Range-Energy Relation for Low-Energy Alpha Particles in Si, Ge, and InSb*

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The range-energy relations for alpha particles in Ge, Si, InSb, Al, Cu, Ag, and Au were determined by measuring the air equivalents of thin foils of the materials. The incident alpha particles had energies between 0.7 Mev and 4.45 Mev, which were obtained from a Po^{210} source with air as a variable absorber. A CsI(Tl) crystal was employed as the detector and the pulse-height distributions of the alpha particles were observed with a 20-channel pulse-height analyzer. Approximate analytical expressions for the ranges in microns in Si, Ge, and InSb for alpha-particle energies above 0.5 Mev are: $R_{Si}=2.13E^{1.45}+2.20$, $R_{Ge}=1.95E^{1.34}+1.72$, and $R_{InSb}=2.08E^{1.30}+1.65$. The ranges for the semiconductors interpolate smoothly between those of the metals, which are in good agreement with available data.

INTRODUCTION

DURING alpha-particle irradiation experiments of germanium semiconductors, it became evident that the interpretation of the results could be much simplified if the samples irradiated were considerably thinner than the range of the incident alpha particles. The alpha-particle source for the experiments is polonium, deposited on a circular disk and covered with a thin steel foil; the emergent alpha energy being somewhat less than 5 Mev.

The only published range-energy measurements on semiconductors known to the author are those of Heller and Tendam[1] for deuterons of about 2 to 9 Mev; they found that the relative stopping powers per electron of Si and Ge can be obtained by interpolation from the metals.

When the available data[2–6] on alpha-particle ranges in the energy region 0 to 5 Mev are investigated, it is found that the ranges reported for noble gases are somewhat lower than expected, when compared to the ranges for the metals. Uncertainty as to whether to include the data for the gases or to use only the data for the metals as a basis for interpolation to the Z value of germanium prompted the experimental determination of the range-energy relation for alpha particles in germanium.

Since similar irradiation experiments are planned with Si and InSb, the ranges in these substances were determined simultaneously. Measurements with Al, Cu, Ag, and Au were included in order to check the performance of the equipment.

EXPERIMENTAL PROCEDURE AND APPARATUS

Apparatus

The experimental method employed was to measure the amount of energy intercepted from an incident alpha particle by a given thickness of the material. Rather than to measure this intercepted energy for a number of foils of the given material of varying thicknesses, a very thin foil was employed and the intercepted energies were determined for many different incident alpha energies. These were obtained by varying the pressure of dry air in the bombardment chamber (Fig. 1). The residual energies were measured with a thallium-activated cesium iodide scintillator.

It was preferable to calibrate the scintillation crystal response to various alpha-particle energies during the performance of the experiment, in order to eliminate errors that might arise due to aging or contamination of the crystal. Therefore the chamber was constructed so that it was possible to measure in quick succession the pulse-height spectrum of alpha particles after passing through the samples and the spectrum of the incident alpha particles, which had a known energy. This was done by mounting the samples on a movable holder, allowing one to insert either a sample or a blank aperture before the detector crystal.

Samples

The samples of the four metals were quite easily prepared, being small areas of commercially available one-tenth mil foils which were carefully weighed with a microbalance.

The samples of the three semiconductors were ground from single-crystal blanks. Since previous work indicates that the range of polonium alpha particles in

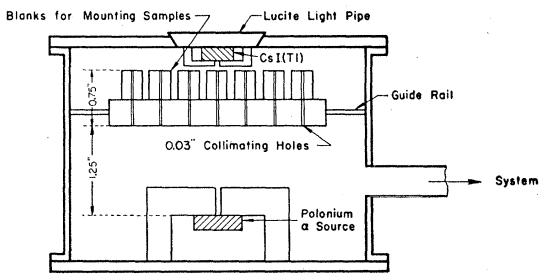

FIG. 1. Cross section of bombardment chamber. The tray holding the sample mounts is moved horizontally by means of a rack and pinion drive operated through an O-ring seal.

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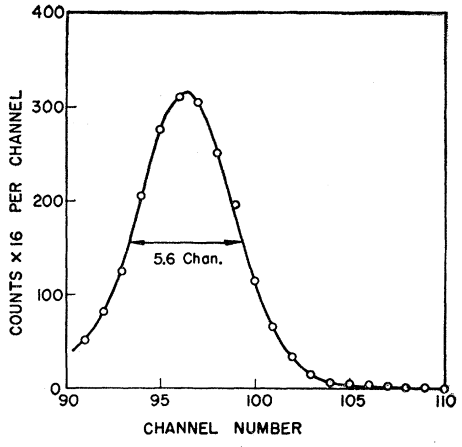

FIG. 2. Observed alpha-particle pulse-height distribution.

germanium is about 20 microns,[7] it was necessary to obtain samples less than 5 microns thick. Samples of comparable thicknesses are required also for silicon and indium antimonide.

The samples were bonded to glass plates with dental wax and were ground and polished to the required thicknesses. A Michelson-type interferometer, using the polished sample surface as one mirror, was used to measure the step distance from the sample to the glass substrate, both from the front and the back.

The thicknesses of the samples were calculated from these measurements and the index of refraction of the dental wax. The samples were then removed by dissolving the wax in benzene and mounted on the blank sample holders.

Where the quality of the surface permitted, the thickness was also measured by infrared transmission fringes on a Perkin Elmer model 12-C infrared spectrometer. When this was not possible, the samples were fractured after the range measurements were completed and the thickness was measured with a Vickers projection microscope by looking at the broken edge.

Owing to the difficulty encountered in accurately preparing, mounting, and measuring the thickness of such samples, three samples of each material were prepared, in order to cross check the results of the measurements.

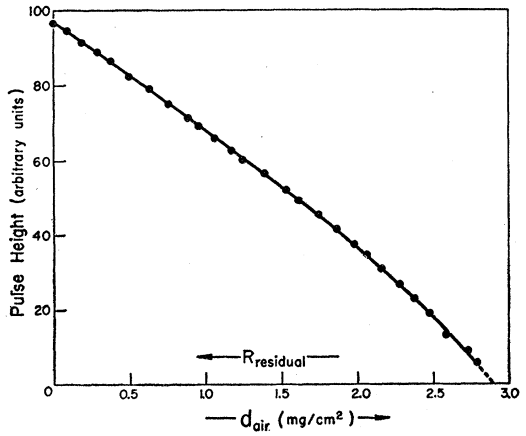

FIG. 3. Pulse height *vs* absorber thickness, d_{air}.

Procedure

The system was evacuated in order to obtain the highest possible alpha-particle energy incident on the sample. The energy of the alpha particles emergent from the polonium source used in these experiments was determined by the manufacturer[8] to be approximately 4.3 Mev. When the calibration curve for the cesium iodide crystal (described below) is extrapolated to zero pulse height, the intercept gives an energy of 4.45 Mev. The pulse-height distribution from the scintillator was determined with an Atomic Instrument Company 20-channel pulse-height analyzer, and the observed spectrum had the shape indicated in Fig. 2. The full width at half-maximum was 6% of the mean pulse height. If the alpha energy was reduced the absolute width of the pulse-height distribution remained the same.

Then air was admitted through a P_2O_5 drying column in small amounts to obtain lower alpha energies. The centers of the corresponding pulse-height distributions were located graphically as accurately as possible and a calibration curve of mean pulse height in arbitrary units as a function of air absorber thickness (or residual range in air) was constructed (Fig. 3). By referring to the range-energy curve[9] one could construct a curve of pulse height *versus* residual energy. Because of noise problems in the equipment at the low-energy end, the lowest such pulse height considered reliable corresponded to a residual range in standard air of 0.245 cm, or an energy of 0.38 Mev.

The pulse-height distribution from alpha particles emergent from a sample was observed, the center of the distribution determined, and the corresponding residual range in standard air was read from the calibration curve for the crystal. One could then calculate the average air range of the alpha particle while traversing the sample. Also, the air equivalent of the sample at the energy corresponding to this average air range was found.

A complete set of such measurements for each sample for many different average energies in the sample was obtained.

RESULTS

From these data, the range-energy curves indicated in Fig. 4 were constructed. It should be noted that the

[7] W. H. Brattain and G. L. Pearson, Phys. Rev. **80**, 846 (1950).

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range in the four metals was determined directly in mg/cm², whereas the range in the semiconductors was determined in microns and changed to mg/cm² by use of the density of the materials ($d_{Ge}=5.35$ g/cm³, $d_{Si}=2.4$ g/cm³, $d_{InSb}=5.85$ g/cm³).

For practical reasons, the range in microns as a function of energy for the three semiconductors is given in Fig. 5.

The principle of construction of the range-energy curves is illustrated in Fig. 6. The air equivalents, ΔR_{air}, of the aluminum sample are plotted as a function of $\bar{R}_{air}$, which is the average of the air ranges of the incident and the corresponding exit alpha particles.

The curve is first extrapolated smoothly toward zero mean air range as indicated in the figure. The range in

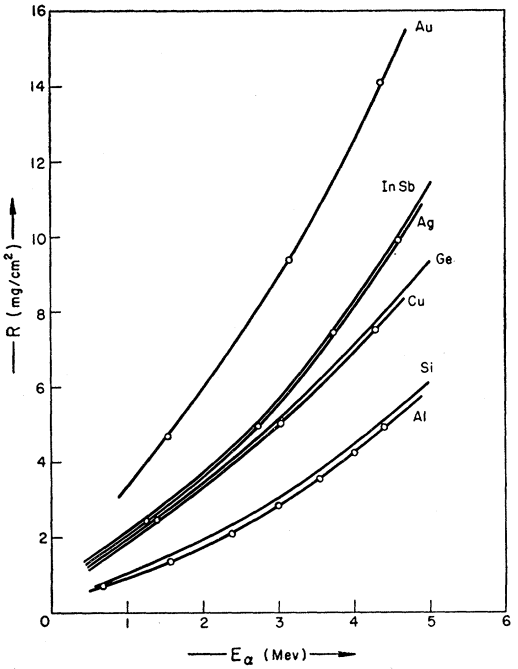

FIG. 4. Range-energy curves for low-energy alpha particles in various materials.

air, R_1, of an alpha particle whose range in Al is 1 sample thickness is equal to twice the mean range in this interval, R_{1m}. This mean range is determined by the intersection of a line of slope two through the origin with the air equivalent curve. Then using R_1 as a new origin, the process is repeated to obtain R_2, the range in air of an alpha particle whose range in Al is two sample thicknesses. Similar procedures yield R_3, R_4, $\cdots$.

By plotting the data for the three semiconductors on log-log paper, it was found that over the energy range investigated, the range-energy relation could be expressed as

$$R_{Si}(\text{microns})=2.13E^{1.45}+2.20,$$
$$R_{Ge}(\text{microns})=1.95E^{1.34}+1.72,$$
$$R_{InSb}(\text{microns})=2.08E^{1.30}+1.65.$$

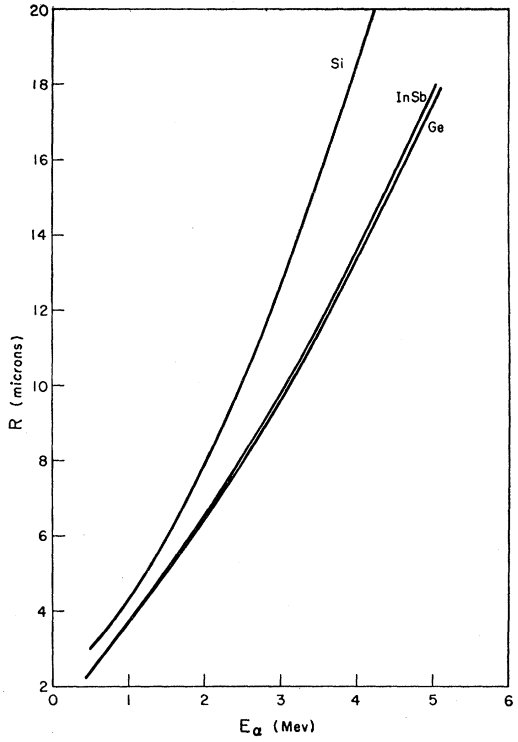

FIG. 5. Range in microns as a function of alpha-particle energy for three semiconductors.

There is some uncertainty in the ranges at low energies because of the lack of accurate data for the energy region below 0.5 Mev. The results for the different samples of each of the semiconductors agreed well.

For considerations involving range differences (ΔR) for energies above 0.5 Mev, the standard errors are given in Table I. These errors arise principally from the errors present in the determination of the sample thicknesses.

Since the stopping power per electron has been found to decrease linearly with $\ln Z$ (e.g., reference 1) a check of the present results may be obtained by plotting $A/(Z\Delta R/\Delta E)$ (which is inversely proportional to the number of electrons/cm² over the range interval considered) *vs* $\ln Z$ for the energy intervals 1 to 2, and 2

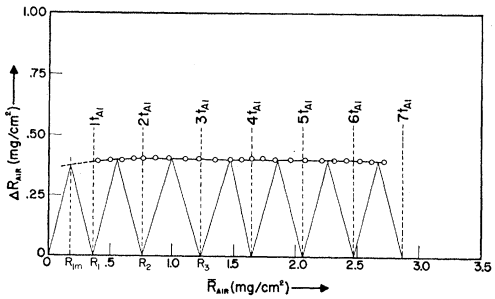

FIG. 6. Principle of construction of range-energy curve for Al. Sample air equivalent (ΔR) is plotted as a function of $\bar{R}_{air}$, which is the average of the air ranges of the incident and corresponding exit alpha particles.

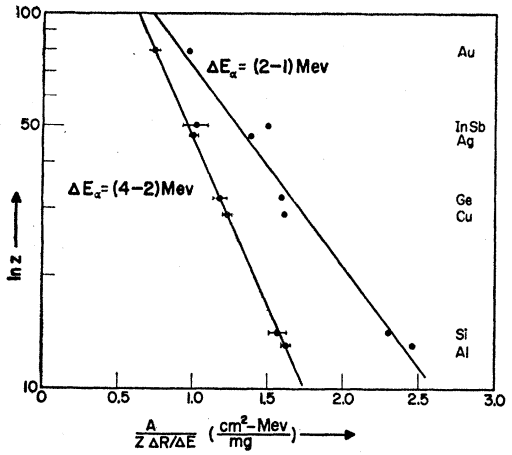

FIG. 7. Plot of $A/(Z\Delta R/\Delta E)$ (inversely proportional to the number of electrons per cm^2) as a function of ln$Z$. The errors indicated are taken from Table I.

to 4 Mev (Fig. 7). The experimental points fall reasonably well on a straight line, especially for the higher energy interval which is the region of greatest interest for the irradiation experiments.

DISCUSSION

The range-energy curves of Fig. 4 for aluminum, copper, and silver are in very good agreement with similar curves previously determined for these substances over the energy region 2 to 4 Mev.[3]

In the case of gold, there is some disagreement in the literature[3,4,6] concerning the range in this energy region (e.g., the range for $E_\alpha = 3.0$ Mev is given as high as 12.5 mg/cm^2[4] and as low as 7 mg/cm^2,[6] while the measurements given here yield 8.9 mg/cm^2). This discrepancy can be attributed largely to the uncertainty in the low-energy region. In all cases, including the results given here, range differences in gold agree closely for alpha energies above 2 Mev.

These results are therefore considered to be in agreement with the data previously obtained for metals.

TABLE I. Relative standard errors of range differences, (ΔR) ($E_\alpha > 0.5$ Mev).

aluminum	2.0%	germanium	3.3%
copper	2.5%	silicon	3.5%
silver	2.3%	indium antimonide	7.4%
gold	2.6%		

The ranges for Si and Ge interpolate smoothly between those of the metals while the range in InSb is approximately 5% lower than one would expect from interpolation between the metals. This discrepancy, however, is within the experimental error.

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