weak. The microwave magnetic field is always perpendicular to the static field.

Such anomalous absorptions cannot be explained by a single ion in the ^2D state in any allowable crystalline field. The first possibility for the origin of this anomaly may be that ions are not in the ^2D state in this case of very strong crystalline fields. The second possibility is that the absorption is not effected by a single Cu^{++} ion, but by a molecule containing Cu^{++} and other atoms. The third one is that a number of Cu^{++} ions are located at small distances from each other so that their electron spins mutually interact strongly. We note that the absorption of $Mn(CH_3COO)_2 \cdot 4H_2O$ shows a single peak with $g=2.0$.

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Electron-Hole Recombination in Germanium

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POWER rectifiers have been described that consist of thin wafers of high purity germanium whose opposite faces are heavily doped with donor and acceptor impurities.[1] Since the current flow depends largely upon the generation and recombination of holes and electrons within the high purity region, this geometry is well adapted to the study of the recombination process. A two-body collision mechanism leads to a rate that is proportional to the square of the carrier concentration at high levels of injection where holes and electrons are present in nearly equal numbers. Measurements show, however, that the rate varies linearly with concentration over a wide range of concentration and temperature.[2] These observations can be accounted for by assuming that recombination takes place largely through the agency of recombination centers distributed throughout the germanium.

A steady-state recombination rate given by[3]

$$R=(np-n_i^2)/[t_p(n+n_0)+t_n(p+p_0)], \qquad (1)$$

results from a simple model in which the centers give rise to an energy level lying in the forbidden band. The electron and hole concentrations are given by n and p, their product under equilibrium conditions being n_i^2. The lifetime for electrons when the centers are completely empty is given by t_n; t_p is the hole lifetime with all centers occupied by electrons. The recombination centers lie at an energy level defined by n_0 and p_0 which are the equilibrium electron and hole concentrations in a sample whose Fermi level coincides with the position of the recombination centers.

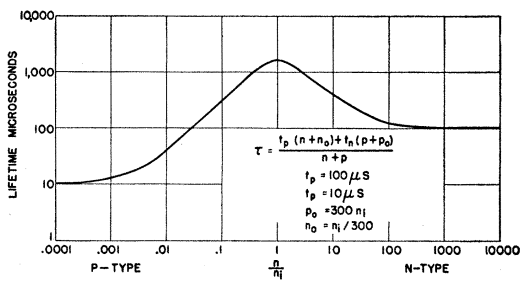

FIG. 1. Variation of lifetime with impurity content.

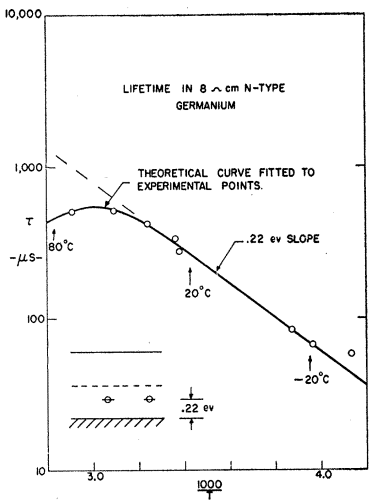

FIG. 2. Variation of lifetime with temperature.

In the derivation of Eq. (1), it is assumed that the rate of capture of electrons is proportional to the number of empty centers and to the number of free electrons. The rate at which electrons are emitted by these centers is proportional to the number of occupied centers. Analogous statements apply to the capture and emission of holes.

It is readily seen that Eq. (1) can account for the linear relation between carrier concentration and recombination rate mentioned in the first paragraph. With high level injection, n and p become equal and much greater than n_i, n_0, or p_0 so that $R \simeq n/(t_n+t_p)$. Rectifier characteristics calculated on the basis of Eq. (1) can be fitted to the data in a very satisfactory manner.[4] The lifetime for holes and electrons at high level injection (t_n+t_p) is usually found to be approximately 100 μsec.

The equilibrium lifetime which results from Eq. (1) is

$$\tau \equiv \mathrm{Lim}_{\delta n \to 0}(\delta n/\delta R)=[t_p(n+n_0)+t_n(p+p_0)]/(n+p). \qquad (2)$$

The variation of τ with impurity content is illustrated in Fig. 1 for a choice of parameters which gives reasonable agreement with lifetimes observed in samples of germanium at room temperature.

Since n_0 and p_0 vary exponentially with $1/T$ while t_n and t_p should be relatively insensitive to temperature, the lifetime should assume its limiting values t_n and t_p for p- and n-type samples at low temperatures. At higher temperatures, the lifetime increases with temperature as long as the sample remains extrinsic and then decreases again in the intrinsic range. Measurements of lifetime illustrating the variation with temperature in the upper two temperature ranges are shown in Fig. 2. The slope indicated on the graph gives a tentative value of 0.22 electron volt for the position of the recombination centers above the valence band or below the conduction band.

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[4] A detailed treatment of the germanium power rectifier will be published shortly.

An Experimental Test of the Shell Model

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IN a recent letter, Bethe and Butler[1] proposed an experiment to give direct information on the accuracy of the shell model of nuclear structure in ascribing definite orbital angular momen-