Compact HPD

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Abstract

In order to be utilized in such application fields as high energy physics or medical imaging, where a huge number of photodetectors are assembled in designated small area, the world's smallest HPD, the compact HPD, has been developed. The overall diameter and the length of the tube are 16mm and 15mm, respectively. The effective photocathode area is 8mm in diameter. At applied voltage of -8kV to the photocathode, the electron multiplication gain of a PD incorporated HPD (PD-HPD) is 1,600, and that of an APD (APD-HPD) is 65,000. In the pulse height distribution measurement, photoelectron peaks up to 6 photoelectrons are clearly distinguishable with the APD-HPD. Experiments established that there was no degradation of gain in magnetic fields up to 1.5T, an important performance characteristic of the compact HPD for application in high energy physics.

I. INTRODUCTION

A comparatively new photodetector incorporating a silicon device in a vacuum tube, called the hybrid photodetector (HPD) here, has been developed for several years [1], [2], [3], [4], [5], [6]. Recently it is expected to be utilized in real application fields [7], [8]. In operation, photoelectrons are emitted from the photocathode of the HPD in response to incident photons. They are highly accelerated up to approximately 10keV in the tube and bombard the silicon device. Then the energetic electrons deposit their kinetic energy in the silicon device and generate thousands of electron-hole pairs per bombarding electron. Applying a photodiode (PD) as the silicon device, the generated charges can be readily read out by front end electronics. Because this large electron bombardment gain is considered to be the magnification factor at the first multiplication stage, and it is more than two orders of magnitude higher than conventional PMTs, the HPD can be expected to have an S/N ratio and energy resolution far superior to those of traditional PMTs. Furthermore, utilization of an avalanche photodiode (APD) as the silicon device makes it possible to obtain gains higher by a multiple of several tens. The total gain of the APD-HPD is approximately 10^5, while the gain of the PD-HPD is a few thousand.

In order to be applied in such application fields as high energy physics and medical imaging, where it is necessary to assemble a huge number of photodetectors in small designated area, the world's smallest HPD, the compact HPD, has been developed. Assembling the required pieces of this new device to form a multi-pixel detector, in contrast with the proximity focused HPD whose semiconductor device is commonly segmented as multi-pixel, will give no cross-talk between adjacent pixels, because cross-talk is considered to take place in the faceplate and the semiconductor device. Therefore, forming a multi-pixel detector by assembling a lot of compact HPDs will eliminate cross-talk because its faceplates and semiconductor devices are completely independent each other. There will also be a small dead space between tubes in such multi-pixel assembly.

The compact HPD design concept, tube configuration, and obtained performance are shown below.

II. DESIGN CONCEPT

In order to assemble a large number of tubes in a small area, the compact HPD was designed as small as possible. As a result, the stem size of TO-8 was adopted. The diameter of the tube is 16mm without potting (20mm with potting), and the effective area of the multi-alkali (S-20) photocathode is 8mm in diameter. Utilizing a ceramic envelope of 15mm in length, it is possible to apply 8kV between photocathode and the silicon device. The outline drawing of the tube is shown in Figure 1.

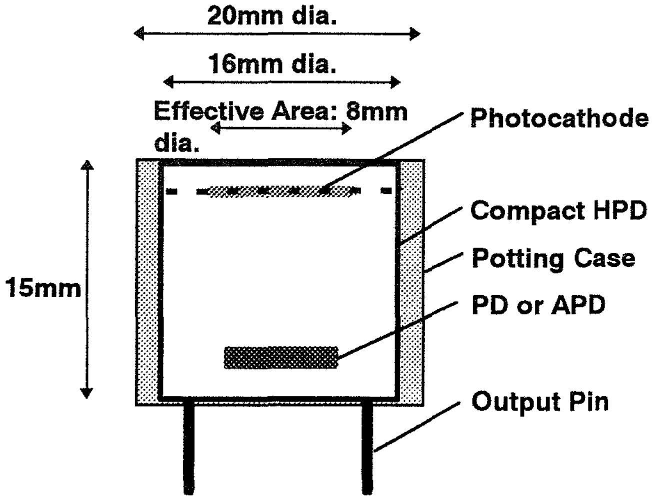

Figure 1: Outline drawing of compact HPD.

As a silicon device, a Si-PD of 7mm in diameter was adopted for the PD-HPD, and a Si-APD of 3mm in diameter was adopted for the APD-HPD. In both tubes, the electrons from the 8mm diameter photocathode are accelerated by the

[This paper was presented at "IEEE Nuclear Science Symposium", Nov. 5-7, 1996]

electric field and are focused slightly to an area of less than 3mm in diameter onto the silicon device.

In a strong magnetic field, an electro-static focusing lens does not work, and the electron trajectory is determined by the direction of the magnetic field. Because there is no electrode to interrupt the photoelectrons from the photocathode to the silicon device, theoretically, the compact HPD can be operated in a strong magnetic field more than 2T parallel to the tube axis. The effective area of the compact HPD is determined by that of the silicon device. Therefore, in a strong magnetic field, the effective area of the PD-HPD is 7mm in diameter, and that of the APD-HPD is 3mm in diameter.

III. PERFORMANCE OF THE COMPACT HPD

Characteristics of the compact HPD such as photocathode sensitivity, gain, uniformity, time response, output variation in a magnetic field, and pulse height distribution for multi-photoelectron were measured.

A. Photocathode Sensitivity

The spectral sensitivity of the compact HPD is shown in Figure 2. As shown in the figure, the compact HPD has a sensitivity from ultra-violet to near infrared region. The quantum efficiencies at 400nm, 500nm, and 600nm are 23%, 15%, and 8%, respectively. The photocathode sensitivity of the compact HPD is almost the same as that of a photomultiplier tube with an S-20 photocathode.

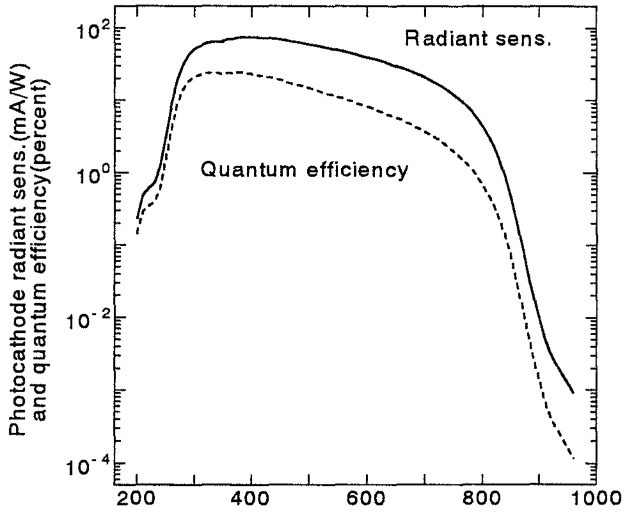

Figure 2: Compact HPD spectral sensitivity.

B. Gain

The gain of the HPD was calculated by dividing the value of the output current from the semiconductor device by the value of the input current. The gain characteristic of the PD-HPD in relation to the photocathode voltage is shown in Figure 3.

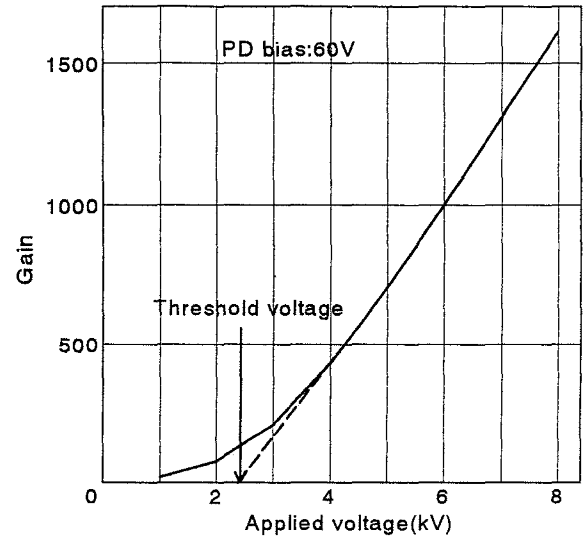

Figure 3: Gain characteristic for PD-HPD.

The gain is linearly proportional to the photocathode voltage above the threshold voltage, which is considered to be determined by the surface dead region of the semiconductor device. At the maximum applied voltage of -8kV to the photocathode, the gain of the PD-HPD is 1,600.

Generally, the gain "G" of the HPD is expressed by the equation (1),

$$G = (Vp - Vt) / 3.6 \qquad (1)$$

where Vp is the photocathode voltage and Vt is the threshold voltage. Vt, here, is 2.4kV. In theory, the average energy required to generate an electron-hole pair is 3.6eV [9] in Si material. The measurement result gives good agreement with the value calculated with the equation (1).

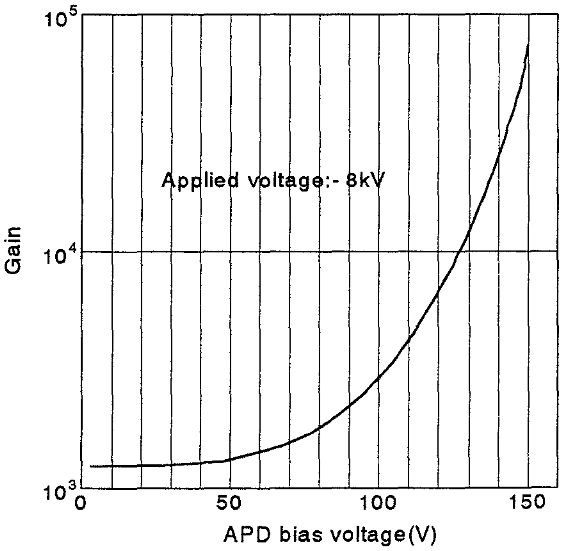

Figure 4: Gain characteristic for APD-HPD.

The gain characteristic of the APD-HPD is shown in Figure 4, where the photocathode voltage is fixed at -8kV, and the APD bias voltage is the variable parameter. The total gain, which is the product of the initial electron bombardment gain and the avalanche gain of the APD, is 65,000 at the photocathode voltage of -8kV and the APD voltage of 150V.

C. *Uniformity*

To measure the uniformity of the compact HPD, the output signal was measured by scanning a small light spot over the entire photocathode of the tube. The spot size was 1mm in diameter and the wavelength was 400nm. The result of the APD-HPD is shown in Figure 5. The output varied less than 7% in the whole effective area. In the case of the APD-HPD, the output uniformity is determined by the factors such as the photocathode sensitivity, the electron bombardment gain, and the avalanche gain. Because the PD-HPD uniformity characteristics are nearly identical and the electron bombardment gain is considered to be uniform, it can be concluded that the photocathode sensitivity is the main factor determining the uniformity.

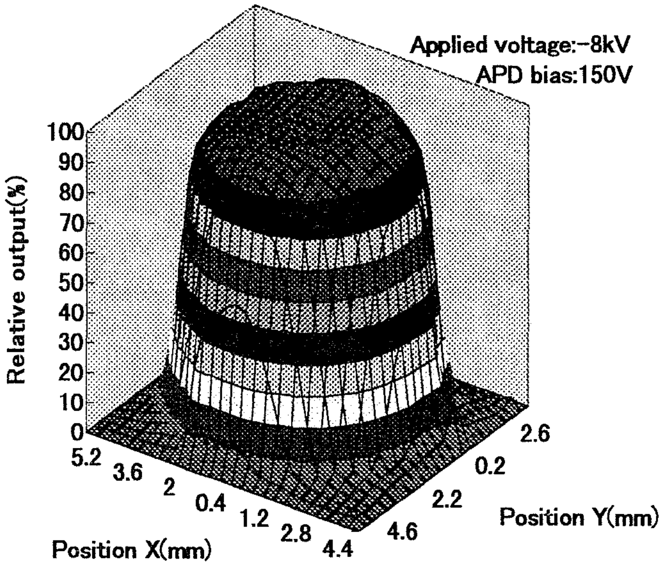

Figure 5: APD-HPD output uniformity.

D. *Time Response*

The time responses of compact HPDs were measured as an output waveform corresponding to a light impulse incident. Hamamatsu Picosec. Light Pulser (C4725) was utilized as a light source. The pulse width was less than 50ps and the wavelength was 780nm. The output waveform was measured by an oscilloscope (Tektronix, 7854). In the case of the PD-HPD, 60V was applied to the PD, while 150V was applied to the APD as well. In both tubes, the photocathode voltages were -8kV.

The output waveforms are shown in Figure 6. The rise times of the PD-HPD and the APD-HPD are 2.3ns and 1.2ns, and the fall times are 4.5ns and 13ns, respectively. The time response of the HPD is determined by the transit time spread of electrons in the vacuum area, the drift time of the signal charge in the semiconductor device, and the CR constant. Among those factors, the primary limitation of the time response here is considered to be the CR constant, where C is the capacitance of the semiconductor device, and R is the input impedance of the oscilloscope. It is considered to be the limiting factor because in computer simulation, the transit time spread of photoelectrons is under 100ps when -8kV is applied to the photocathode, a negligible value here. Also no improvement of the time response was observed when the bias voltage of the PD, which determines the charge drift time in the semiconductor device, was increased.

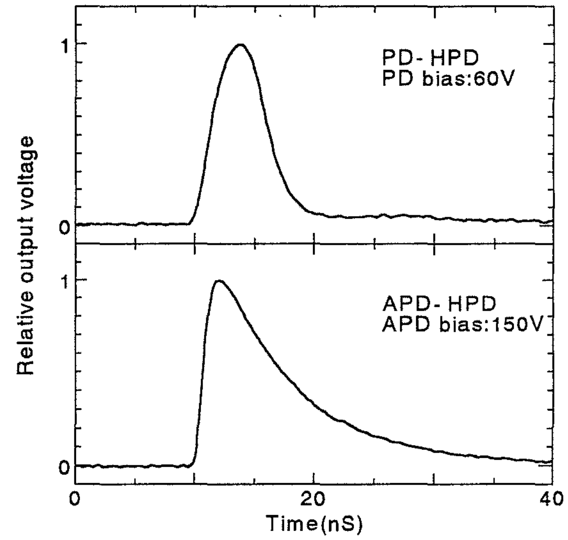

Figure 6: PD-HPD and APD-HPD time responses.

E. *Output variation in magnetic fields*

The output variation of the PD-HPD in magnetic fields up to 1.5T was measured under the following conditions. The light spot size was 6mm in diameter on the photocathode. The direction of the magnetic field was parallel to the tube axis. The photocathode voltage was -8kV, and the PD voltage was 30V. As shown in Figure 7, the output is almost constant in magnetic fields up to 1.5T. Therefore, it is

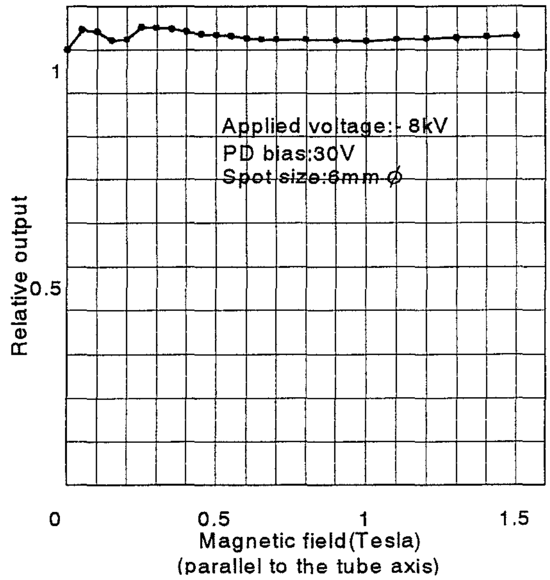

Figure 7: Output variation of PD-HPD in magnetic fields.

experimentally proved that the compact HPD can be operated in a strong magnetic field paralleled to the tube axis as it was designed. The maximum magnetic field of 1.5T in this measurement was restricted by the capability of the facility. Since there is, theoretically, no limitation on the strength of the magnetic field for the compact HPD, it can be operated in stronger magnetic fields, such as 4T, for example.

F Multi-photoelectron Spectrum

The pulse height distribution for multi-photoelectron was measured with the APD-HPD. The pulsed light of an LED was utilized as a light source. The photocathode voltage was -8kV, and the APD voltage was 150V. The output signal from the APD was first amplified by a charge amplifier (ORTEC,142A), further amplified by a linear amplifier (CANBERRA, 3100-02), and analyzed by a multi-channel analyzer (NAIG).

The measured pulse height distribution is shown in Figure 8. From the result in this figure, it is proved that peaks corresponding to photoelectrons up to 5 or 6 can be distinguished. The sharpness of each peak is considered to be limited by the noise of the measurement system, especially by the charge amplifier, because better results were observed when the gain of the tube was increased. Therefore, it was hard for the PD-HPD of smaller gain than the APD-HPD to observe photoelectron peaks. Decreasing the noise would enable the PD-HPD to measure photoelectron peaks, but the APD-HPD additional gain of approximately 50 is useful especially in the usage of fast or wide-band electronics which are inherently noisy.

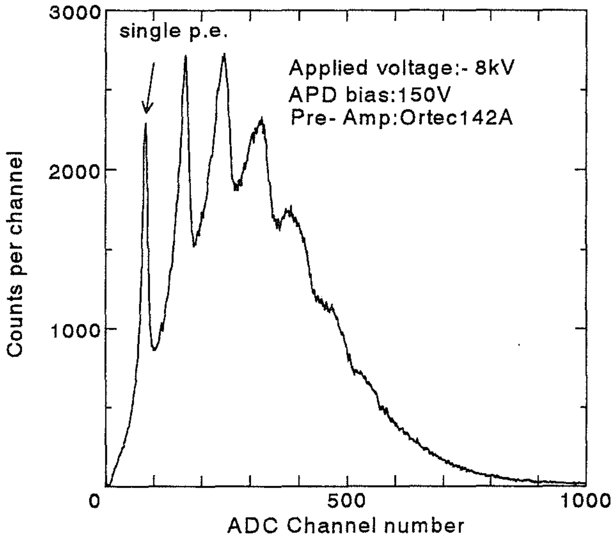

Figure 8: APD-HPD multi-photoelectron spectrum.

IV. FUTURE DEVELOPMENT

As a multi-pixel assembly, 16 tubes (4 x 4) will be potted together with front end electronics as depicted in Figure 9. The size is 70mm x 70mm and the height is approximately 20mm. A negative high voltage for the photocathodes is applied to all of the tubes in common via a high voltage cable. In this arrangement, no cross-talk between adjacent pixels is expected, and the dead space between each tube is minimized.

In future development of the tube itself, a more sensitive solid state photocathode will be applied. Applying a GaAsP photocathode yields a quantum efficiency of more than 40% from 400nm to 650nm.

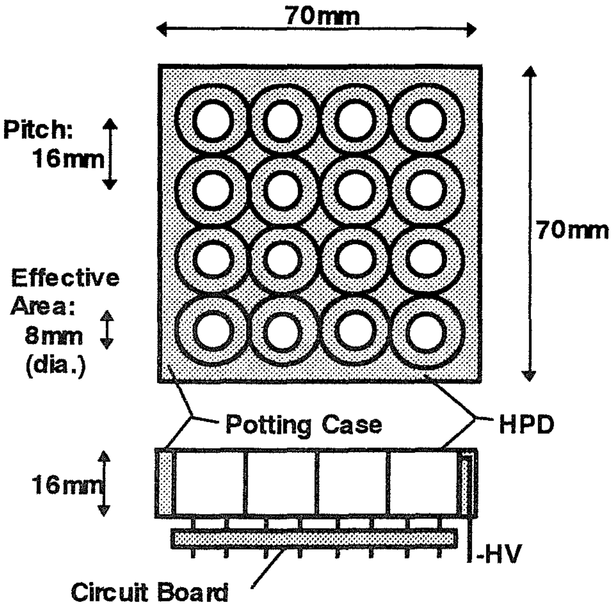

Figure 9: Design concept of multi-pixel assembly utilizing 16 compact HPDs.

V. CONCLUSION

The world's smallest HPD, the compact HPD, has been developed, and its fundamental performance was measured. The PD-HPD demonstrated, in accordance with its design, operation in magnetic fields up to 1.5T parallel to the tube axis. Photoelectron peaks were clearly measured by the APD-HPD in the pulse height distribution measurement. One method for assembling large numbers of these tubes has been suggested. There will be no cross-talk between adjacent pixels in that assembly.

VI. REFERENCES

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