A Hybrid Photodetector (HPD) with a Ⅲ-Ⅴ Photocathode

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Abstract

A hybrid photodetector (HPD) combined with a Ⅲ-Ⅴ photocathode is considered to be an ideal photodetector, because the quantum efficiency (QE) is high, the collection efficiency is 100%, and the excess noise factor is negligible. As the first step, an HPD combined with a GaAs photocathode or a blue-enhanced GaAs (BE-GaAs) photocathode has been developed. Presently, the QE is approximately 20% from 550nm to 850nm, which is much higher than that of a conventional multi-alkali (S-20) photocathode. The 100% collection efficiency calculated by the computer simulation is supported by the test result of the flat uniformity. Considering the application in high energy physics using a wavelength shifter, energy resolutions of both the BE-GaAs-HPD and the conventional S20-HPD were measured using 650nm LED light pulse. The BE-GaAs-HPD shows a resolution of 17%, finer than 34% of the S20-HPD. The experimental results are consistent with the theoretical estimation. The QE of the HPD is especially important, because the electron multiplication process is noiseless.

Ⅰ. INTRODUCTION

An electron tube called a hybrid photodetector (HPD), which incorporates a semiconductor device as the target for electrons from a photocathode, has been developed for several years [1][2][3][4][5]. Since the electron bombardment gain is the first multiplication factor and is more than one thousand, the electron multiplication process of the HPD is theoretically noiseless. However, an S/N ratio as a photodetector is not always satisfactory because of the poor quantum efficiency (QE) of a commonly used multi-alkali (S-20) photocathode.

The QE can be significantly improved with Ⅲ-Ⅴ photocathodes, which are sometimes applied in image intensifier tubes. For example, the QE of a GaAs photocathode is 25%, approximately from the visible to the near infrared region. However, the collection efficiency of 60 to 70% and large gain fluctuation of the micro-channel plate (MCP) degrade the S/N ratio of the image intensifier. On the other hand, an HPD combined with a Ⅲ-Ⅴ photocathode is considered to be an ideal photodetector because the collection efficiency is 100% and noiseless amplification is available.

As the first step, the HPD with a GaAs photocathode (GaAs-HPD) and a blue-enhanced GaAs photocathode (BE-GaAs-HPD) has been developed. The tube configuration and characteristics such as the photocathode sensitivity, the uniformity, the gain and the energy resolution are shown below. The energy resolution is theoretically estimated.

Ⅱ. TUBE CONFIGURATION

A small ceramic envelope formerly applied in a compact HPD [6] is also used. When potted, the outer diameter is 20mm and the overall length is 16mm. In the development here, the conventional S-20 photocathode is replaced by the GaAs photocathode, the effective area of which is 5mm in diameter. -8kV can be applied to the photocathode at the maximum. As a target for electrons, a PD of 7mm in diameter or an APD of 3mm in diameter is mounted on the stem opposite the photocathode. The dimensions are summarized in Table 1.

In case of the GaAs photocathode, a GaAs crystal is bonded to an input faceplate in advance. Following a heat cleaning and activation by Cs, it is sealed onto the ceramic tube body in a vacuum chamber and functions as a photocathode. When the thickness of the window layer of the GaAs crystal is changed, the sensitivity under 500nm is increased. This photocathode is called a blue-enhanced (BE-) GaAs here. HPDs combined with the GaAs photocathode or the BE-GaAs photocathode were manufactured.

Table 1
Dimensions of the developed GaAs-HPD.

Outer Diameter	20mm
Overall Length	16mm
Photocathode	GaAs or Blue-enhanced GaAs
Effective Area	ϕ5mm (S-20: ϕ8mm)
Target	PD (ϕ7mm) or APD (ϕ3mm)
Gap between Photocathode and Target	12mm

Ⅲ. TEST RESULTS

A. Photocathode Sensitivity

The spectral responses of the developed GaAs-HPD and the BE-GaAs-HPD are shown in Figure 1, compared with the conventional S20-HPD. The quantum efficiency (QE) of the GaAs-HPD is approximately 20% from 580nm to 850nm, and that of the BE-GaAs-HPD is 10% at 470nm and 15% to 18% from 560nm to 850nm. These results were obtained from several early tubes. Based on our experience with image intensifier tubes, the QE can be improved to 25% in the near future.

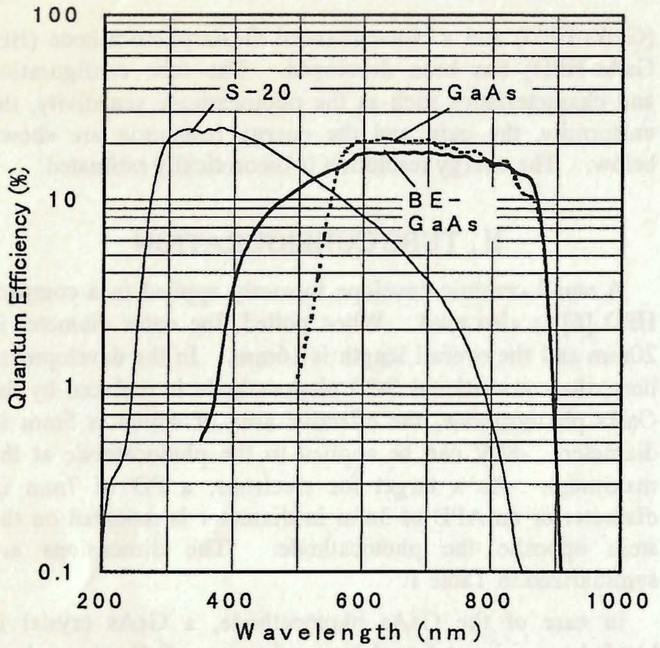

Figure 1: Spectral responses of the GaAs-HPD and the BE-GaAs-HPD, compared with that of the S20-HPD.

B. Gain and Time Response

Gain characteristics of the developed GaAs-HPD, which incorporates an APD as the target, are shown in Figure 2. The horizontal axis is the photoelectron energy determined by the photocathode voltage, and the vertical axis is the gain. The APD voltage is varied as a parameter. At the APD voltage of 30V, the APD has no avalanche gain and it functions as a PD. At this APD voltage, the gain is 1,200 at the photocathode voltage of -8kV. At the APD voltage of 150V, the gain is 52,000 at the same photocathode voltage. The gain characteristics of the GaAs-HPD are the same as those of the S20-HPD.

The time response characteristics of the developed HPD are also the same as those of the S20-HPD. The rise time and the fall time of the APD incorporated HPD are 1.2ns and 13ns, respectively. Those of the PD incorporated HPD are 2.3ns and 4.5ns, respectively.

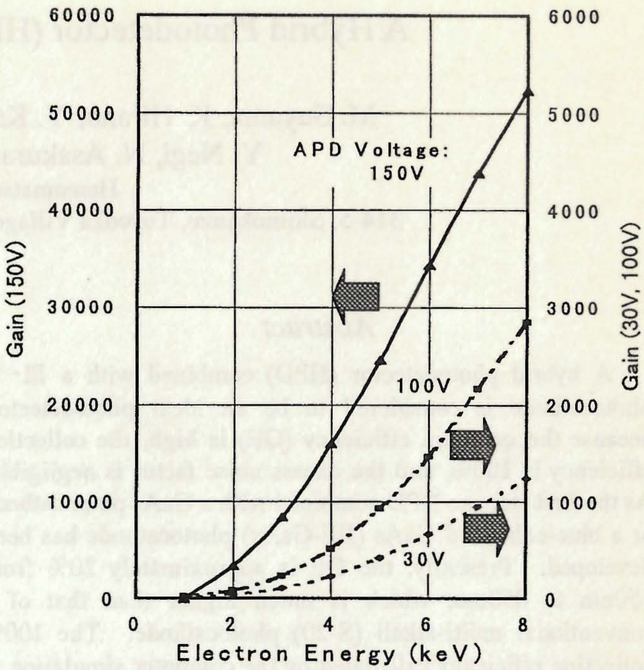

Figure 2: Gain characteristics of the APD incorporated HPD using the APD voltage as a parameter.

C. Uniformity

The uniformity was measured by scanning a 1mm spot of light over the photocathode of the BE-GaAs-HPD. The photocathode voltage was -8kV, and the APD voltage was 150V. The result is shown in Figure 3. The output current variation is from 92% to 100%. From this result, it seems that all electrons from the entire photocathode of 5mm in diameter enter the APD. The 100% collection efficiency is confirmed by the computer simulation. The variation in the measurement comes from the uniformity of the BE-GaAs photocathode sensitivity.

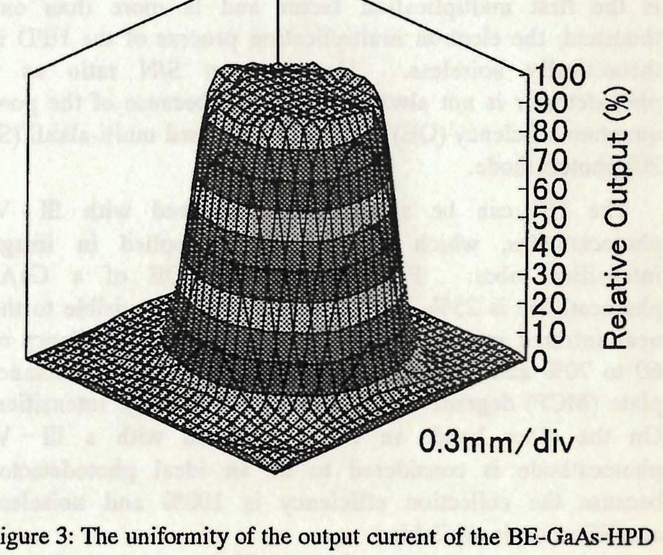

Figure 3: The uniformity of the output current of the BE-GaAs-HPD scanned by a 1mm spot of light.

D. Energy Reso. of BE-GaAs-HPD and S20-HPD

Energy resolutions of the BE-GaAs-HPD and the S20-HPD were measured under the identical light conditions. Considering the application using a wavelength shifter in high energy physics application, an LED of 650nm was used as the light source. The photocathode voltage was -8kV, and the APD voltage was 150V. Output signal corresponding to the incident light pulse was amplified once by the charge amplifier (EG&G, 142A), further amplified by the linear amplifier (CANBERA, 3100-02), and analyzed by the multi-channel analyzer (Laboratory Equipment corp., MCA/AT). Due to the aperture in front of the photocathode, a 2mm diameter of the photocathode was irradiated. In the measurement, the average photon number was measured to be 930. Considering the QEs of 17.7% and 4.3% of these tubes, the average photoelectron number of the BE-GaAs-HPD was 165, and that of the S20-HPD was 40.

The pulse height distributions for the BE-GaAs-HPD and the S20-HPD are shown in Figure 4. The differences in the peak channel position and the energy resolution between these two tubes can be observed. These results can be simply explained by the QE difference at 650nm. The energy resolution of the BE-GaAs-HPD is 17% and that of the S20-HPD is 34%, where the energy resolution is defined as the division of the full width at half maximum (FWHM) by the peak output channel. Note that the ratio of the peak positions for these tubes in this measurement does not directly indicate the ratio of the QEs, because the APD gains of these tubes are not the same at the operation voltage of 150V.

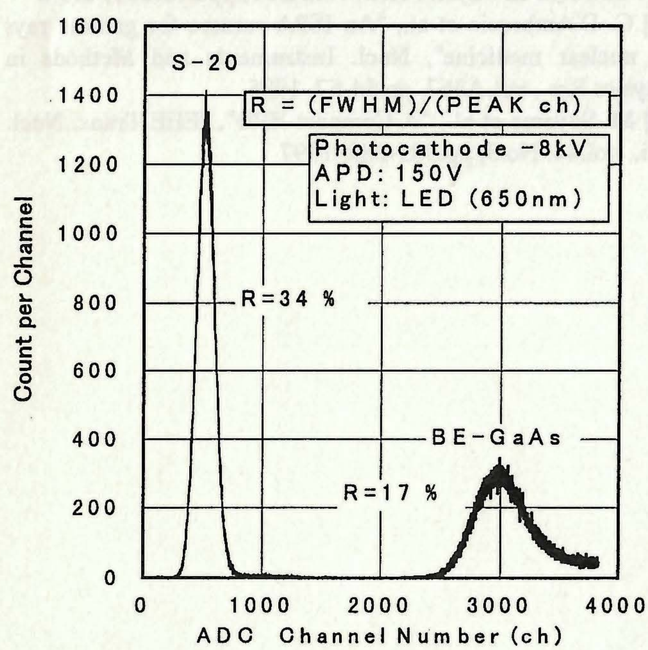

Figure 4: Pulse height distributions of the BE-GaAs-HPD and the S20-HPD at the average input photon number of 930, showing the large output and the good energy resolution of the BE-GaAs-HPD.

The energy resolution R of the APD incorporated HPD is estimated by the following equation (1),

$$R = 2.35 \times No / So$$

$$= 2.35 \times (F_{HPD} / Si)^{0.5} \qquad (1)$$

$$F_{HPD} = Fb + (Fa - 1) / Gb \qquad (2)$$

$$Fb = (Ni \times Gb)^2 / \{ (Ni \times Gb)^2 + Si \times Nb^2 \}$$

$$= 1 + 1 / Gb \qquad (3)$$

where So is the average output electron number per pulse, No is the standard deviation of the output electron number, F_{HPD} is the noise figure of the APD incorporated HPD, Fa is the noise figure of the APD, Fb is the noise figure of the electron bombardment gain, Si is the average photoelectron number from the photocathode determined by the product of the input photon number and the QE, Ni is the standard deviation of the photoelectron number assumed to follow the Poisson distribution, Gb is the electron bombardment gain, and Nb is the standard deviation of the gain fluctuation assumed to follow the Poisson distribution. The dark current of the photocathode, that of the APD, and the readout electronics noise are ignored here. Since the electron bombardment gain Gb is 1,200 and the noise figure of the APD is approximately 3, the equation (1) and (2) are rewritten as equations (4) and (5),

$$R = 2.35 \times (1.003 / Si)^{0.5} \qquad (4)$$

$$F_{HPD} = 1.003 \qquad (5)$$

These equations mean that the electron multiplication of the HPD is noiseless, and that the information from the photocathode is ideally amplified and put out as a signal. This also indicates the importance of the photocathode sensitivity, which determines the quality of the photoelectron information converted from the input light information. Regarding the readout noise, since it is usually far below the gain of 52,000 of the APD incorporated HPD, it does not degrade the energy resolution. However, it sometimes affects the resolution in case of the PD incorporated HPD, because the gain of approximately 1,200 is not large enough against the readout electronics noise.

Using the equation (4), the theoretical energy resolutions of the BE-GaAs-HPD and the S20-HPD are calculated to be 18% and 34%, respectively, at the average input photon number of 930. These estimated resolutions have good agreement with the test results.

The comparison of the pulse height distribution of these two tubes at the average photon number of 20 per pulse is shown in Figure 5. The experimental setup was the same as that mentioned above. In this case, the gains of two tubes were adjusted to be equal. The difference of the peak channel position and the photon detection efficiency can be observed. The photon detection efficiency is estimated by the total count number of the output signal. 1.8×10^7 events are measured by the BE-GaAs-HPD and 4.2×10^6 events by the S20-HPD. On the other hand, at this light level, peaks corresponding to discrete photoelectron number from 1 to 6 can be measured. This peak observation for each photoelectron number is further proof of the low noise in the electron multiplication of the HPD.

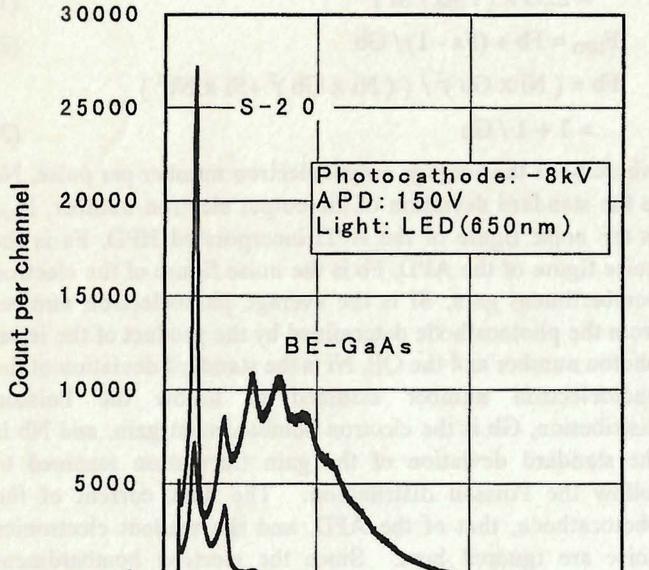

Figure 5: Pulse height distributions of the BE-GaAs–HPD and the S20-HPD at the average input photon number of 20.

IV. FUTURE DEVELOPMENT

Investigation to improve the sensitivities of the GaAs photocathode and the blue-enhanced GaAs photocathode will be continued. Stability and reliability of the HPD combined with these photocathodes will be measured. A GaAsP photocathode, which has higher QE in visible region than the GaAs photocathode, is under investigation.

V. CONCLUSION

The HPD combined with the high QE III - V photocathode has been developed. The QE of the GaAs photocathode is approximately 20% from 580nm to 850nm, and that of the BE-GaAs-HPD is 10% at 470nm and 15% to 18% from 560nm to 850nm. The energy resolution of the BE-GaAs-HPD is superior to the conventional S20-HPD at the 650nm light input. The experimental result can be explained theoretically by the noiseless amplification of the HPD.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCE

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