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NEUTRON DAMAGE IN SILICON FROM NEUTRONS WITH ENERGY NEAR 1-MEV.(U)
JUL 77 J E YOUNGBLOOD, C E HOLLANDSWORTH
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MEMORANDUM REPORT NO. 2768

NEUTRON DAMAGE IN SILICON FROM NEUTRONS WITH ENERGY NEAR 1-MeV

J. E. Youngblood
C. E. Hollandsworth
W. R. Van Antwerp

July 1977

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USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
USA BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Silicon diodes have been used to evaluate the damage introduced in silicon by monoenergetic neutrons at several neutron energies near 1 MeV. Eight diodes were irradiated at each of the neutron energies; 0.70, 0.96, 1.16, 1.63 and 2.37 MeV. The results are compared with diodes exposed to 14 MeV neutrons and with calculations of displacement (permanent) damage. It is shown that the damage fluctuates severely for neutron energies near 1 MeV.

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TABLE OF CONTENTS

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LIST OF TABLES

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I. INTRODUCTION

Permanent neutron damage in silicon plays a predominate role in nuclear weapons effects and a substantial effort has been expended on determining the energy dependence of this neutron damage. Threat spectra, simulator spectra, and a "1-MeV equivalence" definition each present a need for an energy dependence relation sufficiently reliable and detailed for a variety of military applications. There have been a large number of theoretical curves prepared to describe the deposition of energy, and its fractionation into displacement and ionization, in silicon, as a function of neutron energy. In contrast to this, a very limited amount of experimental work has been done, and, if one considers only experiments on displacement damage using mono-energetic neutrons, there are almost no measurements since the early works of Smits and Stein,[1] and of Cleland, Bass and Crawford.[2]

This memorandum report presents an experimental evaluation of the permanent damage in silicon caused by mono-energetic neutrons at five energies near 1 MeV. Wide-base conductivity-modulated silicon diodes have been shown[3,4] to be sufficiently sensitive for monoenergetic-neutron experiments at an accelerator, and facilities at the University of Kentucky were used for the irradiations. The results are compared with the response of the same diodes exposed to 14 MeV neutrons and with calculations of the energy available for displacement damage using a BRL-formulated computer program.[5]

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[1] *F.M. Smits and H.J. Stein, "Energy Dependence of Neutron Damage in Silicon-Experimental," Bull. Am. Phys. Soc., Vol. 9, No. 3, p 289, 1964. F.M. Smits, "On the Energy Dependence of Neutron Damage in Semiconductors," Sandia Report No. SC-R-64-196, 1964.*

[2] *J.W. Cleland, R.F. Bass, and J.H. Crawford, Jr., "The Nature and Yield of Neutron-Induced Defects in Semiconductors," Conference on Radiation Damage in Semiconductors, Paris, 1964, Proc of the 7th Int. Conf. on Physics of Semiconductors, Vol. 3, Radiation Damage in Semiconductors, Paris-Royaument, 1964, pp 401-406, Academic Press, New York, 1965.*

[3] *R.R. Spears, "Neutron Energy Dependence of Excess Charge Carrier Lifetime Degradation in Silicon," IEEE Trans. Nucl. Sci., Vol. NS-15, No. 5, pp 9-17, 1968.*

[4] *J.E. Youngblood, W.R. Van Antwerp, and R.M. Tapphorn, "Displacement Damage in Silicon Irradiated with 6- to 10-MeV Neutrons," USA BRL Memorandum Report No. 2738, April 1977.*

[5] *J.E. Youngblood and W.R. Van Antwerp, "Calculated Energy Dependence of Neutron-Induced Displacement Damage in Silicon," USA BRL Memorandum Report* **No. 2759, June 1977.**

The need for a 1-MeV equivalence for the damage produced in a silicon device by a neutron fluence of any given energy spectrum and the need for a proven curve giving neutron-induced displacement damage as a function of neutron energy arise from the question of the relative damage effectiveness of fusion (14 MeV) versus fission neutrons. The problem of 1-MeV equivalence, as a standard or just as a question of equivalent neutron fluence at other energies, is made difficult by the fact that resonance structure in the silicon cross sections near 1 MeV causes similar structure in detailed damage calculations. These detailed calculations are represented by the work of Holmes,[6] Rogers et al.,[7] and ours.[5] At the same time, a number of those concerned with standards have noted that there is no experimental evidence that the actual damage fluctuates in a manner similar to the calculations, and this has been used as an argument for acceptance of a Messenger[8] type equation to approximate the energy-dependence of neutron damage. Although a Messenger curve is probably satisfactory for most applications, the choice of the best curve and its verification would seem to depend on a detailed calculational treatment, such as one of those cited,[5,6,7] which has been experimentally confirmed in some reasonable detail.

Experimental confirmation in reasonable detail would, with the emphases stated above, necessarily include a 14 MeV/1 MeV damage ratio and a measure of the extent to which fluctuations in the calculated damage curve are replicated in actual damage observed. Correct determination of the neutron fluence is difficult, even for monoenergetic neutrons, and this has deterred experiments. However, the most serious problem in measurements on energy dependence has been the difficulty in the production of sufficient fluences of monoenergetic neutrons. One solution is indicated by the work of Lohkamp and McKenzie[9] who make use of a weapon for a source.

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[6] *R.R. Holmes, "Energy Dependence for Carrier Removal and Lifetime Damage by Fast Neutrons in Silicon," Bell Telephone Laboratories Weapons Effects Studies, Report to ABMDA, Vol. II, Suppl. III, pp 67-88, October 1970.*

[7] *V.C. Rogers, L. Harris, Jr., D.K. Steinman, and D.E. Bryan, "Silicon Ionization and Displacement Kerma for Neutrons from Thermal to 20 MeV," IEEE Trans. Nucl. Sci., Vol. NS-22, No. 6, pp 2326-2329, December 1975. (Also, see Erratum, Op. Cit., Vol. NS-23, No. 1, pp 875-876, February 1976.*

[8] *G.C. Messenger, "Displacement Damage in Silicon and Germanium Transistors," IEEE Trans. Nucl. Sci., Vol. NS-12, No. 2, pp 53-74, April 1965.*

[9] *J.E. Lohkamp and J.M. McKenzie, "Measurement of the Energy Dependence of Neutron Damage in Silicon Devices," IEEE Trans. Nucl. Sci.. Vol. NS-22, No. 6, pp 2319-2325, December 1975.*

In order to utilize a time-of-flight technique with this source, the authors used many transistors mounted on two wheels rotating at high speed. In an experiment with much more limited resources, we attempt here to provide confirmation of detailed calculational treatments.

II. EXPERIMENTAL TECHNIQUES

A general analysis of the current-voltage characteristics of wide-base silicon diodes including the effects of neutron irradiation has been given by Swartz and Thurston.[10] For the present experiments a p^+pn^+ or PIN structure was used with a base width of about 1.3 mm and, by operating the diode at a fixed forward current (0.1A), a constant level of charge injection was maintained. This was true because the low level of neutron exposures used changed the injected-carrier lifetime without significantly changing any other physical property of the diode. Although the observed property of the diodes was the forward voltage before and after neutron irradiation, only the carrier lifetime had changed and the results can be considered a direct evaluation of lifetime degradation. Use of these diodes for energy dependence measurements has been described before,[3,4] so further discussion of technique will be limited to the procedures used on this test.

The measurements were performed in the Nuclear Physics Laboratory, Department of Physics and Astronomy, University of Kentucky, Lexington, KY. A Model CN 5.5 MeV HVEC* Van de Graaff accelerator was used to produce neutrons through the $T(p,n)\,^3He$ reaction between a proton beam and a gaseous tritium target cell. The gas cell was isolated from the accelerator vacuum by a thin molybdenum window. The diodes to be irradiated were positioned approximately 4.78 cm from the end of the gas cell, in a planar array perpendicular to the beam axis. The distance from the end of the gas cell to each diode as well as the displacement of each diode from the beam axis was accurately determined. These data were required in order to determine, for each diode, a neutron fluence appropriately corrected for distance from the source and for the slight anisotropy in the yield of neutrons from the source reaction. The neutron flux was monitored with a calibrated long counter located at 90 degrees to, and 325 cm from, the gas target. These data permitted one to calculate absolute values for the flux and fluence. The relative accuracy of the flux measurements is estimated to be 4%, whereas the absolute accuracy is estimated as 7%.

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[10] *J.M. Swartz and M.O. Thurston, "Analysis of the Effect of Fast-Neutron Bombardment on the Current-Voltage Characteristic of a Conductivity-Modulated p-i-n Diode," J. Appl. Phys., Vol. 37, No. 2, pp 745-755, 1966.*

* *High Voltage Engineering Corporation, Burlington, MA.*

A preliminary run, at the University of Kentucky, was carried out in February 1975. One to two hours of irradiation for sets of three diodes were done at each of five neutron energies and the radiation-induced change in forward voltage was determined a few hours later. This run established the feasibility of the proposed measurements and planning for a more detailed and more accurate series of measurements was initiated.

A large fluctuation in the silicon total cross section near 960 keV seemed an ideal place to test the energy dependence of neutron damage in silicon. This result would test our model of energy-dependence calculations and it would directly indicate whether or not actual amounts of damage in silicon followed the fluctuations in total cross section near 1 MeV. Calculations with the computer code discussed elsewhere[5] suggested that measurements at 696, 957, and 1157 keV, with an energy spread of approximately 50 keV, should show about a factor of two more damage at 957 keV, where there is a peak in the cross section, than at the neighboring energies. In addition, it was thought desirable to obtain measurements at neutron energies of 4 MeV and 5 MeV for comparison with previous diode data obtained at BRL, where flux monitoring was accomplished by a different technique, one using a proton-recoil counter telescope.

Seven neutron energies were finally selected as those providing particularly useful information, and the irradiations were carried out in May 1975. Typical energy-widths (ca. 50 keV) were selected at each of these energies and the average damage was calculated over this energy interval so that the exposure fluences could be chosen to give an approximately constant amount of damage. However, the choice of neutron energy spreads actually used in a measurement is restricted by the requirement that the pressure in the tritium gas cell must always be less than one atmosphere for safety reasons. Pressures from 300 Torr to 630 Torr were used in these measurements. At each energy at least eight diodes were irradiated to obtain good estimates of the average change in forward voltage. After irradiation (at room temperature) the diodes were placed in a temperature controlled oven at 30°C and they were read periodically for 125 hours. As in previous work,[4] a 100-hour (after mid-exposure time) value of forward voltage at constant current was determined for each diode.

The calculation of damage prior to exposure was mentioned in the paragraph above. Typical results are shown in Table I; however, these calculations were done after the exposure and apply to the results that will be presented. The damage is calculated in MeV•b, and the expected factor-of-two difference between the damage at 0.957 MeV and at nearby points at both higher and lower energy is seen. The footnotes to Table I indicate the detailed way in which the "line-shape" and all other aspects of the source were considered in calculating the damage. The same details of the source and exposure conditions were used in determining the fluence to which each diode was exposed. The non-linear response of

TABLE I. CALCULATED DAMAGE

Neutron Energy (MeV)	Energy Spread[a)] (keV)	Cal. Damage[b)] (MeV·b)
0.696	60	0.0582
0.957	49	0.114
1.157	44	0.0502
1.630	38	0.193
2.370	37	0.108
3.990	35	0.131
4.990	30	0.152

a) *The energy distribution of neutrons incident on the diodes is not symmetric but is skewed by finite geometry and target thickness effects. The tabulated energy spreads define an interval which contains 90% of the total neutrons incident on the diode samples.*

b) *The calculated damage includes the effect of the skewed energy distribution and the same calculations are used to determine the (average, damage effective) neutron energy. As a consequence, the calculated damage is not exactly the average over the energy spread interval and the energy-spread interval is not exactly centered on the given neutron energy (these differences are very slight, however).*

the diodes was corrected for by a polynomial fit to experimental calibration data, and the number of neutrons in exposures were entered in calculations in units of 2.351 x 10^{10} n/cm^2. With these choices, the damage/neutron that resulted ranged from 1.4 to 5.7 (for 14.2 MeV, 4.25). With the calculated damage being a few-tenths of a MeV·b (for 14.2 MeV, 0.187), the ratio of experimental-to-calculated damage produces numbers of the magnitude of 25 (for 14.2 MeV, 22.7). The constancy of this number, nominal magnitude 25, is an indication that the calculated damage at different energies is proportional to the experimentally measured damage at those energies.

The presentation of results in relative terms is considered fully satisfactory in all cases except for those concerned with applications of the specific wide-base diodes used. Further, the non-linear response, a function of both the initial voltage and the radiation-induced voltage change, makes a sensitivity constant inappropriate. All diodes, prior to any irradiation, with a 0.1A forward current, read approximately 0.8 V.

If the diodes are irradiated, annealed at 200°C, and read at room temperature as 1.0 V at 0.1A; then, the sensitivity to 14 MeV neutrons is $dV/d\phi = 0.100V/2.0 \times 10^{10}$ ncm^2. The actual 14 MeV neutron fluences required to produce voltage changes of 0.1, 0.2 and 0.5 V are 1.85 x, 2.52 x, and 8.10×10^{10} n cm^{-2}. Similar, but different, numbers apply if the initial voltage (1.0 V) is replaced by another value, or if different energy neutrons are used.

III. RESULTS AND DISCUSSION

The results of measurements done at the University of Kentucky are shown in Table II. The techniques for both the experimental measurements and for calculating the expected damage have been described in the section above. The ratio, experimental damage/calculated damage, is shown in column three. The estimated errors, column four, include every known facet of the present work. Additional information on the neutron energies and energy spreads can be found in footnotes to Table I. There is a singular interest in the ratio of damage from 14 MeV neutrons to damage at other energies and these ratios, both calculated and measured, are given in Table III. The results in Table III, in particular the measured ratios, may be affected by the two methods used to determine fluence. This is further brought out by a comparison of all measurements made at BRL grouped according to method used to determine the fluence as shown in Table IV. In addition to the data already discussed, Table IV contains the results from a number of measurements at the BRL tandem Van de Graaff. A major portion of the results with fluence measured by sulfur and beam-current integration have been reported.[4] However, the diode voltages have been corrected using the techniques described above.

TABLE II. DAMAGE IN SILICON FOR NEUTRON ENERGIES NEAR 1 MeV

Neutron Energy (MeV)	Energy Spread (keV)	Exp. Damage / Calc. Damage	Error (%)
0.696	60	24.7	13
0.957	49	23.7	13
1.157	44	30.3	13
1.630	38	26.4	13
2.370	37	24.7	13
3.990	35	20.8	12
4.990	30	18.9	12

TABLE III. Damage Ratios, 14 MeV/E_n

Neutron Energy (MeV)	Calculated Damage		Measured Damage[a]	
	MeV·mb	Ratio (14/E_n)	D/n	Ratio (14/E_n)
--	--	--	--	--
0.696	58.2	3.21	1.421	2.99
0.957	114.	1.64	2.709	1.57
1.157	50.2	3.73	1.520	2.80
1.630	193.	0.97	5.114	0.83
2.370	108.	1.73	2.651	1.60
3.990	131.	1.43	2.730	1.56
4.990	152.	1.23	2.874	1.48
14.2	187.	1.00	4.254	1.00

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a) *Measured damage ratios here compare 14 MeV damage, with fluence determined by proton-recoil telescope, and damage at lower energies where fluences were measured with a long counter.*

TABLE IV. EFFECT OF FLUENCE MEASUREMENT TECHNIQUE

Neutron Energy (MeV)	Number of Measurements	Source(a	Energy Spread (keV)	Fluence Measurements Tech(b	Average Damage Ratio (Exp/Calc)	Variance of Mean
14.2	1	C-W	Unk	PRT	22.7	--
5 to 10	41	Tandem	~100	S	28.8	0.47
5 to 10	26	Tandem	~100	PRT	26.8	0.39
5 to 10	62	Tandem	~100	I	25.3	0.31
.7 to 5	7	U of KY	~ 50	L	24.2	1.40
All	(5 rows above)	--	--	--	25.6	0.20

(a *The noted sources are the BRL Cockcroft-Walton accelerator (C-W), the BRL Tandem Van de Graaff (Tandem), and the University of Kentucky Van de Graaff (U of KY).*

(b *The fluence measurement techniques are proton-recoil telescope (PRT), sulfur activation (S), beam-current integration (I), and long counter (L).*

The tandem results with fluence measured by beam-current integration and proton-recoil telescope have not been presented before. Since these results contribute to the discussion, even though they are in a different energy range, they are given in detail in Table V. (These are tabulated in the order they were measured.)

TABLE V. 5- to 10-MeV Damage Results

E_n (MeV)	Damage (Telescope) (D_{exp}/D_{calc})	Damage (Beam Current) (D_{exp}/D_{calc})	Damage (Calculated) (MeV·b)
6.23	25.4	22.9	0.155
8.99	29.0	26.8	0.182
8.53	30.2	27.6	0.172
5.53	21.0	19.7	0.139
6.59	26.8	24.3	0.131
6.70	24.2	20.8	0.165
6.81	25.1	23.4	0.156
6.25	26.9	24.5	0.166
6.30	25.5	24.4	0.172
6.35	27.7	26.0	0.162
6.40	26.6	27.2	0.149
6.49	26.9	27.6	0.134
6.60	26.5	26.7	0.133
6.70	25.1	25.6	0.163
6.00	28.8	25.2	0.148
6.15	28.0	25.2	0.146
6.30	27.1	23.4	0.172
6.45	26.9	25.4	0.144
6.60	26.6	25.0	0.133
9.02	31.0	28.5	0.184
7.50	26.5	24.4	0.163
10.0	27.3	25.7	0.205
3.98	26.5	23.7	0.128
4.98	25.6	23.3	0.164
7.99	27.8	25.0	0.173

The correction of results for non-linear effects in the diode voltage was done in a straight-forward way and does not need further comment. However, this correction presupposes assumptions which should be stated. It is assumed that the desired quantity, "Damage," to be measured at some neutron energy is proportional to the number of defects (point, cluster, or combination). Also, it is assumed that the number of defects is proportional to the number of neutrons to which the sample has been exposed. Finally, it is assumed that the extent of non-linearity between voltage and fluence is not itself a function of neutron energy. The first two assumptions are, in fact, common to almost all neutron-damage studies. The final one we have confirmed experimentally.

Tables II and III indicate that the experimentally measured damage near 1 MeV follows the fluctuations that are predicted[5,6,7] by all calculated damage curves. The measured damage near 1 MeV varies by a factor of 3.6 (1.6 MeV vs 0.7 MeV), and it is possible to calculate damage as a function of neutron energy in a way that will produce results consistent with experiment. Tables IV and V show further evidence that calculated/measured damage is in a constant ratio. Coppage[11] has recently described the problems in determining the fluence at reactors, and he suggests an error of 25-30 percent in earlier damage equivalence ratios. Table IV indicates a much smaller problem exists with accelerator experiments. Still, a major portion of the uncertainty in results could be attributable to fluence measurement accuracy. Specifically, the damage ratios at 4 and 5 MeV based on long-counter measurements seem low (high estimate of fluence) and the sulfur results appear to give a consistently high ratio (12%). Also, there continues[4] to be evidence of structure in the S(n,p) reaction that affects its use as an activation detector in experiments with monoenergetic neutrons.

IV. CONCLUSIONS

Experimental evidence has been presented which shows that the actual neutron-induced damage in silicon for neutron energies near 1 MeV fluctuates severely, and, as a consequence, any satisfactory definition of "1-MeV equivalence" would have to indicate clearly the reference 1-MeV neutron-energy spectrum. The results are based on voltage changes in wide-base silicon diodes which are a reflection of the degradation of injected-carrier lifetimes. However, it is expected that the results

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[11] *F.M. Coppage, "The Influence of Dosimetry on Earlier Damage Equivalence Ratios,"* *<u>IEEE Trans. Nucl. Sci.</u>, Vol NS-22, No. 6, pp 2336-2339, December 1975.*

also apply to carrier removal. In this connection, van Lint and Leadon[12] have noted that carrier removal is more likely to be related to the fraction of energy available for displacements than is lifetime degradation. A proposed technique for calculating the energy-dependence of neutron damage[5] has been found to predict damage in reasonable agreement with experiment.

ACKNOWLEDGEMENTS

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[12] *V.A.J. van Lint and R.E. Leadon, "Implications of Cluster Model of Neutron Effects in Silicon," Lattice Defects in Semiconductors, 1974,* *Inst. Phys. Conf. Ser., No. 23, The Institute of Physics, London and Bristol, pp 227-232, 1975.*

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