and a field of E_g/W_0 is assumed.

It can easily be shown that if the phenomenological law,

$$J_p = K \exp(-\beta E_g^{\;n}), \qquad (3)$$

governs tunneling, then the slope of the plot in Fig. 3 would be divided by n. It is apparent that the data on phonon-assisted tunneling obviate values of n which depart greatly from unity. On the other hand, the plot for the low-pressure slope of units (b) seems to fit with Eq. (3) for $n=2$. This plot is also consistent with Eq. (2) if E_g is interpreted to be the gap between the (000) minima of the valence and conduction bands.[9] This suggests that the process involved may be a second order one in which there is virtual tunneling between the zone center states.[10]

Measurements on two units of type (b) at liquid N_2 temperature to a maximum pressure of 5000 kg/cm^2 indicate that the pressure dependence of $\ln J_p$ is about 25% larger at the low temperature than at room temperature. This is not easily understood on the basis of a phenomenological law like Eq. (2), since J_p is almost independent of temperature. However, these low-temperature pressure measurements are complicated by the possibility of nonhydrostatic effects. More careful measurements are necessary.

There are two general features of the data in Fig. 1 which are not understood at the present time. The first is the abrupt change in slope of units (b) at 8000 kg/cm^2. Nothing drastic is known to happen to the band structure at this pressure. The second is the difference in shape of curves (c) and (b).

We wish to express our appreciation for the hospitality extended to us by Dean Harvey Brooks and the members of the high-pressure group at the Gordon McKay Laboratory, Harvard University. We thank our colleagues at the IBM Research Laboratories for stimulating discussions and for assistance in fabricating diodes.

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SPIN RESONANCE OF CONDUCTION ELECTRONS IN InSb

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Among the interesting properties of InSb is the very high and negative magnetic moment of its conduction electrons.[1]

We have observed directly spin resonance of conduction electrons in n-type InSb in the concentration range between 2×10^{14} electrons/cm^3 and 3×10^{15} electrons/cm^3. The $|g|$ values varied between 48.8 and 50.7 depending on the electron concentration. The experiments were performed at temperatures of 1.2°K and 4°K. By observing the resonance at two different frequencies (9000 Mc/sec and 24 000 Mc/sec) we verified that it was due to spin rather than plasma resonance. The magnetic field at which the resonance was observed was directly proportional to the microwave frequency while the plasma resonance gives rise to an inverse dependence of the magnetic field on the electronic frequency.[2] Cyclotron resonance can also be ruled out on the basis that the observed resonance occurs at approximately 2.5 times the field value of the cyclotron resonance. The widths of the observed lines (see

Table I. Experimental and calculated results.

Electron concentration (cm^{-3})	Fermi level (ev)	$\lvert g\rvert_{exp}$	$(m^*/m_0)_{exp}$	$(m^*/m_0)_{theor}$[a]	ΔH
2×10^{14}	9.6×10^{-4} ev	50.7	0.0131	0.0130	2φ
7×10^{14}	2.2×10^{-3} ev	50.3	0.0132		3φ
1.5×10^{15}	3.6×10^{-3} ev	49.6	0.0134		5φ
2.5×10^{15}	4.9×10^{-3} ev	48.8	0.0136	0.0136	8φ
3×10^{15}	5.5×10^{-3} ev	48.8	0.0136		23φ

[a]See reference 7.

Table I) are also more than an order of magnitude less than in the case of cyclotron resonance.[3]

Figure 1 shows the barely resolved spin resonance line superposed on a plasma line. Figure 2 shows the spin resonance line greatly amplified. In this case the sample, 10^{-2} cm^3 in volume, was positioned directly at the end of the waveguide. Runs were also performed with much smaller samples in rectangular cavities. The lines are isotropic with respect to the field orientation.

The InSb band structure has been treated by Kane who has derived expressions for curvature of the nonparabolic conduction band.[4] Cyclotron resonance has shown that the conduction electrons possess a low effective mass, $m^* = 0.013m_0$, near the bottom of the conduction band.[3] A variety of other experiments have given values of m^* as a function of the energy of electrons above the bottom of the band.[5]

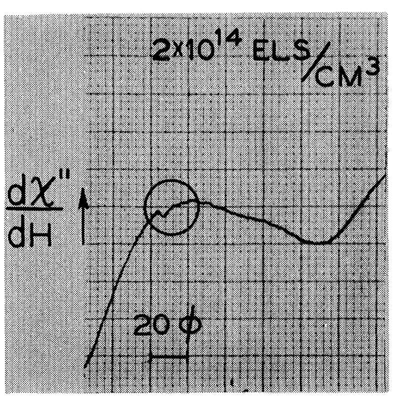

FIG. 1. Plasma resonance line in n-type InSb at 1.2°K. Encircled is the superposed electron spin resonance line.

Roth et al.[1] have calculated the expression for the magnetic moment μ:

$$\mu = \frac{e\hbar}{2m_0 c}\left[1 - \left(\frac{m_0}{m^*} - 1\right)\frac{\Delta}{3E_g + 2\Delta}\right],$$

where Δ is the spin-orbit interaction = 0.9 ev as

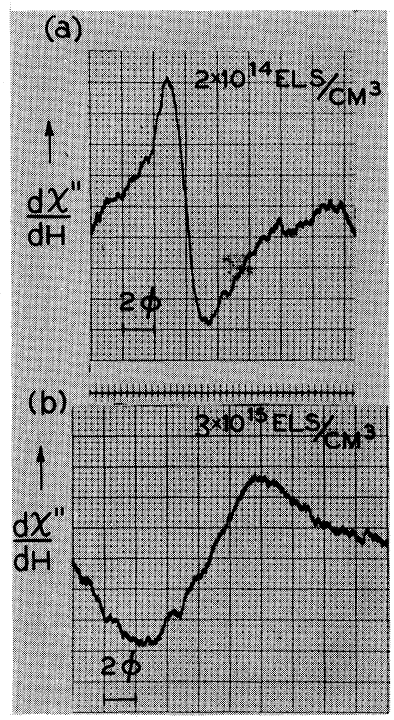

FIG. 2. (a) Electron spin resonance absorption in n-type InSb with 2×10^{14} electrons/cm^3. (b) Similar resonance absorption in a sample with 3×10^{15} electrons per cm^3.

calculated by Kane, and E_g is the energy gap of 0.25 ev at helium temperature.[5] Zwerdling, Lax. and Roth[1,6] have observed magneto-optical transitions to the lowest Landau Level ($l=0$) in the conduction band which gave the value of $\mu = 26\mu_B$.[1]

In the present experiments the shift of the g value with concentration is also believed to be associated with the increasing mass of the electrons. Table I shows the close agreement between the observed g's and those calculated by using Eq. (1). The values of m^* were calculated from the known Fermi energy in the samples.[7] All samples were degenerate at helium temperatures with the purest sample having a degeneracy temperature of 11°K. Since the only electrons which participate in the resonance absorption belong to the highest occupied Landau level, the amplitude of the signal does not increase with the concentration of electrons. We were unable to observe resonance in a sample with 10^{16} electrons/cm^3. This is probably due to the progressive broadening of the lines with concentration (Table I).

I would like to thank C. Lee and R. Logan for the InSb samples, G. Feher for the use of the X-band spectrometer and B. Szymanski and E. Gere for help with the experiments.

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MILLIMETER CYCLOTRON RESONANCE IN SILICON*

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A cavity spectrometer operating at 2.1 mm (136 kMc/sec) has been constructed and cyclotron resonance absorption experiments have been performed on high-purity n-type silicon from 1.2°K to about 50°K.

About 50 microwatts of 2.1-mm microwave energy are generated as the second harmonic from a crossed guide crystal harmonic generator which is fed with 4-mm fundamental power from a Philips DX 151 klystron. The harmonic output is transmitted through an oversized waveguide to a circular TM_{015} cavity located at the bottom of a helium Dewar. The sample, which is about 0.020 in. diameter and about 0.040 in. long, is coupled to the high electric field region of the cavity through a small axial hole beyond cutoff in the end wall of the cavity. The sample is fastened to a quartz rod which extends to the top of the Dewar and serves to position the sample in the cavity and as a light pipe for carrier excitation. Temperature is monitored with a carbon resistance thermometer fastened to the top of the cavity. The cavity, waveguide, and quartz rod are encased in a shield to prevent direct contact with liquid helium, thus eliminating noise due to bubbling of liquid helium in the system. A low pressure of He gas inside the shield provides heat transfer from the cavity and sample to the helium bath. Stabilization of the klystron frequency is accomplished by applying a small 1-kc/sec signal to the reflector of the klystron, and feeding back the synchronously detected signal to the reflector. Resonance lines are observed as a function of the static magnetic field in the standard way by modulating the carrier density with a light chopper at a low audio frequency and synchronously detecting the signal as the magnetic field is swept.

Very pure n-type silicon (3000 ohm cm at room temperature) has been used to obtain the effective-mass parameters of the constant energy ellipsoids associated with the conduction band minima. Orientation data were taken to obtain experimental values for the sum $1/m_1^2 + 1/m_2^2 + 1/m_3^2$ (see Fig. 1) which is constant for all orientations and is given by

$$\frac{1}{m_1^2}+\frac{1}{m_2^2}+\frac{1}{m_3^2}=\frac{3}{(m^{*2})_{[111]}}=\frac{1}{m_t^2}+\frac{2}{m_l m_t}. \quad (1)$$

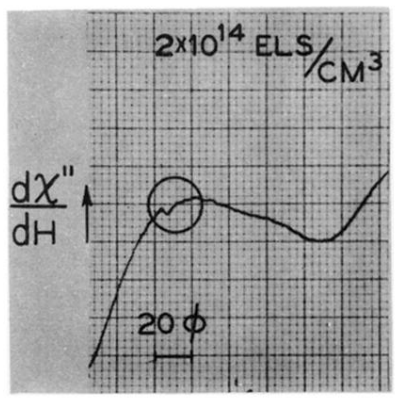

FIG. 1. Plasma resonance line in n-type InSb at 1.2°K. Encircled is the superposed electron spin resonance line.

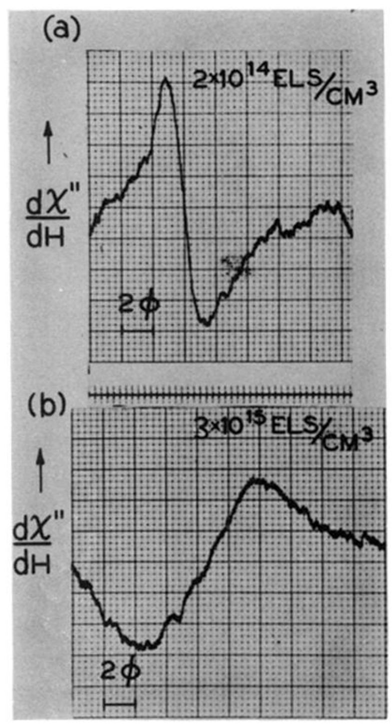

FIG. 2. (a) Electron spin resonance absorption in n-type InSb with 2×10^{14} electrons/cm^3. (b) Similar resonance absorption in a sample with 3×10^{15} electrons per cm^3.