Theor and Application of Transmission Mode
Metal (Aluminum) Photocathode

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**Motivation**

- **Motivation for metal transmission photocathode**
  - Stability in air
  - Externally producible
  - Robust, long life time.
  - Easy to fabricate

  - **Scientific interest**
    - Ultra fast timing response (~ femto seconds)
1. Reflection / Optical absorption
2. Transport of the excited electron to the surface (electron may lose energy during this process)
3. The escape of the electron across the surface into vacuum.

Ref. SLAC-PUB-13535
Theory: Physics of Photoemission from Transmission Mode Metal Cathodes
- Reflection from the surface / Optical Absorption

- Aluminum is good reflector
- Thickness of Al for transmission mode cathode must be in the order of skin depth.
- Work function of aluminum is 4.08 eV (~303.88 nm)

Skin Depth of Aluminum at 300 nm is 2.6 nm.

\[
\delta = \sqrt{\frac{\rho}{\pi \times f \times \mu}} = \sqrt{\frac{2.65 \times 10^{-8} \, \Omega \cdot m}{\pi \times (9.9931 \times 10^{14} \, \frac{1}{s}) \times (4\pi \times 10^{-7} \, \frac{H}{m}) \times \left(\frac{\Omega}{s}\right)}}
\]

\[
= 2.6 \times 10^{-9} \, m = 2.6\text{nm}
\]

- \(\rho\) = resistivity (\(\Omega\cdot m\))
- \(\mu\) = permeability (\(4\pi\times 10^{-7}\) H/m), note: H = henries = \(\Omega\cdot s\)

http://unitmath.com/um/p/Examples/PulsedPower/SkinDepth.html
Theory: Physics of Photoemission from Transmission Mode Metal Cathodes
- Energy dependence of quantum efficiency

Model simplifications:
- Electron is considered as “free” electron; arbitrary angle distribution independent from $E_{\text{Ph}}$
- Kinetic energy normal to surface is larger than work function
- All other electrons are neglected
Theory: Physics of Photoemission from Transmission Mode Metal Cathodes
- Electron Escape Depth

Thermalization

Potential energy is transferred to kinetic energy

Electron escapes if
- Kinetic (normal to surface) energy is larger than barrier
- Limited tunneling probability for lower kinetic energy

Scattering probability depends (Fermi’s Golden Rule):
- Density of states (occupied and non occupied)
- Matrix element (neglecting energy dependence)

Mean-free path of Al is approximately 15 nm at room temperature


Simplification:
Only electrons within the slice of 1 mean free path length are considered
Approach: *Model development* to predict $\text{QE}(E_{\text{Ph}})$

- **Implementation of Model**
  - Reflection loss / Optical absorption
  - Work function of the metal
  - We are neglecting Schottky effect (e-h interaction)
  - Penetration depth / mean free path
  - Kinetic energy distribution depends on occupied and unoccupied DOS (Fermi Golden Rule)
  - Escape depth – assuming mean free path length

- **Method**
  - Simple model based on three step Spicer model
  - Microscopic theory (Ab-initio) can be easily implemented
  - Allows to correlate transmission and reflection behavior
Approach: *Model development* to predict $\text{QE}(E_{\text{Ph}})$
- Optical Absorption
Approach: Model development to predict QE($E_{ph}$) - Optical Absorption

- How much light will be transmitted through window material:

$$T = \frac{I}{I_0} = 10^{-\alpha l}$$
**Approach: Model development to predict QE(E_{Ph})**

- **Optical Absorption**

\[
A_\lambda = \log_{10} \left( \frac{I_0}{I} \right)
\]

### Optical Properties of Al at \( \lambda = 300 \text{ nm} \)

<table>
<thead>
<tr>
<th>Film thickness (Å)</th>
<th>A %</th>
<th>R %</th>
<th>T %</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>7</td>
<td>19</td>
<td>74</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>43</td>
<td>47</td>
</tr>
<tr>
<td>120</td>
<td>11</td>
<td>62</td>
<td>27</td>
</tr>
<tr>
<td>160</td>
<td>10</td>
<td>74</td>
<td>16</td>
</tr>
<tr>
<td>200</td>
<td>9.4</td>
<td>81.5</td>
<td>9.1</td>
</tr>
<tr>
<td>240</td>
<td>8.9</td>
<td>86.0</td>
<td>5.1</td>
</tr>
<tr>
<td>280</td>
<td>8.5</td>
<td>88.4</td>
<td>3.1</td>
</tr>
<tr>
<td>320</td>
<td>8.2</td>
<td>90.0</td>
<td>1.8</td>
</tr>
<tr>
<td>360</td>
<td>8.1</td>
<td>90.9</td>
<td>1.0</td>
</tr>
<tr>
<td>400</td>
<td>8.1</td>
<td>91.4</td>
<td>0.5</td>
</tr>
<tr>
<td>500</td>
<td>7.9</td>
<td>92.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

How much light will be **absorbed** into metal:
Approach: Model development to predict $\text{QE}(E_{\text{Ph}})$

- Fermi Golden Rule: Optical Absorption

⇒ distribution function for Kinetic energy of the electron

⇒ distribution function can be calculated using Fermi’s Golden Rule

⇒ Influence of materials properties (Density of states)
Approach: Model development to predict QE(EPh) - Electron escape probability

- Electron Escape Probability for given Energy:

\[ \phi < E_{nor}^{\text{kin}} = E^{\text{kin}} \cdot \cos(\alpha) \]

\[ \phi \leq E_{\text{kin}} \cdot \cos \alpha \]

\[ \frac{\phi}{E_{\text{kin}}} < \cos \alpha \]

\[ P[\%] \propto \frac{4 \alpha}{4 \pi} = \frac{\cos^{-1} \left( \frac{\phi}{E_{\text{ph}}} \right)}{\pi} \]

- Simplest model (no materials properties): \( E_{\text{kin}} = E_{\text{ph}} \)

\[ P[\%] \propto \frac{1}{\pi} \cdot \cos^{-1} \left( \frac{\phi}{E_{\text{ph}}} \right) \]
Approach: Model development to predict $\text{QE}(E_{Ph})$
- Absorbed photons within escape length

- Number of absorbed photons within escape depth

$$\frac{\Delta \text{ph}}{I_0} = (e^{-\mu(d-x)} - e^{-\mu d})$$

- Expected $\text{QE}(E_{ph})$

$$\text{QE}(E_{ph}) = \frac{\Delta \text{ph}}{I_0} \cdot P[\%] \propto (e^{-\mu(d-x)} - e^{-\mu d}) \cdot \frac{1}{\pi} \cdot \cos^{-1}\left(\frac{\phi}{E_{ph}}\right)$$

Model parameter can be determined by measurement of cathode with various thicknesses.
Approach: Model development to predict $\text{QE}(E_{ph})$
- Expected $\text{QE}(E_{ph})$

\[ QE(E_{ph}) = \frac{\Delta ph}{I_0} \cdot P[\%] \propto (e^{-\mu(d-x)} - e^{-\mu d}) \cdot \frac{1}{\pi} \cdot \cos^{-1}\left(\frac{\phi}{E_{ph}}\right) \]

Model parameter can be determined by measurement of cathode with various thicknesses

Table 3
Metalic cathodes: $\text{QE} = f(\lambda)$

<table>
<thead>
<tr>
<th>$\lambda$ [nm]</th>
<th>$E$ [eV]</th>
<th>$\text{QE}$</th>
<th>$\phi_s$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>193</td>
<td>6.42</td>
<td>$8.4 \times 10^{-4}$</td>
<td>4.3</td>
</tr>
<tr>
<td>213</td>
<td>5.82</td>
<td>$3.2 \times 10^{-5}$</td>
<td>5.1</td>
</tr>
<tr>
<td>266</td>
<td>4.66</td>
<td>$3.4 \times 10^{-7}$</td>
<td>5.1</td>
</tr>
<tr>
<td>308</td>
<td>4.03</td>
<td>$3.4 \times 10^{-7}$</td>
<td>4.6</td>
</tr>
<tr>
<td>355</td>
<td>3.49</td>
<td>$8.0 \times 10^{-9}$</td>
<td>4.6</td>
</tr>
<tr>
<td>Al</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$1.5 \times 10^{-4}$</td>
<td>4.6</td>
</tr>
<tr>
<td>Cu$^a$</td>
<td>$1.5 \times 10^{-3}$</td>
<td>$4.2 \times 10^{-4}$</td>
<td>4.6</td>
</tr>
<tr>
<td>St steel</td>
<td>$9.0 \times 10^{-5}$</td>
<td>$1.6 \times 10^{-4}$</td>
<td>3.1</td>
</tr>
<tr>
<td>Sm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>$2.7 \times 10^{-6}$</td>
<td>$1.1 \times 10^{-6}$</td>
<td>3.1</td>
</tr>
<tr>
<td>Y$^a$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WK$^a$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Approach: Model development to predict $\text{QE}(E_{\text{ph}})$ - $\text{QE}(E_{\text{ph}})$ Estimation

![Graph showing estimate of QE for different thicknesses of aluminum and incident wavelengths.](image-url)
Approach: Model development to predict $\text{QE}(E_{\text{ph}})$
- $\text{QE}(E_{\text{ph}})$ Estimation

![Diagram of light intensity and reflection](image)

**Estimate of QE (with B33)**

- **Incident 300nm**
- **Incident 275nm**

![Graph showing QE vs. Thickness of Aluminum](image)
Approach: Design and growth of test cathodes

- **Resources:**
  - Sputtered cathode:
    - transport on air/modification of workfunction
  - Thermally evaporated in growth and characterization chamber:
    - continuously in UHV
  - Sample systems
    - Thickness
    - Workfunction

- **Measurement:**
  - Determination of $QE(E)$, $QE(E, \phi)$, $QE(E, d)$
  - Goals:
    - Model verification
    - Determination of escape length $x$
    - Commissioning of optical setup
Conclusions

- Developed experimental plan

- Develop simplified model for QE
  - Only non-scattered electrons are considered
  - Full optical description
  - Functional dependency: \( QE_x(d, E_{ph}, \phi) \)
  - Should work for \( E_{ph} \gg \phi \)
  - Can be generalized including tunneling effects