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Development of Contactless Method of the DUT Heating during Single-Event Effect Tests

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Abstract: This paper presents two approaches to perform the electronic device heating during radiation hardness assurance tests. Commonly used conductive heating approach is compared with contactless laser-based approach, characteristics and limitations of these methods are described. Experimental results for temperature dependence of single-event latchup (SEL) cross-section during heavy ion irradiation along with some aspects of physics-based numerical simulation of heat transfer processes are presented.

Key words: Single-event effect (SEE) tests, heavy ions, radiation hardness, heating methods, SEL.

1. Introduction

Single-event effects (SEEs) in electronic devices and systems are an important reliability issue for many space applications. One of the most critical effects is single-event latchup (SEL), which has been identified on a range of devices based on CMOS (complementary metal oxide semiconductor) technology [1-4]. SEL is a potentially catastrophic condition that can occur in *pnpn* structures where a low resistance path develops between power supply and ground on a device. The parasitic bipolar structure is triggered that leads to an increase in current to high values. If the power is not removed from the device, catastrophic failure may occur from excessive heating of silicon regions or metal interconnections.

According to the radiation hardness testing standards SEE tests should be performed at the temperature range including the maximum allowable operating temperature in order to achieve the highest sensitivity of the test samples to SEE. This requirement is particularly important for SEL effect testing because high temperatures lead to an increase in SEL sensitivity of the device [4-7].

The effects of temperature on the SEL cross section of the test structure are shown in Fig. 1 [4], as determined by the heavy ion tests performed by Kolasinski et al. [7].

An increase in temperature results in a decrease in SEL threshold and increase in cross section. Moreover, those sensitive parts, which did not latch at room temperature, could latch at elevated temperatures. There are experimental data for CMOS devices fabricated with low-resistivity epitaxial substrate indicating that they are more resistant to SEL than the bulk *n*-well structures [5].

These experiments show the importance of taking into account the temperature dependence of SEL effect in order to obtain relevant experimental data during radiation hardness tests. However, there are no standardized approaches to perform the electronic device heating for SEE tests. Usually the “conductive” heating approach is used, although it has some substantial drawbacks and restrictions. This method will be described in the next section along with an alternative method of heating based on the use of near infrared laser emission.

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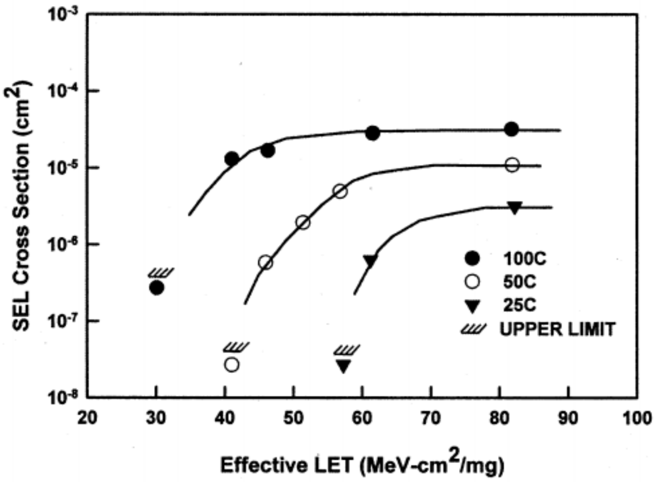

Fig. 1 Temperature dependence of SEL [4].

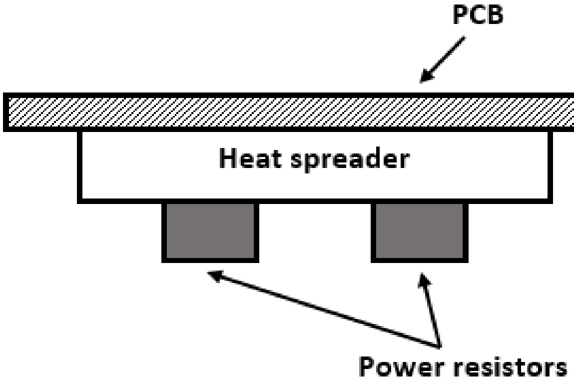

Fig. 2 Schematic of the conductive heating approach.

2. Conductive and Laser-Based Heating Approaches

The conductive (or resistive) heating approach is often used in radiation hardness testing when it is necessary to perform SEE tests of electronic components at elevated temperatures. The schematic of this approach is shown in Fig. 2. Several components with high heat dissipation capability such as power resistors and a copper heat spreader are contacted with a printed circuit board (PCB) near the place where the device under test (DUT) are mounted.

This approach has some substantial disadvantages. Firstly, since whole structure (PCB, socket, device package) is heated in order to achieve elevated temperature of a particular chip, it may cause undesirable loss of expensive working time of the testing facility. Secondly, the conductive heating approach is usually inefficient for electronic modules because it is impossible to place heating elements in close vicinity to the DUT. In addition, overheating of the PCB and other electronic components near the DUT is often detected for surface-mounted components with high thermal resistances due to inefficient heat transfer between device package and the PCB. Overheating leads to mechanical damage or even melting of the components, and disturbance of electrical testing regime can be observed.

Due to the fact that the conductive heating approach is not efficient, a new method based on the use of a near-infrared laser with emission wavelength of 1,200-1,300 nm was proposed in Ref. [8]. Fig. 3 shows the LFO-450 laser, which has been used in the experiments. The emission with such wavelength is not absorbed by semiconductors because the photons have energy below the band gap, which is not sufficient to excite electron from the valence band.

It is worth pointing out that the energy density of the laser emission is several orders of magnitude (10^5 to 10^6) lower than the energy density deposited during SEE tests. Thus, two-photon absorption is not observed and photon-induced currents have no effect on electrical characteristics of the DUT, which had been monitored permanently during the tests.

Since the devices are decapsulated for SEE tests with heavy ion irradiation, the laser emission affects directly on the die surface and the heat deposition is released in close vicinity to the active region of the device. As a result, the disadvantages of the conductive heating approach mentioned above do not exist in the proposed laser heating method. Elevated junction temperatures could be achieved without overheating of the surrounding elements. In addition, since the laser beam spot could be narrowed to expose only particular die it is possible to perform radiation hardness tests at elevated temperatures for the DUT being a part of an electronic module.

For the majority of the tested devices the time needed for heating by resistive method was the same as by the laser-based approach. However, laser emission is focused directly on the die surface that creates relatively small volume of high temperature in comparison with the volume of the whole PCB, which is heated when resistive approach is used.

It is interesting to compare velocities of the cooling process of the device after specified maximum temperature has been achieved in both approaches. Fig. 4 shows the results of temperature control for the

Fig. 3 Infrared laser LFO-450 for the heating procedure.

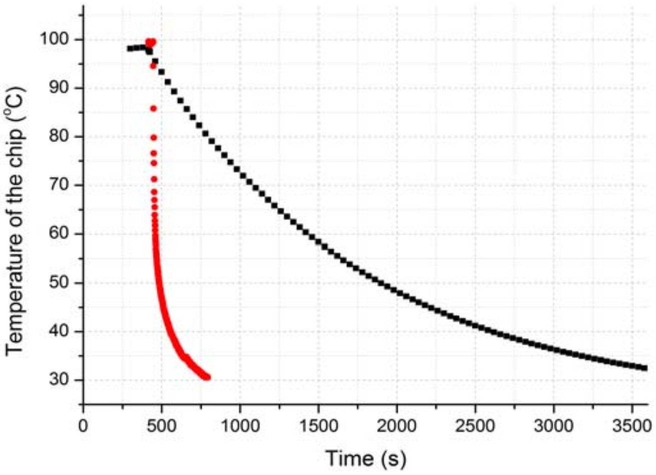

Fig. 4 Time dependence of the chip temperature after the heating procedure by resistive (black squares) and laser-based method (red circles) for the TMP04 device.

TMP04 device during the cooling phase in the vacuum chamber. Although absolute values may vary for other devices due to different thermal characteristics, the ratio of cooling time intervals remains the same for each device.

This experiment clearly shows that testing time increases substantially in case of using the resistive heating approach if the device should be tested under a wide range of conditions.

3. Experimental Results and Discussion

The laser-based heating approach has been successfully tested for the devices of different types. Time-dependent temperature characteristics of the TMP04 and the LM2901 devices obtained in a vacuum chamber and in air environment are presented in Ref. [8]. Infrared LFO-450 laser with power of 0.5 W was used in the experiments. It is possible to regulate power of the laser in order to reach specific temperature effectively.

The TMP04 is a monolithic temperature detector that generates a modulated serial digital output that varies in direct proportion to the temperature of the device. For this reason, the TMP04 device is suitable for testing of the heating approach. Data from the internal temperature-sensing element (drain-source diode of the output MOSFET) and the digital output of the device were compared after the heating test resulting in identical time-dependent temperature characteristics. Consequently, the laser emission has no impact on the device functionality. The same procedure has been performed for the LM2901 device.

After verification of the heating approach for different devices in the vacuum chamber and air environment, the laser-based method was implemented in hardness assurance tests for SEL effect at elevated temperatures. Test devices were placed on a special fixture in an evacuated chamber of the IS OEPP Test Facility designed and created by Branch of JSC URSC-ISDE with Russian Space Agency support on the FNRL JINR cyclotron U-400M basis.

The junction temperature of the DUT was controlled with high accuracy (± 1 ^{o}C) using a temperature-sensing element during radiation hardness tests. The protection diode can be used as a temperature-sensing element because it is implemented in most of medium and high-scale integrated circuits. Current-voltage characteristic of the diode is calibrated in the vacuum chamber first and then is used to define the junction temperature of the device during hardness assurance tests for SEL.

SEL was detected by measuring the power supply current transient. In order to prevent SEL, it is necessary to limit the current. The number of latchup events was measured with a counter and SEL cross section was calculated for all test samples at each temperature reference.

Experimental results for temperature dependence of SEL cross section of device A obtained during radiation hardness test with Xe ion irradiation are shown in Fig. 5. Elevated temperatures of the DUT were achieved using the laser-based heating approach. Table 1 shows the number of registered SEL effects for each temperature reference (junction temperature of the die).

These experimental results clearly show that SEL cross section strongly depends on the chip temperature. There is an increase in SEL sensitivity of the devices with increasing temperature.

The laser-based heating approach could be used in SEE tests in order to achieve elevated temperatures of the DUT, however this approach is not so efficient for multi-die devices in comparison with single-chip ones. In this case, a system of beam splitters, which divides an incoming laser beam into several distinct beams, is needed. This optical system must be redesigned for each testing procedure and should provide unobstructed path for the ion beam during SEE tests.

4. Physics-Based Simulation of Heat Transfer

In order to achieve better understanding of heat

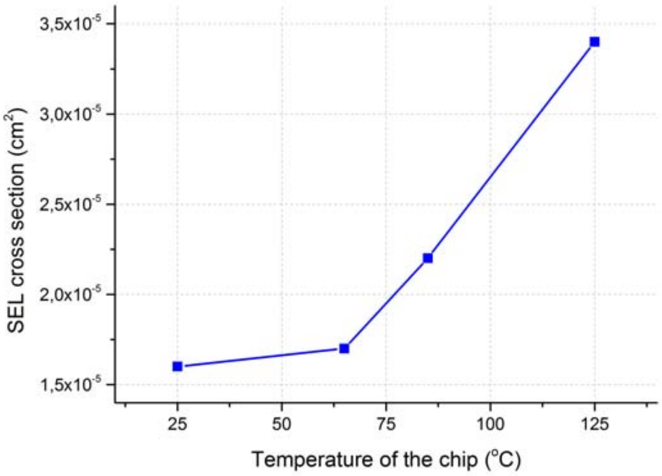

Fig. 5 Temperature dependence of SEL cross section of device A obtained during Xe ion irradiation with laser-based heating approach.

Table 1 Experimental results for SEL effect testing of device A at elevated temperatures achieved by the laser-based heating approach.

Sample #	Fluence (cm^{-2})	Junction temperature (°C)	Number of SEL
1	2.02E + 06	25	32
1	2.22E + 06	65	37
1	2.44E + 06	85	53
1	2.02E + 06	125	69

transfer in electronic components, numerical simulation of this process using the finite element method has been performed. It is a complex problem because the quality of thermal analysis strongly depends on the model inputs including all physical dimensions and key thermal properties of the materials.

The geometric model is based on real dimensions of the device obtained from the datasheet and from the inspection of the device surface after decapsulation. Temperature-dependent material properties (thermal conductivity, heat capacity and density) should be defined in the device model.

Heat transfer is characterized by conduction, convection and radiation. These mechanisms are included in heat transfer equation with all necessary boundary conditions. As a result, temperature distribution for each surface of the modeled device and surrounding objects is obtained. Numerical simulation for different devices in vacuum and air environment was performed earlier and resulting temperature characteristics are in good agreement with the experimental data [8]. These models have been used to clarify some details of the heat transfer processes and to predict a safe power range of the laser in order to exclude undesirable overheating of the components, which are placed in close vicinity to the DUT during SEE tests.

Physics-based simulation of heat transfer could also be used for calculating thermal resistances of the device in specific application. It is impossible to derive thermal resistances of the device from the datasheet and application notes because these documents do not include information about correct way of using thermal resistance data to perform thermal management for the device in specific application [9-11]. The manufacturer obtains thermal resistances in the standard test environment that usually differ from real application of the device. Physics-based simulation of the heat transfer processes provides all necessary information for calculating these thermal resistances.

5. Conclusions

Based on the performed experiments and simulations, we might conclude that the laser-based heating approach is applicable for the majority of tested devices if metallization layers do not completely cover the die surface. Heating of the DUT up to 125 °C (or cooling down to the room temperature) may last from 4 to 8 minutes for different devices in the vacuum chamber during SEE tests. It depends on the ability of the device to evacuate heat from the die, i.e., from the thermal properties of the device.

The laser-based heating approach could be used in SEE testing even if the device is a part of an electronic module. The laser emission affects directly on the die surface and the heat deposition is released in close vicinity to the active region of the device without overheating of the surrounding components on the PCB.

Cooling process of the devices in the laser-based approach takes far less time than cooling in the resistive heating approach. This is particularly important for SEE tests performed under a wide range of conditions, because the time needed for the device cooling should be minimized in order to prevent undesirable loss of expensive working time of the testing facility.

Simulation of the heat transfer processes may complement the radiation hardness assurance and reliability tests in terms of clarifying the heat transfer details (stationary and time dependent) of the tested devices in the vacuum or air environment.

It is also important to note that the laser infrared emission has low energy density. As a result, no impact on the device functionality has been registered in our experiments.

The laser-based heating approach could be used to achieve elevated temperature of the device during radiation hardness assurance tests with heavy ion irradiation and during laser testing.

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