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Pulse-height measurements with a cooled avalanche-photodiode detector

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A cooled avalanche-photodiode (APD) detector has been developed for X-ray diffraction experiments. Although an APD is normally used at room temperature and a high internal gain, the energy resolution can be improved by decreasing temperature and gain. The APD device was cooled to 253 K by a thermoelectric cooler. When the gain was $M = 13$, the energy resolution was 5% (FWHM) at 16.53 keV with a charge-sensitive preamplifier. By scanning the discriminator threshold level of a fast-counting system, energy spectra were obtained at $M \simeq 50$ and count rates of up to 4.7×10^7 s^{-1}.

Keywords: avalanche photodiodes; high rates; energy resolution.

1. Introduction

Avalanche photodiodes (APDs) have been used for experiments in time spectroscopy with synchrotron X-rays. In particular, the APDs have sub-nanosecond resolution that is suitable for Mössbauer time-spectroscopy. Fast counting is also suitable for APD detectors. The output of the detector has a pulse width of nanoseconds, which contributes to a short dead time of the counting system.

APDs have energy resolutions better than NaI(Tl) scintillation detectors at room temperature. For example, the resolution is 10–25% (FWHM) at 5.9 keV (Squillante *et al.*, 1986; Farrell *et al.*, 1994). Although an APD is normally operated at room temperature and a high internal gain, the energy resolution can be improved by decreasing temperature and gain (Webb *et al.*, 1974). The dark current of the device decreases at a low temperature, and the deviation caused by the electron multiplication decreases with a smaller gain. Therefore, an APD has a better resolution at a low temperature and at a small gain. However, the internal gain has a tendency of rapidly increasing with low temperatures. This is because the electron carriers can accept a larger energy from the electric field during the period between collisions with atoms. A moderately low temperature provides stable operation of an APD. The suitable condition has to be found for each APD device, depending on the structure of each APD. If both fast counting and energy resolution, such as in an Si(Li) detector, are realized under the same condition for operating APDs, the APD detector is also useful for energy analysis at high count rates, such as $>10^6$ counts s^{-1}.

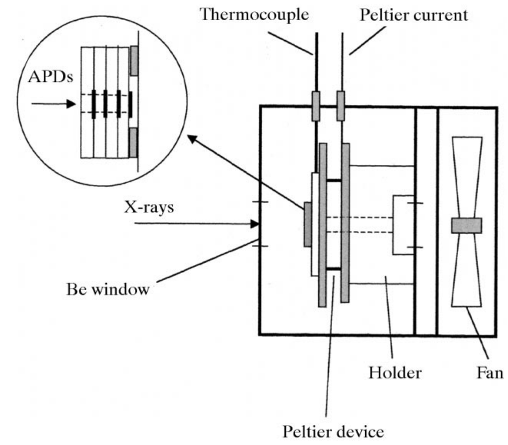

Figure 1
Set-up of the APD detector. Four APD devices (Hamamatsu SPL2625, channel 1–4 from the injection side) were mounted in a stack. A thermoelectric cooler was used to cool the stack to 253 K.

Here, the results were measured with a detector using a stack of APDs, cooled with a thermoelectric device. Energy spectra for X-rays were first recorded at low rates with a normal spectroscopy system. Energy resolutions were measured at temperatures of 294, 273 and 253 K, and at internal gains of $M < 100$. Moreover, the pulse-height distribution of the detector outputs was investigated with a fast-counting system at $M \simeq 50$ and output rates of up to 4.7×10^7 counts s^{-1}.

2. Cooled APD detector

A stack of four APD devices (Hamamatsu Photonics SPL2625) was used for an X-ray detector. Fig. 1 illustrates the set-up of the APD detector. An SPL2625 silicon APD device was developed for high-count-rate measurements (Kishimoto *et al.*, 1997). The device has a transmission structure in which no thick dead regions and no metallic layers exist inside the sensitive area. The thickness of the sensitive region is 120–130 µm, although the total thickness is 135 µm. The detector has a stack of four APDs and the X-rays arrive at the p+ side of the APD device. Signals from each APD are independently obtained from each n+ electrode, while a negative reverse-bias voltage is commonly applied to each p+ electrode. The stack is cooled with a thermoelectric cooler. The Peltier device has a cooling power of 5.4 W, and the hot side of the device is in contact with the wall of the aluminium chamber. The outer side of the chamber has a fin structure cooled by a fan. The temperature is monitored at the aluminium holder of the APDs by a Chromel/Alumel thermocouple. The lowest temperature was 253 K by this system.

The temperature dependence of the APD's gain was investigated for 16.53 keV X-rays. Curves of gain (M) *versus* applied voltage are shown in Fig. 2 for one APD (channel 2) at temperatures of 294, 273 and 253 K. At voltages lower than 95 V,

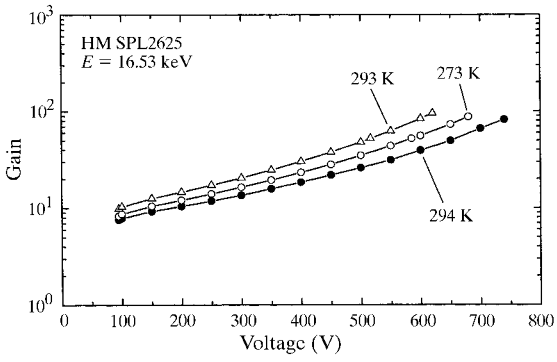

Figure 2
Gain–voltage curves for the APD (SPL2625, channel 2) at temperatures of 294, 273 and 253 K.

the peak of the X-rays was masked by the dark current, and at voltages larger than 750 V the energy resolution was actually lost at 294 K. Similar to the result at 294 K, the resolution rapidly worsened at voltages of >680 V at 273 K and >620 V at 253 K. It is shown that the gain at an applied voltage increases with decreasing temperature.

3. Energy spectra of SPL2625

The pulse-height distribution for 16.53 keV X-rays was first investigated using a charge-sensitive preamplifier (CANBERRA 2001 A) and a spectroscopy system (main amplifier: ORTEC 572; ADC: CANBERRA 8077; MCA: FAST ComTec MCD/PC). The shaping time of the main amplifier was 0.5 µs. The results shown here were recorded from the second device behind the front APD, because signals from the first APD had a slight modulation due to inadequate wiring. The energy spectra at $M \simeq 50$ are shown for 294, 273 and 253 K in Figs. 3(*a*)–3(*c*). The energy resolution (FWHM) improved to 13.5% at 253 K from 21% at 294 K. Next, the gain was altered, while the temperature was kept at 253 K. The results are shown in Figs. 4(*a*)–4(*c*). When $M = 13$, the energy resolution became better, 5% (FWHM), as shown in Fig. 4(*c*), although the FWHM of 17.8% was observed at $M = 62$, in Fig. 4(*a*). In these energy spectra, a small tail is seen in the lower-energy side of the peak. This is probably due to a smaller gain of the carriers that generated in the multiplication region than that in the drift region of the APD device.

4. Pulse-height measurements at rates >10^6 counts s^{-1} with a fast-counting system

By scanning the discriminator threshold of a fast-counting system, energy spectra were obtained at count rates higher than 10^6 s^{-1}. The fast-counting system consists of fast amplifiers (Phillips Scientific 6954), a discriminator (Technoland Co. C-TM415) and a scaler (Technoland Co. C-KP402). This is almost the same as the

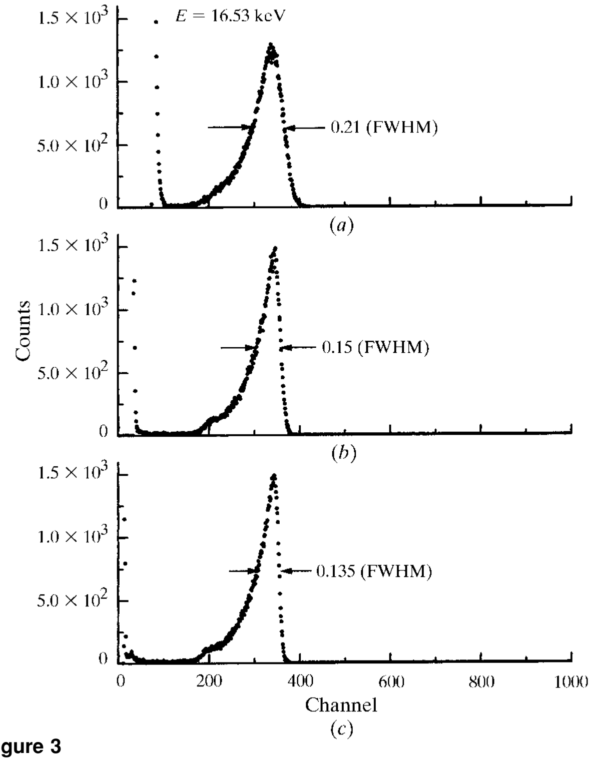

Figure 3
Energy spectra for 16.53 keV X-rays at (*a*) 294 K, $M = 49$, (*b*) 273 K, $M = 52$, and (*c*) 253 K, $M = 52$.

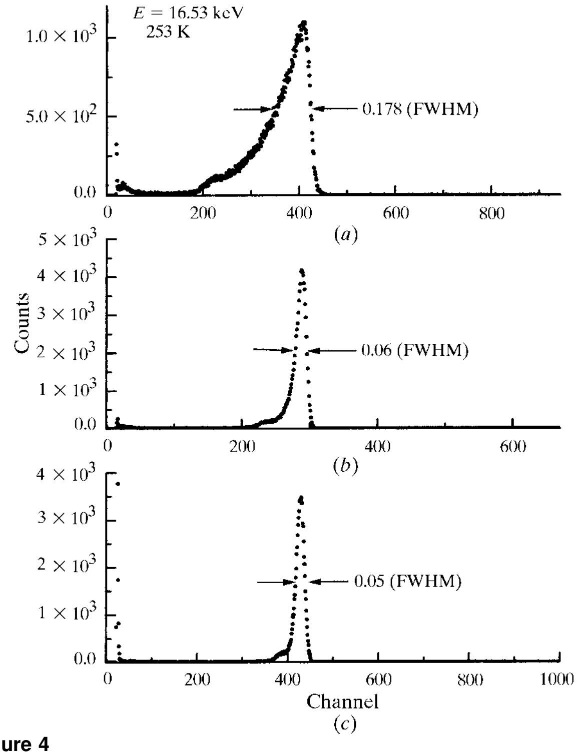

Figure 4
Energy spectra at 253 K for 16.53 keV X-rays at (*a*) $M = 62$, (*b*) $M = 21$ and (*c*) $M = 13$. The peak width decreased with decreasing gain, although a small tail remained.

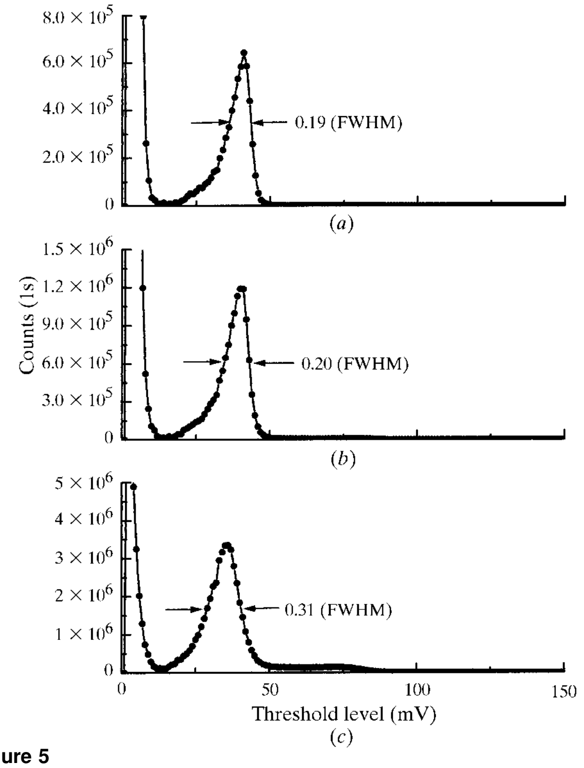

Figure 5
Pulse-height distribution by single-channel discrimination. The spectra for 16.53 keV X-rays were measured at (*a*) 6 Mcounts s^{-1}, (*b*) 12 Mcounts s^{-1} and (*c*) 47 Mcounts s^{-1}.

system described by Kishimoto *et al.* (1997). The outputs from the fast amplifiers are processed at the discriminator having a pulse-pair resolution of 3.3 ns. The discriminator threshold can be set by ten-bit resolution for the -1 V range. A 300 MHz scaler is used for counting the outputs from the discriminator.

If the threshold level is repeatedly scanned to cover a range of pulse heights and the counts at each discriminator threshold are recorded, one obtains a pulse-height distribution by subtracting the number of counts at an upper level from that at a lower level. This is called single-channel sequential discrimination (Knoll, 1989). This method needs a large pulse-height to obtain a better resolution, *i.e.* a better signal-to-noise ratio. Therefore, the gain of the APD was set to a relatively high value, $M = 52$. The energy spectra with the cooled detector were investigated at 253 K, as shown in Figs. 5(*a*)–5(*c*). The resolution of the 16.53 keV X-rays was 20% even at 12 Mcounts $\rm s^{-1}$, as seen in Fig. 5(*b*). However, the resolution was worse than 13.5% measured by the charge method. This is due to high-frequency noise at the outputs of the fast amplifier and due to a coarse resolution of the discriminator (1.3 mV $\rm bit^{-1}$). We can expect a better resolution by eliminating the noise from outside of the detector chamber and by a fine resolution of discriminator threshold. At a rate of 47 Mcounts $\rm s^{-1}$, shown in Fig. 5(*c*), the width became broad because pulse pileup often occurred at such a high rate. The structure due to the two-photon events is also seen at the channel number two times larger than that of the peak for the single-photon events. This is caused by the increasing probability of observing two photons per bunch. At 1.1×10^8 counts $\rm s^{-1}$, the resolution was lost by the pileup.

5. Conclusions

An APD detector consisting of a stack of four devices has been fabricated and the devices were cooled to 253 K. The energy resolution of the detector was measured with a charge-sensitive preamplifier and a multichannel analyser system. For 16.53 keV X-rays, a FWHM of 13.5% was recorded at 253 K and a gain of 52. At a smaller gain of 13, the resolution was improved down to 5% at the same temperature. The pulse-height distribution was also measured at a relatively high gain ($M \simeq 50$) by sequential single-channel discrimination. This method enables us to record energy spectra even at count rates higher than 10^6 counts $\rm s^{-1}$. At rates up to 10^7 counts $\rm s^{-1}$, the energy resolution was not so deformed, although the resolution obtained by this method was worse than by the charge method. This is due to high-frequency noise and a coarse resolution of discriminator threshold. An improved detector is now prepared for X-ray diffraction experiments.

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