Photoemission Properties of LaB$_6$ and CeB$_6$ Under Various Temperature and Incident Photon Energy Conditions


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Outline

• Background
• Research object
• Experimental setup
• Results and Discussion
• Summary
Requirement for photocathodes

High QE  Long lifetime  Low cost

Material that satisfy ALL of these requirements has not been found yet.

Comparison of photocathode characteristics.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Semiconductor (GaAs with Cs layer)</th>
<th>Metal compound (LaB$_6$ (100) ※2,3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Efficiency</td>
<td>&gt; 10 % (with 3.5 eV laser)</td>
<td>&lt; 0.1% (with 3.5 eV laser)</td>
</tr>
<tr>
<td>(room temperature)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work function</td>
<td>≤1.4 eV</td>
<td>2.66 eV</td>
</tr>
<tr>
<td>Lifetime</td>
<td>&lt; 20h@10$^{-9}$ Torr</td>
<td>$10^3$h@10$^{-9}$ Torr</td>
</tr>
</tbody>
</table>

※1 K.Uhchida et al., IPAC (2014) MOPRI032
※2 S. Garrbe, phys. stat. sol. (a) 2, 497 (1970)
※4 D. Satoh et al., PASJ (2013) 540-543
To improve property of photocathode materials, in previous researches:

**Lifetime improvement of Semiconductor.**

- **GaAs**\(^1\):  
  Deposition of \(\text{Cs} - \text{Te} \) film on the surface.  
  → Lifetime improvement with keeping the QE high is intended.

**QE improvement of thermionic cathode materials.**

- **LaB\(_6\)**\(^2\):  
  By heating, cathode surface is cleaned and it prevents the QE drop.  
  → Temperature dependence of QE has also been observed.
- Iridium – Cerium compound:  
  With new methods, new compound Ir\(_5\)Ce\(^3\) has been developed for photocathode.  
  → High QE(0.27% @266nm), long lifetime (>>1000h,LaB\(_6\)) and lower vacuum requirement (~10\(^{-8}\)Torr) accomplished.

\(^1\) K. Uhchida et al., IPAC (2014) MOPR1032  
\(^3\) D. Satoh et al., PASJ (2013) 540-543
Approach for photocathode improvement

Metal hexaboride thermionic cathode have **low work function** and **long lifetime** → Preferable thermionic cathode materials for photocathode use.

**Additional electron excitation by heating** the cathode is assumable to be one of the ways to **improve the QE of them**

- Number of electrons which can be extracted by a given wavelength of laser will increase.
- Thermally excited electrons can be extracted by **laser with lower photon energy than the work function**.
Objective

Acquire a basic knowledge on:
The photoemission properties of metal hexaboride materials over various laser wavelength and temperature and feasibility of QE improvement by Assistance of Thermal Excitation for further applications.

LaB$_6$ and CeB$_6$ are used as photocathodes with 266, 355, 532 nm lasers under wide range of temperature.
Experimental setup

<table>
<thead>
<tr>
<th>Repetition Rate (Hz)</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse width (ns)</td>
<td>4-6</td>
</tr>
</tbody>
</table>

Nanosecond YAG Laser
Continuum® SL II-10
532 nm or 355 nm

For 266 nm
(convert from 532 nm)

Mirrors
Focusing lens
BBO crystal

Flipper mirror
Laser power meter
Iris diaphragm
Shutter
Radiation Thermometer

Vacuum Chamber
(5~10 × 10^-8 Torr)

Cathode
(D=1.72 mm)
Anode
with holes

Fused Silica Window
Current Measurement

- Heating the thermionic cathode cause DC current.
- It is required to distinguish DC thermionic current and Pulsed photoemission current.

**Equivalent Circuit**

Photoemission pulse current is measured by oscilloscope with AC coupling.

**Typical Waveform**

LaB$_6$, 355 nm, $\sim$ 1400 K
Definition of QE in this study

With our experimental setup, it is difficult to discuss the absolute value of QE:
• Laser didn’t perfectly overlap on the cathode
• Polarization of laser was not measured and controlled.
• Calibration of measurement system has not been done precisely.

→ For relative QE comparison, we used:

\[
\eta = \frac{\text{number of electrons detected}}{\text{number of incident photons}}
\]

that resembles to the external quantum efficiency.

Calculations were done by

\[
\eta = \frac{C/e}{P_L/E_P}
\]

\( C: \text{Photoemission charge} \) [C]

\( e: \text{elementary charge} \) [C]

\( P_L: \text{Laser Power} \) [J]

\( E_P: \text{Photon Energy} \) [J]
Comparison between $\text{LaB}_6$ and $\text{CeB}_6$

LaB$_6$ has better performance than CeB$_6$ as photocathode with thermal excitation.

- Difference: Richardson constant.
  - $\text{LaB}_6$ has larger number of electrons which are thermally excited, at the same Tc.
- Life time comparison is required for further application of those materials for accelerator.

### Properties for LaB$_6$ and CeB$_6$.

<table>
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<tr>
<th>Properties</th>
<th>LaB$_6$</th>
<th>CeB$_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work function(eV)</td>
<td>2.66</td>
<td>2.59</td>
</tr>
<tr>
<td>Richardson constant (A/cm$^2$/K$^2$)</td>
<td>29</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Feasibility test of photoelectron emission by 532 nm laser (2.3 eV < $\phi$ 2.65 eV)

Tendency of Photo electron emission of the two materials

 ✓ Measurable photoemission current appeared at higher temperature.
 ✓ About one order of magnitude of QE improvement observed by heating up the cathode for both the materials.
→ With the assistance of thermal excitation, photoelectron emission by 532 nm laser (2.3 eV < $\phi$ 2.65 eV) is feasible.

\[ \eta = \frac{\text{number of electrons detected}}{\text{number of incident photons}} \]
Photoemission by laser with photon energy $< \phi$

One possible reason for photoemission by laser under $\phi$ is multi photon excitation. \[ \text{Prob}_2 \propto \text{Pulse energy}^2 \]

Prob$_2$ : Probability of 2 photon excitation.

It has linear dependence. ↓ Single photon excitation with the assistance of thermal excitation is dominant.

Laser pulse energy dependence of photoemission from CeB$_6$ @532 nm

- $I= P^3/2500$
- $I= P^2/1200$
- $I= P/55$

T$_c$ $\sim$ 1400 K

3 lines: Linear, Square, Cubic
For practical use

Assistance of thermal excitation is effective but: 
*Thermionic emission current is not negligible at higher temperature.*

Practical condition for applications:
✓ High photoemission current with negligible thermionic current.

✓ QE measurement under more higher temperature are required for evaluating the availability of LaB$_6$ photocathode with 532 nm laser incidence.

![Graph showing Photo/Thermal emission current comparison of LaB$_6$ @32.5μJ, 532 nm.](graph.png)
Temperature Dependence of Photoemission Current from $\text{LaB}_6$ for Higher Photon Energy Case

- Photoemission currents depend on the cathode temperature.
- QE improvement effect is larger for 355 nm case than that for 266 nm.
Comparison of Photoelectron Yields of $\text{LaB}_6$ under Various Temperature and Photon Energy

Effect of QE Improvement by Thermal Excitation
$266 \text{ nm} < 355 \text{ nm} < 532 \text{ nm}$

Quantum Efficiency
$532 \text{ nm} < 355 \text{ nm} < 266 \text{ nm}$

Thermal excitation can contribute to increase the quantum efficiency. For some applications, dark current due to thermionic emission must be considered.

$\eta = \frac{\text{number of electrons detected}}{\text{number of incident photons}}$
Summary

• The photoemission properties of LaB$_6$ and CeB$_6$ were compared.

• LaB$_6$ has higher photoemission than CeB$_6$ at the same heating temperature.

• Photoemission with 3 different incident laser wavelengths (266, 355, 532nm) under various temperature was examined.

• Longer wavelength had stronger dependence of QE on temperature.

• With increasing photon energy, lower the dependence on cathode temperature was observed.

• Further research about the comparison of photoemission and thermionic emission current is required for real applications.
References

1. K. Uhchida et al., IPAC (2014) MOPRI032
2. S. Garrbe, phys. stat. sol. (a) 2, 497 (1970)
4. D. Satoh et al., PASJ (2013) 540-543