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Lifetime test of photoemission from Cs_3Sb photocathode coated with W or Cr film

Takayoshi Kimoto[a,*], Yoshihiro Arai[b], Xiaobing Ren[a]

[a] Materials Processing Unit, National Institute for Materials Science, Tsukuba, Ibaraki 305-0047, Japan
[b] Terabase Inc., Okazaki, Aichi 444-8787, Japan

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ABSTRACT

Cs_3Sb photocathodes were fabricated at 8–16 °C with sandwiched layers of Sb, Cs, and Sb deposited onto the fine tips of three cathodes at 15 °C. After examining the influence of the cathode tip temperature on the changes in the quantum efficiencies of the Cs_3Sb photocathodes during and after additional Cs depositions, we performed lifetime tests of the three Cs_3Sb photocathodes using a 405-nm semiconductor laser and 488-nm Ar ion laser. The decrease in the photocurrent with time was more rapid with the 488-nm laser irradiation than with the 405-nm laser irradiation, and continuous laser irradiation caused a much more rapid decrease in photoelectrons with time than intermittent laser irradiation did. We deposited a 0.32–0.64-nm-thick W film or a 0.43-nm-thick Cr film onto the Cs_3Sb photocathode during the lifetime test at 0.9–1.0 × 10^{-7} Pa. We found that the passive WO_3 or Cr_2O_3 film, which was formed at a reduced vacuum level of 1.6 × 10^{-7} Pa or during the continuous 405-nm laser irradiation, increased the lifetime of the Cs_3Sb photocathode by effectively protecting its surface against oxidation and evaporation of Cs. This protection effect was most effective at approximately 90 °C.

1. Introduction

There are several photoemissive materials with extremely high quantum efficiencies in the visible light region. For example, the quantum efficiency of a Cs_3Sb photocathode is approximately 11% at wavelength of 405 nm, and 4.5% at 488 nm [1]. Based on these data, a cathode tip coated with Cs_3Sb photocathode can emit photoelectrons with a current of approximately 18 mA and initial kinetic energies lower than 2.54 eV, if it is irradiated using a laser of with a wavelength of 488 nm and intensity of 1 W. In comparison, the electron beam current in a transmission electron microscope (TEM), where the initial energy spread of the electron beam should be as small as possible, is usually approximately 50 μA with LaB_6 thermal-type electron source, and 5–20 μA with cold field emission-type source [2]. The electron current from a laser-irradiated Cs_3Sb photocathode could therefore be much larger than those from the usual electron sources for TEM. Because the quantum efficiencies of photocathodes of K_3Sb, Rb_3Sb, Na_2KSb, (Cs)Na_2KSb, K_2CsSb, Cs_2Te, GaAs(Cs), etc., are of the same order of magnitude as that of Cs_3Sb photocathode in the visible region [3], it is expected that a cathode tip coated with one of these photoemissive materials could be an electron source of extremely high intensity for TEM. Besides extremely high intensity, the photocathode has the advantage that the interval of electron beam emission is easily controlled by controlling the laser irradiation. For example, a pulsed electron beam can be obtained by irradiating with a pulsed laser. We could coat Cs_3Sb photocathode on a small selected area of a cathode tip by limiting the area of Sb and Cs deposition using an aperture with a small hole [4]. Therefore, another advantage is the ability to easily change the size and shape of the electron beam by changing the shape of the photoemissive material coating. In addition, it was conveniently found in our previous research that the photocurrent from the Cs_3Sb photocathode increased with increasing anode voltage from 0.4 kV to 7.0 kV [4].

The most important problem in the use of a photocathode coated with a photoemissive material such as Cs_3Sb for TEM is that the amount of photoelectrons rapidly decreases with time in a vacuum chamber. In the case of a photocathode coated with Cs_3Sb, the decrease in photoelectron emission is thought to be caused by the destruction of the crystal structure as a result of the oxidation of the Cs_3Sb photocathode and the gradual loss of Cs from it [5]. The use of other photoemissive materials such as K_3Sb, Rb_3Sb, Na_2KSb, (Cs)Na_2KSb, K_2CsSb, Cs_2Te, and GaAs(Cs), poses the same problem because these materials are extremely chemically active. They have been used in evacuated glass tubes such as photodiodes, photomultipliers, and imaging tubes, but they have extremely long lifetimes. In the case of a Cs_3Sb photocathode in an evacuated glass tube, for example, its extremely long lifetime seems to be the result of

* Corresponding author. Tel.: +81 29 8592733; fax: +81 20 8592701.
E-mail address: KIMOTO.Takayoshi@nims.go.jp (T. Kimoto).

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the presence of a small amount of residual Cs vapor in the tube, because this residual Cs vapor replaces any Cs that may be lost from the cathode surface, and also getters any oxygen that might poison the cathode [5]. On the other hand, in the use of Cs_3Sb photocathode for TEM or other vacuum chambers, the evaporation of Cs from Cs_3Sb photocathode occurs much more frequently than in evacuated glass tubes. Partly because of this, the lifetime of a Cs_3Sb photocathode used for TEM or other vacuum chamber facilities is thought to be much shorter than that in an evacuated glass tube. The short lifetime of a Cs_3Sb photocathode in a vacuum chamber has been reported [4,5], and efforts to increase the lifetimes of Cs_3Sb and K–Cs–Sb photocathodes have also been made recently [6–9]. The main objective of the present research was to obtain information to solve this problem. Because the experimental data on the lifetimes of Cs_3Sb photocathodes are very limited, the other research objectives were to examine the effects of the laser wavelength, the continuous laser irradiation, vacuum level, cathode tip temperature, etc., on the lifetime of a Cs_3Sb photocathode.

The conventional method to fabricate a Cs_3Sb photocathode is to deposit Sb and Cs alternatively on a cathode plate at approximately 130 °C [3,5]. However, this method is not suitable for use with our specially developed deposition equipment, which allows us to coat Cs_3Sb photocathode on a small area of a fine cathode tip [4], because it is almost impossible to change the deposition of Sb and Cs in a short time with our developed equipment. Therefore, we also attempted to obtain information for the development of a new method to fabricate a Cs_3Sb photocathode with high quantum efficiency that is suitable for use with our equipment.

2. Experimental

We previously developed vacuum deposition equipment for coating Cs_3Sb photocathode on a small area of a cathode tip with a diameter of 0.2 mm [4]. In order to perform a new experiment to detect photoelectrons under the additional Cs deposition, we modified our original deposition equipment by making a 2-mm-diameter hole in the center of the soleplate of the Faraday cup and a 1–1.5-mm diameter hole in the center of the wedge prism used to reflect the laser inside the Faraday cup. Fig. 1 shows the modified deposition equipment for coating Cs_3Sb photocathode on a small area of a fine cathode tip in a vacuum chamber. As shown in this figure, we could perform the additional Cs deposition on a cathode tip while detecting photoelectrons with the Faraday cup. Because the details of our originally developed vacuum deposition equipment were described in our previous report [4], we provide only brief outline of it in this paper. With the developed equipment, we can deposit Sb, Cs, etc. on a cathode tip by heating a boat using an electron beam. Cs_3Sb photocathode can be coated on a small area of the fine cathode tip by limiting the Cs and Sb deposition area using the aperture. After confirming the formation of Cs_3Sb on a cathode tip by the detection of photoelectrons using a Faraday cup, we set the cathode unit within the small vessel shield in a high vacuum with the cover by using the wobblestick (or a kind of 3-D manipulator). We can then transfer it from the vacuum deposition equipment to the TEM without exposing it to air or oxygen. During the deposition of Sb, Cs, etc., the vacuum level in the upper chamber is 10^3 to 10^4 times higher than that in the lower chamber as a result of the effective differential evacuation and high evacuation speed of the cryopump. The cathode tip can be heated using the ceramic heater and cooled by the Peltier device. The evaporation thicknesses of Sb, Cs, etc., were measured by measuring the small weight change of a quartz oscillator that had them deposited on its surface.

Usually, a Cs_3Sb photocathode is fabricated on a metallic plate, whose temperature is controlled to approximately 130 °C, using alternate doses of Cs and Sb [3,5]. However, this method is not suitable for use with the developed deposition equipment described above, because only one boat can be heated by an electron beam, which makes the use of alternate doses of Cs and Sb almost impossible in a short time interval. Therefore, we had to develop a new method to fabricate a Cs_3Sb photocathode suitable to our deposition equipment. In addition, for practical reasons, we previously examined whether Cs reacted with Sb at the lowest temperature possible in our deposition equipment, and it was found that the sandwiched layer that was formed by depositing a Cs layer between two Sb layers on a cathode tip at −20 °C using our deposition equipment became Cs_3Sb photocathode after maintaining it approximately −20 °C [4]. The quantum efficiency of the Cs_3Sb photocathode made from the sandwiched layer was very low, probably because the reaction temperature was very low. In the present research, we attempted to fabricate a Cs_3Sb photocathode with the higher quantum efficiency from the sandwiched layer of Sb and Cs. Fig. 2 shows a schematic diagram of the present method used to fabricate the three Cs_3Sb photocathodes. We examined three Cs_3Sb photocathodes, called "cathode A", "cathode B", and "cathode C", in our previous research [4]. In order to distinguish them, the present three Cs_3Sb photocathodes are called "cathode D", "cathode E", and "cathode F." All three cathodes were fabricated from the sandwiched layer shown in Fig. 2a. The surface of the cathode tip was first smoothed using a lapping film sheet coated with aluminum oxide particles with a diameter of 0.3 μm.

The present cathode tips were made of Ni, but Sb reacts chemically with Ni [3]. For this reason, after baking the cathode tip at 200 °C for 2 h to clean its surface, we deposited an 8-nm-thick Cr layer on the cathode tip at approximately 16–18 °C, because Cr reacts with neither Sb nor Cs [3]. After the deposition of Cr, the cathode tip was again baked at 200 °C for 2 h to clean the coated Cr surface. Subsequently, a 4-nm-thick Sb layer was deposited onto the cathode tip at approximately −15 °C, and then, its temperature was maintained at approximately −15 °C. Approximately 18–20 h after the first Sb deposition, a 93-nm-thick Cs layer was deposited on the cathode tip at approximately −15 °C and then, its temperature was maintained at approximately −15 °C. Approximately 4 h after the Cs deposition, another 4-nm-thick Sb layer was deposited at approximately −15 °C. After the second Sb deposition, the temperature of the sandwiched layer was increased from approximately −15 °C to 8–16 °C. The exact thickness of the deposited Cs layer corresponding to the 8-nm-thick Sb layer used to form the stoichiometric Cs_3Sb was approximately 60 nm. Considering the experimental error in measuring the thickness of the deposited Sb and Cs, we deposited an approximately 93-nm-thick Cs layer, which was 1.55 times as thick as the 60-nm-thick layer. The excess Cs was not detrimental because it is known that excess Cs simply desorbs [3,5].

After the detection of photoelectrons from the fabricated Cs_3Sb photocathode, we examined the effect of additional Cs deposition on the change in the quantum efficiency, and then proceeded to perform the lifetime test of the Cs_3Sb photocathode. During the lifetime test, a 0.32-nm-thick W layer was deposited on cathode D. A 0.63-nm-thick W layer was deposited on cathode E, and a 0.43-nm-thick Cr layer was deposited on cathode F. The evaporation of the Sb, Cs, etc., was described in detail in our previous report [4]. We irradiated the cathode tip using a semiconductor laser with a wavelength of 405 nm and an Ar ion laser with a wavelength of 488 nm to examine the photoemission from the Cs_3Sb photocathode. The photoelectrons detection was carried out at an anode voltage of 1 kV.

It was important to determine the laser intensity at the cathode tip in order to calculate the quantum efficiency of the Cs_3Sb photocathode in each experiment. Before each experiment, we adjusted the diameter of the laser at the cathode tip to be larger than 1 mm.