Development, Fabrication and Test of a Highly Segmented Hybrid Photodiode

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In memory of our dear friend and collaborator
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Abstract

Hybrid Photodiodes (HPD) represent one of the most promising options for high granularity single photon detection. We report about the development of the Pad HPD, a 5-inch device with a bialkali photocathode and encapsulated analog electronics for the readout of the 2048 channels. The design of the Pad HPD was optimised for the use in the RICH detectors of LHCb. Several HPDs have been fabricated in a dedicated UHV facility at CERN. We briefly summarise the fabrication process and the excellent performance figures obtained in a lab set-up and with Cherenkov radiators in test beams. Emphasis is put on the performance increase which resulted from recent minor design changes.

Keywords: Photodetector; Hybrid Photodiode; HPD; Photocathode; Bialkali;

1 The design of the Pad HPD

The Hybrid Photodiode (HPD) principle combines the sensitivity to single photons of a conventional photo multiplier tube (PMT) with the spatial and energy resolution of a solid state sensor [1–5]. The cascade amplification process of a PMT with its intrinsic limitations due to the statistical fluctuations in the number of electrons at the first dynodes is replaced by a single stage gain mechanism. The photoelectron is accelerated in an electric field to energies of typically 15-20 keV. The relatively large number of electron-hole pairs ($\approx 4000 - 5000$), which are created when the photoelectron dissipates its energy in the silicon sensor, leads to the superb energy resolution of this device. The design and the fabrication of the Pad HPD has been described in detail elsewhere [6]. The Pad HPD is a round Hybrid Photodiode of 127 mm (5 inch) diameter (see Figure 1) with a visible-light transmittive bialkali photo-cathode of 114 mm active diameter. The spherical entrance window of the HPD is made of an UV extended borosilicate glass (T = 50% at λ = 250nm). The window and the tube body are joined by a Kovar skirt in order to adapt to the slightly different thermal expansion coefficients of the glass types. In the first generation of the Pad HPD a set of 4 stainless steel ring electrodes defines a fountain shape electrostatic configuration, which de-magnifies the photocathode image by a factor ≈ 2.5 onto a silicon sensor of 50 mm diameter. The silicon sensor comprises 2048 pads of size 1×1 mm^2 and is read out by multiplexed analogue electronics (16 IDEAS VA chips[7]) enclosed in the vacuum envelope. Both the sensor and the electronic chips are mounted on a ceramic carrier, which is wire bonded to the vacuum feedthroughs of the stainless steel base plate. The design cathode voltage is $U_{cath} = -20$ kV.

2 Fabrication of the Pad HPD

The design parameters of the Pad HPD reflect the specific requirements of the LHCb[8] RICH counters, but are also driven by the chosen fabrication process, which consists of an external photocathode evaporation followed by an in-situ cold indium sealing of the base plate to the HPD envelope. The Pad HPD is fabricated in a dedicated UHV evaporation plant[9] designed and built at CERN. All HPD components undergo thorough multi-step mechanical and chemical cleaning procedures[?] prior to installation in the evaporation system. The cold indium sealing method requires a careful pre-treatment of the metal surfaces coming in touch with the indium joint.

3 Performance of the first generation Pad HPD

Several Pad HPDs have been produced using the comparably slow VA2 electronics (shaping time 1.3μs). We recall the main performance figures reported in [6]. The quantum efficiency of the bialkali photocathode reached typical peak values ($\lambda = 350$nm) of 15-20%. The HPDs were characterised in a dedicated lab set-up or with Cherenkov radiators in test beams[11]. The tube showed a linear demagnification of about 2.7 over the full accepted diameter of 114 mm. A point spread function of 300 μm at $U = -20$ kV was observed (pixelisation error $\sigma_{pixel} = 1$ mm $/\sqrt{12} = 288$ μm). A single photoelectron at $U_{cath} = -20$ kV was found to produce a signal of 5450 e^- in the silicon sensor. The energy loss in the back side n^+ and aluminium layer of the sensor was about 550 e^-. The low pedestal noise spread of the VA2 chip of 285 e^- (RMS) leads to a signal to noise ratio of 19 (at 20 kV). The detection efficiency for a single photoelectron was about 90%.

4 Modified design of the second generation Pad HPD

Small design modifications of the HPD envelope have allowed to correct for an unreliable glass-metal seal at the tube window and substantially improved the operational stability of the tube. The glass metal seals developed micro cracks during the vacuum bake out (T$\approx$ 300°) and caused a significant fraction of the HPD envelopes to leak. The seat of the Kovar flange has now been increased from 1 to 2 mm. In addition, the envelope manufacturer could improve the uniformity of the welding method. The two measures have reliably fixed the leak problem.

Most of the first generation detectors were limited in the maximum applicable cathode voltage to values below 15 kV. This deficiency was traced back to imperfections of the ring electrodes (sharp edges, rough surface, positioning) and pollution of the tube's side walls with alkali vapours. Micro discharges and light generation from the de-excitation of atomic levels of the alkali vapours compromised the operational stability.

Based on simulations with the program SIMION[12] a simplified electrode configuration was established which leaves the optical performance (demagnification, linearity, point spread function) essentially unchanged. As shown in Figure 2 the first electrode, the so-called bleeder, consists of a simple nickel wire of 2 mm diameter. The second and third electrodes are made of polished nickel rings with rounded edges. The fourth electrode has been suppressed. All electrodes can be removed for cleaning and inspection.

The photocathode fabrication process has been improved by design changes of the evaporation head carrying the 3 evaporation sources (Sb, K, Cs). The new electrode configuration (larger inner diameter of the electrodes) allows to enclose the source arrangement by a set of cylindrical screens. This results in an efficient protection of the tube side wall from alkali vapours. Also the confinement of the evaporation volume, which is essential for an undisturbed chemical reaction during the cathode processing, is improved. The quantum efficiency of some 2nd generation Pad HPD is shown in Figure 3. Peak values of almost 26% at 350 nm are reached.

The tubes can be operated at cathode voltages up to 20 kV with very low background noise. The noise characteristics of a tube as a function of the cathode voltage is shown in figure 4. At 20 kV the noise per pad and trigger is as low as 5.6×10^{-4}. The background noise is uniformly distributed over the detector surface. The probability of zero fired pads per random trigger is about 60%. A further significant reduction of the noise level is expected from tubes equipped with faster electronics (see below).

The electron optical parameters of the tube are in good agreement with the expectations from the SIMION calculations. As it is shown in Figure 5, a slight 3rd order contribution is observed in the imaging function. The tube acceptance has been found to extend over 120 mm. The active area fraction of the tube is therefore about 90%.

5 Outlook

To widen the potential fields of applications of this detector, HPDs with different chip sets are under preparation. The VA1-PRIME chip, developed by IDEAS and the BELLE collaboration in an 0.35μm AMS technology has an adjustable peaking time of 0.35 to 2μs. Another development line is the SCTA chip[13], a 25 ns peaking time analogue front-end designed for LHC experiment DAQ systems. In both cases the short peaking time is expected to lead to a further reduction of the number of random background counts. For applications, where self-triggering is required, the VA-TAGP 128 channel chip is available from IDEAS. Possible applications are: cosmic ray air shower observation on satellites, neutrino experiments based on RICH counters and general imaging applications.

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Fig. 1. Photograph of a Pad HPD (with first generation envelope).

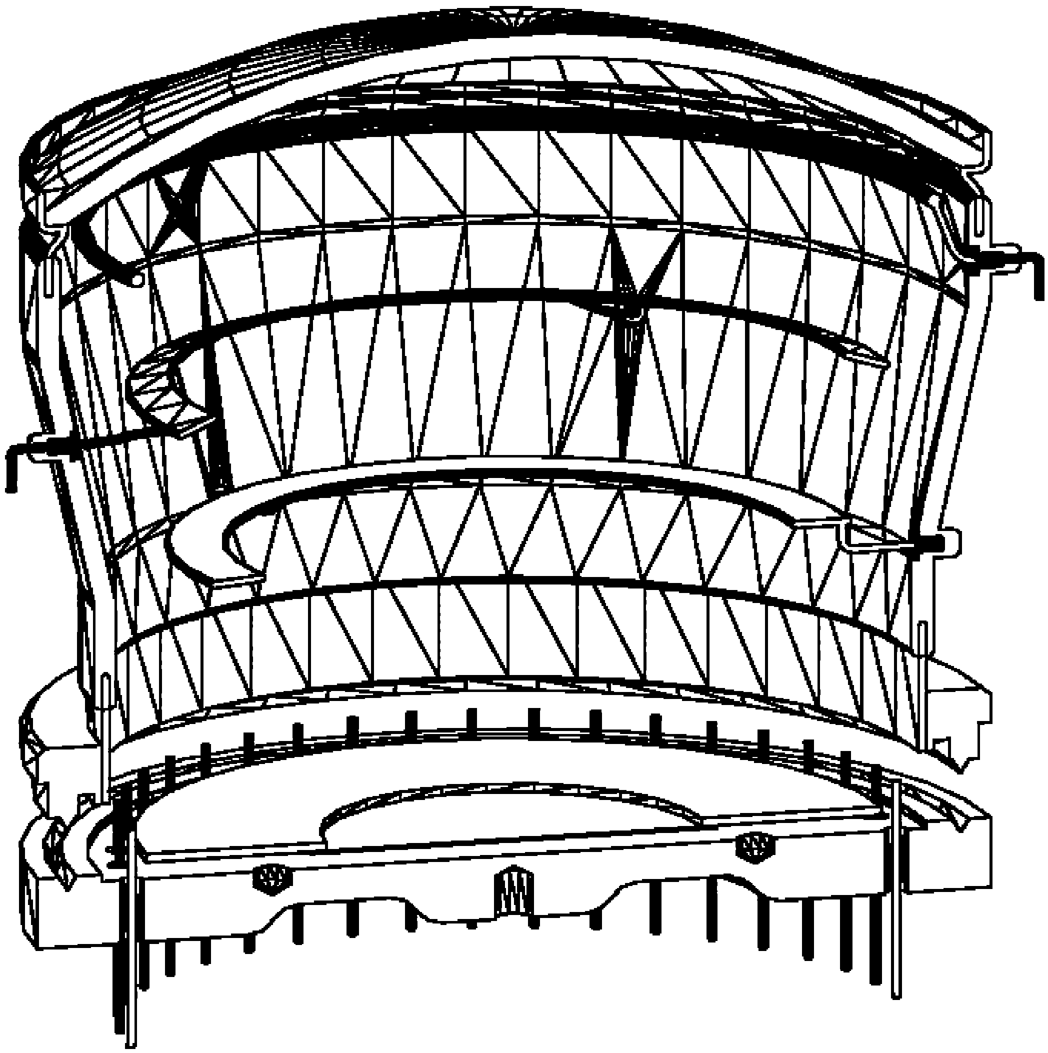

Fig. 2. 3D view of the Pad HPD with second generation envelope.

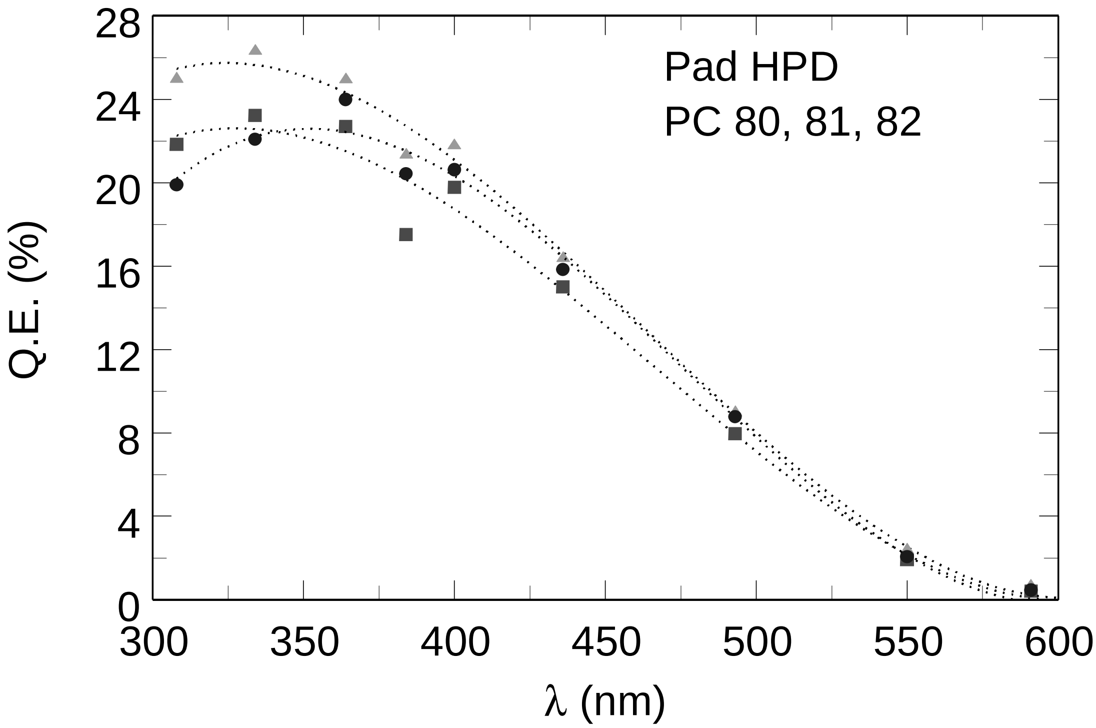

Fig. 3. Quantum efficiency of a series of 2nd generation Pad HPD detectors.

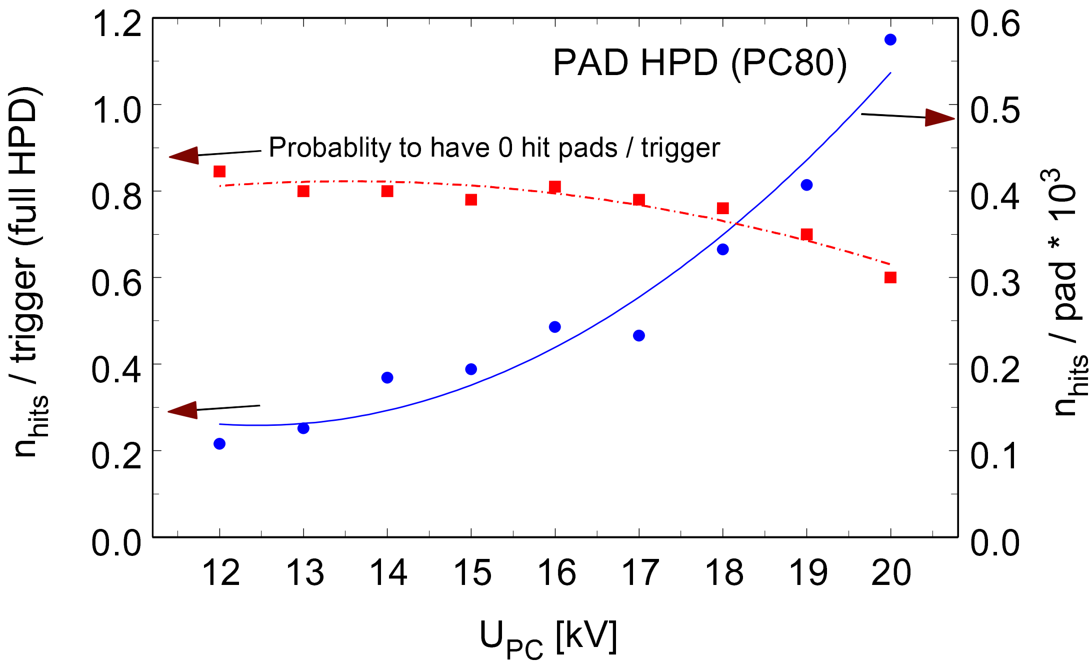

Fig. 4. Noise characteristics versus cathode voltage. Circles: Number of random hits per trigger for the full tube (left axis) and for a single pad (right axis). Squares: Probability to have zero random hits for a random trigger.

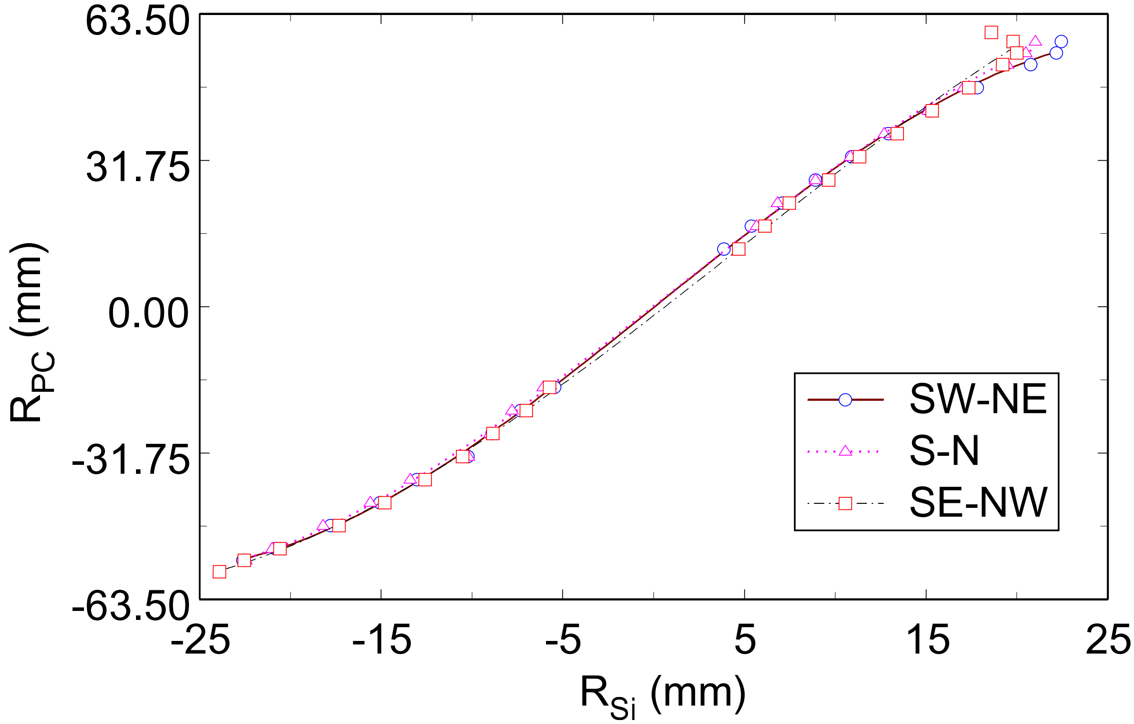

Fig. 5. Imaging function of the 2nd generation Pad HPD. The plot shows the result of three light scans over the full diameter of the HPD. The small distortions at the periphery are due to a field inhomogeneity in the region of the bleeder support wire.