Record-level quantum efficiency from a high polarization strained GaAs/GaAsP superlattice photocathode with Distributed Bragg Reflector

Wei Liu$^{1,2,3}$

Shukui Zhang, Matt Poelker, Marcy Stutzman
Jefferson Lab
Yiqiao Chen, Wentao Lu, Aaron Moy
SVT Associates
# Existing polarized photocathodes

<table>
<thead>
<tr>
<th>Structure</th>
<th>P (%)</th>
<th>QE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk GaAs</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>GaAs/GaAsP (strained well)</td>
<td>92</td>
<td>1.2</td>
</tr>
<tr>
<td>GaAs/GaAsP (strained compensated)</td>
<td>92</td>
<td>1.6</td>
</tr>
<tr>
<td>InGaAs/AlGaAs</td>
<td>77</td>
<td>0.7</td>
</tr>
<tr>
<td>AllInGaAs/GaAs</td>
<td>91</td>
<td>0.5</td>
</tr>
<tr>
<td>AllInGaAs/AlGaAs (with DBR)</td>
<td>92</td>
<td>0.85</td>
</tr>
<tr>
<td>AllInGaAs/GaAsP (with DBR)</td>
<td>92</td>
<td>0.6</td>
</tr>
</tbody>
</table>

These QE values support sustained beam delivery at ~ uA levels.
High Current Electron Accelerators

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>P</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>eRHIC</td>
<td>75%</td>
<td>10 to 50 mA</td>
</tr>
<tr>
<td>Polarized positrons at CEBAF</td>
<td>90%</td>
<td>1 mA+</td>
</tr>
</tbody>
</table>

- Polarized electron beams at mA current will enable new physics experiments and new capabilities
- Most of the incident drive laser light simply heats the photocathode – photocathode cooling required, this is complicated at high voltage
- High polarization photocathodes with QE ~ 10% desired: simplify gun design, reduce requirements on drive laser, prolong operating lifetime
- Bulk GaAs has very high QE but low polarization
- Solution: High polarization photocathode with Distributed Bragg Reflector

* See talk by Joe Grames
Benefits of DBR

- non-DBR Photocathode: absorption in the GaAs/GaAsP superlattice < 5%
- Most light passes into the substrate and leads to unwanted heat
- DBR photocathode: absorption in the GaAs/GaAsP superlattice > 20%
- Less light is required to make required beam, less light means less heat
Schematic structure of photocathodes

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Thickness</th>
<th>Refractive Index</th>
<th>Phosphorus Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>5 nm</td>
<td>p=5E19 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>GaAs/GaAsP&lt;sub&gt;SL&lt;/sub&gt;</td>
<td>(3.8/2.8 nm) ×14</td>
<td>p=5E17 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>GaAsP&lt;sub&gt;0.35&lt;/sub&gt;</td>
<td>2750 nm</td>
<td>p=5E18 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>Graded GaAsP&lt;sub&gt;x&lt;/sub&gt; (x = 0~0.35)</td>
<td>5000 nm</td>
<td>p=5E18 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>GaAs buffer</td>
<td>200 nm</td>
<td>p=2E18 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>p-GaAs substrate (p&gt;1E18 cm⁻³)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Non-DBR Photocathode

<table>
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<tr>
<th>Layer Type</th>
<th>Thickness</th>
<th>Refractive Index</th>
<th>Phosphorus Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>5 nm</td>
<td>p=5E19 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>GaAs/GaAsP&lt;sub&gt;SL&lt;/sub&gt;</td>
<td>(3.8/2.8 nm) ×14</td>
<td>p=5E17 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>GaAsP&lt;sub&gt;0.35&lt;/sub&gt; spacer</td>
<td>750 nm</td>
<td>p=5E18 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>GaAsP&lt;sub&gt;0.35&lt;/sub&gt;/ AlAsP&lt;sub&gt;0.4&lt;/sub&gt; DBR</td>
<td>(54/64 nm) ×12</td>
<td>p=5E18 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>GaAsP&lt;sub&gt;0.35&lt;/sub&gt;</td>
<td>2000 nm</td>
<td>p=5E18 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>Graded GaAsP&lt;sub&gt;x&lt;/sub&gt; (x = 0~0.35)</td>
<td>5000 nm</td>
<td>p=5E18 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>GaAs buffer</td>
<td>200 nm</td>
<td>p=2E18 cm⁻³</td>
<td></td>
</tr>
<tr>
<td>p-GaAs substrate (p&gt;1E18 cm⁻³)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DBR photocathode

Phosphorus content influences the refractive index of each layer, and therefore the **optical path length** which is the key design consideration for this type of photocathode.
Energy level of strained GaAs/GaAsP superlattice

Heavy hole-Light hole splitting: $\delta \approx 0.24x - 0.02x^2$

High $\delta \rightarrow$ High initial polarization, wide high polarization range

$x = 0.35, \delta = 81.6\, meV$

This part of the photocathode design was set in 2004, reported at PESP2004 (part of SPIN2004)
Design of the DBR photocathode

To get high reflectivity for DBR:

\[ n_H(\lambda_{DBR})d_H = \frac{\lambda_{DBR}}{4} = n_L(\lambda_{DBR})d_L \]

To get high absorption for photocathode:

\[ 2 \sum_{i} n_i d_i = m\lambda_R \quad (m: \text{integer}) \]

Precise control the optical path length of each layer!!!
Calculation for absorption of photocathode

Transfer matrix method:

\[
M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = J_{m-1 \rightarrow m} F_{m-1} \cdots F_2 J_{1 \rightarrow 2} F_1 J_{0 \rightarrow 1} \\
\begin{bmatrix}
  k_i + 1 + k_i \\
  2k_{i+1} \\
  k_{i+1} - k_i \\
  2k_{i+1}
\end{bmatrix} \begin{bmatrix}
  k_i + 1 - k_i \\
  2k_{i+1} \\
  k_{i+1} + k_i \\
  2k_{i+1}
\end{bmatrix}
\]

\[
F_i = \begin{bmatrix} e^{ik_i d_i} & 0 \\ 0 & e^{-ik_i d_i} \end{bmatrix}
\]

Reflectivity, Transmission and absorption:

\[
R = \left| -\frac{M_{21}}{M_{22}} \right|^2
\]

\[
T = \left| M_{11} - \frac{M_{12} M_{21}}{M_{22}} \right|^2 \cdot \frac{n_m}{n_0}
\]

\[
A = 1 - R - T
\]
Surface reflection of GaAsP/AlAsP DBR

More pair layers, higher reflection.

For 12 pair layers: highest reflection is 93.2%

Surface reflection of DBR at different numbers of pair layers (n)
Calculation results for DBR photocathode

At 776 nm:

- Absorption: 21.03%
- QE: 6.4%
- Enhancement: 7.4

\[
QE(\lambda) = \frac{P_L F_L A}{\sum} + \frac{P_G \exp[k(-1.42 - \frac{\lambda}{1240})]A}{1 + \frac{1}{\alpha L_G}} [F_G]
\]

Calculated absorption, reflectivity and transmittance of the DBR photocathode, QE for the DBR photocathode, the absorption and QE enhancement factors compared to the photocathode without the DBR.
Experiment results

At 776 nm:

- For non-DBR: QE - 0.89% and Polarization - 92%
- For DBR: QE - 6.4% and Polarization - 84%
- QE Enhancement: 7.2, very close to predicted

(a) The QE and polarization for the strained GaAs/GaAsP superlattice photocathodes with and without DBR as a function of the wavelength; (b) Reflectivity and QE enhancement factor of photocathode with DBR as a function of the wavelength.
## Figure of merit of polarized electron sources

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Ref.</th>
<th>P(%)</th>
<th>QE (%)</th>
<th>Figures of Merit (P^2QE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs/GaAsP(_{0.36}) (no DBR)</td>
<td>SLAC/SVT</td>
<td>86</td>
<td>1.2</td>
<td>0.89</td>
</tr>
<tr>
<td>GaAs/GaAsP(_{0.38}) (no DBR)</td>
<td>Nagoya</td>
<td>92</td>
<td>1.6</td>
<td>1.35</td>
</tr>
<tr>
<td>Al(<em>{0.19})In(</em>{0.2})GaAs/Al(_{0.4})GaAs (with DBR)</td>
<td>St. Petersburg</td>
<td>92</td>
<td>0.85</td>
<td>0.72</td>
</tr>
<tr>
<td>GaAs/GaAsP(_{0.35}) (with DBR)</td>
<td>JLab/SVT</td>
<td>84</td>
<td>6.4</td>
<td>4.52</td>
</tr>
</tbody>
</table>

- The good result comes from precise control of many layers - the biggest challenge!
- Accurate modeling is necessary and very helpful.
Conclusions

- Strained GaAs/GaAsP superlattice photocathodes with DBR show dramatic QE enhancement of 7x, polarization over 84%.
- Further work to tune the wavelength and increase the value of QE peak is going on. Expect higher values at SPIN2018!
- DBR photocathodes will be used to produce high current polarized electron beams soon in CEBAF
Thanks for your attention
apparatus
Schematic of the experiment apparatus

- Load-lock bellows
- Stalk with heater
- GaAs
- Deflector
- Source chamber
- Incident laser
- Transport lenses
- Mott chamber
- Gold Mott target
Results shown in IPAC 2015