CCD based vertex detector for JLC

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Abstract

The CCD based vertex detector is being studied for JLC project. One of the main goal is the operation of CCDs at near room temperature in order to reduce amount of materials between the interaction points and outer detectors, and minimize the thermal distortion of CCD wafers. In this paper, we describe some of the aspect about the operation at near room temperature with the results of radiation immunity and spatial resolution studies for JLC project.

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1 Introduction

The Joint Linear Collider (JLC) project[1] consists of the construction of a linear collider and the experiments therewith, at an initial center of mass energy around 500 GeV which will eventually reach TeV region. High precision tracking and vertex detection are key elements in JLC project. Especially, the reconstruction of secondary and tertiary vertexes is necessary for efficient discrimination of b jets from c jets. Precise spatial resolution with high tracking efficiency is required for the vertex detector to obtain excellent tagging efficiency of the jet flavor.

CCD (Charge Coupled Device) is one of the best candidates for the vertex detector in the JLC detector. Since, in contrast with silicon strip detectors, CCD has unambiguous reconstruction capability by 2-dimensional array of pixels, higher track densities and background can be tolerated and pattern recognition is more efficient. Usually normal CCDs have wafer thickness of about 500 μm, while the thickness of sensitive region is only about 20 μm in the wafer. When used for the vertex detector, insensitive substrate should be thinned as much as possible to reduce the multiple scattering of charged particles. On the other hand, it becomes more difficult to keep thin silicon wafers flat, particularly operated at low temperature[2] due to thermal distortion. From this point of view, operation of the vertex detector at near room temperature is desirable to minimize the distortion of the CCD wafers.

At higher temperature, however, the performance of CCDs is deteriorated by thermally generated background signal, i.e. dark current. Its statistical fluctuation could be a serious source of noise in the detection of minimum ionizing particles. A novel method called as Multi Pinned Phase (MPP) operation[3] is proposed to suppress the dark current. In the MPP mode, the array clocks are biased sufficiently negative to invert all phases and the surface potential is "pinned" to substrate potential. As a result, the thermal excitation of electrons is extremely suppressed. It strongly encourages to operate CCDs at higher temperature.

In this paper, we describe the current configuration of the JLC vertex detector, and key points of our R&D effort for the operation of CCDs at near room temperature ($\sim 0°C$).

2 Detector configuration and background environment

Fig.1 a) shows one possible schematic view of the CCD vertex detector[4], which is put in the JLC detector full simulator. Vertex detector is placed in just outside of the beryllium beam pipe with the coverage angle of $|\cos\theta| < 0.9$ and in detector magnetic field of 3 Tesla. The expected impact parameter resolution (δ) in μm is given by $\delta^2 = 7^2 + (20/p)^2/\sin^3\theta$, where the intrinsic resolution is assumed to be 4.0 μm.

The vertex detector consists of four layers with a minimum radius of 2.4 cm and maximum radius of 6.0 cm. Each layer is built from ladders in which the sensors are connected to each other. The size of a sensor is 1.25 cm $\times$ 5.0 cm $\times$ 300μm. Each CCD sensors has multiple readout nodes so that all pixels can be read out during a train crossing interval of 6.7 ms. If we conservatively assume the readout frequency of 10 MHz, each readout channel can read out the area of 250$\times$250pixels between the train crossing. In this case, a sensor has 16 readout nodes as shown in Fig.1 b). Since the total number of sensors in the vertex detector is 432, the total of 6912 readout channels are necessary. Higher readout frequency can reduce the number of the readout channels.

The main source of backgrounds for the vertex detector is e^+e^- pairs which come from the beamstrahlung process during collisions, so that the background condition is strongly depends on the beam parameters. Background hits due to the beamstranhlung were simulated with detailed geometries by the JUPITER full detector simulator[5], where beamstruhlung process is calculated using CAIN package[6]. The estimated hit density at the inner most layer is $0.35/\mathrm{mm}^2/\mathrm{train}$ and $0.30/\mathrm{mm}^2/\mathrm{train}$, for the beam parameters of TRC(X)[7] and JLC-Y[4], respectively. For one year operation(10^7s), the hit density caused by e^+e^- pairs at the inner most layer is about $0.5\times10^{11}/\mathrm{cm}^2/\mathrm{year}$ for TRC(X) beam parameter.

The estimation of neutron yields due to the photo-nuclear process is currently in progress. In the previous study[8], neutron background was estimated to be $1\times10^9/\mathrm{cm}^2/\mathrm{year}$. But the estimation strongly depends on the design of the beam extraction line that has not been fixed at present.

3 Operation at near room temperature

Our effort has been devoted mainly to the study of spatial resolution and the radiation hardness of CCD sensors at near room temperature. The several kinds of CCDs in MPP operation were used. Three of the four CCDs were S5466, 2-phase device, manufactured by Hamamatsu Photonics K.K[9](HPK), but with different depth of epitaxial layers, 10μm(HPK10) and 50μm(HPK50), respectively. HPK10-notch has an additional narrow implant in the CCD channel. This implant forms a sub-channel, or "notch" in the potential profile of the transport channel and the integrated charge is concentrated to the formed small packet. HPK10 is commercially available, while HPK10-notch and HPK50 are specially fabricated for our studies. HPK types have 512×512 active pixels with the size of $24\mu\mathrm{m}\times24\mu\mathrm{m}$. Another one is CCD02-06[10], 3-phase device, manufactured by EEV Company and is also commercially available. EEV type has 385×578 pixels with the size of $22\mu\mathrm{m}\times22\mu\mathrm{m}$.

3.1 Spatial resolution studies

Spatial resolution had been studied with the 4 layers CCD tracker. The tests were carried out at the T1 test beam line of the 12-GeV proton synchrotron(PS) at High Energy Accelerator Research Organization(KEK). The negative pion beam was exposed with the choice of momentum to be 2.0 GeV/c, 1.0 GeV/c, 0.7 GeV/c, and 0.5 GeV/c. The normal axis of the CCD tracker was aligned to the beam direction. We tested the HPK10, EEV and HPK50 sample. The readout cycle was about 3 seconds with 250kpixels/s. In the 2 by 2 pixel clustering, the S/N is better than 10 even at the $+5^\circ$C as shown in Fig.2. If the readout cycle is assumed to be train interval, the S/N ratio of HPK samples will be improved by the reduction of thermal noise.

The hit position is determined using the Ratio Location Mapping method (RLM)[4], which derive a hit position by a function describing the relation between charge ratio in 2 pixels and the injected position. The RLM function is obtained from experimental data to make a matching the hit data and its charge ratio. Since most of the epitaxial layer is not depleted, the signal charge diffuses thermally in the epitaxial layer and spreads over several pixels even for the normal incident angle. Consequently, higher precision position measurement than the pixel pitch is achieved by charge sharing property. The intrinsic resolution of a test sample is obtained as shown in Table1, by subtracting the contributions from multiple scattering and from the finite resolution of reference CCDs. The result shows that the intrinsic resolution is better than 4 μm even at +5°C.

3.2 Radiation Immunity studies

In the operation at near room temperature, the distortion of signal due to the radiation damage is more serious problem. The effect of the radiation damage in a CCD sensor appears as the increase of the dark current and the increase of the charge transfer inefficiency (CTI).

The radiation damage has been studied by irradiating CCD samples using the radio isotopes, ^{90}Sr and ^{252}Cf, for electrons and neutrons, respectively. The increase of the dark current is observed especially for the electron irradiated samples, because the dark current is supplied at the damage of SiO_2-Si interface by charged particles. Fig.3 a) shows dark current as a function of the negative voltage of the vertical drive pulse for different electron dose[11]. The effective suppression of the dark current is due to transition from normal mode to MPP mode. The shift of this transition voltage with the electron irradiation is so called "flat-band voltage shift" caused by positive charge build-up in the gate oxide.

CTI was measured from the position dependence of the 5.9 keV peak of ^{55}Fe X-ray source. The measurement was carried out at a readout cycle of 3 seconds. Since the CTI depends on the concentration of signal electrons (n_s) and a defect concentration (n_t) as CTI $\propto n_t/n_s$, small geometrical size of packet is feasible to suppress the CTI efficiently. Fig.3 b) shows a measured CTI in vertical register (VCTI) for HPK10-notch and HPK10 as a function of temperature[4]. The CTI of the horizontal register (HCTI) is less than 10^{-4} in the whole temperature range. The effect of VCTI improvement of HPK10-notch is about 3 to 4 times from standard HPK10 sample.

The VCTI of HPK10 was about 4×10^{-4} after $8.9\times10^{9}/\mathrm{cm}^2$ neutron irradiation, and VCTI of 3×10^{-4} was measured in EEV, irradiated with approximately the same fluence. The VCTI of HPK10-notch was below 10^{-4} at the maximum for neutron irradiation of $5.7\times10^9/\mathrm{cm}^2$.

4 Summary and prospects

We have presented the design of the CCD based vertex detector for JLC, and explained the current result of our studies. The commercially available CCD sensors are tested for spatial resolutions and radiation immunity. The spatial resolution better than 4μm have been confirmed at +5°C. The increase of dark current due to the radiation damage is effectively suppressed by the operation with MPP mode, and not a serious source of problem. The measured VCTI at the maximum for HPK10 is about 1.2×10^{-4} and 4.0×10^{-4}, for irradiation of $8.5\times10^{11}/\mathrm{cm}^2$ electrons and $8.9\times10^9/\mathrm{cm}^2$ neutrons, respectively. It is known that the bulk damage by minimum ionizing electron is about 10 times stronger than low energy electrons, so that our electron irradiation experiments is corresponding to about 1.7 years operation. The experimental confirmation of the radiation damage by high energy electron is one of the important issue. But, even if we assume the VCTI is increased to 1×10^{-3} and HCTI is 10% of VCTI, the degradation of S/N is 24%. This is corresponding to the degradation of S/N from -15°C to +5°C for HPK10 in our beam test and is able to keep spatial resolution better than 4μm.

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Table 1
Intrinsic resolution in μm

Temperature	HPK10	HPK50	EEV
$-15°$C	2.76±0.03	2.79±0.09	2.94±0.10
$+5°$C	3.46±0.04	3.67±0.12	2.59±0.16

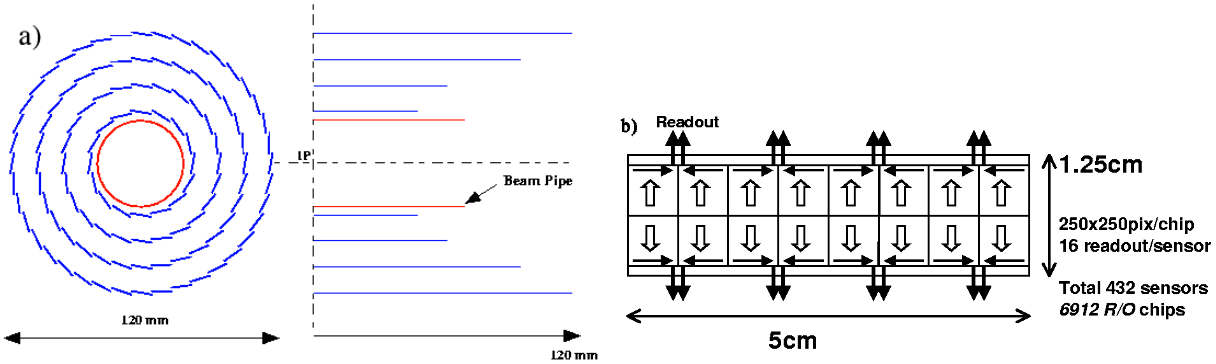

Fig. 1. Schematic design of a)the CCD vertex detector for JLC and b)multi-port readout sensor.

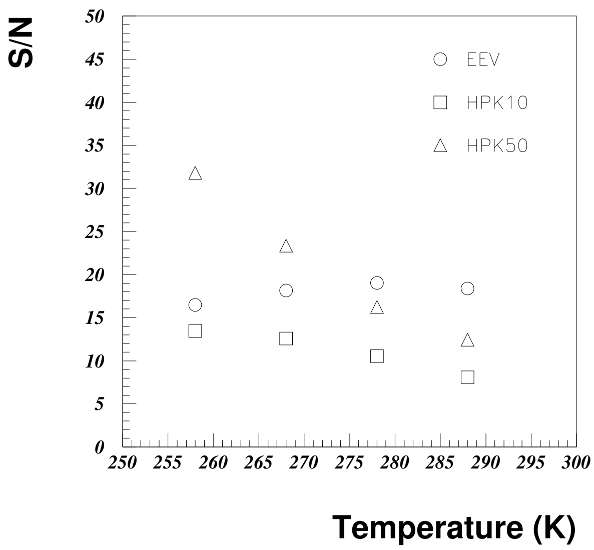

Fig. 2. Signal-to-Noise ratio as a function of temperature

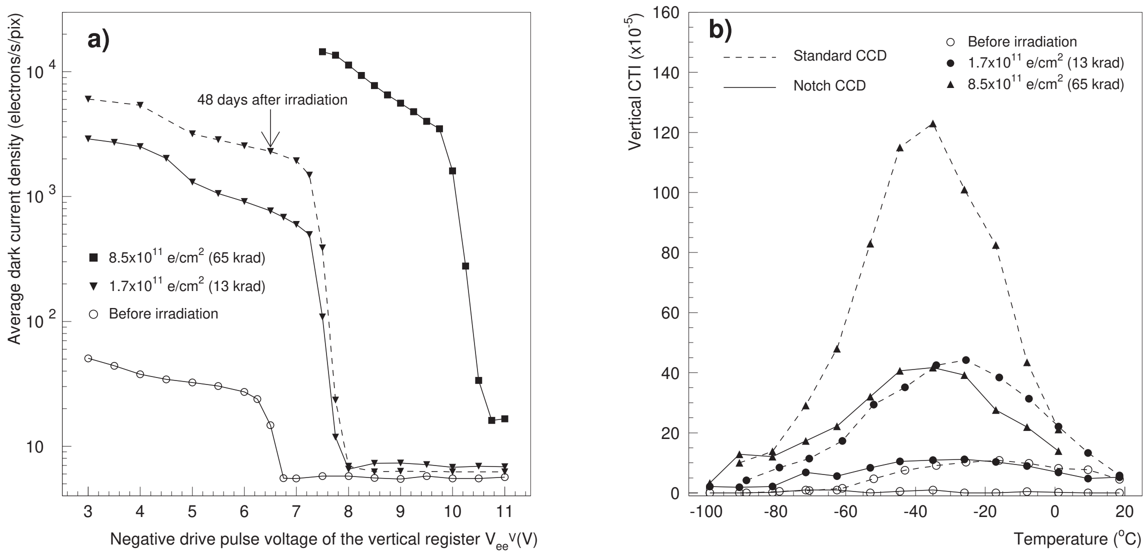

Fig. 3. a)Average dark current density as a function of the electron irradiation fluence and of the negative pulse voltage V_{ee}^{V} for HPK10 at T=-26°C. b)VCTI of HPK10-notch and HPK10 samples.