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***Abstract*—In this paper we report total dose test results of COTS components commonly used on CubeSats. We investigate a variety of analog integrated circuits, popular microcontrollers (PIC24), SD memory cards and a TCXO.**

I. Introduction

In this paper we present the results from total ionizing dose (TID) testing that was completed for components used in the MicroMAS satellite. MicroMAS, the Micro-sized Microwave Atmospheric Satellite, is a 3U CubeSat under joint development by the Space Systems Lab at MIT and Lincoln Laboratory [1]. This three-axis stabilized CubeSat will carry a state of the art passive microwave radiometer. In order to meet challenging budget and schedule constraints, MicroMAS uses a variety of COTS-level components (e.g. Pumpkin CubeSatKit) in addition to a custom-built interface board.

The MicroMAS system is designed for a one-year mission in LEO with a nominal orbit of 402 x 424 km and 51.6 degree inclination. Based on estimates from the SPENVIS tool [2], the expected mission dose is approximately 1.2 krad(Si). Despite the relatively benign dose, we wanted to verify the resilience of certain key components to TID.

II. Component Selection

To best direct our test efforts, we examined the bill of materials (BOMs) for our custom designs as well as the designs of COTS components (where available) to identify components of largest concern. The criteria for selecting components for the test included: 1) lack of existing radiation test data, 2) reliance on technologies known to be vulnerable (e.g. charge pumps) and 3) criticality in overall system design.

The central processor for MicroMAS, a Microchip PIC24F microcontroller embedded in a Pumpkin Inc. Motherboard, was one component of concern due to its integrated flash memory array. Despite the popularity of this microcontroller among nanosatellite developers, surprisingly little radiation test data exists. What data is available is either derived from on-orbit performance, or covers much older devices which differ substantially in both their design and manufacturing process. The team also decided to test the PIC24E (a newer, enhanced smaller process size variant of the PIC24F) because it was being carried by the program as an alternate processor should the PIC24F prove insufficient.

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The MicroMAS design also relies on a variety of RS232-compliant interfaces for connectivity to some of the COTS components. In order to provide RS232 interfaces, the MAX3221-EP line transceiver was selected due to its extended temperature rating and high-reliability characteristics. Nevertheless, the MAX3221-EP still contains a charge pump mechanism and high internal voltages which motivated TID testing.

Another critical part of the MicroMAS CubeSat is the power distribution system. Because conventional relays and breakers are far too large and massive, our team decided to employ integrated high-side current limit switches to provide load switching and over-current protection. The Fairchild FPF2700 was selected for this task because of its size, low on-resistance and current handling capabilities. Many of this device's functions, such as the over-current trip point, rely on a precision internal voltage reference as well as a gate charge pump. Consequently, we wanted to ensure that TID was not going to disrupt the calibration (and consequently the trip point) of this IC.

MicroMAS also incorporates an SD memory card to provide "solid state recorder" functionality for science data. This SD card is attached as a peripheral to the Pumpkin Motherboard and is operated in the SPI interface mode. Three different SD card products were tested: an industrial grade SD card from Delkin (SE02SAMHL-C1000-D [3]) using single-level cell (SLC) technology as well as two consumer grade cards using multi-level cell (MLC) technology (Sandisk SDSDB-002G-AFFP and Transcend TS2GUSD). All of the SD cards tested were 2 GB capacity devices.

Finally, the MicroMAS mission demands precise geolocation which necessitates a stable onboard clock source. A temperature compensated crystal oscillator (TCXO) was incorporated into the avionics design to satisfy this requirement. The TCXO selected is from Fox Electronics and provides 2.5 PPM stability over temperature.

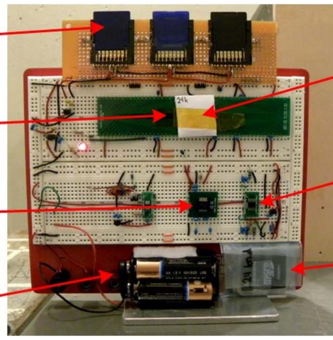

Fig. 1. Test jig used for TID tests

III. Experimental Procedure

TID testing was conducted at the University of Massachusetts Lowell Radiation Laboratory using a high-dose rate Cobalt-60 gamma source. The team selected two exposure levels for the test: 8 krad and 24 krad. These values were selected because they were conservative relative to our mission expected dose of 1.2 krad(Si). In both cases the exposure time was approximately one hour with total dose being selected by varying the distance to the Co-60 source, from the test rigs.

Test support jigs were built to support the devices under test (DUTs) at each of the exposure levels (Figure 1). The test jigs provide mechanical support as well as the appropriate bias voltage for each component. Two of these jigs were constructed, one for each of the two dose levels. A dosimetry tablet was attached to each of these test jigs to measure the actual dose delivered to each set of DUTs.

IV. Characterization & Results

Both prior to and after exposure, a variety of measurements were taken to characterize the performance of each of the DUTs. For some of the components (e.g. SD cards and PIC24 microcontrollers), these measurements included memory contents. For other components, these measurements consisted simply of analog device parameters (e.g. quiescent current, slew rates, etc.).

A. FPF2700 Current Limit Switch

The FPF2700 is a high-side current limit switch with an integrated N-channel MOSFET. The DUT was connected to a 6 V (approx) power supply and the appropriate programming resistor. This device includes a bandgap voltage reference as well as a charge pump that is used to drive the gate of the MOSFET. To characterize the effects of TID on this device, the following measurements were collected:

- Over-current trip point (I_{trip})
- ON resistance (R_{ON})
- Output voltage when OFF (V_{OFF})
- Quiescent current consumption (I_Q)

Table I shows the values for these parameters both before and after exposure. The only notable difference between the two sets of measurements was the decrease observed in R_{ON}. It was determined that the pre-exposure measurement likely included some additional resistance external to the DUT. The FPF2700 datasheet [4] confirms that the nominal R_{ON} value should be approximately 100 mΩ which is much closer to the values observed after exposure.

TABLE I
FPF2700 Measurement Data

DUT	Dose	I_{trip} (A)	R_{ON} (mΩ)	V_{OFF} (mV)	I_Q (μA)
#1	0 krad	0.447	162	2.1	92
#1	8 krad	0.442	90	0.8	89
#2	0 krad	0.509	156	1.6	92
#2	24 krad	0.505	77.2	1.5	105

TABLE II
MAX3221-EP Measurement Data

DUT	Dose	I_S (mA)	V_{open} (V)	V_{load} (V)	t_{HL} (ns)	t_{LH} (ns)
#1	0 krad	0.36	L: -5.579 H: +5.578	L: -5.331 H: +5.429	560	400
#1	8 krad	0.43	L: -5.420 H: +5.484	L: -5.248 H: +5.344	620	430
#2	0 krad	0.33	L: -5.516 H: +5.517	L: -5.316 H: +5.363	580	440
#2	24 krad	0.70	**L: +0.140** **H: +0.047**	**L: +0.004** **H: +0.000**	FAIL	FAIL

B. MAX3221-EP RS232 Interface

The MAX3221-EP is a TIA/EIA-232 compliant line transceiver that can be powered from a 3.3 V power supply. This device contains a charge pump circuit that is used to produce the necessary RS-232 signaling levels. The following device parameters were selected for TID characterization:

- No-load supply current (I_S)
- Driver output voltages without load (V_{open})
- Driver output voltages with 3 kΩ load (V_{load})
- Driver slew rate (t_{HL} and t_{LH}) under load

The slew rate measurements were conducted per the procedure provided in the product datasheet [5] at an equivalent edge rate of 250 kilobaud.

Table II shows the measurement data for this component. The 8 krad device was still functional after exposure although it did exhibit slightly increased power consumption and slightly worse (though still within specification) slew rates. The drivers in the 24 krad device failed after radiation exposure and this failure was accompanied by a doubling of supply current.

C. PIC24 Microcontrollers

The PIC24F and PIC24E microcontrollers that were studied in this test are highly complex, "System on a chip" devices containing a processor, flash memory, SRAM and various analog and digital peripherals. Fully characterizing the radiation tolerance of such a device can be an extremely

TABLE III
PIC24 MEASUREMENT DATA

DUT	Dose	I_{CC} (mA)	Read back	Blank cmd.	Verif. blank	Write
24FJ256-	0 krad	18.60	PASS	PASS	PASS	PASS
GA110 #1	8 krad	18.69	PASS	PASS	PASS	PASS
24FJ256-	0 krad	18.91	PASS	PASS	PASS	PASS
GA110 #2	24 krad	19.41	PASS	PASS	**FAIL**	**FAIL**
24FJ256-	0 krad	18.14	PASS	PASS	PASS	PASS
GB210 #1	8 krad	18.13	PASS	PASS	PASS	PASS
24FJ256-	0 krad	18.14	PASS	PASS	PASS	PASS
GB210 #2	24 krad	18.20	PASS	PASS	**FAIL**	**FAIL**
24EP512-	0 krad	2.678	PASS	PASS	PASS	PASS
GU810 #1	8 krad	2.655	PASS	PASS	PASS	PASS
24EP512-	0 krad	2.740	PASS	PASS	PASS	PASS
GU810 #2	24 krad	2.645	PASS	PASS	**FAIL**	**FAIL**

TABLE IV
SD CARD READ/WRITE RESULTS

Manuf.	DUT ID	Dose	Bias	Read	Write
Delkin	1	8 krad	Yes	PASS	PASS
Delkin	2	24 krad	Yes	PASS	PASS
Delkin	3	8 krad	No	PASS	PASS
Delkin	4	24 krad	No	PASS	PASS
SanDisk	1	8 krad	Yes	PASS	PASS
SanDisk	2	24 krad	Yes	**FAIL**	-
SanDisk	3	8 krad	No	PASS	PASS
SanDisk	4	24 krad	No	**FAIL**	-
Transcend	1	8 krad	Yes	PASS	PASS
Transcend	2	24 krad	Yes	**FAIL**	-
Transcend	3	8 krad	No	**FAIL**	-
Transcend	4	24 krad	No	**FAIL**	-

complex undertaking. For the purposes of this study, we were solely interested in measuring the radiation susceptibility of the FLASH memory array as well as the change in quiescent power consumption (I_{CC}) due to TID-enhanced leakage currents.

The specific part numbers that were tested are listed below.

- PIC24FJ256GA110 (Datasheet [6])
- PIC24FJ256GB210 (Datasheet [7])
- PIC24EP512GU810 (Datasheet [8])

These devices were powered from 3.3 V supplied by a linear voltage regulator during programming and exposure.

In order to measure the performance of the FLASH program memory, we used the manufacturer's in circuit programming tool (Microchip ICD3) to read/write known pseudo-random patterns to/from each device's flash memory. The following procedure was used to exercise the flash memory array:

1) Program device with known pseudo-random sequence and read back to confirm successful programming.
2) Expose to radiation.
3) Read back memory, compare to original pattern.
4) Issue blanking command to erase device.
5) Verify memory is blank (all 1's).
6) Write different pseudo-random sequence and verify.

Confirming that the blanking and write mechanism works after exposure is important for MicroMAS as it will be needed for on-orbit firmware upgrades.

As indicated in Table III, the higher dose parts (both PIC24F and PIC24E) suffered partial failure at the higher dose level. The team believes this failure is attributed to the failure of the internal charge pump circuit that is used to produce the flash reprogramming voltage. Despite the failure, the original memory contents were intact after exposure - only the reprogramming capability was lost.

D. SD Cards

Like the PIC24 microcontrollers, the SD memory card modules are complex devices containing a flash memory array as well as a control/interface circuit. In order to characterize these parts, we took a simplified approach that consisted of writing known data patterns and then verified these files post-exposure. Additionally, we tested the write capability post-exposure by writing additional data to each of the cards. To support this test each of the SD cards was formatted with the FAT16 file system and then populated with different size files containing pseudo-random data.

The MicroMAS team has considered flying a second SD card on the mission to act as a cold spare. One question this raises is whether an unbiased (i.e. powered off) SD card can tolerate more dose prior to failure. To try to answer this question we included a second complete set of SD cards that were left unbiased during exposure.

Table IV shows the read and write test results for the various cards. The Delkin product, which is marketed as an industrial ruggedized card, performed satisfactorily at both dose levels. The consumer grade products from SanDisk and Transcend did not fare as well and suffered numerous failures at both dose levels.

E. FOX924B Oscillator (TCXO)

The FOX924B oscillator tested was a 16 MHz, HCMOS output temperature compensated crystal oscillator from Fox Electronics [9]. In order to characterize the performance of this device, the following parameters were measured:

- No-load supply current (I_S)
- Fundamental frequency, unloaded (f_{open})
- Driver output voltages, unloaded (V_{OL},V_{OH})

As indicated in Table V, the lower dose part performed well after exposure. Although the higher dose part (24 krad) was still oscillating after exposure, it appeared to have suffered a failed output driver and was no longer generating an HCMOS compliant signal. A 20 PPM frequency shift was also observed on the high dose part.

V. CONCLUSION

The results of these TID tests were encouraging to the MicroMAS team. Although our limited resources prevented

TABLE V
TCXO MEASUREMENT DATA

DUT	**Dose**	I_S (mA)	f_{open} (MHz)	V_{OL} (V)	V_{OH} (V)	**Result**
#1	0 krad	2.36	15.9999	0.088	3.210	-
#1	8 krad	2.32	15.9999	0.221	3.250	PASS
#1	0 krad	1.87	15.9999	0.002	3.250	-
#1	24 krad	2.32	16.0002	0.080	**1.040**	FAIL

us from testing larger batches of components, we gained confidence in the components that have been selected for our design. From a TID perspective, the FPF2700 appears to be a good option for designers in search of a load switching solution. The MAX3221-EP interface IC failed at the higher dose rate so we can conclude that it is susceptible to TID, though it appears to be above the level expected during the MicroMAS mission. A substantial amount of work remains to fully characterize the PIC24 microcontrollers and the SD cards due to their internal complexity, however, we can conclude from this study that MLC Flash memory products (e.g. the SanDisk and Transcend SD cards tested) are best avoided for space applications.

In the future we hope to expand our test efforts to consider the single event effect vulnerabilities of these components and to experiment with thermal annealing of parts which have been damaged by TID.

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