ALD of SnO₂ as the active component of a Plastic Microchannel-Based Direct Fast Neutron Detector

Philippe de Rouffignac, Neal Sullivan, Anton Tremsin, Dmitry Gorelikov, David Beaulieu - Arradiance

Adam Hock, Jaeyeong Heo, Roy Gordon – Harvard University
Outline

- Arradiance and the Microchannel Plate Amplifier (MCP)
- Motivation I & II
- Theory behind proposed device
- ALD/Film Requirements for Plastic MCP
- SnO₂ ALD Results
- Plastic MCP Beam line Results
  - Efficiency
  - Timing
- From the lab to the field
What is a Micro Channel Amplifier?

Very Fast – Very Low Noise - Charged Particle Amplifier

- Single Micro Channel Amplifier
- Bias 1000 V
- High Gain up to 1e6
- Low noise – Very fast
- Pico Second Response

Micro Channel Plate (MCP - Array of pores)

Micro Channel Plate Used In Light Amplification

Finished Night Vision Tube

NV Application
A 50 year old MEMS Process

Substrate Fabrication

1" Etch-able Core
Lead Glass Rod

Draw Tower

Stacked
Draw Tower
Repeated

Boule
5-100mm Dia

Diced
0.2-0.3 mm thick

Etched
Producing >5M
2-10 um pores

TABLE 2
Elemental composition of MCP glass.

<table>
<thead>
<tr>
<th>Z</th>
<th>Element</th>
<th>Weight percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>82</td>
<td>Pb</td>
<td>47.8</td>
</tr>
<tr>
<td>8</td>
<td>O</td>
<td>25.8</td>
</tr>
<tr>
<td>14</td>
<td>Si</td>
<td>18.2</td>
</tr>
<tr>
<td>19</td>
<td>K</td>
<td>4.2</td>
</tr>
<tr>
<td>37</td>
<td>Rb</td>
<td>1.8</td>
</tr>
<tr>
<td>56</td>
<td>Ba</td>
<td>1.3</td>
</tr>
<tr>
<td>33</td>
<td>As</td>
<td>0.4</td>
</tr>
<tr>
<td>55</td>
<td>Cs</td>
<td>0.2</td>
</tr>
<tr>
<td>11</td>
<td>Na</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Wiza, Nuclear Inst. & Meth., Vol 162, 1979, 587

Substrate Functionalize

Furnace H₂ Firing
Both conduction and emission layer produced simultaneously; cannot be optimized independently
Arradiance MCP Technology

- **Substrate**
  - Rigid and electrically insulating

- **Conductive layer**
  - $\sim 10^{13} - 10^{14}$ Ohms/Sq
  - Conformal & uniform up to 200 : 1
    - Thickness and Resistivity
  - Low field effects = Low TCR

- **Emissive layer**
  - Conformal & uniform
  - High secondary yield
    - Contaminants can effect yield

- **MCP Device**
  - High Gain
  - Resistance stability and matching
  - Stable gain following “scrub”
  - Low outgassing
Process: Conductive film
Process: Conductive film - TCR

Thermal coefficient of resistance on par ($B_T < 0.01$) with current state-of-the-art for two Arradiance conductive films

<table>
<thead>
<tr>
<th></th>
<th>TCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film A</td>
<td>0.012</td>
</tr>
<tr>
<td>Film B</td>
<td>0.0098</td>
</tr>
</tbody>
</table>

$y = 1.234E+08e^{-1.241E-02x}$
$R^2 = 9.988E-01$

$y = 1.23E+08e^{-9.84E-03x}$
$R^2 = 9.98E-01$
Process: Secondary electron yield & device gain
Results - Incom 66:1, 20um, 60% OAR
March 2010

© 2010 Arradiance® Corporation. All rights reserved.
Improved Lifetime of Thin Film MCP over Conventional

- Reduced ion feedback
  - Reduce diffusion of mobile ions
- Sustained emission layer response with extracted dose
Outline

- Arradiance and the Microchannel Plate Amplifier (MCP)
- Motivation I & II
- Theory behind proposed device
- ALD/Film Requirements for Plastic MCP
- SnO₂ ALD Results
- Plastic MCP Beam line Results
  - Efficiency
  - Timing
- From the lab to the field
Motivation in Two Parts

Scientific Curiosity
- All microchannel plate amplifiers on the market are made from a glass substrate
- Can Arradiance make an MCP out of a seemingly more challenging material like plastic?
- Is there a way to make our high temperature MCP films compatible with plastic?
- What could a functioning plastic MCP be used for?
  - Large area robust MCPs?
  - MCP-PMTs?
  - Detectors?

Revenue Generating Applications
- Detection of Special Nuclear Materials
- Fast neutron counting/spectroscopy
Plastic MCP Applications

**Large area MCP (current)**

- COS detector Hubble telescope
- Plastic MCPs are robust and can be potentially be made in large areas for less cost
- Market (now): $100k/year

**Large Area (>4”) MCP-PMT (Future)**

- Homeland security X-Ray detection: $100M/year
- Medical Imaging: $200M/year
- Scientific (DUSEL et al): $20-50M/year

*BURLE TECHNOLOGIES, INC.  
http://www.burle.com/mcp_pmts.htm
‡ Philips Healthcare

**Nuclear Detection**

- “Nuclear Car Wash” (Livermore Concept)
- Neutron-proton interaction yields detection capabilities
- Potential replacement candidate for He-3 detectors
- Market: >$1B/year
SNM detection technology overview

- Hydrogen-rich PMMA microchannel structure
- Graded Temperature ALD deposition
  - Active films deposition at 140°C
- Neutron-proton recoil reaction within plastic at better than 1% efficiency
- Proton initiated secondary electron cascade
- Output pulse $10^3 - 10^6$ electrons
- Standard readout electronics
- Technology scalable to large format
Outline

- Arradiance and the Microchannel Plate Amplifier (MCP)
- Motivation I & II for a plastic MCP
- Theory behind proposed device
- ALD/Film Requirements for Plastic MCP
- SnO₂ ALD Results
- Plastic MCP Beam line Results
  - Efficiency
  - Timing
- From the lab to the field
Some polymer candidates and a precursor candidate

<table>
<thead>
<tr>
<th>Material</th>
<th>Tg</th>
<th>MP</th>
<th>CTE</th>
<th>Water Absorption</th>
<th>H Content (mol H/cm³)</th>
<th>Is Substrate Manufacturable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radel-R5000 (a polyphenylsulfone)</td>
<td>220°C</td>
<td>360°C</td>
<td>56 µm/m-°C</td>
<td>0.4%</td>
<td>0.018</td>
<td>No</td>
</tr>
<tr>
<td>PMMA</td>
<td>105°C</td>
<td>160°C</td>
<td>75 µm/m-°C</td>
<td>0.3%</td>
<td>0.094</td>
<td>Yes</td>
</tr>
<tr>
<td>HDP Polyethylene</td>
<td>-78°C</td>
<td>130°C</td>
<td>25 µm/m-°C</td>
<td>0.05%</td>
<td>0.073</td>
<td>Yes</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>-10°C</td>
<td>165°C</td>
<td>90 µm/m-°C</td>
<td>0.01%</td>
<td>0.128</td>
<td>Work in progress</td>
</tr>
</tbody>
</table>

- **SnO₂** as conductive layer, **Al₂O₃** as emission layer
- **Tin (II) cyclic stannylene** – Gordon group Harvard
  - 30 Torr at 60°C
  - Reacts readily with hydrogen peroxide
  - **ALD window 50-150°C**
  - Conductive
  - Compatible with TMA
Outline

- Arradiance and the Microchannel Plate Amplifier (MCP)
- Motivation I & II
- Theory behind proposed device
- ALD/Film Requirements for Plastic MCP
- SnO₂ ALD Results
- Plastic MCP Beam line Results
  - Efficiency
  - Timing
- From the lab to the field
SnO$_2$ ALD

For further discussion of ALD characteristics of this precursor system see talks given by Roy Gordon ALD 2010 and Adam Hock ALD 2010
Properties vs Aspect Ratio

- Nanolaminate structure of SnO$_2$ and Al$_2$O$_3$
- Deposition temp 85°C

Gradient of film thickness for current process
Likely resistivity gradient as well
Goal: flatten this curve, then create MCP devices
Plastic substrate MCP (alternative material)

- Reasonable gain for electron amplification, limited by L:D
- Uniform response
- Stable operation
- ALD at higher temperatures (limits plastic choices)
Outline

- Arradiance and the Microchannel Plate Amplifier (MCP)
- Motivation I & II
- Theory behind proposed device
- ALD/Film Requirements for Plastic MCP
- SnO₂ ALD Results
- Plastic MCP Beam line Results
  - Efficiency
  - Timing
- From the lab to the field
Detector Hardware Experimental Setup

- 2 & 5 mm polymer MCP, ~50 µm pores, 20 µm walls, 5° bias angle
- Installed above a chevron stack of 50:1 L/D MCPs
- Phosphor screen readout
- Canberra preamp and postamplifier

Diagram showing:
- H-rich MCP
- Pb-glass MCP Chevron
- Plastic MCP under test
- MCP chevron
- Phosphor screen
- Readout

© 2010 Arradiance® Corporation. All rights reserved.
Neutron detection simulation

\[ P_{\text{detection}} = P_1 \times P_2 \times P_3 \]

- \( P_1 \) – n-p recoil within the MCP substrate
- \( P_2 \) – proton escape into MCP pore
- \( P_3 \) – electron avalanche is formed (MCP ~1)

\[ P_1 \times P_2 \times P_3 = \sim 1\% \] for 2MeV neutrons with 20\( \mu \)m pore walls
Efficiency Results: UNH Beam Line

Isotope sources:
- Placed 6” from detector
- Stilbene scintillator with a single channel PMT (UNH) for calibration
- Cf-252, Am-241/Be (n, γ)
- Cs-137, Co-60, Am-241 (γ)

Cf-252 Neutron Detection Efficiency

Face-on
n QE = 0.747%

Edge-on
n QE = 2.46%

Measured neutron efficiency matches theoretical (0.8%) Low dark counts (dark count ~0.3 c/cm²/s)

Gamma only source

<table>
<thead>
<tr>
<th>γ-energy</th>
<th>Face-on</th>
<th>Edge-on</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.122 MeV</td>
<td>0.15%</td>
<td>0.33%</td>
</tr>
<tr>
<td>0.661 MeV</td>
<td>0.6%</td>
<td>1.5%</td>
</tr>
<tr>
<td>~1.2 MeV</td>
<td>1.3%</td>
<td>2.87%</td>
</tr>
</tbody>
</table>

Gamma energy (MeV) vs. QE
- QE, face-on
- QE, edge-on
Outline

- Arradiance and the Microchannel Plate Amplifier (MCP)
- Motivation I & II
- Theory behind proposed device
- ALD/Film Requirements for Plastic MCP
- SnO₂ ALD Results
- Plastic MCP Beam line Results
  - Efficiency
  - Timing
- From the lab to the field
Experiment Summary

- Using 2 detectors offset and some distance apart
- Measure events in Arradiance and commercial detectors
- Gamma or neutron signal detected by Arradiance starts acquisition window and timer for scintillator
- Time-of-flight is calculated for each event
- Statistics collected on each TOF and analyzed
Coincidence gamma rejection plus timing through TOF

Gamma travel at speed of light – detection in two detectors should happen within ~1 ns

Recoil neutrons arrive with a delay dT to detector2

Temporal Resolution
~3-4 ns

Nanosecond resolution = differentiation between incoming gamma and fast neutron radiation
Outline

- Arradiance and the Microchannel Plate Amplifier (MCP)
- Motivation I & II
- Theory behind proposed device
- ALD/Film Requirements for Plastic MCP
- SnO₂ ALD Results
- Plastic MCP Beam line Results
  - Efficiency
  - Timing
- From the lab to the field
Creating a usable detector that can compete

Combining multiple 50mm plastic MCPs QE goes up

With 10 planes QE is ~60%

In coincidence mode ~10%
Coincidence techniques can differentiate Gammas and Neutrons

Combining coincidence with the high efficiency cube yields a state-of-the-art detector

- Provides directionality
- Provides discrimination between neutrons and gammas
- Is sensitive to a large energy range of neutrons and less sensitive to low energy background gammas (not shown)

- Compares favorably with liquid scintillator technology

Package of Multiple 50mm³ Detection Cubes

3 x 3 x 3 cube array in an aluminum enclosure
Directionality of source in all spatial dimensions
Acknowledgements

- Dr. James M. Ryan, Professor of Physics, University of New Hampshire
- Mr. Jason S. Legere, Research Project Engineer III Space Science Center, University of New Hampshire
- Dr. Richard Lanza, Senior Research Scientist, MIT Dept. of Nuclear Science and Engineering
- Dr. Gordon Kohse, Ph.D; Principal Research Engineer, MIT Nuclear Reactor Laboratory
- The rest of the Arradiance Team
- DOE LAPPD Collaboration
- NASA SBIR NNX10CD59P
Background
Neutron detection simulation: proton recoil - P1

PMMA \((C_5-O_2-H_8)_n\)

- Monomers / cm\(^3\): \(7.16 \times 10^{21}\)
- H atoms / cm\(^3\): \(5.73 \times 10^{22}\)
- C atoms / cm\(^3\): \(3.58 \times 10^{22}\)
- O atoms / cm\(^3\): \(1.43 \times 10^{22}\)

Cross section of neutron interaction

\[ P = [1 - \exp(-N_i \sigma_i L)](1-A) \]

- 50 µm circular pores, 20 µm walls, 1.19 g/cm\(^3\)
D-T Source (Thermo 320) Experimental Setup

Polyethylene shielding around the source

Filters: Lead (2”), polyethylene (1”, 2”), borated plastic (1”)

Lead shielding around the detector

MCPs

5 mm PMMA MCP, ~50 µm pores, 20 µm walls, 5° bias angle installed above a chevron stack of 50:1 L/D MCPs

**Technical Specifications**

- Neutron Yield: 1.0E+08 n/s
- Neutron Energy: 14 MeV
- Typical Lifetime: 1,200 hours @ 1x10⁶ n/s
- Pulse Rate: 250 Hz to 20 kHz, continuous
- Duty Factor: 5% to 100%
- Minimum Pulse Width: 5 µsec
- Pulse Rise Time: Less than 1.5 µsec
- Pulse Fall Time: Less than 1.5 µsec
- Maximum Accelerator Voltage: 95 kV
- Beam Current: 60 uamps