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Extended lifetime MCP-PMTs: Characterisation and lifetime measurements of ALD coated microchannel plates, in a sealed photomultiplier tube

Thomas M. Conneely*, James S. Milnes, Jon Howorth

Photek LTD, 26 Castleham Road, St. Leonards-on-sea, TN38 9NS, UK

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ABSTRACT

Atomic layer deposition (ALD) coating of microchannel plates (MCP) has been shown to offer significant performance advantages in MCP-PMTs (MCP Photomultiplier Tube). ALD is a chemical vapour process used to deposit atomic mono-layers on a substrate. A process has been developed to deposit a surface with improved secondary emission yield (SEY) on to an MCP substrate. The principal advantage of a higher SEY is the ability to achieve significantly higher gain at the same operating voltage across a single MCP. Further to this, it is suspected the atomic mono-layers deposited by ALD coating prevent desorption of gaseous contaminants in the MCP glass. The ions produced during desorption are widely believed to be a direct cause of photocathode ageing in MCP-PMTs, leading to the hope that ALD coating can improve the MCP-PMT lifetime. To fully characterise the performance of ALD coated MCPs, two MCP-PMTs were manufactured, one ALD coated and the other uncoated to be used as a reference. Each detector's gain, DQE, pulse shape and timing jitter were measured followed by a life test of the tubes. The ALD coated tube was found to have a higher gain at the same operating voltage, whilst being equivalent to a standard MCP in other performance characteristics. ALD coating gave a dramatically improved life time, after 5.16 C cm^{-2} total charge extracted, there was no measurable effect on the photocathode QE, although the MCP gain dropped by approximately 35%.

1. Introduction

With an increasing trend towards higher luminosity and bunch crossing rates for particle physics, the lifetime limitations of MCP based photon detectors have become of particular interest. For example the proposed LHCb upgrade TORCH will require an accumulated charge of 5 C cm^{-2} extracted from the MCP detectors during the detector life time [1], while a standard MCP detector does well to reach 0.1 C cm^{-2}.

The dominant ageing mechanism of MCP-PMTs is bombardment of the photocathode by ions released during the electron multiplication process inside the MCP pore. These ions are produced by secondary electrons colliding with the MCP pore walls, desorbing gas from the MCP pore surface or ionising residual gas within the detector vacuum. The ions are then accelerated towards the photocathode by the electric field, where they are either adsorbed into the photocathode or damage the molecular structure. The net effect of the ion bombardment is to reduce the photocathode's quantum efficiency (QE).

In a single photon counting MCP-PMT, with two stacked MCPs, the ion production predominantly occurs towards the end of the pores of the second MCP in the stack where the secondary electron flux is highest. As such, in a two plate MCP-PMT detector each MCP is aligned such that the pore bias angles point in opposite directions, so there is no direct path from the ion production site to the photocathode [2,3]. A more recent development is to deposit a thin barrier film on the MCP input surface, either for the first or second MCP in the stack [4–6]. The film prevents ions from exiting the MCP pore and hence damaging the photocathode. However, the film – when placed on the first MCP – also blocks some photoelectrons from the photocathode, reducing MCP collection efficiency.

This paper characterises the lifetime improvements offered by an alternative approach, atomic layer deposition (ALD). ALD is a chemical process used to deposit atomic mono-layers on a substrate, with a highly tunable chemistry [7]. Arradiance®, Inc., has developed an ALD process to grow a coating with a higher secondary emission yield (SEY) compared to a typical MCP pore surface. The process also allows a number of different substrates to be used in place of the glass used in MCP fabrication [8].

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* Corresponding author. Tel.: +44 1424850555.
E-mail addresses: tom.conneely@photek.co.uk (T.M. Conneely), james.milnes@photek.co.uk (J.S. Milnes), jon.howorth@photek.co.uk (J. Howorth).

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The principal advantage of a higher SEY is the ability to achieve significantly higher gain at the same operating voltage across a single MCP, reducing secondary electron energy and hence the probability of an ion being produced due to electron collisions. Further to this, it is suspected that the atomic mono-layers deposited by ALD coating could prevent desorption of gaseous contaminants on the MCP surface or in the substrate, by effectively completely sealing the surface [9–11]. Hence, ALD provides a promising technique for improving MCP-PMT lifetime by reducing ion bombardment of the photocathode.

Two MCP-PMTs were manufactured each with a 10 mm active diameter, two chevron stacked 10 μm pore MCPs and a Low Noise S20 photocathode [12]. For one tube the MCPs were coated at Arradiance®, using a GEMStar™ ALD tool, whilst the other tube was built as standard to provide a control sample for the characterisation. The characterisation performed included detector gain as a function of MCP bias voltage (Section 2), timing performance as a function of photocathode to MCP voltage (Section 3) and finally accelerated ageing with photocathode quantum efficiency monitoring (Section 4).

2. Gain improvement

To characterise the total detector gain for each MCP-PMT a 500 nm DC light source, calibrated using a silicon photocell to have a power of 7.1×10^{-12} W cm^{-2} at a fixed distance from the light source, was used to illuminate the detector with a flat light distribution. The detector output current was then measured using a nano-amperemeter allowing the detector gain (G) to be calculated using

$$G = \frac{I_s - I_d}{\Phi_{500} P_{in} A}$$

where I_s is the photocurrent during illumination in mA, I_d is the current without illumination in mA (i.e. dark current), Φ_{500} is the photocathode's calibrated sensitivity at 500 nm in mA W^{-1}, P_{in} is the power of the input light in W cm^{-2} and A is the illuminated area in cm^2.

The results of calibrating the ALD coated MCP-PMT and its uncoated twin are shown in Fig. 1, as expected the higher SEY provided by the ALD coating has led to a dramatic improvement in gain compared to an uncoated MCP, with approximately 600 V less bias voltage required to obtain 1×10^6 gain. The slope of the gain curve is also much steeper, so that much higher gains can be achieved before exceeding the maximum voltage stand-off of the microchannel plate glass.

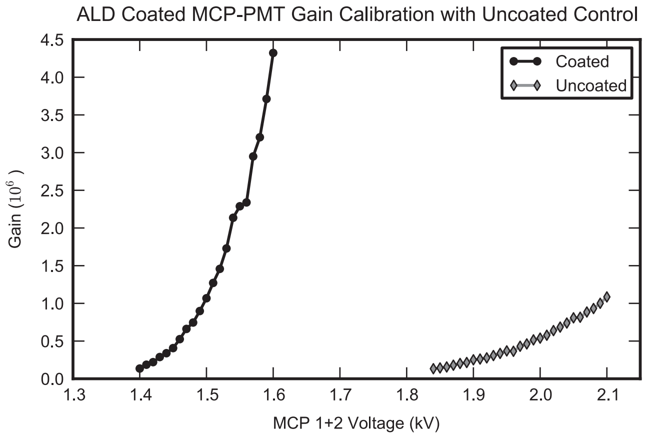

Fig. 1. Detector gain for two MCP-PMTs (one ALD coated and the other uncoated), with two chevron stacked MCPs. The gain is plotted as a function of the total MCP bias across both plates, with the photocathode to MCP input voltage constant at 200 V and the MCP output to anode voltage constant at 1500 V.

3. Timing

Each MCP-PMTs timing performance was measured with a pulsed 650 nm laser diode with a 40 ps FWHM pulse duration (Photek LPG-650) and 3 ps RMS jitter attenuated to single photon levels. The delay of the detector signal from the laser trigger was then measured using a LeCroy 20 GSamples/s, 5 GHz oscilloscope. To account for the broad pulse height distribution (PHD) of MCP detectors, which would result in significant time walk if a fixed threshold was used to measure the detector's leading edge, a dynamic threshold was used that measured the individual pulse amplitudes, and recorded the leading edge time at 50% of the pulse amplitude.

A typical timing histogram for the ALD coated tube is shown in Fig. 2, the distribution has three apparent peaks. The prompt large peak is the main detector response to the laser input, the second (producing a small shoulder to the right of the first peak) is believed to be from electron's scattered off the MCP input webbing. The final peak (delayed approximately 300 ps from the first peak) is explained as a feature present in the light pulse from the laser diode used, as the delay relative to the first peak does not depend on detector operating voltage. Two key parameters were measured from this histogram after fitting three Gaussians; the time of the first peak's maximum was taken as the detector transit time and the FWHM of the first and second peak combined was used as a measure of the detector's transit time spread (or timing jitter).

Fig. 3 shows each MCP-PMT's transit time dependence on the photocathode to MCP input potential (including a contribution from the laser path length). The longer transit time for the ALD coated MCP-PMT is attributed to a lower field in the MCP pores, increasing the time between secondary electron bounces. The transit time spread for each MCP-PMT is shown in Fig. 4, again as a function of photocathode to MCP input potential. This shows no difference between the two detectors, both having approximately 70 ps FWHM above a 25 V photocathode field without subtracting the contribution from the laser's 40 ps FWHM.

4. Lifetime results

Following characterisation, each MCP-PMT underwent accelerated ageing, where a 0.25 cm^2 area was illuminated using a DC broadband light source. During the ageing each tube's output photocurrent was recorded, in addition to a photodiode used to

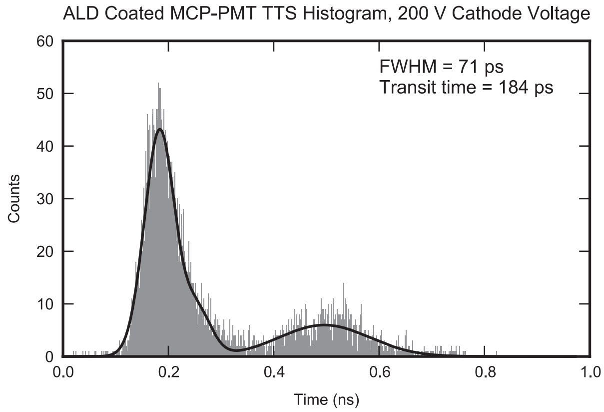

Fig. 2. Timing histogram for the ALD coated MCP-PMT, with time relative to a laser trigger. The timing spread includes detector jitter, a small contribution from the reference photodiode's jitter and a contribution from the laser's 40 ps FWHM.

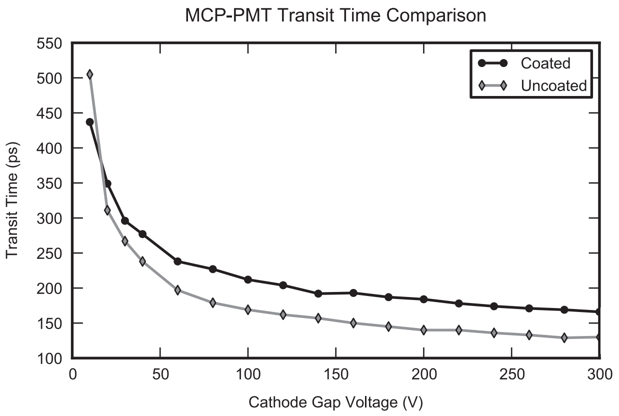

Fig. 3. Detector transit time for two MCP-PMTs (one ALD coated and the other uncoated), with two chevron stacked MCPs.

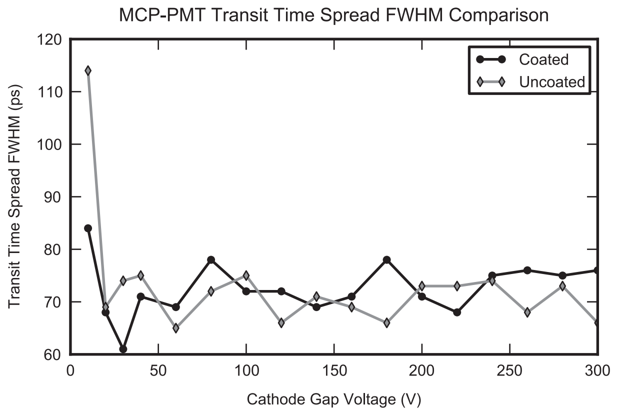

Fig. 4. Detector transit time spread (i.e. timing jitter) for two MCP-PMTs (one ALD coated and the other uncoated), with two chevron stacked MCPs. The measured FWHM includes a contribution from the laser's 40 ps FWHM.

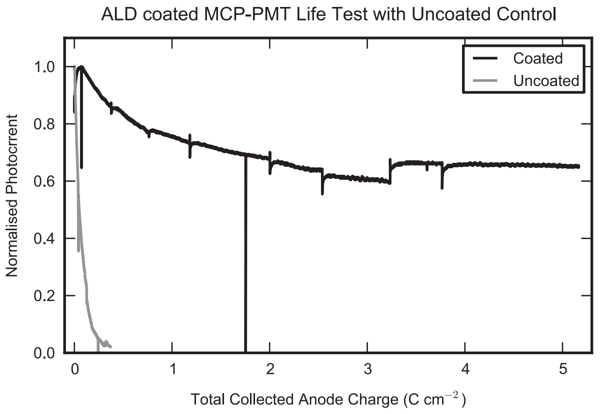

Fig. 5. Output photocurrent of each MCP-PMT over the duration of the life test, plotted as a function of total charge extracted from the MCP stack.

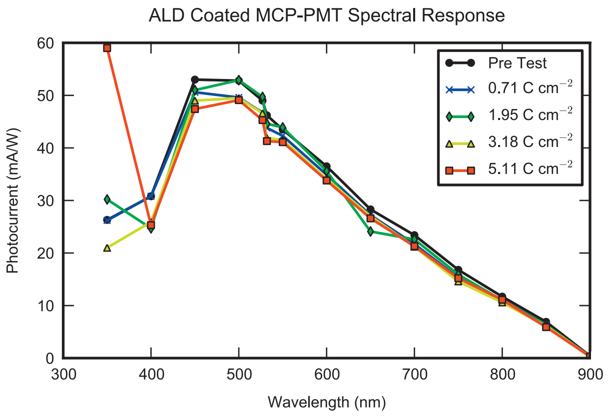

Fig. 6. Quantum efficiency of the ALD coated MCP-PMT at multiple life test stages, with different total extracted charges.

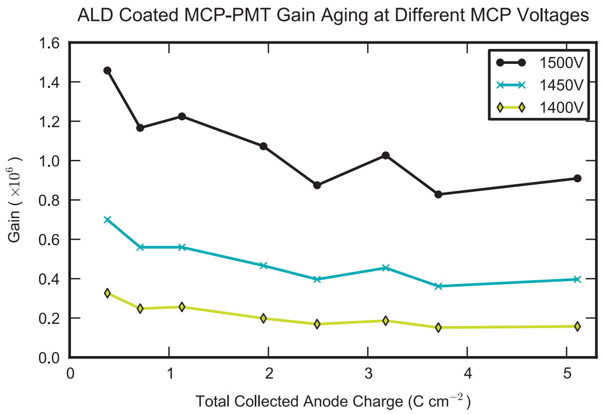

Fig. 7. Gain of the ALD coated MCP-PMT at different total extracted charges, at three different operating voltages.

independently monitor the input light intensity. The initial gain of the MCP-PMT detectors was set to be 1×10^6, and the operating voltage was fixed for the duration of the life test. By integrating the collected current over time the total charge extracted from the MCP was calculated.

Fig. 5 shows the change in photocurrent during the life test for both MCP-PMTs, with the ALD coated MCPs significantly outperforming the uncoated MCPs. The total extracted charge for the ALD coated MCP-PMT was 5.16 C cm^{-2}. After ageing there was no reduction in photocathode QE outside measurement errors, as shown in Fig. 6, with a reduction in MCP gain of approximately 30% as shown in Fig. 7. Most notably, there is no reduction of the photocathode QE even at longer wavelengths, a feature typical of normal photocathode degradation [4]. This was in stark contrast to the uncoated MCP-PMT, after extracting 0.37 C cm^{-2} the peak QE at 504 nm was reduced by approximately 80% and no response was left in the in the wavelength range of 800–900 nm. During the uncoated MCP-PMT life test there was no reduction in MCP gain, since the total charge extracted had not reached a point where MCP ageing would become a factor.

There are a number of notable features in the lifetime data for the ALD coated MCP-PMT shown in Fig. 5. There are a number of small blips in photocurrent, for example at total extracted charges 0.38 C cm^{-2}, 0.71 C cm^{-2} and 1.13 C cm^{-2}. At these points the detector had been removed from the life test setup for QE and gain measurements, and as such had been powered off for a number of hours. Upon powering the tube on in the life test setup, the total output current had dropped a small amount from the value at the end of the previous life test period and over the next 20–30 h would rise back up to previous levels. This effect is not visible for the standard uncoated MCP-PMT. There is currently no explanation for this behaviour, but it may point towards a required warm-up period for ALD coated MCPs to reach peak gain.

A further unresolved question is the correct scrubbing procedure for ALD coated MCPs. The ALD coated MCP-PMT used for these results underwent an identical scrubbing schedule to the uncoated MCP-PMT, which is used as part of the standard tube assembly procedure. As the ALD coated MCP-PMT gain deterioration appears to have reached a stable level in Fig. 5, it is possible that a more aggressive scrub could sacrifice the initial high gain, for a lower but more stable long term gain. Hence, further experimentation with ALD coated MCP scrub procedures is required with follow on life testing.

5. Conclusions

In conclusion ALD coated MCPs offer two distinct advantages for the production of MCP-PMTs; improved gain performance and a major improvement in tube life time due to a higher secondary electron yield and monoatomic layers effectively sealing the MCP surface. Timing performance was found to be unaffected, with a random single photon timing jitter equivalent to an uncoated MCP-PMT, despite the slightly longer transit time for ALD coated channels plates.

Further work is planned to investigate the correct scrubbing procedure for the ALD coating to improve gain stability during the tube life time, study the after pulsing behaviour of ALD coated MCPs and finally alternative substrates for the ALD coating.

Acknowledgements

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