CHIN. PHYS. LETT. Vol. 36, No. 2 (2019) 022901

Development of Preparation Systems with K_2CsSb Photocathodes and Study on the Preparation Process

Fan Zhang(张帆)[1,2], Xiao-Ping Li(李小平)[1,2**], Xiao-Shen Li(李孝燊)[1,2]

[1]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049*

[2]*Key Laboratory of Particle Acceleration Physics and Technology, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049*

(Received 26 September 2018)

The next generation of advanced light sources requires photons with large average flux and high brightness, which needs advanced electron gun matched with excellent photocathode materials. K_2CsSb photocathode has the advantages of high quantum efficiency, long lifetime and instantaneous response. This study introduces the design of a set of K_2CsSb photocathode preparation systems and detailed preparation process of K_2CsSb photocathodes, including sequential deposition process and co-deposition process, and finally develops a K_2CsSb photocathode. The influence of laser power on the quantum efficiency is also investigated.

PACS: 29.25.Bx, 81.05.Hd, 07.30.Kf DOI: 10.1088/0256-307X/36/2/022901

Advanced light sources such as the XFEL and the XERL with high brightness and ultra-short pulses may be emphasized in accelerator research in the future.[1] The key performance of the photocathode has a direct effect on the quality of the beam. Theoretically, photocathode materials should have the characteristics of high quantum efficiency (QE), instantaneous response, long lifetime and low thermal emission.[2] However, no single material used in photocathodes is able to meet all of these requirements. Common metallic cathodes, such as copper and magnesium, are easy to be prepared and applied. However, they have disadvantages of low QE to be driven by ultraviolet laser. High QE semiconductor cathodes such as Cs_2Te, GaAs and K_2CsSb can be operated to a high average flow intensity. In particular, they need to be prepared in special preparation systems because of their vacuum sensitivity. In addition, a Cs_2Te photocathode needs to be driven with an ultraviolet laser at 266 nm.[3] The QE and charge lifetime of the GaAs photocathode are greatly influenced by the vacuum. Compared with the GaAs photocathode, the K_2CsSb photocathode has several advantages, including a relatively required low vacuum, high QE and robust charge lifetime. Therefore, it has become a research hotspot in the field of photocathode electron guns, both domestically and abroad. In applications of PMTs, QE of K_2CsSb photocathodes has reached 43%, as developed by Hamamatsu Photonics since 2007,[4] whereas the maximum QE in the electron source of electron guns at BNL is only 12%.[5]

Based on the hardware support of the 500 kV dc high voltage photocathode electron gun experimental platform located at Institute of High Energy Physics (IHEP),[6] a set of GaAs photocathode deposition systems were designed with QE of 3% in 2013, and the beam experiment has successfully been carried out.

Compared with the GaAs photocathode, the K_2CsSb photocathode has many advantages. Since 2015, the IHEP has started to design the preparation systems for a set of K_2CsSb photocathodes. The developed photocathode will be used in the 500 kV dc high voltage electronic gun platform to carry out the beam experiment. The schematic design of K_2CsSb photocathode preparation systems is shown in Fig. 1.

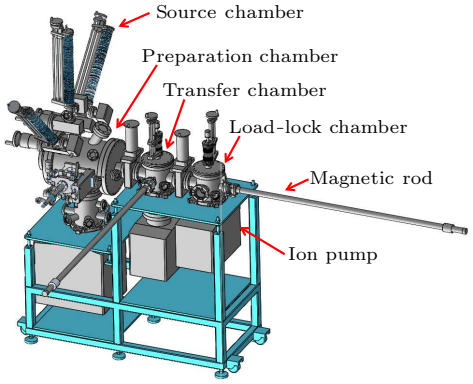

Fig. 1. Design of the photocathode preparation system.

The load-lock chamber is mainly used to replace the cathode substrate because the K_2CsSb photocathode film that is used can only be effectively removed by external force other than the high temperature baking or argon ion gun sputtering. Thus, it is necessary to install a halogen lamp to bake the residual gas that is adsorbed on the surface. The substrate is made from pure metal of molybdenum (Mo) whose roughness is less than 5 nm. The magnetic rod is installed at the end of the load-lock chamber that can realize the straight transmission of the cathode substrate into the three chambers. The function of the transfer chamber is to push the excellent photocathode into the electron gun with a magnetic rod.

The preparation chamber is used to prepare the photocathode film. It is equipped with an evaporation source baffle that can shield the deposition of

**Corresponding author. Email: lxp@ihep.ac.cn

© 2019 Chinese Physical Society and IOP Publishing Ltd

source stream and a front mounted standard single probe monitored by the SQM-160 thickness gauge that uses the principle of the quartz crystal oscillation to calibrate the film thickness. A three-dimensional mobile sample platform is installed to realize the function of heating, cooling, temperature calibration, photocurrent extraction and 3D movement of substrate, as shown in Fig. 2. In addition, there are three independent metal source chambers installed above the preparation chamber. The source chambers are separated by a plugged valve and equipped with a separate sputtering ion pump. The design can ensure that the vacuum of the preparation chamber is not damaged during the replacement of the evaporation source.

Considering that the main residual gases in the ultra-high vacuum environment are H_2, CO and N_2, the sputtering ion pump (SIP) has a low pumping speed to H_2 when the vacuum is less than 1×10^{-8} Pa and the limit vacuum of NEG pump reaches up to 1×10^{-10} Pa.[7] Therefore, the sputter ion pump and getter pump are selected to maintain a high vacuum in the chamber. The specific pump accessories are listed in Table 1. To verify its rationality according to the structure of the preparation chamber and the location of the vacuum pump, the MolFlow+ software based on the Monte Carlo experimental particle method was used to simulate the vacuum distribution inside the preparation chamber.[8] The vacuum at the cathode substrate is 1.70×10^{-9} Pa, which satisfies the vacuum design requirements. After a series of debugging, the ultimate vacuum of the preparation chamber reaches 1.50×10^{-9} Pa.

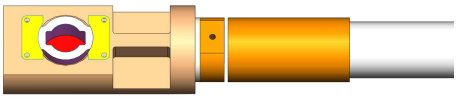

Fig. 2. The sample stage model of the preparation chamber.

Table 1. Accessories statistics of the K_2CsSb photocathode preparation system.

Allocation	Load-lock chamber	Transfer chamber	Preparation chamber
Sputter ion pump	200 L/s	200 L/s	300 L/s
Getter pump	Saes 400 L/s×2	Saes 400 L/s×2	Saes 400 L/s×4

The preparation process of the K_2CsSb photocathode is the steam thermal depositions of Sb, K and Cs. The source materials are as follows: 3 mm pure metal ball of Sb whose purity is 99.9999%, the release agent composed of K_2CrO_4 and Cs_2CrO_4 with their own reducing agent according to a certain proportion that would have chemical reaction and release pure metal vapor from a metal slit.

The photocathode performance including QE and lifetime is greatly influenced by the preparation process parameters, especially deposition rate, substrate temperature and vacuum. The deposition rate affects the compactness of the film, the substrate temperature determines the adsorption, migration, bonding and enrichment of atoms and radicals, and the vacuum determines the purity of the film which has an effect on the electron escape path. In addition, the deviation of relative position between the evaporation source and the substrate may have a great effect on the QE homogeneity. Recently, experiments have been repeated to optimize the process parameters. To optimize the parameters in the process, it is necessary to connect the preparation system and material analysis equipment to research the surface morphology and composition analysis of the photocathode film. However, the economy will be greatly restricted, which leads the performance improvement of the K_2CsSb photocathode more dependent on the guidance of experience.

The specific sequential deposition process is shown as follows: the substrate is heated up to 500℃ for 8 h to remove the hydrogen and oxygen compounds from the Mo surface. Temperature is lowered to approximately 90℃ and then evaporation of 10 nm with an average rate 0.2 Å/s of antimony is performed. Evaporation of K is carried out while the substrate is slowly heated approximately at 125℃ and then evaporation of 20 nm with an average rate of 0.4 Å/s is performed. When the substrate temperature falls below 85℃, Cs evaporation starts and lasts until the photocurrent reaches a maximum value. The substrate is allowed to cool down at room temperature.

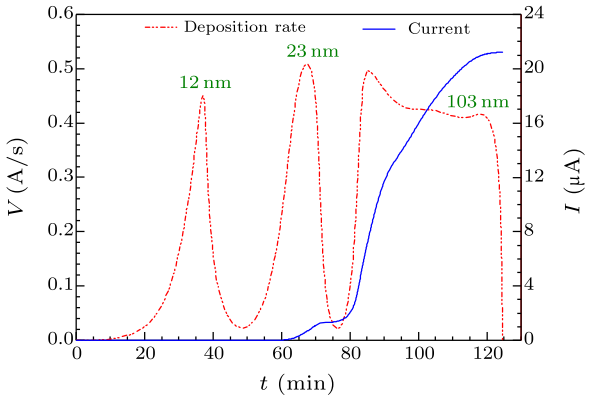

Fig. 3. Deposition rate and photocurrent of evaporation source during photocathode fabrication.

At present, the basic performance index of the K_2CsSb photocathode is QE. The preparation vacuum, sample stage temperature (converted to the substrate temperature), photocurrent and deposition rate have been recorded, as shown in Figs. 3 and 4.

As shown in Figs. 3 and 4, the photocurrent of 21.2 μA and QE of 0.51% can be monitored when it is driven by a green laser of 532 nm with power of 10 mW (in fact, when the laser power is 0.5 mW, the maximum of QE is 0.79%). After the deposition of 10 nm Sb thin film, no more photocurrent is produced. However, the photocurrent increases to a peak of 1.30 μA and then

decreases with the deposition of the K thin film. It can be speculated that K atoms and atomic groups may interact with atoms or atomic groups on the Sb thin film and may create a new phase of K_3Sb which has a lower potential barrier. Subsequently, K atoms begin to aggregate and enrich, the increasing film thickness raises the impossibility for photoelectron to escape, thus the photocurrent decreases. Finally, the photocurrent increases rapidly with the deposition of Cs atoms. It can be assumed that a new phase of K_2CsSb may be generated, which will reduce the work function of the photoelectrons further. Similarly, with the deposition of the Cs atoms, the photocurrent reaches the maximum and the K_2CsSb content reaches the critical value, once this critical value is exceeded, increasing film thickness would impede the escape of photoelectrons, thus the photocurrent curve tends to be stable when the increasing film thickness balances the loss of the escaping energy with the reduction of the energy barrier. After successful preparation, liquid N_2 should be used to cool K_2CsSb quickly at room temperature. Generally, the QE remains stable for a long time.

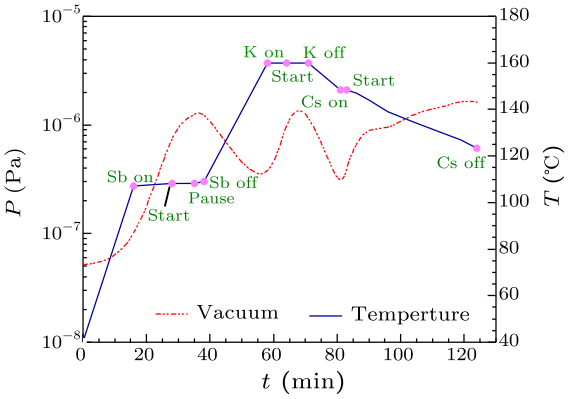

Fig. 4. Preparation chamber vacuum and cathode temperature during photocathode fabrication.

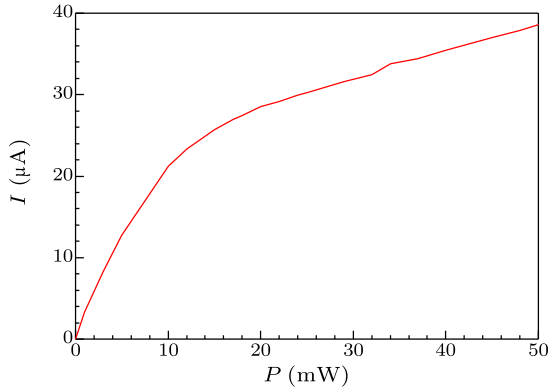

Fig. 5. Photocurrent value during the continuous increase of the laser power.

Figure 5 shows the photocurrent value during the continuous increase of the laser power. In general, the photocurrent increases linearly with the laser power. However, the curve increases slowly when the power exceeds about 12 mW, where the laser power represents the number of photons on the unit area. The photon absorption rate is high when the laser power is low. With the increase of the laser power, it is clear that more and more photons can be absorbed by electrons. However, the number of electrons that can absorb photons to transit in a unit time is limited, and utilization of less photons would cause a decline of the slope (QE).

The co-deposition growth of the K_2CsSb photocathode uses the following procedure. The substrate is heated up to 500℃. Temperature is lowered to approximately 85℃ and keeps it, then the evaporation of 10 nm with an average rate 0.2 Å/s of antimony is performed. K and Cs evaporations start with 4.6 A until the photocurrent reaches a maximum value. The substrate is allowed to cool down at room temperature.

The preparation vacuum and photocurrent have been recorded, as shown in Fig. 6. The low deposition rate of co-deposition process of K and Cs results in a long cathode preparation time, but the maximum photocurrent is 2.68 μA with a 0.5 mW laser and the QE is 1.3%. It can be speculated that the low deposition temperature and deposition rate of K and Cs may make the film atoms fully combine with Sb film atoms at a higher condensation rate, and the chemical compositions of K/Cs/Sb are closer to 2:1:1.

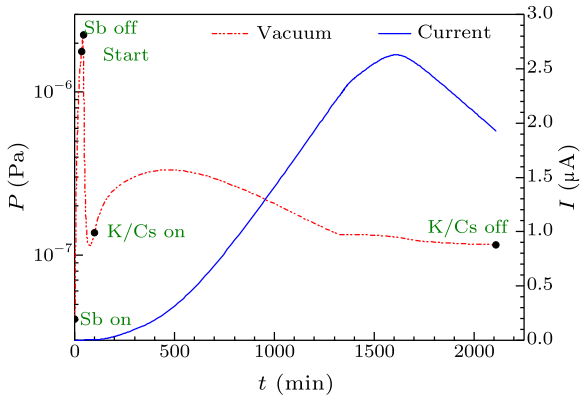

Fig. 6. Preparation chamber vacuum and photocurrent during photocathode fabrication.

In summary, the design and construction of the K_2CsSb photocathode fabrication system have been briefly described. This device can be used to prepare various types of photocathodes for electronic guns. To date, the K_2CsSb photocathode can be prepared by a sequential deposition process. The Sb and K designed film thicknesses are 10 nm and 20 nm, and the QE reaches no less than 0.79% when the 532 nm and 0.5 mW laser illuminates the cathode. The photocurrent grows slowly when the laser power is more than 12 mW. The co-deposition process of K and Cs for the photocathode is also conducted preliminarily, the Sb film thickness is 10 nm, and K/Cs evaporation with heating current 4.6 A is stopped until the photocurrent reaches a maximum of 2.68 μA with a 0.5 mW/532 nm laser and the QE reaches 1.30%.

In future, we will install an automatic QE monitoring device to study the influence of film thickness, deposition rate, substrate temperature and substrate

materials on QE and lifetime so as to meet the requirements of the next generation of advanced light sources.

References

[1] Yan J X and Mahoney K 2009 *Proc. ICALEPCS* **92** 582
[2] Michelato P, Gallina P and Pagani C 1994 *Nucl. Instrum. Methods Phys. Res. Sect. A* **340** 176
[3] https://www.osti.gov/servlets/purl/780780
[4] An Y B, Xu X Y and Sun Q X 2014 *J. Opt.* **34** 325 (in Chinese)
[5] Mammei R, Suleiman R, Poelker M, Rao T, Smedley J and McCarter J L 2011 *Proc. Ipac* **178** 1443
[6] Li X P, Wang J Q, Xu J Q, Pei S L, Xiao O Z, He D Y, Lv K, Kong X C and Peng X H 2017 *Chin. Phys. Lett.* **34** 072901
[7] Li X P, Peng X H, Zhang T, Wang G W, Guo P L and Jiang D K 2014 *Chin. J. Vacuum Sci. Technol.* **11** 1155 (in Chinese)
[8] Liu B Q, Peng X H, Zhai J Y and Gao J 2016 *Chin. J. Vacuum Sci. Technol.* **5** 538 (in Chinese)