down to beyond liquid nitrogen temperature, to 30°K in case of high resistivity samples. The deviation of the Hall curves from flat curves in this region is believed to be due to the fact that the Hall coefficient is not accurately the inverse of the concentration of carriers.[3]

The resistivity in the higher temperature region can be accounted for satisfactorily on the consideration of lattice scattering and impurity ion scattering.[4] The mobility of the carriers, as obtained from the measured resistivity and the Hall coefficient, is of the order of 2000 to 3000 cm²/volt-sec. at room temperature and increases up to 10,000 to 100,000 cm²/volt-sec. at low temperatures. As expected, the mobility increases up to a maximum and then decreases slowly with decreasing temperature. For sample SB-5, due to the high concentration of carriers, consideration of resistivity must be based on degenerate gas theory.[5] Theoretical calculation and experiment again agree.

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* Work assisted by Signal Corps contract.

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[2] C. S. Hung, Phys. Rev. **79**, 727 (1950).

[3] V. A. Johnson and K. Lark-Horovitz, Phys. Rev. **79**, 176 (1950).

[4] C. S. Hung and V. A. Johnson, Phys. Rev. **79**, 535 (1950).

[5] V. A. Johnson and K. Lark-Horovitz, Phys. Rev. **71**, 374 (1947); **71**, 909 (1947); **72**, 531 (1947).

Theory of Resistivity and Hall Effect at Very Low Temperatures*

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THE anomalies in the resistivity and the Hall curves of germanium observed at low temperatures[1] could not be explained on the model of an impurity semiconductor with localized impurity states. The Hall coefficient, in the case of some samples, decreases from its maximum by a factor of over 100 as the temperature is reduced. The concentration of carriers in the conduction band (or the filled band), on the other hand, cannot be expected to increase with decreasing temperature. This leads to the conclusion that the usual expressions for resistivity and Hall coefficient, as represented in Eqs. (1) and (2) are no longer valid at low temperatures

$$\rho = (n_c e b_c)^{-1}, \tag{1}$$

$$R = F/(n_c e), \tag{2}$$

where n_c and b_c are the concentration and the mobility of electrons in the conduction band, and F is a numerical factor of the order of unity. According to the free electron theory F is not expected to vary by more than an order of magnitude. Non-homogeneity in the sample, either macroscopic or microscopic, may cause R to decrease with lower temperature even though n_c, at various parts of the sample, may remain constant or decrease. However, to account for the large drop in R observed requires too artificial a model of inhomogeneity.

The anomalies can be understood only if a mechanism is found which includes a combination of different kinds of carriers with different mobilities. James and Ginzbarg[2] pointed out that due to the interaction between the impurity states, an impurity band is formed. In such a case an electron has the possibility of moving from one impurity state to another one in its spatial neighborhood, so that the states are no longer localized, and conduction in the impurity band is to be expected.

When simultaneous conduction in the conduction band and the donor band (or the filled band and the acceptor band) is considered, the expressions for ρ and R are given as follows:

$$\rho = (n_c e b_c + n_D e b_D)^{-1}, \tag{3}$$

$$R = F(n_c e b_c^2 + n_D e b_D^2)(n_c e b_c + n_D e b_D)^{-2}, \tag{4}$$

where n_D and b_D are the concentration and mobility of electrons in the donor band. The assignment of a definite mobility b_D to the donor band is justified by the observed ohmic behavior of the saturation resistivity at low temperatures. Equation (4) is adapted from the usual expression for R in the intrinsic range; it is assumed here that this equation holds for the case of carriers in the impurity bands also.

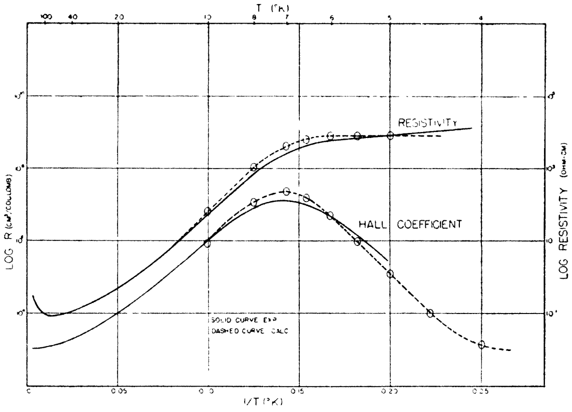

FIG. 1. Resistivity and Hall curves for sample SB-1 (N-type, antimony added). The solid curves are experimental and the dashed curves are calculated theoretically. The carriers in the donor band are assumed to be lectrons.

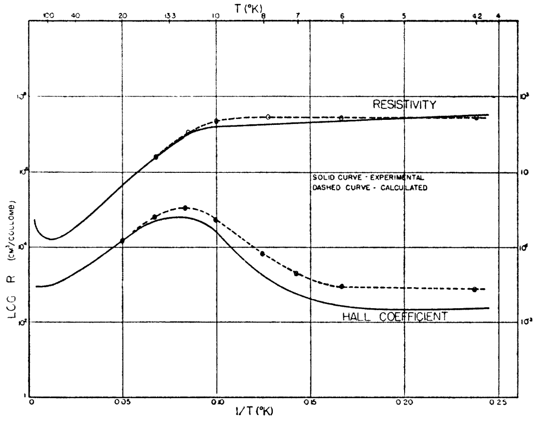

FIG. 2. Resistivity and Hall curves for sample B-1 (P-type, neutron bombarded). The solid curves are experimental and the dashed curves are calculated theoretically. The carriers in the acceptor band are assumed to be holes.

Since b_D is usually small compared with b_c, in the limit of high temperatures, the conduction in the impurity band can be neglected and the values of ρ and R are as given by Eqs. (1) and (2) according to the usual theory. However, since n_c decreases indefinitely with decreasing temperature, conduction in the impurity band becomes increasingly important. In the limit of low temperature, conduction in the conduction band can be neglected, and Eqs. (3) and (4) now reduce to the following:

$$\rho = (n_D e b_D)^{-1}, \tag{5}$$

$$R = F/(n_D e). \tag{6}$$

At low temperatures, all the electrons are in the impurity band, and at room temperature, all of them are excited into the conduction band. Therefore, the Hall coefficients at room temperature and at very low temperatures are expected to be the same. This is in approximate agreement with experiment. The deviation may come from the fact that the electrons in the donor band are far from being free, and Eq. (6) is only approximately true.

At the intermediate temperatures, the values of ρ and R can be obtained from the values of n_c, n_D, b_c, and b_D. n_c and b_c can be obtained by extrapolation from high temperatures. n_D is obtained from the room temperature values of R. b_D is obtained from extrapolation of the resistivity at very low temperatures and with the help of Eq. (5). The calculated resistivity and Hall curves are shown in Figs. 1 and 2 together with the experimental curves for two of the samples. For the other samples, experiment and theory also agree. However, except when the Hall coefficients are measured to very low temperatures, it is not always possible to ascertain whether the carriers in the impurity bands behave as electrons or as holes. The mobility in the impurity bands varies between 10^{-4} and 100 cm²/volt-sec. for impurity concentration between approximately 10^{14} and 10^{17}/cc.

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* Work assisted by Signal Corps contract.

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[2] Ginzbarg, Ph.D. Thesis, Purdue University, Department of Physics, (1949).

Infra-Red Spectra of Condensed Oxygen and Nitrogen*

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June 19, 1950

INFRA-RED absorption spectra of condensed O_2 and N_2 have been obtained using a model 12-B Perkin-Elmer spectrometer. The chemically purified gases were purified further by distillation of the liquids, and were finally condensed in a variable thickness low temperature cell[1] fitted with silver chloride windows. Since induced infra-red absorption is weak, a sample thickness of about 7.5 mm was employed throughout the temperature range investigated, 35° to 85°K. A NaCl prism was used in the study of the O_2 fundamental, and a LiF prism for N_2. Careful corrections for water vapor and carbon dioxide absorption gave a reproducibility of ±2 percent transmission on different runs at the same temperature.

Figure 1 shows the absorption in the 1550 cm^{-1} region of the liquid, solid-γ-, and solid-β-O_2. The central frequency at 1559 cm^{-1} in the liquid is the same within experimental error as that given for the gas by Crawford and his co-workers.[2] There is no detectable frequency shift as the liquid freezes to solid-γ at 55°K, nor is the transmission reduced. β-O_2, however, is highly scattering, and to register spectra of this phase a slit-width ten times greater than that used for the liquid was necessary.

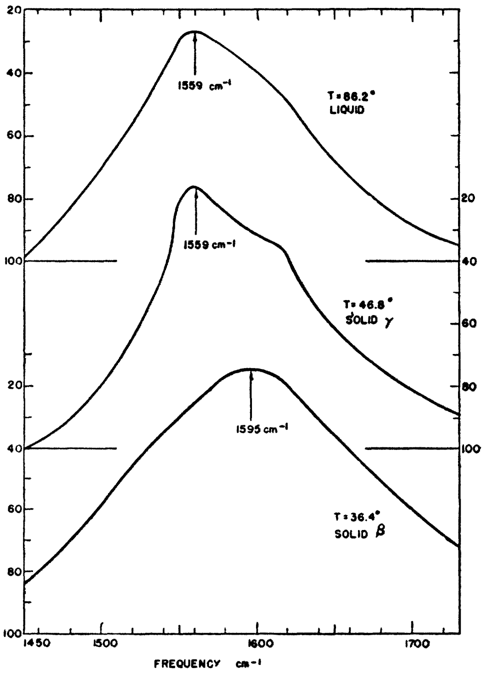

FIG. 1. Infra-red absorption spectra of condensed oxygen.

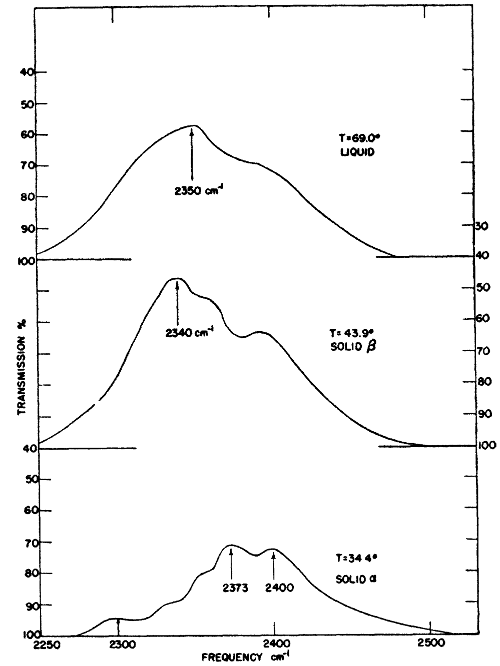

FIG. 2. Infra-red absorption spectra of condensed nitrogen.

The analogous results for the three condensed phases of N_2 are shown in Fig. 2. As the liquid freezes at 63°K the character of the absorption remains unchanged, but as the temperature is lowered further there is a gradual shift of the central peak from 2350 to 2336 cm^{-1} at 39°K. On going from solid-β to solid-γ at 36°K, transmission is somewhat reduced and the band center is replaced by two distinct peaks of equal intensity at 2373 and 2400 cm^{-1}.

The fact that the fundamental vibrational band appears in β-N_2 but only weakly in the α-form suggests that in the former phase the molecules are disordered, while in the latter they are ordered.[3] The two strong peaks in the α-N_2 spectrum are probably librational modes having frequencies[3, 4] of 40 and 69 cm^{-1} in combination with the comparatively weak fundamental; a weaker subtractive combination is found at 2300 cm^{-1}. An interpretation of the spectrum of β-O_2 cannot be made at this time because of the unusually poor resolution encountered.

A more detailed account of this work and a possible interpretation of the observed envelopes will be presented later.

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Beta-Gamma-Angular Correlation Experiments*

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IN recent months several positive examples of beta-gamma-directional correlation have been found. Correlations have been reported for Rb^{86},[1,2] Tm^{170},[2] and Sb^{124}.[3] In many cases, however, no correlation seems to exist.[4]