Performance Characteristics of Atomic Layer Functionalized Microchannel Plates

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ABSTRACT

Microchannel plates that have been constructed by atomic layer deposition of resistive and secondary emissive layers, onto borosilicate glass microcapillary arrays provide a novel alternative to conventional microchannel plates for detection of radiation and particles. Conventional microchannel plates can also benefit from atomic layer deposition of highly efficient secondary emissive layers. Our evaluations of these techniques have revealed unique features of atomic layer functionalized microchannel plates, including enhanced stability and lifetime, low background rates, and low levels of adsorbed gas. In addition borosilicate glass microcapillary arrays show enhanced physical and thermal robustness, which makes it possible to successfully fabricate large area devices (20 cm) with good uniformity of operational characteristics.

Keywords: Microchannel Plate, Imaging, Photon Counting.

1. INTRODUCTION

Microchannel plates (MCPs) are widely used in imaging detector schemes\textsuperscript{1-9} for a variety of applications. Detection of charged particles, photons, and neutrons can be accomplished in analog or single event counting modes using either open faced detectors or ultra high vacuum sealed tube devices in conjunction with detection efficiency enhancing photocathodes\textsuperscript{9}.

A program has been initiated by a collaboration of Universities, National Laboratories and Industry to develop a Large Area Picosecond Detector\textsuperscript{10} that utilizes MCPs constructed by atomic layer deposition (ALD) on borosilicate microcapillary arrays. Beginning with inexpensive hollow borosilicate tubes, the fabrication method is similar to that for conventional MCPs\textsuperscript{8} but without the need to remove a core glass. Hydrogen reduction used for conventional MCP activation is also replaced by resistive layer and secondary emissive layer deposition using the ALD process\textsuperscript{11}. The final contact electrodes can be applied after the ALD process is complete. Each step is largely independent and can be adjusted to establish the MCP resistance as well as several other operational parameters. Borosilicate substrate MCPs have the advantage of a high glass softening temperature (>700 °C) allowing a range of high temperature enhancement processes to be accomplished with these as substrates. We have also shown that the ALD deposition process significantly reduces\textsuperscript{12} the MCP outgassing which may have a direct effect on MCP detector lifetimes specifically for sealed tube devices. The low intrinsic radioactivity of the glass composition results in MCP background lower\textsuperscript{12} than conventional MCPs\textsuperscript{13}. Since ALD depositions can be done at modest temperatures, application of a high secondary yield ALD layer to conventional MCPs can be done. This affords
some of the performance advantages of ALD such as, better lifetime stability and lower overall gas evolution.

A wide range of borosilicate microcapillary substrates have been fabricated by Incom for MCPs. The pore sizes are 40 µm, 20 µm, or 10 µm, with pore length to diameter (L/d) ratios of 80:1, 60:1 and 40:1 and a bias angle cut of 8° to normal, with substrate sizes ranging from 25 mm circular to 200 mm square. The open area fraction varies from 60% to 83%, and high quality substrates (Fig. 1) are now routinely available. ALD functionalization of recent substrates has been performed at Argonne National Laboratory (ANL). The majority of the tests to date have been done with 33mm circular or 20cm square substrate formats. ALD MCP resistances over a wide range, from 5 MΩ up to > 1GΩ have been evaluated, as well as Al₂O₃ and MgO secondary emissive layers. The emissive layers have also been applied to conventional MCPs in several formats (33 mm, 46 mm, 100 mm) to assess their efficacy.

![Figure 1](image-url)  
*Figure 1.* Borosilicate micro-capillary substrates used for atomic layer deposited microchannel plates, left - 40 µm pores with 83% open area, middle - 20 µm pores, 65% open area, right - 10 µm pores, 60% open area.

2. MCP PERFORMANCE USING BOROSILICATE SUBSTRATES WITH ALD

A set of basic tests allow us to determine the general operational characteristics of the ALD borosilicate MCPs. The initial step is to determine the MCP resistance by measuring a current-voltage characteristic. Once the resistance has been established the gain-voltage relationship is measured. For this measurement we use a standard MCP as an electron source. The input current to the test MCP is established and then the output gain can be measured as a function of applied potential. Typical gain – voltage curves for Al₂O₃ coated ALD borosilicate substrate MCPs are presented in Fig. 2. The overall gain values are comparable to that for standard lead glass MCPs, and saturation effects are seen at gains above ~1000 due to the relatively high input signals used. Pairs of MCPs were also tested in detectors with cross delay line imaging, photon counting readouts. These detectors accommodate two MCPs with a 0.7 mm inter-MCP gap that is typically biased at ~200 V. Representative pulse amplitude distributions for a pair of MgO coated ALD borosilicate substrate MCPs in this configuration are shown in Fig. 3. The input illumination is 185 nm UV, showing peaked distributions for photon signal detection, and negative exponential distributions for background events that are attributable to events generated throughout the bulk of the MCP material. The latter are either due to muon detection or radioactive decay of ⁴⁰K in the glass. The
pulse amplitude distributions are in accord with expectations for conventional MCPs in the same configuration\textsuperscript{7,14}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image1.png}
\caption{Gain characteristics of 33 mm diameter borosilicate substrate ALD MCPs, 20 µm pores, 65\% open area, 60:1 L/D.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image2.png}
\caption{Pulse amplitude distributions for a pair of 33 mm borosilicate ALD MCPs, 20 µm pores, 60:1 L/D, 0.7 mm gap.}
\end{figure}

A quick assessment of the imaging quality of sample 33 mm MCPs was accomplished with a detector that accommodates one MCP, and has a < 1 mm gap to a phosphor screen image readout. The phosphor is biased at \(\sim 3\) kV with respect to the MCP output face, and the input of the MCP is illuminated with 185 nm light so that visible images of the amplified MCP signal can be recorded. The imaging quality of current 20 µm pore MCPs is now fairly consistent (Fig. 4). There are hexagonal boundary features due to the deformation of pores close to the multifiber boundaries, and some multifibers have slightly different overall gain. The visibility of hexagonal modulation of the image is indicative of the amount of physical distortion of the pores at the boundary. The image in Fig. 1, shows that the distortions for the 20 µm pore MCPs are restricted to only one pore either side of the boundary, and this correlates with the reduced level of modulations seen for the current fabrication of 20 µm pore MCPs as shown in Fig. 4. The quality of substrates has continued to improve and is approaching that expected of standard MCP production.

The event counting imaging performance of the MCP pairs has been evaluated with the cross delay line detector\textsuperscript{12} with typical spatial resolution of \(<50\) µm FWHM. Images obtained with borosilicate ALD MCP pairs show hexagonal modulation from both the top and bottom MCP of the stack\textsuperscript{12}. The intensity of the modulation is modest, but shows room for further improvements. The gain modulation at these boundaries is found to be of the order 5\% to 10\%. The background event image distribution is uniform (Fig. 5) for the intrinsic background of the MCP in accord with the expected muon event detection and internal radioactive decay. The background event rate measured for the MCP samples is typically 0.07 events cm\textsuperscript{-2} sec\textsuperscript{-1}. This rate compares with \(\sim 0.25\) events cm\textsuperscript{-2} sec\textsuperscript{-1} for standard MCPs with similar configuration and is dominated by \(^{40}\)K beta decay in the MCP glass. The reduced level of \(^{40}\)K in the borosilicate glass MCPs is proportional to the reduction in observed background rates when accounting for the \(\sim 0.02\) events cm\textsuperscript{-2} sec\textsuperscript{-1} for muon detections\textsuperscript{13}. 
3. PERFORMANCE USING CONVENTIONAL MCP SUBSTRATES WITH ALD

ALD coatings may also be used to make, or modify MCPs made with conventional MCP glasses. We have made evaluations of standard, fully processed MCPs that have had MgO or Al₂O₃ secondary emissive layers deposited as a final layer by ALD. Evaluations include the Imaging quality, gain and gain uniformity, pulse amplitude distribution, background event rates and quantum efficiency. Initially, the gain of standard MCPs is reduced by coating with MgO, but is slightly higher with Al₂O₃. Testing a triple MCP “Z” stack we obtain good pulse amplitude distributions.

Figure 4. Image for 185 nm illumination, of a 33 mm ALD borosilicate MCP using a phosphor screen readout. 20 µm pores, 65% open area, 60:1 L/d, 8° pore bias. 1100V MCP.

Figure 5. Background image for a pair of MCPs. Rate 0.075 cm² sec⁻¹. Top MCP ~1200 V, 20 µm pore, 60:1 L/d, 8° bias, Al₂O₃ ALD. 0.7 mm MCP pair gap, 300 V bias. Gain ~ 3 x 10⁶.

Figure 6. Pulse amplitude distributions for a standard 3 x 80:1 L/d 10 µm MCP stack with MgO ALD applied to all the MCPs.

Figure 7. Gain during initial UV burn-in for the MgO ALD coated standard (lead glass) MCP stack shown in Fig. 6.
for a standard 10 µm MCP configuration (Fig. 6) coated with ALD MgO, even at gains that are comparatively low (<2 × 10^6). Doing a UV illuminated “burn-in” (~1 µA output current) with this stack extracting a small level of charge (0.023 C cm^-2) serves to increase the gain by a factor of two (Fig. 7). Similar behavior is also seen where an ALD (Al2O3) MCP is used as the top MCP of a pair, with a MgO ALD coated standard MCP beneath (Fig. 8). The gain initially drops rapidly and then increases and begins to level off above ~ 0.02 C cm^-2.

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**Figure 8.** 33mm MCP pair UV burn-in. Al2O3 ALD 20µm, 60:1 borosilicate ALD MCP on top, MgO ALD on bottom MCP (6µm pore, 80:1 lead glass).

**Figure 9.** Electron burn-in for a 33mm MCP (6µm pore, 80:1 L/d, lead glass, 12° bias) with MgO ALD layer applied.

**Figure 10.** Gain during burn-in for a 33mm MCP (6µm pore, 80:1 L/d, lead glass, 12° bias) with MgO ALD layer applied.

**Figure 11.** Post burn-in stability for a 33mm MCP (6µm pore, 80:1 L/d, lead glass, 12° bias) with MgO ALD layer applied.
A similar test with another MgO ALD coated lead glass MCP as the output MCP shows the same kind of behavior (Fig. 9). Using the top MCP as an electron source the gain of the bottom MCP was measured throughout the burn-in. At all voltage settings the gain first dips then increases to a peak after about 0.07 C cm\(^{-2}\) is extracted. The gain-voltage curves at each point in the burn-in process are shown in Fig. 10. The highest gains obtained at the end of the burn-in show saturation due to the relatively high levels of output current. Usually a typical MCP burn-in requires 0.25 C cm\(^{-2}\) extracted before the gain stabilizes after dropping. The MgO seems to stabilize much faster and rises to a higher gain level. The data for the behavior of MgO surfaces indicates that the secondary emission coefficient is increased to a higher asymptotic level by cleaning procedures\(^{15}\). If the MgO secondary emission coefficient increases this way then we would expect the gain of the MCP to increase during burn-in. Furthermore, we have tested (Fig. 11) the stability of the gain after burn-in by leaving the detector unpumped for 10 days which resulted in a vacuum pressure of \(~400\ mTorr\). This resulted in a gain increase of \(~50\%\) at normal operational gain levels \((~1000)\). This gain level did not change in any significant way after an additional exposure of 148 hours in atmospheric dry nitrogen. This stability is a useful property for the purposes of handling and transport for MCP detector systems.

Another test that was performed is comparison of MCP “Z” stacks from the same fabrication batch. In one case the bottom MCP of the stack was MgO ALD coated. During the early phases of burn-in the drop in relative MCP gain (Fig. 12) for the untreated stack follows the same trend we have observed for other standard MCP “Z” stacks\(^{16}\). The stack with the MgO ALD coat on the bottom MCP dropped far less in gain and showed signs of stabilization after only 0.01 C cm\(^{-2}\). Expectations indicate that the uncoated stack would require >0.2 C cm\(^{-2}\) or more to stabilize (Fig. 13). We expect that the top two MCPs in the stack with the MgO coated bottom MCP will reduce in gain, so to obtain a better comparison we will need to make more detailed measurements with a full “Z” stack coated with MgO (Fig. 7).
Other observations made in the course of these tests on ALD coated standard MCPs show that there are no significant changes to the imaging or background properties of the MCPs. The QDE is similar to a bare MCP\(^{17}\), and coating the MCP with a CsI photocathode on top of the secondary electron emissive ALD layer we achieve a standard CsI/MCP QDE response\(^{17}\).

4. ATOMIC LAYER MCP PERFORMANCE USING BOROSILICATE SUBSTRATES

4.1. **10µm pore borosilicate substrates with ALD functionalization**

Recently we have obtained 33 mm borosilicate ALD MCPs with 10 µm pores and MgO secondary emissive layers. The gain of a representative MCP is shown in Fig. 14, and is commensurate with the data for other ALD MCPs (Fig. 2). The imaging was also evaluated with the phosphor readout and cross delay line readout detectors. The phosphor detector image shows more single multifiber distortions than the current 20 µm pore MCPs (Fig. 4), but overall this is not an unreasonable performance level for the first attempt at the smaller pore size MCPs. Further development of 10 µm pore substrates is underway. Background levels for the 10µm pore ALD MCPs were found to be the same as the 20 µm pore ALD MCPs.

![Figure 14.](image.png) **Figure 14.** Gain curve for a single borosilicate-ALD 33 mm MCP with 10 µm pores, 80:1 L/d, 8° bias with MgO ALD top layer.

![Figure 15.](image.png) **Figure 15.** UV (184 nm) image (phosphor screen). Borosilicate ALD MCP with 10 µm pores, 80:1 L/d, 8° bias, MgO, 1100V.

4.2. **Borosilicate ALD MCP Preconditioning and Lifetime Characteristics**

The preconditioning\(^{16}\) of borosilicate ALD MCPs has also been studied to establish their stability and longevity. The secondary emissive layer for ALD MCPs is likely the most important factor for the behavior of the performance of ALD MCPs. Therefore two cases were examined, both were 20 µm pore, 60:1 L/d borosilicate substrates, but one had an Al\(_2\)O\(_3\) (Fig. 16) secondary emissive layer and the other a MgO emissive (Fig. 17) layer. Both were illuminated with a uniform source of electrons from a standard MCP and operated at an output current of ~1 µA to accomplish “burn in”. Periodically the gain versus applied voltage curves were remeasured to assess the progress of the burn-in. The Al\(_2\)O\(_3\) coated MCP decreases (~factor of 3) in gain during burn-in and
seems to stabilize after about 0.02 C cm\(^{-2}\). Conversely the MgO coated MCP increases in gain by a factor of \(-5\) during burn-in and seems to begin stabilizing at 0.03 C cm\(^{-2}\). The observations for the MgO coated MCP are in keeping with our prior observations (Fig. 9) and relates to the increase in MgO secondary emission coefficient during surface cleaning. Under similar conditions\(^{15}\) Al\(_2\)O\(_3\) shows a decrease in the secondary emission coefficient during surface cleaning, so our result is not unexpected. Nevertheless, in both cases the total charge extraction for stabilization is smaller than standard MCPs, which is an important issue, for example in the processing of sealed tube devices.

**Figure 16.** Gain characteristics for a 33mm MCP. Al\(_2\)O\(_3\) ALD 20µm pore, 60:1 L/d borosilicate MCP during burn-in using 200 eV electrons. Shows a modest overall gain decrease.

**Figure 17.** Gain characteristics for a 33mm MCP. MgO ALD 20µm pore, 60:1 L/d borosilicate MCP during burn-in using 200 eV electrons. Shows a modest overall gain increase.

**Figure 18.** Gain curves for a pair of borosilicate-ALD MCPs with 20 µm pores, 60:1 L/d, 8° bias, as preconditioning (350°C bake-out, UV burn-in) steps are done in ultra high vacuum.

**Figure 19.** Gain at specific bias voltages for a borosilicate-ALD MCP pair (20 µm pore, 60:1 L/d, 8° bias) as a function of extracted charge during UV burn-in (after 350°C bakeout).
To evaluate full preconditioning processes one borosilicate MgO ALD MCP pair was subjected to a 350 °C vacuum (< 10^{-5} Torr) bake. After the bake the gain was found to have increased by a factor of 10 (Fig. 18). So the increase in MgO secondary yield was fully achieved by baking and out-gassing the surface in this case. Subsequently a “burn-in” with a high flux of 185 nm UV light at output currents up to ~0.5 μA cm^{-2}, at a relatively low overall gain (~3 x 10^{4}), was done (Fig. 19). The gain change after 7 C cm^{-2} extracted was almost negligible for normal operational gain settings (2 x 10^{6}). Also the gas evolution was not measurable (<1 x 10^{-10} Torr) after the first 0.1 C cm^{-2}. These observations seem to confirm the anticipated behavior for MgO ALD layers, and offer a unique enhancement to MCP preconditioning and operational stability.

5. 20 cm BOROSILICATE SUBSTRATE, ATOMIC LAYER MCPS

One of the advantages of borosilicate microcapillary substrates is the robustness of the glass compared with standard MCP glass. 20 μm pore borosilicate microcapillary arrays with 20 cm square format have been constructed and ALD functionalized as MCPs with 60:1 L/d ratio. These retain excellent flatness and are mechanically and thermally (700 °C softening point) durable. Establishing performance that is uniform over the 20 x 20 cm area requires significant optimizations of the ALD processes. To assist this process we have implemented an imaging detector with a cross delay line readout capable of 50 μm FWHM spatial resolution and event rates in excess of 1 MHz. This provides images and average gain maps as well as pulse amplitude distributions. The gain achieved for the large 20 cm MCPs is similar to that attained with the 33mm ALD MCPs (Fig. 18). The pulse amplitude distributions (Fig. 20) for UV (185 nm) is somewhat broader than the 33mm ALD MCPs but this is expected due to variations in MCP gain across such large MCPs. The background pulse amplitude distributions are of negative exponential shape, as expected from the generation of events by radioactive beta decay throughout the bulk of the MCP glass.

![Figure 20. Pulse amplitude distributions for a pair of 200 mm square ALD MCPs with 20 μm pore borosilicate substrate, 60:1 L/d, 8° bias, 185 nm illumination, 1000v bias on each MCP.](image)

![Figure 21. Integrated image using 185 nm illumination for a pair of 200 mm square ALD MCPs (20 μm pore, borosilicate, 60:1 L/d, 8° bias). Inter-MCP 0.7 mm gap with 200v bias.](image)
Images accumulated under 185 nm UV illumination show (Fig. 21) patterning that is due to the coarseness of the anode readout. However, examining the fine scale structure of the image (Fig. 21, inset) show the same hexagonal modulation effects seen with the 33 mm MCPs as a result of the multifiber boundary pore distortions. The gain of each event is also recorded and an “image” of the average gain of the MCP pair (Fig. 22) can be derived. This shows a smoothly varying gain where the largest variations are about 20% (Fig. 23). Although not visible in Fig. 22, the MCP hexagonal modulation boundaries have lower gain at their interfaces, as one might expect from the pore distortions (Fig. 1). Recently fabricated 20 cm ALD MCPs with resistances as low as ~10 MΩ have been operated continuously over periods of several days without any changes of resistance or other performance parameters.

**Figure 22.** Integrated gain map using 185 nm illumination for a pair of 200 mm square ALD MCPs (20 µm pore, borosilicate, 60:1 L/d, 8° bias). Inter-MCP 0.7 mm gap with 200V bias.

**Figure 23.** Overall gain histograms for the image in Fig. 22. Each MCP MCP has a 1000 V bias giving an average gain of 6.5 x 10^6. Variations are modest, given the large MCP area.

Examination of the imaging performance of the 20 µm pore 20cm MCPs in greater detail has been accomplished with a 10 x 10 cm cross strip readout detector system. This shows that the MCP pores can be resolved (Fig. 24) and shows the bright/dark modulation effects of pore distortions at the multifiber boundaries. The gain is high in the bright areas and low in the dark areas, which is typical affirmation of the effects of pore distortions at these boundaries.

The background rate of pairs of 20 cm ALD functionalized borosilicate MCPs has been the subject of considerable scrutiny. With such a large area (400 cm^2) it is difficult to maintain a completely debris free surface. In a number of cases there were event rate “warm spots” where debris was on the MCPs. Some MCPs show no sign of this problem and the background rate is as low (Fig. 25) as that seen on the 33 mm MCP samples, and spatial distribution is very uniform. Even in the case of MCPs with “warm spots”, the general background rate is always at the same overall level of ~0.075 events cm^-2 sec^-1. Substrate fabrication and ALD methods continue to improve, offering an excellent opportunity for realization of large area, high spatial resolution event counting MCP detector systems. However, even at this stage the 20 cm MCP performance is
adequate for a number of potential applications that would not be addressable with smaller format MCPs.

**Figure 24.** High resolution image of a section of a 20 cm square ALD MCP pair with 20 µm pore borosilicate substrate, 60:1 L/d, 8° bias, using a 10cm cross strip readout system. MCP pores are just resolved, as well as the multifiber boundary distortion effects.

**Figure 25.** Background event image accumulation (1000 sec) for a 20 cm square, 60:1 L/d ALD borosilicate MCP pair, L/d, 8° bias, 185 nm UV illumination. 0.7 mm pair gap at 200v bias, gain ~7 x 10^6. Average rate of 0.075 events cm^-2 sec^-1.

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