MAR 16 1965

GENERAL ATOMIC

DIVISION OF **GENERAL DYNAMICS**

GA-6136

MASTER

IONIZATION ENERGY DEPOSITION FROM 14-MeV NEUTRON BOMBARDMENT
OF SILICON AND GERMANIUM

Si Ge
by

D. K. Nichols

February 10, 1965

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

GENERAL ATOMIC
DIVISION OF
GENERAL DYNAMICS

JOHN JAY HOPKINS LABORATORY FOR PURE AND APPLIED SCIENCE

P.O. BOX 608, SAN DIEGO, CALIFORNIA 92112

GA-6136

IONIZATION ENERGY DEPOSITION FROM 14-MeV NEUTRON BOMBARDMENT
OF SILICON AND GERMANIUM

by

D. K. Nichols

Harry Diamond Laboratories
U. S. Army Materiel Command
Contract DA-49-186-AMC-65(X)
General Atomic Project No. 344

February 10, 1965

IONIZATION ENERGY DEPOSITION FROM 14-MeV
NEUTRON BOMBARDMENT OF SILICON AND GERMANIUM

Bombardment of silicon and germanium with 14-MeV neutrons creates energetic recoil atoms and light charged particles which lose some or all of their energy in ionizing collisions. An estimate of the amount of energy deposited in ionizing processes and the rate of formation of electron-hole pairs is calculated from recent experimental data.

SILICON

The most recent cross-section data is listed below. ⁽¹⁾

$$\sigma_{\text{total}} = 1.95 \text{ barns}$$

$$\sigma_{\text{non-elastic}} = 1.02 \text{ barns}$$

$$\sigma(n, p) = 0.160 \text{ barns for } E_p > 2.9 \text{ MeV}$$

$$\sigma(n, p) = 0.265 \text{ barns}$$

$$\sigma(n, np) = 0.027 \text{ barns}$$

$$\sigma(n, \alpha) = 0.052 \text{ barns.}$$

It can be assumed that the difference in the value for the non-elastic cross section and the reaction cross sections is due to inelastic $(n, n'\gamma)$ processes and that the differences in the two values for $\sigma(n, p)$ are due to the failure of the first measurement to account for low energy protons. It can also be seen that small error will arise if it is assumed that the energy of the protons from the (n, np) reaction is the same as that for the (n, p) reaction so that the two cross sections can be added together. Thus, the useful cross sections become:

$$\sigma_{\text{elastic}} = 0.93 \text{ barns}$$

$$\sigma_{\text{inelastic}} = 0.68 \text{ barns}$$

$$\sigma(n, p) = 0.29 \text{ barns}$$

$$\sigma(n, \alpha) = 0.05 \text{ barns.}$$

The energy deposition for the reaction products, α particles and protons, is then readily calculated since these particles lose all of their energy within a distance that is small compared to the distance between neutron collisions, and small compared to the thickness of typical silicon samples. The average energy for the protons is ⁽²⁾ $\langle E_p \rangle = 5$ MeV, and the average energy for the α 's is ⁽³⁾ $\langle E_\alpha \rangle = 9.5$ MeV. Hence, for an energy deposition per unit neutron flux given by:

$$E_{\alpha, p} = \sigma N_o \langle E_{\alpha, p} \rangle \quad (1)$$

where N_o is the density of atoms/cm³, we have

$$E_\alpha = 25 \text{ keV/cm}^3$$

$$E_p = 75 \text{ keV/cm}^3.$$

The energy deposition from the elastic and inelastic collisions is due to the ionization energy loss of the recoil atoms, the gamma rays from the inelastic reaction being scarcely attenuated. It can be shown ⁽⁴⁾ that the recoil energy from each reaction is approximately the same with an average value $\langle E_{\text{recoil}} \rangle = 200$ keV. The theory of Lindhard ⁽⁵⁾ shows that about one-third of this energy is lost in displacement collision with the lattice so that ~ 140 keV is available for ionization. Hence,

$$E_{\text{recoil}} = 10 \text{ keV/cm}^3.$$

The total energy deposition $E = E_\alpha + E_p + E_{\text{recoil}}$ is thus

$$E = 100 \pm 20 \text{ keV/cm}^3$$

per unit flux of neutrons. The corresponding rate of electron-hole pair formation is given by:

$$N = E/E_{\text{pair}} \quad (2)$$

where E_{pair} is the energy needed to form one pair. From Bussolati et al., ⁽⁶⁾ $E_{\text{pair}} = 3.7$ eV so that $N = 2.7 \times 10^4$ pairs/cm³-sec/unit neutron flux.

GERMANIUM

The most recent cross section data are listed below. ⁽⁷⁾

$$\sigma_{\text{total}} = 3.34 \text{ barns}$$

$$\text{Ge}^{74}; \sigma(n, \alpha) = 0.015 \text{ barns}$$

$$\text{Ge}^{70}; \sigma(n,p) = 0.130 \text{ barns}$$

$$\text{Ge}^{72}; \sigma(n,p) = 0.065 \text{ barns}$$

$$\text{Ge}^{75}; \sigma(n,p) = 0.140 \text{ barns}$$

$$\text{Ge}^{70}; \sigma(n,2n) = 0.70 \text{ barns}$$

$$\text{Ge}^{76}; \sigma(n,2n) = 1.80 \text{ barns.}$$

In addition, from p. 363 of Ref. (7), it is possible to estimate $\sigma_{\text{non-elastic}} = 1.5 \pm 0.2$ barns. It is clear that the $(n,2n)$, (n,α) and (n,p) reactions will account for the non-elastic events and that the (n,α) contribution is small compared to the (n,p) reaction. Thus, the useful cross sections become:

$$\sigma_{\text{elastic}} = 1.84 \text{ barns}$$

$$\sigma(n,p) = 0.11 \text{ barns}$$

$$\sigma(n,2n) = 1.4 \text{ barns,}$$

where $\sigma(n,p)$ is a weighted average based on the isotopic abundance of five germanium isotopes.

The energy deposition for the protons is based on an assumed average proton energy of 8 MeV determined from the average spectrum of like atomic number elements and the theoretical expectation that larger energies are needed for germanium than for Si because of the greater Coulomb barrier of the nucleus. The average energy of the recoil atoms from the elastic reaction is ⁽⁴⁾ 60 keV of which ~ 10 MeV is lost via ionization collisions. The average recoil energy of the atoms after a $(n,2n)$ collision is assumed to be one-half that from elastic scattering due to momentum cancellation from the two neutrons. Thus from Eq. (1),

$$E_p = 38 \text{ keV}$$

$$E_{2n} = < 1 \text{ keV}$$

$$E_{\text{recoil}} = 1 \text{ keV}$$

for a total ionization energy deposition per unit neutron flux of

$$E = 40 \text{ keV/cm}^3$$

within a factor of two. The corresponding rate of pair formation can be estimated by taking $E_{\text{pair}} = 3.0 \text{ eV}^{(8)}$. From Eq. (2), $N = 1.3 \times 10^4$ pairs/ $\text{cm}^3\text{-sec/unit neutron flux}$.

REFERENCES

1. Brookhaven National Laboratories Report BNL 325, 2nd Ed., Suppl. 2, (1964).
2. D. L. Allan, Nucl. Phys. 24, 274 (1961).
3. L. Colli, I. Iori, and M. G. Marazzan, Nucl. Phys. 43, 529 (1963).
4. E. G. Wikner, H. Horiye and D. K. Nichols, Phys. Rev. 136, A1428 (1964).
5. J. Lindhard, V. Nielsen, et al., Kgl. Danske, Videnskab. Selskab, Mat.-Fys. Medd., 33, No. 10 (1963); J. Lindhard, M. Scharff, and H. E. Schiøtt, ibid, 33, No. 14 (1963).
6. C. Bussolati, A. Fiorentini, and G. Fabri, Phys. Rev. 136, A1756 (1964).
7. Brookhaven National Laboratories Report BNL 325, 2nd Ed., (1958).
8. V. S. Vavilov, L. S. Smirnov, and V. M. Patskevich, Sov. Phys. Dokl. 2, 93 (1957).