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QUPID, a single photon sensor for extremely low radioactivity

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ABSTRACT

We have successfully developed a new photon sensor, the Quartz Photon Intensifying Detector (QUPID), for experiments such as dark matter searches and observation of double beta decay. The QUPID is a type of hybrid-photo-detector (HPD), consisting of a special bialkali photocathode considering the operation under extremely low temperature such as the temperature of liquid xenon, −108 °C, and a special avalanche photodiode for electron bombardment. The QUPID is constructed solely from extremely low radioactive materials, such as quartz and Si-avalanche photodiodes (APDs), which allows it to reach radiation levels of less than 1 mBq while being able to detect single photons. In this paper, we report superior characteristics of the QUPID confirmed by the evaluation.

1. Introduction

Observation and characterization of rare events, such as dark matter interactions and double beta decay, are one of the most important and challenging experiments in particle physics [1]. One of the greatest challenges in these types of experiments is to reduce the background to a level such that rare events can be observed. Presently, the dominant source of the background is known to be due to radio isotopes (RI) in photon sensors and therefore should be reduced as much as possible. The photon sensors for these experiments require (1) single-photon detection capability, (2) a large photosensitive area of 50–100 mm in diameter, and (3) linearity of photocathode current up to 100 nA at −108 °C (in the case of liquid xenon) or event at −186 °C (in the case of liquid argon). To achieve all of these requirements, we have developed a new photon sensor, the QUPID.

The QUPID produced by Hamamatsu Photonics K.K., is a type of hybrid-photo-detector (HPD) [2–8], consisting of a photocathode and an avalanche photodiode (APD), with the outstanding feature that its vacuum vessel is made of quartz, known to have the lowest radioactivity of UV transparent materials. Quartz is also known as a difficult material for processing. We have successfully manufactured a vacuum vessel made of quartz, installed vacuum-tight pins, assembled an APD for receiving electrons from the photocathode in a vacuum system, and finally sealed the vessel with indium. A photograph of the QUPID is shown in Fig. 1. Hereafter, the structure and performance of the QUPID is reported.

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2. Structure and operational principle

As shown in Fig. 2, the QUPID has a semi-spherical faceplate connected to a cylindrical side wall of inner diameter 65 mm defining the effective photosensitive area. The side wall is connected to a stem, where a 3 mm diameter APD is located at the center supported by a quartz pole. Every part of the vacuum vessel is made of quartz. A small amount of Kovar and aluminum is used for sealing the vacuum tight pins and an alloy of indium and tin is used for hot-sealing of the envelope and the stem.

Electrons emitted from the photocathode are focused on the APD by electrostatic fields formed inside the tube. Electrons deposit their energy inside the APD and produce thousands of electron–hole pairs in the depletion layer of the APD.

Fig. 1. A photograph of QUPID is shown.

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This multiplying process is called electron bombarded gain. After that, electrons are drifted into the avalanche region with strong electric fields in the APD (with a strength of about 3×10^8 V/cm), and are further multiplied by about 100. The gain obtained by this multiplying process is called avalanche gain. The total gain of the QUPID is determined by the product of the two kinds of gain. The maximum gain is about 100,000.

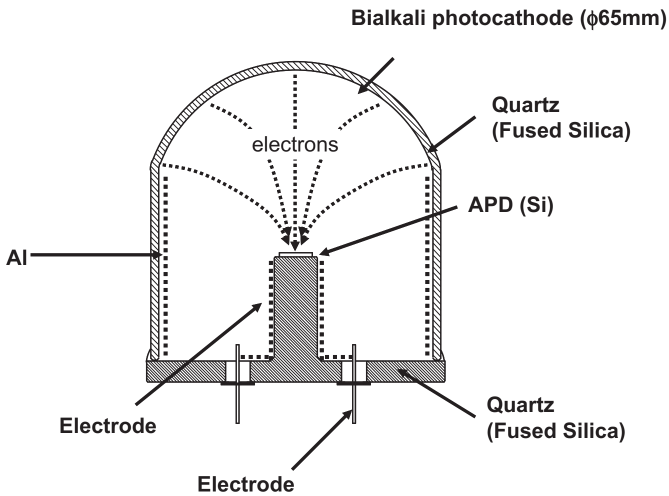

Fig. 2. A structure of developed QUPID is shown.

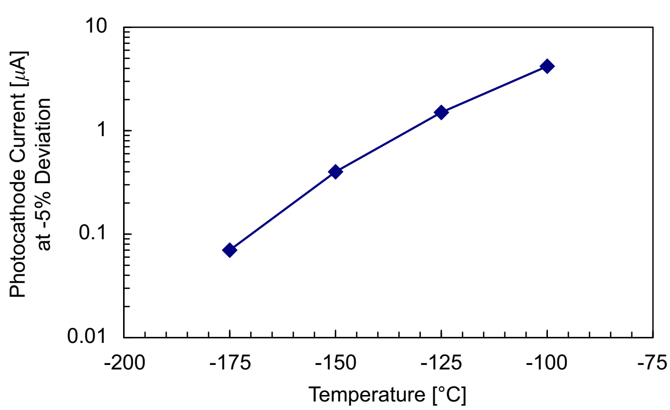

Fig. 3. A linearity of the photocathode current of developed QUPID, as a function of temperature, is shown.

3. Performance

3.1. Characteristics of photocathode

A specifically modified bialkali photocathode is activated on the faceplate of the QUPID for high linearity in liquid Xe and Ar temperature. The most recently produced four QUPIDs show quantum efficiencies of 18–26% at 175 nm (scintillation wavelength of Xe). The linearity of the photocathode current as a function of temperature is shown in Fig. 3. A linearity of up to 200 nA in the photocathode current is observed, which is required assuming neutrino-less double beta decay (at 2.5 MeV) produces $\sim 10^6$ photoelectrons per 1 μs (in gas Xe). In this measurement, it has also confirmed that the QUPID is operational in extremely low temperatures, such as the temperature of liquid xenon, $-108\,^{\circ}$C. Though excellent characteristics of the developed QUPID up to a temperature of $-175\,^{\circ}$C is confirmed, the measurement in liquid Ar temperatures of $-186\,^{\circ}$C, is one of the future assignments.

3.2. Single photon counting capability

The setup for testing single photon counting capabilities is shown in Fig. 4. By applying a voltage of -6 kV to the

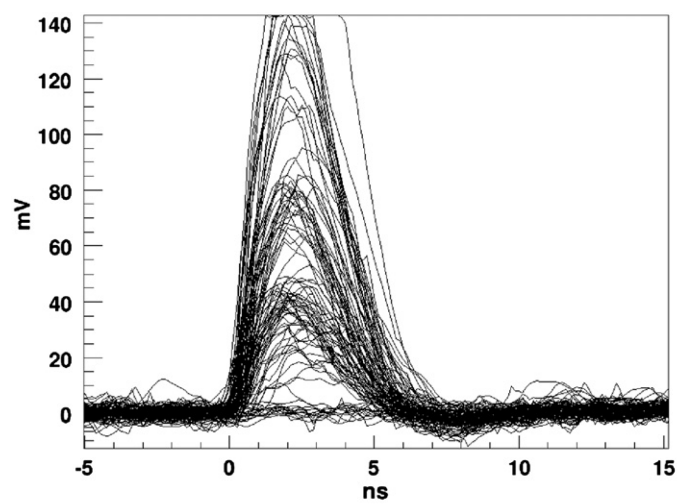

Fig. 5. The traces for the output signal of the QUPID observed by a digital oscilloscope, with a bandwidth of 1.5 GHz and 8 G Sa/s. Peaks of photoelectron corresponding single, double, and triple photons is clearly observed.

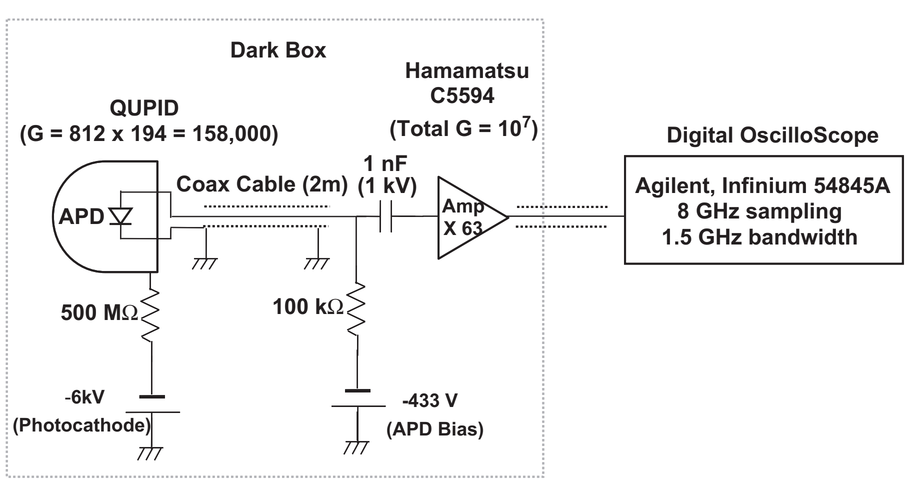

Fig. 4. A setup for observation of the output for single photoelectron is shown.

photocathode and 433 V to the APD a total gain of 1.6×10^5 is achieved. At these voltages, the electron bombarded gain from the photocathode to the APD and avalanche gain of the APD is 800 and 200, respectively. Output traces for single, double, and triple photoelectrons are clearly observed on an oscilloscope (Infiniium 54845A, 1.5 GHz, 8 G Sa/s) even after a 2 m long coaxial cable followed by a high speed preamp (Hamamatsu C5594, gain 36 dB, 50 kHz to 1.5 GHz bandwidth) as shown in Fig. 5.

3.3. Radioactivity

The radioactivity of four QUPIDs was measured for one month at Gran Sasso, and upper bounds (95% CL) of 0.49, 0.40, and 0.21 mBq per QUPID for U, Th, and Co, respectively, were obtained using Bayesian statistics methods. It is more than an order of magnitude lower than any other low-radioactive PMT to date.

4. Summary

We have succeeded in the development of a new hybrid photodetector, the QUPID, for research of dark matter and observation of double-beta decay. Four important requirements for these applications are (1) single-photon detection capability, (2) a large photosensitive area of 50–100 mm in diameter, (3) linearity of photocathode current up to 100 nA at $-108\,^{\circ}$C (in the case of liquid xenon) or even at $-186\,^{\circ}$C (in the case of liquid argon) and (4) radioactivity less than 1 mBq. We have confirmed that the newly developed QUPID has superior characteristics compared to conventional PMT.

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