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Investigation of Radiation Damage in the SLD CCD Vertex Detector

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Abstract — **Early in the operation of the SLD CCD vertex detector (VXD3) at the SLC, radiation damage to the CCDs was observed. It is well known that low energy light particles (electrons and photons) are a few orders of magnitude less effective than heavy particles (neutrons or heavy charged particles) in the generation of radiation damage effects in silicon. The SLD environment was known to be dominated by electrons and photons with a small fraction of neutrons. The estimated radiation damage by these particles can not account for the observed damage. Therefore, this damage is puzzling.**

A CCD based detector is a leading option for vertex detection at the future linear collider. A full understanding of background models in linear colliders and the associated damage is needed.

Earlier results on neutron damage to an SLD CCD were reported at the 1999 IEEE NSS, and these new results complement our old results. In addition to tests on controlled exposures of individual CCDs, we have studied the nature of the traps produced in the SLD vertex detector to assess their origin - heavy or light particles?

I. Introduction

The SLD CCD based vertex detector [1] has achieved outstanding performance. Such a detector is ideally suited for the requirements of vertex detection at the future high energy linear collider (LC). However, CCDs are known to be much more sensitive to radiation damage than other silicon detectors, due to the long charge transfer path within silicon from the point of generation to the output of the device. Additionally, signals generated within a CCD are about 20 times smaller than in a microstrip detector since the sensitive thickness of the CCD is so much thinner. These factors lead to an estimation of maximum allowable exposure of the CCD to neutron irradiation of the order of 10^9 – 10^{10}n/cm^2, while microstrip detectors are expected to operate up to 10^{13} n/cm^2 and higher.

The estimated neutron fluence in the future linear collider may exceed 10^9n/cm^2 per year, and the electron/positron background in the inner layer of the vertex detector is expected to be more than 10^{11} particles/cm^2 per year. This demands a careful examination of all of the factors involved. One needs to understand the accuracy of background calculations, the effect of different types of backgrounds on generation of radiation damage, and the effects of radiation damage on detector performance. This report presents recent results of such measurements, performed on the CCDs which operated in the SLD VXD3 for about 3 years, and suffered some degree of radiation damage early in its operation. Comparison is made to spare CCDs of the same type, which were later irradiated with known amounts of neutrons and high energy (60 MeV) electrons. This work continues the investigation of radiation damage effects in CCDs reported earlier in [2]. Radiation damage effects in silicon detectors have been extensively discussed in the literature [3], [4].

The effects observed in our work are due to displacement damage in the silicon. The chain of events, following release of a knock-out silicon atom, leads to creation of silicon-impurity complexes, or other non-mobile objects, like the bound two-vacancy complex. Some of these objects can capture minority carriers (electrons in the n-channel CCD) long enough to remove them from the charge packet, resulting in charge transfer inefficiency. In the following discussion we will refer to such objects as traps. Each trap can capture one and only one electron. With time, which depends on the detector temperature, trapped electrons are released, recreating an empty trap.

When the energy of a knock-out silicon atom is large enough, a cluster of such traps can be created in a compact region of the size of order 0.1 μm.

II. Method

In order to distinguish the effects of electrons and photons from those of neutrons, two methods have been employed.

The first method was described in [2]. Briefly, the “flat light field” technique is used to generate a small charge (about 30 e$^-$) in every pixel of the CCD. In the damaged pixels some of the

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charge is collected by the traps. A decrease in the readout signal from these pixels is observed. Because this decrease is much smaller than the electronics noise, the measurement is repeated many thousands of times to reduce the average noise value to about one electron of charge.

In this method, the individual damaged pixels are identified and the loss of charge can be determined. Since all traps in every pixel are filled by signal light, no additional loss happens during readout of the signal, and therefore no additional correction for charge transfer inefficiency is applied for remote rows.

The first method works well with neutron induced damage, where one usually finds clusters of traps. A pixel containing such a cluster will show a significantly reduced signal compared to its neighbors. Thus, such pixels are easily distinguished from undamaged ones.

However, electron irradiation results in distributed individual traps, and many more pixels may be damaged. While the small loss of charge on each individual pixel is very difficult to detect, the accumulated loss of charge due to the charge transfer inefficiency (CTI) over many pixels, is more sensitive. One could use the signal from a radioactive Fe^{55} source, for example, and measure the change in the observed signal as it passes along a column of the CCD.

The second method is based on this approach, but with a more convenient source: a narrow line of light directed on the CCD surface. Ideally this line should be parallel to a row of pixels on the CCD. However, the absence of a reset after each pixel in our readout, forces us to orient the line at an angle to the row, to generate the signal in just a few pixels in each row. The propagation of the generated signal is then observed. This method has the advantage of a known time of the signal generation. It enables the comparison of the measurement under two different test conditions:

1.) The first measurement is made after all the traps are saturated with a “sacrificial charge” (a specially generated large charge of about a thousand electrons in every pixel). This charge is removed by a fast cleaning process (shifting the image from the CCD without reading out the output register), followed immediately (total delay between charge generation and signal pulse is 33 milliseconds) by a signal pulse. The method of a sacrificial charge injection was proven to work in [2].

2.) The second measurement is made for a signal generated after all the charge is removed from the CCD by continuously shifting the image from the CCD for a long period (1 sec), when all the traps should be empty. All measurements were made at -73° C.

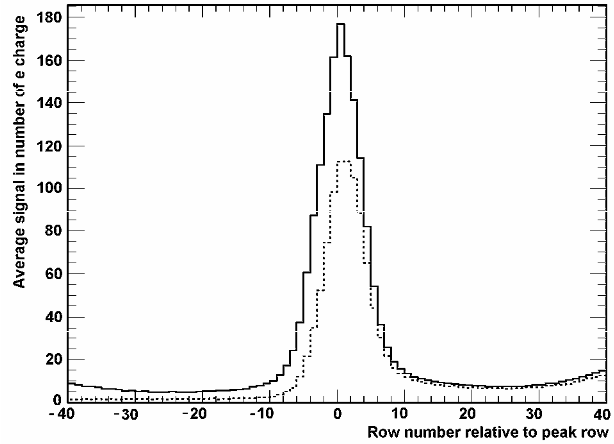

Fig. 1. Average (over 400 columns) signal value from thin line light pattern as function of row number. The larger signal corresponds to the case when all traps are filled, and smaller signal is observed when all traps are empty.

The difference between these two measurements (as seen in Fig. 1, which represents measurements with a CCD from the VXD3 detector) indicates how many traps the signal has encountered between the generation point and the output register of the CCD. This measures the integral of the loss to the traps even if they are small and uniformly distributed. The tails on this plot are due to reflection of the light from collimator walls, which were not perfectly black. These reflections had small maxima at about 50 rows before and after the maximum of the collimated light. It is interesting to observe, that the negative tail disappears in the case of empty traps. It shows that this small amount of charge is completely trapped. But after passage of the maximum (large amount of charge) all traps are filled, and there is no trapping seen on the positive tail.

The number of traps observed in each of the two methods above can be compared. The expected signal degradation is calculated as the number of traps along a column (“expected loss”). The number of traps in individual pixels is measured by the first method. The integral signal loss (“observed loss”) is measured by the second method. If the damage has resulted from neutron inflicted damage, one expects relatively good agreement, as seen in Fig. 2 where we analyze the data reported previously [2]. This is true since most of the damaged pixels in this case have large signal losses and so are easily identified by the first method. However, for electron inflicted damage, it is unlikely that the charge loss in individual damaged pixels is significant. The effect is only observed by measuring the integrated attenuation.

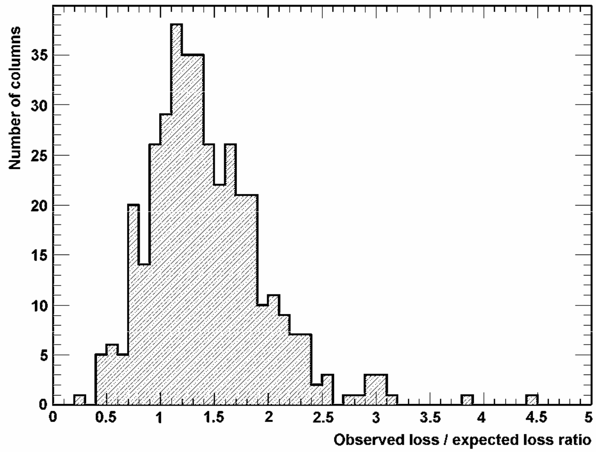

Fig. 2. Ratio of observed signal loss in each CCD column to the expected loss in the same column for neutron irradiated CCD. Expected loss is calculated by counting all traps observed in individual pixels and includes only pixels with number of traps greater than 4. The mean value of the distribution (1.43) is close to 1, as expected from the model .

III. Experiment with Electron Beam

We performed an irradiation of a spare VXD3 CCD by the electron beam of the Next Linear Collider Test Accelerator (NLCTA) facility at SLAC [5]. The energy of the electrons was 60 MeV, and the total dose corresponded to about 10^{12} e/cm^2. Observation of the damage resulting from this irradiation confirmed our ability to distinguish between neutron and electron inflicted damages by the method described above.

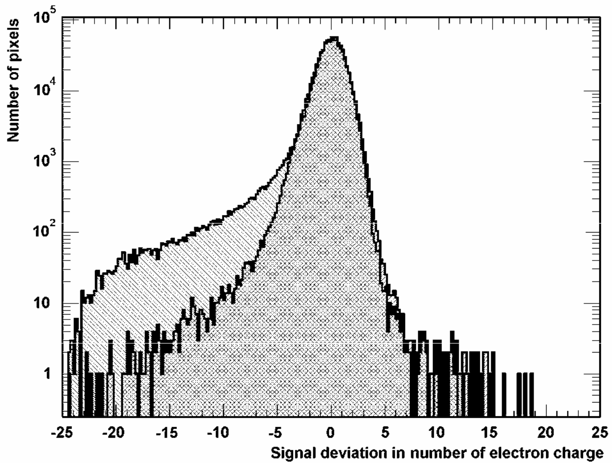

Fig. 3. Deviation of the signal from individual pixels from the average of 24 surrounding pixels. The upper curve corresponds to damage created by neutron irradiation while the lower curve corresponds to damage from electron irradiation.

The CCD used in this test was the same as was used in the neutron damage study reported in our previous publication [2]. The additional signal loss after an exposure to the electron beam was about the same as that generated by the neutron irradiation (5×10^9 n/cm^2).

Fig. 3 shows the comparison of the deviation of the signal from individual pixels from the average signal of 24 neighboring pixels for the neutron and electron irradiated CCD. As expected from the model ([3],[4]), electron irradiation creates a smaller number of pixels with a large number of traps, than neutron irradiation. The distribution for electron irradiation is obtained by removing from consideration pixels with clusters of traps, identified after neutron irradiation which preceded electron irradiation. We checked this method by applying it between multiple neutron irradiations – in that case the shape of the distribution remained unchanged.

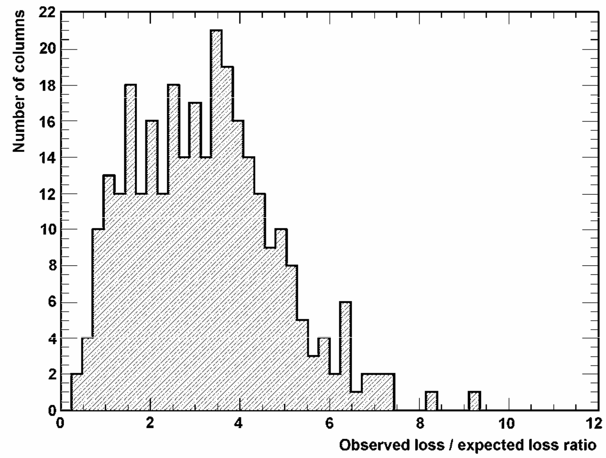

Fig. 4. Ratio of observed signal loss in each CCD column to the expected loss in the same column for the CCD irradiated both with neutrons and with electrons. Expected loss is calculated by counting all traps observed in individual pixels and includes only pixels with number of traps greater than 4. The mean value of this distribution is 3.23

Fig. 4 shows the same parameter (the ratio of observed to expected loss in the CCD columns) as in Fig. 2, but for the combined neutron and electron exposure.

The mean value of the distribution has increased compared to pure neutron irradiation because the signal loss doubled, while the number of pixels containing large numbers of traps changed very little. Consequently, this ratio can be very large for CCDs exposed to only electrons or photons. We do not calculate exactly what value of this ratio we should expect, because we don't have a sophisticated model of trap cluster formation. Low energy electrons have a very low limit on the energy transferred to a nucleus, and this excludes the creation of multiple traps in one pixel volume. In that case the value of the parameter may approach infinity. Alternatively, for the very high energy electrons we may expect values closer to what we have from neutrons (however, the momentum dependence of the maximum energy transfer to a nucleus for electrons reaches plateau at about 30 MeV and at this energy it is still very different from neutrons).

IV. Annealing

Before disassembling VXD3 and making measurements on its CCDs, the damage observed during the SLD experiment six years ago has been reassessed.

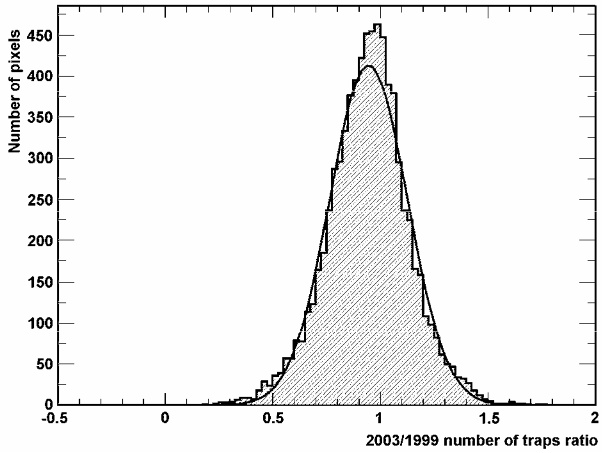

Fig. 5. Ratio of the number of traps in each damaged pixel of a spare CCD observed in the 2003 measurement to the number of traps in the same pixel from the 1999 measurement.

In [2] we concluded that most of the observed traps (at the working temperature of about 190° K) in the neutron irradiated spare ladder were VP complexes. The model of radiation damage effects in silicon used in [6] predicts that such complexes should anneal at room temperature with an annealing time of less than one year. If this were true, the traps would have annealed by now. To check this expectation, the neutron damaged CCDs reported in [2] were re-investigated. Fig. 5 shows that there does not appear to be significant annealing in the four years since these CCDs were exposed in 1998-99.

The amount of observed damage in 2003 is at least 94% of what was seen in 1999. Our conclusion on the nature of the damage being VP complexes could be wrong, or the annealing time constant for VP complexes at room temperature might be longer than one year. In any case, we should not expect significant annealing of the VXD3 radiation damage, as it was created not more than 6 years ago.

V. Nature of the VXD3 Damage

The SLD Vertex Detector (VXD3) was disassembled early in 2003. The detector was split into its two half-barrels to get access to the innermost CCDs, which encountered the most significant damage. The measurements which had been performed on a spare CCD were repeated on the VXD3 CCDs.

Fig. 6 shows the distribution of the observed to the expected signal loss ratio, similar to what was shown in Fig. 2 and Fig. 4 for the spare CCD. The large mean value of this ratio (23.7) indicates that damage in the VXD3 detector was created by light particles (electrons or photons). Less than 5% of the total damage effect can be attributed to neutrons or other heavy particles.

We can assume that a large amount of electromagnetic radiation could have irradiated the VXD3 CCDs during an accident in the SLC damping rings, when undamped beams were allowed to pass through the detector.

The amount of damage is similar to that we observed in the experiment described in section III. That means that about 10^{12} electrons/cm^2 has passed through inner layer CCDs during this accident.

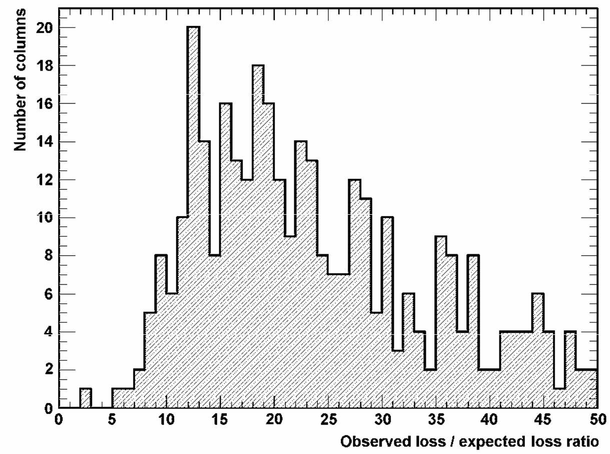

Fig. 6. The ratio of observed signal loss in each CCD column to the expected loss in the same column for the VXD3 CCD. Expected loss is calculated by counting all traps observed in individual pixels and includes only pixels with number of traps greater than 4. The mean value of this distribution is 23.7

VI. Other Results

In the process of our investigation we have observed an effect which was not reported (to the best of our knowledge) in other papers about radiation damage in CCD detectors. We present this observation and its possible interpretation here.

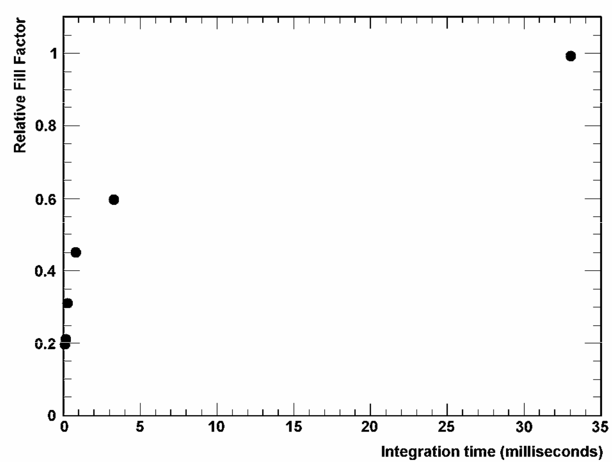

Fig. 7. Number of traps observed in the damaged CCD pixel (normalized to the value at 33 milliseconds) as a function of time charge packet sits in the location of the pixel.

It is well established in the theory of radiation damage effects, that the time required for a charge trap created by radiation damage to capture an electron from the signal charge packet passing through the location of the trap is of the order of 1 μsec or less. However, as we have observed, the number of traps detected by the above described method depends on the time the signal charge spends in the location of damaged pixel up to about 30 milliseconds. This time is larger than predicted by theory by at least 4 orders of magnitude. Fig. 7 illustrates this observation.

We think that this effect can be explained if one assumes that traps outside the charge containment volume can capture electrons. This may result from the long range tail of the electron wave function extending inside the potential barrier (tunneling effect). The wave function is exponentially falling with distance from the containment volume, and leads to a very low, but non-zero, probability for an electron to be captured in this region.

Another possible explanation arises from the electron energy distribution, fixed by the temperature. Since the potential in the charge transfer channel has a parabolic shape, higher energy electrons occupy a larger volume. The highest energy levels have a very low population density, which also can lead to a low capture probability for the traps, accessible only by such higher energy electrons.

In fact, both effects (tunneling and the electron energy distribution) may be working here.

The observed effect could play an important role in the radiation hardness of the CCDs because it leads to a decrease of the charge transfer inefficiency (CTI) due to radiation damage with increased readout speed. For example, the readout time of the CCDs planned for the NLC/JLC design for the future linear collider would be about 30 times less than for the VXD3 detector at the SLC. This would lead to a three times higher radiation tolerance for the CCDs used in VXD3. This estimation is based on the following considerations:

1) At the VXD3 readout speed, charge spends 100 μsec under each pixel. Because of ≈50 times higher charge density in the MIP charge packet compare to our experiment with uniform light, the relative fill factor in that case would correspond to the 5 milliseconds point in Fig. 7. The relative fill factor at this point is about 0.65

2) The readout which is 30 times faster corresponds to the 0.17 milliseconds point on Fig. 7. Relative fill factor at this point is about 0.22, which is 3 times smaller than 0.65 for VXD3.

VII. Conclusions

Our measurements indicate that the VXD3 CCDs experienced degradation of performance due to radiation damage at a neutron fluence of 5×10^{9} n/cm^2 and at a high energy electron fluence of about 10^{12} e/cm^2. This is close to the estimate of expected background levels for the future linear collider. Increased radiation tolerance of CCD detectors will be needed.

In Ref. [2] we demonstrated that the method of “sacrificial charge injection” can increase radiation tolerance at least by a factor of 10. The use of a “notch channel” can, we believe, give another factor of 5. Increased readout speed, as was shown here, can increase radiation tolerance by a factor of 3. Altogether we can improve the tolerance by two orders of magnitude with these three improvements. Further investigations are needed to demonstrate this, and the feasibility of a CCD based vertex detector for the future linear collider.

VIII. Acknowledgment

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IX. References

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