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DOSE CHARACTERISTICS OF HIGH-ENERGY NEUTRONS FOR RADIATION DAMAGE EVALUATION OF SILICON SEMICONDUCTOR DEVICES

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Abstract

Alekseev A.G. et al. Dose Characteristics of High-Energy Neutrons for Radiation Damage Evaluation of Silicon Semiconductor Devices: IHEP Preprint 94-65. – Protvino, 1994. – p. 14, figs. 9, tables 3, refs.: 17.

Energy dependences of some dose characteristics of neutron radiation simulating radiation damage efficiency of silicon semiconductor devices have been calculated. Such factors as the diameter of an object and the dependence of damage efficiency on the type of secondary particles have been taken into account. The calculations have been made for the energy range from 20 to 600 MeV wherein the computer code HADRON has been used to calculate the secondary particles spectra. At the energies below 20 MeV the published data on neutron kerma have been used. The uncertainty arising with the use of different models for radiation damage efficiency simulation and the uncertainty concerning the application of the reactor data for radiation resistance of semiconductor devices at the IHEP accelerator radiation fields have been estimated. The data and procedure presented in the paper allow one to significantly decrease the uncertainty concerning the neutron damage efficiency for semiconductor devices in the accelerator radiation fields.

Аннотация

Алексеев А.Г. и др.Дозовые характеристики высокоэнергетических нейтронов для оценки радиационного воздействия на полупроводниковые приборы на основе кремния: Препринт ИФВЭ 94-65. – Протвино, 1994. – 14 с., 9 рис., 3 табл., библиогр.: 17.

Проведены расчеты энергетических зависимостей дозовых характеристик нейтронного излучения, моделирующих степень радиационного повреждения полупроводниковых приборов на основе Si, с учетом таких факторов, как размер объекта и зависимость эффективности воздействия от типа вторичных заряженных частиц. Расчет выполнен для энергетического диапазона 20-600 МэВ, в котором для расчета спектров вторичных заряженных частиц использовалась программа HADRON; в низкоэнергетической области использовались известные данные по удельной керме нейтронов. Оценены погрешность, возникающая при использовании разных моделей для прогнозирования радиационного воздействия на полупроводниковые приборы, и погрешность, связанная с переносом реакторных данных по радиационной стойкости на ускорительные поля ИФВЭ. Представленные в работе данные и подход позволяют снизить неопределенность при прогнозировании радиационного воздействия нейтронов на полупроводниковые приборы в ускорительных радиационных полях.

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INTRODUCTION

The use of semiconductor (SC) devices in radiation fields involves knowledge of its parameters degradation produced by radiation. Neutrons are the most effective over all kinds of radiation. The great volume of information on radiation damage yield in neutron irradiation of the SC materials has been stored for the reactor radiation fields. However, the extrapolation of these data to evaluate the SC device workability in the high-energy radiation fields available at IHEP may result in a significant error. The problem has two aspects: 1) the correct choice of the quantitative characteristic of neutron radiation for adequate simulation of the radiation efficiency not only in the reactor energy range, but in the high-energy range too; 2) the calculation of the chosen characteristic in the whole energy range covered (up to 600 MeV).

The calculations of the energy dependences of some neutron dose characteristics for ^{28}Si and the corresponding integral values for some IHEP radiation fields used in the SC devices radiation tests are presented. On this basis the conclusion on applicability of some neutron radiation characteristics as a measure of the SC radiation damage efficiency in accelerator fields is made; the practical recommendations for their application are given.

1. CALCULATION METHOD

As a standard model of SC neutron damage efficiency of neutrons in the reactor energy range one usually assumes the quantitative change of the SC parameters to be proportional to such values as neutron fluence F or kerma K for the irradiated material (see [1-3], for example). The neutron kerma is the sum of kinetic energy of secondary charged particles liberated in material as a result of neutron interaction with nuclei, related to unit of material mass. The

kerma factor (i.e. kerma per fluence unit) for neutrons with the energy E_n can be calculated as:

$$k(E_n) = A\sum_i(\sigma_j(E_n)\int Ef_i(E_n, E)dE), \quad (1)$$

where A is the constant for conversion into Gy.cm^2; $\sigma_i(E_n)$ is the cross-section of i-type secondary particles generation; $f_i(E_n,\ E)$ is the spectrum of secondary particles of i-type normalized by incident neutron fluence; E is the energy of secondary charged particle.

For neutron energies below 70 MeV and for a widely-used group of elements and compounds the detailed kerma factor data are available in [4-6]. However, it is noteworthy that in case when the dimensions of an irradiated object are comparable with secondary particles ranges, the energy absorbed in the object can differ from the kerma; the difference increases with the object dimensions decrease and with neutron energy increase. Besides, for different secondary particles produced in interaction the effect dependences on the absorbed energy distinguish and can depend on the particle energy or linear energy transfer (LET). So in [3] the dependences of the damage efficiency versus recoil nuclei energy have been derived for GaAs irradiated by neutrons from the degradation lifetime and the carrier removal data. When the ion energy increases from 0.1 to 500 keV, the damage efficiency decreases from 1 to 0.02. The damage efficiency versus particle LET [7,8] is shown in Fig.1.

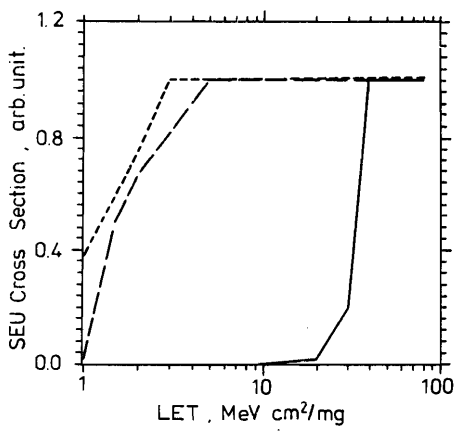


Fig. 1. Cross-section of single upsets in semiconductor devices versus linear energy transfer of charged particle.

The above circumstances require the consideration as a measure of the SC neutron damage efficiency along with fluence and kerma other dose characteristics for which: a) the damage efficiency of secondary particles, generally, is

not equal to 1 and depends on the secondary particle LET; b) the dimensions of the object are taken into account.

In assumption of weak distortion of primary neutron field by the object the absorbed dose factors (i.e. absorbed doses per fluence unit), $d_l(E)$, can be calculated as:

$$d_l(E_n) = A\sum_i(\sigma_i(E_n)\int \varepsilon(E)f_i(E_n,E)Q_l(E,L)dE), \qquad (2)$$

where $\varepsilon(E)$ is the energy of a secondary charged particle absorbed in sensitive volume; $Q_l(E,\ L)$ is the damage efficiency of a charge particle with energy E or LET L; l is the index of the adopted model. Note, that the functional given by Eq.(2) is reduced to kerma factor (1) when $\varepsilon(E) = E$ and $Q_l(E,L) = 1$.

The computer code HADRON describing inelastic hadron-nucleus interactions on the base of the cascade-exiton model was used to calculate secondary particle spectra $f_i(E_n, E)$ in the incident neutron energy range 20-600 MeV. The code description, the analysis of uncertainties and application scope are given in [5]. The code allows one to calculate the secondary particle spectra with sufficient accuracy and without using approximation parameters for distinct nuclei. The statistical uncertainty of secondary proton spectra at evaporation peak maximum reduces from 3% to 1.3% with the incident neutron energy increasing from 20 to 600 MeV. At the residual part of secondary proton spectra the statistical uncertainty increases and becomes 9-20%.

The irradiated object – SC – was simulated as a sphere made from Si with uniform density 2.33 g/cm . The absorbed dose factors in the energy range from 10 to 600 MeV for the sphere diameters from 0.05 to 1 cm were calculated. The charged particle absorbed energy $\varepsilon(E)$ was calculated in the CSDA approximation. The angular distribution of incident neutrons was taken as isotropical.

The damage efficiency function $Q_l(E,\ L)$ for the secondary charged particle is represented by the following models:

I. $Q_l(E,\ L) = 1$ – for any kind of secondary particle and energy E;

II. $Q_l(E,\ L) = 0$ – for all particles with $L \leqslant 0.8$ MeV·cm^2/mg (corresponds to the secondary particle charge $Z \leqslant 1$); $Q_l(E,\ L) = 1$ – for all particles with L >0.8 MeV·cm^2/mg ($Z > 1$);

III. $Q_l(E,\ L) = 0$ – for all particles with $L \leqslant 1.5$ MeV·cm^2/mg (corresponds to the secondary particle charge $Z \leqslant 2$); $Q_l(E,\ L) = 1$ – for all particles with $L > 1.5$ MeV·cm^2/mg ($Z > 2$);

The range of particles with $Z > 1$ does not exceed several tens of microns, therefore for any size of the sphere used in the calculations the absorbed dose for

cases II and III was taken equal to the part of kerma concerned with particles with $Z > 1$ and $Z > 2$, respectively.

For neutron energies below 10 MeV data [4] for kerma factors were used. The neutron kerma for ^{28}Si was assumed to be entirely determined by nuclei with $Z > 2$ for neutron energies below 5 MeV . Then for the three models the corresponding absorbed doses were assumed to be equal to kerma in the energy range below 5 MeV, since the value of charged particle range as compared with the sensitive volume sizes is negligible. In the energy range of 5-10 MeV the contribution of the lighter (with $Z \leqslant 2$) particles into silicon kerma becomes noticeable. The contributions of (n, p) and $(n,\ \alpha)$ reactions have been estimated for the energy 6 MeV as 50% and for 10 MeV as about 80 %. This allows us to estimate the model dose factors in this range on the base of data [4].

The obtained energy dependences of the absorbed dose factors simulating the neutron damage efficiency in the whole energy range from thermal energies to 600 MeV are used for the calculation of the correspondent integral values for the neutron spectra set. The integral values have been calculated both for the reactor and the accelerator spectra groups as follows:

$$d_l = (\int d_l(E_n)\phi(E_n)dE_n)/(\int \phi(E_n)dE_n). \tag{3}$$

Here $\phi(E_n)$ is the neutron energy spectrum.

The following neutron spectra have been chosen for calculations:

I. The set of classified spectra BKS-2 [9] including the reactor-range reference and standard field data. This set contains neutron spectra occuring at reactors when researches on SC device radiation resistance are carried out.

II. Neutron leakage spectra from aluminium absorber irradiated by incident 100 MeV protons (data of [10-12]). This secondary radiation field on base of linear accelerator I-100 is widely used in IHEP experiments on radiation resistance of materials and devices. Spectra arising at two angles are used.

III. Spectra of neutrons and charged particles induced by protons with 70 GeV incident energy interacting with small berillium target of 3 mm in diameter and 30 mm long surrounded by the magnet yoke. The field occurs at the IHEP experimental hall in the location of the SORBEX system (the system of radiobiological experiments maintenance, block 27) and is also used for experimental investigation of SC devices radiation resistance. The calculation has been fulfilled with the computer code MARS93 [14], the calculation geometry is represented in Fig.2 where the target is situated at the M3 point. Such geometry could be also applied for estimation of neutron spectrum in the SORBEX system location.

We have also used the neutron spectrum measured by A.Sannikov with the passive neutron dosimeter-spectrometer (PNDS) [13] on the base of threshold detectors.

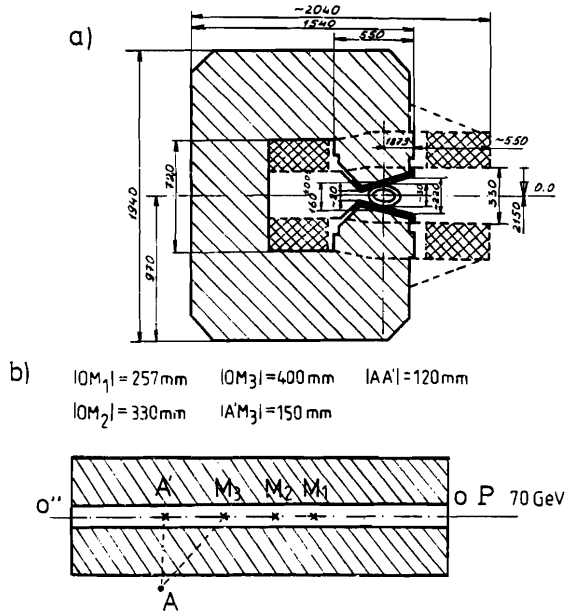


Fig. 2. Geometry of the magnet №27 which is the source of secondary radiation field near the SORBEX device (a) and calculational geometry (b). Dimensions – in mm. M1, M2, M3 are the points of the target location. A is the point where the spectrum has been calculated.

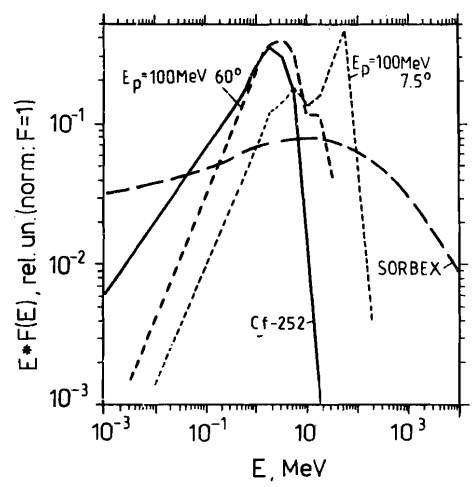


Fig. 3. Neutron spectra: ^{252}Cf (—); from 100 MeV protons stopped by Al absorber at angles of 8° (- - - -) and 60° (– – –); from 70 GeV protons interacting with thin target (27 block of the U-70, near the SORBEX device) measured by PNDS (— — —).

IV. Neutron spectrum at 3 cm shift from the beam axis and at 158 g.cm^2 depth in the CERN iron absorber [15] irradiated by 200 GeV protons.

Some of these spectra such as: neutron leakage spectrum from Al target irradiated by 100 MeV protons at the angle of 8° (E_{mean}=31 MeV) and of 60° (E_{mean}=5.2 MeV); experimental neutron leakage spectrum from the iron absorber irradiated by 70 GeV protons (SORBEX, E_{mean}=170 MeV), together with the standard neutron spectrum of ^{252}Cf fission (E_{mean}=2.1 MeV) are presented in Fig.3.

The neutron and charged particle (p, $\pi^{\pm}$) spectra calculated with the MARS93 code are presented in Fig.4.

2. RESULTS

The absorbed dose factors calculated for the simulation of SC neutron damage efficiency on the base of ^{28}Si in the energy range from thermal to 600 MeV are shown in Table 1 and in Fig.5,6 as compared with kerma factors. The original data on the kerma factor for Si calculated in [5] by using the HADRON code are listed in the Table 1. The difference of the present calculational data lies in the one energy point of 20 MeV and is explained by the direct evaluation of the elastic scattering yield into kerma instead of the approximation [16] of elastic scattering cross-section used in [5]. The comparison of our kerma factor data with the data of other authors gives a maximal discrepance at the same energy of 20 MeV where the kerma factor for Si is 1.6×10^{-11} Gy·cm^2 [4], 0.96×10^{-11} Gy·cm^2 [6] 1.07×10^{-11} Gy·cm^2 [5] and 1.17×10^{-11} Gy·cm^2 according to the present calculation.

In Fig.5 the energy dependences of absorbed dose factors $d_{II}(E_n)$ and $d_{III}(E_n)$ (calculated according to models II and III, respectively) are presented together with kerma factor energy dependence. As is seen from Fig.5, the kerma factor above 10 keV is strongly dependent (nearly proportonally) on neutron energy. On the other side, heavy particle parts of the absorbed dose (models II and III) increase weakly in the energy range 10-200 MeV and, for example, at 100 MeV are about 10% of kerma value.

The absorbed dose factors $d_I(E_n)$ (model I) for different diameters of the object from 0.05 to 1 cm are given in Fig.6. At 100 MeV the $d_I(E_n)$ value for the object diameter 0.05 cm is less than for that of 1 cm by a factor of 3, and less than kerma factor by a factor of 6.

Table 1. Energy dependences of the neutron kerma factor and absorbed dose factors d_I, d_{II}, d_{III} in silicon for different object diameters, pGy·cm^2

E, MeV	Kerma	d_{II}	d_{III}	d_I		
				0.05 cm	0.3 cm	1.0 cm
5.00	1.76	1.76	1.76	1.76	1.76	1.76
5.80	2.29	1.90	1.76	2.29	2.29	2.29
7.00	4.73	3.01	1.78	4.73	4.73	4.73
8.20	7.13	4.40	1.82	7.13	7.13	7.13
9.40	8.47	5.30	1.92	8.47	8.47	8.47
10.50	10.0	6.00	2.40	10.0	10.0	10.0
20.	11.7	4.00	2.60	7.19	8.00	10.2
30.	14.8	3.80	2.54	6.91	10.7	13.2
50.	21.7	3.50	2.40	7.08	11.8	16.0
70.	29.6	3.30	2.30	7.00	12.2	17.4
100.	39.0	3.15	2.20	6.60	12.4	18.0
200.	77.3	3.20	2.22	7.25	13.3	19.8
400.	166.	6.61	3.36	11.8	19.7	27.8
600.	300.	8.78	3.77	15.1	27.0	40.6

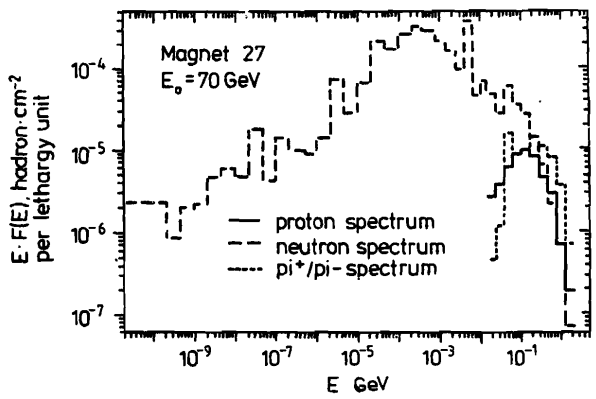


Fig. 4. Secondary charged particles and neutron spectra from 70 GeV protons interacting with thin target (block 27 of the U-70, near the SORBEX device) calculated using the MARS93 computer code.

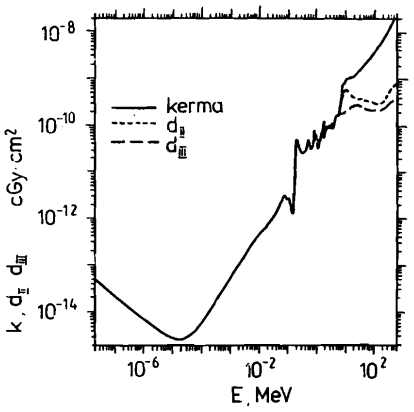


Fig. 5. Kerma factor for ^{28}Si (———); partial absorbed dose factors concerned with secondary particles of $Z > 1$, model II (- - - -) and of $Z > 2$, model III (— — —).

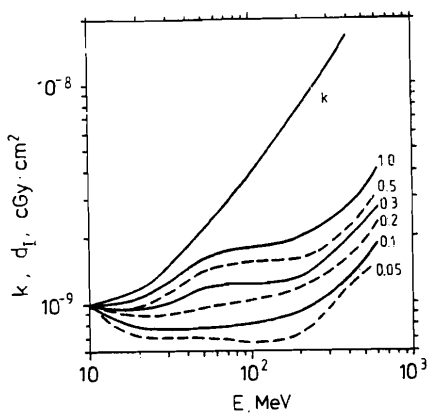


Fig. 6. Absorbed dose factors for neutrons in silicon sphere of some diameters. Numbers near the curves - diameters of the sphere in cm. k_n is the kerma factor for silicon.

Integral dose values calculated according to Eq.(3) for the above reactor and accelerator neutron spectra are given in Table 2 and in Figs.7-9. In general, for the reactor spectra the integral absorbed doses for the three models coinside with the kerma, as could be expected. It should be noted that the strong dependence on neutron spectra hardness has been observed. So, the kerma factors for spectra with different hardness (E_{mean} from 0.2 to 2.1 MeV) vary by a factor of 8.6.

Fig. 7. Kerma factors for silicon for various neutron spectra versus mean spectrum energy.

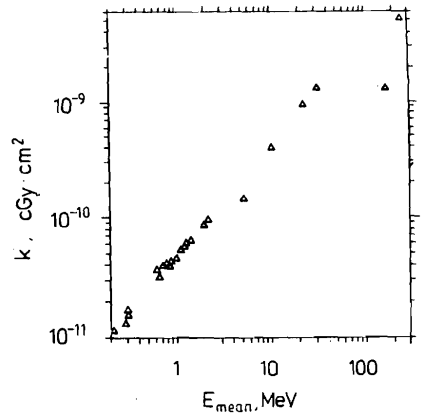


Fig. 8. The same as in Fig.7, for partial absorbed dose factors in silicon: d_{II} (triangles) and d_{III} (circles).

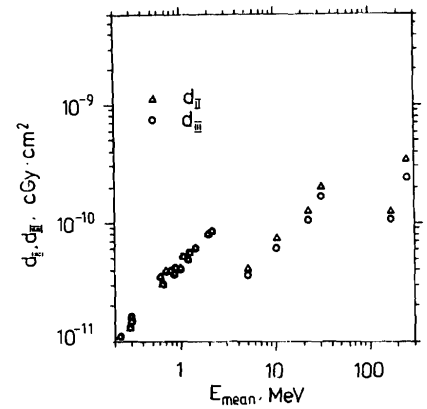
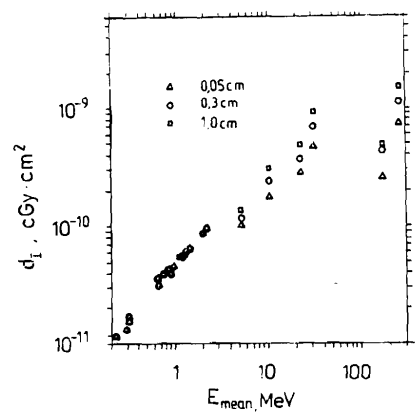


Fig. 9. The same as in Fig.7, for absorbed dose factor d_I in silicon sphere of some diameters.



For the accelerator neutron spectra the integral absorbed dose depends essentially on the diameter, its variance reaches 100 % for the taken diameter range 0.05-1 cm. Using the kerma as a model in the case of the accelerator neutron fields one could obtain an overestimation about 5-9 times. The difference between the model absorbed dose factors $d_{II}(E_n)$ and $d_{III}(E_n)$ is less than 10 %. Both of the model values $d_{II}(E_n)$ and $d_{III}(E_n)$ are less than the $d_I(E_n)$ by a factor of 1.5-3. It is noteworthy that the threshold character of the secondary particle damage efficiency dependence on LET underlying models II and III, as it follows from [3], gives the uncertainty of about 50-100% which is comparable with that when choosing between model I and models II, III.

Since the ratios of absorbed dose in the accelerator fields to the mean value of absorbed dose in the reactor fields vary from 3 to 20, the choice of the neutron fluence as a model and direct application of the reactor results can lead to the error of about 1000% when investigating the SC parameters in the accelerator fields. On the base of the more adequate model (absorbed dose $d_I(E_n)$ or partial absorbed dose $d_{II}(E_n)$, $d_{III}(E_n)$ one can apply the reactor results to SC irradiation in accelerator fields using the data from Table 2 for deriving the correction coefficient. It can be estimated from Table 3 where the ratios of the model values (kerma and absorbed doses d_I, d_{II}, d_{III}) calculated for the accelerator spectra to the same values for typical reactor spectrum with the mean energy 1 MeV are presented.

It should be born in mind that the damage efficiency simulated by model III is does not take into account the recoil nucleus energy. Such approximation can lead us in some cases to overestimation or underestimation of radiation damage efficiency by a factor of 1.5-2 [3]. Available experimental and calculation data on the relative damage efficiency of neutrons with different mean spectrum energies may serve as a criterium of the considered model adequacy. So the damage efficiency of 14 MeV neutrons is 1.7-2.7 as high as that of the reactor neutrons (depends on considered parameter, for example, lifetime or equilibrium concentration), as it follows from [1] where the estimations have been fulfilled on the base of the collisions integral calculations (the atomic shift clusters density distribution). And from experiments [17] for some SD the damage efficiency of 14 MeV neutrons is 3.0-3.4 as high as that of the reactor neutrons. The dosimetric approach, i.e. model I, gives us the ratio of 15 (20 in the case of kerma) meanwhile the partial absorbed dose estimation d_{III} leads to ratio 4.6 which is also overestimated but a conservatism degree is lower in this case. Besides, the 14 MeV neutron field can not be classified as "accelerator field". Nevertheless, further improvement of the model accuracy seems to involve the use of more specified relationship between damage efficiency and recoil nuclei

LET and the obtaining of the experimental information concerned with neutron damage efficiency for fields with different neutron spectra including accelerator ones.

Table 2. Integral values of the neutron kerma factors and absorbed dose factors d_I, d_{II}, d_{III} in silicon for different object diameters, pGy·cm^2, for reactor and accelerator spectra

N Sp,	E_{mean}, MeV	Kerma	d_{II}	d_{III}	d_I		
					0.05cm	0.3cm	1.0cm
				Reactor spectra			
1	1.97	0.87	0.87	0.86	0.87	0.87	0.87
2	2.12	0.95	0.94	0.94	0.95	0.95	0.95
3	0.76	0.41	0.41	0.41	0.41	0.41	0.41
4	0.60	0.36	0.36	0.36	0.36	0.36	0.36
5	0.77	0.41	0.41	0.41	0.41	0.41	0.41
6	1.07	0.54	0.54	0.54	0.54	0.54	0.54
7	0.62	0.36	0.36	0.36	0.36	0.36	0.36
8	0.84	0.39	0.39	0.39	0.39	0.39	0.39
9	0.98	0.45	0.45	0.45	0.45	0.45	0.45
10	0.87	0.39	0.39	0.39	0.39	0.39	0.39
11	1.19	0.57	0.56	0.56	0.56	0.57	0.57
12	0.30	0.17	0.17	0.17	0.17	0.17	0.17
13	0.28	0.13	0.13	0.13	0.13	0.13	0.13
14	0.22	0.11	0.11	0.11	0.11	0.11	0.11
15	0.31	0.16	0.16	0.16	0.16	0.16	0.16
16	0.89	0.44	0.44	0.44	0.44	0.44	0.44
17	0.64	0.31	0.31	0.31	0.31	0.31	0.31
18	0.70	0.39	0.39	0.39	0.39	0.39	0.39
19	1.25	0.60	0.60	0.60	0.60	0.60	0.60
20	0.87	0.43	0.43	0.43	0.43	0.43	0.43
21	1.42	0.65	0.65	0.65	0.65	0.65	0.65
				Accelerator spectra			
22	31.2	14.0	2.99	2.63	5.15	7.73	9.92
23	5.16	1.66	1.02	0.96	1.17	1.43	1.57
24	170.1	13.5	1.76	1.52	2.69	3.89	4.99
25	7.3	3.38	1.02	0.71	1.26	1.58	1.92
26	22.4	9.63	1.95	1.73	2.96	4.17	5.19

2 - ^{252}Cf; 22 - *Al* target, 100 MeV, 8°; 23 - *Al* target, 100 MeV, 60°; 24 - 70 GeV, SORBEX (experimental data); 25 - 70 GeV, SORBEX (MARS93 calculation); 26 - *Fe* absorber, 200 GeV.

Table 3. Relative damage efficiency of the neutron radiation of various spectra according to models used in comparison with published data, rel.un. The calculations have been fulfilled for 14 MeV neutrons and for accelerator spectra group. The values have been divided on that for typical reactor spectrum with mean neutron energy 1 MeV

	14 MeV/reactor	acceler./reactor
Kerma	20	26-36
d_I	15	5-18
d_{II}	9.3	3.3-5.6
d_{III}	4.6	1.3-4.8
Cluster model [1]	1.7-2.7	-
Experimental data [17]	3.0-3.4	-

Monitoring of the SD radiation tests in the accelerator radiation field which is formed both by charged particles and neutrons requires careful interpretation of the results. So, in the radiation field mentioned above (near the SORBEX device, block 27 of the 70-GeV accelerator) there are also protons and pions with the spectra given in Fig.4. The contribution of charged particles to fluence is 1.3% (protons) and 2.0% (pions) and to total absorbed dose in a silicon SD device is 75% and 16%, respectively. (The dose has estimated on the base of the particle stopping power). So the neutron absorbed dose d_I^n is only about 10% of the total absorbed dose, whose value is usually monitored in radiation resistance tests. Thus, the value of the total absorbed dose cannot be used as an adequate measure of the efficiency of accelerator radiation with complicated component structure. On the other hand, the model value of d_{III}^n for neutrons will nearly coincide with the total absorbed dose d_{III}^{tot}, including contributions from all particles, because of neutron domination in the total fluence whereas the difference in the inelastic cross-sections for neutrons and for protons and pions is not considerable.

Attention should be paid to weak energy dependences of absorbed dose factor $d_I(E_n)$ and its parts $d_{II}(E_n)$ and $d_{III}(E_n)$ in the energy range above 20 MeV, since for radiation resistance monitoring goals one can use the mean value of the absorbed dose factor for this range and measure neutron flux instead of neutron spectrum. Measurements of neutron flux in the energy range above 20 MeV, for example, with threshold detectors, is, obviously, much simpler task than neutron spectra measurements. Thus, this must essentially simplify the radiation monitoring procedure for the SC devices radiation resistance investigation.

CONCLUSION

The above analysis shows that the values usually applied to SC devices damage efficiency estimation such as neutron kerma and absorbed dose can

give appreciable errors if the data obtained at reactors are applied to accelerator neutron fields.

For the comparative estimation of damage efficiency of the accelerator and reactor neutrons in silicon SD one should use the partial absorbed dose d_m induced by secondary charged particles with Z greater than 2. Using the data from Table 2 one can realize simple neutron fluence monitoring in the radiation resistance experiments. The ratios of the neutron damage efficiencies of accelerator fields to a standard reactor field are in the range of 1.3-5.

The data and procedure presented in the paper allow one to significantly decrease the uncertainty concerned with the neutron damage efficiency for SC in the accelerator radiation fields.

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