and a 6s free-electron contribution of -6.5×10^{-6} emu/mole. χ_{5d}^{orb} and χ_{4f}^{orb} are then taken to be the difference between the observed susceptibility and these calculated contributions from the other sources. H_{HF}^{6s} is obtained from the hyperfine field measured by optical hfs spectroscopy in the $^2S_{1/2}$ state of the free Yb^{+1} ion.[18] This must be reduced by a factor of approximately 0.5 to account for the reduced amplitude of the 6s electron wave function at the nucleus in the metallic environment.[19] A further reduction by a factor of 0.7 results from the change of H_{HF} with ionicity. H_{HF}^{5d} is an estimate of the core polarization hyperfine field of 5d electrons based on NMR results in Pt metal.[20] H_{HF}^{4f} is based on hyperfine interactions observed in EPR measurements of Gd^{3+} ions. We take $\langle 1/r^3\rangle_{5d}=2.5$ a.u. as a reasonable estimate for the 5d electrons.[21] For 4f electrons, the EPR hyperfine interaction of Yb^{3+}, taken with our measured Yb^{171} nuclear magnetic moment value, indicates $\langle 1/r^3\rangle_{4f}=12.4$ a.u. As seen from Tables I and II, the observed Knight shift lies between the predicted values for exclusively 4f character and exclusively 5d character. Inclusion of 4f and 5d bands simultaneously would improve the agreement with experiment. Rocher[22] has suggested that the 4f levels in pure Yb metal may lie very near the Fermi level. Our results indicate that in $YbAl_2$ such 4f levels may actually form part of the conduction band and have important effects on the magnetic properties.

An approximate value of the nuclear spin-lattice relaxation time T_1 was also measured in $YbAl_2$ by observing the saturation of the resonance absorption. At 1.8°K, we find $T_1T=0.12$ sec °K. A Knight shift of 0.85% arising from 6s conduction electrons would be expected[23] to produce a T_1T of 0.13 sec °K, nearly enough to account for the observed relaxation. Core polarization and orbital hyperfine interactions should also produce relaxation, but will likely be less effective than the direct contact interaction of 6s electrons.

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Production of Displacement Radiation Effects by Recoils from Photoneutron Reactions*

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The photoneutron method of producing displacement radiation effects has been established. The displacement effects produced by recoils from $Si(\gamma,n)$ reactions have been detected by measurement of the change in excess-carrier lifetime. The change in the reciprocal of the lifetime is approximately proportional to the total number of primary reactions at various irradiating bremsstrahlung energies between 15 and 38 MeV, with a proportionality constant of $(2.0\times10^{-4}\pm25\%)\mathrm{cm}^3\,\mathrm{sec}^{-1}$. The data can be explained on the basis that the primary energy loss of the recoil atoms is due to ionization. Other possible explanations are offered and a comparison of the results with those of 30-MeV electron irradiations is made.

I. INTRODUCTION

A PHOTONUCLEAR reaction resulting in the emission of a neutron imparts a significant recoil energy to the residual nucleus. If this residual nucleus is in a crystal lattice, it will be displaced from its lattice position and will subsequently displace a large number of other atoms before its energy is dissipated. The resulting cascade of displacing collisions is very similar to that produced by elastic scattering of high-energy (~1 MeV) neutrons from the same nucleus. Hence, the defects introduced are expected to be similar to those produced by nuclear reactor irradiation.

The purpose of the work described here was to measure the relative rates of defect production in silicon by various energy bremsstrahlung spectra and, hence, to

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confirm the photonuclear-recoil method of producing displacement radiation effects. Furthermore, the absolute rate of change of a physical property (excess-carrier lifetime in this case) can be related to the calculated rate of introduction of displacement cascades.

To perform this experiment, samples of silicon at room temperature were irradiated with bremsstrahlen which were generated in a thick platinum target by high-energy electrons from a traveling-wave linear accelerator. The excess-carrier lifetime in the silicon sample was measured before irradiation and during various interruptions in the irradiation. This measurement was performed by irradiating the sample with a single bremsstrahlung pulse and observing the decay time of the radiation-induced excess conductivity following the pulse. The integrated bremsstrahlung intensity was monitored by means of a $Au^{197}(\gamma,n)Au^{196}$ reaction.

In the next section the experimental techniques are discussed, including the irradiation methods, monitoring, and calibration, as well as the techniques used to measure excess-carrier lifetime. In Sec. III the background and theory are presented, especially the calculations performed to evaluate the bremsstrahlung photon spectrum, intensity calibration, energy spectrum of primary recoil atoms, and total number of displaced atoms. In Sec. IV the experimental results will be presented and compared with two theoretical models. A comparison will also be made with the results of a 30-MeV electron irradiation.

II. EXPERIMENTAL PROCEDURE

In this work, the material used was 7-Ω/cm, phosphorus-doped, quartz-crucible-grown silicon crystals obtained from Knapic Electro Physics, Inc. Rectangular samples, 1×2.5×12 mm, were used, with the voltage, current, and copper-constantan thermocouple leads soldered to gold buttons on the sample. The sample was mounted in an aluminum can on an anodized surface to provide electrical insulation and good thermal exchange with a coolant chamber on the other side of this surface. Water flowing through this chamber maintained the sample at a constant temperature. A slight excess pressure of helium was admitted to the sample chamber to aid in the cooling.

The gamma irradiations were performed at the General Atomic linear accelerator by using a platinum foil to convert the high-energy electrons into gamma rays. Figure 1 shows the experimental arrangement. The collimated electron beam impinged on the 0.040-in. platinum foil, producing a gamma beam which was then passed through an aluminum block to degrade the energy of the electrons still in the beam. The lead collimator confined the gamma beam to the target area, and the sweeping magnet deflected any electrons still in the beam so as to ensure that all changes in the sample properties were due only to gamma irradiation.

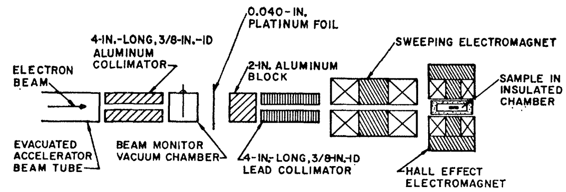

FIG. 1. Experimental arrangement for measurement of lattice displacements caused by Si atom recoils during photoneutron emission.

During the irradiation, the intensity of the electron beam was monitored by passing it through a 0.0007-in.-thick titanium foil and observing the current of secondary electrons emitted from the foil.[1] The relative dosages delivered to the sample for each of the irradiations at a given electron energy were determined from the monitor reading. The absolute intensity of the irradiations was determined from the number of photoneutron reactions produced in a small gold wire placed adjacent to the sample. The number of reactions was measured after irradiation by determining the disintegration rate of the Au^{196} products of the photoneutron reaction by counting the rate of emission of gamma rays associated with the beta decay.

The lifetime measurements were performed by generating excess carriers in the silicon sample with a single short low-intensity pulse of gamma rays.[2] The intensity was adjusted so as to change the conductivity in the sample by approximately 20% immediately after the radiation pulse. The lifetime was measured by deducing the rate of decay of the photoconductivity from an observation of the change in voltage between the two voltage probes. The current through the sample was constant during this decay because the impedance in the external circuit was much greater than the resistance of the semiconductor sample.

A differential amplifier with push-pull output was used to measure the photoconductive decay. It consisted of a Tektronix type-G input, a main amplifier consisting of a replacement vertical amplifier for a Tektronix 545 oscilloscope, and, as the output stage, a specially designed high-current cathode follower which drove two 150-ft cables leading to the remote control room. This system had a rise time of 30 mμsec when utilized with a Tektronix 551 oscilloscope having another type-G differential preamplifier. The use of the push-pull feature of the main amplifier and cable driver minimized rf noise in the measuring circuit.

The output from the amplifier system was recorded with an oscilloscope and camera. Two measurements were made with equal and opposite currents through the

[1] S. I. Taimuty and B. S. Deaver, Jr., Rev. Sci. Instr. **32**, 1098 (1961).

[2] The experimental procedure is similar to one used by G. K. Wertheim in his lifetime experiments in silicon. G. K. Wertheim, Phys. Rev. **105**, 1730 (1956).

sample, so that a subtraction technique would eliminate undesired background signals.

The data from the oscilloscope photographs were reduced by a semiautomatic data-handling system which employed an IBM-7090 computer. The results were a tabulation of the change in conductivity as a function of time, together with a least-squares adjusted value of the lifetime associated with an exponential fit to these data. The reciprocals of the lifetimes were then plotted as a function of integrated flux during a particular irradiation. The slope of this curve, as normalized by the total irradiation dosage determined from the number of Au(γ,n) reactions, was used to determine the rate of introduction of damage by the silicon photoneutron recoils.

III. BACKGROUND AND THEORY

The interpretation of this experiment requires the following specific calculations:

(1) The bremsstrahlung photon spectrum from an electron beam of known energy impinging on a target of known geometry.

(2) The absolute bremsstrahlung intensity from a measured concentration of $Au^{197}(\gamma,n)Au^{196}$ transmutations.

(3) The number and energy spectrum of the recoil atoms produced in silicon by photoneutron reactions induced by the photon spectrum calculated above, followed by a measure of the total amount of displacement radiation effects by these recoils.

(4) The relation between amount of displacement radiation effects and change in excess-carrier lifetime.

Bremsstrahlung Photon Spectrum

During the irradiation, the monoenergetic beam of electrons from the linear accelerator impinged on a converter consisting of 0.04 in. of platinum backed by 2 in. of aluminum. The bremsstrahlung spectrum from the platinum was evaluated as the average-over-angles spectrum per unit solid angle from a thin target, using the numerical values reported by Hansen and Fultz.[3] The contribution from the aluminum was evaluated assuming it to be a thick target with monoenergetic incident electrons whose energy was degraded from the accelerator's energy by the average energy loss in the platinum. The values calculated from the Hansen and Fultz[3] curves represented only a small addition to the contribution from the platinum, and, hence, small errors in this portion will not affect the over-all spectrum significantly. The resultant spectra calculated for primary electron energies of 38, 24, and 15 MeV are shown in Fig. 2. Only the energy distribution of the photons was calculated by this procedure. The absolute number was evaluated separately by means of $Au^{197}(\gamma,n)Au^{196}$ reactions.

[3] N. E. Hansen and S. C. Fultz, University of California, Lawrence Radiation Laboratory Report UCRL-6099, 1960 (unpublished).

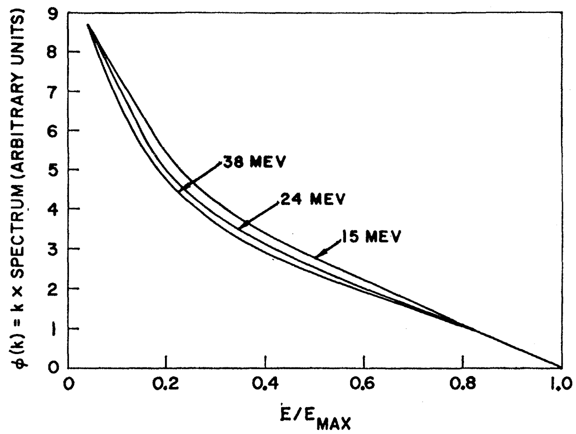

FIG. 2. Bremsstrahlung spectrum from 0.04-in. platinum and 2-in. aluminum targets for 15-, 24-, and 38-MeV electrons.

Absolute Bremsstrahlung Intensity

The absolute bremsstrahlung intensity was evaluated experimentally by placing a short piece of gold wire near the silicon sample during irradiation. After irradiation, the number of $Au^{197}(\gamma,n)Au^{196}$ transmutations was measured. It was then necessary to evaluate a normalization factor for the bremsstrahlung spectrum calculated above.

Assume the bremsstrahlung spectrum (in arbitrary units) is $\phi(E_0,k)dk$, where E_0 is the energy of the incident electrons and k is the photon energy. Then the actual total number of photons bombarding the sample during an irradiation is given by the spectrum $K_n\phi(E_0,k)dk$, where K_n is a constant referring to a specific irradiation experiment. The total number of $Au^{197}(\gamma,n)Au^{196}$ transmutations produced per gram of gold, $N_g(Au^{196})$, by this same irradiation was

$$N_g(\mathrm{Au}^{196})=\frac{K_nN_0}{A_{\mathrm{Au}}}\int_0^{E_0} dk\phi(E_0,k)\sigma_{\mathrm{Au}}(k)\,, \qquad (1)$$

where N_0 is Avogadro's number (6.025×10^{23}), A_{Au} is the atomic weight of gold (197), and $\sigma_{\mathrm{Au}}(k)$ is the cross section[4] for producing the reaction $Au^{197}(\gamma,n)Au^{196}$ with a photon of energy k. K_n can then be determined, since all other quantities in Eq. (1) are known either from this experiment $[N_g(\mathrm{Au}^{196})]$, the foregoing calculation[3] $[\phi(E_0,k)]$, or the literature $[N_0,A_{\mathrm{Au}},\sigma_{\mathrm{Au}}(k)]$.

Recoil-Atom Spectrum and Displacement Radiation Effects

The number of photoneutron reactions in silicon produced per unit volume $[N_V(\mathrm{Si}-\gamma,\,n)]$ by photons of energy k within dk can be calculated in a similar manner.

$$N_V(\mathrm{Si}-\gamma,\,n)dk=\frac{K_nN_0\rho_{\mathrm{Si}}}{A_{\mathrm{Si}}}\phi(E_0,k)\sigma_{\mathrm{Si}}(k)dk\,, \qquad (2)$$

[4] S. C. Fultz, R. L. Bramblatt, J. T. Caldwell, and N. A. Kerr, Phys. Rev. **127**, 1273 (1962).

where ρ_{Si} is the density of silicon (2.33 g/cm^3), A_{Si} is the average atomic weight (28.1), and $\sigma_{Si}(k)$ is the (γ,n) cross section[5] for a photon of energy k averaged over the natural abundances of the isotopes Si^{28}, Si^{29}, and Si^{30}.

The spectrum of neutrons resulting from this reaction is evaluated by adding a statistical evaporation spectrum[6] and a contribution of resonance-direct transitions.[7] For a given photon capture, the evaporation neutron spectrum, $f_{ev}(E_n)$, has the form

$$f_{ev}(E_n)dE_n=\frac{E_n \exp\{2[\alpha(k-E_t-E_n)]^{1/2}\}}{\int_0^{k-E_t} E \exp\{2[\alpha(k-E_t-E)]^{1/2}\}}, \quad (3)$$

where E_n is the neutron energy, $\alpha=A/20$ (MeV), and E_t is the photoneutron threshold.

The resonance-direct contribution was assumed to have the form

$$f_{rd}(E_n)dE_n=\frac{1-U(k-E_t-E_n-E_c)}{\min(k-E_t,\,E_c)}dE_n\,, \quad (4)$$

where $U(x)$ is a step function having the value 0 for $x<0$ and the value 1 for $x>0$, E_c is an effective thickness of contributing-state energies (assumed to be 8 MeV), and min $(k-E_t, E_c)$ takes on the minimum value of the two quantities in its argument. It is assumed that the residual nucleus after neutron emission has equal probability of being at any energy between its ground state and E_c above its ground state, within restrictions of the conservation of energy. If the relative contribution of resonance-direct neutrons is assumed to be b, the over-all neutron spectrum emitted per unit volume of silicon by the irradiation is evaluated as

$$F(E_n)dE_n=\frac{K_nN_0\rho_{Si}}{A_{Si}(1+b)}\int_{E_t+E_n}^{E_0} dk\phi(E_0,k)\sigma_{Si}(k) \times[f_{ev}(E_n)+bf_{rd}(E_n)]dE_n. \quad (5)$$

The energy spectrum of silicon atoms is also influenced by the momentum of the incident photons and gammas emitted during de-excitation of the residual nucleus. However, these momenta are small compared with the neutrons' momentum, and it can be assumed that their directions are uncorrelated with the neutrons' momentum vector. Thus, to a first approximation, their contribution to the average energy spectrum can be ignored, and the energy of a silicon recoil E_{Si} is assumed on the average to be

$$E_{Si}=E_n/A_{Si}. \quad (6)$$

The primary silicon-recoil spectra resulting from this calculation are shown in Fig. 3. The integrated spectrum is normalized to have a value equal to N_d/N_g(Au) appropriate to each bremsstrahlung energy.

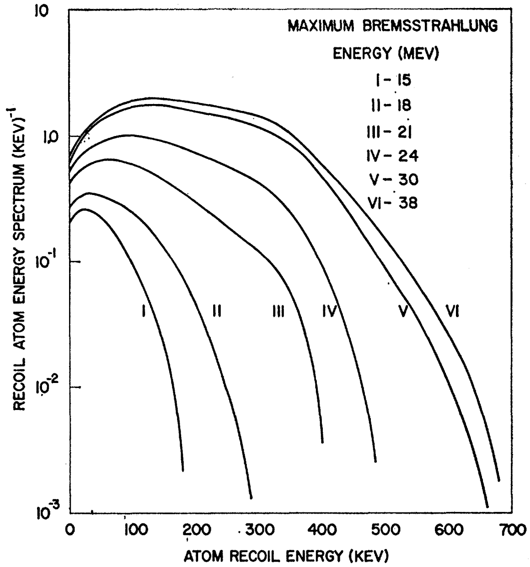

FIG. 3. Recoil-atom energy spectrum for three incident electron energies.

A measure of the total amount of displacement radiation effects produced by the silicon recoils is now required. Two alternative mechanisms can be considered. In one case, case A, if no ionization of the recoil atom occurs it can be assumed that the total number of displacements is proportional to the recoil energy. In the second case, case B, if ionization is the dominant energy-loss mechanism as occurs at the high recoil energies (>57 keV, compare Sec. IV), it can be assumed that each recoil produces a fixed number of displacements, independent of its energy. In case A, a measure of the total number of displaced atoms is calculated using the formula[8]

$$N_d(\mathrm{Si})=E_{Si}/2E_d\,, \quad (7)$$

where E_d is an effective displacement threshold energy. In this calculation, a value $E_d=25$ eV was chosen, although a much lower value has been measured for the true threshold.[9] The justification for this choice is based on the estimate that the effective threshold for this calculation, which should be averaged over all possible directions for the displacing collisions and should consider the probability that a displacement occurs in a given collision, will be appreciably higher than the minimum displacing threshold for the optimum direction.

It cannot be assumed that the actual number of defects introduced into silicon is N_d, since appreciable annealing is known to take place below room temperature and since clustering of lattice defects produced by such high-energy recoils is important. However, in ap-

[5] L. Katz, R. N. H. Haslan, J. Goldemberg, and J. G. V. Taylor, Can. J. Phys. **32**, 580 (1954).
[6] J. Blatt and V. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), pp. 365–374.
[7] D. H. Wilkinson, Physica **22**, 1039 (1956).
[8] F. Seitz and J. S. Koehler, *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press Inc., New York, 1956), Vol. II, p. 305.
[9] J. J. Loferski and P. Rappaport, Phys. Rev. **111**, 432 (1958).

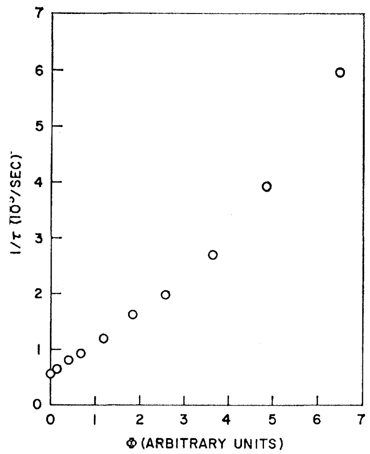

FIG. 4. Typical change of reciprocal lifetime during an irradiation (24-MeV-maximum bremsstrahlung).

plication to this experiment, N_d will be a valid relative measure of displacement effects as long as the qualitative nature of the displacement cascades, including annealing and clustering, does not change between the different irradiation energies. Considering the relatively small change in the resultant average silicon-atom recoil energy for different bremsstrahlung energies, this assumption is reasonable. Hence, the measure of displacement damage for case A was calculated by the relation

$$N_d(\mathrm{Si})=\frac{1}{2A_{\mathrm{Si}}E_d}\int dE_nF(E_n)E_n. \tag{8}$$

For case B, the number of displaced atoms is proportional to the total number of primary recoil atoms N_r. Hence, N_r is used as a measure of the displacement damage and is given by

$$N_r(\mathrm{Si})=\int dE_nF(E_n). \tag{9}$$

Effect of Lattice Defects on Excess-Carrier Lifetime

One of the most sensitive sensors of defects in semiconductors is the excess-carrier lifetime. Recombination of excess carriers usually occurs via recombination centers whose energy states fall within the forbidden gap. According to Shockley and Read,[10] this lifetime is calculated for a single active recombination center to be

$$\tau=\frac{\tau_{n0}(p_0+p_1+\Delta n)+\tau_{p0}(n_0+n_1+\Delta n)}{n_0+p_0+\Delta n}, \tag{10}$$

where $\tau_{n0}=1/N\bar{c}_p$; $\tau_{p0}=1/N\bar{c}_p$; N is the density of recombination centers; $\bar{c}_n$ and $\bar{c}_p$ are the capture rates per center for electrons and holes, respectively, assuming the center to be in a receptive state; n_0 and p_0 are the thermal-equilibrium electron and hole concentrations, respectively; Δn is the excess-carrier density (excess electron and hole concentrations are assumed to be equal); and n_1 and p_1 are the electron and hole densities which would exist in the conduction and valence bands, respectively, if the Fermi level were at the energy level of the recombination center. This formulation assumes that $N<\Delta n$, a valid assumption in this case, so that carrier trapping can be neglected.

During these experiments, the residual conductivity of the samples did not change appreciably; hence, the thermal-equilibrium concentrations, n_0 and p_0, and the position of the Fermi level remained constant. Since all measurements of τ were made at corresponding value for Δn, the only quantity in Eq. (10) which changed during irradiation was N, and it increased linearly with irradiation flux. Assuming then that the recombination processes occurring before irradiation are unaffected by the radiation-induced recombination centers, the following relation may be used:

$$(1/\tau)=(1/\tau_0)+KN, \tag{11}$$

where τ_0 is the lifetime before irradiation and K is a constant. Since N is proportional to the number of displaced atoms, a constant value for ratio $\Delta(1/\tau)/N_d$ is predicted independent of the irradiating bremsstrahlung energy for case A. On the other hand, if a large number of the recoil atoms dissipate energy by ionization (case B), the number of displaced atoms is equal to the product of the number of recoil atoms and the constant number of displacements per recoil.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A typical set of lifetime data during an irradiation is shown in Fig. 4, corresponding to an experiment at 24-MeV maximum bremsstrahlung energy. The results of all the experiments performed are summarized in Table I. The ratio $N_d(\mathrm{Si})/N_g(\mathrm{Au})$ was calculated by the technique described in Sec. III. The quantity $N_g(\mathrm{Au}^{196})$ was determined from the count rate of 290- to 480-keV gamma rays emitted from the gold wire. The counting efficiency of the crystal was estimated to be 37% by calibrating with a Ba^{133} standard. (An additional counting-efficiency factor of 90% was the assumed fraction of the Au^{196} decays, which results in gamma rays within the energy window.) The calculated value of $N_d(\mathrm{Si})$ was derived from the product of the measured gold transmutations per gram, and the calculated ratio N_d/N_g. N_r is obtained in a similar manner. The $\Delta(1/\tau)$ is deduced from the experimental results, such as those shown in Fig. 4, by measuring the increment in ordinate between the beginning and end of the radiation as measured along the best straight-line fit to the data. The total number of photons delivered during the irradiation was calculated from the Au^{196} activity and the known photoneutron cross sections producing this action. The remainder of the quantities listed in Table I are deduced from these quantities. The effect of the neutron background from the targets and other experimental equipment was determined by placing a silicon sample where the gamma-ray flux was an order

[10] W. Shockley and W. T. Read, Jr., Phys. Rev. 87, 835 (1952).

TABLE I. Photoneutron experimental results.

	Bremsstrahlung energy									
	38 MeV	38 MeV	30 MeV	24 MeV	24 MeV	21 MeV	18 MeV	15 MeV	15 MeV	10 MeV
N_d(Si)/N_g(Au), g/cm^3	750	750	650	320	320	165	58	28.3	28.3	0
N_g(Au^{196}),g^{-1}	5.95×10^{10}	9.65×10^{9}	3.9×10^{9}	2.56×10^{10}	3.02×10^{10}	3.3×10^{9}	8.1×10^{9}	1.23×10^{10}	8.66×10^{9}	3.72×10^{8}
N_d(Si) (calc.), cm^{-3}	4.45×10^{13}	7.2×10^{12}	2.54×10^{12}	8.2×10^{12}	9.6×10^{12}	5.45×10^{11}	4.7×10^{11}	3.44×10^{11}	2.42×10^{11}	0
$\Delta(1/\tau)$, sec^{-1}	2.04×10^{6}	0.415×10^{6}	0.115×10^{6}	0.365×10^{6}	0.57×10^{6}	0.048×10^{6}	0.07×10^{6}	0.084×10^{6}	0.0655×10^{6}	0.022×10^{6}
$\Delta(1/\tau)/N_d$(Si), cm^3 sec^{-1}	4.6×10^{-8}	5.75×10^{-8}	4.53×10^{-8}	4.45×10^{-8}	5.95×10^{-8}	8.8×10^{-8}	1.5×10^{7}	2.44×10^{-7}	2.7×10^{-7}	0
$\Delta(1/\tau)/N_r$, cm^3 sec^{-1}	1.7×10^{-4}	2.14×10^{-4}	1.7×10^{-4}	1.35×10^{-4}	1.8×10^{-4}	2.15×10^{-4}	2.3×10^{-4}	2.65×10^{-4}	2.9×10^{-4}	0
Total photons	4.7×10^{14}	7.5×10^{13}	6.15×10^{13}	3.1×10^{14}	3.66×10^{14}	5.7×10^{13}	1.3×10^{14}	4.75×10^{14}	3.33×10^{14}	6.7×10^{14}
$\Delta(1/\tau)$/photons, sec^{-1}	4.3×10^{-9}	5.5×10^{-9}	1.9×10^{-9}	1.18×10^{-9}	1.56×10^{-9}	0.84×10^{-9}	0.54×10^{-9}	0.17×10^{-9}	0.20×10^{-9}	3.3×10^{-11}

of magnitude smaller, but where it would intercept the neutrons arising especially from the (γ,n) reactions in platinum and lead which have cross sections 40 or 50 times larger than that of silicon. The change in carrier lifetime due to these neutrons is less than 5%.

The rate of introduction of lifetime-decreasing defects by bremsstrahlung irradiations of various energies can be used to check the consistency of our model. The quantity $\Delta(1/\tau)/N_d$(Si) should be approximately constant if case A is valid, i.e., if the total energy of the recoil is partitioned in recoil production. However, from Table I it is seen that the discrepancy in $\Delta(1/\tau)/N_d$(Si) between low (15, 18, and 21 MeV) and high (24, 30, and 38 MeV) energies is more than a factor of 5. It is difficult to account for this difference even if the various sources of error are taken into account. First, the photoneutron cross section and especially the photoneutron spectrum are not well known just above the threshold, but they are known within a factor of 2. Another source of error could be the displacement production by secondary electrons. For a given geometry, the number of secondary electrons is expected to be approximately proportional to the number of gamma photons and almost independent of their energy spectrum; also, the number of displaced atoms produced per secondary electron is a very weak function of the electron energy. Hence, the 10-MeV data can be used to estimate the background due to secondary electrons. It can be seen from the data in Table I that the background is less than 20% even for the 15-MeV experiments and decreases at the higher energies. Thus, it is difficult to account for the difference in the low- and high-energy results by the known sources of error.

Considering case B, which states that each recoil produces the same number of displacements independent of its energy, it is seen that the predicted constancy of $\Delta(1/\tau)/N_r$ is in reasonable agreement with the experimental data. These results indicate that each recoil's displacement cascade produces a given amount of displacement damage, which is independent of the energy of the primary recoil atom. This result can be explained by assuming that the recoils have a high enough energy that the ionization energy loss is initially the most important loss mechanism. Then, as the recoil atoms lose energy, displacement production eventually predominates. According to Seitz and Koehler[8] the criterion for energy loss via electron excitation is

$$E \geq (M/m_e)\epsilon_b\,, \tag{12}$$

where E is the energy of the atomic recoil, ϵ_b is the binding energy of the electron, M is the atomic mass, and m_e is the mass of the electron. For silicon the lowest binding energy is 1.1 eV (the band-gap energy) so that the ionization energy limit is 57 keV. Thus, according to Fig. 3, a considerable fraction of the recoil atoms can lose energy via electron excitation for all bremsstrahlung spectra sufficient to eject neutrons from the atoms. This conclusion will be tested by performing a similar experiment with germanium for which the Seitz and Koehler theory[8] predicts a negligible ionization-energy loss.

There are other possible explanations to account for the results. The displacement cluster could produce a change in carrier lifetime which is independent of its size. If all the displacements occurred within a single large disordered region, this interpretation would be possible, since the effectiveness of such a disordered region for carrier trapping can increase less rapidly than its volume. However, the range of the silicon recoil atoms considered here ($\gtrsim$100 keV) is very large ($\gtrsim$3000 Å), and it is unlikely that all the interactions, especially those occurring at high energies, produce overlapping disordered regions. It is also possible that the defects responsible for the change in lifetime are formed at a rate independent of initial recoil energy. Annealing processes presumably could also influence the results, for it has been established by experiments at General Atomic that annealing does occur below 300°K, where the present experiments are performed.

V. COMPARISON WITH 30-MEV ELECTRON IRRADIATIONS

The displacement clusters produced by photonuclear reactions are expected to be similar to those produced by neutron irradiations. The effects of neutron bombardment on silicon have been studied for a number of years and for example have been compared with 1-MeV electron irradiations.[11] It is also of interest to compare the photoneutron displacement effects with those produced by high-energy electron irradiations. Irradiation of silicon with 30-MeV electrons is expected to produce recoils with an average energy of 180 eV, leading to approximately 4.5 displaced atoms per primary collision, compared with an average of $\sim$5000 for the (γ,n) recoils. Hence, the defect cluster produced will be much smaller than those produced in the (γ,n) experiments and fast-neutron irradiations.

The rate of change of reciprocal lifetime for 30-MeV electrons has been measured to be $d(1/\tau)/d\phi = 4.5\times10^{-8}$ cm^2/sec. The calculated rate of introduction of displaced atoms is

$$dN_d/d\phi = 17 \text{ cm}^{-1}.$$

Therefore, the rate of change of lifetime per displaced atom, without considering annealing, is

$$d(1/\tau)/dN_d = 2.6\times10^{-9} \text{ cm}^3/\text{sec}.$$

This value is smaller by a factor of more than 20 than even the highest energy (γ,n) results (see Table I) and becomes even smaller when compared to the lower energy (γ,n) results. A similar result is obtained upon comparison of the result for the change in reciprocal Hall coefficient $1/R_H$, which measures the rate of acceptor introduction in n-type silicon. This observation is similar to the results of Wertheim[11] who concluded that neutrons produce localized damage regions containing a large number of recombination centers.

[11] G. K. Wertheim, Phys. Rev. 111, 1500 (1958).

VI. SUMMARY

The production of displacement radiation effects by photoneutron recoils has been established by measuring the relative rates of defect production in silicon by various energy bremsstrahlung spectra. The change in the reciprocal of the lifetime is approximately proportional to the total number of primary reactions, with a proportionality constant of $(2.0\times10^4\pm25\%)$ cm^3 sec^{-1}. The data can be explained on the basis that the primary energy-loss mechanism is due to ionization. Similar experiments in germanium should establish the validity of this conclusion.

Another interesting result is that the rate of change of reciprocal lifetime and reciprocal Hall coefficient are found to be about an order of magnitude smaller for high-energy electron irradiations. No explanation of this result is possible at this time, but is probably caused by a high density of recombination centers being formed by the photoneutron reactions.

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Characteristic K-Shell X-Ray Production in Magnesium, Aluminum, and Copper by 60- to 500-keV Protons*

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Characteristic K-shell x rays produced when protons of 60- to 500-keV energy are stopped in thick targets of magnesium, aluminum, and copper have been studied using a proportional counter of conventional design. The thick target yields were measured. The x-ray production cross sections have been calculated for the K shells. Ionization cross sections have been estimated and were found to be smaller than the values predicted by the Born approximation in all cases.

INTRODUCTION

CHARACTERISTIC x rays produced when charged particles pass through matter were detected as early as 1913.[1] Early experiments, in studying the energy losses suffered by heavy, high-speed ions, attempted to determine average atomic ionization cross sections and also average atomic ionization potentials. Another approach is to measure separately the ionization cross sections of the various atomic shells. The conventional method involves detection of the radiation emitted following an ionizing event. (This number must, however, be corrected for the radiationless reorganization of the atom.)

When the bombarding ions (protons in the case considered here) are of low energy they may lose all of their energy in even the thinnest self-supporting target. Under these "thick" target conditions the x-ray yield is measured. From this thick target yield it is possible to obtain the x-ray production cross section. When corrected for the fluorescent yield of the shell, this then gives the ionization cross section.

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[1] J. Chadwick, Phil. Mag. 25, 193 (1913).