Cryogenic single particle detection enabled by high aspect ratio ALD of functional nanofilms

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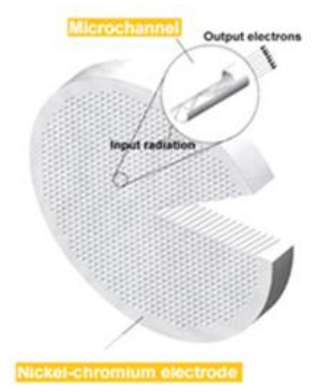
Abstract

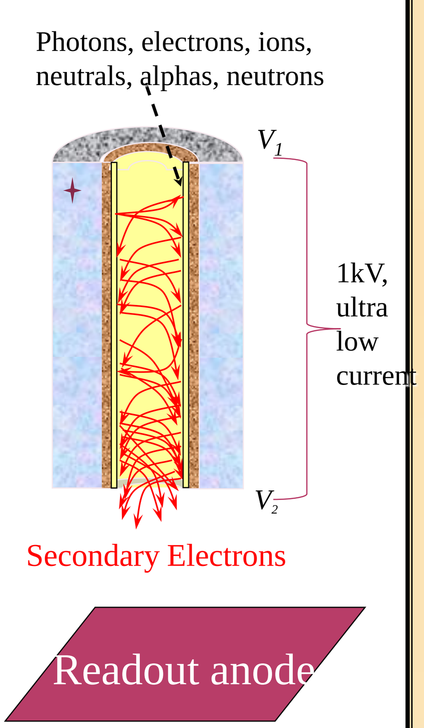
Atomic Layer Deposition technique optimized for film growth in structures with large aspect ratio (>50:1) has enabled substantial improvement of particle detectors in various applications such as Astrophysics, High energy physics, Biomedical imaging and many others. These detectors based on Microchannel Plate (MCP) electron amplifiers are capable of single event detection with high spatial (~10 µm) and temporal (<100 ps) resolution and no readout noise. The growth of nano-engineered films inside the MCP pores enabled novel MCP manufacturing technology which substantially improves their performance and extends their use into novel applications. Arradiance has developed custom tools and recipes for the growth of conformal films with a given conductance and films with optimized secondary electron emission inside very long channels (~6 µm diameter and >600 µm length, with tens of millions of channels per single MCP). The unique ability to tune the characteristics of these films enables their optimization to applications where time-resolved single particle imaging can be performed in extreme conditions, such as high counting rates at cryogenic temperatures.

The custom-designed ALD tools for high aspect ratio structures enable very accurate control of nanolaminate films inside the MCP pores. With that the resistance of conduction film deposited on the pores of glass MCP substrates can be controlled in a very wide range of more than 15 orders of magnitude. Due to the negative coefficient of resistance the operation of electron amplifiers at cryogenic temperatures required the development of specific films exhibiting very low resistance at room temperature and optimal resistance at temperatures of ~10K. The adhesion of these films to the glass substrates with 5-20 µm pores and their mechanical stability in a very wide range of temperatures (10K – 700K) as well as their optimized resistance and thermal stability were confirmed by our experiments. The resistances of our novel MCPs optimized for the cryogenic temperatures enables event detection at <20K temperatures with high count rates not available with the conventional MCP technology.

MCP electron multipliers and their applications in single particle detection



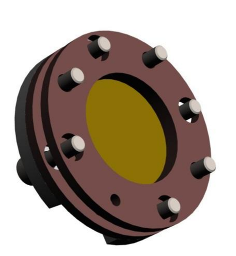
- Pores are typically 6-20 µm ∅
- Active area ~25 mm – 200 mm
- Resistance 10-100 MΩ at room T with negative coefficient of resistance

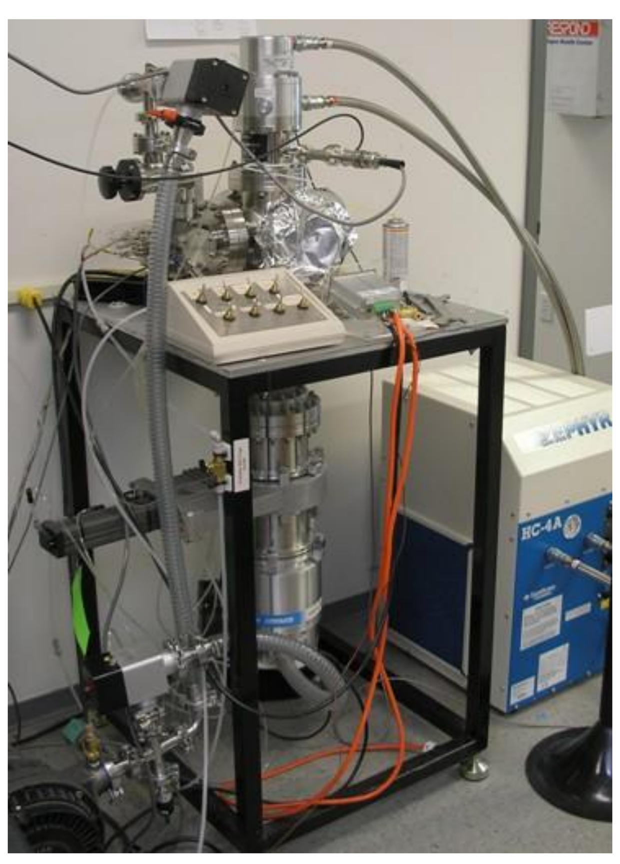


- Detection of single photon (visible with special photocathodes, UV, soft X-ray), electron, ion, neutral, alpha, neutron.
- High gain – 10^5 from a single MCP and up to 10^7 from a stack.
- Low background count rate < 0.1 count/cm²/s.
- Large dynamic range.
- High spatial (10-20 µm) and temporal (10-50 ps) resolution.
- Event counting (Particle Detector) or integrating (Image Intensifier) modes are possible.
- Output current limited to ~10% of strip/conduction current – that introduces limitation on count rate per pore. Both MCP resistance and operational gain define the maximum count rate per pore.
- Event counting with ~1 GHz rate per MCP is possible with fast low-noise readout electronics (e.g. Timepix requiring gain of only ~5x10⁴).

- Night vision goggles; Mass spectroscopy; Astrophysics; Biomedical research (FLIM, FRET,…); Diagnostics of storage rings; High energy physics; Synchrotron instrumentation;

Custom table-top ALD tool optimized for structures with deep aspect ratio and cryogenic calibration facility





GEMStar-8 system is designed for extreme surface area, high aspect ratio structures: Multi-channel precursor delivery system isolates & distributes precursors combine with a tapered exhaust to provide exceptional nanofilm uniformity.

The differentially pumped system seals eliminate gas permeation which along with separate and actively heated Oxidant and Metal-Organic manifolds eliminate parasitic nanofilm production.

Metrology Interface for QCM, ellipsometry , FTIR, OES and room for up to six high capacity precursor cylinders (2 heated) with 2 independent gas lines, maximizes system productivity.

MCP resistance and stability under applied bias was measured in the cryogenic vacuum chamber at temperatures down to 10K.

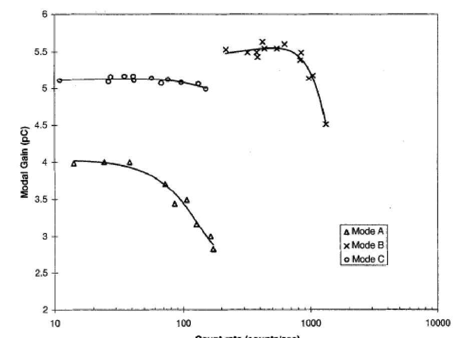
Enabling MCP ALD technology

- Substrate-independent functional MCP characteristics. Wide choice of substrate material – plates have been made from lead-glass, conventional borosilicate glass, silicon, ceramic and even plastic.
- Substrates with no radioactive traces can be used – very low dark count rates.
- Scalability to large areas – plates have been made up to 200mm x 200mm
- High gain – up to 20x conventional plates at similar bias voltages
- Long Life – up to 50 times as long as conventional MCPs
- Low dark noise/outgassing – pure films do not have the impurities present in conventional lead-glass
- **Tunable Resistance – from a few Ω to many GΩ**
- **Performance at a wide range of temperatures. Experiments have shown performance down to 10 degrees Kelvin (low resistance MCPs at room T)**

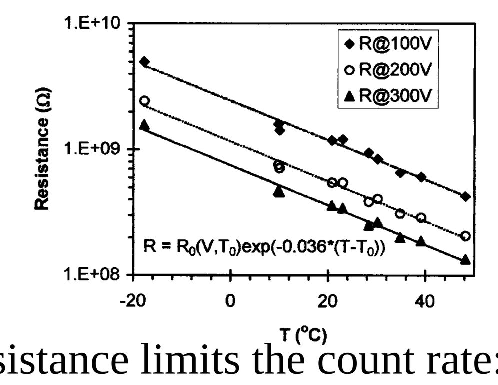
Event counting at cryogenic temperatures

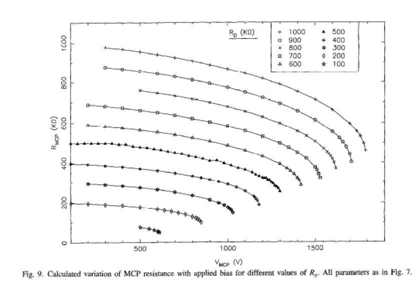
$$R_{MCP}(T_{MCP}, V_{MCP}) = R_0[1-\alpha_v V_{MCP}]\exp\{-\beta_T(T_{MCP}-T_0)\}$$

A.S. Tremsin, et al., (1996), (2004)



Typical count rate saturation at output equal to ~10% of strip current

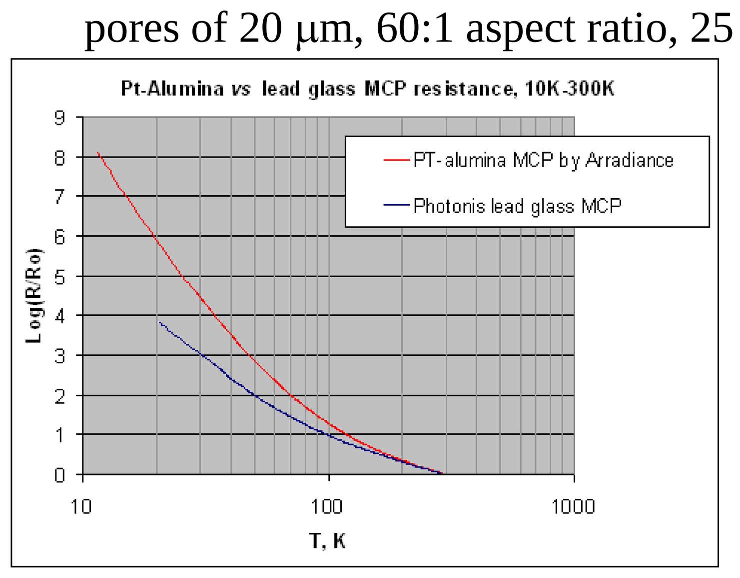




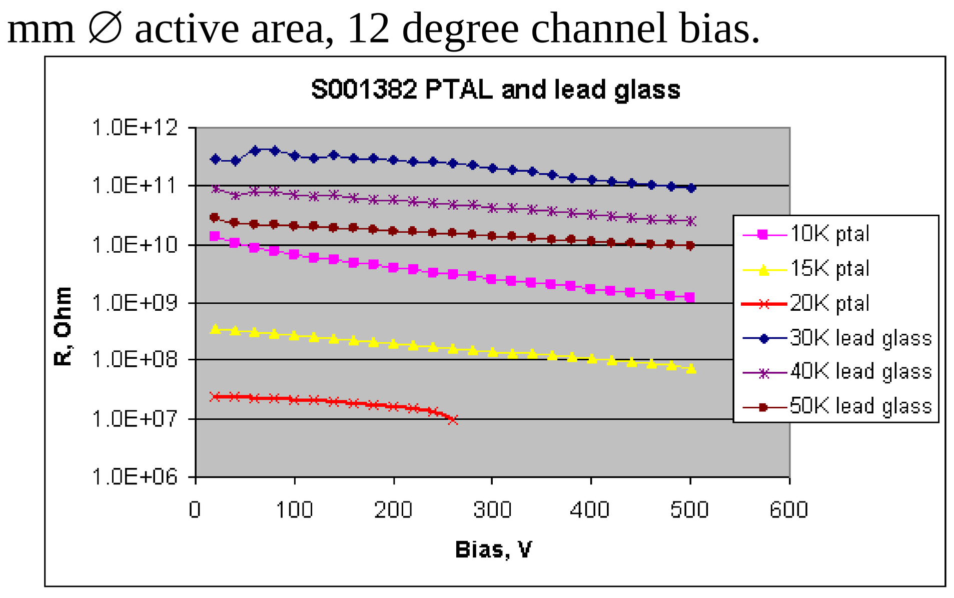
- MCP resistance limits the count rate: the charge replenishment is defined by the MCP strip/conduction current.
- Negative TCR leads to 4-6 orders of magnitude increase of MCP resistance with cool down to 10-20 K.
- **Nano-engineered MCPs can be tuned to optimal resistance at cryogenic temperatures.**

Event counting at cryogenic temperatures

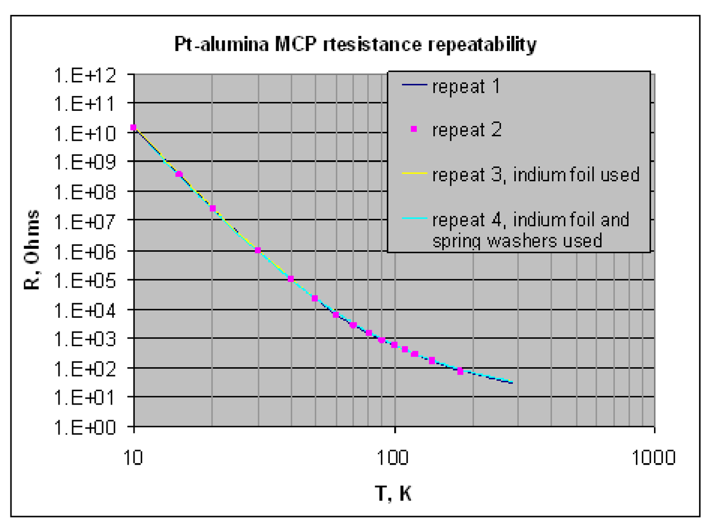
MCP geometry
pores of 20 µm, 60:1 aspect ratio, 25 mm ∅ active area, 12 degree channel bias.



MCP resistance (R) vs. temperature (T) normalized to resistance R_o at room T. Red curve is Arradiance's nano-engineered ALD MCP; blue curve is a standard lead glass MCP shown for comparison. The R_o resistance values were different by orders of magnitude.



MCP resistance in Ohms vs bias voltage for the Arradiance cryogenic MCP and a conventional lead glass MCP shown for comparison. The resistance of the conventional MCP was above 10GΩ at temperatures below 50K. The counting rate capability of detector with such MCP is limited to very low values.



Stability of MCP to thermal cycling.

Multiple cycling of MCP between room temperature and 10K did not lead to any measurable change in MCP characteristics. No pore film de-lamination, no change in resistance was observed.

Summary

Microchannel plates optimized for the high count rate operation at cryogenic temperatures have been manufactured and tested for their mechanical and electrical stability at cryogenic temperatures down to 10K. In-vacuum measurements demonstrated the MCP resistance of ~100 MΩ at 15K and 1 GΩ at 10K temperatures. Nano-engineered conduction and emission films were deposited on the conventionally sized MCP of 25 mm active area. Multiple cycling through the temperatures between 10 and 273 K did not lead to any measurable or visible changes of MCP characteristics. These cryogenic MCPs should allow substantial improvement of single particle detectors operating at cryogenic temperatures in various applications, including diagnostics system in cryogenic storage rings, quantum computing and others.

Acknowledgements

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