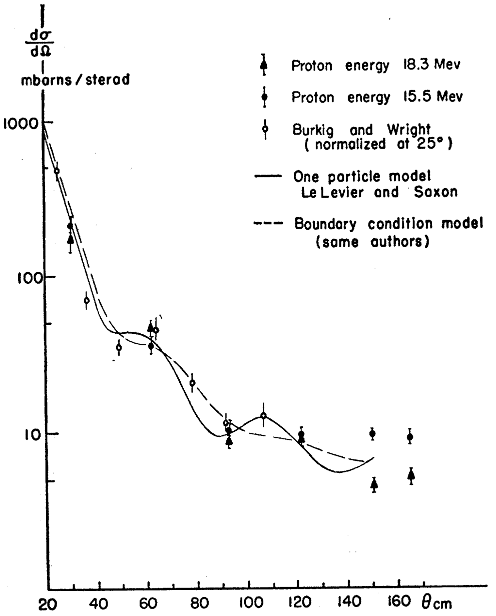

FIG. 1. Differential cross section for the elastic scattering of protons by Al

The errors were estimated on the basis of the fluctuations of the different measurements and of the following uncertainties. For the small angles the cross sections vary rapidly with the angle, and a misalignment of the beam spot of 0.5 cm causes a change in the measured cross section by as much as 17 percent. Such changes in alignment may occur because of fluctuations in the operation of the cyclotron. At the larger angles of observation the subtraction of the inelastic scattering introduces an uncertainty. Both effects are several times larger than the statistical error.

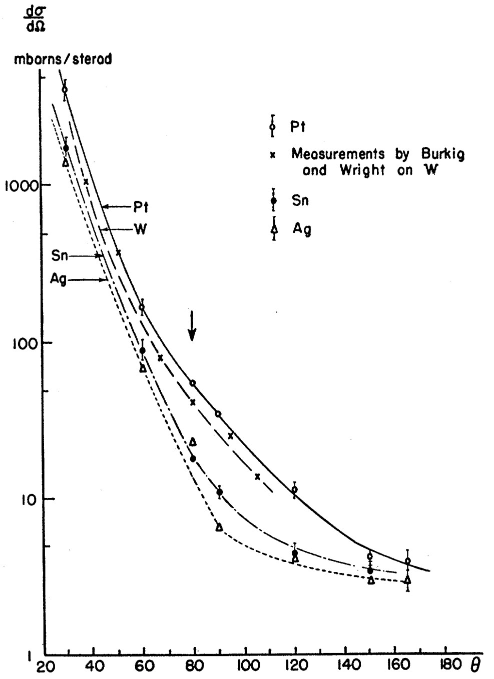

FIG. 2. Differential cross sections for the elastic scattering of protons by Pt, W, Sn and Ag. The points below the arrow are measured by Burkig and Wright and normalized for Pt.

Figure 1 represents the scattering cross section for Al. The measurements of Burkig and Wright are shown on the same graph. These are normalized at 25° on the cross-section curve calculated by Le Levier and Saxon[3] on the basis of a complex potential. These authors also calculate the scattering cross-section on the basis of a boundary condition model proposed by Feshbach and Weisskopf[4] as shown in Fig. 1.

The scattering cross sections of the medium heavy and heavy elements are difficult to analyze at the present since Coulomb wave functions up to $L=10$ have to be employed. Figure 2 shows the results obtained for the heavy elements.

The following results can be deduced from these measurements. The back scattering cross sections seem to be little dependent on the size of the scattering nucleus; their values being of the order of 3 millibarns/sterad for 18-Mev protons.

If the incoherent scattering leading to the ground state is as intense as the inelastic scattering leading to neighboring excited states, then the fraction of the incoherent scattering compared to the diffraction scattering may be as much as 30 percent for Cu and 5 percent for Pt for a scattering angle of 165°.

Another feature of the backward elastic scattering is its energy dependence. Britten[5] obtained a cross section of 0.6±0.1 milli-barns/sterad for the elastic scattering of 31.5-Mev protons by Al at 161°. Comparing this value with the Al cross sections at the same angle for protons of 15.5 Mev and 18.3 Mev, one finds that the 161°-scattering cross section is inversely proportional to the third power of the proton energy. The same energy dependence is obtained by comparing the 155° Pb cross section for 31.5-Mev protons (0.8±0.2 milli-barns/sterad[7]) with the 155° cross sections of 15.5-Mev and 18.3-Mev protons on Pt.

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* This work has been supported by the AEC and the Higgins Scientific Trust Fund.

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Copper as an Acceptor Element in Germanium

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(Received June 11, 1952)

THE experimental results reported below strongly suggest that copper is a surface impurity responsible for the familiar "thermal conversion" of germanium.[1] In a previous publication,[2] the solid solubilities of thermal acceptors[3] and their diffusion rate in germanium were given. In the present work, the solid solubility and the diffusion constant of copper have been determined with radioactive[4] Cu^{64}. The data for the thermal acceptor and for copper agree within the limit of error of the experiments.

The specimens (1.0×0.5×0.15 cm) cut from 9.6 ohm cm single crystal[5] germanium were treated by wetting the surface with 0.1 percent radioactive copper nitrate solution for two minutes. In one set of experiments, (Fig. 1) only one of the 1.0×0.5 cm faces was so treated on each of two specimens. Both specimens were heated together in helium at 1 atmos at a mean effective temperature[6] of 825°C for two minutes and rapidly quenched. One specimen (A) was analyzed for copper as a function of distance from the treated surface by recording the activity of grindings from successive layers. The other (B) was sectioned perpendicular to the treated surface so as to provide a prism, 0.25×0.125×0.15 cm. The variation of acceptor[3] concentration with distance was calculated from the incremental change in resistivity of the prism which was rendered p-type by the heat treatment. These data are plotted in Fig. 1, curves A and B, respectively. It is evident from the slopes of the two curves that the diffusion rates are identical within experimental error, the average value of the diffusion constant, 1.3×10^{-5} cm² per second is lower than, but in reasonable agree-

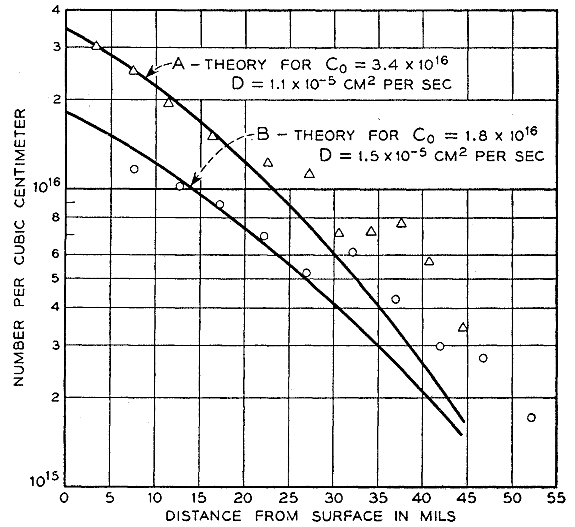

FIG. 1. Concentration *versus* distance for copper nuclei (A) and thermal acceptors (B) in germanium (heated two minutes at 825°C).

ment with the value at 825°C calculated from $D = 0.02\exp(-12000/RT)$, which has been found to apply approximately to thermal acceptor diffusion.[2]

In another set of experiments, six of the germanium specimens were immersed in the radioactive copper nitrate solution for two minutes and heated in helium at 1 atmosphere at temperatures of 654, 712, 765, 812, 868, and 919°C for 16 hours, 1 hour, 1 hour, 50 minutes, 40 minutes, and 30 minutes, respectively. These times were sufficient to ensure that the specimens were within at least 5 percent of saturation. Resistivities were determined after removal of excess copper from the surfaces and the copper concentrations then measured by crushing the entire specimens and counting the radioactivity. The results plotted in Fig. 2 are the same within the limit of error and the uncertainty in the value of the mobility.[7] Deviations from the theoretical diffusion curves at low concentrations may be due to diffusion from the rear surfaces.

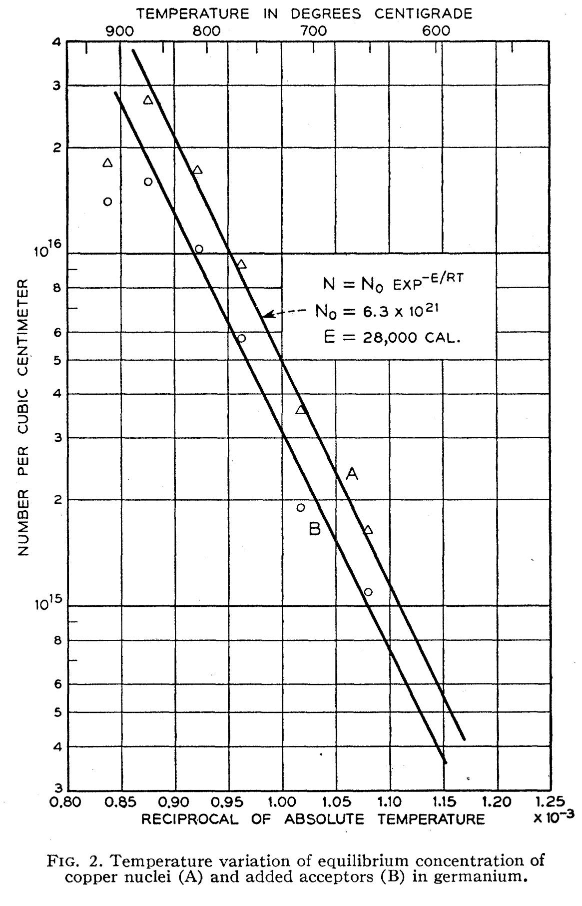

FIG. 2. Temperature variation of equilibrium concentration of copper nuclei (A) and added acceptors (B) in germanium.

Heat treatments at 500°C have been carried out on *p*-type germanium (originally 13.5 ohm-cm *n*-types) which had been saturated with Cu^{64} at 924°C. After 18 and 48 hours the copper concentrations (on separate specimens) were 3.0×10^{16} and 1.4×10^{16} respectively compared with the original 3.0×10^{16}. The 500°C specimens showed high surface activities indicating that some copper had come to the surface. The 18-hour specimen was still partly *p*-type, whereas the 48-hour specimen had an *n*-type resistivity of 20 ohm cm. Thus, most of the copper remained in the crystal even though it returned to nearly its original resistivity. This indicates that the copper is no longer in solid solution after annealing, but has precipitated as a separate phase.

Experiments on silicon at 1100°C show that copper diffuses into it at a rate comparable to that found for germanium and that an increase in hole conductivity occurs. As yet, no direct correlation of the numbers of copper atoms with the number of added holes has been made.

The authors wish to acknowledge useful comments by J. A. Burton, and assistance of Miss Katherine Wolfstirn and J. A. Ditzenberger.

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Impurity Effects in the Thermal Conversion of Germanium

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(Received June 11, 1952)

It was shown by Theuerer and Scaff[1] that polycrystalline *n*-type germanium is converted to or toward *p*-type when heated for a few minutes above about 600°C, and the process is reversed when the material is heated for about 24 hours at 500°C. Theuerer, Fuller, and Slichter[2] have found that the same effects occur with single-crystal germanium, except that the original resistivity is restored only after several days of heating at 500°C. It might be expected, then, that with the high temperatures encountered in the crystal-growing process of Teal and Little,[3] there would be an appreciable and variable concentration of thermally-induced acceptors. The present studies, however, have revealed no thermal acceptors as a consequence of the growing process and have shown that conversion may be associated with the presence of impurities on the germanium surface prior to heating.

In these experiments, a crystal of very high purity germanium (resistivity>45 ohm-cm) was partly grown (in hydrogen), and then the growth was halted, keeping the crystal in contact with the hot melt for a prolonged period (in one case an hour, in another, 2 hours). The growth was then resumed and completed in about ten minutes. A study of the resistivity throughout the length of the crystal showed no detectable difference between the first portion, which had undergone prolonged heating, and the second, which