# Proton Damage in Advanced Laser Diodes†

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***Abstract*** - *Damage from 50 MeV protons is investigated for several types of laser diodes with wavelengths from 650 to 1550 nm. Key parameters include slope efficiency, threshold current, and the transition characteristics between LED and laser operation. Some of the devices exhibited nonlinear relationships between threshold current and proton fluence. All of the lasers, including VCSELs, were strongly affected by recombination-enhanced annealing.*

## I. Introduction

Many advances have been made in laser diode technology that have extended the wavelength range over which semiconductor lasers can be used, and also reduced the threshold current required for operation. Key technical advances include the use of thin heterostructures that depend only weakly on minority carrier lifetime for carrier injection, special means of confining carriers within the laser cavity (including interspersed oxide or semiconductor layers), strained layers that reduce losses due to Auger recombination , and small, precise lateral dimensions that provide quantum wells to limit the number of allowable states within the cavity [1-4].

Proton displacement damage has been studied in only a few types of laser diodes [5-8] and little information is available on damage in more advanced devices. This paper compares proton damage in six different types of lasers, with wavelengths from 650 to 1550 nm. The lasers use different semiconductor materials, and represent a broad range of current laser technology. One of the devices is a vertical cavity surface-emitting laser (VCSEL) that provides light output from the top surface, and uses a distributed Bragg reflector with oxide confinement in order to obtain high efficiency and low threshold current [9]. Some properties of these devices are listed in Table 1.

Devices with asterisks have internal monitor diodes that are typically used as part of a feedback circuit to control operating conditions. Degradation of the monitor diodes is an important consideration for many laser diode applications.

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†The research in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration under the NASA Electronic Parts and Packaging Program (Code AE).

Table 1
Wavelength and Threshold Current of Lasers in the Study

| Manufacturer | Wavelength (nm) | Nominal Threshold Current [mA] |
|---|---|---|
| Lumex | 650* | 20 |
| EG&G | 915* | 50 |
| Honeywell (VCSEL) | 980 | 5 |
| Fermionics | 1300 | 10 |
| Lumex | 1300* | 10 |
| Mitsubishi | 1550* | 10 |

## II. Technical Approach

Older work on laser diodes has shown that damage is stable for long time periods provided that the temperature remains below about 200 °C, but that considerable annealing occurs when devices are biased after (or during) irradiation because of recombination-enhanced annealing. Thus, in order to study the damage that results just after irradiation it is important to carefully control and limit the amount of current and time (essentially charge) that flows through the device after irradiation. Lang and Kimerling demonstrated that recombination-enhanced annealing depends on current at low injection levels, but saturates at higher radiation levels (about 1 $A/cm^2$ for their samples, which represent much older laser technologies) [10]. Annealing of damage in more advanced laser diodes was also reported by Zhao, et al. [8].

Devices were irradiated at UC Davis using 50-MeV protons. Irradiations were done with all pins grounded. Electrical characterization and optical power measurements were made between successive irradiation steps using a temperature-controlled test fixture with a precision of ±0.1 °C. All measurements were done at 25 °C. The measurement sequence was designed to limit measurement time and current in order to minimize recombination-enhanced annealing. Measurements were repeatable to 1% or better.

Optical measurements were made to determine the dependence of optical power on current, as well as the optical power produced by the monitor diode (where applicable). Forward voltage measurements were also made, as well as wavelength measurements. The characterization included optical performance at currents well below the lasing threshold (where lasers function as LEDs) as well as currents above the threshold. An Agilent Technologies 4156B parameter analyzer was used to make the measurements. Special test fixtures were designed that provided precise mechanical alignment between the laser and the external photodiode used to measure optical output power. The lasers were mounted in a plate, using a thermoelectric cooler to control the temperature to 25 ± 0.05 °C. Measurement precision was typically 1% or better.

## III. RESULTS

### A. *Optical Power Characteristics*

Optical power and threshold current are two of the most critical laser diode parameters. The effect of proton damage on output power is shown for the Mitusbishi 1550 nm laser in Figure 1 where the percent change in threshold voltage is plotted vs. fluence. For this device there is a very sharp transition between the LED mode (at low current) and the laser mode, and the main effect of the radiation damage is a shift in threshold current. Note that the slope efficiency is essentially unchanged after irradiation. Most earlier work on semiconductor lasers has shown similar results; i.e., nearly constant slope efficiency (until extreme degradation occurs). There was some variability in damage between different units of the same type. The coefficient of variation (σ/mean) was 0.12 to 0.2 for the various types of lasers.

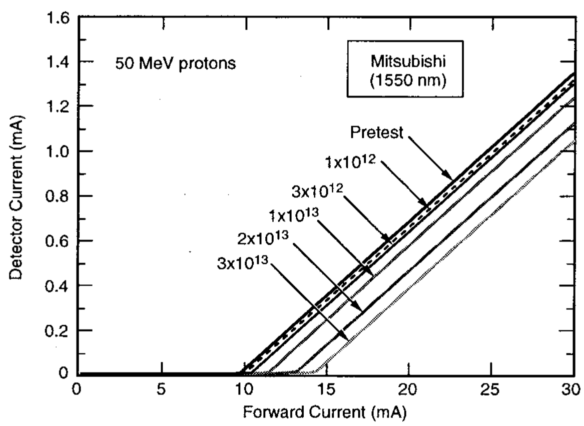


Figure 1. Degradation of the Mitsubishi 1550 nm laser.

However, not all laser diodes exhibit such ideal characteristics after irradiation. Figure 2 shows the effect of proton damage on the Lumex 650 nm laser. Two features should be noted. First, the slope efficiency changes; a significant change is observed in slope efficiency even after the first radiation level where the threshold current changes by only about 2%. Second, this device exhibits a more gradual transition between the LED and lasing modes near the threshold current compared to the Mitsubishi laser diode of Figure 1. This transition region for the Lumex laser extends over a wider range of current after irradiation, which is shown more clearly by the log-log plot of the same data in Figure 3. The gradual transition is most likely caused by emission from several different lasing modes.

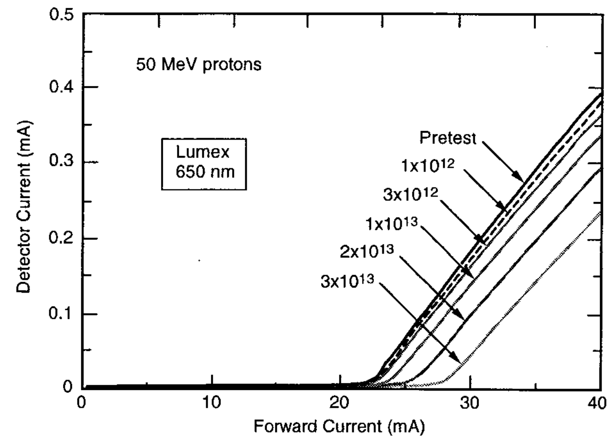


Figure 2. Degradation of light output of the Lumex 650 nm laser showing change in slope efficiency and "softening" of the transition region between LED and laser operating modes.

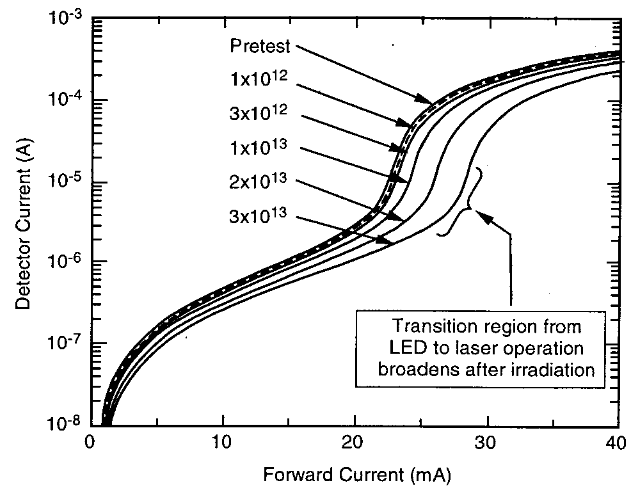


Figure 3. Lumex 650 nm laser results in Figure 2 plotted logarithmically to show transition characteristics in more detail.

VCSEL structures do not have constant slope efficiency (even prior to irradiation) largely because the active region heats up significantly at higher currents [9]. VCSEL power curves may also exhibit substructure because of slight variations and mismatch in the many layers that make up the Bragg reflector within the VCSEL, which can cause the number of modes to vary with input power.

The optical power characteristics of a typical Honeywell VCSEL are shown in Figure 4. In this example there is a substructure in the slope efficiency after irradiation that is probably related to differences in mode structure within the laser. Some VCSELs exhibited a significant discontinuity (step) in the output power characteristics prior to irradiation that was reduced after irradiation. Threshold current changes after irradiation in the Honeywell VCSELs are similar in magnitude to those reported by Barnes, et al. for a VCSEL with the same wavelength, manufactured by Sandia National Laboratories [11]. However, our tests were done at a lower energy (50 MeV instead of 192 MeV) and used a measurement sequence that was designed to limit annealing.

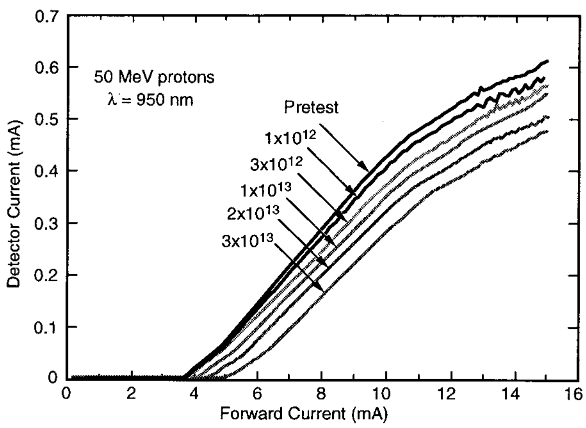


Figure 4. Degradation of light output of the Honeywell VCSEL (950 nm).

*B. Annealing*

All of the laser diodes exhibited recombination-enhanced annealing. This can create severe difficulties during experiments that are intended to evaluate damage unless the operating conditions are carefully controlled, both during and after irradiation. Less damage will occur in devices that are operating during irradiation. However, it is difficult to make comparisons of biased and unbiased irradiation results because of the interplay between operating current and damage, and uncertainty about how to relate experiments done for relatively short times with bias to longer, less intense irradiations that occur in space. In this study we elected to do the irradiations without bias, and then evaluate annealing separately.

Annealing in laser diodes is difficult to evaluate because lasers operate at high power densities. We performed an isochronal annealing experiment on some of the irradiated samples in order to determine the temperature where thermal annealing started to become important. The highest temperature used was 220 °C (the maximum temperature available with standard ovens in our laboratory). Changes in threshold current were less than 2% during these tests. This is consistent with annealing results for proton damage in GaAs solar cells, which showed minimal annealing at temperatures below 250 °C [12]. Because such high temperatures are required for thermal annealing it appears unlikely that thermal annealing takes place in these laser diodes when annealing experiments are done using current within the normal operating range with the case temperature at 25 °C.

One case of interest is the situation where radiation damage has caused the threshold current to increase to the point where the operating current is no longer sufficient to drive the device into the lasing mode. Figure 5 shows annealing of the EG&G 915 nm laser after radiation damage has caused the threshold current to increase from 42 to 66 mA. Current in a detector is shown (with 50 mA of forward current applied to the laser during measurement). The same condition was used during annealing, with 50 mA applied for several hours after irradiation. This experiment shows how the laser would recover if the bias current was left in a constant current condition that was insufficient to overcome the degradation in threshold current after irradiation. In order to interpret this figure one should note that current in the diode detector when the device is in the lasing mode is about 1 mA, more than two orders of magnitude above the detector current in the LED mode, which is shown in the figure. Thus, annealing is taking place at a far lower *optical* power density than when the device operates in the lasing mode even though the electrical power density is unchanged. After the annealing period, the threshold current decreased from 64 mA to 56 mA. Although 50 mA is still well below the threshold current, the optical power begins to increase sharply during annealing because the device is beginning to enter the transition region between LED and laser operation.

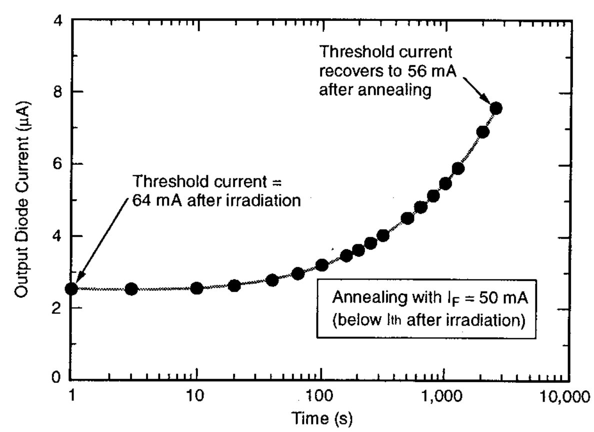


Figure 5. Annealing of a 915 nm laser diode with current applied that is below the post-irradiation threshold current.

Annealing in LEDs at different currents depends on the total injected charge after irradiation [13], with a charge threshold of about 0.001 C. That is, recombination-enhanced annealing in LEDs starts to become significant at that value of charge, and progresses until the total charge is 1000 C or more. Our initial experiments indicate that annealing in laser diodes also depends on total charge, with comparable sensitivity to total charge after irradiation. However, it is more difficult to make comparisons between different types of lasers because of differences in geometry and material type. For example, the EG&G laser is designed with a very small cavity, nominally 1 x 3 μm, resulting in a much larger optical power density compared to LEDs.

Note further that although injection-enhanced annealing is quite significant for amphoterically doped LEDs, double-heterojunction LEDs exhibit only slight damage recovery, even after 1000 C of charge. The doping levels and materials used in double-heterojunction LEDs are very similar to those used in laser diodes. The reason for the increased sensitivity of laser diodes to annealing may be due to the much higher optical power densities and the requirement for high internal optical gain, neither of which occurs in LEDs.

*C. Monitor Diode Degradation*

Many applications rely on current from an internal monitor diode to provide input to a feedback circuit that is designed to control the laser power output within a narrow range. The monitor diodes are usually placed to the side of the device, reflecting a small amount of light from the exit window to the monitor diode.

Figure 6 shows degradation of monitor diodes for two of the lasers, along with degradation of a typical silicon photodiode. For the 1300 nm laser, degradation in the photodiode is much greater than degradation in the laser, which could have a serious impact on applications that rely on the internal diode responsivity to control current in the laser. The internal diode in the 650 nm laser is significantly harder. Note also that degradation of the monitor diodes will anneal very little compared to annealing in the laser diodes because they operate at very low currents.

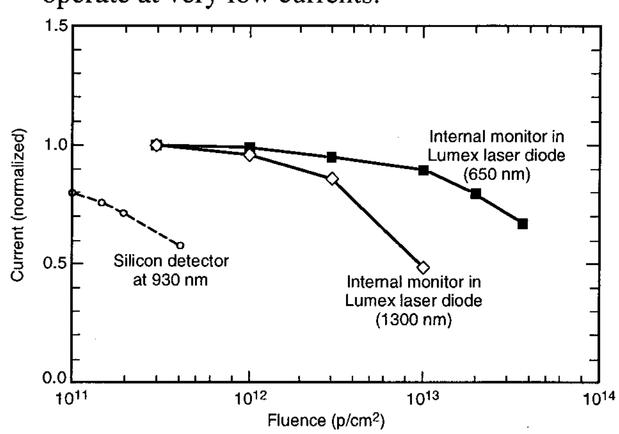


Figure 6. Degradation of internal monitor photodiodes of the two lasers manufactured by Lumex.

Degradation of a typical silicon p-n silicon detector is also shown in Figure 6 for comparison. The III-V detectors are far less sensitive to displacement damage, which is expected because their operation does not require long minority carrier lifetime.

## IV. Discussion

*A. Damage Linearity*

Although threshold current is not the only parameter of interest, it remains one of the most important parameters for characterizing radiation degradation. Earlier experimental work showed that the change in threshold current change after irradiation is linearly dependent on proton or neutron fluence [5-8]. Four of the laser diodes in our study also behaved linearly, as shown in Figure 7. These data are mean values of six different units of each type, measured just after irradiation, and do not take recombination-enhanced annealing into account.

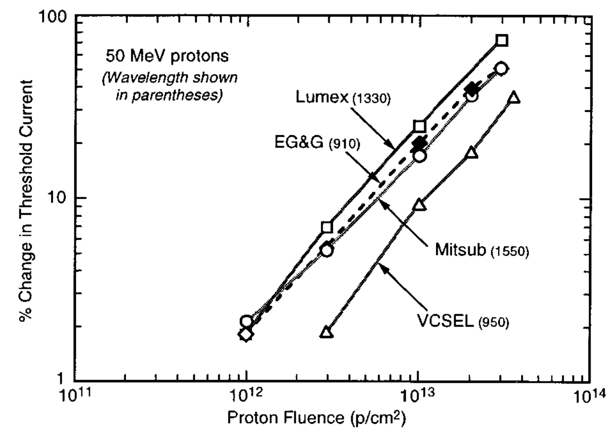


Figure 7. Dependence of threshold voltage increase on fluence for laser diodes with linear damage relationships.

Wavelength measurements and spectral width were also made before and after irradiation. The spectral width was typically changes in wavelength after the highest radiation level were less than 0.2 nm. The same temperature controlled fixture was used for wavelength measurements, which is an important detail because of the dependence of wavelength on temperature.

Two of the laser diode types had nonlinear relationships between threshold voltage change and fluence. Those results are shown in Figure 8. This nonlinear dependence is important because it makes it more difficult to compare laser damage under different conditions or fluences. Reasons for the nonlinear behavior are discussed in the next subsection. Note that both types of lasers with nonlinear behavior had more gradual transitions between the LED and laser operating modes compared to the other four lasers that had sharp transition regions (and linear fluence dependence). The lasers in Figure 7 also exhibited significant changes in subthreshold slope after irradiation. The nonlinear behavior was consistent among different samples of the same laser type, not atypical behavior of one or two units. Note that the 1300 nm laser from the other manufacturer exhibited linear behavior.

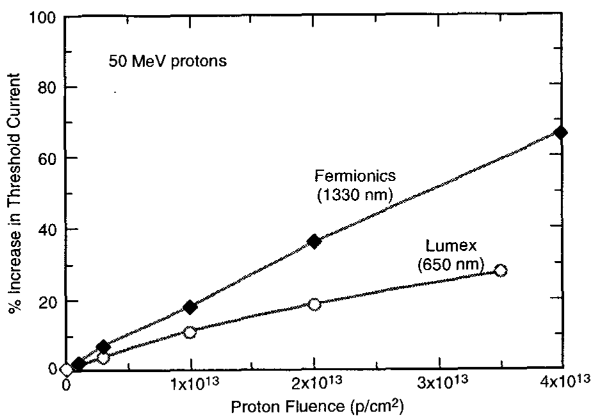


Figure 8. Dependence of change in threshold voltage on fluence for the Lumex 650 nm and Fermionics 1300 nm lasers.

*B. Theoretical Considerations*

Modern semiconductor lasers usually have extremely small lateral dimensions. Charge injection from heterojunctions does not depend on minority carrier lifetime, and the lifetime within the lasing region is on the order of a few nanoseconds in unirradiated devices [14]. The main effect of displacement damage in these structures is increased non-radiative recombination because of bulk defects within the laser cavity.

The threshold current $I_{th}$ can be described by the equation

$$I_{th} = \frac{qVBN_{tr}^{2}}{\eta_i} e^{2<\alpha i>\Gamma g} \qquad (1)$$

where q is electronic charge, V is the volume of the laser cavity, B is the bimolecular recombination coefficient for bulk recombination (~$10^{-10}$ $cm^3/s$), $N_{tr}$ is the carrier density at threshold (transparency condition), $\eta_i$ is the internal quantum efficiency, $\alpha_i$ is the transverse mode loss, $\Gamma$ is the transverse mode confinement factor, and g is the cavity gain. By expanding the exponential one can show that the parameter $\alpha_i$ is proportional to the number of bulk defects for small arguments. To first order, the threshold current depends on the square of the injected carrier density. Thus, the effect on operating conditions within the cavity is considerably larger than indicated by changes in threshold current.

Damage linearity depends on the relationship between cavity gain and carrier density of the material, which is approximately logarithmic. Therefore damage is only linear over a restricted range of conditions. When the threshold current increases by 40%, the damage begins to become noticeably sublinear with fluence. That is in reasonable agreement with our results, as well as with older results for neutron damage in laser diodes [15].

Material properties also affect laser degradation. Although the gain of InP-based lasers (such as the 1550 nm devices) is considerably higher than that of GaAs-based lasers, Auger recombination losses are much higher in InP. This causes the output power at low injection (below threshold) to increase sublinearly with increasing current, whereas the relationship is linear for materials with low Auger coefficients. It also affects the relationship between threshold current and carrier density.

In addition to the increase in bulk recombination, radiation defects also cause carrier removal. For GaAs and related III-V devices, carrier removal rates are typically between 300 and 500 $cm^{-1}$[16]. Carrier densities in semiconductor lasers can be estimated from the value of the bimolecular coefficient, B, as well as the other parameters in Equation 1. Typical values are 2-4 x $10^{18}$ $cm^{-3}$, which are also verified by processing data from the literature [17,18]. This suggests that carrier removal effects may begin to become important at radiation levels above about 2 x $10^{13}$ $p/cm^2$, which may also contribute to nonlinear damage at high fluences. However, at lower fluences carrier densities should change by less than 1%.

*C. Measurement and Characterization*

Characterization of laser diode damage is considerably more complex than that of characterizing light-emitting diodes for many reasons. First, this study uses lasers with different composition and structure. Second, the specific geometry of a laser can have a pronounced effect on threshold current and output power characteristics, and these factors have to be sorted out in order to make meaningful comparison between different types of lasers.

Although threshold current is clearly important, measurement of the optical power characteristics over a wide range of currents can provide insight into damage mechanisms, including the importance of Auger recombination. Because annealing is so strongly dependent on injection conditions, measurements need to be carefully set up to limit the time and current (essentially total charge), otherwise the measurements will inadvertently cause a significant amount of the damage to anneal, underestimating the effects of radiation on device performance.

Lifetime measurements can also be made on laser diodes, although modern lasers require measurements at frequencies above 1 GHz, which are difficult to make. A revised approach has been developed by Schtengel, et al., which allows lifetime to be measured from electrical characteristics [19], eliminating the need for high-speed optical power measurements.

## V. Conclusions

This paper has investigated proton damage in several types of laser diodes. The lasers that were tested cover a wide range of wavelengths and include several different material characteristics.

The key parameters are threshold current and slope. For most lasers, threshold current increases linearly with fluence provided the relative increase is less than 40%, in agreement with theoretical predications assuming that bulk recombination is the dominant mechanism. Nonlinearities are expected at higher levels, and carrier removal effects may also become important for fluences above approximately 3 x $10^{13}$ p/cm$^2$. Characterization of laser characteristics below the threshold level can provide additional information about degradation mechanisms.

Recombination-enhanced annealing is an important factor for all of the lasers in the study, unlike LEDs that are fabricated with similar material technologies. The reason for the difference is the requirement for high gain and low recombination within the laser cavity when the laser operates in the lasing mode. Experimental measurements have to be carefully planned to avoid interference from annealing, which will underestimate the amount of damage in cases where the laser operates intermittently or below threshold.

The effect of displacement damage on wavelength is minimal, changing the wavelength by less than 0.2 nm for all of the lasers in our study. However, the spectral width may change if the threshold current increases significantly, which could be important in some applications.

Finally, we used 50 MeV protons in our study because there is better agreement about how NIEL calculations agree with experimental results at that energy compared to results at higher energy [20]. Although energy dependence of damage in laser diodes is an important topic, it is beyond the scope of the present work.

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## Introduction

Laser Diode Technology Advances

- Buried heterostructures
- Multiple quantum wells
- Strained lattices
- VCSELs

Threshold Current Densities < 400 A/cm2

New Material Technologies

- Quaternary compounds
- Wide range of wavelengths

Very Few Radiation Studies

- Earlier work done with neutrons
- Proton damage, new structures limit applicability of older results



Introductory slide showing key advances in commercial laser technology, reduction in threshold current, and material issues. The slide provides background material and motivation for the work.

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## Outline

Experimental Procedure

Degradation of 650 nm Laser Diode

Recombination-Enhanced Annealing

Monitor Diode Degradation

Models for Radiation Degradation

Damage Linearity

Critical Parameters and Characterization Methods

Conclusions



Outline of talk.

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## Experimental Procedure

Six Types of Laser Diodes Selected

- Wavelengths from 650 to 1550 nm
- One vertical cavity semiconductor laser (VCSEL)

Irradiated with 50 MeV Protons at UC Davis

- Unbiased irradiation
- Extreme care to limit total charge during measurements

Characterization Methods

- Temperature controlled test fixture
- Parameter analyzer used to measure I-V and L-I characteristics
- Spectrometer used to measure wavelength and spectral width



This slide discusses the types of commercial lasers that were used, the source of radiation (protons at UC Davis), and the basic approach used to measure devices before and after irradiation.

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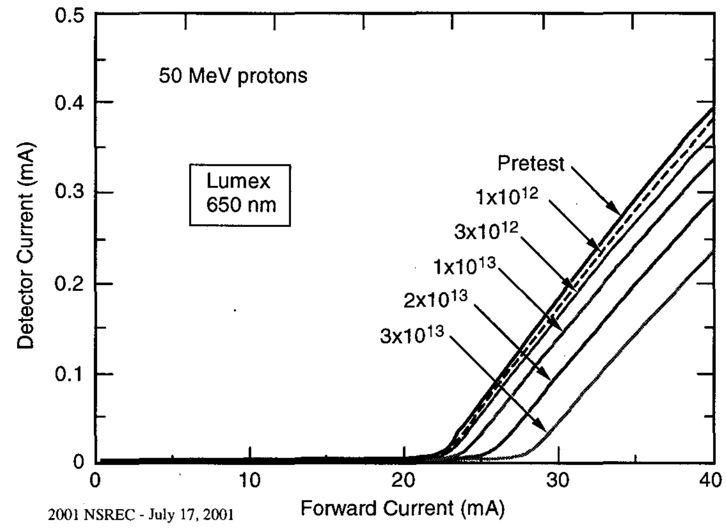
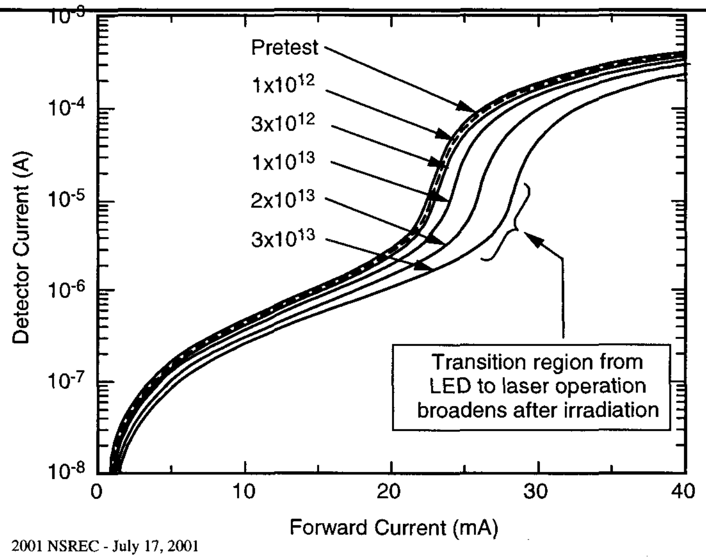
## Threshold Current Degradation of a 650nm Laser Diode






This slide shows how radiation increases the threshold current of a laser diode. In this example the slope efficiency changes somewhat in addition to the increase in threshold current.

JPL Logarithmic Plot of 650nm Laser Degradation

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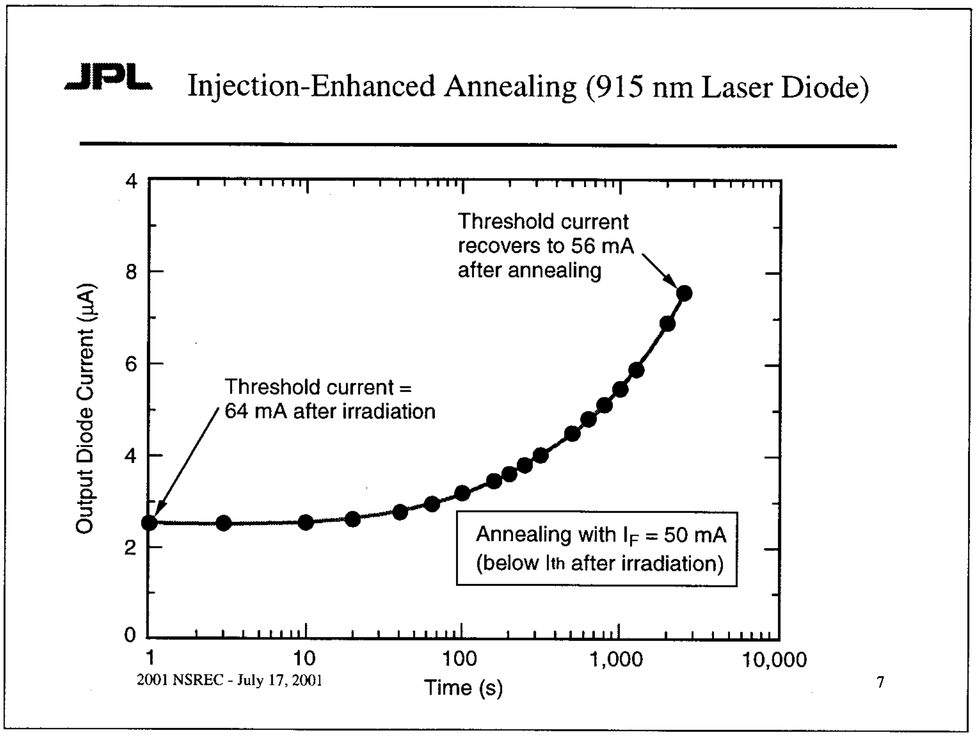
This is a logarithmic plot of the results in the previous slide. Plotting the data in this way provides more specific information about the region where the device makes the transition from LED to laser operation. Radiation damage causes the transition region to extend over a wider range of forward currents.




This slide shows how the optical output power (measured as current in an external detector) changes with time when a current somewhat below the post-radiation threshold current value is continually applied to the device. The optical power rises more abruptly at longer times because the transition region also shifts as the part anneals.

Note that the optical power is still several orders of magnitude below the typical power level of the device in the lasing mode.

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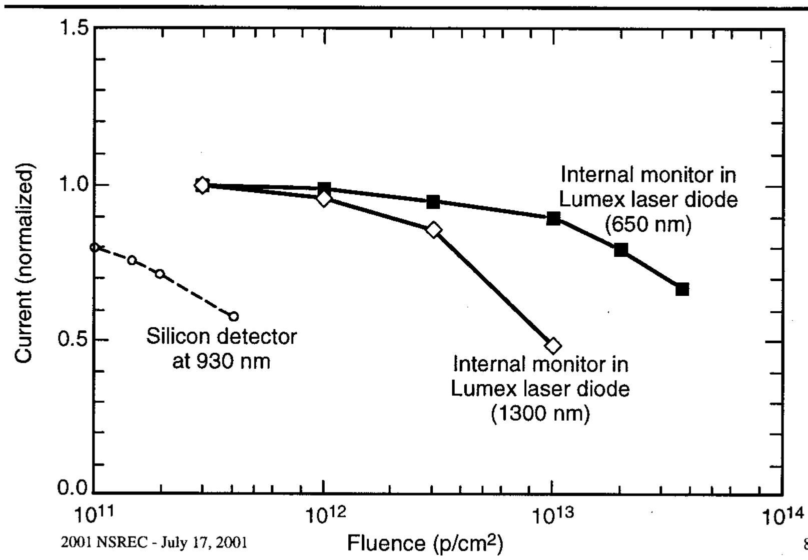
## Monitor Diode Degradation






This slide shows how the internal monitor diodes of two types of lasers are affected by radiation damage. For the 1300 nm laser the monitor diode degrades more than the laser, which could have a large effect in applications. Note also that although much of the damage in the laser will recover due to injection-enhanced annealing, the monitor diode will not recover significantly.

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## Degradation Mechanisms

Effect of Radiation Damage

- Increase in bulk recombination
- Increase in surface recombination
- Carrier removal effects

Laser Diode Parameters

- Threshold current
  - Depends on volume, cavity length, gain and recombination loss
  - Gain depends logarithmically on injected carrier density
    - Predicts linear dependence of threshold current on fluence
    - Nonlinear behavior predicted when Ith increases more than 40%
- Slope efficiency affected by carrier removal
- Subthreshold behavior (LED mode) – provides diagnostics

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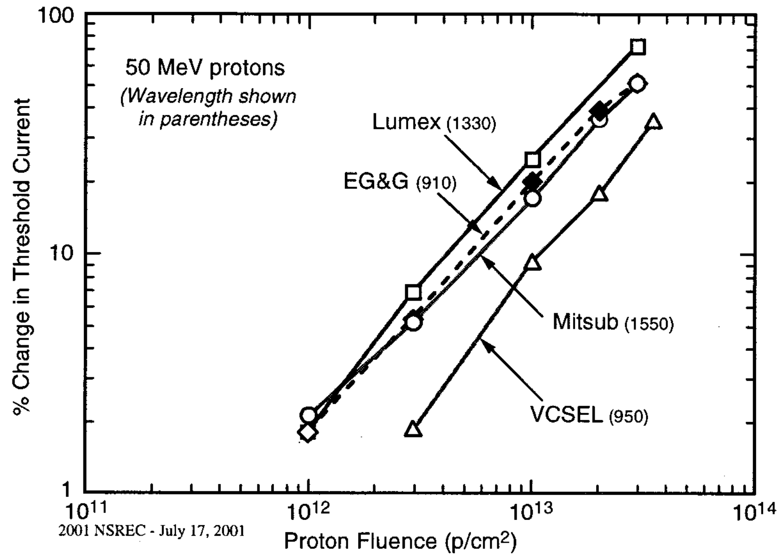
This slide lists mechanisms for radiation damage along with their effects on laser diode parameters.

## Linearity of Threshold Current Degradation

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This slide shows the linear relationship between changes in threshold current and proton fluence for four of the six types of lasers. Note how similar the results are, even though these devices have a wide range of wavelengths and use different materials.

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## Other Factors

Carrier Removal

- Lasers have high doping levels in active region (2-4 x $10^{18}$ $cm^{-3}$)
- Consequence of bimolecular recombination rate (~ $10^{-10}$ $cm^3/s$)
- Carrier removal rate 300-500 $cm^{-1}$
- Potentially significant for fluences > 4 x $10^{13}$ $cm^{-2}$
- Primarily affects slope efficiency

Auger Recombination

- Limits gain of InP-based lasers
- Complicates damage interpretation for 1300-1550 nm lasers

Wavelength Essentially Unaffected by Radiation Damage

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This slide discuses the effects of carrier removal and Auger recombination on laser operation. Auger recombination rates are about 30 times higher for InP-based materials compared to GaAs-based materials, and can be a significant factor for lasers with longer wavelengths that use that material.

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## Conclusions

Laser Degradation Very Similar for Wide Range of Laser Diode Technologies

Lasers Strongly Affected by Injection-Enhanced Annealing

- Very high optical power density
- Requirement for high cavity gain

Key Parameters

- Threshold current
- Slope efficiency
- Subthreshold characteristics

Experimental Issues

- Strong dependence on temperature
- Mechanical alignment of detector
- Potential interference of measurements because of annealing

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The main points of the paper are first, laser degradation is quite similar in character and magnitude for a wide range of laser types, even when different materials are involved.

Injection-enhanced annealing is very important for all of the lasers in the study. This is somewhat surprising because work in last years's paper showed that very little annealing occurred in light-emitting diodes that are fabricated with the same materials, using heterojunctions. The reason for the difference in behavior is the requirement for high internal cavity gain along with the much higher optical power density in laser diodes.

Key parameters include threshold current, slope efficiency, and subthreshold characteristics. The subthreshold behavior can be used as a diagnostic tool to determine what internal mechanisms are occurring that affect the laser operation.

The main experimental issues are strong temperature dependence, close tolerances for alignment between the laser and detector, and the strong influence of annealing.