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Complex influence of space environment on materials and electronic devices in the conditions of microgravity

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Abstract

The paper presents a new physical model describing the processes in materials and electronic devices under the influence of cosmic rays in microgravity. The model identifies specific features of formation of the area of radiation defects (ARD) in the electronic materials in microgravity. The mechanism of interaction between the ARD and memory modules in microgravity causing malfunction and failure of onboard electronics is considered. The results of failure of memory modules under real conditions are presented.

Keywords: Radiation defects; Failures; Errors; Memory modules; Space factors

1. Introduction

It is known that during the operation of a spacecraft, a complex influence of space factors causes failures in automated systems leading to the reduction in their service life in the orbit, and, in some cases, to their failure. The failures of the on-board electronic equipment can be caused by different factors. Most authors explain the failures of the onboard equipment by solar flares. However, numerous on-board experiments showed that various failures of the on-board electronics were recorded in the absence of solar flares on days with no magnetic disturbance. For example, the emergency situations on “KazSat-1” and “Phobos-Grunt” were caused by the failures in the control system and operating conditions (Didenko and Usoltseva, 2009).

Space factors affect the onboard equipment differently. Such factors of space environment as magnetospheric plasma, solar electromagnetic radiation and space vacuum affect only the surface. They cause changes in surface properties of spacecraft materials. For example, under the influence of magnetospheric plasma, the solar wind, the optical properties (transmittance) of the solar cell (SC) coating change. Therefore, the main problem of solar cells in space is a decrease in their power.

Solar Cosmic Rays (SCR), Galactic Cosmic Rays (GCR), particles of the Earth’s radiation belts (ERB) and other particles are the penetrating factors of the outer space, which may affect errors and failures of the on-board electronic equipment. They penetrate the volume of the spacecraft and damage the on-board equipment. It should be noted that in real conditions the on-board electronic equipment is exposed to the action of cosmic rays in microgravity and changing geophysical and geomagnetic conditions in the space environment.

This paper presents an alternative approach to the explanation of the mechanism of errors and failures of onboard electronic equipment under real conditions and the effect of microgravity on the mechanism of failures.

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To justify such an approach the authors:

- Analyzed the models of interaction of high-energy heavy nuclei in materials and electronic structures used in space technologies;
- Studied radiation-induced defects in basic electronic materials caused by the passage of single high-energy heavy nuclei;
- Evaluated α-activity of basic electronic materials;
- Studied faults and failures of memory modules exposed to high-energy heavy ions in the simulated ground-based and real conditions.

Based on these data a physical model of the mechanism causing failure of memory modules in microgravity has been developed.

2. Models of interaction of single high-energy heavy nuclei in electronic structures

Various models describing passage of particles in the material of electronic components are used to explain the failures in on-board electronic equipment in simulated ground and real conditions. The list includes the following models:

- The model of elastic and inelastic interaction of alpha particles and neutrons with a CMOS – structure (Henry et al., 2004);
- The model of nuclear interaction of protons with energies $E = 125$, 158, 180 MeV in a thin layer of the NMOS-structure (Ngo et al., 1991);
- The model of formation of failures during the passage of protons in the test SRAM-structure (Schwank et al., 2006);
- The model of errors in CMOS 130 nm SRAM caused by alpha particles from Si (Martinie et al., 2010);
- Transport models taking into account physical phenomena (quantum effect, tunneling current) in the structures with the new architecture (Munteanu and Autran, 2007).

Each model uses its own instruments to describe the mechanism of failures in electronic structures. For example, to calculate the occurrence of single failures, the nuclear-physical model takes into account the formation of secondary particles (Pickel and Blandford, 1980; Rollins, 1990; Calvel et al., 1996; Oldfield and Underwood, 1996; Doucin et al., 1994).

Barashenkov (1993) showed that even at such low energy of protons as 10 MeV, the disintegration of the target nucleus gives alpha particles, neutrons, pions and fragments with charges of Z from 3 to 13, the number of which increases with increasing proton energy. The authors concluded that only alpha particles might cause single failures in SRAM.

Based on the model of nuclear mechanism of single effects in SRAM, Kuznetsov (Kuznetsov, 2005) developed a methodology of calculation of the cross section of single failures for protons with energies ranging from 10 MeV to 10 GeV and forecasted the frequency of failures in the SRAM of spacecraft onboard electronics.

To calculate the frequency of failures, scientists widely use computational models, mainly taking into account linear energy Transfer (LET) of heavy charged particles in sensitive volumes of the onboard equipment (Binder, 1998; Kuznetsov and Panasuk 2001).

The programs predicting the failure of memory modules on various space vehicles, based on AE8 and AP8 models were developed. To solve such problems it is necessary to carry out monitoring of doses absorbed on board of various satellites and to compare the calculated values of absorbed doses with the measured ones.

The software package COSRAD developed by Kuznetsov et al. (2011) enables scientists to calculate the dependence of the dose rate on the year of flight. A comparison of the failure rates in the XTE satellite registered in SRAM HM628128 with the calculated values showed that the absolute values of failure rates calculated using the COSRAD program gave a better agreement with the flight data than the results of the CREME96 model.

Some authors (Harboe-Sorensen et al., 1993; Calvel et al., 1994; Calvel et al., 1996; Doucin et al., 1996) also compared $\sigma_p(E)$ dependences for different types of RAM SBIS. It should be noted that SPENVIS program calculates the dose rate only for the minimum and maximum solar activity (SA). It means that there is no model that can fully describe the experimental data (Petit et al. 2006; Craig 2003; Sasada et al. 2006).

The discrepancy between the experimental data and the results of simulations can be explained by the following factors:

- All computational models are based on the LET data for different nuclei in terrestrial conditions;
- The dynamics of radiation and geophysical conditions as well as the presence of additional excitation at a given moment in the orbit point are not known;
- The models use simulated values for fluxes of various particles on an orbit averaged per day, which also gives averaged values of cross section and intensity of failures.

Long-term studies have shown that in the terrestrial conditions it is impossible to create test facilities simulating the complex influence of Space. Therefore, it is necessary to find such a criterion that would be connected with the result of influence of Space factors. As such a criterion, it is proposed to consider the radiation damage in materials and onboard electronics of the spacecraft.

3. Radiation defects in silicon irradiated by protons, α-particles and high-energy heavy ions

Recently, much attention has been paid to the failures of onboard electronic equipment caused by the influence of