Radiation Damage of Electronic and Optoelectronic Devices in Space†

A. H. Johnston
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California USA

Abstract

The effects of radiation damage on modern electronic and optoelectronic is discussed. Ionization damage causes degradation in transistors and integrated circuits, and there are new effects -- including enhanced damage at low dose rate -- that have to be considered when devices are tested and qualified for space use. For optoelectronic devices displacement damage is usually the main concern. Some types of optical emitters are extremely sensitive to displacement damage effects. Displacement damage is also a major concern for optical detectors as well as for some types of linear integrated circuits.

I. INTRODUCTION

Electrons and protons in space can cause permanent damage in some types of electronic and optoelectronic devices that can lead to operational failure. Successful operation in space requires an understanding of the mechanisms that cause degradation as well as radiation testing of components in order to assure that they will withstand the harsh environments encountered in space systems. The actual environment that components must withstand depends on many factors [1]. For earth-orbiting satellites, the environment depends on altitude and inclination (high inclination orbits pass near the poles where geomagnetic shielding is no longer effective), the total mission life, and assumptions made about solar flares, which occur at random times. Actual environments vary over a broad range. One example that is frequently used is a 705 km, 98 ° orbit that has been used for many earth-orbiting missions. Figure 1 shows how the total dose of components used in such an orbit depends on the amount of shielding that is present around the spacecraft. Five-year operation is assumed. For small amounts of shielding the total dose level is very high, and it is dominated by electrons. However, most electronics contained within spacecraft have sufficient shielding so that high energy protons are the dominant source of ionizing radiation. Protons also produce displacement damage, as discussed in Section III.

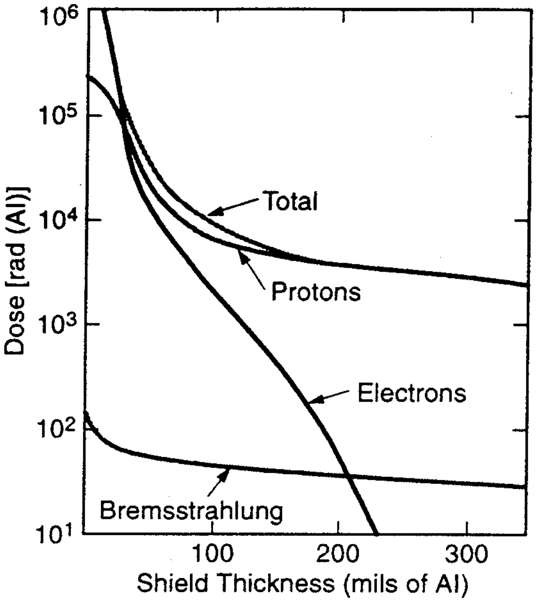


Figure 1. Effect of shielding on total dose for a five-year mission at 705 km, 98 degrees.

Solar particle events (solar flares) are important for most space applications (except for very low inclination orbits). Solar flares vary with the sun's sunspot activity, with a periodicity of approximately 11 years. Statistical models have been developed to provide a way to estimate the likely fluence from individual solar flares during periods of enhanced solar activity [2]. An intense solar flare can produce fluences of approximately 3×10^{10} p/cm^2, and most environments include the effects of such a flare in the overall specification.

II. IONIZATION DAMAGE IN MICROELECTRONICS

A. Mechanisms

Ionization damage is caused by electron-hole pairs that are generated in silicon dioxide and other insulators. The damage is the result of trapping of excess charges at interface regions -- usually holes -- at or near the interface region between the oxide

---

†The research in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, Code AE, under the NASA Electronics Parts and Packaging Program (NEPP).

(or other insulator) and semiconductor [3]. For example, charge trapping at the interface causes the threshold voltage of an MOS gate oxide to change. Charge trapping also affects field oxides which have a more complex structure, but are usually much thicker than gate oxides.

Although ionization damage depends on the type of particle and the particle energy, this energy dependence is usually incorporated into the concept of absorbed dose which refers to the total deposited energy from ionization. In addition to absorbed dose, one must consider the way that excess holes and electrons that are generated by the radiation are transported within the oxide. When low electric fields are present in the oxide, it is possible for many of the holes and electrons to recombine before they are transported to critical interface regions (this is referred to as charge yield). If the charge yield is low, then the net effect of the deposited dose is reduced. The charge yield depends on electric field as well as the type of particle that is causing the ionization. For example, protons with energy below 5 MeV produce a dense ionization track that increases the probability of recombination compared to electrons, which produce tracks with low charge density.

Ionization damage will often anneal after the irradiation has stopped., although not all device technologies exhibit annealing under room temperature conditions. Annealing is a complex topic that will not be addressed in this paper, but is covered in Reference 3.

B. CMOS Devices

For older CMOS devices charge trapping in the gate region was the dominant mechanism. This mechanism is still important for devices with thick gate oxides, such as those in flash memories or in power MOSFETs which require oxides that can withstand higher voltages, but it has become less important for conventional CMOS devices because the oxides have become so thin (to first order, the threshold shift depends on the square of the oxide thickness). However, some high density circuits are still affected by gate threshold shifts from radiation. Figure 2 shows the degradation of the internal charge pump of an advanced flash memory. The charge pump subcircuit is very sensitive to threshold voltage, and once the charge pump degrades it is no longer possible to erase or write to the memory. However, it still functions in the READ mode.

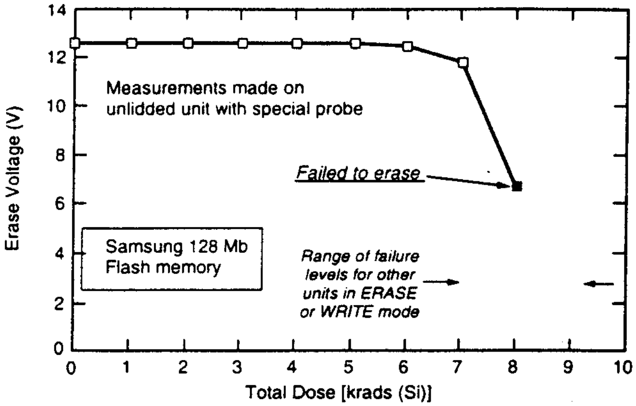


Figure 2. Decrease of internal charge pump voltage in an advanced flash memory after irradiation.

Charge trapping in field oxides is usually the dominant mechanism for advanced CMOS devices because the field oxides are so much thicker than gate oxides. Figure 3 shows catastrophic failure of a flash memory due to field oxide inversion. This type of failure typically occurs at significantly higher total dose levels than the failure level associated with charge pumps in those technologies, and typically causes a large increase in power supply current. For many modern circuits threshold shift in gate oxides is not a significant problem and the ultimate limit of circuit performance is set by field oxide inversion.

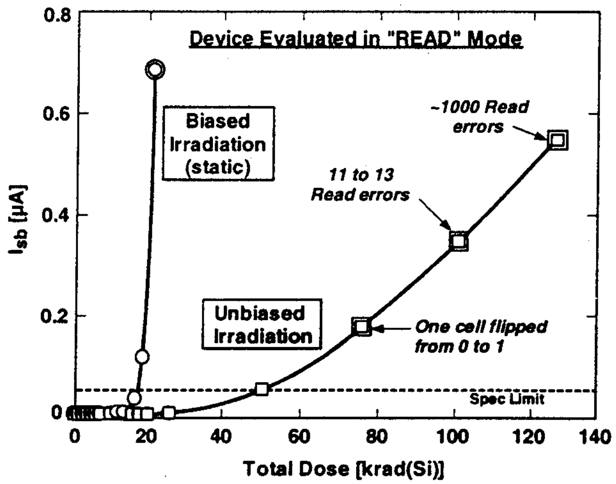


Figure 3. Catastrophic failure of a CMOS device due to field oxide inversion.

C. Bipolar Devices

In bipolar devices the primary effect of ionizing radiation is gain reduction. This is usually due to an increase in surface recombination near the emitter-base region. Ionization damage also causes leakage current to increase. Bipolar devices with regions that are lightly doped are usually more sensitive to gain and leakage current degradation. Consequently, bipolar devices with high maximum voltage ratings are generally more affected by ionization damage. Total dose effects in discrete transistors and basic linear circuits have been studied for many years, and there is considerable information in the literature [4,5].

A new phenomenon was discovered about eight years ago in which more damage occurs at the low dose rates in space [6-9] compared to the damage that is observed at high dose rates (typically used for laboratory testing). This effect is called enhanced degradation at low dose rate (ELDR).

Many types of linear circuits have been found to exhibit low dose-rate effects. Circuit parameters related to pnp transistors are usually the most sensitive. Figure 4 shows how the output error of a temperature sensor, manufactured with conventional linear circuits, is degraded when tests are done at low and high dose rate.

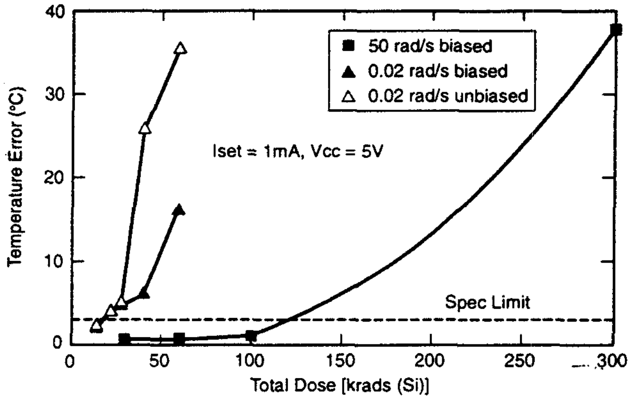


Figure 4. Effect of total dose on output error in a temperature sensing circuit.

The ELDR effect appears to be significant only for cases where relatively thick oxides are used in the construction of the device. The mechanism is not completely understood, but it is appears to be related to the buildup of internal fields due to the trapped charge at regions near the interface as well as to the extremely slow transport of trapped holes in oxides where the electric field is low.

The only certain way to deal with the ELDR problem is to test devices under low dose rate conditions. Typically the dose rate must be 0.005 rad(Si)/s or lower to get the maximum damage. Alternative test methods have been investigated, including testing devices at high dose rate at elevated temperature in order to speed up the hole transport process [10,11]. However, this works only in some cases, and cannot be relied upon without doing a great deal of exploratory work. One difficulty is that the circuit response is affected by both npn and pnp transistors, and the elevated temperature acceleration method requires different temperatures for different transistor types.

D. *Testing and Hardness Assurance*

Ionizing radiation tests are usually done with cobalt-60 gamma rays because they are convenient, low cost sources. Bias conditions can have a large effect on the damage that results, and care must be taken to make sure that the test conditions encompass the range of bias conditions that are expected in the application. Many devices are less degraded when they are irradiated without bias, but some types of bipolar structures are more sensitive when they are irradiated in an unbiased condition.

Many linear circuits have a wide range of electrical conditions that are covered in their overall specifications. In many cases the radiation degradation will be widely different, which severely complicates radiation characterization and testing. For example, many operational amplifiers are used with power supply voltages of ±15 V, and radiation testing is often done under those conditions. However, some circuits can also be used with much lower power supply voltage (for example, ±2.5 V) and the test results with the higher voltage cannot be applied to the lower voltage condition. The only way to deal with this is to do tests on larger numbers of samples, using subsets with different test conditions.

III. DISPLACEMENT DAMAGE IN MICROELECTRONICS

A. *Mechanism and Energy Dependence*

Displacement damage is caused by lattice collisions between energetic protons or electrons that transfer sufficient energy to the lattice to move an atom within the lattice out of its normal position. The damage results from movement of the target atom within the material. For cases where large amounts of energy are transferred to the target atom microscopic damaged regions are produced with a characteristic dimension of about 60 μm [12].

Displacement damage depends on energy. For electrons there is a sharp energy threshold. Protons, which are usually of more interest, have a different energy dependence because their larger mass allows a larger fraction of the incoming particle energy to be transferred to the target atom.

Figure 5 shows the dependence of displacement damage on particle energy in silicon [13].

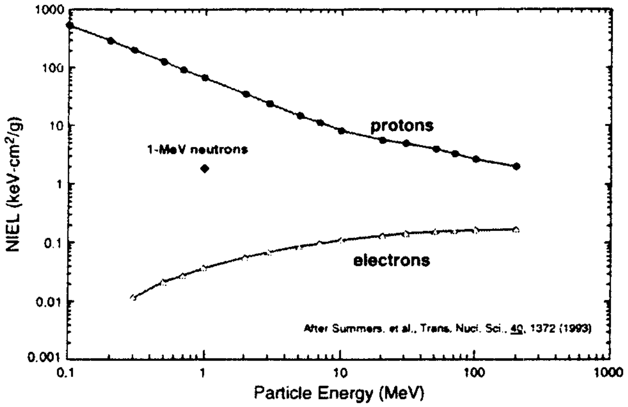


Figure 5. Dependence of non-ionizing energy loss on proton energy in silicon.

B. *Proton damage in bipolar devices*

Proton damage is usually only important for devices with relatively wide base regions unless the fluence levels are unusually high. Lateral and substrate pnp transistors that are used in many linear integrated circuits are affected by relatively low levels of proton radiation.

There are cases where different damage mechanisms occur when tests are done with protons that cause far lower failure levels compared to tests with gamma rays [14]. Figure 6 shows an example for a negative voltage regulator. When the device is irradiated with protons the start up circuit is degraded and the device fails *catastrophically* at equivalent total dose levels between 18 and 35 krad(Si); the spread in failure levels represents unit-to-unit variability of a small test sample from one date code. That failure mode does not occur when the equivalent tests are done with gamma rays.

Displacement damage effects can easily be overlooked because routine displacement damage tests are usually not done. It is extremely important to examine all linear circuits (as well as hybrid modules that may contain linear circuits) to determine whether proton displacement testing should be included.

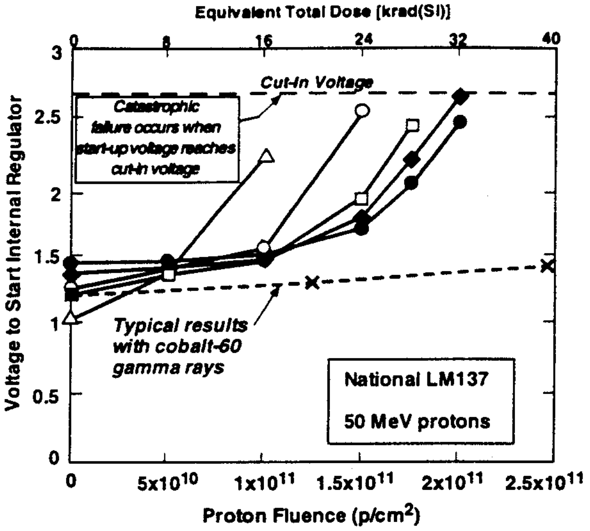


Figure 6. Comparison of damage from gamma rays and protons for a linear integrated circuit. The increased damage with protons is caused by displacement damage

C. *Solar cell damage*

Solar cells are affected by displacement damage from electrons as well as from protons because the relatively thin cover glass material is ineffective in shielding energetic electrons (see Figure 1). This problem is well known, and computer models are available that can predict solar cell damage for moderate electron fluences. However, at high fluences carrier removal effects, which are not included in the standard models, can cause catastrophic failure.

This effect has been studied by Yamaguchi, et al. [15]. They developed a model that includes carrier removal which agrees closely with experimental results, as shown in Figure 7.

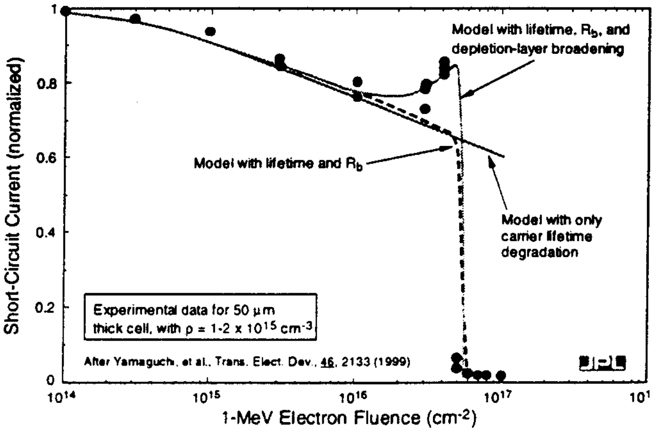


Figure 7. Degradation of solar cell at high electron fluences.

D. Testing and Hardness Assurance

Proton (or electron) testing is considerably more costly than tests with gamma rays, and it is further complicated by the strong dependence of proton damage on energy (see Figure 5). Usually tests are done at only a single energy in order to minimize costs. The damage at that energy can be related to damage at other energies using the established energy dependence, along with the spectrum of proton energies in the application. The effects of shielding must be taken into account when this calculation is done, because most of the low energy protons will be removed by even thin amounts of shielding.

One important practical difficulty for proton testing is activation of circuits and test boards during the irradiation. This makes it necessary to limit handling by personnel. It also makes it necessary to take electrical test equipment to the proton test facility because it can take up to a week for the induced radioactivity to die down to levels that allow shipping to other facilities.

IV. DISPLACEMENT DAMAGE IN OPTOELECTRONICS

A. Mechanisms

Although ionizing radiation causes some damage in optoelectronic devices, in almost every case (other than optical fibers) displacement damage is the dominant mechanism. Mechanisms for displacement damage in optoelectronics are essentially the same as those in conventional semiconductor devices, but it is necessary to consider other material types as well as silicon. Typical materials include GaAs, AlGaAs, GaP, and InGaAs.

There is less agreement about non-ionizing energy loss in the more complex structures of ternary and quaternary structures used in optoelectronics. For example, calculations of NIEL for GaAs do not agree very well with experimental measurements of light-emitting diodes for proton energies above 50 MeV [16-18]. Consequently, testing at energies above that value introduces potential ambiguity in interpreting the damage at lower energies, which is of critical importance when considering the effect of the continuous spectrum of proton energies on the device.

Displacement damage in many of these structures anneals after irradiation. Generally the annealing depends on charge injection after irradiation; in other words, little or no annealing will take place until current is applied to the device, at which point recovery will begin. Annealing adds a further level of complication to mechanisms and data interpretation.

B. LEDs

Highly efficient LEDs with wavelengths between 860 and 930 nm can be manufactured with a process that is referred to as amphoteric doping. Amphoteric doping relies on the property of silicon (as an impurity) in GaAs or AlGaAs which causes the impurity to change from n- to p-type depending on the growth temperature. This allows a p-n junction to be formed with only a single dopant by gradually changing the temperature during the epitaxial growth process.

Amphoterically doped LEDs have very high efficiency, but their response time is relatively slow because the fabrication process produces a relatively wide junction with a graded impurity level. The wavelength of amphoterically doped LEDs is near the peak in the silicon responsivity curve, and they are widely used in optoelectronic devices, particularly optocouplers.

Amphoterically doped devices are extremely sensitive to displacement damage. Figure 8 shows representative results. Note that about 50% of the light output has been lost at a fluence of only about 2×10^{10} p/cm^2. This is equivalent to a total dose of about 3 krad(Si), but of course the damage is caused by displacement effects, not ionization. Amphoterically doped devices are sensitive to injection-enhanced annealing.

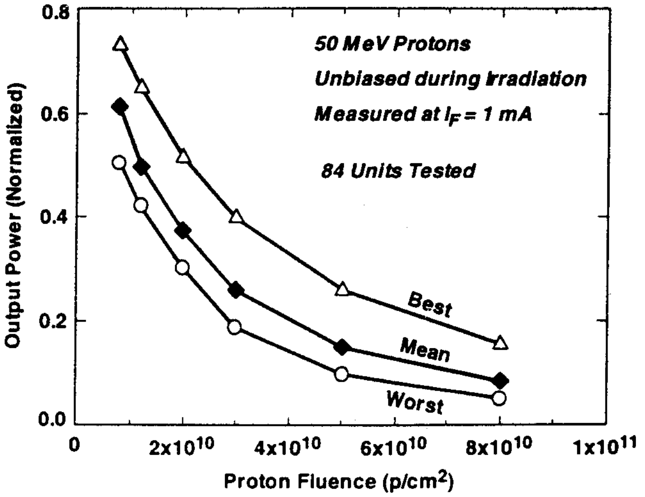


Figure 8. Degradation of a typical amphoterically doped LED after irradiation with protons.

An alternative way to fabricate LEDs is deposition of thin layers of different material types. This results in a heterojunction structure that is highly efficient in confining optical photons as well as in injecting carriers over short distances. The fabrication process for this type of LED is far more complex, producing LEDs with lower efficiency as well as introducing some defects because slight lattice mismatch of the different material types. In spite of these technical difficulties, many LEDs are fabricated with heterojunctions.

Most heterojunction LEDs are far more resistant to radiation damage than amphoterically doped LEDs, although this is partly offset by the lower initial light output. Figure 9 shows typical results; this device did not exhibit annealing after irradiation, which is typical of most heterojunction LED structures [19].

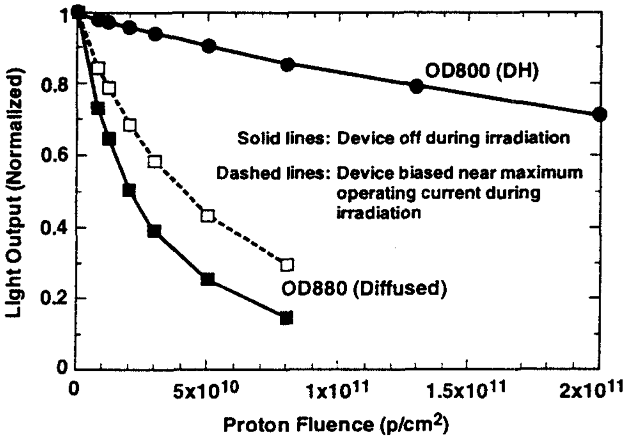


Figure 9 showing degradation of an advanced double-heterojunction LED compared with a similar LED made with an amphoterically doped process.

For both types of LEDs the main parameter of concern is light output. The threshold current at which the LED begins to emit light changes only slightly, even after the LED is severely degraded.

C. Laser Diodes

Light output of a laser diode is highly nonlinear. At moderate currents the device functions very much like an LED. As the current increases the light output begins to increase abruptly as soon as the current exceeds the threshold current. At this point the spectral width of the light decreases from 50-70 nm to 1-2 nm. The critical parameter for a laser diode is the threshold current.

Figure 10 shows how the threshold current of four different types of laser diodes depends on proton damage. In all cases the threshold current exhibits a nearly linear increase with proton fluence. Note that relatively high fluences are required in order to affect the threshold current.

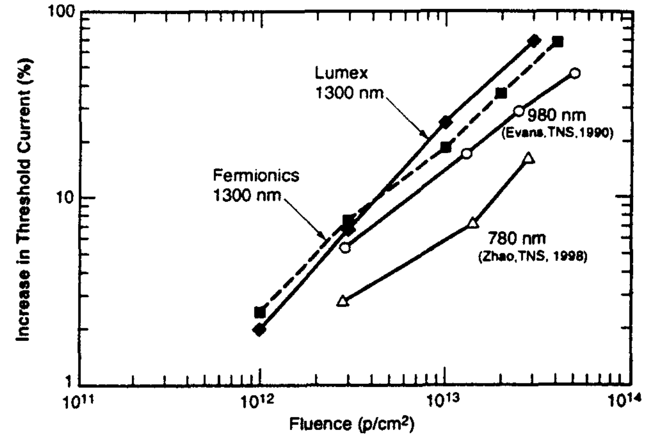


Figure 10. Degradation of threshold current for four different types of semiconductor lasers.

The threshold current depends on temperature, and many laser diode incorporate internal monitor diodes that can be used with external feedback circuitry to maintain stable operating conditions. The internal photodiode is also affected by radiation, as shown in Figure 11. Note that degradation of the photodiode is considerably higher than the increase in the threshold current of the laser. This needs to be taken into account when selecting and applying lasers in space because degradation of the monitor diode will over compensate the laser degradation and may potentially affect device reliability.

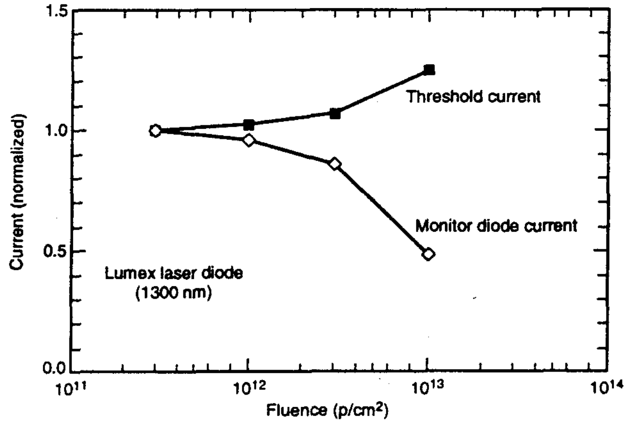


Figure 11. Degradation of laser diode and internal photodetector.

D. Detectors

There are many different ways to fabricate optical detectors. Two structures that are commonly used are (1) conventional p-n diodes, which collect light by a combination of drift from the depleted region of the junction and diffusion from extended regions; and (2) p-i-n diodes, which interpose a lightly doped i-region between the p- and n- layers. The p-i-n detector operates with a sufficiently high reverse bias to completely deplete the central region. Consequently, all of the charge is collected by drift.

Figure 12 compares the degradation of these two types of detectors at three different wavelengths. At short wavelengths degradation in the two types of detectors is similar because the light has a relatively shallow absorption depth. At longer wavelengths much of the light is absorbed in deeper regions, and lifetime damage in the conventional p-n structure affects the diffusion component of the photocurrent. The p-i-n diode is unaffected by lifetime damage, and consequently very little degradation occurs at longer wavelengths.

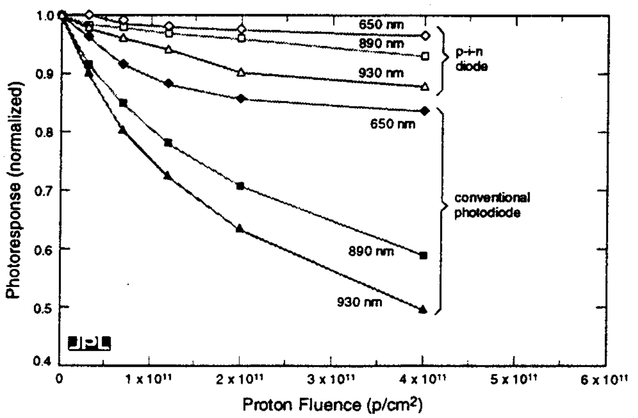
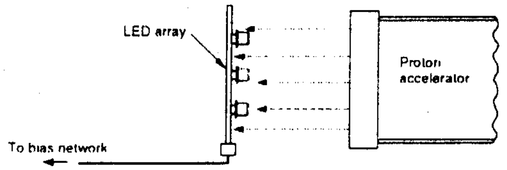


Figure 12. Degradation of a silicon detector at three different wavelengths.

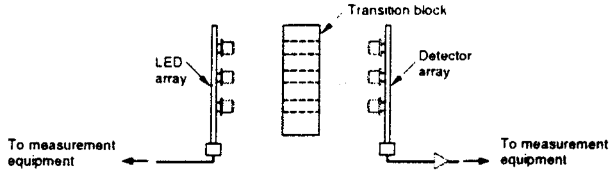
Although light collection efficiency in p-i-n diodes is less affected by radiation damage, leakage current in the lightly doped intrinsic region is sensitive to displacement damage. This can be an important factor in detector performance, particularly in applications requiring high sensitivity and low noise.

E. Testing and Hardness Assurance

Proton testing is relatively expensive, and it is generally necessary to use special test approaches that allow several devices to be irradiated simultaneously and measured quickly and accurately between successive irradiations. Figure 13 shows an example of a test configuration which uses a circular array of LEDs (or laser diodes). A special transition block is used for precision alignment of a corresponding array of detectors with the LEDs. This allows accurate, repeatable measurements to be made.



a) Irradiation



b) Measurements

Figure 13. Configuration used for proton tests of light-emitting diodes.

Optical devices are often not controlled to nearly the same extent as conventional microelectronics. The optical output can be affected by physical factors -- surface roughness, misalignment between internal reflecting surfaces, and the presence of index matching materials -- which can cause much wider initial variability in light output. LEDs and laser diodes also degrade with time during extended operation. For these reasons, larger sample sizes are recommended for optical component characterization. Lot-to-lot variability is also important, particularly for applications where the optical power margin is less than five. Aging and temperature effects need to be added to radiation degradation in order to determine overall operating margins.

V. DISCUSSION

A. Total Dose Effects in Advanced Devices

Many advanced devices are less sensitive to ionizing radiation than older devices with similar technologies because of the continued reduction of gate oxide thickness required by device scaling. Some devices, particularly flash memories, continue to fail at relatively low radiation levels, but advanced microprocessors and ASIC devices often will function at levels of 50 krad(Si) or more.

DRAMs, which are frequently used in extended memory applications such as solid-state recorders, have special properties that must be taken into account when they are evaluated. DRAMs require very low standby current, and some cells within typical DRAMs are more affected by total dose damage than the majority of the cells because of statistical fluctuations in the number of dopant atoms and the cell structure. DRAM leakage current is also affected by temperature. Radiation characterization must take this temperature dependence into account.

B. New Effects: Gate Rupture in Scaled Devices

An important new phenomenon that has investigated during the last five years for digital devices is catastrophic dielectric breakdown from heavy ions [20, 21]. Most of this work was done on capacitor test structures. One key result from that work was that breakdown in thin oxides manifests itself differently from the hard breakdown that occurs in conventional thick oxides. For oxides with thickness below 6 nm, the breakdown is effectively a slight increase in leakage current, which is termed soft breakdown. Soft breakdown effects are more difficult to measure, but are potentially quite important because the leakage current can be high enough to load down an MOS device with very small area (with drive currents less than 1 μA) even though it may not appear to be very significant on a large area test structure.

The effects of thin oxides and scaling effects on breakdown from heavy ions has not been thoroughly investigated, and remains an area of current research. Initial work indicates that the sensitivity depends on capacitor area, suggesting that defects within the oxide create a localized region that is more sensitive to breakdown. If this is the case, then lower fields for breakdown will occur for an ion to strike within a neighborhood of a defect. This introduces an area dependence for breakdown.

Very recent work by Lum, et al. showed that similar breakdown effects occur in linear devices that contain large-area capacitors [22]. Their work showed that the dielectric breakdown field strength was somewhat lower for linear devices than for capacitors from digital processes. Figure 14 shows an example of their results, along with the results for the earlier studies of capacitor test structures from digital processes. They also noted that the cross section for gate rupture was typically less than 10% of the total capacitor area, reinforcing the idea that defects within the oxide are important in determining sensitivity to gate rupture.

This work suggests that catastrophic breakdown from heavy ions may be a significant issue, particularly for systems that use large numbers of devices. This type of breakdown may occur in random logic as well as in memories or registers, and additional work is needed to increase the level of understanding of this phenomenon.

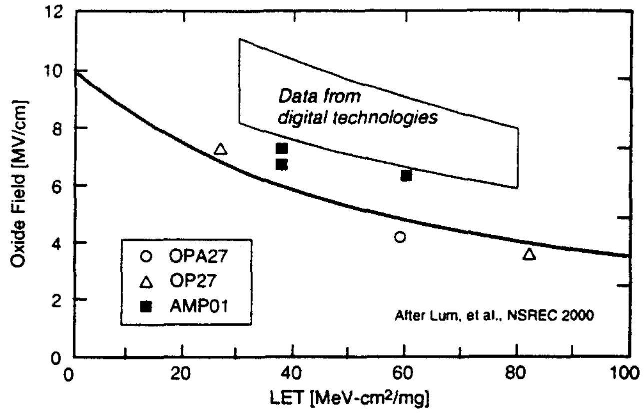


Figure 14. Critical voltage for failure of capacitors in analog circuits, compared with capacitors in digital technologies.

VI. SUMMARY AND CONCLUSIONS

This paper has discussed permanent damage caused by space radiation when it interacts with electronic and optoelectronic devices. Ionization damage is still important for many types of devices, but device scaling has generally improved the performance of CMOS devices to much higher levels than in the past. Ionization damage is still important for linear circuits, and the increased damage in those types of devices at low dose rates makes it more difficult and costly to evaluate their radiation performance.

Displacement damage is often overlooked because the majority of microelectronic devices are relatively insensitive to displacement effects. However, displacement damage is important for some linear circuits, and it the most significant environment for optoelectronic devices.

There are additional permanent damage effects caused by heavy ions. These include microdose damage, and the problem of gate rupture in thin oxides which is less well understood. The new work on catastrophic damage in linear circuits shows that this remains a significant problem in space, and more work needs to be done on that topic in order to ensure that gate rupture does not cause failures in space when large numbers of highly scaled devices are used.

REFERENCES

[1] J. L. Barth, Part I of the Radiation Effects Short Course presented at the Nuclear and Space Radiation Effects Conference, Snowmass, Colorado, July, 1997.

[2] M. A. Xapsos, G. P. Summers, J. L. Barth, E. G. Stassinopoulos and E. A. Burke, "Probability Model for Worst-Case Solar Proton Event Fluences," IEEE Trans. Nucl. Sci., 46, pp. 1481-1485 (1999).

[3] *Ionizing Radiation Effects in MOS Devices and Circuits*, T. P. Ma and P. V. Dressendorfer, editors, John Wiley: New York, 1989.

[4] R. L. Pease, "Total Dose Issues for Microelectronics in Space Systems," IEEE Trans. Nucl. Sci., 43, pp. 442-452 (1996).

[5] G. C. Messenger and M. S. Ash, "The Effects of Radiation on Electronic Systems, Van Nostrand Reinhold: New York, 1986.

[6] E. W. Enlow, R. L. Pease, W. Combs, R. D. Schrimpf and R. N. Nowlin, "Response of Advanced Bipolar Processes to Ionizing Radiation," IEEE Trans. Nucl. Sci., 38, p. 1342 (1991).

[7] S. McClure, R. L. Pease, W. Will and G. Perry, "Dependence of Total Dose Response of Bipolar Linear Microcircuits on Applied Dose Rate," IEE Trans. Nucl. Sci., 41, p. 2544 (1994).

[8] R. D. Schrimpf, R. J Graves, D. M. Schmidt, D. M. Fleetwood, R. L. Pease, W. E. Combs and M. DeLaus, "Hardness Assurance Issues for Lateral PNP Bipolar Junction Transistors," IEEE Trans. Nucl. Sci., 42, p. 1641 (1995).

[9] A. H. Johnston, B. G. Rax and C. I. Lee, "Enhanced Damage in Linear Bipolar Circuits at Low Dose Rate," IEEE Trans. Nucl. Sci., 42, p. 1650 (1995).

[10] S. C. Witczak, R. D. Schrimpf, K. F. Galloway, D. M. Fleetwood, R. L. Pease, J. M. Puhl, D. M. Schmidt, W. E. Combs and J. S. Suehle, "Accelerated Tests for Simulating Low Dose Rate Gain Degradation of Lateral and Substrate PNP Bipolar Junction Transistors," IEEE Trans. Nucl. Sci., 43, p. 3151 (1996).

[11] S. C. Witczak, R. C. Lacoe, D. C. Mayer, D. M. Fleetwood, R. D. Schrimpf and K. F. Galloway, "Space Charge Limited Degradation of Bipolar Oxides at Low Electric Fields," IEEE Trans. Nucl. Sci., 45, p. 2239 (1998).

[12] V.A. J. van Lint, R. E. Leadon and J. F. Colwell, "Energy Dependence of Displacement Damage Effects in Semiconductors," IEEE Trans. Nucl. Sci., 19, No. 6, p. 181 (1972).

[13] G. P. Summers, E. A. Burke, C. J. Dale, E. A. Wolicki, P. W. Marshall and M. A. Gelhausen, "Correlation of Particle Induced Displacement Damage in Silicon," IEEE Trans. Nucl. Sci., 34, 1134 (1987).

[14] B. G. Rax, A. H. Johnston and C. I. Lee, "Proton Damage Effects in Linear Integrated Circuits," IEEE Trans. Nucl. Sci., 45, 2632 (1998).

[15] M. Yamaguchi, A. Khan, S. Taylor, M. Imaizumi, T. Hisamatsu and S. Matsuda, "A Detailed Model to Improve the Radiation Resistance of Si Space Solar Cells," IEEE Trans. Elect. Dev., 46, 2133 (1999).

[16]G. P. Summers, E. A. Burke, M. A. Xapsos, C. J. Dale, P. W. Marshall and E. L. Petersen, "Displacement Damage in GaAs Structures," IEEE Trans. Nucl. Sci., 35, 1221 (1988).

[17] A. L. Barry, A. J. Houdayer, P. F. Hinrichsen, W. G. Letourneau and J. Vincent, "The Energy Dependence of Lifetime Damage Constants in GaAs LEDs for 1-500 MeV Protons," IEEE Trans. Nucl. Sci., 42, 2104 (1995).

[18] R. A. Reed, C. J. Marshall, K. A. LaBel, P. W. Marshall, H. S. Kim and L. Xuan, "Energy Dependence of Proton Damage in AlGaAs Light-Emitting Diodes," to be presented at the Nuclear and Space Radiation Effects Conference, Reno, Nevada, July 25-28, 2000.

[19] A. H. Johnston, B. G. Rax, L. E. Selva and C. E. Barnes, "Proton Degradation of Light-Emitting Diodes," IEEE Trans. Nucl. Sci., 46, pp. 1781-1789 (1999).

[20] F. W. Sexton, D. M. Fleetwood, M. R. Shaneyfelt, P. E. Dodd and G. L. Hash, "Single Event Gate Rupture in Thin Gate Oxides," IEEE Trans. Nucl. Sci., 44, pp. 2345-2352 (1997).

[21] A. H. Johnston, G. M. Swift, T. Miyahira and L. D. Edmonds, "Breakdown of Gate Oxides During Irradiation with Heavy Ions," IEEE Trans. Nucl. Sci., 45, pp. 2500-2508 (1998).

[22] G. K. Lum, H. O'Donnel and N. Boruta, "The Impact of Single Event Gate Rupture in Linear Devices," presented at the IEEE Nuclear and Space Radiation Effects Conference, Reno, Nevada, July, 2000; submitted for publication in the Dec. 2000 issue of the IEEE Trans. on Nucl. Sci.