

Test Results of Total Ionizing Dose Conducted at the Jet Propulsion Laboratory

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Abstract—This paper reports recent Total Ionizing Dose (TID) test results obtained at JPL. Several device samples were analyzed exhibiting significant failure levels and ELDRS effects under biased and unbiased condition.

Index Terms—Bipolar, Complementary Metal Oxide Semiconductors (CMOS), Enhanced Low Dose Rate Sensitivity (ELDRS), High Dose Level (HDL), Low Dose Level (LDL), and Total Ionizing Dose (TID)

I. INTRODUCTION

THIS paper reports recent Total Ionizing Dose (TID) test results obtained at the Jet Propulsion Laboratory (JPL). The results discussed in this paper refer to testing performed during the past year. These microelectronic devices were candidates for applications in space missions. Two of these part types are built on bulk CMOS processes. The other parts are fabricated on conventional linear bipolar processes which make them susceptible to enhanced low dose rate sensitivity (ELDRS) [1]–[5]. In addition, unbiased bipolar devices are often more sensitive to radiation damage at low dose rates than biased devices [6]. The objective in most cases is to determine whether the biased or unbiased condition represents the worst-case condition during irradiation and to determine if these devices are susceptible to ELDRS. The results described below characterize these devices for use in a wide range of dose environments of space.

Results from total dose characterization tests of six specific device types from different manufactures are reported. Table I provides the part number, die manufacturer and date codes of tested part types. These devices were acquired directly from the manufacturer for flight purposes.

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II. SETUP AND APPROACH

A. Total Dose Facility

Total dose irradiations for the AD823, LM136-2.5, LTC1417, MC35072, DG304A, and the AD590 were performed at the high and low dose rate (HDR and LDR) Co-60 range sources at the Jet Propulsion Laboratory, Pasadena, CA. These facilities each have a Shepherd Co-60 irradiator, which irradiates into an open vault. High dose rate exposure for the LTC1417 and AD823 was 25 rad(Si)/s. Low dose rate exposures for the AD823, and LM136-2.5 device samples were 0.005 rad(Si)/s. The gamma ray tests corresponding to the AD590 devices were done at a dose rate of 0.005 rad(Si)/s, in a series of steps up to a total dose of 60 krad(Si). Samples of the MC35072 were tested in both biased and unbiased condition at low dose rates of 0.01 rad(Si)/s. The DG304A devices were irradiated under biased conditions at high dose rate using specific cumulative dose levels in order to obtain subsequent parametric measurements.

B. Electrical Tests

The AD823, LM136-2.5 and MC35072 electrical tests were performed on the Eagle ETS-300 mixed-signal automated test system. The LTC1417 devices were electrically tested at successive dose levels on a LTS2020 mixed signal automated test system. Samples of the AD590 were mounted on a temperature-controlled plate (part of a Melles-Griot DTC 101 temperature controller) that established the device temperature. The temperature sensitivity was determined by making electrical measurements at three temperatures: 10°C, 30°C, and 50°C. An Omega MDSS 41TC thermometer was used to monitor the device temperature during electrical measurements. The Eagle test system was utilized to perform the electrical measurements on the DG304.

C. Procedure

The LM136-2.5 device samples were irradiated in two separate groups. One group was irradiated without bias (all pins grounded), while the other group was irradiated with a nominal forward current of 1 mA. The voltage across the device was nominally 2.5 V for the biased samples. Sixteen AD823 device samples were irradiated in four separate groups.

Two parts in biased conditions and two in unbiased conditions

TABLE I
CLASIFICATION OF TESTED PARTS

Part Number	Generic	Description	Die Manufacturer	Date Code	Technology	Package	Failure Parameters
AD823AR	AD823	Dual, 16 MHz, Rail-to-Rail FET Input Amplifier	Analog Devices	0237 Non Flight 9821 Flight	Bipolar	8 lead SOIC (SO-8)	Offset voltage Input offset current \pm Input Bias Current
8E501-K001-RB	LM136-2.5	Voltage Reference Diode	National	C1-R11	Bipolar	5 parts: 14 pin DIP by Interpoint 10 parts TO-46 COTS	Reference voltage Dynamic impedance
LTC1417AGC	LTC1417	14-bit Serial Analog to Digital Converter	Linear Technology	0240	CMOS	8 pin SOIC	Positive supply current I_{DD} Integral Non Linearity
8E505-K001-RB	MC35072	Operational Amplifier	Motorola	B1-R13	Bipolar	14 pin DIP	Offset voltage under unbiased conditions
5962-8757104XA	AD590	Temperature Transducer	Analog Devices	0145	Bipolar	1 part: TO-52 metal can 16 parts: 2-lead, 0.087in ceramic flat package	Output current under unbiased conditions "Off" leakage current
JM8510/11605B IC	DG304	Dual Analog Switch	Siliconix	9739	CMOS	10 pin TO-5	On resistance Switching time

were exposed to high rate while six parts in biased conditions and six parts in unbiased condition were exposed to low rate irradiations.

Ten samples of the LTC1417 were procured from a flight lot. One of these samples was retained as a control unit. General test procedure was in accordance with MIL-STD-883, method 1019, although the dose rate was shortly low. Samples of the MC35072 device were divided into two groups of two parts for biased and three unbiased low rate irradiations. Sixteen AD590 devices were obtained from JPL Flight Stores from a single date code. One of the sixteen flight devices was used as a control device along with a commercial AD590. The remaining fifteen devices were split into three groups of five. Each of the three groups was irradiated with different bias conditions. One group was unbiased during irradiation, the second group was irradiated with 5 volts, and the third group was irradiated with 15 volts. The radiation levels used for this test ranged from 1.3 to 60.4 krad(Si).

Eight samples of the DG304A were irradiated at high dose rate under the bias condition of $V_{DD} = 12V$ and $V_{SS} = -12V$. These devices were separated into two groups of four parts each. Both groups (G2 and G3) had cumulative dose levels with subsequent parametric measurements made at various increments varying from 0.5 to 5.0 krad(Si) and from 0.5 to 2.5 krad(Si), respectively. After the last irradiation level, devices were annealed (with bias applied) at 100 degrees C for 168 hrs. A final parametric measurement corresponding to an effective total dose at low dose rate of 1.65krad(Si) was expected to be made at the end of the 168 hr period at ambient temperature. However, due to equipment malfunctions it was not possible to make measurements after the 48 hr period. Table II describes the irradiation bias conditions of parts that were tested under bias. Devices tested under unbiased conditions had all leads shorted.

TABLE II.
IRRADIATED PARTS UNDER BIAS CONDITIONS

Device	Function	Bias Conditions
AD823	Op-Amp	$V^+ = 5V$ & $15V$, $V^- = -5V$ & $-15V$, $V_{cm} = 0V$, voltage follower
LM136-2.5	Voltage reference	$I_f = 1mA$, $400\mu A$ & $1mA$ $V_z = 2.5V$
LTC1417	A/D Converter	$V_{DD} = +5V$, $V_{SS} = -5V$
MC35072	Op-Amp	$V^+ = 5V$, $V^- = -5V$ & $V^+ = 15V$, $V^- = -15V$
AD590	Temperature transducer	$V_{CC} = 5V$ & $V_{CC} = 15V$
DG304	Analog switch	$V_{DD} = 12V$, $V_{SS} = -12V$

III. TESTS RESULTS

A. AD823

The AD823AR dual, 16 MHz, rail to rail FET input amplifier exhibited some susceptibility to ELDRS. In general, all parameters corresponding to these samples revealed moderate degradation. However, no device failed the manufacturer's specification limit at any of the stated levels. All biased and unbiased devices exposed to low dose irradiation continued to meet specification to 16 krad. Effects with the change in input bias current are observed in Figure 1, which is roughly twice as large for the unbiased group than for the biased group. Extreme changes in the input offset voltage under biased conditions for both flight and non flight parts (illustrated in Fig. 2) exceeded the manufacturer's specs. Note that only selected plots showing the device outstanding behavior are observed in the figure for simplicity purposes.

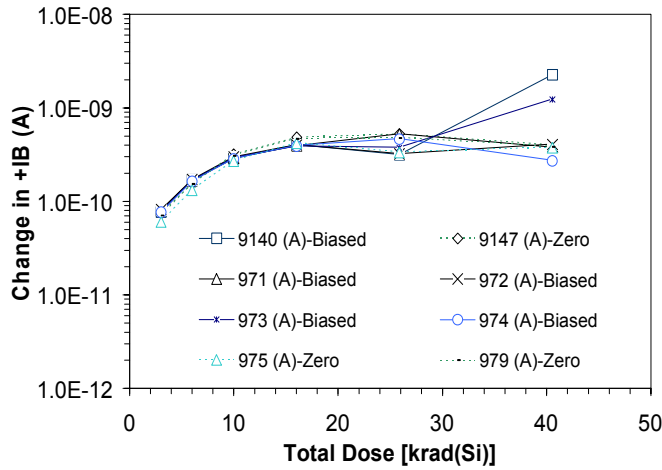


Fig. 1. AD823 rail to rail FET input amplifier exhibits effects with the change in positive input bias current versus total dose after low dose irradiation exposure (biased condition is $\pm 15V$).

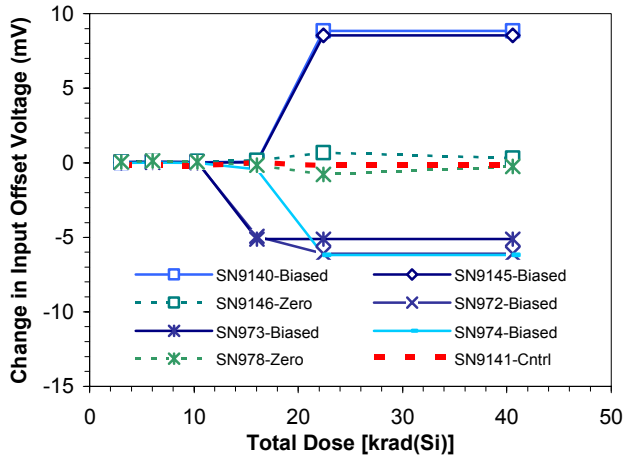


Fig. 2. The AD823 amplifier reveals extreme changes in input offset voltage versus total dose under $\pm 15V$ biased conditions. Both flight and non flight parts failed parametric specs.

B. LM136-2.5

This LM136-2.5 voltage reference diode exhibited electrical specifications that allow the voltage to be $2.5 \pm 0.04 V$. Thus, small changes in voltage after irradiation were generally well within the specification limit (nominally $\pm 1.6\%$). However, the specifications also included a long-term stability condition, typically 20 ppm, which was about three orders of magnitude smaller than the initial voltage tolerance. The radiation degradation was considerably larger than the long-term stability specification, which would affect applications where the circuit had been adjusted for a specific voltage from the LM136, relying on long-term stability. The test results were analyzed, evaluating changes in each parameter at various radiation levels (from 2krad to 20krad) and derating the results by the mean value plus three times the standard deviation. Parametric degradation was observed in voltage reference and dynamic impedance (Figures 3 & 4, respectively), under both biased and unbiased conditions. Note that in Fig. 3, the device behavior of eight parts is observed and in Fig. 4, the plots of five devices are shown for simplicity purposes.

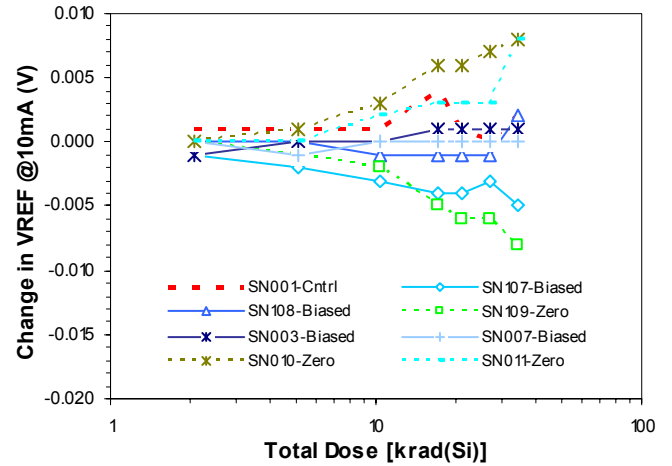


Fig. 3. LM136-2.5 voltage reference diode exhibits changes in voltage reference versus total dose for both biased condition at 10mA and unbiased condition.

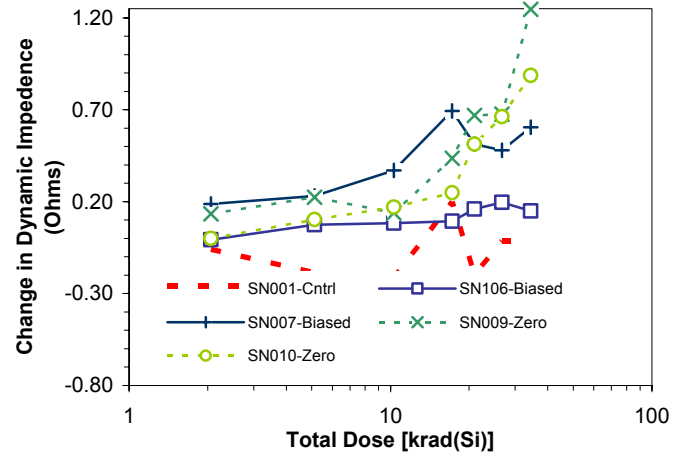


Fig. 4. The LM136-2.5 device shows changes in dynamic impedance versus total dose under biased and unbiased conditions.

C. LTC1417

The Linear Technology LTC1417 analog to digital converter exhibited severe parametric degradation and failure at levels greater than 30 krad(Si), with significant increase in all parameters especially integral nonlinearity (INL) as shown in Figure 5, differential nonlinearity (DNL), Bipolar Offset, and Bipolar Gain Error. All device parameters remained within the manufacturer's pre-radiation specification for test levels up to and including 30 krad (Si). The only parameters showing any significant changes were the positive and negative supply currents, I_{DD} (Fig. 6) and I_{SS} , increasing to 1mA and 100uA, respectively. As a result of these increases in supply current, modest increases in both bipolar and unipolar power dissipation were observed.

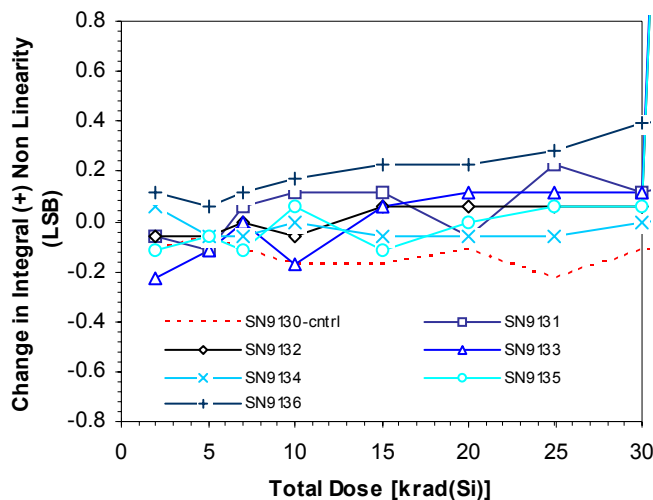


Fig. 5. The LTC1417 14-bit serial analog to digital converter reveals changes in integral nonlinearity (INL) versus total dose under biased conditions.

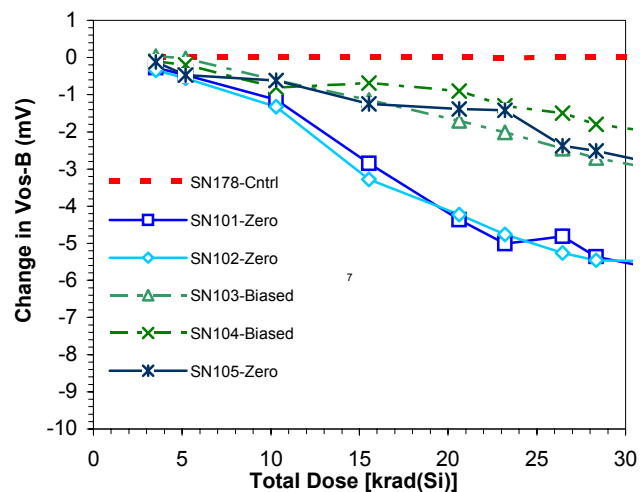


Fig. 7. The MC35072 operational amplifier in unbiased condition exhibits parametric failures in the (B) sides of input offset voltage.

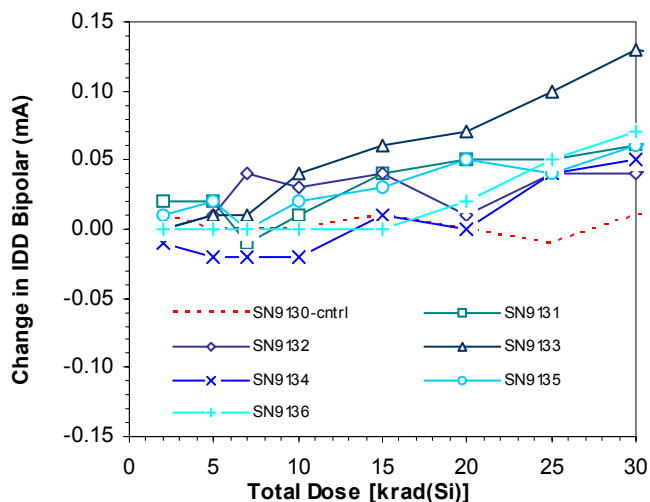


Fig. 6. LTC1417 device exhibits a significant positive supply current change increasing to 1mA under biased conditions.

D. MC35072

The Motorola MC35072 operational amplifier devices performed within specification (in both biased and unbiased conditions) to 20 krad(Si). At 30 krad(Si), two of the zero biased test devices were exhibiting parametric failures in the (B) sides of the devices for input offset voltage at supply voltages of $\pm 5V$ and $\pm 15V$. Parametric failure for input offset voltage was only seen for the zero biased case, no failures were seen in the biased units. All of the failures seen for input offset voltage were marginal. Figure 7 illustrates the failing input offset voltage marginally at 30 krad when devices were biased with $\pm 15V$. Similar behavior applies for the $\pm 5V$ biased devices. All other parameters meet specification to the highest level tested to 30 krad(Si).

E. AD590

The AD590 devices irradiated with an applied bias voltage of 5 volts and 15 volts were far less affected by radiation exposure than the unbiased samples. Both of the biased groups had their output currents reduced by approximately 2 to 5% at the maximum radiation level tested of 60 krad(Si). Much larger changes occurred for the group of devices that was unbiased during irradiation. Figure 8 shows an example of device current degradation for parts that were irradiated unbiased (worst case) and measured at 30°C. Initially, only small changes occurred with a nearly linear dependence on total dose. The response became highly nonlinear above approximately 15 krad(Si). The transition between linear and nonlinear behavior depends on the device applied voltage, occurring at lower total dose levels for low power supply voltages. The transition dose varied somewhat among the five samples in the test group. For $V_{cc} = 5V$ the transition region started between 15 and 22 krad(Si) for the five parts.

Corresponding to the devices that were unbiased during irradiation, the slope of the temperature sensitivity became highly nonlinear at about the same total dose level where large changes in the 30 °C temperature value occurred. Figure 9 shows the output current for the three temperatures that were used at all radiation levels for a typical device that was irradiated without bias. The slope is particularly nonlinear between approximately 15 and 30 krad(Si). The slope of the devices that were irradiated with bias applied remained nearly the same after irradiation. However, some evidence of nonlinearity was seen at the higher total dose levels.

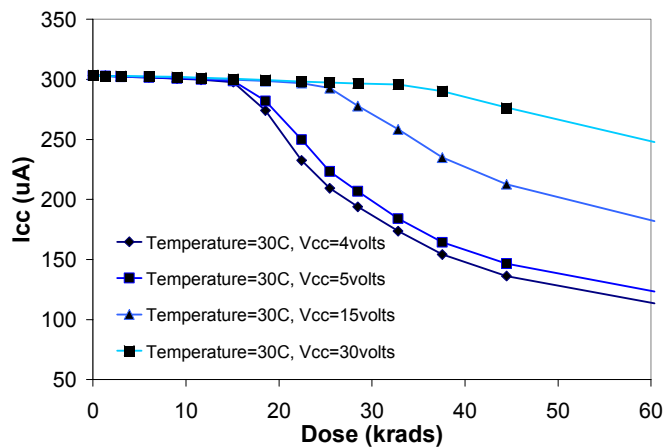


Fig. 8. The AD590 temperature transducers exhibited output current degradation for parts irradiated under unbiased conditions and measured at 30°C. The transition region started between 15 and 22 krad(Si).

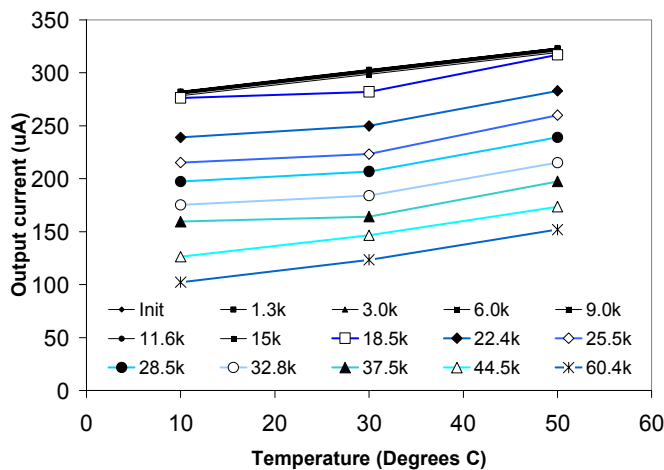


Fig. 9. This AD590 device exhibits outstanding changes in the output current for the three temperatures utilized in all radiation levels for a typical device under unbiased irradiation conditions.

F. DG304

This DG304 exhibited large changes in three key parameters: – “off” leakage current, on resistance, and switching time – after irradiation at high dose rate (Figures 10, 11 and 12, respectively). The leakage current of this switch in the “off” condition increased after irradiation (Figure 10). The specification limit for this parameter is 100nA. Very low total dose levels cause this leakage current to increase by about four orders of magnitude above the specification limit at 5 krad(Si). This degradation is caused by subthreshold conduction in the n-channel transistors. Data for the unirradiated control device is also shown in the figure.

In addition, preliminary results corresponding to this DG304 devices with an effective low dose rate of 1.6krad(Si) exhibited changes in the parameters of drain leakage current, on resistance and switching time (Figures 13, 14, and 15, respectively). These devices were irradiated to 2.5 krad(Si) and annealed for 1, 2 and 24 hours. Devices annealed at 48hr period exhibited increasing conditions in all three key parameters. The large leakage current observed under high

dose rate conditions recovered. This was expected because the hole traps that produced negative threshold shift at high dose rate anneal, leaving a net positive threshold shift after high-temperature annealing and the on resistance increased. This effect was consistent with expected behavior where interface traps “stretch” the subthreshold conduction characteristics, increasing the subthreshold slope. The switching time continued to increase with annealing time, requiring a correction factor to adjust for the expected increase after 168 hours.

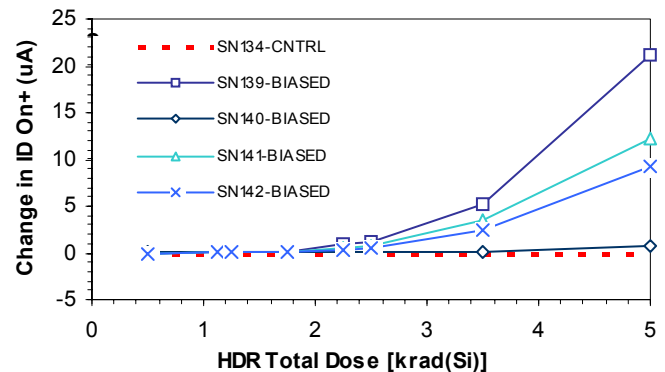


Fig. 10. The DG304 devices exhibited change in drain leakage current for the G2 series of devices during irradiation at high dose rate.

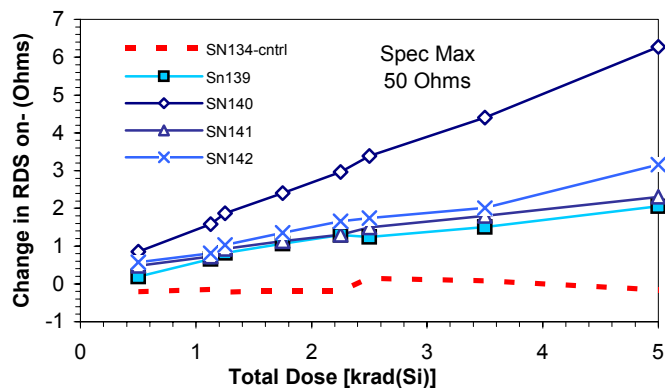


Fig. 11. The DG304 revealed change in $R_{DS(on)}$ for the G2 series of devices during irradiation at high dose rate.

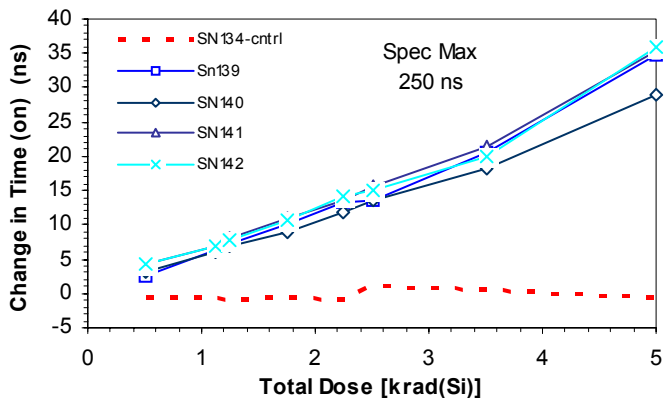


Fig. 12. The DG304 demonstrated change in (on) switching time for the G2 series of devices after irradiation at high dose rate.

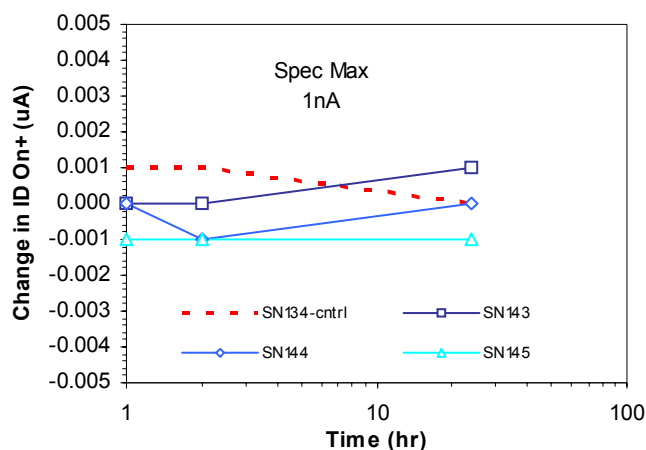


Fig. 13. The DG304 (G3 series) showed evidence of recovering condition in "On" drain leakage current after 24hrs of high-temperature annealing.

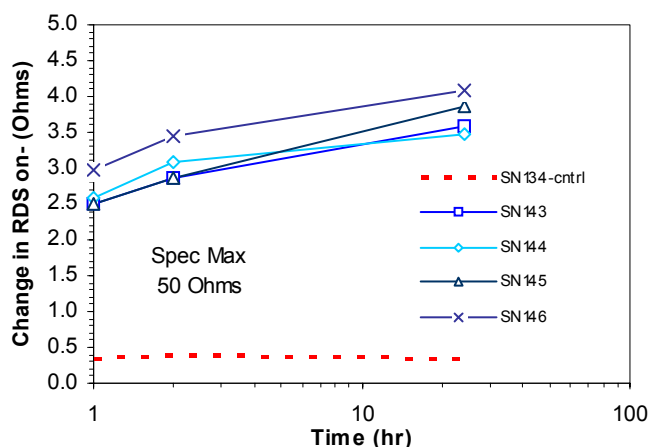


Fig. 14. The DG304 (G3 series) exhibited increasing change in on resistance after 24hrs of high-temperature annealing.

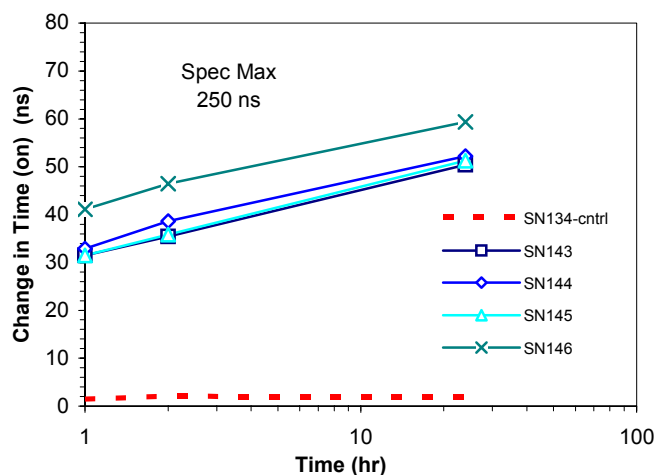


Fig. 15. The DG304 G3 series revealed change in switching time after 24 hrs of high-temperature annealing.

IV. DISCUSSION

The devices tested with the low dose rate test condition exhibited improved low dose rate sensitivity resulting in more parametric degradation than the high dose rate case. The worst case represented by the biased or unbiased conditions with

respect to radiation effects was dependent on the device type and its specific parameter. The AD823 device samples tests have been performed for the MRO program. The LM136 and the AD590 were fabricated with bipolar linear integrated circuit processes which are sensitive to enhanced damage at low dose rate (ELDRS).

The LTC1417 device samples were tested to characterize this device for use in ionizing dose environments of space and to determine Radiation Lot Acceptance Testing (RLAT) acceptance. The MC35072 tests were performed to characterize an element in a hybrid DC/DC converter design. However, due to limited sample size, it was necessary to test to higher TID levels to obtain statistical data to ensure 99/90 confidences that the flight lot of parts meet the TID requirement. The DG304 data reported is considered preliminary since the 168 hr time interval was not achieved due to malfunctions after the 48 hr period.

V. CONCLUSION

The radiation results described in this paper are an expansion of previous efforts to characterize standard bipolar and CMOS devices for total dose environments. These results provide the essential information to determine whether biased or unbiased condition yields the worst case scenario during irradiation. Significant TID effects for CMOS devices under bias conditions were observed. Bipolar devices under unbiased conditions exhibited more damage than the bias case. For instance the AD590 output current degradation failure occurred only for the unbiased devices. The JFET input bias current exhibited significantly higher levels of degradation for unbiased units. In addition, all bipolar devices demonstrated ELDRS susceptibility. Thus, the JFET input op-amp exhibited moderate degradation in the input bias current parameter up to 25 krad(Si) with significant increases in input bias current for TID levels greater than 30 krad(Si). This data is intended to be used as a model to improve designs in space applications.

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