Fast APD detector with a short tail in the timing response for an experiment using synchrotron radiation X-ray beam

Takahiko Masuda1, Takahiro Hiraki1, Hiroyuki Kaino1, Shunji Kishimoto2, Yuki Miyamoto1, Koichi Okai1, Sho Okubo1, Ryota Ozaki1, Noboru Sasaki1, Kent Suzuki1, Satoshi Uetake1, Akihiro Yoshimi1, Koji Yoshimura1

1Research Institute for Interdisciplinary Science, Okayama University, Okayama 700-8530, Japan
2Institute of Materials Structure Science, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
E-mail: masuda@okayama-u.ac.jp

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We developed a fast X-ray detector system for a nuclear resonant scattering experiment of thorium-229. The system employs silicon avalanche photo-diode as a fast X-ray sensor. The design of the system mainly focuses on the small tail of the timing response in a high rate condition. To reduce the tail component, the system acquires three parameters for each single X-ray photon: the constant fraction timing, the trailing edge timing with a fixed threshold, and the pulse height. The performance of the system was investigated in KEK-PF. A quite small tail of $10^{-9}$ level at 0.5 ns apart from the peak was achieved by using the correlation between the pulse height and the pulse width information.

KEYWORDS: Thorium-229, avalanche photodiode, synchrotron radiation, single photon detection

1. Introduction

Silicon avalanche photodiodes (Si-APDs) are widely used in a variety of research fields. While they are mainly used as visible or near-infrared light sensors, they are able to detect X-rays at a single photon level with good signal-to-noise ratio. In particular, they are widely used in synchrotron radiation X-ray experiments because of their fast time response for a single X-ray photon and their rate tolerance which enables high rate measurement; such fast timing response takes advantage of the high intensity in recent synchrotron radiation facilities [1].

We developed a fast single X-ray photon detection system by using thin Si-APDs. The system is used for the nuclear resonant scattering (NRS) measurement of the second excited state of thorium-229 [2–4]. We use intense synchrotron radiation X-ray beam to excite the nuclei. We measure the scattered X-ray timing profile in the measurement; the NRS signal appears as an exponential slope with lifetime of the second excited state in a huge amount of instantaneous background scattering due to other electronic processes than the nuclear process. The problem is poor signal-to-noise ratio due to the quite short lifetime of $\sim 100$ ps and narrow excitation linewidth of $\sim 1$ neV. That is why, the detection system needs quite fast timing response.

The developed system had an overall time resolution of $\sigma = 65$ ps and a short tail apart from the peak in the timing response. The short tail of $10^{-9}$ level at 0.5 ns apart from the peak was achieved even at a high rate of more than $10^6$ counts per second. This performance is unprecedented level compared to previous works [5, 6]. The component and structure of the detector system were reported in our previous work [7], and this work focuses on the short tail component in the timing response.
2. Beam test

We measured the detector performance in a beam test at the BL-14A beam line of KEK Photon Factory (KEK-PF) [9]. The experimental set up around the detector is shown in Fig. 1. The beam was injected directly into the Si-APD perpendicular to the surface. The attenuator adjusted the beam intensity and the beam slit defined the beam size. The nominal beam energy and the bandwidth were 18 keV and 4 eV, respectively. The bunch structure of the beam was 53 bunches with a time interval of 2 ns, and each 53-bunches came in every 156 ns. The number of photons in a bunch was constant among the bunches.

The Si-APD we use was a reach-through type Hamamatsu Photonics S12053-05 whose sensitive area was 0.5 mm in diameter. The device was placed in an aluminum box as an electrostatic shield. It was operated at room temperature. The applied reverse bias voltage was 150 V and the nominal gain was 50. The output signal was amplified by a preamplifier, and it was sent to a constant fraction discriminator (CFD) and a pulse shaping circuit. The CFD also provided a start signal to the following amplitude to timing converter (ATC) [8] which converted the pulse height to a time delay. The ATC also equipped a trailing edge (TE) discriminator. All the three logic information (CFD, ATC, and TE) and an accelerator reference signal were digitized by a multi-stop TDC (FAST ComTec, MCS6) at a sampling rate of 100 ps. The block diagram and the pulse processing schematic are shown in Fig. 2. The CFD had a threshold which defined event occurring. The count rate was $(0.7–1.0)\times10^6$ counts per second, which gradually decreased due to the decay of the beam current in the electron storage ring.

![Fig. 1. Photo of the experimental setup around the detector. The X-ray beam comes in from the left side through the attenuator and the beam slit. The APD (not shown in the picture) is placed in the aluminum box.](image1.png)

![Fig. 2. Block diagram of the data acquisition (left) and schematic of the pulse data acquired in the system (right). Start signal in the right figure is the same as the accelerator reference signal in the left figure.](image2.png)
3. Results and discussion

The correlation among the three parameters (CFD, ATC, and TE) for each X-ray photon are shown in Fig. 3. In Fig. 3a, the constant fraction timing is shifted so that the peak locates at \( t = 0 \). The pulse height distribution had a clear peak corresponding to the incident beam energy. There were also lower height and higher height components on each side of the peak; these were due to Si-APD response. The tail component along the horizontal axis in the lowest height region was due to the CFD response near its threshold. Figure 3b shows the correlation between the pulse height and pulse width defined as the time difference between the trailing edge and the constant fraction timing on the leading edge. There were a clear ridged line and widely distributed component.

To obtain the timing response for a single photon at the energy peak, we applied the pulse height selection as shown in Fig. 3a. In addition, we applied a selection by using the correlation between the pulse height and the pulse width. We binned the pulse height and defined \( \Delta TC \) of an event as the difference from the peak in the bin along the pulse width (see Fig. 3b). Figure 4 shows the \( \Delta TC \) selection effect on the timing response. The overall timing resolution which was defined as sigma of a Gaussian fit was 65 ps; it includes the quantization error of \( 40 \) ps due to the sampling rate of 100 ps. Whereas the timing resolution were not change by tightening the \( \Delta TC \) selection, the tail component of the timing response was evidently reduced: from 1 ns at \( 10^{-9} \) of the peak in case of \( \Delta TC < 1.6 \) ns to 0.5 ns at \( 10^{-9} \) of the peak in case of \( \Delta TC < 0.1 \) ns. The total number of events was almost conserved even though the selection was tightened; the event loss was only 13%.

This effect is able to be understood by considering that the \( \Delta TC \) represents the pulse shape distortion. The events with large \( \Delta TC \) consist of distorted pulse shapes; thus, the \( \Delta TC \) selection effectively picks up events with almost identical pulse shapes and the resultant tail component is suppressed. When we reduced the beam intensity so that the counting rate was lower than the presented data, we found that the ratio of the large \( \Delta TC \) component decreased. Therefore, the pulse shape distortion can be explained as high counting rate effects, such as double pulse overlap and baseline shift. In either case, by selecting normal pulse shape events using the correlation between the pulse height and width, we can reduce the slow tail component effectively.

![Fig. 3.](https://example.com/f3.png)

(a) Pulse height vs. Constant fraction timing. (b) Pulse height vs. two-edge difference. The data integrated in a 100 s run are shown without any offline selection. The black curve in (b) connects the peak position along the ridged line.
4. Conclusion

The developed system acquires the three parameters for a single X-ray photon: constant fraction timing on the leading edge, trailing edge timing with a fixed threshold, and pulse height. The correlation among the three parameters can reduce the tail component of the timing response to $10^{-9}$ level at 0.5 ns apart from the peak. This feature is essential to search for NRS of the second excited state of $^{229}$Th whose lifetime is shorter than 100 ps and excitation width is only ~1 neV. Recently, we have succeeded in the observation of the NRS signal of the second excited state of $^{229}$Th by using this system [10]. This observation also supports the usefulness of the system especially for time-resolved X-ray synchrotron radiation experiments.

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