Proton Displacement Damage in Light-Emitting and Laser Diodes†

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Abstract

The effects of proton displacement damage on light-emitting diodes and laser diodes are discussed, comparing the radiation sensitivity of current technology devices with older devices for which data exists in the literature. Injection-enhanced annealing is discussed, along with the issue of energy dependence of proton displacement damage. New characterization methods are proposed for LEDs that complement measurement of light output and provide a better indication of non-radiative recombination centers.

I. INTRODUCTION

Displacement damage in light-emitting devices is a complex issue that has been made still more difficult because of the many changes that have occurred in the design and fabrication of GaAs and related devices used in optoelectronics. Because of these changes, older data on light-emitting diodes (LEDs) and laser diodes is often not applicable to current production devices. For example, laser diodes take advantage of advanced processing techniques to fabricate quantum-well structures with strained lattices that reduce the threshold current and increase efficiency. Related improvements have been made in light-emitting diodes, particularly for devices with longer wavelengths that are intended for fiber optic applications.

This paper discusses displacement damage effects in advanced LEDs and laser diodes, along with design details that affect their radiation response. High-energy protons -- 50 MeV -- were used for all of the experimental work. A number of properties were measured to evaluate the effects of degradation, including measurement of wavelength and spectral width using a spectrometer. Careful attention was given to limiting the currents and duty cycle during characterization to minimize injection-enhanced annealing.

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II. LIGHT EMITTING DIODES

A. General Considerations

Light-emitting diodes are usually the preferred choice for light emitters in space because they can be used without elaborate methods of temperature control, and have longer operating life compared to older laser diode technologies. Very efficient LEDs with wavelengths in the 850-930 nm region -- compatible with most silicon detectors -- can be produced by an older process that relies on amphoteric doping, creating the p-n junction by gradually decreasing the temperature during the epitaxial growth process[1]. Although those devices are very efficient, the transition region between the n- and p-regions occurs over a wide region -- 50 µm or more -- and consequently their operation requires long carrier lifetime to maintain high efficiency.

Because of the need for long carrier lifetime, amphoterically doped LEDs are extremely sensitive to displacement damage effects [2-5]. They are frequently used in optocouplers because of their high efficiency at wavelengths that are closely matched to the peak in the responsivity of silicon detectors. Optocouplers that are not specifically designed to be radiation tolerant often fail at very low radiation levels because of the sensitivity of amphoterically doped LEDs to radiation damage [6,7].

Figure 1 shows the degradation of optical power output for two amphoterically doped LEDs, along with that of a double-heterojunction LED. The vertical axis shows the relative amount of optical power, normalized to typical pre-irradiation values for the OD880 device, which has the highest initial light output. The two amphoterically doped devices are significantly degraded at proton fluences of about 1×10^{10} p/cm^2. That is equivalent to a total dose of about 1.4 krad(GaAs) in an environment that is dominated by protons, but of course the damage is caused by displacement effects, not ionization. The double-heterojunction LED is far less sensitive to radiation damage, but also has considerably less initial light output compared to the amphoterically doped LEDs (all three devices have the same maximum current ratings and similar package styles).

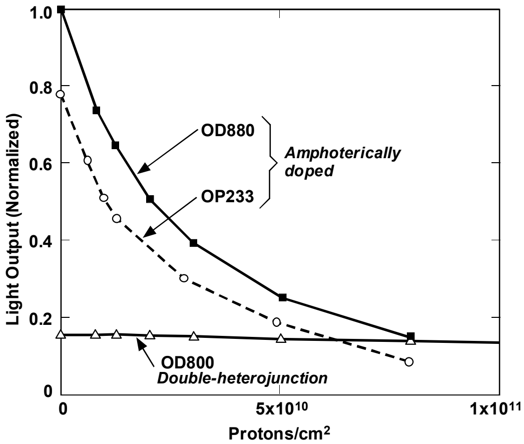

Figure 1. Degradation of amphoterically doped LEDs normalized to account for differences in initial light intensity. Degradation of a double-heterojunction LED is also shown for comparison.

Damage in amphoterically doped LEDs is affected by bias conditions during irradiation, as shown in Figure 2. The effect of bias is more pronounced when post-irradiation measurements are restricted to low current levels. Note that damage in the double-heterojunction LED is nearly independent of bias.

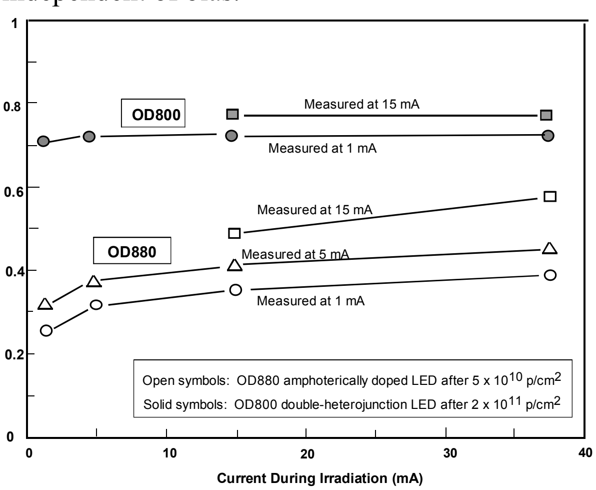

Figure 2. Effect of bias conditions on degradation for an amphoterically doped and double heterojunction LED.

B. Injection-Enhanced Annealing

The dependence of damage on bias is due to injection-enhanced annealing [2-5], which can cause up to half the damage to recover. Annealing is very important in amphoterically doped LEDs, but is much less important in newer LED structures that are fabricated with heterojunctions.

Rose and Barnes noted that damage in LEDs was superlinear. They derived the relationship

$$\left[(I_o/I)^{2/3} - 1\right] = K\,\tau\,\Phi \qquad (1)$$

for the case where minority carrier lifetime is the degradation mechanism and the device is measured at constant injection level. In this equation I_o is the initial light output, I is the light output after degradation, K is the damage constant, τ is the initial minority carrier lifetime (prior to irradiation), and Φ is the fluence (note that K depends on several additional factors, including the injection level and proton energy).

Damage in most amphoterically doped devices can be adequately described by Equation 1 over a wide range of fluences, with a linear dependence between the 2/3 power of the light intensity and fluence. Because of the linearity, it is useful to describe injection-dependent annealing with that relationship.

The effect of applying current to a damaged device is shown in Figure 3, using the damage factor (with the 2/3 power relationship) to describe the annealing behavior rather than normalized light intensity that was used in Figure 1. Previous tests showed that the effect of different operating and measurements currents could be normalized by considering the total charge [5]. The data in Figure 3 shows that at short times (small amounts of charge) the current has little effect, but that the rate of annealing increases after about 1/100 coulomb has passed through the device. The charge corresponding to 50% recovery of the radiation-induced damage was between 3 and 8 coulombs for four different types of amphoterically doped LEDs (including both AlGaAs and GaAs materials).

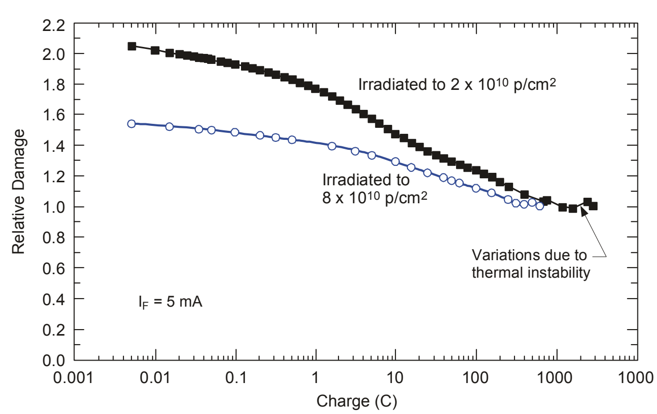

Figure 3. Evaluation of injection-dependent annealing using total charge and the linear damage factor of Equation 1.

Using the damage factor to describe annealing provides many advantages. It also provides a way to evaluate annealing in a less time consuming manner by extending the detailed measurements only to a charge of about 10 coulombs. The final equilibrium point can be determined by letting the annealing continue for extended periods, and doing relatively few measurements at longer times where it is awkward to continue detailed measurements. Thermal effects -- the LED output typically has a temperature coefficient of about -1% per degree Centigrade -- limit the reproducibility of measurements, and introduce some uncertainty into determination of the time at which annealing effects are saturated.

C. Other Factors that Influence Damage Sensitivity

In general, LED technologies with thin active regions are more resistant to displacement damage. However, they also have lower light output. Figure 4 shows the relationship between LED output power and bandwidth based on an earlier study [8]. The optical power and bandwidth of four types of LEDs that are included in this paper are superimposed on the curve. This shows that LEDs with short lifetimes have significantly lower initial light output, and that these earlier trends are still applicable to modern devices. That relationship needs to be kept in mind when devices are selected

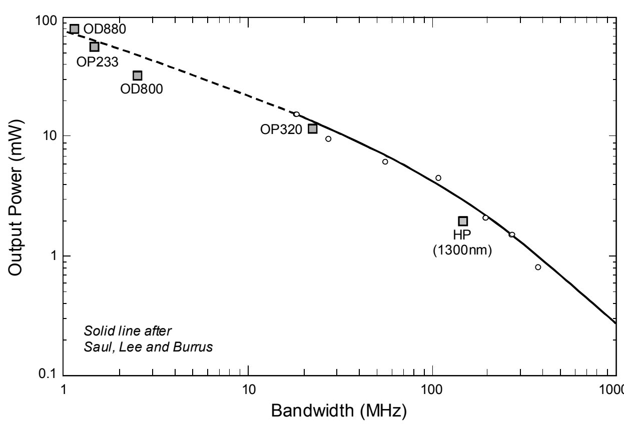

Figure 4. Relationship between optical power and bandwidth for various LEDs.

An example of radiation damage in a very hard LED technology is shown in Figure 5. This particular device is fabricated with InGaAs and operates at 1300 nm. The device has a modulation bandwidth above 100 MHz. The two sets of curves shown in the figure are LED forward current vs. forward voltage, and the current in an optical detector corresponding to the optical power output at the same LED forward voltage condition.

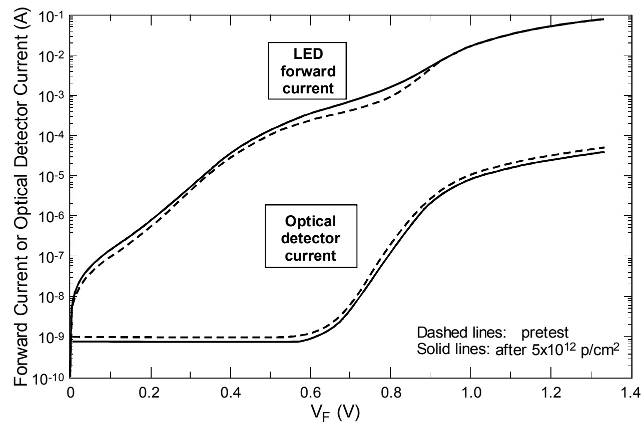

Figure 5. Degradation of a very hard LED technology operating at 1300 nm.

Note that the radiation level in Figure 5 is 30 times higher than the level for the amphoterically doped LEDs in Figure 1, and that the optical power only changes by about 25%. Even though the LED is relatively resistant to radiation, the initial light output is far lower than that of amphoterically doped AlGaAs LEDs (see Figure 1). Note also that the threshold current for light output is not affected by radiation damage, only the efficiency.

III. LASER DIODES

A. Laser Diode Technology

Laser diodes have evolved rapidly during the last thirty years [8-12]. Initial improvements used heterojunctions and bandgap engineering to increase efficiency and reduce threshold current. Newer structures are far more complicated, and have used advanced fabrication methods that allow extremely thin layers of material to be grown. This makes it possible to form laser diodes that are confined in discrete quantum states. Quantum-well lasers are less affected by temperature than older laser diode technologies, although the fabrication steps to produce such lasers are quite involved. The use of strained layers (with deliberate lattice mismatch over short lattice distances) provides a way to increase laser efficiency and provide more stable operation [12,13]. Table 1 shows how the threshold current and active layer thickness of laser diode technologies has evolved. The complex structure of modern lasers increases the difficulty of interpreting older data, which is often not applicable to new laser technologies.

Table 1. Threshold Current Trends for Various Laser Technologies

Technology	Year	Threshold Current (A/cm^2)	Active Region Thickness (Å)
Homojunction	1965	≃ 100,000	25,000
Single Heterojunction	1968	12,000	4,000
Double Heterojunction	1970	1,600	1,800
Quantum Well	1980	500	120
Strained Quantum Well	1990	65	60

B. Radiation Degradation

Older work, primarily based on neutron irradiation, showed that semiconductor lasers were much less damaged by radiation than amphoterically doped LEDs [14]. However, the degradation mode was quite different from LEDs. At moderate radiation levels the main effect of the displacement damage on laser diodes was to increase the threshold current. In contrast, the threshold current level for the onset of light output in LEDs changes very little after irradiation, but the light output at constant injection conditions generally decreases.

Newer laser structures are also quite resistant to displacement damage effects. Figure 6 shows the degradation of a strained quantum well laser after irradiation with 5.5 MeV protons [15]. (Note that 5.5 MeV protons are about 20 times more damaging than 200 MeV protons, so the fluences in Figure 6 are correspondingly lower even though this structure is only slightly affected by displacement damage except at very high fluences.)

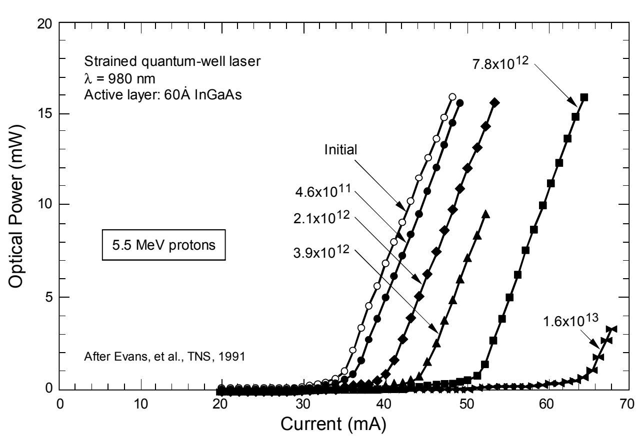

Figure 6. Proton degradation of a strained quantum-well laser diode.

The data in the figure shows how the threshold current increases at successively higher radiation levels. Note however that the slope -- which is essentially the internal efficiency of the laser -- is unchanged except at the highest levels. Contrast this behavior with that of the 1300 nm LED in Figure 5, where the threshold conditions are essentially unchanged, but the LED power output is degraded.

Similar results have been obtained by Zhao, et al. for a commercial multiple-quantum well laser that operated at 780 nm [16]. The slope efficiency of the lasers that they tested remained unchanged until comparable radiation levels, taking into account the effective damage of the 200 MeV protons used in their study.

New results for degradation of a 1300 nm laser diode are shown in Figure 7, using logarithmic scales. Note that at currents below the laser threshold -- where the device functions as an LED -- the light output is more severely degraded than at high current, when the device functions as a laser. Characterization of the device at low currents adds additional information about device operation that is not as obvious as measurements at high currents.

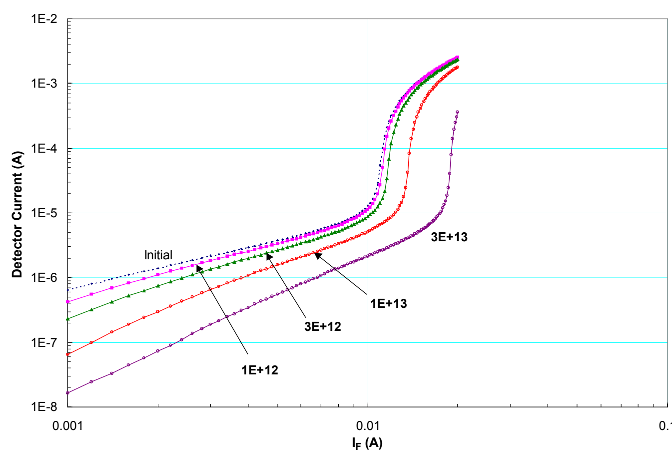

Figure 7. Degradation of a 1300 nm laser diode plotted logarithmically.

The degradation of the device in Figure 7 is plotted on a linear scale in Figure 8. Note the similarity to the older results of Figure 4, although the threshold current of the 1300 nm device requires a fluence that is about twice as great as that of the older device for threshold current degradation. Just as for the older devices, the slope efficiency is essentially unchanged by radiation damage.

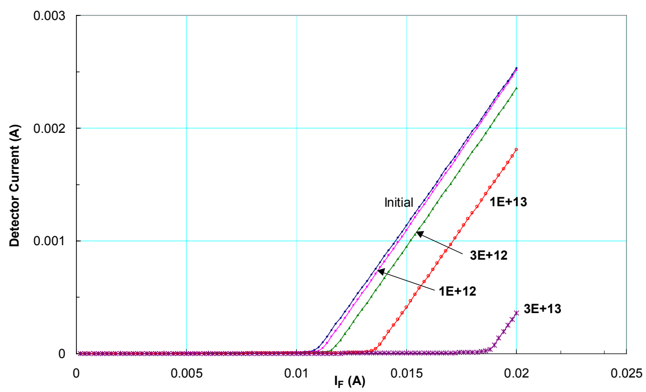

Figure 8. Degradation of a 1300 nm laser diode plotted linearly.

Laser threshold current increases with proton fluence. The results of our new tests on two 1300 nm laser diodes are compared with older results for 980 and 780 nm laser diodes in Figure 8. The older results were taken at 5.5 and 200 MeV proton energies, respectively and were reported in References 15 and 16. The data were modified using the NIEL values for light-emitting diodes [21] that show a continual decrease in NIEL at energies above 100 MeV instead of the flat relationship of older calculations [19] in order to provide a direct comparison with the new results.

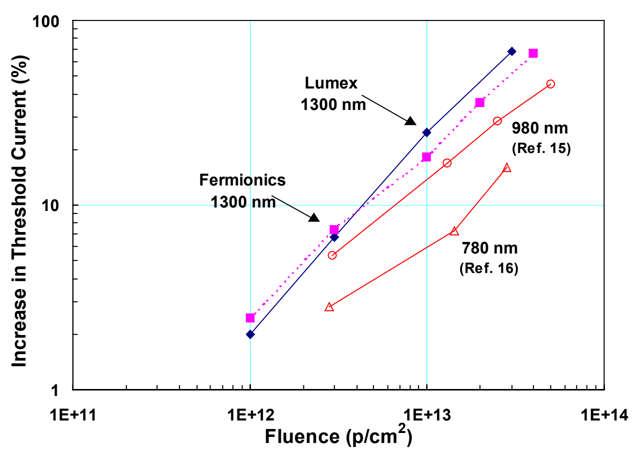

Figure 9. Dependence of laser diode threshold current on proton fluence Results from the older studies are normalized to equivalent 50 MeV proton damage using experimental values of non-ionizing energy loss from references

The results in Figure 9 show that there are differences in the damage sensitivity of threshold current between different types of lasers, varying by about a factor of five. Although one data set deviates slightly (other data in that reference indicates some potential problems with reproducibility), the data for most lasers shows that threshold current is linearly dependent on proton fluence.

C. *New Laser Structures: VCSELs*

Vertical cavity surface emitting lasers (VCSELs) provide a different technique for fabricating lasers. A VCSEL uses a distributed series of layers -- with spaces between layers that are nearly exactly one-half the operating wavelength -- to produce a distributed Bragg reflecting cavity [17,18]. The region where light is produced can be restricted to a small area within the device by using various methods of confinement, including oxide isolation. Such lasers are extremely efficient, with very low threshold currents and emit light vertically rather than from the edge. However, they have lower optical power than conventional semiconductor laser devices.

An example of VCSEL degradation is shown in Figure 10 for an oxide-confined VCSEL technology manufactured by Sandia National Laboratories [22]. Data in that figure was taken with 192 MeV protons. More degradation occurs in the slope efficiency of the VCSEL device compared to that of typical quantum-well lasers after irradiation. The slope efficiency changes even for unirradiated devices, mainly because of thermal effects in the VCSEL, which has a small volume and is sensitive to self-heating at high currents. The large change in slope efficiency at high radiation levels may be caused by carrier removal effects.

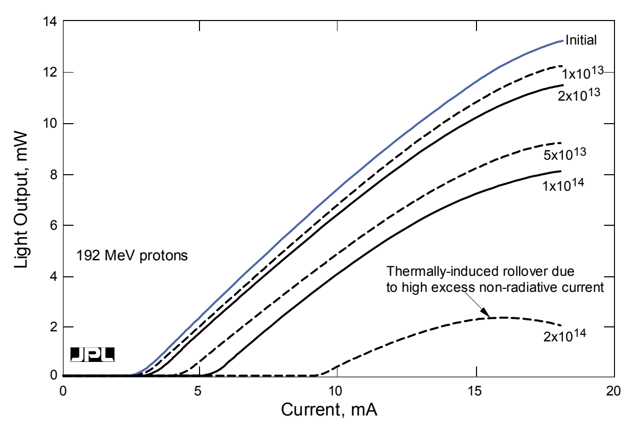

Figure 10. Proton degradation of an oxide-confined VCSEL.

Although VCSELs clearly are quite resistant to radiation damage, they can tolerate less shift in threshold current compared to conventional laser diodes where the nearly constant slope efficiency allows operation at current well above the threshold current.

IV. DISCUSSION

A. Trends in Device Hardness

Different mechanisms are important for the various types of light emitting devices, and those mechanisms have to be understood in order to do radiation tests and evaluate the performance of lasers and LEDs for space applications. Fortunately, many of the new technologies can withstand much higher radiation levels than older device types. However, some devices rely on complex internal structures. Variations between components and the presence of defects in heterojunction or thin layers of material can cause some devices in a larger sample to respond quite differently after irradiation compared to typical devices. Heterojunction LEDs and most advanced laser diodes sometimes have large unit-to-unit variations within a manufacturing lot that are not observed for older technologies.

There are many possible reasons for such variability. Heterojunctions always involve some degree of lattice mismatch. Internal defects caused by lattice imperfections can alter the characteristics of LEDs or laser diodes, possibly changing the way in which defects induced by radiation damage affect the device. Test sample sizes of 10 or more should be used to get a better idea of the uniformity of radiation damage in these structures.

Another useful technique is to extend electrical characterization measurements to the low current region, even though that regime is of little interest for applications which require relatively high current densities for significant light output. Work on LED reliability has shown that defects increase non-radiative recombination at low current which provides a better indicator of the presence of defects than operation at high currents [8,9,23]. LEDs with abnormal radiation damage responses also exhibit changes in characteristics at low current [50]. However, more work needs to be done on damage uniformity to determine whether laser diodes can also be "probed" by low current characteristics as well as on damage uniformity of large samples.

B. Energy Dependence

The energy dependence of proton damage in III-V devices is somewhat uncertain, particularly for energies above 50 MeV (we used 50 MeV protons in the new results presented in this paper because of the uncertainty in energy dependence). Energy dependence is extremely important in practice because of the need to interpret damage at a single test energy in the context of the spectrum of proton energies that occur in space, as well as establishing equivalent damage between neutron and proton effects because of the body of neutron displacement damage.

Initial theoretical work on non-ionizing energy loss disagreed with experimental results for GaAs JFETs, which are dominated by carrier removal effects, not lifetime. Summers, et al. modified the calculations of energy loss at high energies, applying a correction that reduced the energy loss due to cascade-evaporation [19]. That resulted in better agreement with the JFET data, but no comparison was made with data on photonic devices (which was very limited at that time).

Later work was done by Barry, et al. on amphoterically doped LEDs [20]. Their results, taken over a wide range of energies, did not agree at all with the earlier calculations of NIEL in Reference 19. The energy dependence that they measured showed a continual decrease in NIEL at high energies. A very limited study in 1999 [24] suggested that damage in laser diodes agreed with the theoretical values for NIEL. However, that work was based on very small sample sizes, and the authors failed to address unit-to-unit variability which seriously limited the usefulness of the work.

During the last year, Goddard Space Flight Center re-examined energy dependence, subjecting two types of LEDs to tests over a wide range of proton energies [21]. Damage in the amphoterically doped device and the double-heterojunction device were in close agreement with the data of Barry, et al. in 1995, suggesting that the NIEL calculations done by Summers et al. in 1988 are not applicable to optoelectronic devices. Thus, the best available results indicate that NIEL continues to decrease at energy for optoelectronic components with III-V compounds. The discrepancy is about a factor of three at 200 MeV. Using energies well below 200 MeV is one way to avoid possible problems in data interpretation until more systematic studies of energy dependence are done.

V. SUMMARY

This paper has examined proton damage in two types of optical emitters -- LEDs and laser diodes -- that are of interest for space applications. Advances in device design and processing techniques have resulted in very complex devices compared to older devices for which data exists in the literature.

New results for laser diodes show that the latest devices are at least as resistant to radiation damage as older devices. Threshold current changes remain small for fluences below 3 x 10^{12} p/cm^2, which is much higher than the environmental requirements for most space systems.

VCSELs are a promising new laser technology that appears to have comparable hardness to conventional laser diodes. Because of their compact construction, VCSELs do not have constant slope efficiency. As a result less change in threshold voltage can be tolerated compared to other laser diode technologies.

Energy dependence remains a somewhat uncertain issue. Older work, based primarily on experimental results for GaAs JFETs and theoretical calculations, concluded that the energy dependence of NIEL was relatively flat for energies above 50 MeV. Experimental work on LEDs conflicts with that conclusion, showing a continued decrease in NIEL at high energies. Additional work needs to be done to establish the energy dependence for damage in laser diodes with layered structures that may be sensitive to different mechanisms than light-emitting diodes.

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