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Radiochromic films in Radiation Hardness Space Application

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Abstract. The characteristics of radiochromic films such as the direct visualization of radiation field, ease of use and data analysis are suited for the dosimetry monitoring in tests of radiation hardness space applications. In particular, in this work, in order to study the dependence of radiation type, energy and dose rate, as well as the dynamic range of EBT3 Gafchromic films, a set of films was exposed to radiation sources used in total ionizing dose (^{60}Co gamma- and ^{90}Sr/^{90}Y beta-rays). The results have been found to be particularly suited for the employment of this kind of films in radiation hardness assurance tests.

1. Introduction

The electronic devices employed in space applications (e.g. satellites, cubesats, spacecraft, batteries, sensors, power units, payload equipment, among others) need to be tested due to the high exposure to radiation in the space. The space radiation environment is made of several radiation types and energies, not homogeneously distributed in space and time. In particular, it is composed by particles trapped by Earth's magnetic field, Galactic Cosmic Rays (GCRs) and Solar Cosmic Rays (SCRs). The terrestrial magnetic field traps charged particles such as electrons and protons, by creating two radiation belts known as Van Allen belts [1]. The inner belt, which extends from 100 to 6000 km in altitude is known as Low Earth Orbit (LEO) and is mainly populated by high-energy protons in the range 10-100 MeV with density 15 particles/m^3 and electrons in the range 50-1000 keV. The outer belt is populated by electrons up to 10 MeV at altitudes up to 60000 km. Moreover, because of the difference between the magnetic and geographical poles, the Van Allen belts are closer to one part of Earth that is the South Atlantic area. The subsequent radiation anomaly is known as South Atlantic Anomaly (SAA). GCRs follow helical trajectories because of their interaction with strong magnetic fields in the galaxy; GCRs and SCRs mainly consist of protons with a lower contribution of alfa particles, but also heavy nuclei are part of primary cosmic rays. For these reasons, radiation tests for quality checks of electronics must be accurately designed by taking into account the typical characteristics of the space mission such as time, orbit, altitude and shielding.

The electronic devices employed in space missions must be therefore declared radiation hardened or tolerant before their usage. A useful schematization of the effects of radiation on silicon can be done in term of long- and short-term effects. The firsts are total ionizing and displacement damage effects and the seconds are Single-Event-Effects (SEEs). Total Ionizing Dose (TID) tests are usually performed with gamma rays from radioactive sources of ^{60}Co, but also protons from accelerators in the range from a few keV to 500 MeV or electrons in a wider range from some eV to 10 MeV. TID causes long-term degradation of electronic devices due to cumulative energy deposited in the Si-matrix for ionization processes. Displacement Damage Dose (DDD) also implies long-term degradation of electronic devices, but in this case the basic mechanism of damage consists in the displacement of the atoms of the Si-lattice. The characterization of devices for DDD is more complicated than that for TID. In DDD tests, the contribution to non-ionizing energy loss (NIEL) should be accomplished, in agreement with the formula

$$DDD = NIEL \cdot \Phi$$

where Φ is the particle fluence in cm^{-2}. Similarly, for TID tests, the evaluation of linear energy transfer (LET) has to be done accordingly to the formula

$$TID = LET \cdot \Phi$$

Tables of both LET and NIEL values are available in literature [2]. Fig. 1 shows a picture with a SEE on an integrated circuit. It results in the direct breakdown of the device.

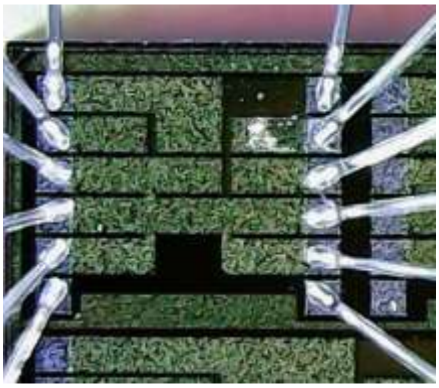

Fig. 1: Picture of a SEE on an integrated circuit.

SEEs are stochastic and occur when a single ion interacts with the DUT Si-matrix, by inducing direct or indirect ionization (e.g. neutrons). SEE probability is a characteristic function of the LET of the incident ion.

The characterization of electronic devices for TID, DDD and SEE tests is usually performed in facilities able to provide charged particle beams and radioactive sources of suited characteristics. The guide-lines for the testing of devices, defined by the International Standards such as the U.S. military standard guidelines MIL-STD-883 and the ESA ESCC22900 standard guidelines [4,5], impose conditions for radiation hardness quality assurance tests and consequently for the typologies of dosimeters and radiation detectors employed in these tests. In this work, a full characterization of some types of radiochromic films, the EBT3 Gafchromic films, has been accomplished for the specific application of radiation hardness assurance tests.

2. Radiochromic Films

Nowadays several detectors and dosimeters are available and each detector has its own features which make it more suitable for some specific application rather than another. Detectors and diagnostic techniques typically employed in radiation hardness applications are e.g. the gas-filled chambers such as ionization chambers and parallel-plate avalanche counters, Faraday cup, resistive or capacitive pick-up systems, scintillators and phosphor screen, among the others. The required information is often achieved by making use of more than one detector. Furthermore, in tests with particle beams it is common that the energy needed can be provided by reducing the initial incident energy. This can be performed by means of suited materials (degraders) that slow down and straggle the particles. The change of characteristics of the original beam leads to the loss of definition of relevant physical quantities like energy, fluence and dose in the experimental position. As an example, Fig. 2 shows a picture of the beam line of the proton irradiation facility (PIF) at *Paul Scherrer Institute* (PSI).

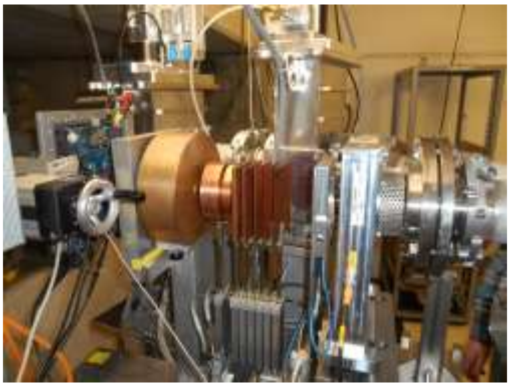

Fig. 2: PSI PIF beam line for irradiation of electronic devices.

It is noticeable the series of copper degraders needed for the modulation of the initial energy. In order to accurately monitor physical quantities needed for guarantee the reliability of different types of tests (TID, DDD and SEE) in radiation hardness applications, the ideal detector should be independent of incident radiation type, energy and dose rate, as well as non-perturbative and easy to use. A good compromise between these needs is the Radiochromic Film (RCF).

RCFs consist of a thin film made of a single or double layer of radiation-sensitive material that has the chemical property to exhibit an increased darkness with the increase of the radiation dose [6]. RCFs are commonly used in photon and ion radiotherapy and in many other applications of radiation physics such as industrial irradiations for modification of materials, food and medical instrumentation sterilization, among the others. The main characteristics of RCFs are reliability, ease of use, cost, and portability. Furthermore, RCFs are non-invasive dosimeters providing accurate and permanent values of dose. The direct visualization of the radiation field and micrometric thickness of the active layers are very useful characteristics in radiation hardness applications. The interaction of radiation with the radiochromic medium causes a progressive darkening of the film that can be related to the radiation dose. Differently from silver-halide films, RCFs are self-developing and the reading, usually made with commercial flat-bed scanners and densitometers, can be made after the time needed for the stabilization of the polymerization process which is taken for convenience 24 hour. Scanner and densitometers allow the evaluation of the Pixel Value (PV) on a particular region of interest of the digitized film. In this way the calibration (PV vs. dose) can be carried out by exposing a set of films to a-priori known radiation field. Several types of RCFs are currently available and a wide dynamic range can be investigated, from a few mGy up to several hundred of kGy. This range covers the most of doses in radiation hardness tests.

3. Results

In this Sec. we report the results of calibration of a set of EBT3 Gafchromic films, a kind of RCF intensively employed in medical physics application, to ^{60}Co gamma- and ^{90}Sr/^{90}Y beta-rays. It has to be noticed that ^{60}Co gamma sources constitute the standard sources for TID tests. The employment of a ^{90}Sr/^{90}Y beta-source for TID tests is a novelty in this field and represents a valid alternative to ^{60}Co sources [7]. In particular, the exposure of devices to beta-rays results in a better representation of the complex space radiation environment composed of several types, energies and dose-rates. The contribution of electrons to space radiation is mainly due to trapped electrons in the outer Van Allen belt. In addition, the use of a compact and easy handling beta source allows exposures of electronic devices without any damage to other auxiliary circuits. Fig. 3 shows the calibration (PV as a function of the dose) of a set of EBT3 Gafchromic films exposed to ^{60}Co gamma-rays from the GammaCell220 of ISOF-CNR in Bologna.

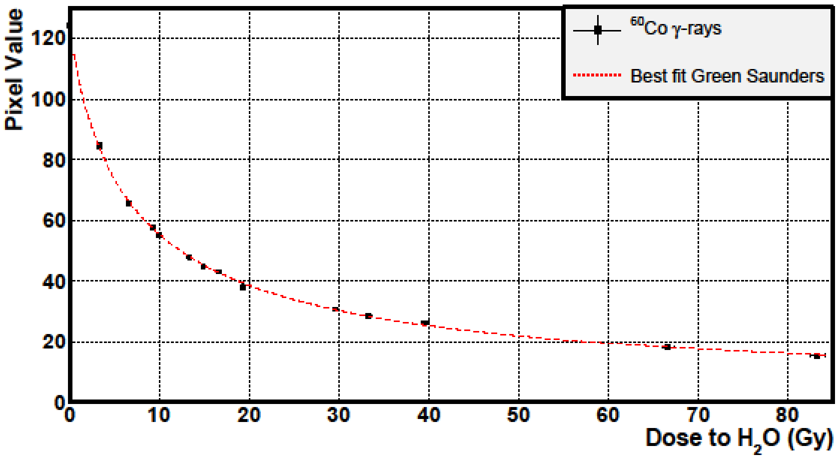

Fig. 3: Calibration of EBT3 Gafchromic films with ^{60}*Co gamma rays.*

The sensitivity range declared by the manufacturer is up to 40 Gy. For higher doses the sensitivity decreases, but it is possible to discriminate doses up 80 Gy (8 krad). The function which best fits to the experimental data has been found to be the Green-Saunders equation [8]. It is represented by the dotted red curve in Fig. 3. The agreement of the fit is excellent and the calculated value of the reduced chi-squared is 0.8. Fig. 4 shows the calibration of a set of EBT3 Gafchromic films to beta-rays from the radioactive source ^{90}Sr/^{90}Y.

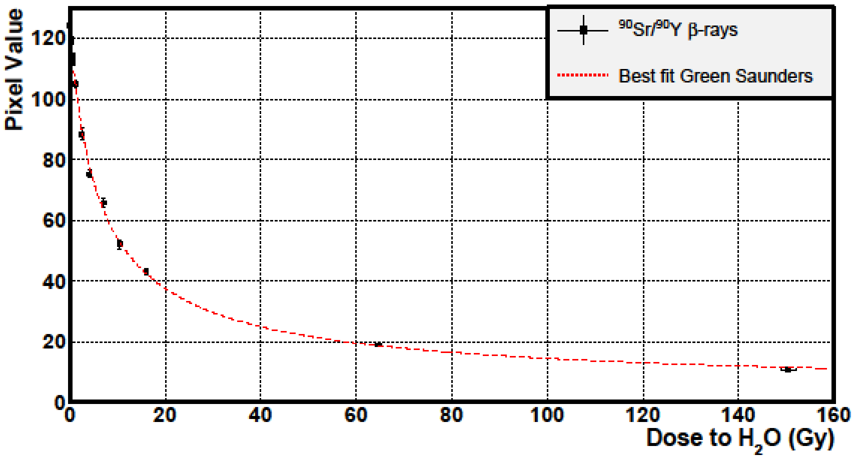

Fig. 4: Calibration of EBT3 Gafchromic films with ^{90}*Sr/*^{90}*Y beta rays.*

This source is currently used at University of Naples Federico II as accurate and reliable radioactive source for TID tests as alternative to the most common ^{60}Co. Also in this case, the best fit to the experimental data is provided by the Green-Saunders equation and the calculated value of the reduced chi-squared is 0.7. Data were acquired up to 160 Gy (16 krad).

4. Discussion and Conclusion

Tests of electronic devices in radiation hardness space application need reliable and easy to use instrumentation for the monitoring of dose and radiation field characteristics. Owing to the peculiar features of spatial radiation environment, consisting of several kinds of radiation, energies and dose-rates, radiochromic films are adapt to these purposes. In this work, a set of EBT3 Gafchromic films was exposed to the ^{60}Co gamma source (the mostly used one) and to the recent proposed ^{90}Sr/^{90}Y beta source. The results show that EBT3 Gafchromic films can be employed for most of tests carried out within this application. In fact, the dynamic range of these films goes from 1 cGy (1 rad) to hundreds of Gy (dozens of krad). For higher doses, other films, such as HDV2 Gafchromic films, sensitive in this range can be used.

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