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Radiation hardness studies of VCSELs and PINs for the opto-links of the Atlas SemiConductor Tracker

M.L. Chu[a], S. Hou[a,*], T. Huffman[b], C. Issever[b], S.C. Lee[a], R.S. Lu[a], D.S. Su[a], P.K. Teng[a], A.R. Weidberg[b]

[a] *Institute of Physics, Academia Sinica, Taipei, Taiwan*
[b] *Department of Physics, Oxford University, Oxford, UK*

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Abstract

We study the radiation hardness of the Vertical Cavity Surface Emitting Laser diodes (VCSELs) and the epitaxial silicon PIN diodes that will be used for the Atlas SemiConductor Tracker at the CERN Large Hadron Collider. The tests were conducted with 200 MeV protons to a fluence of $4\times10^{14}\,p/cm^2$ and with 20 MeV (average energy) neutrons to $7.7\times10^{14}\,n/cm^2$. The radiation damage of the VCSELs and PINs and the annealing characteristics are presented.

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Keywords: LHC; Optoelectronic; Radiation hardness

1. Introduction

The SemiConductor Tracker (SCT) of the Atlas detector at LHC will consist of 6.2 M channels of silicon micro strips [1]. Optical links will be used for receiving the Timing, Trigger and Control (TTC) data, and for data transmission at 40 Mbit/s from the detector modules to the off-detector electronics [2,3]. The opto-package is illustrated in Fig. 1. It consists of two Vertical Cavity Surface Emitting Laser diodes (VCSELs) emitting light around 850 nm and an epitaxial silicon PIN diode.

The radiation damage expected for the SCT opto-electronics is caused by the high flux of charged particles and low energy neutrons in the Atlas experiment. The predicted fluences over a 10-year operating life are 2×10^{14} neutrons and 1.5×10^{14} charged-hadrons per cm^2 [1]. Applying the NIEL scaling [4] and a safety factor of 1.5, the radiation tolerance is required for the equivalence of 1 MeV neutrons of $2\times10^{14}\,n/cm^2$ for silicon devices (the PIN diodes), and $1\times10^{15}\,n/cm^2$ for GaAs devices (the VCSELs).

In previous studies the VCSELs and PINs were exposed to gamma to a total dose of 600 KGy, and to 30 MeV protons to a fluence of $2\times10^{14}\,p/cm^2$ [5,6]. In this report we present studies with 200 MeV protons at the Indiana University Cyclotron Facility (IUCF), and with neutrons of an average energy of 20 MeV at the Cyclotron Research Centre (CRC), Louvain-la-Neuve, Belgium. The samples include two types of VCSELs used in SCT,[1] and epitaxial silicon PINs of two manufacturers.[2]

2. Radiation damage to VCSELs

The VCSELs are made from a GaAlAs multi-quantum well structures. The radiation is expected to cause atomic displacement damage by nuclear interactions. The defects

[1]The proton-implant VCSEL (TSD-8A12) is used on the SCT opto-package, and the oxide-confined VCSEL array (TSA-8B12, 12 channel) is used on off-detector readout module. The manufacturer is Truelight, Taiwan.

[2]AEPX-10 of Centronic, UK, and TPD-8D12 of Truelight, Taiwan. TPD-8D12 is used in SCT.

*Corresponding author.
E-mail address: suen@phys.sinica.edu.tw (S. Hou).

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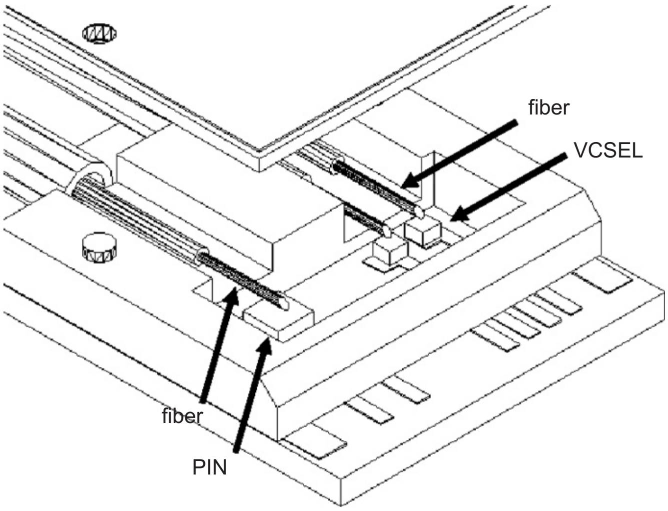

Fig. 1. A schematic drawing of the SCT opto-package.

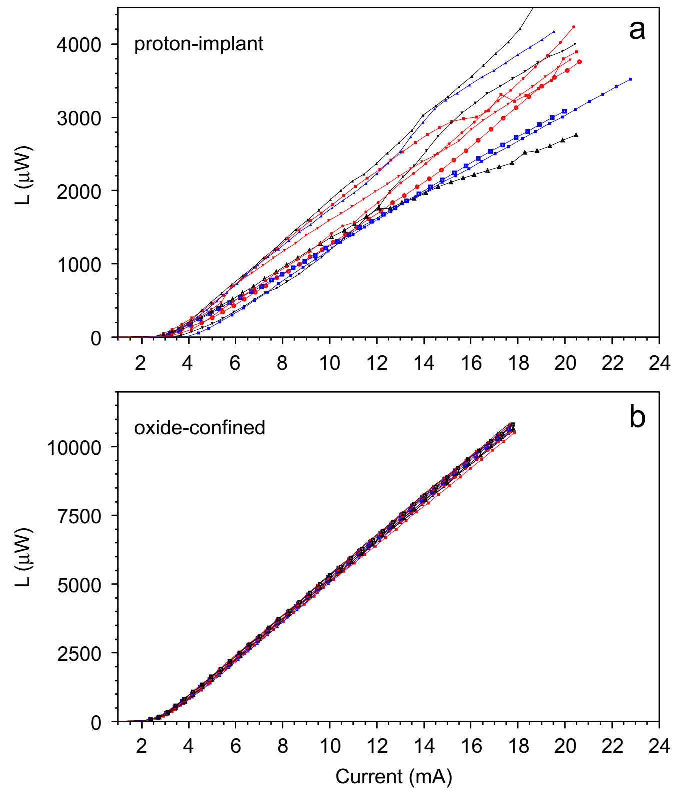

Fig. 2. Optical power versus current of channels of a typical (a) proton-implant, (b) oxide-confined VCSEL array.

can act as non-radiative recombination centers, which decreases the minority carrier lifetime and results to increase in laser threshold current. However, most of this damage can be removed by injection annealing.

The VCSELs in use by SCT are of two fabrication technology applying proton-implant or oxide-confined layer for current confinement. The test samples for irradiation were prepared in arrays of bare die VCSELs bonded on circuit board. The laser optical power (L) as a function of the drive current (I) was measured by a large area germanium photo-diode.[3] The L–I distributions of channels of a proton-implant VCSEL array and of an oxide-confined VCSEL array taken before irradiation are shown in Fig. 2. The annealing of VCSELs is a fast process with the normal operating current applied. In order to study the time dependence of annealing, some of the VCSELs were not biased during irradiation. The temperature dependence was also examined. The error caused by deviation in room temperature is within 2%.

2.1. Radiation damage with 200 MeV protons

The radiation tests at IUCF were conducted with 200 MeV protons at a flux rate of about 3×10^{14} p/cm^2 s with an uniform beam profile of about 3 cm in diameter. In one of the test setups, the VCSEL optical power was measured during irradiation. The laser light was transmitted by Fujikura ribbon fibers[4] out of the beam area. The $L-I$ curves observed for an oxide-confined VCSEL channel are plotted in Fig. 3. Each $L-I$ curve is fitted to a linear function. The distributions of the optical power at 10 mA, threshold current, and slope (Fig. 3b–d, respectively) show a linear degradation to fluence.

The radiation hardness of the two types of VCSELs was compared in a test setup with arrays of each type mounted in parallel on a test board for irradiation. The VCSELs were biased at 10 mA during irradiation to the desired fluences at a rate of 1×10^{14} p/cm^2 per hour. The distributions shown in Fig. 4 are the increase in threshold current versus the degradation of optical power and slope of the $L-I$ curve. The proton-implant VCSELs (10-channel arrays) show a large fluctuation in $L-I$ distributions, while those of the oxide-confined VCSELs (12-channel arrays) are uniform and the degradation rates are consistent between channels. These measurements are summarized in Fig. 5 for the corresponding proton fluence. Each data point is the average of channels of a VCSEL array. The radiation damage to the two types of VCSELs are compatible. The VCSEL arrays irradiated with 4×10^{14} (200 MeV) p/cm^2 had the threshold current increased by about 1.5 mA, and the optical power at 10 mA degraded by about 30%. The systematic error is estimated to be 3% for deviation in sample preparation, alignment of optical power measurement, and temperature.

The annealing was conducted for the oxide-confined VCSELs with half the channels of an array kept at 6 mA, and the rest at 10 mA. The $L-I$ parameters measured during annealing for channels irradiated with 4×10^{14} (200 MeV) p/cm^2 are plotted in Fig. 6. Channels biased at 10 mA show a faster recovery. After 80 h of annealing, the recovery corresponds a threshold current of about 0.7 mA

[3] GM10HS, 10×10 mm^2, GPD Optoelectronics Corp.

[4] The Fujikura S-12T-40/50/125-R fiber is investigated for radiation hardness [7].

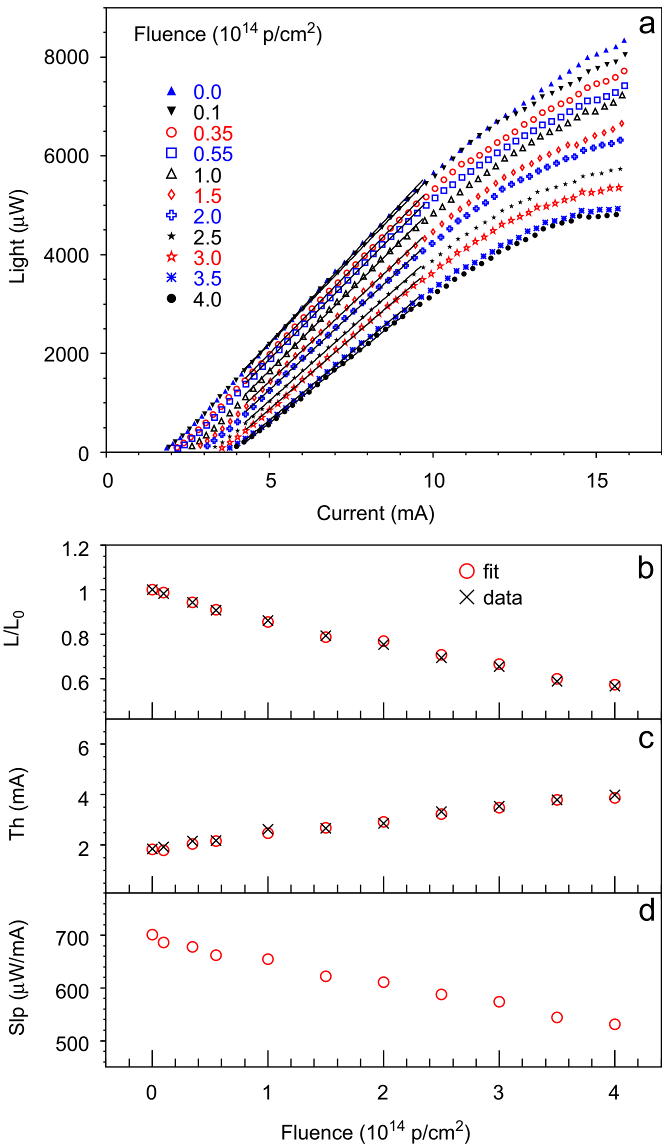

Fig. 3. (a) $L-I$ of an oxide-confined VCSEL channel in proton irradiation up to 4×10^{14} (200 MeV) p/cm^2. The linear fits of the $L-I$ curves are summarized for (b) the ratio of optical power at 10 mA, (c) threshold current, and (d) slope.

higher than that before irradiation, and the optical power at 10 mA is about 15% lower. The annealed $L-I$ parameters of oxide-confined VCSELs are also plotted in Fig. 5.

2.2. Radiation damage with 20 MeV neutrons

The oxide-confined VCSELs were tested at the CRC with neutrons of an average energy of 20 MeV. The neutrons were produced by bombarding a beryllium target with 50 MeV deuterons. The test setup consists of three circuit boards each having two VCSEL arrays (8 channels each) of two manufacture batches. The distances of the VCSEL arrays to the target correspond to the fluences of 2.3×10^{14}, 3.7×10^{14}, and 7.7×10^{14} ($\sim$20 MeV) n/cm^2 accumulated in 20 h. For differentiation of the annealing effect, on each circuit board one VCSEL array was biased at 10 mA and the other was open-circuit. Annealing was conducted after irradiation with all channels biased at 10 mA and the $L-I$ curves were measured.

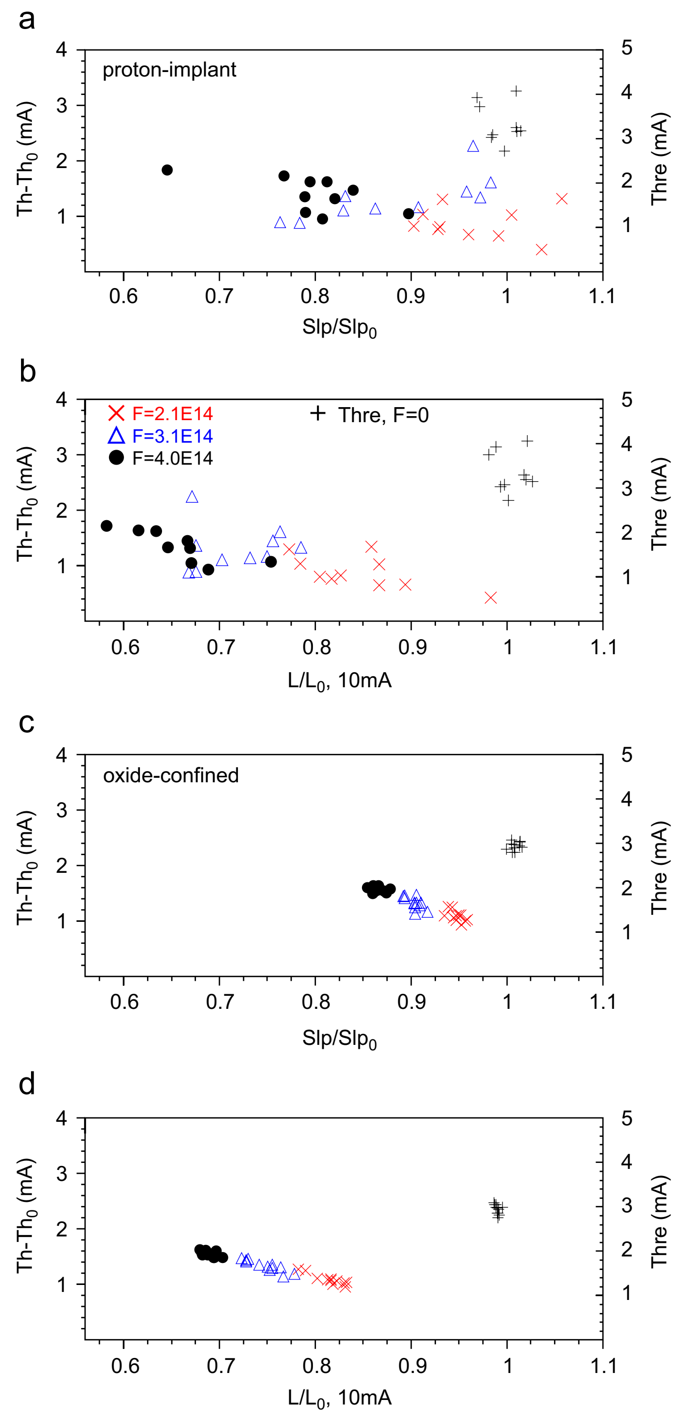

Fig. 4. Degradation of (a,b) proton-implant and (c,d) oxide-confined VCSELS irradiated with 200 MeV protons. Plotted are threshold currents before irradiation and the increases after three fluences, versus the changes in $L-I$ slope and light power at 10 mA.

The changes of $L-I$ parameters in annealing for the VCSELs not biased during irradiation are plotted in Fig. 7. The annealing characteristics follow roughly a exponential function characterized by a recovery time τ,

$$f(t) = f_\infty - b \cdot \exp(-t/\tau) \quad (1)$$

where f_∞ is the value of recovery ($t = \infty$). The $L-I$ parameters in recovery (Fig. 7) were fitted to Eq. (1) for each VCSEL channel. The recovery times were obtained for the threshold current and the optical power at 10 mA. The means of the fits are shown by the curves in Fig. 7. The

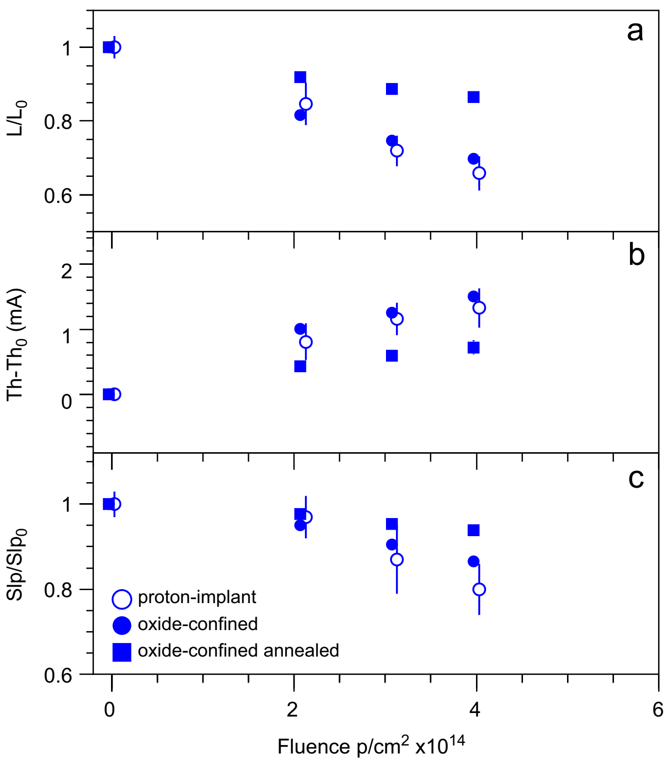

Fig. 5. VCSEL (a) optical power at 10 mA, (b) threshold current, and (c) $L-I$ slope normalized to the values before irradiation of 200 MeV protons. The data point are the mean of channels of a VCSEL array with RMS errors.

$L-I$ slopes (Fig. 7c) had shown little changes in annealing and the recovery times were not fitted. The normalized optical power, increase in threshold current, and slope, are plotted in Fig. 8. The fit values and recovery times are listed in Table 1. The VCSELs of the two production batches show compatible light degradation. The annealed optical power is about 14% lower for 3.7×10^{14} ($\sim$20 MeV) n/cm^2. The difference in threshold current and $L-I$ slope are more significant (Fig. 8).

In comparison, the radiation damages caused by 200 MeV protons and $\sim$20 MeV neutrons are compatible

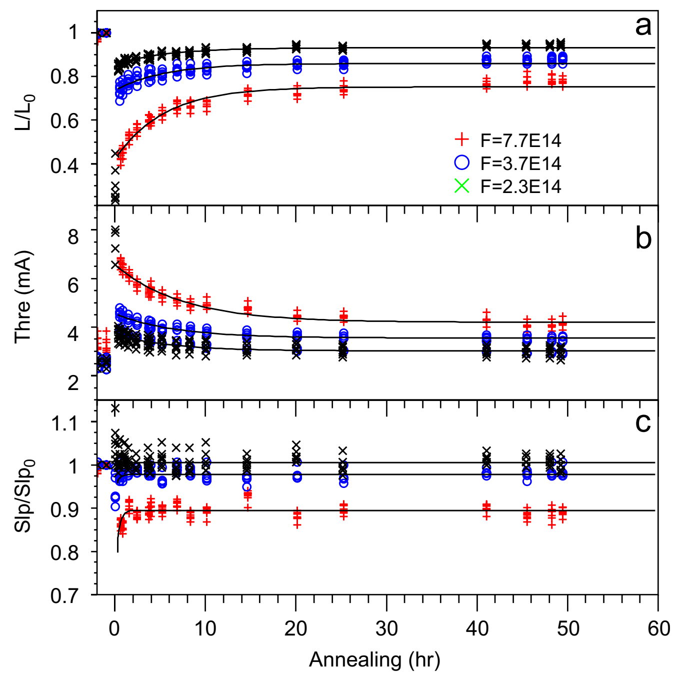

Fig. 7. The $L-I$ parameters of VCSELs measured in annealing. These VCSELs were not biased in neutron irradiation. The curves are the fits to exponential functions for each neutron fluence.

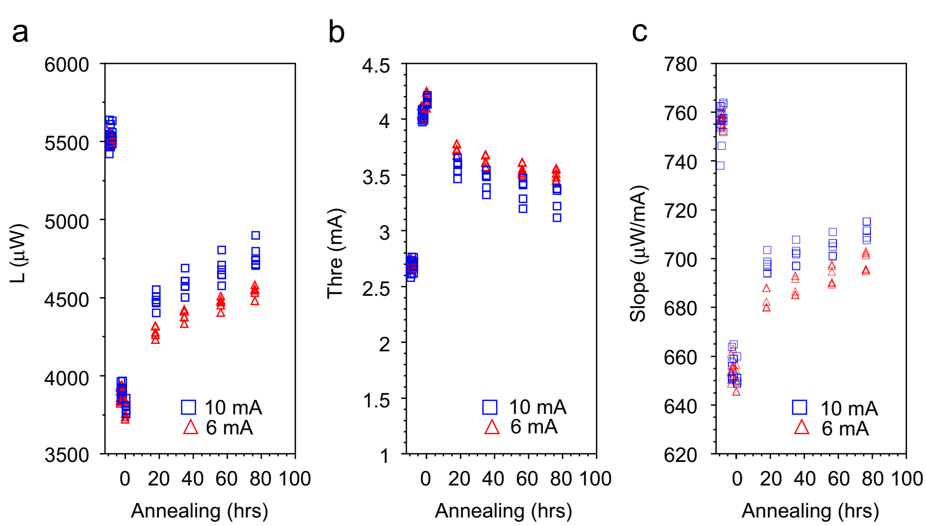

Fig. 6. The $L-I$ parameters measured in annealing for oxide-confined VCSELs irradiated with 4×10^{14} (200 MeV) p/cm^2. The first data points (annealing time <0) show the values measured prior to irradiation.

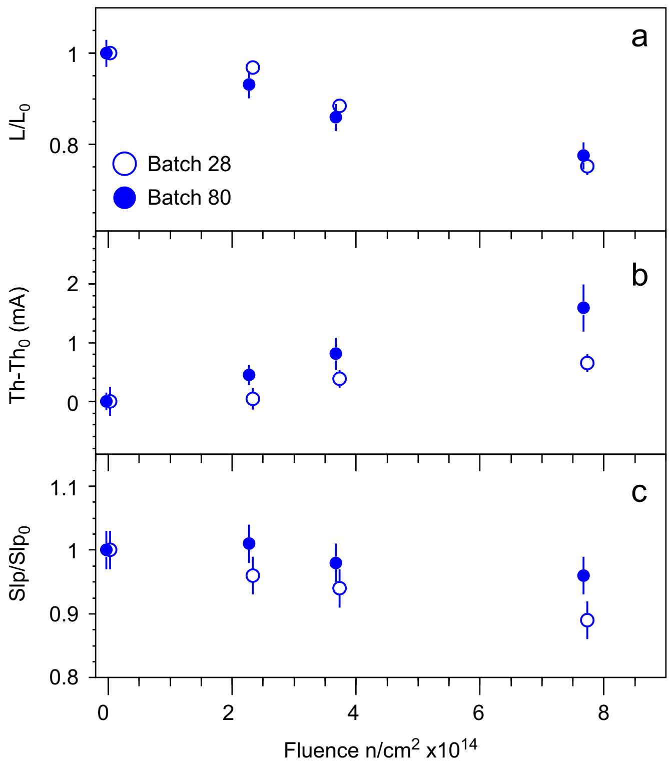

Fig. 8. VCSEL (a) optical power at 10 mA, (b) threshold current, and (c) $L-I$ slope normalized to the values before the irradiation of ~20 MeV neutrons. The data point are the mean of channels of a VCSEL array with RMS errors.

Table 1
Fit parameters of annealing curves to Eq. (1)

Fluence (n/cm^2)	L/L_0		Thre (mA)	
	f_∞	τ (h)	f_∞	τ (h)
2.3×10^{14}	0.93 ± 0.01	5.6 ± 0.7	3.0 ± 0.2	6.0 ± 1.2
3.7×10^{14}	0.86 ± 0.01	5.4 ± 0.7	3.4 ± 0.3	6.5 ± 0.5
7.7×10^{14}	0.75 ± 0.02	5.4 ± 0.3	4.2 ± 0.2	7.4 ± 0.3

The fits were conducted to each VCSELs. Listed are the means of VCSEL arrays.

for the same fluence. The NIEL scaling suggests that 200 MeV proton would cause twice more damage than the ~20 MeV neutrons.[5] The discrepancy observed may be compared to previous test results [8]. The radiation damage caused by energetic protons to GaAs devices is reported to be less than the NIEL calculations.

2.3. Accelerated lifetime test

The lifetime test was conducted with a set of 12 oxide-confined VCSEL arrays biased at 10 mA on heat plates kept at 60 and 85 °C over a 6 months period. These VCSELs were mounted on three circuit boards. Two of them were irradiated with 200 MeV protons to a total fluence of 2×10^{14} and 3×10^{14} (200 MeV) p/cm^2, respectively. The burn-in was in part for detecting possible decrease in lifetime after irradiation.

The lifetime of VCSELs is characterized by the Arrhenius equation with a temperature dependence of

$$\mathrm{AF} = \exp\frac{E_A}{k_B}\left(\frac{1}{T_1}-\frac{1}{T_2}\right) \tag{2}$$

where k_B is the Boltzmann constant and E_A is the activation energy that depends on the fabrication process. With $E_A = 1$ eV [9], the acceleration factors of ageing at $T_2 = 60$ and 85 °C to the operating conditions at room temperature ($T_1 = 30$ °C) are 32 and 359, respectively.

The $L-I$ curves of the VCSELs during the 6 months period show good consistency within the 3% systematic error including the alignment of VCSEL light measurements and deviation in temperature. The ageing tests have not shown obvious difference for the two temperature settings and the proton fluences. As there is no sign of failure nor light degradation observed, the VCSEL is expected to be reliable for the required 10-year operation for Atlas at LHC.

3. Radiation damage to PINs

The epitaxial silicon PIN diode has quantum efficiency matching well with the 850 nm light of the VCSEL. In addition, the epitaxial structure provides high frequency response and the thin active layer provides a more radiation tolerant device than bulk silicon PINs.

The PIN diodes of two manufacturers (Centronic and Truelight) were irradiated with 200 MeV protons at IUCF. In a test setup, the PIN diodes were biased at full depletion

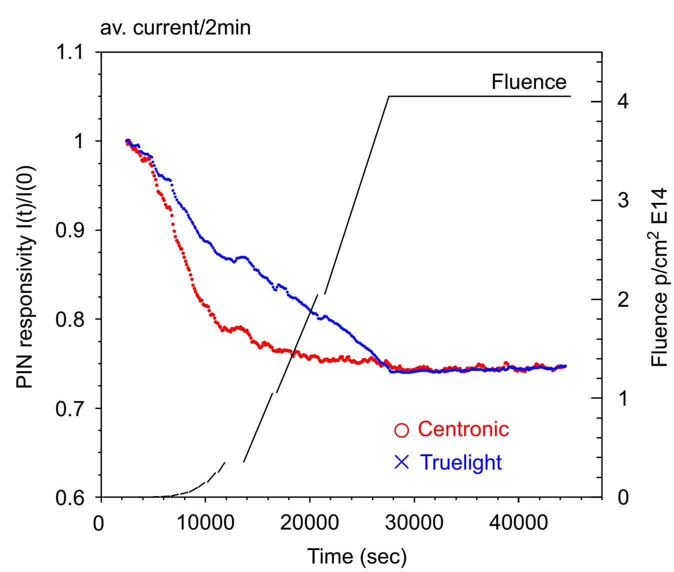

Fig. 9. The normalized responsivities versus (200 MeV) proton fluence for the PIN diodes of Centronic and Truelight.

[5]NIEL values (GaAs) are 0.55 and 2.3 keV cm^2/g for 1 MeV and 20 MeV neutrons, and 3.9 keV cm^2/g for 200 MeV protons, respectively [4].

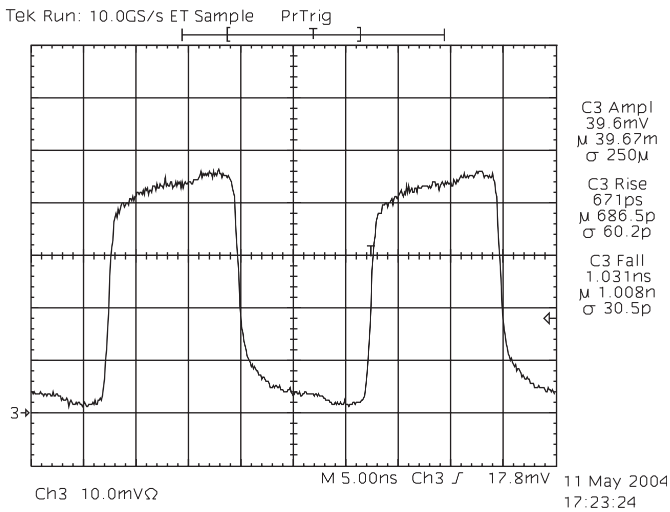

Fig. 10. Responsivity of a Truelight Epitaxial Si PIN to pulsed laser light after a fluence of 4×10^{14} p/cm^2 (rise, fall time are of 20–80% of the wave form).

voltage (-20 V for the Truelight PINs and -10 V for the Centronic) and were coupled to Fujikura ribbon fibers to VCSEL light in DC mode. The PINs were aligned perpendicular to the proton beam. The irradiation was initiated with low beam flux and the PIN currents were recorded in time. The responsivities of typical PINs of the two manufacturers are plotted in Fig. 9. The degradation of responsivity is steeper at the initial fluence. The two epitaxial silicon PINs have different degradation rates in response to beam fluence. The Centronic PIN drops faster at the beginning fluence to a degradation rate much slower than the Truelight PIN.

The Truelight PINs were irradiated in several test setups of different bias voltage and geometrical orientation. The results with bias voltages of -5, -10, and -20 V are consistent. The degradation of the PIN responsivity with proton traversing in a normal direction to the active layer is $20 \pm 5\%$ for a fluence of 2×10^{14} (200 MeV) p/cm^2. With the PINs aligned in parallel to the proton beam, the responsivity reduced by $38 \pm 5\%$ for 2×10^{14} (200 MeV) p/cm^2.

The PINs are required for fast response for the SCT data transfer. Shown in Fig. 10 is the response of a Truelight PIN diode irradiated with 4×10^{14} p/cm^2. The fast rising and falling edges are within 1 ns and are compatible to those before irradiation that satisfies the SCT specification.

4. Summary

The radiation hardness of the VCSELs and PINs of the Atlas SCT optical links has been studied. The degradation of the VCSEL threshold current is linear to fluence. The annealing is a quick process which can be parameterized by an exponential function with a recovery time of less than 10 h. The increase in threshold current is 0.7 mA after 2×10^{14} (200 MeV) p/cm^2 and 0.8 mA after 2×10^{14} ($\sim$20 MeV) n/cm^2. The epitaxial PIN diodes show a fast degradation at the beginning fluence. The PIN responsivity degrades by 20% after 2×10^{14} (200 MeV) p/cm^2. The radiation tolerance of both the VCSELs and PINs will suffice the requirement of 10-year operation in the LHC environment.

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