Proton Damage in LEDs with Wavelengths Above the Silicon Wavelength Cutoff

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Abstract**-- Proton damage is investigated for LEDs with wavelengths of 1050 and 1550 nm. The results are compared to results for an advanced AlGaAs double heterojunction LED. Unlike the AlGaAs LED, light output degradation for the long wavelength LEDs became nonlinear with current after irradiation; more degradation was observed at lower forward currents. Minimal annealing was observed in the long wavelength LEDs during forward current injection. Mechanisms are proposed that are related to the material properties.**

Index terms **– AlGaAs, InGaAs, InGaAsP, LED, proton damage, radiation.**

I. 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 micron cutoff for silicon detectors. Such devices use different materials and are typically designed for high-speed operation in fiber optic communications 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.

II. 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 I
LEDs Selected for the Study

LED Manufacturer & 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	InGaAs	2.5	10
Epitex L1550-03	1550	InGaAsP	2	10

The devices were irradiated with 63-MeV protons at Crocker Nuclear Laboratory, UC Davis. The maximum fluence was $3\times10^{12}\ p/cm^2$. Five samples of each device were irradiated in an unbiased condition (all leads grounded). In order to compare radiation effects at different proton energies, an additional three samples of each device were irradiated unbiased with 30-MeV protons. Analysis of the epoxy packaging with version 2003.26 of SRIM/TRIM found the proton energies at the die to be 58-MeV (63-MeV) and 19.9-MeV (30-MeV). Irradiations were performed unbiased in order to minimize the effects of injection-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 $25^\circ C \pm 0.1^\circ C$ 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 100 mA, 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 injection-

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enhanced annealing during characterization. Measurement repeatability was typically 1% or better.

III. Experimental Results & Analysis

A. Radiation Response of Light Output

Fig. 1 shows light output at two forward currents, 10 and 50 mA, vs. 58-MeV proton 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 [9].

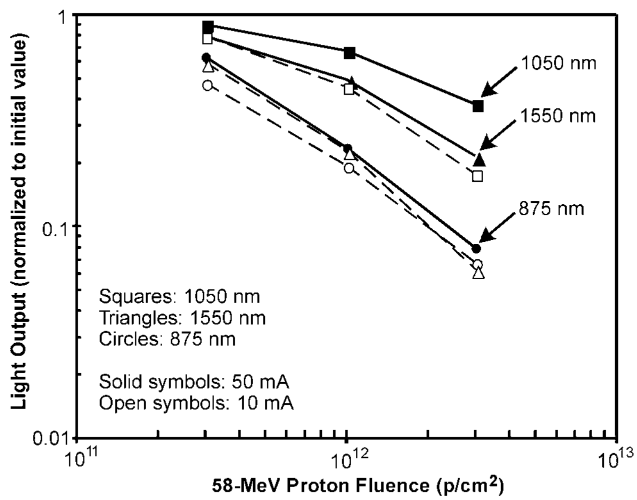

Fig.1 Normalized degradation of LED light output with forward current = 10 and 50 mA.

The 875 nm LED degraded only slightly more when the forward current was reduced to 10 mA, whereas *both of the long wavelength 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 of forward current.

Although the normalized light output shown in Fig. 1 is a relatively intuitive 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 light 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 with $n = 2/3$, but more advanced AlGaAs LEDs with narrow heterostructures and fast response times usually fit Eq. 1 more closely with $n = 1$ [5]. This implies that lifetime damage is not the dominant mechanism for those structures.

To determine the applicability of (1), a value of n is selected that results in a linear relationship between the quantity at the left and particle fluence, *with unit slope*. That approach was used to evaluate the damage in our devices. In Figs. 2-4, our data are plotted using (1) with $n = 1$ and $n = 2/3$. A reference line with unity slope is included in each of these figures. Note that the lines do not represent best fits, they merely join data points as a guide for the eye. Comparing the data sets to the reference line of unit slope allows us to determine which value of n gives a better fit to the data for each type of LED.

Fig. 2 compares test results for the Agilent 875 nm LED at 10 and 50 mA. For both currents the fit is better (with slope = 1) with $n = 1$ compared to $n = 2/3$, although the 50 mA data is still sublinear with $n = 1$. These results are similar to earlier results for other heterojunction LEDs using AlGaAs [5].

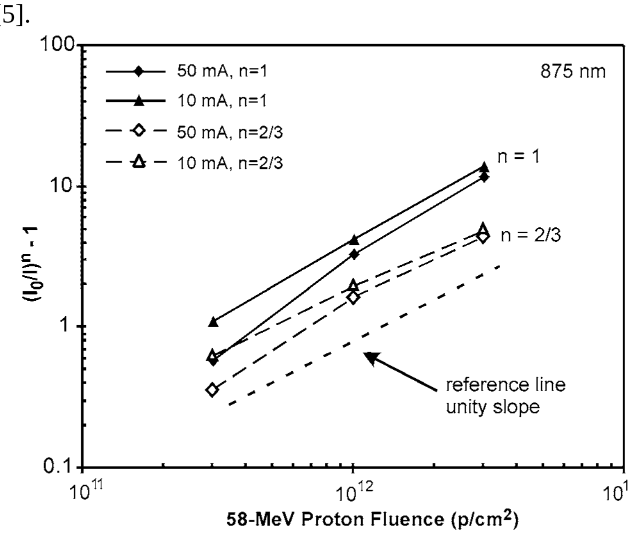

Fig. 2 Data for the Agilent 875 nm LED, using the power law with n = 2/3 and n = 1.

A similar analysis of the results for the 1050 nm LED is shown in Fig. 3. For this device, the data fit (1) far more closely with $n = 2/3$ instead of $n = 1$. Unlike the previous case, the fit is applicable with that slope for both currents. 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.

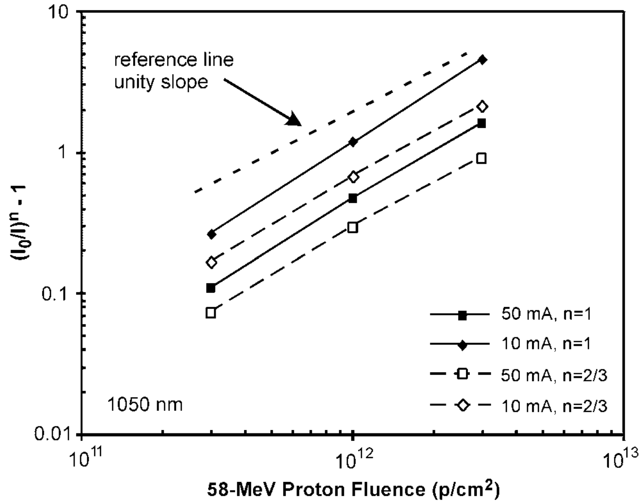

Fig. 3 Data for the Epitex 1050 nm LED using the power law with n = 2/3 and n = 1.

We are not aware of other studies of LEDs where such large differences in behavior at lower currents have been observed. However, to the best of our knowledge, modern InGaAs LEDs operating at 1050 nm have not been investigated previously.

It is encouraging that our 1050 nm data agree more closely with $n = 2/3$. This result is similar to that reported by Walters et al. [10] for a 980 nm InGaAs quantum-well LED. An exact fit of their data using Rose and Barnes theory was achieved using a value of 0.6 for n. Unlike our results, Walters et al. found their results to be independent of the forward current used in their measurements (although the currents used in that study were very low, ranging from 0.1 to 1.0 mA). However, their results for light output degradation vs. 50-MeV proton fluence are very similar to ours for the 1050 nm LED at 10 mA.

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

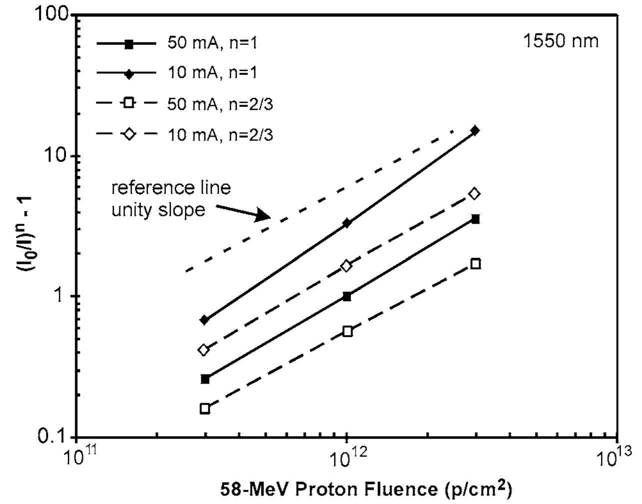

Fig. 4 Data for the Epitex 1550 nm LED using the power law with n = 2/3 and n = 1.

Data taken with 30-MeV protons (19.9-MeV at the LED die surface level) also fit the Rose and Barnes power law well with $n = 1$ (875 nm) and $n = 2/3$ (1050 nm and 1550 nm). Fig. 5 shows 58-MeV and 19.9-MeV data for the 1550 nm LED with a forward current condition of 50 mA and $n = 2/3$. Looking at the data in this way allows relatively easy comparison of LED damage for different particle energies. The 19.9-MeV to 58-MeV proton damage ratio for the 1550 nm LED is approximately 1.6. This value is in good agreement with the NIEL ratios of Summers et al. [11] for GaAs and InP at these proton energies.

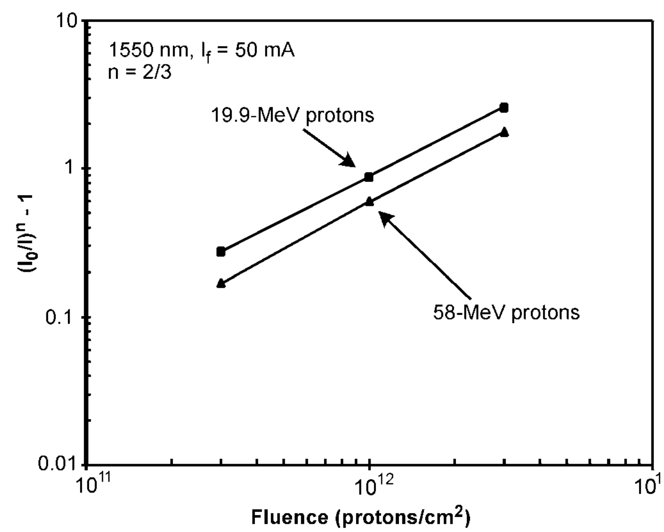

Fig. 5 Comparison of 58-MeV and 19.9-MeV proton damage in the 1550 nm LED.

B. 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. 6 shows annealing for devices biased with 5 mA of forward current. All LEDs were irradiated to a 58-MeV proton fluence of

$3 \times 10^{12}\ p/cm^2$, 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* (this is in contrast to laser diodes that use the same materials). There is a logarithmic dependence for annealing with a very shallow slope. 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 [9].

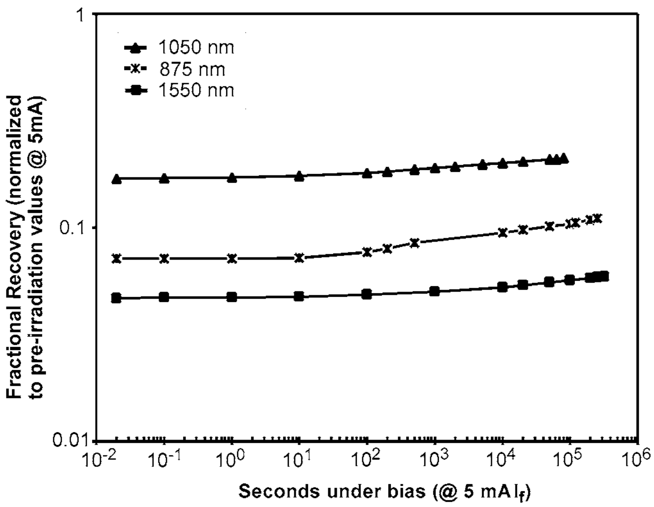

Fig. 6. Annealing of the three types of LEDs with a forward current of 5 mA. The damage is referenced to pre-irradiation optical power levels.

Additional samples of all three LEDs were annealed while biased with 20 mA of forward current. Fig. 7 compares the data for annealing at 5 mA and 20 mA for the three LEDs. Annealing data for the 1050 nm and 1550 nm LEDs at 50 mA are also included. The annealing proceeds much more slowly with the forward bias condition of 5 mA compared to the rate that is observed with annealing currents of 20 and 50 mA.

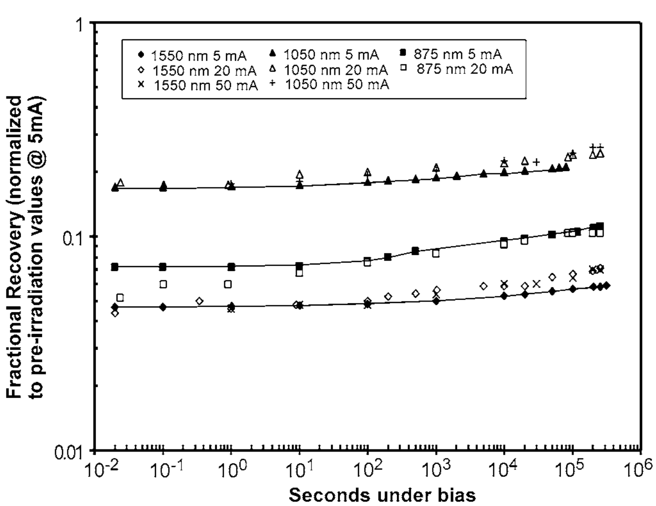

Fig. 7. Annealing of the three types of LEDs with forward currents of 5 mA, 20 mA, (and 50 mA for the 1050 nm and 1550 nm LEDs). The damage is referenced to pre-irradiation optical power levels.

However, the fractional amount of annealing can not be normalized to the total amount of charge injection, as has been observed with amphoterically doped LEDs in the past [13]. This would be an important consideration during device characterization for applications in a radiation environment, because annealing measurements would have to be done under conditions that closely approximate actual use conditions.

IV. DISCUSSION

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 [14]. 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. 8 shows this dependence for a representative sample of our 875 nm AlGaAs LED. 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. These slopes were measured over the middle third of the range of currents plotted in the figure.

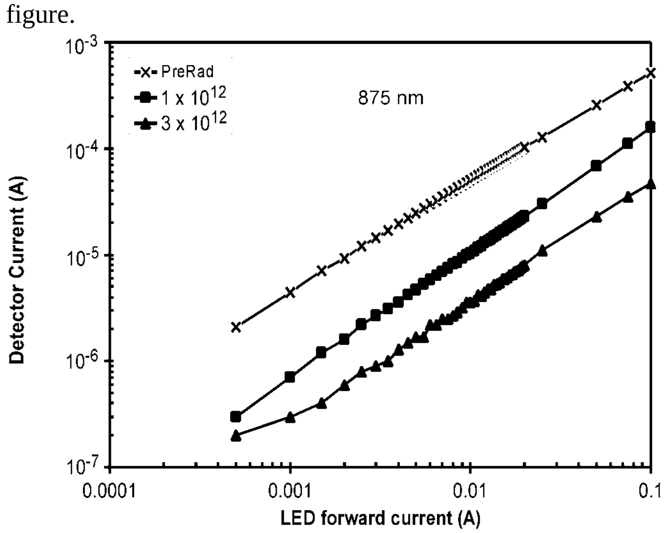

Fig. 8. Dependence of output power on forward current over an extended current range for a typical 875 nm LED.

The 1050 nm LED behaves very differently, as shown in Fig. 9. 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. Slopes were measured in a manner similar to that used in Fig. 8.

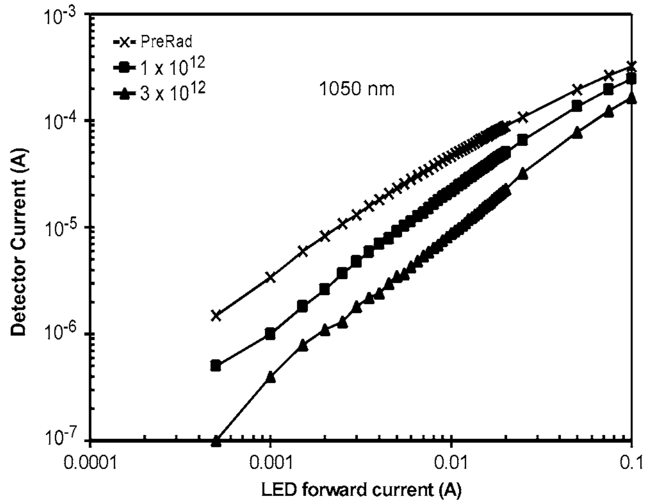

Fig. 9. Dependence of output power on forward current over an extended current range for a typical 1050 nm LED.

Consequently the damage at high currents is a great deal lower than the damage under lower forward current conditions. As seen above, the 1050 nm LED exhibited large differences in damage when we compared 10 mA and 50 mA injection conditions, although the difference was smaller than for the 1550 nm LED.

According to the manufacturer this device is fabricated with GaAs. However, the wavelength is well above the cutoff wavelength for GaAs, and our suspicion was that this device uses other materials on a GaAs substrate, such as InGaAs [15]-[16]. In order to learn more about the structure of the 1050 nm LED, energy dispersive spectroscopy (EDS) was performed on the edge of a decapsulated die sample. A high presence of both In and P were found, indicating that the 1050 nm LED and 1550 nm LED (made by the same manufacturer) have very similar compositions, based not only on Ga and As, but In and P as well. The 1050 nm wavelength is below the range of wavelengths that are available with lattice-matched InGaAsP. However, LEDs and laser diodes with that wavelength can be fabricated with strained-layer InGaAs technology [17]. The 1050 nm LED most likely uses an InGaAs active region and an InP substrate.

Barnes studied the neutron radiation response of an older 1060 nm InGaAs LED by analyzing changes in light intensity as a function of LED forward current [18]. The 1060 nm LED in that earlier study had only one tenth the output power at 50 mA of our 1050 nm LED – 0.2 mW. Many advances in strained-layer InGaAs have been made since the first work in the early 1980s. The relatively low efficiency of the 1060 nm LED studied by Barnes is likely due to the deficiencies in material technologies that were available at the time. Unlike our results for the 1050 nm LED, the light intensity curves at low and high currents remained parallel as irradiation proceeded in the Barnes study. He concluded that parallel curves indicate that no major changes in radiative or total current flow mechanisms occurred.

Nonlinearities in damage were also observed in the 1550 nm LED. Fig. 10 illustrates the higher damage that occurred at lower forward injection levels. However, if we compare Figs. 9 and 10 it is clear that the damage is more strongly affected by operating current for the 1550 nm LEDs. One possible reason for this is Auger recombination, which has a cubic dependence on carrier density [19]. The Auger recombination coefficient is so high in InGaAsP at 1550 nm that it increases the threshold current in laser diodes with that wavelength by a factor of 3-5 [20].

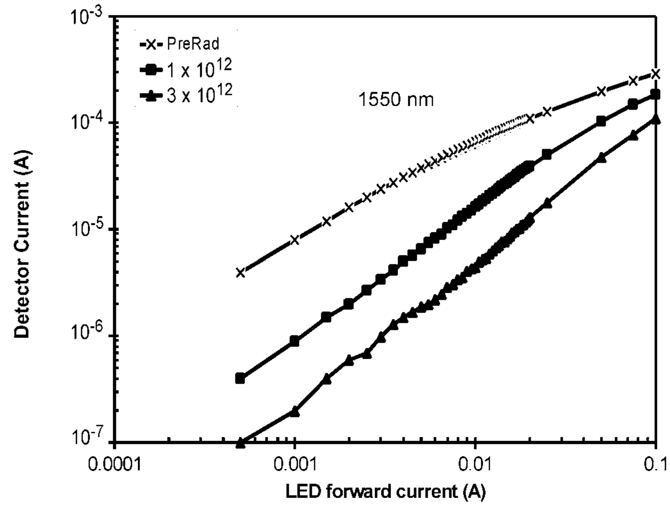

Fig. 10. Dependence of output power on forward current over an extended current range for a typical 1550 nm LED.

Thus, 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 [15], and this is one possible mechanism for the change in linearity after irradiation in the longer wavelength LEDs.

Doping levels greater than $10^{18} cm^{-3}$ are required to achieve the short risetimes of our IR LED samples. Carrier removal rates are approximately 30 cm^{-1} [21], 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.

Overall, less damage was observed in the long wavelength LEDs than in AlGaAs LEDs or amphoterically doped 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. Khanna et al. [22] made a similar observation in a study of a 980 nm quantum-well LED. It was also found to be harder than double heterojunction or amphoterically doped LEDs.

V. CONCLUSIONS

This paper has examined the effects of proton damage on two types of LEDs in the wavelength region above the silicon bandgap limit for detectors. 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. In addition, annealing was found to not be linearly dependent on charge injection as with amphoterically doped LEDs. This could complicate radiation damage mitigation, and interpretation of radiation damage tests.

However, both of the longer wavelength LED technologies show less degradation compared to AlGaAs LEDs. We propose that this is likely related to the short response times that require thin active regions and high carrier densities, both of which decrease radiation sensitivity. Unlike AlGaAs LEDs with high bandwidth, the fit of the damage to the Rose-Barnes equation with $n = 2/3$ implies that lifetime degradation is the dominant recombination mechanism for LEDs with longer wavelength.

VI. ACKNOWLEGEMENTS

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