Surface-Engineered Photocathode for Tunable Photoemissive Properties

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Program

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   • Theoretical Model

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   • Diffraction
   • SEM & STM
   • XPS

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   • Work Function
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   • Angular Emission
What is a photocathode?

- Electron source used to exploit the photoelectric effect

### Photocathode Applications

- HEP detectors
- Night vision devices
- Time-resolved spectroscopy
- Ultra-fast electron diffraction
- **Electron sources for photoinjectors**

\[ E_{kin} = h\nu - \Phi \]

- \( \lambda = 700 \text{ nm} \)
  - \( h\nu = 1.77 \text{ eV} \)
  - No \( e^- \)
- \( \lambda = 550 \text{ nm} \)
  - \( h\nu = 2.25 \text{ eV} \)
  - \( E_{kin} = 0.25 \text{ eV} \)
- Potassium, \( \Phi \sim 2.0 \text{ eV} \)
- \( \lambda = 400 \text{ nm} \)
  - \( h\nu = 3.1 \text{ eV} \)
  - \( E_{kin} = 1.1 \text{ eV} \)
Photoemissive Properties of Photocathodes

- The ratio of e- emitted per incident photons is called **Quantum Efficiency (QE)**
- Beam size and collimation is called **Emittance (ε)**

\[
QE = \frac{N_{\text{electrons}}}{N_{\text{photons}}} \times 100\%
\]

- For Cs₂Te:
  - 10 photons, hv = 254 nm
  - 1 photoelectron
  - QE = 10%

- For Ag:
  - 50000 photons, hv = 254 nm
  - 1 photoelectron
  - QE = 2 x 10⁻³ %
Photoemissive Properties of Photocathodes

- The ratio of e- emitted per incident photons is called **Quantum Efficiency (QE)**
- Beam size and collimation is called **Emittance ($\varepsilon$)**

\[
\varepsilon^2 = \varepsilon_{sc}^2 + \varepsilon_{int}^2
\]

\[
\varepsilon_{int,||} = \varepsilon_{int,x} \varepsilon_{int,y}
\]

1D intrinsic emittance

\[
\varepsilon_{int,x} = \frac{1}{mc} \sigma_x \sigma_{p_x} = \frac{\hbar}{mc} \sigma_x \sigma_{k_x}
\]
Figures of Merit of Photocathodes for Photoinjectors

<table>
<thead>
<tr>
<th>Feature</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Efficiency (%)</td>
<td>0.002 (Nb)</td>
<td>15 (Cs$_2$Te)</td>
</tr>
<tr>
<td>Emittance (µm/mm)</td>
<td>0.44 (GaAs)</td>
<td>1.35 (GaN)</td>
</tr>
<tr>
<td>Lifetime in UHV (hrs)</td>
<td>~10$^2$ (Na$_2$KsB)</td>
<td>~10$^4$ (Cu)</td>
</tr>
<tr>
<td>Response Time (ps)</td>
<td>&lt;1 (Cu)</td>
<td>&gt;1 (GaN)</td>
</tr>
</tbody>
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1 Introduction: Theoretical Model

**Multilayer structure:**

- $n$ ML MgO
- 4 ML Ag
- $n$ ML MgO

$n = 1, 2, 3, 4...$

**Model Predictions:**

**Work function [eV]**
- $n=0$ $\Phi = 4.25$
- $n=1$ $\Phi = 3.34$
- $n=2$ $\Phi = 3.08$
- $n=3$ $\Phi = 3.11$

**Emittance @ $E_F$ [$\mu m/mm$]**

\[
\left( \frac{\varepsilon_{n,int}}{\sigma_x} \right) \left[ \frac{\mu m}{mm} \right] = 3.86\sigma_{k_x}[\text{Å}^{-1}] 
\]

- $n=0$ $\varepsilon / \sigma_x \sim 0.58$
- $n=1$ $\varepsilon / \sigma_x \sim 1.16$
- $n=2$ $\varepsilon / \sigma_x \sim 0.06$
- $n=3$ $\varepsilon / \sigma_x \sim 0.06$

Pulsed Laser Deposition at IIT

**Highly tunable deposition parameters:**
- Target to sample distance
- Chamber pressure
- Fluence (Energy/area)

**Resulting in:**
- Highly tunable deposition rate: 
  $<1 \text{ Å/sec}$ to a few nm/sec
- Chemical and physical structure precision 
  (stoichiometry transfer, homoepitaxy)
Ag film growth at various temperatures: Ag/MgO(001)

(a) 25 °C

(b) 102.3 °C

(c) 115 °C

(d) 130 °C

(e) 146.3 °C

(f) 163 °C

(g) 181.2 °C

(h) 200 °C
Ag film growth at various temperatures: Ag/MgO(001)

(a) Coverage per Crystallite Size

Coverage vs Deposition Temperature

(b) Fractional Surface Coverage

Temperature (°C)
Epitaxial Growth of Ultra-Thin Multilayers

MgO(3 ML)/Ag(4 ML)/MgO(3 ML)
Epitaxial Growth of Ultra-Thin Multilayers
MgO(3 ML)/Ag(4 ML)/MgO(3 ML)
XPS shows stages of multilayer growth

- MgO(001) substrate
- 3 ML MgO
- 4ML Ag
- 3 ML MgO
- 40 nm Ag

$\hbar \nu = 1486.6$ eV
PE = 15 eV

Intensity (a.u.) vs. Kinetic Energy (eV)
Tandem KP/Photocurrent-detectort

(a) Turbo pump
   Ion pump
   KP
   UV lamp
   Pico-ammeter & VDC source
   electrode
   sample manipulator
   sample

(b) Tip diameter = 2 mm
    Sub-millimeter sample to tip separation ~ 100 µm

(c) Sample surface
    Reference tip

\[ i(t) = \frac{dQ}{dt} = \Delta V \frac{dC}{dt} \]
\[ \Delta V = V_b + V_{CPD} \]
\[ i_{pp}(V_b) = (V_b + V_{CPD}) \left( \frac{dC}{dt} \right)_{pp} \]
Work Function of measurements: MgO/Ag and Multilayer surfaces

(001) orientation

(111) orientation

Photoemissive Characterization of Multilayers: QE vs WF

QE vs WF of Multilayers $n = 2-4$ ML

* QE(Mg @ 266 nm) $\in (0.01 \%, 0.06 \%)$
Electron refraction: conservation of surface-parallel $k$

Low momentum spread $\rightarrow$ low angular spread $\rightarrow$ low intrinsic emittance

$$E_{int,i} = \frac{\hbar}{mc} \sigma_\parallel \sigma_{k_\parallel}$$
3 Photoemissive Characterization of Multilayers: Emittance

Emittance: Ag/MgO(001) vs Multilayer (001) \( n = 3 \) ML

\[
\epsilon_{n,int} \left[ \frac{\mu m}{mm} \right] = \frac{\hbar}{mc} \sigma_{k_x} = 3.86 \sigma_{k_x} \left[ \AA^{-1} \right]
\]

**Integrated \( I \) vs Wavevector**

\( h\nu = 22 \) eV

- Ag/MgO(001) \( \rightarrow 3.28 \mu m/mm \)
- Multilayer \( n = 3 \) ML \( \rightarrow 4.36 \mu m/mm \)
Summary

• Epitaxial deposition of metallic substrate surfaces: highly controllable roughness with temperature

• Synthesized epitaxial stoichiometric multilayer structures.

• Work Function vs multilayer thickness (decreased with thickness).

• Measured Quantum Efficiency vs multilayer thickness (increased with thickness).

• Limited measurements of Angular Emission show narrowing of momentum dispersion for ML.
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