

MULTI-ALKALI ANTIMONIDE PHOTOCATHODE DEVELOPMENT FOR HIGH BRIGHTNESS BEAMS

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Abstract

Photocathode R&D at the Helmholtz-Zentrum Berlin (HZB) is driven by the motivation to produce high brightness electron beams for the SRF photoinjector test facility, Sealab/ bERLinPro. Multi-alkali antimonides are the choice photocathode material due to high quantum efficiency (QE) and low intrinsic emittance in the visible range. In this work a more robust alternative to the tried and tested Cs-K-Sb is considered. Na-K-Sb offers similar advantages to Cs-K-Sb including, high QE at green wavelengths but moreover, it offers excellent stability at elevated temperatures. This property could lengthen the cathode lifetime by enhancing the robustness of the photocathode inside the SRF gun. In this work, a status report showcasing first results towards the development of a growth procedure for Na-K-Sb is presented by means of spectral response and XPS measurements conducted in the HZB photocathode lab.

INTRODUCTION

The operation of a SRF photoinjector with a normal conducting photocathode has successfully been demonstrated at several research labs including BNL, HZB, HZDR and KEK, thanks to developments in photocathode integration technology [1]. Though significantly more challenging than using superconducting metals such as niobium or lead, integrating high QE semiconductor photocathodes enables the generation of high brightness beams and is therefore necessary for many applications.

At HZB, removable bi-alkali antimonide photocathodes will be used to drive the SRF photoinjector [2] to generate high brightness beams. For this, a non-contact, thermally insulated cathode insert design was developed to allow cathode cooling. Gun studies in the commissioning process revealed that the photocathode insert was damaged due to high thermal heat load from RF losses [3]. Consequently the insert design has been modified and tested to circumvent this issue [4]. Furthermore, we also consider the use of a more robust bi-alkali antimonide photocathode material, namely Na-K-Sb. Compared with Cs-K-Sb, there are relatively fewer studies on Na-K-Sb. Nevertheless, the aim is to develop a reproducible growth procedure for high QE Na-K-Sb photocathodes to provide a viable alternative to Cs-K-Sb for use in the Sealab/ bERLinPro SRF gun.

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EXPERIMENTAL SETUP

A "Work-Horse" Plug

To develop a growth procedure for Na-K-Sb photocathodes, the single use molybdenum plug substrate was traded in for a reusable all-molybdenum plug (see Fig. 1), or the so called "work-horse plug." The work-horse plug was prepared in-house from a single molybdenum block and surface polished using a series of diamond polishing paste solutions (6, 3, and finally 1 μ). Using the same substrate is advantageous in developing a growth procedure as this allows for direct comparison between the films. This is otherwise problematic if different substrates are used due to inconsistencies in surface preparation. Furthermore, reusing the sample substrate speeds up the turnaround time between growths. A substrate preparation procedure was devised to ensure a clean molybdenum surface is the starting point for each subsequent growth for this study.

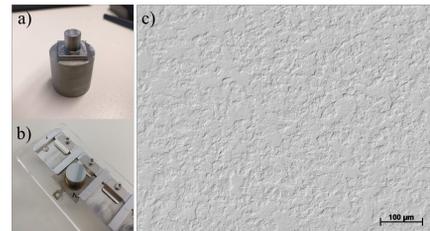


Figure 1: All-Mo plug with 10 mm diameter shown a) before, b) after polishing, and c) an optical microscope image of the polished surface.

Preparation and Analysis System

The preparation and analysis system is part of the infrastructure developed for the preparation, characterization and transport of photocathodes for the photoinjector. A full description of the system can be found in [5]. Multi-alkali antimonide films are grown in the preparation chamber under UHV conditions (base pressure 2×10^{-10} mbar) and XPS measurements are conducted in the adjoining analysis chamber. A spectral response set-up is attached to the preparation chamber to enable photocurrent measurements.

In the current configuration, one sample position is required for antimony deposition and another for alkali deposition; this chamber geometry therefore limits growth method options to either sequential or alkali co-evaporation onto an antimony layer, both of which are employed for the samples grown in this study.

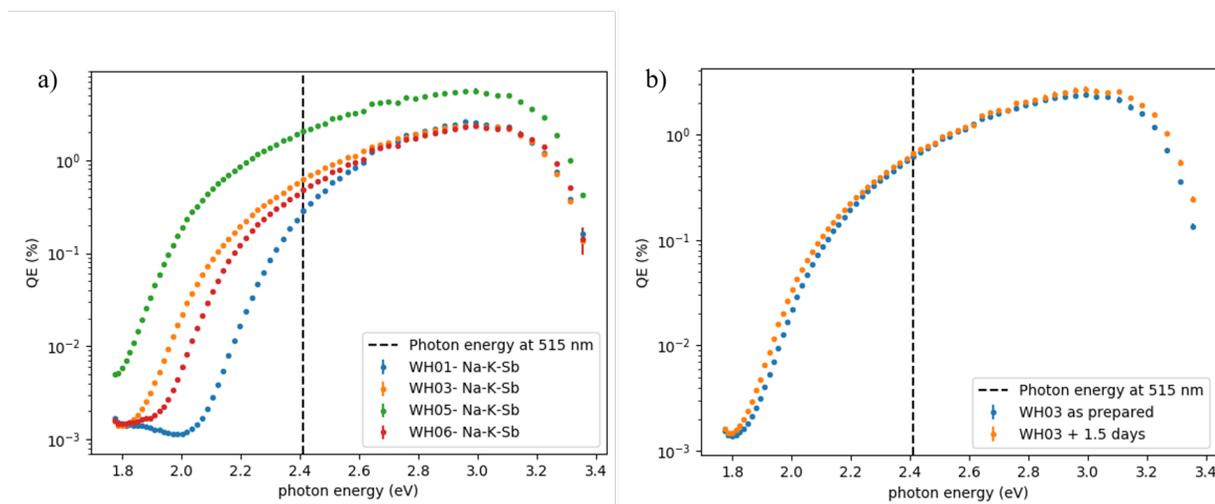


Figure 2: QE measurements for WH01, WH03, WH05 and WH06. The QE at 515 nm (black dotted line) is 0.3, 0.6, 2.0, and 0.5 % for WH01, WH03, WH05 and WH06 respectively, and (b) comparison of QE data for WH03 as-grown and after 1.5 days show no degradation with respect to performance.

RESULTS

Spectral Response Measurements

Preliminary spectral response and XPS results for six Na-K-Sb photocathodes are presented and evaluated in this section. The alkali co-evaporation method developed at HZB [5] for the growth of Cs-K-Sb was employed for five samples (WH01, WH02, WH03, WH05 and WH06) whereas the traditional sequential deposition method was used for one reference sample (WH04).

The growth parameters initially chosen were guided by the procedure outlined by Cultrera *et al.* in [6]. For the sample grown by sequential deposition method, a 40 nm thick antimony film was deposited at a substrate temperature of 90 °C. This was followed by potassium deposition at the same temperature. Lastly, sodium was deposited starting at 130 °C and then reducing the sample temperature stepwise. In the case of the samples grown by alkali co-evaporation, the same parameters were used for antimony deposition. For the alkali evaporation, the sample temperature was varied from sample to sample to optimize for photocurrent. In each case, the sample was first heated to higher temperatures than for antimony deposition (between 130-200°C) and then, as for sequential evaporation, the temperature was reduced stepwise.

Spectral response curves for WH01, WH03, WH05 and WH06 are shown in Fig. 2 a) along with reference data from a Cs-K-Sb photocathode, G002.

Studies by Cultrera *et al* on the growth of Na-K-Sb report QE values of 6 % at 520 nm [6], and so in comparison, the results reported here are lower in absolute terms. However, this is not unexpected at this early stage of developing a growth procedure. Further iterations are necessary to optimize the growth parameters to reliably produce high QE Na-K-Sb photocathodes. The highest yielding photocathode was WH05, with a QE of 2% at 515 nm. Disappointingly,

the QE degraded rapidly soon after taking spectral response measurements. In the Cultrera *et al* study, a decrease in photocurrent was observed during sodium deposition which was attributed to an excess of sodium on the surface [7]. This offers a possible explanation for the instability of the WH05 photocathode film.

In the case of WH03, repeated measurements after 1.5 days demonstrated no degradation in the QE as evidenced in the spectral response plot shown in Fig. 2 b). This further corroborates the premises for enhanced operational lifetime of Na-K-Sb versus Cs-K-Sb. No QE data was obtained for sample WH02 due to technical issues in controlling the temperature during alkali deposition, nor for WH04; the reason for which is discussed in the section below.

XPS Measurements

Chemical analysis of one sequentially grown photocathode (WH04) and one grown by alkali co-evaporation (WH05) is presented in this section below. In Fig. 3 a), the Sb 3d region spectra are shown for each stage of the growth. The first step for both samples is the deposition of an antimony layer onto the molybdenum substrate; the Sb 3d spectra for this first step for both samples is shown in the bottom plot. The Sb 3d 5/2 and the Sb 3d 3/2 peaks are positioned at 528.5 and 537.9 eV respectively for both WH04 and WH05, corresponding to Sb(0), metallic antimony [8].

In the case of WH04, the next step is the deposition of potassium onto the antimony layer; this is shown in the middle plot of Fig. 3 a). Though the peak positions still lie in the energy range corresponding to Sb(0), a 0.3 eV shift to lower binding energies is observed. Furthermore, it is possible to discern a broadening of the Sb 3d peaks that hint to a mixture of phases.

The final step is the evaporation of sodium onto the K-Sb film for WH04 and the co-evaporation of the alkalis onto the antimony layer for WH05. The Sb 3d region spectra after

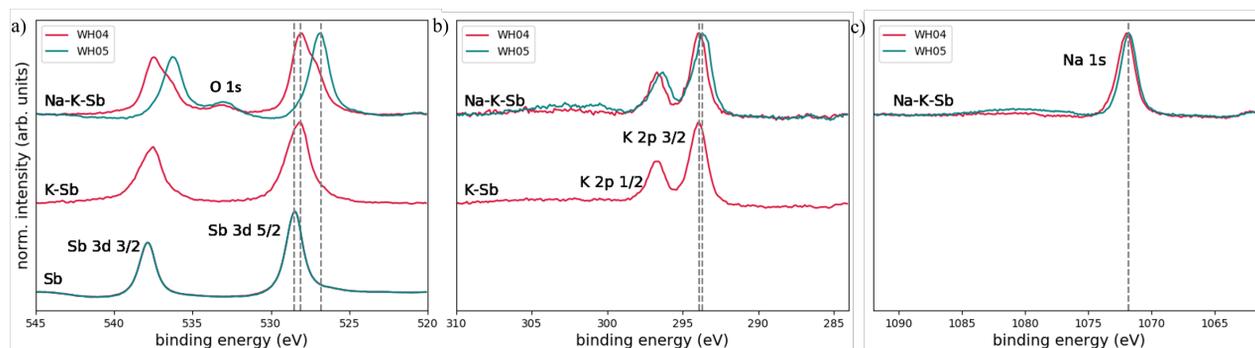


Figure 3: XPS spectra of two Na-K-Sb samples: WH04 was grown by sequential deposition and WH05 by alkali metal co-evaporation. Comparison of a) Sb 3d spectra, b) K 2p spectra and c) Na 1s spectra.

the final steps are shown in the top most plot of Fig. 3 a). For WH04, the broadening of the peaks previously observed have further broadened with the deposition of sodium to more strongly suggest a mixed phase. A shoulder is apparent at a lower binding energy indicating a reduced antimony component. However, the dominant peaks for Sb 3d 5/2 and the Sb 3d 3/2 are found at 528.2 and 537.5 eV that correspond to non-reacted Sb(0). This could partly explain the particularly poor performance of WH04 with respect to QE. In the case of the WH05, a sizable shift of -1.6 eV to lower binding energies is observed for Sb 3d peaks; the Sb 3d 5/2 and the Sb 3d 3/2 peaks are shifted to 526.9 and 536.3 eV respectively corresponding to Sb(3-), reduced antimony according to reference data from [9].

In Fig. 3 a), weak O 1s signals are observed at approximately 533 eV for both WH04 and WH05, indicating trace levels of oxygen. In previous Cs-K-Sb growth studies, similar weak O 1s signals are also sometimes observed in both K-Sb and Cs-K-Sb films [5]. This was previously attributed to either residual gases or from the potassium or caesium dispensers. In this study, it is evident that the O 1s signal only appears after sodium deposition suggesting that the origin of the contamination was the sodium dispensers for these samples. The presence of oxygen contamination may also be a contributing factor to the low QE values reported here.

Fig. 3 b) shows the K 2p region spectra for the intermediate K-Sb film for WH04 (middle) and the Na-K-Sb film (top) for both samples. For WH04, the K 2p peak positions remain equal for the second (K-Sb) and third step (Na-K-Sb) of the deposition. The K 2p 3/2 and 1/2 appear at binding energies of 293.9 and 296.7 eV respectively. Compared with metallic K 2p, these values are shifted by 0.8 eV to lower binding energies [9, 10]. The K 2p binding energies reported here are in reasonably good agreement with values found in literature for K-Sb [5, 9]. No further shift is observed for the final step to Na-K-Sb. This might be indicative that the transition from a K-Sb lattice to a Na-K-Sb lattice did not fully occur. In the case of WH05, the K 2p peak positions are shifted by 1 eV compared to metallic potassium K(0). As shown in Fig. 3 b), the potassium core level values are shifted to a lower binding energy for WH05 compared with WH04.

The Na 1s region spectra for the final growth step for WH04 and WH05 are compared in Fig. 3 c). The Na 1s peak binding energy occurs at 1071.9 eV corresponding to metallic sodium [8]. There are several possible explanations for such an occurrence: either the evaporated sodium did not fully react with the potassium and antimony due to incorrect sample temperature, or an excess of sodium was evaporated and so only the surface layers of non-reacted sodium were probed with XPS. It is also possible that the shift in peak position for Na 1s was too small to be observed with our set-up; the region spectra from which peak energy positions were obtained have an uncertainty of 0.19 eV.

CONCLUSION

In this work first results towards developing a growth procedure for Na-K-Sb photocathodes are presented. QE values up to 2% at 515 nm were achieved for a selection of six Na-K-Sb photocathodes grown by alkali co-evaporation and one sample grown by sequential method for reference. To reach higher reproducible values further growth iterations must be carried out. Optimizing substrate temperature, and flux of alkalis to ensure a stable Na-K-Sb lattice is formed is critical and will be central to further studies in the development of a growth procedure.

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