

CCD Vertex Detector R&D for Linear Collider and Radiation Damage Study

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Oregon and Yale groups

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Plan

- Introduction – LC Vertex Detector Challenge
- US CCD Vertex Detector R&D group
 - Composition
 - Goal and plans
- Radiation Damage Study
 - Goal
 - What has been done in 1998
 - Plans and current status

LC Vertex Detector challenge

- Compare to SLD VXD3 detector:
 - Readout time: need to be ~10 times faster for NLC/JLC or ~1000 faster for TESLA.
 - Impact parameter resolution – limited by multiple scattering in detector – need to push to the lowest possible thickness.
 - Radiation damage – backgrounds at new LC will be about 100 times higher. This is the sensitive issue for CCD based detector.

Joint Oregon/Yale group for CCD Vertex Detector R&D

- *People having good deal of experience with CCD detectors - major contributors to the design and construction of the SLD VXD3 detector (along with Rutherford, SLAC and MIT)*
 - Jim Brau – VXD3 project manager
 - Nick Sinev - lead detector physicist for the construction, commissioning and operation of VXD3
 - VXD3 detector was assembled at Yale before final delivery and installation at SLAC
 - The Yale physics group recently built and operated a CCD detector for a Schmidt telescope in Venezuela and is currently completing work on a 112 CCD detector for the Palomar Schmidt telescope (the QUEST project)
- *Resources available:*
 - Experience, engineers, clean rooms, test stands, irradiation facilities

Commitments

University of Oregon:

- Lead role in the radiation hardness measurements of the VXD3 CCDs
- Collaborate with the Yale group in developing commercial silicon fabrication houses to partner in the design and fabrication of CCDs
- Consult with the Yale group in the mechanical engineering designs of the CCD support mechanisms

Yale University:

- Provide support to the Oregon group in the SLD CCD radiation hardness measurement.
(design and construction of fixtures to support CCDs during irradiation, transportation, and measurements, use of the Yale clean room, etc...)
- Take the lead role in developing potential silicon fabrication partners for the design and fabrication of the CCDs.
- The Yale mechanical engineering staff, with CCD detector experience from both the SLD vertex detector and the QUEST project will take the leading role in the preliminary engineering study of the CCD support mechanism.

Outline of Program

Year 1

- *remove CCDs from the SLD vertex detector (VXD3) to study in detail the amount and nature of the radiation damage accumulated over its three years of use*
- **make contacts with silicon fabrication houses to develop potential sources for both the CCDs needed for the R&D program and the eventual detector fabrication**
- **preliminary design studies of the possibility of stretched unsupported CCDs**

Radiation hardness challenge – how to address it

Two types of radiation damage effects:

- Charged layer forms on the silicon-insulator interface because of ions creation in the insulator by ionizing particles
- Trapping centers are formed in the bulk silicon, which remove electrons from the signal charge packet by trapping them and holding for long enough time.

Radiation hardness challenge – how to address it

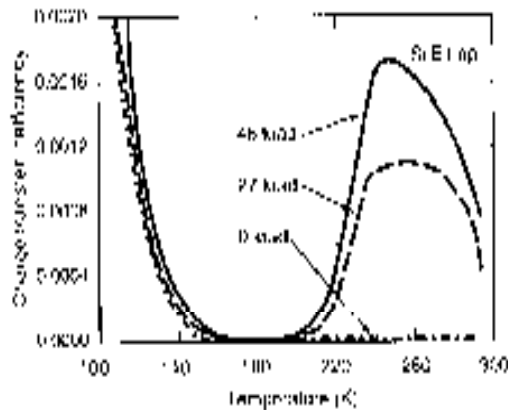
- The ways to reduce interface charge:
 - Reduce the thickness of insulator ($\Delta V \sim t_{\text{ox}}^2$)
 - Use special “radiation hard” types of insulator
 - Keep detector unbiased during heavy radiation conditions (beam tune up)
 - Compensate interface charge effect by adjusting operational voltages
- The ways to reduce bulk damage effects:
 - Reduce the width of the channel in which charge travels along CCD (“supplementary channel”)
 - Use “sacrificial charge” (“fat zero”) technique
 - Properly select detector operation temperature
 - Increased oxygen concentration in silicon used for detector production may reduce generation of trapping centers

Radiation damage study

- The goal is to understand all details of radiation damage effects and develop the way to minimize impact of such effect on detector operation
- Use the VXD3 spare CCDs to study effects caused by neutrons and other particles.
- Use CCDs which operated in VXD3 and sustained radiation damage to verify our knowledge of background conditions in SLD and in general.
- Test CCDs from different vendors made with different technologies to understand technology impact on radiation hardness
- Test CCD prototypes, developed on the basis of our understanding of radiation damage reduction technique .

What different technology could yield: one example

- Charge transfer inefficiency:



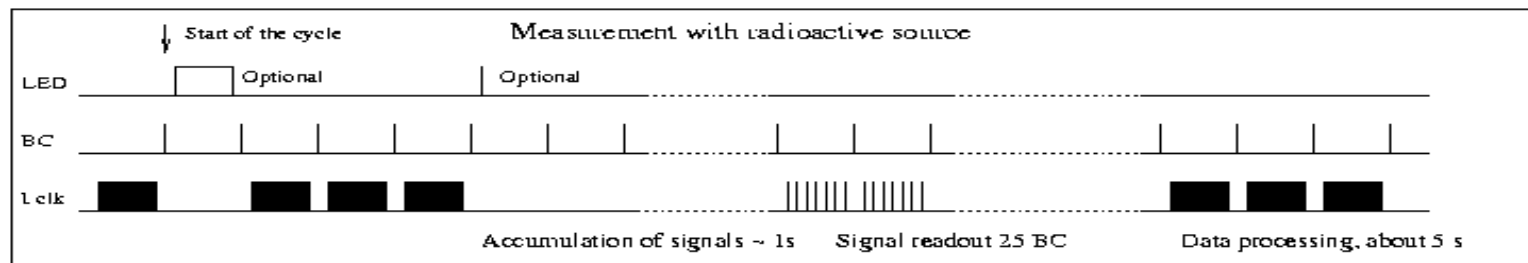
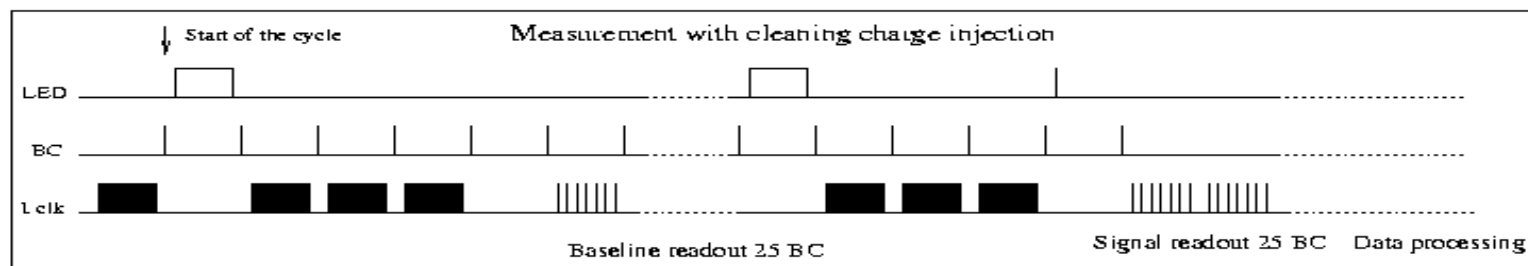
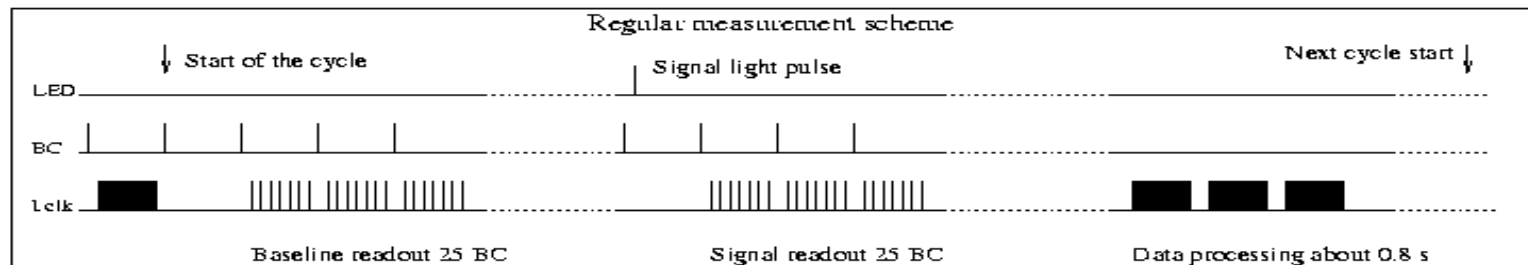
Charge transfer inefficiency as function of temperature from the early measurements of Hopkins (left) and recent of Stefanov (for electron irradiated CCDs – middle and neutron irradiated CCDs – left). Curves on Stefanov plots are calculated assuming two energy levels of defects EC-0.44 and EC-0.37

If we could work at room temperature.... **But Hamamatsu CCD can!**

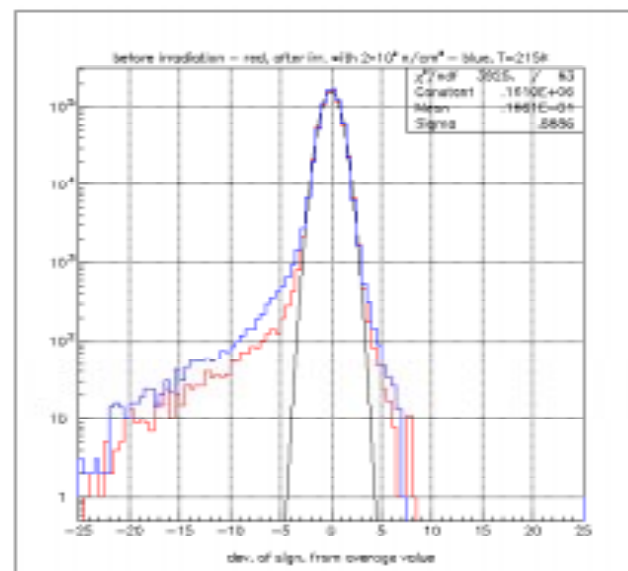
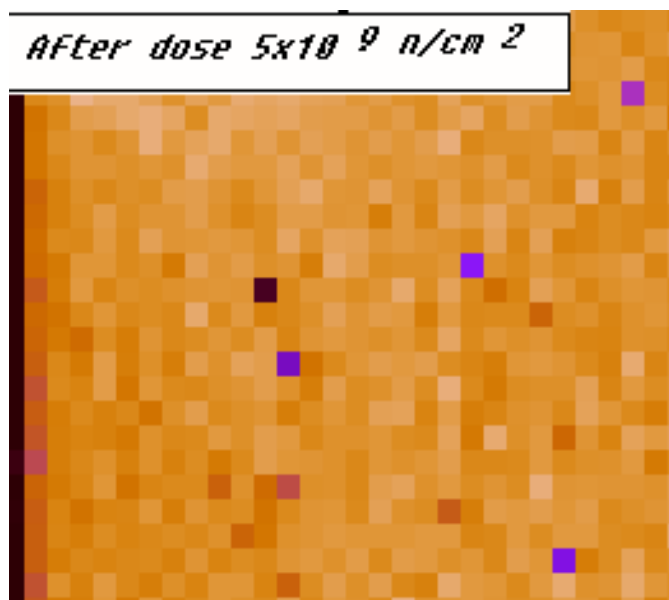
Measurement Technique

- Measurement of the charge transfer by every pixel in CCD :
 - Inject small equal amount of charge in each pixel
 - Read out charge signal from the CCD
 - Compare output from different pixels
- Accuracy
 - The amount of charge traps in each pixel is expected to be small – may be just one or few traps, each trap can capture only 1 electron
 - To achieve charge measurement accuracy of the order of 1 electron repeat the process tens of thousands times and average readings.
- What can be measured
 - The distribution of number of traps per pixel – depends on the spectrum of momentum transfer from irradiating particles to silicon atoms
 - The charge retention time by traps and it's temperature dependence – this depends on traps energy level and so defined by traps nature
 - The temperature and speed of damage annealing – also defined by traps nature.
 - Space distribution of damaged pixels – allows to estimate space distribution of particles, causing damage

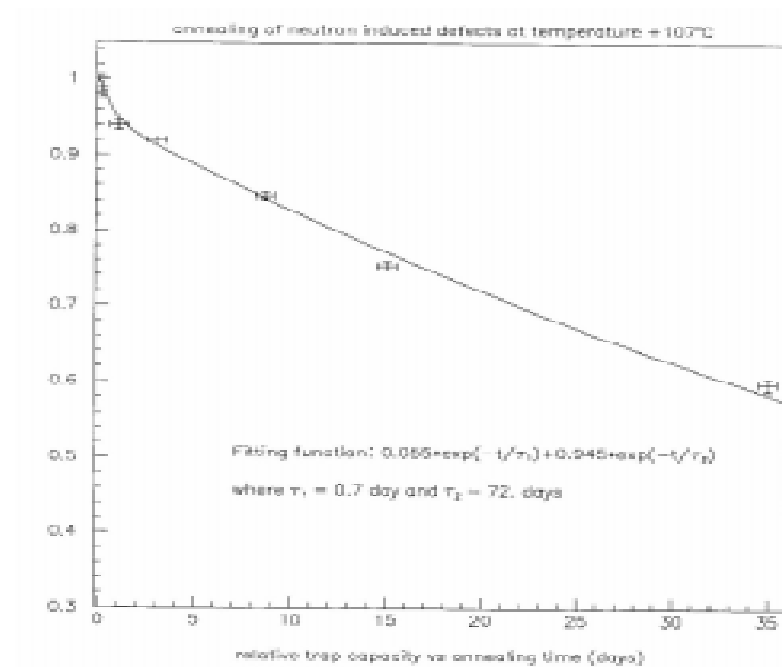
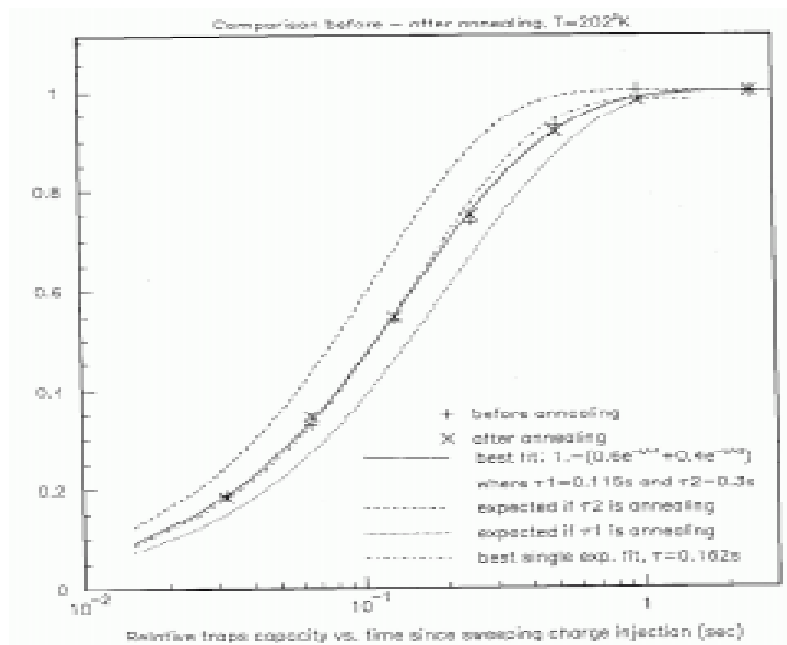
Measurements timing diagram



Some examples for neutrons irradiated CCDs (test made in 1998)



Traps nature



Traps lifetime

can tell us energy level of traps: $\tau = e(E_c - E_{tr}) / K T / \sigma n \chi \nu n N_c$

not all values in denominator are well known. But:

$$\ln(\tau_1/\tau_2) = (E_c - E_{tr}) * (T_2 - T_1) / K * T_1 * T_2$$

What these measurements can tell us ?

- Deviation of each pixel charge from average – depends on the number of traps created in each pixel – should be different for damage caused by light particles (electrons, positrons, gammas) and heavy ones, because of difference in the energy transferred to recoil silicon atom.
- The lifetime of the trapped state and its dependence on the temperature – depends on energy level of the trap, and so can tell us trap nature (see next slide)
- Annealing behavior – also depends on traps nature

Defects in the bulk silicon, caused by irradiation

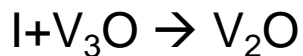
- Defect state and energy levels

Defect identity	Energy level	Defect type	Anneal temp
VO	$E_C - 0.17$	acceptor	350° C
V ₂ O	$E_C - 0.50$	acceptor	?
V ₂	$E_C - 0.23$	acceptor	300° C
V ₂	$E_C - 0.42$	acceptor	300° C
V ₂	$E_V + 0.25$	donor	300° C
VP	$E_C - 0.45$	acceptor	150° C
CC	$E_C - 0.17$	acceptor	?
CO	$E_V + 0.36$	donor	?

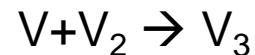
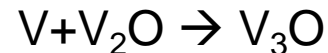
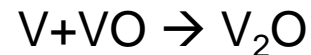
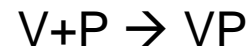
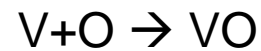
Defects dynamics

- Drift of the vacancies (V) and interstitials (I) through silicon: (Cs – substitution carbon, Ci – interstitial carbon (mobile))

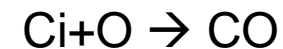
Interstitials reactions



Vacancies reactions



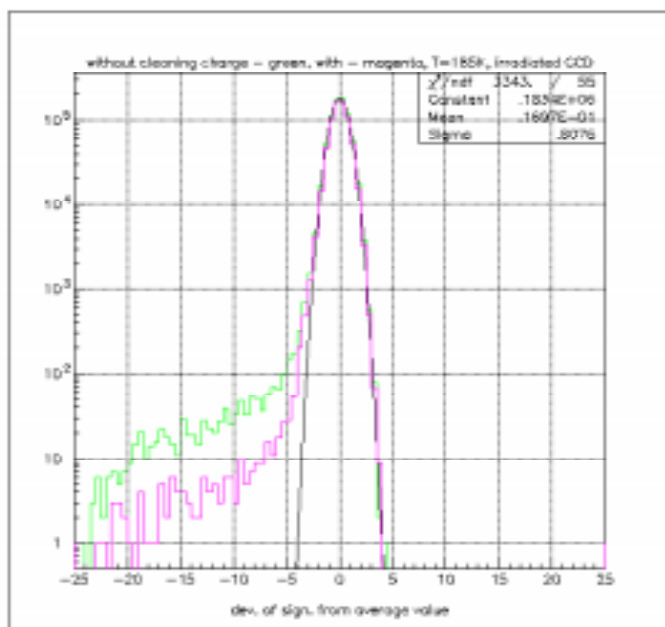
Ci reactions



Reactions in terminal cluster:



Effect of sacrificial charge



Here we could not have 100% of traps filled because we needed about 25 msec to do fast clear on CCD after injecting clearing charge, using LED. In real life we will not need to stop image clocks during beam crossing (permanently moving image), Which will allow us to have small sacrificial charge (10-20 e-) injected in every pixel simultaneously with signal. This will keep all traps filled all the time.

Conclusions from 1998 measurements

- Radiation damage from $5 * 10^9$ neutrons/cm² caused noticeable degradation of charge transfer efficiency (signal loss about 35% for far end of CCD), however could be dealt with by providing small background “sacrificial” charge.
- The energy level of the traps created by irradiation was measured to be $E_c - 0.47 \pm 0.03$ eV. This is consistent with VP complex and V₂O complex. Annealing at ~100 °C consistent with VP hypothesis, but there is no known data about annealing temperature of V₂O. If it is not much higher than 200 °C it may be also a candidate. Annealing behavior rules out V₂ hypothesis, though V₂ also has close energy level.
- If traps nature is VP or V₂O, increased concentration of oxygen in CCD silicon should increase radiation hardness.

Plan for VXD3 postmortem study

Extraction

- VXD3 will be extracted from SLD together with cryostat
- Cryostat will be opened and VXD3 split into two half-barrels
- Beam pipe will be replaced with special fixture to provide illumination of inner CCDs
- Cryostat will be closed and connected to cryogenic system

Examination

- The measurements, using developed algorithm will be done
- The distribution of number of traps/pixel and distribution of damaged pixels in azimuth and Z co-ordinate will be analyzed

Status

- Test Stand, used for 1998 measurements, has been moved to collider hall (the only place where SLD VAXes still running)
- Fastbus crate is connected to SLD VAX.
- CCD front end electronics (A/D board) used for test stand is powered and it's communication with fastbus LFM module is verified
- Currently working on timing module which simulates SLC timing – something does not work there (or may be I simply forgot how it should work)
- Hope to start measurements by end of January.
- Marty is gathering team to extract VXD3.