CONSIDERATIONS ABOUT LARGE AREA–LOW COST FAST IMAGING PHOTO-DETECTORS*

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The Large Area Picosecond Photodetectors described in this contribution incorporate a photocathode and a borosilicate glass capillary Micro-Channel Plate (MCP) pair functionalised by atomic layer deposition (ALD) of separate resistive and secondary emission materials. Initial testing with matched pairs of small glass capillary test disks has demonstrated gains of the order of 10^5–10^6. Compared to other fast imaging devices, these photodetectors are expected to provide timing resolutions in the 10–100 ps range, and two-dimension position in the sub-millimeter range. If daisy chained, large detectors read at both ends with fast digitising integrated electronics providing zero-suppressed calibrated data should be produced at relatively low cost in large quantities.

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1. Introduction

Vacuum devices such as Photo-multiplier tubes and Micro-Channel Plate devices allow achieving large area, large fill-factor, photo-cathodes tailored to the specific needs in terms of spectral response, large charge gains exceeding 10^6. The well-known sensitivity of the photo-multiplier tubes to magnetic field is reduced by orders of magnitude in the case of Micro-Channel

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Plate where the low energy electron drift distance is reduced to a few millimetres, thanks to the small thickness of the device; conversely, the ion feedback can reduce their lifetime, although some improvements have been obtained recently by the use of thin blocking aluminium foils. On the other hand, the semi-conductor based photo-detectors (silicon, gallium arsenide, mercury cadmium telluride) such as the Charge Coupled Devices (CCDs), Avalanche Photo-Diodes (APDs), Silicon Photo-Multipliers (SiPMs)/Multi Pixel Photon Counters (MPPCs) cannot be larger than monocrystal wafers, are limited in fill factor, are fairly sensitive to radiation and exhibit non negligible noise due to reverse current avalanches. Also, their spectral sensitivity cannot extend beyond the limits of the substrate material. Conversely, the readout and the signal processing electronics can be integrated and they are not sensitive to magnetic fields.

2. Fast timing imaging photo-detectors

Table I compares the main features of Multi-Anode PMTs, Silicon Photo-multipliers, and Micro-Channel Plates.

TABLE I

Main features of Multi-Anode PMTs, Silicon Photo-multipliers, and Micro-Channel Plates.

Item	MA PMTs	Silicon PMs	MCPs
Quant. eff.	30%	90%	30%
Coll. eff.	90%	70%	70%
Rise-time	0.5–1 ns	250 ps	50–500 ps
TTS (σ)	150 ps	100 ps	20–30 ps
Pixel size	$2 \times 2\,\mathrm{mm}^2$	$50 \times 50\,\mu\mathrm{m}^2$	$1.5 \times 1.5\,\mathrm{mm}^2$
Detector	$3.5 \times 1\,\mathrm{cm}^2$	arrays of $1.2 \times 1.2\,\mathrm{cm}^2$	$2.54 \times 2.54\,\mathrm{mm}^2$
Dark counts	1–$10\,\mathrm{Hz/cm}^2$	$1\,\mathrm{Hz}$–$1\,\mathrm{kHz/cm}^2$	—
Dead-time	5 ns	100–500 ns	$1\,\mu\mathrm{s}$
Magnetic field	no	yes	15 kG
Rad hard	—	1 kRad = noise ×10	good

2.1. Silicon Photo-multipliers

Silicon Photo-multipliers are basically reverse biased PN junctions operated over the breakdown voltage as shown in Fig. 1. The avalanche is quenched by an integrated series resistance. They exhibit a high QEs of 90% and a gain of 10^3–10^6 but a low fill factor is due to the space taken by the access electrodes and series resistances. In addition, the noise is high at room temperature and the afterpulses may show up due to carriers trapped on impurities inducing levels within the gap, optical crosstalk, and they need some local recovery time to recharge the pixel capacitance after an avalanche. They are relatively cheap but cannot be implemented as a very large area detectors due to the limited size of the current semi-conductor wafers.

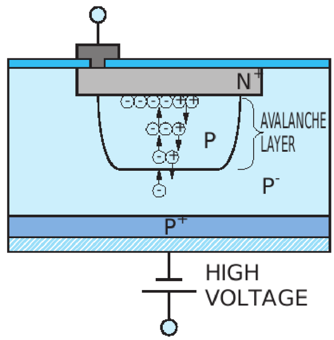

Fig. 1. Silicon Photo-multiplier structure (from Martin Haigh, Univ. of Oxford).

2.2. Micro-Channel Plates

Micro-Channel Plate is shown in Fig. 2. It consists of a vacuum vessel under a pressure of 10^{-6}mm/Hg and a photocathode which is deposited onto the inner surface of a window. Between the photocathode and the segmented anode a block made of a glass or alumina substrates with a regular array of tiny tubes or pores is located. Its surface is parallel to the photocathode layer. The pores are at certain angle to the layer surface and with a diameter of 1–30 μm. The pores are internally covered with a thin layer of a material

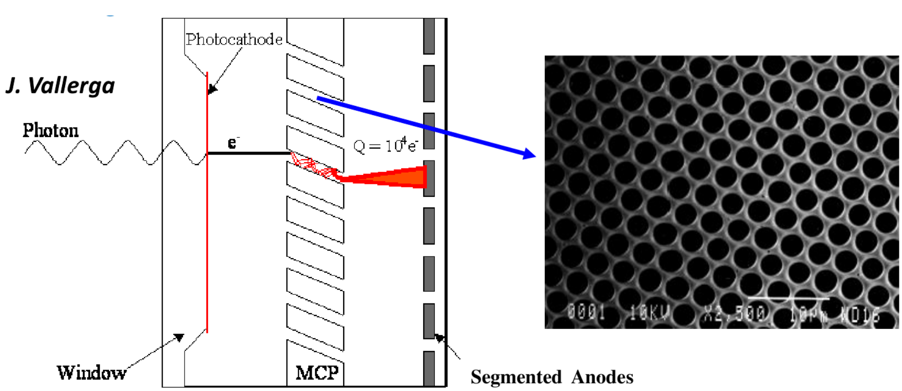

Fig. 2. Micro-Channel Plate structure (from John Vallerga, Univ. of California, Berkeley).

having a large electron secondary emission coefficient, and a highly resistive coating allowing keeping a constant electric field along the pore. An array of anodes parallel to the outer glass surface collects the electrons multiplied in the pores and provides a fast current pulse to the external world. These anodes are usually connected to an array of pads covering the outer surface of the vessel. The photocathode is biased negative by a few thousands volts with respect to the anode plane. In this work, the transmission lines anodes allowing a two-dimensional readout scheme using fast timing at both ends have been implemented.

A photo-electron is accelerated towards the pores and enters one of them through a small orifice and creates a cascade that propagates through the pore. This gives amplification of the original signal by several orders of magnitude depending on the device geometry and the electric field strength.

2.3. Micro-Channel Plates signals

Figure 3 (left) shows the signals at the output of a 25 μm tube comprising 1,024 anodes square pads for high voltages between 1,975 and 2,225 V. Figure 3 (right) shows the superimposed waveforms of MCP processed at Argonne National Laboratory with Atomic Layer Deposition (ALD). Figure 4 shows the waveforms of the very fast MCPs from Photek, with 3.2 and 6 μm pores, corresponding to the single photo-electron signals.

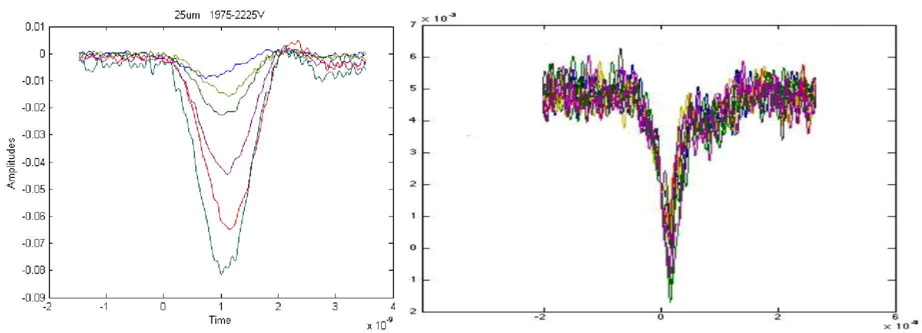

Fig. 3. Left: Burle-Photonis Micro-Channel Plate signals (time in nanoseconds), Right: Atomic Layer Deposition processed Micro-Channel Plate signals.

2.4. Micro-Channel Plates efficiency and baseline noise

Efficiency plateaux of both 10 μm and 25 μm Micro-Channel Plates are 250 V wide for a discriminator threshold set at 3 photo-electrons. Some afterpulses show at the end of plateaux for higher voltages and are not taken into account.

2.5. Micro-Channel Plates timing resolution

Micro-Channel Plates have been investigated in many worldwide laboratories, such as the Enrico Fermi Institute at the University of Chicago — H. Frisch, the Argonne National Laboratory — E. May, the University of Hawaii — G Varner, the Lawrence Berkeley National Laboratory, the Brookhaven National Laboratory, the University of Texas Arlington, the Nagoya University, Japan — K. Inami, the University of Louvain la Neuve (Belgium) and CERN, Switzerland — K. Piotrzkowski and many others. All investigations report a time transit spread of 30–40 ps for single photo-electron signals. Figure 4 (right) shows a Fourier spectrum of a 10 μm MCP output for a 50 photo-electrons input signal. Ultimately, the signal rise-time and the signal-to-noise ratio dictate their timing performance.

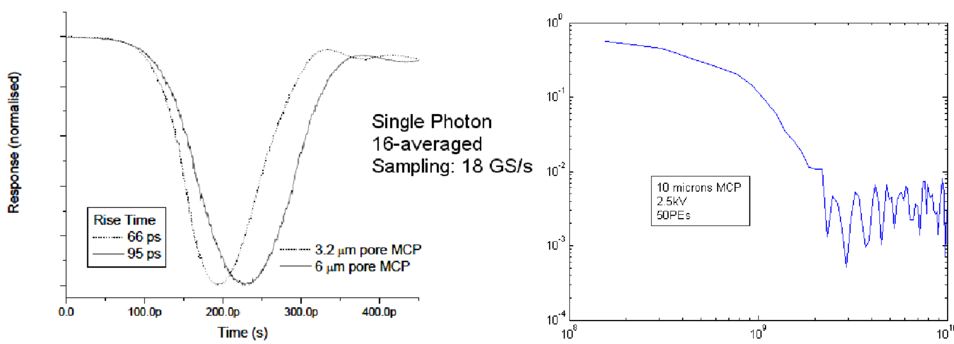

Fig. 4. Left: 10 μm signals (from Photek), Right: 10 μm MCP signal Fourier spectrum; (frequencies in Hz).

2.6. Micro-Channel Plates position resolution

With analog charge division techniques making the use of *ad hoc* patterned anodes and a 200 ns integration time, a resolution of 2 μm has been reported by Bellazzini *et al.* allowing resolving 15 μm MCP pores [1]. A sub-millimeter position resolution has been obtained with $5 \times 5\,\text{cm}^2$ Micro-Channel Plate devices (see Sec. 3, Fig. 5) measuring the propagation time difference between the two ends of transmission lines coupled to the anodes.

2.7. Micro-Channel Plates noise

The impulse noise, of the order of $0.2\,\text{Hz/cm}^2$, is high compared to the gaseous detectors but low when compared to other solid-state devices such as Silicon Photo-multipliers. Possible contamination of the device by rubidium and potassium has to be carefully avoided during the production process [2].

2.8. Micro-Channel Plates life-time

The life time of the Micro-Channel Plates is limited by the ion feedback towards the photocathode. As an order of magnitude, the life-time of the current MCPs in terms of the total charge collected is about $1\,\mathrm{C/cm}^2$. Possible improvements are under investigations. They include the use of a 100 Å thick aluminium foil blocking the ions drifting back as well as an insulation between the gaps preventing also the diffusion of neutral molecules. It should be stressed that not a much loss in the Photon Detection Efficiency is observed [3].

3. Large area devices

Although relatively large Silicon Photo-multiplier devices appear on the market ($60 \times 60\,\mathrm{mm}^2$ from SensL, Ireland) then the very large devices cannot yet be implemented using the semi-conductor detectors. The Large Area Pico-second Photo-Detectors (LAPPD) Collaboration with teams from the University of Chicago, the Argonne National Laboratory, the University of Hawaii, Fermilab, the Lawrence Berkeley National Laboratory and three private companies aim at developing $20 \times 20\,\mathrm{cm}^2$ Micro-Channel panels and the associated integrated readout electronics, and complete assemblies of several daisy-chained panels. The use of gigahertz bandwidth transmission lines as the anodes would reduce significantly the number of electronics channels. A spacial resolution below one millimeter obtained by timing has been already measured [4] on $5 \times 5\,\mathrm{cm}^2$ Micro-Channel Plate devices from Burle-Photonis.

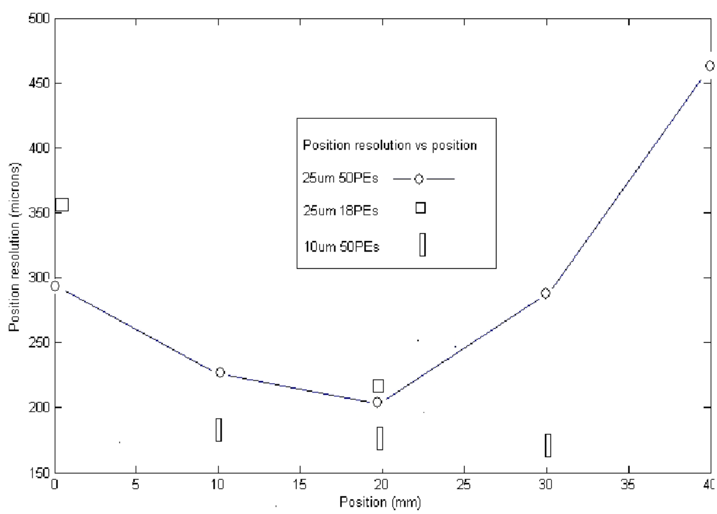

Fig. 5. Longitudinal position resolution obtained using pico-second timing.

4. Electronics

Many fast timing techniques such as the constant fraction discrimination, the multi-threshold, take benefit from the availability of fast integrated technologies such as deep sub-micron silicon CMOS, silicon-germanium, and even make use of combinations of these with the recent 3D integration techniques. It is now possible to store the full information contained in the detector pulse using the waveform sampling, at gigahertz range frequencies. Sampling analog memories are developed in many laboratories in the world (Orsay/Saclay (France), PSI (Switzerland), U.S. Universities (Hawaii, Chicago). Digitising the output of these device and using optimized signal processing allow getting the best possible timing information from the detectors.

5. Conclusion

Based upon today experience, the Micro-Channel Plates may provide at low cost large, very fast timing (10–100 ps) and 2D position sensitive (100 μm–1 mm) detectors in the next years. However, there is still a long way to get a full commercial device available. Current efforts deal with high quantum efficiency photo-cathodes, hermetic packaging, spacers, device uniformity and the integration of the digitising readout electronics.

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