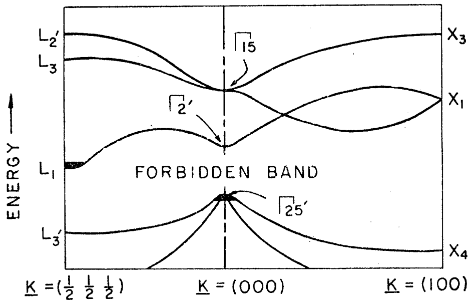
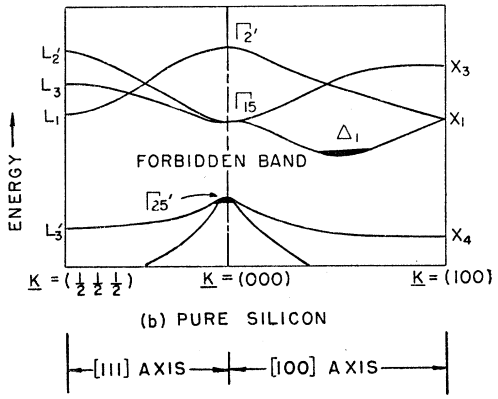
raised relative to the conduction band having [100] minima. Both of these conduction bands move away from the valence bands, the lowest conduction band at a faster rate than the next-to-the-lowest conduction band. (3) The top of the valence band structure remains at the central point of the reduced zone over the entire range of alloy composition. (4) The optical absorption edge is determined by nonvertical electronic transitions over the entire range.

Referring now to reference 1, Fig. 3 [E_{gap} *vs* mole percent Si], we suggest that electrons occupy states at the [111] minima in the range 0 to about 15 mole percent Si. In the region of the break in the E_{gap} *vs* mole percent Si curve, the [100] and the [111] minima are both populated. These minima are here separated in energy by a quantity of the order of kT. As the silicon content is increased above about 15 mole percent, the [111] minima are pushed above the [100] minima.

The optical absorption edge, i.e., the measured energy gap, is thus determined by electronic transitions from valence band states near $k=(000)$ to the conduction band states near $k=(\frac{1}{2}\,\frac{1}{2}\,\frac{1}{2})$ in the range 0 to 15 mole percent Si. The absorption edge in the range above 15 mole percent Si is determined by transitions from the top of the valence band to states at the bottom of the conduction band, which here lie along the [100] axes.



(a) PURE GERMANIUM



(b) PURE SILICON

FIG. 1. a and b. Schematic diagrams of energy band contours in perfect germanium and silicon crystals along [111] and [100] axes in the reduced zone. States normally occupied by electrons and holes at room temperature are shown darkened. The symbols give the symmetry classification of the various states in the notation of reference 3. The removal of degeneracy by spin-orbit interaction is not shown.

It is conceivable that these ideas could be verified by performing magnetoresistance or cyclotron resonance measurements on single-crystal suitably-doped Ge-Si alloys of varying compositions. (Johnson and Christian[1] report that single crystals have already been produced in the range 0 to 12.6 mole percent Si.) Magnetoresistance measurements on both *n*- and *p*-type single Ge-Si alloy samples have been initiated at these Laboratories. It is hoped that these experiments will bear out the speculations presented above.

It has occurred independently to Paul and Brooks[8] and to the author that the application of high pressure to perfect single crystals of germanium could raise the [111] minima above the other minima, i.e., above the [100] minima or the (000) minimum. Dr. R. H. Parmenter of these Laboratories is currently engaged in a theoretical study of the modifications in the band structure of germanium produced by changes in lattice constant or addition of silicon atoms.

The author wishes to thank Dr. D. O. North and Dr. R. H. Parmenter of the RCA Laboratories for stimulating conversations. The author is grateful to Dr. B. Lax, Dr. R. N. Dexter, and Dr. H. J. Zeiger of the Lincoln Laboratory, Massachusetts Institute of Technology; Dr. C. Herring and Dr. G. L. Pearson of the Bell Telephone Laboratories; and Professor H. Brooks and Dr. W. Paul of Harvard University for discussing their work with him prior to publication.

[1] E. R. Johnson and S. M. Christian, Phys. Rev. (to be published).

[2] H. M. James and A. S. Ginsbarg, J. Phys. Chem. **57**, 90 (1953); R. Landauer and J. C. Helland, J. Chem. Phys. (to be published).

[3] F. Herman (to be published); see also F. Herman, Phys. Rev. **93**, 1214 (1954).

[4] Dresselhaus, Kip, and Kittel, Phys. Rev. **92**, 827 (1953); Lax, Zeiger, Dexter, and Rosenblum, Phys. Rev. **93**, 1418 (1954); R. N. Dexter *et al.*, Phys. Rev. (to be published).

[5] C. S. Smith, Phys. Rev. **94**, 42 (1954).

[6] G. L. Pearson (private communication); see also G. L. Pearson and C. Herring (to be published). Dr. Herring discussed the significance of Pearson's data and of Smith's results at the Stanford Meeting of the American Physical Society, December, 1953, Invited Paper C1.

[7] Dr. B. Lax has just informed the writer that the top of the valence band in silicon appears to lie at the central point of the reduced zone, and to have a form similar to that in germanium. Lax and Dexter's data on silicon also indicate that the states normally occupied by electrons lie along the [100] axes in the reduced zone.

[8] W. Paul and H. Brooks, Phys. Rev. **94**, 1128 (1954).

Electrical Conductivity of Magnesium Oxide Single Crystals

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MEASUREMENTS of the electrical conductivity of magnesium oxide have been performed by two or three investigators. Lempicki[1] made measure-

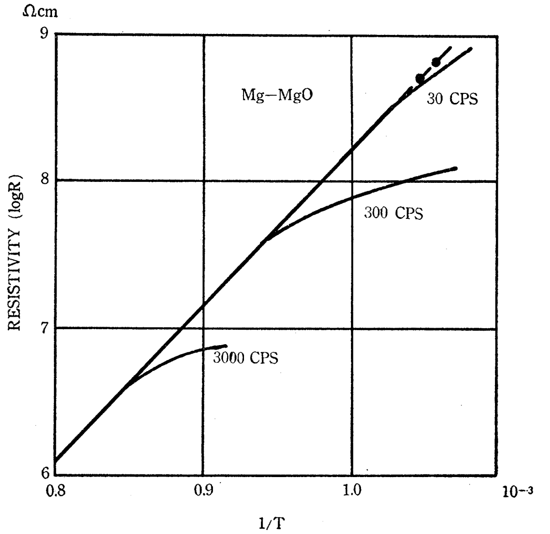


FIG. 1. Plot of resistivity *vs* $1/T$. The frequencies used were 30, 300, and 3000 cps. The solid circles show the values calculated from the resistivities at 30 and 300 cps by using the equivalent circuit shown in Fig. 2.

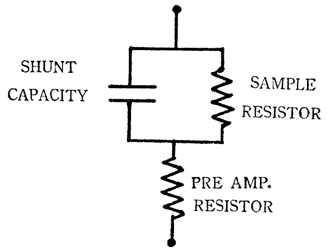
ments on single crystals by a dc method and concluded that the energy gap between the full band and the conduction band was 4.6 ev by assuming that the conductivity was electronic and intrinsic. Mansfield,[2] on the other hand, deduced that magnesium oxide was a defect-type semiconductor from the positive sign of the thermoelectric power. In addition, he concluded by using Nijboer's theory[3] that the value of E in the expression $\sigma=\sigma_0 \exp(-E/kT)$ was not half the band gap but corresponded to the work function for the impurity level available to holes. Recently Day[4] found from his photoconductivity measurements that the charged carriers released by light from magnesium-excess absorption bands were holes. Therefore it is important to determine whether the 2.3-ev energy level available to the charged carriers originates from excess magnesium or excess oxygen atoms.

In order to eliminate the effects of ionic current, measurements were made by an ac method. However, its frequency had to be as low as about 30 cps because of the effect of shunt capacity. The low conductivity of the samples compelled us to make our measurements in a nitrogen gas flow in order to avoid thermionic emission from the electrodes at high temperatures. The samples were placed between Pt electrodes and heated by an electric furnace around a fused silica tube. Temperatures were measured by a Pt-PtRh thermocouple.

Samples were cleaved on the order of one-half centimeter thick from large clear (uncolored) single crystals supplied by the Norton Company. Coloring with magnesium was obtained by heating the crystals in magnesium vapor at temperatures of about 1300°C for one hour (magnesium colored) and coloring with oxygen was obtained by heating in a dry oxygen gas flow at about 1300°C for two hours (oxygen colored). The measurements of optical absorption indicated: (a) uncolored crystals already have an absorption band in the ultraviolet region due to excess oxygen; (b) oxygen-colored crystals have an intensified band in the ultraviolet region; (c) magnesium-colored crystals reveal broad absorption bands in the visible region caused by excess magnesium, in addition to a weakened band in the ultraviolet region.

The curves of $\log R$ *vs* $1/T$ in uncolored, magnesium-colored, and oxygen-colored crystals were the same as the curve shown in Fig. 1. The deviation from the straight line occurred at high resistivity. In order to ascertain whether the deviation was due to different impurity levels or to shunt capacity, the frequency of the oscillator was varied from 30 cps to 300 and 3000 cps, and the results are also shown in Fig. 1. The resistivity of the sample was calculated from the simple equivalent circuit shown in Fig. 2; the value obtained lay on the extrapolated part of the straight line as shown in Fig. 1. This indicated that the deviation was due not to different impurity levels, but to shunt capacity.

FIG. 2. The equivalent circuit used.



The activation energies in uncolored, magnesium-colored, and oxygen-colored crystals were the same, being from 2.2 ev to 2.4 ev. However the specific resistivities of magnesium-colored crystals were lower than those of uncolored and oxygen-colored crystals as shown in Table I. Furthermore it was observed that the resistivity became larger, in contrast with the constant activation energy, when the sample was heated at high temperatures such as 1100°C, especially in magnesium-colored samples. From these experimental facts the following conclusions may be drawn: (a) The 2.3-ev

TABLE I. Specific resistivity at 977°C and activation energy of MgO single crystals.

	Uncolored			O-colored		Mg-colored			
Sample	a	b	c	a	b	a	b	c	d
Specific resistivity[a] (Ω cm)	37	80	15	28	12	4	5.8	1.2	0.5
E (ev)	2.2	2.3	2.3	2.4	2.2	2.3	2.4	2.2	2.3

[a] The values of resistivity are at 977°C.

energy level available to charged carriers originated from excess magnesium and no levels were from excess oxygen. (b) Excess magnesium could move through the lattice comparatively easily so that impurity levels disappeared by heating samples at high temperatures. This conclusion was also reached from the fact that heat treatment destroyed the coloration due to excess magnesium in the visible region. (c) Furthermore, by taking account of Day's results,[4] it was deduced that the charge carriers due to excess magnesium levels were holes, the positive sign of the thermoelectric power obtained by Mansfield[2] being thus explained. These results are not understood by a simple electronic structure model. However, a definite model cannot be established yet.

A full report will be given in the *Journal of the Physical Society of Japan*.

[1] A. Lempicki, Proc. Phys. Soc. (London) **B66**, 281 (1953).
[2] R. Mansfield, Proc. Phys. Soc. (London), **B66**, 614 (1953).
[3] B. R. A. Nijboer, Proc. Phys. Soc. (London) **51**, 575 (1939).
[4] H. R. Day, Phys. Rev. **91**, 822 (1953).
[5] H. Weber, Z. Physik **130**, 392 (1951).

Experiments on Nucleon-Nucleon Scattering with 312-Mev Polarized Protons

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In a previous paper[1] we reported our results on p-p scattering using polarized protons. In the framework of our general program of studying nucleon-nucleon scattering, we would have liked to investigate n-p scattering with polarized neutrons; however, we are still unable to obtain highly polarized neutrons and the next best possibility is to bombard deuterons with highly polarized protons.[2]

Neglecting in first approximation the binding of the deuteron, the processes that occur in p-d bombardment are p-p and p-n scattering in which a p-p or an n-p pair escapes at approximately 90° in the laboratory system. In addition to this there is elastic scattering of the protons. These processes are schematically represented in Fig. 1.

We have detected and measured processes (a) and (b) by coincidence techniques and we have also counted single neutrons and single protons.

In Figs. 2 and 3 we show the asymmetrical part of the cross section, $P\sigma$:

$$P\sigma=\tfrac{1}{2}[\sigma(\theta,0)-\sigma(\theta,\pi)], \tag{1}$$

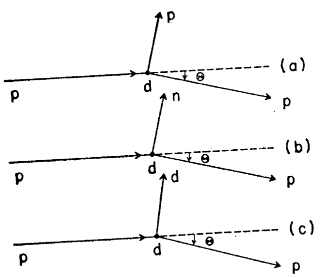

FIG. 1. Processes occurring in p-d scattering.

where $\sigma(\theta,\varphi)$ is the differential cross section for a completely polarized beam scattering on an unpolarized target. The incident protons travel in the z direction and are polarized along the y axis. The quantity $P\sigma$ is computed from the relation

$$P\sigma=e\sigma_{\text{unpolarized}}/P', \tag{2}$$

where P' is the polarization of the incident beam used. The deuterium scattering experiment yields e; $P'=0.73$ is obtained from measurements of the asymmetry when the scattering is elastic and targets A and B are identical; for p-p scattering $\sigma_{\text{unpolarized}}$ is assumed to be 3.75 mb/sterad,[3] and for n-p scattering it is taken from previous work.[4]

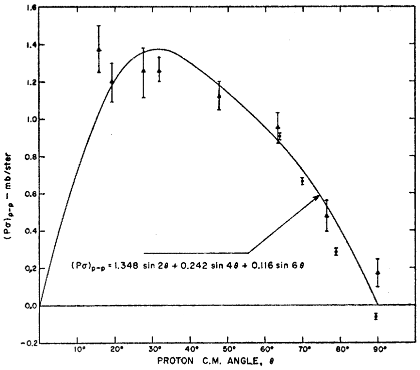

FIG. 2. $P\sigma$ in p-p scattering as a function of θ. Triangles are from reference 1 (290 Mev); dots are from this experiment (312 Mev).

Figure 2 refers to the asymmetric part of the p-p scattering with some points taken from previously reported data[1] using a hydrogen target, and some

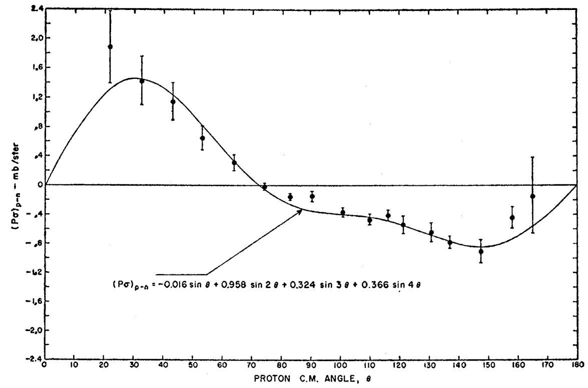

FIG. 3. $P\sigma$ for n-p scattering from d-p scattering measurements, as a function of θ. Energy of incident protons is 312 Mev.