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Enhanced Low Dose Rate Sensitivity at Ultra-Low Dose Rates

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35-word Abstract: We observed ELDRS for dose rates from 10 to 0.5 mrad(Si)/s in commercial and radiation hardened devices. We discuss the implications of the results for radiation hardness assurance of linear bipolar circuits.

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I. Introduction

Linear bipolar circuits are known to exhibit enhanced-low-dose-rate-sensitivity (ELDRS) in an ionizing radiation environment. ELDRS has introduced new challenges for radiation hardness assurance. The primary difficulty is the significant irradiation time required to examine a part for ELDRS, which is a burden to a project's schedule and budget. The current accepted lot acceptance test, MIL-STD-883G, TEST METHOD 1019.8, requires irradiation at an agreed dose rate, with a maximum dose rate of 10 mrad(Si)/s, or using an accelerated test [1]. The low dose rate enhancement factor (LDR EF) is the ratio of the radiation-induced shift of a device parameter at low dose rate to that at high dose rate. The part is considered ELDRS susceptible if the EF is ≥ 1.5, given that the post irradiation parameter is above the pre-irradiation specification limits [1]. Although several accelerated test methods exist, such as the switched-dose rate and elevated temperature irradiation, their applicability is inconsistent, impractical and/or unproven for a large enough sample of circuit types [3]–[4]. The most reliable test method is to irradiate at a dose rate ≤ 10 mrad(Si).

There has been a substantial amount of research in efforts to understand the physical mechanisms for ELDRS [2], [5]–[11]. A widely accepted model discusses the presence of metastable delocalized hole traps, which help to create a space-charge effect in the oxide during high dose rate irradiations [2]. The space-charge effect reduces the charge yield and creates a higher trapped electron density near the interface, thereby decreasing the oxide trapped charge and reducing the degradation at high dose rate [2]. More recent studies have also revealed the important role of hydrogen to ELDRS [7]–[8]. Hydrogen can react with a transporting hole or a metastably trapped hole and release a proton, which can survive recombination with greater probability at low dose rates [8]. Therefore more protons are available to form a higher density of interface traps at low dose rate [8]. In devices with higher hydrogen content, the degradation at a given dose rate increases [7]. We believe that a similar phenomenon will occur at ultra-low dose rates for devices that originally showed no ELDRS at ≥ 10 mrad(Si)/s, so that the transition point for exhibiting ELDRS is reduced to a lower dose rate. We show that the current standard dose rate of 10 mrad(Si)/s cannot safely bound the degradations at lower dose rates across various devices.

II. Experimental

We include more than twenty different part types from Linear Technology (LT), Texas Instruments (TI), National Semiconductor (NSC) and ST Microelectronics (STM) in this study. The parts consist of radiation hardened, which includes ELDRS-free (lot tested at 10 mrad(Si)/s), and commercial-off-the-shelf devices. Some devices are also available in a variety of package types: Flatpacks, TO metal cans, etc. A complete list of parts involved in this study can be found in the data workshop compendium [12].

The irradiations are performed with a ^{60}Co gamma ray source at room temperature. The dose rates are 10, 5, 1, and 0.5 mrad(Si)/s. Four to five samples of each part type are irradiated at each dose rate. And at least two samples of each part are used as controls. Most of the parts, including voltage regulators and references, are irradiated with all pins grounded. Some operational amplifiers are irradiated with both biased and unbiased (grounded) conditions.

III. Results

Figure 1 summarizes the low dose rate enhancement factors for several devices, at the initial total dose levels for which the enhancement factor exceeded 1.5 at any dose rate. The LM117 and TL750L voltage regulator also showed significant low dose rate enhancement. However, the magnitudes of the low dose rate enhancement for these two parts are much higher than those of devices in Fig. 1. Hence we will discuss their results in separate figures for clarity. Here we discuss results for several select parts.

We observed the most notable dose rate sensitivity response in the TL750L05CDR, a commercial low-dropout voltage regulator manufactured by TI. In our previous data workshop publication, we showed results for devices irradiated from 0.5 to 5 mrad(Si)/s [12]. We now include a more complete set

of results, with additional data at 10 mrad(Si)/s. Figure 2 shows the total dose level at which the first functional failure(s) occurred for each dose rate. The initial failures occurred after 60, 35, 20, and 10 krad(Si) for the parts irradiated at 10, 5, 1, and 0.5 mrad(Si)/s, respectively. The functional failures are characterized by the output regulation failure with 100 mA load, while remaining functional with 10 mA load. In some cases the output failed for both the 100 mA and 10 mA loading conditions. The failures were abrupt, without gradual degradation to the output voltage or any other measured parameter. The degradation behavior is similar to that of the 29372 low-dropout regulator from a previous study [10]. The failure is caused by the radiation-induced degradation to the maximum output drive current [10]. Consequently the output failed to regulate for the 100 mA load prior to failure with the 10 mA load. It is also possible that the radiation-induced leakage current becomes significant, so that the internal current limiting protection circuitry shuts down the device.

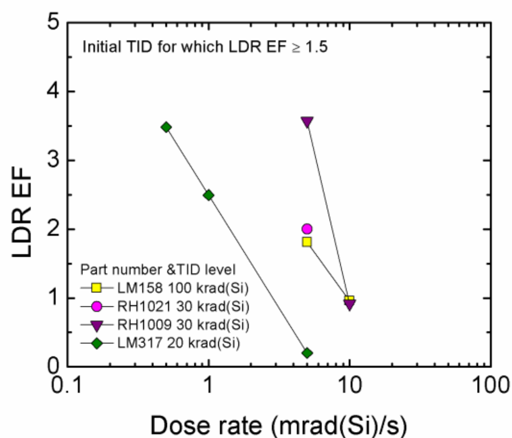

Fig. 1. Low dose rate enhancement factor (LDR EF) for various commercial and radiation hardened devices at the initial dose level that the EF ≥ 1.5.

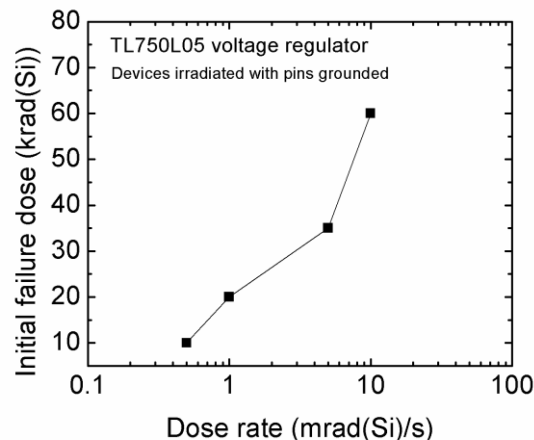

Fig. 2. Initial failure total dose vs. dose rate for the TL750L05CDR voltage regulator.

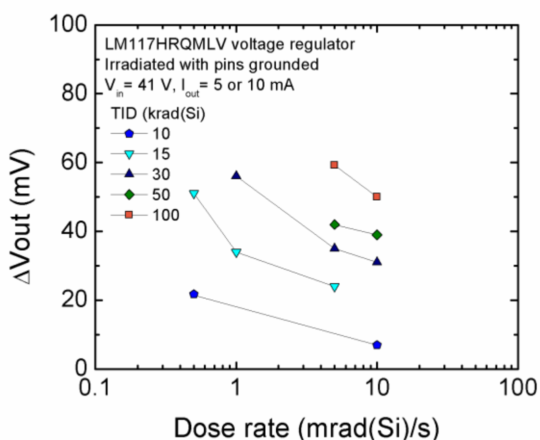

Fig. 3. Change in the output voltage vs. dose rate for the LM117HRQMLV radiation hardened (qualified at 10 mrad(Si)/s) voltage regulator.

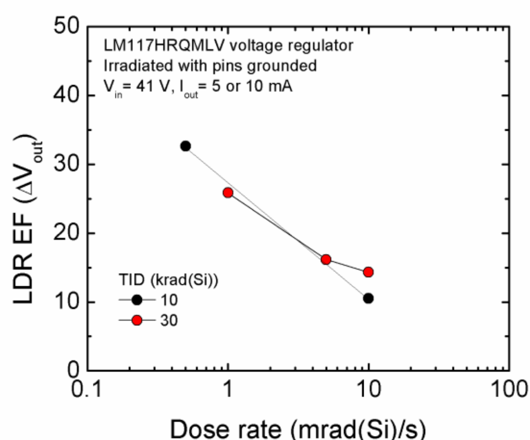

Fig. 4. Low dose rate enhancement factor for the LM117HRQMLV vs. dose rate at 10 and 30 krad(Si).

The LM117HRQMLV is an adjustable positive voltage regulator manufactured by NSC, qualified up to 100 krad(Si) at 10 mrad(Si)/s. We examine the dose rate sensitivity with Fig. 3, which shows the average change in the output voltage (ΔV_{out}) vs. dose rate. We observed evidence of dose rate sensitivity, where ΔV_{out} increases with decreasing dose rate. The trend becomes distinct after 10 krad(Si) total dose. The magnitude of ΔV_{out} also increases with increasing total dose. However at this stage of the irradiation,

we have yet to see the degradation saturation point. Figure 4 shows the LDR EF for ΔV_{out}. Although the parameter is within specification at 10 and 30 krad(Si) for all dose rates, the enhancement factor illustrates the significant low dose rate enhancement exhibited at dose rates lower than 10 mrad(Si)/s.

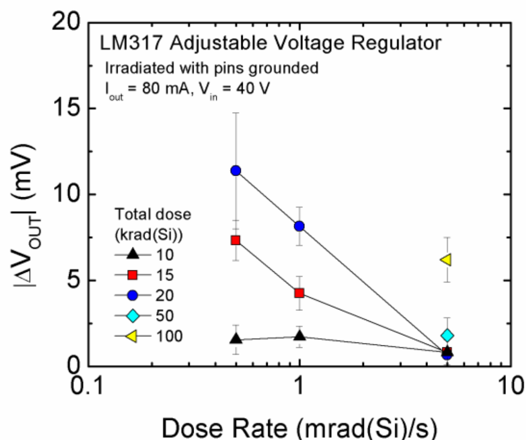

Fig. 5. Change in the output voltage vs. dose rate at 10, 15, 20, 50 and 100 krad(Si), for the LM317KTTR adjustable voltage regulator .

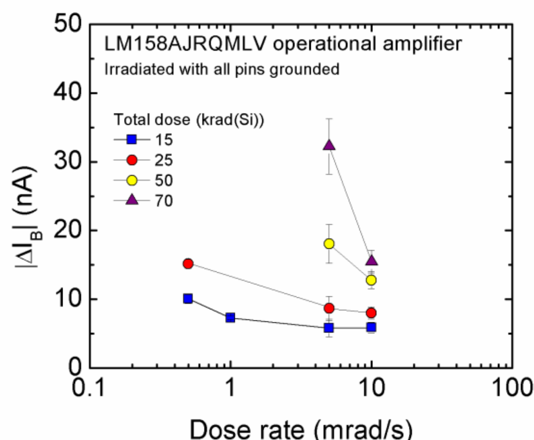

Fig. 6. Change in the input bias current vs. dose rate at 15, 25, 50, and 70 krad(Si), for the LM158AJRQMLV radiation hardened (qualified at 10 mrad(Si)/s) operational amplifier.

The LM317KTTR is a commercial adjustable voltage regulator from TI. Figure 5 shows the average ΔV_{out} vs. dose rate, with V_{in} = 40 V and I_{out} = 80 mA. We observed initial low dose rate sensitivity after 15 krad(Si). The LDR EF is less than 1 for all dose rates after 10 krad(Si), but increases with decreasing dose rate (with an value of ~ 3.5 at 0.5 mrad(Si)/s) after 20 krad(Si), as shown in Fig. 1. The fact that the LDR EF at 5 mrad(Si)/s is less than 1 suggests the degradation is lower than at high dose rate. This may be due to a higher standard deviation observed for the devices irradiated at high dose rate. We note that the parametric degradations are within specifications at this stage of the test.

The LM158AJRQMLV is a low power dual operational amplifier manufactured by NSC, qualified up to 100 krad(Si) at 10 mrad(Si)/s. Figure 6 shows the average change in the input bias current (ΔI_B) vs. dose rate. We observed the degradation increasing with decreasing dose rate after 25 krad(Si). However the LDR EF remained at less than 1 for all dose rates until after 70 krad(Si), where the parts irradiated at 5 mrad(Si) showed an EF of 1.2. The parametric degradation levels are within specification limits, with the exception of one part each at 0.5 and 5 mrad(Si)/s, which showed significantly higher degradations levels. We have not included the data from these two rogue devices here, but will discuss the results in further detail in the full paper. Although the parameters are within specification at this stage of the test, the trend suggests that the parts irradiated at 1 and 0.5 mrad(Si) will establish a higher LDR EF at a much lower total dose level.

IV. Discussion

We observed the dose rate sensitivity across commercial and radiation hardened devices. Several parts begin to show dose rate sensitivity after 10 to 30 krad(Si) for dose rates lower than 10 mrad(Si)/s. The degradation level increased with decreasing dose rate, down to the lowest dose rate tested at 0.5 mrad(Si)/s. While most devices which exhibited dose rate sensitivity still remain within specification, we also observed functional failures in the TL750L voltage regulator. The initial failure dose levels are noteworthy: 60 and 10 krad(Si), for devices irradiated at 10 and 0.5 mrad(Si)/s, respectively. Many space missions have requirements that lie within these total dose levels. Therefore, such a large difference in the TID tolerance level, caused by the enhanced sensitivity at ultra-low dose rates, will introduce critical mission risks. While some devices exhibited substantial dose rate sensitivity and degradation levels, other devices from similar wafer processes showed minor radiation-induced changes.

The effects of ELDRS on a linear bipolar circuit will vary significantly depending on the transistor layout and circuit design. In addition, the devices may have utilized different components on the same process. One design may be comprised of mostly vertical NPN transistors, while the other may consists of more lateral PNP transistors, which are relatively more susceptible to radiation-induced gain degradation at low dose rates [9], [11]. The different ICs may have also employed different design margins, which allow for varying degrees of degradation to a particular parameter. Previous studies by Johnston showed that the low dose rate degradation in linear circuits can be significantly higher than that of discrete bipolar transistors [9]. Therefore while the degradation rate of bipolar transistors from two different devices of the same wafer lot will be similar, the parametric degradation for the devices can contrast substantially.

The results here show that the current standard test method for total ionizing dose hardness of linear bipolar circuits cannot safely bound the degradation levels at dose rates lower than 10 mrad(Si)/s for all devices. The issue is further complicated by the high variance in the magnitudes of degradation levels exhibited by different devices. Consequently, it may not be sufficient to bound the degradation at these ultra-low dose rates by applying either a fixed overtest factor to the specification dose or increasing the parameter delta design margins, for a 10 mrad(Si)/s irradiation test or an accelerated test. The most reliable method is to test at the mission required dose rate. However, when a target mission dose rate is not given, it will be difficult to decide on a suitable dose rate to characterize ELDRS.

V. Conclusion

We have presented results of ultra-low dose rate irradiations (≤ 10 mrad(Si)/s) for a variety of radiation hardened and commercial linear bipolar devices. We observed low dose rate enhancement factors exceeding 1.5 in several parts. The worst case of dose rate enhancement resulted in functional failures, which occurred after 10 and 60 krad(Si), for devices irradiated at 0.5 and 10 mrad(Si)/s, respectively. Devices fabricated with radiation hardened processes and designs also displayed dose rate enhancement at below 10 mrad(Si)/s. Furthermore, the data indicated that these devices have not reached the damage saturation point. Therefore the degradation will likely continue to increase with increasing total dose, and the low dose rate enhancement will further magnify.

The cases presented here, in addition to previous examples, illustrate the significance and pervasiveness of low dose rate enhancement at dose rates lower than 10 mrad(Si) [9], [12], [13]. These results present further challenges for radiation hardness assurance of bipolar linear circuits, and raise the question of whether the current standard test dose rate is conservative enough to bound degradations due to ELDRS.

VI. References

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