way of their formation. Their effects then superpose on the semiconductor properties which would otherwise be observed.

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[1] See, for instance, N. Mostovetch and B. Vodar in *Semiconducting Materials* (Butterworths Scientific Publications, Ltd., London, 1951).

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Hall Effect in Ferromagnetics*

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THE Hall effect in ferromagnetics is given by[1]

$$E_h = R_0 H + R_1 M, \tag{1}$$

where E_h is the Hall electric field, H is the applied magnetic field, M is the magnetization, and R_0 and R_1 are the ordinary and extraordinary Hall constants, respectively. This letter reports measurements of R_1 as a function of resistivity for iron-silicon alloys of 0 percent to 5 percent silicon.

Karplus and Luttinger,[2] in their theory of the extraordinary Hall effect, have found that in a certain approximation R_1 should depend on the square of the resistivity. Their mechanism uses the spin-orbit interaction of the d electrons. R_1 has been measured as a function of resistivity[3,4] for pure iron and nickel where the resistivity was changed by changing the temperature. Since $\rho \propto T$, this does not tell whether ρ or T is the significant quantity. Our measurements were done on iron-silicon, whose resistivity was changed by changing the silicon content.

Our samples were cut from commercial rolled iron-silicon sheet with no heat treatment and no attempt to cut them at any particular angle with respect to the direction of rolling. A primary current density of about 30 amperes/cm^2 at 600 cps was used and the Hall voltage measured with a narrow band amplifier and a lock-in detector. The resistivities were measured by measuring the current and the voltage drop in a sample. The resistivities do not all agree with previous measurements of resistivity *versus* silicon content.[5] This could be due to special rolling and heat treatment at the rolling mill.

TABLE I. Extraordinary Hall constant R_1 as a function of resistivity ρ.

ρ $\mu\Omega$ cm	R_1 volt cm / amp gauss	Percent Si	Temp. °K
76.5	240×10^{-11}	5.09	300
66.1	200	5.09	77
63.7	202	3.91	298
54.3	159	3.91	77
46.6	120	3.01	299
33.1	66.2	3.01	77
32.5	62.3	1.30	300
21.4	29.5	1.30	77
11.0	8.20		298

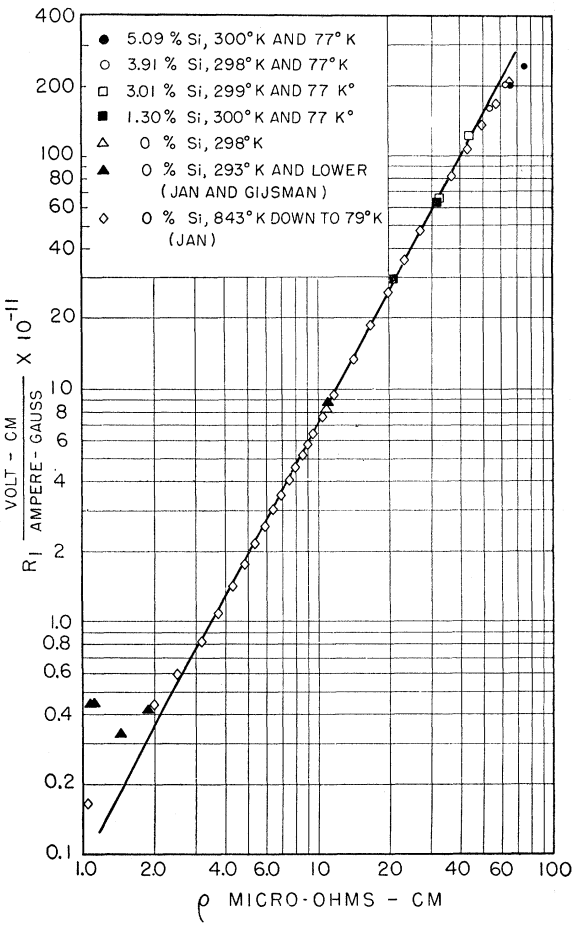

FIG. 1. Extraordinary Hall constant as a function of resistivity.

The results are shown in Table I and in Fig. 1. The measurements of Jan[3] and of Jan and Gijsman[4] for iron are also shown in Fig. 1. The equation of the straight line is

$$R_1 = 0.89\rho^{1.9}, \tag{2}$$

where ρ is in ohm-cm and R_1 is in volt-cm/ampere gauss. This is in good agreement with the theory of Karplus and Luttinger which predicts

$$R_1 \propto \rho^2, \tag{3}$$

with a constant of proportionality of the order of unity. The departure from a straight line at low resistivities is due to the fact that R_1 includes the effect of the magnetization as well as the spin-orbit interaction. Equation (3) was derived for spin-orbit interaction only. At low resistivity the spin-orbit part is of the same order of magnitude as the magnetization part.

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Hyperfine Splitting in Spin Resonance of Group V Donors in Silicon

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ADDITIONAL observations of the electron spin resonance absorption in n-type silicon[1] at 4.2°K have (1) confirmed the interpretation of hyperfine splitting by the donor nucleus, (2) shown that the hyperfine lines are replaced by a single line at high donor concentrations, (3) indicated that the line breadth of the hyperfine lines is of the inhomogeneous type, suggesting residual hyperfine broadening, and (4) revealed the existence of weak satellite lines attributable to forbidden transitions. These observations were made by the same method as described previously[1] on undeformed single crystal bars of silicon.

Fourteen clearly resolved resonance lines (Fig. 1) have been found in antimony-doped silicon (4×10^{71} atoms/cc). These lines naturally fall into two groups, each with lines of about equal intensity and separation. The six lines of the first group have an intensity 1.70 ± 0.05 times and an overall separation 1.32 ± 0.01 times the eight lines of the second group. The number of lines, their relative intensities, and their relative separations appear to be conclusive evidence that the six lines are attributable to interaction with the Sb^{121} nucleus ($I=5/2$, $\mu=3.360$,[2] abundance=56 percent) and the eight lines to the Sb^{123} nucleus ($I=7/2$, $\mu=2.547$,[2] abundance=44 percent).

A variety of samples with different concentrations of three donor materials, phosphorus, arsenic, and antimony, have been measured (Fig. 1). With all three it is found that if the concentration exceeds a certain amount (*ca.* 1×10^{18}) the multiplicity of lines disappears, being replaced by a single narrow line (<3 oersteds).

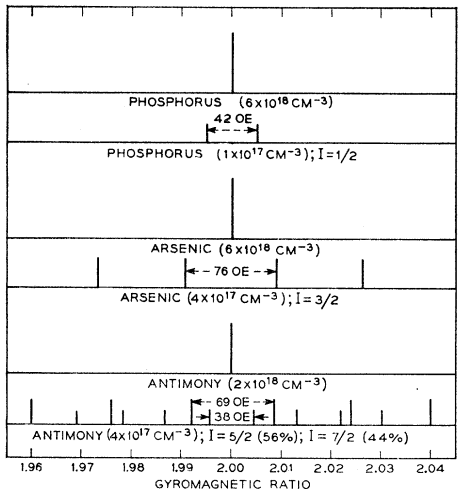

FIG. 1. A schematic representation of the absorption lines observed in silicon doped with various amounts of phosphorus, arsenic, and antimony.

This line has the same g factor and apparently is the same line which Portis *et al.*[3] have attributed to conduction electrons.

In our experiments there is an as yet unexplained shift (≈25 oersteds) in the resonance lines with respect to the calibration line (diphenyl picryl hydrazyl) when the magnetic field is rotated around the cavity containing the sample. This effect accounts for the difference between the g factor of the arsenic-doped silicon of Fig. 1 and the previously quoted value.[1] All the samples of Fig. 1 were taken in the same orientation with the dc magnetic field parallel to the transverse rf magnetic field and along the ⟨100⟩ crystal direction. In this orientation all the lines have the same center of gravity at $g=2.0004\pm0.0005$.

An investigation of the saturation behavior with rf field of the hyperfine lines of an arsenic-doped sample reveals it to be of the inhomogeneous type described by Portis.[4] This suggests that the remaining line breadth of the hyperfine lines is still caused by hyperfine interactions, presumably with the nuclei of Si^{29} (5

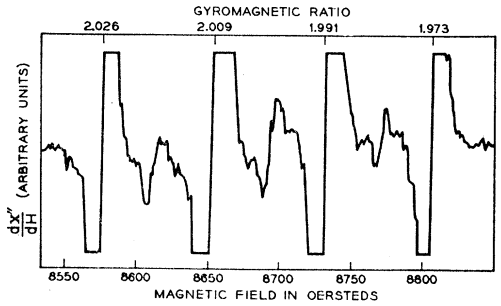

FIG. 2. A reproduction of the observed derivative of the resonance absorption lines of arsenic-doped silicon (4×10^{17} cm^{-3}) showing three satellite lines between the four principal hyperfine lines.