CCD VERTEX DETECTOR AND BEAM BACKGROUND

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Results of beam tests and radiation damage tests of CCD sensors are described. Spatial resolution, signal-to-noise ratio, and radiation tolerance against electrons and neutrons are given. Feasibility of CCD vertex detector in the beam background environment at JLC is discussed.

1 Introduction

As a vertex detector at linear collider experiments, CCD sensors are very attractive candidate because of their high two-dimensional granularity and excellent spatial resolution although their radiation immunity is still controversial.

We have started basic studies on commercially available CCDs as a first step of R&D for CCD vertex detector. Spatial resolution and signal-to-noise (S/N) ratio for the minimum ionizing particles have been studied in a series of beam tests. Radiation damage of the CCDs by electron and neutron irradiation are also studied. Results of these studies are reviewed in this article.

In the future linear collider experiments, $e^{\pm}$ and neutron backgrounds are expected to cause radiation damage to CCD sensors. The $e^{\pm}$ are created by beam-beam interaction and those $e^{\pm}$ creates the neutrons through interaction with materials along the beamline. By comparing an estimate of the beam background level and the results of the radiation damage test, we discuss on the feasibilty of CCD vertex detector and on the radius of the innermost layer of the detector.

2 Study of CCD sensors

As a goal of the present R&D activity, we are investigating the feasibility of normal temperature ($> 0°C$) operation of CCD vertex detector in the environment of JLC experiment. By operating at normal temperature, thermal

Table 1: CCD samples.

	Hamamatsu S5466	EEV CCD02-06
Pixel size	24 μm	22 μm
Epitaxial layer thickness	10 μm/50 μm	20 μm
Gate oxide	SiO_2	SiO_2-Si_3N_4-SiO_2
Clock	2-phase	3-phase
Gain	2 μV/electron	1 μV/electron
Mode	Inverted	Inverted

distortion of the wafers can be avoided and more free space can be reserved for beam monitors and forward trackers.

In the beam tests[1−3] three types of CCD sensors were studied: CCD-02-06 manufactured by EEV and two types of S5466 with different epitaxial layer thicknesses manufactured by Hamamatsu Photonics Company(HPK). For the study of radiation damage, CCD sensors of HPK S5466 with 10 μm thick epitaxial layer have been used. The details of the sensors are listed in Table 1. All CCDs were operated in inverted mode which can strongly suppress the dark current from surface levels.

2.1 Spatial resolution — Test beam results

In order to study the spatial resolution of CCDs as a tracking device, a CCD telescope consisting of 4 layers of sensors have been exposed to π^- beam at T1 beamline of the KEK Proton Syncrotron (PS). For the first two layers and the 4-th layer, CCD sensors of S5466 with 10 μm thick epitaxial layer were used. The S5466 chip used for the second layer has a square hole in the ceramic package behind the fiducial area of the silicon wafer to minimize multiple scattering of the particles. A test sample, S5466 with 10 μm/50 μm epitaxial layer thickness or CCD02-06 was placed on the third layer. The data were taken at momenta of 0.5, 0.7, 1.0, and 2.0 GeV/c in the temperature range between $-15°C$ and $+15°C$. The CCDs were operated with a readout cycle of 3 seconds, which is the cycle time of the PS machine operation.

Usually signal charge generated by a charged particle passing through the epitaxial layer of the CCD spreads over several pixels due to thermal diffusion in non-depleted region of the epitaxial layer. This charge sharing is very important in realizing the excellent spatial resolution.

The residual resolutions at $-15°C$ are plotted in Fig. 1 as a function of the

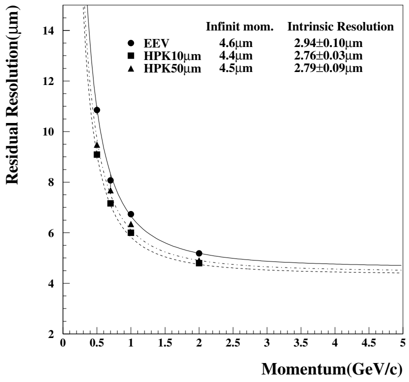


Figure 1: Spatial resolution at $-15°C$.

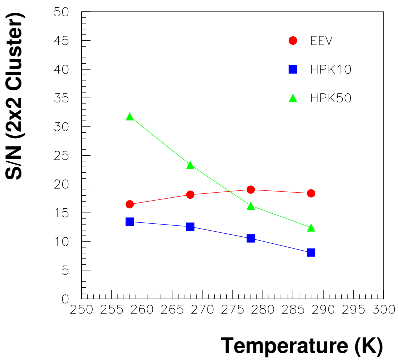


Figure 2: Temperature dependence of S/N ratio of the CCDs.

incident momentum.[3] Here the residual is defined as the distance between the position measured by the CCD on the third layer and the expected point from the first and the second layers extrapolated to the third layer. The CCD on the fourth layer was used only for track finding. The intrinsic resolution of a CCD is obtained by subtracting the contributions from the multiple scattering and from the resolution of the first two layers. We can see that the spatial resolution better than 3 μm is achieved for all three types of CCDs.

Fig. 2 shows temperature dependence of S/N ratio in case of 2×2 clustering.[3] From this result, it can be seen that S/N ratio better than 20 can be expected even at normal temperature if the CCD has the epitaxial layer thicker than 20 μm. Note that this measurement was carried out with a long readout cycle (3 sec) and the S/N ratio of HPK samples at higher temperature can be easily improved as thermal noise can be reduced by fast readout.

2.2 Radiation hardness test

In the operation of CCD vertex detector at the linear collider experiment, the radiation immunity is one of the major concerns. When CCD sensors are exposed to radiation background, the following effects appear: (1)increase of the dark current, (2)shift of the operation voltages (called “flat-band voltage shift”), and (3)increase of the charge transfer inefficiency (CTI). The effect (2) is due to surface (gate oxide) damage and the effect (3) is due to bulk damage.

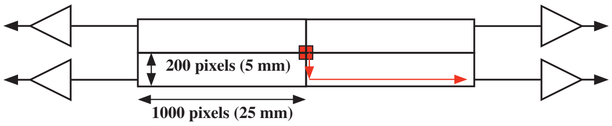


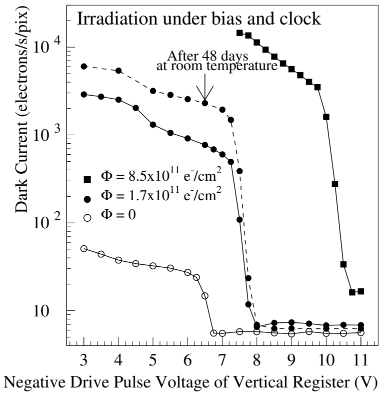
Figure 3: Model CCD chip for CTI consideration.

Both surface and bulk damage are responsible for (1).

To set a criterion for the acceptable upper limit of the CTI, let's consider a model chip which has four output nodes in one wafer as shown in Fig. 3. In this model chip, signal charge packet in the most distant pixel from the output node will be transferred 200 times in vertical direction and 1000 times in horizontal direction. If CTI in vertical shift (VCTI) of 1×10^{-3} and CTI in horizontal shift (HCTI) of 0.2×10^{-3} are assumed, the original signal charge will be reduced to $(1 - 1 \times 10^{-3})^{200} \times (1 - 0.2 \times 10^{-3})^{1000} = 0.82^2 = 0.67$ after the transfer to the output node. This amount of signal loss looks reasonable acceptable limit. Therefore, VCTI of 1×10^{-3} and HCTI of 0.2×10^{-3} are used as acceptable upper limits of the CTI later in this article.

Electron damage to CCD sensors has been studied by irradiating CCD samples with 10 mCi ^{90}Sr β source.[4,5] Fig. 4 shows dark current as a function of the negative voltage of the vertical drive pulse for different electron doses.[5] The abrupt decrease of the dark current (at ~ -6.5 V in the case of $\Phi = 0$) is due to transition from normal mode to inverted mode. The shift of this transition voltage with the electron irradiation is due to the flat-band voltage shift caused by positive charge build-up in the gate oxide. From this figure it can be seen that the inverted mode operation is very effective to suppress the surface current which is much more sensitive to electron damage than the bulk current. From the measurement of the reset current of the CCD during the electron irradiation, it was found that the mean ionizing energy loss of electrons from ^{90}Sr is about three times larger than that of MIPs. Since the surface damage is proportional to ionizing energy loss, three times larger dose will result the same effect as shown in Fig. 4 in linear collider experiments.

For the CTI measurement we used ^{55}Fe X-ray source. The CTI was obtained from the position dependence of the 5.9 keV peak of the spectrum. The measurement was carried out at a readout cycle of 3 seconds. Fig. 5 shows the CTI as a function of temperature. Increase of HCTI at low temperature at the highest dose is presumably due to distortion of potential shape caused by surface damage. At higher temperature ($> -20°C$) the CTI decreases because increased dark current fill up the traps. If much shorter readout cycle is used, the CTI will keep increasing at higher temperature. In that case the



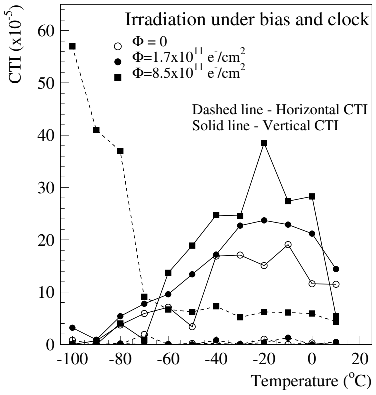


Figure 4: Dark current of S5466 before and after electron irradiation at $-30°C$.

Figure 5: Charge transfer inefficiency of an electron irradiated CCD sample as a function of temperature.

VCTI at $\sim 0°C$ would be about 5×10^{-4} with $\Phi = 8.5 \times 10^{11} e/\mathrm{cm}^2$. To keep the allowable VCTI limit of 1×10^{-3}, the electron dose has to be less than $\sim 1.5 \times 10^{12} e/\mathrm{cm}^2$. It is known that the bulk damage by MIP electrons is stronger (few times but less than $\times 10$) than low energy electrons used in our measurement.[6] Therefore the conservative limit for the electron background in the linear collider experiments would be $\sim 1.5 \times 10^{11} e(MIP)/\mathrm{cm}^2$.

The CTI of a neutron irradiated CCD sample is shown in Fig. 6 as a function of temperature.[5] For the neutron irradiation ^{252}Cf source was used. The CTI again decreases at higher temperature due to the increase of the dark current. From this figure we can deduce the limit of the CCD against neutron background as $\sim 1.5 \times 10^{10} n/\mathrm{cm}^2$.

3 Beam background and R_{min}

Recently a simulation study on the beam background at JLC experiment has been started. The preliminary result shows the neutron background level near the interaction region to be $1 \times 10^9/\mathrm{cm}^2\mathrm{y}$ and the electron/positron background $1.5 \times 10^{11}/\mathrm{cm}^2\mathrm{y}$ at $r = 2.4$ cm (magnetic field of the detector solenoid is 2T). Compared with these values, we can conclude that the CCD samples tested here have enough radiation immunity to be used in the JLC experiment if we can replace the innermost layer with new one once a year.

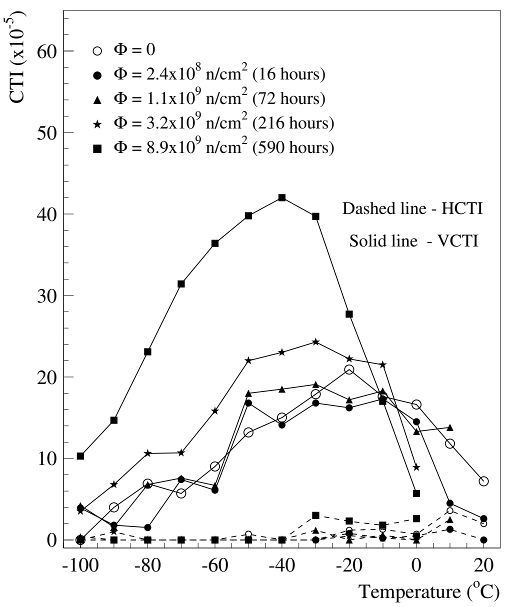


Figure 6: Charge transfer inefficiency of a neutron irradiated CCD sample as a function of temperature.

To get better vertex resolution the radius of the innermost layer R_{min} of the vertex detector should be as small as possible. There are several ways to make R_{min} smaller. One method is to use stronger solenoid field and confine low energy $e^{\pm}$ background within smaller radius. Another way is to make CCDs more radiation hard. For the hardening of CCDs we should consider technologies such as narrower charge transfer channel, fat-zero charge injection, high speed readout, and low temperature operation of the CCD.

4 Conclusion

The properties of commercially available CCD sensors have been studied. It has been found that CCD vertex detectors can achieve the S/N ratio of greater than 10 at $5°C$ even with relatively thin epitaxial layer of 10 μm thickness and that the spatial resolution better than 3 μm can be achieved. The radiation tolerance of the CCD sensors is found to be roughly $1.5 \times 10^{12}/\mathrm{cm}^2$ for e^- from

^{90}Sr and $1.5 \times 10^{10}/\mathrm{cm}^2$ for neutrons from ^{252}Cf with near room temperature operation. If energy dependence of the electron damage is taken into consideration, the radiation tolerance against $e^{\pm}$ beam background is $1.5 \times 10^{11}/\mathrm{cm}^2$. By comparing the results with the expected background level, it can be concluded that the CCD sensors can be put at $R_{min} = 24$ mm in the JLC experiment. To make R_{min} of the vertex detector smaller, stronger magnetic field is preferable. Otherwise more R&D effort and/or low temperature operation is needed.

Acknowledgments

The authors would like to express thanks to the members of the JLC vertex detector study group for their contribution to this work.

References

1. T. Tsukamoto *et al.*, KEK Preprint 98-19 (1998), submitted to Nucl. Instr. and Meth. A.
2. T. Tsukamoto *et al.*, "Performance of a CCD tracker at room temperature", Presented at International Pixel Detector Workshop (PIXEL 98), Fermilab, 7-9 May 1998.
3. T. Aso *et al.*, KEK Preprint 99-84 (1999), submitted to Nucl. Instr. and Meth. A.
4. K.D. Stefanov *et al.*, KEK Preprint 98-221 (1999), to be published in Nucl. Instr. and Meth. A.
5. K.D. Stefanov *et al.*, "Electron and Neutron Radiation Damage Effects on a Two-phase CCD", submitted to IEEE Trans. Nucl. Sci.
6. C.J. Dale *et al.*, IEEE Trans. Nucl. Sci., NS-35 (1988) 1208.