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Optimization of Transmission Mode Metallic (Aluminum) Photocathodes

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Abstract

Transmission mode metallic photocathodes are studied, especially for aluminum ones, to test complete 8"x8" large-area planar photodetectors in ambient condition. We have derived a quantitative model for transmission mode metallic photocathodes which permits optimization of the thickness of these cathodes (approximately 15–20 nm) and estimation of quantum efficiency based on the theory and the known parameters from the literatures.

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1. Introduction

Photocathodes are the materials which release electrons through the photoelectric effect when the energy of the absorbed photon is larger than the work function. They are widely used for various applications in radiation detectors, photoinjectors, image intensifying devices, etc. [1–3] There are several fundamental parameters to be considered for high performance photocathodes: high quantum efficiency, fast response time and long operational lifetime. In general semiconductor photocathodes have a higher quantum efficiency, but have a slower response time and require ultra high vacuum condition. In contrast, metal photocathodes have very low quantum efficiency, but have ultra fast timing response in the range of femto seconds. They are often used in the applications which require a robust, easy-to-handle and well characterized electron source and possible to transport them in ambient condition, making this class worthwhile to study in detail. Figure 1 shows the schematic of the cross-section of the 8"x8" large-area photodetector. Borosilicate glass is used as a substrate and photocathodes are deposited inside window materials to absorb photons and emit electrons. Argonne National Laboratory (ANL) has been developing

economical and robust 8”X8” photodetectors for various applications such as medical imaging, astrophysics, particle detection, etc. It is necessary to design and build large-scale growth & assembly vacuum chamber facilities to deposit photocathodes on such a large area window, assemble as a complete device and test the detector’s characteristics. Metallic photocathodes are stable in air, externally producible, easy to fabricate, inexpensive, robust and have a long lifetime. Therefore, metallic photocathodes fulfill most of the requirement to test a 8”X8” large-area photodetector. Mostly metallic photocathodes are used as reflection mode photocathodes. For our application, we use metallic photocathodes in transmission mode. In this paper, we discuss fundamentals of transmission mode aluminum photocathodes. We estimate the optimal thickness and performance of metallic (aluminum) photocathode from the various known physical parameters.

2. Physics of Transmission Mode Metal Photocathodes: Three-Step Photoemission Model

Figure 2 shows the three-step Spicer photoemission model of metal photocathodes [4-7]. The first step is the photo-excitation. There are several factors to be considered in photo-excitation: 1) reflection of the light from the metal surface, 2) penetration depth of the incident light, 3) absorption of incident photons. Aluminum thin film is often used as a very good optical reflector. Initially large portion of the light will be lost by the reflection from the metal surface. The penetration depth is an important property of the material which determines the range of the thickness that light can be absorbed. Penetration depth is dependent on frequency and is significantly reduced at higher frequencies. Electrons are excited when they absorb the energy of the incident photons larger than work function. The second step is the migration to the surface. Photo-excited electrons migrate to the aluminum surface. The mean free path determines how far the electrons can travel and it varies depending on the temperature. While the electrons migrate into the surface, electrons might lose some of their energy due to electron-electron scattering since metal is abundant in electrons. In the third step, the emission, electrons that still have enough kinetic energy after collision process are able to overcome the potential barrier and escape into the vacuum.

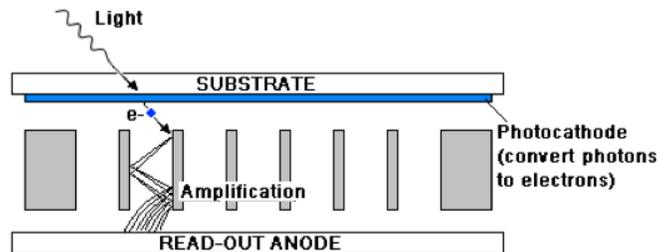


Fig. 1. Schematic of the cross-section of the large-area photodetector. Photocathodes are deposited inside window materials.

3. Estimation of Optimal Thickness of Photocathode and Quantum Efficiency

This section is to get a rough estimation on growth of testable metallic photocathodes for 8”X8” large area photodetector. Here, we discuss which parameters we have considered for quantum efficiency of transmission mode aluminum photocathode. We present the way we get approximate calculation of quantum efficiency based on the parameters that affect overall quantum efficiency.

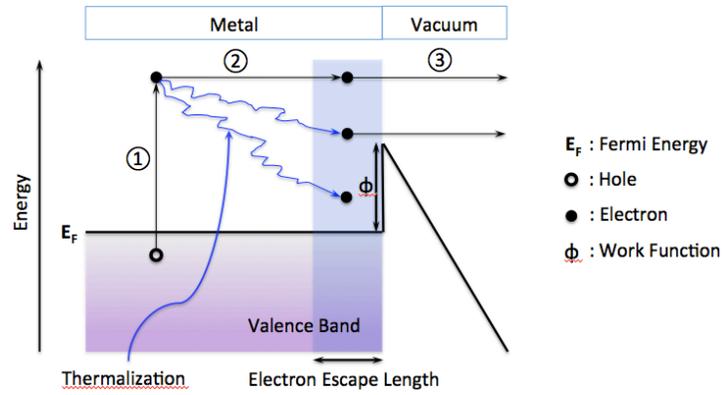


Fig. 2. Three-step photoemission model of metal photocathodes includes: (1) photo-excitation by photon absorption (2) drift of electrons (3) electron emission [4,7]

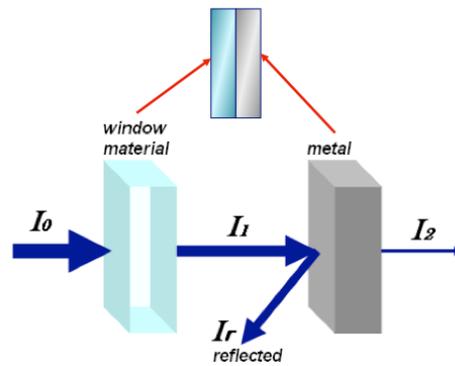


Fig. 4. Quantum efficiency is correlated with transmission through the window material, reflection from the metal surface, optical absorption of aluminum.

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

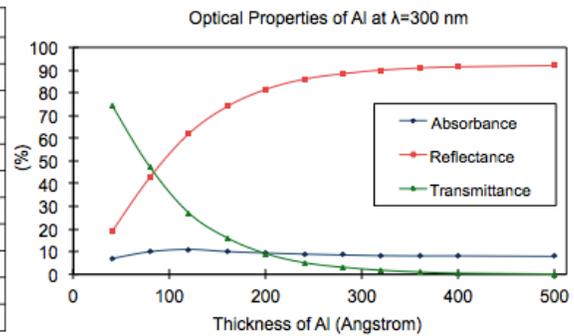


Fig. 3. Optical properties of aluminum [8].

3.1. Transmission / Reflection / Absorption

For the model development to predict the quantum efficiency, reflection losses from the metal surface and optical absorption must be taken into account. Transmission mode metal photocathodes are grown on a transparent window material. In Figure 3, the window material and the metal layer are separated just for clarity when we consider each of the material. There are three things to consider: how much light will be transmitted through window material, how much light will be lost from reflection on the aluminum surface and how much light will be absorbed by the cathode. To estimate the quantum efficiency, we considered borosilicate (B33) glass as a transparent substrate, since it is being used for current large area photodetector development project. It is important to take into account the UV cutoff ranges of each substrate since the incident light must have higher energy than the work function of the photocathodes, that is, wavelengths shorter than 303.88 nm. The UV cutoff ranges vary depending on each substrate and different thickness. Transmittance curves were taken from the product information from the manufacturer to obtain transmission rate for different wavelength of light [11].

The optical properties of aluminum thin film are shown in Figure 4. Aluminum is often used as optical coating to make a good reflector. Reflection loss is a significant factor affecting optical absorption of aluminum. As shown in Figure 4, reflection and transmission of aluminum depends on the thickness. More or less 10% of the incident light is absorbed into aluminum and contributes to optical transition. The absorption rate decreases as reflectance starts to rapidly increase for thicker aluminum film. Maximal absorption occurs around 120 Angstrom.

3.2. Estimation of considerable factors

Work function of the aluminum is 4.08 eV, corresponding to 303.88 nm [9]. Therefore, the wavelength of the incident light must be shorter than 303.88 nm for the electron emission. The amplitude of the incident light decreases by a factor of e^{-1} . Penetration depth δ of aluminum is 2.6 nm at 300 nm. The electrons in the range of the penetration depth will absorb the incident photon energy and contribute to electron emission process. Mean free path is the average distance between two consecutive collisions. The mean free path of aluminum is approximately 15 nm at room temperature [10]. Therefore, the thickness of aluminum for transmission mode photocathode must be of the order of the sum of the penetration depth and mean free path.

3.3. Energy dependency of quantum efficiency

Electrons that absorbed the photon energy scatter inside the materials into all different directions. They will reach to the aluminum surface with every possible angle. Electrons might lose their energy due to electron-electron scattering while they are traveling inside materials. But at the end, the electrons which have wave vector nearly normal to the surface will have kinetic energy larger than work function. Only a small fraction of electrons inside an angular cone that may have momentum close enough perpendicular to the surface will escape into the vacuum. All other electrons out of the angular cone coming with different angle are scattered inside material, not emitted from the surface and not considered for quantum efficiency estimation.

3.4. Electron Escape Probability

Electron escape probability strongly depends on the kinetic energy of electrons when they reach the metal-vacuum interface. Electrons within the penetration depth absorb the photon energy and get photo-excited. Electrons migrate into the surface. Electrons lose energy while they are travelling by collision. The probability to get to the surface without losing energy depends on the mean free path of the material and scattering angle of electrons (Equation (1)). Figure 5 shows the electron momentum distribution depending on the scattering angle. Angular cone will be smaller and smaller when the energy is reduced. The probability of electron emission Everything in the cone has same probability to escape into vacuum as long as their energy is over the work function. α is the maximum possible angle for electrons to escape into vacuum.

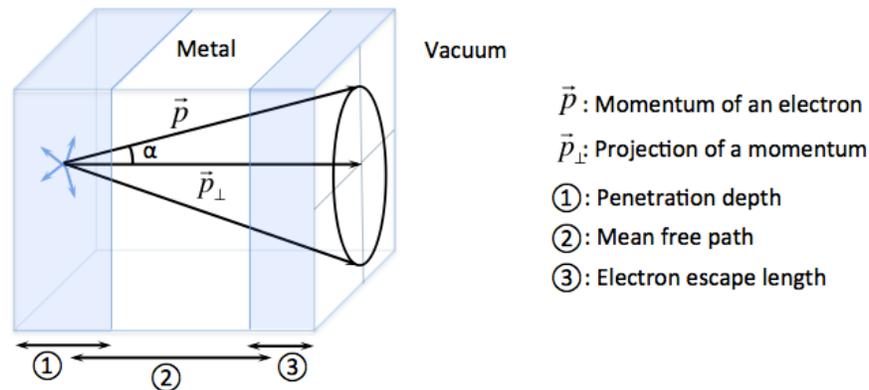


Fig. 5. Electron escape probability depends on the scattering angle [4].

- Electron escape probability for a given energy is proportional to:

$$\phi < E_{\perp}^{kin} = E_{kin} \cdot \cos(\alpha) \tag{1}$$

$$\frac{\phi}{E_{kin}} < \cos(\alpha) \tag{2}$$

$$assume : E_{kin} = E_{ph} \tag{3}$$

$$P(\%) \propto \frac{\pi\alpha^2}{4\pi} = \frac{1}{4} \cdot \left(\cos^{-1} \left(\frac{\phi}{E_{ph}} \right) \right)^2 \tag{4}$$

3.5. Quantum Efficiency Estimation

In the Figure 6, X is the escape length, the region in which we have electron emission, which is an unknown physical parameter. Model parameter can be determined by measurement of cathode with various thicknesses.

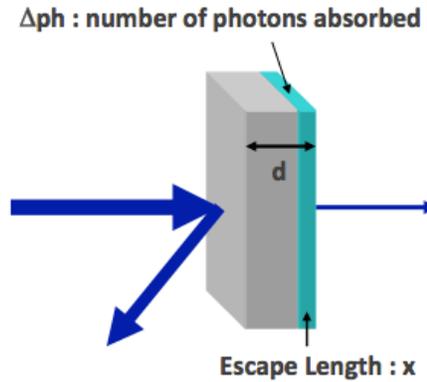


Fig. 6. Absorbed photons within the escape depth

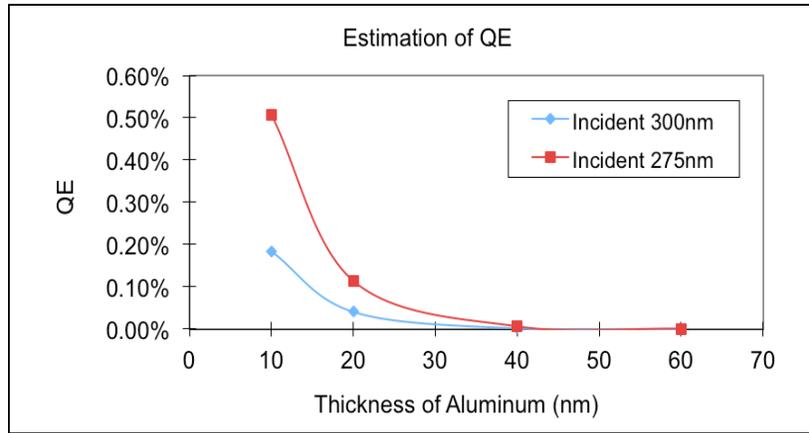
- Number of absorbed photons within escape length:

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

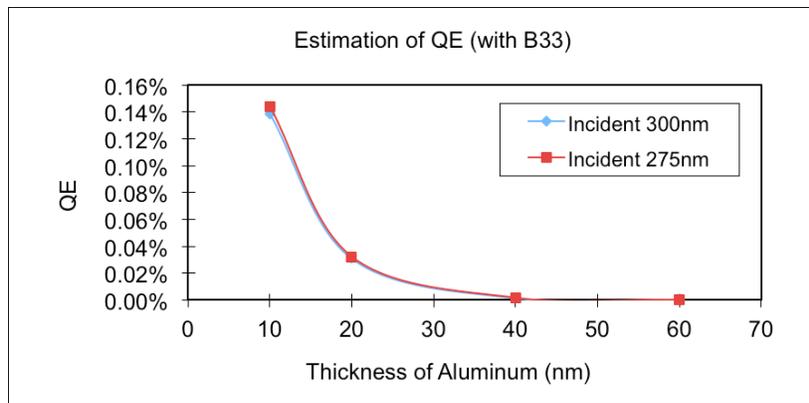
- Expected quantum efficiency $QE(E_{ph})$:

$$QE(E_{ph}) = \frac{\Delta ph}{I_o} \cdot P(\%) \propto (e^{-\mu(d-x)} - e^{-\mu d}) \cdot \frac{1}{4} \cdot \left(\cos^{-1} \left(\frac{\phi}{E_{ph}} \right) \right)^2$$

Quantum efficiency of aluminum is in the order of 10^{-3} to 10^{-5} depending on the thickness. Escape depth can be calculated by inserting quantum efficiency value and solve for unknown parameter. In this paper, quantum efficiency values are taken from the literature [12,13] for two different wavelength. Figure 7(a) is the estimation of quantum efficiency only for the aluminum thin film. Quantum efficiency is higher when incident photons have higher energy. With window material, more light will be lost when incident light has higher energy due to absorption for shorter wavelength of light through window material (Figure 7(b)). We have to comprise those parameters to optimize QE. When we consider penetration depth, mean free path, escape depth and so on, optimized thickness of aluminum photocathode would be approximately 15~20 nm. Thickness below 10 nm is not considered here since thin film may not be formed and there might be broken aluminum islands on the surface.



(a)



(b)

Fig. 7. QE(E_{ph}) estimation (a) for aluminum thin film only (b) for aluminum thin film deposited on the window material .

4. Conclusion

In this paper, we estimate the optimal thickness of the transmission mode aluminum photocathode. After the consideration of various physical parameters, we concluded the optimal thickness would be approximately 15~20 nm. Quantum efficiency would be in the range of 10^{-3} ~ 10^{-4} for the optimal thickness. The result obtained here will be used to fabricate aluminum photocathode on B33 glass to test detectors.

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