

STUDY ON THE PERFORMANCE IMPROVEMENT OF ALKALI ANTIMONIDE PHOTOCATHODES FOR RADIO FREQUENCY ELECTRON GUNS

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Abstract

Semiconductor photocathodes such as Cs-Te and Cs-K-Sb are used as electron sources in accelerators to generate high brightness beams using radio frequency (rf) electron guns. Alkali antimonide photocathodes have a high QE of about 10%, and the excitation wavelength is in the visible light region (532 nm), which reduces the number of wavelength conversions and facilitates optical path adjustment, thus reducing the load on the optical system and increasing the amount of electric charge compared to Cs-Te. However, alkali antimonide photocathodes have a short lifetime and degrade under poor vacuum conditions, so it is beneficial to improve the durability by protective film coatings. Therefore, we are currently working on the fabrication of high QE alkali antimonide photocathodes that can withstand the QE reduction during coating. In this conference, we will report the results of the comparison between the fabricated alkali antimonide photocathode and Cs-Te photocathode, and future prospects.

INTRODUCTION

Recently, there is a growing demand for accelerator experiments such as energy recovery linac (ERLs) and free electron lasers (FELs) that require high-brightness electron beams. Photocathodes, which extract electrons by the photoelectric effect using laser irradiation, as an electron source for accelerators are mostly adopted to meet such requirements. Especially, alkali antimonide photocathodes (such as Cs-K-Sb and Cs-Sb), a type of semiconductor photocathode, have high QE and excitation wavelengths in the visible light region, and are being studied to fabricate photocathodes with performance that exceeds that of existing photocathodes.

However, despite these excellent characteristics, alkali antimonide photocathodes have some disadvantages like having a short lifetime of only a few weeks; the $1/e$ lifetime of Cs-Sb photocathodes were reported to be 20 to 500 hours under high-frequency electric fields [1].

Therefore, we fabricated and evaluated a Cs-Sb photocathode coated with CsBr, an alkali halide protective film for the higher performance photocathode with the higher QE and the longer lifetime. We also compared the results with those of our previous work in our laboratory on Cs-Te photocathodes coated with an alkali halide protective film [2].

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EXPERIMENT

Experimental Equipment

The Cs-Sb photocathode and the coating of the CsBr protective film in this experiment were made in the vacuum evaporation chamber shown in Fig. 1. The pressure inside the chamber during the evaporation is about $10^{-7} \sim 10^{-6}$ Pa, and the pressure inside the chamber during the lifetime measurement is about 5×10^{-8} Pa. This ultra-high vacuum was achieved by 6 vacuum pumps, a dry roots pump (Kashiyama: NeoDry30E), 2 turbo molecular pumps (PFEIFFER HiPace® 300 DN 100 CF-F EDWARDS STP-301), an ion pump (ULVAC: PST-100CX) and 2 NEG pumps (SAES Getters: CapaciTorr®), and the degree of vacuum during the experiment is monitored by a B-A vacuum gauge (Canon ANELVA: M-922HG).

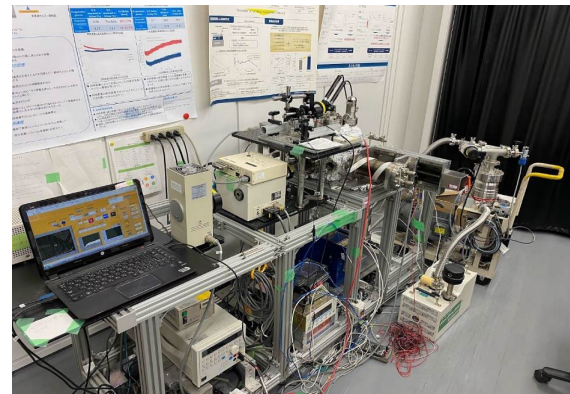


Figure 1: Appearance of the vacuum evaporation chamber.

Figure 2 shows the setup of the evaporation source holder (ESH) in this experiment. The ESH is equipped with a Cs dispenser (SAES Getters), which uses the principle of reduction reaction with chromium oxide, and Sb (Nilaco) and CsBr (Pier Optics) crystals in a tungsten basket. During the experiment, the total amount of material deposited on the surface of the cathode is measured in real time using a quartz crystal microbalance (QCM) thickness meter, which has a deposition rate of 0.1 \AA/s and a resolution of 1 \AA for the deposited film thickness.

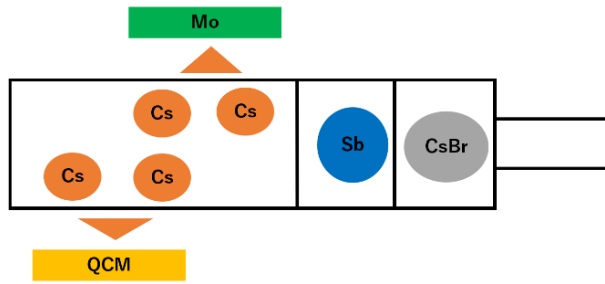


Figure 2: Schematic of the ESH setup.

Experimental Procedure

In this experiment, the Cs-Sb photocathodes was prepared by sequential deposition on a Mo substrate whose surface has been treated by ethanol and ultrasonic cleaning. The QE was calculated by the incident optical power and the photocurrent. As incident light, a laser diode (THORLABS: CPS532) with a laser power of about 1500000nW, green light (wavelength: 532 nm), and a current meter (ADCMT: 6243 DC Voltage/Current Monitor) is used to measure the photocurrent. In addition, a mechanical shutter (SURUGA SEIKI: F116) is used to shut off the incident light at regular intervals to remove background noise from the current value to be measured. Here, the definition formula of QE [%] is expressed as.

$$QE = \frac{\text{Number of emitted electrons}}{\text{Number of incident photons}} \times 100, \\ = \frac{100h\nu I}{eW} \times 100, \quad (1)$$

where, I : photocurrent [A], h : Planck's constant [$J \cdot s$], ν : frequency [1/s], e : electron elementary charge [C], W : irradiated light energy [J].

Experiments were taken by the following steps.

- (i) 20 nm Sb is deposited on Mo substrate.
- (ii) Cs is deposited until QE is near its peak value.
- (iii) Coat with 5 nm of CsBr protective film.
- (iv) Apply fitting and analyze the data.

As detailed experimental conditions, after 20 nm of Sb was deposited, Cs deposition was conducted while measuring QE terminated at the peak QE value. The thickness of the protective film to be coated was 5 nm, which is the thickness at which the change in QE can be sufficiently observed.

In calculating the $1/e$ lifetime, fitting was applied using equation (2). Here, $1/e$ lifetime is defined as the time it takes for QE to reach $1/e$ the initial value.

$$QE(t) = \alpha_0 \exp\left(-\frac{t}{\tau_e}\right), \quad (2)$$

where, t : elapsed time [hour], α_0 : initial QE [%], and τ_e : $1/e$ lifetime [hour].

RESULTS & DISCUSSION

QE Behavior During Protective Film Coating

Figure 3 the relationship between the relative QE and the thickness of the protective film. The reason for using relative QE for the vertical axis is to account for the difference in QE before the coating. It was found that the QE decreased rapidly at the first few nm of protective film thickness, and then the QE decreased gradually as the protective film thickness increased. First, the main reason for the rapid QE decrease is considered that a potential barrier is created at the boundary between the cathode and the protective film, making it difficult for electrons to escape [3]. Other possible causes include lattice defects due to incompatibility between the cathode and the protective film, and sputtering of the cathode during the protective film coating. As for the subsequent gradual QE decrease, the increase we considered that the electron scattering increase in the protective film.

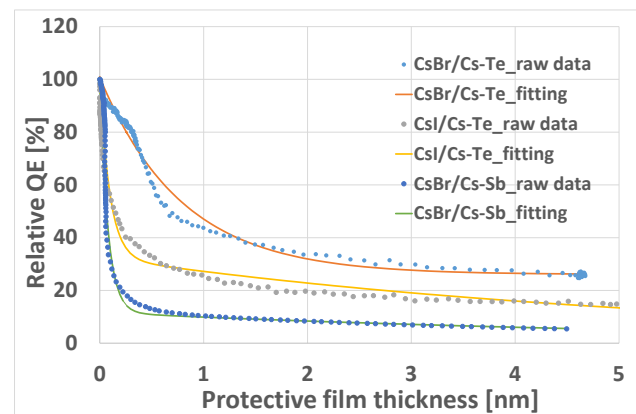


Figure 3: Relationship between relative QE and protective film thickness for three types of photocathodes.

We also elucidate the affinity between the photocathode and the protective film by fitting the QE change during coating. Also, in order to distinguish T_1 and T_2 , it is $T_1 < T_2$, where T_1 corresponds to the rapid QE decrease and T_2 corresponds to the gradual QE decrease.

$$\alpha(x) = A \exp\left(-\frac{x}{T_1}\right) + B \exp\left(-\frac{x}{T_2}\right) (+ \text{const.}) \quad (3)$$

where, α : QE [%], x : protective film thickness [nm], A , B , T_1 and T_2 are fitting parameters.

Table 1 shows the values of fitting parameters for each coating material.

Table 1: Fitting Parameters

Coating/ photocathode	A[-]	T ₁ [nm]	B[-]	T ₂ [nm]
CsBr/Cs-Te	78	0.20	22	70
CsI/Cs-Te	83	0.20	17	52
CsBr/Cs-Sb	88	0.076	12	6.1

The results in Fig. 3 and Table 1 show that the value of A is larger and the value of T₁ is smaller, for Cs-Sb compared to Cs-Te. In addition, about one order of magnitude smaller with respect to T₂. B is always 100 – A. From this result, the value of A is larger than that of B, indicating that the rapid decrease due to the first few nm coating is the dominant factor of QE change in the protective film 5 nm coating.

First, with respect to A, this value corresponds to a rapid QE decrease, and a smaller value means that the QE decrease is suppressed. This means that Cs-Te and CsBr are the best match in terms of QE. Second, we compare T₁ and T₂ for CsBr or CsI coating on Cs-Te and CsBr coating on Cs-Sb. The value of T₁ was found to depend on the type of cathode being coated. This value means the physical amount of protective film required to cover the cathode surface, which is significant in that Cs-Sb can coat the entire cathode with a smaller protective film thickness than Cs-Te. The value of T₂ is considered to be related to the difference in optical energy due to the difference in excitation wavelengths, as expressed in equation (4).

$$E = \frac{hc}{\lambda} \quad (4)$$

where, E : energy of light[eV], λ : wavelength of light[nm], h : Planck's constant[J• s], c : speed of light[m/s].

From Eq. (4), the kinetic energy of the electrons extracted is smaller for Cs-Sb because UV light has more energy imparted to the cathode than green light; T₂ is the amount of material related to the energy lost by the electrons due to scattering as they pass through the protective film, which depends on the kinetic energy of the electrons, we believe this result is reasonable.

1/e Lifetime of Cs-Sb Photocathode

Table 2 shows the 1/e lifetime of Cs-Sb photocathodes with and without coating and laser irradiation. No Q.E. decrease was observed when lifetime measurements were made without excitation light on a 5 nm coated Cs-Sb photocathode with a CsBr protective film. The results show that the 1/e lifetime differs with and without coating and laser irradiation. Considering that the manufacturing process of the Cs-Sb photocathode is the same as above, we believe that the difference in 1/e lifetime is due to the excitation light. When the lifetime measurement was performed with continuous excitation light irradiation, the

laser power of the excitation light caused thermal desorption of Cs atoms from the cathode surface, which likely degraded the photocathode, resulting in a shorter lifetime.

Comparing the 1/e lifetime with and without coating under the same irradiation light conditions, the lifetime is longer with the protective film coating, indicating that the CsBr protective film coating is effective in extending the lifetime of the Cs-Sb photocathode.

Table 2: Lifetime of Cs-Sb Photocathodes

CsBr [nm]	Green light	1/e lifetime	Initial QE [%]
5	on	17	0.081
5	off	-	0.13
0	on	9.6	1.8
0	off	140	0.91

CONCLUSION

We evaluated the Cs-Sb photocathodes coated with CsBr, an alkali halide protective film, and compared the results with Cs-Te photocathodes. As a result, it was found that Cs-Te photocathode and CsBr protective film are compatible in terms of QE. It was confirmed that the 1/e lifetime of Cs-Sb photocathodes is shortened due to cathode degradation caused by excitation light irradiation and that the CsBr protective film coating extends the lifetime. Elongation of the lifetime by CsBr protective coating on the Cs-Sb photocathode was confirmed.

As a future prospect, we aim to fabricate a photocathode with higher QE and longer lifetime by utilizing the knowledge obtained in this study for Cs-K-Sb photocathodes, which are also alkali antimonide photocathodes and are considered to be compatible with CsBr protective films [4].

ACKNOWLEDGEMENTS

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