

TABLE I. Corrections (percentage) for skin-depth effects.

Temperature ($^{\circ}\text{K}$)	Correction for skin depth
1.4 (and lower)	0
1.5	0.5%
1.6	0.8%
1.7	2.3%
1.8	4.0%
1.9	4.3%
2.0	3.2%
2.1	1.5%
λ point	0

bined with, apparently, a relatively low viscosity at temperatures in the region of 1°K precluded unmanageably large skin depths.

Portions of the density data are given in Fig. 1. Uncorrected data are indicated by the points and the solid curve — drawn through them. The observed effective mass densities of the excitations (rotons, phonons, plus helium-3) have been normalized to unity for the 3.3% mixture immediately above the λ point on the basis of an "ideal" (no correction) disk system; and are expressed in terms of the customary "normal fluid" concentration (ρ_n/ρ). The orders-of-magnitude of correction for skin-depth effects are indicated in Table I. These values were deduced from observations of oscillational damping of the disk system in the mixture. Besides the generally small extent of corrections needed, it should be noted that below about 1.5°K they become unimportant. The broken curve --- of Fig. 1 represents the corrected value of the observed "normal fluid" concentration (ρ_n/ρ).

The most significant feature of these (ρ_n/ρ) determinations shown in Fig. 1 is the evident leveling off of

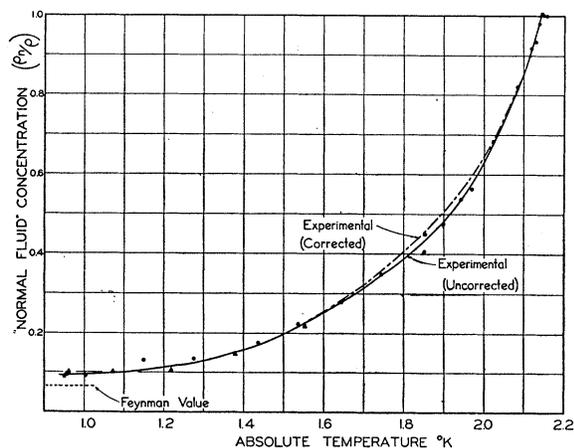


FIG. 1. "Normal fluid" concentration (ρ_n/ρ) for 3.3% (by mass) liquid helium-3-helium-4 mixture versus temperature ($^{\circ}\text{K}$). Basic Andronikashvili disk measurements, normalized for "ideal" (no correction) system to density of liquid mixture just above λ point. Circles (O) represent data taken with 5.220-sec period (in vacuum) system, triangles (Δ) with 3.589 sec system. Solid line — through these points represents uncorrected values; broken line --- represents corrected dependence on temperature. Feynman limiting value indicated by dotted line - - - -.

the observed effective (mass) density to a value at the lowest temperatures considerably greater than the mass density of the helium-3 present. In fact, the mass density observed using this method is apparently approaching the same value of *twice* the mass density of contained helium-3 earlier indicated indirectly by King and Fairbank³ from second sound velocity measurements and predicted independently by Feynman.⁴

In Feynman's theory the motion of a helium-3 atom through a background of helium-4 atoms in the lowest energy state (superfluid) may be treated as a microscopic hydrodynamic problem. The helium-4 "backflow" about the helium-3 "obstacle" contributes the additional effective mass. At the lowest temperatures reached in the present direct investigation, the disks were thus essentially towing helium-3 atoms through a superfluid background, gaining the additional momentum of the helium-3 plus that of the participating "superfluid" (in the presence, of course, of some remaining rotons).

Although the coefficient of viscosity (η) for the mixture is not readily evaluated by this method, semiquantitative results show a distinct decrease with temperature. For example, the skin depth at 1°K is about that for the λ point, indicating a decrease in (η) roughly proportional to that in (ρ_n). Present measurements indicate a value of 4 or 5 micropoise at 1°K .

In a paper now in preparation the complete density data will be given in corrected form, plus the associated damping measurements and a discussion of their application to the corrections. Semiquantitative evaluation of the viscosity for this mixture as a function of temperature will be given.

* Supported in part by the National Science Foundation.

¹ E. L. Andronikashvili, J. Phys. (U.S.S.R.) **10**, 201 (1946).

² Obtained from Isotopes Division, Oak Ridge National Laboratory, U. S. Atomic Energy Commission.

³ J. C. King and H. A. Fairbank, Phys. Rev. **93**, 21 (1953).

⁴ R. P. Feynman, Phys. Rev. **94**, 262 (1954).

Impedance Measurements on CdS Crystals*

HARTMUT KALLMANN, *Department of Physics, New York University, New York, New York,*

BERNARD KRAMER, *Department of Physics, New York University, New York, New York, and*

Physics Department, Hunter College, Bronx, New York

AND

PETER MARK, *Department of Physics, New York University, New York, New York*

(Received June 28, 1955)

PREVIOUS measurements of changes in the impedance of ZnCdS luminescent powders due to excitation by light and high-energy radiation¹ has been extended to CdS crystals. These crystals were grown by the Standard Piezo Company of Carlisle, Penn-

sylvania using the Frerichs-Warminsky method.^{2,3} The crystals are about 2 cm long, 0.5-1 cm wide, and several tenths of a millimeter thick; the electrodes are transparent gold layers evaporated on the flat sides of the crystals.

The values of the measured capacitance (C) and dissipation factor (D) were obtained using a General Radio 650-A impedance bridge (1000 cps). The results of measurements on 8 crystals are given in Table I. The first column gives the dark value; the second the value under visible illumination (tungsten source, Corning 4-96 filter, ≈ 100 microwatts/cm²); the third under visible illumination plus infrared irradiation (tungsten source, Corning 7-56 filter, 10 milliwatts/cm²); and the fourth with the visible illumination only but using a bridge output of 12 volts rather than the usual 0.05 volt.

The tremendous increase in capacitance from the dark value is seen by comparing columns 1 and 2; if the system is looked upon as a parallel capacitance-resistance circuit consisting of the constant capacity C_0 (dark capacity of the sample) and a resistance changing with excitation, the measured capacitance would increase as $C_m = C_0(1 + D^2)$. This is not the case, the increase is much larger than according to this formula. The very high capacitance values obtained under visible excitation indicate that the bulk of the crystal becomes so highly conducting that it acts like a very low resistor in series with less conductive thin layers adjacent to the electrodes, which alone contribute effectively to the parallel capacitance-resistance circuit. Even these layers, however, are quite conducting, as can be calculated from the C and D values. For the most sensitive crystals these calculated resistances are of the order of 10^2 ohms at high light intensities (large D), and agree with the measured dc photoconductivity. Using the measured C and D values, the thicknesses of these layers are found to be about 10^{-6} cm for the most sensitive crystal. Such layers have also been investigated in semiconductor work.

When infrared irradiation is added to the visible excitation, a quenching effect (decrease in capacitance change) is noted for all crystals except X-4. With this crystal, quenching is observed only at lower levels of light excitation. In column 4 it is seen that the increased ac field applied to the crystal also acts as a quenching agent except for crystal X-16 which shows a larger capacitance increase with the higher potential; perhaps in this case some barrier layers have been broken down by the higher field.

The capacitance change dependence on wavelength of one of these crystals (X-1) at various intensities is shown in Fig. 1. The capacitance change is a maximum around 5000 Å, which is close to the absorption edge and corresponds to the peak observed in dc photoconductivity.⁴ The large capacitance change found even at 4000 Å, where the incident energy is completely

TABLE I. Capacitance^a and dissipation values under various conditions of illumination.

Crystal	Dark		Visible		Visible+infrared		Visible+12 volt ac	
	C	D	C	D	C	D	C	D
X-1	12	0.02	2.0×10^4	5.0	1.7×10^4	4.9	1.9×10^3	2.1
X-3	17	0.02	405	0.3	79	1.0	57	0.2
X-4	34	0.03	8×10^3	1.1	8×10^3	1.5	3.3×10^3	1.4
X-8	19	0.02	146	0.36	45	0.43	34	0.16
X-13	25	0.03	7.1×10^3	2.3	6.6×10^3	1.9
X-16	7	0.06	105	0.78	90	0.72	2×10^3	3.9
X-17	13	0.06	1.3×10^5	9	1.0×10^5	9
X-18	34	0.35	1.7×10^7	11	1.4×10^7	11

^a Capacitance in micromicrofarads.

absorbed in a small fraction of the total thickness, indicates that this layer reradiates some of the absorbed energy, thus exciting the remainder of the crystal by its own fluorescent light. The capacitance change increases roughly proportionately to the intensity; this is in marked contrast to the behavior with powders where the capacitance change increases roughly as log (intensity) tending to a saturation value¹ which is of the same order of magnitude as the dark capacity.

These results support the idea that the much smaller capacitance changes observed in highly photoconductive powders are due to their grain structure (high resistance between grains), and further they indicate clearly that the increased capacitance of these crystals is due to the large increase in the conductivity of the sample, since it is difficult to imagine any polarization due to trapped electrons or activators increasing the dielectric constant by a factor of up to 10^6 . They also show that the simple model containing a fixed capacitor shunted by a light-sensitive resistance cannot explain the results; actually with increasing excitation the effective capacitive layers seem to shrink to small fractions of the initial thickness.

In addition the effects of fields on conductivity is appreciable. In almost all cases an increased field results in a marked decrease in conductivity; in one case an increase was noted.

Finally, the negligible effect of filled traps on the capacitance change can be pointed out. Upon cessation of excitation the capacitance drops quickly (within

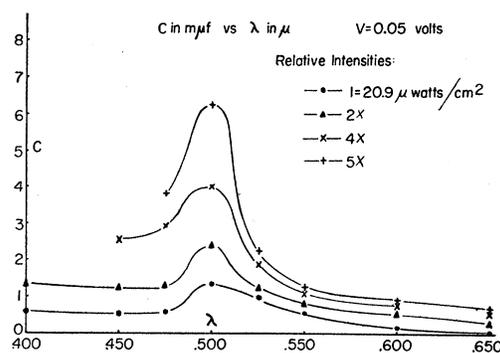


FIG. 1. Capacitance change as a function of wavelength at various intensities.

minutes) to the dark value although there is an appreciable number of traps which remain filled for many hours (as measured by succeeding rise curves).

* This investigation was supported by the Standard Piezo Company, Carlisle, Pennsylvania.

¹ Kallmann, Kramer, and Perlmutter, Phys. Rev. **89**, 700 (1953).

² R. Frerichs, Naturwiss. **33**, 281 (1946).

³ R. Warminsky, PhD thesis, Technical University of Berlin, 1948 (unpublished).

⁴ R. Frerichs, Phys. Rev. **72**, 594 (1947).

Magnetic Indications of Electronic Structure of the Conduction Band in Ge

J. H. CRAWFORD, JR., H. C. SCHWEINLER, AND D. K. STEVENS
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received June 27, 1955)

CYCLOTRON resonance experiments^{1,2} have firmly established that in the conduction band of Ge the energy surfaces are best represented by ellipsoids in k -space whose axes lie along the $[111]$ directions. Moreover, since the minima of E vs k surfaces do not lie at $k = (0,0,0)$, this configuration leads to spatial degeneracy of states: eightfold if the minima lie within the Brillouin zone or fourfold if they lie at the zone boundaries. The magnetic susceptibility of charge carriers in semiconductors^{3,4} yields information complementary to the results of cyclotron resonance. Moreover, such data provide a means of deciding whether four or eight ellipsoids best describe the states in the conduction band of Ge. In this letter, besides comparing the elec-

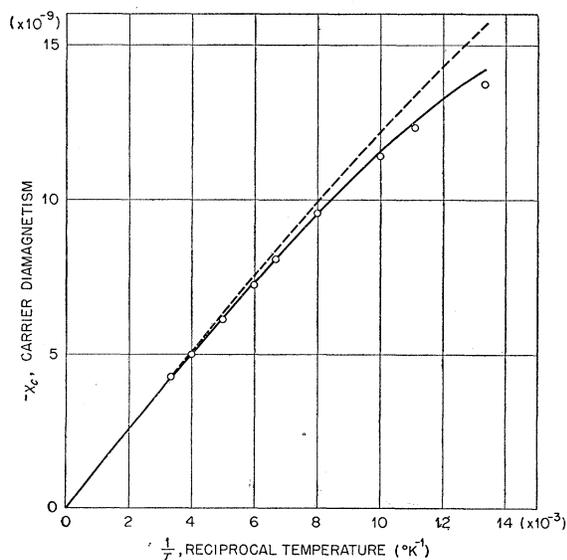


FIG. 1. Diamagnetic susceptibility resulting from conduction electrons vs reciprocal temperature. The points are experimental, the dashed curve calculated for $\omega_s = 8$, the solid curve for $\omega_s = 4$. In both cases $n = 6.4 \times 10^{17} \text{ cm}^{-3}$ (see text).

TABLE I. Electron concentrations and values of $\langle f^2 \rangle$ obtained from the high temperature slopes of the χ_c vs $1/T$ curves for 5 n -type Ge specimens.

Sample	n (cm^{-3})	$\langle f^2 \rangle$
1 ^a	$\sim 3 \times 10^{16}$	~ 50
2	7.3×10^{17}	48
3	9.0×10^{17}	44
4	3.6×10^{18}	36
5	9.0×10^{18}	19

^a The electron concentration of this specimen was appreciably temperature dependent.

tron masses yielded by the two methods we wish to present tentative evidence for fourfold spatial degeneracy.

In the classical range of electron concentration, the susceptibility of extrinsic electrons in n -type Ge is given to first order by

$$\chi_c = n(\beta^2/3\rho kT)(3 - \langle f^2 \rangle), \quad (1)$$

where n is the electron concentration, β the Bohr magneton, ρ the density, and $\langle f^2 \rangle$ is the square of the reciprocal mass-ratio tensor averaged appropriately for orbital motion in the magnetic field. For ellipsoidal surfaces it can be shown that $\langle f^2 \rangle = (2M_t + M_l)/(3M_t^2 M_l)$, where M_t and M_l are the transverse and longitudinal mass ratios ($M_i = m_i/m_0$) whose values are 0.083 and 1.4 respectively.¹ These values yield $\langle f^2 \rangle = 54$. In Table I we list the values of $\langle f^2 \rangle$ determined on several specimens from the temperature dependence of χ_c in the classical range. Values of n were obtained from Hall coefficient measurements.⁵ The reliability of these $\langle f^2 \rangle$ values is $\sim 10\%$. Although agreement with the expected value of $\langle f^2 \rangle$ is quite good at the lowest electron concentration, a significant decrease occurs with increasing n . Although this behavior is not yet completely understood, Herring⁶ has predicted that a change in mass ratio might result if an impurity band is present which overlaps the conduction band at high donor concentration.

At high electron concentrations or low temperature, transition from classical to Fermi-Dirac statistics occurs. Under these conditions Eq. (1) becomes

$$\chi_c = (\beta^2/3\rho k)CT^{3/2}\omega_s(M^N)^{3/2}(3 - \langle f^2 \rangle)F_{3/2}'(\eta) \quad (2)$$

where $C = [4\pi(2m_0k)^{3/2}]/h^3$, ω_s is the number of ellipsoids, and M^N is the density of states mass given by $(M_t^2 M_l)^{3/2}$. $F_{3/2}'(\eta)$ is the first derivative of the Fermi integral which can be obtained from the McDougall-Stoner tabulation⁷ provided η or $F_{3/2}(\eta)$ is known. The value of $F_{3/2}(\eta)$ is obtained from n and the relation

$$n = C\omega_s(M^N T)^{3/2}F_{3/2}(\eta). \quad (3)$$

Hence by fitting χ_c vs $1/T$ curves in the transition range, it should be possible to determine whether ω_s is four or eight. There is a factor of two difference in the