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Displacement Damage in Bipolar Linear Integrated Circuits†

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Abstract

The effects of proton and gamma radiation are compared for several types of integrated circuits with complex internal design and failure modes that are not as straightforward as the input bias current mechanism that is frequently used to study damage effects in linear devices. New circuit failure mechanisms were observed in voltage regulators that cause them to fail at much lower levels when they are irradiated with protons compared to tests with gamma rays at equivalent total dose levels. Protons caused much larger changes in output voltage than tests with gamma rays, which limits the maximum radiation level of some types of voltage regulators in environments dominated by protons.

I. INTRODUCTION

Although many different processes can be used to manufacture linear integrated circuits, the process that is used for most circuits is optimized for high voltage -- a total power supply voltage of about 40 V -- and low cost. This process, which has changed little during the last twenty years, uses lateral and substrate pnp transistors that are available within the normal processing steps required for npn transistors. These pnp transistors have very wide base regions [1], increasing their sensitivity to displacement damage from electrons and protons. Although displacement damage effects can be easily treated for individual transistors [2,3], the net effect on linear circuits can be far more complex because circuit operation often depends on the interaction of several internal transistors. Note also that some circuits are made with more advanced processes with much narrower base widths [4,5]. Devices fabricated with these newer processes are not expected to be significantly affected by displacement damage for proton fluences below 1 x 10^{12} p/cm^2.

This paper discusses displacement damage in linear integrated circuits with more complex failure modes than those exhibited by simpler devices, such as the LM111 comparator, where the dominant response mode is gain degradation of the input transistor [6]. Some circuits fail catastrophically at much lower equivalent total dose levels compared to tests with gamma rays. For example, Figure 1 shows test results for a radiation-hardened op-amp with a JFET input stage. The device works satisfactorily up to nearly 1 Mrad(Si) when it is irradiated with gamma rays, but fails catastrophically between 50 and 70 krad(Si) when it is irradiated with protons.

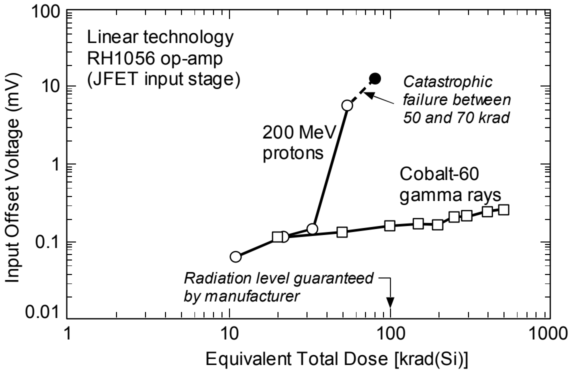

Figure 1. Degradation of the RH1056 op-amp from protons and gamma rays.

II. EXPERIMENTAL APPROACH AND CIRCUIT TECHNOLOGIES

The devices in this study were irradiated at the cyclotron at the University of California, Davis, using 50 MeV protons. The dose rate used for irradiation was approximately 40 rad(Si)/s, similar to dose rates often used for cobalt-60 irradiation of components. Dosimetry was determined with a series of thin secondary emission monitors, as described in Reference 7. One 50-MeV proton produces 1.59 x 10^{-7} rad in silicon [(1 x 10^{11} p/cm^2 is equivalent to 15.9 krad(Si)], and this equivalence factor is used throughout the paper to compare test results for protons with cobalt-60 gamma rays at equivalent levels. Differences in charge yield between gamma rays and protons results in slightly less transported charge in thick oxides with low fields [8], but that distinction is of secondary importance in the current study because the differences between circuit response are generally far larger.

Gamma ray testing was done at the JPL colbalt-60 irradiation facility at a dose rate of approximately 50 rad(Si)/s. The dose rates used for proton and gamma ray testing were nearly identical to ensure that dose-rate effects, which can be important for these types of devices, was not a factor in comparisons between the two environments. Electrical measurements were made with an LTS2020 integrated circuit test system and a Hewlett-Packard 4156 parameter analyzer.

The devices that were selected for the study are shown in Table 1. They include hardened and unhardened versions of the LM137 negative voltage regulator, and hardened and unhardened versions of the OP27 op-amp. Both circuits use far more complex internal designs than the basic comparators and op-amps that are usually used to study degradation in linear devices. The OP27 has a compensated input stage, which uses a lateral pnp current source to provide a compensated (negative) input bias current that nearly cancels

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Table 1. Devices Selected for Proton Testing

Device	Function	Manuf.	Comments
OP-27	Op-amp	Anal. Dev.	
OP-27	Op-amp	Lin. Tech.	
RH-27	Op-amp	Lin. Tech.	Hardened device
LM117	Voltage reg.	National	Positive reg.
LM137	Voltage reg.	National	Negative reg.
LM137	Voltage reg.	Linear Tech.	Negative reg.
RH137	Voltage reg.	Lin. Tech.	Hardened device

the positive input bias current required by the npn input transistor, as shown in Figure 2. Although this reduces the input bias current, it causes circuit operation to depend on the balance of this compensation scheme, which involves several different types of transistors.

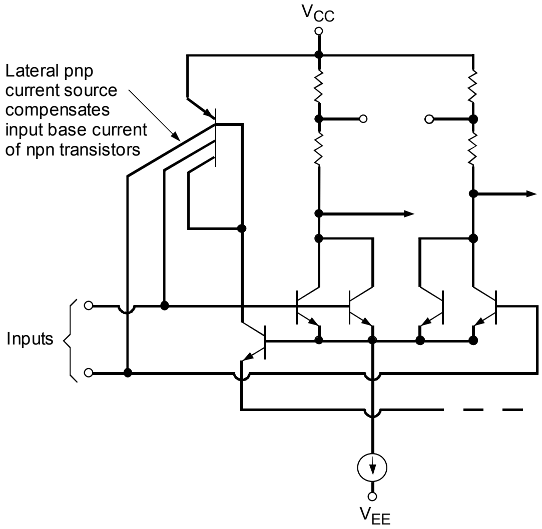

Figure 2. Simplified diagram of the compensated input stage used in the OP-17 op-amp.

The hardened process from Linear Technology is designed to withstand ionization damage, using a proprietary method for oxide growth. The process uses lateral and substrate pnp transistors that are physically similar to lateral and pnp transistors in conventional (unhardened) processes. The pnp structures in both the hardened and unhardened processes are inherently sensitive to displacement damage because of the relatively wide base regions.

III. EXPERIMENTAL RESULTS

A. LM137 Negative Voltage Regulator

Output voltage is one of the key parameters for voltage regulators, and most voltage regulators rely on bandgap reference circuits with npn transistors [7]. Figure 3 compares the output voltage degradation of the commercial and hardened LM137 voltage regulators when they are tested with protons. Both device types exhibit similar changes in that parameter. However, the commercial device stops functioning at about 2 x 10^{11} p/cm^2; the failure is catastrophic and does not recover even after extended time periods.

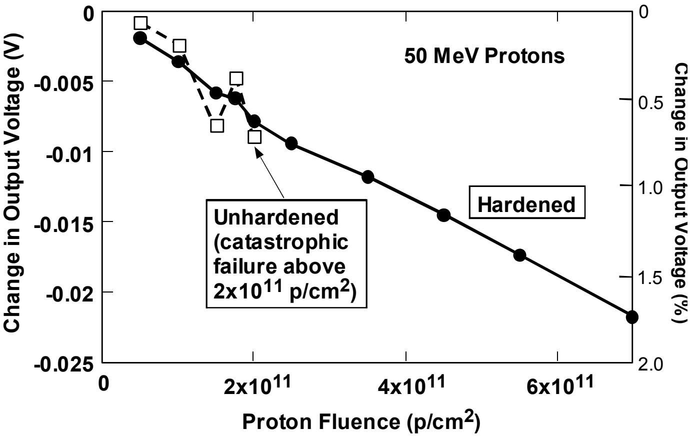

Figure 3. Effect of proton irradiation on output voltage degradation of hardened and commercial versions of the LM137 voltage regulator.

As shown in Figure 4, the unhardened LM137 devices continue to function with moderate output degradation up to 50 krad(Si) when they are tested with cobalt-60 gamma rays *[the devices continue to function at 100 krad(Si)]*. However, a different failure mechanism comes into play when the devices are irradiated with protons which causes catastrophic failure. For the particular unit shown in Figure 4 catastrophic failure occurred between 24 and 28 krad(Si); the shaded region shows the range of failure levels observed for 8 different units from the same date code. Note that the spread in failure levels was about a factor of two.

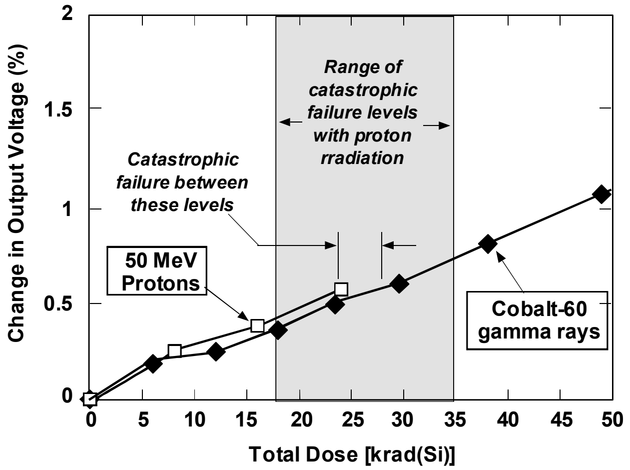

Figure 4. Change in output voltage of unhardened LM137 regulators when they are irradiated with protons and gamma rays.

Special input/output measurements were made to characterize this mechanism. Figure 5 shows how the transfer characteristics of the unhardened LM137 changed after proton irradiation. The curve labeled “0” shows the preirradiation behavior. The output voltage begins to increase even at very low input voltages, but there is a slight nonlinearity at about 0.8 to 0.9 V. This nonlinear region occurs when the start-up circuitry begins to operate. Preirradiation values of the startup voltage defined by that nonlinearity ranged from 0.9 to 1.45 V for different units. As the input voltage increases, the output voltage continues to increase until it reaches the cut-in voltage (2.7 V) at which point the output regulates to a very precise voltage level.

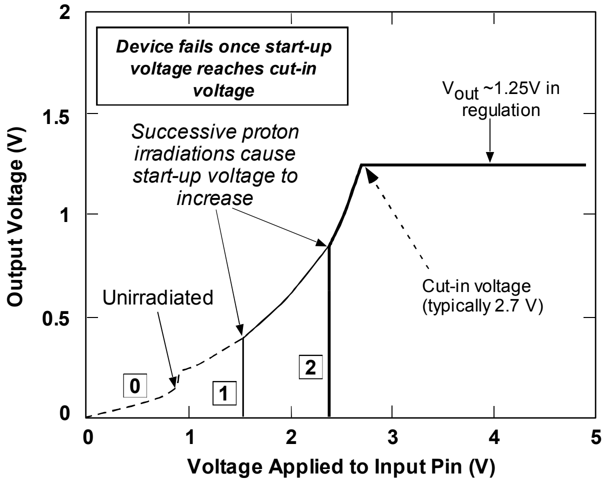

Figure 5. Input output characteristics of the unhardened LM137 voltage regulator before and after two proton irradiation levels.

After the first irradiation level (5 x 10^{10} p/cm^2), the output voltage no longer responds to the input voltage until it reaches approximately 1.3 V. At that point there is an abrupt increase in output voltage, and for voltages above that transition point the circuit behaves much like it did prior to irradiation. It continues to operate for input voltages above the cut-in voltage, with only about a 1% change in the regulated output voltage compared to the preirradiation level.

After the second irradiation level (1 x 10^{11} p/cm^2), the abrupt transition voltage condition has increased to 2.3 V. The output voltage remains stuck at zero volts until the input voltage increases above that value, at which point the device begins to operate normally.

After the third irradiation to 1.5 x 10^{11} p/cm^2 the device no longer functions, and the circuit will not operate even when the input voltage is raised to 40 V. From these measurements, it is clear that the minimum input voltage required to cause the device to operate has increased to a level above the cut-in voltage, and the device has failed catastrophically

A similar characterization method was used by Beaucour, et al., in a study of dose-rate effects of the LM137 [9]. However, there is an important difference in our results with protons. Beaucour, et al. showed that for ionization damage the devices that he studied would eventually start to regulate if the input voltage was increased beyond the “new” start-up voltage condition that occurred after irradiation. Consequently, the increase in start up voltage in their tests would only be important for applications with very low input/output voltage conditions.[†]

The characteristics of the National LM137 were markedly different when they were irradiated with protons. After the start-up voltage degraded to the point where it exceeded the cut-in voltage, the device could not be made to operate even when the input voltage was raised to the maximum input voltage level. Thus, failure will occur even in applications with high input/output voltage “headroom.”

The changes in start-up conditions after various levels of proton irradiation are shown for several devices in Figure 6. The start-up voltage increases in a smooth, regular way as the radiation level increases. However, there are substantial differences in the radiation level at which catastrophic failure occurs. Note that only small changes occurred when one of the devices was irradiated with gamma rays; the startup failure mode does not occur with gamma rays, only with protons.

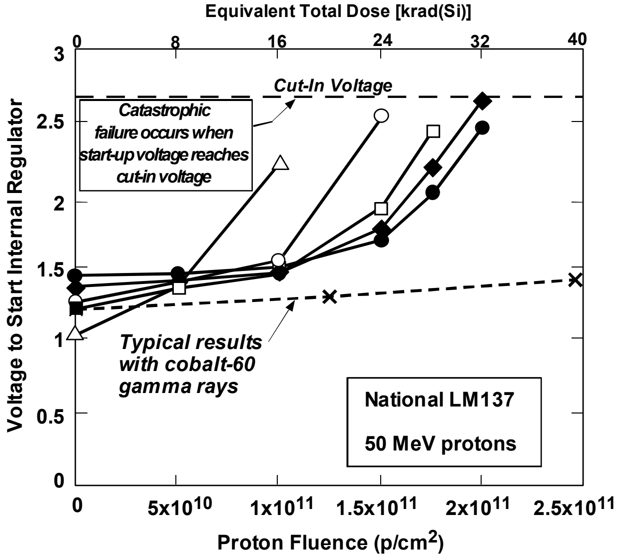

Figure 6. Dependence of start-up voltage on proton fluence for five devices illustrating the range of failure levels.

LM137 devices from Linear Technology (LT137) were also evaluated in this way. The LT137 parts did not show any evidence of the start-up failure mechanism observed for the National version of the part, even when tested at levels up to nearly 10^{12} p/cm^2. The parts from Linear Technology also exhibited smaller changes in output voltage compared to the parts made by National. This illustrates that the importance of proton damage can vary by a large amount between different manufacturers. In this case the parts from Linear Technology are far less affected by ionization damage (cobalt-60 tests) compared to parts from the other vendor. Proton damage produces a combination of displacement and ionization damage, and the reason for this difference may be due more to that difference than in differences in the sensitivity of internal parts to displacement damage.

[†] Beaucour, et al. did not identify the specific manufacturers of the LM137 devices that they tested in their study, and it is possible that the devices for which the startup conditions changed were from a different manufacturer.

B. LM117 Positive Voltage Regulator

Proton and cobalt-60 tests were also done on the LM117, a positive regulator. The LM117 showed some evidence of the same start-up failure mechanism exhibited by the LM137, as shown in Figure 7. However, the effect did not become significant until much higher radiation levels were reached.

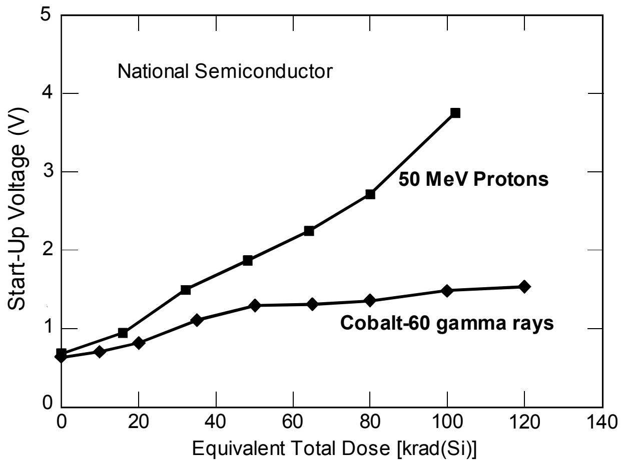

Figure 7. Dependence of start-up voltage on equivalent levels of protons and gamma rays for the National LM117 voltage regulator.

One important difference was observed for the LM117. Much larger changes in output voltage occurred for that part compared to the LM137. These results are shown in Figure 8. With protons, the change in output voltage at equivalent radiation levels is about five times larger for the LM117 compared to the LM137 (see Figure 4 for the LM137 results). The changes in reference voltage observed for the LM117 are also substantially higher than the typical voltage changes exhibited by conventional bandgap reference circuits [8]. The unusually large changes that occur for this circuit are potentially important in many applications, even though the start-up mechanism is not a factor for that particular device design.

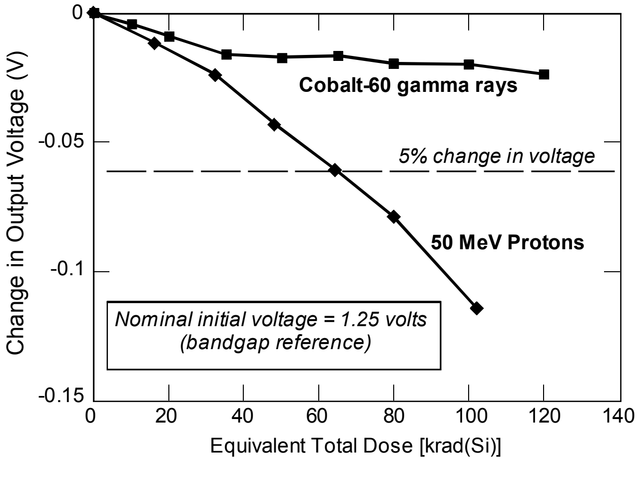

Figure 8. Dependence of the output voltage of the National LM117 on proton fluence.

C. OP-27 Operational Amplifiers

Proton tests were also done for the OP27 and RH27 op-amps. These devices use the compensated input stage described previously in Figure 2, employing a current source (with a multiple-collector pnp transistor) to provide a "bucking" current for the input current of the npn transistor at each input. As shown in Figure 9, the OP27 and RH27 devices continued to operate at high levels, even above 100 krad(Si) [*equivalent total dose*] when they were irradiated with protons. This is an interesting contrast with the RH1056 result, where a hardened device failed catastrophically at levels well below the design specification value when it was irradiated with protons (see Figure 1).

Note however that there are very large increases in input bias current for the commercial OP27 devices that were not observed for the hardened version of the part. These changes, which were always in the negative direction, occur because the lateral pnp compensation stage no longer operates properly. It overcompensates, causing very large negative input currents at both the inverting and noninverting inputs. However, other circuit parameters such as input offset voltage, open-loop gain and output drive current are only slightly degraded. Note also that considerably more degradation occurs when the commercial devices are irradiated without bias compared to the results under bias. This suggests that ionization damage is the main reason for the degradation, not displacement damage, because displacement damage is not affected by bias conditions during irradiation.

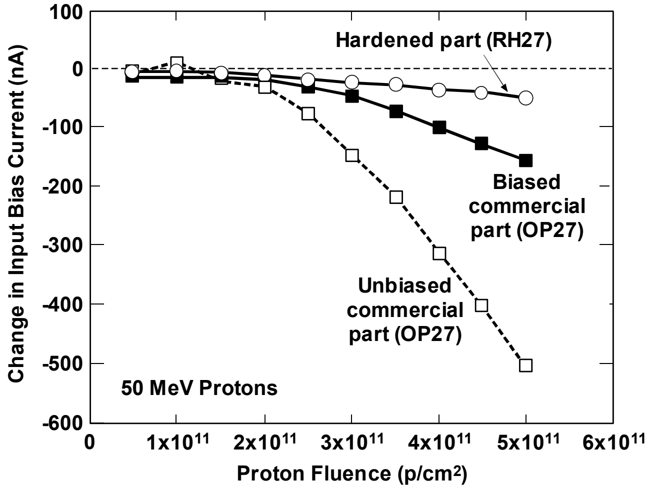

Figure 9. Degradation of input bias current of unhardened and hardened versions of the OP27 op-amp. The RH27 is made with a special process by Linear Technology; the OP27 is made with a commercial process by Analog Devices.

Tests were also done on commercial parts manufactured by a different vendor, Linear Technology. Results for the LT27 were quite different than the results for the commercial OP27 from Analog Devices. As shown in Figure 10, the input bias current of the Linear Technology version of the part increased in the positive direction (implying that the current source is turning off, undercompensating the input stage), exactly opposite to the behavior of the OP27 in Figure 9.

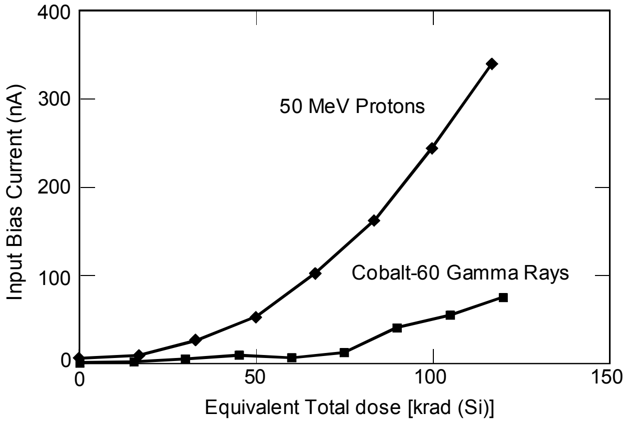

Figure 10. Degradation of input bias current of the LT27 op-amp from Linear Technology showing opposite behavior to that of the OP27.

IV. DISCUSSION

Because wide-base pnp transistors are sensitive to displacement damage, protons will always cause more damage to occur from protons in these structures compared to the damage produced by equivalent total dose levels from gamma rays. The npn transistors used in typical linear integrated circuits have much narrower base regions, and are relatively insensitive to displacement damage effects. The net effect of displacement damage at the circuit level depends on the details of the circuit design. Many linear integrated circuits are designed to tolerate wide variations in the gain of internal pnp transistors, and for such circuits the increase in damage from displacement effects may be unimportant.

In cases where substantial degradation occurs from ionization damage (note the LM111 reported in reference 6), the net impact of the increased displacement damage may be slight. However, for circuits like the RH1056 and LM137, displacement damage causes catastrophic failure to occur, and the circuit failure appears to be the result of mechanisms that do not occur during tests in ionization environments, even when the tests are carried out at very high levels. This type of catastrophic failure is of extreme concern for space applications, and illustrates the need to test linear integrated circuits in proton environments.

Using data in the literature to determine doping levels and base width [11,12], it is possible to calculate the nominal gain and resulting effects from displacement damage for substrate and lateral pnp transistors. The Messenger-Spratt equation was used, increasing the damage constant by a factor of 2.2 to correct for the increased non-ionizing energy loss factor for 50 MeV protons [14]. These results are shown in Figure 11. The results are in close agreement with earlier circuit results for LM111 comparators from National Semiconductor, but slightly overestimate the displacement damage in LM111 devices made by Analog Devices [6]. It shows that even lateral pnp transistors retain a substantial amount of their initial gain at equivalent total dose levels of 40-50 krad(Si) when one considers only displacement damage. Note however that lateral pnp transistors with "split collectors" -- typically used in current sources -- will undergo considerably more degradation because all of the base current flows into only a single section of the split device [1]. Thus, changes in current source values of 10-20% can occur at those radiation levels when current sources are used, even without considering the additional damage from ionization, which is not included in the figure.

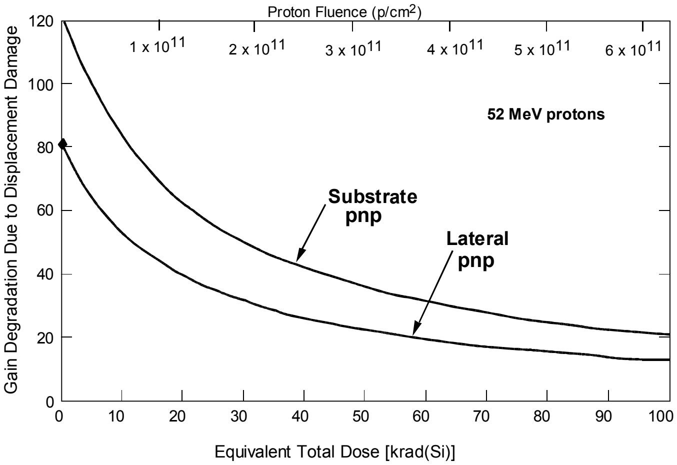

Figure 11. Typical gain degradation from protons for substrate and lateral pnp transistors (equivalent total dose levels are shown).

The issue of whether such changes are important depends on the circuit configuration. Note for example that proton displacement damage causes much larger changes in the output reference voltage of the LM117 than in the LM137 from the same manufacturer. This clearly has to be due to differences in internal circuit design. The markedly different response of the LT27 and OP27 op-amps is also indicative of internal design differences.

In some cases failure modes depend on the detailed balance (or imbalance) of transistors in specific subcircuits, as shown by Barnaby et al. in their study of the LM117 at different dose rates using gamma rays [9]. Similar issues could easily occur when proton damage is compared with ionization damage at high dose rates if the particular circuit design relies on balancing or matching of internal transistors of different types. This is the likely reason that the reference voltage of the LM117 is so much larger than that of the LM137 in our proton tests on those two device types. Note also that both ionization and displacement damage effects are significant for most circuits. Thus, it is difficult to do separate testing with neutrons to determine how displacement damage will combine with ionization damage at the circuit level, even though such an approach would be very useful with discrete transistors or test structures. It is also clear that simply doing ionization tests at higher radiation levels ("overtesting') cannot be counted on to bound the proton damage issue when different failure mechanisms are introduced by displacement damage effects.

[†] In our tests with gamma rays the LM117 reference voltage decreased, in the opposite direction compared to the results obtained by Barnaby, et al. [15]. However, the reference voltage of conventional bandgap reference designs is sensitive to slight mismatches in gain degradation and current matching, and can change in either direction [10]. This is the likely reason for the different results between the two sets of data for the LM117. Note that the absolute changes in voltage are relatively small.

In principle, one could use neutrons as an alternative to proton testing, provided the neutron environment could be adjusted to provide equivalent ratios of ionization and displacement damage. However, protons produce two to three orders of magnitude more ionization for equivalent displacement damage compared to a fast-burst reactor or other hard neutron source. Although it is possible to degrade the neutron source to increase the relative ratio of ionization to displacement damage, the inevitable result is severe degradation of the neutron spectrum with higher uncertainty about the effective value of the displacement damage component. The advantage of using protons is that protons are the dominant environment for many space systems, and 50 MeV protons are near the peak in the proton energy spectrum for many applications.

Proton testing is costly, and it is probably unnecessary to include proton tests for all space applications even when protons are the dominant source of ionization damage. The testing done to date suggests that displacement damage will only be important for equivalent total dose levels above 20 krad(Si), which is consistent with the calculated post-radiation gain values in Figure 11. However, it is possible that devices operating at very low power or with very low internal voltages could be affected at lower levels. Proton damage is likely to remain an important issue, particularly for new circuit designs that operate with low power and low voltages.

V. CONCLUSIONS

This work has shown that proton displacement damage can introduce different failure modes with catastrophic failure for some circuit types. Such effects can occur in both hardened and unhardened circuits. The reasons for such failures are complex, and depend on the internal design and margin for gain degradation. Catastrophic failure in voltage regulators is especially important because their failure can impact the operation of key subcircuit elements. It is important to recognize the importance of these effects and to include proton testing for certain types of linear integrated circuits.

Proton damage is a complex issue, made still more difficult by the large number of ways that transistors with displacement damage sensitivity can be used in circuit designs. Many circuit-level effects are inherently nonlinear, with failure modes that only surface after the internal gain of a critical transistor falls below the minimum value for the circuit. These characteristics can vary widely, even between different units from the same process, as shown by the LM137 catastrophic failure mechanism. This may make it necessary to evaluate proton damage effects on a lot-by-lot basis for some circuit types.

Many linear integrated circuits continue to be designed with the older junction-isolated process that can withstand relatively high voltages, but is inherently sensitive to displacement damage because of the limited performance and wide base regions of the pnp transistors. Differences between the radiation tolerance of parts with protons and gamma rays are potentially more important for new circuit designs with more stringent specifications and low power supply values that use this type of process.

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