Fine Pixel CCD Option for the ILC Vertex Detector

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As a candidate of the vertex detector for ILC, we propose a vertex detector based on 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 this article, we describe the basic idea of the FPCCD vertex detector and challenges to be studied in the future R&D.

1. INTRODUCTION

At linear collider experiments, low energy $e^{\pm}$ pairs are generated through the beam-beam interaction at the collisions of bunches. This beam background is called "pair-background". Because the energy of the pair-background particles is relatively low, they are confined in a small radius region in the magnetic field of the detector solenoid. The hit rate of the innermost layer of the vertex detector by this background is estimated to be ~ 1.5 hit/cm^2 at $R = 2.0$ cm and $B = 3$ T per one bunch crossing (BX) for the TESLA machine parameter [1]. If the hits are accumulated for one train of 2820 BX, the hit density is ~ 40 hits/mm^2. Because one track hit makes several pixel hits due to diffusion in the epitaxial layer of the sensor, the pixel occupancy for a pixel detector with 25 μm pixel size exceeds 10%, which is not acceptable.

One method to keep the pixel occupancy acceptable level ($\sim 0.5\%$) is to read out the sensor 20 times in one train. There are R&D activities by several groups based on this method. In some technologies, such as column parallel CCDs (CPCCD), monolithic active pixel sensors (MAPS), and depleted FET (DEPFET), the signal is read out 20 times during a train. This method requires very fast readout speed ($\gtrsim 50$ Mpixels/s). Some other technologies, such as in-situ storage image sensors (ISIS) and flexible active pixel sensors (FAPS), will have 20 pipeline registers on each pixel, and the signal is read out in 200 ms interval between trains. These technologies will have very complicated structure, and may have disadvantage in fabrication of large area sensors and in the yield rate.

We propose a totally unique and simple scheme of the vertex detector using fully depleted fine pixel CCDs (FPCCD), in which hit signals are accumulated during a train and read out between trains.

2. DESIGN CONCEPT OF FPCCD VERTEX DETECTOR

In the FPCCD vertex detector, we use very fine (~ 5 μm) 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. Since the readout time is long (200 ms), low temperature operation would be necessary to keep dark current negligible.

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 $\sigma_x \sim 1.4$ μm 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.

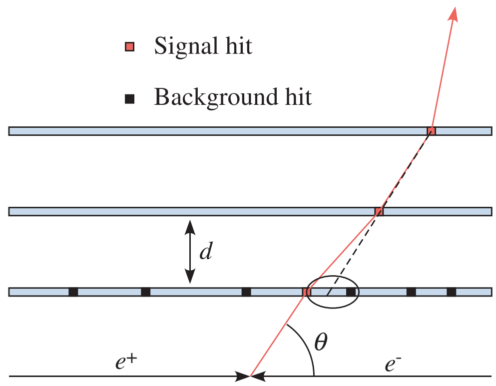

Figure 1: Mis-identification of signal hit with background hit

3. CHALLENGES OF FPCCD VERTEX DETECTOR

3.1. Pixel Size

The pixel size of the FPCCD we expect is not so extraordinary. A camera company recently developed CCDs with a pixel size as small as 2 μm square for the digital camera application. Small pixel gives small full-well capacity of few thousand electrons. For our application, however, the smallness of the full-well capacity is not a problem. Fast readout of a large area requires metal layers with sub-micron width. But recent semi-conductor technology can handle this. The FPCCD with 5 μm pixel size seems quite feasible.

3.2. Tracking Efficiency

Although the pixel occupancy is satisfactorily low, the hit density is still as high as $\sim$ 40 hits/mm^2 at B=3 T, R=20 mm, $L = 3.4 \times 10^{34}/\mathrm{cm}^2\mathrm{s}$. 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 mis-identification probability p_{mis}. For a normal incident track, p_{mis} is given by

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

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

$$p_{mis} \propto p^{-2} \sin^{-4}\theta \quad (2)$$

where p is the momentum and θ is the polar angle (see Figure 1).

The mis-identification probability for 1 GeV/c particles is plotted as a function of $\cos\theta$ in Figure 2 assuming the layer thickness of 50 μm Si. As can be seen from this figure, mis-identification probability quickly goes up in the forward 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/mm^2. To reduce the mis-identification 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 $\sigma = 2/\mathrm{mm}^2$, 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 than that of the large p_t particles.

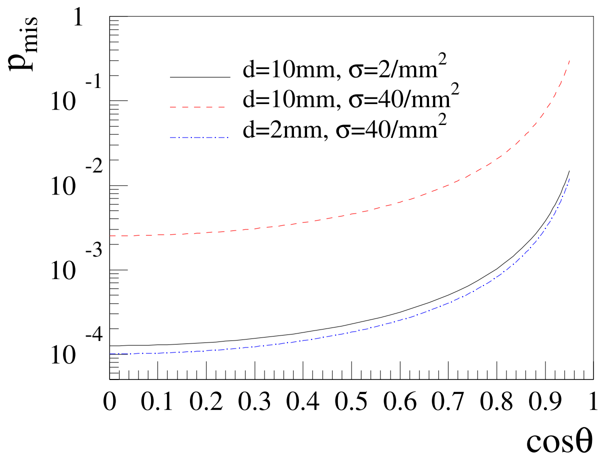

Figure 2: Mis-identification probability of signal hit with background hit as a function of $\cos\theta$ for several layer configurations. The layer thickness of 50 μm and the particle momentum of 1 GeV/c is assumed.

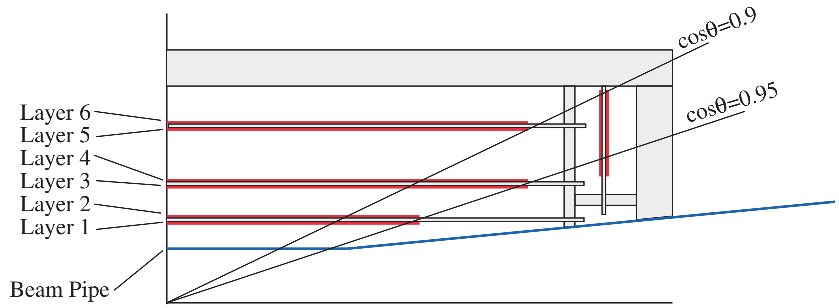

Figure 3: Schematic view of a possible design of the FPCCD vertex detector for ILC.

This consideration leads to a possible schematic design of the vertex detector as shown in Figure 3. Two CCD layers in proximity make a doublet with local tracking capability.

The tracking efficiency is one of the crucial criteria for the feasibility of the FPCCD vertex detector. The detailed simulation study is indispensable.

3.3. Thin Wafer

As mentioned in the previous subsection, thin wafer is essential for high tracking efficiency, as well as for excellent impact parameter resolution. The target thickness would be 50 μm per layer.

There are several ideas and R&D efforts by several groups for thinning and support structure of CCD vertex detectors, such as stretched thin wafer and partially thinned wafer. In case of FPCCD, two layers of CCD wafers are put close to each other. Therefore, a structure of rigid foam sandwiched by thin wafers may be one possibility.

3.4. Lorentz Angle

The epitaxial layer of the FPCCD has to be fully depleted in order to suppress the charge diffusion in field-free non-depleted region. In fully depleted region, electrons created by ionization of charged particles move rapidly due

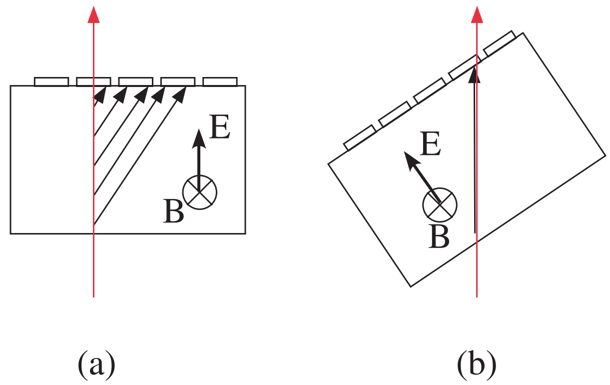

Figure 4: Effect of Lorentz angle. Charge spread shown in (a) can be cancelled by tilting the wafer as shown in (b).

to the electric field. When used in magnetic field perpendicular to the electric field, they are subject to the Lorentz force. The trajectory of the electrons have some finite angle with respect to the electric field. This Loretz angle θ is related with the magnetic field as

$$\tan\theta = vB/E = \mu B, \tag{3}$$

where v is the velocity of the electrons, B is the magnetic field perpendicular to the electric field E, 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 Lorents angle as shown in Figure 4(a). At high electric field, the carrier velocity saturates and the mobility decreases. At the electric field of 1×10^4 V/cm in the epitaxial layer, the electron mobility is 0.07 m^2/Vs [2], and the Lorents angle is 12 degrees in 3 T magnetic field. If the Lorentz angle is as small as this, the charge spread can be suppressed by tilting the sensor wafer to cancel the Lorentz angle as shown in Figure 4(b).

3.5. Readout Electronics

Since the pixel size is extremely small, the charged particle in the forward direction traverses the sensitive region of a pixel with very short path length. The signal charge can be as small as $\sim$ 500 electrons. Therefore, very low-noise readout electronics is indispensable. We may have to consider the use of electron-multiplying CCD (EMCCD).

In order to readout all pixels in 200 ms, CCDs used for the vertex detector must have multi-port readout capability. If one CCD wafer has an area of 20×100 mm^2 and 32 readout ports with 0.64 mm pitch, all of the 5 μm square pixels can be read out within 200 ms at a rate of 15 Mpixels/s. In order to accommodate the 32 readout ports at the edge of the CCD, a multi-channel readout ASIC has to be developed. The ASIC should have variable gain amplifiers, correlated double sampling circuits, analog-to-digital converters, and a data compaction circuit. Although the size of CCD pixel is small enough to get an excellent spatial resolution with digital readout, the ADCs in the ASIC should have 5 to 8 bit resolution in order to keep enough dynamic range.

3.6. Radiation Hardness

We have studied very hard on radiation hardness of CCDs for the vertex detector at a “warm machine”, GLC [3, 4]. We have also sought capability of room temperature operation of CCD vertex detector at GLC. At GLC, the readout cycle of 6.7 ms is assumed. With this short readout cycle, the increase of dark current due to radiation damage is manageable even at near room temperature.

In ILC, however, we use 200 ms readout cycle period. The accumulated dark current is 30 times larger than GLC, and it is not practical to operate CCDs at room temperature. Once we decide to operate the CCDs at low temperature (-80 $^\circ C$, for example), things become much easier. The low temperature operation also gives better results in charge transfer inefficiency (CTI) caused by trap centers created by radiation.

The FPCCD has the small charge-transfer channel corresponding to the small pixel size. As a result, the transferred charge packet encounters less trap centers, and less CTI can be expected.

The radiation immunity of FPCCDs is, however, worse than that of CMOS pixel sensors. We have to demonstrate that FPCCDs have enough radiation immunity for the use as a vertex detector for ILC.

4. SUMMARY AND OUTLOOK

In this article, we have proposed a totally unique concept of a vertex detector for ILC. In this vertex detector, fine pixel CCDs (FPCCDs) with 5 μm-square pixel size are used as the sensor. These FPCCDs accumulate hit signals of one train (2820 bunch crossings) and the hit information is read out in 200 ms between trains. The FPCCD must be fully depleted in order to suppress the charge diffusion in the epitaxial layer and to reduce the number of hit pixels per track. In order to pick up signal hits out of huge background hits, two layers of thin FPCCDs make a doublet (super layer).

The expected performance of the FPCCD vertex detector has been estimated by back-of-envelope calculations. The pixel occupancy of the FPCCD vertex detector is $\sim 0.5\%$ for the innermost layer placed at $R = 2$ cm at $B = 3$ T. The wrong tracking probability due to multiple scattering is less than 1.2% for 1 GeV/c particles in $\cos\theta < 0.95$ if each layer has a thickness of less than 50 μm and distance between first and second layer is 2 mm. Still better tracking efficiency can be expected by background rejection using hit cluster shape.

Because the tracking efficiency is the most crucial criteria of the feasibility of the FPCCD vertex detector, detailed detector simulation study is indispensable. Charge spread due to Lorentz angle could be a problem. We are planning to measure the Lorentz angle of a fully depleted CCD with a standard pixel size in the near future.

References

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