Radiation Effects on Optoelectronic Devices in Space Missions

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Abstract: *Radiation degradation of optoelectronic devices is discussed, including effects on optical emitters, detectors and optocouplers. The importance of displacement damage is emphasized, including the limitations of non-ionizing energy loss (NIEL) in normalizing damage. Failures of optoelectronics in fielded space systems are discussed, along with testing and qualification methods.*

Introduction

The sensitivity of optoelectronic devices to space radiation varies over an extremely wide range. Some types of devices have failed in space applications where the radiation levels are well below the threshold expected for electronic device degradation, while others are extremely resistant to radiation damage. This paper discusses degradation in various types of optoelectronic devices, along with testing and qualification methods.

The sensitivity of certain types of detectors is consistent with the mechanisms involved with light absorption and leakage current. However, the extreme sensitivity of some types of light-emitting diodes is less obvious, requiring additional knowledge about LED fabrication and operation.

Optocouplers are another important class of optoelectronic devices. Their operation depends on the interaction of their internal components, which can lead to highly nonlinear behavior when they are exposed to radiation.

The paper begins with a discussion of LED degradation, followed by sections on detectors and optocouplers. Damage normalization and NIEL are discussed in the fourth section. The last part of the paper includes examples of failures on space systems and conclusions.

Optical Emitters

Light-emitting diodes are widely used in space applications. They have high reliability, and can be operated in a more straightforward manner than laser diodes, which require close control of temperature and operating current. LEDs can be made with several different materials. The AlGaAs material system is widely used because the wavelength range – 780 to 930 nm – is compatible with silicon detectors. LEDs with wavelengths between 860 and 930 nm are frequently made with amphoteric doping, a special property of some types of dopants where the dopant changes from p- to n-type when the temperature is changed during the growth process. LEDs that are made in this way have high efficiency, but require high minority carrier lifetime because the transition region between the p- and n-type dopants is on the order of 50 μm. That makes them highly sensitive to radiation damage [1].

The other LEDs technology uses heterojunctions, which provide very shallow junctions. Those devices have much thinner active regions, as well as higher doping levels, both of which improve radiation resistance.

Fig. 1 compares the degradation of an AlGaAs LED (880 nm) with amphoteric doping to degradation of several other LEDs, made with heterojunctions. The 660 nm LED is made with InGaP; the others are made with AlGaAs. Note the extreme sensitivity of the amphoterically doped LED to proton displacement damage (for reference, 10^{10} p/cm^2 corresponds to 1.6 krad , an extremely low level).

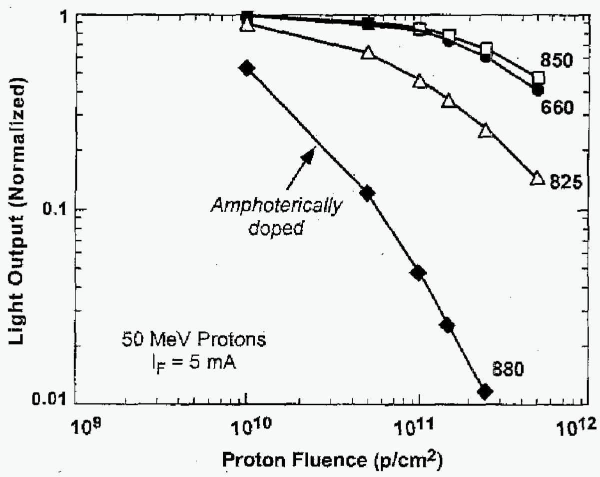

Figure 1. Comparison of proton damage for different LED technologies.

Another concern for amphoterically doped LEDs is that their radiation response varies more widely between different devices than for conventional electronic components. Fig. 2 shows the variabitliy in proton damage for 84 units, procured from a single batch from one manufacturer. For a fluence of 10^{10} p/cm^2, the fractional light output (normalized to initial value) ranges from 0.78 to 0.50. In order to deal with this it is necessary to test larger

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numbers of devices to determine the range in radiation response. Other factors that need to be considered are temperature sensitivity – LED light output decreases about 1% per degree Celsius- and annealing of radiation damage [2].

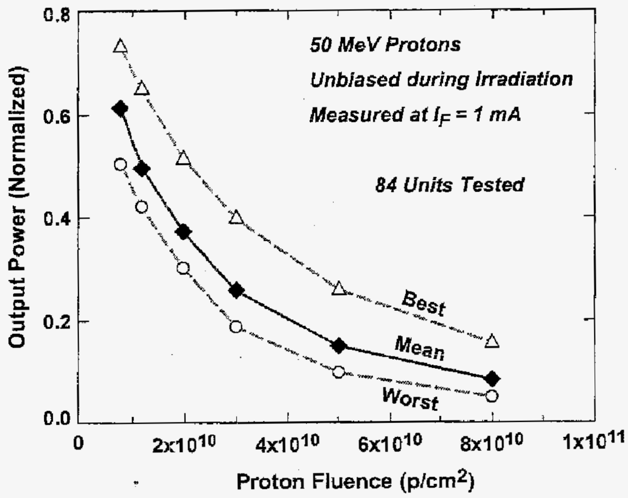

Figure 2. Variabiltiy in radiation response of a lot of 84 LEDs from a single manufacturer.

In contrast to LEDs, laser diodes are far more resistant to radiation damage [3]. Fig. 3 shows degradation of a 650 nm laser diode after irradiation with 50-MeV protons. The key parameters for laser diodes are threshold current, which is the current for the onset of lasing, and slope efficiency, which is the differential slope for incremental currents above the threshold current. From this figure, it can be seen that negligible degradation takes place for fluences < 10^{12} p/cm^2, a fluence that is two orders of magnitude higher than the fluence where amphoterically doped LEDs begin to show severe degradation. Although lasers are degraded by radiation, very high fluences are required.

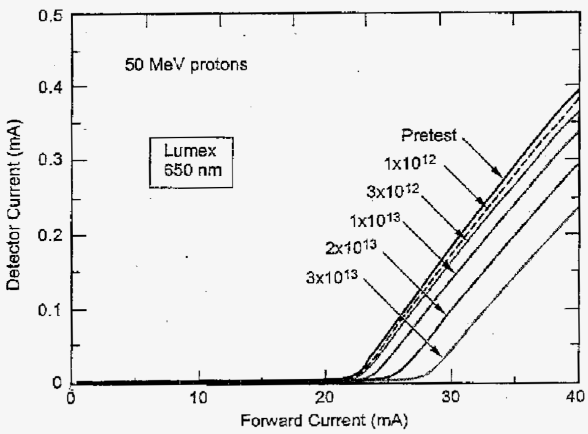

Figure 3. Degradation of a 650 nm laser diode after irradiation with 50-MeV protons.

Other laser technologies require fluences of about the same magnitude before significant degradation occurs [4]. The basic reason for this is that laser operation requires very high carrier densities – on the order of 10^{18} carriers/cm^3 – in order to create the conditions required in the lasing material for stimulated emission. Those carrier densities are very nearly the same for many different semiconductor lasers, including InGaAsP, InGaAs, and AlGaAs. The threshold current increases after irradiation because of increased levels of non-radiative recombination within the material [3,4]. The values of non-ionizing energy loss vary by less than 30% for those materials, and consequently fluence required for measurable damage is about the same.

Detectors

Degradation of conventional p-n silicon detectors is dominated by lifetime degradation. The absorption depth is much longer near the bandgap edge, causing more degradation at long wavelengths compared to shorter wavelengths. Fig. 4. compares degradation of a silicon detector at 930 nm, with the degradation of internal monitor diodes from two different laser diodes. The detectors used in the laser structures are fabricated with III-V technologies that have direct bandgap, making them less sensitive to displacement damage compared to silicon detectors.

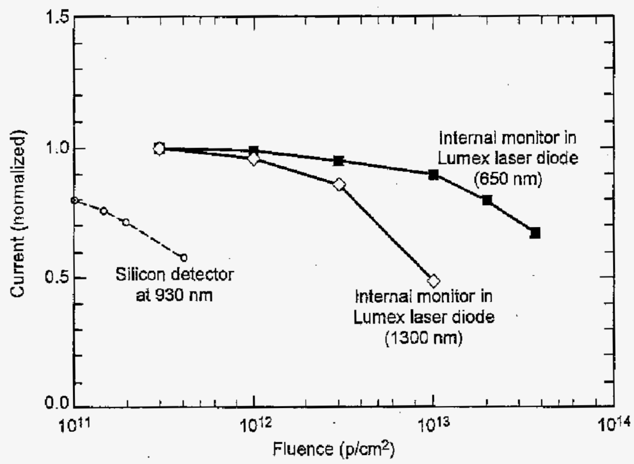

Figure 4. Degradation of a silicon p-n detector compared to III-V detectors used within laser diode modules.

Damage mechanisms for other detectors are different. Although p-i-n detectors are fully depleted, eliminating diffusion mechanisms in light collection, leakage current increases dramatically at low radiation levels for those types of detectors.

Avalanche photodetectors are far more complicated. Fig. 5. shows how leakage current in a silicon APD is affected by total dose [5]. The experiments were done with two different radiation sources, protons and cobalt-60 gamma rays. For this particular structure, leakage current in the two environments was dominated by displacement damage at low total dose levels (cobalt-60 gamma rays produce about 1% of the equivalent displacement damage of 51MeV protons). However, the dependence of leakage current on total dose becomes superlinear above approximately 20 krad(Si). That effect was only observed for some of the samples, but it was attributed to surface inversion at the periphery of the device structure.

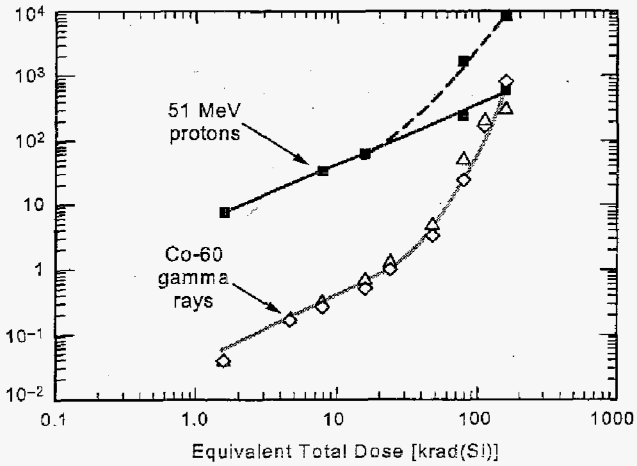

Figure 5. Degradation of a silicon APD from protons and gamma rays.

Optocouplers

There are many different types of optocouplers, but most can be divided into two basic categories: (1) devices with simple phototransistors, designed to operate at low forward currents; and (2) devices with high-speed internal amplifiers, requiring higher input current, but operating at much higher speed than the first type. Fig. 6 shows a diagram of the first type of optocoupler. The key parameter is current transfer ratio (CTR), the ratio of the collector current to the forward current of the LED. Energy transfer from LED current to light and back to current (in the collector region) is relatively inefficient, ≈ 0.1%, and typical values of CTR are between 1 and 10 for this type of structure. Amphoterically doped LEDs are frequently used because the response time of this type of optocoupler is relatively slow.

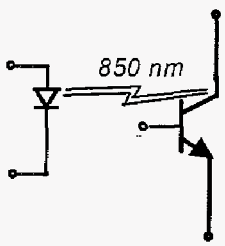

Figure 6. Diagram of a basic optocoupler with a simple phototransistor.

If we compare degradation of detectors and optical emitters, it is apparent that amphoterically doped LEDs will dominate degradation in these types of optocouplers. Fig. 7 shows degradation of a simple optoocupler. Special measurements were done, showing degradation of CTR (with the phototransistor connected as a transistor), photoresponse (measuring current through the collector and base, with the emitter open), and transistor gain.

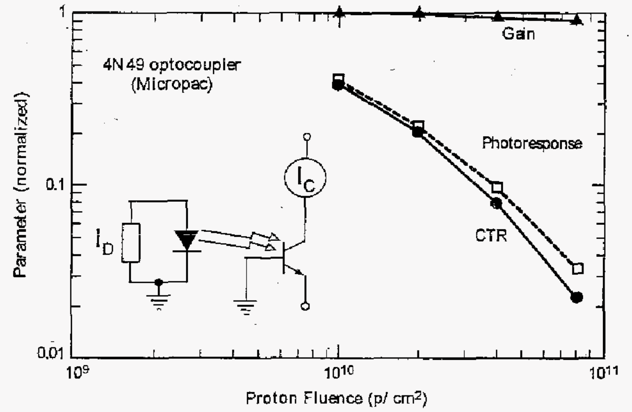

Figure 7. Degradation of a basic optocoupler showing the effect of different factors on the overall degradation.

For optocouplers with less sensitive LED technologies, optocoupler degradation is more complex. Fig. 8 shows degradation of an improved version of a basic optocoupler where degradation of CTR is affected by gain degradation and the dependence of CTR on operating current, as well as LED degradation. In this figure the CTR has been analyzed with a power law that would result in unit slope if the damage were linear with fluence. The dashed line shows a linear result for collector-base photocurrent measurements in this structure. However, CTR degradation becomes superlinear with fluence when the device is operated normally because of the influence of the other factors.

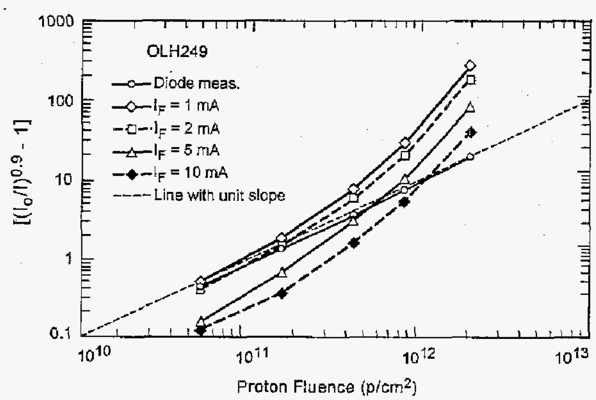

Figure 8. Degradation of an improved optocoupler where the damage becomes nonlinear because of the interaction of several different mechanisms.

High-speed optocouplers are generally more resistant to radiation damage. However, the presence of the high-gain internal amplifier masks radiation degradation unless special measurements are made to determine the threshold conditions for operation. There is a basic difficulty with those types of devices because they exhibit catastrophic failure modes when the light output of the LED is inadequate to meet the internal threshold conditions for operation. Although this type of failure typically does not occur below fluences of 10^{13} p./cm^2, the catastrophic failure is a major concern. The failure conditions depend on temperature (they are significantly lower, even at relatively modest temperatures above room temperature), and also vary widely between different devices.

Damage Normalization

There are a wide range of energies in space environments, making it necessary to understand the energy dependence of proton damage in order to interpret the effect of the actual range of proton energies on damage in optoelectronics. Non-ionizing energy loss is often used to normalize displacement damage. Although that concept works reasonably well for silicon, it fails for energies above 40 MeV for GaAs, as well as some other types of compound semiconductors. Work by Barry et al, showed that damage at high energies can depart from NIEL calculations for some types of LEDs [6]. Therefore we recommend normalizing damage to experimental values measured at 50 MeV, where discrepancies with NEIL are relatively small. That energy is very close to the peak energy in the spectrum of proton energies that are typical for earth-orbiting spacecraft with effective shielding thickness of approximately 200 mils.

Fielded Space Systems

Nearly all space systems use conservative specifications for the space environment as well as for optoelectronic devices. Despite this, failures have occurred in fielded space systems because of radiation damage in optoelectronics. The first example is Topex-Poseidon, a high-incination earth orbiting spacecraft operating at 1338 km. Optocoupler failures occurred after two years, but only in status indicators that had been designed with less conservatism than other applications (including thruster activation). Although additional failures occurred as the mission progressed, it was able to continue operating for 13 years, well beyond its 5-year requirement until failures in the other optocoupler circuits disabled the thrusters. The failures were due to lack of awareness about the sensitivity of optocouplers to displacement damage from protons.

A similar problem occurred on the JPL Galileo mission, which successfully orbited Jupiter for about 20 years. The on-board tape recorder used for data acquisition failed during the 34th orbit, which went through a more severe region of the radiation belts than previous orbits. The reason for the failure was degradation of an LED within the tape recorder electronics. It was possible to restore normal operation by forcing steady-state current through the LED for an extended time period, annealing a significant fraction of the radiation damage with injection-dependent annealing [7]. Fortunately, both missions operated well beyond their expected operating life. The conservative design that was used in critical circuits allowed them to operate even with severe degradation in the optoelectronic components, but failures would have occurred much earlier in each mission if such extreme conservatism had not been applied by circuit designers.

Conclusions

This paper has discussed degradation of several types of optoelectronic devices in space. In most cases the most important effect is displacement damage, making it necessary to do displacement damage tests with protons and/or electrons in order to characterize damage in space. It is important to realize that conventional tests using gamma rays will severely underestimate damage in typical space environments.

Optoelectronic devices have a very wide range of sensitivity to radiation damage. Certain types of LEDs and many detector technologies are among the most sensitive, while laser diodes are generally very resistant to radiation damage.

In most cases optoelectronic devices are used in conjunction with other components and the overall response will often depend on several mechanisms, as evidenced by the discussion of damage in optocouplers. It is also important to take the effects of temperature and reliability into account when optoelectronic devices are characterized for space applications.

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