Study of silicon sensors for precise timing measurement

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\textbf{Abstract}: Silicon sensors with high timing resolution can help particle identification in the International Linear Collider (ILC). We are studying Low Gain Avalanche Detectors (LGADs) as a sensor with high timing resolution. As a step to develop LGADs we are now characterizing Avalanche Photo Diodes (APDs), which have similar multiplication structure as LGADs. Particles from radioisotopes are used for studies in this paper.

\textbf{Keywords}: Photon detectors for UV, visible and IR photons (solid-state); Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc); Instrumentation and methods for time-of-flight (TOF) spectroscopy

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1 Introduction

The International Linear Collider (ILC) [1, 2] is an electron-positron linear collider, which is planned to be constructed in Japan. The main purposes of the ILC are discoveries of new particles and precise measurement of the Higgs boson and the top quark. The center of mass energy will be 250 GeV with 20 km tunnel length. In the future, the center of mass energy can be upgraded to 1 TeV with 50 km tunnel length.

In the International Large Detector (ILD) [3], one of two validate detector concepts for the ILC, particle identification can be achieved with dE/dx and momentum measurement with Time Projection Chamber (TPC), but it is insensitive in energy range where different kinds of particles give similar dE/dx with multiple kinds of particles. With a precise Time-of-Flight (ToF) measurement combined with the dE/dx measurement, performance on the particle identification can be improved. We are investigating Low Gain Avalanche Detectors (LGADs) to realize the particle identification on wider momentum range.

We are now characterizing Avalanche Photo Diodes (APDs), which are usually used to measure optical photons, with charged particles. Since APDs have similar multiplication structure as LGADs, this should help in determining the structure of the LGADs. We studied the characteristics of APDs with particles from radioisotopes.
2 Particle identification

Figure 1 shows the separation power of particles with ILD TPC. The light green and green lines show the separation power between $\pi/K$ and between $K/p$ only with TPC. There is a point on each line where the separation power is 0. We suggest the TPC particle identification be complemented with ToF. The orange and light blue lines show the separation power between $\pi/K$ and between $K/p$ with dE/dx and ToF combined. The plot shows improvements of the separation power up to 5 GeV/c, which covers ~90% of particles in jets, if timing resolution of 50 ps is achieved.

![Figure 1. Separation power of particles with ILD TPC][1]

3 Silicon sensors

3.1 LGAD

LGADs are silicon sensors with the internal amplification mechanism, which have already been proved to realize the timing resolution down to 30 ps [5]. However, normal reach-through LGADs have an issue that the amplification factor heavily depends on the position of the hit, because the amplification region is not uniformly formed due to the surface structure. To overcome this, inverse-type LGADs have been proposed, which has amplification region at the bottom, in contrast to the reach-through type with amplification occurring just below the surface.

3.2 APD

APDs are silicon sensors used as photon detectors, which have similar structure as LGADs. Table 1 shows the list of APDs owned by Kyushu University, made by Hamamatsu. The pkg-10 and pkg-20 are prototype APDs tuned for LGAD-like usage in Hamamatsu. In this paper, we used these APDs to study their characteristics.
Table 1. The list of APDs owned by Kyushu Univ.

| APD serial No. | type       | $V_{br}$ | active area |
|---------------|------------|----------|-------------|
| S12023-10A    | reach-through | 139 V   | $\phi$ 1 mm |
| S8664-10K     | inverse     | 417 V   | $\phi$ 1 mm |
| pkg-10        | reach-through | about 250 V | $\phi$ 1 mm |
| pkg-20        | reach-through | about 120 V | $\phi$ 1 mm |
| S3884         | reach-through | 159 V   | $\phi$ 1.5 mm |
| S2384         | reach-through | 189 V   | $\phi$ 3 mm  |
| S8664-20K     | inverse     | 425 V   | $\phi$ 2 mm  |
| S8664-55      | inverse     | 433 V   | $5 \times 5$ mm$^2$ |

4 Measurements using radioisotopes

4.1 Setup

We used a testboard with a Skiroc2-CMS [6] ASIC (Application-Specific Integrated Circuit) to readout signals from the APDs. The testboard is a printed circuit board to evaluate the characteristics of ASICs. It can be connected to the APDs using sensor boards as shown in figure 2 to acquire data from APDs. The Skiroc2-CMS can perform charge and time measurements. We put the setup into an aluminum box for noise shielding during the following measurements.

We used a $^{90}$Sr beta source and a $^{133}$Ba gamma source. The beta source is used to observe the behavior with a MIP passing through the APDs. The gamma source is used to measure the gain of the APDs.

![Figure 2](image-url)  
*Figure 2. Testboard (with APD connected and which soldered Skiroc2-CMS).*
4.2 β source measurement

Figure 3 shows ADC histograms of APDs using the beta source. These histograms showed that the signal height of the reach-through type APDs have slightly larger tail than that of the inverse type, and S8664-55, which has the largest active area, is larger than other inverse type APDs for the peak of the distributions.

\[ f(x) = \frac{2a}{\sqrt{\pi}} \int_{-\infty}^{x} e^{-t^2} dt + bx + c \]  

(4.1)

where \( \mu \) and \( \sigma \) are the position and width of error function. We used the position of this shoulder to calculate active thickness of S12023-10A.

4.3 γ source measurement

In order to calculate the active thickness, we have to measure the gain of the APD. In this paper, we measured the gain of S12023-10A using the gamma source.

Figure 5 (left) shows ADC distribution of S12023-10A with the bias voltage of 129 V. The edge of ADC distribution at about 300 ADC counts is assumed to be a Compton edge of 207 keV, corresponding to 356 keV gamma emission of \(^{133}\)Ba. We fitted this edge using the same function as beta source measurement (4.1), and calculated the gain using the mean of this function. The voltage dependence of the position of the shoulder is shown in figure 5 (right).

4.4 Active thickness

We calculated the active thickness of S12023-10A using the results of beta and gamma sources measurements. A MIP makes 76 electron and hole pairs per 1 µm in a silicon sensor, so the formula
for calculating active thickness can be described by

$$\text{Active thickness} \ [\mu m] = \frac{\mu}{a} \cdot \frac{1}{\text{Gain}} \cdot \frac{1}{76 \cdot e} \quad (4.2)$$

where the $\mu$ is the mean of error function with the beta source and $e = 1.602 \times 10^{-19} \text{C}$. The $a$ is a coefficient between ADC and charge in Skiroc2-CMS. The active thickness of S12023-10A is calculated as $\sim 1000 \mu m$.

However, the active thickness of APDs should be a few tens of $\mu m$ and the gain of APD at 129 V is about 500 (according to the datasheets). Assuming the gain value is 500, the active thickness is $\sim 30 \mu m$ calculated by (4.2).

5 Summary

We are studying LGADs to identify charged particles in ILD. As a step to develop LGADs we are now characterizing APDs. We measured the characteristics of the APDs using a beta source, and estimated the active thickness of S12023-10A. We plan to measure the active thickness of inverse type APDs to investigate the LGAD usage for the ILC.
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