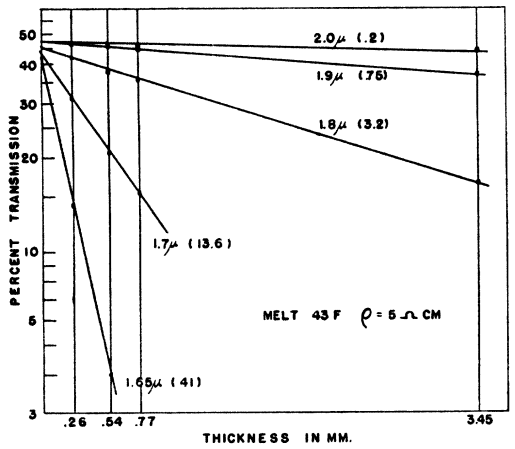

FIG. 2. Percentage transmission of germanium as a function of thickness for various wave-lengths. The figures in the parentheses give the absorption coefficient in cm^{-1} for each wave-length.

Union concentrated arc, or a Nernst glower as light sources, and a vacuum thermopile as detector. Curves for three samples of different thicknesses, 0.26 mm, 0.77 mm, and 3.45 mm, of N-type germanium from the same melt are shown in Fig. 1. The samples are single crystals with reistivity of about 5 ohm cm.[3] Figure 2 gives the logarithm of percentage transmission plotted against sample thickness for different wave-lengths. To determine the absorption coefficient from transmission measurements it is necessary for the samples to have the same reflecting power R. To insure this both surfaces of the samples were optically polished. It is seen from Fig. 2 that at wave-lengths where the absorption is small and the transmission is determined primarily by surface reflections, there is no irregular variation of transmission for the different samples. This shows that the surfaces of the samples as prepared do have nearly the same reflecting power.

If the transmitted light is given by

$$I/I_0=(1-R)^2e^{-\epsilon l}, \quad l=\text{thickness of material},$$

then ϵ and R are determined from the slope and intercepts of the straight lines in Fig. 2. However, when the transmission is high, multiple reflections ot both surfaces have to be taken into account. Starting from known formulas[4] and taking into account the finite width of the spectrum used in the measurement of each point, it can be shown that

$$I/I_0=[(1-R)^2+4R\sin^2x]/(e^{\epsilon l}-R^2e^{-\epsilon l}),$$

where $x=\tan^{-1}[2k/(n^2+k^2-1)]$, n being the index of refraction. The term involving x is negligible in the range of our measurements. Using this expression to analyze the experimental data we find that the reflecting power $R=0.35$ (in agreement with results in I), is constant within the spectrum covered by our measurements. The absorption coefficient, $\epsilon=4\pi kv/c$, is plotted in Fig. 3.

The absorption increases rapidly for wave-lengths below 2μ. For measurements below 1.6 much thinner samples have to be used. For wave-lengths above 2 the absorption is so small that much thicker samples, i.e., several cm, should be used for accurate measurement. A single crystal 15 mm thick was cut from a melt of about the same resistivity, 5 ohm cm. The transmission curve for this sample is included in Fig. 1 and the absorption coefficient, calculated using $R=0.35$, is given in Fig. 3. The absorption coefficient curves for the two similar melts agree in shape and in order of magnitude. The discrepancy may be due to inaccuracy on account of insufficient thickness of samples used.

Similar measurements were made on samples from a melt of much lower resistivity, 0.015 ohm cm. These samples are polycrystalline with 2 or 3 grain boundaries in the light beam. The curve of absorption coefficient is also shown in Fig. 3. The absorption is seen to be higher than that of high resistivity single crystal samples. The reflecting power is constant for the spectrum covered and is the same, $R=0.35$, as for the high resistivity samples.

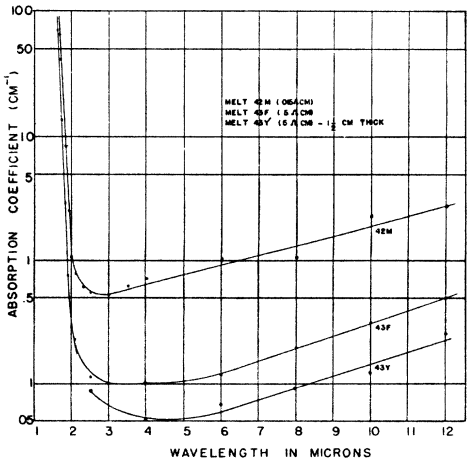

FIG. 3. Absorptivity of germanium as a function of wave-length for different resistivities. The curve for 43 Y is drawn assuming the same reflectivity as the other melts since only one thick piece was available.

* Signal Corps Contract W36-039-sc-38151; Progress Report (February, May, 1949). A summary of this work was presented at the Ad Hoc Crystal Meeting at M.I.T. (June, 1949).

[1] W. H. Brattain and H. B. Briggs, Phys. Rev. **75**, 1705 (1949).
[2] L. R. Ingersoll, Astrophys. J. **32**, 286 (1910).

[3] The authors wish to thank Mr. W. E. Taylor for preparing the single crystal, high resistivity melts.

[4] R. B. Barnes and M. Czerny, Phys. Rev. **38**, 338 (1931).

Optical Properties of Semiconductors. III. Infra-Red Transmission of Silicon*

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October 3, 1949

LIKE germanium, bulk silicon also shows appreciable transmission in the infra-red. This can be directly demonstrated photographically since high transmission begins at 1.0μ. Type I-Z photographic plates are sensitive to 1.3μ. Spot images of a parallel light beam can be photographed on such plates through a piece of silicon 0.3 mm thick in a few seconds of exposure. (In the case of germanium, high transmission begins at 1.6μ, beyond the sensitivity of the plates. Thirty-six hours of exposure through germanium does not affect the plate at all.)

Using basically the same experimental arrangement described in the companion letter on germanium, transmission measurements were made on low resistivity ($\rho=0.03$ ohm cm) P-type silicon from liquid air temperature to 380°C. The reflecting power deduced from these measurements is constant for the spectral region covered: $R=0.27$, in agreement with earlier measurements by K. Lark-Horovitz and K. W. Meissner. Figure 1 shows the absorption curves for different temperatures. The absorption is seen to decrease with decreasing temperature over the entire spectrum covered by the measurements. The values of extinction coefficient obtained by Ingersoll[1] are several orders of magnitude higher than our results. This may very well be due to the fact that the material used in these early experiments was very impure. For instance, germanium strongly doped with aluminum (~0.005 ohm cm) shows absorptions at least several orders of magnitude higher than the data presented in the companion letter.

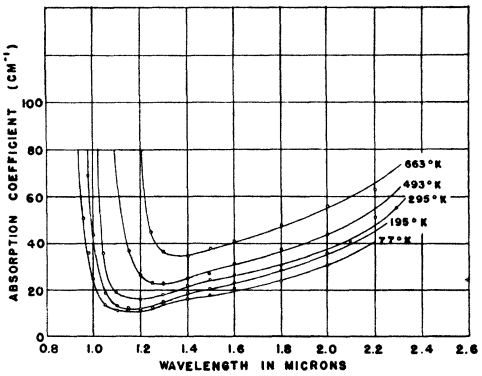

FIG. 1. Temperature dependence of the infra-red absorptivity of low resistivity silicon as a function of wave-length.

The sharp increase of absorption for both germanium and silicon toward short wave-lengths is apparently due to quantum transitions from the filled to the conduction band. The energy gap between these bands as determined from intrinsic conductivity measurements is about 0.76 ev for germanium and about 1.1 ev for silicon. The absorption band is then expected to begin at about 1.6μ and 1.1μ respectively. Our measurements show that at room temperature absorption begins to rise at about 2μ for germanium and at about 1.2μ for silicon. The results for silicon shown in the figure indicate a definite temperature dependence.

For wave-lengths longer than required for excitation between bands absorption can be caused by free electrons and holes. Such absorption can be calculated according to the Drude-Zener theory which gives the conductivity

$$\sigma(\nu)=nk\nu=[\gamma^2/(\nu^2+\gamma^2)]\sigma_0,$$

where σ_0 is the d.c. conductivity, and γ is related to the mobility, b, by

$$\gamma=e/2\pi mb,$$

n being the number of carriers.

The values of b for the samples used were determined by Hall effect and resistivity measurements. The absorption so calculated is only about one-tenth of the observed values for silicon. For germanium the calculated absorption is two to three orders of magnitude too small. This fact has yet to be explained.

* Work supported by the Signal Corps.
[1] L. R. Ingersoll, Astrophys. J. 32, 286 (1910).

Protons from the Bombardment of He^3 by Deuterons*

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September 26, 1949

THE $He^3(d, p)He^4$ reaction has long been a tantalizing gap in experimental studies of nuclear transmutations. The expected Q-value for the reaction can be calculated from the masses of the particles, and is 18.368 ± 0.042 Mev according to the mass tables of Bainbridge.[1] This is larger than any other known Q-value for a d, p reaction. Recently Hatton and Preston[2] observed the reaction at 90° and found a single group of protons which had approximately the expected range. They found no excited states of He^4.

A study of $He^3(d, p)He^4$ has been made at Yale University using a 1.13-cm^3 sample of helium gas containing 88 percent He^3 and 12 percent He^4.† The objectives of this study were to determine the angular distribution of the proton yield, to search for excited states of the He^4 nucleus at several angles, and to determine experimental Q-values for the reaction by measuring the ranges of the emitted protons. Comparison of the experimental Q-value with the calculated Q-value gives an experimental point on the range-energy curve for high energy protons.

The apparatus used in the experiment is shown in Fig. 1. The deuteron beam was collimated by two $\frac{1}{8}$-in. holes and approximately 0.03 μa entered the helium target through a calibrated aluminum foil. The mean beam energy in the target was 3.17 ± 0.05 Mev. The thickness of the aluminum chamber wall was 158 ± 7 mg/cm^2 which was thick enough to stop protons from all reactions except those from $He^3(d, p)He^4$. Protons from the target could be observed at any angle from 0° to 130°. A description of the spectrometer apparatush as been given previously.[3] The solid angle presented by the counter aperture corresponded to the Livingston and Bethe[4] criteria for "good geometry."

The proton yield was large indicating an exceptionally large reaction cross section. Curves of yield *vs.* total absorption were obtained at 0°, 45°, and 90°. Two typical curves obtained at 0° are shown in Fig. 2. Curve A was taken with the discriminator set to accept all pulses slightly larger than noise. For curve B the discriminator was adjusted so that only the largest pulses would record. Curves of type A were used to determine the extrapolated range at each angle. The extrapolated range was converted to mean range according to the procedure outlined by Livingston and Bethe,[4] account being taken of the fact that a small part of the absorbing path was in air and the remainder in aluminum. The proton energy was obtained from the mean range by using the range-energy curves of Bethe.[5] Table I lists for each angle the corrected mean ranges, the proton energies, the experimental Q-values and the proton energy expected from the 18.368-Mev Q-value. The proton ranges taken with the calculated proton energies give experimental determinations of the proton range-energy relation. These points agree with the range-energy curve of Bethe to within ±1 percent, which is the precision of the experiment.

TABLE I. Summary of experimental ranges, proton energies, and Q-values for $He^3(d, p)He^4$ compared with expected proton energies calculated from $Q=18.368$ Mev.

Angle of observation	Mean range (cm)	Proton energy (Mev)	Experimental Q (Mev)	Calculated proton energy (Mev)
0°	423 ± 5	20.6 ± 0.17	18.45 ± 0.17	20.53
45°	367 ± 6	19.2 ± 0.2	18.5 ± 0.2	19.08
90°	269 ± 6	16.1 ± 0.2	18.5 ± 0.2	15.96

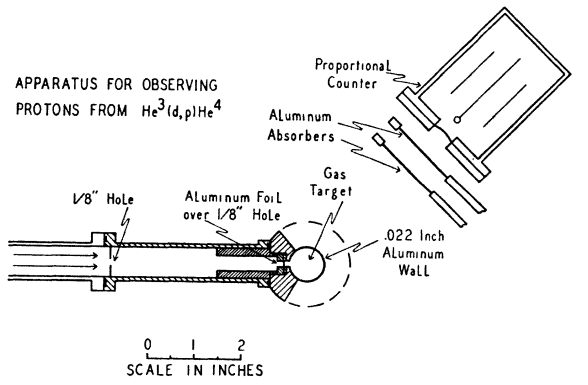

FIG. 1. Target chamber and counter. The target chamber was constructed from an aluminum cylinder; only two gaskets were necessary. Counter and absorbers could be rotated about target so that protons from the target could be observed at any angle from 0° to 130°.