Table I. Effect of pressure on band intensity ratio.

Temp °C	R for 40 000 psi
19	0.96
9.5	0.98
0	1.04
0	1.07
0	1.05

under observation. Since a straightforward extension of the Williams and Johnson configuration coordinate curves for the first excited state of KCl(Tl) coupled with their assumption of thermodynamic equilibrium requires very large changes in the emission ratio, these results do not lend support to their model. It appears that alternatives of the sort considered by Patterson and Klick and by Knox may be better able to describe the actual situation. These latter suggestions can be arranged to predict small changes in intensity ratio due to pressure.

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g FACTOR OF ELECTRONS IN GERMANIUM*

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The failure, until recently, to detect spin resonance of electrons in germanium can be attributed to the anomalous character of the g factor. Two sets of experiments, one on the Zeeman effect of the indirect exciton[1] and a second on spin resonance of shallow donors in germanium,[2] have shed some light on this matter. In order to account for the g factor in the Zeeman experiments, Roth[3] has extended the perturbation calculation developed for spherical bands[4] and has applied these to the conduction band. The results of these calculations when only the nearest bands are considered and small terms due to more distant bands are neglected, show that the g factor of the electrons on a single ellipsoidal energy surface is anisotropic and is given by

$$g_{\parallel} - 2 \approx (-\delta/\Delta\mathcal{E}_{13}')[m/m_t - 1], \quad (1)$$

$$g_{\perp} - 2 \approx (-\delta/\Delta\mathcal{E}_{13}')[m/m_l - 1] + \Delta g_{\perp}', \quad (2)$$

where δ is the spin-orbit splitting of the L_3' valence band at the [111] edge of the Brillouin zone. We can estimate δ by using the wave functions at the center of the zone, giving $\delta \approx (2/3)\Delta$ where $\Delta = 0.3$ ev is the splitting of the valence band at $k = 0$. Hence $\delta \approx 0.2$ ev. $\Delta\mathcal{E}_{13}'$ is the energy separation of the L_3' and the L_1 band edges, the latter being the conduction band. The value of $\Delta\mathcal{E}_{13}'$ can be estimated from the experiments of Philipp and Taft[5] who find a strong absorption at ~2 ev which we believe corresponds to a vertical or direct transition of electrons from the L_3' band to the L_1 band.[6] The effective masses $m_t = 0.082m_0$ and $m_l = 1.68$ are those obtained from cyclotron resonance[7] and $g_{\parallel}$ and $g_{\perp}$ are the components of the g factor along and transverse to the principal axis of the ellipsoid, respectively. $\Delta g_{\perp}'$ is a small correction contributed by a term involving the L_3 band which is 5 ev above the L_1 band.[8] The sign of this term is uncertain

but the magnitude can be estimated. If we use the numbers above we find that

$$g_{\parallel} \approx 0.9, \qquad g_{\perp} \approx 2.04 \pm 0.04, \tag{3}$$

where the plus or minus sign reflects the ambiguity of sign of $\Delta g_{\perp}'$. For a free electron which is moving in a single ellipsoidal surface, the effective g value is given by

$$g^2 = g_{\parallel}^2 \cos^2\phi + g_{\perp}^2 \sin^2\phi, \tag{4}$$

where ϕ is the angle which the magnetic field makes with the principal axis. If all the ellipsoids are taken into account then the g factor for the electrons would show an anisotropic character in the (110) plane as shown in Fig. 1.

This anisotropy should show up in the Zeeman experiments of the excitons. However, the present experiments[1] have as yet not explored this although the spin value of $1.6 \pm 15\%$ obtained from them in the [100] direction is consistent with the theoretical results. For the spin resonance experiments of Feher, Wilson, and Gere,[2] the results for bound donors of arsenic and phosphorus indicate that the electrons are in the singlet state in which the electron wave function is a symmetric linear combination of the four minima. The g factor in this case becomes isotropic and is given by

$$g = \tfrac{1}{3} g_{\parallel} + \tfrac{2}{3} g_{\perp}. \tag{5}$$

The g value obtained by the spin resonance for these two impurities is $g = 1.57$. Since $g_{\perp}$ is close to 2, using Eq. (5) we deduce that $g_{\parallel} = 0.63 \pm 0.08$. This is smaller than the value predicted from room-temperature data for the bands. Using Eq. (1) we find that $\Delta \mathcal{E}_{13}' \approx 1.6$ ev, which is somewhat smaller than the value obtained from the data of Philipp and Taft. The possibility exists that the bands L_1 and L_3' move closer to one another as the temperature is lowered, although this is in contrast to the change of the indirect gap with temperature. The alternative is that the estimate of δ may be too small.

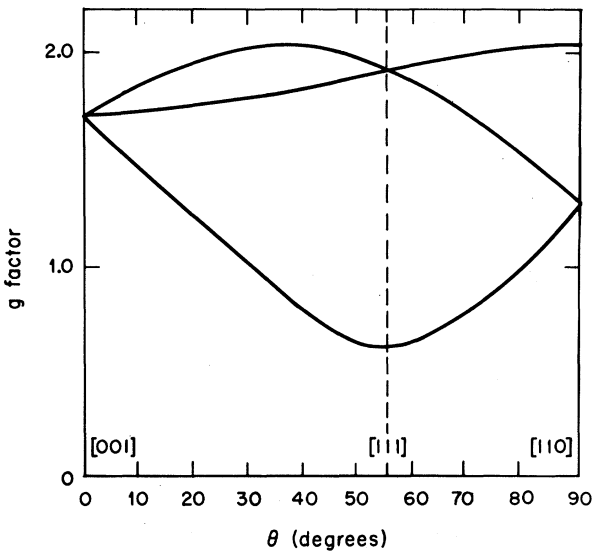

FIG. 1. Anisotropy of the g factor of free electrons in germanium with $\vec{H}$ in the $(1\bar{1}0)$ plane.

In antimony-doped germanium the g factor shows an anisotropy which varies from 1.6 with $H \parallel [100]$ to 1.9 with $H \parallel [110]$ direction.[2] Since this is a shallower impurity than arsenic or phosphorus, the degeneracy of the singlet and the triplet states is probably not split as much. The experimental[9] values of the binding energy are 14.0×10^{-3} ev, 12.8×10^{-3} ev, and 9.8×10^{-3} ev for As, P, and Sb, respectively, as compared to the theoretical value[10] of 9.2×10^{-3} ev. The estimated separations between the singlet and triplet are thus 5.8×10^{-3} ev, 3.6×10^{-3} ev, and 0.6×10^{-3} ev. Consequently the anisotropy may be due to the presence of the triplet state for antimony impurity. There are three g factors in this instance which must be obtained by solving a six-by-six secular equation. The results obtained to first order in the anisotropy, good to about 10%, are, for $\vec{H}$ in a $(1\bar{1}0)$ plane,

$$g_1 = \bar{g} + \tfrac{1}{3}(g_{\perp} - g_{\parallel}) \sin^2\theta,$$

$$g_{2,3} = \bar{g} - \tfrac{1}{6}(g_{\perp} - g_{\parallel})\{\sin^2\theta + \sin\theta\,(1 + 15\cos^2\theta)^{1/2}\}, \tag{6}$$

where $\bar{g}$ is given by Eq. (5), and θ is the angle of the magnetic field with the [001] axis. The anisotropy of the g factors associated with the triplet is shown in Fig. 2. Higher order terms in $(g_{\perp} - g_{\parallel})$ split the degeneracy as is indicated by the dashed lines in the figure. This structure has not yet been observed by the spin resonance experiments.

It is suggested that experiments at higher temperatures, i.e., 77°K, should permit the observation of the free-electron resonance corresponding to Fig. 1, whereas 4°K experiments with antimony or possibly lithium impurities should permit the anisotropy observations of the triplet. Such experiments in these and other semiconductors can apparently provide information about the bands, from the deviation of the g factor from 2 and from the anisotropy. This is particularly

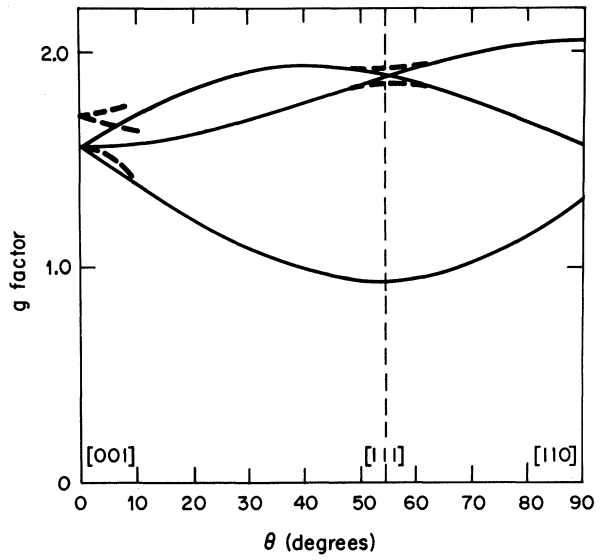

FIG. 2. Anisotropy of the g factor of bound electrons in the triplet state in germanium with $\vec{H}$ in the (110) plane. The solid lines are the first-order theory [Eq. (6)] and the splitting of the degeneracies are indicated by the dashed lines.

promising where the spin-orbit effect is large.

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INELASTIC ELECTRON SCATTERING FROM CARBON*

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We have measured the energy spectrum of electrons inelastically scattered from nuclei, with the aim of studying the giant-resonance region of nuclear excitation. Scattered electrons corresponding to excitation of the giant resonance have been observed at large angles for targets of Si and C. The scattering distribution from C has been investigated in some detail, and a scattering peak corresponding to a nuclear excitation of 15 Mev is also observed. The results indicate that the investigation of nuclear properties by inelastic electron scattering, which has already been successful in the study of many low-lying states,[1] can be extended to other types of nuclear excitation and can be carried out with lower-energy electron beams.

The Mark II linear accelerator[2] and an 18-in. double-focusing spectrometer[3] were used for the experiment. The double magnetic deflecting system of Mark II was set to $E_0 = 42.6$ Mev, with an energy spread of 1%.

For the measurement of the energy distribution of electrons scattered through 160°, we used a graphite target 0.327 g/cm^2 thick. The scattered and magnetically analyzed electrons were detected by means of two plastic scintillators, one mounted directly on the photocathode of an RCA-6810 photomultiplier, the other supported on an aluminum reflector, $1\frac{3}{4}$ in. in front of the second photomultiplier. The output pulses of the photomultipliers were fed directly into a coincidence circuit with a 6-mμsec resolution time. Use of coincidences significantly reduced the background, which was mainly due to neutrons. Beam monitoring initially was done with a secondary-emission monitor and later with a Faraday cup.

Figure 1 shows the results. The target-out background has been subtracted from each meas-