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Proton and Heavy Ion induced SELs in the Xilinx XC95108 CPLD

T. J. Wijnands, S. Dubettier-Grenier, Q. King, B. Todd, F-X Guerre

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***Index Terms*—Radiation Effects, Single Event Latch up, Xilinx XC95108PQ100, Heavy Ions, protons, High Energy Physics**

I. Introduction

The Xilinx9500 series are in-programmable devices for general purpose logic integration based on 0.35 micron Advanced CMOS 5V FastFLASH™ technology [1]. The device was first put into production in 1998 and commercialization will probably be stopped by the end of the year 2010. A very large number of these devices (order of 10^4) are presently in use in radiation environments for controls applications at the CERN laboratories.

First irradiations of the device were performed in 2003 using 60 MeV protons at the LIF facility at Louvain la Neuve [2]. The study was mainly focused on studying the soft error rate and to verify the use of the standard soft error correction codes such as EDAC and TMR. The irradiations were performed in air, using nominal incidence while the device operated at a temperature of 50 degrees. No SELs or Single Event Functional Interrupts (SEFI) were observed in these experimental conditions for a total of 3 devices irradiated. The total ionizing dose limit, characterized by the onset of an exponential increase in the current consumption, was found to be at 120 Gy. Based on these results, the part was accepted for use in the CERN accelerator complex.

In 2007, the part was exposed to High Energy Physics (HEP) particle radiation from one of the CERN accelerators. The maximum proton and neutron energy in this radiation field is in the GeV range. The device was exposed in application specific conditions, i.e. mounted on a board which was inserted in a front end computer located in a standard air cooled 19” control rack. The front end computer was operating in line with the technical design specifications and the part was operating a a temperature of approximately 80°C.

Permanent destruction of the XC95108 part occurred in the early stage of the test and post mortem analysis of the bare die revealed electrical overstress in the device. SEL was immediately suspected but could not be confirmed because the experimental data was incomplete. To make this issue more precise, extensive heavy ions and high energy proton irradiation tests were carried out with at the PROSCAN facility (230 MeV protons) at the Paul Scherrer Institute [3], the RADEF Heavy Ion facility at Jyvaskyla [4] and the HIF facility at UCL [5].

II. Post Mortem Analysis of the XC95108

Figure 1 shows a picture of the silicon die of the permanently damaged XC95108 device that was irradiated in a HEP radiation environment at CERN.

In the first damage zone, fracturing and lifting of the silicon occurred close to the interconnect with the current lead. In the second damage zone, thermal damage and partial melting of the metal layers is visible. As the damage in zone no.2 is circular in shape, it could be related to localized area with a very high current density. In literature [6], melting and open circuit failure has been predicted at current densities of $5x10^7 A/cm^2$ for durations as short as 200 ns. Such values would thus easily be exceeded when a SEL event would cause a current rise of 1.6 A in an interconnect with a cross section of $10\mu m^2$ (see also figure 4).

It cannot be excluded that other damaged areas exists on the die but with simple optical microscopy other damaged areas could not be detected. At the time of the analysis, the authors did not have access to Scanning Electron Microscopy, a tool indispensible to find, for example, latent damage in a complex device structure such as that used in the XC95108 CMOS.

Nevertheless, the post mortem analysis raised a couple of important questions: did the damage in two locations occurred

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at the same time, was the damage caused by a single and unique event or was it due to a series of events (latent damage) and, finally, is the device still functional when it is in a latched state ? In the remainder of this paper, some of these issues will be addressed.

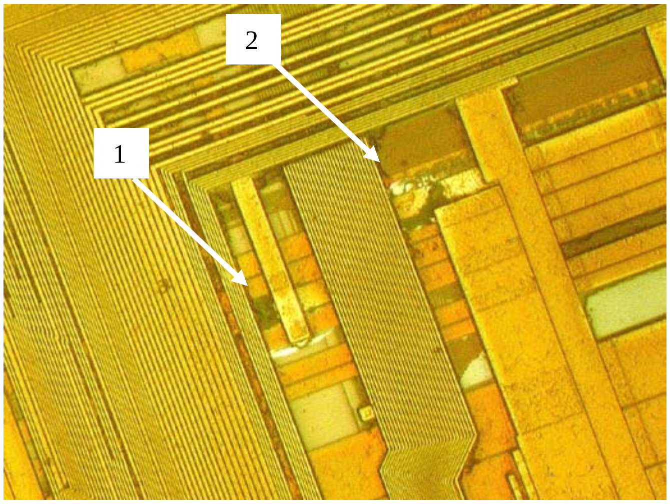

Fig. 1 : The silicon die of the permanently destroyed XC95108 showing two damaged zones : significant voiding of the silicon close to the interconnect metal (1) and thermal damage of the silicon (2).

III. Experimental

A. Test set up

The test setup is based on a standard Virtex5 FPGA developments board with 168 I/Os which can be configured using several I/O standards. SEL detection is performed via voltage and current monitoring of a maximum of 16 channels. On line data is stored in on-boards DDR2 memory and then up or down loaded via a100 Mbit/s Ethernet link between the front end computer and the test boards. The Ethernet connection also allows for fast up and down loading of the configuration data.

The DUTs are commercially available parts in a plastic packaging (table I). For HI testing, the plastic package was removed mechanically.

TABLE I
Devices Under Test

Part Reference	XC95108PQ100	
Manufacturer	Xilinx	
Package	PQFP-100	
Package marking:	PQ100AMM0937	F4009718A 20C
Die marking	Xilinx 1998	X5150 8A
Die dimensions	4.75x5.70 mm	

The radiation tests in a HEP radiation field did not use the specific test board but were conducted in the application specific configuration, i.e. the part was mounted on a PCB, inserted in the controls crate and operating under nominal operating conditions using the standard application program for the CPLD.

B. Test procedures

The test configurations that were used in this work are both based on a register chain (shift register) of 36 Flip Flops either with or without inverter stage registers inserted before each flip flop. To detect Single Event Upset (SEUs) and Single Event Functional Interrupts (SEFIs), the shift register was filled with a test pattern (checkerboards, all 1 or all 0). Comparison of the output pattern to the input pattern at each clock cycle can indicate an SEU (in the case of a single mismatch) or a SEFI (in the case of a continuous error stream).

If a continuous error stream would be observed, a global set/reset would be initiated first trying to recover the correct operation of the device. If successful, a SEFI (type 1) would be counted and the test would continue. If the continuous error stream would persist, a global power reset would be initiated and a SEFI (type 2) would be counted.

For SEL characterization, the device current consumption was continuously monitored. When the current would increase above a preset limit, a latch up was recorded and the power supply voltage was removed. To minimize the influence of total dose, displacement damage and latent effects on the latch up cross section measurements, the maximum current in a latched up state was set to 350 mA. This allowed detecting multiple latch ups (up to 47) in a single device. Almost all devices would eventually stop operating correctly after a certain amount of SEL events.

For the testing of the parts in the HEP radiation field, only the correct functionality of entire control system was monitored. This means that failure (or partial failure) of a single device would not be detected when the entire system is still fully functional.

C. Radiation Facilities

Heavy Ions irradiations were performed at the UCL HIF facility in Belgium and the RADEF facility at Jyvaskyla Finland. The devices were placed in vacuum tank and aligned with a laser. Mounted on the DUT table, the position of the devices can be adjusted in the X,Y and Z directions and the devices can be rotated in the direction of the Y-axis.

TABLE II
Heavy IonS used at the UCL Facility

Ion	**LET [MeV.cm²/mg]**	**Range (Si) [µm]**
40 Ar 8+	14.1	42
20 Ne 4+	5.85	45
15 N 3+	2.97	64
84 Kr 17+	34	43
132 Xe 26+	55.9	43

Table II and III are summarizing on the ions that were used at the UCL facility and the RADEF facility. Note that the high LET ions at the RADEF facility have approximately twice the range of the high LET ions at the UCL facility (43 micron for a 84 Kr 17+ ion at an LET of 34 MeV.cm^2/mg.

TABLE III
HEAVY IONS USED AT THE RADEF FACILITY

Ion	LET [MeV.cm²/mg]	Range (Si) [µm]
15 N+4	1.83	202
20 Ne+6	3.63	146
40 Ar+12	10.2	118
56 Fe+15	18.5	97
82 Kr+22	30.2	94

Proton Irradiations were performed at the GANTRY high energy proton facility at PSI. The proton energy used was 230 MeV at a flux of 1-2x10^8 protons /cm^2/s.

Exposure to a complex particle radiation from High Energy Physics took place at CERN in the CNGS neutrino facility [7] named CNRAD. The hadronic flux in this radiation field is dominated by neutrons with energies ranging from thermal to several GeVs. Equipment can be exposed in the stay radiation of a primary proton beam at 450 GeV on a fixed target.

IV. MEASUREMENTS OF LATCH UP CROSS SECTIONS

A. *Heavy Ion induced latch ups*

Figure 1 shows the HI induced latch up cross section as a function of LET for the ions used in the RADEF facility for 2 different temperatures of the device.

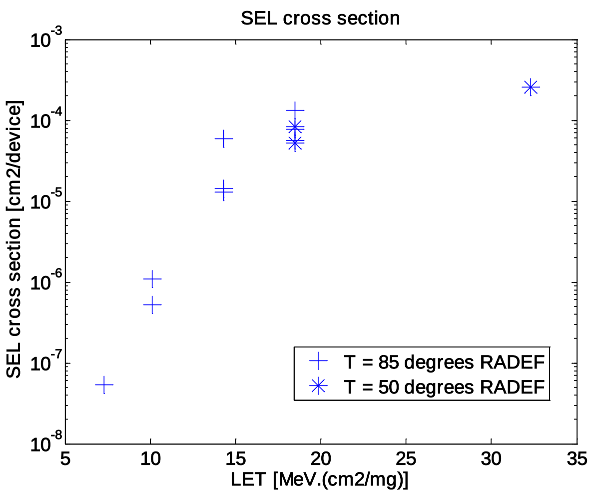

Fig. 1 : Heavy Ion induced SEL cross section of the XC95108 CPLD device using high penetration ions at the RADEF facility.

As expected, the onset threshold for SEL is lower at higher temperatures and can be as low as 7.3 MeV.cm2/mg for a device operating at 85 degrees. When the UCL HI data is superimposed (figure 2), the variation in the threshold LET for latch up with temperature is even more striking.

For high values of the LET, the temperature dependence of the saturated SEL cross-section is less pronounced and the ratio between the saturated SEL cross section at 85 degrees and the saturated SEL cross section at 50 degrees is 1.7. Note that at high values of the LET, the cross section measured at the RADEF facility at a temperature of 50°C and a LET of 32MeV/(mg/cm2) is higher than the cross section measured at the UCL facility measured at 50°C or 85°C and an LET of 34 MeV/(mg/cm2). This may seem contra dictionary at first sight. However, for heavy ion irradiation, the ion energy should be high enough such that the ion penetrates easily to a depth much deeper than the sensitive volume. A possible explanation may therefore be found in the fact that the ion penetration at UCL is approximately 2 times smaller the ion penetration at RADEF.

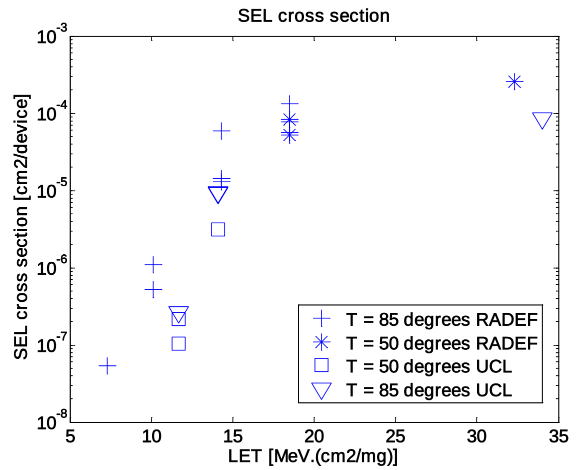

Fig. 2 : Heavy Ion induced SEL cross section of the XC95108 CPLD device comparing high penetration ions from the RADEF facility and low penetration ions from the UCL facility.

Only very few SEFIs of type 1 (recoverable via a global set/reset) and very few SEUs were observed in the two Heavy Ion campaigns. However, SEFIs of type II (requiring a power cycle of the device for it to regain normal functionality) occurred rather frequently (figure 3). The onset of the SEFI type II was equally found to be as low as 7.2 MeV.cm2/mg for a device operating at 85°C.

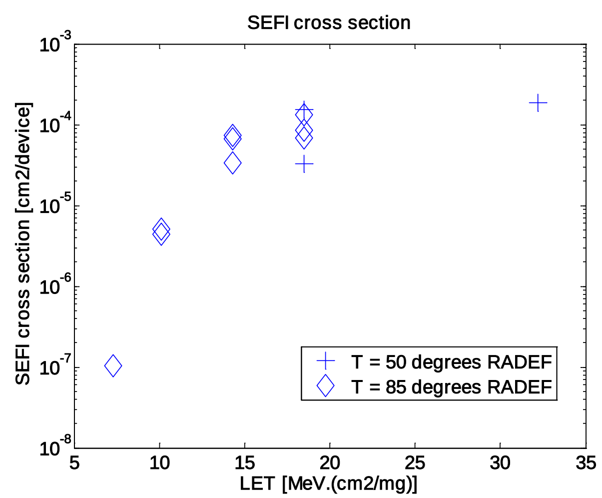

Fig. 3. Heavy Ion induced SEFI (type 2) cross section the XC95108 CPLD device as a function of LET.

The current consumption after the occurrence of a SEFI type II in the device and the subsequent loss of functionality of the DUT was investigated in more detail. Hereto the SEU detection mechanism was disabled and the beam switched of immediately after the onset of the SEFI type II. The core supply current showed a stepwise increase from 140 mA to 160 mA with a step size of 8 to 12 mA over a period of 200 seconds. After a power set/reset, the device regained its normal functionality.

Both the SEFI and the SEL cross sections show saturation at high LETs at values around 1x10^{-4} cm^2 per device.

B. *Other failures induced by Heavy Ions*

After heavy ion irradiation, some functional configured devices failed to be reprogrammed with a different configuration but then also failed to be reprogrammed to the previous configuration. One possible explanation is that the internal DUT Erasing/writing process was damaged by repeated HI strikes (JTAG failure). This phenomenon was equally observed during low energy proton testing at 60 MeV after a accumulating a total dose of approximately 100 Gy.

TABLE IV
PROTON CROSS SECTIONS

Single Event Effect	**Proton Energy [MeV]**	**Device Cross section [cm^2]**
SEU	230	3.33E-12
SEFI type II	230	2.48E-11
SEL	230	3.29E-12

C. *Proton induced latch ups*

With a SEL threshold LET of only 7.2 MeV cm^2/mg this part is likely to latch up in proton and neutron radiation environments. This was indeed observed during proton irradiation at 230 MeV at nominal incidence although at a less frequently than what was to be expected on the basis of the Heavy Ion data. On the average, a single SEL event and 7 SEFIs were recorded per device before the total ionizing dose limit was reached. A total of 8 devices were irradiated in the proton campaign and the cross sections for SEFI, SEUs and SELs are given in table IV.

The proton induced latch up signature is shown in figure 4. In this test run, the maximum current in the device was not limited but the duration of the latched up state was set to 1 minute. After power cycling the device, it regained full functionality.

The stepwise increase in the core current consumption after the occurrence of a SEFI type II was equally investigated (figure 5). In this example, the SEFI and SEU error detection was removed and only the SEL protection was kept operational. The current limitation for SEL was set to 500 mA.

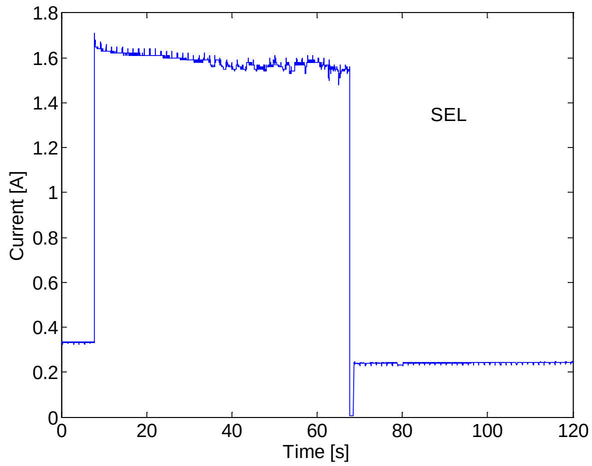

Fig. 4 : Proton induced latch up signature of the XC95108 device. The core current consumption of the device is maintained at 1.6 A for a duration of 1 minute. After a power cycle the device regains functionality.

During irradiation, the core current consumption is increasing in a stepwise manner, equally to what was observed during HI irradiation. This increase is due to the occurrence of a SEFI type II which is not detected or processed since the error detection is switched off. When the current consumption is reaching 500 mA after the second step, the SEL detection mechanism is triggered and the maximum current is maintained for the duration of 1 minute. After a power cycle the device regains normal functionality.

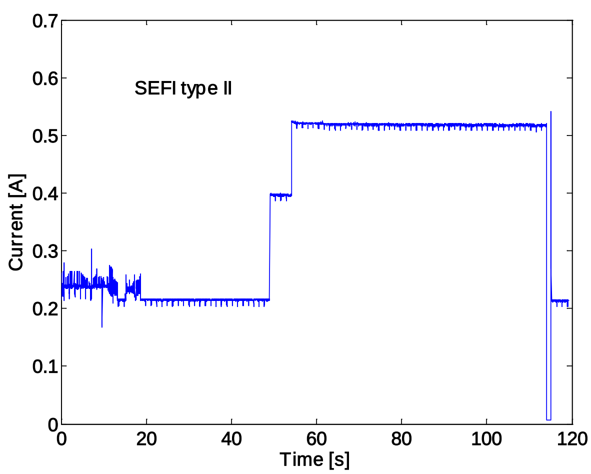

Fig. 5 : Evolution of the core current consumption of the XC95108 device after the occurrence of SEFI type II while the error detection mechanism is disabled. After the second stepwise current increase, the SEL protection mechanism is triggered and the core current is maintained at 500 mA for the duration of 1 minute.

Based on these radiation data, we suspected that all induced SELs would be potentially destructive, provided the current consumption increase was sufficiently high and provided the device was maintained in a latched state for a sufficiently long period of time. This appeared to be not the case. When the SEL protection was removed, permanent destruction of the device in a single instant could not be produced with either proton or HI irradiation. In the most extreme case, a SEL event caused induced by a HI strike caused a current of 1.8 A to flow through the device. After the duration of 1 minute the device was power cycled and regained its normal functionality. However, with HI beams, every device could only be latched a limited number of times before permanent destruction the device occurred.

V. Observations on related parts

A. *Xilinx XC95144 and XC95288XL*

Two different parts of the same family as the XC95108 CPLD were exposed at CERN radiation facility named CNRAD [7]. Both the Xilinx XC95144 and XC95288XL devices are used on a very large scale in the CERN accelerator complex in areas with prompt radiation. The characteristics of these devices are similar to the XC95108 and summarized in table VI. Note that the XC95288XL part is operated at 3.3 V while the XC95144 part is operated at 5.0 V.

TABLE VI
Devices Under Test

Part Reference	XC95288XL	
Manufacturer	Xilinx	
Package	TQ-144	
Package marking:	TQG144AWN0905	03631628A 6C
Die marking	Xilinx 1997	-
Die dimensions	4.75x5.70 mm	
Supply voltage	3.3 V	

Part Reference	XC95144	
Manufacturer	Xilinx	
Package	PQFP-100	
Package marking:	PQG1604MM0905	F3632631A 15C
Die marking	Xilinx 1997	-
Die dimensions	4.75x5.70 mm	
Supply voltage	5.0 V	

The XC95288XL part has 4 metal layers and 0.35 μm feature size. The XC95144 part is a 3-layer CMOS device with a 0.5 μm feature size.

B. *Experimental setup*

A total of 64 devices (34 of each type) were simultaneously irradiated in the CNRAD facility where the radiation spectrum and particle types are similar to those close to the CERN accelerators but where the dose rate and particle flux is approximately 50 times higher (20-30 Gy/week, depending on the operational efficiency of the driving accelerator).

The devices were mounted on PCB and inserted in an electronic test bed shown in figure 6. The rack has 2 x 4 boards with 8 CPLDs each. The test bed is powered by a current source of 30 A to anticipate increase of the current consumption due to single events or increase of current consumption due to total dose damage.

Fig. 6: Experimental test setup for the 2x32 CPLD devices from Xilinx. The DUTs are the XC95144 operating at 5.0 V and the XC95288XL operating at a bias voltage of 3.3. V.

The 32 XC5144 devices are programmed to compare any changes of inputs to changes of the outputs with a 96-channel I/O board. The address lines (inputs) are changed every 300 seconds and a log file is written in case of inconsistency in the outputs of the CPLD (XNORs). Power cycling of all boards is used if one of the devices does not respond anymore. In all other cases, the test continues. In case of a SEL, the XC5144 device would be maintained in a latched state for a maximum of 5 minutes.

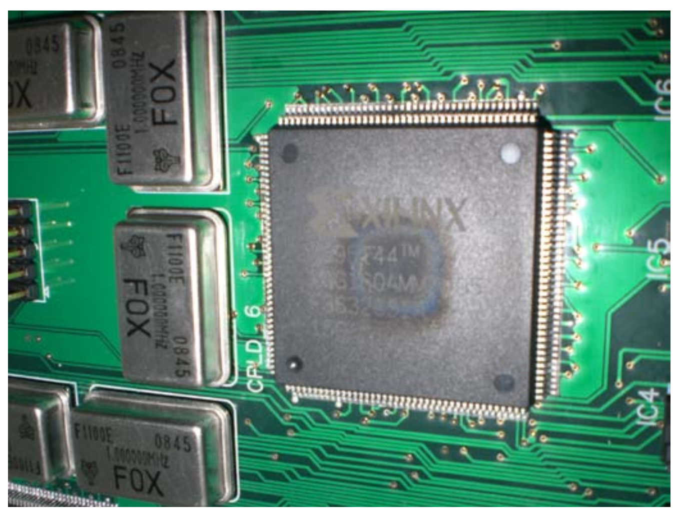

Fig. 7 : Damage from electrical overstress visible on the Xilinx XC95144 device after exposure in a radiation field from HEP.

The 32 XC95288XL devices are programmed in a similar fashion, using a 96 channel digital I/O board and scanning all 32 devices for errors in the outputs at a rate of 2 Hz. If one of the devices would not respond, first a soft reset would be initiated followed by a hard reset (power cycling) in case the soft reset would not have restored the full functionality of the device. The maximum time at which the XC95288XL devices would be maintained in a latched state is 0.5 seconds.

During the test that continued over a period of several weeks, many radiation induced soft errors were detected on both types of devices. The XC95288XL devices all continued to operate until their total dose limit was attained using an occasional hard reset to regain full functionality of the device.

A few of the XC95144 devices however, stopped operating before their total dose limit and these devices were then disabled from the test and the test was continued. Post mortem analysis showed visible damage due to overheating in at least 9 out of the 32 devices that were exposed. Figure 7 shows an example of one of the devices that stopped operating before reaching the total dose limit. The damage from excessive heating of the die is clearly visible.

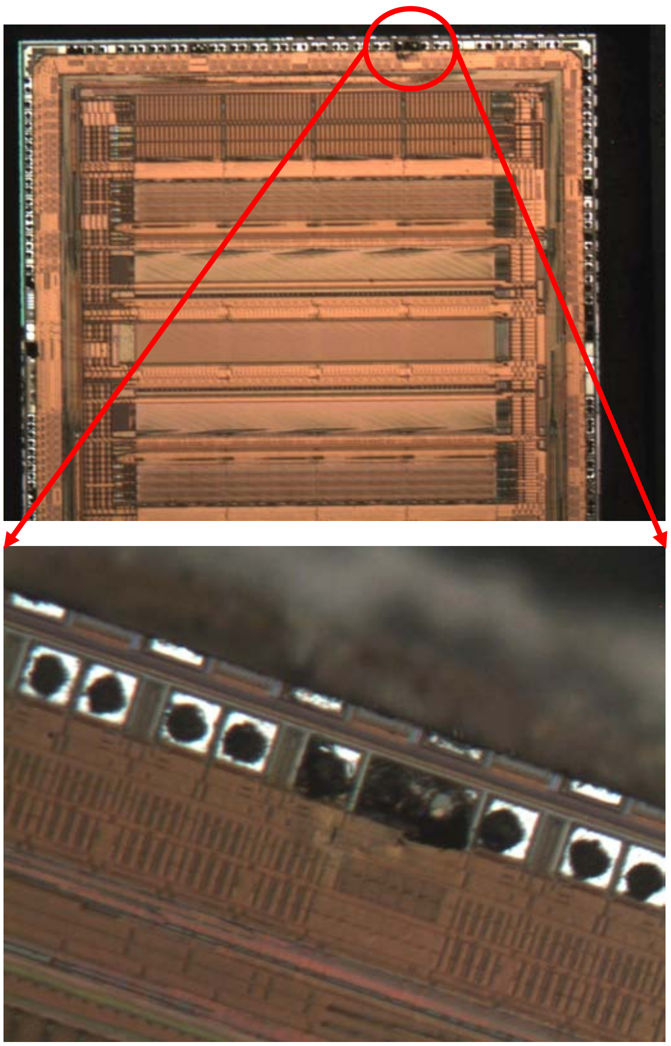

Fig. 8. Damage from electrical overstress visible on the Xilinx XC95144 silicon die at the location of one of the interconnect to ground. Note the change of the color on the silicon die in the vicinity of the connection.

Figure 8 shows pictures of the silicon die of the same device as shown in figure 7 after removing the plastic packaging with an acid and cleaning the die of packaging residuals with alcohol. The encircled area in the top figure shows the location of the damage area on the die which occurred at a interconnect to ground. The figure below is a magnification of the area damaged by overheating and electrical stress. A physical explanation could be overheating of the interconnect in case the current density is maintained above a critical level and for a sufficiently long period of time. The differences in thermal expansion coefficients of metal and insulator would then create mechanical stress. If the heating is sufficient to melt the device, the event could be catastrophic.

VI. Discussion

From the data presented here it is concluded that *a single* SEL event in these parts is rarely sufficient to destroy the device permanently. The only exception to this observation could be when the device is latched by a radiation event and kept in the latched state at a sufficiently high current consumption (between 1.5 A and 2 A) and for a sufficiently long period of time (between 1 and 5 minutes).

A more likely explanation for the catastrophic failure discussed in the introduction is latent damage that is created after each latch up event. With latent effects, devices can remain functional despite structural damage from a single radiation event.

It remains difficult to put an upper limit on the number of times these devices can be latched and fully recovered with a power cycle. The current consumption increase during a SEL will depend on the charge deposited by the radiation event and the exact location of the charge deposition in the device. In HEP environments, a large variety of particles at a wide range of energies is present which makes it difficult to estimate the maximum charge that can be deposited in the critical area. Furthermore, a systematic study of the failure rate as a function of the macroscopic parameters (number of latches, current consumption increase and latch up duration for each latch) is unlikely to give an exact answer because failure may be determined by quantity of microscopic damage from previous latches. Microscopic damage can be the reduction of an interconnect cross section or the quantity of released matter due to the induced stress. SEL circumvention for these parts may therefore be difficult to implement successfully.

VII. Summary

The XC9108 in system programmable CPLD from Xilinx is sensitive to Single Event Latch up in proton environments. With low energy protons at 60 MeV no latch ups were observed while for protons at 250 MeV the latch up cross section is $3.3\mathrm{x}10^{-12}$ cm^2 per device. At high protons energies, the probability of a functional interrupt (SEFI) is approximately ten times higher as compared to the probability of an SEL. When the device is in SEFI state, the current consumption is increasing stepwise and the device is producing a continuous stream of errors. Power cycling is needed to regain the correct functionality. For the system engineer, there is no difference between the SEFI and the SEL state since both lead to a continuous error stream and require a power cycle to regain full functionality. The combined device failure cross section for SEFI (type II) and SEL is $3.5\mathrm{x}10^{-12}$ cm^2 per device.

Single destructive latch up events were observed in a HEP environment but could not be produced in a virgin XC9108 part with heavy ion or proton beams. On the contrary, more than 100 SEL events per device could be observed during irradiation with heavy ions provided the SELs were detected in a very early stage and then terminated by cutting the power.

Radiation test on related parts of the same CPLD family (the Xilinx XC95144 and the XC95288XL) revealed that thermal damage following a single SEFI or a SEL event can occur if the devices are maintained in a faulty state for a sufficiently long time.

Based on the data present here, the permanent destruction of the XC95108 part that occurred in the early stage of an application oriented radiation test in a HEP radiation field (see introduction) is therefore attributed to a SEL event. It is unlikely that a single SEL event destroyed the device instantaneously. However, the persistent and abnormal high current consumption was maintained for a sufficiently long period of time and this eventually caused catastrophic electrical overstress and heat damage.

To date, there is no data on the current densities and event durations involved for nondestructive SELs which is why SEL circumvention for these parts may be difficult to implement successfully on a short timescale. Other options that could be considered to significantly reduce the SEL probability are lowering of the bias voltage or the use of displacement damage to degrade the minority carrier lifetime in the region of chips responsible for latch up [9].

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