Improvement methods of reflective photocathode QE of X-ray frame camera

Xiaohong Bai (白晓红)[1,2], Yonglin Bai (白永林)[1*], Zhurong Cao (曹柱荣)[3], Junping Zhao (赵军平)[1], Baiyu Liu (刘百玉)[1], Junjun Qin (秦君军)[1], Bo Wang (王 博)[1,2], Wenzheng Yang (杨文正)[1], Yongsheng Gou (缑永胜)[1], and Xian Ouyang (欧阳娴)[1]

[1]*Xi'an Institute of Optics and Precision Mechanics of CAS, Xi'an 710119, China*

[2]*Graduate University of Chinese Academy of Science, Beijing 100049, China*

[3]*Institute of Nuclear Physics and Chemistry, Chinese Academy of Engineering Physics, Mianyang 621900, China*

[*]*Corresponding author: bxh@opt.ac.cn*

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Time-resolved diagnosis of the transient process using X-ray frame cameras (XRCs) is an important means in inertial confinement fusion (ICF) experiments. The sensitivity of the photocathode is a key parameter of the entire camera system. This letter aims to raise the quantum efficiency (QE) of the photocathode. With the changes in the deposition parameters, such as deposit angle, thickness of the coating in the channel, and vacuum of evaporation, the QE results are different. After testing and theoretical calculation, we find that there is a best matching value among these parameters. When the coating parameter meet this best value, the gain of the XRC can be improved significantly.

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The X-ray framing camera (XFC) is an important radiographic tool employed in the field of inertial confinement fusion (ICF) and high-energy-density physics to diagnose a wide variety of phenomena[1]. The camera system is mainly divided into three parts: photocathode, microchannel plate (MCP) multiplier, and phosphor screen. The photocathode can be divided into transmission cathode and reflective cathode in structure. There are many materials that can be used to create a photocathode according to different bands. For high quantum efficiency (QE) and stability, CsI is one of the best photocathode materials used in ultraviolet and X-ray band[2]. The technology behind the production of CsI is more mature[3], however, because it easily absorbs moisture in the rainy season, the CsI photocathode is mainly used in the vacuum system. In this letter, the Au cathode, which can be used in the open framing tube system, is studied in detail[4].

Given that the metal photocathode is relatively easy to deposit, researchers who have focused on different metals gained results with different QEs in certain wavelengths. Although the influence of evaporation depth as determined through the incident angle on QE has been calculated, the influence of the Au photocathode thickness and film density on the QE of MCPs has often been ignored by researchers[5]. Thus, many studies have been conducted to examine the QE of photocathode in MCPs. We considered the changes of evaporating incident angle, thickness of the Au coating in the channel and vacuum of evaporation, after which we discussed the QE of MCP separately.

The basic physical mechanisms behind the photocathode emission are explained by quantum and solid band theories[7]. Due to light exposure, there are electrons escaping from the solid surface called photoelectrons. Subsequently, when photoelectrons hit the surface of the channel, secondary electrons are generated that are multiplied by applying a bias voltage across the MCP. The total signal amplification coefficient is then defined as the QE of the photocathode. As the light reflection coefficient of the metal is higher than its absorption coefficient, the metal cathode cannot be adopted as visible and infrared photoelectric emitters. We can choose metal cathode used in MCPs because X-ray and UV radiation have been applied in XFCs.

The theory of metal optoelectronics has been perfectly developed, and the Fowler theory has been widely used in quantitative analyses and discussions. We want to combine the characteristics of evaporating optical film with photoemission law to improve the QE of the photocathode. In practice, the emission characteristics of the photocathode depend on its film structure, thickness, and coating process.

We set up a test system to test the coated optical effect of the film on the QE. The system consists of the light source, the frame camera, and the image record media (contacting film or CCD camera) (Fig. 1). These UV or X-ray images were first converted to electron images by the photocathode. Subsequently, the electron images were gated and multiplied by the MCP by feeding the micro-strip-line with a high voltage. The electron images were then converted to optical images by the phosphor screen and recorded by film. Figure 2 shows the experimental set-up. In the experiments, we used different projects to make the cathode. We replaced the cathode in the framing camera and tested the conversion efficiencies of the different cathode structures we devised[8].

Different thicknesses of Au photo-cathodes were deposited on the input plane of MCP to test their influence on the QE. The arrangement of the reflective photocathode is illustrated in Fig. 3. The incident area of each MCP was divided into four zones.

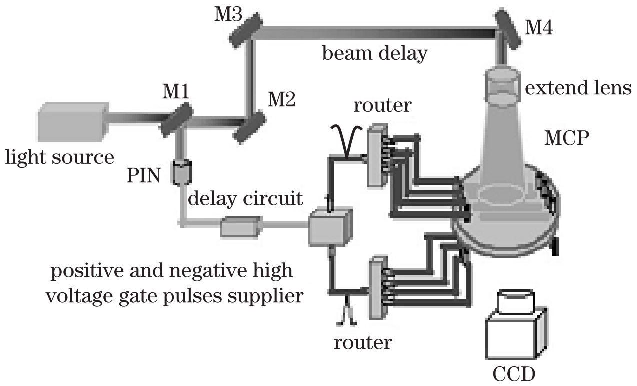


Fig. 1. Testing system.

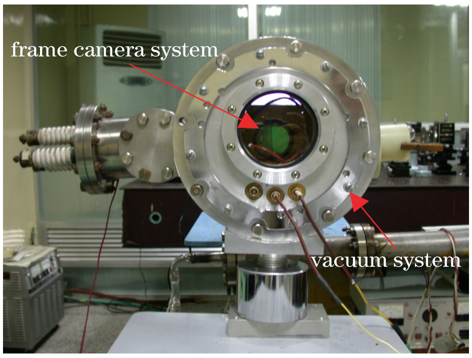
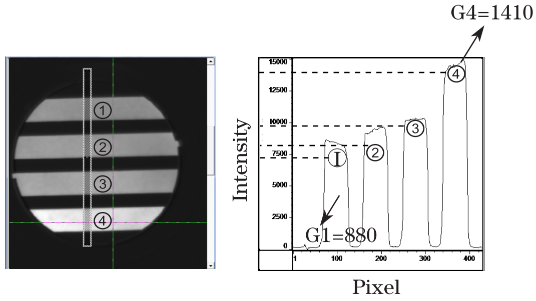


Fig. 2. Experimental set-up.

The metal photocathode consisted of two layers: Cu film and Au film. The Cu substrate was deposited in the system for a dual purpose: to obtain lower resistance transmission line across the MCP and improve the adhesive ability of Au to the MCP substrate. A typical resistance across the standard coating on the front surface of the MCP is 1–2 Ω. This resistance can reduce the electric pulse voltage propagating through the micro-strip-line. Given that the loss is proportional to V^9[9], where V is the voltage applied on the input plane of the MCP, the impedance of the micro-strip can affect the gain of the MCP. Although thick film can reduce impedance, the thicker the film, the worse the structure. Therefore, the thickness of the metal coatings should be optimized in the experiment. Micro-strip-line zones were divided into several parts. Different thicknesses of Au and Cu coatings were then deposited on the MCP. Figure 3(a) shows the image brightness in different zones. Among these zones of photocathodes, there were some with 500, 1000, and 2000-nm-thick Cu coated films underneath the 300-nm-thick Au film in the ①, ②, and ③ zones. To assess the effect of Au thickness, there are some coated with 600 nm of Au in zone above 500-nm Cu film. The thickness of Au film in zone ④ is double that of zones ①, ②, ③. The Cu film thickness in zone is the same as that in zone ①. Figure 3(b) shows the integral intensities corresponding to the same area of the different strip lines.

Figure 3(b) shows the integral intensities in different strip lines. G1 is the QE in zone ①, and G4 denotes the QE in zone ④. The ratio of G4 to G1 is 1.6; whereas G1, G2, and G3 have little differences. QE is mainly decided by the thickness of the Au film (Fig. 3(b)). The thickness of the Cu film has a minor effect on the QE, which can be ascribed to the photoelectron emission occurring only on the metal surface. If the film is thinner, the high-energy photos can penetrate the Au film and incident on the Cu film. However, due to lack of enough energy, it may be difficult for the photoelectrons to escape from the Cu to the Au film. Therefore, the Au film should be thick enough because this is an important factor to improve the QE and impedance.



(a) (b)

Fig. 3. The effect of different metal thicknesses of the photocathode on the QE.

To assess the effects of the incident depth in MCP of the coatings on the overall level of the output signal intensity, different incident angles were chosen in the coating procedure. Figure 4 shows the schematic diagram used to calculate the incident depth of coating in MCP. The QE results of three different incident angles are shown in Fig. 5. The average QE of different incident angles is shown in Table 1.

During the process of depositing the Au photocathode, the deeper the gold atoms penetrated into the MCP tunnel, the shorter distance remained for the secondary electron to multiply. Less multiplication times of the electron led to relatively low XFC gain. If the cathode is plated too thin, its QE can decline as well because the quantum conversion region is reduced.

Similar gain coefficients under three different incident angles are presented in Fig. 5. This is due to the corresponding film depths in the micro-channel that are almost the same. As a result, 45° was found to be the more suitable incident angle to create a photocathode.

The influence of film density on the QE is shown in Fig. 6. In the current study, the coating density was controlled by changing the evaporation rate. We obtained different evaporation rates but the same incident angle of 45° in zones ⑧ and ⑨. The evaporation rate in zone ⑧ was twice higher than that in zone ⑨. They had the same thickness of 300 nm. G9 was also 2.3 times higher than G8, indicating that the QE was very different. This means that the structure of the metal film greatly affects the QE. Film density can be controlled by altering

Table 1. Gains of Different Angles

Number	Incident Angle d	Depth δ/μm	Average Gain
⑤	30°	9.72	12451
⑥	45°	10.57	13025
⑦	0°	12.12	12110

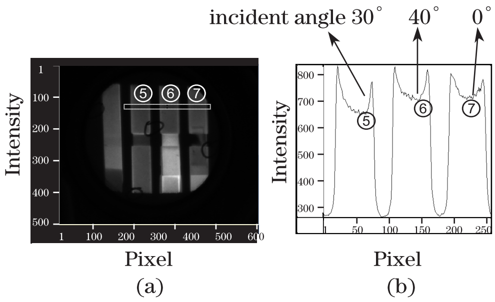


Fig. 4. The effect of the incident angle of the photocathode on the QE.

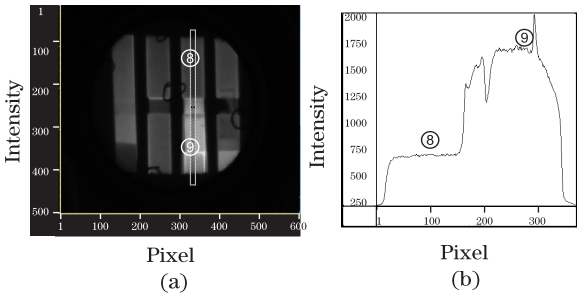


Fig. 5. The effect of different coating velocity.

the vacuity and speed of evaporation. However, the optimal structure has not been obtained yet.

The reflective ($\eta_{\rm R}$) QE of the photocathode includes the absorption probability ($\alpha_{\rm ab}$), the luminous reflectivity of the metal photocathode (R), and so on, defined as

$$\eta_{\rm R} = \frac{i}{I_0} = P_0(1-R)(1-{\rm e}^{-\beta\alpha_{ab}t})/\beta,$$
$$\beta = \left(1 + \frac{1}{\alpha_{\rm ab}d_{\rm es}}\right).$$

The formula is the main basis for making a reflective cathode[11]. Considering that higher photon energy corresponds to deeper penetration, together with the penetrating capability of X-ray through the cathode layer, in this formula, i is the field emission current density, I_0 is the primary incident light intensity, P_0 is the number of photoelectrons, R is the luminous reflectivity of the metal photocathode and the largest factor affecting $\eta_{\rm R}$, and $d_{\rm es}$ denotes the electron escaping depth.

In this formula, if R is lower, $\eta_{\rm R}$ is higher. Based on the metal deposition, the looser the film structure is, the lower R becomes. The ratio of secondary electrons emitted from the reflected photocathode depends on its thickness and structure. The emission region of the photocathode is limited to the volume within the electron range of the emission surface. The response of the photocathodes with thickness greater than the electron range can be reduced due to the attenuation of the X-ray signal before it reaches the emission region. Theories are in accordance with the experimental results presented. However, optimum R value is still in its infancy and requires further development.

The uncoated MCPs used in our experiments were made by Northern Night Vision Corporation. Each MCP had a thickness of 0.5 mm and an outside diameter of 56 mm. Channel diameter was 12 μm and center-to-center distance was 15 μm. In all cases, the bias angle was 8°. The open area ratio was up to 55%. The minimum gain of each MCP was 4000 at 1000 V. During the experiment, the photocathode in MCP was operated in the DC voltage mode. A 3000 V bias voltage was applied to P20 phosphor coupled to a CCD camera. The UV lamp provided a constant light source of 4.9 keV. These data were all taken at vacuum pressure of $\sim 3\times10^{-5}$ Torr.

The emission characteristics of the photocathode made by the Au and Cu films with various thicknesses, incident depths, and different film densities have been evaluated in this article. The performance of the photocathode made with new parameters has been found to be better than that of the original photocathode.

The experimental results also indicate that the QE of the photocathode increases when the incident angle is selected as 45°. The Au film has the sufficient thickness to lower impedance, and the QE of the overall thickness of the cathode film, which is 2500 μm, is nearly twice as much as 1500 μm. From the above results, when the film structure is loose, the generated secondary electrons can escape easily, resulting in increased number of photoelectrons. The gain of the XRC can thus be improved effectively using the three methods. Nevertheless, these still require further studies.

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