Studies of CCDs for Vertex Detector Application

K. D. Stefanov[a], T. Tsukamoto[a], A. Miyamoto[b], Y. Sugimoto[b], N. Tamura[c], K. Abe[d], T. Nagamine[d] and T. Aso[e]

[a]*Department of Physics, Saga University, Saga 840-8502, Japan*
[b]*High Energy Accelerator Research Organization (KEK), Ibaraki 305-0801, Japan*
[c]*Department of Physics, Niigata University, Niigata 950-2181, Japan*
[d]*Department of Physics, Tohoku University, Miyagi 980-8578, Japan*
[e]*Toyama National College of Maritime Technology, Toyama 933-0293, Japan*

Abstract. In this paper we summarize the research activities at the JLC Vertex group. A simulation study of the vertex detector performance has started, which has as a goal optimization of its design. Attention has been paid to the mechanical distortions of CCD chips and their supporting ladders, caused by cooling. Laser measurement system to investigate the distortions has been assembled and preliminary measurements on CCDs have been obtained. Radiation damage effects on CCDs have been extensively studied and some important conclusions on preferable device structure and operation conditions have been drawn. A study of charge sharing between the CCD pixels, which is important in particle detector applications, is also under way.

INTRODUCTION

In the last several years, significant research effort has been concentrated to study the properties of charge-coupled devices (CCD) for application in a vertex detector. Due to their two-dimensional resolution and high precision, CCDs are the main candidate for the vertex detector at the future e^+e^- linear collider [1]. To obtain maximum performance, precise mechanical support of the CCD chips, as well as mounting and thinning techniques are very important and require detailed investigation.

A major part of the research has been dedicated to the radiation damage effects in CCDs at near-room temperature because of the advantages associated with this operation [2]. The study is needed to select the optimal CCD design and operating conditions, as well as to estimate the device lifetime in a radiation environment.

MECHANICAL DESIGN STUDIES

The current vertex detector model consists of 4 CCD layers at radii 24, 36, 48 and 60 mm. This design is considered preliminary and has not been optimized. A work to simulate and optimize the current concept has started, using the simulation tools available at the JLC group. The simulation should help determine the optimal number and configuration of CCD layers and their radii, taking into account the physics requirements, constraints of the mechanical support and CCD properties.

Cooling causes mechanical distortions of the vertex detector structure because of the different coefficients of thermal expansion of silicon and the material of the supporting frames. To ensure minimum distortion, mounting methods and mechanical support structures have to be selected carefully. For this study a two-dimensional laser distance measurement system with a precision of 1μm has been assembled and tested on commercial CCDs.

An optical cryostat, using nitrogen vapor cooling will be added to the existing equipment to measure the thermal distortions of silicon test structures and CCDs, mounted on beryllium supports.

RADIATION DAMAGE EFFECTS

Flat band voltage shifts, dark current and charge-transfer inefficiency (CTI) were studied in Multi-Pinned Phase (MPP) mode CCDs. Such devices are attractive for near-room temperature applications, because their dark current is more than one order of magnitude lower than in conventional CCDs [3]. CTI increases because of radiation-induced bulk traps [4] and measures have to be taken to reduce its value.

CTI improvements

One important method to decrease the CTI is to use an additional narrow implant in the CCD channel ("notch"), confining the signal charge into a fraction of the pixel volume and increasing its density [5]. This concept was tested on electron-irradiated notch S5466 CCD, manufactured by Hamamatsu Photonics. Due to the additional 3μm-wide notch channel, its CTI is about 3 times lower than that in a conventional S5466 device.

A model for the CTI in 2-phase [4] and 3-phase CCDs was developed and used to compare the two structures. It showed, that under equal conditions the CTI of 3-phase devices is about 2.5 times higher than in 2-phase CCDs because of the higher signal density in 2-phase devices. Experimentally a factor of 4 was observed due to the different operating conditions.

The theoretical study of the frequency dependence of the CTI showed, that at speeds higher than several Mpix/s the horizontal CTI (HCTI) decreases rapidly, because charge dwell time becomes shorter than the capture time constant of the defects. Vertical CTI (VCTI) is much less influenced due to the longer time the charge spends in the image section.

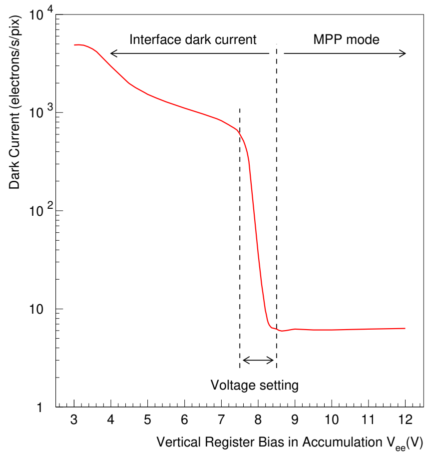

FIGURE 1. Principle of thermal "fat zero" generation.

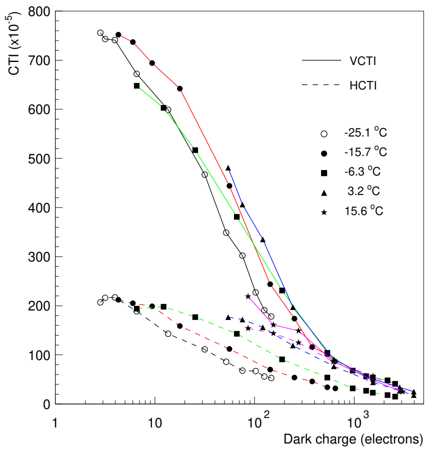

FIGURE 2. CTI reduction by "fat zero" effect in EEV02-06 CCD.

One of the most powerful ways for CTI improvement is to inject additional charge ("fat zero") into the CCD registers. It reduces the CTI mainly by filling the traps in the CCD channel, so that less electrons can be captured. Reducing the dominating VCTI by "fat zero" injection through the CCD input port is not a simple task because of the large non-uniformity of the injected charge [6]. Another method to inject "fat zero" in MPP-mode CCDs has been developed. By varying the gate bias voltage V_{ee}, the CCD is driven into semi-MPP mode and its dark current can be controlled over a wide range (Fig. 1). At high temperatures, this current is sufficient to provide charge of the order of >1000 electrons even if the CCD readout cycle is very short. The experimental data on Fig. 2, obtained by this method, shows that the CTI can be greatly reduced by the "fat zero" effect.

Recent simulations have set the worst-case limit for the accumulated 10-year fluence at 1.5×10^{13} electrons/cm^2 and 5×10^9 neutrons/cm^2. Neutron-induced CTI is negligibly smaller than that caused by electrons, and only the latter is being considered. The main danger comes from the VCTI, which can reach 1.5×10^{-1} at the expected radiation level in a 3-phase CCD. Using the above mentioned improvements, the VCTI can be reduced more than 60 times, as described in Table 1.

TABLE 1. Vertical CTI improvements.

Option	VCTI improvement
Readout speed >5 Mpix/s	≈1.3 times
Use 2-phase CCD	≈2.5 times
Use notch CCD	3 to 4 times
"Fat zero" >1000 e$^-$	6 to 8 times

CCD drawbacks

Large radiation-induced voltage shifts of the gate bias voltages, caused by trapping of holes in the oxides [7] was observed in the investigated CCDs. In biased S5466 CCD the shift of the gate bias voltages is 0.07 V/krad, which limits the device irradiation level to less than 100 krad. Another weak point, observed in S5466 devices, is the spurious dark charge [8], created by impact ionization by holes. It prohibits the use of the devices at higher temperatures. In both Hamamatsu and EEV devices, irradiated by neutrons, dark current spikes ("hot pixels") were observed. Some of the hot pixels exhibit random telegraph signals (RTS), which requires fast reading or cooling to suppress their influence.

CONCLUSION

Simulations on the vertex detector design are doing to study its optimal configuration from the point of view of physics goals. Laser measurement system to investigate the thermal distortions of CCD chips and their supporting ladders has been assembled and tested. The study has shown several measures to decrease the CTI and prolong the CCD lifetime in a radiation environment. Improvement is needed to reduce some additional radiation damage effects. The future radiation hard CCD should use notch channel and fast 2-phase clocking. Additional "fat zero" charge in the vertical register is required to futher reduce the VCTI and a method to do that has been proposed.

ACKNOWLEDGMENTS

This work was supported in part by the KEK Joint Research and Development Program, and Grant-in-Aid for Scientific Research (C)(2)09640366, (C)(2)11640295 and on Priority Areas (Physics of CP violation) (A)(2)11127211 of the Ministry of Education, Science and Culture of Japan. The support from the JSPS Japanese-German Cooperative Program is also appreciated.

REFERENCES

1. Burrows, P. N., *Nucl. Instrum. Methods* **A447**, 194–201 (2000).
2. Tsukamoto, T. *et al.*, *Nucl. Instrum. Methods* **A383**, 256–259 (1996).
3. Saks, N. S. *IEEE Electron. Dev. Letters* **EDL-1**, 131–133 (1980).
4. Stefanov, K. D. *et al.*, *IEEE Trans. Nucl. Sci.* **NS-47**, 1280–1291 (2000).
5. Janesick, J., *Proc. SPIE* **1447**, 87–108 (1991).
6. Sugimoto, Y. *et al.*, JLC VTX internal report, KEK (2000).
7. Roy, T. *et al.*, *Nucl. Instrum. Methods* **A275**, 545 (1989).
8. Stefanov, K. D. *et al.*, *Nucl. Instrum. Methods* **A436**, 182–187 (1999).