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Letters to the Editor

Cyclotron Resonance at Infrared Frequencies in InSb at Room Temperature

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CYCLOTRON resonance investigations at microwave frequencies have thus far been limited to a small number of materials—germanium, silicon, InSb, and bismuth—and to low temperatures where the collision relaxation time, τ, is long compared to the period of the electromagnetic radiation ($\tau > 1/\omega_c$, where $\omega_c = eH/m^*c$). By using higher magnetic fields and carrying out measurements at infrared frequencies, it should be possible to extend cyclotron resonance experiments to higher temperatures and to other materials. Toward this end we have been carrying out infrared cyclotron resonance experiments on InSb at room temperature using magnetic fields up to 60 000 gauss [obtained with the Naval Research Laboratory (NRL) 4-in. Bitter magnet] and wavelengths in the region of 25 to 42 microns. The measurements were carried out with unpolarized radiation.

The experiments, which included both reflection and transmission measurements, were carried out with a specimen[1] of p-type InSb which was intrinsic at room temperature and had an electron mobility of approximately 6×10^4 cm^2/volt sec. From the mobility and the value of $0.013m$ for the effective mass of electrons which Dresselhaus and co-workers[2] obtained from low-temperature cyclotron resonance measurements at microwave frequencies, the τ at room temperature is estimated to be 5×10^{-13} sec. The plasma frequency, which in intrinsic InSb is determined predominantly by electrons ($\omega_p^2 \approx 4\pi n_i e^2/m^*\epsilon_0$, where $n_i = 2\times10^{16}/\text{cm}^3$ and $\epsilon_0 = 16$), is calculated to be ω_p 1.75×10^{13} sec^{-1}, corresponding to a wavelength of 108 microns in agreement with the value indicated by the free-carrier reflection data of Yoshinaga and Oetjen.[3] The conditions for a well-defined resonance absorption that $\omega_c\tau > 1$ and that $\omega_c > \omega_p$ are therefore satisfied for electrons for wavelengths less than 100 microns.[4] However, since InSb exhibits a strong lattice absorption band at 53 microns, resonance measurements cannot be effectively carried out in the region of 42 to 60 microns.

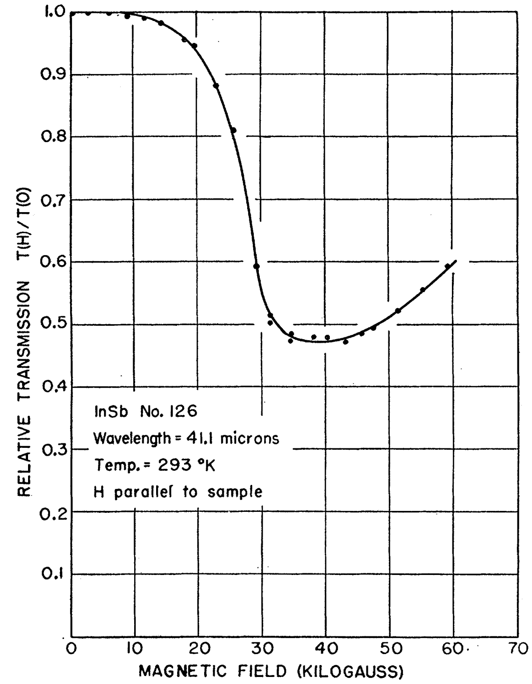

FIG. 1. Cyclotron resonance relative transmission curve. Relative transmission [ratio of transmission $T(H)$ in the presence of the magnetic field to the transmission $T(0)$ in the absence of a magnetic field] *vs* magnetic field at a wavelength of 41.1 microns for an intrinsic specimen of InSb (approximately 0.02 mm thick) at room temperature.

In Fig. 1, the relative transmission, $T(H)/T(0)$, at a fixed wavelength (41.1 microns) is plotted as a function of magnetic field. In Fig. 2, the reflectivity at a fixed wavelength (41.1 microns) is plotted as a function of magnetic field. The transmission experiments were carried out on a thin section, approximately 0.02 mm thick, with H parallel to the face of the specimen, while the reflection experiments were carried out on a 1-mm thick specimen with H perpendicular to the face. According to the simple classical theory of cyclotron resonance, the effective absorption constant at the resonance peak for H parallel to the face of the sample is one-half that for H perpendicular to the face. The H-parallel configuration is therefore the desirable one in transmission experiments where the specimen is too thick. The H-perpendicular configuration is the desirable one in the reflection experiments where a large absorption constant is wanted.

The experimental transmission curve is not symmetrical but rather shows a pronounced broadening on the high magnetic field side of the minimum. A similar effect is also present in the reflection data, as shown by comparison of the experimental reflection curve with the theoretical one calculated for spherical energy surfaces (Fig. 2). From the position of the minimum in the transmission curve, one obtains a value of $0.015m$ for the effective mass of electrons, which is somewhat

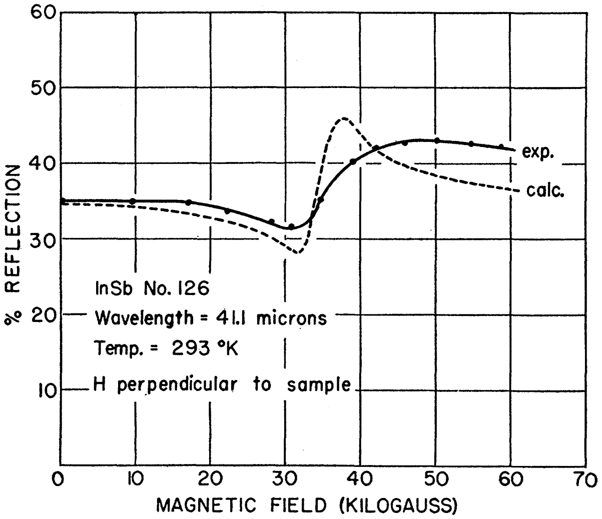

FIG. 2. Cylotron resonance reflectivity curve. Reflectivity *vs* magnetic field at a wavelength of 41.1 microns for an intrinsic specimen of InSb (0.5 mm thick) at room temperature. The reflectivity is that of one surface only since the sample was strongly absorbing. The calculated curve is based on $m^*=0.015m$ 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 $\alpha=4\pi\sigma_0/nc \approx 2\times 10^4$ 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

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

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 $k_z\neq 0$ 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 ($m_p^*\approx 0.2m$) 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]

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

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