Study of 144-channel Hybrid Avalanche Photo-Detector for Belle II RICH Counter

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Abstract

For the upgrade of the Belle detector at the KEKB collider, we are developing a proximity focusing ring imaging Cherenkov detector using a silica aerogel as a radiator. An array of 144 channel HAPD (Hybrid Avalanche Photo Detector) will be used as the photodetector. We have measured performance of the HAPDs, and succeeded to read out single-photon signals from the HAPD using custom-made ASICs that have been developed for this purpose. We have also performed a beam test with a 2 GeV/c electron beam and demonstrated more than 4σ K/π separation performance at 4 GeV/c.

Key words: HAPD, Photo-detector, ASIC, RICH, Belle

1. Introduction

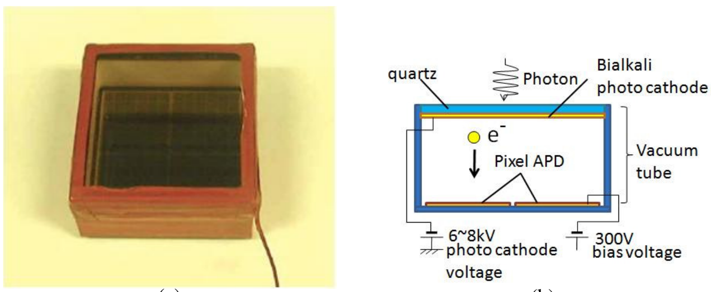
Particle identification (PID) has been a key issue in the B factory experiments[1]. In the Belle experiment at the KEKB[2] collider, a threshold-type Cherenkov detector with aerogel radiator(ACC)[3] is used for K/π separation above 1 GeV/c. However, ACC does not provide separation for high momentum particles around 4 GeV/c in the forward end-cap region for the upgraded Belle II experiment. We have been developing a proximity focusing ring imaging Cherenkov counter with an aerogel radiator (aerogel RICH)[4] as a new PID device to improve separation capability in this region. Our target is to provide more than 4σ K/π separation in the kinematical range from 1 to 4 GeV/c. Due to space limitation, the detector must be of the proximity focusing type with an expansion gap of around 20 cm. If we use aerogel with refractive index of $n = 1.05$, the difference of Cherenkov angle between π and K is 23 mrad at 4 GeV/c.

There are several requirements to the photo-detector. It must have high sensitivity to single photons and must be position-sensitive with a granularity of about 5×5 mm^2. It must have large effective area in order to collect as many photons as possible. It needs to be immune to the 1.5 T magnetic field perpendicular to the photon detector plane. The photo-detector must be immune to the 1×10^{12} neutron/cm^2 irradiation for Belle-II operation of 10 years. Finally, the photo-detector must cover the forward region in Belle of around 4 m^2, resulting in a total number of readout channels of about 10^5.

One of the candidates is a multi-anode Hybrid Avalanche Photo-Detector (HAPD) which we have developed in a collaboration with Hamamatsu Photonics K.K.(HPK).

2. Development of new 144ch HAPD

Fig.1(a) shows the 144ch HAPD. Fig.1(b) shows the structure of the multi-anode HAPD. Photoelectrons are accelerated by the high electric field over a voltage difference of around 10 kV inside the vacuum tube, after which they enter the avalanche photo diode(APD), creating 10^3 electron-hole pairs. Amplification by the avalanche process inside the APD provides an additional gain of 50. As a result, the total gain of the HAPD is $10^4 - 10^5$. Because of the large gain in the first stage, the statistical fluctuation of the gain is rather small compared to conventional photomultipliers.



(a) (b)

Figure 1: (a) 144ch multi-anode HAPD; (b) Structure of the HAPD

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We measured the single photon detection performance of HAPDs with a preamplifier (Clear-Pulse 580K) and a shaper (Clear-Pulse 4417), where the peaking time is set to be 1 μsec. Fig.2(a) shows pulse height distribution for single photon irradiation. We confirm good separation between the pedestal and single photo-electoron signal. We achieved S/N ratio of 16.

To increase Quantum Efficiency (QE), the Super Bialkali (SBA) photocathode technique was applied to the production. Fig.2(b) shows the quantum efficiencies for the HAPDs with SBA and conventional bialkali photocathode. We confirm quantum efficiency of the SBA samples reaches 32% at maximum and is better than that of conventional bialkali at entire wavelength range. Fig.2(c) shows photo cathode uniformity. The SBA sample achieve a QE of more than 30% on whole HAPD surface at 380 nm.

3. High-density readout electronics for 144-channel HAPD

Because the gain of HAPD is lower compared to conventional photo-multipliers, a high gain and low noise electronics is necessary to detect single photon signals. In order to cope with a large number of channels (up to more than 80k in total), we have developed ASICs (Application Specific Integrated Circuit) for the readout of HAPD signal since 2003. The newest ASIC consists of a charge-sensitive preamplifier and a shaper, followed by a comparator for the digitization of analog signals to convert to on/off hit information. The hit information from ASIC is passed to output pins and is handled by an external FPGA (Field Programmable Gate Array) for flexible readout. The first version of the ASIC, called SA01, has only 12 channels, while the second version, SA02, has 36 channels (Figure 3-(left)). Both ASICs were produced at MOSIS using TSMC CMOS 0.35 μm process.

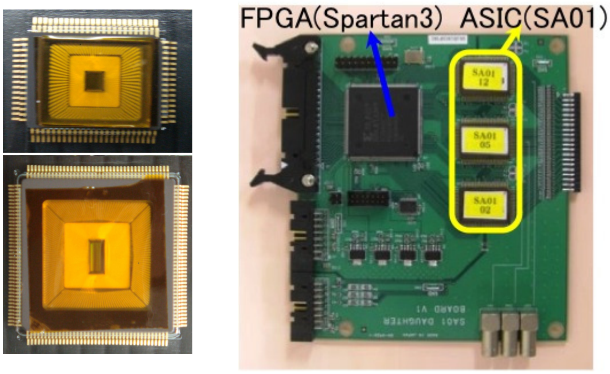


Figure 3: ASICs of 144-channel HAPD (upper left: SA01, lower left: SA02) and test board of SA01 (right).

The specification of the SA01 is as follows. The noise level is 1200 e^- at a 80 pF input capacitance which is equivalent to the detector capacitance of the HAPD. The gain of the preamplifier is adjustable from 70 to 290 V/pC, and the shaping time is also variable from 250 to 1000 ns. The threshold voltage is common to all channels, but the offset can be adjusted for each channel in the range of ±500 mV using two 4-bit DAC (fine and coarse adjustments). Therefore, we can effectively choose threshold level for each channel. The performance was examined by connecting ASICs with the HAPD and single photon signal was successfully detected. However, at the same time, HAPD output signal and amplification in the ASIC was found to be not well matched. This problem is fixed in SA02 by reducing the gain of the ASIC to one-fourth (the other performance of SA02 is almost same as SA01).

We connected the test board of SA01 (Figure 3-(right)) to an HAPD, and readout the HAPD signal with SA01 and FPGA. Figure 4-(left) shows hit counts in a channel when we irradiate a LED light to a single HAPD channel, with varying threshold level of ASIC, and Figure 4-(right) shows analog signal in ASIC at this measurement. We found the distribution clearly separated between pedestal, single photo-electron and two photo-electron and the estimated noise level is about 1900 e^- and S/N ratio 17 (an HAPD gain is 32000). This result shows successful readout of HAPD signal using the developed ASIC and FPGA, and very good performance of the readout system.

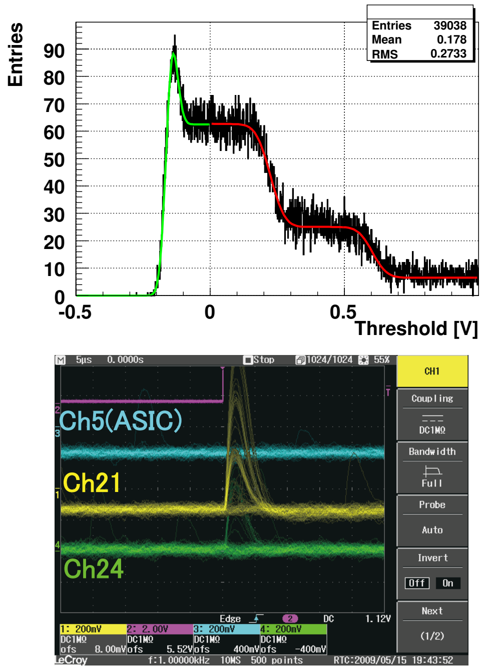
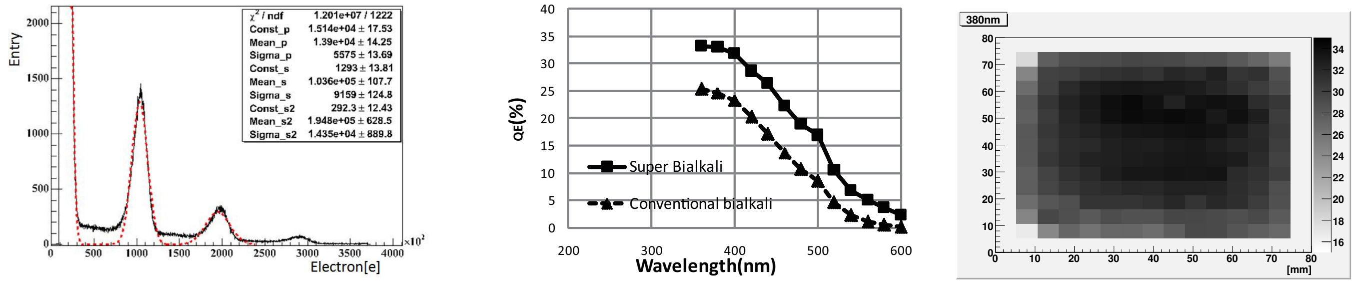


Figure 4: Readout of HAPD with ASIC, FPGA. **Top:** Result of threshold scan (fit with gaussian (green line) and triple error function (red)). **Bottom:** Analog signal in ASIC (LED right irradiation on ch21 (yellow)).

4. Performance in magnetic field

Because we have to use HAPD in the Belle II solenoid magnet, the HAPD needs immunity to 1.5 Tesla magnetic field. We measured the HAPD performance in the 1.5 Tesla magnetic field by using electromagnet "Ushiwaka" in KEK. We have set up a special equipment to scan the HAPD surface in the magnetic field with pulse laser.

We studied two subjects, one is position detection uniformity and the other is photoelectron back scattering on the APD surface. Because the photocathode and the side wall metal are at



(a) (b) (c)

Figure 2: (a) Pulse height distribution for single photon irradiation; (b) Wavelength dependence of the quantum efficiency. (c) Uniformity of the quantum efficiency for the SBA sample.

the same electric potential in the HAPD, the electrical field near the side wall is distorted and carries photoelectrons to the neighboring APD pixel. The position resolution of the HAPD gets worse by this effect. A part of photoelectrons hitting the APD are backscattered and detected at different position. With HV of 8,000 V the backscattering probability is about 20% and the spread is about 40 mm. Because photoelectrons follow a spiral path in the magnetic field, we expect that the performance is improved in these two points.

Figure 5 shows result of one dimensional scan on the HAPD. The distributions of different colors correspond to the hit count of 12 APD pixels. Vertical lines show the boundary of pixels. Under 0 T, distributions near the side wall are distorted. However in the magnetic field of 1.5 T, the distortion near the side wall disappears. We have achieved 5 mm position resolution all over the HAPD surface in 1.5 T.

Figure 6 shows results of photoelectron back scattering effect study. Under 0 T, we observe the backscattered photoelectrons spreading within 40 mm. In 1.5 T, we confirmed reduction of photoelectron backscattering effect. A spread of the distribution within 15 mm remains in the magnetic field, which is due to reflection of light on the APD surface.

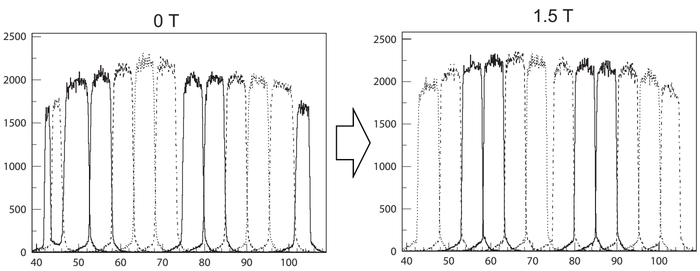


Figure 5: Position detection distribution

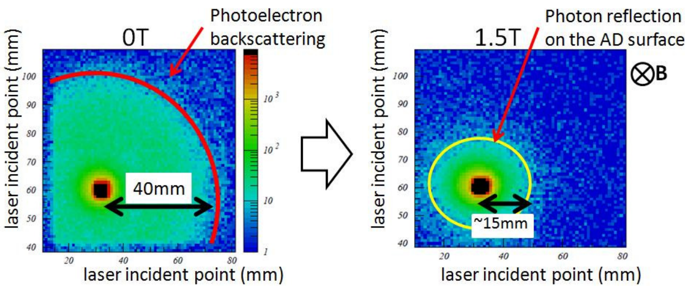
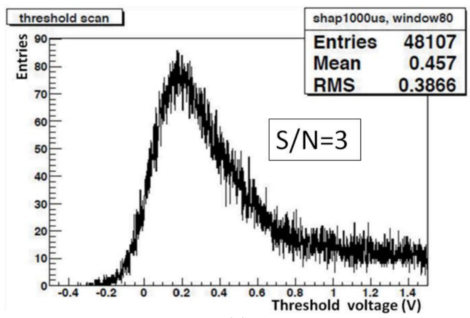


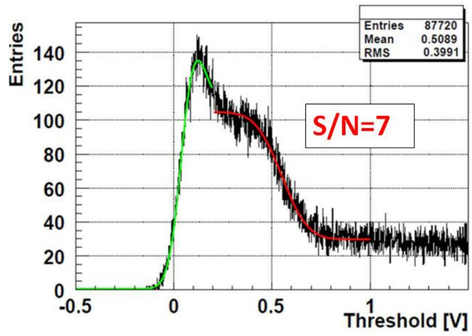
Figure 6: Photoelectron backscattering effect

5. Neutron irradiation test

It is known that neutron irradiation damages semiconductor detectors. We concern especially about the noise of APD. That could increase the leakage current caused by the neutron induced lattice defects in silicon. The neutron dose is estimated to be 1×10^{12} neutron/cm^2 for Belle II operation of 10 years. We carried out neutron irradiation test in October 2009 at the nuclear reactor Yayoi in Tokyo University. The neutron flux is



(a)



(b)

Figure 7: Threshold scan: (a) $1\mu s$ peaking time and -7,000 V; (b) 250 ns peaking time and -8,500 V

$2{\times}10^8$ neutron/cm^2/s. the neutron energy range is 100 keV to 1 MeV. We irradiated up to $5{\times}10^{11}$ neutron/cm^2.

Quantum efficiency does not change before and after $5{\times}10^{11}$ neutron/cm^2 irradiation. We observe that the leak current is increased proportionally to the irradiation. At $5{\times}10^{11}$ neutron/cm^2, the leak current is 9 μA for one APD chip (36 channels).

Before the irradiation, the S/N is 17 by using 1 μs peaking time and HV of 7,000 V. After the irradiation, the performance of HAPD is studied by measuring S/N ratio for the single-photon signal using ASIC. S/N target is more than 7 for the single photon signal for aerogel RICH. After $5{\times}10^{11}$ neutron/cm^2 irradiation, we measured HAPD with same parameters. S/N ratio dropped down to 3 (fig.7(a)). However, S/N is improved to 7 by using 250 ns peaking time and HV of -8,500 V (fig.7(b)). We confirm that the HAPD has single-photon detection capability after 5 years in Belle II detector. Irradiation test up to $1{\times}10^{12}$ neutron/cm^2 is underway.

6. Beam test of Aerogel RICH with HAPD

We performed a beam test of a prototype Aerogel RICH counter in November 2009 at the Fuji beam line, where a 2GeV/c electron beam converted from Bremsstrahlung photons of the KEKB electron ring is available. The experimental setup is shown in Fig.8(a). The prototype counter is composed of focusing type aerogel radiators and 2×3 array of HAPDs, whose photo-detection plane is parallel to the radiator face, keeping a separation distance of 20 cm. Track parameters were determined by two multi-wire proportional chambers. For the read out, we used an electronics system based on ASICs describeed in the previous section. Aerogel tiles with the thickness of 2 cm each and refractive index of 1.054 and 1.065 with improved transmittance[5] are used in the test. Fig.8(b) shows the hit distribution at the photo-detection plane. A clear Cherenkov ring is observed. The Cherenkov angle distribution is shown in Fig.8(c). From a fit to this distribution, the number of detected photo-electrons per track ($N_{p.e.}$) is calculated to be 15.3. The resolution per photon (σ_{θ_C}) is found to be 13.5 mrad from the fit. The resolution per track ($\sigma_{\theta_C} / \sqrt{N_{p.e.}}$) is calculated to be 3.5 mrad, which corresponds to 6.6σ π/K separation at 4 GeV/c.

7. Conclusion

We have developed a 144 channel HAPD for the Belle II Aerogel RICH counter in a collaboration with HPK. We have shown that the HAPD has excellent performance. We observed a single photon peak well separated from the pedestal. We achieved more than 30% peak quantum efficiency and good photocathode uniformity for the SBA sample. The HAPD has 5 mm position resolution and immunity to the 1.5 T magnetic field. Remaining issue is to prove the single-photon detection capability after $1{\times}10^{12}$ neutron/cm^2 irradiation. We have also developed an ASIC with low noise and high gain, and have successfully read out the signals from the HAPD. The excellent K/π separation of Aerogel RICH with HAPDs has been confirmed by the beam test. We have selected the new HAPD as the baseline photodetector for the Belle II Aerogel RICH.

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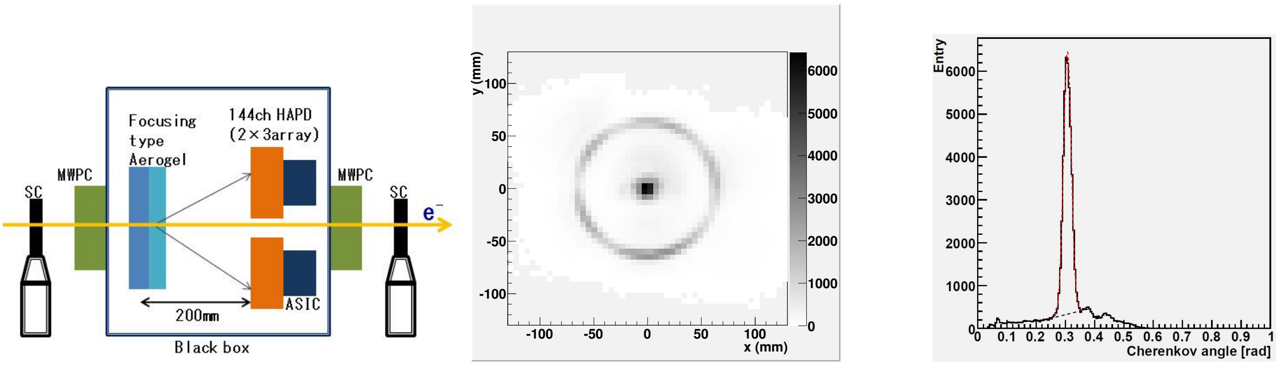

(a) (b) (c)

Figure 8: (a) The experimental setup; (b) Hit distribution at the photo-detection plane; (c) Cherenkov angle distribution