

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN, Vol. 29, No. 3, SEPTEMBER, 1970

Cyclotron Resonance in the Valence Band of Germanium under Uniaxial Stress

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(Received March 25, 1970)

The inverse mass parameters, deformation potential constants and g -factor of the valence band of germanium are determined through a cyclotron resonance study. By means of 35 and 70 GHz microwave spectrometers, several quantum lines are observed with good resolution between 1.5 and 4.2°K under the application of uniaxial compression along particular crystal axes. Analyses of these quantum lines yield: $A = -13.50 \pm 0.05$, $B = -8.80 \pm 0.09$ and $N = -35.20 \pm 0.23$ in the unit of $(\hbar^2/2m_0)$; the shear deformation potential constants $D_u = 3.14 \pm 0.20$, $D_u' = 4.00 \pm 0.20$ and the dilatational one $D_d^V = -5.2_{-1.0}^{+0.5}$ or $+3.3_{-1.0}^{+0.5}$ in the unit of (eV); while the g -value is found to be 7.8.

§ 1. Introduction

Cyclotron resonance is one of the most straightforward and precise techniques to determine the band parameters of solids. Supported by theoretical considerations, Lax, Zeiger and Dexter¹⁾ and Dresselhaus, Kip and Kittel²⁾ played the pioneer roles in cyclotron resonance for unveiling the band structures of germanium and silicon.

The valence band is more complex than the conduction band. Its band edge is located at $k=0$, or the Γ'_{25} point, in the Brillouin zone. This band has degeneracy due to the cubic symmetry and consequently the warped equipotential energy surfaces. The values of inverse mass parameters A , B and N can be obtained through measuring

the cyclotron resonance peaks of the so-called light and heavy holes. Their precise determination, however, has been difficult, since the resonance line, especially that of heavy hole, is broadened on account of the so-called quantum effects. The Landau levels of the degenerate band are not of equal spacing, depending on the quantum number n and the wave number k_H along the applied magnetic field. In the absence of uniaxial stress, which lifts the Γ'_{25} point degeneracy, the quantum effects have been theoretically investigated by Luttinger and Kohn,³⁾ Luttinger,⁴⁾ Wallis and Bowlden,⁵⁾ while are experimentally observed first in cyclotron resonance of germanium by Fletcher *et al.*,⁶⁾ at 1.3°K. Goodman⁷⁾ compared their experimental results with Luttinger's theory.⁴⁾ Later Hensel⁸⁾ made

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more detailed experiments and Okazaki⁹⁾ successfully explained Hensel's new lines through a theoretical calculation which is more precise than Goodman's one.

The quantum-mechanical treatment of cyclotron resonance in the presence of band degeneracy is difficult and tedious, particularly so in the linewidth problem. Hensel and Feher¹⁰⁾ avoided the difficulty by applying uniaxial stress on silicon, followed by Hasegawa's theoretical interpretation.¹¹⁾ Application of uniaxial stress removes the cubic symmetry from the crystal and thus lifts the Γ'_{25} point degeneracy. In zero magnetic field, the decoupled states are degenerate Kramers doublets designated by quantum numbers $\pm M_j$. The decoupled bands have nearly ellipsoidal surfaces which, like the conduction band, give cyclotron resonance masses amenable to a straight interpretation. On compression, $M_j = \pm \frac{3}{2}$ bands go down both for silicon and for germanium on account of the plus signs of the deformation potential constants. The band parameters A , B and N of silicon have been determined by Hensel and Feher more accurately than in earlier works. They used a 9 GHz microwave spectrometer, in which $\omega_c\tau$ is not large enough to resolve quantum lines even at 1.2°K. They obtained the deformation potential constants D_u and D_u' , analyzing the linewidth and position of the so-called split hole resonance which consist of different quantum transitions. In 1966 Hensel¹²⁾ and Otsuka, Murase and Fujiyasu¹³⁾ took the same procedure for germanium and observed several quantum lines at 50 GHz and 35 GHz, respectively. For germanium, analysis is simpler than for silicon because of a large spin-orbit coupling. Values of A , B and N as well as those of D_u and D_u' have thus been obtained. Recently Hensel¹⁴⁾ observed combined resonance and determined the valence band g -factor precisely.

The uniaxial stress apparatus used in our earlier work was a kind of the so-called perpendicular squeezer with which the degree of freedom of the geometry is limited and hence not much analysis could be carried out. Success in making a parallel squeezer has enabled us to get more precise values of the above mentioned parameters. The linewidth of the primary quantum line ($n=0 \rightarrow 1$, $M_j = -\frac{1}{2}$) is measured as a function of temperature and the dilatational deformation potential constant D_v' undetermined so far has been obtained with the help of theoretical works developed by Bardeen-Shockley¹⁵⁾ and Herring-Vogt,¹⁶⁾ as well

as the experimental works by Bagguley *et al.*¹⁷⁾ and by Ito *et al.*¹⁸⁾ In order to make a quantum-mechanical calculation of the conductivity, modification¹⁹⁾ of Ito's formula has been made, with the k_H -broadening¹¹⁾ being taken into account.

§ 2. Experimental

For the experimental study of solid which is uniaxially compressed, it is required to have a precise stress apparatus and samples having the shape of strictly rectangular parallelepiped. Wafers with [110] surfaces are cut from a single crystal ingot to a thickness of about 1.0 mm by a conventional slicing machine furnished with a diamond blade. The sliced wafer is fixed on a flat glass plate with shellac and the glass plate is further mounted on an unglazed ceramic base with sealing wax. The pasted wafer is cut through the glass base by the diamond blade with extreme care. In this way a rectangular rod is obtained whose size is $11.0 \times 1.0 \times 1.0$ mm³. It is then pasted with fine sealing wax on the surface of a polishing matrix. The latter is made of massive brass block at the precision of 1/1000 so that polished surfaces are necessarily made parallel to each other. Finally this rod is polished with diamond paste on silk cloth and etched with CP4 solution for a few minutes.

It has been difficult to apply uniaxial compression in a homogeneous and reversible way, since the space restriction is very acute in such a low temperature measurement under a magnetic field. Especially the parallel squeezer, in which the direction of the compressive force is parallel to the horizontal plane within which the magnetic field is rotated, is more difficult to produce than the perpendicular squeezer, in which the relevant directions are perpendicular to each other. In Figs. 1 and 2 the parallel squeezer system is shown. Its residual friction is very small. Stress as high as 2×10^8 kg/cm² is obtained through a lever arm having a mechanical advantage of 2.79 and making the cross section of the sample as small as 5×10^{-3} cm². The essential part of the squeezer consists of brass piston and small non-magnetic stainless-steel balls which are used to change the direction of force by 90°. In the course of changing stress, the [110] plane of the sample is always kept strictly within the plane of the magnetic field rotation.

In order to study hole scattering by lattice vibrations, it is required to have extremely pure samples, for neutral impurities have strong effects on