The Effects of Space Radiation on Linear Integrated Circuits*

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Abstract

Permanent and transient effects are discussed that are induced in linear integrated circuits by space radiation. Recent developments include enhanced damage at low dose rate, increased damage from protons due to displacement effects, and transients in digital comparators that can cause circuit malfunc-tions. Methods of selecting and testing devices for space applications are discussed, along with examples of radiation effects in fielded space systems.

I. INTRODUCTION

Linear integrated circuit perform many critical functions in spacecraft, particularly in instruments, interfaces between analog and digital functions, and power control. This paper discusses the effects of space radiation on linear circuits. Topics include dose-rate effects, permanent damage in linear devices, which is caused by a combination of ionization and displacement damage, as well as transient effects, which are due to high-energy cosmic rays or reaction products from high-energy protons that produce short-duration charge tracks.

The majority of linear integrated circuits are made with bipolar technology, and the main focus of the work in this paper is directed towards mainstream bipolar devices. However, it is also possible to use BiCMOS and CMOS technologies to design linear integrated circuits, as well as more advanced bipolar processes.

II. IONIZATION DAMAGE

Protons from trapped radiation belts and solar flares and trapped electrons primarily interact with materials by creating electron-hole pairs within materials (ionization loss). The radiation levels that spacecraft must withstand varies widely for different orbits and scenarios. For deep space missions that do not involve trapped radiation belts, the total dose due to ionization is typically only a few kilorad(Si). Total dose level requirements for high-inclination Earth orbiting spacecraft are much higher, approximately 20 krad(Si). Even higher total dose levels -- well above 100 krad(Si) -- are experienced by spacecraft at outer planets with trapped radiation belts, such as Jupiter.

Ionizing radiation produces electron-hole pairs within the high-quality oxides that are used to isolate different regions of bipolar transistors and circuits, as well as in the gates of MOS transistors. Holes, which are less mobile than electrons, can be trapped at the interface between the silicon surface of an active device and the silicon-dioxide region, altering the surface potential and increasing the recombination rate for minority carriers. The latter factor is the mechanism that causes ionizing radiation to change the gain of bipolar transistors [1,2].

The process that is most widely used for linear integrated circuits is intended for circuits with relatively high maximum power supply voltages (≈ 40 V). Because of the high voltage requirement, relatively thick oxides are required in the initial processing steps, and that oxide is still present over the emitter-base region of lateral and substrate pnp transistors that are typically used in the process. The oxide over the emitter-base region of npn transistors is grown in later processing steps, and is much thinner. The lateral and substrate transistors also have much wider base regions that the npn transistors used in the process.

Relatively recent work has shown that the transistors used in typical bipolar integrated circuits are affected by dose rate, exhibiting significantly more damage at the low dose rates encountered in space compared to the high dose rates typically used in laboratory testing [3-5]. This effect was unanticipated, and had escaped discovery for many years. Figure 1 shows an example for a digital comparator that is widely used, incorporating a substrate pnp transistor at the input. To first order, changes in input bias current are proportional to the change in base current of the input

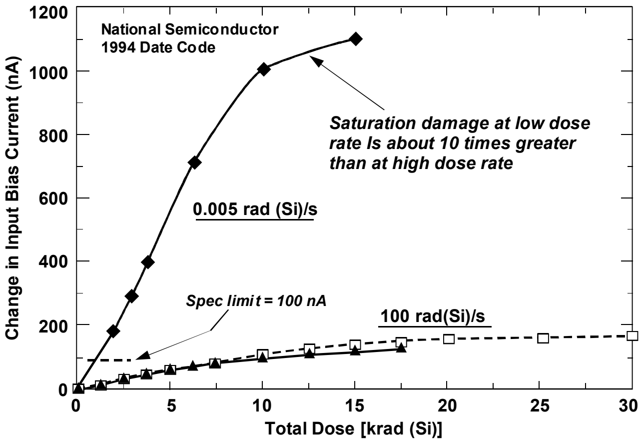

Figure 1. Increased degradation of a bipolar comparator when it is irradiated at very low dose rate.

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transistor. Note that about ten times more damage occurs at low dose rate compared to the high dose rate case. Much less difference occurs for npn transistors in these processes, primarily because the oxide region over the emitter-base junction is much thinner. Thus, parameters that depend mainly on npn transistor gain will be less affected by dose rate. The large increase in damage that actually occurs at low dose rates in space causes degradation to be severely underestimated when laboratory tests are done under accelerated conditions, with high dose rate.

A second example of low dose-rate effects is shown in Figure 2. This device, an operational amplifier, uses a slightly different process that incorporates additional processing steps to provide a junction field-effect transistor (JFET). The JFET is used at the input stage. Although the circuit is not designed to be hardened, older data at high dose rate shows that the device continues to operate when it is tested at high dose rate up to 1 Mrad(Si), and the manufacturer's data sheet states that the part has excellent radiation hardness. However, as shown in Figure 2, the input offset voltage changes drastically when the tests are done at low dose rate. The changes are more and more severe as the dose rate is decreased, and the practical failure level is about 10 krad(Si) when dose-rate effects are taken into account Note that these effects are permanent, and do not anneal after irradiation.

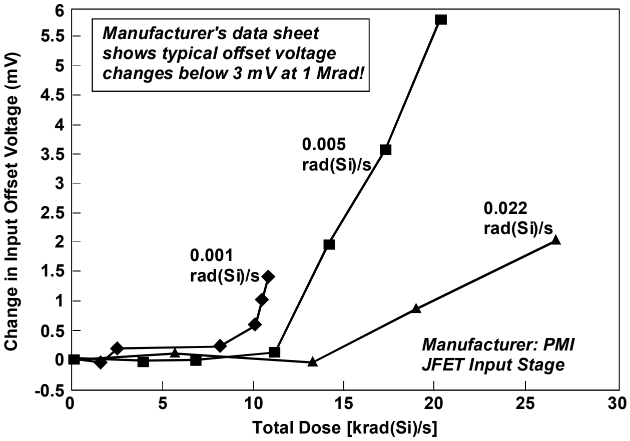


Figure 2. Degradation of input offset voltage of the OP42 bipolar op-amp when the device is irradiated at different dose rate.

Linear circuits fabricated with CMOS technology are also degraded by ionization damage, but are not sensitive to dose-rate effects in the way that bipolar devices are affected. Although input parameters such as Vos and Ib are degraded in irradiated devices, the power supply current of CMOS op-amps is often one of the most sensitive parameters. Figure 3 shows how power supply current of two CMOS op-amps is affected by total dose, along with the power supply current of a bipolar linear circuit. Note that one of the two CMOS circuits still operates with some degradation at very high radiation levels, whereas the other fails catastrophically below 20 krad(Si). In general there is more variability in the radiation tolerance of CMOS op-amps compared to their bipolar counterparts, and it is more difficult to select radiation-tolerant linear devices because of this variability.

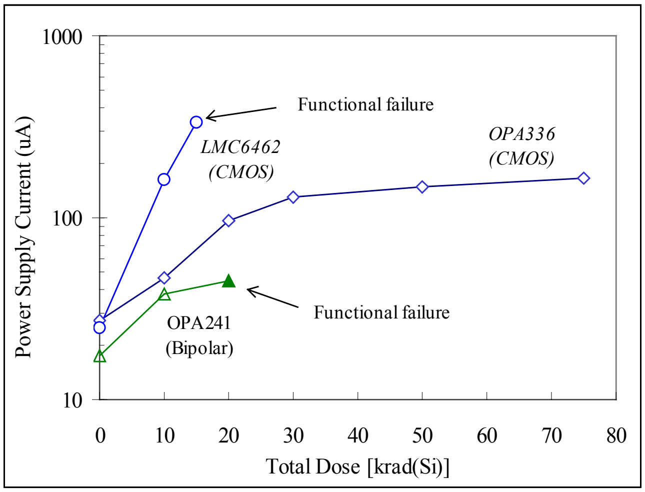


Figure 3. Degradation of power supply current for two CMOS and one bipolar op-amp.

III. DISPLACEMENT DAMAGE

Although ionization is the primarily loss mechanism for electrons and protons, some of the energy is also lost via lattice damage, which displaces atoms from their normal lattice sites. Displacement damage from high-energy protons is an important damage mechanism for electronics in many spacecraft.

The wide-base pnp transistors that are used in linear circuits are affected by displacement damage as well as ionization damage [7,8]. Wide-base transistors require relatively long lifetimes in order for minority carriers to be transported through the base region. Because of this, they can be more heavily damaged by protons compared to damage produced by ionization from gamma rays at equivalent total dose levels. Figure 4 shows how typical lateral and substrate pnp transistors are affected by displacement damage from 50 MeV protons. Substrate transistors have narrower base regions than lateral pnp transistors, and are less affected by displacement damage.

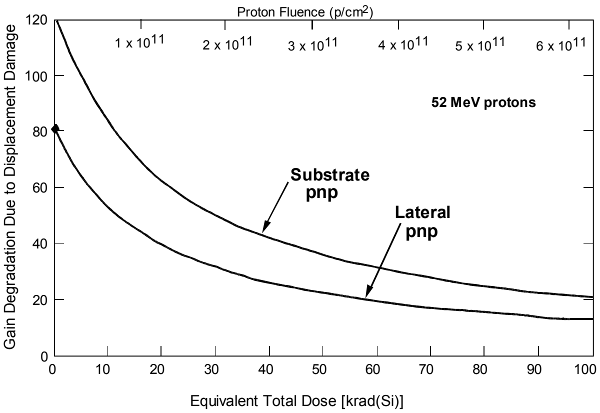


Figure 4. Displacement damage degradation of a typical lateral pnp transistor when it is irradiated with 50-MeV protons.

The LM137 voltage regulator is an example of a circuit where proton damage is a severe issue [8]. Figure 5 shows how the minimum voltage for the circuit to begin regulating (the start-up voltage) is affected by protons for five different devices from the same date code. Once the start-up voltage exceeds 2.7 volts, the circuit will no longer operate. The exact point where that failure mode begins varies over about a factor of two for the five parts. The dashed line in the figure shows how the same parameter is affected when the part is tested with gamma rays at equivalent total dose levels. Only slight changes occur in the transfer characteristics, and the failure mode shown by the proton tests is not present when tests are done with gamma rays, even when the tests are extended to very high levels. This shows the importance of including tests with protons for bipolar integrated circuits.

Hardened circuits can also be affected by displacement damage. Figure 6 shows how gamma rays and protons affect the input offset voltage of a hardened operational amplifier, the RH1056. With gamma rays, the change in offset voltage is very small, and the circuit operates at levels approaching 1 Mrad(Si). When protons are used, large changes in offset voltage begin to occur at about 50 krad(Si), and the circuit stops functioning at 70 krad(Si). The reason for this difference is that the process uses lateral and substrate pnp transistors with wide base regions that are sensitive to displacement damage effects. The manufacturer did not consider displacement damage in the circuit design, and only guarantees performance for ionization damage.

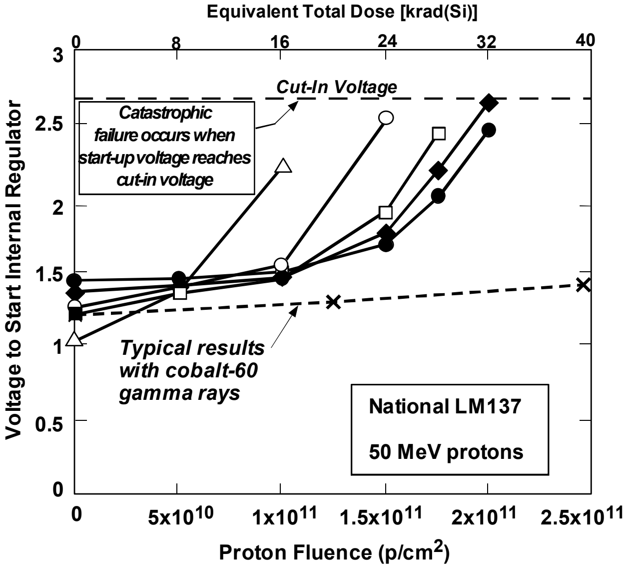


Figure 5. Change in start-up conditions of the LM137 negative voltage regulator when it is irradiation with protons. The dashed line shows typical results with gamma rays, where there is little effect on that parameter.

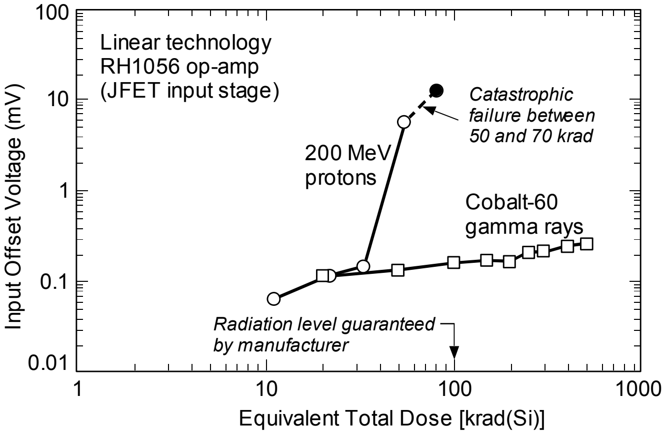


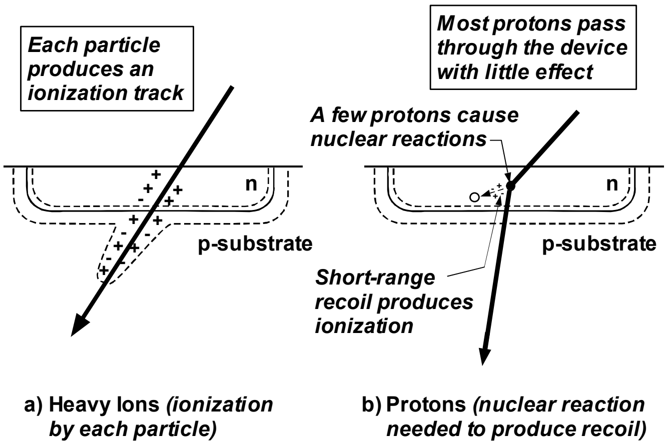
Figure 6. Comparison of damage in a hardened op-amp when it is irradiated with equivalent total dose levels from protons and gamma rays. The increased damage with protons is caused by displacement damage.

IV. TRANSIENT EFFECTS

A. Internal Response Mechanisms

Heavy ions from galactic cosmic rays or solar flares produce an intense, highly localized track of ionization within a semiconductor, as shown in Figure 7. When the charge track passes through or in close proximity to a p-n junction, some of the charge will be collected at the junction, resulting in a short pulse of current. If the current occurs at the input circuitry of a high-gain amplifier, it can be amplified, producing a voltage pulse at the output. Circuits with low operating currents in the input stage are more susceptible to single-event transients. The track density of a heavy ion is proportional to the linear energy transfer in units of MeV-cm^2/mg (an LET of one corresponds to nearly exactly 10 fC of charge per micrometer of material in silicon). Galactic cosmic rays have LET values up to 100 MeV-cm^2/mg, decreasing strongly for LET values above about 30 MeV-cm^2/mg. The net effect on a circuit depends on (a) the distribution of particle LETs, (b) the dependence of cross section on LET for the particular device, and (c) the volume of charge within the device over which charge is collected. The upset probability can be calculated by integrating all three quantities, using the LET distribution that corresponds to the specific environment.

Figure 7. Ionization processes near a p-n junction from high-energy cosmic rays and recoil products from proton reactions.



a) Heavy Ions ***(ionization by each particle)***

b) Protons ***(nuclear reaction needed to produce recoil)***

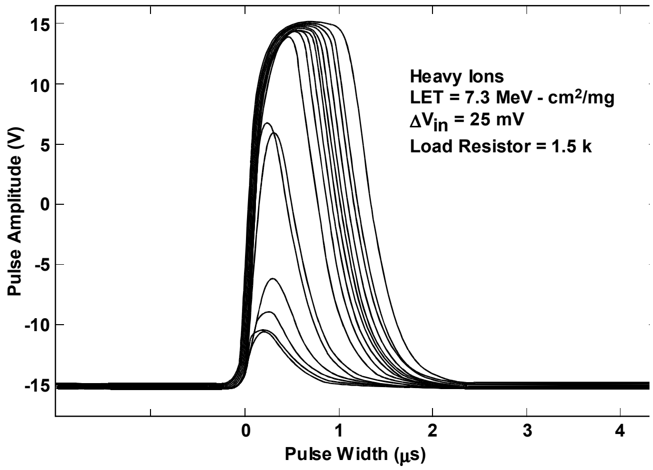
Recoil atoms from proton reactions with the silicon lattice also produce ionization. Figure 7 shows this process schematically. The proton recoils have much shorter range than galactic cosmic rays. The cross section for proton reactions is on the order of 10^{-4} cm^2, causing the cross section for proton-induced transients to be much lower than the cross section for transients from cosmic rays. Proton reactions occur at random locations, with a distribution of recoil energies.

In CMOS circuits, it is possible for heavy ions to cause latchup because of the parasitic p-n-p-n path that is formed by the parasitic bipolar transistors associated with the NMOS and PMOS transistors [9]. In principle, latchup can also occur in bipolar linear circuits, but the presence of buried layers and the need to take saturation from overdrive conditions into account when the circuit is designed generally makes it impossible for the small currents produced by cosmic rays to cause latchup in bipolar circuit technologies.

B. Transients from Heavy Ions and Protons

Figure 8 shows the results of a particle accelerator test to determine how heavy ions with LET of 10 MeV-cm^2/mg affect a differential comparator. The figure shows a superposition of several different events. The amplitude and time duration differ for different particle strikes, depending on the exact location within the circuit. If the particle strikes near the edge of a sensitive internal junction, less charge is produced compared to the response of an ion that strikes the most sensitive region. Note that the majority of the events in Figure 8 correspond to full-scale output transients of about 30 volts.

Figure 8. Distribution of output pulses from a linear comparator when it is irradiated with high-energy ions from a particle accelerator.



Transients from comparators are heavily influenced by circuit conditions. If the input differential voltage is small, then the device can respond with full-scale output pulses when it is irradiation with ions that have low LET, or from proton recoils. On the other hand, using a large differential input voltage reduces the sensitivity to transients, requiring a much higher internal charge -- which is only possible with ions that have high LET -- to cause the circuit to respond. Figure 9 shows how the cross section and threshold conditions depend on input voltage when the LM139 comparator is tested with heavy ions from an accelerator.

The extreme difference in threshold LET causes the upset rate in applications to vary by several orders of magnitude. Output loading also affects upset sensitivity. Circuits with low load conditions and low application voltages are far more sensitive.

Transient upsets from heavy ions and protons have only been investigated in detail for a small number of circuits [10-14], and at the present time there are no adequate models to describe the way that the different electrical conditions affect results.

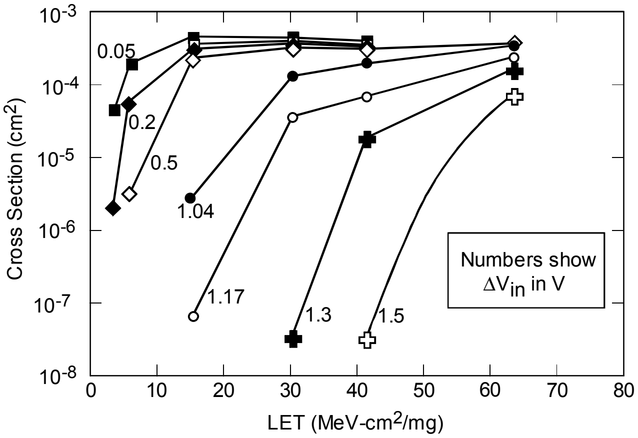


Figure 9. Single-event cross section vs. LET for the LM139 comparator for different input voltage conditions.

C. System Effects

Although transients can occur in all types of linear integrated circuits, the transients typically die away after time intervals of a few microseconds or less. The majority of linear circuit applications are insensitive to transients of such short duration. However, transients in voltage comparators and some types of analog-to-digital converters can be extremely important in system applications because they are typically used to provide inputs to digital circuits, and it is those types of circuits that are of most concern.

Transients from linear devices have caused operational difficulties with two operational systems, the Hubble Space Telescope, and power control modules in the Cassini spacecraft. In 1997 an upgraded set of electronics was installed as part of the servicing mission to modify the optical components on Hubble. After the modifications were installed, the spacecraft experienced operational problems -- a power supply would shut down -- when the orbit of the spacecraft passed through the South Atlantic anomaly, where the proton belts are located much closer to the earth's surface. The problem was traced to transients from optocouplers, which contained linear integrated circuits that amplified small photocurrents from the LED (produced by proton recoils) in the integrated photodetector contained within the optocoupler [14]. The output of the optocoupler was used in an asynchronous circuit that shut down the power system. Optocouplers also respond to cosmic rays, producing pulses with larger amplitudes and pulse widths compared to those from proton recoils [15].

Recent work has shown that proton-induced transients in optocouplers are highly sensitive to the angle at which the proton strikes the circuit [16]. This is caused by the relatively large area of the photodiode. Protons that are incident at high angles produce sufficient energy by direct ionization -- without requiring a nuclear reaction to occur -- to cause the optocoupler to upset. Figure 10 shows how the cross section increases with angle for various proton energies. Note that it rises nearly three orders of magnitude for protons below 50 MeV. The increased cross section at high angles causes the upset rate to be significantly higher in space than would be estimated from tests that only considered protons at normal incidence.

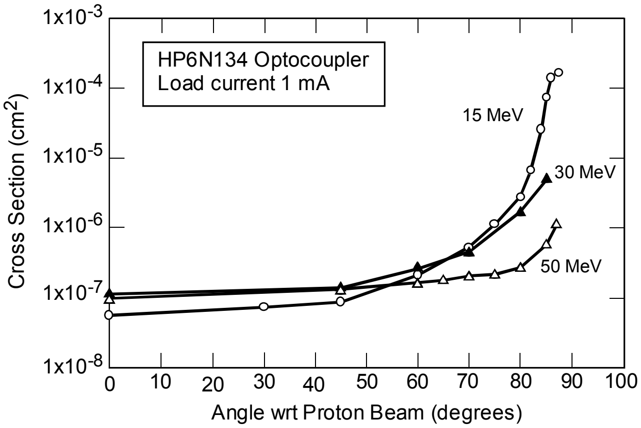


Figure 10. Dependence of the cross section on incident angle for proton-induced transients in a high-speed optocoupler.

A transient effect problem also occurred in power control switches used on the Cassini spacecraft. Occasionally a switch would be found in the standby mode, even though no standby command had been given. Tests on unused modules purchased by the program were made at a high-energy accelerator after the problem was observed in space. The laboratory tests showed that the standby mode was triggered by transients at the output of an LM139 comparator circuit that was used in an asynchronous circuit application within the module. The transients could be induced by ions with LET values of 20 MeV-cm^2/mg or higher. Fortunately, the cross section for these transients was low, causing only a few events per year, which is an acceptable upset rate. The low cross section was due to conservative design practice, which used a high differential input voltage on the comparator.

V. SELECTING LINEAR DEVICES FOR SPACE APPLICATIONS

A. Environments

The first consideration when selecting devices for space is the radiation environment. Obviously there are many possible scenarios, but the majority fall into three general categories [17]:

(a) deep space (or geosynchronous orbits),where there are no trapped radiation belts, and the environment is dominated by solar flares and galactic cosmic rays;

(b) high-inclination low-earth orbits where the major concern is the effects of high-energy protons, along with cosmic rays that escape the magnetic shielding near the poles; and

(c) low-inclination low-earth orbits where the proton flux is reduced because the orbit is further away from the south-Atlantic anomaly, and galactic cosmic rays are attenuated significantly.

Approximate proton fluence levels for these three missions are shown below, assuming a 100-mil aluminum shield and operation for five years.

Table 1. Proton Fluence for Five-Years for Three Mission Scenarios (100 mil Al shield)

Mission	Proton Fluence (p/cm^2)
Deep space	1.7 x 10^{10} (due to solar flares)
LEO (98°, 705 km)	4 x 10^{10}
LEO (28°, 600 km)	1.2 x 10^{10}

In deep space and geosynchronous orbits the proton flux is due entirely to solar flares. The protons are distributed over a wide range of energies, and it is necessary to take the energy dependence of the damage that the protons produce in silicon into account in order to determine how they damage devices. That factor increases the effective proton fluence by approximately 50% when comparing the fluence values in the table with experimental data using 50 MeV protons.

Note that Table 3 does not include planetary missions to Jupiter or Saturn, which have intense radiation belts. The specific requirements for those missions vary widely, depending on how close the spacecraft must travel to the planet and the time spent traversing the belts.

B. Circuit Selection

Most older linear circuits were designed to tolerate wide variability in internal pnp transistors because of fabrication tolerances. However, parameters in many new circuits use pnp transistors in more critical ways because manufacturing technology has reduced the variability in pnp transistor electrical parameters. Note however that the radiation susceptibility of pnp transistors is still a problem.

In addition to the dependence on pnp transistors, overall operating margins of linear circuits are a key factor in circuit selection. For example, newer operational amplifiers and comparators can be used with very low power supply voltages. The performance of those devices with low supply voltages is often far worse after irradiation than results with nominal operating voltages (±5 and ±15 V).

Electrical parameter tolerances are also important. Circuits that are selected for applications with very low input offset voltage (<0.1 mV) or high accuracy and precision have a strong likelihood of degrading well beyond the parameter limits at low radiation levels, although may still operate from an overall functional level. Very high precision devices should be avoided if possible because of the risk of parameter drift at low radiation levels.

VI. SUMMARY AND CONCLUSIONS

This paper has addressed several new issues that are important when linear integrated circuits are used in space. One key problem is the large increase in ionization damage that occurs in many types of linear circuits at low dose rate. Tests at high dose rate can seriously underestimate radiation damage in actual applications, and it is essential that the enhanced low dose rate damage problem is taken into account when linear circuits are qualified and tested for space use.

Displacement damage from protons is also an important issue, particularly for earth-orbiting spacecraft that usually pass through the Earth's proton belts. Displacement damage adds to ionization damage, producing more damage and different failure modes in some device types compared to tests with gamma rays. This effect can even be important for hardened linear circuits if they use lateral or substrate pnp transistors.

Linear circuits are also affected by galactic cosmic rays and proton recoils. Interactions of a single cosmic ray or energetic proton can cause a linear circuit to produce a spurious output pulse, beyond the control of the input conditions, if the particle strikes a sensitive internal node. The effect of the spurious pulse depends on the circuit application. Although many applications are insensitive to such pulses, there are many instances where transient pulses from digital comparators, analog-to-digital converters, or optocouplers can introduce faulty operating conditions within a system. This problem needs to be carefully considered when linear circuits are used in space.

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