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Large-aperture hybrid photo-detector

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Abstract

We have developed the first complete large-aperture (13-inch diameter) hybrid photo-detector (HPD). The withstanding voltage problem has been overcome and we were able to attain an HPD operating voltage of +20 kV. Adoption of our newly developed backside illumination avalanche diode (AD) was also critical in successfully countering the additional problem of an increase in AD leakage after the activation process. We observed single photon signal timing jitter of under 450 ps in FWHM, electron transit time of ~12 ns, and clear pulse height separation up to several photoelectron peaks, all greatly superior to the performance of any conventional large-aperture photomultiplier tubes (PMTs). In addition, our HPD has a much simpler structure than conventional large-aperture PMTs, which simplifies mass production and lowers manufacturing cost. We believe that these attributes position our HPD as the most suitable photo-detector for the next generation mega-ton class water-Cherenkov detector, which is expected to be more than 20 × larger than the Super-Kamiokande (SK) detector.

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1. Introduction

Water-Cherenkov detectors, as typified by Super-Kamiokande (SK), have been very important tools in identifying new phenomena and in providing evidence related to current theories. Recently, the next generation of massive water-Cherenkov detector has been proposed. In one, the "Hyper-Kamiokande (HK) Project" in Japan [1], the total mass of the water tank will approach 1 mega-ton (20 times SK tank mass) and the total number of photosensors will exceed 200,000. The photosensors for these new projects must combine unprecedented performance with economical production costs. We have developed a large-aperture hybrid photo-detector (HPD) to fulfill these requirements.

In this paper, we first briefly introduce the structure and operation principle of our HPD, then explain the problems we had with former prototype HPD and how we countered them. Major evaluation results are reported in Section 4, and we summarize our study in the last section.

2. Structure and operation principle

Fig. 1 diagrams the structure of our HPD and its operation principle. Photoelectrons from the photocathode are injected directly into the avalanche diode (AD) and there each photoelectron generates numbers of secondary electrons proportional to the voltage applied between the photocathode and the AD. This multiplication mechanism is referred to as "electron bombardment (EB) multiplication." Each newly produced electron then yields

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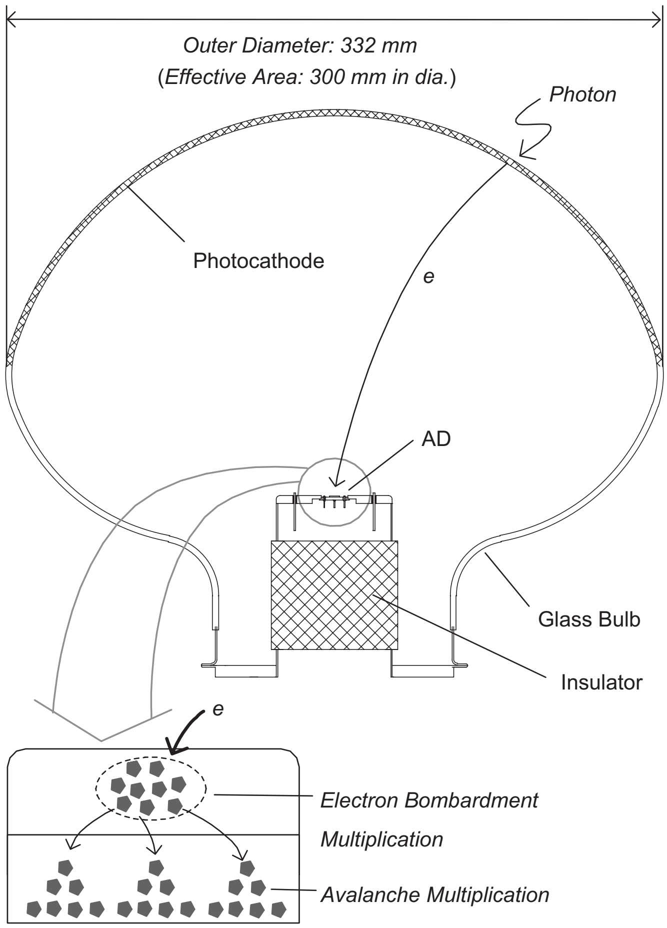

Fig. 1. Outline of the large-aperture HPD and operation principle.

another few dozen electrons in the subsequent avalanche multiplication stages. Those two kinds of gains are referred to as EB gain and AD gain, respectively, and the total gain of the HPD is the product of the two.

3. Problems and countermeasures

The many fundamental challenges in the development of our former prototype HPD are described in Ref. [2]. The two major problems were (i) deterioration in ability to withstand high voltage, and (ii) increase of the AD leakage current after the activation process. Both were caused by contamination of the AD and insulator surface by alkali vapor. In operation, HV is applied between both ends of the insulator (Fig. 1), which has intrinsically very high-voltage endurance. Once alkali vapor stains its surface, however, the field on the surface of the insulator becomes unbalanced, which leads to local discharge and flashing. As a countermeasure, we applied a slight conductive finish on the surface of the insulator to coercively balance the field. We were then able to achieve an operating voltage of +20 kV, the voltage necessary for efficient collection of the photoelectrons from the photocathode.

The direct cause of the second problem is deterioration of the insulating capacity of the path between the P and the N areas of the AD surface. We applied our newly developed AD whose backside illumination configuration isolates the PN path surface from contamination by alkali vapor (Fig. 2). The backside illumination structure is also preferable in maintaining long-term operating stability because it eliminates vulnerability to EB to the path mentioned [3].

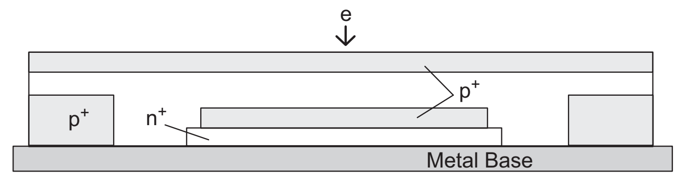

Fig. 2. Simplified drawing of backside illumination AD.

4. Evaluation results

4.1. Gain

Two kinds of gain characteristics were measured (Fig. 3). We evaluated the EB gain by measuring photocathode current and AD output current and calculating their ratio for each electron energy (corresponds to each operating voltage) with AD bias voltage fixed to 30 V in order to disable avalanche multiplication. We obtained an EB gain of more than 4500 at an electron energy of 20 keV. The EB gain curve is proportional to the electron energy above threshold voltage and its slope is approximately 0.28, in close agreement with the theoretical value. The threshold electron energy is considered to be determined by the thickness of the silicon surface dead region of the AD [4]. Avalanche gain characteristics were measured using a 10 keV energy electron source. The leakage curve indicates that breakdown occurs at AD bias voltage of ~400 V. Therefore, the maximum operable AD bias voltage is ~390 V, at which bias voltage an AD gain of ~50 is attainable. The maximum total gain of the HPD is calculated to be $\sim 2.3 \times 10^5$, the product of the two gains.

4.2. Impulse response

The HPD impulse response was measured. Fig. 4 shows the waveform observed with a 1 GHz bandwidth oscilloscope[1] in response to an impulse laser.[2] Under an operating voltage of +20 kV and an AD bias of 370 V, a rise time of ~1 ns and pulse width of ~2.2 ns were observed, 10 times faster than the photomultiplier tubes (PMTs) used in the SK. The waveform of the HPD is defined by the impulse response of the AD, and it depends on the bias voltage because the drift speed of carriers and value of the parasitic capacitance vary with bias voltages. Generally, waveform

[1]LeCroy WaveRunner 6100A.
[2]Hamamatsu M8903-02 (wavelength: 405 nm, pulse width: 70 ps).