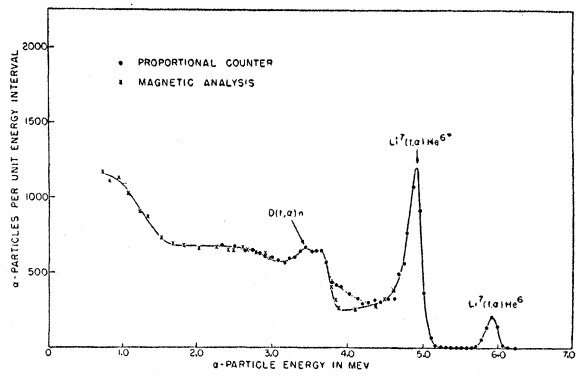

FIG. 1. The energy distribution of α-particles from the Li^7+T reactions observed at 90° to a 240-kev triton beam.

conditions and at the counting rates used, space charge did not noticeably affect the pulse heights obtained. The pulses from the counter were amplified and sorted according to size by a thirty-channel pulse-height analyzer. A correlation between pulse heights and α-particle energies was established by allowing α-particles of known energy to enter the counter immediately before and after each run. The following energy calibration points were obtained from the sources shown: U^{233}—4.82 Mev, Pu^{240}—5.16 Mev, Am^{241}—5.47 Mev, Cm^{242}—6.11 Mev, $T(d,\alpha)n$—3.43 Mev,[4] and $Li^7(p,\alpha)He^4$—8.75 Mev.[4]

In Fig. 1 is shown the energy distribution of the α-particles emitted at 90° to the beam. The data obtained by magnetic analysis have been corrected for charge exchange[5] in the target. At 5.95 Mev is a group attributed to α-particles associated with the formation of He^6 in its ground state. The energy of these α-particles was accurately determined by allowing them to enter the counter simultaneously with the α-particles from Cm^{242} which have nearly the same energy. An expanded portion of the pulse-height distribution (Fig. 2) shows the 6.11-Mev α-particles from the curium clearly resolved from the high energy group of α-particles from the reaction $Li^7(t,\alpha)He^6$. Using the measured separation of the two peaks of 0.165±0.017 Mev, the Q of reaction (1) is calculated to be 9.79±0.03 Mev. It can be shown that the energy equivalent of the mass difference He^6-Li^6 is $(Q_1+Q_2)-(Q_3+Q_4)$, where Q_1, Q_2, Q_3, and Q_4 are the Q values of the reactions $Li^7(p,\alpha)He^4$, $T(\beta^-)He^3$, $Li^6(p,\alpha)He^3$, and $Li^7(t,\alpha)He^6$, respectively. Taking 9.79±0.03 Mev for Q_4 and using the data of Li *et al.*,[6] the He^6-Li^6 mass difference is computed to be equivalent to 3.55±0.03 Mev. This value differs considerably from that of 3.215 ±0.015 Mev obtained by Perez-Mendez and Brown[7] for the end point of the He^6 β-spectrum. It is, however, in agreement with earlier determinations.[8] Knox[8] has found no evidence for a γ-ray associated with the He^6 β-particles.

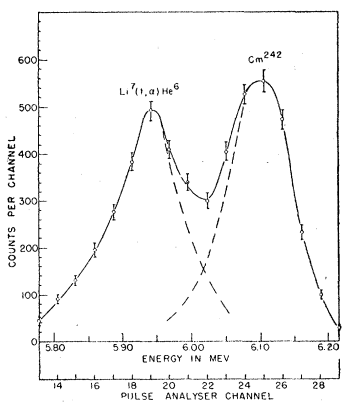

FIG. 2. The pulse-height distribution obtained when α-particles from the $Li^7(t,\alpha)He^6$ reaction and from Cm^{242} are admitted to the counter simultaneously through the same window. Observations at 90° to 240-kev triton beam.

The intense group of α-particles at 4.91±0.02 Mev is believed to be associated with an excited state of He^6 formed in the reaction $Li^7(t,\alpha)He^{6*}$. From the measured energy of the α-group, the Q of this reaction is computed to be 8.08±0.03 Mev. Thus the excited level in He^6 is 1.71±0.01 Mev above the ground state and is unstable by 0.78±0.03 Mev against break-up into an α-particle and two neutrons. The width of this level is probably less than 50 kev, as there is no observable broadening of the associated α-particle group.

In Fig. 1 the difference between the two sets of points in the neighorhood of 3.9 Mev represents the contribution of the ground state He^6 particles, whose ionization enables them to be detected in the proportional counter but whose magnetic rigidity is too great to permit their detection with the magnetic analyser. The small peak at about 3.4 Mev is due to α-particles from the $D(t,n)He^4$ reaction, which is usually present when low energy tritons are used as bombarding particles. Unless there are unresolved excited states of He^6, the broad continuum shown in Fig. 1 is composed of α-particles from reaction (2) proceeding via one or more steps and α-particles from the break-up of the observed excited state of He^6. If one subtracts the latter α-particles; the remaining continuum accounts for 80 percent of the disintegrations emitting particles at 90° to the beam.

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$p-n$ Junction Method for Measuring Diffusion in Germanium*

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(Received March 10, 1952)

THE diffusion of an n-type impurity into a p-type semiconductor creates a $p-n$ junction which can be detected electrically by the thermoelectric effect of a hot needle or by a rectification probe.[1] Study of the rate of penetration of the $p-n$ junction into the semiconductor can be used to measure the diffusion coefficients of various impurities in such semiconductors as germanium or silicon.

The object of the present study was to establish a foundation for the validity of this method by the direct measurement of diffusion, by the $p-n$ junction method, and by the radioactive tracer method. For this purpose, antimony 124 was chosen as the impurity to be used. This material served the double purpose of changing the conduction type from p to n as it diffused and, at the same time, creating a radioactive layer in which the concentration of the diffusing impurity could be evaluated by standard counting procedures.

Samples of single crystal p-type germanium were prepared in the form of wafers about 1 cm^2 in area and 50–60 mils thick. These samples were ground on a special grinder which made the surface flat and parallel to about 0.1 mil. After cleaning and etching with HF, a thin layer of the radioactive antimony (2–10 microgram/cm^2) was evaporated onto one face of the sample.

The sample was then sealed in small quartz tubes containing argon at a pressure of 70-cm Hg at room temperature. Following heating in a carefully controlled oven (±5°C) for the desired time, the tubes were broken open, and the surface activity removed by grinding from all parts of the sample except for one face. The sample was then ground off on the same grinder with which the faces were originally prepared. The surface layers were ground into

sheets of fine grade emery paper, in such a way that all the activity was retained on the paper. The $p-n$ character of each new face was checked by means of a thermoelectric probe. The activity of the paper was measured in a fixed geometry with a scintillation counter. The weight of the sample was measured after each grinding. The results for two samples are shown in Fig. 1. Here are

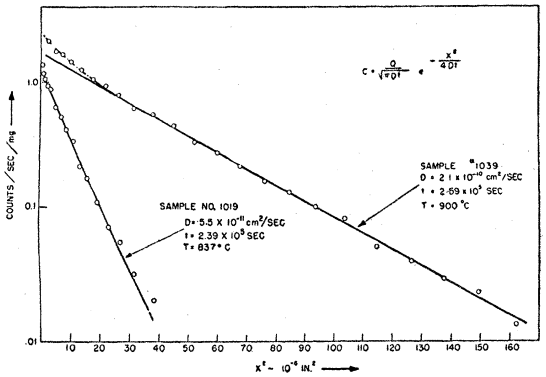

FIG. 1. Plot of log (counting rate) *vs* x^2 for the diffusion of radioactive antimony 124 into a germanium single crystal at two temperatures, 900°C and 837°C. The linearity of the plot on this chart is a test of the applicability of the "δ-function" solution of the diffusion equation.

plotted the counting rate per unit weight of material removed, *versus* the square of the distance from the original surface. This plot is chosen to check an important point. If the original surface layer could legitimately be considered to represent an infinitely sharp distribution (δ-function), the theoretical distribution of impurity should be given by the relation[2]

$$C=Q/(\pi Dt)^{-\frac{1}{2}}\exp(-x^2/4Dt),$$

where C is the concentration of diffusing impurity (atoms/cm³), Q is the original surface density of impurity (atoms/cm²), x is the distance in centimeters, t the time in seconds, and D the diffusion coefficient (cm²/sec). Thus, the linearity of the curves on this plot is a check on the validity of the δ-function solution, and the slope of the lines obtained determines the diffusion coefficient. The good linearity obtained in all our tests shows that in spite of uncertainties that do exist regarding the actual initial conditions, including such effects as the formation of a liquid surface layer, 2-phase solid layers, effect of evaporation of the antimony, etc., all these effects either involve such a negligibly thin surface layer or are over within such a short time that they do not affect the diffusion in any important way.

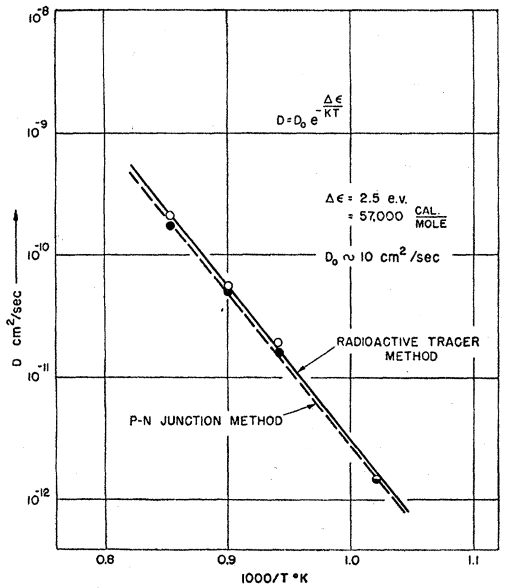

FIG. 2. Plot of the temperature variation of the diffusion coefficient for antimony in germanium determined by the $p-n$ junction method and by the radioactive tracer method. The good agreement observed justifies the use of the $p-n$ junction method for the measurement of diffusion in semiconductors.

Figure 2 shows the diffusion coefficients for antimony at various temperatures as measured by the $p-n$ junction method and by the radioactive tracer method. The results are seen to be in excellent agreement. The average difference between the values of D determined by the two methods is about 10 percent. The $p-n$ junction method gave uniformly lower values. The reason for this may be sought in the tendency of a thermoelectric probe to balance between p and n slightly on the n-type side, because of the tendency of surfaces to be p-type and because of the higher mobility of electrons than holes. However, a factor neglected in the radioactive tracer method was the absorption of the emitted β-rays in the germanium powder itself, and this may also affect the results slightly.

The activation energy determined from the slope was 2.5 ev, or 57,000 cal/mol. The value of D_0, the intercept of D on the $1/T=0$ axis, was about 10 cm²/sec. A calculation of D_0 based upon the Langmuir-Dushman[3] diffusion equation gave a value $D_0\sim 0.3$. The two values are in satisfactory agreement considering the uncertainty involved in the Langmuir-Dushman equation, the error in extrapolating for D_0, and the possibility that the activation energy is slightly dependent on temperature. Thus the diffusion is a true volume diffusion and does not involve the "short circuits" found by Nowick[4] to play a part in many diffusion studies.

We should like to thank R. N. Hall for single crystal samples, and J. H. Hollomon, J. C. Fisher, D. Turnbull, J. A. Burton, and W. Shockley for helpful discussions.

* A partial report of these studies was presented at the meeting of the American Physical Society, January 31, 1952 [Bull. Am. Phys. Soc. **27**, No. 1, 41 (1952)].

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Unusual $\pi-\mu$ Decays in Photographic Emulsions

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THE search for unusual $\pi-\mu$ decays in photographic emulsions has been continued.[1] Electron sensitive G-5 plates have been exposed in the positive meson beams[2] of the University of Chicago cyclotron. A total of 10,686 $\pi-\mu$ decays have been observed in C-2 and G-5 plates where both the π- and μ-meson tracks stopped in the emulsion. Thirteen unusual events were found among the 10,674 normal $\pi-\mu$ decays. The data concerning the unusual $\pi-\mu$ decays are given in Table I.

Event 12 is interpreted as a decay in flight of a negative π-meson and has been described elsewhere.[3] The μ-meson in event 13 did not stop in the emulsion. The length of the μ-meson track is 975 microns. The number of gaps along the μ-meson track has been measured and compared with the gap density along a μ-meson track from a π-decay which stops within 100 microns of the μ-meson track of event 13. Using this method it was found that the residual range of the μ-meson track in event 13 is about 60 microns. The long range of the meson track of event 13 is most probably due to the decay in flight of the positive π-meson. The observed short ranges of the μ-meson tracks in events 8 through 11 are possibly due to the decay in flight in the backward direction of the π-mesons. Assuming that the short ranges of the μ-meson tracks in