Total Ionizing Dose Effects in Bipolar and BiCMOS Devices

Rosa M. Chavez, Bernard G. Rax, Leif Z. Scheick and Allan H. Johnston

Abstract—This paper describes Total Ionizing Dose (TID) test results performed at JPL. Bipolar and BiCMOS device samples were tested exhibiting significant degradation and failures at different irradiation levels. Linear technology which is susceptible to low-dose dependency (ELDRS) exhibited greater damage for devices tested under zero bias condition.

Keywords-Bipolar, Complementary Metal Oxide Semiconductor (CMOS) Enhanced Low Dose Rate Sensitivity (ELDRS), Low Dose Level (LDL), and Total Ionizing Dose (TID)

I. INTRODUCTION

The purpose of the TID tests described in this paper is to characterize these microelectronic devices in total ionizing dose environments in order to determine if they can be used in spacecraft designs. Most tested devices described in this paper are processed using bipolar technology with lateral pnp structures, having susceptibility to enhanced low dose rate sensitivity (ELDRS) [1]. Total dose test results from earlier tests have revealed greater degradation at low dose rate for these types of linear integrated circuits [2-3]. The bias condition during the test is an important factor for this type of devices. Previous work has shown that bipolar devices tested under zero bias condition are more sensitive to gamma irradiation damage at low dose rates than biased devices [4].

The characterization of five different bipolar linear circuits and one BiCMOS device is presented in this summary. They consist of four voltage regulators, an operational amplifier and a digital to analog converter. Thus, the results obtained on the six specific device types provide valuable information to spacecraft projects and device designers. All devices were obtained directly from specific manufacturers for flight purposes.

TABLE I. DEVICE DESCRIPTION

| Part Number | Description of Tested Devices |
|-------------|-------------------------------|
| LP2951      | National Semiconductor H9D0248D CERPACK 10-PIN |
| LM2941      | National Semiconductor 0317 & 0337 CERPACK 16-PIN |
| OP97        | Analog Devices 0415K 8-PIN plastic IC |
| DAC8413     | Analog Devices 0424F 28-lead plastic DIP |
| HYSE117RH   | Intersil 0303 & 0343 TO-257 |
| RH137       | Linear Technology 0211A TO-39 |

B. Electrical Tests

The Eagle ETS-300 mixed-signal automated test system was utilized to measure electrical tests on the LM2941, LP2951, DAC8413, HYSE117RH, and RH137 devices. The OP97 samples were electrically tested on the LTS2020 mixed signal automated test system. Device samples were tested at consecutive dose levels within 1 to 2 hours of each exposure level, interrupting the irradiation for relatively short time periods. A control device was measured before each set of measurements to ensure that the tester, socket and test fixture operated as expected throughout the several week period.
required for the tests. Irradiation exposure was performed at ambient temperature (20-25 °C).

C. Test Procedure

For the LM2941 devices, six samples from two different date codes (total of 12 samples) were provided from flight lots. The samples were split into two groups; the first group was irradiated to the dose corresponding to a 3-year mission, and the second group was irradiated to the dose corresponding to a 5-year mission. A power supply voltage was applied to the biased test samples during irradiation, and the output loaded to about 10 mA. The unbiased devices were irradiated with all pins at ground potential. Bipolar devices under unbiased conditions are often more sensitive to radiation damage at low dose rates than biased devices [4]. The test procedure was in accordance with MIL-STD- 883, method 1019.

A total of 10 samples of the LP2951 device were used for testing. Five devices were irradiated with a six-volt bias applied, with a nominal output voltage of 5 V. The load current during irradiation was 1 A. The five other devices were irradiated with all pins grounded. The radiation tests for the OP97 were performed at the same cumulative dose levels for both biased and zero bias condition. Six samples were irradiated under bias, and five parts were irradiated without bias. The DAC8413 was tested under both bias and zero bias condition. The bias condition loads the full-scale value into the digital to analog converter. Six samples were irradiated under bias, and five parts were irradiated without bias. Parts under zero bias condition had all pins shorted with respect to ground.

The HYSE117RH devices were obtained from two lot date codes; six samples from each date code were tested. These devices were pre-irradiated with protons, and exposed to low dose irradiation afterwards. The samples were split into two groups; the first group was irradiated to the dose corresponding to a 3-year mission, and the second group was pre-irradiated corresponding to a 5-year mission. The RH137 device samples were tested under both biased and unbiased conditions. These parts were pre-irradiated to a dose of a 3 and 5 year missions, respectively. Table II lists the irradiation bias conditions of all devices. Devices tested under zero bias had all pins grounded.

### Table II. Bias Condition

| Technology | Device Function | Bias Condition |
|------------|----------------|----------------|
| Bipolar    | Voltage Regulator | V = 6V & I1 = 5mA, V = 6V & I1 = 1A |
| Bipolar    | Voltage Regulator | V = 6V & I1 = 1mA |
| Bipolar    | Operational Amplifier | Vcc = -12V, Vee = -12V |
| BiCMOS     | Digital to Analog Converter | V = 6V & I1 = 10mA |
| Bipolar    | Voltage Regulator | V = 5V & I1 = 500mA, V = 5.5V & I1 = 25, 75mA, V = 12V & I1 = 25, 75mA, V = 6V & I1 = 50, 100, 500mA |
| Bipolar    | Negative Voltage Regulator | V = -10V & I1 = 100mA, V = -15V & I1 = 100mA |

D. LM2941

The LM2941 low-dropout voltage regulator with a high load of 1A exhibited a catastrophic failure. The test results with high circuit load are due to the lateral pnp pass transistor gain which has a large effect on circuit performance with maximum load. The results for unbiased devices for a 1A load are shown in Figure 1. The general nature of the response is nearly the same for both test groups. Initially the voltage begins to decrease gradually with increasing levels of radiation. However, there is an abrupt decrease in voltage (it essentially falls to zero) that is almost certainly due to decrease in the gain of the lateral pnp pass transistor to the point where it can no longer support the 1-A load condition.

All three devices (under unbiased condition) from Date Code 0337 were closely grouped, exhibiting catastrophic failure at approximately 19 krad(Si). Devices from the other date code exhibited far greater variability, with a catastrophic failure range of 17 to 24 krad(Si). This indicates that devices from the date code 0337 are a better choice because of their improved uniformity.

The samples that were biased during irradiation behaved differently. None of the devices from Date Code 0337 (5-year proton pre-irradiation) exhibited catastrophic failure, unlike the unbiased samples from that same group. That is consistent with other results on similar low dropout regulators as well as tests of more fundamental circuits where the enhanced damage at low dose rate is significantly higher for samples that have been tested without bias.

In addition, parts tested with a light load of 5mA exhibited some degradation and no failures. The output voltage corresponding to the unbiased case decreased gradually as the radiation level increased for both the 3 and 5 year missions. Damage in the biased samples was two to three times less than that for the unbiased case. Unlike the unbiased samples, the response modes were different for the 3 and 5-year units that were biased during irradiation. The output voltage of the 3-year samples decreased with increasing radiation levels. In
contrast, the output voltage of the 5-year units increased with increasing levels of total dose. This effect could be caused by the higher proton fluence used to pre-irradiate the 5-year samples, or perhaps by different characteristics of the two different date codes.

E. LP2951

Two basic failure modes were observed in the LP2951 devices. The first mode was a gradual decrease in output voltage that was consistent with changes in the internal reference voltage. Figure 2 shows the behavior of one of the devices for a load current of 1 mA. Although the figure shows positive changes to make it compatible with logarithmic plotting conventions, the output voltage actually falls after radiation. It is important to note that the internal reference voltage degradation reduces the output voltage by approximately 100mV at a total dose of 20 krad(Si).

F. OP97

The OP97 operational amplifier exhibited severe parametric degradation and failures at levels greater than 7.5krad(Si). Thus, above 7.5krad irradiation level, the bias current of the two inputs was drastically different. Bias current of the positive input continued to increase in a smooth, regular way, with the same sign. Bias current of the inverting input changed sign, becoming positive, and increased by nearly an order of magnitude as illustrated in Figure 4. This will cause an imbalance in typical circuit applications. The radiation level at which the input current changed sign was much larger for one of the five unbiased devices. This suggests that there will be large unit-to-unit variations in the level at which the second failure mode becomes important.

Input bias current was affected quite differently for this device compared to that of most op-amps. At low radiation levels, the input bias current of both the positive and negative (inverting) inputs increased in a smooth, regular way (the current was negative, indicating that the pnp current source provided slightly more current than the base current required for the npn input transistor). The degradation of both inputs “tracked”, providing first-order cancellation in a typical circuit application with similar source resistance values for both inputs.
G. DAC8413

Devices were tested up to a total ionizing dose level of approximately 20 krad(Si). Samples tested under the biased condition exhibited more parametric degradations than the zero bias samples up to the highest tested radiation level. All devices remained functional with some degradation to a radiation level of 10 krad(Si). Failures at greater levels were observed. The supply current showed significant changes between dose levels of 14 krad(Si) and 20 krad(Si) as illustrated in Figure 5. Both the positive and negative Integral Nonlinearity Error (±INL) and the positive and negative Differential Nonlinearity Error (±DNL) parameters behaved closely similar, exhibiting the same failures. The Negative Scale Error showed a constant failure which was observed at a dose level of 14 krad(Si).

H. HYSE117RH

These devices were tested according to two specific applications requested by the project in which the load currents were near 75 mA, far lower than the maximum load current of 1.25 A. Figure 6 shows changes in output voltage for the 5-year mission with an input voltage of 5.5 V. Two mechanisms are evident. The output voltage initially increases during the low dose rate irradiation, but becomes negative as the total dose level increases. Larger changes occur in the group of devices that were unbiased, but the unit-to-unit differences are greater for the biased devices. Note that similar results apply to the 3-year mission tests.

Reference voltage was measured with a 200mA load current. The effects of total dose irradiation on reference voltage are shown in Fig. 8 for the 5-year mission (irradiated without bias). Similar results were observed for the 3-year mission. The mean value and de-rated value are also shown in the figure. The absolute value of the reference voltage decreased steadily with increasing total dose levels, similar to that of other voltage regulators with internal bandgap references [6]. Output voltage was measured at 100mA load for both of the output voltage conditions (10 and 15 V). Relatively small changes occurred.

I. RH137

The RH137 negative voltage regulator exhibited some degradation. Reference voltage was measured with a 200mA load current. The effects of total dose irradiation on reference voltage are shown in Fig. 8 for the 5-year mission (irradiated without bias). Similar results were observed for the 3-year mission. The mean value and de-rated value are also shown in the figure. The absolute value of the reference voltage decreased steadily with increasing total dose levels, similar to that of other voltage regulators with internal bandgap references [6]. Output voltage was measured at 100mA load for both of the output voltage conditions (10 and 15 V). Relatively small changes occurred.
Figure 8. Mean and adjusted mean of reference voltage vs. total dose for the 5-year mission. Devices were unbiased during the irradiation.

II. CONCLUSIONS

The radiation results reported in this paper are a collection of previous tests achieved in the low dose irradiation facility at JPL in order to characterize bipolar and BiCMOS devices for total dose environments. These results provided the fundamental information to determine whether biased or unbiased condition yields the worst case situation during gamma irradiation. Bipolar devices under unbiased conditions exhibited severe degradation and failures. The biased condition for the BiCMOS technology was shown to be the worst case where severe degradation was observed. The obtained results are intended to be used in space applications and to improve microelectronic designs.

The LP2951 device samples tests were intended for the Mars Reconnaissance Orbiter (MRO) program. The LM2941, HYSE117RH, and RH137 parts were used in the Ocean Surface Topography from Space-Missions (OSTM) project on the Advance Microwave Radiometer (AMR). Both the OP97 and the DAC8413 device tests were performed for the Space Technology 7 (ST7) mission.

REFERENCES

[1] A. H. Johnston, B.G.Rax and C. I. Lee, “Enhanced Damage in Linear Integrated Circuits at Low Dose Rate,” IEEE Trans. Nucl. Sci., 42(6), pp. 1650-1656 (1995).
[2] S. S. McClure, et al., “Dose Rate and Bias Dependency of Low Dropout Voltage Regulators,” 2000 IEEE Radiation Effects Data Workshop Record, pp. 100-105.
[3] R. L. Pease, et al., “Enhanced Low Dose Rate Sensitivity of a Low-Dropout Voltage Regulator,” IEEE Trans. Nucl. Sci., 45(6), pp. 2571-2576 (1998).
[4] S.S. McClure, J. L. Gorelick, C. C. Yui, B. G. Rax, M. D. Wiedeman, “Continuing Evaluation of Bipolar Linear Devices for Total Dose Bias Dependency and ELDRS Effects,” 2003 IEEE Radiation Effects Data Workshop Record, pp. 1-5, 2003.
[5] B. G. Rax, C. I. Lee and A. H. Johnston, “Degradation of Precision Reference Devices in Space Environments,” IEEE Trans. Nucl. Sci., 44(6), pp. 1939-1944 (1997).