

## Study of the radiation-hardness of VCSEL and PIN

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The silicon trackers of the ATLAS experiment at the Large Hadron Collider (LHC) at CERN (Geneva) use optical links for data transmission. An upgrade of the trackers is planned for the Super LHC (SLHC), an upgraded LHC with ten times higher luminosity. We study the radiation-hardness of VCSELs (Vertical-Cavity Surface-Emitting Laser) and GaAs and silicon PINs using 24 GeV/c protons at CERN for possible application in the data transmission upgrade. The optical power of VCSEL arrays decreases significantly after the irradiation but can be partially annealed with high drive currents. The responsivities of the PIN diodes also decrease significantly after irradiation, but can be recovered by operating at higher bias voltage. This provides a simple mechanism to recover from the radiation damage.

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## 1.Introduction

The SLHC is designed to increase the luminosity of the LHC by a factor of ten to  $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ . Accordingly, the radiation level at the detector is expected to increase by a similar factor. The increased data rate and radiation level will pose new challenges for a tracker situated close to the interaction region. The silicon trackers of the ATLAS experiment at the LHC use VCSELs to generate the optical signals at 850 nm and PIN diodes to convert the signals back into electrical signals for further processing. The devices have been proven to be radiation-hard for operation at the LHC. In this paper, we present a study of the radiation hardness of PINs and VCSELs using 24 GeV/c protons at CERN to the dose expected at the SLHC.

## 2.Radiation damage in VCSEL and PIN

The main effect of radiation in a VCSEL is expected to be bulk damage and in a PIN diode the displacement of atoms. We use the Non Ionizing Energy Loss (NIEL) scaling hypothesis to estimate the SLHC fluences [1-2]. The silicon trackers will be consisted of a pixel detector followed by a strip detector. For the pixel detector, we expect the optical links to be mounted off detector to reduce the radiation exposure and simplify the detector construction. In fact, the electric signals from the front-end electronics will be transmitted on micro-coax cables to a location  $\sim 6$  m away. At this location, the radiation level is expected to be lower than that for the strip detector. The optical links for the strip detector will be mounted close to the detector which starts at a radius of  $\sim 37$  cm. At this location, after five years of operation at the SLHC, we expect a GaAs device (VCSEL and PIN) to be exposed to a fluence [3-4] of  $2.8 \times 10^{15}$  1-MeV  $n_{\text{eq}}/\text{cm}^2$ . The corresponding fluence for a silicon device (PIN) is  $7.2 \times 10^{14}$  1-MeV  $n_{\text{eq}}/\text{cm}^2$ . We study the response of the optical devices to a high dose of 24 GeV/c protons. The expected equivalent fluences at SLHC are  $5.4$  and  $12 \times 10^{14}$  p/cm<sup>2</sup>, respectively.

## 3.Radiation Hardness of VCSEL

In the past four years, we have irradiated a small sample of devices (typically 2-4 arrays per year) from three vendors, Advanced Optical Components (AOC), Optowell, and ULM Photonics with various bandwidths [5]. For the AOC, we irradiated three varieties of devices, 2.5, 5, and 10 Gb/s. For the ULM, we irradiated two varieties, 5 and 10 Gb/s. For the Optowell, we irradiated 2.5 Gb/s devices. Based on the multi-year study, we identified the AOC devices as more radiation hard and selected the 10 Gb/s device for further study with higher statistics. We packaged six VCSEL arrays at The Ohio State University for the irradiation [6].

The VCSEL arrays were mounted on a shuttle to allow the devices to be moved out of the beam for periodic annealing by passing the maximum allowable current ( $\sim 11$  mA per channel) through the arrays for  $\sim 12$ -16 hours each day. This periodic annealing was to ensure that the devices would still be functional after receiving the full dose. The devices under irradiation were not actively cooled and hence were operated at several degrees above the room

temperature; we expect to operate the devices at room temperature or below in the final system. The optical power vs. dosage of two 12-channel VCSEL arrays irradiated in 2008 is shown in Fig. 1. The devices received an equivalent dose of  $7.6 \times 10^{15}$  1-MeV  $n_{eq}/cm^2$ . The optical powers of 14 channels from two 12-channel arrays are shown; the total number of channels monitored during irradiation was limited to 14 by the test setup. The optical power decreased during the irradiation but increased during the annealing as expected. There was insufficient time for a complete annealing and the arrays were further annealed after returning to Ohio State. It is evident that the optical power recovery is logarithmic like and hence slow, but the arrays recover much of the original power. However, there is a channel which has low power,  $\sim 200$   $\mu W$ . Further measurement on a different setup after the annealing indicates that the channel does indeed have good power as shown in Fig. 2 where the power is plotted vs. the channel number for various temperatures. It is evident that power increases with decreasing temperature and hence it is important to operate the VCSEL at low temperature (room temperature or below) to maximize the power output.

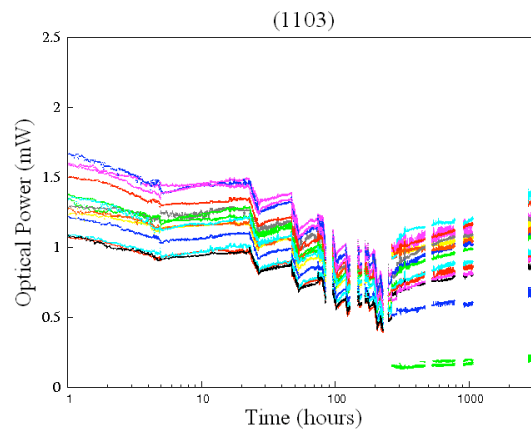


Figure 1: Optical power of two 10 Gb/s VCSEL arrays of AOC as a function of time. The power decreased during the irradiation but increased during the annealing. The extended annealing started at slightly past 200 hours.

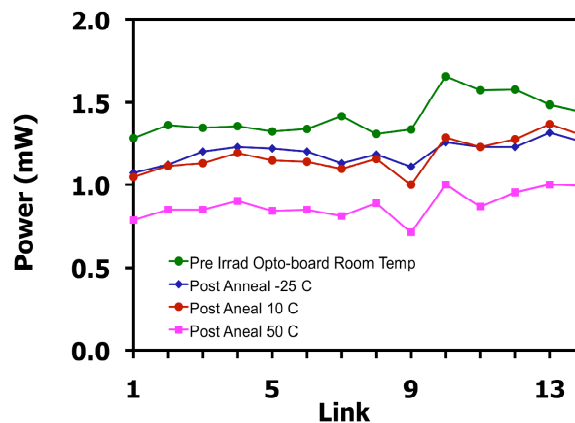


Figure 2: Optical power of two 10 Gb/s VCSEL arrays of AOC at four different temperatures.

The result from the irradiation of the six 10 Gb/s VCSEL arrays of AOC in 2009 is shown in Fig. 3. The devices received an equivalent dose of  $7.6 \times 10^{15}$  1-MeV  $n_{eq}/cm^2$ , which is the same as the year before. The behaviour of the optical power as a function of time is also similar to that shown in Fig. 1. The last segment shows a linear rise in the optical power. This line is added so that the last power measurement of each channel can be differentiated from the last data point measured after the long annealing. The length of this segment, the time separating the two measurements, is arbitrary and hence not physically meaningful. The last measurements were performed without the long fibres used in the irradiation which were twisted and hence most of the measured power is higher. It is evident that all channels except one have optical power in excess of  $300 \mu\text{W}$ . The lowest power is  $145 \mu\text{W}$ . This channel has lower power ( $\sim 250 \mu\text{W}$ ) at the beginning of the irradiation in contrast to the good power measurement at the Ohio State prior to the shipment to CERN. We will investigate the cause of the lower power once the arrays have been returned to Ohio State after the activation has subdued. The arrays will be annealed for an extended period and we expect more recovery of the optical power. The radiation hardness of these six AOC arrays is therefore acceptable for the SLHC applications. We plan to repeat the irradiation with a much larger sample, twenty arrays, in August of 2010, to fully qualify the arrays.

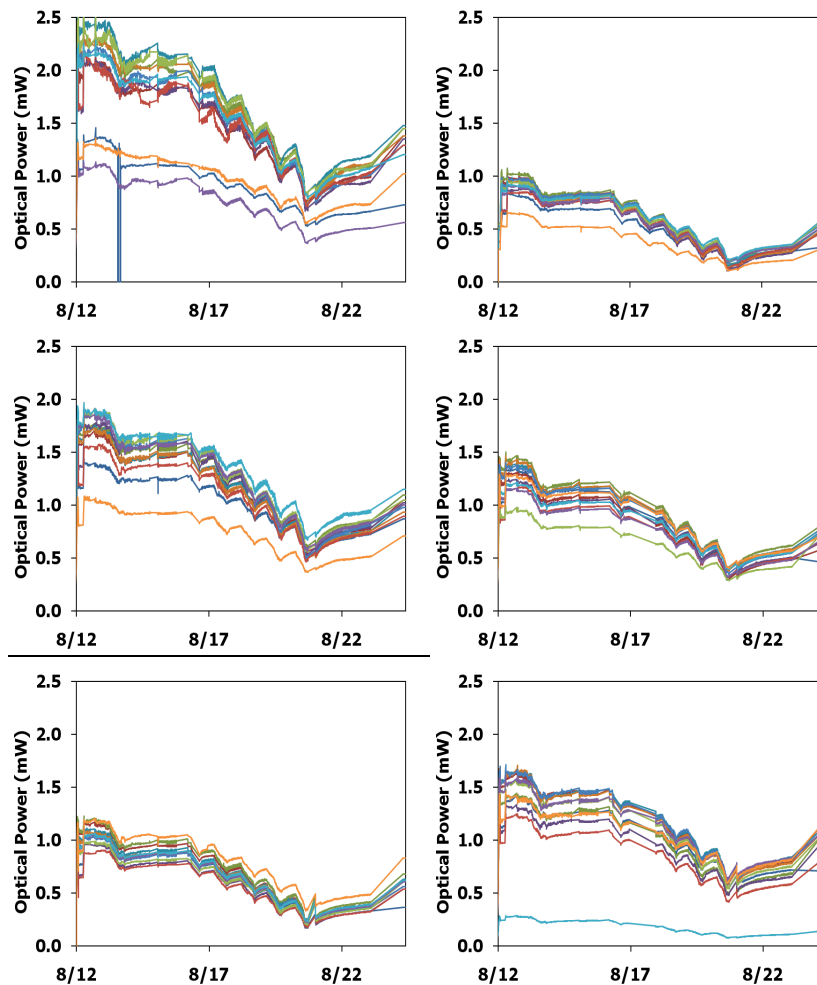


Figure 3: Optical power of six 10 Gb/s VCSEL arrays of AOC as a function of time. The power decreased during the irradiation but increased during the annealing. See the text for the comment on the last segment of the measurements.

#### 4. Radiation Hardness of PIN

In 2008, we irradiated both single channel and array PIN diodes from several sources. This includes two GaAs PIN arrays from AOC, Optowell, ULM Photonics, and Hamamatsu. We packaged these arrays at The Ohio State University for the irradiation [6]. In addition, we also irradiated silicon PINs, two Taiwan arrays and eleven single-channel silicon diodes from Hamamatsu (five S5973 and six S9055). These arrays were delivered pre-packaged.

We monitored the PIN responsivities during the irradiation by illuminating the devices with light from VCSELs and measuring the PIN currents. Table 1 summarizes the responsivities before and after irradiation. The responsivity is for a dose of  $4.4 \times 10^{15}$  1-MeV  $n_{eq}/cm^2$  for the GaAs devices and  $7.5 \times 10^{14}$  1-MeV  $n_{eq}/cm^2$  for the silicon devices. For the GaAs arrays, Optowell and Hamamatsu have the highest responsivities after the irradiation. As expected, the silicon devices are more radiation hard, with Hamamatsu S5973 having the highest responsivities. However, it should be noted that the bandwidth of the silicon PIN diodes is somewhat low. It should also be noted that we observed no annealing in the responsivities after irradiation and the leakage currents remained negligible.

Table 1: Responsivities (R) of PIN diodes from various sources before and after irradiation. The bandwidth (BW) of each device is also indicated.

	BW (Gb/s)	R (A/W)	
		Pre	Post
GaAs			
ULM	4.25	0.50	0.09
AOC	5.0	0.60	0.13
Optowell	3.125	0.60	0.17
Hamamatsu G8921	2.5	0.50	0.28
Si			
Taiwan	1.0	0.55	0.21
Hamamatsu S5973	1.0	0.47	0.31
Hamamatsu S9055	1.5/2.0	0.25	0.20

The PIN responsivity is expected to be a constant as a function of the bias voltage before irradiation. Figure 4 shows a typical example of the measurement for an Optowell PIN array. However, after a PIN is exposed to radiation, the responsivity increases with the bias voltage as shown in Figure 5 for the arrays from the three vendors that were exposed to a dose of  $4.4 \times 10^{15}$  1-MeV  $n_{eq}/cm^2$ . Figure 6 shows the responsivity of Optowell as a function of the bias voltage up to the specified maximum of 40 V by the vendor. It is evident that by operating the array at this high bias voltage, the responsivity can reach the pre-irradiated value. However, the integrity of the signal at this high bias should be verified. Figure 7 shows the eye diagram of an 1 Gb/s signal at 40 V. The test is performed at this relative low speed because of the limitation of the array carrier board. It is evident that the eye diagram is quite open, indicating the operation at this speed is quite adequate. However, the interest in the SLHC applications is for a much higher speed and the high-speed performance will be verified in the future. Nevertheless,

the design of the PIN receiver for the SLHC applications should allow the operation of the PIN diode at high bias voltage to take advantage of this interesting observation.

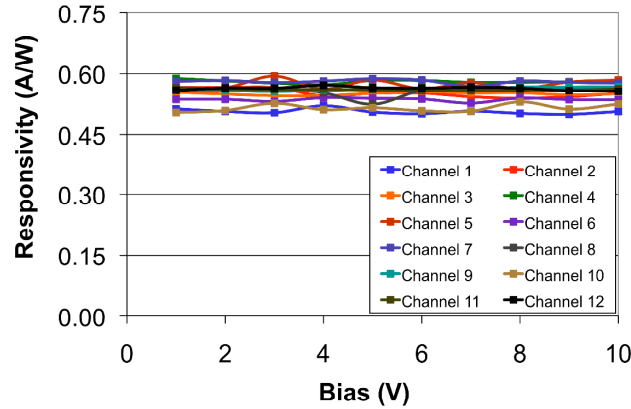


Figure 4: Responsivity as a function of bias voltage for a 12-channel Optowell PIN array before irradiation.

We chose to irradiate a larger sample of twenty Optowell PIN arrays in 2009 based on the results of the 2008 irradiation. This allowed us to test the uniformity of the radiation-hardness in a sample.

We irradiated the samples in two batches of ten arrays each. Unfortunately, the beam was not properly aligned in one of the batches, resulting in non-uniform dosage across the arrays. Consequently we will only present the results from the batch with uniform illumination. The analysis of the degradation in the responsivity of the other batch is more complicated and will be presented at a future conference.

The responsivity of the ten arrays with a uniform proton illumination is shown in Fig. 8. The estimated dose is  $8.1 \times 10^{15}$  1-MeV  $n_{eq}/cm^2$ . The responsivity after irradiation is  $\sim 0.3$  A/W with a minimum of 0.15 A/W. This is certainly quite adequate for the SLHC applications. For example, with a modest incident optical power of 1 mW, the PIN current is 150  $\mu A$ . This is significantly above the expected operation threshold of 100  $\mu A$  to minimize single event upset (SEU) from traversing particles [7]. We are awaiting the return of the irradiated devices for more detailed characterization after the activation has subsided.

## 5. Summary

We have studied the radiation hardness of PINs and VCSELs up to the SLHC dose. The optical power of the VCSEL arrays decreases significantly after the irradiation but can be partially annealed with high drive currents. The responsivities of the PIN diodes also decrease significantly after irradiation, but can be recovered by operating at higher bias voltage. This provides a simple mechanism to recover from the radiation damage.

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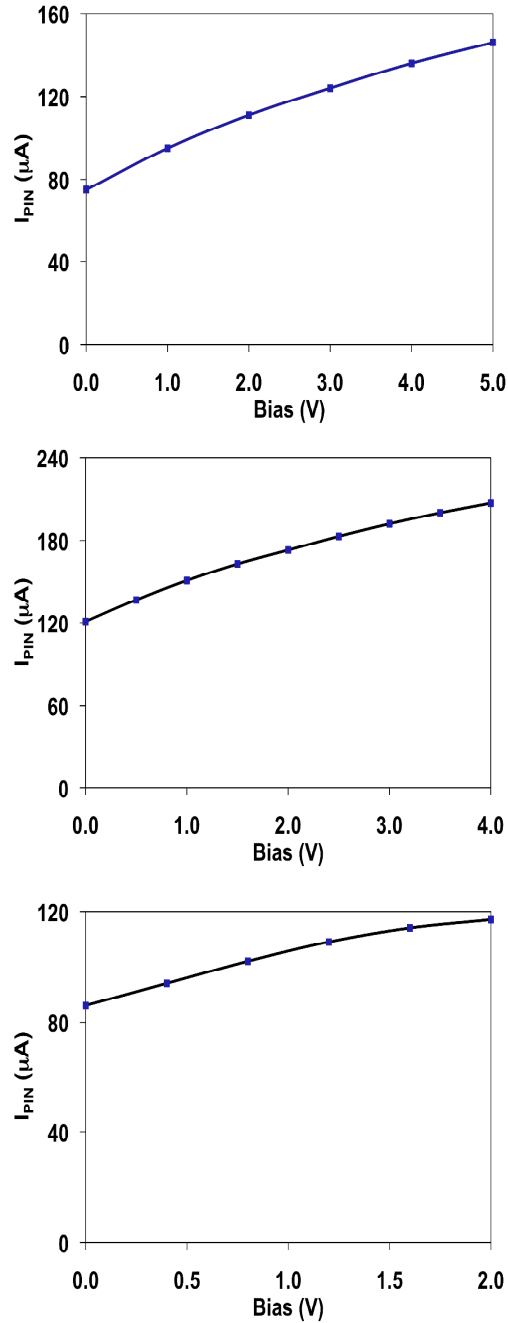


Figure 5: Responsivity as a function of the bias voltage for a channel in a 12-channel PIN array after irradiation. The PIN arrays are from three vendors, Optowell (top), AOC (middle), and ULM (bottom).

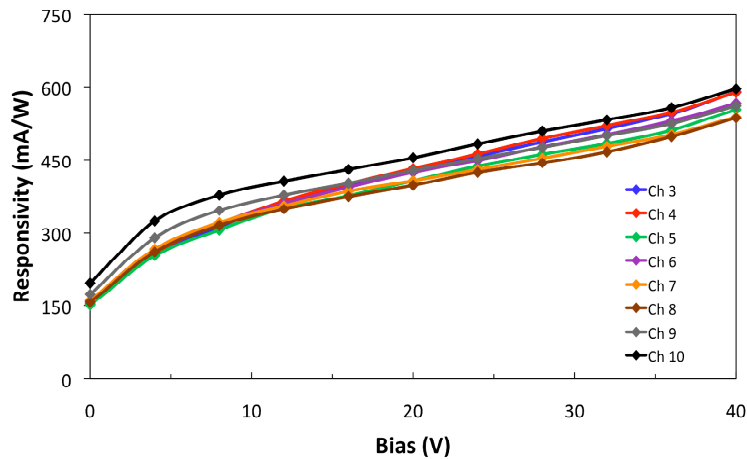


Figure 6: Responsivity as a function of the bias voltage for a 12-channel Optowell PIN array after irradiation.

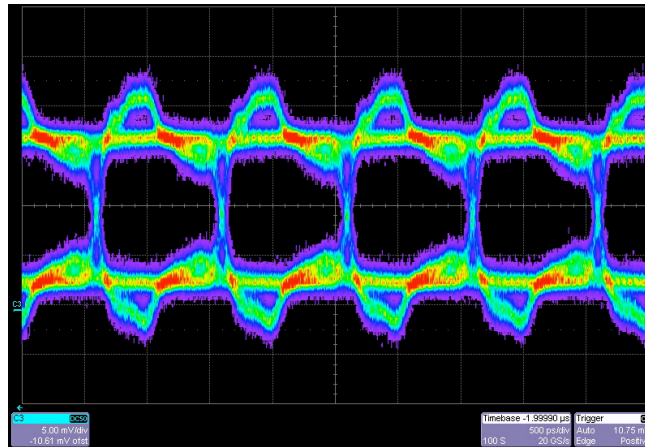


Figure 7: Eye diagram of the response of an irradiated Optowell PIN array operating at 40 V. The speed of the incident optical signal is 1 Gb/s.

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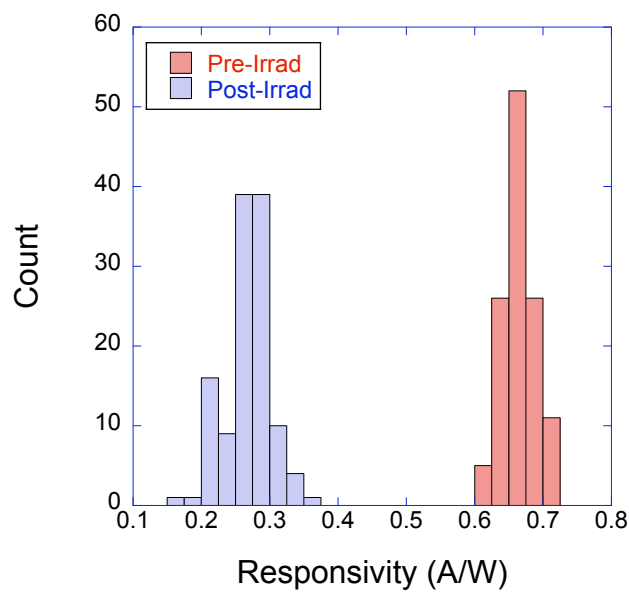


Figure 8: Responsivity of ten 12-channel Optowell PIN arrays before and after irradiation.

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