Theory and Application of Transmission Mode Metal (Aluminum) Photocathode

Seon Woo Lee[1], Klaus Attenkofer[1], Dean Walters[1], Marcel Demarteau[1], Henry Frisch[1,2], Junqi Xie[1], Zikri Yusof[1]

1. Argonne National Laboratory

2. University of Chicago

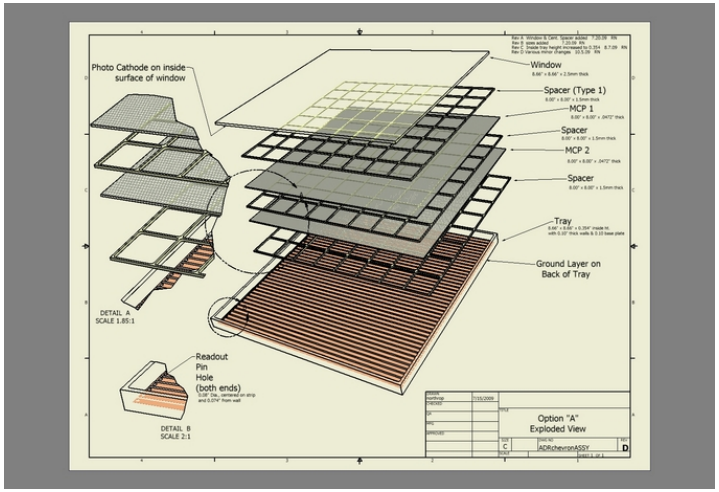
Saturday, June 11, 2011

Contents

- Motivation
- Theory : physics of photoemission from transmission mode metal cathodes
- Approach :
  - Model development to predict QE(E_{Ph})
  - Design and grow of test cathodes to verify QE model
  - Use test cathodes to “calibrate” optical characterization tools
- Conclusion & Future Plan

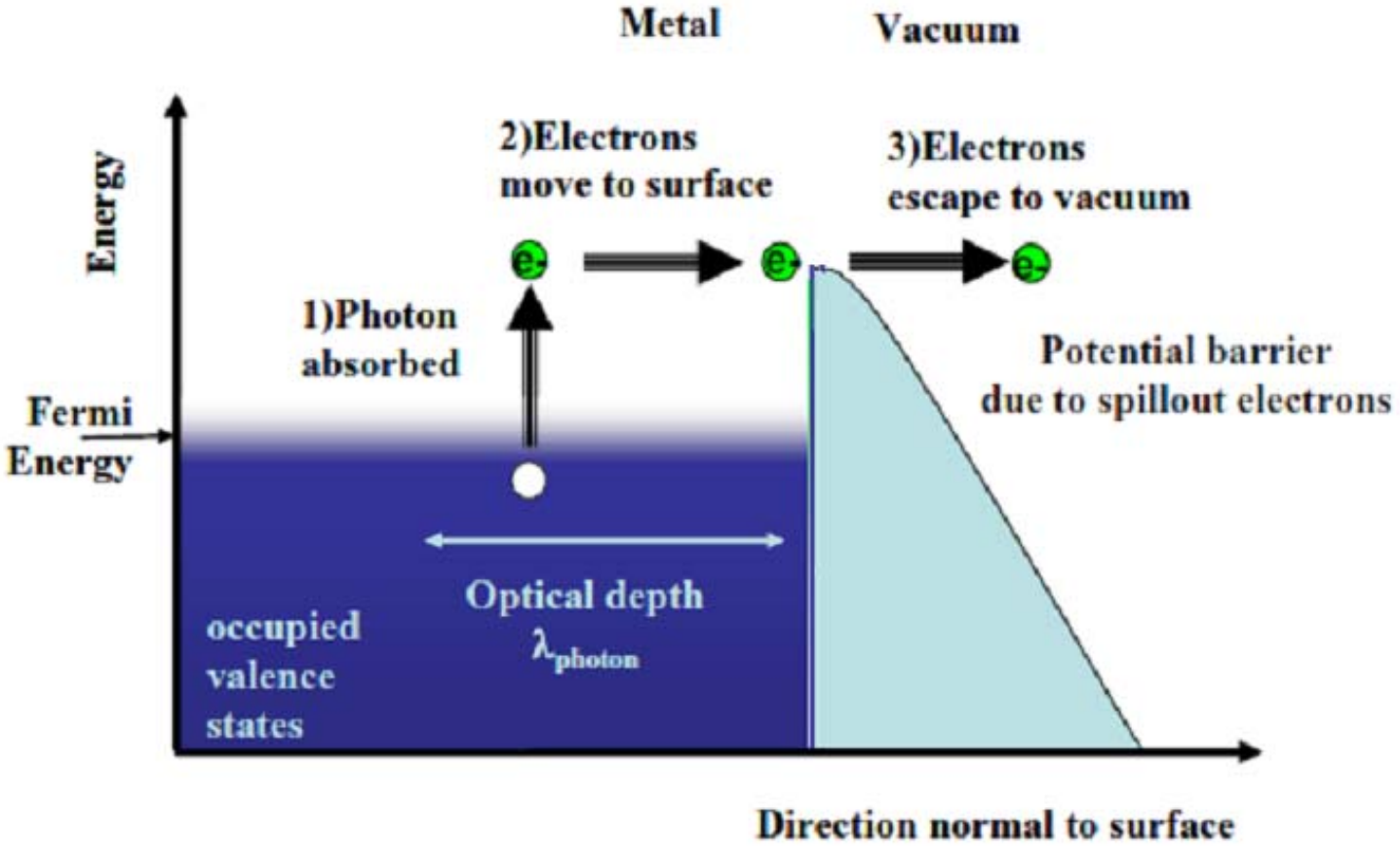
Motivation

- 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)

Theory : Physics of Photoemission from Transmission Mode Metal Cathodes
-The Three-Step Photoemission model



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

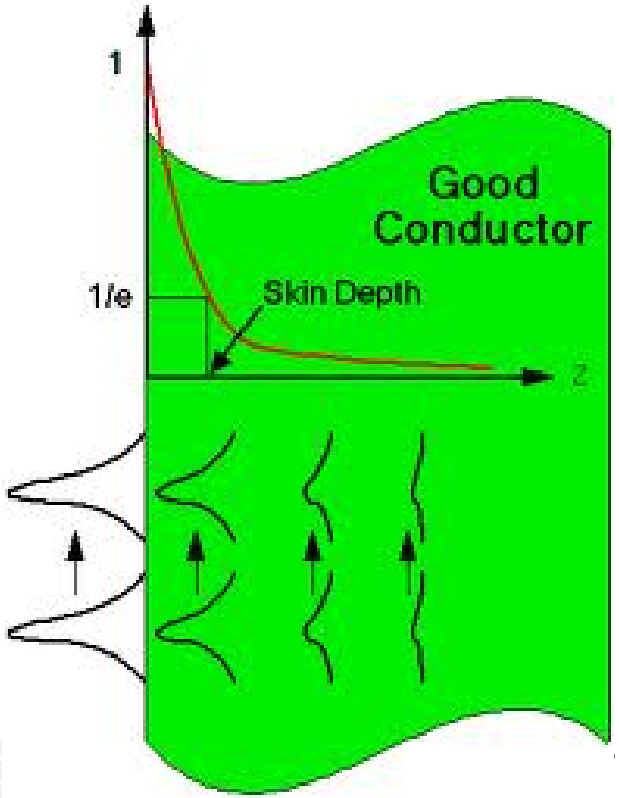
- Aluminum is good reflector
- Thickness of Al for transmission mode cathode must be in the order of skin depth.
- Work function of aluminum is 4.08 eV (~303.88 nm)

Skin Depth of Aluminum at 300 nm is 2.6 nm.

$$\delta = \sqrt{\frac{\rho}{\pi \times f \times \mu}} = \sqrt{\frac{2.65\times10^{-8}\,\Omega\cdot m}{\pi\times(9.9931\times10^{14}\,\frac{1}{s})\times(4\pi\times10^{-7}\,\frac{H}{m})\times(\frac{\Omega s}{H})}}$$

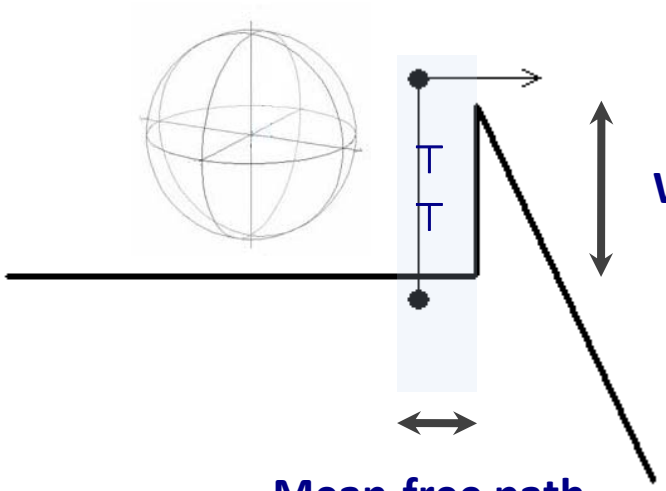
$$= 2.6\times10^{-9}\,m = 2.6nm$$

ρ = resistivity (Ω·m)
μ = permeability ($4\pi*10^{-7}$ H/m), note: H = henries = Ω*s



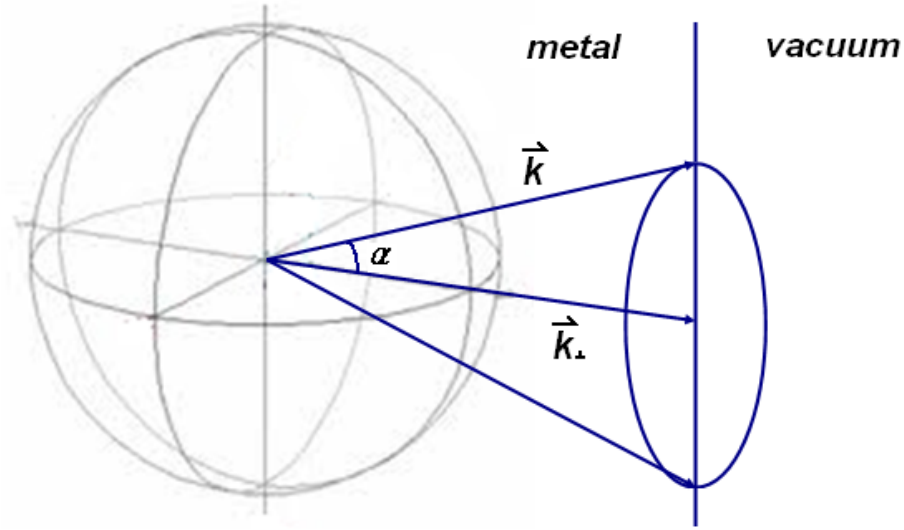
Theory : Physics of Photoemission from Transmission Mode Metal Cathodes

- Energy dependence of quantum efficiency



Work Function

Mean-free path

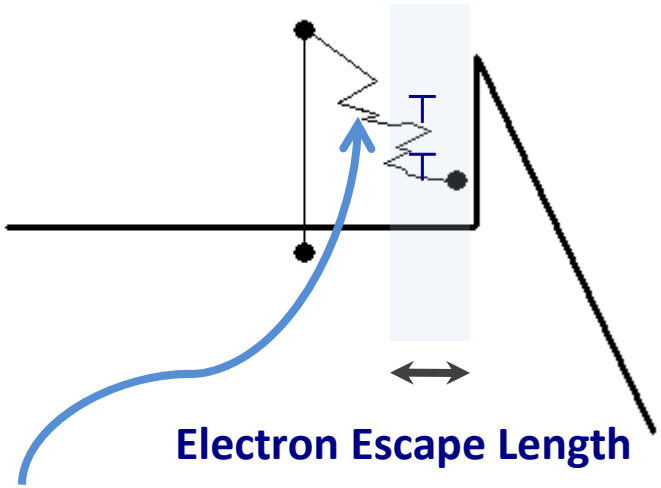


- Escape Probability

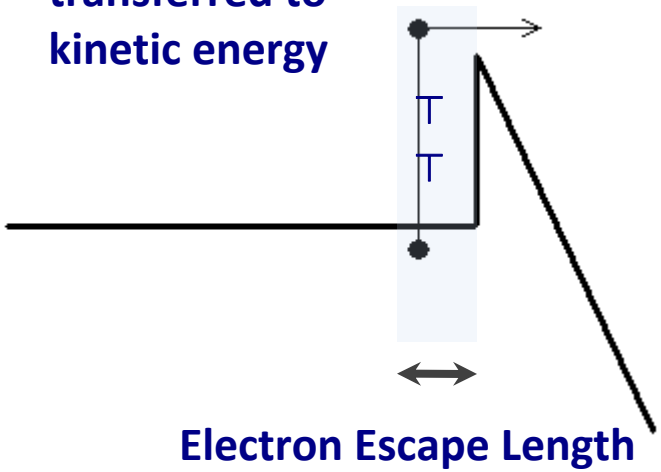
- Model simplifications:
  - Electron is considered as “free” electron; arbitrary angle distribution independent from E_{Ph}
  - Kinetic energy normal to surface is larger than work function
  - All other electrons are neglected

Theory : Physics of Photoemission from Transmission Mode Metal Cathodes - Electron Escape Depth

Thermalization



Potential energy is transferred to kinetic energy



Scattering probability depends (Fermi's Golden Rule):

- Density of states (occupied and non occupied)
- Matrix element (neglecting energy dependence)

Electron escapes if

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

Mean-free path of Al is approximately *15 nm* at room temperature
Thin Solid Films, 121 (1984) 201-216

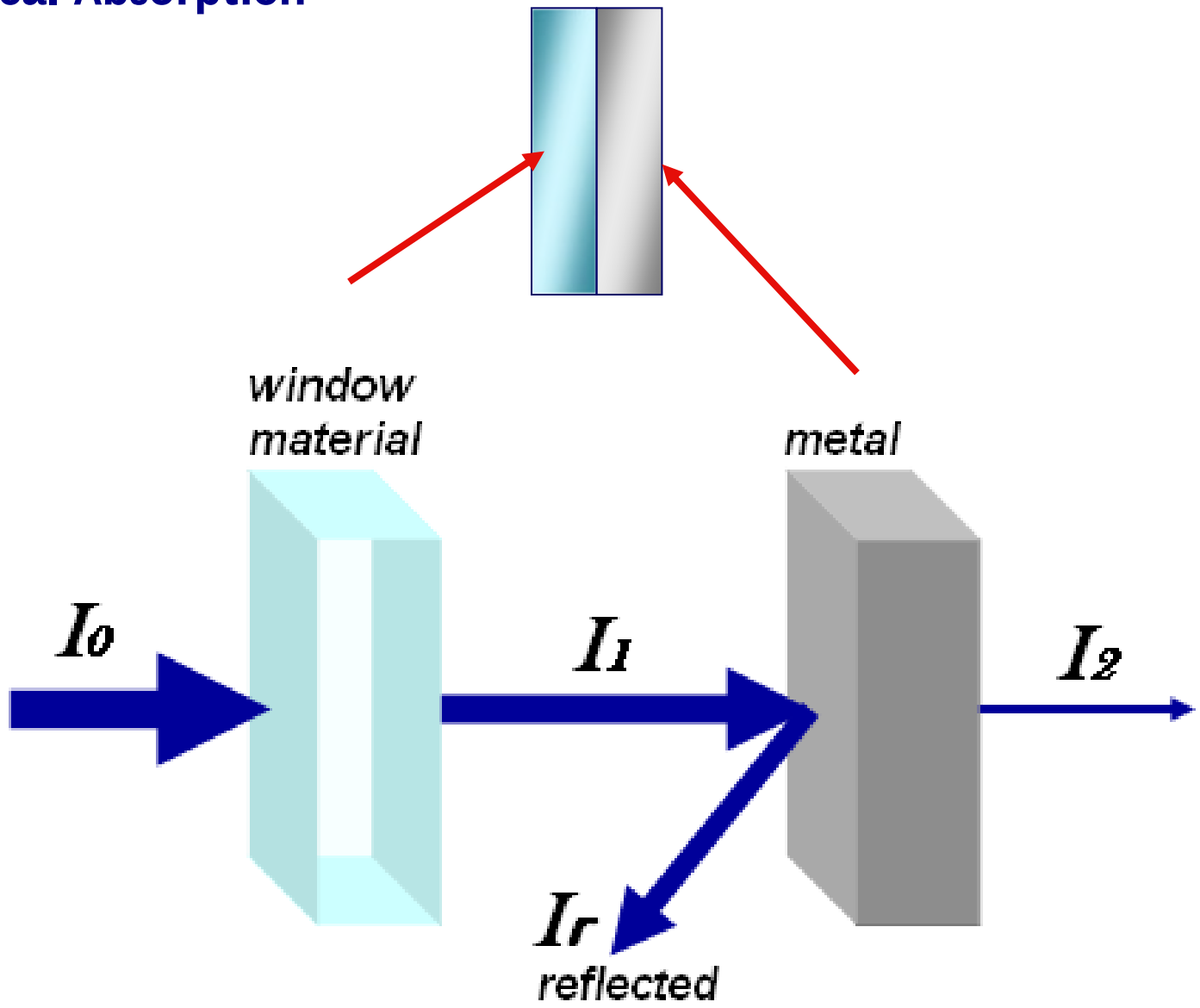
Simplification:
Only electrons within the slice of 1 mean free path length are considered

Approach : *Model development* to predict QE(E_{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

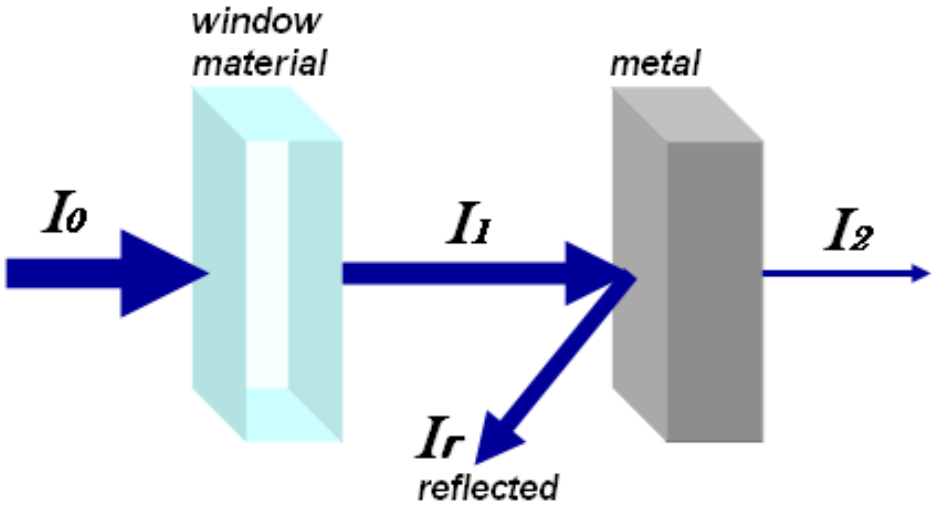
Approach : *Model development* to predict QE(E_{Ph})

- **Optical Absorption**



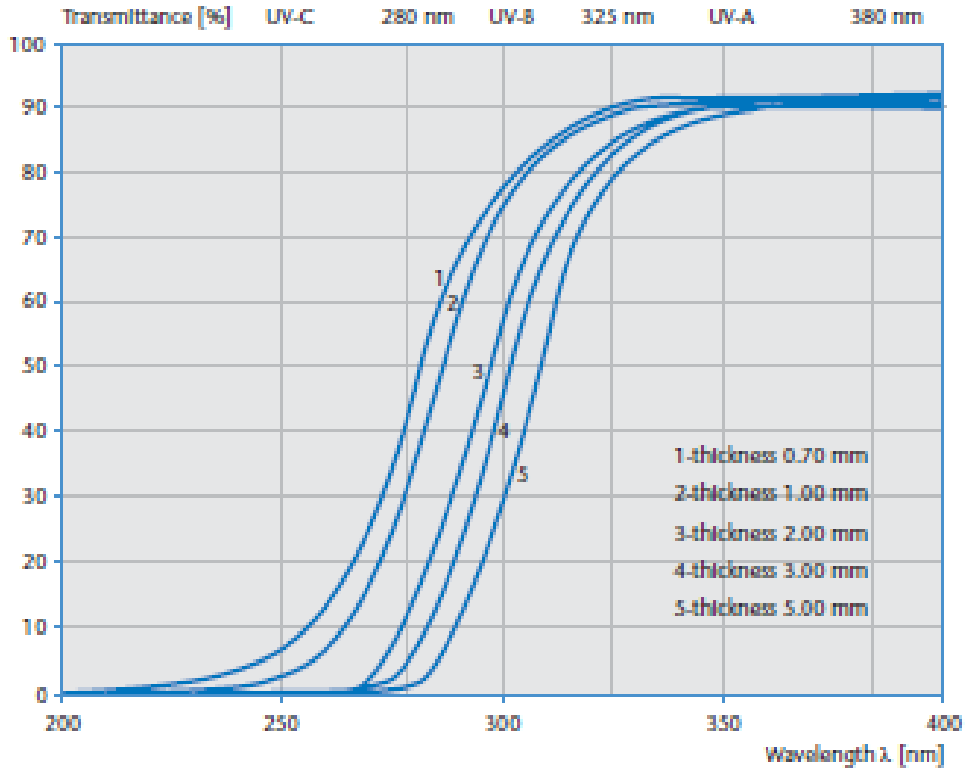
Approach : Model development to predict QE(E_{Ph})

- Optical Absorption



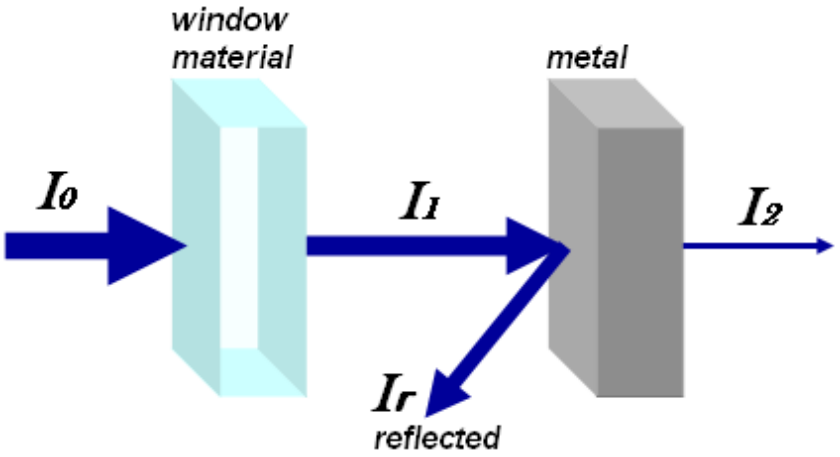
- How much light will be ***transmitted*** through window material :

$$T = \frac{I}{I_0} = 10^{-\alpha \ell}$$



Approach : Model development to predict QE(E_{Ph})

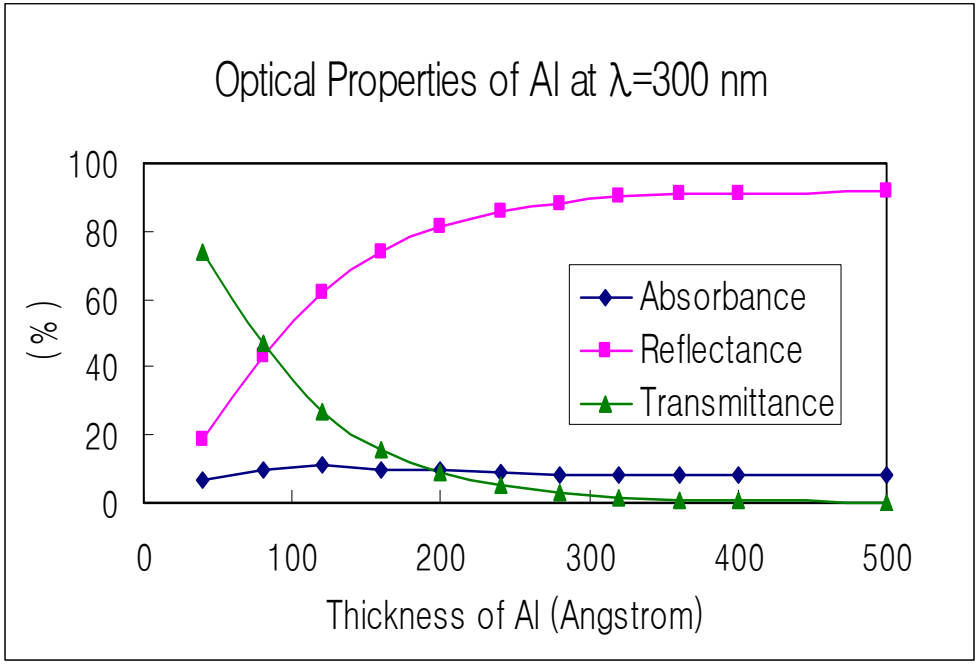
- Optical Absorption



- How much light will be ***absorbed*** into metal:

$$A_\lambda = \log_{10}(I_0 / I)$$

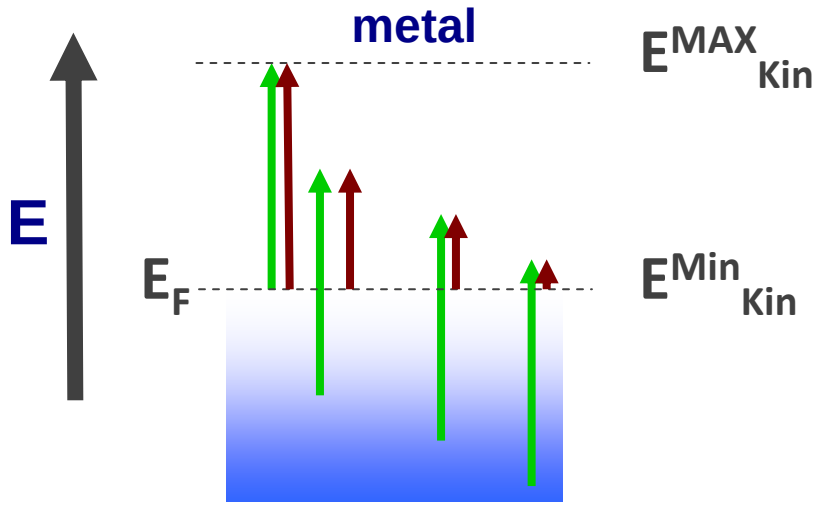
Film thickness (Å)	A %	R %	T %
40	7	19	74
80	10	43	47
120	11	62	27
160	10	74	16
200	9.4	81.5	9.1
240	8.9	86.0	5.1
280	8.5	88.4	3.1
320	8.2	90.0	1.8
360	8.1	90.9	1.0
400	8.1	91.4	0.5
500	7.9	92.0	0.1

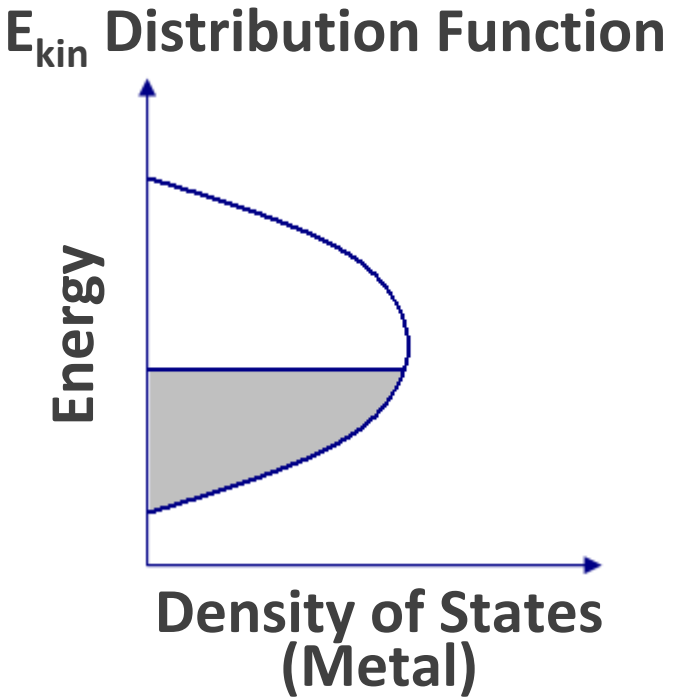


J. Opt. Soc. Am. 51, 7 (1961)

Approach : Model development to predict QE(E_{Ph})

- Fermi Golden Rule: Optical Absorption



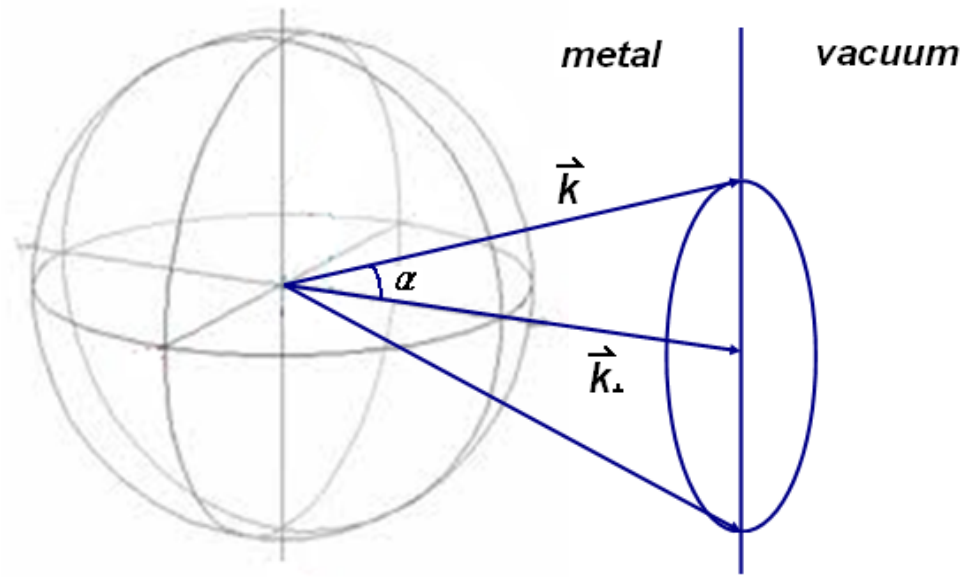


⇒ distribution function for Kinetic energy of the electron

⇒ 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:**

$$\phi < E_{nor}^{kin} = E^{kin} * \cos(\alpha)$$
$$\phi \le E_{kin} \cdot \cos\alpha$$
$$\frac{\phi}{E_{kin}} < \cos\alpha$$

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

- **Simplest model (no materials properties): $E_{kin}=E_{ph}$**

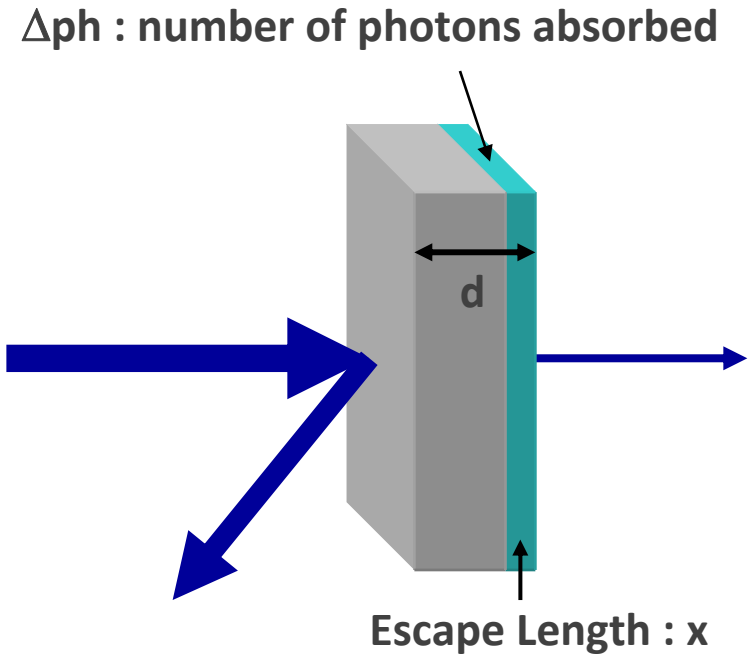
$$P[\%] \propto \frac{1}{\pi} \cdot \cos^{-1}(\frac{\phi}{E_{ph}})$$

Approach : Model development to predict QE(E_{Ph})

- Absorbed photons within escape length

- Number of absorbed photons within escape depth

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



- Expected 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

Approach : Model development to predict QE(E_{Ph})

- Expected QE(E_{ph})

- Expected 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

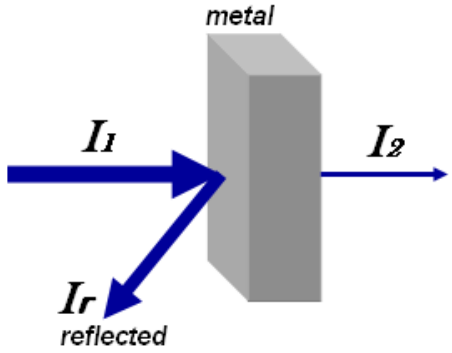
Table 3
Metallic cathodes: QE = $f(\lambda)$

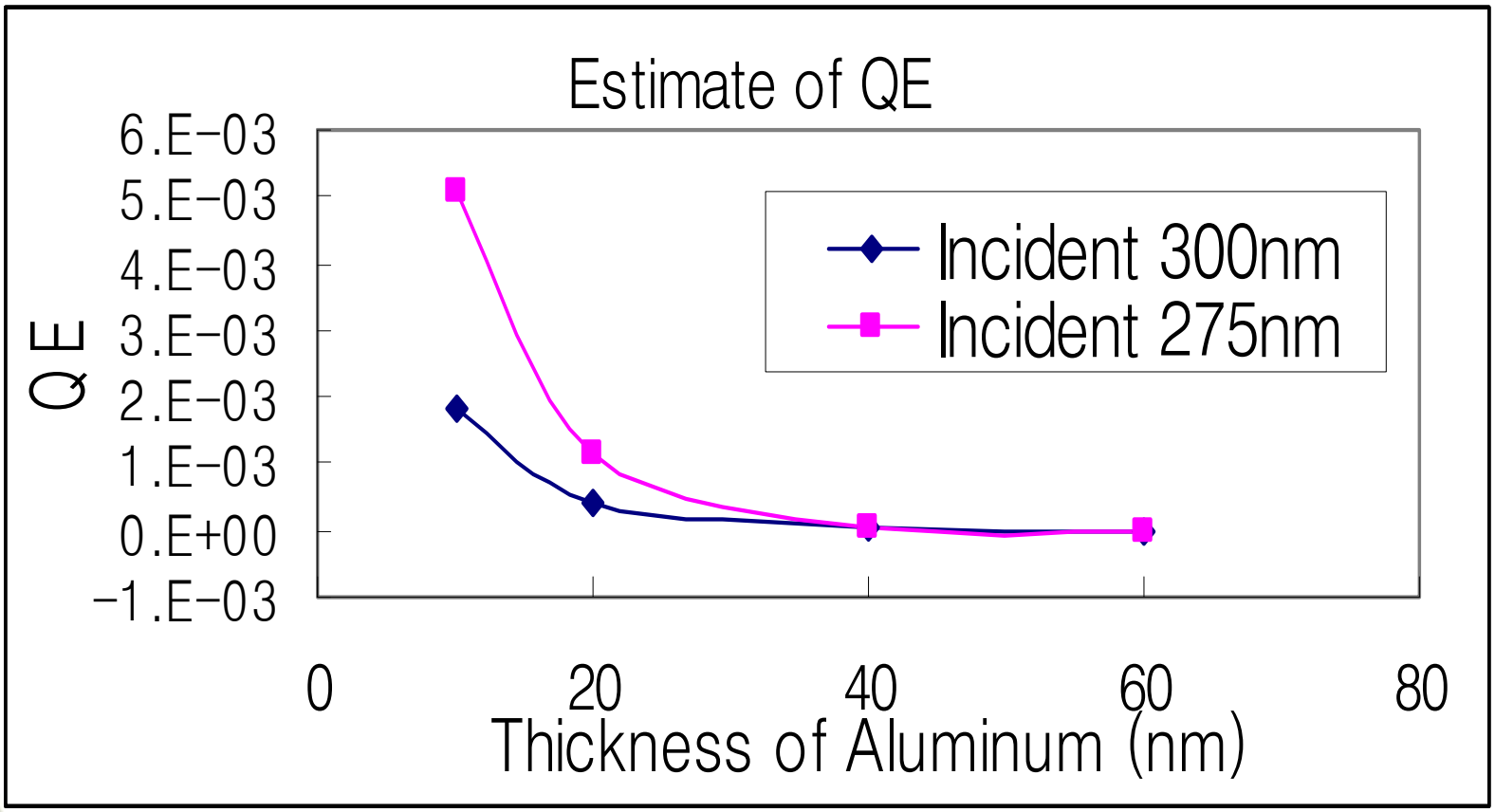
λ [nm]:	193	213	266	308	355	ϕ_s
E [eV]:	6.42	5.82	4.66	4.03	3.49	[eV]
Al		8.4×10^{-4}	3.2×10^{-5}		3.4×10^{-7}	4.3
Au		4.0×10^{-4}	1.3×10^{-5}			5.1
Cu	2.0×10^{-4}	1.5×10^{-4}	2.2×10^{-6}	1.6×10^{-7}	8.0×10^{-9}	4.6
Cu [a]	1.5×10^{-3}	4.2×10^{-4}				4.6
St steel		9.0×10^{-5}	1.6×10^{-4}			
Sm				1.6×10^{-6}		2.7
Y			2.7×10^{-6}	1.1×10^{-6}		3.1
Y [a]			1.8×10^{-4}			3.1
WK [a]				1.2×10^{-5}		2.8

Ref. Nucl. Instrum. Methods A 340, 146 (1994)
Ref. Appl Phys B 98, 839-849 (2010)

Approach : Model development to predict QE(E_{Ph})

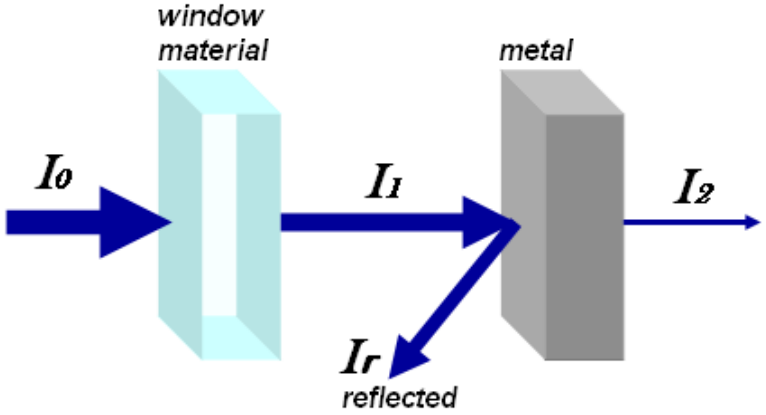
- QE(E_{ph}) Estimation

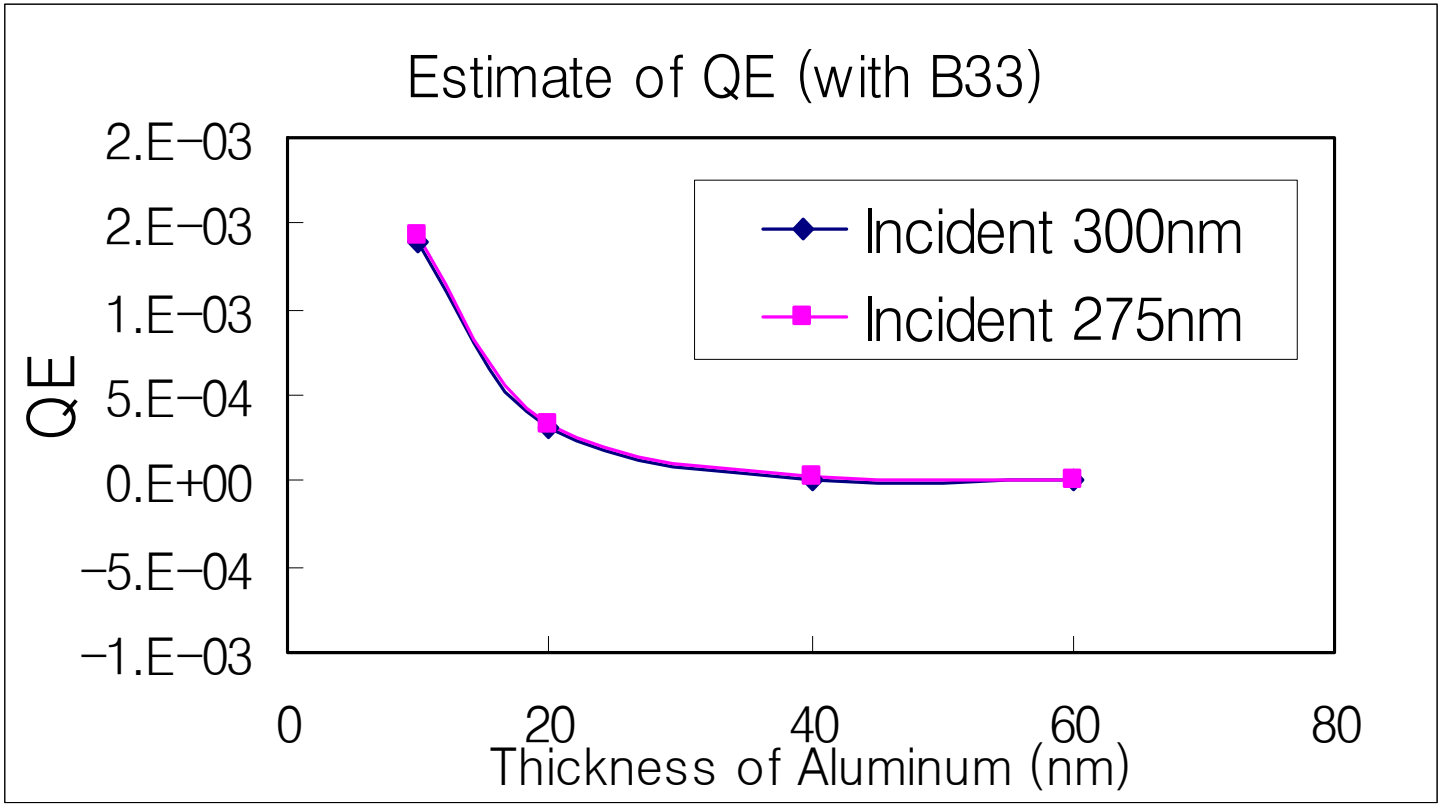




Approach : Model development to predict QE(E_{Ph})

- QE(E_{ph}) Estimation





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, ϕ), 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 $E_{ph} >> \phi$
  - Can be generalized including tunneling effects