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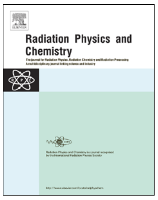

Short Communication

Radiation effect on silicon transistors in mixed neutrons–gamma environment

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HIGHLIGHTS

- We measure the gain degradation after irradiation of BJT and JFET transistors.
- We model the reactor and transistors in order to calculate irradiation dose.
- The gain degradation was higher in BJT than in JFET.
- Neutrons and gamma dose contributions of reactor were 2% and 98%, respectively.
- The highest neutron contribution comes from the fast and resonance absorption neutrons.

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ABSTRACT

The effects of gamma and neutron irradiations on two different types of transistors, Junction Field Effect Transistor (JFET) and Bipolar Junction Transistor (BJT), were investigated. Irradiation was performed using a Syrian research reactor (RR) (Miniature Neutron Source Reactor (MNSR)) and a gamma source (Co-60 cell). For RR irradiation, MCNP code was used to calculate the absorbed dose received by the transistors.

The experimental results showed an overall decrease in the gain factors of the transistors after irradiation, and the JFETs were more resistant to the effects of radiation than BJTs. The effect of RR irradiation was also greater than that of gamma source for the same dose, which could be because neutrons could cause more damage than gamma irradiation.

1. Introduction

Electronic components are widely used in control and measurement of military, aerospace, nuclear and high-energy physics systems and can be exposed to nuclear radiation (Candelori, 2001; Colder et al., 2002; Schrimpf, 2004; Dalla Betta et al., 2007). Studies of radiation effects on semiconductor devices are useful for industrial companies to produce devices that are more resistant to radiation.

In general, the structure of electronic components consists of different junctions and contacts of Si, SiO_2 and metal. The most radiation-sensitive areas of these components are the Si, SiO_2 and the Si/SiO_2 interface. Radiation creates defects in these areas that cause damage to the component functions, such as decreasing gain, increasing noise, etc.

The amount of radiation delivered to the components and the effects of that radiation depend on the radiation energy, types of radiation and the structure and composition of the components (Messenger, 1992).

In general, gamma rays and neutrons react with semiconductors via ionization and atomic displacement to different degrees (Akkerman et al., 2001; Pien et al., 2010). The contribution of ionization is high for gamma rays, while the contribution of displacement is high for neutrons. Moreover, the radiation effects depend on the dose that is absorbed by the component materials. For reactor neutrons, the flux is measured directly, and the dose is then calculated, whereas, for a gamma source, the dose is directly measured. To compare the effects of different radiation types on component behavior, similar doses must be used. In this work, the radiation effect of neutron irradiation in RR is compared with that resulting from a gamma source.

2. Irradiation facilities and irradiated component materiel

The tested components were irradiated by gamma radiation from a gamma irradiation cell and by neutrons from Syrian RR. The

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Table 1
Measurement irradiation ranges and an example of transistors gain factors reduction ratio after irradiation.

Transistor type	Measurement irradiation ranges		Gamma dose and irradiation time producing a gain factor reduction of 65%	
	Gamma source (kGy)	Reactor (s)	Gamma source (kGy)	Reactor (s)
JFET	0.1–10,000	5–2000	10,000	1000
BJT	0.1–1	5–50	0.35	10

average radiation energy of the gamma source was 1.25 MeV. The MNSR reactor is classified as a thermal neutron reactor. A thermal neutron flux achieved, at the nominal power of 30 kW, a maximum of about 1×10^{12} neutrons/s cm^2. In addition, neutrons with higher energy and associated fission gamma rays were also present. The beams produced by the reactor consist of thermal, resonance absorption, epithermal and fast neutrons.

The studied components were JFET and BJT discrete commercial transistors (N-JFET (2N5434) and NPN-BJT (2N2222)) with metallic and Teflon cover cases (packages), respectively. The transistors were irradiated to different gamma source dose levels, as measured by a chemical dosimeter, or were irradiated inside one of the RR internal channels for different irradiation times. The ranges of gamma doses and irradiation times are shown in Table 1 (columns 2 and 3).

3. Experimental results

The resistance to radiation of the irradiated components was characterized by the behavior of their gain factors, such as the transconductance (g_m) for JFETs and current gain (h_{FE}) for BJTs.

The variations of g_m and h_{FE} were characterized and reported. The results showed that, in general, the gain factors decreased with increasing dose/irradiation time for both types of transistors. This decrease is much lower in JFETs than in BJTs, i.e. h_{FE} reduction is much higher than that of g_m for the same dose/irradiation time. For example, the dose/irradiation time required to produce a reduction of 65% for both gain factors is measured and is reported in Table 1 (columns 4 and 5).

4. Dose calculation using MCNP code

The total absorbed dose, contribution of fission gammas and neutrons from irradiation inside the RR is proportional to the exposure time. It is difficult to experimentally measure the radiation dose inside the RR. Therefore, the dose must be calculated using adequate code. In this study, the dose was calculated using the MCNP through the following steps:

- Modeling of MNSR reactor.
- Testing the accuracy of the model and verifying the validity of the modeling.
- Modeling of the studied electronic components.
- Calculating the absorbed doses by the electronic items according to the established models.

4.1. Modeling of the reactor

The details of modeling the reactor were similar to those described by other work (Hainoun and Alissa, 2005). The goal of this modeling is to better understand the full energy spectrum (energy versus flux) of different neutron beams and fission gamma rays to calculate the doses. The calculated fission gamma energy ranges from 0.05 MeV to 10 MeV.

4.2. Modeling the structure of the transistors

The studied electronic components were modeled according to the axis of the core. The geometric design was set to resemble the real shape and dimensions of the transistors as closely as possible. The functional parts of transistors are mainly composed of Si, SiO_2 and doping elements. Because the gamma and neutron interaction coefficients are similar for Si and SiO_2, the model can be simplified by considering only Si in the calculated model. The materials that cover the body of the transistors have also been considered. Therefore, from a modeling point of view, the calculated dose is then the dose absorbed by Si shielded by stainless steel or by Teflon. The two configurations are designated in the text as M-Si and I-Si corresponding to metal and isolator packages, respectively.

4.3. Basic of dose calculation

The dose rate is calculated using the following equation (Li et al., 2009):

$$\dot{D}_{Cal} = \left(\frac{1}{\rho}\frac{dE}{dx}\right) \times \varphi \tag{1}$$

where $1/\rho(dE/dx)$ is the ratio of the change of particles energy dE to path length dx normalized to the density of matter ρ, which is known as the stopping power. Finally, φ is the radiation flux.

If the following units are used for the terms of Eq. (1) as $1/\rho(dE/dx)$ in MeV cm^2 g^{-1} and φ in cm^{-2} s^{-1}, then the unit of $\dot{D}_{Cal}$ will be MeV g^{-1} s^{-1} and the calculated dose D_{Cal} in MeV g^{-1}.

To calculate the absorbed radiation dose through MCNP, the amount of deposited energy in the unit weight per second has been calculated within the cell representing the silicon core of the electronic item estimated by MeV g^{-1} s^{-1}. This value was multiplied in the next step by three other values: the flux of specific neutron beam φ, the irradiation time, and conversion factor to Gy which is equal to 1.602×10^{-10} Gy g MeV^{-1} (Li et al., 2009).

4.4. Results of the calculated doses

According to the spectra of neutrons and gamma fission, the doses received by the transistors models were calculated using MCNP. These calculations include the different contributions of neutron doses corresponding to different neutron beams and the total dose of fission gamma rays. The calculation was performed for several irradiation times. Silicon film thicknesses of 10, 100 and 1000 μm in both structures were also considered. The results showed that the absorbed dose is independent of the Si volume at this scale. Because the Si thickness of the real structure is close to 10 μm, the doses corresponding to this thickness value were chosen for all subsequent analyses. Table 2 illustrates the obtained values of $\dot{D}_{Cal}$ for both modeled structures. The two structures receive similar gamma doses, while the dose of neutrons 25% lower with the metallic shielding.

4.4.1. Details of the dose contributions

As shown in Table 2, the fission gamma contribution is much higher than that of the neutrons in both structures. The ratios of these contributions are shown in Table 3, where the neutrons and gamma rays constitute approximately 2% and 98% of the total, respectively.

The total neutrons and fission gamma doses versus irradiation time are shown in Fig. 1. A similar result was obtained for the Si-M