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Measurement of the NIEL-scaling factor of thick target p+Be neutrons at E_p = 17.4 MeV proton energy for silicon

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Abstract. Radiation tolerance tests of silicon based devices are regularly done at ATOMKI with thick target p+Be neutrons at E_p = 17.4 MeV. Measurements were done to estimate their NIEL-scaling factor for silicon. The neutron spectrum was measured by the multifoil activation technique. Saturation activities of different neutron induced reactions were measured and the neutron spectrum was unfolded from them. Displacement KERMA data were taken from literature and their energy spectrum averaged value was calculated. The obtained NIEL-scaling factor was = 1.1 ± 0.20. Following the ASTM E1855-05el standard, a second type of measurement was done, too. 2N2222 bipolar transistors were irradiated by p+Be neutrons and by fission neutrons. The emitter current gain of the transistors was measured before and after the irradiation. The NIEL-scaling factor could be determined from the differences of the gains using the Messenger-Spratt equation. The obtained NIEL-scaling factor was 1.1 ± 0.23 from this measurement.

1 Introduction

Space and avionics applications and high-energy physics experiments at the Large Hadron Collider at CERN (Geneva, Switzerland) are examples of the case where a system or a structure is planned for operation in a harsh radiation environment and mixed field of different particles has to be considered. Frequently, it is not feasible to perform the necessary radiation tolerance tests at the real operation circumstances and a method has to be found to make extrapolations for the real field from the results obtained in the test field.

In many cases effects of bulk damage that are caused by radiation induced atomic displacements (non-ionising energy transfers to the lattice) have to be studied. Many types of displacement damage effects are proportional to the total **K**inetic **E**nergy of the displaced **R**ecoils in unit **MA**ss (displacement KERMA, $D(E)$). For an energy spectrum of the bombarding particles of the external radiation field $\varphi(E)$, the I_{tot} total intensity of a specific displacement damage effect can be calculated as

$$I_{tot} = C^* \int_0^{E\,\max} \varphi(E)D(E)dE. \tag{1}$$

In equation (1) E is the particle energy and C is a constant independent from the type of the primary particle of the cascade. This enables the introduction of the well known 1 MeV neutron equivalent fluence concept and a scaling based on NIEL (**N**on-**I**onizing **E**nergy **L**oss). The NIEL-scaling factor (hardness parameter) is defined as

$$\kappa = \Phi(E_n = 1\mathrm{MeV})/\Phi \tag{2}$$

where Φ is the spectrum integrated fluence

$$\Phi = \int_0^{En;\max} \varphi(E)dE \tag{3}$$

and E_n denotes the neutron energy. The definition of the $\Phi(E_n = 1\,\mathrm{MeV})$ 1 MeV neutron equivalent fluence is the following

$$\Phi(E_n = 1\,\mathrm{MeV})^* D(E_n = 1\,\mathrm{MeV}) = \int_0^{En;\max} \varphi(E)D(E)dE. \tag{4}$$

The displacement KERMA of neutrons with E_n = 1 MeV energy is $D(E_n = 1\,\mathrm{MeV})$ = 95 MeV.mb for silicon.

In the case of bulk effects that can be scaled in this way, the method enables a comparison of results obtained in different fields used for radiation damage tests of a specific device.

Radiation tolerance tests of silicon based devices are frequently done at ATOMKI with p+Be neutrons emitted by a thick beryllium target bombarded by E_p = 17.4 MeV protons. This work reports the results of estimations of the NIEL-scaling factor of p+Be neutrons for silicon at E_p = 17.4 MeV.

2 Experimental

p+Be neutrons were produced at the Cyclotron Laboratory of ATOMKI (Debrecen, Hungary). Details of the irradiation site have been described elsewhere [1]. The target was a 3 mm thick beryllium target and it was bombarded with E_p = 17.4 MeV protons. Two methods were used for estimating the NIEL-scaling factor of the emitted p+Be neutrons.

2.1 Method based on measured neutron spectrum

The first method is based on equation (4). The $\varphi_{p+Be}(E)$ spectrum of p+Be neutrons was measured by the multifoil activation technique. Saturation activities of the $^{24}Mg(n,p)\,^{24}Na$,

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$^{27}Al(n,p)^{27}Mg$, $^{27}Al(n,\alpha)^{24}Na$, $^{45}Sc(n,2n)^{44}Sc$, $^{45}Sc(n,\alpha)^{42}K$, $^{47}Ti(n,p)^{47}Sc$, $^{48}Ti(n,p)^{48}Sc$ $^{56}Fe(n,p)^{56}Mn$, $^{58}Ni(n,p)^{58}Co$, $^{58}Ni(n,np)^{57}Co$, $^{90}Zr(n,2n)^{89}Zr$ and $^{197}Au(n,2n)^{196}Au$ neutron induced reactions were measured.

Cross section data of the reactions were taken from the ENDF/B-VI and IRDF-90 libraries. The neutron spectrum was unfolded using the SULSA code [2]. The code does not need input spectrum. In this way the errors of an input spectrum can be avoided.

The relative displacement KERMA data were taken from the SNL RML Recommended Dosimetry Cross Section Compendium [3]. This data base has been used in many cases by different groups for estimating displacement damage of silicon based structures developed for high energy experiemnts at CERN (Geneva, Switzerland).

Then Φ_{p+Be}, $\Phi_{p+Be}(E_n = 1\,\mathrm{MeV})$ and κ_{p+Be} were calculated for the unfolded spectrum.

2.2 Method based on the Messenger-Spratt equation for bipolar transistors

In the second method the procedure specified in the ASTM E1855-05el standard [4] was followed. Groups of 2N2222 bipolar transistors were formed. The common emitter current gain (h_{FE}) was the same as possible within each group. There were 9 transistors in each group. One of the groups was used for monitoring the environmental effects and it was never irradiated. Irradiations were carried out both with p+Be neutrons in the "test field" and fission neutrons in the "reference field".

The transistors were irradiated in plastic bags at SSD = 32 cm **S**ample **S**ource **D**istance measured from the geometrical centre of the beryllium target. The typical current of the bombarding proton beam was $I_p = 10\,\mu A$. The irradiations lasted typically for $t_{irr} = 12\,h$ until $\Phi_{p+Be} = 6.5 \times 10^{12}\,cm^{-2}$ spectrum integrated fluence was delivered.

The neutron field at the irradiation position in channel D5 of the Nuclear Training Reactor of INT BUTE (Budapest, Hungary) was used as ref. [5]. The groups of the transistors were put in polyethylene sample holders and then they were moved to the irradiation position and back with a pneumatic rabbit system. The following irradiations were carried out: $\Phi_1 = 6.5 \times 10^{12}\,cm^{-2}$ at P = 280 W, $\Phi_2 = 6.5 \times 10^{12}\,cm^{-2}$ at P = 2.8 kW, $\Phi_3 = 1 \times 10^{13}\,cm^{-2}$ at P = 280 W, $\Phi_4 = 2 \times 10^{13}\,cm^{-2}$ at P = 280 W, where Φ is the fluence delivered to the samples and P is the reactor power.

Irradiations with photons (E_γ = 1173 keV and 1332 keV) emitted by a ^{60}Co source were also done at ATOMKI to check the gamma sensitivity of the transistors.

EXRADIN T2 and M2 thimble type ionisation chambers with different neutron and gamma sensitivities and ribbons of Harshaw thermoluminescent detectors (^{nat}LiF:Mg,Ti (TLD-100), ^{6}LiF:Mg,Ti (TLD-600), ^{7}LiF:Mg,Ti (TLD-700), CaF_2:Tm (TLD-300), CaF_2:Mn (TLD-400)) were used to estimate the contribution from the gamma dose components of the mixed neutron-gamma fields.

Before each irradiation an annealing was applied at T = 460 K temperature for 24 hours to cancel long lived defects. Then the $h_{FE;0}$ common emitter current gain was measured. After irradiation the shortest lived defects were annealed at T = 370 K for 2 hours. On the next 10 weeks, the common emitter current gains were measured 6 times for each transistor. Then the obtained trends were fitted and their saturation $h_{FE;\Phi}$ values were used for further evaluations. The $\Phi_{p+Be}(E_n = 1\,\mathrm{MeV})$ 1 MeV neutron equivalent fluence was determined on the basis of the Messenger-Spratt equation [6]

$$\Phi_{p+Be}(E_n = 1\,\mathrm{MeV}) = \frac{1}{K} * \left[(1/h_{FE;\Phi}) - (1/h_{FE;0})\right]_{p+Be} \quad (5)$$

where K was calculated from the results of the measurements for the reference field

$$K = \frac{\left[(1/h_{FE;\Phi}) - (1/h_{FE;0})\right]_{ref}}{\Phi_{ref}(E_n = 1\,\mathrm{MeV})}. \quad (6)$$

Finally the NIEL-scaling factor was calculated using the Φ_{p+Be} spectrum integrated fluence obtained from the multifoil activation measurements.

Table 1. Comparison of the NIEL-scaling factors for thick target p+Be neutrons at around E_p = 18 MeV proton energy.

E_p (MeV)	κ	Comment
17.4	1.1 ± 0.20	This work, calculated from spectrum measurements with activation method & unfolding
17.4	1.1 ± 0.23	This work, from measurements with 2N2222 transistors
17.24	1.31	Calculated using the TOF spectrum of Brede et al. [8]
18	1.03	Calculated using the TOF spectrum of Lone et al. [7]
19.08	1.47	Calculated using the TOF spectrum of Brede et al. [8]

3 Results and discussion

At E_p = 17.4 MeV bombarding proton energy $\kappa_{p+Be} = 1.1 \pm 0.2$ was calculated by us for the NIEL-scaling factor from the neutron spectrum measured by the multifoil activation technique. The measurements with bipolar transistors resulted $\kappa_{p+Be} = 1.1 \pm 0.23$.

For comparison we calculated the hardness parameter for the spectra obtained with time of flight (TOF) spectrometry by Lone et al. [7] at E_p = 18 MeV proton energy, and by Brede et al. [8] at E_p = 17.24 MeV and at E_p = 19.08 MeV.

Table 1 shows a summary of the data obtained for the NIEL-scaling factors for thick target p+Be neutrons at around E_p = 18 MeV proton energy.

The results obtained here using two independent methods seem to be consistent.

At the same time the data listed in Table 1 show a discrepancy. The value of the NIEL-scaling factor is very sensitive to the measured shape of the $\varphi(E_n)$ neutron spectrum. Thus the differences of the spectra measured by the different authors are the most important reasons for the observed discrepancy of the obtained NIEL-factors.

The neutron yields, especially below E_n = 2 MeV neutron energies, measured by Brede et al. [8] are significantly lower than the neutron yields published by Lone et al. [7] and this is reflected in the NIEL-scaling factors obtained using spectra measured by the two groups.

The neutron spectrum we measured at ATOMKI at E_p = 17.4 MeV proton energy is somewhat "softer" than the spectrum measured by Brede et al. at E_p = 17.24 MeV proton energy. The difference can be partly understood by considering neutron scattering from the radiation protection shielding structures at around the neutron irradiation site at ATOMKI.

The NIEL-scaling factor obtained from measurements with 2N2222 bipolar junction transistors seems to be significantly different from the value that was calculated using the spectrum measured by Brede et al. at E_p = 17.24 MeV. The observed difference suggests that further investigations are necessary to check the relative displacement KERMA data of the SNL RML evaluation [3].

The discrepancies of the data listed in Table 1 suggest that it would be useful to use always the procedure described in the ASTM E1855-05el standard for estimating 1 MeV neutron equivalent fluences. It has to be emphasized, however, that it takes much time and effort to obtain h_{FE} values with the desired accuracy because of the finite life times of the radiation induced defects and the underlying defect kinetics.

4 Conclusion

Further investigations can be useful to check the displacement KERMA data of the SNL RML evaluation for Silicon.

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