Partition of the Average Energy Deposited in Silicon as a Function of Incident Neutron Energy*

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This paper presents calculations and experimental data of the partition of the average energy deposited in crystalline silicon per incident neutron as a function of incident neutron energy. The study is confined (1) to the energy imparted from elastic and inelastic neutron scattering, and (2) to that imparted from charged-particle production. As the incident neutron energy increases from 200 to 14 keV, the average ionization energy deposited increases from $\approx 1\times10^{-9}$ to $\approx 1\times10^{-7}$ (erg/g) per (neutron/cm^2), and the energy available for displacements (nonionization) increases from $\approx 3\times10^{-9}$ to $\approx 6\times10^{-9}$ (erg/g) per (neutron/cm^2). The calculations of ionization are in good agreement with the experimental data. In addition, carrier-removal experiments in silicon performed with monoenergetic neutrons show agreement when normalized at 14 MeV with the calculations of the energy available for displacements.

I. INTRODUCTION

A VERY significant amount of energy can be imparted to a crystalline solid through nuclear reactions. A full understanding of neutron-induced effects requires a knowledge of the partition of energy of the reaction products between electronic and atomic processes. A knowledge of the amount of energy going into electronic processes is especially important in the prediction of transient ionization effects in neutron-irradiated silicon. A knowledge of the amount of energy going into atomic processes is equally important in studies of permanent radiation effects, for it is this component of energy that is available for the production of neutron displacement damage.

This paper is the third in a study of the partition of energy of energetic particles in crystalline solids. The first paper[1] (hereafter noted as I) gave the ionization produced by an energetic silicon atom within a silicon crystal relative to that of an electron of the same energy as a function of the energy of the silicon atom. The second paper[2] (noted as II) was a similar study for germanium. The present paper gives calculations and experimental data on the partition of the average energy per incident neutron imparted to a silicon crystal by neutron-induced reactions, as a function of incident neutron energy. A preliminary account of this work has already been given.[3,4]

Measurements were presented in I and II of the ratio of the number of pairs produced by a heavy recoil atom to those produced by an electron of the same energy. Such ionization data yielded information about the partition of energy between electronic and atomic processes. It was assumed that the number of pairs produced per unit amount of energy going into electronic processes is constant and independent of particle energy, and, in addition, that this number is independent of the particle, i.e., it is the same for an electron in silicon or a silicon atom in silicon. Since an energetic electron in Si loses virtually all of its energy to electronic processes, the measured ratios in I and II give, on the basis of this assumption, the fraction of the energy of the recoil atom going into electronic processes. The theoretical and experimental arguments presented in I and II and in the present work indicate that this assumption is valid, and it is this assumption that is the basis for predicting the partition of energy in the present investigation. The term "ionization," therefore, will be used in the rest of this paper to represent the amount of energy going into electronic processes.[5]

Neutron-induced events in a solid can produce heavy recoil particles, light-charged particles, and photons. It is these reaction products that transfer energy to the crystal. The present study is confined (1) to the energy imparted to the crystal from elastic and inelastic neutron scattering and (2) to that imparted to the crystal from the production of charged particles. The effect of photons generated in Si by neutron-induced reactions is neglected since the Z of silicon is relatively low. Furthermore, the Si samples exposed to neutrons generally have dimensions of only a few cubic millimeters, and their efficiency in absorbing high-energy photons is quite low.

An earlier calculation by Stein[6] gave the partition of energy for Si recoil atoms in Si as a function of incident neutron energy. In contrast to the present paper, the ionization from charged particles was not considered. At the time Stein's calculations were performed, neither the data from I nor differential cross section data for Si were available. Consequently, the theory of Lindhard[7] (discussed below) and differential

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1 A. R. Sattler, Phys. Rev. **138**, A1815 (1965).
2 A. R. Sattler, F. L. Vook, and J. M. Palms, Phys. Rev. **143**, A588 (1966).
3 A. R. Sattler, Bull. Am. Phys. Soc. **10**, 319 (1965).
4 A. R. Sattler and F. L. Vook, Bull. Am. Phys. Soc. **11**, 192 (1966).
5 To produce an ionization event, i.e., one electron-hole pair, requires on the average 3.6 eV deposited in the electronic system of Si.
6 H. J. Stein, Bull. Am. Phys. Soc. **9**, 288 (1964); J. Appl. Phys. **38**, 204 (1967).
7 J. Lindhard, V. Nielsen, M. Scharff, and P. V. Thompsen, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **33**, No. 10 (1963).

cross-section data from neighboring elements, Al and Mg, were used to calculate the partition of energy for the Si recoils. In addition, Stein assumed that for a given neutron energy all nonelastic events were as effective as elastic scattering events in producing Si displacements.

In order to calculate the partition of the average energy imparted to silicon by neutron-induced events, a knowledge is required of the partition of energy between electronic and atomic processes for the energetic reaction products. Equally important for such calculations is a complete knowledge of the total and differential cross sections for all neutron-induced reactions as a function of incident neutron energy. The partition of energy for Si recoils in Si from neutron scattering has recently been determined in I, and the partition of energy for light-charged particles in Si (from charged-particle production to mass 4), is trivial since almost all of the energy of fairly energetic ($\gtrsim$100 keV) protons and alpha particles goes into ionization. Furthermore, adequate Si total and differential neutron cross-section data also exist.[8,9] In the present paper, these data are combined in calculations of the average amount of energy going into ionization per incident neutron and the average amount of energy going into the atomic system per incident neutron as a function of incident neutron energy.

In the first part of the paper, the model used for the calculations is described and is followed by a presentation of the results of the calculations and corresponding experimental data. Calculations of the average amount of energy going into ionization are then compared with the experimental data on ionization. Finally, the calculations of the average amount of energy going into atomic processes are compared with previously reported calculations and experimental work on the production of permanent damage in silicon by monoenergetic neutrons.

II. MODEL FOR CALCULATIONS

A. General

The separate contributions to the average ionization and to the average energy going into atomic processes from neutron scattering and from charged-particle production are calculated at each incident neutron energy. These separate contributions are then added to give the total average ionization and the total average energy going into atomic processes per incident neutron. The component of energy going into ionization plus the component of energy going into the atomic system accounts for the total energy going into the Si crystal. Initially these separate contributions are calculated per neutron-induced event; finally, they are given per incident neutron/g per unit neutron flux. Some simplifying assumptions were necessary because the cross-section data are not complete. These assumptions are discussed in Appendix A.

Calculations were made over a range of incident neutron energies from 200 keV to 14.1 MeV. In the energy range below 9 MeV, the energy interval is $\approx$1 MeV, and an additional point was calculated at 14.1 MeV. The partial contributions to the total average ionization per incident neutron from heavy recoils, from neutron elastic and inelastic scattering, from the (n,p) reaction, and from the (n,α) reaction are also given throughout the entire energy range. At 14.1 MeV, however, the contributions of the (n,d) and (n,np) reactions are also discussed. Contributions from the (n,γ) reaction are neglected.

B. Energy Partition of Si Recoil Atoms for Neutron Elastic and Inelastic Scattering

The energy spectrum of Si recoil atoms (from neutron elastic and inelastic scattering) is deduced from differential-cross-section data at each neutron energy. The results from I which give the partition of energy between ionization and atomic processes as a function of the energy of Si recoils are then folded into this energy spectrum. This yields the contributions of the Si recoils to the average energy going into ionization and the average energy going into atomic processes.

The energy (T) imparted to a Si atom by an incident neutron of laboratory energy (E_n) in an elastic or inelastic scattering event is

$$\frac{T}{E_n}=\left(\frac{m}{M+m}\right)\left(\frac{M}{m+M}+\frac{Q_i}{E_n}\right)+\frac{mM}{(m+M)^2}-(\cos\theta)\left(\frac{2m}{m+M}\right)\left[\frac{M}{m+M}\left(\frac{M}{m+M}+\frac{Q_i}{E_n}\right)\right]^{1/2} \quad (1)$$

where Q_i= the energy balance for inelastic scattering from the ith excited state of Si^{28} ($Q=0$ for elastic scattering in the center-of-mass system), M= the mass of the silicon atom; for most of the calculations it is assumed that Si is monoisotopic, Si^{28}; m= the mass of the incident neutron; θ= the neutron scattering angle in the center-of-mass system. Furthermore, the number of heavy recoil particles from neutron elastic (and inelastic) scattering per recoil energy interval in the laboratory system is a function of $\cos\theta$. Therefore, the curve of the number of heavy-recoil particles as a function of recoil energy is, within a proportionality factor, identical to the curve of the differential elastic (inelastic) neutron scattering cross sections, $\sigma(\theta)$, as a function of $\cos\theta$.[10] Therefore, from a knowledge of $\sigma(\theta)$, an energy

[8] J. R. Stehn, M. D. Goldberg, B. A. Magurno, and R. Wiener-Chasman, *Brookhaven National Laboratory Report No. 325* (U. S. Government Printing and Publishing Office, Washington, D. C., 1964), 2nd ed., Suppl. 2.

[9] M. D. Goldberg, V. M. May, and J. R. Stehn, Brookhaven National Laboratory Report No. BNL 400, 2nd ed., Vol. 1, 1964 (unpublished).

[10] H. B. Willard, L. C. Biedenharn, P. Huber, and E. Baumgaertner, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1963), Part 2, pp. 1217–1316.

spectrum of heavy silicon recoils can be deduced at incident neutron energy E_n.

The ionization produced by recoils from neutron elastic and inelastic scattering can then be deduced with a knowledge of the fraction of energy going into ionization, $f(T)$, given in I. The average energy transfer, $\bar{T}(E_n,Q,\cos\theta)$, the average ionization per recoil, $\bar{I}(E_n)$, and the fraction of energy not going into ionization per neutron-induced event, $\langle[1-f(T)]T\rangle_{\text{av}}$ are, respectively,

$$\bar{T}(E_n,Q,\cos\theta)=\int_0^{T_{\max}}\frac{T\sigma(E_n,T)dT}{\sigma_{\text{total}}(E_n)}, \tag{2}$$

$$\bar{I}(E_n)=\langle f(T)T\rangle_{\text{av}} =\int_0^{T_{\max}}\frac{f(T)T\sigma(E_n,T)dT}{\sigma_{\text{total}}(E_n)}, \tag{3}$$

$$\langle[1-f(T)]T\rangle_{\text{av}}=\int_0^{T_{\max}}\frac{[1-f(T)]T\sigma(E_n,T)dT}{\sigma_{\text{total}}(E_n)}, \tag{4}$$

where $\sigma(E_n,T)$ is the differential (elastic and inelastic) neutron-scattering cross section as a function of T, and $\sigma_{\text{total}}(E_n)$ is the total neutron cross section at incident neutron energy E_n.

C. Energy Partition of Charged Particles

The contribution of charged-particle reaction groups to ionization can be calculated to a good approximation simply from a knowledge of the cross section of each charged-particle group, the Q values of the reaction, and the energy levels of the residual nuclei. For certain neutron energies, charged-particle production can impart significantly more energy to the lattice than can a neutron-scattering event. The products of a charged-particle reaction can absorb the incident neutron energy minus the Q value, whereas in an elastic-scattering event the energy transferred to the recoil Si atom is $\geq 0.133E_n$.

Recently, cross-section measurements for the $Si^{28}(n,p)Al^{28}$ and $Si^{28}(n,\alpha)Mg^{25}$ reactions have been made in fine detail over a considerable range of neutron energies.[8] If we assume that all the energy from light-charged particle production including the energy of the associated recoil nuclei goes into ionization, then the average contribution from proton production ($\bar{I}_p$) to the total average ionization at incident neutron energy E_n can be expressed by

$$\bar{I}_p=\frac{\sum_{i=0}^{n}(E_n-Q_i)\sigma(n,p_i)}{\sigma_{\text{total}}(E_n)}, \tag{5}$$

where $\sigma(n,p_i)$ = the cross section for the production of protons from the ith excited state of Al^{28} ($i=0$, ground state), and Q_i = the energy balance in the excitation of the ith state of Al^{28}.

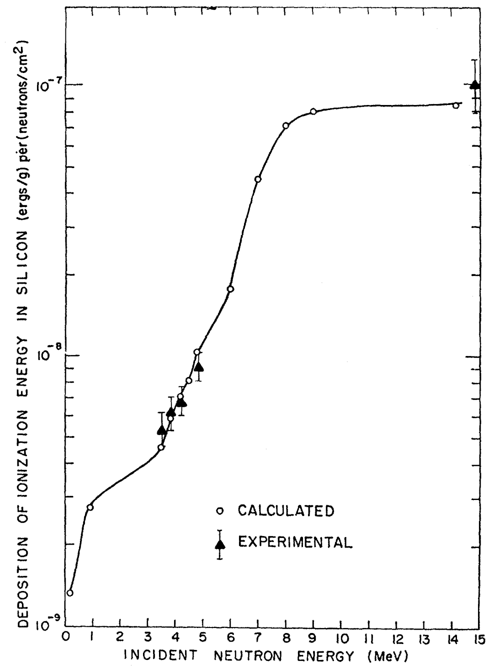

FIG. 1. Average energy deposited in Si as ionization per incident neutron (ergs/g) per (neutron cm^{-2}). Experimental data points are included.

The expression for the ionization produced by alpha groups, $\bar{I}_\alpha(E_n)$, and other charged particles is similar. The total average ionization per neutron-induced event, $\bar{I}^*(E_n)$, can then be expressed by

$$\bar{I}^*(E_n)=\langle f(T)T\rangle_{\text{av}}+\bar{I}_p(E_n)+\bar{I}_\alpha(E_n)+\bar{I}\times(\text{other reaction products}).$$

The average ionization $\bar{I}(E_n)$ per incident neutron per gram of Si per unit flux is then

$$\bar{I}(E_n)=\bar{I}^*(E_n)\sigma_{\text{total}}(N/A), \tag{6}$$

where N = Avogadro's number and A = the atomic weight of Si.

III. RESULTS

A. Calculation

Figure 1 shows calculations of the average total ionization as a function of incident neutron energy for incident neutron energies from 200 keV to 14.1 MeV. The ionization per incident neutron increases about two orders of magnitude over this energy range. Figure 2 shows the calculated contributions to the total average ionization from the various neutron-induced reactions as well as the total average ionization.

Figure 3 shows the calculated average amount of energy per incident neutron going into the atomic system (nonionization) and hence available for neutron displacement damage. The increase of this component of the energy transfer, about a factor or 2, between

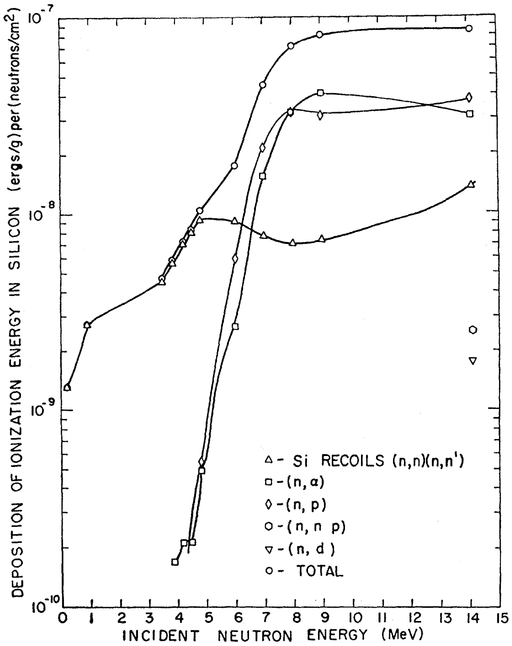

FIG. 2. Contributions of various nuclear reactions to the total average energy deposited in Si as ionization (ergs/g) per (neutron cm^{-2}). The total average ionization is also included.

200 keV and 14.1 MeV seems rather modest in view of over a tenfold increase in the incident neutron energy. However, the neutron cross section decreases fivefold in this range, and the ionization accounts for a larger and larger fraction of the recoil energy as the neutron and the recoil energies are increased. The energy transfer to the lattice also increases at a slower rate as E_n increases because neutron elastic scattering becomes more forward-peaked.

B. Experimental Results

Experimental spectra of ionization were produced by heavy recoils in a Si solid-state detector and were integrated to give the average ionization per neutron. Experimental results of the average ionization per incident neutron are included in Fig. 1. For two energy regions (3.5–4.8 MeV and at 14.1 MeV) where differential elastic and inelastic neutron-scattering cross sections were known, comparisons between experiments and calculations were obtained. As seen in Fig. 1, experiments and calculations agree within $\approx 10\%$.

Ionization produced by heavy recoil atoms was also calculated from neutron cross-section data and from data on the ionization produced from Si recoils. In the lower energy range considered ($3.5 \leq E_n \leq 4.8$ MeV), almost all the ionization emanates from Si recoils. The calculated spectrum of ionization $\sigma^*(I)$ of the Si recoil atoms of energy T generated from differential-cross-section and ionization data[1] for monoenergetic neutrons of energy E is

$$\sigma^*(I)=\sigma^*[f(T)T]=\sigma(E_n,T)/[Tdf(T)/dT+f(T)]. \quad (7)$$

TABLE I. Contribution of neutron scattering to total average ionization per incident neutron. E_n=6–10 MeV.[a]

E_n	Energy deposition in Si[b] [10^{-8} (erg/g) per (neutron/cm^2)]
6 MeV	0.91
7	0.77
8	0.71
9	0.74
10	0.82

[a] In this energy range, cross-section scattering data are not available to compare experiment with calculation. These data are the basis for the contribution of neutron scattering to the total ionization shown in Fig. 2.
[b] Accurate to $\approx \pm 18\%$.

Figure 4 shows that reasonable agreement in the shapes of the measured and calculated spectra of ionization were obtained.

Since measurements of the ionization agreed with calculations in the energy range between 3.5 and 4.85 MeV (Fig. 1) where complete cross-section data were available, these measurements were then extended to the energy range between 6 and 10 MeV where neutron-scattering cross-section data do not exist. The experimental results between 6 and 10 MeV are given in Table I and are the basis for the contribution from neutron scattering to the total ionization shown in Fig. 2. The contribution to the total ionization by charged particles in this energy range was calculated using charged-particle cross-section measurements (which themselves were based on ionization measurements in Si detectors).[8]

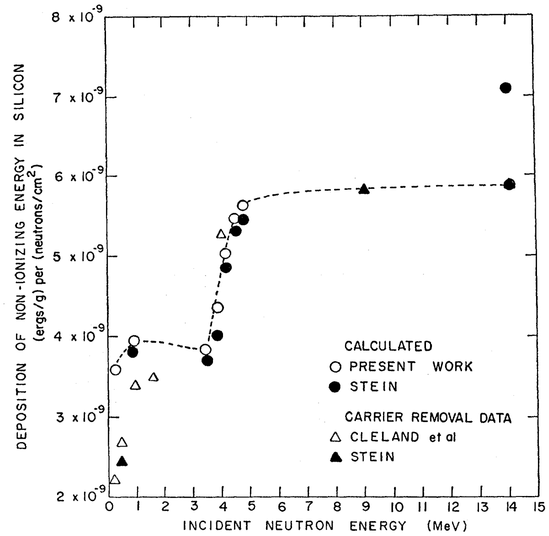

FIG. 3. Average energy deposited in Si per incident neutron which does not go into ionization (ergs/g) per (neutron cm^{-2}). For comparison purposes, experimental carrier-removal data in *n*-type Si of Stein and Cleland *et al.* are normalized in arbitrary units to the energy calculations at 14 MeV. The low-energy datum point of Stein is positioned at the most probable neutron energy of a Godiva reactor spectrum. Calculations in the present work were performed at energies where Si cross-section data were available. Stein's calculations at these points are also shown.

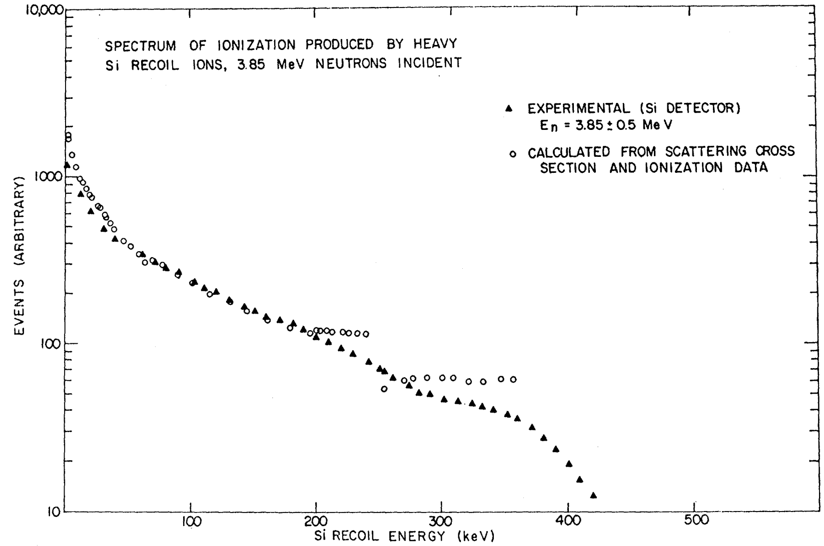

FIG. 4. Spectra of ionization produced by heavy Si recoil atoms, 3.85-MeV neutrons incident. Spectra generated by (1) experiment, (2) elastic and inelastic cross-section data at 3.85 MeV and I. Energy calibration for experiment was obtained by means of conversion electrons.

Another measurement of the average ionization per neutron-induced event was made at 14.7 MeV using silicon solid-state detectors thick enough (1000 and 3000 μ in depletion depth) to have a reasonably good efficiency for the charged particles generated. This result is included in Fig. 1. The detectors were surrounded by silicon so that the energy carried out of the sensitive volume by charged particles was compensated on the average by an equal amount of energy coming into the sensitive volume. Normalization was carried out on the most energetic alpha group (from the ground state of Mg^{25}) which is the most energetic structure (peak) in the spectrum of ionization produced in Si^{28} under bombardment by 14.7-MeV neutrons.

The experimental result at 14.7 MeV was somewhat higher than calculation, probably because of a contribution from photons which are produced in abundance at 14.7 MeV. A detector thick enough to have a high efficiency for the charged particles generated at this energy would have a small but significant photon efficiency. The experimental result would also be expected to be slightly higher than the calculations since the measurements corresponded to an incident neutron energy $\approx$600 keV higher than the calculations.

IV. DISCUSSION

A. Average Ionization and Partition of Energy between Electronic and Atomic Processes

Figure 1 shows the good agreement obtained between calculations and experiments of the average ionization produced per incident neutron in Si.[11] Good agreement is also obtained between the observed and calculated spectra of ionization of Si recoils as shown in Fig. 4. Figure 2 shows that for $E_n \leq 5$ MeV the heavy recoils account for most of the ionization, whereas above 7 MeV, charged-particle production accounts for most of the ionization. The Coulomb barrier against charged-particle emission and the threshold energies for proton and alpha production in Si^{28} (3.78 and 2.75 MeV, respectively) inhibit charged-particle production at low energies.

The measurements and calculations in this investigation are closely related to the partition of energy between atomic and electronic processes in a solid. A model[7] proposed by Lindhard, Scharff, Nielsen, and Thompson gave (prior to the appearance of any actual detailed data) a comprehensive theoretical treatment of the partition of energy between electronic and atomic processes. Integral equations were presented governing cumulative effects of general physical properties caused by an energetic atom slowing down in a solid. As important examples, solutions of these equations give for an energetic particle of energy E in a solid that portion $\bar{\nu}(E)$ which goes into atomic processes and that portion $\bar{\eta}(E)$ which goes into electronic processes where $\bar{\eta}+\bar{\nu}=E$.

The theory of Lindhard has been discussed extensively in I and II, and applies for recoils from $\approx$1 keV to 100 MeV. The theory is appropriate for the study of neutron-induced effects, since most heavy primaries energized by neutron scattering fall in this range. As discussed in I and II, the assumption that the number of pairs per unit amount of energy going into electronic processes is constant and independent of energy and that this number is the same for an electron in silicon or a silicon atom in silicon is the basis for predicting the partition of energy in this investigation. The theoretical and experimental arguments in I and II

[11] D. K. Nichols, [General Atomic Report No. GA 36, 1965 (unpublished)] computed the average ionization at 14 MeV for Si, and it is in close agreement with the present work. Calculations and experiments of E. C. Smith *et al.* are in agreement with the present work. IEEE Trans. Nucl. Sci. **13**, 11, 1966.

and other work[12] indicate that this assumption is valid.

Moreover, more recent theoretical and experimental data further substantiate this assumption. W. Van Roosbroeck[13] in his treatment of the theory of the yield and Fano factor of electron-hole pairs generated in semiconductors by high-energy particles concluded that the statistics of ionization are largely determined at secondary electron energies of just a few ionization thresholds. This conclusion presumably implies that as long as the energy requirements are satisfied (secondaries sufficiently energetic), the yield per unit energy is independent of the nature and energy of this particle creating secondaries. In a recent work,[14] Boring, Strohl, and Woods studied charge-pair production of various low-energy heavy ions in nitrogen gas. Using the Lindhard theory, they conclude that the number of pairs produced per unit amount of energy going into the electronic system is independent of ion energy and nearly constant for various ions in nitrogen (H^+,He^+,D^+,N^+,O^+,Ar^+). Therefore, the bases for comparing experiment with the Lindhard theory appear quite sound.

In a neutron reaction, the partition of energy between electronic and atomic processes cannot readily be predicted for the heavy recoil atoms; for the light charged particles almost all the energy goes into electronic processes. Since the ionization data for heavy recoil atoms agree with the theories of the partition of energy,[1,2] it is therefore justified here to use ionization data to calculate the amount of energy going into electronic processes from all the reaction products. That part of the energy not going into electronic processes goes into atomic processes and is available for the production of permanent damage.

B. Disposition of Nonionization Energy

Previous work has been concerned largely with the component of the energy going into the atomic system rather than into ionization. Specifically, the predominant interest has been in the energy available to produce permanent damage. Stein's calculations[6] of the energy going into the atomic system (and available for permanent damage) are generally in good agreement with the present results shown in Fig. 3. The agreement is better than 10% for 200 keV$\leq E_n \leq$5 MeV and within 30% for E_n=14 MeV. The discrepancy at 14 MeV may be in some part due to Stein's approximations for the nuclear reaction products. The good agreement at low energies where neutron elastic scattering is dominant reflects the fact that either the experimental ionization data in I or the Lindhard theory give about the same energy partition for heavy Si recoils.

The ratio of 14-MeV to reactor-neutron damage has been of particular interest since neutrons of these energies are produced most abundantly by available neutron sources. H. J. Stein[6] finds a ratio of damage of 2.8 from carrier removal experiments. Wikner, Horiye, and Nichols[15] measured changes in excess carrier lifetime from 14 MeV and from fission neutrons. They show that damage from 14-MeV neutrons is $\approx$2.1 times that of a fission spectrum. The average neutron energy of these fission spectra (Sandia SPERF reactor, General Atomic TRIGA reactor) is $\approx$1 MeV. It might be expected that such data give information on the energy dependence of neutron damage. However, even if the reactor spectrum is well known, some caution should be exercised in comparing fission-spectra data and data from monoenergetic neutrons. The average energy transfer per neutron to the atomic system by fission neutrons is not the same as the energy transfer of the average energy neutron of this fission spectrum. Primarily because present calculations do not detail the low-energy region, a proper comparison of calculations with fission spectrum data can be done only with difficulty.

A better comparison of calculations and experiments on the energy dependence of neutron damage can be obtained for monoenergetic neutrons. Stein[6] and Cleland *et al.*,[16] measured carrier removal rates over a number of incident neutron energies (including 14 MeV). Since the carrier removal rates might be expected to be proportional to the energy deposited into the atomic system, these data are included with the calculations shown in Fig. 3. The carrier removal experiments are normalized to the present calculation at 14 MeV, and agreement is good except for a point at 200 keV. At this energy the calculations reflect a sharp resonance[8] in the neutron cross section. If the calculations were averaged over a finite spread of neutron energy, as exists in an actual experiment, the calculated value would be smaller and would show greater agreement with experiment. Exact agreement of normalized carrier removal measurements with calculations of nonionization energy deposition would be expected only if the amount of energy deposited in the atomic system that results in the removal of one carrier is independent of neutron energy. The general agreement of the calculations and the carrier removal experiments suggests that this is very nearly the case.

APPENDIX A: DISCUSSION OF ASSUMPTIONS

1. General Considerations

Exact calculations at all neutron energies are not possible because of the absence of complete cross-section data. A number of simplifying assumptions

[12] H. H. Morganstern, Hahn Meinter Institut für Kernforschung, Berlin, Sektor Kernphysik Report No. 5, 1955 (unpublished).

[13] W. Van Roosbroeck, Phys. Rev. **139**, A1702 (1965).

[14] J. W. Boring, G. E. Strohl, and F. P. Woods, Phys. Rev. **140**, A1065 (1965).

[15] E. G. Wiker, H. Horiye, and D. K. Nichols, Phys. Rev. **136**, 1428 (1964).

[16] J. W. Cleland, R. F. Bass, and J. H. Crawford, Jr., in *Proceedings of the 7th International Congress on the Physics of Semiconductors* (Dunod Cie, Paris, 1964), Vol. 3, p. 401.

were made with small sacrifice in accuracy since the uncertainty in the existing cross-section data[8,9] is 5–20%.

Neutron-induced reactions include scattering (elastic and inelastic), charged-particle production, and photon emission. Photon emission may occur from neutron absorption (n,γ) or from inelastic scattering or charged-particle production from excited states of the residual nucleus. Heavy recoils have a range $\approx 10\ \mu$ in Si. Alpha particles have a range $\approx 100\ \mu$. Protons have a range of $1000\ \mu$ in Si. Appreciable photon efficiency implies thicknesses of Si in the order of centimeters. Therefore, only the effects of heavy recoils and charged particles were considered. This is realistic for small Si samples, device size, with an efficiency $\approx 100\%$ for charged particles ($m \geq 1$ mass units) and heavy recoil atoms, but with a very small efficiency for photons.

In calculating the contribution of charged-particle reactions to the total average ionization, it is assumed that the total energy of a light charged particle and the recoil of the associated residual nucleus go into ionization. Since on the average greater than 90% of the energy transferred to the lattice comes from the light charged particles (all of which goes into ionization) and on the average well over half of the energy of the recoiling residual nuclei goes into ionization, this assumption overestimates the ionization of charged particles by $\approx 3\%$.

In calculating the component of energy from charged-particle production going into the atomic system it is assumed that at a given neutron energy the average energy going into the atomic system per neutron-induced event is the same for both heavy recoils from neutron elastic and inelastic scattering and from recoils emanating from charged-particle production. The angular distributions of each charged particle group are generally not known[17]; thus the accuracy of this approximation is difficult to determine. The charged-particle production cross section, 5 MeV$\leq E_n \leq$14.1 MeV, averages only $\approx 20\%$ of the scattering cross section; therefore, the accuracy of this assumption is not too critical.

2. Assumptions Made at 14.1-MeV Incident Neutron Energy

At these high incident neutron energies, a large number of reaction channels are available. The cross-section data here are quite sketchy. The actual differential-scattering cross sections as measured by Clarke and Gross[18] for the ground and first-excited states of Si^{28} were used. Isotropy was assumed for the next two excited states (4.61 and 4.97 MeV) as well as the group of states at 6.9 MeV. There the measurements quoted at 61° for these groups are assumed appropriate for all angles.[19] There is some excitation of even higher states (and continuum) which were not determined in their experiment. The continuum is isotropic (in contrast to forward-peaked elastic scattering); contributions of the continuum may raise the average contribution of the components of ionization (and energy going into the atomic system) by a few percent. The effect on ionization is small, because charged-particle production is the predominant source of ionization.

Individual groups of protons from states in the residual Al^{28} nucleus range up to 4.24 MeV. The individual groups were divided into four larger groups of energies between 0 and 30 keV, 0.97 and 1.02 MeV, 2.14–2.66 MeV, and 2.99–4.24 MeV,[17] since data are available for these larger collections of charged-particle groups. An average energy was taken as characteristic for each group. The ionization contribution of the remaining groups (higher-energy states and a continuum) was estimated to have an average of 5 MeV,[20] which would account for 10% of the total ionization at 14.7 MeV. The (n,α) cross section is known for the ground and first 14 states of the residual nucleus.[21] This was considered adequate since the larger Coulomb barrier should still make the effect of an alpha particle continuum quite small. The (n,np) and (n,d) reactions at 14.1 MeV are assumed to go to the ground state of the residual Al^{27} nucleus, and they account for 5% of the contribution of ionization.

In summary, enough cross-section data are available to attempt calculations, but the information is far from complete.[22] Information exists about the more energetic groups in each type of reaction; fortunately it is these groups which impart a disproportionally large amount of energy to the lattice. The calculations are estimated to be accurate to 20% for $0 \leq E_n \leq 9$ MeV and 30% at 14.1 MeV.

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[22] The 1-MeV data-point intervals are inadequate to account for rapid fluctuations in neutron cross section from ≈ 30 keV to ≈ 2 MeV. These fluctuations are due to resonances, and a separate investigation of the resonance region is necessary. Experiments are in progress to fill in gaps in neutron-scattering data for Si, $E_n > 5$ MeV. These results will be included with the calculations over the resonance region.