribution, the average phonon couplings to the defects, as well as the possibility of an interaction between them (1,2). However, with the acceptor system one has more experimental parameters at hand to investigate these problems. We would like to give here some results that have been obtained taking advantage of the application of an external magnetic field: It lifts the degeneracy of the Γ_8 state totally, thus spreading the distribution and changing the effective deformation potential constant.

Experimental

We shall discuss our results for the two types of interaction that are effective for the ultrasonic attenuation at low temperatures separately.

1. The resonance attenuation is given by

$$\alpha_{res} \propto N(\delta) \cdot D^2_{res} \cdot (\nu^2/T) \qquad /1/$$

where $N(\delta)$ is the spectral density of those splittings of the distribution that are in resonance ($\delta = h\nu$) with the ultrasonic wave of frequency ν and D_{res} is an effective deformation potential constant. We have shown for Ge(In),

Ge(Ga) (1) and GaAs(Mn) (3) that $N(\delta)\cdot D_{res}^2 \sim$ const. up to $\delta' \sim 8\ \mu eV$, since at low temperatures, the attenuation rises as ν^2/T up to $\nu' \sim 2$ GHz. If we knew the nature and symmetry of the random internal fields we could determine D_{res} from the two well-known deformation potential constants D_u^a and D_u^a'. At least, a lower limit can be obtained from these experiments, since $2N(\delta)\cdot\delta' \leq N$ (N is the known total acceptor concentration). We can confirm the interpretation that the measured 1/T rise in attenuation is due to the resonance interaction by measuring the reduction of the attenuation at high intensities I (2):

$$\alpha = \alpha_{res} / \sqrt{1+I/I_c} \qquad /2/$$

$$I_c \propto 1/(D_{res}^2 \cdot \tau_1 \cdot \tau_2) \qquad /3/$$

(I_c is the critical intensity, τ_1 the longitudinal and τ_2 the transverse relaxation time in a Bloch-equation formalism. (2))

This could be verified for the case of Ge (1) and also for Si(In) (4). In GaAs(Mn) (3) we could not see any saturation effects, because the attenuation, due to the higher doping, was so high that even within the first echos the critical intensity could not be reached. This difficulty could be overcome by the application of a magnetic field: It reduces the attenuation drastically, mainly because the number of splittings δ on speaking terms is reduced due to the spreading of the levels in the magnetic field (Fig. 1). Disregarding the change in the coupling, Fig. 1 gives an indication of the form and the width of $N(\delta)$. The value we obtain is in accordance with our analysis of $\alpha(\nu)$ (3). The intensity dependence was obtained in determining the change of α within the echo train (Fig. 2). It turns out that I_c is proportional to T^2 for the two temperatures at 650 MHz. The same is true at 1 GHz in a wider temperature range (Fig. 3). This latter curve was obtained by a somewhat different procedure and gives only the relative change of I_c. From the absolute values of I_c (Fig. 2) the quan-

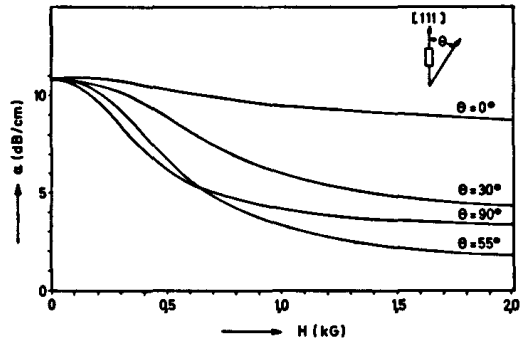

Fig. 1 Resonance attenuation in GaAs(Mn) at 800 MHz, 1.3 K as a function of the magnetic field.

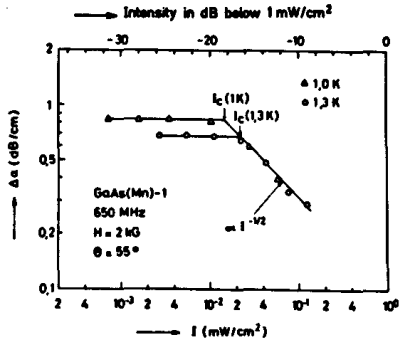

Fig. 2 Intensity dependence of the ultrasonic attenuation.

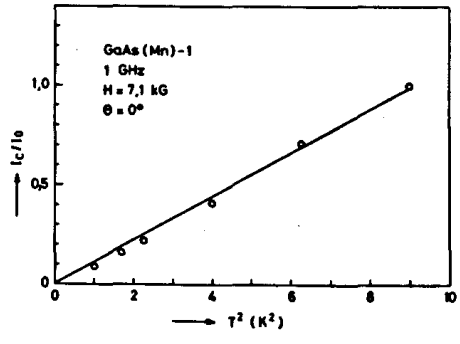

Fig. 3 Temperature dependence of the critical intensity I_c.

tity $\tau_1 \cdot \tau_2$ can be estimated. (Eq. /3/) The value we obtain is smaller by two orders of magnitude than would be expected if only direct relaxation processes are effective. Analogous results have been found in the case of p-Ge (1) of Si(In) (4) and for glasses (2). Since $I_c \propto 1/(\tau_1 \cdot \tau_2)$ we have $\tau_1 \cdot \tau_2 \propto T^{-2}$. If τ_1 is determined by direct relaxation processes then $\tau_1^{-1} \propto T$, that is $\tau_2^{-1} \propto T$. The same has also been found in the case of glasses. From measurements in Si(B), where we could compare I_c in zero field and at moderate field under similar conditions as above, we find that I_c is not changed very much in the magnetic field. By measuring the concentration dependence of I_c we hope to get information on the importance of a proposed (7) interaction mechanism for the small value of $\tau_1 \cdot \tau_2$.

2. The second type of ultrasonic interaction is relaxation attenuation. in the case of GaAs(Mn) and Si(In) it can approximately be written as (3,4):

$$\alpha_{rel}(\nu,T) = \int \alpha_{rel}(\delta,\nu,T)\,d\delta \propto \frac{N \cdot D^2_{rel}}{T} \cdot \frac{(2\pi\nu)^2 \tau}{1+(2\pi\nu)^2 \tau^2} \qquad /4/$$

since τ is independent of δ and $N(\delta)$ is negligibly small for $\delta > kT$ at $T \sim 7$ K. It follows from /4/ that the variation of α_{rel} in a magnetic field B is completely determined by the dependence of D_{rel} on B, if τ is independent of B. The latter is the case for GaAs(Mn) and Si(In), since the relaxation peak is not shifted by B. At high enough fields α_{rel} should be constant. Our results for GaAs(Mn) are shown in Figs. 4,5,6,7 (similar results have been obtained for Si(In) (5)). They are in excellent agreement with an approximate calculation by Yafet (6). We see that the attenuation for certain directions of B may even be larger than the zero field attenuation, which is not the case for resonance attenuation. From these measurements of the angular dependence of α_{rel} in moderately large magnetic fields the following information can be obtained: (i) The absolute value of α_{rel} in the peak maximum (approximate condition $2\pi\nu = 1$) determines N, the total number of acceptors interacting with the ultrasonic wave, which may be compared to N, as derived from electrical conductivity. (ii) From Figs. 6,7 the ratio $D = D_u^a/D_u^a$, of the two deformation potential constants can be determined absolutely, and (iii) comparison with the zero field attenuation gives the so-called reduction factors for the average deformation potential constant D_{rel} (B = 0). We obtain: (i) For GaAs(Mn) the ultrasonically determined N is by 14 % larger than the N from electrical conductivity. (ii) The D values obtained ultrasonically are in excellent agree-

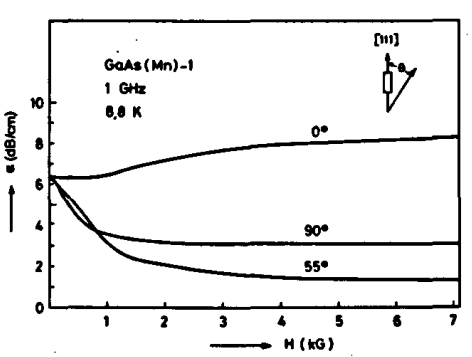

Fig. 4 Relaxation attenuation in a magnetic field for longitudinal phonons in [111].

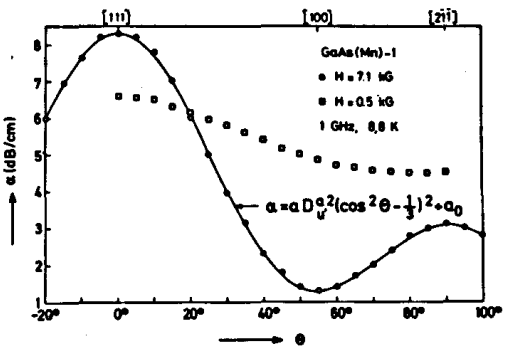

Fig. 5 Angular variation of the relaxation attenuation with magnetic field for long. phonons in [111].

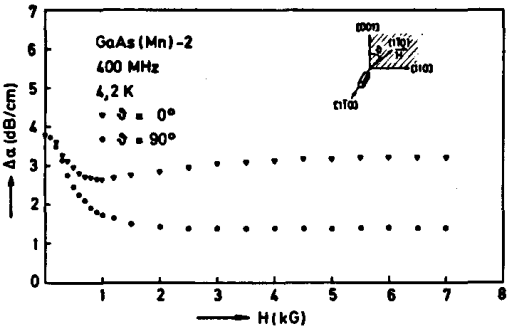

Fig. 6 Relaxation attenuation in a magnetic field for longitudinal phonons in [110].

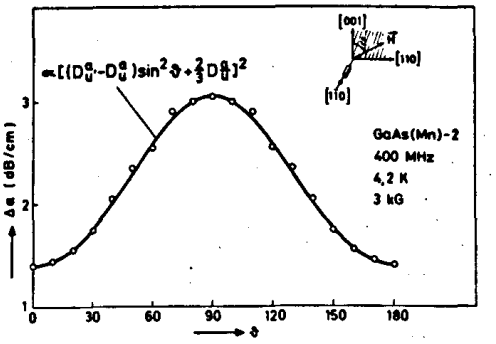

Fig. 7 Angular variation of the relaxation attenuation with magnetic field for longitudinal phonons in [110].

ment with those determined from static pressure experiments for both Si(In) and GaAs(Mn), and (iii) the reduction factors ß, defined by (5)

$D^2_{rel} = ß^{[111]} (\frac{2}{3} D^a_{u'})^2$ for a longitudinal wave in [111] direction

$D^2_{rel} = ß^{[110]} (\frac{1}{3} D^a_{u'})^2$ for a longitudinal wave in [110] direction

are $ß^{[111]} = 0.4$ (GaAs(Mn)) and $ß^{[111]} = 0.3$ (Si(In))

and $ß^{[110]} = 0.7$ (GaAs(Mn)) and $ß^{[110]} = 1.0$ (Si(In))

It is hoped that from the determination of ß for various ultrasonic modes some information on the symmetry of the random internal fields can be obtained.

This work has been supported by the Deutsche Forschungsgemeinschaft (SFB 67, Stuttgart).

References

(1) E. Ortlieb, Hp. Schad, K. Laßmann: Sol. St. Comm. 19, 599 (1976)
(2) S. Hunklinger, W. Arnold in: W.P. Mason and R.N. Thurston, Physical Acoustics, Vol. XII
(3) K. Laßmann and Hp. Schad: Sol. St. Comm. 18, 449 (1976)
(4) Hp. Schad and K. Laßmann: Physics Letters 56 A, 409 (1976)
(5) Hp. Schad: Thesis, Universität Stuttgart 1976
(6) Y. Yafet: J. Phys. Chem. Sol. 26, 647 (1965)
(7) J. Joffrin, A. Levelut: Journ. de Physique 36, 811 (1975).