Development of GaN Photocathodes for UV Detectors

O.H.W. Siegmund, J. Vallerga, J. McPhate, J. Malloy, A. Tremsin
Experimental Astrophysics Group,
Space Sciences Laboratory, U. California at Berkeley

M. Ulmer, B. Wessels,
Northwestern University

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Photocathode Overview

**Semi-transparent cathodes** (thin film on entrance window) are commonly used in the visible/NIR (night vision, etc).

**Opaque cathodes** are often used in the UV (astronomy) and usually deposited onto microchannel plates.

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>Wavelength</th>
<th>QE</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI (alkali halides)</td>
<td>10-150 nm</td>
<td>high</td>
<td>Somewhat stable in dry air</td>
</tr>
<tr>
<td>CsTe/RbTe</td>
<td>100-300 nm</td>
<td>modest</td>
<td>Ultra high vacuum (UHV)</td>
</tr>
<tr>
<td>Multi-alkali (Na/K/Sb/Cs)</td>
<td>200-900 nm</td>
<td>modest</td>
<td>UHV (Red cathodes cooled)</td>
</tr>
<tr>
<td>GaAs</td>
<td>400-900 nm</td>
<td>good</td>
<td>UHV, cooled for low background</td>
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</table>
Alkali Halide UV Photocathodes have improved substantially as a result of better fabrication techniques.

CsI Photocathodes - MCP substrate, opaque mode, photon counting. Background rate is negligible for CsI.

CsTe Photocathodes - are used in the 100-300nm region. Need to be in windowed sealed tubes - no air exposure.

CsTe semitransparent photocathodes, diode mode or MCP - photon counting. Background rate is negligible for CsTe.
Visible & NIR Photocathodes

S20/S25 cathodes, and GaAs are used in the 200nm to 900nm region. Ambient noise is high, needs cooling (-20°C) to get <100 cnts/sec. All need sealed tubes and cannot be exposed to air without destruction.

Multi-alkali semi-transparent diode mode photocathodes (commercial)

GaAs wafer, diode mode photocathodes (ITT-NV)
Prospective GaN Photocathodes

- “Solar blind” efficient cathode for 100nm-400nm
- Band gap energy 3.5 eV, (~355nm)
- Alloys (Al\textsubscript{x}Ga\textsubscript{1-x}N, In\textsubscript{x}Ga\textsubscript{1-x}N) can change the bandgap
- Robust, compatible with sapphire substrates
- p (Mg) doped to promote bulk electron transport
- NEA can be established by surface cesiation
- 100nm to 1\(\mu\)m GaN layers are suitable

Numerous processes affect the QE
GaN Photocathode test samples

- NWU by MOVPE (Chemical vapor deposition)
- SVT associates by MBE (molecular beam epitaxy).
- Thin layer of AlN between the substrate and bulk material,
- Mg (p) doped to levels $\sim 10^{17} \text{ cm}^{-3}$.

GaN coated 2” sapphire wafer (SVT) diced to produce test samples.
### GaN Photocathode test samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Source</th>
<th>Thickness</th>
<th>Resistivity</th>
<th>Hole Conc’</th>
<th>Mobility</th>
<th>Polish</th>
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<tbody>
<tr>
<td>2702</td>
<td>SVT</td>
<td>0.1um</td>
<td>8.65</td>
<td>7.22E+16</td>
<td>10</td>
<td>double</td>
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<tr>
<td>2704</td>
<td>SVT</td>
<td>0.1um</td>
<td>&gt;25</td>
<td>-</td>
<td>-</td>
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<tr>
<td>O202</td>
<td>SVT</td>
<td>0.15um</td>
<td>&gt;25</td>
<td>-</td>
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<tr>
<td>3102</td>
<td>SVT</td>
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<td>2.96</td>
<td>7.80E+16</td>
<td>26.9</td>
<td>double</td>
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<tr>
<td>1602</td>
<td>SVT</td>
<td>0.25 um</td>
<td>1.00E+17</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>BH071</td>
<td>NW</td>
<td>1um</td>
<td>3.64</td>
<td>1-2E17</td>
<td>10</td>
<td>front</td>
</tr>
<tr>
<td>BH091</td>
<td>NW</td>
<td>0.1um</td>
<td>9.44</td>
<td>1.21E+17</td>
<td>5.48</td>
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<tr>
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<td>7.78</td>
<td>1.81E+17</td>
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<td>front</td>
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<tr>
<td>JG219</td>
<td>NW</td>
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<td>2.8</td>
<td>2.20E+17</td>
<td>10</td>
<td>front</td>
</tr>
<tr>
<td>JG220</td>
<td>NW</td>
<td>1um</td>
<td>2.7</td>
<td>2.30E+17</td>
<td>10</td>
<td>front</td>
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<tr>
<td>JG238</td>
<td>NW</td>
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<td>2.93</td>
<td>1.83E+17</td>
<td>11.7</td>
<td>front</td>
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<tr>
<td>JG243</td>
<td>NW</td>
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<tr>
<td>BH184</td>
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<td>BH190</td>
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<td>16.3</td>
<td>5.32E+17</td>
<td>0.697</td>
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<tr>
<td>BH195</td>
<td>NW</td>
<td>0.68</td>
<td>? High resistivity</td>
<td>?</td>
<td>?</td>
<td>single</td>
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<tr>
<td>BH196</td>
<td>NW</td>
<td>0.9</td>
<td>? High resistivity</td>
<td>?</td>
<td>?</td>
<td>double</td>
</tr>
<tr>
<td>BH197</td>
<td>NW</td>
<td>0.2</td>
<td>? High resistivity</td>
<td>?</td>
<td>?</td>
<td>double</td>
</tr>
<tr>
<td>BH044</td>
<td>NW</td>
<td>0.5</td>
<td>? High resistivity</td>
<td>?</td>
<td>InGaN</td>
<td>single</td>
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<tr>
<td>BH045</td>
<td>NW</td>
<td>0.5</td>
<td>? High resistivity</td>
<td>?</td>
<td>InGaN</td>
<td>single</td>
</tr>
</tbody>
</table>

*Beaune 2005*
GaN Cathode Processing

The process necessary for good GaN cathodes is typical of III-V materials to achieve NEA:

1. Aggressive chemical cleaning of the samples
2. A general vacuum bake process (10^-10 torr regime)
3. High temperature bake of the sample to eliminate all contaminants
4. Activation by deposition of Cs onto the GaN while monitoring the photo-response

At Berkeley:
- Up to 4 samples processed simultaneously
- QE measured v.s. wavelength and angle
- Both opaque and semitransparent modes
Progress with GaN UV Photocathodes

- Early tests showed poor QE with Cs activation - except at short wavelength.
- Cutoff is quite sharp at 370-390nm.
- Initial sealed photodiode tubes were better QE, and showed no degradation over > 6 months.
- Improvements in processing increase the QE substantially at >200nm.
- ~40% QE for < 250nm is much better than CsI or CsTe.

Development of opaque GaN photocathodes on sapphire substrates, with Cs activation

Ulmer et al 2001

Early sealed tube, MgF₂ window

JG238 early attempt

JG238/T/TT samples 2003

Quantum Detection Efficiency vs Wavelength (nm)
• Samples with similar composition processed by different groups give similar characteristics.

• The same samples processed with differing cleaning and activation techniques give significantly different QE results.

• Preliminary data indicates that the surface conditions (NEA) are more important than the bulk material properties. Many very different samples (Thick/thin, CVD/MBE) give similar results with the same process run conditions.

• Semitransparent mode QEs are generally lower (1% - 10%) and peak at the longer wavelengths.
GaN Opaque Cathode QE Results

Processing of many samples shows that better surface activation improves the long wavelength response.

The short wavelength response is good, and is affected less by the surface conditions.

Ultimately QE “plateau” of ~50% should be possible, with short wavelength QEs >60%.

Initial InGaN performance is worse than GaN, and has a less well defined long wavelength cutoff.

Various process runs and samples of opaque GaN photocathodes on sapphire.
The GaN QE above the 380nm edge is important for “solar blind” instrument designs.

Measurements were made on several samples using lasers and emission lines.

QE of $10^{-5}$ at 500nm is a good leakage level for many uses.

QEs above 550nm are upper limits.

Various process runs on samples of opaque GaN photocathodes on sapphire processed at Berkeley.
GaN is a robust material with good handling properties.

Samples have been fully re-cleaned and reprocessed many times with no reduction in the QE reached.

GaN sample in sealed tube has not changed in QE measurably in over three years.

Exposure to pressures of $10^{-7}$ torr for about one day do reduce the QE by 30% at 200nm, and a factor of 10 at 350nm. This strongly suggests surface NEA impairment.
GaN Photocathode Stability

Cesiated GaN QE is remarkably robust to high pressure exposure and can be partially restored by vacuum bakeout.

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Red - original
Blue - $10^{-7}$ torr for ~1 day

Relative degradation of cesiated GaN samples before and after exposure to 700 torr nitrogen (!) and a 250C vacuum bakeout.
GaN Sealed Tube Prospects

• Prior sealed tubes are opaque GaN only.

• Sealed tubes are a good tool to make long term detailed measurements.

• Modified design shown here has a window at both ends, (MgF₂ and Al₂O₃) allowing semitransparent and opaque mode QEs to be measured v.s. angle and wavelength.

• We are selecting GaN samples and making a series of tubes

Double window sealed tube device for sample evaluation in opaque and semitransparent modes
GaN cathodes for MCP Sensors

- Microchannel plate imaging tubes could be made with semi-transparent GaN or opaque.
- A key issue is determination of the GaN background event rate.
- A processed GaN was installed above an MCP detector. GaN photoemission was assessed by turning an input bias on and off.
- GaN + MCP detects UV in semitransparent mode with good pulse height and gain.
- GaN “event” background is less than a few events/sec, which is comparable with MCP intrinsic background.
Plans for GaN Cathode Development

- GaN offers high >100nm QE & cutoffs from 330nm to 450nm
- More stable/robust than CsTe, also with higher QE.
- GaN has low background, and can be repeatably activated

Test Plan
- Sample work to determine the best surface activation and bulk properties will continue
- Double windowed GaN sealed tubes will be used to assess best sample processes, and probe angular response
- Initially semi-transparent GaN will be used in MCP image tubes
- GaN can also be deposited on ceramic MCP structures to establish high efficiency opaque cathodes for imaging
END