netic field. The real part of the permeability, which causes a shift in cavity resonance frequency, has also been measured.[2]

It is well known that ferromagnetic materials become anisotropic upon application of a magnetic field, and that consequently the permeability must be described by a tensor. The experimental results cited above yield only the diagonal tensor components. If Polder's theory[3] is assumed to hold, then the off-diagonal terms of the tensor can, in principle, be computed from measurements of the diagonal components. According to a suggestion by Lax,[4] the off-diagonal terms can be determined experimentally if the sample is placed in a microwave cavity which is degenerate in two orthogonal modes. If a microwave field excites one mode of oscillation, the electron spins which are precessing about the applied dc magnetic field will couple to and excite the orthogonal mode. The dc field removes the cavity degeneracy and causes a splitting of the cavity resonance—analogous to optical Zeeman splitting.

We have constructed a single input, right-circular cylindrical cavity, resonating at 9060 Mc/sec in the circular TE_{111} mode, which proved to be perfectly degenerate. Figure 1 shows the effect

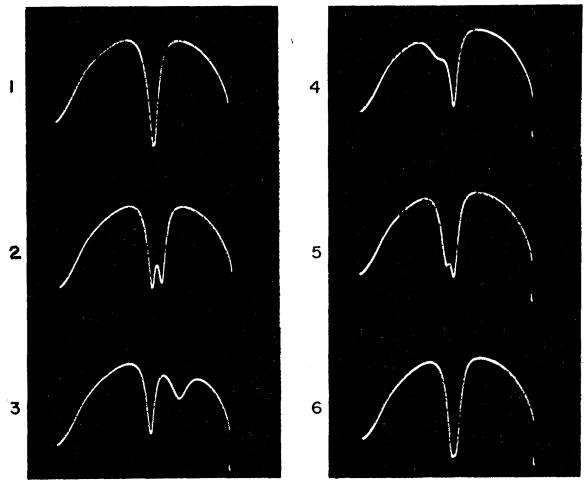

FIG. 1. Splitting of degenerate cavity modes in magnetic field. 1: 0 gauss; 2: 1400 gauss; 3: 2400 gauss; 4: 3600 gauss; 5: 4150 gauss; 6: 4950 gauss.

of introducing a small ferrite sample (Ni—Zn) into a region of maximum H and minimum E fields and applying a dc magnetic field perpendicular to the microwave H vector. The dips represent resonance absorption as seen by observing the microwave signal reflected from the cavity. The horizontal axis is proportional to the microwave frequency. As the dc magnetic field is applied, the single resonance is seen to split into two. The two linear orthogonal modes can be combined into either one of two oppositely rotating vibrations; that mode which rotates in the same direction as the electron spin precession may be designated as the "extraordinary mode." As expected from theory, the frequency shift of the extraordinary mode at first increases with the field; it then becomes negative beyond resonance, reappearing on the other side of the so-called ordinary mode. At approximately twice the resonance field the two modes coalesce again.

A plot of frequency shift *vs* magnetic field is shown in Fig. 2. It has the dispersion character described above. The solid curve is the frequency shift derived from theory[4] and has the form

$$\Delta\omega = C\omega(x'+k') = C\omega_r M/(H_r - H),$$

where x' and k' are the real parts of the diagonal and off-diagonal tensor components, respectively; ω_r is the fixed cavity resonant frequency; H_r is the magnetic field corresponding to gyromagnetic resonance at ω_r ($\gamma H_r = \omega_r$, where γ is the gyromagnetic ratio); C is a constant depending on the cavity geometry and size of ferrite; and M is the saturation magnetization, which is measured

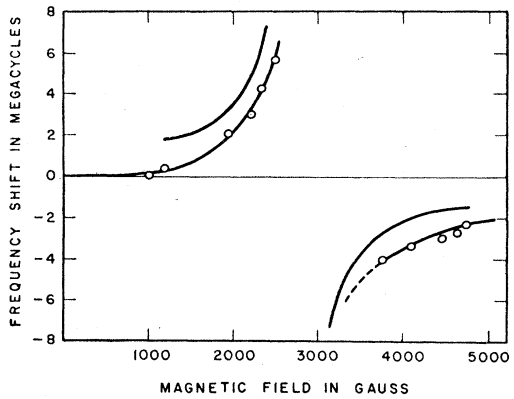

FIG. 2. Frequency shift of "extraordinary" mode due to ferrite in a dc magnetic field. Solid line is theoretical curve.

independently. Because it neglects resonance losses, the seconds equality holds provided H is not close to H_r.

The complete perturbation theory also gives expressions for the frequency shift of the ordinary mode and for the changes in Q of the ordinary and extraordinary modes as a function of magnetic field. The ordinary shift is too small to be measured accurately by our present frequency measuring techniques. We have qualitatively verified the changes in Q, but data which are interpretable in terms of the theory have been limited so far to the small region of H between saturation of the sample and resonance. At K-band frequencies this region would be extended because resonance occurs at a higher magnetic field strength. We have constructed a K-band cavity and have demonstrated the splitting effect.

Experimental refinements are in progress which we expect will make possible complete determination of the permeability tensor components.

We should like to express our thanks to Dr. Benjamin Lax for his stimulating interest.

* The research in this paper was supported jointly by the U. S. Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.

[1] See e.g., H. G. Beljers, Physica **14**, 629 (1948); W. A. Yager *et al.*, Phys. Rev. **80**, 744 (1950); D. W. Healy, Cruft Laboratory Report No. 135, Harvard University, August 15, 1951 (unpublished).

[2] H. G. Beljers, reference 1.

[3] D. Polder, Phil. Mag. **40**, 99 (1949).

[4] B. Lax and A. D. Berk, Convention Record of the Meeting of the Institute of Radio Engineers, March 1953 (unpublished).

Thermal Acceptors in Vacuum Heat-Treated Germanium

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WE wish to report studies on the solubility of thermal acceptors in copper-free germanium. Finn[1] has shown by measurements using radioactive copper as well as by electrical measurements that copper can be evaporated from germanium in high vacuum. In order to take advantage of evaporation as a means of purifying the germanium before heat treatment, we heat our specimen at a pressure of less than 4×10^{-7} mm of Hg by passing current directly through the germanium. Only the germanium becomes hot; and the possibility of contamination of the germanium is greatly reduced because the walls of the vacuum chamber cannot act as a source of impurity atoms as might the hot walls of a conventional vacuum furnace.

The germanium single crystal has dimensions $0.10\times0.33\times1.10$ cm and tantalum current leads are welded to its ends. Hall measurements give a value of the excess of donor impurities over

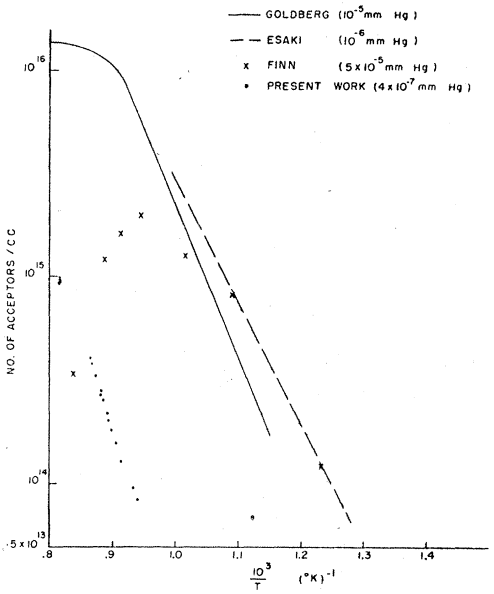

FIG. 1. The number of acceptors quenched into germanium after vacuum heat treatment at the temperature T as found by Goldberg, Esaki, Finn, and present work.

acceptor impurities, before any heating, of 2.1×10^{13}/cc. Resistivity measurements at 195°K serve to determine the number of acceptors quenched into the germanium. The sample is cooled by radiation with an initial cooling rate from temperatures near the melting point of 100°C/sec. All measurements are made while the germanium is contained in a kinetic vacuum system. Therefore, there is no opportunity to contaminate the germanium by handling during the experiments.

The temperature of a heat treatment is determined by measuring the resistivity of the germanium and determining the temperature by using the resistivity *vs* temperature data of Keyes.[2] In the temperature range above 700°C, an optical pyrometer serves to check the temperature. We estimate our error in temperature to be ±5°C.

In Fig. 1, we have plotted the number of acceptors quenched into the germanium in our experiment as a function of the reciprocal of the heat treatment temperature along with similar data obtained by Goldberg,[3] Esaki,[4] and Finn[1] who used conventional vacuum furnaces. The concentration of acceptors introduced in our experiments is as much as a factor of 80 smaller than the concentrations reported by the other workers. Figure 2 gives our data in more detail.

We believe that the thermal acceptors we observe are actually lattice vacancies and not impurity atoms such as copper for the following reasons. We heat at each temperature until no acceptors are lost or gained with further heating. Next, we observe no hysteresis effect; the same equilibrium number of acceptors is obtained at a given temperature whether or not the germanium was previously treated at a higher or a lower temperature. These observations are compatible with vacancies acting as the acceptors. The crucial difference between vacancies and impurities arises from the fact that the surface of the germanium is an infinite source and sink for vacancies, but not for impurities. In fact, since in our heating arrangement only the germanium is heated while the walls of the vacuum chamber are kept at room temperature, one might expect that as the temperature is increased more impurity atoms would leave the germanium surface than would strike it from the surrounding vacuum. Therefore, if the acceptors observed were impurities, the number of acceptors should be decreased with increasing heat treatment temperature. This is contrary to our observations.

The equilibrium density of lattice vacancies is described by the equation,

$$v=v_0e^{-E/kT},$$

where $v_0=(1.0\pm0.5)\times10^{24}$/cc and $E=2.15\pm0.04$ ev. Notice that v_0 is twenty times greater than the number density of Ge atoms $N_{Ge}(4.47\times10^{22}$/cc). Theoretically, it is to be expected that v_0

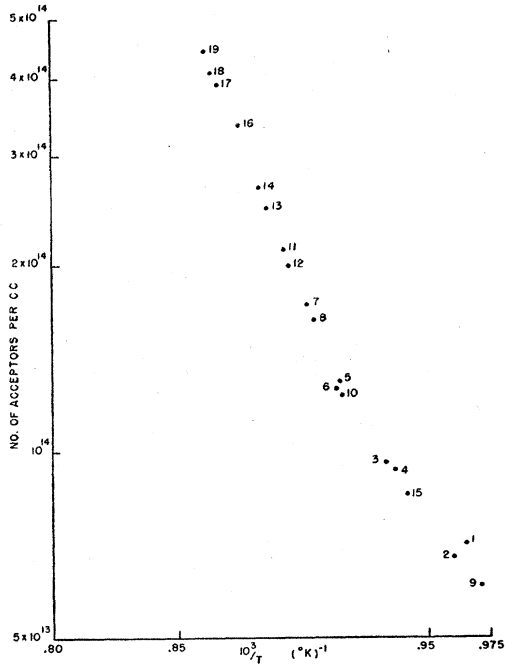

FIG. 2. Data of Mayburg and Rotondi on acceptors. The number associated with each point represents the order in which the heat treatments were performed. Notice that there is no hysteresis.

will be greater than N_{Ge} because the vibrational frequency of an atom next to a vacancy is less than the frequency of an atom surrounded by other atoms.[5]

We are indebted to R. W. Keyes of the Institute for the Study of Metals of the University of Chicago for making available to us his unpublished data on the resistivity of germanium at high temperatures.

[1] G. Finn, Phys. Rev. **91**, 754 (1953).
[2] R. W. Keyes (private communication).
[3] Colman Goldberg, Phys. Rev. **88**, 920 (1952).
[4] G. Esaki, Phys. Rev. **89**, 1026 (1953).
[5] N. F. Mott and R. W. Gurney, *Electronic Processes in Ionic Crystals* (Clarendon Press, Oxford, 1948), p. 30.

Thickness of the Saturated Helium II Film

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THIS letter describes the salient features of an investigation of the saturated helium II film, using a gravimetric method. The method involves determining the effective increase in weight of a specimen as the helium II film forms on it.[1]

The thickness of the helium II film has been measured by a number of workers, but different investigations have yielded widely differing results. Estimates of the film thickness varying from 50 to 160 atomic layers, and there seems to be little underlying consistency in the data of different workers.[2] The present investigation was undertaken in an attempt to resolve some of these disparities.