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Characterization of Proton Damage in Light-Emitting Diodes[†]

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Abstract

Proton damage is investigated for several types of modern light-emitting diodes, examining the damage from the standpoint of older models based on lifetime degradation as well as the simpler method of normalized degradation. An empirical model is developed to describe injection-enhanced annealing in amphoterically doped LEDs. Experimental results on "aged" devices show that wearout degradation does not decrease the sensitivity of devices to radiation damage.

I. INTRODUCTION

Displacement damage in light-emitting diodes is an important issue for space applications [1-6]. Some LEDs are highly susceptible to displacement damage, making them among the most sensitive components with severe degradation at very low radiation levels in environments dominated by protons. Although other types of LEDs are far less affected by displacement damage, the harder device technologies have much lower initial light output than the softer LED types. Selection of LED technologies for space is a complex issue, requiring tradeoffs of several different factors.

Damage in some types of LEDs is affected by injection conditions during and after irradiation [1-5]. This adds a further level of complexity to radiation characterization because measuring the device at high currents during a sequence of irradiation-and-measurement steps will inadvertently cause some of the damage to recover, invalidating the radiation characterization for applications where the device is operated infrequently or operated at low currents. Such conditions are frequently encountered in many system applications, as well as in optocouplers (which contain LEDs) [7-9]. Investigation of injection-enhanced annealing is one of the main objectives of the present paper.

Another important factor is degradation during normal operation (wearout) which causes gradual decrease in light output [10]. Wearout degradation produces changes in LED characteristics that have many similarities to displacement damage. One question that needs to be answered is whether wearout degradation can be added independently to radiation damage, or whether it reduces or increases the sensitivity of LEDs to radiation.

II. EXPERIMENTAL APPROACH

Devices were selected from several commercial suppliers, including Optodiode, Optek, Hewlett-Packard and Hamamatsu. They included one visible LED fabricated with GaAsP, amphoterically doped and double-heterojunction devices in the 800 to 950 nm range that are compatible with silicon detectors and use AlGaAs, and one 1300 nm device that uses a quaternary material (InGaAsP). Properties of the device types used in the study are shown in Table 1.

Table 1. Devices Selected for the LED Study

Type	λ(μm)	Manufact.	Technology
L3882	660	Hamamatsu	Diffused
OD800	810	Optodiode	Double-heterojunction
L7558	830	Hamamatsu	Double-heterojunction
L3989	850	Hamamatsu	Double-heterojunction
OP233	870	Optek	Amphoteric
OD880	880	Optodiode	Amphoteric
OP130	930	Optek	Amphoteric
LST0400	1300	H-P	Double-heterojunction

All irradiations were done at the University of California Davis cyclotron using 50-MeV protons.[††] Samples were mounted on special circuit boards that allowed irradiation of groups of 12 parts. Devices were measured before and after each irradiation using a Keithley 230 current source and a Hewlett-Packard data sequencer, controlled by a small computer. Light output was measured with a silicon phototransistor, connected as diode, with a Keithley 617 electrometer.

For these experiments, all devices were irradiated without bias (the effects of bias were studied in detail last year [5] as well in older studies [2,3]. The duty cycle of measurements between irradiations was limited to minimize injection-enhanced annealing.

Special measurements, including post-radiation annealing measurements, were made using a Hewlett-Packard 4156 parameter analyzer, along with a photodiode to monitor light output. Wavelength and spectral width were measured for samples of each device with a spectrometer.

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[††] Proton damage depends on energy. There is some disagreement between theoretical calculations [11] and experimental results at high energies [12], but the energy dependence agrees up to 50 MeV, which is also near the mean energy of many spectra in Earth orbiting systems. More recent work [13] corroborates the strong decrease in damage reported in Reference 12 for amphoterically doped LEDs at proton energies above 50 MeV.

III. DEGRADATION OF VARIOUS LED TYPES

A. Parameter Degradation

For many LEDs, light output is the critical parameter to characterize degradation. This approach has been used in the past to measure LEDs and optocouplers. An unambiguous way to evaluate such data is to normalize the results to pre-irradiation values. Such degradation is easily interpreted, and allows unit-to-unit variability to be easily incorporated. Figure 1 shows the typical degradation of four types of LEDs normalized to initial light intensity. Note that amphoterically doped devices are damaged significantly at far lower radiation levels than the other device types. Damage in the amphoterically doped devices also depends on bias conditions during irradiation because of injection-dependent annealing (see Section IV), as well as in the GaAsP visible LEDs. In contrast, damage in the double-heterojunction devices that we have studied is unaffected by bias conditions during or after irradiation.

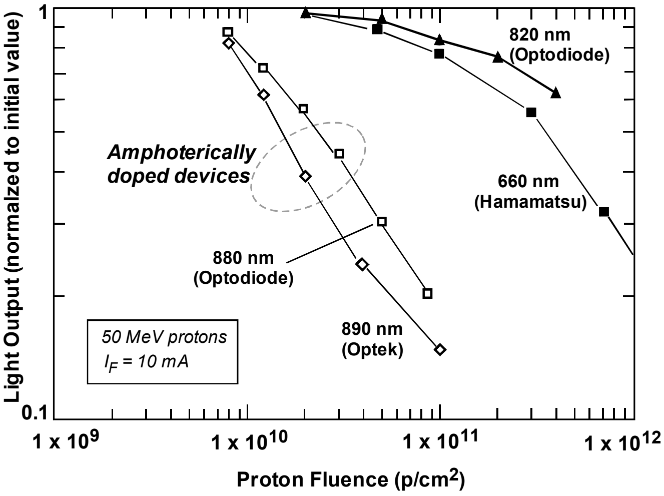


Figure 1. Degradation of four types of LEDs at moderate current levels.

Although degradation of light output is always of importance, some types of LEDs exhibit large increases in recombination current at low injection after irradiation, and that type of degradation can be more important than degradation of light output in some cases [5]. Most amphoterically doped LEDs have nearly ideal forward voltage characteristics that exhibit a definite change in slope when the device begins to produce light. This transition point is essentially unchanged even after the device has degraded to the point where the light output is less than 10% of the pre-irradiation level, as shown in Figure 2. The output of a photodetector is also shown in the figure.

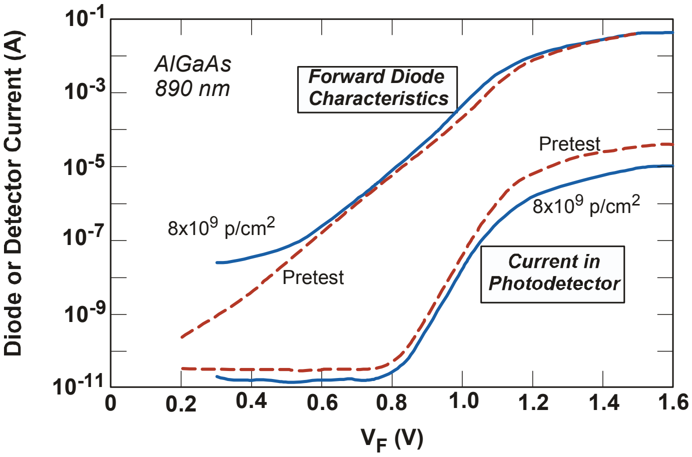


Figure 2. Forward voltage and light output of the Optek OP233 LED before and after irradiation.

Harder LEDs behave quite differently. Figure 3 shows the forward voltage and light output characteristics (measured with an external photodetector) for the HP LST0400 LED. The forward voltage characteristics prior to irradiation do not show the ideal characteristics exhibited by amphoterically doped LEDs. There are two regions where the slope changes, and neither transition point corresponds to the threshold region for light output.

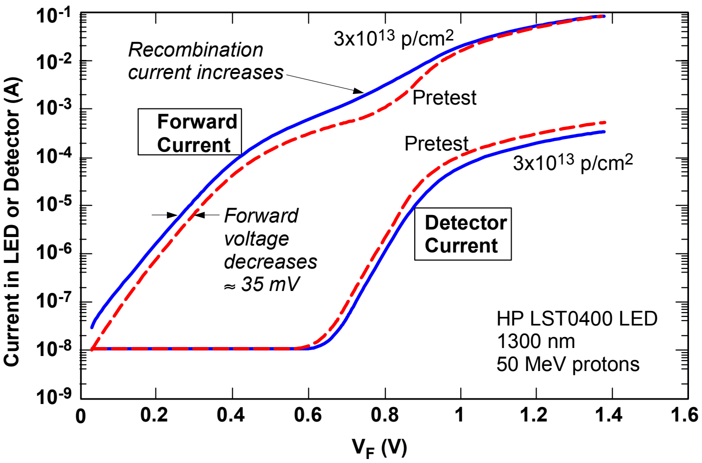


Figure 3. Forward voltage and light output of the HP LST0400 LED before and after irradiation.

After irradiation the forward voltage is substantially lower, even at low currents. At higher currents there is a large increase in recombination current that occurs in the region of normal operation. The threshold current changes somewhat, shifting to higher levels after the device is damaged. Although these differences are too small to be of much importance in typical applications, they show that the general nature of the degradation is quite different for this class of device compared to amphoterically doped LEDs. This is important in interpreting damage as well as in developing models for radiation degradation.

B. Diffusion-Limited Damage Parameter

The dependence of LED degradation on fluence is more complex than for conventional components (such as discrete transistors). At low currents surface recombination within the LED is important, and non-radiative recombination often dominates device behavior. At moderate currents, above the threshold region, light output is approximately proportional to forward current through the LED. It becomes sublinear at high currents primarily because of internal voltage drops within the device [14].

An older study by Rose and Barnes [2] showed that damage could be described using a parameter related to lifetime by a power law using the equation

$$\Gamma \;=\; [\,(I_o/I)^n - 1\,] \;=\; \tau_o\, K\, \Phi \qquad (1)$$

where I_o is the pre-irradiation light intensity, I is the (reduced) intensity after irradiation, n is an exponent between 0 and 1,τ_o is the initial minority carrier lifetime, K is the damage constant, and Φ is the proton fluence. In this work we use Γ as a shorthand notation to describe this power law relationship. Note that K depends on proton energy [11] and injection level. They used the product [τ_o K] to compare radiation sensitivity of different LED types. It is worth commenting that Equation 1 is equivalent to the lifetime damage equation used for displacement damage in silicon devices (such as transistors and solar cells) for the case where n = 1. However, LED damage has a stronger dependence on fluence, leading to linear fits for exponents below one.

Rose and Barnes derived relationships for LED damage with various assumptions about the mechanisms that govern light output as well as the conditions used for measurements. Assuming constant LED current, the exponent n = 2/3 for the case where both forward current and light output are dominated by diffusion (the case for a high-quality LED). Where forward current is controlled by space-charge recombination, but the light output is controlled by diffusion, the damage in Equation 1 is expected to be linear with n = 1/3. Thus, for the case where diffusion dominates both processes the parameter Γ should be linear with fluence for n = 2/3. Most of the older technology devices in their study fit that relationship quite well.

This is a useful way to examine LED data, although it is less straightforward than simply plotting normalized optical power output I/ I_o (as in Figure 1). Degradation of a typical amphoterically doped device using Equation 1 is shown in Figure 4. Two sets of curves are plotted: one using am exponent of one, the other with the 2/3 value predicted theoretically for an LED operating in a diffusion-limited mode. The slope is almost exactly 1 in the latter case, although there is a slight departure at low fluences. This change in slope at low fluences was observed for four different types of amphoterically doped LEDs, obtained from three different vendors, and appears to be a general characteristic of damage in those structures.

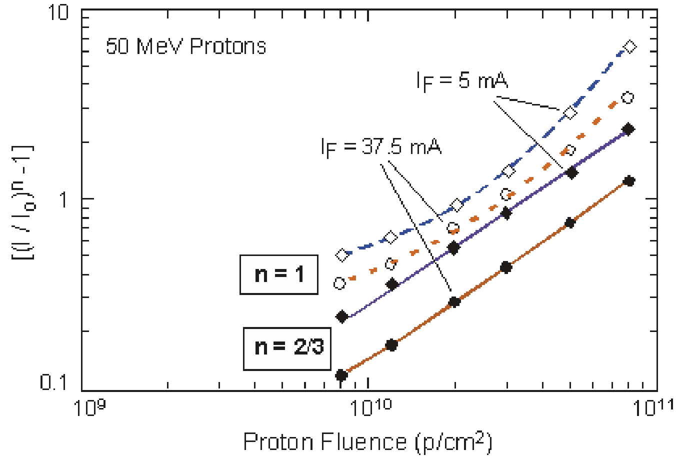


Figure 4. Damage factor for a typical amphoterically doped LED using the power-law relationship of Equation 1.

Damage in the double-heterojuction devices that we tested was not as well described by Equation 1. Figure 5 shows damage for the Optodiode OD800 double-heterojunction LED using two different exponents. The slope is linear, assuming n = 2/3 in Eq. 1, but has a value below one (approximately 0.8). The slope is further reduced at high fluences, possibly because of carrier removal, which is not considered in Equation 1.

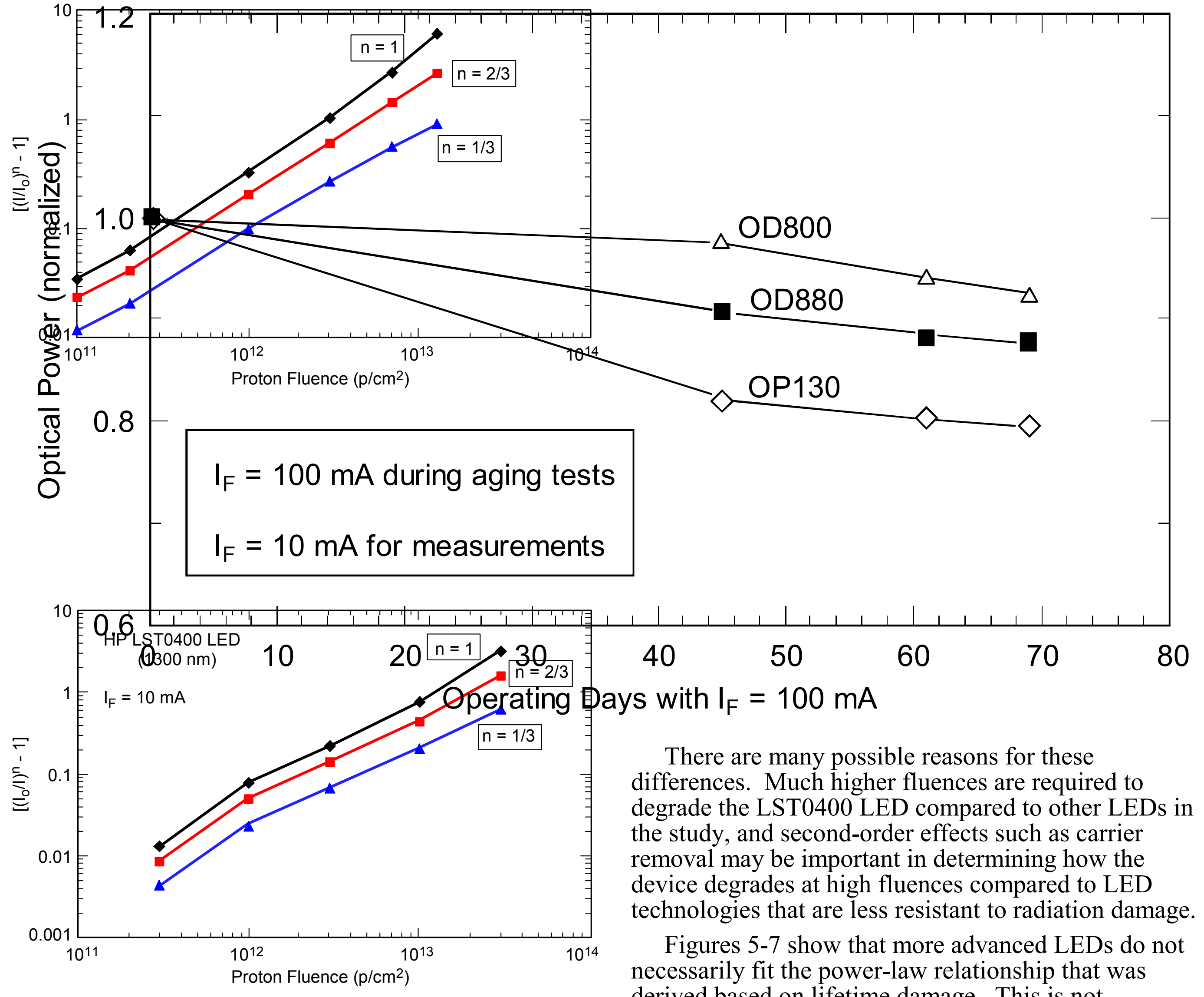


Figure 5. Damage factor for a typical double-heterojunction LED using the power law relationship of Equation 1.

The damage factor of the Hamamatsu L7558 LED, another double-heterojunction LED, is shown in Figure 6. Degradation in that heterojunction LED fits the idealized damage factor relationship more closely than that of the OD800 shown in Figure 5, even though both device types begin to degrade at comparable fluences.

The HP LST0400 is an example of a device where the damage factor relationship does not describe the damage very well. Figure 7 shows the results of fitting data in that device using three different values of n.

Figure 6. Damage factor for the Hamamatsu L7558 LED.

The slope is much higher at the fluences where the light output begins to degrade significantly for all three exponents, in contrast to the results for the OD800 in Figure 5 where there was less damage at higher fluences.

Figure 7. Damage factor for the HP LST0400 LED.

There are many possible reasons for these differences. Much higher fluences are required to degrade the LST0400 LED compared to other LEDs in the study, and second-order effects such as carrier removal may be important in determining how the device degrades at high fluences compared to LED technologies that are less resistant to radiation damage.

Figures 5-7 show that more advanced LEDs do not necessarily fit the power-law relationship that was derived based on lifetime damage. This is not completely surprising because modern double-heterojunction LEDs have very small lateral dimensions. Their efficiencies are less dependent on minority carrier lifetime than older LEDs, and it may be confusing to interpret LED damage with the power-law relationship in Equation 1. However, the power-law relationship appears to fit all of the amphoterically doped LEDs quite well.

IV. ANNEALING STUDIES

Last year we compared injection-dependent annealing in three types of amphoterically doped LEDs and noted that the annealing under different injection conditions could be normalized to the total injected charge that passed through the device after irradiation [5]. However, those tests were done after all devices had been irradiated to 8 x 10^{10} p/cm² and were done over a limited time period. The present study investigates the dependence of annealing on fluence, and also examines annealing from the standpoint of the damage parameter Γ (see Equation 1), as well as extending the annealing time interval to the point where the damage no longer depends on charge injection.

Figure 8 shows how the light output of a typical OD233 LED recovers with time when it is continuously biased with a forward current of 5 mA after the irradiation is stopped (devices were irradiated without bias). The damage is stable after irradiation, and only recovers during time periods when the device is forward biased. A significant amount of the damage recovers, both at low and high fluences.

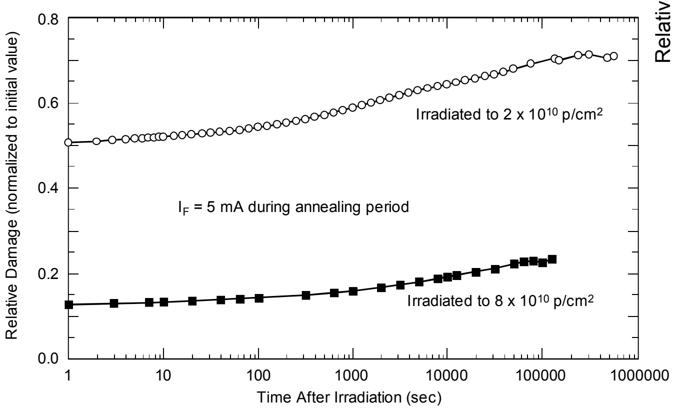
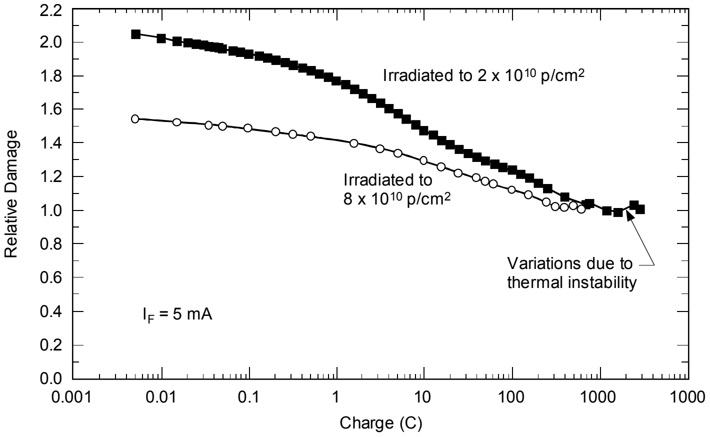


Figure 8. Recovery of light output after irradiation for the Optek OP233 amphoterically doped LED.

A different way to examine this data is to note first that the recovery depends on the total charge, and that the relative damage is more accurately described using the parameter Γ in Equation 1 (with $n = 2/3$). The data in Figure 8 is plotted in this manner in Figure 9. Note that a larger fraction of the damage recovers when the device is irradiated to a low fluence (with about a factor of two decrease in light output) compared to the results at high fluence, where the light output is further reduced., although the reason for this has not been established.



All of the amphoterically doped devices exhibited annealing with similar relationships. Figure 10 shows an additional example for the Optodiode OD800 LED. In general the recovery saturates for a total charge in the range of 1,000-10,000 coulombs.

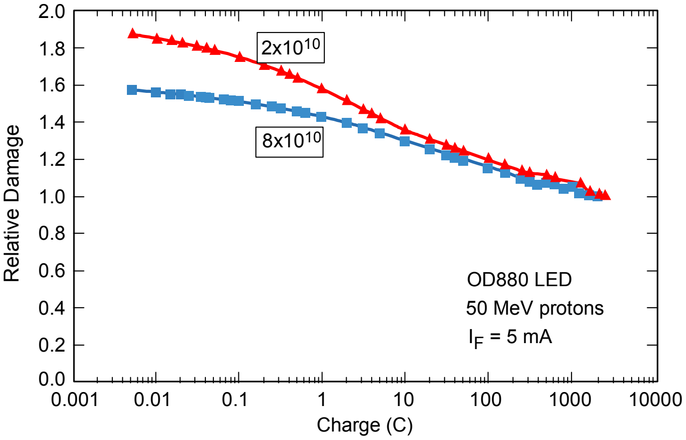


Figure 9: Results of Figure 5 plotted to reflect the damage factor and charge dependence.

Figure 10. Injection-dependent annealing for the OD880.

Examining Figures 9 and 10 shows that very little annealing takes place initially, but that the rate of annealing increases steadily as Q increases. The maximum annealing rate occurs at the charge which corresponds to the midpoint (corresponding to 50% recovery in the damage parameter Γ. The charge for 50% recovery was between 3 and 8 coulombs for all four amphoterically doped device types. As Q increases, the annealing rate slows down, eventually saturating.

Injection-dependent annealing was also observed for the Hamamatsu L3882 device (660 nm, diffused technology) with similar results. None of the double-heterojunction technology devices were susceptible to injection-enhanced annealing.

The general shape of the annealing response of the parameter Γ after a charge Q in Figures 9 and 10 can be described by the equation

$$\Gamma(Q) \;=\; (\Gamma_o - \Gamma_f) / (1 + Q/Q_{1/2}) \;+\; \Gamma_f \qquad (2)$$

where Γ_o is the initial value of damage at short time (zero charge), Γ_f is the final damage value at infinite charge, and $Q_{1/2}$ is the charge corresponding to recovery of half the damage. This equation allows the effects of annealing to be calculated for arbitrary time and current values.

Relatively small amounts of charge are required to cause a significant amount of annealing to occur. For example, a current of 10 mA applied for 60 seconds will reduce the parameter Γ by about 12%. This is large enough to be of critical importance in characterizing devices, particularly if the characterization includes measurements over a wide range of forward current conditions.

It is also possible to take advantage of injection-enhanced annealing in system applications to reduce the damage that occurs in these types of LEDs. It is clearly essential to include characterization of this type of annealing response when radiation tests are done on LEDs.

V. Effects of Aging and Wearout

Unlike conventional semiconductors, unirradiated LEDs exhibit continual degradation when they are operated over extended time periods [10]. GaAs and AlGaAs devices are particularly affected. The parameters that change with aging are light output and forward voltage characteristics. The forward voltage decreases slightly because of increased non-radiative recombination.

One issue in applying LEDs in space is whether radiation degradation adds directly to the degradation that is expected from "wearout," or whether the wearout damage introduces internal damage that would normally be expected from irradiation, reducing the sensitivity to radiation damage. Samples of six types of devices were operated for periods of more than one thousand hours at room temperature. Samples of each device type were split into two subgroups. One group was biased at 100 mA (the maximum operating current), and the other was biased at 50 mA.

None of these devices was subjected to burn-in before the life tests were started. However, one manufacturer (Optodiode) operates all of their devices for a minimum of 250 hours as part of the normal reliability process. Figure 7 shows the degradation of light output for typical "aged" devices, with 100 mA (maximum rated current) applied during aging, and measurement made at a forward current of 10 mA. All of those devices are amphoterically doped LEDs that are highly sensitive to radiation damage. Note that there is a significant drop in light output after only a few hours of operation, with much smaller changes as the life test progresses. There were significant variations in the degradation of individual samples of the various devices within each group.

Figure 7. Degradation of various LED types (unirradiated) after extended operation at maximum rated current.

Radiation tests were done on those devices after they were operated for 1200 hours to compare their response with that of devices from the same lot that had not been subjected to life testing. Degradation of the "aged" samples was indistinguishable from samples that had not been subjected to high currents prior to irradiation. The important point is that damage produced by aging appears to be independent of the damage produced by radiation, and thus must be added to radiation damage for applications that involve operation over extended time periods.

Less degradation from aging occurred for double-heterojunction devices, but aging did not affect the subsequent radiation sensitivity of those devices either. Thus, the general conclusion is that aging and radiation are additive, and must be considered separately when determining overall specifications for LEDs.

VI. Discussion

Characterization of LED radiation degradation is more difficult than for conventional silicon-based electronic devices. Several factors need to be taken into account, as delineated below:

(1) Damage depends on current, and is generally less at high currents.

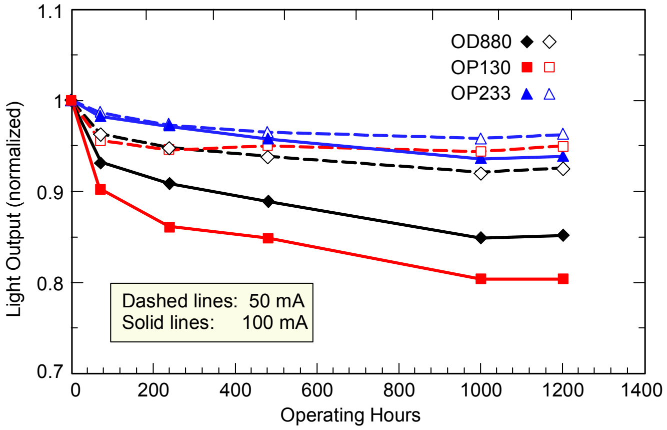
(2) I-V characteristics change as well as light output, and I-V measurements are recommended in addition to measurement of optical intensity.

(3) A substantial fraction of the radiation damage may recover due to injection-enhanced annealing, which is extremely important in planning radiation tests and in interpreting test results.

(4) LED optical power depends on temperature, affecting measurement precision; temperature variability in the eventual application must also be considered in interpreting radiation degradation.

(5) Some devices may degrade in an abnormal manner, with large increases in non-radiative current at moderate injection levels.

(6) Degradation of light output during normal operation adds to radiation degradation and also leads to operation of devices at currents significantly lower than maximum rated values.



Measurements of wavelength and spectral width showed no significant changes, even after the highest radiation levels used for characterization. In most cases the light output was reduced by a factor of 10 or more after the last radiation level, implying that the effects of radiation on wavelength and spectral width can be ignored for all of the device types that were included in this work.

Another important practical point is the angular dependence of the light output. Most LEDs are available in different package types, some of which contain internal lenses to reduce the angular output of the light. In some cases ionization damage can affect light transmission through the lens, causing differences in the net degradation for otherwise identical parts in different packages. Devices with internal lenses also require closer attention to alignment between the LED and photodetector when measurement are done.

As discussed earlier, all experimental work was done using 50 MeV protons. This energy was selected because there is reasonable agreement between theoretical calculations of non-ionizing energy loss and experimental results for all types of LEDs, including amphoterically doped devices. At higher energies there is a serious discrepancy between NIEL calculations and experimental results which makes it very difficult to interpret test data at high energies for actual space environments, which have a wide spectrum of energies. Although many other studies have used 200 MeV protons, the factor of three between experimental and theoretical energy dependence creates a dilemma when experimental results at such energies are interpreted for actual space environments.

VII. CONCLUSIONS

This study has examined various aspects of radiation damage in modern LEDs. The three types of amphoterically doped devices behaved in much the same way as older amphoterically doped devices, with extreme sensitivity to radiation degradation. Proton fluences of 2 to 3 x 10^{10} p/cm^2 (50 MeV) caused the light output to degrade by a factor of two. Thus, amphoterically doped devices are extremely sensitive to displacement damage. They are also sensitive to injection-dependent annealing, which can be normalized to the total charge applied to the device after it is irradiated.

The power-law relationship developed many years ago describes damage in amphoterically doped devices using an exponent of 2/3, and that approach is recommended for analyzing degradation and annealing in amphoterically doped LEDs where lifetime degradation is the dominant degradation mechanism.

The other LED technologies were far more resistant to radiation damage, and can operate in many space environments with relatively little degradation. Damage in those devices often deviates substantially from the simple power law based on lifetime degradation. Consequently there is little advantage in analyzing the degradation from the standpoint of a power law dependence; it may be unnecessarily confusing to do so. Double-heterojunction devices show significant changes in current-voltage characteristics along with decrease in light output, and those measurements should be included when characterizing such devices.

The 1300 nm LEDs which are fabricated with InGaAsP are less affected by displacement damage than any of the AlGaAs heterojunction LEDs. Thus, LEDs fabricated with that material appear to be well suited for space applications.

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