of the magnetic field. This appears to be consistent with gyro-interaction theory of radiowaves in the ionosphere.[3]

A detailed discussion of the phenomenon of interaction of electromagnetic waves in a gaseous discharge plasma will be published at a later date.

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[*] Supported by Air Force Cambridge Research Center and Wright Air Development Center.

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Ultrasonic Attenuation Measurements in Germanium

ROHN TRUELL AND JOSEPH BRONZO
Metals Research Laboratory, Brown University, Providence, Rhode Island

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ULTRASONIC attenuation (scattering and absorption) in solid materials has been studied as a function of the ultrasonic frequency and as a function of the state or condition of the material for a number of materials. In particular, it has been found that differences in the state of a semiconductor can be examined by these attenuation measurements.[1] Single crystals of germanium[2] with various histories were examined over a frequency range from 15 to 100 Mc/sec. The attenuation measurements show large differences among the germanium samples; differences caused both by heat treatment and by impurities deliberately introduced.

Figure 1 shows the attenuation as a function of frequency for four samples of germanium in the frequency range from 15 to 45 Mc/sec. The top curve, marked 1, was obtained from measurements on a sample of N type germanium with resistivity $\rho \cong 0.6$ ohm cm. This sample had a lot of N type impurities deliberately introduced. Curve number 2 was obtained from measurements on a sample of P type germanium, in this case with a lot of P type impurities deliberately introduced and again with $\rho \cong 0.6$ ohm cm. Curve number 3 was obtained from a sample of basic germanium with as small an amount of impurities as can readily be obtained. The resistivity was 12.7 ohm cm. The lowest curve, number 4, was obtained from a sample of germanium which was produced from pure germanium with $\rho = 13.2$ ohm cm and then raised in temperature to 915°C for one hour and quenched. The final germanium crystal was P type with $\rho = 0.2$ ohm cm. All of these single crystals were carefully oriented so that the propagation is normal to the 100 planes.

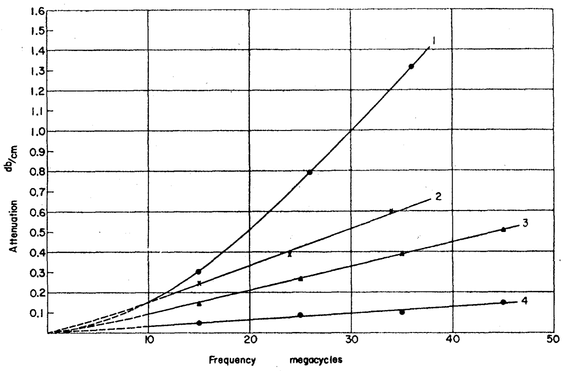

FIG. 1. Ultrasonic attenuation in germanium, as a function of frequency. Propagation normal to 100 planes.

It is clear that above 20 Mc/sec there is a large difference among the samples as far as ultrasonic attenuation measurements are concerned. It seems reasonable that curves 1 and 2 should give rise to higher attenuation than curve 3, since the former samples should have many more defects than the latter sample. It is perhaps surprising that the pure germanium which has been heat treated to P type should have lower attenuation than the original crystal, especially since the heat treatment included quenching. It seems that this heat treatment has removed some of the "defects" from the germanium, but it is difficult to determine the nature of the "defects." It is of interest to note that while for each of the two samples with N and P type impurities the resistivity is 0.6 ohm cm, the attenuation differs by as much as a factor of two at 35 Mc/sec. Between the heat-treated sample and the N type impurity sample the attenuation differs by a factor of about ten to one at 35 Mc/sec.

The data pertaining to curve 4 is not quite as satisfactory as regards accuracy[3] as the other data for the remaining three curves, but the relative position of curve 4 with respect to the other curves is as shown.

It is believed that the attenuation measurements can be used to show relative amounts or numbers of defects present. It is desirable, of course, to separate or sort out the relative amounts of various types of defects. Measurements over a wide range of frequency and over a set of specially prepared samples may permit this separation or sorting of types of defects.

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[2] The germanium single crystals used in this experiment were kindly supplied to us by Dr. W. P. Mason of the Bell Telephone Laboratories.

[3] These low attenuation values are at present difficult to measure.

Temporary Traps in Silicon and Germanium

J. R. HAYNES AND J. A. HORNBECK
Bell Telephone Laboratories, Murray Hill, New Jersey

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EVIDENCE indicating the existence of trapping centers other than recombination centers for minority carriers in germanium and silicon has been obtained[1] from drift velocity measurements. Specifically, in p-type silicon at room temperature and n-type germanium at -80°C and lower temperatures some of the carriers appeared to suffer an additional time delay in their transit between emitter and collector. This straggle could be eliminated by increasing the ambient light falling on the semiconductor specimens. A qualitative explanation of these observations was made in terms of a simple trap model. For low external illumination some of the carriers are caught in "traps" where they sit for a time and then are ejected back into the conduction stream. High external illumination, however, creates sufficient electron-hole pairs to keep the traps filled, and no straggle is observed. By adjusting the external illumination so that a few of the carriers arriving at the collector are trapped once and the rest are not trapped at all, an estimate of the mean lifetime in a trap, τ_g, can be made.

Photoconductivity and lifetime experiments recently have furnished independent evidence for the existence of traps and have led to a quantitative empirical description of traps in a uniform crystal of 28-ohm-cm p-type silicon.[2] The basic experiment with the silicon crystal is the following. The darkened crystal is first illuminated by a light source; then the source is cut off, and the decay in photoconductivity is measured as a function of time. The decay occurs in three well-defined steps: first comes a rapid decrease in conductivity with a time constant of 20 μsec; there follows a slower decrease in conductivity which asymptotically is exponential with a final time constant of 10^{-2} sec; this is followed by a very slow decrease in conductivity with a final time constant of 260 sec.

The experiment is interpreted as follows. Illumination creates electron-hole pairs at a rate sufficient to fill two sets of volume traps, deep and shallow, and also add electrons to the conduction band. When the illumination is removed, the electrons in the conduction band recombine ($\tau_r = 20$ μsec) before the occupancy of the traps changes appreciably. Somewhat later the shallow traps empty ($\tau \sim 10^{-2}$ sec), and this occurs before the occupancy of the deep traps changes appreciably. Finally, the deep traps empty ($\tau \sim 260$ sec). Each set of traps gives a long decay time because the average electron is trapped many times before it recombines. The photoconductivity associated with trapping comes from the additional free holes in the valence band which, due to space charge neutrality, are exactly equal in number to the number of trapped electrons.

It can be shown that the final decay time τ is related to τ_r, τ_g (the mean time an electron spends in a trap for a single trapping event), and τ_t, the mean free time an electron spends in the conduction band before trapping when most of the traps are empty. Approximately, $\tau = \tau_r \tau_g / \tau_t$. Because the time constants are so well separated, it can be shown that this formula applies to each set of traps independently.

For the shallow traps $\tau = 10^{-2}$ sec, $\tau_g = 50$ μsec, and since $\tau_r = 20$ μsec, $\tau_t = 1 \times 10^{-7}$ sec. For the deep traps τ_g cannot be measured independently, but it can be estimated from the agreement between the theory of the multiple trapping process and experiment. Thus for the deep traps, $\tau = 260$ sec, $\tau_g \simeq 1$ sec, $\tau_t \simeq 1 \times 10^{-7}$ sec. The concentration of normally empty trapping sites N can be obtained from the amplitudes of the conductivity changes. For the shallow traps $N_1 = 2 \times 10^{12}$ cm^{-3}, for the deep traps $N_2 = 9 \times 10^{12}$ cm^{-3}. If we may write $1/\tau_t = N\sigma v$, where σ is the trapping cross section and v is thermal velocity, then $\sigma_1 = 4 \times 10^{-13}$ cm^2 and $\sigma_2 \simeq 1 \times 10^{-13}$ cm^2.

From the ratios $(\tau_g/\tau_t) = (\tau/\tau_r)$, the energy ϵ of the traps below the bottom of the conduction band may be computed by using the principle of detailed balance which relates σ and τ_g. We find $\epsilon_1 = 0.57$ and $\epsilon_2 = 0.79$ ev. The Fermi level for this specimen, $\epsilon_F = 0.72$ ev.

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[2] Trapping effects have also been observed in *n*-type silicon at room temperature.

The Magnetoresistance Effect in InSb

G. L. Pearson and M. Tanenbaum
Bell Telephone Laboratories, Murray Hill, New Jersey

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Welker[1] has recently shown that the compound indium antimonide is a semiconducting material with properties akin to the fourth column elements germanium and silicon and that it has unusually high electron and hole mobilities. This letter describes the preparation of the compound in a highly purified form as well as the results of magnetoresistance measurements which verify the high electron mobility. Analysis of the data indicates that the energy surfaces in InSb are spherical in nature as contrasted with the more complicated structure proposed for germanium.

The compound was prepared by melting together stoichiometric amounts of indium and antimony metals. InSb crystallizes in the zincblende lattice[2] and melts at 523°C.[1] The starting materials and the resulting compound were purified by extensive zone-refining.[3] In this manner polycrystalline specimens of 0.03-ohm cm resistivity were obtained. The primary impurity in the final material is arsenic in concentrations of approximately 0.01 percent. By spectrographic analysis all other impurities were shown to be below 0.005 percent. The compound is stoichiometric to within 0.2 percent of antimony which is the reliability of chemical analysis. All material prepared to date has been *n* type at room temperature and shows a reversal to *p* type near 175°K.

Samples suitable for making magnetoresistance measurements were prepared as previously described.[4] With **H** perpendicular to **I**, it was found that at room temperature $\Delta\rho/\rho = 8 \times 10^{-9} H^2$ over the entire range of measurement from 0 to 13 000 gauss. For this alignment simple theory[5] predicts that

$$\mu^2 = 2.6 \times 10^{16} H^{-2} \Delta\rho/\rho,$$

where μ is the electron mobility in cm^2/volt-sec. Substitution of the experimentally determined value of $H^{-2}\,\Delta\rho/\rho$ gives an electron mobility of 15 000 cm^2/volt-sec at room temperature. Hall measurements[6] on the same sample gave a value of 23 000 cm^2/volt-sec. Welker has reported[1] Hall mobilities as high as 25 000 cm^2/volt-sec. As the temperature is lowered and the magnetic field held constant, $\Delta\rho/\rho$ reaches a maximum at 270°K and then decreases.

Figure 1 is a plot of $\Delta\rho/\rho$ for the InSb sample as a function of the angle θ between the applied field **H** and the current **I** at a fixed magnetic field of 13 000 gauss. It is seen that the effect is maximum for **H** perpendicular to **I** and approaches zero for **H** parallel to **I**. This behavior is in agreement with simple theory[5] which assumes spherical energy surfaces and is in contrast with the measurements on *n*-type germanium[4] where nonspherical energy surfaces have been proposed by Shockley[7] to explain the results.

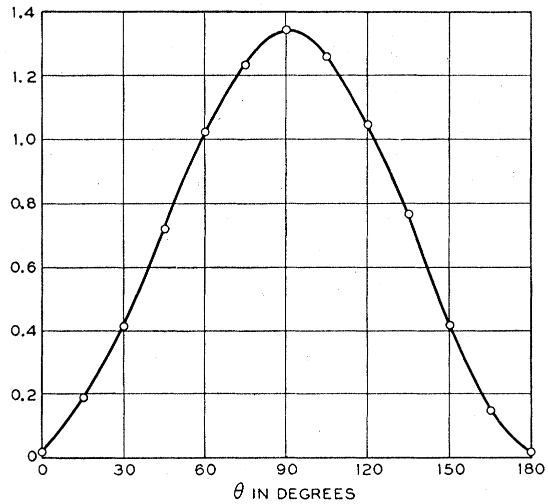

FIG. 1. Variation of $\Delta\rho/\rho$ in InSb as H is rotated through an angle θ from 0 to 180 degrees. H is 13 000 gauss and T is 300°K

We wish to acknowledge the valuable correspondence received from H. Welker prior to the publication of his work on InSb. We wish to thank W. Shockley for his helpful discussions regarding the results reported here and W. L. Feldmann for assistance with the experimental measurements.

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The Continuous Layer Formation in the Atmosphere under the Influence of Solar Radiation*

H. K. Kallmann
University of California, Los Angeles, California

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The ionized layer formation in the atmosphere under the influence of a quiet sun and under the influence of a disturbed sun has been investigated. It has been found that a continuous layer formation in the ionosphere for both cases can be obtained, if account is taken of the variation with height of dissociation of molecular constituents and of the variation with height of ionization of the different constituents present at the various altitudes. By "continuous layer formation" we refer to continuous increase and decrease of the electron density with height, throughout the entire ionosphere.