

Proton Irradiation Effects in Oxide-Confined Vertical Cavity Surface Emitting Laser (VCSEL) Diodes*

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Abstract

The results of a proton irradiation study of vertical cavity surface emitting lasers (VCSELs) are presented. It is shown that the primary damage effect is due to displacement damage rather than ionization effects, and that recovery can occur through forward bias annealing.

INTRODUCTION

Recent space experience has shown that the use of commercial optocouplers can be problematic in spacecraft, such as TOPEX/Poseidon, that must operate in significant radiation environments. Radiation-induced failures of these devices have been observed in space and have been further documented at similar radiation doses in the laboratory [1,2]. The ubiquitous use of optocouplers in spacecraft systems for a variety of applications, such as electrical isolation, switching and power transfer, is indicative of the need for optocouplers that can withstand the space radiation environment. In addition, the distributed nature of their use implies that it is not particularly desirable to shield optocouplers for use in radiation environments. Thus, it will be important for the space community to have access to radiation hardened/tolerant optocouplers.

For many microelectronic and photonic devices, it is difficult to achieve radiation hardness without sacrificing performance. However, in the case of optocouplers, one should be able to achieve both superior radiation hardness and performance for such characteristics as switching speed, current transfer ratio (CTR), minimum power usage and array power transfer, if standard light emitting diodes (LEDs), such as those in the commercial optocouplers mentioned above, are avoided, and VCSELs are employed as the emitter portion of the optocoupler. The physical configuration of VCSELs allows one to achieve parallel use of a two dimensional array of devices and construct a multichannel optocoupler in the stan-

dard fashion with the emitters and detectors "looking at" each other. In addition, detectors similar in structure to the VCSELs can be fabricated which allows bidirectional functionality of the optocoupler. Recent discussions [3,4] suggest that VCSELs will enjoy widespread applications in the telecommunications and data transfer fields.

For VCSEL-based optocouplers to be broadly applicable to a variety of space missions, the radiation hardness of these devices must be sufficient to survive a variety of radiation environments from LEO to GCR to Mars missions to the stringent requirements of a Jupiter – Europa mission. As clearly demonstrated in previous work on the optocouplers in TOPEX/Poseidon [1,2], protons cause extensive displacement damage in the semiconductor lattice resulting in the formation of non-radiative recombination centers that, in turn, cause degradation of light output from LEDs. One can expect that proton-induced displacement damage results in similar degradation mechanisms in laser diodes. Near the laser threshold current, the losses experienced by the light beam as it traverses the optical laser cavity are equal to the optical gains due to stimulated emission. Thus, if the rate of non-radiative recombination is increased due to irradiation, the cavity losses will increase and the threshold current will increase correspondingly. In addition, heating effects due to increased total current flow will adversely affect VCSEL operation at high currents well into lasing. While some work has been done on radiation effects in VCSELs [5-8], the efforts to date are not extensive enough to provide a complete radiation hardness assurance (RHA) description, particularly for oxide-confined VCSELs.

EXPERIMENTAL DETAILS

The 850 nm emitting VCSELs irradiated in this study were grown and fabricated at SNL using selective oxide isolation to provide carrier and optical confinement. In addition to the ability to fabricate large laser arrays on the same substrate, these devices have several attractive features including low threshold current, high modulation bandwidth capability, high

efficiency and reduced sensitivity to temperature. The details of laser growth, fabrication and construction, along with performance attributes, have been discussed in the literature [9-12]. For purposes of radiation testing, each packaged VCSEL array contained a minimum of 4 operating individual VCSEL diodes. Sample designations in the test results given below have a numerical designation for each packaged VCSEL array and letter designations for each of the four individual lasers.

Proton irradiation studies were performed at the Indiana University (IU) Cyclotron Facility. Current-voltage (I-V) and laser spectral output measurements were performed onsite, but outside the beam line area prior to and following the complete series of irradiations for each VCSEL. Total light output – current (L-I) and I-V measurements were performed *in situ* using a large area Si p-i-n photodiode detector placed outside the beam line. The detector was calibrated periodically during the tests with an 827 nm laser with known power output so that VCSEL output could be measured directly in mW. The calibrated laser and photodiode were outside the beam line, and to measure the VCSEL L-I properties the VCSEL was moved in front of the photodiode using a linear translator. Care was taken to minimize laser operating time at large currents in order to minimize forward bias-induced annealing of radiation damage, a recognized phenomenon in irradiated III-V devices operating at high current densities [13,14]. Attempts were then made subsequent to irradiation to study the extent of such annealing. In addition, some of the VCSELs were purposely forward biased during irradiation in order to detect possible recovery of damage during irradiation. If such annealing is observed, it could be a viable technique for minimizing damage in very high proton dose applications. For the majority of proton irradiations, the beam energy was set at 192 MeV, the normal operating energy of the IU facility. The beam current was 200 nA, equivalent to a flux of approximately 1×10^{11} protons/cm²-s. All exposures and measurements were performed at room temperature. Note, however, that the actual junction temperature in the VCSELs may be higher because of very high current densities within the devices at high currents.

EXPERIMENTAL RESULTS

Typical L-I curves for a VCSEL irradiated at 192 MeV with no bias during irradiation are shown in Figure 1. Note that as irradiation proceeds, not only does the power output decrease, but also the threshold current, as defined by the intersection of the L-I curve with the abscissa, increases as we briefly noted above for the effects of displacement damage. As irradiation proceeds, the slopes of the L-I curves decrease as one might expect since the slope is equal to the differential quantum efficiency, which decreases with fluence as a greater and greater fraction of the injected current recombines non-radiatively at displacement damage-induced recombination centers. At the highest fluence, power output is greatly reduced and the L-I curve exhibits a peak due to strong thermal effects associated with the large increase in non-radiative recombination. At this fluence, the input electrical power is much greater than the optical output power leading to strong

thermal effects. Lastly, note that the reduction in power output at the Europa requirement of 1.66×10^{13} p/cm² is relatively modest – less than 10%. Irradiating with a forward bias current of 10 or 18 mA produced qualitatively similar results, except that, the increase in threshold current was smaller for the VCSELs irradiated under bias than the VCSELs irradiated without bias. This is discussed in more detail below.

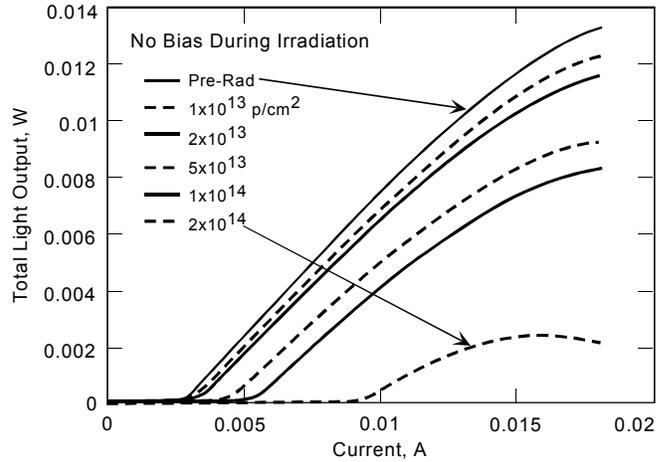


Figure 1. Total light output power for VCSEL-9d irradiated with 192 MeV protons.

The relative degradation in power output at the Europa requirement is shown more clearly in Figure 2 for another VCSEL on the VCSEL-9 array. Note also the stronger rate of decrease of light output with fluence at the highest current where thermal effects cause a greater change. This result emphasizes a general rule of thumb for use of laser diodes in radiation environments: select a laser with a low threshold current and a wide operating current range so that application currents (power outputs) stay well below maximum allowable drive currents over the entire radiation dose/fluence range.

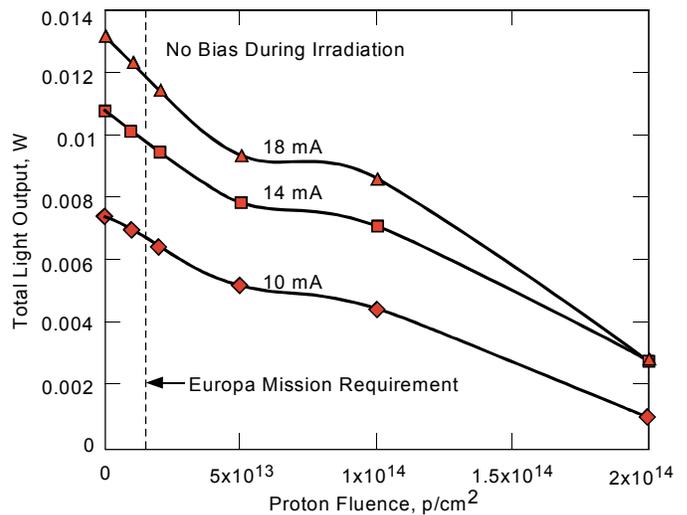


Figure 2. Total light output power for VCSEL-9a as a function of 192 MeV proton fluence at different measuring currents.

Generally, the lasers responded uniformly to proton irradiation at a given device current. This result is illustrated in Figure 3 for VCSEL array 9 at an operating current of 10 mA. Note that all four lasers responded in approximately the same manner to increasing proton fluence, and that the decrease in power output at the Europa requirement is relatively small.

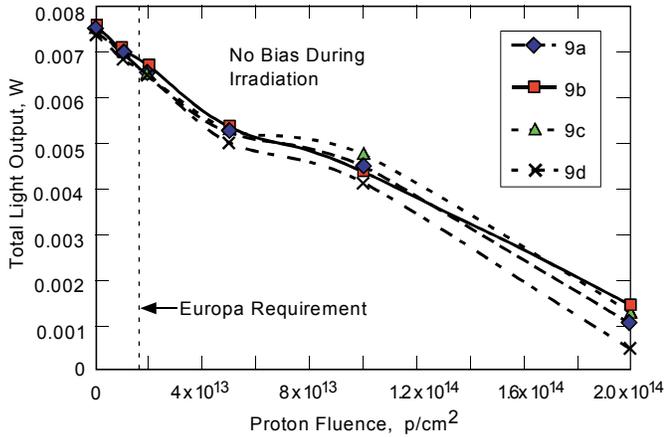


Figure 3. Response of VCSEL array 9 lasers to proton irradiation at a laser current of 10 mA, no current during irradiation.

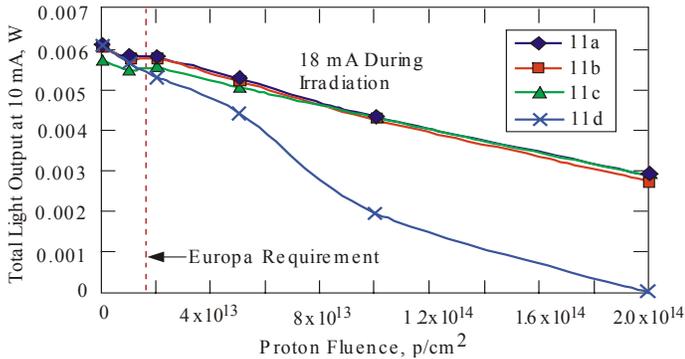


Figure 4. Response of VCSEL array 11 lasers to proton irradiation at a measuring current of 10 mA with 18 mA during irradiation.

In contrast with the uniform response shown in Figure 3, laser array number 11 exhibited one outlier that was significantly more sensitive, as shown in Figure 4. Of the 41 devices studied two other similar outliers were observed, and one must pay particular attention to such devices when attempting to qualify a flight lot of lasers.

Also note another difference in Figure 4 compared with Figure 3 is that the lasers were heavily forward biased during irradiation at a current of 18 mA. We attribute the lower rate of degradation of light output shown in Figure 4 to forward bias-induced annealing.

Additional results showing the effect of forward current during irradiation on the proton-induced VCSEL degradation is shown in Figure 5 for lasers from arrays 1, 9 and 11. Note that both the 10 mA and 18 mA curves show signifi-

cantly less degradation of power output than the 9a curve for no forward bias during irradiation. While it is not clear why the 10 mA curve shows less degradation than the 18 mA curve (one might expect the opposite), examination of all the data for the 41 individual lasers that were studied clearly shows that there is forward bias-induced annealing taking place during irradiation. The effectiveness of such annealing will of course depend on the proton flux during irradiation, and it is clear that for essentially all space radiation environments the flux will be much less than at the IU accelerator so that forward bias annealing will be relatively more effective.

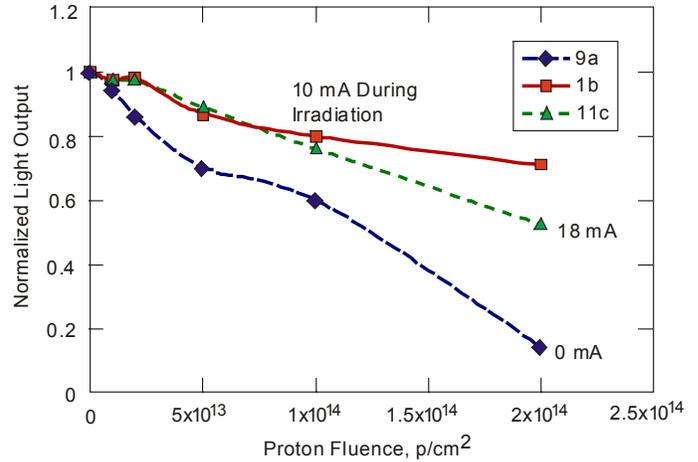


Figure 5. Response of VCSEL array lasers to proton irradiation at measuring current of 10 mA for various forward bias currents present during irradiation.

L-I curves such as those given in Figure 1 can be used to determine the approximate threshold current for the lasers as a function of proton fluence. The threshold current is approximately defined by the intersection of the linear portion of the L-I curve with the 0 power output abscissa. Using this simple determination of threshold current, we obtain data such as that shown in Figures 6 and 7 for lasers from the three arrays that were each irradiated with a different forward bias current present during irradiation. As expected the threshold currents increase with proton fluence. As noted above, this is due to the increased competition between stimulated radiative recombination, responsible for the laser output, non-radiative recombination at defect recombination sites introduced by the proton-induced displacement damage in the semiconductor lattice of the active region of the laser, and forward bias-induced annealing of defect recombination sites for the VCSELs irradiated under bias. The growing disparity between electrical power input and laser power output due to the reduced efficiency also leads to greater thermal effects at a given operating current. By normalizing these curves to the pre-irradiation threshold current, as in Figure 7, one can clearly see the impact of forward bias-induced annealing during irradiation. Note that the normalized threshold current is about a factor of 2 larger for the unbiased laser at the largest fluence.

Next we examine some of the features of the VCSEL spectrum. Shown in Figure 8 are laser output spectra as a function of laser operating current for a typical VCSEL. The shape of the spectra, in particular the full width at half maximum, are indicative of the limited resolution of the experimental setup at the accelerator rather than the true laser spectra which are significantly narrower in wavelength. Note that above about 5 mA, the spectral peak shifts to longer wavelength with increasing current due to heating effects.

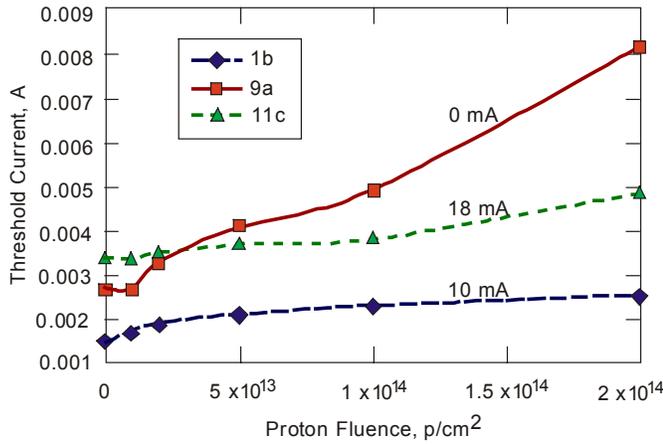


Figure 6. Laser threshold currents as a function of forward bias current during irradiation.

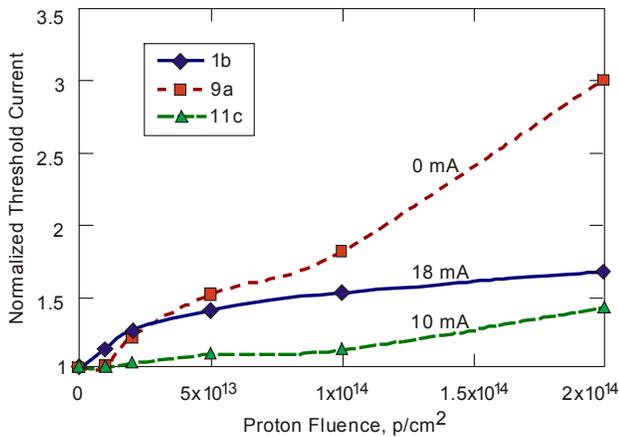


Figure 7. Normalized laser threshold currents as a function of forward bias current during irradiation.

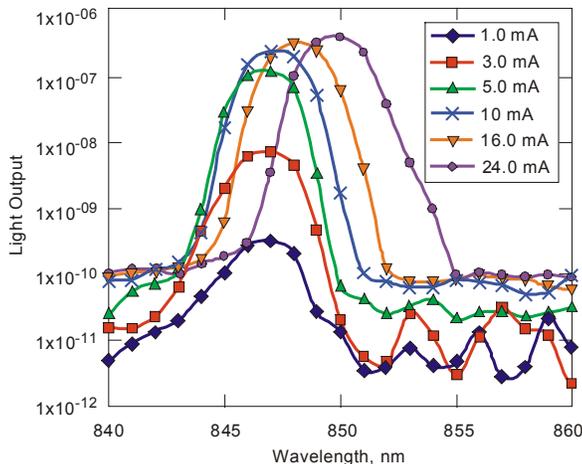


Figure 8. VCSEL spectra as a function of operating current.

The effect of proton irradiation on the laser spectrum is shown in Figure 9 for VCSEL-9a following a proton fluence of 2×10^{14} p/cm², and a 36 hr anneal at a forward current of 10 mA at ambient room temperature. Of particular interest is the fact that there is a shift to longer wavelength which does not exhibit any recovery due to forward biased anneal. Recall from Figure 1 that at this fluence, the current threshold has increased to a high enough level such that VCSEL-9 is only slightly above laser threshold at 10 mA. Thus, the laser is functioning in a highly inefficient state, and a thermally-induced shift to longer wavelengths is not surprising. However, it is somewhat surprising that the peak wavelength did not recover with forward bias anneal since this anneal did result in a recovery of the light output to near pre-irradiation levels.

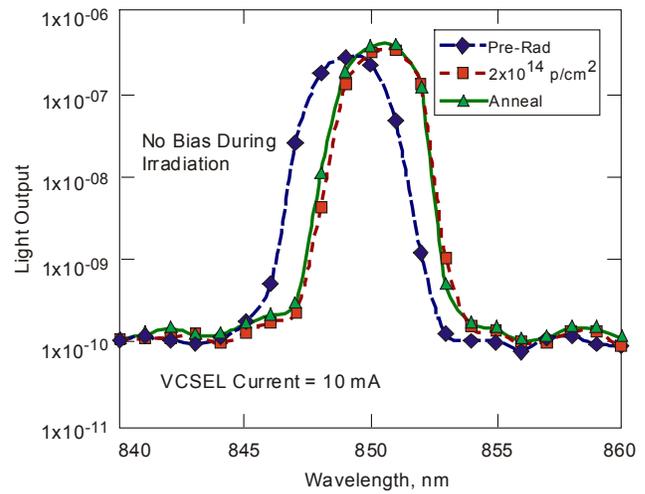


Figure 9. Laser spectral output for VCSEL-9a following proton irradiation and anneal.

DISCUSSION AND CONCLUSIONS

As noted above, there have been only a few reported studies of radiation effects in VCSELs [5-8]. Recent work [5] on Co-60 gamma irradiation revealed little if any effects even at dose levels near and above 1×10^8 rad(Si). The small reductions in power output at these very high Co-60 doses suggest that these are also due to displacement damage effects that are growing at a very slow rate. Although the Compton electrons created when 1 MeV Co-60 gamma rays interact with matter can cause displacement damage, these are rare events. Low energy (4.5 MeV) proton irradiations [6-8] of VCSELs have shown similar results to those reported herein. These studies were conducted on Sandia implanted VCSELs which had significantly higher threshold currents than the oxide isolated VCSELs we have studied. At a fluence of 2×10^{13} 4.5 MeV protons/cm², a reduction in power was observed from a pre-irradiation value of about 3 mW to approximately 2.5 mW, a 17% reduction in output. While this reduction is significantly larger than our average value of 6.3%, it should be noted that at an operating current of 10 mA, the earlier implanted devices were very close to their thermal rollover peak because of their

initially high threshold currents of about 4 mA. Comparing this situation with the results in Figure 1 clearly demonstrates the advantages of using low threshold current, high maximum operating current lasers, such as the oxide isolated lasers in this study, in a radiation environment.

We conclude that the oxide-confined vertical cavity surface emitting lasers examined in this study show more than sufficient radiation hardness for nearly all space applications. The observed proton-induced decreases in light output and the corresponding increases in laser threshold current can be explained in terms of proton-induced displacement damage which introduces non-radiative recombination centers in the active region of the lasers and causes a decrease in laser efficiency. These radiation effects accentuate the detrimental thermal effects observed at high currents. We also note that forward bias annealing is effective in these devices in producing at least partial recovery of the light output, and that this may be a viable hardness assurance technique during a flight mission.

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