Displacement Damage Characterization of Laser Diodes

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Abstract – **Displacement damage effects from protons and neutrons are compared. Differences in the annealing properties were observed which are due to the different microscopic structure of the damaged regions from the two types of particles. The annealing properties affect testing and characterization methods, and limit the ability to normalize damage in different environments using non-ionizing energy loss (NIEL). Key parameters for laser degradation include threshold current, slope efficiency, and the current dependence of optical power output near threshold where the laser shifts from light-emitting diode to laser operation.**

I. INTRODUCTION

Characterization of radiation damage in laser diodes is more complex than for light-emitting diodes. Different testing and characterization approaches - including tests with different types of particles and particle energies - have been used by various laboratories making it difficult to compare test results. Continued advances in laser diode technology have further exacerbated this problem. Modern laser diodes are very complex structures, using strained layers, quantum-well confinement and quaternary materials.

The earliest work on laser diode damage was done in 1967 by Compton and Cesena [1]. The GaAs laser diodes that they evaluated were fabricated quite differently than modern devices, and would only work reliably at liquid nitrogen temperatures. They showed that 1-MeV electrons increased the threshold current, which they attributed to an increase in the number of recombination centers. The threshold current increased linearly with fluence. They showed that laser degradation was due to radiation-induced defects within the cavity that increased recombination losses.

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Figure 1 shows how the threshold current density of laser diodes has evolved since that earlier work [2]. The current density has decreased by more than three orders of magnitude. Advances in the understanding of heterostructure fabrication methods – including using strained layers that can be tailored to reduce internal loss mechanisms - are the main reason for this improved performance. The ability to fabricate very thin regions that allow quantum carrier confinement has also contributed to improvements in laser technology [3]. Although Fig. 1 shows overall trends, it incorporates results for several different types of material technologies. The low current densities shown for the latest technologies are for InGaAsP technology, which has higher material gain compared to InGaAs. Typical devices have current densities that are somewhat higher than the trends shown in the figure.

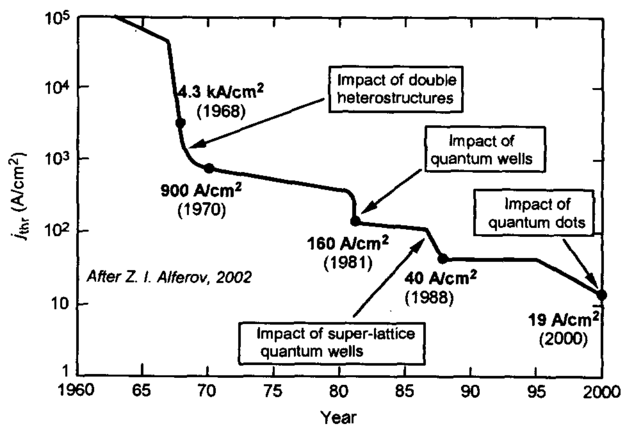

Fig. 1. Evolution of laser threshold current density.

The earliest work on strained quantum-well lasers was done by Evans, *et al.* [4]. They investigated degradation in InGaAs laser diodes, with a wavelength of 980 nm, that were irradiated with 5-MeV protons. The lasers were optimized for operation over an extended temperature range, with a threshold current density of about 150 A/cm^2 at room temperature. The parameters that were used for characterization included slope efficiency, threshold current, and measurements of the optical power below threshold current. They observed a strong injection-dependent annealing effect by comparing devices that were irradiated with and without power applied, but did not quantify the annealing behavior. They restricted the power in the laser during measurements in order to avoid extremely high injection and minimize self heating.

More recent work has included tests of 1300 and 1500 nm laser diodes, fabricated with InGaAsP [5]. Despite the differences in material properties and lower threshold current densities, the effect of displacement damage on threshold current was nearly the same as that reported by Evans, *et al.* in their 1993 study when the results are normalized using accepted values of non-ionizing energy loss to account for the difference in effective damage for protons with different energy. The fluence of 50-MeV equivalent protons for a 10% increase in threshold current was about 3 x 10^{12} p/cm^2, regardless of the technology.

II. Material Characteristics

A. Basic Properties

Three types of materials are used to fabricate laser diodes with wavelengths in the extended visible and near infrared region. Key properties include lattice matching between the different materials used to form heterostructures; Auger recombination, which is an important loss mechanism for some materials at the high carrier densities required for laser operation; optical gain, which differs for various material combinations; and the barrier height of the heterojunctions.

The material gain of InGaAsP is about twice that of InGaAs [6]. Thus, without considering additional improvements from strained layers or quantum confinement, the threshold current density of InGaAsP-based lasers should be half that of equivalent InGaAs lasers.

Although InGaAsP is inherently more efficient as a laser material, Auger recombination is higher, increasing loss factors at high current density. Auger recombination increases as the third power of carrier density, restricting the maximum current density in that material. Auger recombination can be reduced by using strained layers to decrease the threshold current density, which is essential to realize the advantage provided by the higher material gain. For irradiated InGaAsP devices, the increase in carrier density that is required for degraded devices may increase Auger recombination, leading to nonlinearities in the dependence of threshold current on particle fluence.

B. Energy Dependence of Displacement Damage

Non-ionizing energy loss (NIEL) is usually used to compare displacement damage for different types of particles and particle energy. NIEL calculations have shown good agreement with experimental results for silicon [7], but not for GaAs [8]. Disparities of a factor of three or more have been reported for GaAs between NIEL calculations for 200-MeV protons compared to experiment However, there is close agreement at energies below 50 MeV. Therefore proton displacement damage in this paper will be based on equivalent 50-MeV protons.

NIEL calculations have not been done for the complex material combinations used in modern lasers. This difficulty can be overcome by comparing test data at proton energies of (or near) 50 MeV, but may lead to large uncertainties if it is necessary to compare test results at low or high energies, or for different particle types.

Another important issue is annealing. The non-ionizing energy loss concept deals only with the energy that goes into non-ionizing processes. Some of the damage may anneal, particularly for damage that results in large clustered damage regions. This will cause less net damage in device properties than predicted by NIEL calculations. As discussed later in the paper, this can be a major source of confusion in interpreting test results from different experimenters. It also creates potential confusion in relating laboratory test data to actual use conditions.

III. Laser Damage Comparisons

Marshall, *et al.* studied degradation of InGaAsP lasers fabricated by Mitsubishi in 1992 [9. They irradiated their devices with 62-MeV protons. The lasers in their study were coupled through a GRIN lens, and consequently their results are affected by increased absorption within the lens. The change in threshold current that they observed is shown in Fig. 2. The departure from linearity is likely due to the effects in the lens. Their work showed severe changes in slope efficiency after irradiation, which have not been observed in other laser degradation studies. They noted this, and suggested that it was also likely due to degradation in the lens. They also noted far more degradation in the laser assembly after irradiation with gamma rays compared to results from other laser diode studies.

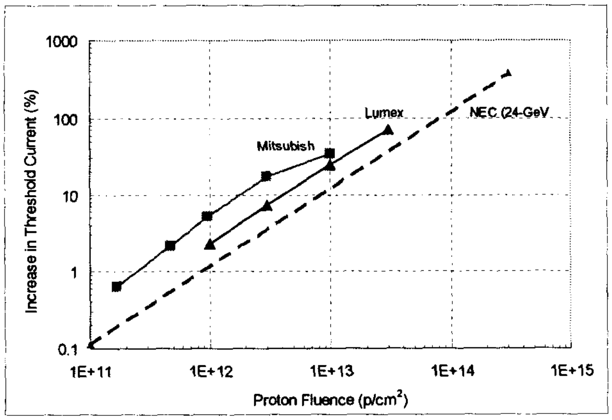

Fig. 2. Comparison of threshold current degradation in tests of laser diodes by three different groups.

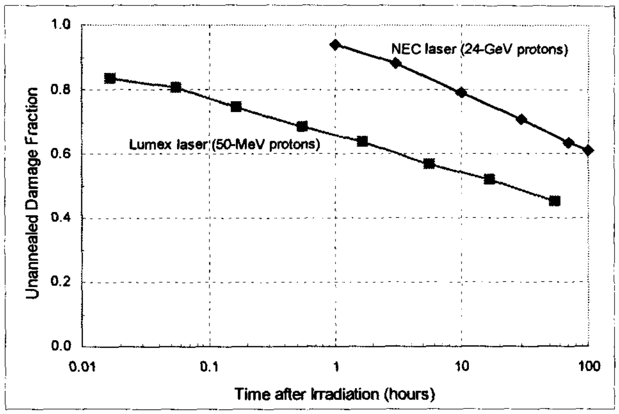

Fig. 3. Comparison of annealing with devices biased approximately 10 mA above threshold.

Two other results are shown in Fig. 2. The triangles show degradation of a 1300 nm laser from Lumex, irradiated with 50 Mev protons by JPL. The dashed line shows results from Gill, *et al.*, using very energetic protons (24 GeV) for applications at CERN [10 The CERN measurements were only done at a single irradiation level, and have been extrapolated with the assumption that the threshold current changes linearly with fluence. They have not been corrected for NIEL, because most work on non-ionizing energy loss has not considered such high energies [7].

Even though threshold current degradation in the various experiments done with 1300 nm laser diodes were roughly the same, very different annealing results were observed by the various groups. Annealing was carefully evaluated by Gill, et al. in their 1997 work with 24-GeVprotons [10] as well as in later work with neutrons [11]. They used the unannealed fraction of damage to characterize annealing. Fig. 3 shows their results, for the case where the lasers were operated approximately 10 mA above the threshold current during annealing. The annealing proceeded about three orders of magnitude more slowly compared to annealing of the Lumex devices, biased in a comparable manner; those devices were irradiated with 50-MeV protons.

Although not shown in the figure, annealing results with no applied bias were dramatically different. Measurements by the CERN group showed that about 30% of the damage recovered in unbiased samples after 350 hours, while the JPL group observed little or no recovery in experiments done on their samples during unbiased annealing [5], even after time intervals of several months. Annealing experiments on lasers with other wavelengths (including 850 nm VCSELs) also showed no recovery during unbiased annealing. All of the JPL tests were done with 50-MeV protons.

Annealing measurements in neutron-irradiated lasers by Gill, *et al.* [11] yielded results that were similar to their earlier results for the same device types after irradiation with 24-GeV protons. Just as for the proton-irradiated samples, significant recovery occurred in unbiased samples after neutron irradiation.

Several factors may contribute to the different effects of applied bias on annealing observed by the two groups. First, 50-MeV protons produce isolated defects as well as cascade regions, and it is possible that the difference in annealing behavior is caused by the different microscopic nature of the defects. Neutrons and highly energetic protons produce multiple cascades, which may anneal more rapidly [12]. Second, the construction of the lasers is not the same.

IV. Discussion

Threshold current is relatively insensitive to displacement damage because modern lasers have very compact laser cavities that are relatively insensitive to defects. A small increase in recombination rate can easily be compensated with a very slight increase in current because the overall gain depends on the square of the injected carrier density [13]. In order to observe degradation in threshold current, either the defect density has to be high enough to require a significant increase in current, or carrier removal has to be sufficiently high to affect the injection efficiency. Doping levels in modern lasers are typically $> 3 \times 10^{16}$ cm^{-3}, and consequently carrier removal is only important for 50-MeV proton fluences of about 10^{14} p/cm^2 [14].

Recent results by Kalavagunta, *et al.* developed a model for degradation of vertical-cavity surface-emitting lasers that incorporated carrier removal effects [15]. That work was done using 2-MeV protons. Fluences above 2 x 10^{13} 2-MeV protons were required to observe measurable changes in slope efficiency and threshold current, which is equivalent to approximately 5 x 10^{14} 50-MeV protons, a very high radiation level, further corroborating calculations of carrier removal effects based on the earlier work of Pease, *et al.*, [14],which was based on GaAs JFETs, not lasers.

Measurement of the light efficiency below threshold provides a more sensitive measurement that can be used as a precursor for laser degradation. Figure 4 shows how the light output of the 1300 nm Lumex InGaAsP laser is affected at various injection levels. After the first irradiation (10^{12} p/cm^2), the threshold current increases very slightly, and in fact is difficult to measure with sufficient accuracy to show that any change has actually occurred. In contrast, light emission at a forward current of 1 mA has changed by about 20%. In this region the injected carrier density is too low for laser operation, so the device operates as an LED. Light emission in the LED region is very sensitive to defects, which increase the recombination rate, decreasing the light output. The light emission degrades in a manner similar to discrete LEDs when recombination is the dominant mechanism. Less damage occurs at low injection for lasers that exhibit changes in slope efficiency.

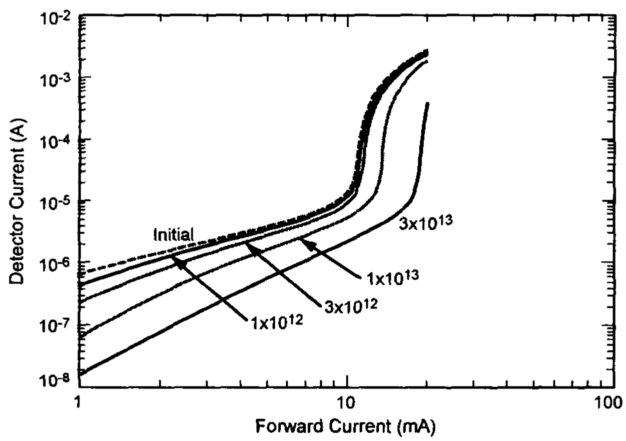

Fig. 4. Light emission from the Lumex 1300 nm measured over a wide range of operating currents

Similar results for a 650 nm laser are shown in Fig. 5. The laser is fabricated with AlGaAs. In this example, relatively small changes in power output occur at low currents until the current increases to the point where it is near the threshold region. This is due to the lower gain coefficient of AlGaAs, which requires higher current densities to bring the overall cavity gain to the transparency region.

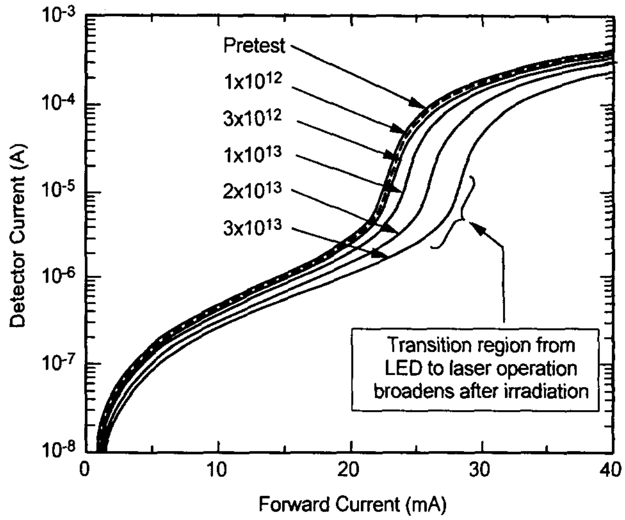

Fig. 5. Light emission from a Lumex laser with 650 nm wavelength after irradiation with 50 MeV protons.

Low-injection measurements can also be used to investigate annealing effects. Fig. 6 shows how light output recovers during an annealing experiment where the laser has been degraded to the point that the injected current required for normal operation is below the lasing threshold. In this case the total injected charge after irradiation is used as the parameter on the x-axis. Immediately after irradiation the output power is only 2% of the light output that was measured at the threshold region prior to irradiation. As the annealing (under forward bias) continues, there is a gradual recovery in power. However, after approximately 10 C of charge the optical power increases sharply because the device has recovered to the point that the bias current used for annealing is approaching the threshold region. The increase in power output of a light-emitting diode that is sensitive to injection-enhanced annealing is shown for comparison [16]. Note the more gradual recovery for the LED. Note in addition that before the laser starts its sharp recovery the increase in power output is more gradual, and closely resembles annealing in the LED. This diagnostic method is particularly useful for heavily damaged devices where the transition to laser operation is more gradual compared to unirradiated devices.

Earlier work was done by Zhao, *et al.*, on multi-quantum well laser diodes using 200-MeV protons [17]. Although they did not use low current measurements to characterize their devices, they also observed nearly linear increases in threshold current with increasing fluence.

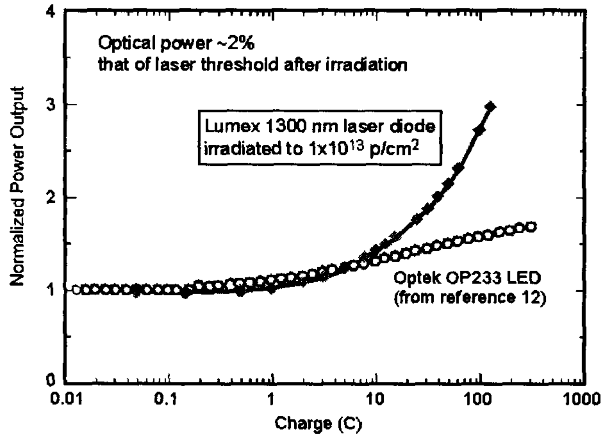

Fig. 6. Increase in power output for a heavily damage laser diode where the current applied during annealing is below the threshold current.

Comparisons of quantum-well devices are more involved than for laser diodes without such small lateral regions because the effective gain depends on the cavity dimensions. Stohs, et al. [18] have shown that the bimolecular coefficient, which depends on the square of the injection level, is effectively lower in structures with small dimensions because the energy levels in the quantum structures have a fundamental dependence on layer thickness. Consequently, the "B" coefficient that is used for large-area devices loses its significance for narrow quantum-well structures. This may explain the more gradual transition for the 650 nm laser diode characteristics in Fig. 4, which is a broad-area structure.

There are also similarities in the properties of lasers that have been degraded during extended operation (an important reliability problem) and the properties of lasers that have been degraded because of radiation. Kallstenius, *et al.* have shown that degradation during extended operation is primarily due to increases in non-radiative recombination centers, using measurements of differential carrier lifetime as a diagnostic method [19]. The net recombination rate is also affected by the second-order term simply because the carrier density must be higher to achieve the required gain for laser operation. Auger recombination remained low for devices where the threshold current increased by as much as 20%.

V. Conclusions

This paper has discussed damage in laser diodes, noting the large differences in annealing characteristics that have been reported by different experiments using 1300 nm GaInAsP lasers. Of particular interest is the gradual annealing of unbiased devices in the experiments done with neutrons and extremely energetic protons by the CERN group, contrasted with studies at lower proton energies by JPL where essentially no annealing occurred without applied bias, even over time periods of several months. This is a critical point for laser diode characterization that not only affects experimental results, but limits the ability to apply radiation data from different radiation sources using the NIEL concept, because NIEL does not consider annealing effects. Protons with energies below 200 MeV have negligible annealing, provided devices remain unbiased. However, damage in neutron-irradiated devices is not stable, which is likely caused by the different microscopic damage of devices that are irradiated with neutrons or protons with energies in the multi-GeV region.

Although the different measurement and characterization methods used by various groups are appropriate for their specific applications, it is clearly necessary to develop recommendations for more standard measurement and characterization approaches. Injection conditions may affect both annealing and characterization because of self heating, which is strongly evident in vertical cavity semiconducting lasers because of the decrease in slope efficiency at higher currents [20]. This can be important for edge-emitting laser diodes as well.

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