Letters to the Editor

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Optical Absorption of Single-Crystal Strontium Titanate

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A BRIEF investigation of the optical absorption of single-crystal strontium titanate in the spectrum range from 0.35 to 15.0 microns has been carried out in this Laboratory. The crystals measured were obtained through the courtesy of National Lead Company where they were grown by the flame fusion technique.[1] Data from 0.35 to 1.0 microns were taken with a Beckman Model DU spectrophotometer while the region from 1.0 to 15.0 microns was investigated with a Perkin-Elmer Model 12C spectrophotometer equipped with rocksalt optics.

The absorption coefficient was obtained by measuring optically polished samples of several thicknesses ranging from 0.20 mm to 17.0 mm. By applying the equation for the absorption coefficient,

$$a=\ln(T_1/T_2)/(x_2-x_1),$$

where T_1 and T_2 are transmission values for samples of thickness x_1 and x_2, respectively, a was computed as a function of wavelength throughout the range where it was possible to detect transmission in the samples measured. The results of these calculations are shown in Fig. 1.

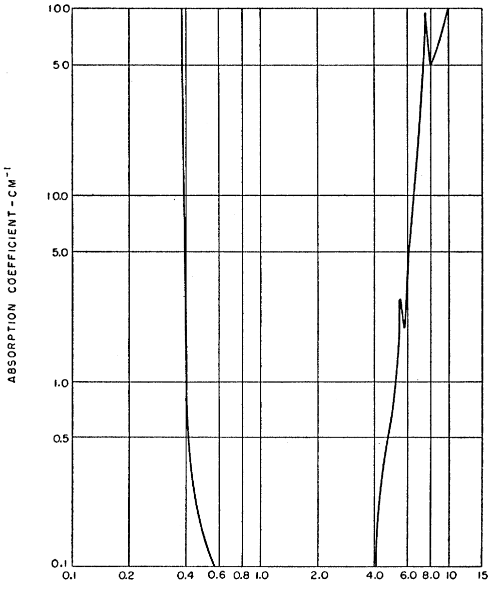

FIG. 1. Absorption coefficient of single crystal $SrTiO_3$ as a function of wavelength.

The ultraviolet cutoff for strontium titanate is found to be 0.385 micron. This edge is probably associated with the energy gap from the valence band to the conduction band, and therefore this gap is evaluated by optical methods to be 3.22 electron volts. Because of the low absorption in this material, a transmission of better than 70 percent was obtained from 0.55 to 5.0 microns for a 1.0-mm thick sample. A maximum transmission of 80 percent was found at 4.0 microns for this sample. It is possible that this high transmission in the near infrared could make strontium titanate applicable as a window material for this spectral region. The absorption bands observed at 5.5 and 7.5 microns are presumably due to vibrations of the crystal.

According to Linz,[2] an absorption is observed at about 2.0 microns for strontium titanate single crystals. However, no such absorption was observed at this laboratory. Since the crystals studied here and the ones reported on by Linz were obtained from the same source and grown in the same way, no explanation is advanced at this time for this apparent discrepancy in transmission data.

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[1] L. Merker and L. E. Lynd, U. S. Patent 2,628,156, February 10, 1953 (unpublished).

[2] Arthur Linz, Jr., Phys. Rev. 91, 753 (1953).

Hall Mobility of Electrons and Holes in Silicon*

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THE mobility of charge carriers has been investigated as a function of the resistivity in a number of silicon single crystals,[1] all of which were grown from Dupont hyperpure material. The *n*-type crystals ranged in resistivity from 0.01 to about 94 ohm cm and the *p*-type crystals from 0.025 to about 110 ohm cm.

Slices were cut from the crystals perpendicular to the direction of growth, and proper sample shape[2] was obtained by using an ultrasonic machine tool.[3] All data were taken at room temperature (295 Kelvin).

The measured values ($R\sigma$) for the mobility as a function of resistivity are given for electrons in Fig. 1 and for holes in Fig. 2.

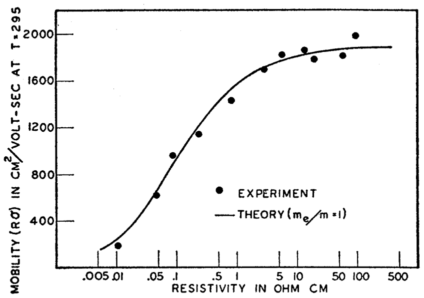

FIG. 1. Hall mobility of electrons in silicon as a function of resistivity.

The solid line represents the theoretical relationship which was calculated from the Herring[4] expression for the impurity mobility μ_I:

$$\mu_I=\frac{2^{7/2}\kappa^2(kT)^{\frac{3}{2}}}{\pi^{\frac{3}{2}}m_e^{\frac{1}{2}}e^3N_I}\,\frac{1}{\ln(1+b)-b/(1+b)},$$

where

$$b=\frac{6}{\pi}\,\frac{\kappa m_e k^2T^2}{n\hbar^2e^2}.$$

In this formula the dielectric constant κ was taken as 12, the absolute temperature was $T=295$, and the effective mass m_e of the charge carriers was the electron mass. The density of the ionized impurities N_I was assumed to be equal to the density of conduction electrons n. The theoretical Hall mobility plotted in Figs. 1 and 2 was obtained by combining the lattice mobility μ_L and the im-

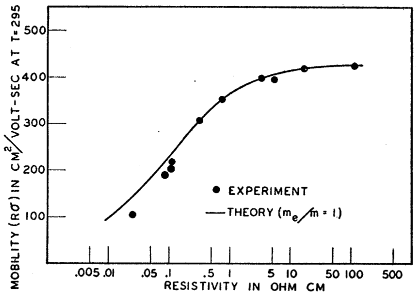

FIG. 2. Hall mobility of holes in silicon as a function of resistivity.

purity mobility μ_I. This was done by assuming a lattice drift mobility of 1600 for electrons and 360 for holes and then using the plot μ/μ_L *versus* μ_L/μ_I published by Conwell.[5] The drift mobility obtained from this was then converted into Hall mobility by using the curve published by Jones.[6]

The agreement of theory and experiment seems to be quite good, with the possible exception of the low-resistivity region in *p*-type silicon. In material of high purity the Hall mobility is apparently about 1900 cm²/volt-sec for electrons and 425 for holes, but it may be well to recall at this point the results on germanium, where—over a period of years—a gradual rise of the measured mobility was observed. This presumably was due to increasing perfection of the crystals and a similar development may manifest itself for the case of silicon.[7]

* This work was supported in part by the U. S. Bureau of Ships, U. S. Signal Corps, and U. S. Air Force.

[1] The crystals were grown by W. D. Straub and A. Adams, Jr., of the Research Division, Raytheon Manufacturing Company, Waltham, Massachusetts.

[2] Similarly shaped samples were used for the measurements described by P. P. Debye and E. M. Conwell, Phys. Rev. **93**, 693 (1954).

[3] J. P. Aloisio and N. Clark, Jr., A.S.T.E. annual collected papers of Industrial Exposition, April 26–30, 1954 (to be published). The sample preparation was done by Ann Cassola.

[4] C. Herring (private communication). See also H. Brooks, Phys. Rev. **83**, 879 (1951).

[5] E. M. Conwell, Proc. Inst. Radio Engrs. **40**, 1331 (1952), Fig. 3.

[6] H. Jones, Phys. Rev. **81**, 149 (1951). See also V. A. Johnson and K. Lark-Horovitz, Phys. Rev. **82**, 977 (1951).

[7] G. deMars (private communication). Preliminary result of drift mobility measurements seem to indicate good agreement for the case of electrons; however, the measured drift mobility for holes is considerably larger than the measured Hall mobility.

Atomic Hydrogen Hyperfine Structure in Irradiated Acids*

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PARAMAGNETIC resonance absorption lines have been observed in a variety of substances after irradiation with Co^{60} gamma rays at 77°K, and are attributed to free radicals. One of the radicals formed and trapped in $HClO_4$, H_2SO_4, and H_3PO_4 has been identified as atomic hydrogen.

Samples were frozen in Pyrex capillaries (usually to glasses), irradiated in liquid N_2 at a dose rate of about 3000/min for several days, and stored in liquid N_2 until measured.

The spectrometer operated at 23 000 Mc/sec and used a rectangular cavity excited in the TE_{102} mode. The magnetic field, of about 8000 gauss, was applied normal to the H vector of the rf field, and was modulated sinusoidally at 60 cps. The lines were displayed on an oscilloscope, and the magnetic field was measured with a proton magnetic resonance signal superimposed on the paramagnetic resonance line. The microwave frequency, held constant during each set of measurements, was measured by proton resonance superposition on the line from a sample of diphenyl picryl hydrazyl placed simultaneously in the cavity beside the tip of the Dewar vessel holding the capillary sample.

TABLE I. Hyperfine separations ν_H and electron g factors for hydrogen in irradiated acids.

Acid[a]	Mole ratio H_2O: acid	Microwave freq., Mc/sec[b]	High-field line, gauss[c]	Low-field line, gauss[c]	ν_H, Mc/sec	g
$HClO_4$	7.0	23 033.5	8462.7	7960.2	1407.1	2.0022
		23 033.7	8462.6	7960.6	1405.6	2.0022
		23 033.7	8462.9	7960.2	1407.3	2.0022
H_2SO_4	2.1	23 045.1	8467.0	7961.4	1415.7	2.0025
		23 042.7	8466.8	7961.5	1414.9	2.0023
		23 043.7	8466.6	7961.4	1414.5	2.0024
H_3PO_4	0.0	23 065.2	8475.3	7967.0	1423.5	2.0025
		23 064.7	8475.6	7967.3	1423.3	2.0024
		23 065.5	8475.8	7967.5	1423.4	2.0024

[a] The measurements on each acid were made in succession on a single sample.
[b] From measurements on hydrazyl radical; see text.
[c] From proton resonance measurements, using $\gamma_p = 2.67523 \times 10^4$ sec^{-1} gauss^{-1}; Thomas, Driscoll, and Hipple, Phys. Rev. **78**, 787 (1950).

Four lines were observed in concentrated H_2SO_4. Two of these were near the g value of the free electron, one rather sharp and one very broad and probably complex. The other two were symmetrically placed on either side of the central pair, were of about equal strength and width (about 4-gauss width at half-height), and were about 500 gauss apart. $HClO_4$ and H_3PO_4 showed the same satellites but different central lines. Irradiated mixtures of these acids with D_2O showed three additional lines, one near the g value of the free electron and two located like the sharp satellites above, but much closer together.

No changes in the strengths of the lines were observed on prolonged storage at 77°K. However, they disappeared at higher temperatures that were still well below the softening points. A marked dependence of relative line intensities on water content was observed. In the case of H_2SO_4, dilution first strengthened the satellites and weakened the sharp central line, the latter almost disappearing at a water-to-acid mole ratio of about 2:1. The satellites behaved similarly in the other two acids. Extreme dilution weakened the whole pattern.

The microwave frequency in each experiment was calculated from the observations on the diphenyl picryl hydrazyl radical using $g = 2.0037$ for this radical,[1] and was always in good agreement with that given by a cavity wave meter used simultaneously. Since the separations of the satellite lines in the samples suggested atomic hydrogen hyperfine structure, the frequencies and magnetic fields for these lines were reduced to the hyperfine separation and the electron g factor by the Breit-Rabi formula.[2,3] The transitions measured (Nafe and Nelson's[2] notation) were $(0, 0 \rightarrow 1, 1)$ and $(1, -1 \rightarrow 1, 0)$ for hydrogen. The polarization described above permits only those transitions for which $\Delta m = \pm 1$.

The data and calculated results are summarized in Table I. All of the values for the g factor are equal, within our present experimental error, to the free electron value of 2.0023. The ν_H values are strikingly close to Nafe and Nelson's[2] atomic beam value of 1420.410 Mc/sec. This indicates that the unpaired electron is represented very well by an atomic hydrogen 1*s* wave function, and that the hydrogen has no chemical bond in the usual sense. The spread in values between the different acids is, however, outside the experimental error, and indicates a small environmental effect on the wave function.

One set of preliminary measurements has been made on H_2SO_4 diluted with D_2O. The three lines observed for deuterium were the satellites $(\frac{3}{2}, -\frac{3}{2} \rightarrow \frac{3}{2}, -\frac{1}{2})$ and $(\frac{1}{2}, \frac{1}{2} \rightarrow \frac{3}{2}, \frac{3}{2})$ and the unresolved central doublet $(\frac{1}{2}, -\frac{1}{2} \rightarrow \frac{3}{2}, \frac{1}{2})$ and $(\frac{1}{2}, \frac{1}{2} \rightarrow \frac{3}{2}, -\frac{1}{2})$. The calculated hyperfine separation for deuterium ν_D and for hydrogen ν_H in the same sample gave a ratio $\nu_H/\nu_D = 4.342$, in good agreement with Nafe and Nelson's[2] more accurate value of 4.33867.

A more detailed study of these acids is now under way. We wish to thank J. Jauch for helpful discussion.

* This work was performed for the U. S. Atomic Energy Commission.

[1] C. A. Hutchison and R. C. Pastor, Phys. Rev. **81**, 282 (1951).

[2] J. E. Nafe and E. B. Nelson, Phys. Rev. **73**, 718 (1948).

[3] G. Breit and I. I. Rabi, Phys. Rev. **38**, 2082 (1931).