Operation of a CCD particle detector in the presence of bulk neutron damage

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Abstract

The use of CCDs in future linear collider experiments will require immunity to large neutron fluences, in excess of $10^9/cm^2$/year. The effects on charge transfer efficiency of neutron induced bulk damage are presented along with a demonstration of a technique to fill the traps with sacrificial charge. Operation is then possible at fluences in excess of $10^{10}/cm^2$.

I. INTRODUCTION

Physics studies for future linear colliders have demonstrated the importance of good flavor tagging. [1] New physics opportunities may be abundant at a future linear collider, and the tracking concepts developed for the SLD experiment using CCDs [2] provide an excellent basis for designing the vertex detector which will capitalize on these physics opportunities.

The SLD vertex detector, built from 96 large area (13 cm^2) CCDs, has demonstrated exceptional performance in the measurement of secondary vertices associated with the weak decays of heavy quarks. [2] Single point precision of about 3.5 microns over 307,000,000 pixels has been achieved. This is unmatched by any other vertex detector technique. It leads to very pure heavy flavor tagging: 98 percent purity with 50 percent efficiency.

The CCD vertex detector being conceived for a future linear collider [3] would achieve even better performance. A 5-barrel system, with generous radial spacing of the barrels extending from 12 mm radius (barrel 1) to 60 mm (barrel 5), enables efficient stand-alone tracking. Tracks could be found in barrels 2-5, and extrapolated in to barrel 1 for linking and improved resolution. One key to performance would be advances in ladder design, building on the VXD3 experience. One can imagine a ladder thickness of $\sim\ 10^{-3}X_0$, partially resulting from further thinning of the CCD, perhaps to 30 μm. Further improvement in performance would result from increasing the readout speed, where the achieved 10 MHz rate might be increased to 50 MHz. This increase would result from moving the drive pulse generation right to the CCDs. The anticipated impact parameter resolution at the IP is:

$$\sigma_{xy} = \sigma_{rz} = 3\ \mu m \oplus \frac{10\ \mu m}{\mathrm{p}\ \sin^{\frac{3}{2}}\theta} \tag{1}$$

Excellent flavor separation follows from the topological classification possible with the precise measurements of the CCD vertex detector, as well as the excellent kinematic differences measureable with it. These techniques have been demonstrated at SLD [4], and follow from the superb resolution and the ability to do nearly full reconstruction. Heavy quark tagging performance is strongly dependent on the vertex detector resolution.

One important requirement of the future linear collider vertex detector which allows the inner CCD barrel of 12 mm radius is a strong field solenoid (3-6 Tesla) to constrain to a small radius the intense flux of e^+e^- pairs generated by the beam-beam interaction. Such solenoids are included in future linear collider detectors under study.[5]

Large neutron fluences are expected in the interaction regions of future linear colliders. The use of CCDs will require immunity to these large neutron fluences, expected to exceed $10^9/cm^2/year$ at the X-band Linear Collider, for example. [6] Therefore, measurements of and countermeasures to the effects on charge transfer efficiency of neutron induced bulk damage is extremely important. We have investigated the effect of neutrons on a CCD of the SLD design, and demonstrated a technique to reduce the impact of the damage on performance.

II. NEUTRON DAMAGE STUDIES

The bulk damage to the silicon, introduced by the irradiation with neutrons accompanying normal operation of a CCD in a future collider, will manifest itself in the creation of charge traps. Charge packets, created by ionizing particles in the CCD detector, must travel long paths (centimeters) before they can be registered on the output node. If there are locations along these paths where electrons are trapped and held for considerable time (exceeding the time of transfer of the packet from one pixel to another), than the amplitude of the signal (charge in the charge packet) will be reduced. If there are many such traps on the way, even small losses can render the signal undetectable.

We have exposed a spare SLD vertex detector CCD to neutrons in three steps. First it was exposed to $2.5\times10^9\ n/cm^2$ from a Pu(Be) source. These neutrons had an average energy of about 4 MeV. Next, it was exposed to $3\times10^9\ n/cm^2$ from a reactor. [7] Finally, it was exposed to $1.5\times10^9\ n/cm^2$ from the reactor while kept cold, at about 200K. The average energies of the reactor neutrons were about 1 MeV. Tests were conducted following each of these exposures, and an annealing phase was attempted following the first exposure.

To investigate the neutron induced damage, we used a “flat light field” technique. We illuminated the tested CCD with light from a light emiting diode (LED), generating the same amount of charge in each pixel. With this technique we can observe the pixels where charge traps are present after reading out the signals from the CCD - such pixels have a smaller charge registered. We are concerned about even small loss of charge in each pixel, since the typical signal from a minimum ionizing particle is about 1000 electrons and the most distant packet must travel through 2000 pixels in the SLD vertex detector. To achieve sensitivity to small losses in the presence of an electronics noise of about 60-100 electrons, we repeated the measurements more than 10,000 times and averaged the response. This reduced the effective noise level of the measurements below one electron charge.

The effect of the charge traps on the charge transfer along the CCD may be reduced, if not completely eliminated, by filling the traps with a sacrificial charge prior to the passage of a charge to be measured. At low operating temperatures (below 200 K) the lifetime of the bound electrons caught in a charge trap become very long (exceeding a second). The trap remains filled for a long enough period of time to pass a charge packet through the trap's location. This effect may be used to fill all the traps in the CCD by sweeping it with artificially created charge packets (injected in the last row, for example) through the CCD prior to the appearance of signals from ionizing particles. Our test CCDs did not have this ability built-in, but we could simulate the sweeping charge with a light flash. We created charge (about 600 electrons) in every pixel with a higher intensity light, and swept this charge through the CCD. After waiting a controlled period of time, we measured the transfer efficiency with the flat light field of about 25 electrons per pixel. This allows us to measure the lifetime of the bound state of electrons in the traps. It may also be used to determine the nature of the defects creating the traps, because the lifetime depends on the bound state energy level, which is different for different types of defects.

Figure 1 shows the distribution of charge measured in each pixel before and after exposure to neutrons, operated at 215K. The mean has been subtracted, so that deviations from zero are a combination of electronic noise, illustrated by the superimposed gaussian, and bulk defects. The increased loss of charge with the neutron exposure of $2 \times 10^9\ n/cm^2$ is clear.

This loss of charge transfer effect may be significantly reduced by the sacrificial charge technique. Figure 2 shows the result of applying a sacrificial charge to the CCD following its exposure to $2 \times 10^9\ n/cm^2$. In this case the CCD is operated at 185K, which suppresses the transfer losses from those seen in figure 1.

Table 1 summarizes the results of our studies with a count of the number of defects per 800,000 pixels. Smaller defects of greater than 6 electrons charge, as well as those greater than 20 electrons are included in the table.

We have also made measurements with a radioactive source (Fe-55), which produces a charge signal close to that of a minimum ionizing particle. At the higher level of irradiation, the signal loss from charge transfer inefficiencies of the charge from an Fe-55 exposure with the sacrificial charge technique was 11% at 178K. This loss was exaggerated by the test set-up employed, since following the pulse of sacrificial charge, a delay of a second passed before the Fe-55 exposure could be completed and readout. In actual operation at a linear collider, much less time would pass between charge injection and readout. We estimate that the CCDs can operate efficiently up to and just beyond $10^{10}\ n/cm^2$. Further tests are needed to establish the upper limit of operation.

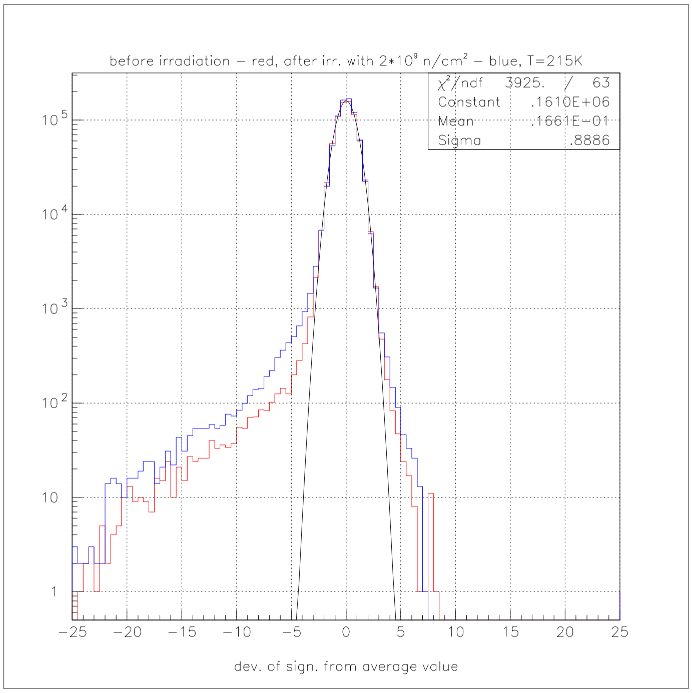

Fig. 1 Deviation from the mean (in electrons) of charge collected at 215 K, before (lower histogram) and after (upper histogram) exposure to $2 \times 10^9 n/cm^2$.

Another test was made to investigate the nature of the defects: baking of damaged CCDs to anneal the damages. Table 2 lists the defect states considered to be most important in irradiated silicon detectors[8], along with the characteristic annealing temperatures.[9] Some defects (such as vacancy-phosphorus (VP) complexes) should anneal at about 150° C. Though the support structure of our CCD ladder could not survive heating to 150° C, we did heat it to about 110° C. We observed slow annealing during the 35 day test. This is illustrated by Figure 3. The long term annealing has a time constant of about 72 days. However, the lifetimes of the traps did not change. This is illustrated by Figure 4. Since vacancy-phosphorus (VP) complexes are the most likely traps to anneal at low temperature, and a single dominant trapping mechanism is implied by the unchanged trap lifetimes, we postulate the damage is dominated by vacany-phosphorus (VP) complexes.

Further investigations of the nature of the traps supports the dominant role of the vacany-phosphorus (VP) complexes. The trap lifetimes are temperature dependent, and by measuring the lifetime at different temperatures, an effective trap energy level can be extracted. The trap lifetime scales with the trap energy (E) and temperature (T) as

$$\tau \sim exp((E_C - E)/kT),$$

where E_C is the conduction band energy level. Then the ratio of lifetimes at two temperatures reveals the effective trap energy:

$$E_C - E = ln(\tau_1/\tau_2)kT_1T_2/(T_2 - T_1).$$

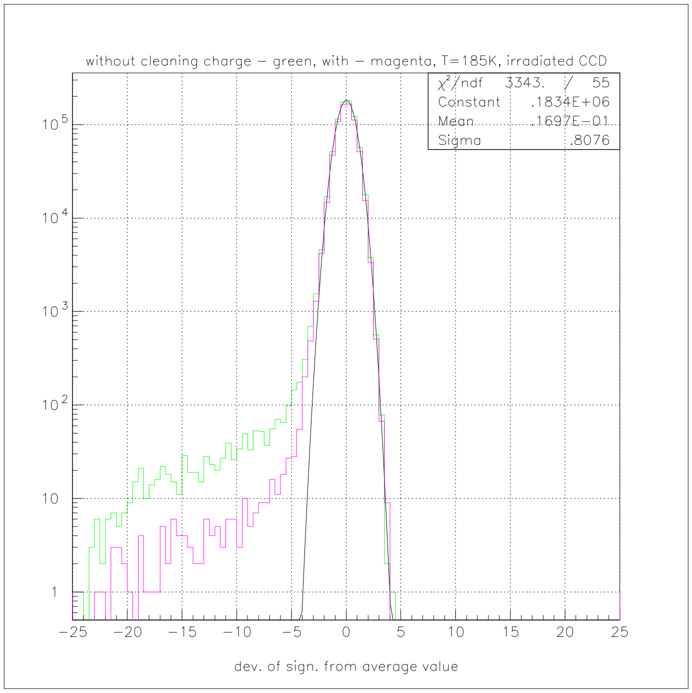

Fig. 2 Deviation from the mean (in electrons) of charge collected, after exposure to $2 \times 10^9 n/cm^2$, with (lower histogram) and without (upper histogram) the sweeping charge to fill traps. Operating temperature of the CCD is 185 K.

Measurements at 202K (Figure 4) and 191K produced a trap energy E of $E_C - 0.45$ eV, consistent with the vacany-phosphorus (VP) complex dominance

Finally, as mentioned above, the third exposure was conducted with the CCDs cooled to about 200K. This tests whether the defect creation rate is different at the detector operating temperature of about 180K. The defects which create the traps result from the diffusion of knock-out ions and vacancies and their combination with impurities in silicon. The defect creation process is complicated, and involves competing effects. Different temperatures may create advantages for some effects over others, affecting the rate of trap creation. We conclude from the measurements presented in Table 1 that the defect generation is not larger at cold temperatures. Further investigations under more controlled conditions would be required to conclude that the rate is lower.

Table 1
Defect history (defects in 800,000 pixels)

	Number $> 6\ e^-$	Number $> 20\ e^-$
Prior to Exposure	125	24
Following $2 \times 10^9\ n/cm^2$ (source)	916	160
Additional $2 \times 10^9\ n/cm^2$ (reactor)	5476	442
Additional $1.2 \times 10^9\ n/cm^2$ (reactor)	7036	298†

† This drop in defect count is not understood, but may be related to thermal cycling.

Table 2
Defect levels[8, 9]

Defect	Energy level	Defect state type	Characteristic annealing temperature
VO	$E_C - 0.17$eV	acceptor	350 C
V_2O	$E_C - 0.50$eV	acceptor	
V_2	$E_C - 0.23$eV $E_C - 0.42$eV $E_V + 0.25$eV	acceptor acceptor donor	300 C
VP	$E_C - 0.45$eV	acceptor	150 C
CC	$E_C - 0.17$eV	acceptor	
CO	$E_V + 0.36$eV	donor	

III. SUMMARY

Our measurements have shown that neutron irradiation of vertex detector CCDs with a dose of a few times $10^9\ n/cm^2$ creates noticable effects on the CCD charge transfer efficiency. However, this effect may be significantly reduced by the sacrificial charge technique. We estimate that the CCDs can operate efficiently up to and just beyond $10^{10}\ n/cm^2$. Further tests will establish the upper limit of operation. The main contribution to the trapping defects in the neutron irradiated CCDs from the SLD vertex detector appears to be from vacancy-phosphorus (VP) complexes. The effect of cooling the CCDs during irradiation is not large. These measurements indicate that a CCD vertex detector probably can operate in the environment of a TeV energy linear collider, such as the NLC [10]. Further work on quantifying the expected radiation backgrounds at future linear colliders is called for.

ACKNOWLEDGMENTS

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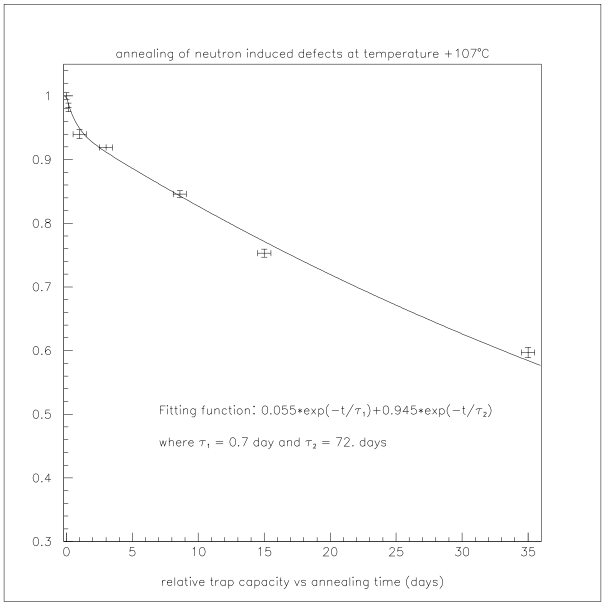

Fig. 3 Relative trap capacity versus annealing time.

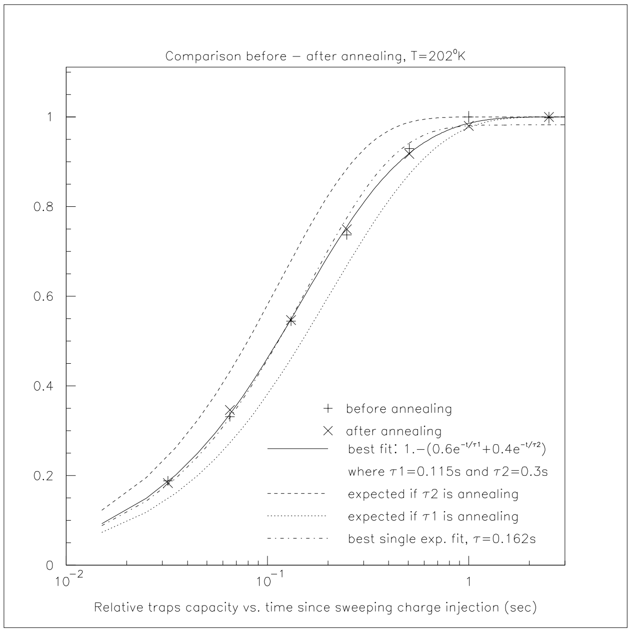

Fig. 4 Relative trap capacity as a function of time since charge injection, before annealing (+) and after annealing (×).

IV. REFERENCES

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