Proton Damage in LEDs with Wavelengths Above the Silicon Wavelength Cutoff

Heidi N. Becker and Allan H. Johnston
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Abstract

Proton damage is investigated for LEDs with wavelengths of 1050 and 1550 nm. Light output becomes nonlinear with current after irradiation, unlike AlGaAs LEDs. Mechanisms are proposed that are related to the material properties.

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INTRODUCTION

Displacement damage effects have been studied in light-emitting diodes for many years [1-6]. However, the majority of the work was done on AlGaAs or GaAs LEDs emitting in the 800 – 900 nm region. Little work has been done on LEDs that operate beyond the 1 μm cutoff for silicon detectors. Such devices use different materials and are typically designed for high-speed operation in fiber optic communication applications. This paper evaluates radiation damage in two LEDs in that extended wavelength range that are designed with fast response times for fiber communications applications, where they are alternatives to laser diodes. Those results are compared with tests of an advanced 875 nm LED that uses advanced fabrication techniques that enhance light extraction.

EXPERIMENTAL PROCEDURE

Table 1 lists the LEDs in this study and some of their key properties. The Agilent HSDL-4230 uses an advanced fabrication technique with a transparent substrate that eliminates absorption loss in the substrate region [7,8]. The other two devices use different material technologies, and are designed for fast response time. All three devices were mounted in epoxy packages.

Table 1. Devices Selected for the Study

LED Manufacturer and Part Number	Peak Wavelength (nm)	Material	Optical Power Output @ I_F = 50 mA (mW)	Rise Time (ns)
Agilent HSDL-4230	875	AlGaAs TS/Double Heterojunction	16	40
Epitex L1050-03	1050	GaAs	2.5	10
Epitex L1550-03	1550	InGaAsP	2	10

The research in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).

The devices were irradiated with 63-MeV protons at Crocker Nuclear Laboratory, UC Davis. The maximum fluence was 3 x 10^{12} p/cm^2. Five samples of each device were irradiated in an unbiased condition (all leads grounded). Irradiations were performed unbiased in order to minimize the effects of recombination-enhanced annealing during irradiation. Changes in light output were measured between irradiation steps using a special testing fixture that coupled the LED under test to a silicon photodiode for the 875nm LED, or an InGaAs phototransistor (diode-connected) for the longer wavelength LEDs. The LEDs were mounted on an aluminum plate that was attached to a thermoelectric cooling (TEC) module during measurements. The TEC maintained device temperature at 25°C ± .1°C during characterization, reducing measurement variability because of the sensitivity of LED light output to temperature. An Agilent 4156B parametric analyzer was used to measure changes in optical power of the LEDs at several forward currents, up to 100mA, the maximum rated current for the LEDs. The measurement program limited the amount of time and forward current at each measurement step in order to minimize recombination-enhanced annealing during characterization. Measurement repeatability was typically 1% or better.

EXPERIMENTAL RESULTS

Figure 1 shows light output at two forward currents, 10 and 50 mA, vs. fluence. This range of forward current is within the region where these LEDs would be operated in a typical application. Data has been normalized to pre-irradiation values. All three types of LEDs exhibit much less degradation compared to the highly sensitive amphoterically doped LEDs that have received so much attention in previous work. The 875 nm LED degraded only slightly more when the forward current was reduced to 10 mA, whereas both of the other LEDs were degraded by a much larger amount with lower forward current; note in particular the large difference for the 1550 nm LED with 10 and 50 mA forward current.

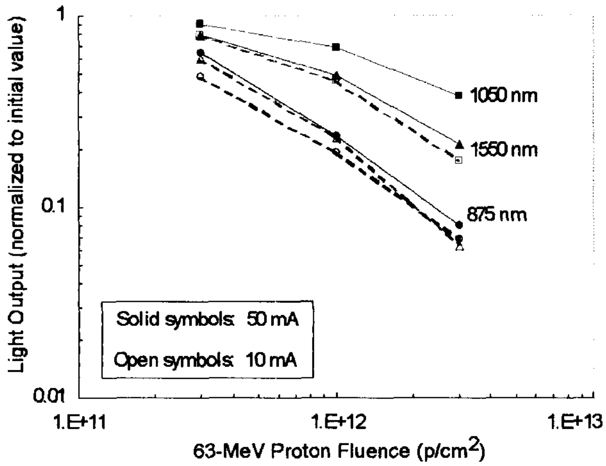

Fig.1. Normalized degradation of LED output with forward current = 10 and 50 mA

Although the normalized light output shown in Fig. 1 is a useful way to examine LED damage, it is possible to fit the damage to a power law that provides some insight into the degradation mechanisms as well as providing a parameter that has a well defined relationship with particle fluence. Rose and Barnes [3] showed that damage in LEDs with long lifetime could be described by the power law relationship below:

$$\left[\left(\frac{I_o}{I}\right)^n - 1\right] = \tau_o K\Phi \qquad (1)$$

where I_o is the initial light output and I is the reduced power output after irradiation, n is an exponent between 1/3 and 1, τ_o is the initial minority carrier lifetime, K is the lifetime damage constant, and Φ is the particle fluence. For an LED that is controlled by lifetime damage with a uniform distribution of impurities in the bandgap, n should have the value of 0.67. Amphoterically doped LEDs usually fit that equation very closely, but more advanced AlGaAs LEDs with narrow heterostructures usually fit Eq. 1 far more closely with n = 1 instead of 2/3 [5].

Fig. 2 compares test results for the Agilent 875 nm LED at 10 and 50 mA. For both currents the slope is nearly linear with n = 1 compared to n = 2/3. At 50 mA the parameter calculated from Eq. 1 at the first radiation level departs somewhat from the slope at higher fluences. These results are similar to earlier results for other heterojunction LEDs using AlGaAs [5].

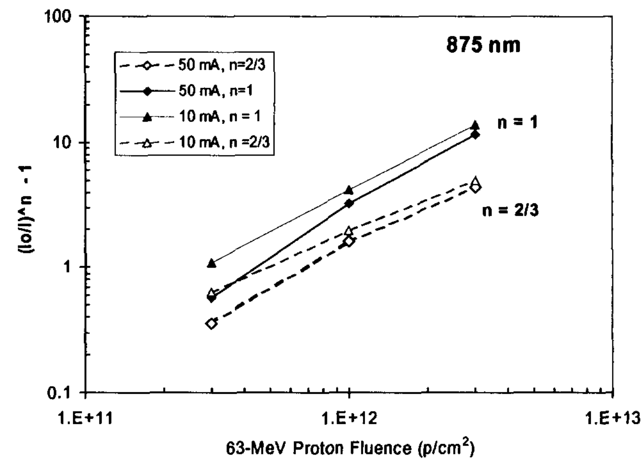

Fig. 2 Data for the Agilent 875 nm LED, using the power law with n = 2/3 and n = 1.

A similar analysis of the results for the 1050 nm LED is shown in Fig. 3. For this device, the data fit (with a slope closer to 1) Eq. 1 far more closely with n = 2/3 instead of n =1. Another important difference is that the damage is *considerably* higher when the LED is measured with a forward current of 10 mA compared to the results with I_F = 50 mA. That behavior has not been observed in other studies of LEDs. However, LEDs operating at 1050 nm have not been investigated previously.

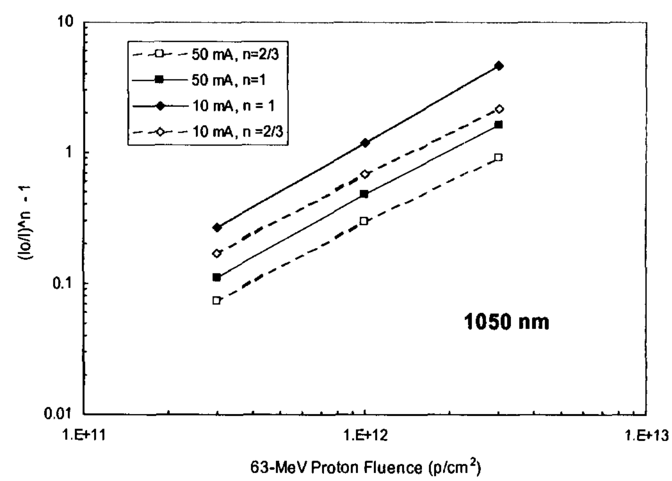

Fig. 3 Data for the Epitex 1050 nm LED using the power law with n = 2/3 and n = 1.

Analysis of the results for the 1550 nm LED are shown in Fig. 4. Just as for the previous case, a nearly exact fit (with the slope = 1) is provided with n = 2/3. The damage at lower currents is much higher compared to the 875 nm LED, and the difference is greater than for the 1050 nm device.

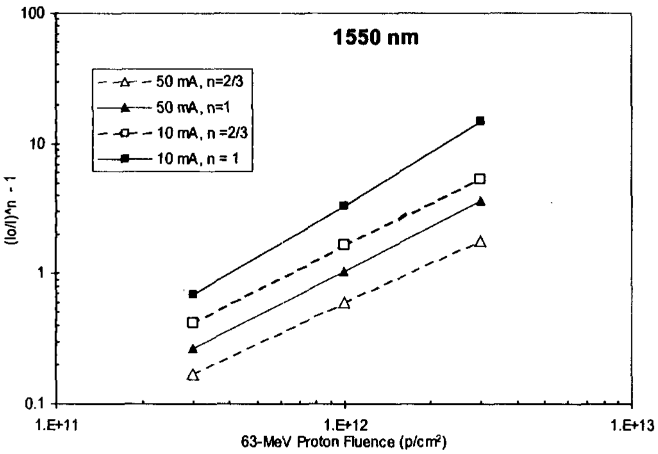

Fig. 4 Data for the Epitex 1550 nm LED using the power law with n = 2/3 and n = 1.

DISCUSSION

Damage Mechanisms

Reliability studies of LEDs have shown that defects within the space charge region increase the number of non-radiative recombination centers, decreasing light output at low currents [9]. Radiation damage produces similar effects [5]. This can be examined by evaluating the dependence of optical power output on forward current over an extended range of currents. Fig. 5 shows this dependence for a representative 875 nm AlGaAs LED sample. Before irradiation the optical power is nearly linear with input current over more than two decades (initial slope =1.03). After irradiation to 10^{12} p/cm^2 the slope increases slightly, to 1.14; it increases to 1.18 after the last fluence.

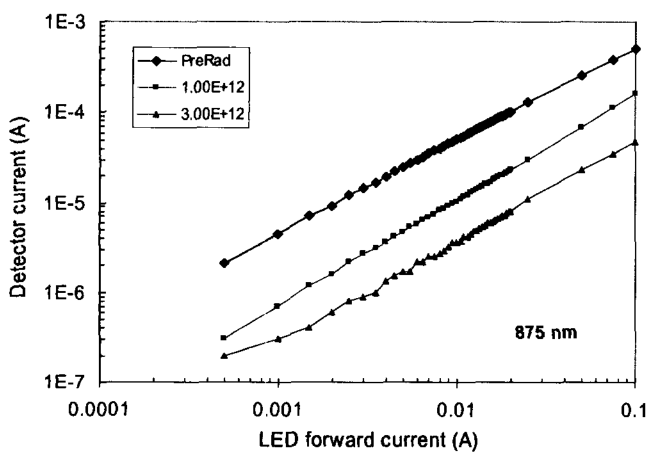

Fig. 5. Dependence of output power on forward current over an extended current range for a typical 875 nm LED.

The 1050 nm LED behaves very differently, as shown in Fig. 6. Initially the slope is almost exactly one. After the first radiation level it increases to 1.25, and continues to increase to a value of 1.36 after the last irradiation level. Consequently the damage at high currents is a great deal lower than the damage under lower forward current conditions. According to the manufacturer this device is fabricated with GaAs. However, the wavelength is well above the cutoff wavelength for GaAs, and it is likely that this device uses other materials on a GaAs substrate, such as InGaAs [10].

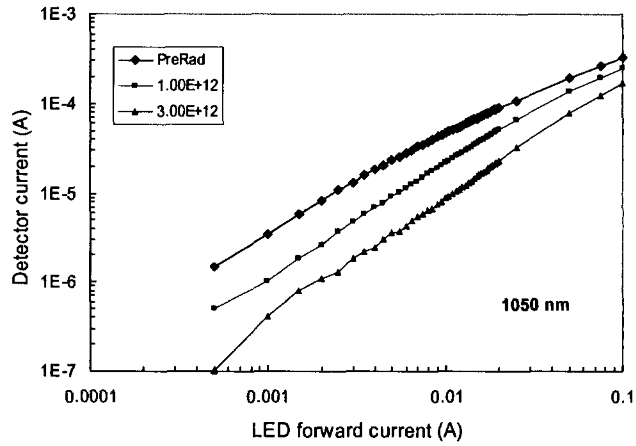

Fig. 6. Dependence of output power on forward current over an extended current range for a typical 1050 nm LED.

The 1050 nm LED also exhibited large differences in damage when we compare 10 mA and 50 mA injection conditions, although the difference was smaller than for the 1550 nm LED.

Basic material characteristics may be a factor in the change in linearity after irradiation. The AlGaAs material system has higher heterojunction barriers compared to InGaAsP, and is also less sensitive to Auger recombination. Degraded linearity in InGaAsP LEDs was attributed to electron leakage through heterostructures in one study [11], and this is one possible mechanism for the change in linearity after irradiation in the longer wavelength LEDs.

Doping levels >10^{18} cm^{-3} are required to achieve the short risetimes of our IR LED samples. Carrier removal rates are approximately 30 cm^{-1}, probably too low to affect the layers in LEDs of this type. However, bulk recombination centers are more important in InGaAs and InGaAsP compared to AlGaAs because bimolecular recombination rates are slightly lower, and devices made with the longer wavelength materials are limited to lower injection levels because of the importance of Auger recombination under high injection conditions.

Annealing

Annealing measurements were done on representative samples of the three types of LEDs. The devices were placed in a temperature-controlled test fixture during the extended annealing period, with forward bias applied. Fig. 7 shows annealing for devices biased with 5 mA of forward current. All LEDs were irradiated to a proton fluence of 3 x 10^{12} p/cm^2, which decreased the power output by factors of approximately 5 to 20, depending on the LED technology. Some annealing occurred for all three types of LEDs, but when referenced to the preirradiation value it is clear that only a small fraction of the damage actually recovered. In contrast, about 40% of the damage in amphoterically doped LEDs recovers after annealing under comparable conditions [12]. Thus, all three types of LEDs are relatively insensitive to annealing, just as for older results for AlGaAs LEDs made with heterojunctions.

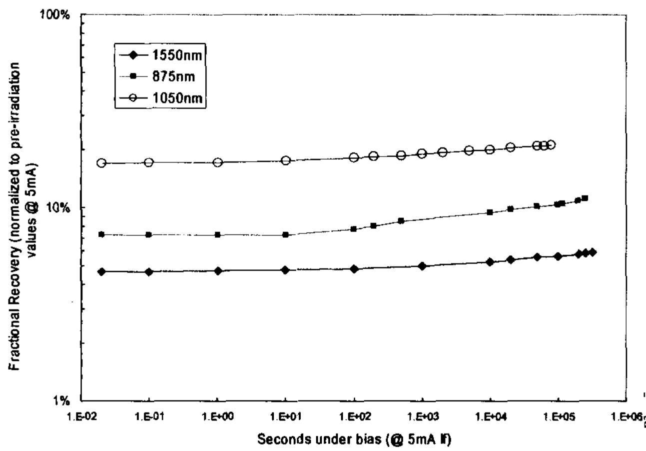

Fig. 7. Annealing of the three types of LEDs with a forward current of 5 mA. The damage is referenced to pre-irradiation optical power levels.

CONCLUSIONS

This paper has examined the effects of proton damage on two types of LEDs in the wavelength region above the silicon bandgap limit. Unlike AlGaAs LEDs, the optical power linearity in both types of devices changes significantly after irradiation. This may be caused by the lower heterojunction barriers associated with these materials.

From a practical standpoint the change in linearity requires more extensive characterization compared to AlGaAs devices where linearity is only slightly affected. However, both of the longer wavelength LED technologies show less degradation compared to AlGaAs LEDs. This is likely related to the short response times that require thin active regions and high carrier densities, both of which decrease radiation sensitivity.

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