Development of HPDs with an 18-mm-diameter GaAsP photo cathode for the MAGIC-II project

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A new type of Hybrid PhotoDetectors (HPDs) with an 18-mm-diameter GaAsP photo cathode was developed in order to lower the energy threshold of the MAGIC-II project down to 15 GeV. The peak value of the Quantum Efficiency (QE) of these novel sensors reaches ~ 50 % at around 500 nm. Application of the wavelength shifting technique can further enhance the sensitivity in the UV region by another ~ 10 %. Compared to the currently used classical Photo Multiplier Tubes (PMT) with bialkali photo cathodes, the new HPDs provide practically twice as high photon conversion efficiency. Simulation studies of the new HPDs indicate that they have a sufficiently long lifetime for being used in the MAGIC telescope imaging camera. In this report we present the evaluation results and the performance of these new photo detectors.

1. Introduction

The development of the Imaging Atmospheric Cherenkov Telescopes (IACTs) technique has successfully established them as powerful tools for ground-based multi-GeV and TeV gamma-ray astronomy. Detection of gamma-ray fluxes at very low energies from 10 GeV to a few hundred GeV can be very interesting for the study of high red-shift objects such as active galactic nuclei and gamma-ray bursts. Because of the interaction of gammas from distant sources with the cosmic infrared background radiation fields, their measured intensity on the earth can be strongly attenuated. Only at very low energies is the universe becoming transparent for gammas. Use of photo sensors with higher photon conversion efficiency can be considered as an economic method to lower the threshold setting of telescopes.

The MAGIC (Major Atmospheric Gamma-Imaging Cherenkov) telescope [1], with a reflector diameter of 17 m, is the world's largest IACT. Since fall 2003 it has been in operation on the Canary Islands of La Palma (28.75° N, 17.90° W and 2200 m a.s.l.). In order to further lower the threshold setting our project will be upgraded by building the second 17-m diameter telescope (MAGIC-II) located at 85-m distance from the first telescope. In the MAGIC-II Project, one of the key tasks is to develop high QE Hybrid PhotoDetectors (HPDs) with a GaAsP photo cathode [2][3] as an alternative photo sensor to PMTs that are used in IACTs. For a high QE photo cathode, the Negative Electron Affinity (NEA) photo cathodes are regarded as the preferred candidates. Especially the NEA GaAsP type photo cathode is a prime candidate to be used in IACT photo sensors because of its high blue sensitivity.

An HPD consists of a photo cathode and of an Avalanche Diode (AD) serving as an anode. When applying a ~ 8kV high tension to the photo cathode, the photo electrons are accelerated in the high electric field and impinge onto the AD producing ~ 1600 electron-hole pairs. This is the so-called electron bombardment amplification. Those electrons subsequently induce avalanches in the active volume of AD and provide an additional gain of ~ 30-50 when a bias voltage of a few hundred volts is applied.

In the conventional HPDs, the size of the GaAsP photo cathode is too small (< 8mm) to be used as a pixel element in the MAGIC telescope camera (the necessary pixel size is 30 mm). Recently, together with Hamamatsu Photonics, we succeeded to produce HPDs with a GaAsP photo cathode of 18 mm size. By using non-imaging light concentrators like, for example, Winston cones, one can efficiently compress the light flux from the necessary 30 mm pixel input size to the 18 mm size of the above mentioned HPDs.
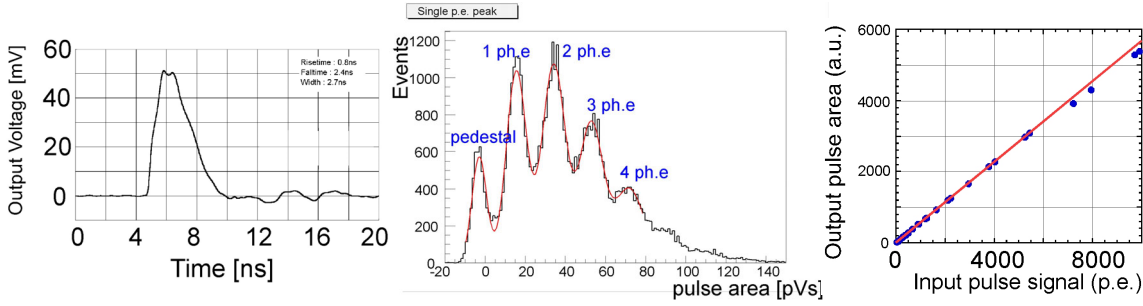
Figure 1. Examples of the measurement results.
[(a) left] The output signal for a very fast laser diode pulse. Photo cathode voltage; -8.0 kV, AD bias voltage; 330 V.
[(b) middle] Signal amplitude resolution. The peaks correspond to pedestal, 1 p.e., 2 p.e., 3 p.e. and 4 p.e..
[(c) right] Dynamic range measured by comparing the output signal area with input pulse signal of up to ~ 10,000 p.e..

2. Results and Discussions

HPDs including AD provide an overall gain of (3-8) x 10^4. Due to the high signal gain of the first stage, HPDs have a very good amplitude resolution. Cherenkov light flashes from gamma-ray air showers have a time spread of 2-3 ns. Fast response is required in order to reduce the contribution from light of the night sky (LONS) for a short signal integration time. The QE of the HPD is dependent on the wavelength. Application of the Wavelength Shifting (WLS) technique can provide an increase in sensitivity in the UV region [4], where Cherenkov photons from air showers are more abundant. Although the photo sensors of IACTs are constantly exposed to the LONS during the operation, the photo cathodes of the light detectors shall not lose their sensitivity over several years of operation.

For the measurement of below, the laser diode (PDL 800B, PicoQuant GmbH) was used as the pulse generator. Its wavelength is 393 nm and the time width is several tens of ps (FWHM). A fast pre-amplifier (voltage gain 32.0 dB at 500 MHz) was used to amplify the HPD signal. The signal was acquired by a 1 Gsample/s digital oscilloscope (LC564A, LeCroy).

- **Gain:** the electron bombardment gain was measured at a photo cathode voltage of up to –8.5 kV. In the range of a few kV the gain is rising slowly due to the energy loss in the passive layer at the AD entrance window. Above 4 kV, the gain shows a linear relation with the photo cathode voltage. It reaches 650 at –5.0 kV and 1600 at –8.0 kV. On the other hand, the avalanche gain of the AD is 30 at 320 V. The breakdown voltage of the AD is about 350 V. Finally, the overall gain becomes about 50,000 at –8.0 kV of the photo cathode bias and 320 V for the AD bias voltage.
- **Time response:** Figure 1-(a) shows the output signal with –8.0 kV for the photo cathode and an AD bias voltage of 330 V. The intensity of the light was estimated to the hundreds of photoelectrons (p.e.). The output signal shows 2.7 ns FWHM. Although this can match the requirements for the IACT camera photo sensors, a faster response will nevertheless provide a shorter integration time.
- **Amplitude resolution:** As one can see in Figure 1-(b), multi-photoelectron peaks were well resolved at low light intensity. These peaks correspond to pedestal, 1 p.e., 2 p.e., 3 p.e. and 4 p.e. (from the left to right). The light level was adjusted to provide <1.95> p.e.. The relative amplitude resolution of the single p.e. distribution can be described by $\sigma_{gauss} \sim 18$ % after removing the contamination due to the pedestal fluctuations.
- **Dynamic range:** In the small signal range, the multi-photoelectron peaks (in Figure 1-(b)) appear at regular interval within a 1% error. Figure 1-(c) shows the result of the dynamic range measured by the output signal area with input pulse signal of up to ~ 10,000 p.e.. The output signal area keeps a linear relation to the input pulse signal up to 5,000 p.e. and begins to deviate by 5% at 7,000 p.e..
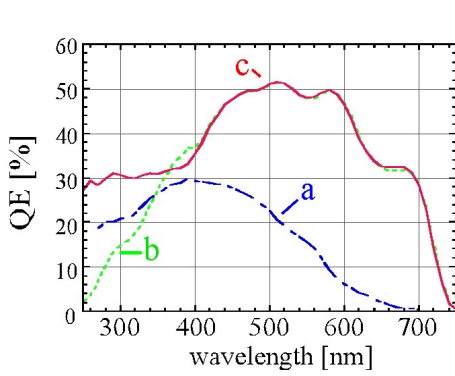
Figure 2. Measured QE spectra. **[broken (a)]** PMT ET-9116A with milky lacquer used in MAGIC-I [5]; **[dotted (b)]** non-coated HPD; **[solid (c)]** HPD with WLS

Figure 3. An example of a lifetime simulation study of relative photo cathode sensitivity compared with its initial value. This case shows the result after 5 years of operation.
[(a)left] The histogram of the number of tubes.
[(b)right] Distribution of damaged pixels on the camera. The HPD tube area was assumed inside the dotted line. Each color represents a different relative sensitivity value. The damaged tubes mainly follow the track of ζ-Tauri.

Zenith Angle	0°	25°	45°	60°
Non-coated	1.90	1.92	2.00	2.14
with WLS	1.99	2.00	2.07	2.17

Table 1. Relative improvement of overall Cherenkov photon conversion efficiency when using GaAsP HPD compared to PMT.

Quantum efficiency

We measured the QE in the range from 250 to 750 nm in 10 nm intervals using a spectrometer. The current of the HPD was measured by shorting the AD anode with the cathode, and by applying –800 V to the photo cathode. A calibrated pin-photo diode (S6337-01, Hamamatsu Photonics, calibration accuracy 2 %) was used to get the absolute value of light intensity. Figure 2 shows the measured QE of the HPD photo cathode as well as the QE of the PMT used in the telescope of MAGIC-I [5] as a function of wavelength. The peak value reaches 51 % at around 500 nm.

The first tests of WLS technique were made with a mixture of 0.03 g POPOP, 0.03 g Butyl-PBD and 1.5 g Paraloid B72 dissolved in 20 ml of Toluene. This solution was dripped on the entrance window of the HPD, and thus obtaining thin and transparent layer. In Figure 2 the obtained QE spectra with and without application of the WLS are shown. The enhancement can be seen clearly below 360 nm. However, a small drop in sensitivity exists at around 400 nm because of the absorption by the shifter film. Further studies could provide better results.

In order to quantify the anticipated improvement when using HPDs for the MAGIC telescope, overall Cherenkov photon conversion efficiency was estimated by folding the QE and the expected Cherenkov photon spectrum from gamma-ray showers. Table 1 shows the improvement of the efficiency for four values of the observation zenith angle. The obtained value is normalized to that of the currently used PMT. The spectral peak position of the Cherenkov spectrum shifts towards the longer wavelengths at higher zenith angles, because the shorter wavelengths are stronger absorbed and scattered by the atmosphere. This calculation includes the differences in the collection efficiency of the different light guides (94 % for PMT, 87 % for HPD) and in the first anode (dynode) collection efficiency (90 % for PMT, 100 % for HPD). The results show that the total light conversion efficiency could be improved by about a factor 2 compared to the PMTs. At the high zenith angle range, the improvement could be even higher due to the red-extended sensitivity of the HPD. Depending on the observation zenith angle the WLS can provide an additional improvement of 3-9 %.
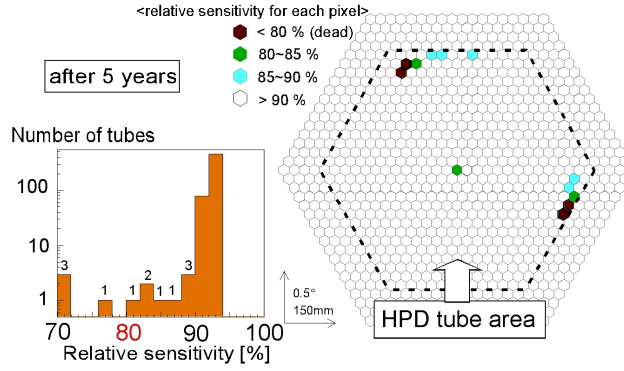
Lifetime of the GaAsP photo cathode

A GaAsP photo cathode lifetime was predicted empirically from the information of conventional image intensifiers with GaAsP photo cathodes. The lifetime is defined as the period after which the sensitivity degrades by 20 % from the initial value. On can assume that the lifetime only depends on the amount of total charge produced in the photo cathode. Then the lifetime corresponds to 3.5 mC of total charge from the photo cathode and about 100 C in the AD output charge with a gain of 30,000. The rate of p.e. due to LONS is estimated to be 0.45 p.e./ns/pixel (calculation based on the measured LONS spectrum [6]). At this LONS level the lifetime is ~13,500 hours.

In order to confirm the durability of the GaAsP photo cathode under real conditions, simulation of the starlight and LONS were performed. Figure 3-(b) represents an example of the camera pixel arrangement. In this simulation, we selected 10 known TeV sources (Crab Nebula, 3C66A, Mkn421, 1H1426, Mkn501, 1ES1959, BL-Lac, 1ES2344, Galactic Center, CasA) and picked up those of neighboring stars that are brighter than 11th magnitude in the V-band. The brightest star of all objects is ζ-Tauri (3.02 mag., located 1.13 deg. off the Crab). Observation time was assumed to be 100 hours per year for each of the sources, thus in total 1000 hours per year. Figure 3 shows the result after 5 years of operation. The relative photo cathode sensitivity compared with the initial value is shown. Figure 3-(a) is a histogram of the number of tubes as a function of the relative sensitivity. Most of the tubes still have a sensitivity of more than 90 %. The distribution of damaged pixels on the camera is shown in Figure 3-(b). The value of the relative sensitivity is shown by using the scale of four colors. The damage is mainly due to the intense light from ζ-Tauri. In the real operation, many other objects will be observed. But the expected number of the bright stars (brighter than 3.5 mag.) in the field of view of the HPD camera (~ 5 deg^2) is 0.034. Therefore the result of this simulation indicates that the HPD camera can keep good quality over several years with a small number of replacements of dead tubes.

3. Summary

The new type of HPD with the 18 mm GaAsP photo cathode is almost ready to be used in low threshold setting IACTs. The QE peak value reaches over 50 % at around 500 nm and the first tests of WLS technique demonstrated an increase of sensitivity in the UV region. Compared to the currently used PMTs in MAGIC-I, the overall Cherenkov photon conversion efficiency with the GaAsP photo cathode HPD is improved by a factor 2. This can be seen as equivalent of increasing the mirror diameter from 17 m to 24 m. Lifetime simulations showed that the GaAsP photo cathode is expected to have sufficiently a long lifetime to survive starlight and the light of night sky. In the next step further improvements of the QE as well as the development of a new AD with even higher gain and faster time response is planned. The GaAsP photo cathode lifetime studies are planned with a few tens of HPD tubes under different conditions in this summer. A HPD camera shall be built in 2006 in order to access the 15-GeV energy threshold for the MAGIC-II project.

Acknowledgements

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