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Temperature control system for the study of single event effects in integrated circuits using a cyclotron accelerator

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ABSTRACT

The temperature control system for the study of single event disruptions produced by hard ion impacts in integrated circuits is described. Heating and cooling of the irradiated device are achieved using thermoelectric modules (Peltier modules). The thermodynamic performance of the system is estimated. The technique for the numerical estimation of the main parameters of the temperature control system for cooling and heating is considered. The results of a test of the system in a vacuum cell of an accelerator are presented.

1. Introduction

The wide application of integrated circuits in space projects leads to the need for qualification tests of microelectronic devices for the estimation of their performance in the radiation environment of space. The topological sizes of the elements of modern integrated circuits are less than 100 nm. Therefore, hard ion impact is a critical issue that should be considered for the correct estimation of the reliability of integrated circuits during space missions [1–5]. Local radiation effects are the most dangerous because hard ions are able to generate a relatively large amount of charge as they pass through the constituents of the microcircuits. These hard ions are atomic nuclei of hard chemical elements, the energy of which is much greater than the energy of the protons and electrons in the radiation belts of the Earth. The active regions of semiconductor devices collect the charge generated by hard ions (Fig. 1). This process may lead to the unexpected switching of the device output and to failure of microelectronic equipment in the space environment.

Usually, hard ion failures of integrated circuits are related to the switching of single triggers or with memory damage in digital devices (single event upset, SEU). Other failure types include single event lutchup, single event burnout and single event gate rapture [1–5].

Qualification tests must be performed to understand how hard ions impact integrated circuits of different functionality types. The results of qualification tests could be used to improve the reliability of electronic devices for space applications.

To produce hard ions for use in qualification tests, particle accelerators are used. Usually, integrated circuits are irradiated using particle accelerators at room temperature, and the temperature of the integrated circuits tested is not controlled during experiment. To avoid the scattering of the accelerated particles by molecules of air, irradiation must be performed in vacuum. In this case, it is impossible to dissipate the heat of the irradiated device by convection to the ambient temperature. This lack of dissipation of heat can lead to uncontrolled self-heating of the microelectronic chip. Under real conditions, the temperature value of the microcircuit may be indeterminate because it depends on the variation of the ambient temperature or on the self-heating of the chip in active mode. There are two temperature dependent processes that are directly connected with single failure probability. The first process is charge generation by hard ions, and the second process is the collection of charge by the active regions of the irradiated device. To correctly perform qualification tests on hard ion impact, control of the temperature of the irradiated chip is required during the experiment. Temperature control enables one to obtain representative results of the test, which can be used by designers of electronic devices for space applications. The system for the remote control of the temperature of the integrated circuits irradiated in a vacuum cell of a particle accelerator is presented in this work.

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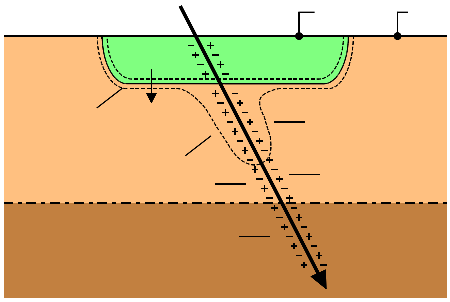

Fig. 1. Hard ion passing through a microelectronic structure [5].

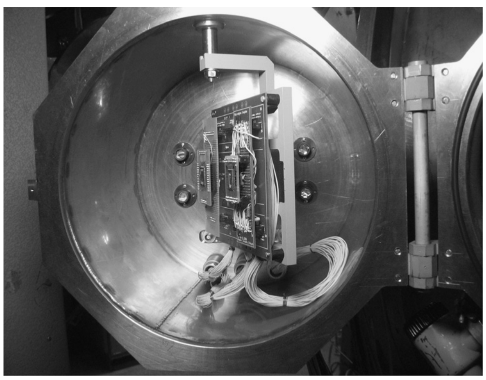

Fig. 2. Vacuum cell for mounting integrated circuits for irradiation by hard ions.

1.1. *Requirements for temperature control*

A vacuum cell for mounting integrated circuits for irradiation by hard ions is presented in Fig. 2. For irradiation, printed circuit boards with mounted microcircuits are placed on the frame, which is able to rotate. The ability to rotate is necessary for the investigation of radiation effects produced by hard ions in the microcircuits at different impact angles.

The temperature control system must satisfy the following requirements:

1. The system must provide temperature control and stabilization in the temperature range of 25–125 °C to accommodate the self-heating power of the testing object up to 1 W. A temperature stabilization accuracy of ± 1 °C is required. The transient process time of the temperature stabilization must be minimized.
2. The emission of gas from the materials of which the temperature control system is comprised must satisfy the vacuum requirements of the particle accelerator over the entire temperature range.

1.2. *Temperature stabilization technique*

The temperature stabilization technique is based on the balance of heating and heat removal from the vacuum cell through a heat-conducting path. The temperature difference between the ends of the heat-conducting path is determined by the thermal resistance of the path and by the power dissipation of the heater. This technique enables temperature control of the irradiated object by adjusting the power of the heater.

The schematic diagram of the temperature control system is presented in Fig. 3. The irradiated integrated circuit (1) and the heater (2) are in good thermal contact. Heat removal from the integrated circuit and the heater is performed via a flexible heat-sink (3). The thermoelectric module (Peltier module) (4) operates as a heat pump. The cold side (5) of the module is in thermal contact with the heat-sink. The hot side (6) is mounted on the radiator (7), which is located on the outside of the vacuum cell.

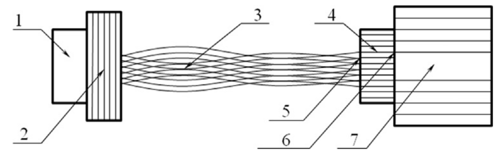

Fig. 3. Schematic diagram of the temperature control system.

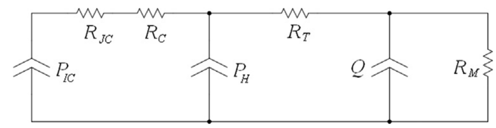

Fig. 4. Thermal circuit of the temperature control system: P_{IC} denotes the self-heating power of the integrated circuit, P_H denotes the thermal power of the heater, R_{JC} denotes junction to case thermal resistance of the microcircuit, R_C denotes the thermal resistance of the contact between the heater and the integrated circuit, Q denotes the cooling capacity of the thermoelectric cooler, and R_M denotes the thermal resistance of the thermoelectric module.

The thermal circuit of the temperature control system is presented in Fig. 4. The thermal power of the heater and the self-heating power of the integrated circuit are represented by thermal power sources P_{IC} and P_H, respectively, and R_T is the thermal resistance of the flexible heat-sink. The cooling capacity of the thermoelectric cooler is simulated by heat-sink Q. The thermal resistance of the thermoelectric module is R_M. The thermal resistance of the contact between the heater and case of the integrated circuit is R_C, and R_{JC} is junction to case thermal resistance, which enables estimating the temperature of microcircuit junction. In the following analysis, it is assumed that thermal contact of the heater with case of the microcircuit is good and $R_C \ll R_{JC}$. Numerical estimation of the thermal contact enables us to conclude that use of thermal compound and metalized via holes under the microcircuit enables obtaining value of R_C not more than 1 °C/W. It is significantly less, than typical values of junction to case thermal resistance R_{JC} of majority types of integrated circuits.

The temperature control system is designed to provide temperature stabilization of the heater within 25–125 °C range. If thermal resistance of the contact between case of the microcircuit and the heater is less than 1 °C/W and maximum value of self-heating power is 1 W the temperature difference between the case and the heater is less than 1 °C. It means that temperature values of the heater and the case are approximately equal. This assumption, thermal boundary conditions and the self-heating power of the integrated circuit are used as base data for estimation of the thermodynamic parameters of the temperature control system. Case temperature of the irradiated object and the radiator temperature are used as boundary conditions. Setting of the lowest case temperature value ($T_{Cmin}=25$ °C) at the maximum value ($P_{ICmax}=1$ W) of the self-heating power of the integrated circuit is the most complicated issue for practical implementation. Nevertheless, for investigation of temperature dependence of physical processes in semiconductor structures under heavy ion impact, it is necessary to control junction temperature of the microcircuit. If case temperature T_C is defined, the junction temperature T_J is determined by following expression:

$$T_J = T_C + P_{IC} R_{JC} \quad (1)$$

where P_{IC} is self-heating power of the microcircuit and R_{JC} is junction to case thermal resistance.