Influence of cesium on the stability of a GaAs photocathode*

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The stability of a reflection-mode GaAs photocathode has been investigated by monitoring the photocurrent and the spectral response at room temperature. We observe the photocurrent of the cathode decaying with time in the vacuum system under the action of Cs current, and find that the Cs atoms residing in the vacuum system are helpful in prolonging the life of the cathode. We examine the evolution and analyse the influence of the barrier on the spectral response of the cathode. Our results support the double dipolar model for the explanation of the negative electron affinity effect.

Keywords: GaAs photocathode, negative electron affinity, activation, photocathode stability

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1. Introduction

The negative electron affinity (NEA) GaAs photocathode has become increasingly important to the efficiency of emitters in night vision devices and polarized electron sources because of its high quantum efficiency, good long-wavelength response, and low energy spread.[1−3] Co-adsorption of cesium (Cs) and oxygen (O) on a GaAs surface is an important technology for preparing a NEA GaAs photocathode.[4,5] Although a high quantum efficiency NEA photocathode has been prepared by "yo–yo" (Cs,O) activation techniques, and its structure and composition have been studied for many years and correlated with its photoemission properties, our understanding of the system is still incomplete and the prepared photocathode is still not very stable, thus studies of some factors affecting its life are of great importance.

The stability of GaAs photocathodes in a vacuum system has been widely investigated. The life of cathodes dramatically decreases with an increase in water pressure in the vacuum system.[6,7] An excellent operating lifetime is related to low vacuum pressure.[8] The degradation of NEA GaAs cathodes is mainly caused by the adsorption of harmful gases on the cathode surface instead of the desorption of cesium.[9,10] Despite a long history of investigation into the stability of the photocathode, there are few reports concerning Cs influence on the stability of the NEA GaAs photocathode. In this paper, we report the photocurrent changes with time and the changes in spectral response of the NEA GaAs photocathode in the vacuum system under the action of different Cs currents, and we analyse the influence of the barrier on the spectral response of the cathode.

2. Experiment and results

The preparation experiments for reflection-mode GaAs photocathodes were performed in an ultrahigh vacuum (UHV) system. A Keithley electrometer was used for measurement of the photocurrent and a spectral instrument was used for measurement of the photocathode's spectral response.[11,12] All small samples used in the following experiments were cut from the same large wafer grown on a Be-doped p-type GaAs wafer (100) by molecular beam epitaxy (MBE). The p-type doping concentration is 1×10^{19} cm^{-3} and the emission-layer thickness is 2.6 μm.

Before (Cs,O) activation, the GaAs material should be chemically cleaned and subsequently heat cleaned. The GaAs material was degreased and chemically etched to remove carbon traces from its surfaces. After chemical cleaning, the GaAs material was flushed with distilled water, dried, and quickly put into the vacuum chamber. Once the vacuum pressure

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was better than 1×10^{-7} Pa, heat cleaning started. The heating temperature was 600 °C (measuring accuracy ±1 °C) and the duration of heat cleaning was 50 min. When the GaAs material was cooled to 60 °C and the vacuum pressure returned to 1×10^{-7} Pa in the UHV system, two-step (Cs,O) activation began. The activation process ended after achieving the maximum quantum efficiency.[13−15] The Cs:O ratio of the freshly activated cathode was approximately 0.9 to 1. During the activation process and degradation process, the photocurrent was monitored while the photocathode was illuminated by a tungsten–halogen lamp with 12 V/50 W.

A comparative degradation experiment has been carried out to study the Cs influence on the stability of a GaAs photocathode under the action of different Cs currents. When activation ended, the oxygen current was turned off immediately, and the cathode degradation with time started in the UHV system. Whether the Cs current should be kept open depends on the following experiment. The total pressure in the UHV system was about 9×10^{-8} Pa on average during the experimental process.

With the aid of the Keithley electrometer, the photocurrent was monitored and recorded over the whole degradation process. The photocathode degraded under three conditions: the Cs current kept the constant value, the Cs current was turned down in regular order, and the Cs current was turned off. The photocurrent curves are shown in Fig. 1. As shown in Fig. 1, the photocurrents after activation all fall rapidly in the initial stage, then fall slowly and tend to stabilize gradually. However, there is no doubt that a larger Cs current is helpful to keep a larger photocurrent. The ultimate photocurrent in curve 1 is 63% of the peak photocurrent, but the ultimate photocurrent in curve 3 is almost zero. In curve 2, each decrease in the Cs current results in the photocurrent falling rapidly and then tending towards stability. Obviously, the phenomena are not merely under-explained from the perspective of detrimental impurities. The amplitude of the photocurrent is closely related to the Cs partial pressure in the UHV system controlled by Cs current.

In the measured spectral response curves, we find an interesting phenomenon. There is a clear change in the shape of the spectral response curves for the photocathode during the degradation process, as shown in Figs. 2 and 3. The lower the incident photon energy, the faster the quantum efficiency (QE) degradation rate. This phenomenon is related to the operating mode of reflection-mode cathodes and the evolution of the surface potential barrier during these processes.

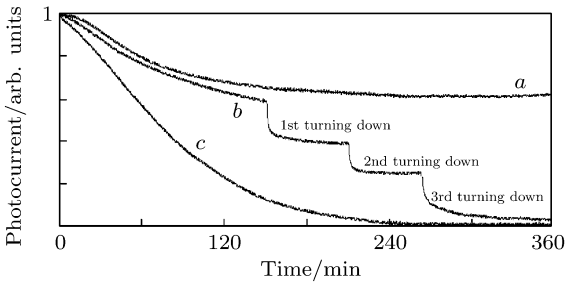


Fig. 1. Photocurrent degradation as a function of time after activation. In curve *a*, Cs current keeps 1.7 A from beginning toe end. In curve *b*, Cs current is 1.6 A in the initial stage, then turned down to 1.5 A and 1.4 A at the 2.5th hour and 3.5th hour respectively, and then turned off at the 4.5th hour. In curve *c*, Cs current is turned off from beginning to end.

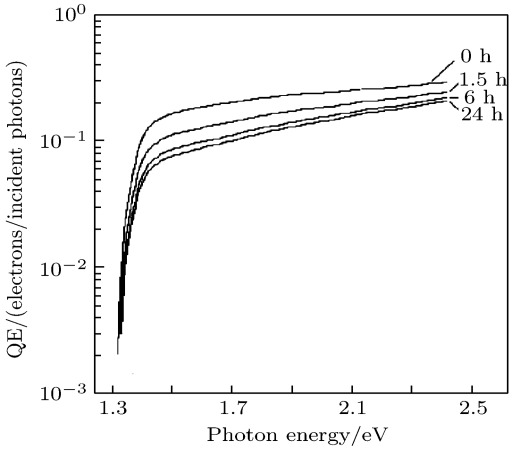


Fig. 2. Spectral response of the GaAs photocathode as a function of degradation time under the action of Cs current (corresponding to curve *a* in Fig. 1). The four curves represent the spectral response of the original cathode and the spectral responses of the original cathodes after degrading for 1.5, 6, and 24 hours in the UHV system, respectively.

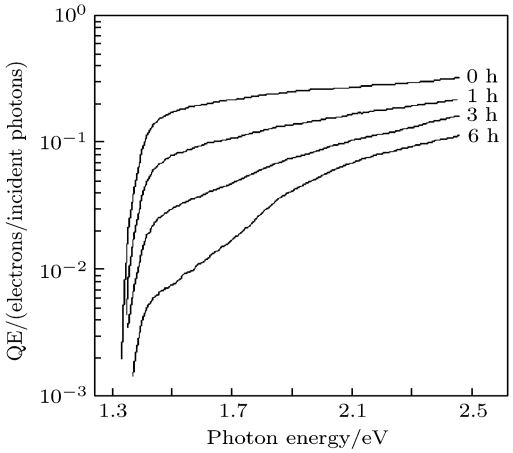


Fig. 3. Spectral response of the GaAs photocathode as a function of degradation time without the action of Cs current (corresponding to curve *c* in Fig. 1). The four curves represent the spectral response of the original cathode and the three spectral responses of the original cathodes after degrading for 1, 3, and 6 hours in the UHV system, respectively.

3. Discussion

Photoemission from a NEA photocathode is a three-step process of optical absorption, electron transport to the surface, and escape of electrons across the surface into the vacuum.[15−17] For the GaAs photocathode, the photon excitation leads to electron transition from the valence band to the Γ valley of the conduction band. During electron transport to the surface, if the energy of the excited electrons is high enough, they may be scattered from the Γ valley to the L valley, and some of them escape directly from the L valley. The excited electrons with energy lower than the L valley but higher than the Γ minimum will escape probably in the form of hot electrons.[18,19] Prior to emission into the vacuum, the photoexcited electrons must travel across the surface potential barrier, which is related to the Cs–O activation layer. In view of the relationship between the surface electron escape probability and the surface potential barrier profile, the reason for the decay in photocurrent and the changes in spectral response can be explained by the band structure and surface barrier (shown in Fig. 4) based on the double-dipole model. In the double-dipole model, the most important feature is the separation of the dipole potential drop at the surface into two parts: dipole I across the GaAs–Cs layer and dipole II across the Cs oxide layer, as shown in Fig. 5. The surface potential barrier profile comprises two approximately straight lines with different slopes: barrier I and barrier II.[20,21]

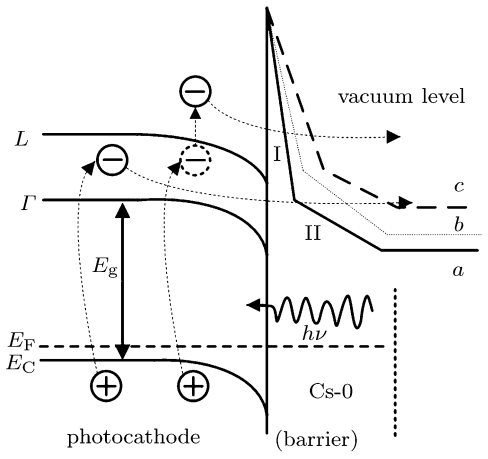


Fig. 4. Band structure and surface potential barrier for the reflection-mode NEA GaAs photocathode. *a*: the surface potential barrier when the activation ends; *b*: the surface potential barrier after the photocathode degrades under the action of Cs current; *c*: the surface potential barrier after the photocathode degrades without Cs current.

The surface potential barrier profile has a significant impact on the quantum efficiency of the photocathode. The quantum efficiency formula for the reflection-mode photocathode is deduced from the diffusion equations, which is given by[22−26]

$$Y(h\nu) = \frac{P_{h\nu} \cdot (1 - R)}{1 + 1/(L_{\mathrm{D}}\alpha_{h\nu})}. \tag{1}$$

where Y $(h\nu)$ is the quantum yield, L_{D} is the electron diffusion length, R is the reflectivity of the photocathode surface, $\alpha_{h\nu}$ is the absorption coefficient of the photocathode material, and $P_{h\nu}$ is the surface electron escape probability, which depends on the incident photon energy and the width and height of barriers I and II.

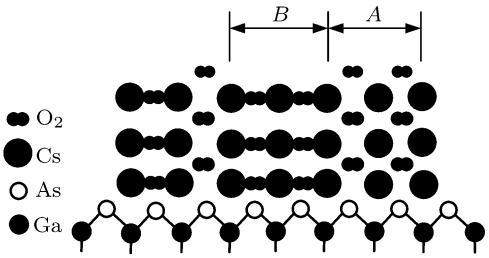


Fig. 5. The structure model of activated GaAs surfaces before and after adsorbing oxygen.

According to the double-dipole model, the Cs/O activation layer is a mixture of different kinds of Cs oxides, such as Cs_2O_2 and CsO_2 (labeled as A and B in Fig. 5, respectively). The existence of mixtures of different Cs oxides in the activation layer implies that this layer is thermodynamically stable against homogenization. The molecular form of oxygen (O_2^{-2} and O_2^{-1}) in the activation layer also enhances this stability. In region B, dipoles formed by the positively charged Cs ions and negatively charged O_2^{-1} anions are in the horizontal direction. No net potential drop is provided in the vertical direction. So there will be no additional electron affinity lowering in region B. However, in region A, there is a Cs–[Cs]–O_2^{-2}–Cs structure in the vertical direction. The second layer of Cs (labeled as [Cs]) is sandwiched between a layer of positive charge Cs layer and a negative charge oxygen layer. This will result in a net polarization of electrons in the second layer of Cs.

When the photocathode degrades, the oxygen molecular anions (O_2^{-2} and O_2^{-1}) from the residual harmful gases in the UHV system are probably adsorbed onto the activation layer surface. Once the oxygen anions attach to the surface, its neighbouring Cs atoms will donate charge to the oxygen molecule and pull it inside the activation layer, because the Cs atoms on the top of the activation layer are positively charged. This chemical transformation corresponds to a change from cesium peroxide (CS_2O_2) to cesium superoxide (CsO_2).

If we combine this information with the structural model (Fig. 5), the reason for photocurrent decay becomes obvious: after the cesium peroxide is converted into cesium superoxide, the oxygen molecules will move from their original positions, which are between the Cs layers and the new positions in the Cs layers (region A transforms into region B in Fig. 5). In region B, dipoles formed by the positively charged Cs ions and negatively charged O_2^{-1} anions are in the horizontal direction. No net potential drop is provided in the vertical direction. Thus the dipole II layer will weaken and eventually disappear. This will make the electron affinity of the surface increase. Furthermore, the adsorption of oxygen or other negative ions (OH^-, CO) pushes the oxygen in the activation layer closer to the strong Cs–GaAs dipole (dipole I) field, so more substrate oxidation is formed. Thus the barrier profile for a degraded photocathode will evolve according to the dashed line in Fig. 4, the surface electron escape probability $P_{h\nu}$ decreases and the photocurrent and the quantum efficiency are greatly reduced.

When the photocathode degrades under the action of larger Cs current, the partial pressure of Cs is higher, and that of harmful gases is distinctly lower in the UHV system. Thus, Cs atoms have a greater chance of being adsorbed on the photocathode surface. Moreover, excessive Cs forms a protective layer on the photocathode surface, which separates harmful gases from the activation layer. The barrier profile of the photocathode degrading under the action of larger Cs current will evolve according to the dotted line in Fig. 4. So the photocathode degrades slowly under the action of a larger Cs current. Once the Cs current is turned down and the protection weakens, the harmful gases have more chance of being adsorbed. This is why the photocurrent falls fast each time turning down the Cs current.

Why does the quantum efficiency degrade faster at the lower incident energy of the photons? In reflection-mode cathodes, since the photons are incident on the cathode surface (semiconductor/vacuum interface), the high-energy electrons are mainly excited in the region near the cathode surface by the high-energy photons. These high-energy electrons, including L valley electrons and hot electrons, may be transported to the cathode surface and emitted before suffering energy relaxation in the Γ minimum. Moreover, the higher the incident photon energy (below 2.5 eV), the more the high-energy electrons are transported to the cathode surface. Because the evolution of barrier II mainly influences the emission of low-energy electrons (Γ valley electrons), the decrease in the vacuum level in barrier II will facilitate the emission of Γ valley electrons and have little influence on L valley electrons. Accordingly, the quantum efficiency that degrades for the low-energy photons is greater than that for the high-energy photons.

4. Conclusion

We have investigated the stability of a reflection-mode GaAs photocathode and observed that the photocurrent of the cathode degrades with time in the vacuum system under the action of different Cs currents. The life of the cathode is longer under a higher Cs current. Nevertheless, the spectral response curve in the entire response wave band, especially in the short-wavelength region, obviously drops after degradation, which is attributed to impurity in the gas, and which decreases the surface electron escape probability related to the adverse evolution of the surface potential barrier profile. This work is significant for the fabrication of long-life photocathodes.

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