Fine Pixel CCD R&D in Japan

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A vertex detector based on fully depleted fine pixel CCDs (FPCCD) is proposed for ILC experiment. In this idea, the hit signal is accumulated during a train and read out between trains. The challenge of this scheme is possible high hit density due to the pair background. In this article, we report on a simulation study concerning the background rejection and on the hardware R&D plan.

1. INTRODUCTION

As a candidate of the vertex detector for ILC, we propose a vertex detector based on fully-depleted fine pixel CCDs (FPCCD). In this idea, the hit signal is accumulated during a train and read out in 200 ms interval between trains.

In the FPCCD vertex detector, we use very fine ($\sim 5\ \mu$m) pixel CCDs. By increasing the number of pixels by a factor of ~ 20 compared with the standard pixel size sensors, the pixel occupancy will be less than 0.5% even if the hit signal is accumulated during a total train of 2820 bunches. In order to suppress the number of hit pixels due to diffusion in the epitaxial layer, the sensitive layer of the FPCCD should be fully depleted. The FPCCD option has several advantages for the ILC vertex detector:

- Since the signal is read out between trains, it is completely free from beam-induced RF noise (EMI).
- Because of its small pixel size, the spatial resolution of $\sigma_x \sim 1.4\ \mu$m is expected even with digital readout.
- The simple structure of CCDs is advantageous for the fabrication of large size sensors.
- Because active circuit locates only on one edge, the temperature control is easy.
- Very fast readout speed is not necessary.

2. BACKGROUND REJECTION

A challenge of the FPCCD vertex detector is the high hit density due to pair-background hits. Although the pixel occupancy is satisfactorily low, the hit density is still as high as 40 hits/mm^2 at B=3 T and R=20 mm with the machine parameter of "Nominal Option". This high hit density could cause tracking inefficiency if the multiple scattering effect is large. When a signal hit candidate on a layer is searched for by extrapolating signal hits of outer layers, the background hits cause misidentification probability p_{mis}. For a normal incident track, p_{mis} is given by

$$\begin{aligned} p_{mis} &= 2\pi\sigma R_0^2, \\ R_0 &= d\theta_0 \end{aligned} \quad (1)$$

where σ is background hit density of the inner layer, d is the distance between inner and outer layers, and θ_0 is the multiple scattering angle by the outer layer. The angular and momentum dependence of p_{mis} is $p_{mis} \propto p^{-2} \sin^{-4}\theta$, where p is the momentum and θ is the polar angle.

The misidentification probability for 1 GeV/c particles is plotted as a function of $\cos\theta$ in Figure 1 assuming the layer thickness of 50 μm Si. As can be seen from this figure, misidentification probability quickly goes up in the forward

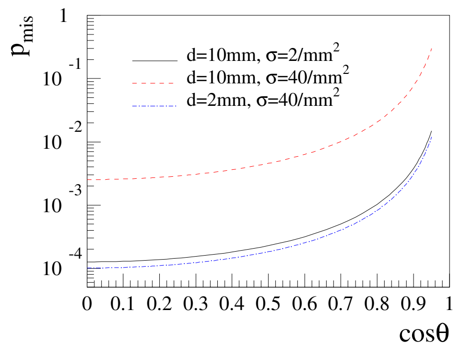

Figure 1: Misidentification probability of signal hit with background hit as a function of $\cos\theta$ for several layer configurations. The layer thickness of 50 μm and the particle momentum of 1 GeV/c are assumed.

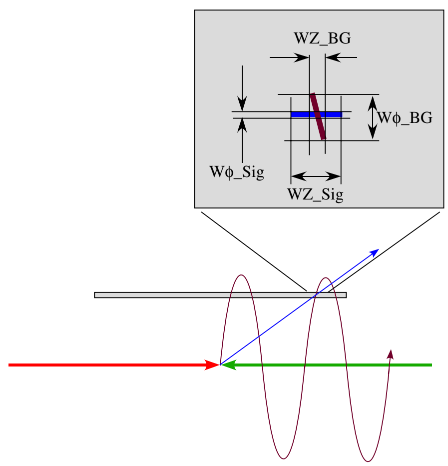

Figure 2: Hit cluster shape of a high p_t track (blue) and a pair-background track(brown).

region. If the distance between inner two layers is 10 mm, p_{mis} is nearly 30% at $\cos\theta = 0.95$ with the background hit density of $40/\text{mm}^2$. To reduce the misidentification probability, the distance between inner two layers should be small. If the distance is 2 mm, p_{mis} is as small as the case of $d = 10$ mm and $\sigma = 2/\text{mm}^2$, which is expected when the sensor is read out 20 times per train. Another way to reduce p_{mis} more is background rejection using hit cluster shape of the FPCCD. The momentum spectrum of the pair-background particles hitting the innermost layer of the vertex detector has a peak around 20 MeV/c at 3 T magnetic field. Therefore, the incident ϕ angle of background particles to the sensor plane is quite different from that of large p_t signal particles. As a consequence, the hit clusters of background particles have larger spread in ϕ direction and smaller spread in z direction than what is expected for the large p_t particles as shown in Figure 2. The background hits can be rejected using a variable dW given by

$$dW = \sqrt{(WZ_{BG} - WZ_{Sig})^2 + (W\phi_{BG} - W\phi_{Sig})^2} \tag{2}$$

where WZ_{BG}, WZ_{Sig}, $W\phi_{BG}$, and $W\phi_{Sig}$ are given in Figure 2. We have made a background simulation study with $B = 3$ T and the "nominal" ILC machine parameter with 2 mrad crossing angle. Figure 3 shows pair background hit density at $R = 20$ mm with and without dW cut and the background rejection ratio as a function of z. The rejection ratio is as large as 20 in the forward region where the background hits could affect the track finding efficiency.

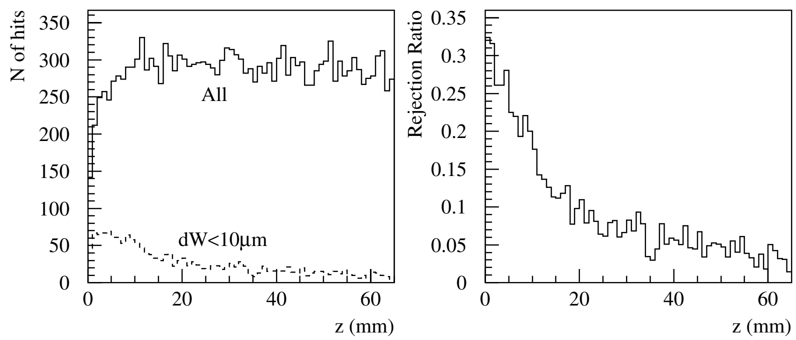

Figure 3: Hit density (AU) due to pair background with and without dW cut (left), and the ratio of those two distributions (right) as a function of z.

3. SENSOR R&D ACTIVITY

The sensitive region of the FPCCD is fully depleted in order to suppress the charge diffusion. In fully depleted region, electrons created by ionization of charged particles move rapidly due to the electric field. When used in a magnetic field perpendicular to the electric field, the signal electrons move with finite Lorentz angle with respect to the electric field which is usually normal to the wafer. This Lorentz angle θ is related with the magnetic field as $\tan\theta \propto \mu B$, where B is the magnetic field perpendicular to the electric field, and μ is the mobility of the electrons.

For a normal incident track, only one pixel would be hit if there is no magnetic field. In the presence of a magnetic filed, however, the signal electrons along the track spread over several pixels due to the Lorentz angle. At high electric field, the carrier velocity saturates and the mobility decreases. At the electric field of 1×10^4 V/cm, the electron mobility is ~ 0.07 m^2/Vs [1], which is significantly smaller than at low electric field. If the Lorentz angle is not very large (say less than 30 degrees), the charge spread can be suppressed by tilting the sensor wafer to cancel the Lorentz angle.

In order to get a rough estimation of the Lorentz angle, we have calculated the electric field in a fully depleted CCD using a finite element analysis program FEMLAB. We found that we can achieve 1×10^4 V/cm in the epitaxial layer by choosing appropriate parameters of the sensor. Since higher positive gate voltage gives higher electric field in the epitaxial layer, the gate voltage should be kept high during the beam train.

Fully depleted CCDs are already developed by Hamamatsu for astrophysics application, although the pixel size is still large and readout speed is slow. As the first step of the sensor R&D of the FPCCD, we will study on the charge spread and the Lorentz angle using these fully depleted CCDs.

Acknowledgments

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References

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