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Simulation of space protons influence on silicon semiconductor devices using the gamma-neutron irradiation

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On the basis of the numerous experimental and theoretical studies the possibility of simulation radiation effects, induced by protons of the natural space environment in silicon bipolar and MOS devices using a ^{60}Co source and fast nuclear reactor have been shown .

Introduction

In the recent years a possibility of simulation radiation effects, induced by space protons in silicon semiconductor devices (SD), using gamma -neutron irradiation, is being widely discussed [1-3].

Not considering single-event effects, it is quite reasonable to take as a physical criterion of such approach the equivalence of the ionization density Wion and the structure defects density Wstr in the sensitive volume of SD under gamma - neutron irradiation to the corresponding values under space protons irradiation. As a rule, the results of calculations of nonionizing energy loss (NIEL) based on Lindhard energy partitioning [4] are used. as the energy dependence of damage functions for protons Wstr (Ep) and neutrons Wstr (En).

Thus , the approach allows to predict the radiation hardness of SD, taking into account a variety of energy spectra of space protons, depending on an orbit altitude and space vehicle's shielding. However, when the problem of simulation is considered in detail, one can note some substantional differences in the processes of formation of primary radiation defects in SD in space environment and under laboratory testing:

1. Generation of primary knock-on atoms (PKA) with different energy spectra under irradiation of silicon by protons and neutrons results in introduction of quasi-stable structure defects (disorded regions, point defects) with different properties.
2. With laboratory simulation of space proton influence on SD , the processes of ionization (under gamma-irradiation) and generation of structure defects (under neutron irradiation) are divided in time by a sufficiently long interval. Therefore , the structure defects under proton irradiation are introduced at the higher density of non-equilibrium charge carriers in comparison with neutron irradiation, which can influence on the yield and properties of quasi-stable defects .

3. The intensities of space radiation and simulated radiation under laboratory tests significantly differ.

Thus for correct simulation of radiation effects induced by space protons in SD under gamma-neutron irradiation conditions , it is necessary to clear up how much the above mentioned differences can reduce the effectiveness of such approach.

A lot of papers has been devoted to investigations of radiation intensity influence on degradation of SD parameters . Therefore, in this study we shall focus , primary, on the problems of simulating the space proton energy spectra under laboratory radiation tests of SD.

Displacement defects

As under laboratory tests of SD by neutron irradiation there is a need for generation , within a material (silicon) of the device sensitive volume , of the displacement defects density , equivalent to the density in case of space protons exposure with a certain energy spectrum, we studied the energy dependence of corresponding damage functions Wstr (Ep) , Wstr (En) in the energy range of space protons ($1\ \text{MeV} < Ep < 1000\ \text{MeV}$) and nuclear reactor neutrons ($0.01\ \text{MeV} < En < 15\ \text{MeV}$) .

Silicon diodes, bipolar transistors and microcircuits of more than 10 types (npn and pnp with various frequency characteristics) with the minimal sensitivity to ionization effects were chosen for experiments. In this case it is supposed, that the dependence Wstr (E) is proportional to the damage factor Kh (E) given by equation :

$$1 / h_{FE}(\sqsupset) = 1 / h_{FE0} + Kh \sqsupset(E)$$

where □ (E) is the incident particle fluence ;

h_{FE} (□) and h_{FEO} are the common emitter dc gains after and before the irradiation, respectively.

The experiments were performed by irradiation of SD by monoenergetic protons (Ep = 5; 10; 22 ; 30 ; 50; 70; 100; 130; 600 ; 1000 MeV) and by 14 - MeV and fission neutrons as well.

On choosing of the universal theoretical dependence Wstr (Ep) and Wstr (En), we admitted the use of the energy dependence of nonionizing energy loss (NIEL) as a damage function independent of a radiation type for comparison of absolute degradation of SD parameters under influence of protons or neutrons with different energy spectra.

The results of NIEL calculations for protons and neutrons are shown in Figure 1. For neutrons we use the results of our calculations ; for protons energy dependence of NIEL was taken from [1], where the nuclear reactions, contributing to the PKA generation in silicon, were most adequately provided for. The experimental damage factors Kh (Ep) normalized to the energy dependence of NIEL at the proton energy Ep = 22 MeV are also shown in Figure 1.

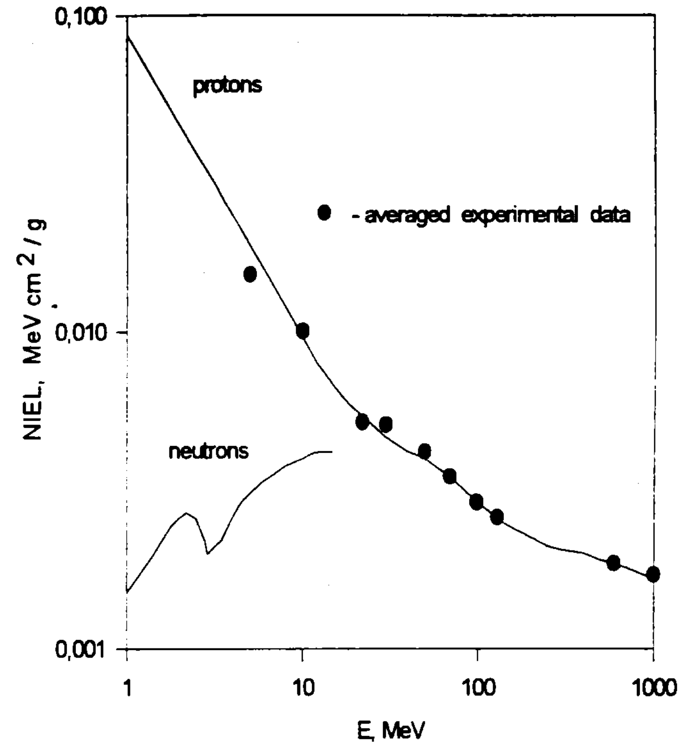

Figure 1. Relative damage factors for protons and NIEL for protons and neutrons

Using the calculated dependence of NIEL, the ratio of damage factors for neutrons and protons with different energies had been obtained. In Table 1 they are compared with experimental data.

Table 1. The ratio of damage factors Kh (Ep) / Kh (En) for different particles energies

Ep , MeV	En , MeV	Kh (Ep) / Kh (En)	
		Theory	Experiment *
30	14	1.1	1.1
100	fission	1.6	1.7

**) an averaged value on 5 types of bipolar tansistors*

The presented experimental and theoretical results show that energy dependencies of NIEL are quite universal to predict the degradation of SD parameters associated with displacement defects in the wide range of proton and neutron energies.

It is important to note that the relatively intensive accompanying ionization under proton irradiation or differences in the energy spectra of PKA caused by protons and neutrons don't have an appreciable effect on the damage factors.

Ionization effects

In simulation of ionization effects induced by space protons, using gamma - irradiation , it was necessary to generate the ionization density in the sensitive volume of SD , equivalent to the corresponding value for space environment. We took a layer of a gate oxide for MOS devices and a layer of a passivating oxide for modern bipolar devices to be a sensitive volume.

The average ionization density in the oxide layer was calculated from the known dosimeter information about energy spectrum and particle fluence at the location of the devices subject to proton and neutron radiation.

Under gamma - irradiation of SD the absorbed dose rate was about 700 rad (SiO_2) , which approximately corresponded to the absorbed dose rate about 1000 rad (SiO_2) under pilot irradiation by monoenergetic proton beams. Thus , it was possible to neglect the effects connected with radiation intensity .

Results of modeling . Discussion

Various types of bipolar and MOS devices sensitive to both ionization and structure defects , were taken for pilot test in order to provide a verification of possibility to simulate space protons influence on SD, using gamma - neutron irradiation.

The irradiation was carried out by monoenergetic protons with energy Epo = 20 MeV, gamma - radiation of ^{60}Co source and fission neutrons.

For given proton fluence □p, proton/cm^2 the corresponding neutron fluence □n , neutron/cm^2 and gamma - radiation dose Dγ , rad (SiO_2) were obtained by the following way. Knowing □p and energy dependence of NIEL (Fig. 1) as well as the ionizing energy loss for protons , we obtained the integral values Wstr (Epo), rad (Si) and Wion (Epo), rad (SiO_2). Proceeding from the value Wstr (Epo) and the known energy dependence of NIEL (Fig.1) as well as the energy spectrum of neutrons , we obtained equivalent neutron fluence.

The value Wion (Epo) defined the time of gamma - irradiation, necessary for generation of the equivalent ionization density in the sensitive volume of SD.

As we intended additionally to investigate the influence of sequence of gamma- radiation and neutron irradiation on degradation of SD parameters, a SD was irradiated, at first, by gamma-radiation and then by neutrons (γ + n), and the other one was irradiated under the reverse sequence (n + γ).

The comparison of results of SD pilot irradiation by protons and gamma-neutrons allows to come the following conclusions.

As one would expect, the MOS devices were turned out to be sensitive to ionization defects only and indicated the same variations of parameters under conditions of equality of ionization density generated by protons and gamma- radiation in the oxide layers.

The results of measuring of common emitter dc gain degradation for different types of modern planar transistors show (Table 2) that h_{FE} is sensitive to both ionization and structure defects.

Table 2. Relative gain h_{FE}/h_{FEO} degradation of bipolar transistors under influence of protons with energy 20 MeV and equivalent neutron fluence and gamma - radiation dose

Transistor type	**Gamma + Neutrons**				**Protons**
	γ	γ + n	n	n + γ	
npn, high- frequency	0.53	0.31	0.4	0.28	0.32
pnp, high-frequency	0.86	0.45	0.45	0.45	0.42
pnp, low-frequency	0.18	0.14	0.34	0.15	0.14

Therefore in simulation of space protons influence on SD it is necessary in general case to generate in the active volume of devices the corresponding density of ionization and structure defects.

As follows from Table 2, the finite quantity h_{FE} after irradiation doesn't depend on the sequence of gamma and neutron irradiation. However the joint influence of ionization and structure defects on gain

degradation is displayed in the complex manner and can't be reduced to a simple summation of contribution of gamma and neutron radiations.

In general, the results of present work allow to conclude that gamma - neutron irradiation can quite correctly simulate under laboratory conditions the primary radiation effects, induced in bipolar and MOS SD by space protons with different energy spectra.

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