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Proton Damage Effects in Linear Integrated Circuits†

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Abstract

Proton tests of linear integrated circuits have identified devices where significantly more damage occurs at equivalent total dose levels with protons than with gamma rays. The difference is attributed to displacement damage, and it can be important for hardened devices as well as for unhardened technologies. Proton testing may be required for applications of circuits that use substrate and lateral pnp transistors in critical circuit functions where protons comprise a significant fraction of the space environment.

I. INTRODUCTION

A great deal of effort has been spent in recent years to investigate ionization damage in linear integrated circuits, including the important topic of enhanced damage at low dose rates [1-4].†† Although the main emphasis has been on ionization effects, the environment of most space systems includes energetic protons, as well as electrons.

Displacement damage produced by both types of particles can cause significant differences in device response compared to gamma irradiation. Consequently characterization and testing approaches based solely on tests with gamma ray may overestimate the radiation levels at which devices can be used in space. Some work has been done on displacement damage in linear devices [5], but the problem has not been addressed in sufficient detail, particularly for more modern circuit designs.

An earlier paper by Raymond and Petersen compared neutron, proton and gamma-ray effects in a variety of semiconductor devices, and concluded that proton ionization effects would be the dominant effect [6]. That work implied that displacement damage from protons can generally be ignored compared to ionization damage, which is true for many technologies. However, there are important exceptions. For example, recent work on precision references showed significant differences between proton and gamma-ray results [7], demonstrating that ionization effects do not always dominate, even in circuits that rely primarily on high f_T npn transistors. The present paper investigates displacement damage from protons in more detail. The results show that for some circuits, proton displacement damage can be the dominant factor compared to ionization damage. Circuit design is an important factor in determining the relative importance of displacement damage. Devices that use substrate or lateral pnp devices as direct inputs or as output stages are generally the most susceptible.

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II. IONIZATION AND DISPLACEMENT DAMAGE COMPARISONS

Differences in ionization charge density cause the charge yield from ionization tracks in SiO_2 to be lower for charged particles compared to the charge yield from gamma rays [8]. Charge yield depends on proton energy and applied field, and may be different for the thick, low-quality oxides used in bipolar devices compared to effects in MOS gate oxides for which a limited number of experiments on charge yield have been done (note that fields across the thick oxides in linear devices are generally quite low). In general, somewhat less ionization damage will be produced by protons. Thus, subtracting the ionization damage produced in an experiment with gamma rays from the damage produced in an experiment with protons (at the same equivalent total dose levels) on the same types of devices may underestimate the proportion of the damage that can be attributed to displacement effects. Nevertheless, comparing experiments with protons and cobalt-60 gamma rays is still a useful approach, even if it is inexact.

Differences in charge yield are estimated to be in the range of 20-30% for oxide thicknesses of 600-800 nm (typical of oxides in pnp transistors [3]), and less than 10% for npn transistors with thinner oxides when 50 MeV protons are used. The effect in space applications depends on the proton spectrum. In most cases there is sufficient shielding to decrease the relative number of low-energy protons so that the peak in the spectrum is between 40 and 100 MeV. Thus, charge yield differences for 50 MeV protons are a reasonable estimate of effects in real systems.

A different technique was used for displacement studies of discrete bipolar transistors by Summers, et al. [9]. They subjected their devices to an initial ionization irradiation, sufficiently high to *saturate* ionization damage. The damage produced by subsequent irradiation with protons (and heavy particles) was then attributed to displacement damage. Although this worked satisfactorily for discrete transistors, it is difficult to apply to linear integrated circuits because the net effect on a circuit depends on the interplay of several different types of transistors, including lateral pnp and substrate transistors where ionization damage usually does not saturate until very high levels of ionization damage are reached. Furthermore, ionization damage does not truly saturate, even for discrete transistors. This is discussed in more detail in Section V.

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††Low dose rate effects are not considered in the present work, even though they are extremely important for some devices. Displacement damage effects are not expected to be dose-rate sensitive.

III. Displacement Damage in Linear IC Transistors

Displacement damage effects in discrete transistors have been widely studied. Extensive work has shown that displacement damage can be described by the equation [10]

$$1/h_{FE} - 1/h_{FEo} = \Phi / [K (2 \pi f_T)] \qquad (1)$$

where h_{FEo} is the initial gain, h_{FE} is the gain after irradiation, Φ is the particle fluence, K is the lifetime damage constant, and f_T is the gain-bandwidth product of the transistor. The damage constant depends on doping level and injection level; it increases about one order of magnitude at low currents compared to the value near the peak gain region. The damage constant also depends on particle type and energy (see Summers, et al. [9]). Displacement damage is often referenced to equivalent 1 MeV neutron damage because of the large body of neutron data in the literature.

Both ionization and displacement damage from protons are energy dependent. However, the *relative* effect of the two energy loss processes is less affected by proton energy. Ionization (dose per incident proton) is about 18% lower for 100 MeV protons compared to 10 MeV protons (a factor of about 5), but the ratio of displacement to ionization processes is only about a factor of two higher at 100 MeV than for 10 MeV protons. Thus, in spite of the strong energy dependence of each individual factor, it is still useful to discuss the effects of displacement damage compared to *equivalent* ionization damage (at a single energy) for protons in that energy range. Comparisons of displacement and ionization damage at 50 MeV are expected to be representative of the relative factors for actual environments, because the peak energy is typically between 40 and 100 MeV when shielding is taken into account.

Figure 1 shows a calculation of the effects of the displacement damage component for substrate and lateral pnp transistors, using damage constants for 52 MeV protons from Ref. 9; f_T values -- 5 MHz for the lateral pnp and 10 MHz for the substrate pnp --were calculated using measured doping profiles and surface topography, and are consistent with published data [11]. The figure shows that significant gain loss from displacement damage occurs, and, as expected, that more gain degradation occurs for the lateral pnp transistor than for the substrate transistor. Note that unlike ionization damage, the displacement damage component does not saturate, but continues to degrade devices as the radiation level increases. At levels above 50 krad(Si) *[equivalent],* displacement effects in npn devices (which have higher f_T values) also start to become significant. The net effect on linear circuits depends on the interplay of degradation from the different types of internal transistors, and is highly design dependent.

The calculations in Figure 1 represent only the displacement damage component of the two types of pnp transistors. Ionization damage will also occur during proton irradiations, lowering the gain beyond that predicted from displacement damage alone.

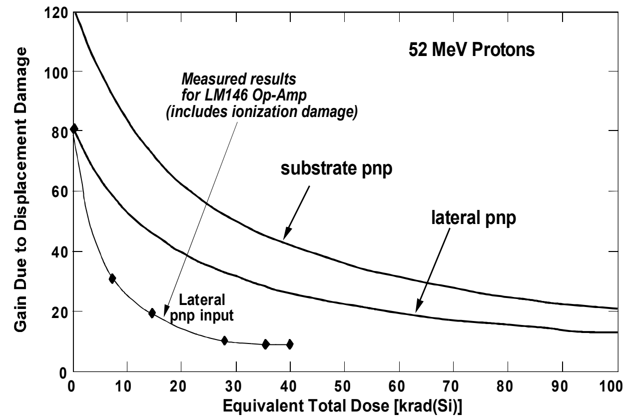

Figure 1. Calculated gain degradation due to displacement damage for pnp transistors used in linear integrated circuits.

IV. Experimental Results

A. Basic Approach

Proton testing was done at Loma Linda University, using 51.8 MeV protons, and also at the University of California, Davis with 50 MeV protons. Irradiations were done on different sets of samples, with and without electrical bias, in order to determine the effects of bias on the results. In most cases biasing the samples had little effect compared to effects in unbiased devices, i.e. results for biased and unbiased devices were nearly the same. (This has been observed previously for pnp devices with thick oxides [3,7], probably because the electric field is very low, even with bias applied). Irradiations to levels of 5 x 10^{10} p/cm^2 required approximately 5 minutes; the equivalent dose rate was about 30 rad(Si)/s. A period of 10 to 15 minutes was required to make electrical measurements between successive irradiations. Measurements of the beam energy and intensity were done using secondary emission foils and a Faraday cup.

Cobalt-60 irradiations were done using a dose rate of 50 rad(Si)/s at the JPL gamma irradiation facility, using a similar procedure. Air ionization chambers, calibrated at the National Institute of Standards and Technology, were used for dosimetry. A lead-aluminum shield was used to reduce the effect of low-energy scattered gamma rays in the cobalt-60 source.

B. Results for Unhardened Technologies

Initial experiments were done on LM111 comparators from two manufacturers, National Semiconductor, which produces devices with extreme low dose rate effects; and Analog Devices, which produces physically similar (and electrically equivalent devices) with *negligible* dose rate effects [3]. The body of work that has been done on the LM111 demonstrates that it will still function (with severely degraded input current) even after the gain of the substrate pnp input transistor is reduced to values near unity. It provides a useful way to evaluate the damage of substrate pnp transistors because the current sources are only slightly affected by radiation damage, and the input current is inversely proportional to substrate transistor gain.

Figure 2 compares the effects of cobalt-60 and protons on the an equivalent total dose of 20 krad(Si) protons produce about twice as much damage as gamma rays. Note also that although the declining slope of the cobalt-60 results indicates the beginning of saturation, the proton results show no evidence of saturation effects.

Similar results are shown in Figure 3 for the PM111. That device is much less affected by ionization damage than the LM111, and consequently the relative importance of proton displacement damage is even greater for the PM111. Thus, even though the PM111 is a far better choice from the standpoint of ionization damage, failure to take displacement damage into account will overestimate the radiation tolerance by a considerable factor.

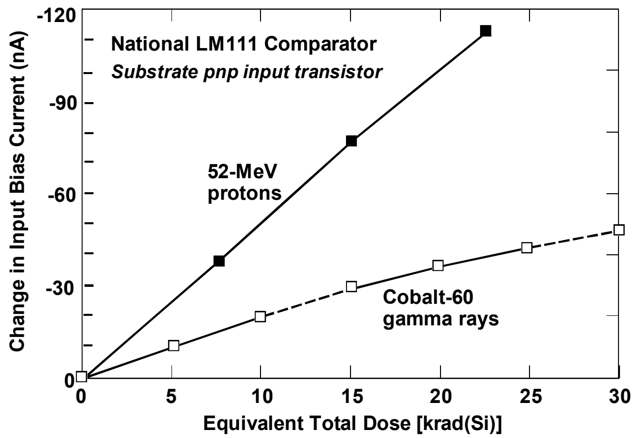

Figure 2. Degradation of LM111 input current from protons and gamma ray experiments.

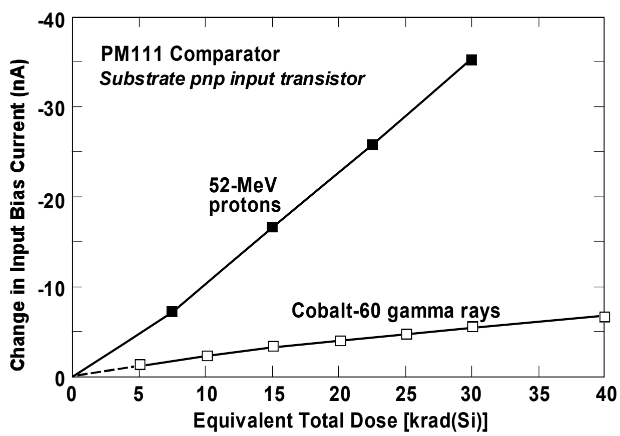

Figure 3. Degradation of PM111 input current from proton and gamma ray experiments.

Although LM111-type devices will operate satisfactorily with extreme degradation of the substrate pnp input transistor, not all circuits can continue to function with such extreme damage. Figure 4 compares cobalt-60 and proton irradiation results for the OP221, a low power op-amp (*unpublished JPL data shows that the OP221 has little or no ELDR effect*). The output stage of that circuit is asymmetrical; it can source up to 10 mA, but it is only guaranteed to "sink" 1 mA. It relies directly on the gain of a substrate pnp transistor to sink current from an external load. When the device is irradiated with protons, it fails the specification limit at an equivalent ionization level that is only 60% of that given by experiments with gamma rays. This is an excellent example of a circuit that is strongly affected by displacement damage because of the specific design techniques used in the circuit.

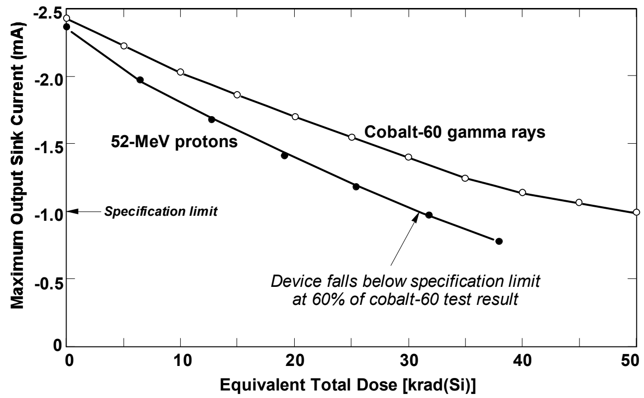

Figure 4. Degradation of output sink current of the OP221 op-amp with proton and gamma ray irradiation.

Proton and gamma-ray experiments were also done on a micropower op-amp (LM146) that uses lateral pnp transistors directly at the input stage. This particular device (manufactured by National Semiconductor) is designed to be used over a wide range of operating currents, set by the user for currents between 1 and 50 µA. Test results for that device are shown in Figure 5 using a bias current of 5 µA. Note that the degradation is much greater than the nominal values shown previously in Figure 2 for lateral pnp transistors.

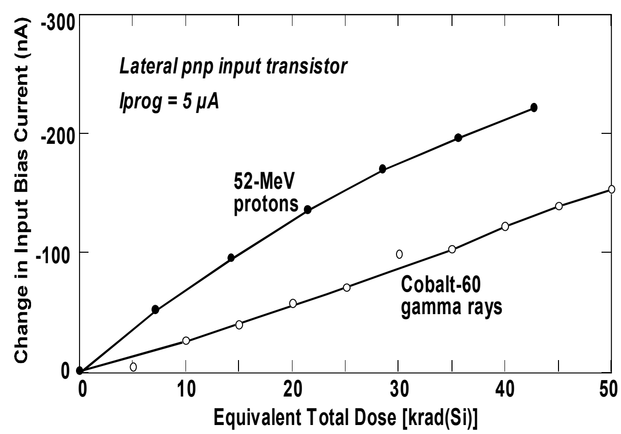

Figure 5. Degradation of input bias current of the LM146 programmable op-amp with proton and gamma ray irradiation (lateral pnp input transistor).

The reason for this difference is in the topology of the transistor. The lateral pnp transistor in the LM146 circuit uses a split-collector, increasing the base current by the number of discrete collector regions, a factor of four for that device. Figure 6 shows the topology of the split-collector lateral pnp used in this device. Split collector pnp transistors are widely used in current mirror. For the case where the base connected to one section of the collector, the collector current of the other sections is reduced by the factor n (ß/ ß+1), where n is the number of sections in the transistor.

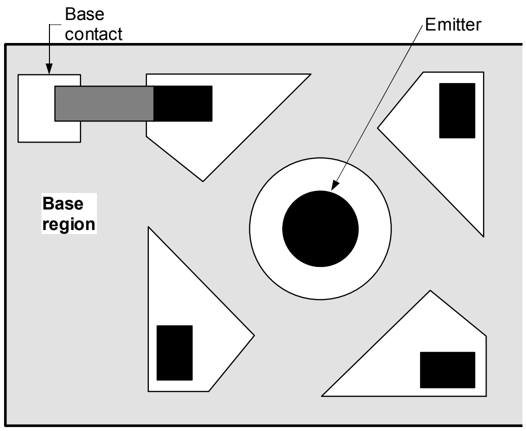

Figure 6. Topology of split-collector lateral pnp transistor used in the LM146 op-amp (four collector regions with single emitter).

C. Hardened Devices

One device that is designed and fabricated with a hardened process was also included in the study. That part, the RH1056, is manufactured by Linear Technology. It uses a JFET input stage.

Although it is guaranteed by the manufacturer to meet its specifications up to 100 krad(Si), the device actually uses internal components that are similar to those used in unhardened linear device technologies, including lateral and substrate pnp devices. The process is designed to reduce sensitivity to ionizing radiation damage. Several other hardened devices are made by the same manufacturer using similar processes.

The RH1056 operates with little change in electrical specifications to levels above 500 krad(Si), as shown in Figure 7, and thus operates well beyond the guaranteed hardness level. However, the performance of the device is strikingly different when it is irradiated with protons to equivalent total dose levels. The solid symbols in Figure 7 show results for protons. Very large changes in input offset voltage occur at levels between 30 and 50 krad(Si), and the device becomes nonfunctional at levels between 50 and 70 krad(Si).

This result shows that proton displacement damage can be a very important issue for hardened linear technologies as well as for unhardened devices. The reason is that the internal pnp transistors still have relatively wide base regions, and are much more sensitive to displacement damage than conventional transistors. In this case, the manufacturer does not consider displacement damage effects, only ionizing radiation damage.

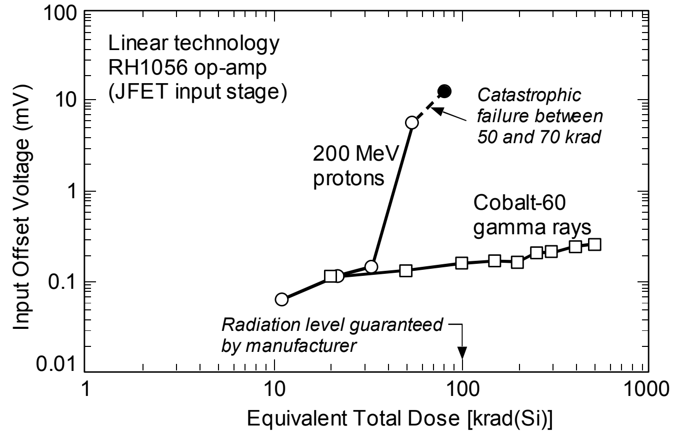

Figure 7. Effect of protons and gamma rays on the RH1056 op-amp.

V. Discussion

A. Comparisons with Other Environments

Our estimates of the displacement damage component of gain degradation with proton irradiation can be compared to neutron test results for similar devices from the same manufacturer. Figure 8 shows how the damage factor associated with $\Delta\ I_b$ compares for the LM111 (the proton damage factor was obtained by subtracting the ionization damage at equivalent levels from gamma irradiation experiments from the total change in input bias current with proton irradiation). Data in the literature for non-ionizing energy loss (NIEL) shows that 50 Mev protons are 1.75 times more damaging than neutrons [9]; the experimental results show a factor of 1.9, which is in reasonable agreement.

It is also useful to compare ionization and displacement damage effects for the specialized pnp transistors used in linear integrated circuits with discrete transistors, which were the basis for earlier studies of displacement damage.† Figure 9 shows how ionization damage (from JPL data) compares with the displacement damage results used by Summers, et al. [9] to investigate displacement damage. Much of their work was based on 2N2222 transistors, using gain degradation at 30 mA. Ionization damage *dominates* degradation in 2N2222 transistors at levels below 1 Mrad(Si). They overcame this limitation by irradiating the transistors to 3 Mrad(Si), saturating the ionization damage in order to systematically study displacement damage in their devices to different particle types. This is further evidence that displacement damage can be generally considered to be negligible for discrete transistors, even when they are used at low currents.

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†Gamma rays also produce displacement damage, as discussed in work by Summers, et al. [12]. However, displacement damage from gamma rays is negligible compared to ionization damage in discrete transistors, which is evident from the body of work on ionization damage in transistors as well as the earlier work on NIEL [9].

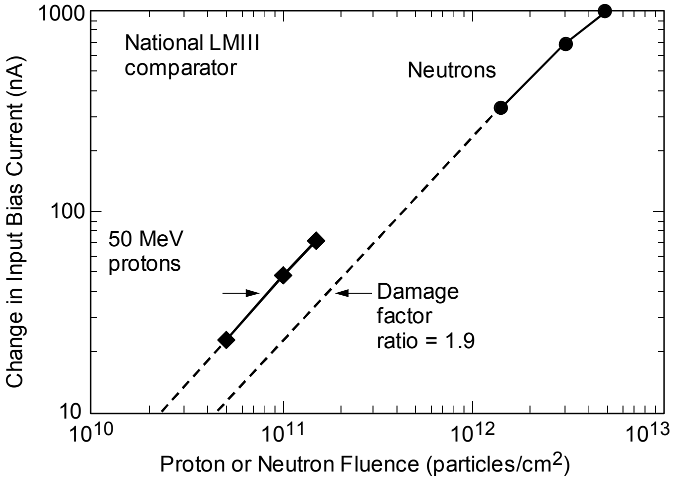

Figure 8. Damage factors for neutron and proton irradiation of the LM111.

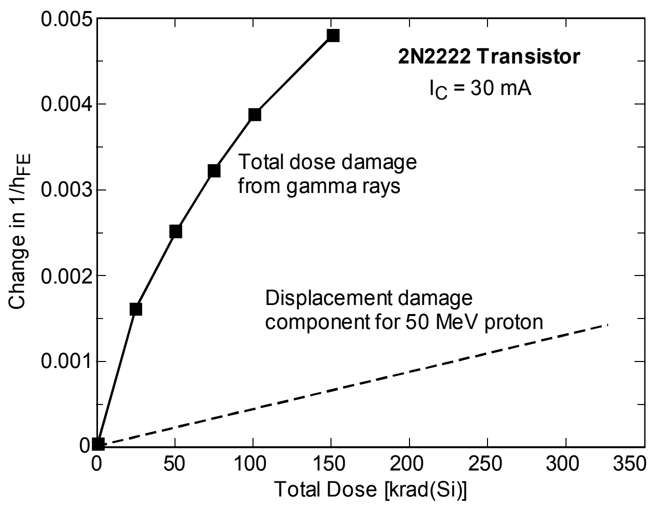

Figure 9. Comparison of ionization radiation damage from gamma rays and displacement damage from 50 MeV protons for a 2N2222 transistor.

However, the situation is quite different for substrate and lateral pnp transistors. For 50 MeV protons, displacement damage is comparable to or greater than ionization damage. As noted earlier, the relative importance of displacement damage is considerably greater for the PM111 devices which are less affected by ionization. Furthermore, the magnitude of the gain loss caused by low levels of proton irradiation is far greater for the linear technology pnp transistors compared to discrete transistors, simply because of the difference in base width (which increases the base transit time).

B. Effects of Circuit Design and Process

Although new processes with higher bandwidth and improved performance are available, the majority of linear integrated circuits are made with a basic junction-isolated process that has changed very little over the last twenty-five years. There are several reasons for this, including (1) most linear circuits are intended for applications with power supply voltages up to ±18 V, imposing indirect requirements on doping levels, interelement spacing, and isolation oxide thicknesses; (2) the need to drive substantial currents with high internal voltages (and power dissipation) causes a large part of the chip area to be dedicated to the output stage, minimizing the value of scaling; (3) maintaining low offset voltage requires close matching of the emitter area of transistors in the input stage, along with minimization of thermal feedback from the output, again reducing potential advantages from scaling; and (4) the basic process is quite inexpensive compared to high-performance alternatives.

Displacement damage effects were generally of less importance for older linear circuit designs made with this basic process, mainly because the design approaches were far more conservative. For example, none of the older designs use lateral pnp transistors as the primary input transistor, and although output stages often used substrate pnp transistors, additional stages are used in circuits such as the LM101 and LM108 op-amps to allow the circuit to operate with very low gain in pnp transistors. Although the LM111 uses a substrate pnp at the input stage, the circuit will continue to operate even after the gain of that transistor has degraded to near unity (with input bias current well above device specifications).

Newer designs have departed from the conservative approach used in the past, probably because processing technology has evolved to the point where “compromise” pnp structures can be made with more reproducible results than in the past. Designs that depend on the gain of internal pnp transistors in a more direct way are often far more affected by proton damage than ionization damage, as shown by the results for the OP221 and LM146.

Ionization damage effects are very sensitive to processing details, and can vary widely for devices of the same type that are produced by different manufacturers. If a device is strongly affected by ionization damage, the effect of displacement damage will be relatively less important than for devices which are more tolerant of ionization damage simply because the ionization component will dominate the device response. This trend is demonstrated by the two LM111 device types in Figures 2 and 3. Thus, selecting devices that are more tolerant of degradation from ionizing radiation may make it even more important to consider the effects of displacement damage. The result for the RH1056 in Figure 7 illustrate that point more dramatically.

C. Guidelines for Proton Testing

Proton testing is considerably more expensive than testing with passive gamma sources, and it is generally impractical to require proton tests of all devices types that are potentially sensitive to that environment. Clearly the first step is to determine the proton fluence that is required in the application. The proton spectrum and energy dependence of proton displacement damage must be taken into account, not just the total fluence, normalizing the damage to a single energy. The results in this paper along with damage constants of lateral and substrate transistors in earlier work can be used to show that displacement effects are generally negligible for 50 MeV (equivalent) fluences that are below 3 x 10^{10} p/cm^2.

The second step is to determine whether the specific circuit is likely to be affected by displacement damage. In many cases the need to do this type of testing can be established by examining the circuit design (even with the limited schematic diagrams that are typically provided in manufacturer's specification sheets). Key factors are the use of lateral pnp transistors in current mirrors or input stages, and the output stage design, as noted in the results for the OP221.

Another issue is that of device requirements. Devices with very demanding electrical specifications – i.e,. very low input offset voltage and/or input offset and bias current, or low noise – are particularly suspect. In many cases such devices are selected with the intent of using them in applications with very demanding requirements. Second-order effects that would be of little importance for circuits with wider initial tolerances can be of vital importance for circuits with very low specification limits. For example, currents in pairs of transistors within a differential amplifier must match within 0.04% in order to maintain an offset voltage of 10 μV.

Proton testing is relatively straightforward, provided the energy is sufficiently high to allow negligible energy loss in the device package (usually energies above 40 MeV are used). The results must be interpreted in the context of the proton spectrum of the application that is corrected to account for the energy dependence of proton damage. Other considerations are the limited size of the beam – typical dimensions are 6-8 cm – along with beam uniformity. Another practical issue is the induced radioactivity in devices and hardware which creates potential personnel hazards.

An alternative approach is to use neutron testing to evaluate displacement damage. However, the net damage to linear circuits depends on both ionization and displacement damage as well on the interplay between npn and pnp transistor types. Displacement effects on circuit parameters may not be evident from neutron tests alone because of the way that different internal components interact at the circuit level, and the fact that the internal components are degraded substantially by both ionization and displacement damage effects.

VI. CONCLUSIONS

This paper has shown that displacement damage from protons can cause substantially more degradation in space than expected from tests with gamma rays in some types of linear integrated circuits. Displacement damage was not important for most older linear circuits, primarily because of the way that pnp transistors, which are the most sensitive components, were used in the circuit design. However, this is not the case for many new circuits, as evidenced by the LM146, which uses lateral pnp transistors as the input stage. Older designs never used lateral pnp transistors in such critical regions because of the difficulty in producing lateral transistors with consistent electrical properties.

For conventional linear circuits it is often possible to identify devices that are likely to be affected by displacement damage by doing a rudimentary circuit analysis. The input stage, output stage, and the precision of the electrical specifications are all factors in identifying devices that may be more susceptible to proton damage. The use of substrate or lateral pnp transistors in subcircuits that require substantial transistor gain for normal circuit functional operation provides a first-order way to examine circuits for potential sensitivity to displacement damage effects.

Although one usually expects such effects to only be a problem for commercial devices, displacement damage caused a very large difference in the failure level of a hardened device compared to its response from ionization damage alone. This demonstrates that proton testing may be required for many different classes of devices.

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