A liquid-helium cooled large-area silicon PIN photodiode x-ray detector

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Abstract

An x-ray detector using a liquid-helium cooled large-area silicon PIN photodiode has been developed along with a tailor-made charge sensitive preamplifier whose first-stage JFET has been cooled. The operating temperature of the JFET has been varied separately and optimized. The x- and γ-ray energy spectra for an \textsuperscript{241}Am source have been measured with the photodiode operated at 13 K. An energy resolution of 1.60 keV (FWHM) has been obtained for 60-keV γ-rays and 1.30 keV (FWHM) for the pulser. The energy threshold could be set as low as 3 keV. It has been shown that a silicon PIN photodiode serves as a low-cost excellent x-ray detector which covers large area at 13 K.

We have developed an x-ray detector to be employed in our solar axion experiment. The axion is a light pseudoscalar particle introduced to solve the strong CP problem [1]. Sikivie [2] proposed an experiment to detect the axions emitted by the sun using a system of a strong magnetic field and an x-ray detector, called the axion helioscope. In the magnetic field, solar axions convert to x rays of black body radiation spectrum with an average energy of 4.2 keV. The conversion can be enhanced by filling the conversion region with dense gas [3]. We are going to adopt cold helium gas as conversion medium with a temperature just above the boiling point at one atmosphere. In the experiment, an x-ray detector with the following specification is needed:

- sensitive to x rays of 3–10 keV
- energy resolution better than a few keV
- operable at low temperature
- sensitive area larger than 10 cm\textsuperscript{2}
- low cost
Although gaseous detectors are often used for the soft x-ray detection, they are unusable at low temperature. By contrast, low temperature is a favorable environment for semiconductor detectors since their leakage currents decrease with temperature, hence high energy resolution is achieved. Among various semiconductor detectors, Si (Li) detectors are commonly used for low energy photon detection, but they are very expensive so that they are not appropriate for a large-area x-ray detector.

Silicon PIN photodiodes usually used as light detectors are known to work also as good radiation detectors at liquid nitrogen temperature [4]. They are commercially available at relatively low price in various size and shapes. The thickness of their active layers is typically 200–500 µm, which is sufficient for the detection of soft x ray, but is so thin that silicon PIN photodiodes are almost insensitive to γ rays of higher energy. The latter feature, the low sensitivity to the background γ rays, makes silicon PIN photodiodes even advantageous over the expensive Si (Li) detectors because lower background is expected for them.

In this letter, we present the result of a measurement we have performed to see whether a silicon PIN photodiode possesses the required performance, namely, sensitivity to the x rays and enough energy resolution, even at the temperature far below liquid-nitrogen temperature.

The experimental setup is illustrated in Fig. 1. Since electronic noise dominates the energy resolution of the detector system, the first-stage junction field-effect transistor (JFET) and the feedback resistor of the charge sensitive preamplifier were cooled together with the PIN photodiode in order to reduce the thermal noise. They were put into a vacuum vessel and the vessel was immersed in a liquid-helium dewar. An $^{241}$Am source was also put inside the vessel.

A silicon PIN photodiode with a thickness of 500 µm, Hamamatsu S3204-06, was used. It is a windowless photodiode with an active area of $18 \text{ mm} \times 18 \text{ mm}$ and is supplied on a ceramic base. The typical capacitance value is specified to be 80 pF at a reverse bias voltage of 100 V by the manufacturer. Between the source and the PIN photodiode is a copper collimator of 1-mm thick and with a hole of $\phi 1.5 \text{ mm}$ in the center. In order to reduce the microphonic noise the PIN photodiode was softly supported with a phosphor bronze ribbon to a liquid-helium cooled copper plate soldered on the end cap. Its temperature was monitored with a carbon resistance thermometer (Allen-Bradley 56-Ω solid carbon resistor) stuck on its back.

Other electronic components, such as the JFET and the feedback resistor, were mounted on a glass-epoxy printed circuit board and cooled with a 1-mm-thick copper-plate cold finger fixed on the end flange at its base. A low-
noise JFET, Hitachi 2SK291, was used at the first stage of the charge sensitive preamplifier. Its transconductance $g_m$ has been measured to be 50 mS at room temperature and 30 mS at liquid nitrogen temperature. In order to obtain the optimum noise feature, the operating temperature of silicon JFETs should be kept at around 120–170 K \[5\]. Therefore, the JFET was mounted on a copper chip and a 6.5-mm-long stainless steel pipe with outer diameter of 4 mm and thickness of 0.2 mm was inserted between the copper chip and the cold finger to keep the JFET at relatively high temperature. In addition, a manganin wire was put around the JFET as a heater and the JFET temperature was separately controlled by varying the power fed to the heater. The temperature of the copper chip was monitored with a platinum resistor (Tama Electric SDT101A).

The schematic description of the charge sensitive preamplifier is shown in Fig 2. The bias voltage fed to the PIN photodiode was set at 100 V, the value which was recommended to produce full growth of the depletion layer. The test input of the charge sensitive preamplifier was connected to a pulser, and the output signal of the preamplifier was fed to a shaping amplifier (Camberra 2026), then digitized with a peak-sensing ADC (Laboratory Equipment 2201A).

Before the vessel was cooled to liquid-helium temperature, pulse shaping and JFET operating temperature were optimized at liquid-nitrogen temperature. To obtain the highest resolution for the pulser inputs, the triangular pulse shaping was chosen and the shaping time constant was fixed at 12 $\mu$s, the longest time constant available with the shaping amplifier. As the leakage current at this low temperature is negligible, the serial noise is dominant. Thus it is quite natural that the longest time constant yielded the best result \[5\]. Then, to optimize the operating temperature of the JFET, we measured the pulser resolutions as a function of the measured JFET operating temperature and searched for the minimum. The optimum operating temperature of the JFET was around 110–140 K, which was consistent with the value shown in the ref. \[5\].

Then the vessel was cooled down to liquid helium temperature. The typical energy spectrum for the $^{241}$Am source measured with the JFET at the optimum temperature is shown in Fig. 3. The temperature of the PIN photodiode was $13 \pm 3$ K. The 60-keV $\gamma$-ray line is clear, and the 26-keV $\gamma$-ray line, the three Np L x-ray lines, and the 8-keV Cu K x-ray line, due to the fluorescence on the copper collimator, are also distinguished in the spectrum. The pulser resolution was 1.30 keV (FWHM), and the energy resolution for the 60-keV $\gamma$-ray line was obtained to be 1.60 keV (FWHM). The latter was calculated only with the data of the higher energy side of the peak as the 60-keV line shape is slightly asymmetric around the peak due to scattered $\gamma$ rays. The energy threshold could be set as low as 3 keV. This is already a promising value for the detection of axion-converted x rays with an average energy of 4.2
keV.

We also tried to lower the temperature of the PIN photodiode by sticking it directly on the cooled copper plate, and observed that the silicon PIN photodiode functioned as an x-ray detector at 6 K, but the microphonic noise was so severe that the measurement of spectra was almost impossible with the simple method, namely the combination of pulse shaping and pulse-height measuring. Either isolation of the vibration itself or a special discrimination of the microphonic noise from the actual signal is necessary to get rid of this problem.

In summary, it has been demonstrated that a silicon PIN photodiode functions as a good x- and γ-ray detector at 13 K. With the charge sensitive preamplifier in which the operating temperature of the JFET has been optimized, the energy resolution for 60-keV γ rays has been obtained to be 1.60 keV (FWHM). The energy threshold could be set as low as 3 keV. The resolution is sufficient and the threshold is a promising value for our requirements.

These values would be improved further if the large capacitance of the PIN photodiode could be reduced, for example, by using two half-sized photodiodes and duplicating the electronics. Such a setup will still be less expensive than to use Si (Li) detector system.

Our next step is to overcome the microphonic problem. The microphonic noise damages the energy spectra both by broadening the peaks and by raising the energy threshold in an un reproducible manner. If the microphonic noise could be eliminated, the temperature frontier would be lowered further.

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Fig. 1. The schematic view of the experimental setup

Fig. 2. The schematic description of the charge sensitive preamplifier. The PIN photodiode is directly coupled to the gate of the JFET. A serial 120-Ω resistor was inserted for the sake of phase correction. The feedback capacitance, shown in dotted lines, is the stray capacitance of the 5-GΩ resistor.

Fig. 3. The typical x- and γ-ray energy spectrum measured for the $^{241}$Am source at 13 K is shown. The operating temperature of the JFET was around 110–140 K. The pulser line is seen at 122 keV. Two γ-ray lines are distinguished at 26 keV and 60 keV, and three Np L x-ray lines at 14 keV, 18 keV, and 21 keV. The line at 8 keV is not originated from $^{241}$Am, but is the fluorescent Cu K x-ray line due to the irradiation of $^{241}$Am γ-rays on the copper collimator.
pulser

+HV

cryostat

2SK291
(120 K)

+24V

output

stray capacitance

1 pF

100 Ω

5 GΩ

51 Ω

PIN
counts (sec$^{-1}$ keV$^{-1}$)

Cu X

Np X

FWHM 1.6 keV

γ

pulser

energy (keV)