JONRA

Journal of Nuclear Research and Applications

Research Paper

Vol. 3, No. 3, P 6-11, Summer (2023)

Cited in: https://jonra.nstri.ir

Received: 27 April 2022, Accepted: 10 August 2022

Improvement of Scintillation Detection System using Plasmonic Aluminum Photocathode

H. Zaki Dizaji*, A. Arabkhorasani, J. Khalilzadeh, Y. Shahamat

Faculty of Science, Imam Hossein University, P. O. Box 16575-347, Tehran, Iran

ABSTRACT

A large category of nuclear radiation detection systems are based on scintillation detectors. One of the most important and effective subsystems in performance of scintillation detectors is photomultiplier tube. Photomultiplier tubes with plasmonic photocathodes increase efficiency and decrease dead time. In this research, in order to improve the efficiency and optical response of the photocathode, the plasmonic phenomenon has been used and a new photocathode has been designed and simulated. By periodic circular nanocavities on the surface of aluminum metal, a structure is presented that by making it possible to pair the incoming light to an electron density wave on the surface, plasmonic intensification is created in the desired wavelength range and the field intensity increases greatly. In this way, the quantum efficiency of the photocathode is improved and the detection efficiency is increased up to 15 times compared to the previous cases.

***Keywords*:** Nuclear detector; Photomultiplier; Photocathode; Quantum efficiency; Plasmonic

1. Introductions

Today, nuclear radiations are present in many aspects of human life and are inevitable. In addition to the advantages and disadvantages of the presence of nuclear radiation, there are some disadvantages and challenges that must be overcome properly. Extensive use of nuclear radiation in various industries, agriculture, health, medicine, etc. It is necessary to pay attention to new methods for measuring radiation-related indicators. Among the many methods, tools, and systems available for detecting and measuring nuclear radiation are scintillation detection systems One of the most important and effective components of the scintillation detector system is the Photomultiplier tube (PMT). The performance indicators and characteristics of the above detection system, such as efficiency, resolution, and dead time depend on the photomultiplier tube. A photomultiplier tube is an optoelectronic device that converts light into measurable current. This device offers very high sensitivity and fast response and is used in various fields of light

---

*. *Corresponding Author name*: H. Zaki Dizaji
E-mail address: kpzaki@ihu.ac.ir

detection, especially for very low intensities [1]. An optical amplifier detector consists of three main parts: a light-sensitive cathode (photocathode), electron amplifiers (dinodes), and an electron collector (anode). When light enters the photocathode and under special conditions, photoelectrons will be emitted from the photocathode. These photoelectrons are moved by the concentrator to the electron amplification system and will be amplified based on the emission of secondary electrons. The amplified electrons are collected by the anode and eventually converted into an output pulse [2].

The most important part of a photomultiplier tube is the photocathode, which affects the performance of the device in terms of quickness and photon sensitivity. Photocathode converts light flux into electron flux based on the photoelectric effect. In a photocathode exposed to light, the electrons are separated from the surface as long as the radiant photons have enough energy to pass through the cathode function. This principle is the basis of creating an electron beam or the phenomenon of electron emission. The phenomenon of electron emission can be divided into three stages: photon absorption, electron transfer to the surface, and crossing the metal-vacuum barrier [3].

In recent years, surface plasmon polaritons (SPPs) have been considered very suitable options for trapping light in nanometer dimensions. By adjusting the properties of surface plasmons, by controlling the geometry of nanostructures, light reflection at selected wavelengths can be greatly reduced and light absorption can be increased [4]. Among different plasmonic nanostructures, plasmonic structures based on aluminum, silver, and gold metals have received much attention due to their unique optical and electronic properties, which are related to the intensification of surface plasmons [5]. Robert et al. in 2010 were able to increase the intensity of light in the active region by 18 times by stimulating plasmons through gold in a photocathode structure [6]. In 2013, Li et al. increased the absorption of light at 800 nm wavelengths by using nanopores in copper [7].

Aluminum is a suitable option for use in nuclear radiation detectors due to the possibility of plasmonic excitation at visible and shorter wavelengths [8].

There are several methods for modeling the interaction between nanostructures and electromagnetic waves, which ultimately lead to solving Maxwell equations in the problem space. Among them, we can mention the computational modeling tool of the Finite-difference time-domain method (FDTD), which is a powerful method for simulating the optical behavior of nanostructures. Finite-difference time-domain methods are powerful engineering tools for simulating different types of optical devices, which are widely used to study nanostructured systems.This technique is able to simulate models of light propagation, scattering, and refraction of light, as well as the effects of reflection and polarization simultaneously and in combination while providing high accuracy and acceptable speed in calculations [9]. The FDTD method was first proposed by Yee and included the spatial and temporal discrete lattice of each of the electric and magnetic field components induced by the Maxwell equations in the Yee cubic cell. Today, the FDTD method is one of the most popular methods for solving electromagnetic problems due to its simple formulations, which has been successfully used in a wide range of applications such as scattering of electromagnetic waves from metals and dielectrics, antennas, integrated circuits and etc [10-11]. In this research, a nanostructured photocathode is presented which has the advantage of fast metal response and improves the performance and efficiency of the metal photocathode. This is done by creating periodic circular nanocavities on the surface of the aluminum metal.

2. Theoretical Foundations

The response of metal to electromagnetic radiation is determined by the complex dielectric function $\varepsilon = \varepsilon' + i\,\varepsilon''$. The real part shows the amount of polarization with the external electrical field and the reduction of the wave phase speed due to the internal polarization effect of the metal, and the imaginary part determines the amount of electrical field attenuation and metal absorption. In general, the study of light propagation in metallic structures is based on accurate modeling of the dielectric function. Wavelength When a light wave lands on the diffraction lattice structure, plasmon surface polaritons are excited at the joint metal-dielectric surface. In this case, the plasmon surface polaritons absorb the incident light and reduce the light reflection. By solving the Maxwell equations, the dispersion relations in the metal-dielectric joint surface as well as in the metal-dielectric-metal layer are calculated and by using those relations, the excitation conditions of plasmon polaritons for the desired structure can be obtained [12-13]. The dispersion relation of the emitted plasmon surface polaritons at the interface between conductor and dielectric is expressed by Eq.(1) [14].

$$\lambda_{SPP} = \lambda_0 \sqrt{\frac{\varepsilon_m + \varepsilon_d}{\varepsilon_m \varepsilon_d}} \tag{1}$$

Where, λ_{spp} is the wavelength of plasmon surface polaritons, λ_0 is the wavelength of the incident light, ε_m is the dielectric constant of the metal and ε_d is the dielectric constant of the non-conductor. Eq. (1) states that the wavelength of the surface plasmon polaritons depends on the dielectric constant of the metal.

Quantum efficiency is an important measure of photocathode performance and is defined as the ratio of output electrons to input photons. This characteristic is described by the three-stage model of absorption, transport, and escape from the surface and is calculated by multiplying the probability of all three stages by each other. The quantum efficiency of a metal photocathode is expressed by Eq.(2)

$$QE(\omega) = F_{e-e}[1 - R(\omega\ \theta)] \times \frac{E_F + \hbar\omega}{2\hbar\omega}\left[1 + \frac{E_F + \emptyset}{E_F + \hbar\omega} - 2\sqrt{\frac{E_F + \emptyset}{E_F + \hbar\omega}}\right] \tag{2}$$

In this relation, E_F is Fermi energy, $R(\omega\ \theta)$ is the surface reflection coefficient depending on the angle of incidence and frequency. Where $\emptyset$ is work function, $\hbar$ is Planck constant, ω is the angular frequency and F_{e-e} is the probability of electron transfer to the surface without scattering with other electrons [15].

Relative quantum efficiency can be used to measure the increase in quantum efficiency of nanostructured surfaces compared to flat surfaces [Eq.(3)] [16].

$$\mathrm{QE_r} = \frac{\mathrm{F_{e-e}^{NgS}}}{\mathrm{F_{e-e}^{FS}}}\left(\frac{1 - \mathrm{R^{NgS}}}{1 - \mathrm{R^{FS}}}\right) \tag{3}$$

One of the factors influencing quantum efficiency is the depth of field penetration in the metal λ_{opt}, which is inversely related to F_{e-e} (Eq. 4) [17].

$$F_{e-e} = \frac{1}{1 + \frac{\lambda_{opt(\omega)}}{\lambda_{e-e}}} \tag{4}$$

If photons are adsorbed on the metal surface, the depth of field penetration decreases and increases F_{e-e}, and ultimately the quantum efficiency increases.

Therefore, using plasmonic structures, incident light can be trapped by surface plasmon plasmons (SPPs) near the metal surface. So as to reduce the depth of field penetration [17].

3. Structure design

One of the methods of stimulating the surface plasmon on the metal surface is to design a network of regular structures with specific dimensions on the metal surface. At certain wavelengths, surface plasmons are intensified and produced depending on the design parameters and metal type. Therefore, in this paper, a network design of circular nanocavities was proposed and created on the surface of aluminum metal. Circular nanocavities on the surface of aluminum metal stimulate the surface plasmon polaritons.

The schematic of the circular nanostructure is shown in Fig.(1-a) and the cross-sectional area of this structure is shown in Fig.(1-b). By adjusting depth(height) of cavities h, width of the cavities W and the periodicity p, the pairing of the input photon wave functions and the surface plasmon is obtained.

Lumerical software based on a finite difference method has been used to analyze the optical behavior of the structure.The periodicity of the proposed structure, periodic boundary conditions are used in the horizontal direction and perfectly matched layer (PML) boundary conditions are used in the vertical direction. To stimulate the structure, a flat wave light source with TM polarization in the wavelength range of 300 to 600 nm was used. In simulating the proposed structure for the dielectric function of aluminum, Palik experimental data are used [18].

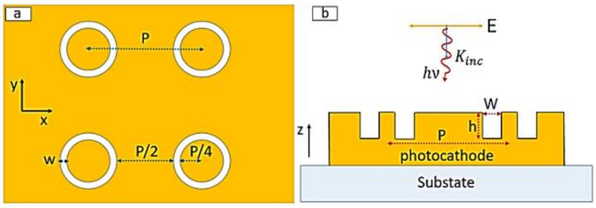

Fig. 1 a. Photocathode scheme consisting of circular nanocavities, **b.** cross-sectional area of a circular nanocavity.

4. Results and Discussion

In this paper, a circular nanocavities structure with a width of 10 nm, a spacing of 400 nm and different heights of 36 to 44 nm is considered in order to compare the spectrum of light reflection and its diagram is shown in Fig.(2). It is observed that the nanostructured surfaces compared to the flat surface, greatly reduce the reflection so that in proportion to the height of the cavity, the spectrum has deep valleys in the range of 400 to 500 nm. As the height of the nono-grooves increases, the resonant wavelength shifts to longer wavelengths.

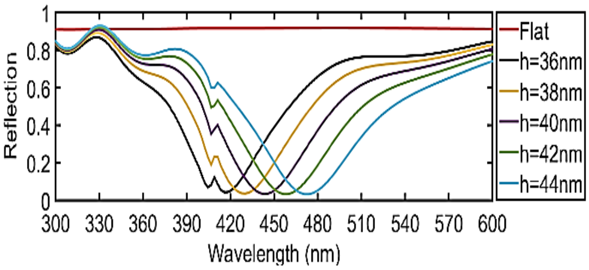

Fig. 2. Reflective response spectrum of Al circular nanocavities with variable cavity height as well as reflection response spectrum of Al metal flat surface.

The electric field density in the circular nanocavitie can be obtained through FDTD simulations. For this purpose, the intensity of the electric field as a sample for h = 40 nm at the resonant wavelength of 441 nm is shown in Figure 3. It can be seen that in grooves and sharp edges, the field density increases significantly, which will lead to maximum absorption and reduced light reflection.

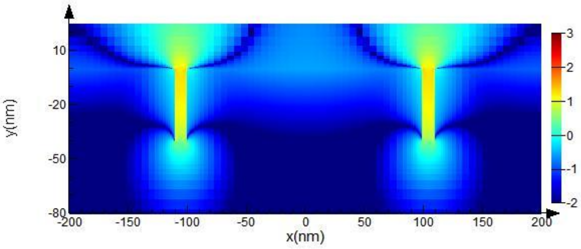

Fig. 3. Electric field profile of an annular aluminum nano-groove structure for h = 40 nm at a resonant wavelength of 441 nm.

Using Eq.(3), the relative quantum efficiencies for photocathodes with a structure consisting of circular nanocavities are calculated and shown in Fig.(3). In comparison with flat surfaces, quantum efficiency has almost 15 times increased for every 5 heights.As a result, the resonance of surface plasmons is an effective way to rise quantum efficiency by increased of the absorption, enhancing, limitation and localization electrical field near the metal surface.

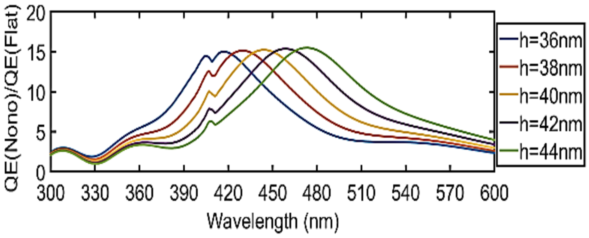

Fig. 4. Relative quantum efficiency of aluminum metal photocathode with circular nanocavities structure (with different heights) compared to photocathode with flat surface.

After investigating the effect of the height of the nono-grooves on the reflection spectrum, it is necessary to examine the changes in the width and repetition period of the nono-grooves and evaluate its effect on the location of the created valleys and the amount of light reflection from the metal surface. Therefore, first, the width of the nono-groove is changed so that the height (40 nm) and periodicity (400 nm) are constant. In Fig (5), the light reflection spectrum for three widths of 8, 10 and 12 nm is presented.

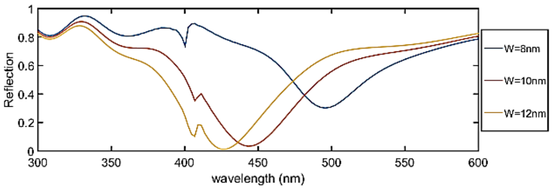

Fig. 5. Reflectance response spectrum of Al circular nanocavities with variable grooves width.

According to Fig (5), it can be seen that for the height of 40 nm, with the change of the width of the nono-groove from 8 to 12 nm in the wavelength range of 400-500 nm, the reflection spectrum of the nono-groove has different valleys. In general, it can be concluded that the widening of the valleys of the reflection spectrum decreasesas the width of the nono-grooves increases.

As mentioned, the repetition period of the nono-groove is effective in determining the valleys wavelength of the reflection spectrum. Therefore, by changing the repetition period with the condition of constant height (40 nm) and width of nono-groove (10 nm), the reflection spectrum diagram of Fig (6) is obtained. It can be seen that as the repetition period increases, the wavelength of the reflection spectrum valleys increases.

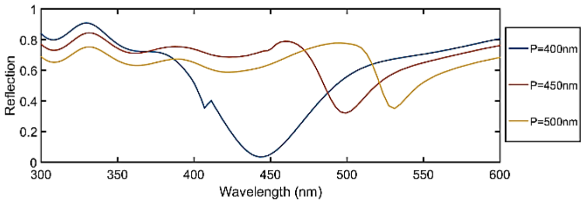

Fig. 6. Reflectance response spectrum of Al circular nanocavities with different repetition period.

With the investigations that were done on the structure parameters of the circular nanocavities, including the width and height of the grooves as well as the repetition period, it can be concluded that by changing each of the parameters, a proper selectivity can be created for the formation of surface plasmon polaritons, and as a result, the wavelength optional control of the plasmonic valleys can be possible.

5. Conclusions

The photocathode is one of the most important parts of an optical detector. Although metal photocathodes are fast, due to the free path of the short electron average and high reflectivity, they cause low efficiency and are an important limitation in detection. By replacing the nanostructured metal photocathode in the optical detector, the efficiency is increased and the efficiency limitation is improved. The circular nanocavities designed on the surface of the metal photocathode, stimulate the surface plasmon polaritons and increase the absorption of light on the surface of the photocathode, and so increasing the quantum efficiency of the photocathode. A metal circular nanocavity photocathode can increase quantum efficiency up to 15 times over a flat surface photocathode. The advantage of this structure is its symmetric nature so that it does not depend on the type of polarization of the incident light. Therefore, both types of S and P polarization will have the same response; even light with annular polarization will be able to pair with surface plasmons.

References

1. Flyckt SO, editor. Photomultiplier tubes: principles and applications. Photonis; 2002.
2. Photonics KH. Photomultiplier tube handbook. Electron Tube Division. 2006.
3. Matsuoka K. Expression for the angular dependence of the quantum efficiency of a thin multi-alkali photocathode and its optical properties. Progress of Theoretical and Experimental Physics. 2018 Dec;2018(12):123H01.
4. Schuller JA, Barnard ES, Cai W, Jun YC, White JS, Brongersma ML. Plasmonics for extreme light concentration and manipulation. Nature materials. 2010 Mar;9(3):193-204.
5. Polyakov A, Thompson K, Senft C, Dhuey S, Harteneck B, Liang X, Schuck JP, Cabrini S, Wan W, Padmore HA. Photocathode performance improvement by plasmonic light trapping in nanostructured metal surfaces. In Nanophotonic Materials VIII 2011 Sep; 8094:30-37.
6. Word RC, Dornan T, Könenkamp R. Photoemission from localized surface plasmons in fractal metal nanostructures. Applied Physics Letters. 2010 Jun;96(25).
7. Li RK, To H, Andonian G, Feng J, Polyakov A, Scoby CM, Thompson K, Wan W, Padmore HA, Musumeci P. Surface-plasmon resonance-enhanced multiphoton emission of high-brightness electron beams from a nanostructured copper cathode. Physical review letters. 2013 Feb;110(7):074801.
8. Li W, Ren K, Zhou J. Aluminum-based localized surface plasmon resonance for biosensing. TrAC Trends in Analytical Chemistry. 2016 Jun;80:486-494.
9. Drachev VP, Chettiar UK, Kildishev AV, Yuan HK, Cai W, Shalaev VM. The Ag dielectric function in plasmonic metamaterials. Optics express. 2008 Jan;16(2):1186-1195.
10. Elsherbeni AZ, Demir V. The Finite-Difference Time-Domain in Electromagnetics. SciTech Publishing Inc. 2015.
11. Yang HW, Yang ZK, Xu DD, Li AP, You X. Analysis on the efficiency of parallel FDTD method and its application in two-dimensional photonic crystal. Optik. 2014 Feb;125(3):1243-1247.
12. Iqbal T, Khalil S, Ijaz M, Riaz KN, Khan MI, Shakil M, Nabi AG, Javaid M, Abrar M, Afsheen S. Optimization of 1D plasmonic grating of nanostructured devices for the investigation of plasmonic bandgap. Plasmonics. 2019 Jun;14:775-783.
13. Eyvazi K, Karami MA. Optimizing Plasmonic Color Filter for Imaging Sensor. Scientific Journal of Applied Electromagnetics. 2020 May;7(2):105-112. [In Persian].
14. Barnes WL. Surface plasmon–polariton length scales: a route to sub-wavelength optics. Journal of optics A: pure and applied optics. 2006 Mar;8(4):S87.
15. Dowell DH, Schmerge JF. Quantum efficiency and thermal emittance of metal photocathodes. Physical Review Special Topics-Accelerators and Beams. 2009 Jul;12(7):074201.
16. Foroutan S, Dizaji HZ, Riahi A. Plasmon resonance-enhanced photocathode by light trapping in periodic concentric circular nanocavities on gold surface. Optik. 2017 Jun;138:223-228.
17. Arabkhorasani A, Khalilzadeh J, Dizaji HZ, Shahamat Y. Performance evaluation of metal photocathodes based on plasmonic nano-grating. Optik. 2022 Feb;252:168538.
18. Palik ED, editor. Handbook of optical constants of solids. Academic press; 1998.

How to cite this article
H. Zaki Dizaji, A. Arabkhorasani, J. Khalilzadeh, Y. Shahamat, *Improvement of Scintillation Detection System using Plasmonic Aluminum Photocathode,* Journal of Nuclear Science and Applications, Vol. **3,** No. **3,** P **6-11,** Summer **(2023), Url:** https://jonra.nstri.ir/article_1479.html, **DOI**: 10.24200/jon.2023.1064.