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Neutron-Induced Radiation Effects in UMOS Transistor

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Abstract. Ground level electronics and avionics systems may suffer from radiation effects induced by neutrons. Neutrons can induce radiation effects in electronic devices via fusion-evaporation nuclear reactions, but few studies have been reported for technologies such as UMOSFET. In this work, estimates and experimental studies on neutron-induced radiation effects via nuclear reactions in a Si-based UMOSFET are presented. Methods for probability estimates of neutron-induced Single-Event Effects (SEEs) in Si-based power transistors and neutron beam energy measurement is presented. The energy spectrum of a UMOSFET subject to fast neutron irradiation was then compared to that of a high charge collection efficiency silicon particle detector.

1. Introduction

It is well known that electronic devices may exhibit operational failures when operating in radiation environments [1]. Currently, the prominent radiation effect in embedded electronics for aerospace application is called Single-Event Effect (SEE), in which the incidence of a single energetic particle may result in an unexpected observable event when penetrating into an electronic device [2]. Although neutrons are not directly ionizing particles, ground level electronics and avionics systems are subject to suffer neutron-induced SEEs through nuclear reactions [3]. For example, the excited compound nucleus formed by the fusion of a neutron with the nuclei of electronic materials can evaporate ejectiles, resulting in a residual recoil particle.

In recent years, the usage of commercial off-the-shelf (COTS) devices in aerospace applications has grown and several device technologies have emerged. It is known that the electronics industry aims to supplant the traditional DMOSFET (double-diffused metal-oxide-semiconductor field-effect-transistor) technology by the UMOSFET (U-shaped trench gate MOSFET) technology [4]. Radiation tests become mandatory before these devices can be used in systems that require high reliability, such as avionics systems. Nevertheless, few studies of SEEs induced by fast neutrons have been published for such technology.

This work aims to present studies on radiation effects induced by fast neutrons in a silicon-based UMOSFET device. The neutron-induced SEE occurrence probabilities in Si-based power

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transistors were estimated from analytical approximations and computational codes. The energy spectra of a UMOSFET and a Silicon Surface Barrier (SSB) detector under fast neutron irradiation were measured by using the charge spectroscopy technique. Due to its high charge collection efficiency, the SSB detector was used to assess the actual energy spectrum of recoil charged particles that results from nuclear reactions of fast neutrons with ^{28}Si. A discussion concerning the charge collection efficiency of the UMOSFET in comparison to that of the SSB detector, also used for neutron beam energy calibration, is presented.

2. Materials and Methods

2.1. Irradiation Facility

The quasi mono-energetic neutron beam was provided by the Deuteron-Tritium Neutron Generator of the *Instituto de Estudos Avançados* (IEAv), *São José dos Campos*, Brazil. The equipment, model Thermo Scientific$^{\mathrm{TM}}$ MP 320, is capable to provide a $\sim 14\,\mathrm{MeV}$ neutron beam with a typical neutron yield of about 10^8 neutrons/s.

2.2. Tested Device

A COTS UMOSFET was considered for fast neutron irradiation tests. The thickness of the semiconductor chip of this device is usually around $300\,\mu$m. The rated breakdown voltage of the UMOSFET device chosen for experiments is 60 V [5]. During electrical characterization, a large increase in the drain-source leakage current was observed for drain-source voltages above $V_{DS} = 82.6\,\mathrm{V}$. Thus, the breakdown voltage of the device under test (DUT) was estimated at about $BV_{DS} \cong 85\,\mathrm{V}$.

2.3. Test Methodology

In our experimental approach, the usual charge/energy spectroscopy technique was used in order to compare the energy spectrum of the DUT with a fully depleted SSB particle detector. SSBs are commonly used as charged particle detectors in nuclear physics experiments and are usually considered to have a collection efficiency of 100%. Remarkable exceptions that may influence their charge collection efficiency are related to the voltage applied to the detector and also energetic particles that can escape from the detector volume. High-energy protons produced by the $^{28}\mathrm{Si}(n,\ p)^{28}\mathrm{Al}$ can have a range much greater than the detector thickness, whereas both SSB detector and DUT can experience relatively rare edge effects of heavy-ions. Nevertheless, since a fully depleted 100 μm thick SSB was used, the range of the vast majority of charged particles produced within the detector volume is much less than the detector thickness. Therefore, disregarding high-energy protons, virtually all particles are detected and the collection efficiency of heavy-ions tends to 100%.

Firstly, the neutron beam energy at the irradiation position was measured by using a fully depleted SSB via the $^{28}\mathrm{Si}(n,\ \alpha)^{25}\mathrm{Mg}$ nuclear reaction. In other words, the neutron beam energy at the standard axial irradiation position was calculated through the measurement of the energy peak of the ^{25}Mg nucleus ground state since the Q-factor of this reaction channel is known [6]. Secondly, the DUT was irradiated in OFF mode, with $V_{GS} = 0\,\mathrm{V}$ and $V_{DS} = 50\,\mathrm{V}$. The V_{DS} value was set below the rated breakdown voltage of the DUT in order to ensure that enhanced charge collection effects, such as ionization impact and/or heavy-ion-induced avalanche multiplication, did not take place. The charge/energy spectroscopy of the power device under fast neutron irradiation was carried out by using standard NIM electronics. In Fig. 1, the electronic acquisition system, that basically consists of preamplifier, spectroscopy amplifier and analog to digital converter, is shown. The acquisition system was properly calibrated in energy produced in Si material (considering 3.6 eV as the average energy necessary to produce an electron-hole pair in Si) by using precision pulse generator and a ^{241}Am alpha-particle source. The SSB detector was irradiated by fast neutrons during 1.5 h, totaling a beam fluence of

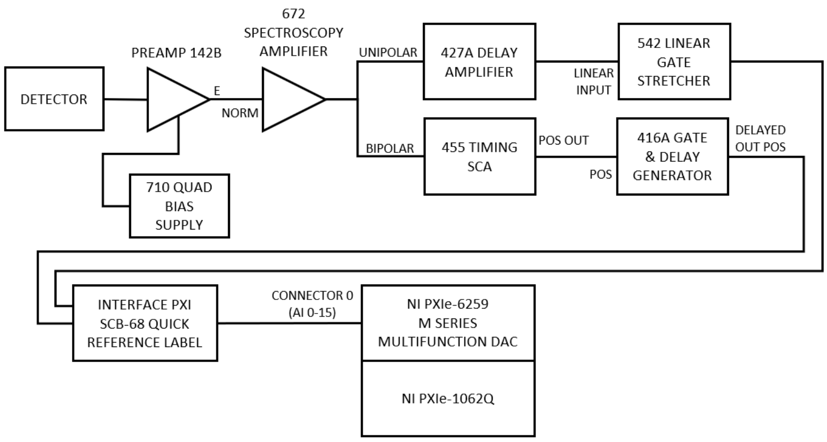

Figure 1: Electronic acquisition system diagram for SEE tests in power transistors.

$7.0(3) \times 10^{8}$ neutrons/cm^2 provided by the IEAv DT Neutron Generator. On the other hand, the DUT was irradiated for about 22 h, totaling a beam fluence of $1.15(4) \times 10^{10}$ neutrons/cm^2.

2.4. Estimates: SEE Probabilities

The feasibility of the experiment can be evaluated from estimates of the SEE probability occurrence. The probability of neutron-induced SEEs in Si-based power transistors was estimated as follows. The reaction probability is given by [7]:

$$P = \sigma n T \tag{1}$$

where σ is the reaction cross section, n is the number of target particles per unit volume and T is the target thickness. Considering the depletion region as the sensitive domain for Si-based power MOSFETs [8], the active thickness T is estimated by [9]:

$$N_d = \left[\frac{5.34 \times 10^{13}}{BV_{DS}}\right]^{4/3} \tag{2}$$

$$T \approx w_d = \left[\frac{2\,\varepsilon_{Si}\,V_{DS}}{e\,N_d}\right]^{1/2} \tag{3}$$

in which N_d is the donor concentration in the epitaxial region, BV_{DS} is the breakdown voltage, w_d is the depletion region width, $\varepsilon_{Si} = 1.05 \times 10^{-12}$ F/cm is the Si permittivity, V_{DS} is the drain-source applied voltage, and $e = 1.602 \times 10^{-19}$ is the electron charge. Considering $BV_{DS} = 85$ V for the DUT, by substituting (2) into (3), the depletion region width at $V_{DS} = 50$ V is estimated to be $T \approx w_d = 3.5\,\mu$m.

The reaction channel cross section values at the neutron energy of interest (14 MeV, for simplicity) can also be estimated by using the Monte-Carlo fusion-evaporation code PACE4 [10, 11]. The corresponding reaction channel probabilities were then estimated by considering the density of Si atoms $n = 5.02 \times 10^{22}$ atoms/cm^3 [12] and substituting the cross section and depletion region values into Eq. 1. These values are presented in Table 1.

Table 1: Probability estimates of Single-Event Effects in Si-based power transistors due to interaction of 14 MeV neutrons with ^{28}Si nuclei. Energy threshold values obtained from [13].

Reaction channel	**Energy threshold [MeV]**	**Percent [%]**	σ **[mb]**	P
$n + {}^{28}$Si	0.00	71	554	9.7×10^{-6}
$p + {}^{28}$Al	4.00	24	187	3.3×10^{-6}
$\alpha + {}^{25}$Mg	2.75	5	39	6.8×10^{-7}

3. Results

3.1. Neutron beam energy calibration

The neutron beam energy at the standard irradiation position was deduced from the interaction of fast neutrons with a SSB detector via the ^{28}Si(n, α)^{25}Mg nuclear reaction. In Fig. 2, the energy spectrum measured is shown. The pronounced peak at the end of the energy spectrum is assigned to the ground state of ^{25}Mg, whereas the subsequent peaks are related to its excited states [14]. The neutron energy corresponding to the centroid of the ^{25}Mg ground state peak was calculated by considering $Q = -2.654$ MeV [6], resulting in $E_n = 13.6(3)$ MeV.

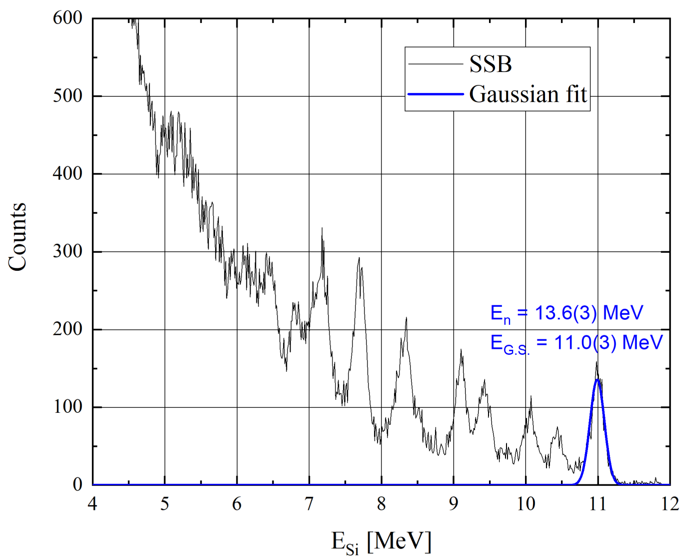

Figure 2: Energy spectrum from interaction of fast neutrons produced by the IEAv Neutron Generator with a fully-depleted SSB detector. A gaussian fit of the ^{25}Mg ground state peak, with centroid $E_{G.S.} = 11.0(3)$ MeV, is indicated by the blue line.

3.2. Neutron-induced SEEs

No destructive radiation effects were observed during neutron irradiation. In Fig. 3, the energy spectra of the power UMOSFET and the SSB detector are shown. The DUT energy spectrum was normalized to the neutron beam fluence on the fully-depleted SSB detector. In Fig. 3 one can see that the detection efficiency of the UMOSFET can be up to 1000 times lower than that of the SSB detector, especially concerning the ^{25}Mg ground state peak. In addition, the ^{25}Mg

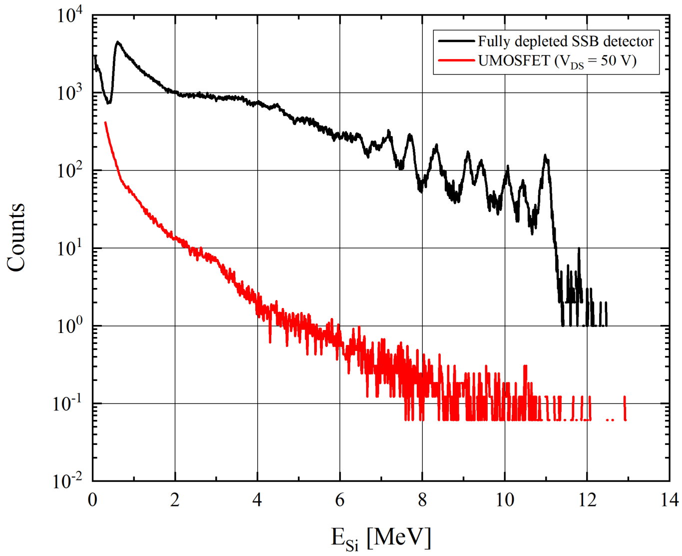

Figure 3: Energy spectra from interaction of 13.6(3) MeV neutrons with a UMOS transistor and a fully depleted SSB detector. The UMOSFET spectrum was normalized to the neutron beam fluence on the SSB detector.

excited states peaks cannot be clearly identified due to low energy resolution. Nevertheless, high-energy SEEs can be detected by the UMOSFET, suggesting a high charge collection efficiency.

Some aspects of the neutron-induced SEE susceptibility and the charge collection efficiency of UMOSFETs can be explained in terms of the device architecture. The relatively lower detection efficiency of the UMOSFET is attributed to differences in the active detection volume of each device, which may differ from each other not only in thickness. As presented in Section 2.4, the depletion region width of the UMOSFET at 50 V was estimated to be 3.5 μm, whereas the depletion region width of the SSB detector is about 100 μm when fully depleted. Furthermore, any other differences concerning detection efficiency can be related to UMOSFET cell width spacing and its complex architecture in comparison with the usual Schottky diode architecture of SSBs. On the other hand, the detection efficiency of SEEs in UMOSFET devices is expected to be higher than in traditional DMOSFETs because of the small cell width spacing usually achieved in the manufacturing process of the UMOSFET technology [15]. It is also known that large electric fields can be produced at the trench corners of UMOSFET structure [15]. Based on this, concerning the charge collection efficiency, the capability of the UMOSFET detect high-energy SEEs is explained as follows. Due to the high transistor cell density, electron-hole pairs produced by charged particles can be collected by neighboring cells, which results in an improved charge collection efficiency. This is especially relevant when reaction products are emitted along the plane of the DUT depletion region. Some of the unique high-energy events detected can also be attributed to the impact ionization process that occurs due to local electric field stress near trench corners.

4. Conclusion

In this work, the neutron beam energy of the IEAv DT Neutron Generator was measured and aspects of neutron-induced SEEs in a Si-based UMOS transistor were assessed. The neutron beam energy was calibrated via the ^{28}Si$(n, \alpha)^{25}$Mg nuclear reaction, resulting in a neutron beam of $E_n = 13.6(3)$ MeV at the standard irradiation position. The energy spectra of an UMOSFET and a fully depleted SSB detector, both irradiated under similar conditions, were compared to each other. It was obtained that, such as the SSB detector, the UMOSFET was able to detect SEEs involving energies up to ~ 11 MeV, which indicates that UMOSFET presents high charge collection efficiency. It was argued that this observation is possibly related to charge collection shared by neighboring transistor cells and even to impact ionization process due to intense electric field near the trench gate corners.

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