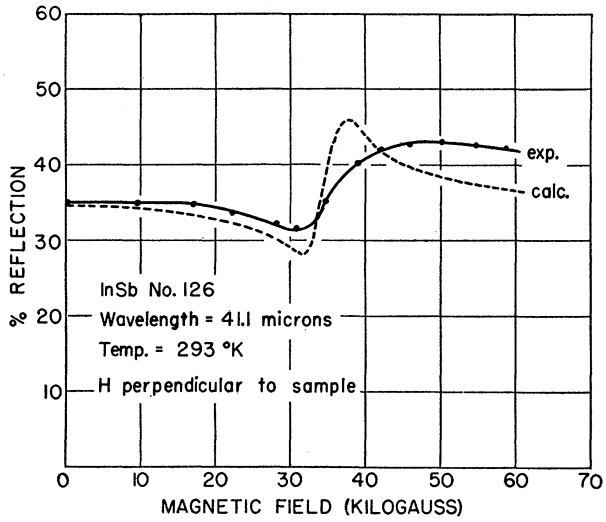

FIG. 2. Cylotron resonance reflectivity curve. Reflectivity *vs* magnetic field at a wavelength of 41.1 microns for an intrinsic specimen of InSb (0.5 mm thick) at room temperature. The reflectivity is that of one surface only since the sample was strongly absorbing. The calculated curve is based on $m^*=0.015m$ and $\omega_c\tau=16$.

larger than the value reported by Dresselhaus and his co-workers.[2] As a result of the extensive broadening of the resonance curve, the absorption constant at the peak is considerably smaller than the value $\alpha=4\pi\sigma_0/nc \approx 2\times10^4$ cm^{-1} which would be expected on the basis of spherical energy surfaces, and the minimum and maximum in the reflection curve are much less pronounced.

In the present experiments, $\hbar\omega_c$, the separation between the magnetic levels, is quite large, reaching, at 60 000 gauss, a value of 0.046 ev which is almost $2kT$ at room temperature. It is therefore likely that the resonance curve at the high fields results from transitions among the lowest four or five magnetic levels. Furthermore, according to Dresselhaus,[5] the energy of the conduction electrons in InSb is given to third order in k by

$$E=c_0k^2\pm c_1[k^2(k_x^2k_y^2+k_y^2k_z^2+k_z^2k_x^2)-9k_x^2k_y^2k_z^2]^{\frac{1}{2}}. \quad (1)$$

At low k values, the energy surface is degenerate and spherically symmetric. At higher k values, corresponding to energies comparable to the band spacing at $k=0$, the degeneracy is split and the energy surface becomes warped because of spin-orbit interaction. It is therefore not unreasonable to expect that variations in the spacing of the magnetic levels will occur which will result in an effective broadening. There may also be an appreciable asymmetric broadening due to $k_z\neq0$ effects. In addition, as pointed out by Adams,[6] the possibility exists that a strong magnetic field may modify the energy surfaces because of interactions between bands, particularly in the case of materials like InSb which have small band gaps and small effective masses. Experiments are now under way to determine the relative importance of these effects.

We wish to acknowledge the active interest and encouragement of P. Egli and R. Webber. We are also indebted to S. Slawson for preparing the polished thin sections used in the experiments, to A. Mister and R. Anonson for operating the Bitter magnet; to W. M. Cole for assistance in setting up the optical equipment; and to E. N. Adams, H. Brooks, J. Kaplan, N. Sclar, and R. Wallis for stimulating discussions.

Note added in proof.—Subsequently to our experiments, Zwerdling and co-workers have observed cyclotron resonance in InSb at 10 microns, using pulsed magnetic fields up to 20 000 gauss.[7]

[1] We are indebted to S. W. Kurnick of Chicago Midway Laboratory for this material.
[2] Dresselhaus, Kip, Kittel, and Wagoner, Phys. Rev. **98**, 556 (1955).
[3] H. Yoshinaga and R. A. Oetjen, Phys. Rev. **101**, 526 (1956).
[4] It should be noted that in intrinsic InSb at room temperature, the resonance for holes ($m_p^*\approx0.2m$) will occur at frequencies much smaller than ω_p even at the highest fields used in these experiments.
[5] G. Dresselhaus, Phys. Rev. **100**, 580 (1955). We are indebted to F. Herman for pointing this out to us.
[6] E. N. Adams, Phys. Rev. **89**, 633 (1953).
[7] Zwerdling, Keyes, Foner, Kolm, Lipson, Warschauer, and Lax, Bull. Am. Phys. Soc. Ser. II, **1**, 299 (1956).

Magnetic Optical Band Gap Effect in InSb

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ASSOCIATED with the small effective mass of electrons in InSb,[1,2] there is a large diamagnetic splitting of the conduction band levels in a magnetic field. It therefore seemed reasonable to expect that the magnetic field would have an appreciable effect on optical transitions between the valence and the conduction band. Room temperature transmission measurements with unpolarized radiation were accordingly carried out at the absorption edge of an intrinsic specimen of InSb (0.5 mm thick) in magnetic fields up to 60 000 gauss applied perpendicular to the face of the sample. Data obtained for H parallel to the face of the sample are essentially the same as for H perpendicular to the face. As shown by the data in Fig. 1, the magnetic field causes an appreciable shift of the absorption edge to shorter wavelengths. This shift in absorption edge to higher energy is interpreted as an increase in the optical band gap.[3]

For free electrons, the energy levels in the presence of a magnetic field directed along the z axis are given by[4]

$$E=\hbar^2k_z^2/2m+e\hbar H(n+\tfrac{1}{2})/m^*c. \quad (1)$$

The energy of the lowest conduction band level in the presence of a magnetic field is, on the basis of such a model, $E_c+e\hbar H/2m^*c$. The corresponding effect of the magnetic field on the energy levels in the valence

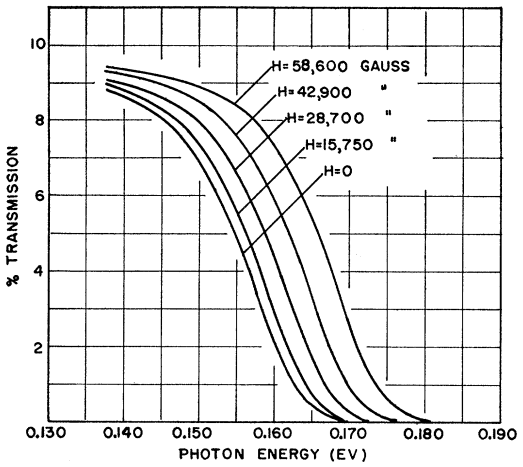

FIG. 1. Intrinsic absorption edge of InSb (No. 124) for various magnetic fields up to 60 000 gauss. Sample used was 0.5 mm thick and the field was perpendicular to the face.

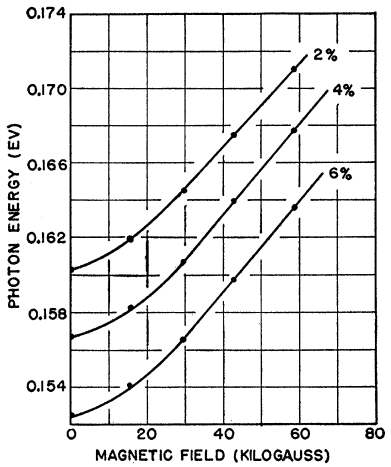

FIG. 3. Shift of points of fixed transmission in the intrinsic absorption edge of InSb (0.5 mm thick) with magnetic field at room temperature.

band of InSb will be much smaller since the effective mass of the holes is approximately 10 times greater than that of the electrons. In the absence of other effects (see below) the separation between the valence and conduction bands of InSb in the presence of a magnetic field will be given, as shown in Fig. 2, by

$$E_G(H)\approx E_c-E_v+e\hbar H/2m^*c=E_G(0)+\tfrac{1}{2}\hbar\omega_c.$$

According to this simple model, the increase in the optical band gap should be proportional to the magnetic field, with a proportionality constant

$$\gamma=\tfrac{1}{2}e\hbar/m^*c=3.85\times10^{-7}\text{ ev/gauss}$$

based on a value of $0.015m$ for the effective mass of electrons obtained from the infrared cyclotron resonance measurements at room temperature.[2]

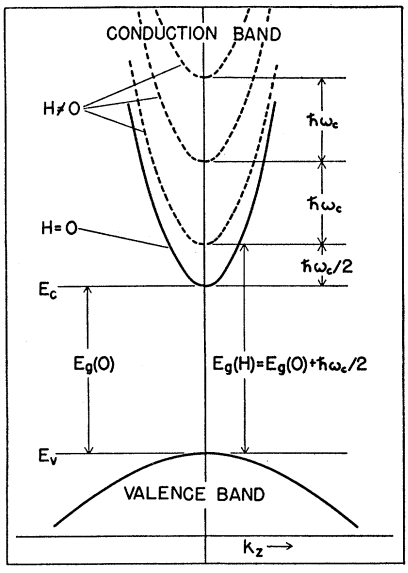

FIG. 2. Energy momentum diagram of the conduction band in InSb in presence of magnetic field. Magnetic effects in the valence band are neglected because the effective mass of holes is about ten times larger than that of electrons.

In the absence of a detailed theory of the absorption edge spectrum in InSb, it is not possible to obtain a precise value for the change in the optical band gap from the experimental data. As an expedient, the shifts of points of fixed transmission in the absorption edge with magnetic field are taken as an estimate of the magnitude of the magnetic optical band gap effect. This procedure obviously neglects effects due to changes in the magnitude of the absorption constant which arise from changes in transition probabilities and from changes in the density of states.

Curves of photon energy *versus* magnetic field for various transmittance values are plotted in Fig. 3. It is seen that the shift in the optical absorption edge increases slowly at low magnetic field and then becomes linear with magnetic field for applied fields greater than 30 000 gauss. The shapes of the various isotransmission curves do not differ appreciably from one another, and the slopes of the curves in the linear region indicate a value of 2.3×10^{-7} ev/gauss for γ, which is 0.60 times the value predicted for the simple model.

A tentative explanation for the shape of the curve of band gap *versus* magnetic field can be given in terms of the variation of the density of states in the conduction band as the field is applied. In the absence of a field, the density of states is zero at $k=0$. In the presence of a magnetic field, the lowest magnetic energy level ($n=0$) has a finite density of states even for $k_z=0$. Consequently in the presence of a magnetic field the absorption edge very likely involves transitions to states of smaller k_z than in the absence of a magnetic field. The net effect is to yield a smaller shift in the absorption edge with magnetic field as measured by $[E_G(H)-E_G(0)]/H$. The value of γ, the slope of the E_G *versus* H curve, should however be relatively

unaffected by density-of-states effects at the higher magnetic fields. A detailed analysis of these effects is complicated by energy level broadening and the fact that, for the range of absorption constants involved ($\alpha \approx 20$ cm^{-1}), the absorption edge probably involves nonvertical transitions.[5]

The discrepancy between the experimental value for γ in the linear high-field region and the theoretical value for the simple model, may be due to a number of other effects: (1) Zeeman splitting of the valence band which is believed to be either p-like or d-like in character. (2) Second-order interactions between the various branches of the valence and conduction bands which may produce displacements of the top of the valence band and the bottom of the conduction band relative to one another[6] and which may result in a modification of the energy surfaces in the presence of a magnetic field.[7] (3) Spin-orbit interaction effects in the conduction band which may produce displacements in the lower magnetic levels so that they do not occur at positions predicted by the simple model.[8]

We are indebted to A. Mister and R. Anonson for operating the Bitter magnet, to B. W. Henvis for assistance in a number of measurements, and to E. N. Adams, F. Herman, J. Kaplan, and R. Wallis for profitable discussions. We also wish to acknowledge the active interest and encouragement of P. Egli and R. Webber.

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Structure Sensitivity of Cu Diffusion in Ge

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We have observed a striking dependence of the diffusion of Cu in Ge upon the structural perfection of the Ge. Electrical-conductivity and radio-tracer (Cu^{64}) studies have been made on Ge samples into which Cu was diffused from a $Cu(NO_3)_2$-coated surface for 15 minutes at $\sim$710°C in H_2. The distance x_d from the surface at which the Cu concentration had dropped to $C_s/2$, where C_s is the concentration at the solubility limit for 710°C, varied from $\sim$0.004 cm in our most structurally perfect samples to >0.20 cm in samples containing multitudes of small-angle grain boundaries. Samples with large numbers of dislocations (10^4-10^6/cm^2), resulting from deformation at elevated temperatures, had x_d's between these limits. We have found that a good correlation exists between the rapidity of the Cu penetration and etch pit densities as brought out with *CP*4 and Superoxol (1 part 49% HF: 1 part 30% H_2O_2) on (111) planes. We have found no such correlation with very tiny etch pits brought out on (100) planes by slow etching, using a method reported by Ellis.[1]

If one assumes that the Cu transport obeys the usual laws of diffusion, then $x_d \simeq (Dt)^{\frac{1}{2}}$. For $t=15$ min and $T=710$°C, one obtains $D\sim 2\times 10^{-8}$ cm^2/sec for the most structurally perfect specimens and $D>4\times 10^{-5}$ cm^2/sec for the samples containing the small-angle boundaries. These values are to be compared with previously reported[2] results giving $D\sim 4\times 10^{-5}$ cm^2/sec in this temperature range. However, we do not feel that it is possible to assign values to the diffusion coefficient on this basis. More extensive measurements have shown that there are large departures from Fick's second law in this system, and that the mass transport of Cu cannot be characterized by a single diffusion coefficient at any given temperature.

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Effect of Melting on Positron Lifetime

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Positrons annihilating in some liquids and solids exhibit a complex two-photon annihilation lifetime.[1] Experimental and theoretical evidence seems to indicate the following: (1) A certain percentage of positrons form bound states (possibly positronium) prior to annihilation. (2) The shorter lifetime, τ_1 ($2-3\times 10^{-10}$ sec), results from free and bound singlet state annihilation, while the longer, τ_2($1-4\times 10^{-9}$ sec), is a reflection of either (a) conversion from bound triplet to bound singlet states and subsequent 2γ annihilation[2] or (b) a pick-off process in which a positron in the triplet bound state annihilates with an overlapping antiparallel atomic electron. Because of the low cross section of the spin flipping processes, the pick-off annihilation should be predominant.

The rate of triplet decay via τ_2 is apparently order-disorder-dependent, as indicated by the observed difference in τ_2 between crystalline and fused quartz.[1] To further examine this dependence, we have measured τ_2 in the molecular crystal naphthalene, as a function of temperatures extending across the melting point of