



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-Horowitz, *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 Co⁶⁰ gamma rays at 77°K, and are attributed to free radicals. One of the radicals formed and trapped in HClO₄, H₂SO₄, and H₃PO₄ has been identified as atomic hydrogen.

Samples were frozen in Pyrex capillaries (usually to glasses), irradiated in liquid N₂ at a dose rate of about 3000/min for several days, and stored in liquid N₂ until measured.

The spectrometer operated at 23 000 Mc/sec and used a rectangular cavity excited in the TE₁₀₂ 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* | Mole ratio H ₂ O: acid | Microwave freq., Mc/sec ^b | High-field line, gauss ^c | Low-field line, gauss ^c | ν_H , Mc/sec | <i>g</i> |
|--------------------------------|-----------------------------------|--------------------------------------|-------------------------------------|------------------------------------|------------------|----------|
| 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 ₂ SO 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 ₃ PO 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 H₂SO₄. 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. HClO₄ and H₃PO₄ showed the same satellites but different central lines. Irradiated mixtures of these acids with D₂O 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 H₂SO₄, 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's² notation) were (0, 0 → 1, 1) and (1, -1 → 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's² 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 H₂SO₄ diluted with D₂O. The three lines observed for deuterium were the satellites ($\frac{3}{2}, -\frac{3}{2} \rightarrow \frac{3}{2}, -\frac{3}{2}$) 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's² 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).