Radiation Resistance of Single Frequency 1310-nm AlGaInAs-InP Grating-Outcoupled Surface-Emitting Lasers

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Abstract—The results of two irradiation tests on fourteen single-frequency 1310-nm grating-outcoupled surface-emitting (GSE) semiconductor lasers that have been exposed to ionizing radiation using 200 MeV/c proton beams are reported. Twelve powered lasers survived a total radiation dose of 22.3 Mrad. One of the two not-powered lasers survived a total dose of 1.5 Mrad. The other failed after an integrated dose of 22.3 Mrad, suggesting that annealing may play an important role in laser performance during irradiation. The static and dynamic characteristics of the lasers after irradiation indicate the suitability of these lasers for medical, space and accelerator based nuclear and particle physics applications.

Index Terms—radiation hard, surface emitting lasers, semiconductor lasers, gratings, high energy physics, space applications

I. Introduction

Grating-Outcoupled Surface-Emitting (GSE) lasers [1,2] consisting of a 500 µm long active ridge, a 15 µm long intracavity grating outcoupler and 200 µm long first-order distributed Bragg reflector (DBR) gratings at both ends were exposed to proton beams with doses up to 22.3 Mrad. A conceptual design of the GSE lasers is shown in Fig. 1. Surface emission allows for complete wafer level processing and testing leading to a reduction in cost and to increases in performance and reliability. Furthermore, the geometrical arrangement of the lasers around a common grating allows for multiple wavelengths with independent modulation into a single fiber [3]. These lasers are well suited for optical interconnects, for the data links used in particle and nuclear physics experiments and for space and medical applications. Typical radiation doses in medical applications range from a few rad to about 10 krad. Radiation doses in space applications are typically a few hundred krad where incident particles are mostly gamma rays, electrons and protons in one to a few hundred MeV energy range. Applications in particle and nuclear physics experiments require a much higher radiation resistance of the electronics components, ranging from a few hundred krad to about 10 Mrad, depending on the location inside the detector and the nature of the colliding particles.

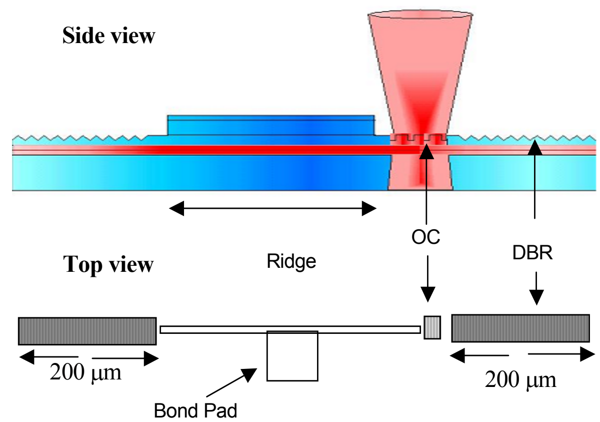

Fig. 1. The side and top views of the GSE laser geometry.

Incidence of heavy particles (protons, neutrons or ions) cause lattice damage in semiconductors, resulting in degraded optical and electrical properties. Ionizing radiation from gamma sources and charged particles produce trapped charges in dielectric layers. For III-V semiconductor lasers, most radiation damage is believed to come from lattice displacement [4,5]. In the case of edge emitting lasers (EEL), the threshold current increases proportionately with the total received fluence, but the slope of the light-current (L-I) curve remains unchanged. In Vertical Cavity Surface Emitting Lasers (VCSELs), the threshold increase is much smaller compared to EEL, but the L-I slope and the thermal roll-over point both decrease with increasing radiation fluence. [4,5]

II. Experimental Results and Discussion

A 200 MeV/c proton beam at the Indiana University Cyclotron Facility was used for tests of the GSE lasers. The facility delivers a beam of protons with a tunable momentum

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in the range of 30 to 200 MeV/c. The highest momentum of 200 MeV/c was chosen to irradiate the lasers. The average beam flux was 3.1x10^{9} protons/cm^2/second, i.e., about a factor of 1000 higher than that in most particle physics experiments.

Two irradiation tests were performed. For the initial test, two passive (not powered) GSE lasers were exposed to an integrated fluence of 2.69 x 10^{13} protons/cm^2 and 4.0 x 10^{14} protons/cm^2, respectively. These fluencies correspond to total doses of 1.5 Mrad and 22.3 Mrad, respectively. Following the exposure, the lasers were stored at the radiation facility for 90 days before they were shipped back to the laboratory and tested. In the second test, twelve GSE lasers were biased at 42 mA during irradiation. The lasers were put in 4 groups with 3 lasers in each group and inserted into the chamber. As each group reached its designated total dose, it was moved out of the beam. All twelve lasers were checked with a hand-held optical power meter after irradiation and were still lasing. The particle fluences and the corresponding ionization doses received by each group are listed in Table I.

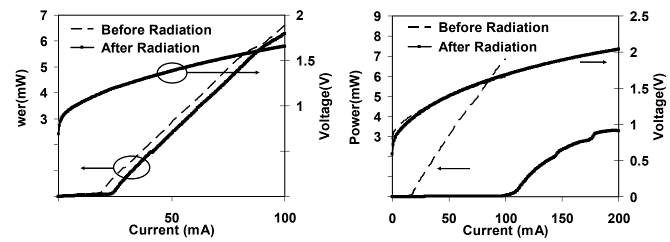
TABLE I. Proton fluence for groups of GSE lasers in the second test.

Group	Fluence (proton/cm^2)	Ionization dose (Mrad)
A	3.15×10^{13}	1.8
B	1.05×10^{14}	5.9
C	2.05×10^{14}	11.4
D	4.00×10^{14}	22.3

After irradiation, the lasers were packaged and stored for an additional 6 months, allowing the activated elements to decay.

The light-current-voltage (L-I-V) curves for the first test, in which the lasers were not biased during irradiation, are shown in Fig. 2. The L-I-V curve for the laser that received 1.5 Mrad dose (Fig. 2a) indicates ~ 10% increase in the threshold current and a similar drop of the output power at a driving current below 80 mA. The slope efficiency dL/dI, however, remains unchanged allowing for error free operation of the laser as illustrated by the eye diagram shown in Fig. 3. In Fig. 3 is shown an open eye diagram for the laser modulated at 2.5 Gbps after a total radiation dose of 1.5 Mrad. The laser is driven by a nonreturn-to-zero, 2^{23}-1 back-to-back pseudo-random signal. It is biased at 35 mA and the modulation depth is 50 mA. The measured rise time is 69 ps and the fall time 118 ps. All performance parameters are consistent with those observed before irradiation. The L-I-V curve, shown in Fig. 2b, indicates that a not-powered laser subjected to a radiation dose of 22.3 Mrad has a factor of 5 increase in the threshold current. Together with the change of slope efficiency, this laser is not functioning after receiving 22.3 Mrad total dose.

The lasers in the second test were biased at 42 mA during irradiation. After the irradiation they all exhibit a small increase in threshold current with no change in the slope of the L-I curve. One laser in group D was mechanically damaged during shipment and was removed for further considerations. The threshold change, the 20%-80% rise and fall times and the bit error rate (BER) after the irradiation are listed in Table II. The L-I-V curves for each group of lasers are shown in Fig. 4. The L-I curves indicate a monotonic increase of the threshold current with increasing dose. However, the BER remain below 10^{-12} for doses up to 11.4 Mrad.



(a) (b)

Fig. 2. GSE L-I-V curves for the GSE lasers that were not powered during irradiation, a) after a 1.5 Mrad radiation dose, b) after a 22.3 Mrad radiation dose.

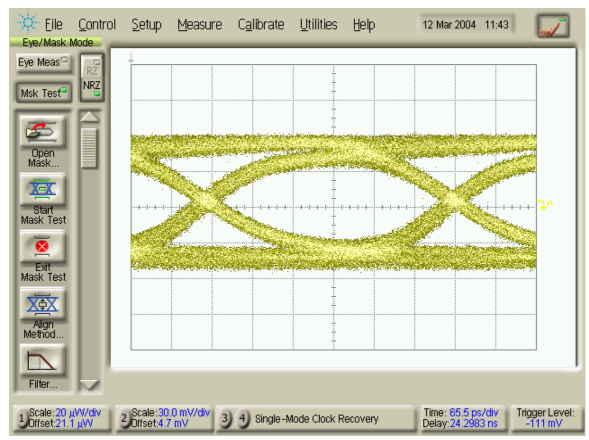


Fig. 3. 2.5 Gbps eye diagram for a not-powered GSE laser irradiated with a 1.5 Mrad dose.

TABLE II. Threshold increase, rise time, fall time and BER of the lasers after irradiation in the second test.

Group	Laser No.	I_{th} increase	Rise/fall time	BER
A	5-85	1.6 mA	48.5 ps/83.4 ps	$< 10^{-12}$
1.8	6-73	2.0 mA		
Mrad	6-74	4.4 mA		
B	5-84	5.2 mA	68.9 ps/86.5 ps	$< 10^{-12}$
5.9	16-79	8.0 mA		
Mrad	13-72	3.6 mA		
C	4-79	17.2 mA	66.7 ps/90.7 ps	$< 10^{-12}$
11.4	5-81	8.43 mA		
Mrad	13-73	5.6 mA		
D	5-66	24.1 mA	67 ps/115 ps	1.9×10^{-11}
22.3	13-80	18.1 mA		
Mrad	16-80	Damaged		

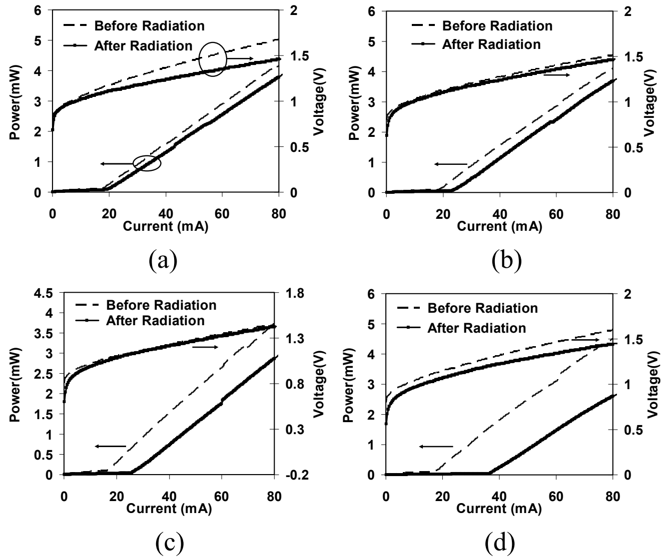


Fig. 4. The L-I-V curves for GSE lasers that were powered during the irradiation test. Dashed lines describe the laser's behaviors before the irradiation. The solid lines describe the laser's behaviors after the irradiation. a) Laser 6-73 in group A, 1.8 Mrad radiation dose. b) Laser 5-84 in group B, 5.9 Mrad dose. c) laser 5-81 in group C, 11.4 Mrad dose. d) Laser 13-80 in group D, 22.3 Mrad.

The laser ID (Table II, Fig. 4 and Fig. 5) indicates the position (row and column) of the laser on the wafer. All lasers are from the same wafer.

The eye diagrams of a laser from each irradiated group are shown in Fig. 5. Degradation in the opening of the eye with increasing dose is observed. However, lasers in group A, B and C still pass the 2.5 Gbps eye mask test.

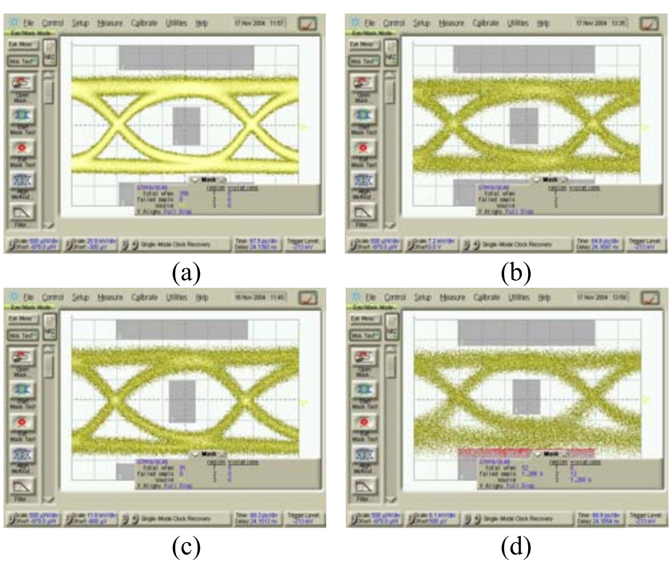


Fig. 5. Eye diagrams of GSE lasers modulated at 2.5 Gbps after irradiation. a) Laser 5-85 in group A, 1.8 Mrad dose. b) Laser 5-84 in group B, 5.9 Mrad dose. c) Laser 4-79 in group C, 11.4 Mrad dose. d) Laser 5-66 in group D, 22.3 Mrad dose.

An SEM analysis of the devices exposed to the lowest and highest amount of radiation revealed no observable damage and suggests that defects occurred internally.

III. Conclusions

All lasers that were operated during irradiation degraded gradually. The initial tests on two lasers that were not powered during irradiation suggest the possibility that annealing may have occurred in the devices that were powered during irradiation in the second test.

All irradiated lasers that were biased during the test perform well at total dose up to 11 Mrad, which exceeds the highest dose expected in space applications and is comparable to the most stringent requirements for nuclear and particle physics experiments. At a total dose of 22.3 Mrad, the lasers still operate at an acceptable but reduced bit error rate.

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