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Proton Degradation of Light-Emitting Diodes†

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Abstract

Proton degradation was investigated for several types of light-emitting diodes with wavelengths in the near infrared region. All irradiations were done with 50-MeV protons. Several basic light-emitting diode (LED) technologies were compared, including homojunction and double-heterojunction devices. Homojunction LEDs fabricated with amphoteric dopants were far more sensitive to displacement damage than double-heterojunction LEDs, and were strongly affected by injection-enhanced annealing. Unit-to-unit variability remains an important issue for all LED technologies. For some technologies, degradation of the forward voltage characteristics appears to be more significant than degradation of light output.

I. INTRODUCTION

The severe degradation of some types of optocouplers in space has been shown to be mainly due to proton displacement damage in the light-emitting diodes that are used within the optocouplers [1,2]. A variety of LED technologies can be used in optocouplers and their sensitivity to proton displacement damage varies by about two orders of magnitude, as shown in Figure 1. The data at 880 nm are from LEDs used by Optek in the 4N49 optocoupler [1]. The other data are for LED evaluation samples provided by Micropac (from unspecified manufacturers) that are intended for use in optocouplers. Optocouplers are very simple hybrid devices, and the type of LED can be readily changed by the manufacturer with little cost impact. Many optocoupler manufacturers purchase LEDs from outside sources with little knowledge or control of the manufacturing process used for the LED, leading to the possibility of very dramatic differences in radiation response (JPL has observed such differences for one type of optocoupler that is used in a hybrid power converter).

Increased understanding of LED degradation is needed not only because of their use in optocouplers, but also for basic applications of LEDs in optoelectronic systems. This paper investigates displacement damage in near-IR light-emitting diodes. Earlier work showed that amphoterically doped LEDs were sensitive to proton irradiation [3-5]. Present-day devices degrade even more than the devices studied at that time.

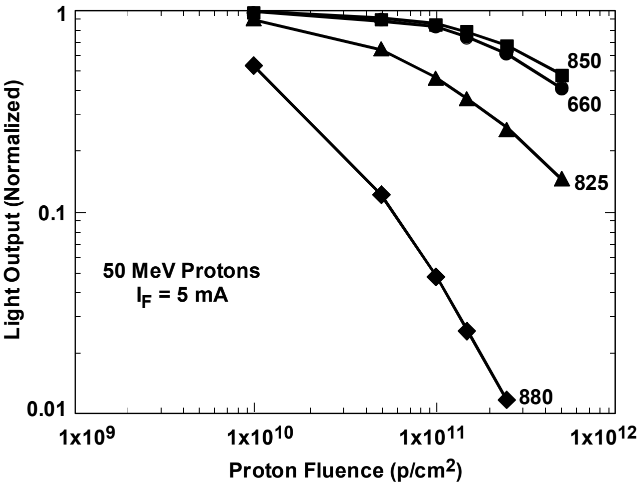

Figure 1. Degradation of LEDs of different wavelengths from 50 MeV protons

II. LED TECHNOLOGIES

A. Diffused LEDs

Two very different approaches can be used to fabricate light-emitting diodes. Categorizing LEDs by the basic type of fabrication process makes sense from two standpoints: first, the physical details of the underlying structure are very different; and second, the evidence to date suggests that LEDs made with these processes have widely differing sensitivities to radiation damage [6].

Many infrared LEDs are fabricated with an older processing technique using liquid-phase epitaxy with an amphoteric dopant (silicon). This process relies on the fact that the impurity is an n-type dopant during epitaxial growth at high temperature, but changes to a p-type dopant when the growth is done below a critical temperature. It is possible to form a p-n junction by gradually changing the temperature during epitaxial growth using the natural transition of the impurity from n- to p-type to create the junction. The resulting structure is shown in Figure 2. It is a simple process because only a single dopant is required. GaAs and AlGaAs LEDs can be made with this process. The fabrication technique produces junctions with a graded impurity profile over a relatively wide region (50 to 100 μm). GaAs LEDs typically have a wavelength of 930 nm. The wavelength of AlGaAs devices depends on the aluminum concentration at the junction and can range from 830 to 900 nm. AlGaAs provides approximately twice as much light output as GaAs. These structures are typically edge emitting. The gradual transition from n- to p-impurity results in a low doping density at the junction; this in turn limits the frequency response to approximately 1-10 MHz [5].

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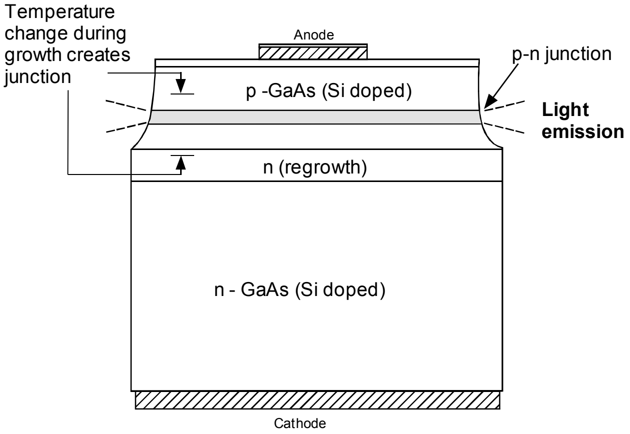


Figure 2. Diagram of an Amphoterically Doped LED

It is also possible to form LEDs by conventional diffusion processes, using dopants of different types in the two junctions. Diffused LEDs have more abrupt doping profiles than those made with amphoteric doping. They have improved frequency response, but diffused LEDs in the near infrared region generally have less light output than comparable LEDs manufactured with amphoteric dopants.

B. Heterojunction LEDs

More sophisticated processes can be use to form double heterojunction structures that confine the direct-gap active region by locating layers with higher bandgap on either side [7,8]. These layers are a different type of semiconductor than the semiconductor in the active region, and form heterojunctions on either side. Figure 3 shows a representative structure for an edge-emitting double-heterojunction LED. The layers in these structures are very thin, on the order of a few µm compared to the regions present in amphoterically doped LEDs, typically 50-100 µm. Processing for heterojunction LEDs requires well controlled growth techniques, involving many more steps than the processes used for diffused LEDs. Heterojunction LEDs have more abrupt doping profiles than amphoterically doped homojunction LEDs, with much faster response time.

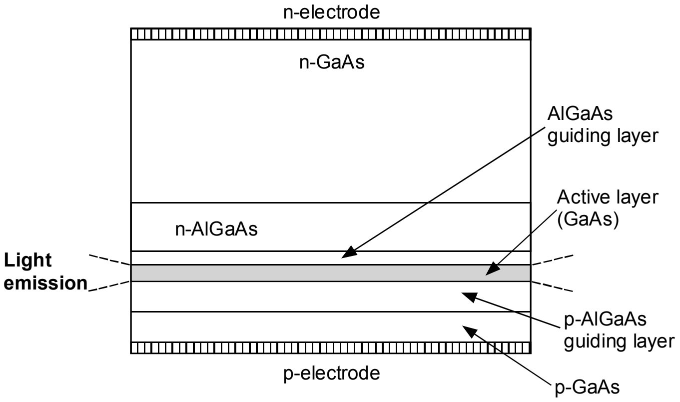


Figure 3. Diagram of a Double-Heterojunction LED

III. EXPERIMENTAL APPROACH

Several different device types were selected for this study, as shown in Table 1. They include simple, low-cost diffused LEDs (amphoterically doped) as well as double-heterojunction LEDs. Some of the LEDs are identical to LEDs contained within various types of optocouplers. The 700 nm LEDs from Hewlett-Packard (made with a conventional diffusion process) are not available commercially other than as part of a complete optocoupler assembly. The devices that were tested were removed from 6N140 optocouplers. All of the other LED types are available commercially as discrete LEDs. They all have a maximum DC operating current of 100 mA, although most space applications will derate the operating current substantially because the light output of LEDs degrades with time under high-current operation [9]. That wearout mechanism has no counterpart in silicon technology.

Table 1. LED Technologies Investigated in this Study

λ (nm)	Construction	Material	Manuf.	Response Time (ns)
930	* Diffused (Si)	GaAs	Optek	1000
890	* Diffused (Si)	AlGaAs	Optek	500
880	* Diffused (Si)	AlGaAs	Optodiode	500
850	Heterojunction	AlGaAs	Optek	6
800	Heterojunction	GaAs	Optodiode	60
700	Diffused (Zn)	GaAsP	HP	<40

* Amphoterically Doped

Absolute comparison of the light output of different LED types is difficult because the high index of refraction of GaAs (and AlGaAs) causes large Fresnel losses when the device is coupled to a medium with low refractive index. The amount of light that is actually transmitted depends on physical details, including the angle over which the light is accepted and the properties of coatings and index matching materials. For this reason, the data in the paper are normalized to the initial light output measured by a silicon photodetector with an acceptance angle of approximately ±20 degrees.

Initial radiation tests on a small sample of devices were done for all of the LED types. More thorough testing with large sample sizes was done for two different device types from Optodiode, Inc. which manufactures high-reliability LEDs that are space qualified as well as for two different types of LEDs from Optek, a second major manufacturer of LEDs.

The wavelength listed in Table 1 is the nominal value for the particular device type. There are substantial variations in wavelength even within specific lots of LEDs, particularly for the amphoterically doped devices. The wavelength of individual LEDs was measured with a spectrometer before and after irradiation. The spectrometer resolution was less than 1 nm. Typical spectral width was 50-70 nm, depending on the type of LED.

Proton testing was done at UC Davis using 50 MeV protons. Irradiations were done in steps of approximately 1-3 x 10^{10} p/cm^2. The beam intensity was varied so that each irradiation step required about 5 minutes to complete.

Devices were removed from the irradiation area after each incremental irradiation step and tested over a range of operating currents using a phototransistor (connected as a photodiode) to measure the light output. A Keithley microammeter was used to measure the detector photocurrent. Measurements of the forward-biased diode characteristics were also made before and after each irradiation step.

A special fixture was fabricated to allow twelve devices to be irradiated simultaneously. Test devices were soldered to a board in a circular pattern. A matching array of photodiodes was used for optical measurements between irradiations (the photodiodes were not irradiated). A spacer block -- carefully machined to line up with the photodiode and LED arrays -- was used to provide a consistent way to align the LEDs and respective photodiodes, clamping the two assemblies so that the spacing between the LED and photodiode was reproducible. Holes in the spacer block were slightly greater than the diameter of the LEDs and photodiodes.

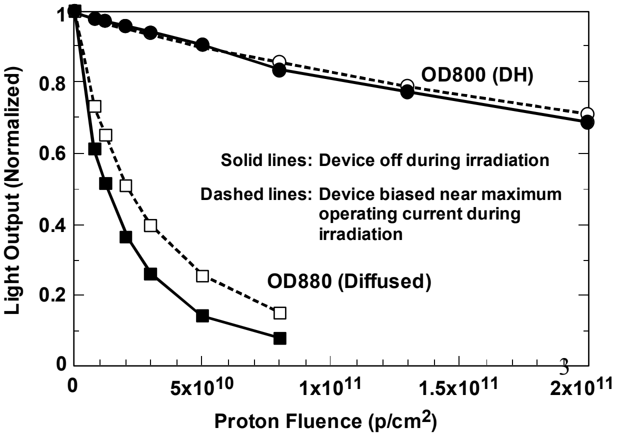
Each measurement sequence could be completed in less than 5 minutes. Different groups of devices were irradiated under different forward bias conditions. Some were unbiased, while others were irradiated at a fixed operating current. The highest current used was near the maximum typical operating current. Measurement currents for the unbiased devices were restricted to low values because of the possibility of current-enhanced annealing.

IV. EXPERIMENTAL RESULTS

A. Devices Produced by Optodiode

Optodiode Incorprated is a major manufacturer of high-reliability LEDs for aerospace and other critical applications. Although that company does not produce optocouplers, they manufacture LEDs with both diffused and heterojunction structures for the aerospace market. Initial work was done comparing two basic technologies from Optodiode because they were being used in JPL systems.

Comparisons of the radiation degradation of diffused and double-heterojunction devices manufactured by Optodiode are shown in Figures 4 and 5. The solid lines show mean values for 12 unbiased devices, while the dashed lines show mean values for 12 devices that were biased at 37.5 mA during irradiation (results for intermediate forward bias currents fell between these two limiting curves). Degradation of the OD880 (diffused, amphoterically doped technology) depended strongly on operating current. Significantly less degradation was observed for devices that were biased at high current during irradiation compared to unbiased devices or devices biased at currents of a few milliamps.



In contrast, the OD800 heterojunction devices exhibited little or no dependence on bias conditions during irradiation. Note also that damage in the OD800s was about the same at low and high measurement currents, whereas significantly less damage -- approximately 30%, depending on the fluence level -- occurred in the OD880s when they were measured at high forward current.

Figure 4. Degradation of two Optodiode LED technologies measured at a forward current of 1 mA.

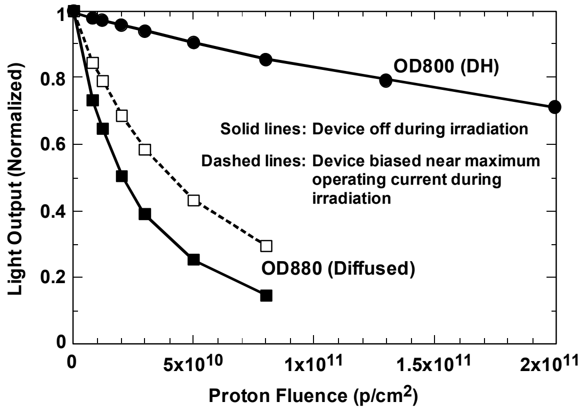


Figure 5. Degradation of two Optodiode LED technologies measured at a forward current of 37.5 mA.

Although it appears from these results that the 800 nm double heterojunction LEDs would be a better choice for space applications because of the lower radiation degradation, the 800 nm LEDs are much less efficient, producing only about 15% of the optical power of the 880 nm devices prior to irradiation. Thus, although the 800 nm LEDs are, on average, much less affected by radiation, their reduced initial light output must also be considered in device selection

Another important issue is the uniformity of the radiation response. More than 80 of the 880 nm devices were subjected to radiation under various bias conditions, and although differences of approximately a factor of two occurred in the relative degradation of the best and worst device from the total population, none of the devices behaved in an abnormal way. Figure 6 shows the variability of the radiation response of a group of 12 OD880 devices, irradiated without bias and measured at low forward current. At the lowest level the light output ranges from just over 50% to nearly 80% of the initial light output. The mean value of devices from a second lot are also shown in the figure. The mean value of the second lot was nearly identical to the worst devices in the first lot.

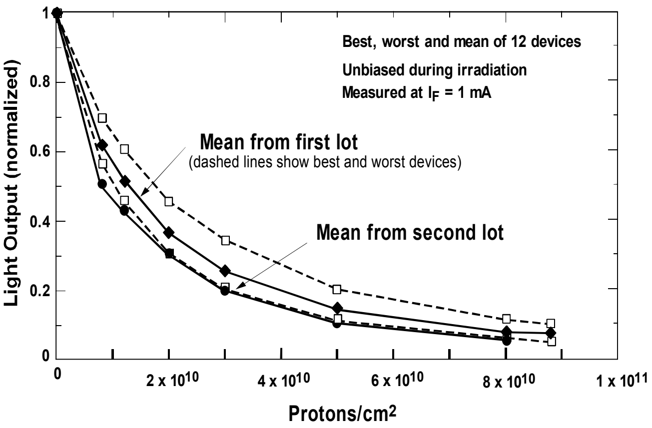


Figure 6. Range of damage exhibited by a group of 12 OD880 LEDs, irradiated with no bias and measured at a forward current of 1 mA. The mean value of a second lot of six devices is also shown.

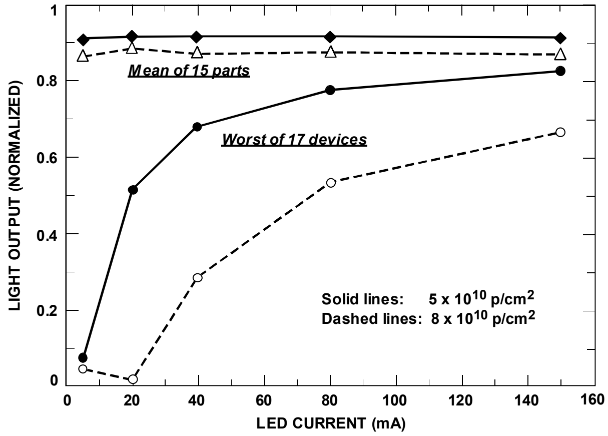


Figure 7. Dependence of normalized output power on forward current for the OD800 LED showing the behavior of an abnormal unit.

Optodiode LEDs from the double-heterojunction process exhibited much more variability than devices from the amphoterically doped process. Two of the 800 nm devices degraded quite differently from the majority of the devices in the test sample (a total of 17 devices). An example is shown in Figure 7. Initially all devices worked satisfactorily even at very low forward currents (1 mA). However, after the first radiation level the minimum current for operation (effectively a threshold current) increased to about 10 mA for one device. Its light output was far lower than that of typical devices from the group until the forward current was increased to about 40 mA. This threshold current continued to increase at higher radiation levels, as shown in the figure. At low current the forward voltage after irradiation was nearly 0.5 V lower than the forward voltage of devices that behaved normally. Forward voltage of typical devices from the group changed by less than 20 mV. A second unit from the population also behaved abnormally, with similar characteristics. The extreme damage that occurred for those two parts at low currents was unaffected by operating current, and appeared to be a stable condition that did not recover after irradiation. Six months after they were irradiated, the I-V characteristics were identical to the results obtained just after they were irradiated.

Results for these two types of LEDs from Optodiode illustrate that variability in radiation response can be very important for some types of LEDs. This must be taken into account in planning radiation tests and in interpreting radiation test data. The two part technologies are intended for the same types of basic applications. One technology performs much better, on average, in a radiation environment, but appears to have far greater unit-to-unit variability. Potential hardness assurance tools for identifying devices with abnormal response are discussed in Section VII of the paper.

B. Devices Fabricated by Optek and Hewlett-Packard

Optek is a major manufacturer of optoelectronic devices, producing discrete light-emitting diodes as well as optocouplers. As shown in Table 1, three types of LEDs from Optek were evaluated: diffused, amphoterically doped GaAs (930 nm); diffused amphoterically doped AlGaAs (890 nm) and a double-heterojunction AlGaAs device (850 nm). The latter device is intended for a different class of applications, and has a much higher bandwidth than the other LED technologies that were evaluated from that manufacturer.

Degradation of the amphoterically doped AlGaAs LEDs from Optek are shown in Figure 8 (mean values are shown). The magnitude of the degradation is very similar to that of the amphoteric AlGaAs LEDs from Optodiode (see Figure 4). Both device types show 20-30% less degradation when they are biased at high operating current during irradiation.

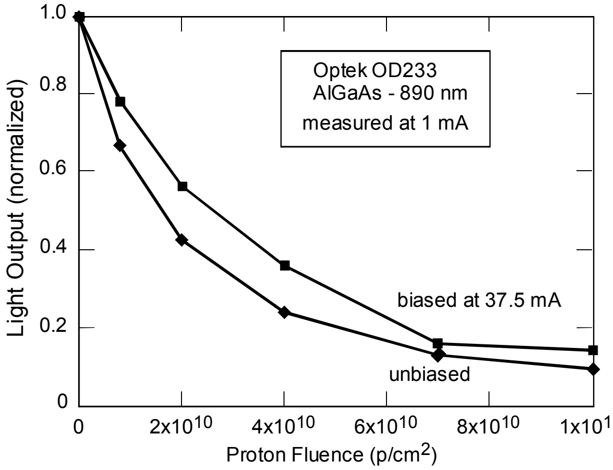


Figure 8. Degradation of AlGaAs LEDs from Optek (amphoterically doped).

Degradation of the Optek GaAs LEDs, which have a slightly longer wavelength, are shown in Figure 9. The magnitude of the degradation is very similar to that of the two other types of amphoterically doped LEDs. However, the GaAs LEDs show somewhat less dependence on bias conditions than the AlGaAs LEDs from either Optek or Optodiode. The optical efficiency of GaAs LEDs is approximately a factor of two lower than that of AlGaAs LEDs, largely because of the longer wavelength which affects internal absorption and coupling efficiency. Thus, AlGaAs LEDs are probably a better choice for most applications.

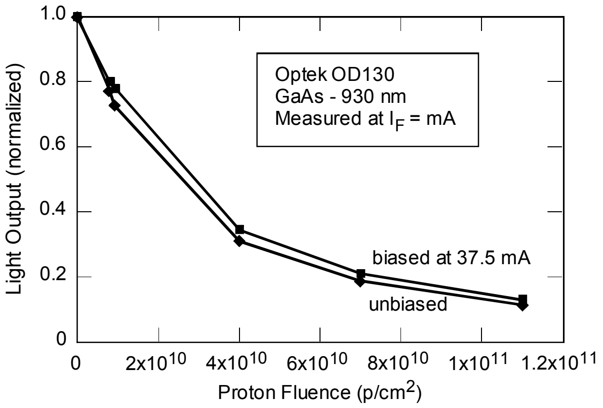


Figure 9. Degradation of GaAs LEDs from Optek. These devices are also amphoterically doped, but have longer wavelengths that AlGaAs LEDs.

Degradation of the heterojunction LEDs from Optek are shown in Figure 10. The figure shows two different parameters: output power and forward voltage characteristics. The output power of those devices degraded much less than any of the other LED types that were tested in this study. They are intended for fiber-optic applications and have much higher bandwidth than the other device types. For those devices, changes in forward voltage were actually more significant than the decrease in output power. Note the large change in forward voltage characteristics that occurred at the highest irradiated level, 3 x 10^{11} p/cm^2.

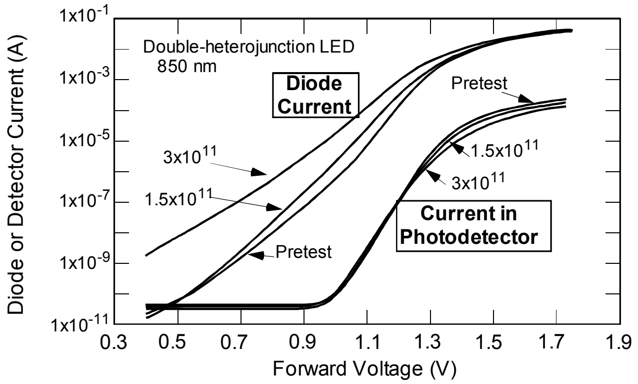


Figure 10. Change in I-V and P-V characteristics of the Optek OPF320 LED at high proton irradiation levels.

The OPF320 LEDs degrade far less than the DH LEDs from Optodiode. Although only 12 units were tested none of the OPF320 LEDs exhibited the abnormal I-V characteristics that were observed in many of the OD800 DH LEDs from Optodiode. Optek does not make double-heterojunction devices for applications that are equivalent to their extensive line of amphoterically doped LEDs. Consequently, direct comparisons of the OPF320 with the other LEDs tested in the study that were produced by Optek do not have the same significance as the comparisons made earlier for the two Optodiode LEDs.

LEDs from a Hewlett-Packard optocoupler (the 6N140) were also tested in order to directly compare LEDs from that manufacturer that are used in most of their optocouplers with the other types of LEDs. The Hewlett-Packard LEDs use GaAsP and have a shorter wavelength (700 nm) than the other LED technologies. They are fabricated with a conventional diffused process using zinc as a dopant.

Degradation of the 700 nm GaAsP devices from Hewlett-Packard is shown in Figure 11. The degradation of that device type was only slightly affected by bias conditions. The HP devices are more than an order of magnitude more resistant to proton damage than LEDs made with amphoterically doped processes.

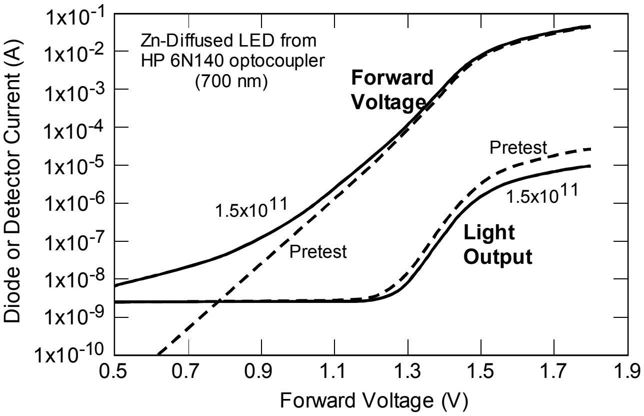


Figure 11. I-V and P-V characteristics of the 700 nm diffused LEDs from Hewlett-Packard optocouplers.

The forward voltage characteristics of those devices also began to degrade at high radiation levels. Although it is difficult to see in the reduced size of the figure, there is a slight change in slope in the preirradiation V-I characteristics that occurs at the same forward voltage that the device begins to emit light. The threshold is not significantly affected by irradiation, although the maximum light output is significantly reduced at higher forward voltages, which correspond to actual use conditions. I-V characteristics are further discussed in Section VI.

V. CURRENT-ENHANCED ANNEALING

Barry, et al. did annealing experiments on unbiased amphoterically doped LEDs over a two-week time interval [10]. They found that less than 5% of the damage recovered. Our measurements of amphoterically doped LEDs that remained unbiased after irradiation are consistent with their results, leading to the conclusion that little or no damage recovery occurs in unbiased devices of that type.

However, LED damage can be annealed under forward injection [2,3]. This was also noted by D'Ordine in studies of optocouplers [11]. Only the amphoterically doped devices in our study were sensitive to that effect. Figure 12 shows how the damage in the three different amphoterically doped devices recovered when a moderate current, 5 mA, was passed through the devices after they were irradiated. All the devices were irradiated without bias. They were irradiated to approximately 8 x 10^{10} p/cm^2, which reduced the light output to 9-12% of the initial value prior to irradiation. The ordinate

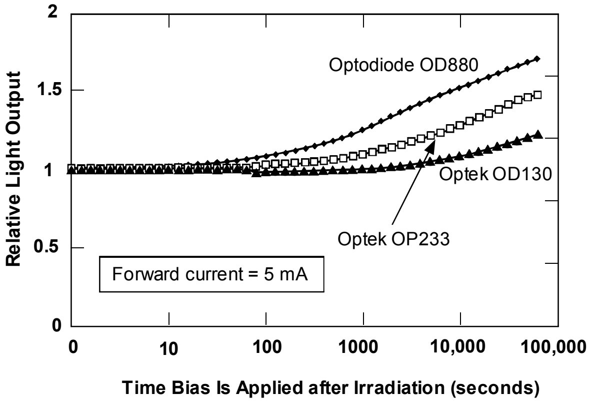


Figure 12. Effect of current on post-radiation damage for the three types of amphoterically doped LEDs.

is normalized to the value after irradiation. Thus, for an LED that degraded to 10% of the initial light level, a factor of 1.5 on that scale corresponds to recovery of the damage from about 10% to 15% of the light output before the device was irradiated.

We examined the effects of different bias conditions on annealing by passing different amounts of current through irradiated devices. Recovery was much more rapid when high currents were used during the post-irradiation recovery period compared to low currents. The maximum current that was used was 50 mA, one-half the maximum rated current of the device. Approximately 1/2 of the damage recovered after several hours of operation at 50 mA, in contrast to the unbiased devices which recovered less than 1% during comparable time periods. The temperature increase during steady-state operation at these currents is very slight, so it is highly unlikely that temperature is a contributing factor.

The effect of operating current on annealing could be analyzed by considering the total charge that flowed through the device after irradiation. Figure 13 shows how data for three different OD880 devices that were annealed under different current conditions compared from the standpoint of total charge. The recovery appears to be logarithmic with time, and begins to saturate for the device that was annealed with the largest current.

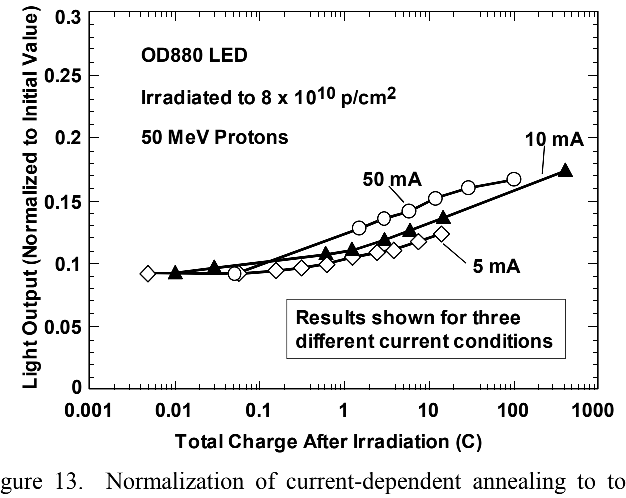


Figure 13. Normalization of current-dependent annealing to total charge.

The amount of damage that recovered during post radiation annealing is roughly the same as the difference in the degradation of devices that were irradiated at low and high currents when the operating current during irradiation is taken into account (compare the degradation at high and low bias conditions in Figures 4 and 5), implying that the same basic effect is involved in reducing the damage for devices that are forward biased during irradiation.

Injection-enhanced annealing adds another layer of complexity when interpreting test data for applications. Testing LEDs at high operating currents will cause some of the damage to anneal, underestimating the amount of damage that will occur in applications that use lower operating currents, or involve devices that are unbiased during most of the time that they are exposed to radiation. The best way to deal with this issue is to carefully control the currents and operating time used for device characterization, and to split the test samples into groups with low and high bias conditions for measurements. Unlike the double-heterojunction devices, amphoterically doped LEDs undergo less damage when they are operated at high currents. The interplay between injection-enhanced annealing and the actual difference in damage at high injection makes it difficult to separate these effects unless irradiation and measurement conditions closely mimic the conditions in the application.

VI. PARAMETRIC DEGRADATION

The earlier studies on LED degradation showed that lifetime damage was the mechanism that caused output degradation [3-5]. Carrier removal, the dominant mechanism for degradation in GaAs JFETs, is unimportant for 50 MeV proton fluences below 10^{13} cm^2 for GaAs devices doped at 10^{16} cm^2 or more [13], which is the approximate doping concentration of the light-emitting region in the various LED structures in this study. Thus, lifetime damage is expected to be the dominant mechanism, at least within the range of radiation levels considered here.

Although optical output power is the most fundamental parameter for light-emitting diodes, forward voltage characteristics provide a way to evaluate the diode characteristics in a more fundamental way. Zhao, et al. have used I-V characteristics to study radiation degradation in laser diodes [12], and Lindquist used I-V characteristics to study aging effects in diffused LEDs [9].

Basic junction theory predicts that the forward characteristics of the LED can be described by the equation

$$J = k_1 e^{(qV/kT)} + k_2 e^{(qV/2kT)} \qquad (1)$$

where J is the total current through the diode, k_1 and k_2 are constants, q is electronic charge, V is the forward voltage applied to the diode, k is Bolzmann's constant, and T is absolute temperature. At low currents, the slope of the diode characteristics is lower, and the first term --which represents recombination current -- dominates. Note that recombination current does not contribute to light emission. As V increases, the second term (corresponding to diffusion current) begins to contribute, and the slope increases. The change in slope corresponds nearly exactly to the threshold for small light output of the LED. That relationship appears to hold for all of the diffused LEDs that were examined in the present study.

For example, a typical OD880 device has an initial slope of 87 mV/decade with a nearly ideal transition to a slope of 110 mV/decade at the threshold. At radiation levels up to about 1 x 10^{11} p/cm^2, the slope in both regions is essentially constant. The threshold current is also unchanged. The main effect of the radiation is to decrease the light output, although the forward I-V characteristics also shift slightly.

The heterojunction devices behaved quite differently. Typical heterojunction structures did not exhibit a clear transition region between the recombination-dominated and diffusion-dominated regions. The slope changed gradually over several decades of current, and it was generally not possible to identify the threshold region for light output from the forward voltage characteristics alone. Furthermore, there were significant differences between different devices of the same type. In some cases the current-voltage characteristics exhibited a nonlinear region well below the threshold current. Figure 14 shows an example for the Optodiode OD880 where nonlinear I-V characteristics were present before irradiation. For some of the devices this nonlinear region changed markedly after irradiation. The effect on the device was to shift the threshold region to very high operating currents (see Figure 7). That behavior was only observed for a small number of the double-heterojunction devices, but is potentially quite important because it could cause failures in space at relatively low radiation levels. Similar changes in I-V characteristics have been observed in reliability studies of DH LEDs by Wittpahl, et al. that appeared to correlate with device sensitivity to current stress [14]. This suggests that I-V measurements should be included in parametric evaluations of LED degradation. However, the underlying mechanism for the nonlinear I-V behavior is not understood, and warrants further study.

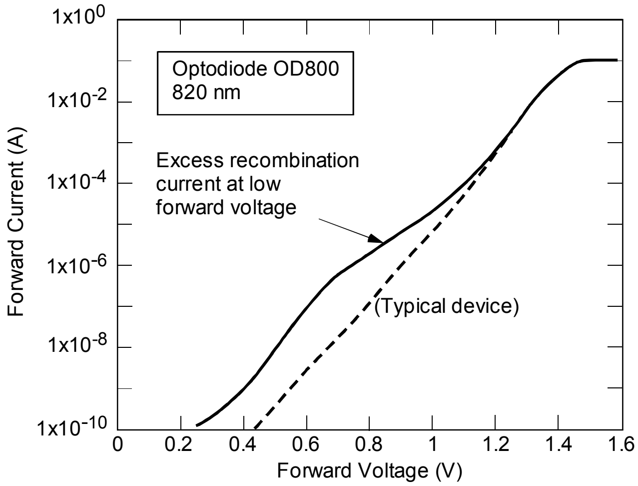


Figure 14. Preirradiation I-V characteristics for an OD800 LED with increased recombination losses at low forward current.

We also measured the wavelength of these devices before and after irradiation. Neither the peak wavelength nor the spectral width was significantly affected by proton damage. Thus, the main parameters that are affected are the light output at moderate to high injection and the forward voltage characteristics.

A number of factors contribute to the differences in sensitivity of different types of LEDs. Amphoterically doped LEDs in the wavelength range of 870-930 nm have very high efficiency, and can be produced at low cost. However, the processing used to produce those devices results in extended transition regions between the n- and p-regions. They require long lifetimes because of the extent of the physical structure [3-5]. This is also evident from the slow response time in their specifications (see Table 1).

The diffused devices from Hewlett-Packard and the double-heterojunction devices from both manufacturers have much shorter response times. Ikeda, et al. have reported an inverse correlation between the doping concentration in the active layer and cutoff frequency in DH LEDs, as well as a dependence on active layer thickness [15]. Thus, high operating frequencies require high doping concentrations in the active layer along with narrow thicknesses. This reduces the dependence of LED operation on minority carrier lifetime, although it also reduces efficiency. The OPF320 devices have a response time of only 6 ns, and exhibited very slight degradation in light output even at a fluence of 3 x 10^{11} p/cm^2. These more advanced structures are less affected by radiation than the best devices in earlier radiation studies [3-5]. Our experimental results suggest that for this class of devices degradation in I-V characteristics due to nonradiative recombination is likely to be a more important failure mode than degradation of optical power. Additional work needs to be done on high-speed LEDs to verify that this conclusion is valid for a broader range of device types.

VII. RECOMMENDATIONS FOR HARDNESS ASSURANCE

The variability in the radiation response of LEDs is made even more important by their extreme sensitivity at very low proton fluence levels. As shown in Section IV, some amphoterically doped LEDs are degraded by more than a factor of five at 50 MeV proton fluences of 2 x 10^{10} p/cm^2. This is equivalent to a total dose level of 2.5 krad(GaAs); 1 x 10^{10} p/cm^2 is equivalent to 1.25 krad(GaAs) or 1.59 krad(Si). This make LEDs among the most sensitive components in environments that are dominated by protons. Failures of optocouplers that contain amphoterically doped LEDs have been observed in Earth-orbiting spacecraft such as Topex-Poseidon at approximately 3 x 10^{10} p/cm^2. Screening the more sensitive devices can be important in successfully applying them in space.

The approximate 50 MeV equivalent proton fluences of two earth-orbiting missions are shown in Table 2, assuming a spherical shield thickness of 100 mils of aluminum. These values take the energy dependence of proton damage into account, but do not include temporal variations in the trapped belt intensities.

Table 2. Annual Proton Fluences for Two Earth-Orbiting Systems

Mission	Altitude (km)	Inclination (deg.)	Annual 50 MeV Equivalent Fluence (p/cm^2)
Topex-Posiedon	1334	66	1.3×10^{10}
EOS	705	98	5.5×10^{9}

Although none of the amphoterically doped devices exhibited the abnormal behavior that was seen for a small number of the 800 nm double-heterojunction LEDs, the amount of degradation of the 880 nm devices varied significantly for different units. There did not appear to be any correlation between initial light intensity and radiation sensitivity. However, there was a correlation between the peak light emission wavelength and radiation sensitivity for the Optek OD880 devices, as shown in Figure 15. The spectral width of a typical LED is about 70 nm, so the range of peak emission wavelength is much smaller than the spectral width. Note that the worst devices degrade by nearly a factor of two at 8×10^9 p/cm^2, while others retain nearly 75% of their light output at the same radiation level. Note also that the increased sensitivity of a second lot of LEDs from that same manufacturer correlated with the different wavelength. Thus, better control and specification of wavelength may be an effective way of limiting the range of radiation behavior. However, this appears to be effective only for diffused LEDs, and there are likely other factors besides wavelength that are important in determining the radiation sensitivity of individual devices. There did not appear to be any correlation between wavelength and radiation sensitivity of the 800 nm double-heterojunction LEDs.

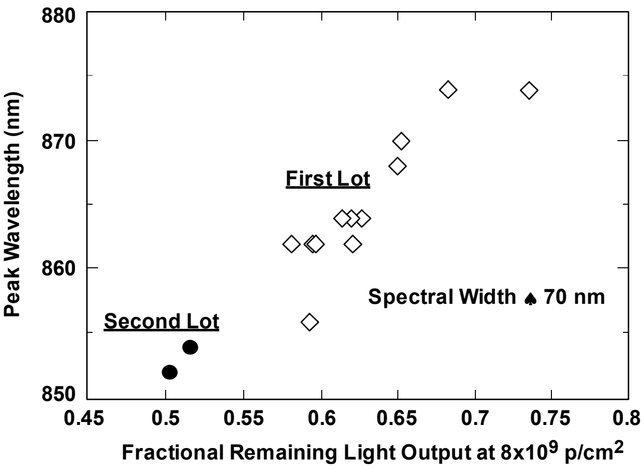


Figure 15. Correlation between degradation and wavelength for Optodiode OD880 LEDs (amphoterically doped).

Barry et al. have shown that lifetime measurements can be used to characterize the behavior of diffused LEDs [10], which was also noted in the earlier work by Rose and Barnes [3]. We made lifetime measurements on some of the amphoterically doped LEDs. Although the lifetime changes somewhat after irradiation, the changes in lifetime were relatively small -- approximately a factor of two after the light output degraded by more than a factor of ten. Although lifetime degrades, the differences in initial lifetime between different samples of the same part are relatively slight. This makes it difficult to use such measurements for hardness assurance at the moderate radiation levels where amphoteric LEDs are severely damaged. Nevertheless, lifetime damage remains a useful way to characterize damage at very high radiation levels.

VIII. CONCLUSIONS

This paper has examined proton displacement damage in light-emitting diodes using a variety of bias conditions and a relatively large number of devices for selected technologies. Although double-heterojunction LEDs are less degraded than amphoterically doped diffused LEDs, the lower output and statistical variability of DH LEDs presents a difficult challenge for their use in space. Amphoterically doped LEDs have higher initial efficiency, and it may be more effective to use them under high injection conditions in space, taking advantage of injection-enhanced annealing, rather than using double-heterojunction devices with much higher unit-to-unit variability in radiation sensitivity.

Damage in amphoterically doped LEDs depends on operating conditions. It is important to characterize the dependence on bias to make sure that the experimental characterization of damage will actually correspond to circuit use conditions. Post-irradiation recovery measurements indicate that the amount of damage recovery depends on the total charge that passes through the junction after irradiation, and this appears to be an effective way to characterize the dependence of damage on operating conditions.

Although degradation in light output is important some types of LEDs exhibit large changes in forward-voltage characteristics at low injection which increase after irradiation. For one device type, the threshold current of some samples increased by several orders of magnitude after irradiation because of the increase in recombination. Forward voltage characteristics should be included along with measurements of optical power for LED technologies.

Many changes have occurred in LED technology during the last 20 years, and some of the earlier work on radiation degradation has to be modified to account for changes in efficiency and processing. Even though several different device types were used in this work, the results are not necessarily applicable to all types of LEDs. LED degradation is a complex topic that deserves further attention, particularly because of increased interest in using optoelectronic devices in space.

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