Total Dose Test Results for CubeSat Electronics

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***Abstract*-- CubeSats are increasingly important for space research. Their low orbits and short mission durations permit using electronics with modest radiation failure thresholds. Total ionizing dose irradiation results are presented for microelectronics interesting for CubeSat applications.**

I. INTRODUCTION

CUBESATS [1] and other small satellites are increasingly important for educational and research initiatives for space missions. The CubeSat format is based on a 10 cm cube weighing 1.33 kg or less. To minimize weight, developers often use a frame based on composite materials that offers little shielding from the space environment. They rely on electronics with high performance-to-power ratios to permit on-board processing while minimizing the requirement for power generation and battery systems. To minimize costs, they use commercial electronics, and rely on low earth orbits and short mission life to avoid radiation and reliability issues that are constraints on systems with more aggressive mission profiles.

Low Earth orbit (LEO) total ionizing dose (TID) exposure can range from 4 Krad(Si)/yr to 40 Krad(Si)/yr for effective shielding thicknesses of 10 mils of aluminum[2]. At these levels, commercial parts may be vulnerable to failure within the course of a 1 year mission. Although the CubeSats are far less expensive than traditional satellites, they still represent launch costs of approximately $100K, and thousands of man-hours invested in design, fabrication, and testing. These expenditures and significant opportunities for research may be jeopardized if a part fails.

The purpose of the work reported here is to survey commercial parts of potential interest to CubeSat missions such as Trailblazer, Rampart, and others. The part types investigated in this effort are listed in Table I. They include devices with desirable functionality and performance, but with previously unknown radiation performance. Only a few devices (often only single unit) have been tested. Reported results represent the performance of a specific device produced at a specific time and local. As with all commercial parts, the design and/or fabrication technology may be changed at any time and may have a significant impact on the device performance in a radiation environment.

II. TEST ENVIRONMENT

All tests were conducted at the Air Force Research Laboratory facilities at Kirtland Air Force Base New Mexico. High dose rate tests were conducted at the ^{60}Co facility, and low dose rate tests were conducted at the ^{137}Cs facility. A typical high dose rate test configuration is illustrated in the schematic diagram in Fig.1, demonstrating the arrangement for EEPROM tests.

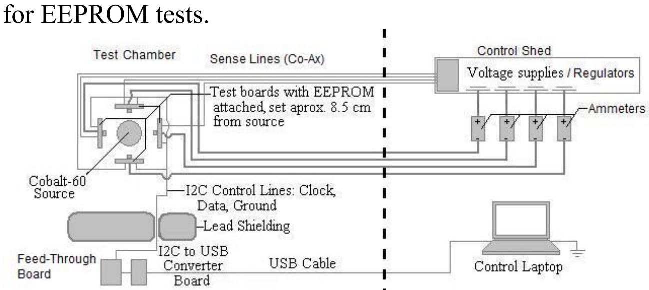

Fig. 1. Schematic of ^{60}Co test arrangement

The ^{60}Co source is a large room irradiator separated from the control room by approximately 150 feet. Devices under test (DUT) are located around the dust cover surrounding the source. The dose rate is determined by the distance from the source. A Radcal ionization gauge with a 0.18 cm^3 chamber with calibration traceable to NIST standards is used to determine the specific dose rate for each test arrangement at the beginning of the experiment. DUTs are typically powered from the control room to permit the power supply current to be monitored during irradiation. The DUTs may also be actively exercised in situ.

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TABLE I. SUMMARY OF TID TESTS ON COMMERCIAL PARTS

	Description	Part Number	Pkg	MNFR	High Dose Rate (rad(Si)/s)	Highest Fully Functional Dose @ High Dose Rate Krad(Si)	Low Dose Rate Milli - rad(Si)/s	Highest Fully Functional Dose @ Low Dose Rate Krad(Si)	Post-Anneal Performance
1	TXB0108 LEVEL TRANSLATOR FOR GPIO	TXB0108	20-TSSOP	Texas Instruments	57	100	NA	NA	Fully Functional after24 hours anneal @25ºC
2	TXS0108 LEVEL TRANSLATOR FOR I^{2}C	TXS0108	20-TSSOP	Texas Instruments	57	80	NA	NA	Fully Functional after 24 hours anneal @25ºC
3	IC MULTIPLEXER QUAD -SOIC	M74HC157RM13 TR	16-SOIC (0.154", 3.90 mm Width)	ST Microelectronics	57	70	NA	NA	Fully Functional after 24 hours anneal @25ºC
4	MOSFET N-CH 60V 115MA SOT23	2N7002	SOT23	Fairchild Semiconductor	57	<10 (See graph below)	NA	NA	NA
5	ATMEL microcontroller	ATMega 1280	TQFP100	ATMEL	17.1	18.3	NA	NA	No recovery after 128 hours anneal @25ºC
6	Microchip Enhanced Flash Microcontroller	PIC16F88 (Embedded in ASIM printed Ckt Board)	28 Pin QFN	MICROCHIP	47.6	20	NA	NA	No recovery after 128 hours anneal @25ºC
7	Signal Processor	OMAP3530		Texas Instruments	10	35	NA	NA	No recovery after 128 hours anneal @25ºC
8	Microcontroller	Nano-RTU		ACTEL ProASIC 3	50	40	NA	NA	No recovery after 128 hours anneal @25ºC
9	Atmel 1 Mbit Flash Memory	AT25FS010N	8 Lead SOIC	ATMEL	117	15 (WRITE) 20 (READ)	NA	NA	No recovery after 128 hours anneal @25ºC
10	EEPROM 128 x 8	AT24C01B-PU	8 PIN DIP	ATMEL	48.8	10 (WRITE) 30 (READ)	2 to 10	6 (WRITE) 6 (READ)	4 of 5 units READ recovery 0 of 5 units WRITE recovery after 168 hrs @ 100ºC
11	EEPROM 8K x 8	AT24C64B-PU	8 PIN DIP	ATMEL	NA	NA	2 to 10	6 (WRITE) 6 (READ)	NA
12	EEPROM	AT24C256B-PU	8 PIN	ATMEL	NA	NA	2 to	8	NA

	32K x 8		DIP				10	(WRITE) 8 (READ)	
13	EEPROM 128 x 8	CAT24C01LI-G	8 PIN DIP	ON Semiconductor	NA	NA	2 to 10	9 (WRITE) 9 (READ)	NA
14	EEPROM 8K x 8	CAT24C64LI-G	8 PIN DIP	ON Semiconductor	48.8	7.5 (WRITE) 7.5 (READ)	2 to 10	21(WRIT E) 21(REA D)	3of 3 units READ recovery 3 of 3 units WRITE recovery after 168 hrs @ 100ºC
15	EEPROM 16K x 8	CAT24C128LI-G	8 PIN DIP	ON Semiconductor	NA	NA	2 to 10	14 (WRITE) 14 (READ)	NA
16	EEPROM 32K x 8	24LC256-E/P	8 PIN DIP	MICOCHIP	48.8	7.5 (WRITE) 7.5 (READ)	NA	NA	1of 3 units READ recovery 0 of 3 units WRITE recovery after 168 hrs @ 100ºC
17	EEPROM 8K x 8	M24C64-WBN6P	8 PIN DIP	ST Microelectronics	48.8	5 (WRITE) 5 (READ)	NA	NA	0 of 3 units READ recovery 0 of 3 units WRITE recovery after 168 hrs @ 100ºC
18	EEPROM 8K x 8	BR24L64-W	8 PIN DIP	ROHM	48.8	2 (WRITE) 10 (READ)	NA	NA	0of 3 units READ recovery 0 of 3 units WRITE recovery after 168 hrs @ 100ºC
19	EEPROM 1K x 8	PCF8598C-2P/02- 112	8 PIN DIP	NXP	48.8	2.5 (WRITE) 2.5 (READ)	NA	NA	3of 3 units READ recovery 1 of 3 units WRITE recovery after 168 hrs @ 100ºC

As shown in Fig. 1, a control computer located in the control room can exercise the DUT and record data over a CAT 5 cable with appropriate bus converters (e.g., USB to I^2C for the EEPROM tests).

A typical test fixture arrangement with provisions for testing four devices simultaneously is shown in Fig. 2. As shown, a lead brick collimator can be inserted into the fixture to permit other components on the test board to be shielded during the irradiation.

The ^{137}Cs source is a small volume irradiator and all tests are conducted in a 1 ft^3 lead/aluminum box. Dose rates are limited to 1-10 mrad(Si)/s depending on the location of the DUT within the box. A typical low dose rate test configuration is illustrated in the schematic diagram in Fig. 3, demonstrating the arrangement for EEPROM testing. For the low dose rate tests reported here, four devices were located on each of three test board with the boards located one behind the other. Dose rates at each position were measured with the Radcal ionization gauge. Dose rates ranged from 8 mrad(Si)/s to 2 mrad(Si)/s for the closest and farthest boards, respectively. DUTs were biased during irradiations and the supply currents were actively monitored. Devices were removed from the irradiator for functional testing and returned to the test chamber within one hour if they were still functional.

III. Total Dose Test Results

Four general types of devices have been tested to date in support of parts evaluation for CubeSat electronics. They include: (1) logic level shifters, (2) multiplexers and NMOS power FETs, (3) microcontrollers, and (4) EEPROMs and flash memory. Results for each device type are described in the following sections.

A. TXB0108 AND TXS0108 Logic Level Translators

CubeSat power busses typically distribute 5 volt power and most of the sensors and analog electronics require 5 volt I/O.

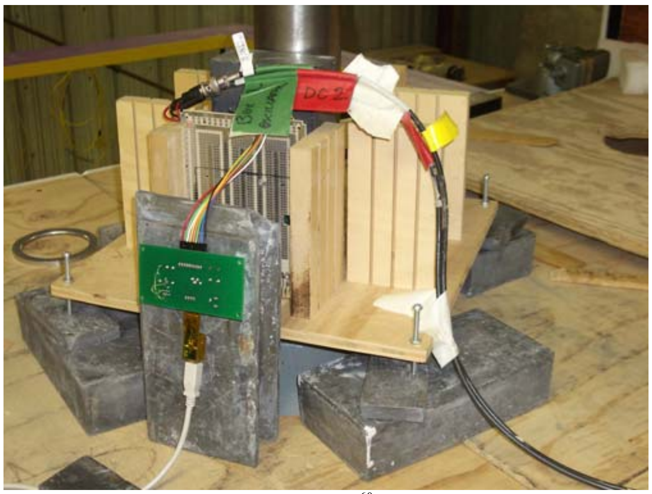

Fig. 2. Test fixture for ^{60}Co irradiation

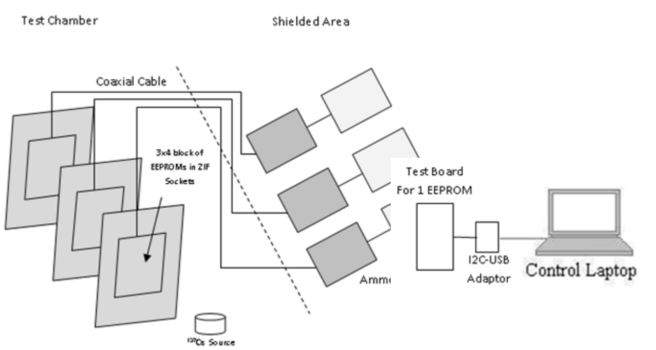

Fig. 3. Schematic for ^{137}Cs test arrangement

However, many of the microcontrollers of interest are fabricated with advanced technologies that only support 3.3 volt or 2.2 volt I/O. Logic level translators are required to bridge between the different voltage domains. Traditionally, logic level translators have been organized x8 or x16 bits and have been bank switched (i.e., the data flow for all bits is either from the higher voltage domain to the lower or vice versa). However, many CubeSat applications require the I/O to be general purpose in the sense that each I/O bit may act independently as either a input or an output.

The TXS0108 and TXB0108 [2]-[3] logic level translators from Texas Instruments are potentially well suited for these applications since each bit automatically senses a transition from either voltage domain and actively drives the signal in the appropriate direction. The TXS devices, shown schematically in Fig. 4, are intended for low frequency operation and are appropriate for low data rate busses such as I^{2}C which requires a resistor pull-up.. The TXB devices, shown schematically in Fig. 5, are intended for higher frequency operation and are appropriate for general purpose I/O.

Four devices each of TXS0108 and TXB0108 (eight bit level translators) were tested in the ^{60}Co source at a dose rate of 57 rad(Si)/s. During irradiation devices were biased with 5 volts on the high side and 3.3 volts on the low side. Supply currents were monitored during irradiation and dynamic performance was monitored after each irradiation level. Average post-irradiation supply currents for the high side supply for both the TXS0108 and TXB0108 are shown in Fig. 6. The TXB0108 was fully function up to a dose of 100 Krad(Si) and the TXS0108 was fully functional up to a dose of 80 Krad(Si). For both devices, failure appeared to be associated with the automatic direction sensing circuit. Fig. 7 and 8 record the pulse response for the TXB0108 at the pre-fail and failure doses.

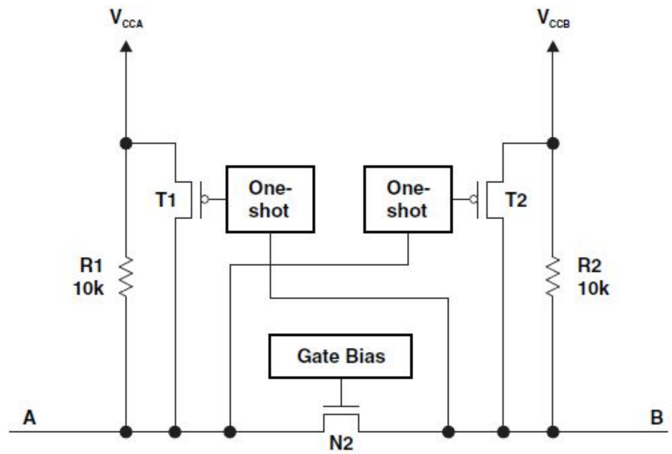

Fig. 4. TXS schematic diagram

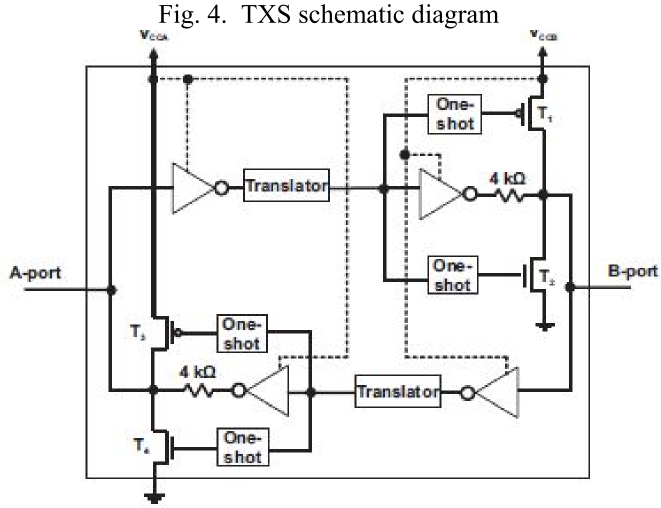

Fig. 5. TXB schematic diagram

The oscillation between the high side and low side levels are typical of the failure response. Both TXS and TXB recovered full functionality after a 24 hour anneal at room temperature.

A. Multiplexer and NMOS Results

1) M74HC157RM13TR Multiplexer

In applications of microcontrollers with a restricted number of I/O, multiplexers are needed to steer the I/O ports to different data channels such as EEPROMs, ADCs, DACs, etc. The M74HC157RM13TR is a quad two channel multiplexer manufactured by ST Microelectronics.

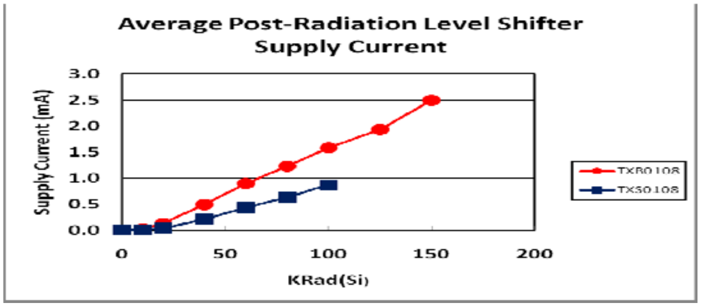

Fig. 6 Average post-irradiation supply current for TXS0108 and TXB0108

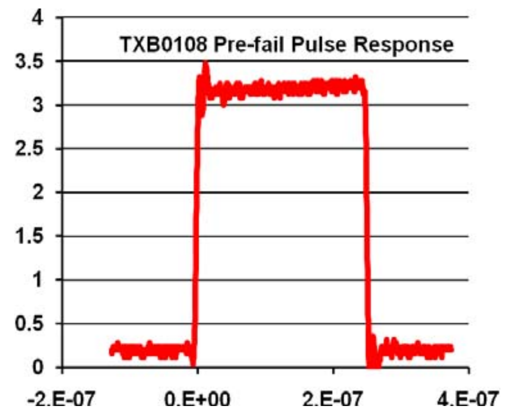

Fig. 7. Pre-fail pulse response for 5 volt to 3.3 volt level translation

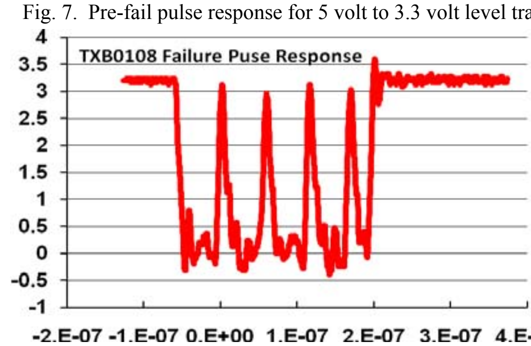

Fig. 8. Functional failure pulse response for 5 volt to 3.3 volt level translation

Four units were tested at the ^{60}Co source at a dose rate of 57 rad(Si)/s. The power supply voltage was set at 3.6 volts and all devices were biased with inputs 1A – 4A at 3.6 volts and inputs 1B – 4B at ground. The A inputs were selected during the irradiation. After each irradiation level the parts were tested for functionality. All devices were fully functional at 70 rad(Si) and all failed at 100 rad(Si). The average post-irradiation power supply currents for each radiation level are plotted in Fig. 9. All devices returned to full functionality after a 24 hour anneal at room temperature.

2) 2N7002K N-channel MOSFET

Discrete MOS transistors can also be used to design multiplexer functions or in many other roles such as analog switching, logic level translation, and power steering. In CubeSat systems using 5 volt power busses, power MOSFETs would be used far below their rated gate and drain voltage limits; consequently, concerns about single event burnout or gate rupture would be greatly diminished.

The Fairchild 2N7002K N-channel enhancement mode transistor was evaluated to determine if its hardness was adequate for CubeSat applications. The parts were biased with the gate at 3.6 volts and the source and drain grounded during irradiation. Post-irradiation I/V characteristics were measured. Fig. 10 is a plot of the threshold voltage characteristic for four transistors irradiated to 10Krad(Si) at 57 rad(Si)/s. The threshold voltage shifted so far into depletion that the part could not be used in the target application.

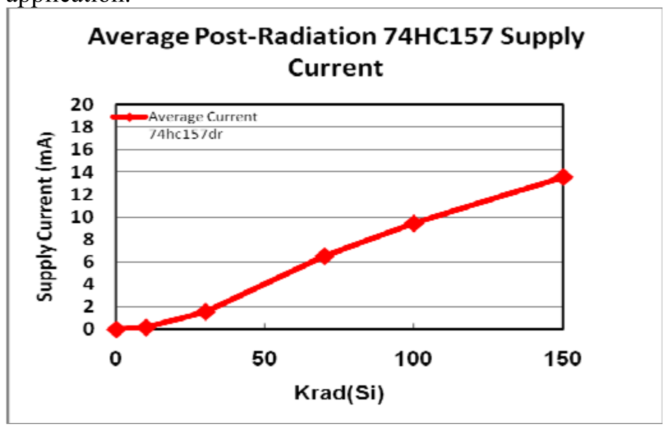

Fig. 9. 74HC157 Multiplexer post-irradiation supply current.

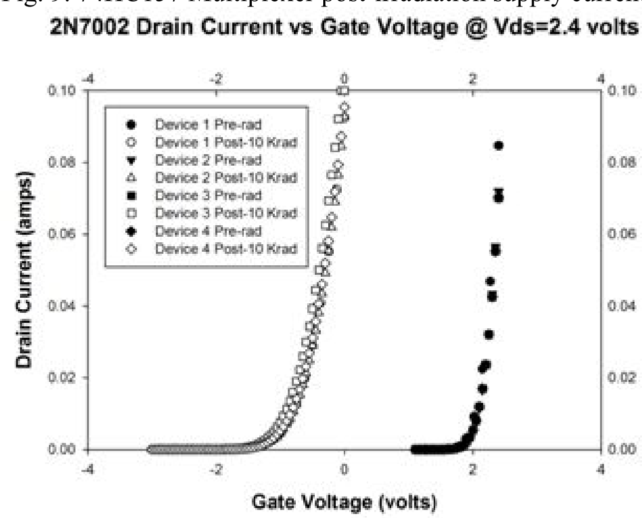

Fig. 10. 2N7002K post-irradiation (10 Krad(Si)) threshold voltage characteristic.

B. MicrocontrollerResults

Microcontrollers play a central role in most CubeSat applications. They act as sensor interfaces to the satellite bus and often as the main processing unit for the entire satellite. Total dose testing results for 4 different microcontroller are presented in the following sections.

1) ATMega 1280 Microcontroller

The ATMega 1280 is an 8-bit microcontroller manufactured by ATMEL. It incorporates 128 Kbits of flash memory, 8 Kbits of SRAM, 4 Kbits of EEPROM, and a 10-bit A/D converter. A single device was tested at the ^{60}Co source at a dose rate of 17.1 rad(Si)/s. The microcontroller was operational on a prototyping board during the test. All other electronics on the board were shielded. The following tests were performed in-situ and used to evaluate the health and status of the device.

1) 4096 bytes of data stored in flash were compared to the same date stored in SRAM. The pattern was alternating 0xAA, 0x55. An error was reported if the patterns were not the same.
2) 1024 bytes were copied from EEPROM to SRAM then the two copies were compared byte by byte. This was an SRAM write test. The bit pattern was the same as in test 1. Each byte that did not match resulted in an error message that included the index into the array where the error occurred.
3) 2048 bytes of the same bit pattern were taken from flash, sent out one UART and received on a different UART. Each received byte was compared with the sent byte and an error message is generated if they did not match. The hex values of both bytes were included in the error message along with the index into the array. Additionally, if a byte was sent but not received an error message was generated indicating the index into the array where the lost character occurred.
4) The voltage of the 3.3V supply was measured and compared to a pre-test captured value. If the resulting ADC counts did not fall within one bit of the pre-test value an error message was generated indicating the erroneous measured value and the pre-test captured value.

The initial failure was detected in the ADC test at 27.3 Krad(Si) followed by complete loss of functionality at 28.3 Krad(Si). The power supply currents for both the 3.3 volt and 5 volt supplies are plotted in Fig. 11 and 12.

1) PIC16F88 Microcontroller & 24AA128 EEPROM

The PIC16F88 microcontroller and the 24AA128 EEPROM were both manufactured by Microchip. They were irradiated

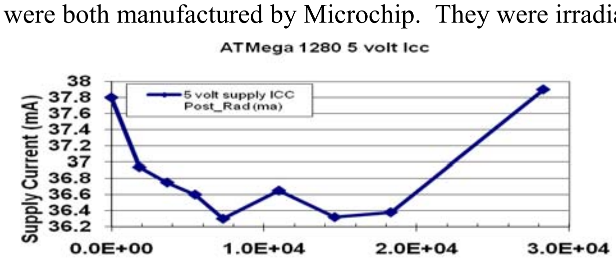

Fig. 11. ATMega 1280 post-radiation 5 volt supply current.

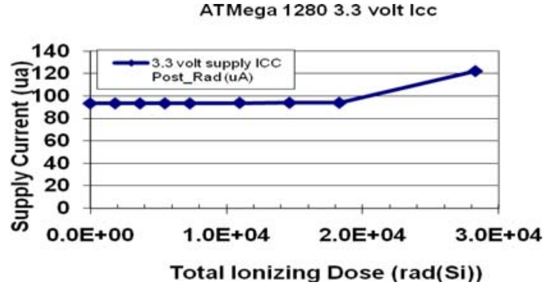

Fig. 12. ATMega 1280 post-radiation 3.3 volt supply current.

simultaneously as part of a small printed circuit card assembly that included the two devices with a 20 MHz crystal oscillator and associated capacitors and resistors. The irradiation was performed at the ^{60}Co source at a dose rate of 47.6 rad(Si)/s. The devices were operational during test and tests were performed in-situ to evaluate the health and status of the EEPROM, UART, flash memory, and A/D converter. The devices were fully functional through 20 Krad(Si). Errors in reading the A/D converter were detected at 21.7 Krad(Si) and all functionality was lost at 24.5 Krad(Si). Post-irradiation supply currents are plotted in Fig. 13.

2) OMAP3530 Processor

The OMAP3530 processor was manufactured by Texas Instruments. It is planned for the command and data handling (C&DH) on the Trailblazer-2 CubeSat to be launched in 2012 or 2013. The device was irradiated as part of the BEAGLE version C4 evaluation board which is an open source design originally developed by Texas Instruments in association with Digikey.

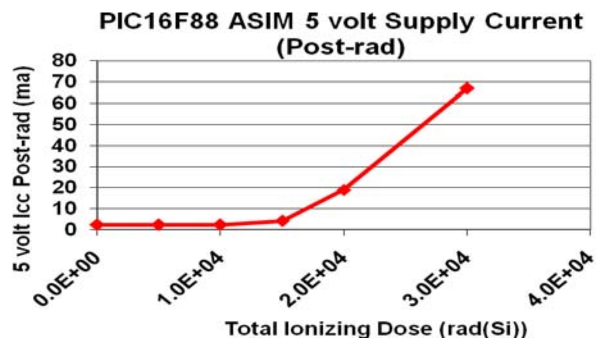

Fig. 13. PIC16F88 post-radiation 5 volt supply current

A full description of the board capabilities is available at http://beagleboard.org/static/BBSRM_latest.pdf. A single device was tested at the ^{60}Co source at a dose rate of 10 rad(Si)/s.. All the board components except the OMAP 3530 were shielded (see Fig. 1). The device was operational during test and health and status were monitored in-situ by loading a Linux Kernel 2.6 and testing the boot process. The process tested the internal memory, I/O, peripherals (USB, HDMI, AUDIO, etc.) and reported the results to a terminal window. Once the chip failed to boot the boot log provided the point of failure.

The OMAP3530 was fully functional to a total dose of 35 Krad(Si). It failed to function after a dose of 40 Krad(Si)/s. The 5 volt power supply current to the BeagleBoard is plotted in Fig. 14.

1) Nano-RTU

The Nano-RTU is a controller board for short term space missions. The heart of the board is a microcontroller implemented on an Actel ProASIC3L with associated AT17KV010-10CU EEPROM, LP3991low drop-out regulator, TLV2548IDW 12 bit A/D converter, and a DAC7552 12 bit D/A converter. The entire controller board was irradiated at the ^{60}Co source at a dose rate of 50 rad(Si)/s. The device was operational during test and health and status were monitored in-situ by software that exercised the I/O, Timers, UART, and Memory of the device. The I/O was tested by writing a value to the output of one port and reading the value on another.

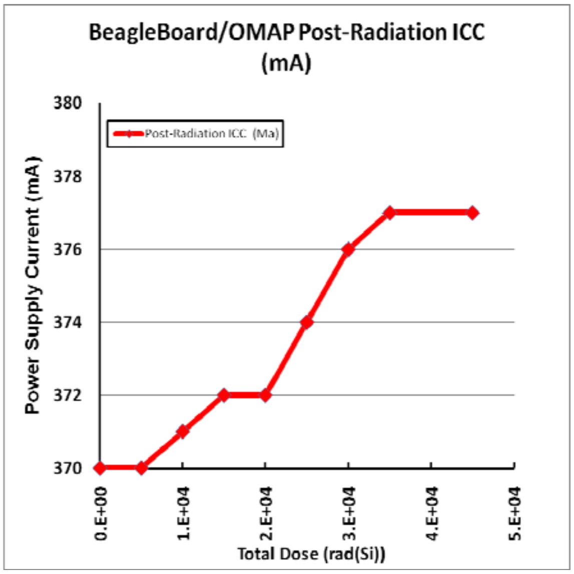

Fig. 14. BeagleBoard post-radiation 5 volt supply current

The timers were tested by setting one and testing when it triggers. The UART was tested by receiving a character from the terminal and outputting it back to the terminal. The memory was tested by performing writes and reading the stored values.

The Nano-RTU board was fully functional to 40 Krad(Si). The read to the A/D converter failed at 50 Krad(Si) and all functionality was lost at 70Krad(Si). The post-radiation supply current to the board is plotted in Fig. 15.

A. Flash and EEPROM Results

Non-volatile memory is a vital element in CubeSat applications. It provides storage for the operating system, application programs, and critical data. The following section present the results of a survey test on a commercial flash memory and an extensive survey of EEPROM from several vendors.

1) AT25SF010N 1 Mbit FLASH Memory

The AT25FS010N flash memory is manufactured by ATMEL. A total of 8 parts were tested at the ^{60}Co source under a static bias of Vnominal + 10% (3.63 volts) and irradiated with a stored memory pattern. Four of the devices (#1, #2,#3, #8) were tested for both read and write functionality following each irradiation step. Devices #4, #5, #6, and #7 were tested for read functionality after each step. For the read operation, all devices were functional at 20Krad(Si) and failed at 40Krad(Si). For the write operation, three devices were functional at 10Krad(Si) and failed a 15 Krad(Si). The write operation for device #3 was functional at 15 Krad(Si) and failed at 20 Krad(Si). Prior to the read fail, increases in supply current were negligible even at those irradiations where the write function failed. However, in the irradiation coinciding with the read current fail, the supply current increased by an average of .79ma for the 8 devices. Figure 16 is a plot of the average post-irradiation supply current.

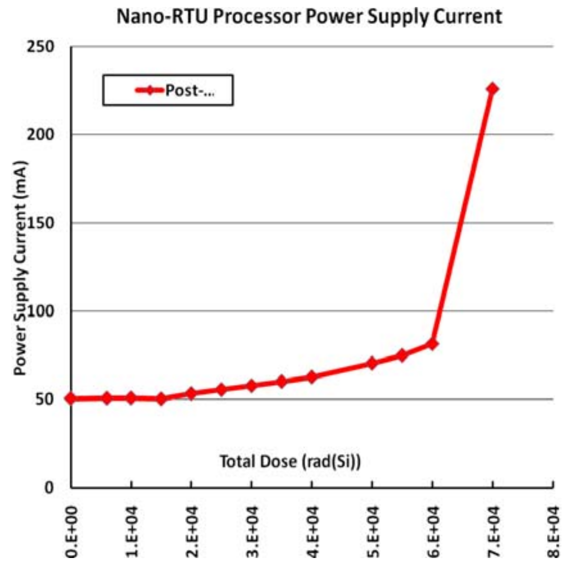

Fig. 15. Nano-RTU post-radiation 5 volt supply current

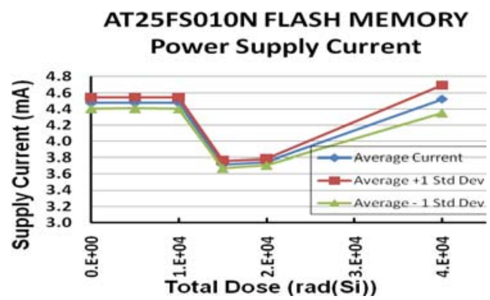

Fig. 16. Nano-RTU post-radiation 5 volt supply current

2) EEPROM Evaluations

In order to identify a commercial EEPROM that could be used for CubeSat applications a sample six devices from different manufacturers were selected for high dose rate screening. The specific devices and manufacturers are listed in Table II.

Table II. Post-Anneal (100°C) Recovery Summary from High Dose Rate Irradiations

Manufacturer	Part Number	Post-Anneal Write Recovery	Post-Anneal Read Recovery
Atmel	AT24C01B-PU	0 of 5 Recovered	4 of 5 Recovered
ON Semi	CAT24C64LI-G	3 of 3 Recovered	3 of 3 Recovered
Micochip	24LC256-E/P	0 of 3 Recovered	1 of 3 Recovered
ST Micro	M24C64-WBN6P	0 of 3 Recovered	0 of 3 Recovered
ROHM	BR24L64-W	0 of 3 Recovered	0 of 3 Recovered
NXP	PCF8598C-2P	1 of 3 Recovered	3 of 3 Recovered

The devices are irradiated with a logical checkerboard pattern stored in memory. After each exposure, the standby current was recorded and the stored pattern was verified. The compliment pattern was then written, verified and the standby current recorded. The original pattern was then rewritten and verified for the next exposure. For EEPROMs, write operations often fail before read operations. In that case, the original pattern cannot be rewritten; therefore, the existing pattern in the memory was recorded as a "new standard" pattern. Subsequent evaluations of the read operations were compared against the new standard pattern. Following high dose rate testing, parts were placed on biased anneal for 168 hours at 100°C.

Fig. 17 and Table II summarize the failure thresholds and the post-radiation anneal results for each of the six device types tested. . Only the Atmel device remained fully functional to 10 Krad(Si). It maintained error free read capability to 30 Krad(Si), and it maintained a low standby current out to 80 Krad(si). Of the 5 Atmel devices tested, 4 returned to full functionality after anneal. Consequently, the Atmel EEPROMs were selected for additional testing at the low dose rates that are more representative of the LEO space environments.

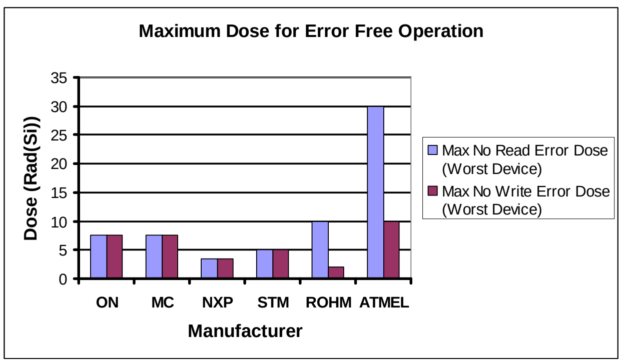

Fig. 17. High Dose Rate Error Free Performance

Of the other device types, only the ON Semiconductor devices were selected for additional testing. Although the ON parts only remained fully functional to 7.5Krad(Si), all three of the parts tested returned to error free performance for both write and read operations after anneal and maintained low standby currents.

The low dose rate tests were conducted in the 137Cs source at a dose rate from 2 mrad(Si)/s to 10 mrad(Si)/s. The part type sample for both the Atmel and ON Semiconductor devices was expanded to include larger memories – 64Kbit (AT24C64B) and 1 Mbit (AT24C1024B) for Atmel and a 2Kbit (CAT24C02) and a 256Kbit (CAT24C256) for ON Semiconductor. As shown in Fig. 18, the Atmel devices exhibited slightly lower error-free performance levels than were recorded in the high dose rate irradiation. Devices of all types failed both read and write operations at levels between 5Krad(Si) and 10Krad(Si). In the case of the 1Kb part, the standby current exceeded the parametric specification (18µA) at approximately 12Krad(Si). The standby current for the larger Atmel device types exceeded the parametric specification (6 µA) at doses estimated to be between 1Krad(Si) and 4 Krad(Si).

The ON Semiconductor parts performed better at low dose rate. The 64Kb part type had error free operation through 21Krad(Si) at low dose rate as compared to 7.5Krad(Si) at high dose rate. The standby currents remained low for all ON device types. The ON 64Kb was the most robust of the three types with a maximum error free operation of almost 3X that of the 2Kb part.

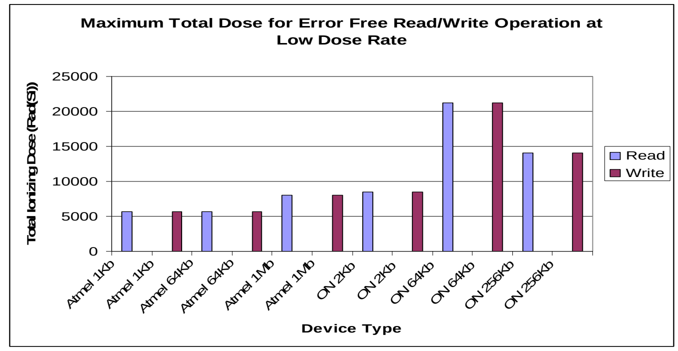

Fig. 18. Low Dose Rate Error Free Operation Summary

IV. References

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