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Final Report on LDRD Project 52722 Radiation Hardened Optoelectronic Components for Space-Based Applications

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Sandia National Laboratories

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Abstract

This report describes the research accomplishments achieved under the LDRD Project "Radiation Hardened Optoelectronic Components for Space-Based Applications." The aim of this LDRD has been to investigate the radiation hardness of vertical-cavity surface-emitting lasers (VCSELs) and photodiodes by looking at both the effects of total dose and of single-event upsets on the electrical and optical characteristics of VCSELs and photodiodes. These investigations were intended to provide guidance for the eventual integration of radiation hardened VCSELs and photodiodes with rad-hard driver and receiver electronics from an external vendor for space applications. During this one-year project, we have fabricated GaAs-based VCSELs and photodiodes, investigated ionization-induced transient effects due to high-energy protons, and measured the degradation of performance from both high-energy protons and neutrons.

* L&M Technologies, Inc.

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Contents

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1. Introduction

1.1. LDRD Project Overview

As satellite-based imaging technology advances, so does the volume of information that is collected. Simply transporting information from the imaging device to an on-board computer, located a few meters away, can be a daunting task when the aggregate data rates exceed 10Gbit/sec. In earth-based systems requiring high throughput, the use of optical data transmission is rapidly becoming dominant, due to the significantly higher bandwidth of optical fibers as compared to coaxial cables. For space-based systems, the incentive to adopt optical transmission technology is doubled, because the satellite launch weight can be significantly reduced by using optical fibers instead of high-performance coaxial cables.

One of the critical issues that must be addressed in adopting any new technology for use on board satellites is whether or not the components can outlive the desired satellite lifespan in a high-radiation environment and whether individual high-radiation events will cause the component to malfunction. In addition to addressing these fundamental component issues, we must also address the issue of inserting these new components in larger circuits and systems, which must then be space qualified.

The goal of this one-year LDRD has been to investigate the radiation hardness of vertical-cavity surface-emitting lasers (VCSELs) and photodiodes by looking at both the effects of total dose and of single-event radiation strikes. The long-term vision is to integrate radiation hardened VCSELs and photodiodes with rad-hard driver and receiver electronics from an external vendor for space applications.

The transient effects due to single-event upsets (SEUs) in a VCSEL-detector optical link will depend largely on the detection/amplifier circuitry following the detector and the threshold level for error in the digital system. The intent of this investigation was to obtain data that allows for a prediction of the soft-error or bit-error rate in any satellite system that uses GaAs-based VCSELs or photodiodes. We have made transient-effect measurements with low-flux, 63.3 MeV protons, and found that irradiating a VCSEL produced unmeasurable and therefore negligible effects, whereas irradiating a p-i-n photodiode led to small but measurable current pulses.

To obtain a better understanding of the degradation of GaAs-based VCSELs and photodiodes due to total dose effects, we irradiated our devices with a 63.3 MeV proton source as well as a fission neutron source. The VCSEL showed about 20% degradation and the photodiode showed about 30% degradation with a total proton fluence level of about $5x10^{13}$ protons/cm^2. Irradiation with a fission neutron source with an accumulated fluence level of $4.4x10^{13}$ neutrons/cm^2 led to a 47% degradation in VCSEL performance, no degradation in GaAs photodiode performance, and 27% degradation in Si photodiode performance.

2. Transient Radiation-Induced Effects

2.1. GaAs VCSELs and Photodiodes

Though total dose effects of GaAs-based emitters and detectors have been well-studied, there is very little known about the transient effects of radiation on these devices. Investigations by LaBel et al. [1] and Reed et al. [2] suggest that high-bandwidth optocouplers (GaAs LED and Si photodiode) are more susceptible to transient effects than low-bandwidth optocouplers. A review of single-event effects on a variety of space-based devices was published recently with an excellent list of references [3]. Our aim in this investigation was to determine what effect, if any, proton-induced single-event transients (SETs) have on the performance of GaAs-based vertical-cavity surface-emitting lasers (VCSELs) and p-i-n photodiodes.

Both the VCSEL and photodiode used in this study were fabricated at Sandia National Laboratories. The VCSEL (EMC7444) contains five 8 nm GaAs quantum wells with 8 nm $Al_{0.2}Ga_{0.8}As$ barriers. The top mirror consists of 21 p-doped AlGaAs distributed Bragg reflector (DBR) pairs and the bottom mirror consists of 36 n-doped AlGaAs DBR pairs. The VCSEL has a roughly 2 µm optical aperture defined by oxidation. Figure 2.1 shows the voltage drop and optical power as a function of the drive current for a VCSEL nominally identical (nearby on wafer) to all the VCSELs used in the transient and total proton dose measurements. The photodiode (EB1884) has 3 µm GaAs intrinsic region between p- and n-doped AlGaAs layers. The photodiode had a responsivity of 0.5 A/W at 850 nm.

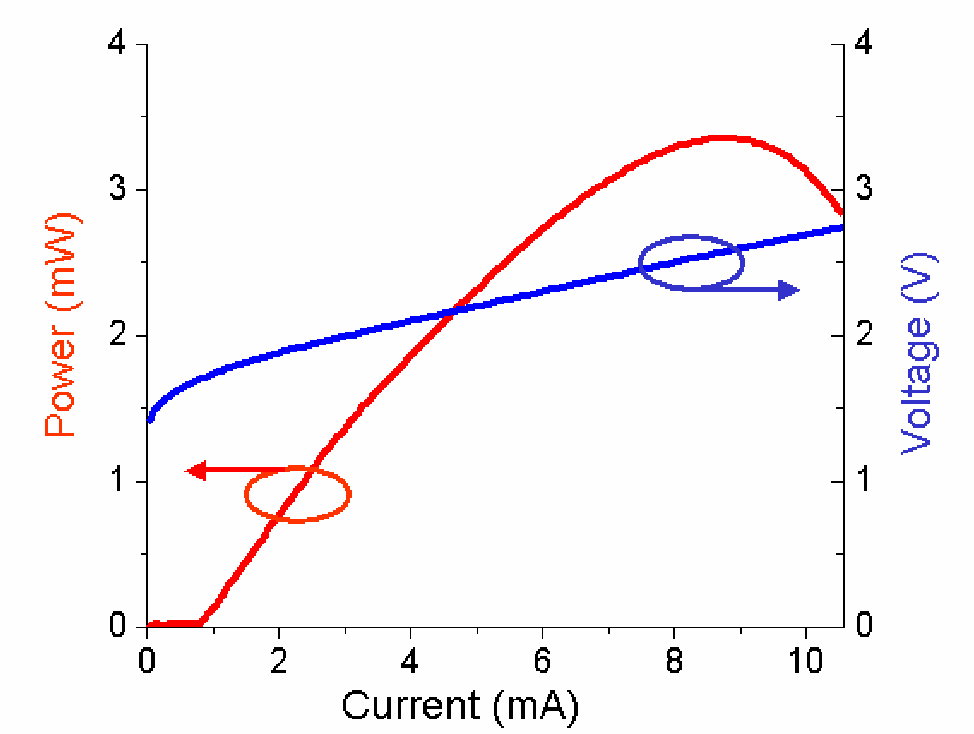

Figure 2.1. VCSEL output power and voltage drop versus drive current. The data are for wafer EMC7444B.

2.2. Proton Irradiation

The radiation tests were performed at the Crocker Nuclear Laboratory at the University of California, Davis with 63 MeV protons from an isochronal cyclotron proton accelerator. Beam dosimetry is accurate to within 10%.

The photodiode was attached to a circuit board and wire-bonded to a homemade linear amplifier circuit with an SMA output connector, as shown in figure 2.2(a). Copper shielding was used to reduce RF noise. Figure 2.2(b) shows a close-up image of the 50 μm aperture detector. The diagram of the amplifier circuit is shown in figure 2.3. The amplifier in the circuit is a Minicircuits ERA-2SM, 6 GHz, 15 dB power gain, linear amplifier. To increase signal-to-noise, we connected the output into a 1.5 GHz, 20 dB power gain, linear amplifier (Broadband Communications Products, Inc 310A). The proton-induced voltage pulses were analyzed using a 4 GHz Tektronix communication signal analyzer, CSA7404. This oscilloscope could obtain single-shot (real-time) waveforms at 20 Giga-samples per second (GS/s). Most of our measurements were performed at 10 GS/s, the highest possible sampling rate with measurement functions activated.

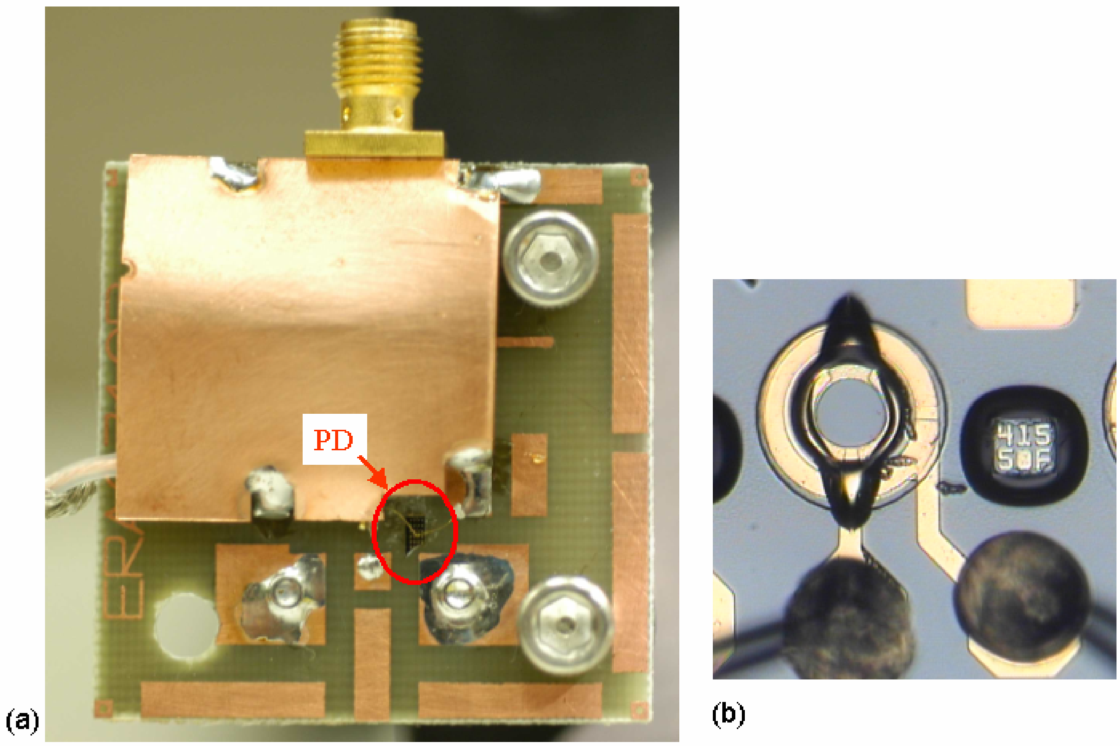

Figure 2.2. (a) Image of photodiode wafer and amplifier circuit used in single-event transients experiment. The photodiode wafer is shown inside the red circle. (b) Image of the 50-µm aperture photodiode used in experiment.

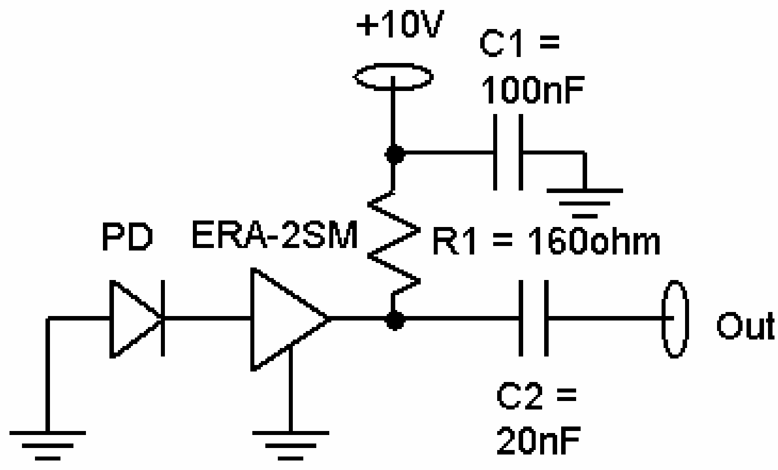

Figure 2.3. Circuit diagram of the photodiode (PD) amplifier circuit.

The VCSEL wafer was attached to an SMA connector and wire-bonded to the leads as shown in figure 2.4(a). A close-up of the VCSEL is shown in figure 2.4(b). The VCSEL was packaged to be modulated at high-speed though it was only DC biased in the experiments described in this report.

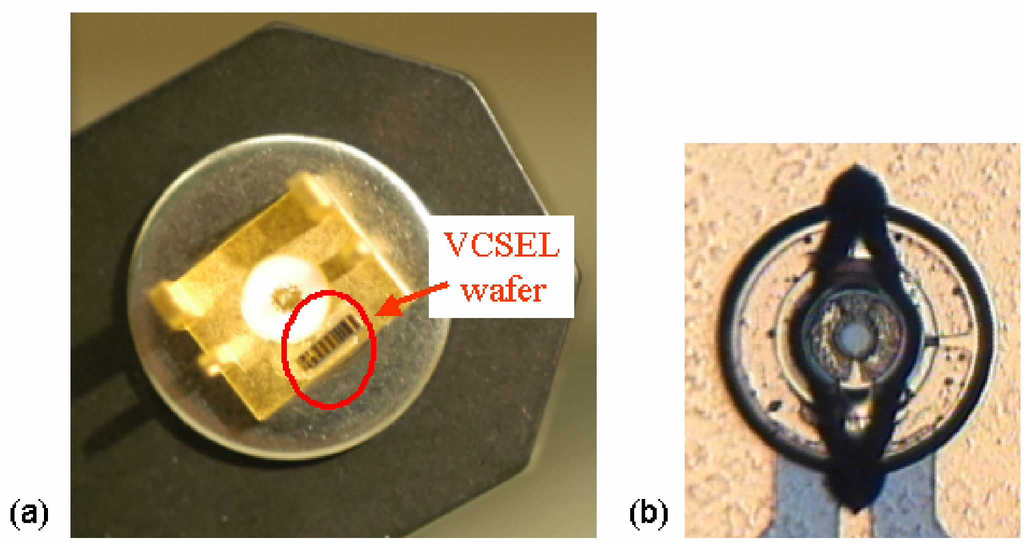

Figure 2.4. (a) The VCSEL wafer mounted on SMA connector used in single-event transients experiment. (b) Close-up of the VCSEL used in the experiment.

Irradiation of the photodiode and VCSEL was done separately. For each, only the device under test was placed in the 6 cm proton beam. The photodiode and VCSEL both had coupling lenses with a working distance of about 1 cm. To insure that the proton beam was not obstructed by the lens and lens mount, the devices were rotated at an angle of 45 degrees relative to the proton beam. This angle had to be taken into account in calculating fluence and dose levels. To prevent transient events due to proton irradiation of the amplifier circuit, a stainless steel block with a small hole was carefully placed in front of the circuit to allow irradiation of only the photodiode wafer.

To obtain waveforms of proton-induced voltage pulses, we set the trigger level at 8 mV, just above the noise. The proton flux was set to about 1×10^6 protons/cm^2-s. This flux was high enough to see frequent voltage pulses, but low enough to obtain accurate waveform counts with the oscilloscope and prevent permanent damage to the detector. Figure 2.5 shows an example of one of the larger voltage pulses captured by the oscilloscope. The rise and fall time of the voltage pulses are limited by the 1.5 GHz amplifier, not by the 4 GHz oscilloscope.

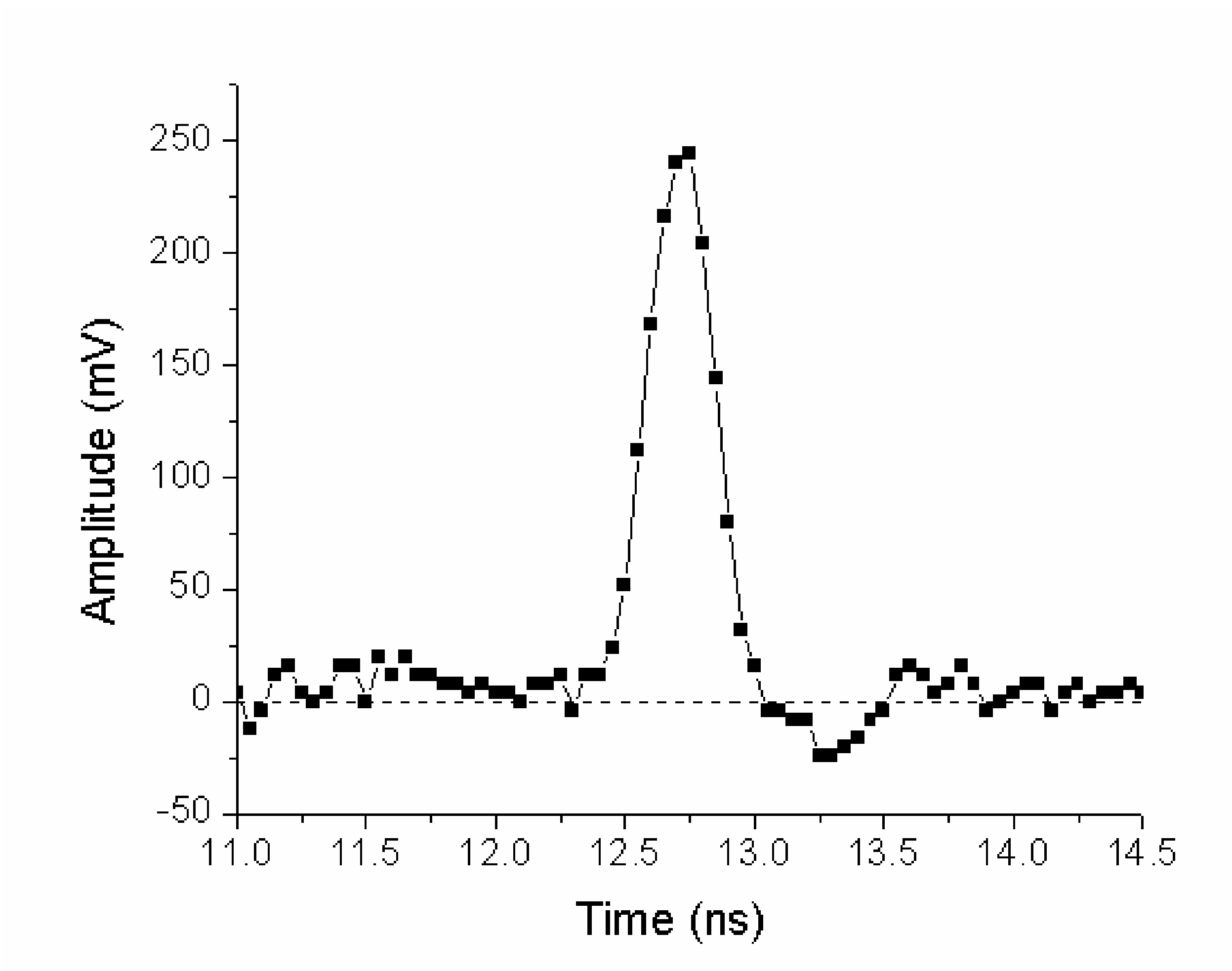

Figure 2.5. Transient voltage pulse induced by proton irradiation of photodiode.

To characterize the statistical nature of the voltage pulses, we adjusted the trigger level, counted the number of triggered pulses, and obtained statistics for the amplitude of the pulses. With less than 10 counts per second, the oscilloscope dead time during waveform display and amplitude measurements did not reduce the count number by more than a few percent. To determine the uncertainty in the number of waveforms counted, we made five identical measurements in 100 seconds and obtained the total counts were all within 5% of the mean. Table 2.1 shows the results of measurements made for trigger levels in a range of 8 to 100 mV. The table gives the number of waveforms, or triggered voltage pulses, in a given period of time and flux. Using these values, we calculated a normalized count that gives the number of counts per second adjusted to a flux of 1.0×10^6 protons/cm^2-s.

Table 2.1. Comparison of signal and noise from electrical and optical interconnects.

Trigger Level (mV)	Counting Time (s)	Flux (protons/cm^{2}s)	Number of Waveforms	Normalized Count[a]	Amplitude Mean (mV)
8	1000	1.29×10^5	1902	14.7	16.7 (7.1)[b]
10	348	1.15×10^6	3198	7.99	21.8 (9.5)
15	200	1.15×10^6	693	3.01	29.5 (8.4)
20	200	1.13×10^6	290	1.28	36.4 (12.8)
30	200	1.20×10^6	38	0.16	57.3 (24.7)
100	1000	1.17×10^6	11	0.0094	181 (50.4)

[a]Normalized Count refers to the number of triggered voltage pulses per second for a flux of 1×10^6 protons/cm^2-s.
[b]Value in parentheses is the standard deviation.

Note that the normalized count increases with decreasing trigger level. It is reasonable to assume that trigger levels below 8 mV would have led to even higher counts. An expected number of counts can be calculated by assuming that every proton that passes through the detector will create an ionization trail that leads to a voltage pulse. The diameter of our detector is 74 μm (50 μm aperture with 12 μm wide metal ring contact) corresponding to an area of 4.3×10^{-5} cm^2. A flux of 1.0×10^6 protons/cm^2-s leads to 43 protons passing through the detector every second. We measured 14.7 counts with an 8 mV trigger level, which is 34% of the total counts we would expect with better signal-to-noise. Of these 43 protons/s, only 3% caused voltage pulses greater than 20 mV, and only 0.02% led to voltage pulses greater than 100 mV. It is the larger events that are of most interest, however, since it is the large pulses that are most likely to lead to single-event upsets (SEUs) in optical data links.

In order to make predictions of bit-error rates in digital systems with an optical data link, we need a calibration of our detector/amplifier electronics. It is reasonable to assume that if we had used amplifiers with a higher bandwidth, the measured voltage pulses would have had larger amplitudes and smaller temporal width. In other words, higher bandwidth electronics will be more susceptible to SEUs. This effect can be seen by comparing some measurements made with and without the 1.5 GHz external amplifier. Without the amplifier, trigger levels of 2.5 and 3.0 mV led to normalized counts of 2.83 and 1.47, respectively. These normalized counts correspond more closely to those obtained with trigger levels of 15 to 20 mV with the external amplifier. This implies a voltage gain of about 6 instead of 10 which we would expect with a 20 dB power gain if the amplifier had a larger bandwidth.

To further characterize our detection system, we used a short pulse laser to simulate the effects of proton-induced ionization. The laser was a mode-locked titanium-sapphire laser (Spectra Physics Tsunami) that produced 100 fs pulses at a repetition rate of 76 MHz. It had a spectral bandwidth of 15 nm centered at 820 nm. We used the same detector with amplifier circuit connected to the 1.5 GHz amplifier circuit. We used a 3 GHz bandwidth oscilloscope (Tektronix TDS694C). As a comparison with the 4 GHz oscilloscope used in the proton measurements, the ratio of measured sine-wave amplitude at 1.5 GHz versus that measured at 100 MHz is 0.98 for the 4 GHz scope and 0.89 for the 3 GHz scope. The measured pulses may have amplitudes that are up to 10% less than what would have been measured with the 4 GHz oscilloscope.

The optical pulses were attenuated sufficiently to prevent saturation of the detector absorption. With an average power of 0.25 µW corresponding to 3.3 fJ of energy per pulse, the mean pulse amplitude measured with the oscilloscope was 58 mV. Given a measured detector responsivity of 0.5 A/W, or 0.5 Coulomb/J, 1.65×10^{-15} Coulomb of charge was generate with each pulse. This corresponds to 1.0×10^4 electron-hole pairs generated during each pulse. Thus, 1.0×10^4 electron-hole pairs lead to a 58 mV pulse using our detector/amplifier system. Similarly, in the proton irradiation experiment, we would expect about 17 electron-hole pairs for every mV of measured voltage pulse amplitude.

How many electron-hole pairs are expected to be generated by a proton passing through our detector? The LET for 63.3 MeV protons in GaAs is 6.5 MeV-cm^2/g. Given a density of 5.32 g/cm^3 for GaAs, average energy loss per distance is 3.5 MeV/cm. For our 3 µm intrinsic region detector at 45 degrees to the beam, we expect an average energy of 1.5 keV deposited in the intrinsic region. Since about 2 in 3 electron-hole pairs generated recombine before being swept out and contributing to the signal [4], about 0.5 keV of energy should have led to long-lived electron-hole pairs. If we assume that each electron-hole pair is at the band-gap energy of 1.42 eV, then we expect about 353 electron-hole pairs generated by a single proton. Using the optical pulse calibration, 353 electron-hole pairs, should lead to a voltage pulse with an amplitude of 2.0 mV. This seems reasonable given our understanding that 66% of the protons that passed through our detector led to voltage pulses with an amplitude less than our lowest trigger level of 8 mV. The occasional large pulse, such as the one shown in figure 2.5 may result from a secondary recoil event. The proton collides with a Ga or As atom which then travels through the device with high energy creating a larger number of ionization-induced electron-hole pairs than the proton would have produced alone.

The results of the tests on with the VCSEL in the beam and the detector out of the beam are simple to describe. With the VCSEL biased below threshold (0.76 mA) or above (3.0 mA), we observed no proton-induced voltage pulses on the detector. The trigger levels were at 10 mV and 40 mV respectively. The flux was 1.2×10^6 protons/cm-s for 500 seconds for each measurement. The trigger levels were set higher due to increased noise resulting from VCSEL intensity fluctuations (largely optical feedback-induced noise when above threshold). The lack of counts is perhaps not surprising given the small active region of the VCSEL coupled with the less-than-unity efficiency in the VCSEL-detector link. There is a total of 40 nm thickness in the active region of the VCSEL compared with the 3 micron thickness of the detector intrinsic region. This difference, coupled with a roughly 30% quantum efficiency (0.3 photons per electron-hole pair), and roughly 50% of light generated absorbed by the detector, gives roughly 500 times less signal generated with the VCSEL irradiated instead of the detector. With a 10 to 100 times improvement in signal-to-noise, we would presumably be able to observe some of the larger recoil events in the irradiated VCSEL.

2.3. Calculated Bit-Error-Rate Example

Though the safest method for verifying radiation hardness to single-event transients is to perform radiation tests, it would be useful to have a simple method for predicting the bit-error-rate one would expect for any satellite optical data link using GaAs based VCSELs and photodiodes such as the ones studied in this investigation.

As a simple example, we assume that our VCSEL and detector is used in a 2.5 Gb/s digital optical data link in which the detector is connected to a commercial limiting amplifier (Vitesse VSC7650). The amplifier achieves its full output swing for all signals larger than 10 μA peak-to-peak and goes low for signals less than about 1 μA. If we assume the threshold level for distinguishing between a logical 1 or 0 is 5 μA, then any proton-induced charge that leads to a 5 μA signal during a bit period will lead to 1 instead of a zero and thus cause a bit-error. A bit period at 2.5 Gb/s is 400 ps. The charge needed to generate a 5 μA signal in 400 ps is 2×10^{-15} Coulombs, or 1.3×10^{4} electron-hole pairs. We assume that the detector-amplifier pair experience a 63 MeV proton flux of 1.0×10^{6} protons/cm-s. With our calibration of 2.0 mV for every 353 electron-hole pairs, the proton-induced events that would lead to a bit-error with the Vitesse amplifier would have led to a voltage pulse with an amplitude of 75 mV in our measurements. Pulses of this magnitude or larger occurred at a rate of approximately 0.1 events per second at a flux of 1.0×10^{6} protons/cm-s. This corresponds to a bit error rate of 4.0×10^{-11}, an acceptable low rate for any well-designed digital system. Actual proton flux levels in a typical satellite orbit will likely be about 3 orders of magnitude less than that assumed in this example, with a correspondingly lower bit error rate.

One must keep in mind, however, that we are ignoring potential effects due to irradiation of the amplifier circuit as well as any optical fiber that may be used in a satellite data link. Single-event effects in Si and GaAs microelectronics have been well-studied [5-7] and rad-hard CMOS circuits are routinely manufactured at Sandia National Laboratories or at companies such as Peregrine Semiconductor. Radiation effects on optical fiber have been investigated [8] and radiation-hardened optical fibers have been manufactured [9].

2.4. Transient Radiation Effect Conclusions

We have investigated the transient effects of 63 MeV protons on GaAs based VCSELs and photodiodes. Due to the significantly thicker active region in the photodiode compared to the VCSEL, along with other factors described above, the proton-induced effects were significantly larger in the photodiode than in the VCSEL. In fact, with our measurement set-up, no single-event transients were observed when only the VCSEL was irradiated.

The magnitude and frequency of the single-event transients in the photodiode were measured. We observed far more transients as we lowered the trigger level to just above the noise and we believe that most of the transients led to signals too small to be measured. To determine the correspondence between measured pulse amplitude and number of electron-hole pairs generated by the passing proton, we calibrated our system with a 100 fs pulsed laser system.

It would be useful to have a simple and reasonably reliable method for predicting the effect high-energy protons will have on the transient behavior of a variety of detector/amplifier systems. It is relatively straightforward to predict the amount of charge generated by a high energy proton given the known Linear Energy Transfer (LET) function for the corresponding proton energy and material.

For GaAs-based p-i-n photodiodes, it is reasonable to assume that the charge Q is swept out of the intrinsic region and leads to a voltage pulse of amplitude Q/C, where C is the capacitance of the photodiode. We have measured the capacitance of our GaAs 3 μm intrinsic region photodiodes to be 0.037 fF/μm^2. Since capacitance varies inversely with intrinsic region thickness, d, the capacitance per unit area for any photodiode with GaAs intrinsic region would be 0.11/d fF/μm^2, with d in microns. In our case, the area of the photodiode was 4.3×10^3 μm^2 giving a capacitance of 0.16 pF. As calculated above, we expect about 353 electron-hole pairs, or 5.6×10^{-17} Coulombs of charge, for each proton that passes through our device. We would then expect a voltage pulse with an amplitude of 0.35 mV at the input of the detector amplifier

To estimate the amplitude of the amplifier output, one must extract a gain from the amplifier gain spectrum. Our first amplifier has a power gain of 15 dB at 2 GHz and 12 dB at 8 GHz. Since our detectors have a bandwidth of roughly 1/RC = 1/(50Ω)(0.16pF)=12.5 GHz, we would estimate an average power gain of roughly 10 dB, or a voltage gain of 5 dB. This lower bandwidth voltage pulse of roughly 3 times its original amplitude, or 1.1 mV, then passes through our 1.5 GHz amplifier which has a 20 dB power gain at low frequencies and drops to 8 dB power gain at 3.0GHz. If we assume our 1.1 mV voltage pulse coming from the 6 GHz detector experiences an average power gain of 8 dB, then our expected measured amplitude for the proton-induced voltage pulses should have been 2.8 mV, similar to the predicted amplitude of 2.0 mV using the optical pulse calibration.

The important piece of information missing in the above analysis is knowledge of the impulse response function of our amplifiers. If one assumes, however, that the frequency spectrum of the detector pulse is flat and cuts off at 15 GHz, reasonable estimates of the power gain can be made. The resulting amplified voltage amplitude can then be estimated as

$$V = 0.36 \frac{d_{eff} dFg}{A}, \tag{2.1}$$

where d_{eff} is the thickness of the detector as seen by the proton (which is $d/\cos\theta$ except for high angles), d is the detector intrinsic region thickness in microns, F is the fraction of electron-hole pairs generated by the proton that do not recombine immediately (we assumed 1/3 in our analysis), g is the average voltage gain of the detector amplifier, and A is the area of the detector in square microns.

Though our measurements and analysis provide useful information regarding the transient behavior of GaAs VCSELs and photodiodes, there is still much that can be learned. Further studies should look into the how the transient events change with different proton energies as well as with varying detector area and intrinsic region thickness.

3. Total Radiation Dose Effects

3.1. Proton Irradiation

In addition to measuring the transient effects due to proton-induced ionization, we measured the degradation of performance of our VCSELs and detectors induced by total proton dose. The measurements were made on a GaAs based VCSEL and p-i-n photodiode nominally identical to those used in the transient experiments and were also irradiated with 63 MeV protons at the Crocker Nuclear Laboratory at University of California, Davis.

The irradiated VCSEL and photodiode were each in a VCSEL-photodiode pair with the output of the VCSEL collected with a lens and refocused into the photodiode with a lens. The irradiated VCSEL and photodiode were within a few cm from each other in the 6 cm diameter beam and were at an angle of 45 degrees relative to the proton beam. All accumulated fluence levels reported here have been reduced by a factor of 0.7 to take into account this angle.

The input current to the VCSEL in each pair was swept using a Keithley 2400 SourceMeter. The photodiodes were reverse biased with 1.0 V and the output was amplified using a Melles Griot Wide Bandwidth transimpedance amplifier. The voltage across the VCSEL and the amplified photodiode output were recorded on a Tektronix TDS3054B oscilloscope and averaged over 16 waveforms. Voltage and power curves are shown for the irradiated VCSEL in figure 3.1 for selected accumulated fluence levels up to 5x10^{13} protons/cm^{2}. The voltage curve remains unchanged indicating that the resistance across the VCSEL did not significantly change during irradiation. The power curves show decreased slope, decreased output power, and a 10% increase in threshold current at an accumulated fluence of 5x10^{13} protons/cm^{2}.

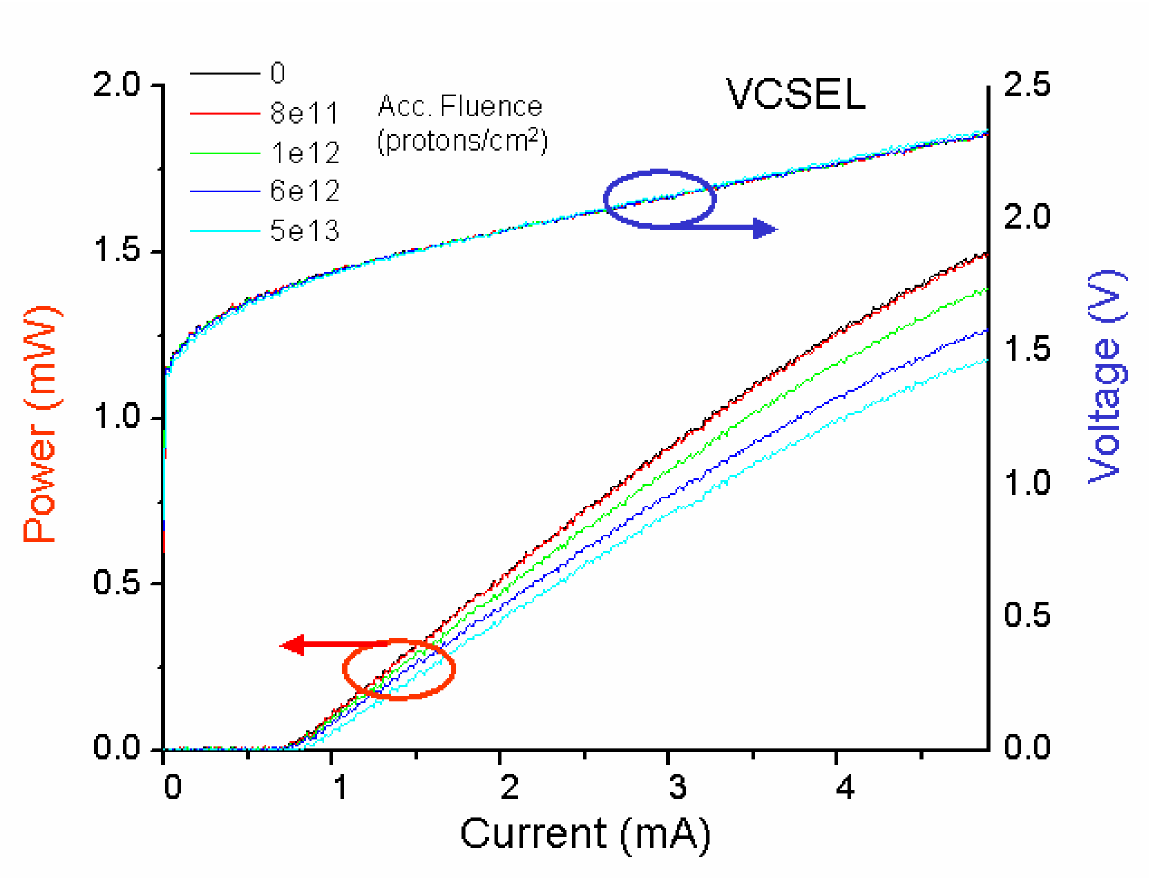

Figure 3.1. LIV curves showing degradation of VCSEL performance with increasing dose.

The results from irradiating the photodiode are shown in figure 3.2. The voltage curve, which indicates the behavior of the VCSEL in the VCSEL-detector pair, should not change since the VCSEL in this pair was not in the proton beam. For the same reason, the threshold current in the power curve should also remain unchanged. The power drops however, due to a decreased responsivity in the photodiode.

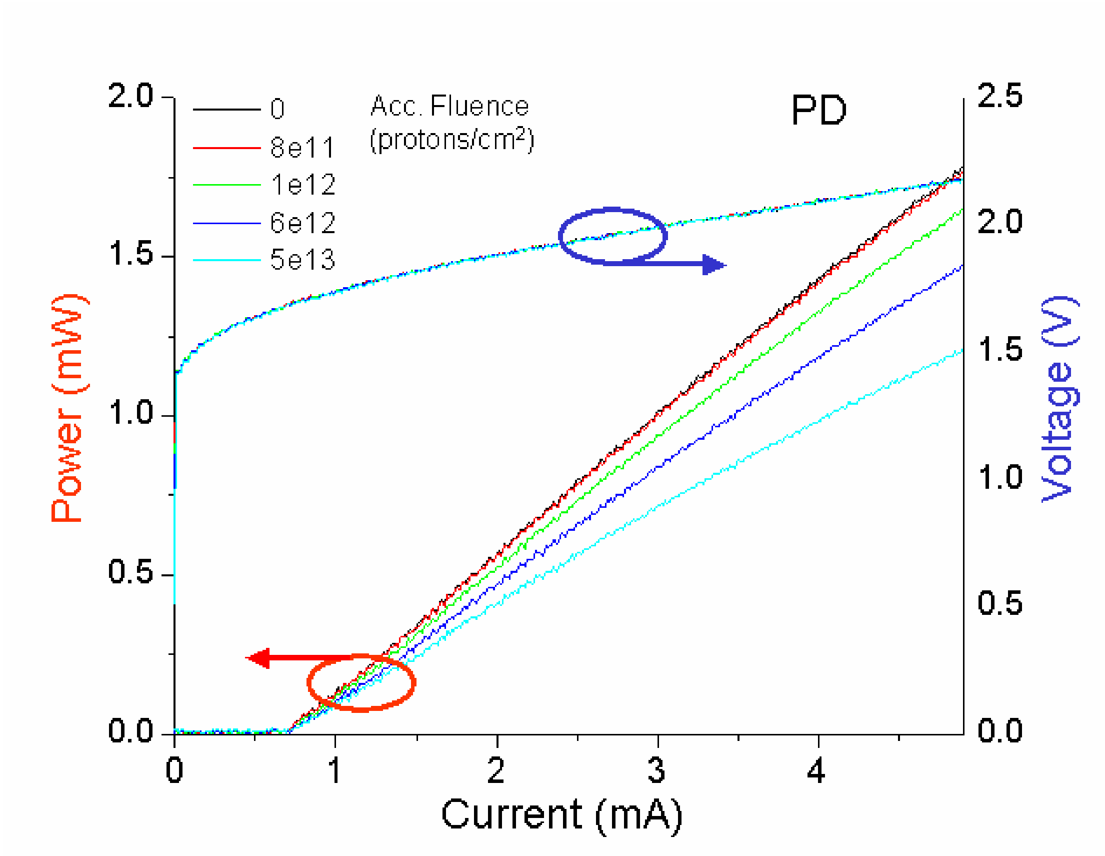

Figure 3.2. LIV curves showing degradation of photodiode responsivity with increasing dose.

In addition to measuring the power and voltage curves, an individual measurement of the measured power with each VCSEL biased at 4.0 mA was obtained to give a summarized look at the degradation in performance of the irradiated VCSEL and photodiode, as shown in figure 3.3. The normalized performance refers to the ratio of amplified detector current after irradiation to the current measured before irradiation. It is interesting that the VCSEL and photodiode curves are nearly identical until an accumulated fluence of about $3x10^{12}$ protons/cm^2. It is also interesting that the VCSEL curve at the higher fluence level seems to imply that the output power would stop decreasing with only a total of 30 to 40% reduction in output power, even at significantly higher fluence levels. Presumably this is not the case and higher fluence levels would show increased degradation.

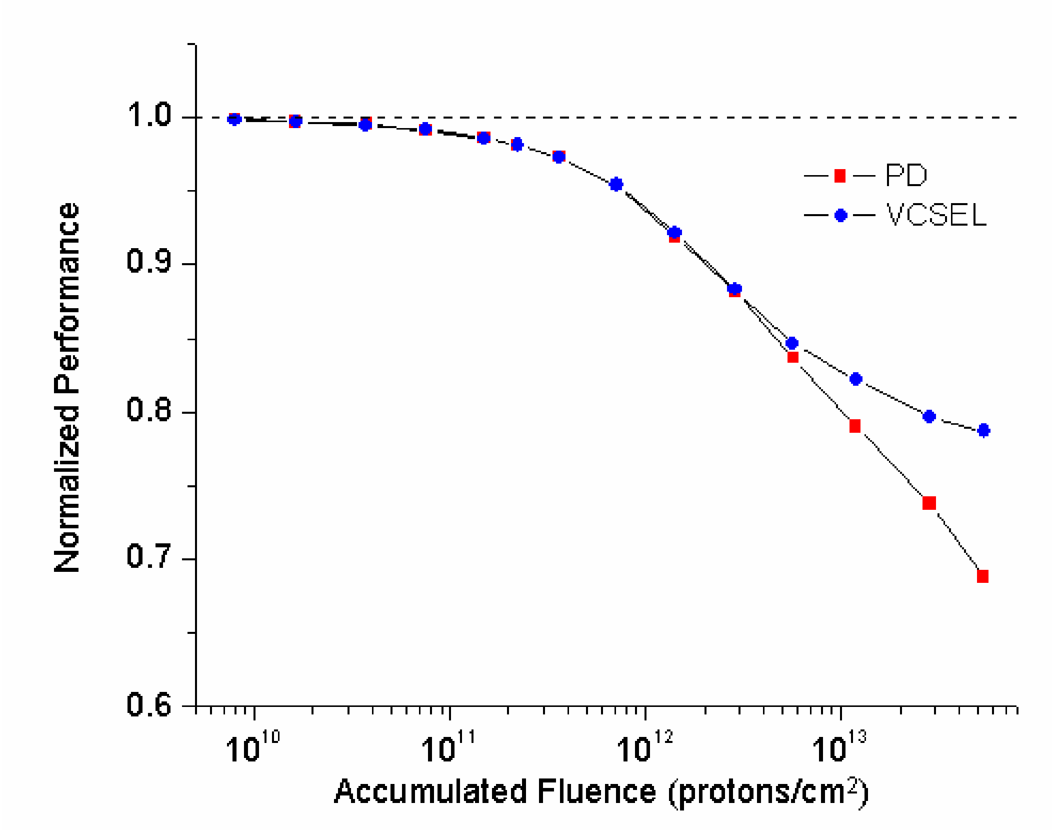

Figure 3.3. Normalized detector response with coupled VCSEL biased at 4 mA. Blue circles indicate irradiation of VCSEL in VCSEL-photodiode (PD) pair and red squares indicate irradiation of photodiode in VCSEL-photodiode pair.

A separate measurement of total dose effects was performed using optocouplers, or coupled VCSEL-detector pairs. The GaAs photodiodes were provided by Peregrine Semiconductor attached to a circuit board with traces and a ribbon connector. The photodiodes labeled GaAs1 and GaAs2 in figure 3.4 were manufactured by Emcore and had a roughly 70 µm diameter aperture. We believe GaAs3 and GaAs4, with similar aperture size, were manufactured by AXT. We attached VCSELs above these detectors and placed both in the proton beam. We also attached VCSELs above silicon photodiodes (EG&G FND100) to obtain a comparison between Si and GaAs photodiodes.

The degradation of signal obtained from the optocouplers is shown in figure 3.4. The noise in the measurement was due to low optical coupling (VCSELs were placed above detectors without coupling lenses) and noise due to RF pick-up. At a total fluence level of 5×10^{13} protons/cm^2, the optocouplers labeled GaAs1 and 2 experienced about 45% decrease in signal, GaAs3 and 4 experienced a 55% reduction in signal, and Si1 and 2 experienced a 75% reduction in signal. From the proton measurements described above, the individual VCSEL experienced a decrease in output power of 20%. Since the VCSELs for each measurement were nearly identical, we can infer that the GaAs1 and 2 photodiodes experienced a reduction in responsivity of about 30%, GaAs3 and 4 experienced a reduction in responsivity of about 45%, and Si1 and 2 experienced a reduction in responsivity of about 70%. Dark current for the Si photodiodes was about 1 nA at the highest fluence level and the dark current for the GaAs photodiodes was below our ability to measure (about 0.1 nA).

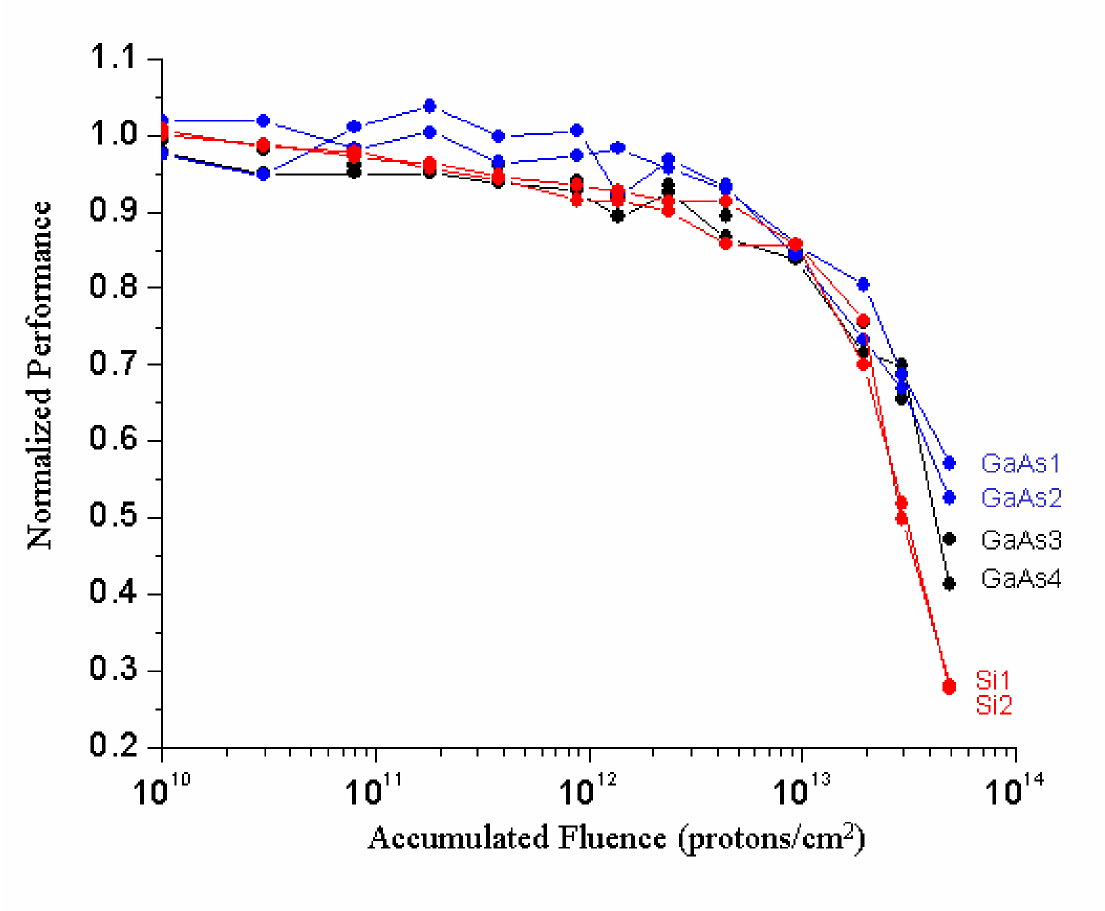

Figure 3.4. Normalized optocoupler (VCSEL-photodiode pair) response with increased proton fluence level. Plots labeled 'GaAs' refer to optocouplers containing GaAs photodiodes and plots labeled 'Si' refer to optocouplers containing Si photodiodes.

3.2. Neutron Irradiation

Neutron radiation measurements were performed at the Army Pulse Radiation Facility located on Aberdeen Proving Ground in Maryland. Devices measured included four GaAs photodiodes that were attached to a circuit board and provided by Peregrine Semiconductor. Two of the GaAs photodiodes were manufactured by EMCORE (GaAs1,2) and two we believe were manufactured by AXT (GaAs3,4). These detectors are presumably identical to those described in the proton measurements above. We also irradiated silicon photodiodes (EGG&G FND100), and GaAs VCSELs that were attached above silicon photodiodes. All the devices were placed a specific distance from the fission source in order to experience a desired fluence level. The fluence levels reported below are 1 MeV equivalent values for silicon. The silicon photodiodes were reverse biased at 10 V and the GaAs photodiodes were reverse biased at 1 V.

After irradiation, the photodiodes were placed into a test station consisting of a 850 nm VCSEL and a coupling lens that experienced no radiation. The response of these photodiodes as well as that of a reference silicon photodiode that was not irradiated was measured. The response of the VCSEL-Si photodiode pairs were also measured, though in this case, the degradation of the VCSEL alone must be determine by comparing to the degradation of the pair to the degradation of the individual Si photodiodes. The normalized response for each detector or VCSEL-detector pair with increased accumulated fluence (1 MeV eq., Si) is shown in figure 3.4. The reference photodiode stays near 1.0 so we only normalized the performance of the other devices relative to their response before irradiation.

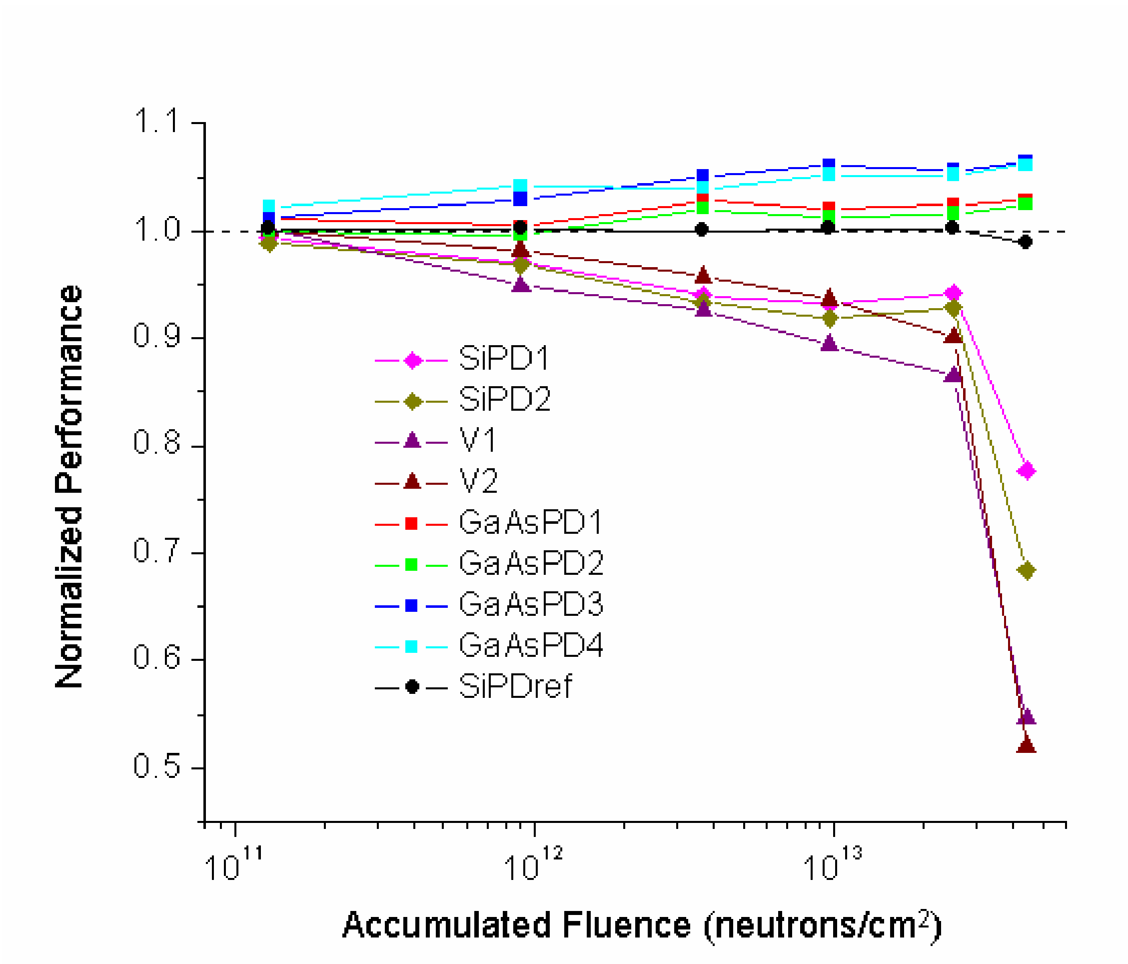

Figure 3.4. Normalized performance of two Si photodiodes (SiPD1,2), two VCSELs coupled into Si photodiodes (V1,2), four GaAs photodiodes (GaAsPD1-4) and a reference Si photodiode that was not irradiated (SiPDref). The fluence levels are 1 MeV equivalent silicon levels.

The silicon photodiodes as well as the VCSEL-silicon photodiode pair show clear degradation with increasing neutron fluence, especially above $2x10^{12}$ neutrons/cm^2 (1 MeV Eq., Si). The GaAs detectors, however, show a slight increase in responsivity with increasing fluence. This increase in responsivity needs further investigation but may result from a known increase in GaAs absorption near the band edge with increased neutron fluence [10,11]. After the total fluence of $4.4x10^{13}$ neutrons/cm^2, the silicon photodiodes had a leakage current of about 2 μA (compared to a signal of about 400 μA with laser on) and the GaAs photodiodes had a leakage current less than 1 pA (compared to a signal of about 30 μA with laser on). Since the Si photodiodes experienced a roughly 30% degradation and the VCSEL-Si photodiode pair experienced a roughly 50% degradation at the highest fluence level, we can deduce that the VCSEL experienced a roughly 30% decrease in output power.

3.3. Total Radiation Dose Conclusions

In conclusion, we measured the effects of proton and neutron total dose on the performance of photodiodes and VCSELs. With irradiation of 63 MeV protons at fluence levels up to $5x10^{13}$ protons/cm^2, our GaAs based VCSEL experienced a reduction in output power of about 20% and an increase in threshold current of 10%. The GaAs-intrinsic region photodiode experienced a reduction in responsivity of about 30%.

We irradiated GaAs photodiodes and VCSELs and Si photodiodes with neutrons from a fission source. At a total fluence level of $4.4x10^{13}$ neutrons/cm^2 (1 MeV Eq., Si), the Si photodiodes and the GaAs photodiodes both experienced a roughly 30% decrease in performance. The GaAs photodiodes, however, showed a slight increase in responsivity, perhaps due to a slight increase in GaAs absorption. The Si photodiodes experienced an increase in dark current to about 2 μA and the GaAs had a dark current lower than we could measure (less than 1 pA).

4. Summary

During this one-year LDRD, we have investigated the effects of radiation on the performance of GaAs based photodiodes and VCSELs, with a focus on single-event transients. Previous total-dose studies have indicated that GaAs optoelectronics are sufficiently radiation hard for most space-based applications. Our investigations support this conclusion. Though single-event transients will occur in GaAs photodiodes, transients of sufficient amplitude to lead to a bit error will be infrequent, and little degradation in digital data in an optical link will be experienced.

The proton-induced transient measurements were performed with a 63 MeV proton source. Amplitude and temporal statistics for proton-induced voltage pulses in our photodiode were measured. No single-event transients were measured with the VCSEL irradiated and therefore it can be assumed that the transients are negligible. With the photodiode irradiated, we believe that most of the proton-induced current pulses were too small to be measured and therefore insignificant. Pulses large enough to lead to bit errors in a digital system were infrequent. With a 2.5 Gb/s digital receiver including a GaAs photodiode, we calculated an expected bit-error rate of 10^{-11} for a proton flux of $1.0x10^{6}$ protons/cm^2-s, or a bit-error rate of 10^{-14} for a more realistic satellite-orbit average proton flux of $1.0x10^{3}$ protons/cm^2-s. As the bit-rate in an optical data system increases, the likelihood that a high-energy proton will lead to a bit error will increase. Whether this will increase the bit error rate or not will depend on the spectrum of deposited energy from the proton as well as the decision current threshold in the digital receiver circuit.

Total dose measurements on GaAs based photodiodes and VCSELs using both protons and neutrons confirmed the general wisdom that these devices are radiation hardened. At a typical satellite lifetime accumulated proton fluence level of 10^{11} protons/cm^2, our photodiode and VCSEL only experienced a few percent degradation in performance. At a total fluence level of $5x10^{13}$ protons/cm^2, photodiode responsivity dropped by 30% and VCSEL output dropped by 20%. When irradiated by neutrons, VCSEL output dropped by 30% with a total fluence of $4x10^{13}$ neutrons/cm^2 (1 MeV Eq., Si) and the photodiode responsivity increased by a few percent, perhaps due to increased GaAs absorption.

Since GaAs photodiodes and VCSELs are shown to be radiation hard regarding both total dose as well as transient effects, it may be that performance of an optical link is limited by the transmitter and receiver electronics, so care should be taken to ensure radiation hardness of the total optical data link.

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