Heavy Ion and Proton SEL Characterization on Selected EEE Component Types Used in ISS Equipment

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***Abstract*—We present data on the vulnerability to proton and heavy ion induced single event latchup of a variety of candidate components for ISS equipment.**

I. INTRODUCTION

Single Event Latch-up (SEL) testing has been performed on selected component types used in equipments and experiments for the International Space Station (ISS). In particular the component types had their application in the Protein Crystallization Diagnostics Facility (PCDF) and the Materials Science Laboratory (MSL).

Both projects had a minimum SEL LET threshold requirement of 36 MeV cm²/mg.

The major test goals were to perform SEL testing on device types for which there where no existing data using either the actual ISS application conditions or worst-case bias. Testing was foreseen on two components of each selected part type up to at least twice the SEL requirements, i.e. 72 MeV cm²/mg.

A total of 38 different part types, mostly of COTS quality, were subjected to SEL testing using the ESA Heavy Ion Facility at UCL. 13 part types failed the relatively low project SEL requirement of which 9 types showed very sensitive results, i.e. thresholds of 14.1 MeVcm²/mg or below.

In collaboration with and under contract to ESA proton SEL testing was performed on the same 13 part types which failed the project heavy ion SEL test requirement. In order to have a basis for direct comparison between heavy ion and proton results the parts were proton irradiated at PSI using the same components, test set-up and test equipment.

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II. TEST TECHNIQUES AND SETUP

A. Test Facilities

The test facility used for heavy ion testing was the ESA Heavy Ion Test Facility at UCL in Belgium. This uses the CYCLONE accelerator which is a multiparticle, variable energy, cyclotron capable of accelerating protons (up to 85 MeV), alpha particles and heavy ions. For the heavy ions the energy range covered is between 0.6 MeV/AMU and 27.5 MeV/AMU with a maximum energy of 110 Q^2/M, where Q is the ion charge state and M is the mass in Atomic Mass Units. The heavy ions are produced in a single stage (6.4 GHz) Electron Cyclotron Resonance (ECR) source and an analysing magnet is then used to select the desired M/Q ratio before the ions are injected axially for subsequent acceleration. The use of an ECR source allows the production of highly charged ions and of ion "cocktails", composed of ions with the same or similar M/Q ratios, which are accelerated together but extracted separately by fine tuning the magnetic field or slightly changing the RF frequency.

For each of the ions the effective LET could be increased from the LET value given in the table I by tilting the test sample so that the ion beam was no longer normal (perpendicular) to the die surface.

The sample chamber has the general shape of a cylinder lying on its side and stretched vertically, with internal dimensions of 71 cm high, 54 cm wide and 76 cm deep. The opening end of the cylinder can be moved 1 m away from the cylinder on a rail system for sample installation. It also supports an internal frame holding the test samples and contains connectors for electrical connections. During operation the complete chamber can pump down to operating vacuum in less than ten minutes.

To set up, control and monitor the beam flux and homogeneity a box in front of the chamber contains a Faraday cup, four scintillators and two parallel plate avalanche counters (PPAC). Two additional surface barrier detectors are placed in the test chamber.

TABLE I
ION COCKTAIL USED FOR TESTING

M/Q	Ion	DUT energy (MeV)	Range (µm Si)	LET (MeV cm²/mg)
5.07	$^{132}Xe^{26+}$	459	43	55.9
4.94	$^{84}Kr^{17+}$	316	43	34
5	$^{40}Ar^{8+}$	150	42	14.1
	$^{20}Ne^{4+}$	78	45	5.85

Proton SEE tests were performed at the proton irradiation facility (PIF) at Paul Scherrer Insitut (PSI) Villingen in Switzerland.

The maximum available proton energy at PSI was 250 MeV which became the starting energy for testing. The device under test (DUT) was irradiated to a fluence of $2 \cdot 10^{10}$ p/cm^2/energy with fluxes of the order of $5 \cdot 10^7$ p/cm^2/sec. All proton tests were conducted in air. For more information about the PIF see also [1].

B. *Test Setup and Test Procedure*

1) *Preparation of Components*

All of the component samples were subjected to some basic parametric measurements to check that they were functional. One component of each type was retained as a control and two components were opened using appropriate mechanical or chemical techniques to expose the die surface. After they were opened the components were again subjected to the basic parametric measurements to determine if there were any significant changes which might indicate that they had been damaged by opening. This testing was repeated before every SEL testing with heavy ions and protons. The test samples were from the same component lots as used in the actual flight equipment.

2) *Test Sockets and Circuit Board Layout*

The heavy ion test chamber is able to take a printed circuit board up to 250 x 250 mm, of which an area of 250 x 120 mm can be scanned by the heavy ion beam. Although the remaining board area cannot be irradiated, and therefore is unusable for mounting test components, it can be used for any connectors or components needed for the biasing and monitoring of the test components.

For testing the components in the vacuum chamber a “piggy-back” configuration was used with one mother board and separate daughter boards for each component type to be tested. The mother board had four identical socket pairs into which four individual daughter boards could be plugged. The daughter boards contained the components to be irradiated and also any wire links, resistors or capacitors necessary for the correct biasing and monitoring of the test samples (see figure 1).

The same test hardware configuration was used for the proton irradiation in air.

3) *Biasing and Monitoring Circuit*

The basic biasing and monitoring circuit was located in a box outside the vacuum chamber and had been designed to fulfill the following main functions:

- To supply to the piggy-backed daughter boards the necessary positive, negative and ground voltages for biasing the components under test.
- To monitor the currents flowing in the positive and negative supply lines.
- To allow preset limits to be set for the supply currents using controls on the monitor box.
- To remove the bias voltages from the components under test if the monitored currents exceeded the preset limits. The voltage was removed within 10 µs.
- To indicate using LEDs outside the chamber when the preset negative and/or positive current limits had been exceeded.
- To allow the circuit to be reset from outside the vacuum chamber thereby re-applying biasing to the components under test.

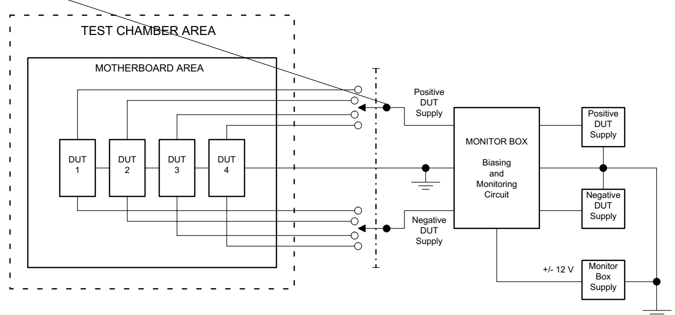

Fig. 1. General test schematic

Figure 2 gives an overview of the monitoring and biasing circuit and of the mounted daughter boards on the mother board.

It should be noted that the circuit could be switched between the different test components which were in the chamber at the same time and was used to bias and monitor only the one component which was being irradiated. Therefore if a latch-up occurred it was obvious which component had failed as only one component was being biased, irradiated and monitored at any one time. As the circuit was designed to remove the biasing before any permanent damage could occur it was possible to re-apply the bias as soon as the component which latched-up was no longer being irradiated.

The circuitry on the daughter boards was intended only to direct the bias voltages to the correct pins on the device under test and to provide any necessary load resistors or capacitors.

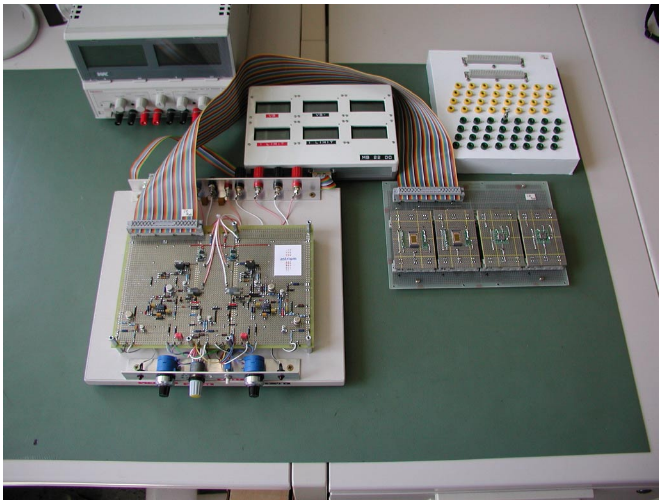

Fig. 1. Monitoring and biasing circuit with daughter test boards mounted on the mother board.

4) Irradiation Procedures

Each sample was subjected to a number of different LET_{eff} levels which were obtained by using different ion species and various tilts of the die with reference to the axis of the impinging ion beam. At each LET_{eff} level the irradiation was continued until a fluence of 10^6 particles/cm² had been reached or until a latch-up had been detected.

The following irradiation procedures were defined for proton testing: All parts were tested with 250 MeV protons. Only parts showing latch-up at this energy will be subjected to lower energy testing at 200, 100, 50 and 30 MeV. For the respective proton energies irradiation was stopped if the fluence reached 10^{10} particles/cm^2 or when a latchup occurred.

During exposure each component was biased using conditions which were based on those which it would experience in the PCDF or MSL project and those which were most likely to support latch-up. These bias conditions were defined in [2, 3]. During testing the supply current(s) to the irradiated component were monitored to detect any large and sudden increase which would indicate the occurrence of a latch-up. For each component type an appropriate latch-up threshold current level was selected and if the current increased above this level the voltage biasing was automatically cut off to prevent permanent device damage due to latch-up. The threshold levels were all set in the mA range and where possible were about an order of magnitude higher than the measured pre-irradiation supply current.

If the biasing to a component was automatically cut off by the monitoring circuit the irradiating heavy ion beam was closed. The biasing was then re-applied to check whether the current increase was due to a reversible latch-up or whether permanent damage had been caused by any other effect such as device burnout, SEB, SEGR, etc. Reapplying the irradiating beam to the component with the biasing applied then allowed an assessment to be made of whether it was only noise in the system which had triggered the monitoring circuit.

Both heavy ion and proton tests were performed at room temperature. There was no possibility that the devices significant increased their temperature because a latchup was only caused at most twice times. This is important because latchup is affected by temperature [4].

III. TEST RESULTS

Heavy ion test results were obtained for two separate parts of each component type. The following two tables summarize the test results for each component type separated between the PCDF and MSL projects. The tables also include the component manufacturer, package type, supply voltage and supply current during radiation tests.

13 out of 38 parts latched and failed the project requirements. The lowest LET threshold was 5.85 $MeVcm^2/mg$ (LM2991 from NSC). Because of the low SEL thresholds proton SEL testing was performed on these 13 parts, they are marked grey in table II and III.

Proton test results were also obtained for two separate parts of each component type. Initially each test part was exposed to the highest available proton energy of 250 MeV up to an accumulated fluence of $2\cdot10^{10}$ p/cm² but no SEL was detected for any component type at this energy. Even establishing the worst case test condition for two component types, i.e. applying maximum supply voltage, did not provoke a latch-up condition at this proton energy.

The total fluence from heavy ion and proton testing was low enough to prevent interference from either total dose damage or displacement damage.

IV. CONCLUSION

We have presented recent data from SEL tests on a variety of selected component types used in equipments and experiments for the International Space Station (ISS) which are mostly of COTS quality. These experiments showed that SEL testing is always required for new component types which are used in space projects even if the SEE requirements are low.

There are two very important results from these SEL tests which are particular relevant for project assurance and defining appropriate project requirements.

There exist a lot of general guidelines for radiation sensitivity of EEE components [5] which exclude bipolar devices from SEL events. This assumption is based on the fact, that in pure bipolar devices no thyristor structure is present. In this study 3 bipolar devices latched within a threshold LET of about 14-34 $MeVcm^2/mg$. This means the special design of these technologies must provide some thyristor structure. One can find recent investigations of latchup mechanisms in special bipolar devices [6]. As a consequence for future investigations concerning SEE events in bipolar devices, SEL events should not be

TABLE II
SUMMARY OF SEL TEST RESULTS FOR THE PCDF PROJECT

COMPONENT IDENTIFICATION			TEST CONDITIONS		SEL RESULT
Description	**Part Type**	**Package Type**	**Supply Voltage**	**Supply Current**	**LET Threshold (MeV.cm²/mg)**
Intersil N-Channel HEXFET 2N6782	JANTXV2N6782	TO-205AF metal can	30 V	0 µA	> 73.0
International Rectifier P-Channel HEXFET 2N6845	JANTXV2N6845	TO-205AF metal can	-30 V	0 µA	> 73.0
Texas Instrument Line Driver SNJ55ALS194J	5962-8864801EA	16-pin CERDIP	5 V	24 mA	> 73.0
Texas Instrument Line Receiver SNJ55ALS195J	5962-8864901EA	16-pin CERDIP	+/- 5V	29 mA	> 73.0
Linear Technology Positive Voltage Regulator LT1086MH/883	5962-8998101YA	TO-39 metal can	5 V	5 mA	28.2 - 34.0
Austin Semiconductor 512k x 8 SRAM	AS5C4008F-25	32-pin flatpack metal lid ceramic	5 V	88 mA	> 73.0
Analog Devices FET Input Op Amp	AD822AR	8-pin SOIC plastic	5 V	2 mA	> 73.0
Analog Devices 12-bit CCD Digital Signal Processor	AD9816JS	44-pin MQFP plastic	5 V	42 mA	9.1 - 14.1
Corning Frequency Control 20 MHz Oscillator	M55310/28-B11A 20000000	4-pin SMT metal lid ceramic	5 V	7 mA	> 73.0
Micrel 12A CMOS MOSFET Driver	MIC 4452BM	8-pin SOIC plastic	5 V	330 µA	> 73.0
National Semiconductor CMOS Hex Inverter	54ACTQ04LMQB	20-pin CLCC metal lid ceramic	5 V	< 0,05 µA	> 73.0
Integrated Device Technology 8-bit Bus Transceiver 54FCT245T	5962-9221401MRA	20-pin CERDIP	5 V	0 µA	> 73.0
National Semiconductor NAND Buffer Driver JD54F38BCA	JM38510/35202BCA	14-pin CERDIP	5 V	13 mA	> 73.0
Texas Instruments Hex Inverter 54HCT04	JM38510/65751BCA	14-pin CERDIP	5 V	0 µA	> 73.0
Analog Devices Instrumentation Op Amp AD620SQ	AD620SQ 883BQ	8-pin CERDIP	+/- 10 V	905 µA	> 73.0
National Semiconductor Voltage Regulator LM2991J-QML	5962-9650501 QEA	16-pin CERDIP	-15 V	7 mA	< 5.85
Siliconix 16 channel CMOS Analog Multiplexer DG406AK/883	5962-9562301QXA	28-pin CERDIP	+/- 10 V	0 µA	> 73.0
National Semiconductor Voltage Regulator LM117H/883Q	LM117H/883Q	TO-39 metal can	30 V	5 mA	9.1 - 14.1

TABLE III
SUMMARY OF SEL TEST RESULTS FOR THE MSL PROJECT

COMPONENT IDENTIFICATION			TEST CONDITIONS		SEL RESULT
Description	**Part Type**	**Package Type**	**Supply Voltage**	**Supply Current**	**LET Threshold ($MeV.cm^2/mg$)**
Infineon 16-bit CMOS microcontroller	SAB80C166M	100-pin plastic flatpack	5 V	20 mA	9.1 - 14.1
STM 8-bit CMOS microcontroller	ST62C65CB6	28-pin plastic DIP	5 V	1 mA	9.1 - 14.1
NSC CMOS operational amplifier	LMC6062/883	8-pin ceramic DIP	5 V	770 µA	> 73.0
NSC CMOS operational amplifier	LMC662AIN	8-pin plastic DIP	5 V	1 mA	> 73.0
TI CMOS operational amplifier	TLC272BCP	8-pin plastic DIP	5 V	1 mA	> 73.0
Linear Technology 12-bit A/D converter	LT1298IN8	8-pin plastic DIP	5 V	240 µA	5.9 - 9.1
Maxim 12-bit D/A converter	MAX538BEPA	8-pin plastic DIP	5 V	240 µA	> 73.0
Fairchild 2k CMOS EEPROM	FM93C56EN	8-pin plastic DIP	5 V	140 µA	9.1 - 14.1
TI bipolar voltage supervisor	TL7705ACP	8-pin plastic DIP	5 V	2 mA	> 73.0
Microchip Technology 8-bit CMOS microcontroller	PIC16-F84-04I/P	18-pin plastic DIP	5 V	180 µA	9.1 - 14.1
Maxim 8-channel CMOS analog multiplexer	MAX328CJE	16-pin ceramic DIP	+/- 15 V	0 µA	> 73.0
AD octal 8-bit BiCMOS D/A converter	AD7228ACQ	24-pin ceramic DIP	15 V	14 mA	> 73.0
AD 16-bit BiCMOS D/A converter	AD7846AQ	28-pin ceramic DIP	+/- 15V	7 mA	> 73.0
Intel 16-bit CMOS microcontroller	80C196KC-20	80-pin plastic flatpack	5 V	3 mA	14.1 - 19.9
Dallas 64k CMOS SRAM	DS1225Y-200	28-pin plastic DIP	5 V	2 mA	14.1 - 34.0
Standard Microsystems 8-bit CMOS LAN controller	COM20020IP	28-pin plastic DIP	5 V	460 µA	9.1 - 14.1
Wafer Scale Integration CMOS programmable peripheral	PSD301-B-90JI	44-pin plastic chip carrier	5 V	5 µA	19.9 - 28.2
Samsung 1M CMOS SRAM	K6T1008C2E-DB70	32-pin plastic DIP	5 V	50 µA	> 73.0
NSC CMOS operational amplifier	LMC6482AMJ/883	8-pin ceramic DIP	5 V	1 mA	> 73.0
Maxim CMOS analog timer	ICM7555MJA	8-pin ceramic DIP	5 V	450 µA	> 73.0

neglected.

A further result of these SEL investigations relate to the comparison of heavy ion and proton induced SELs. An LET threshold of about 10 MeVcm^2/mg is often used as an effective upper limit for concern about proton SEE phenomena [7, 8] which is also supported by prediction of theory and elementary geometrical models. The results of SEL testing herein show that proton latchup is important for devices with heavy ion thresholds lower than 5 MeVcm^2/mg. Some papers concerning proton latchup mechanisms and testing [9, 10] talk about heavy ion thresholds of 2-3 MeVcm^2/mg.

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