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DEVELOPMENT OF MULTI-ALKALI ANTIMONIDES PHOTOCATHODES FOR HIGH-BRIGHTNESS RF PHOTOINJECTORS

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Abstract

Multi-alkali antimonide-based photocathodes are suitable candidates for the electron sources of next-generation high brightness RF photoinjectors due to their excellent photoemissive properties especially, like low thermal emittances and high sensitivity to visible light. The former stands out, paving the way towards CW operations. Based on the previous successful development of Cesium Telluride photocathodes, we are now channelling our efforts toward an R&D activity focused on KCsSb and NaKSb(Cs) photocathodes. Parallel to that R&D activity, the development of a new dedicated photocathode production system at INFN-LASA is going on, in order to start the preparation of these photocathodes for their test in the PITZ photoinjector at DESY in Zeuthen. In this paper, detailed experimental results obtained from the KCsSb, along with a preliminary result from the NaKSb(Cs) photocathode material as well as the status of the overall project are presented.

INTRODUCTION

The modern advancement of electron sources has made possible to develop some pioneer application of electron accelerators such as X-ray free-electron laser (FELs), energy recovery linacs (ERLs), etc., which produce high brightness and ultra-short pulses of photon radiation with a dedicated pulse structure [1]. In order to obtain these features, a high QE and low intrinsic emittance-based photocathode would play a key role. In recent years, different studies show that multi-alkali antimonide-based photocathodes are the promising candidates for these applications. So, our current research domain is mainly focused on the development of these materials which can withstand, as an example, the continuous-wave (CW) operation planned for a future upgrade of the European XFEL facility, which would require continuous MHz extraction of bunches for the photoinjector system.

The research plan is to develop a visible sensitive multi-alkali based photocathode starting from a sequential vapor deposition method on a molybdenum plug and obtain an optimized and reproducible recipe. Such photocathodes would then be tested in the PITZ RF gun and results in terms of QE, lifetime, beam emittance and electron beam quality will be compared to the parameters of the currently used Cs_2Te photocathodes.

EXPERIMENTAL LAYOUT

Currently, we are developing a reliable and reproducible recipe of multi-alkali antimonide-based photocathodes specifically made of K-CS-Sb and Na-K-Sb in our R&D preparation chamber, in which we have implemented our past gathered data related to these types of material [2]. The current R&D activity has been developed in a dedicated UHV (Ultra High Vacuum) system [3] that consists of two inter-connected chambers which are used for cathode growth and storage of samples. The cathode production chamber is maintained with a base pressure in the 10^{-11} mbar range provided by eight SAES Getters NEG St707® modules and a 400 $l \cdot s^{-1}$ ion pump. It is also connected with a μ-metal chamber which hosts a Time-Of-Flight (TOF) spectrometer used for thermal emittance measurements [4].

A Laser Drive Light Sources (LDLS) system accompanied by a set of dedicated optical filters (in a range of 220 nm to 690 nm) is used to measure the spectral response of the photocathode. One Ar^+ and three He-Ne lasers are also used to cover the range from 457 nm to 633 nm.

Photocathode Preparation

Owing to the better handling, the photoemissive materials are produced on a simplified Mo substrate instead of the INFN real plug used in the production preparation chamber. These R&D samples are prepared from a thin slab of high purity molybdenum (99.95 %) through machining. Afterwards, these samples are polished to a mirror-like finishing (reflectivity > 54% @ 543 nm w.r.t. 57% theoretical [5]) to allow reflectivity measurements during and after the photocathode growth. All samples are ultrasonically cleaned before loading them into the UHV system. Before the deposition, each sample is heated up to 450 °C for at least one hour to remove the eventual residuals on the surface.

A custom-made source for Sb and commercially available dispensers for Cs, Na and K are used for the deposition. Each sample is carefully pre-heated, before starting the deposition and calibrated to have the proper evaporation rate during the cathode growth. The calibration is repeated before each growth process. The usual deposition rate is 1 nm/min.

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KCsSb PHOTOCATHODE

So far, a total number of 7 photocathodes have been produced, six of them have already been reported in previous papers [3, 6, 7] and are summarized in Table 1. Here in this report, we explored the thickness of Sb, K and Cs evaporated for the two typologies of photocathodes (i.e., 3 films for Sb 5 nm, 2 films for Sb 10 nm). All the thicknesses were measured by a QCM (Quartz microbalance) and are summarized in Table 2.

Table 1: Summary of Cathode Growing Parameters

Cathode	Sb [nm]	T_{Sb}-T_K-T_{Cs} [°C]	QE @ 514 nm [%]
KCsSb-1	10	120-150-120	$9{\cdot}10^{-3}$
KCsSb-2	5	120-150-120	1.9
KCsSb-3	10	60-60-90*	5.2
KCsSb-4	5	90-90-90	3.9
KCsSb-5	10	90-90-90	4.6
KCsSb-6	5	90-120-90	4.6
KCsSb-7	5	90-120-110	5

*increased from 60 °C to 90 °C during Cs evaporation as reported in [6]

For thin cathodes (i.e., KCsSb-4, 6, 7), the K/Sb ratio does not only depend on the Sb thickness but is also affected by the substrate temperature. In general, if we increase the substrate temperature up to 120 °C during K deposition the ratio is reduced, and this effect can correlate with a faster diffusion process between Sb and K [7].

Table 2: Evaporated Sb, K, Cs Thickness

Cathode	Sb [nm]	K [nm]	Cs [nm]
KCsSb-4	5 ± 0.9	41± 0.1	106 ± 0.5
KCsSb-6	5 ± 0.9	32 ± 0.1	117 ± 0.5
KCsSb-7	5 ± 0.9	34 ± 0.5	121 ± 0.5
KCsSb-3	10 ± 0.9	66 ± 0.5	313 ± 0.9
KCsSb-5	10 ± 0.5	75 ± 0.1	316 ± 0.5

Also, the Sb/Cs ratio depends upon the initial Sb thickness and usually the ratio is higher in Sb = 10 nm photocathodes compared to Sb = 5 nm photocathodes, which elucidates that likely a higher amount of Cs, in general, is deposited in Sb = 10 nm photocathodes. Along with that, a slight improvement of QE @ 514 nm has been noticed for KCsSb-7 compared to the rest of all thin photocathodes (i.e KCsSb-4, 6). Potentially it is due to the higher substrate temperature during the Cs deposition which enables a better chemical reaction and consequently a significant crystallization inside the material [8].

NaKSb(Cs) PHOTOCATHODES

Owing to the excellent photocathode properties such as high sensitivity, comparatively border spectral response and workability at a higher temperature, NaKSb(Cs) photocathode is considered a suitable candidate for our current application. So, a preliminary attempt was made to develop an S-20 (or NaKSb(Cs) photocathode in our R&D preparation chamber). So far there is a total number of two photocathodes produced.

Fabrication Recipes

The fabrication recipe is similar for both the photocathodes, except for the deposition of Sb (of different thickness). In the first cathode, we have deposited an Sb layer with a thickness of about 5 nm at 90 °C followed by K at 120 °C and Na at 130 °C. Afterwards, on top of it, we deposited Sb and Cs at 120 °C, but the final QE was 1% @ 543 nm for this first cathode. Because of the relatively low QE, we modified our recipe for the second cathode as follows:

1. Initially we deposited Sb until the reflectivity was fallen to 30 % from the initial value.
2. Afterwards, K and Na were deposited sequentially at 120 °C and 90 °C respectively until the QE reached a maximum value.
3. Thereafter, to restore the correct Na:K ratio, a small amount of Sb and K were added in an alternated manner until the peak of QE was obtained at 90 °C.
4. Then Cs was deposited until the sensitivity reached a maximum value at 90 °C.

The detailed QE (@ 543 nm) and reflected power history is reported in Fig. 1. Due to some technical problems, the change in reflected power were not recorded during the initial Sb deposition; that is why the reflected power curve is showing a constant line during the Sb deposition in Fig. 1.

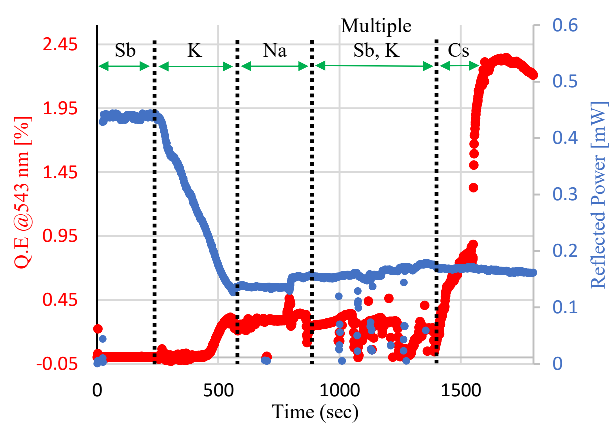

Figure 1: QE (red) and reflected power (blue) during deposition of cathode NaKSb(Cs)-2. The incident power @ 543 nm during photocathode growth was 1.9 mW.

The spectral response of NaKSb(Cs)-2 has been measured after the deposition and is shown in Fig. 2. We also tried to compare the spectral response behavior of a KCsSb (Sb = 5 nm) and NaKSb(Cs) photocathode and found a slight improved QE value for the NaKSb(Cs) cathode at a higher wavelength (typically the response to red laser light). Electron emission could be achieved up to an irradiation with 690 nm laser light (QE was 0.022%), demonstrating a broader spectral response of that photocathode.

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Probably this behavior is caused by the addition of cesium and antimony on the NaKSb material, which potentially could lower the overall electron affinity of the material [9, 10].

Here in this report we also made a comparative study related to the total thickness of KCsSb and NaKSb(Cs) photocathodes, which is reported in Table 3. We found that the total evaporated thickness of NaKSb(Cs) is quite lower compared to the KCsSb compound, which gives a natural advantage in terms of the final roughness of this photocathode. In fact, some recent studies show that usually, the final roughness of a photocathode depends on the film thickness [11]. However, it would be very interesting to test this type of photocathode in the PITZ RF gun. The results in terms of QE (at green wavelength), lifetime and robustness will then be compared to the parameters of the KCsSb photocathode in the near future.

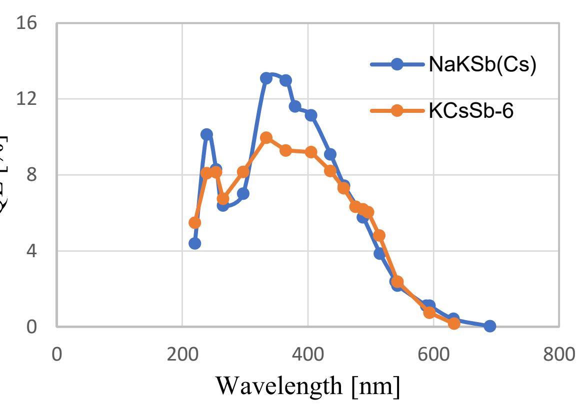

Figure 2: NaKSb(Cs)-2 photocathode spectral response.

NEW PRODUCTION SYSTEM

All the studies presented so far are based on photocathodes that have been grown and characterized in our R&D system. As the molybdenum substrates deployed here are not suitable to be loaded into an RF gun, we decided to build another UHV preparation chamber that works with the standard INFN Mo plugs. This system (currently under installation) is an improved version of the preparation system dedicated to Cs_2Te photocathodes. It will be equipped with the standard UHV devices (pressure gauges, a residual gas analyzer, and manipulators), two vacuum pumps (a combination of sputter-ion pump and non-evaporable getters), a newly designed Mo plug heater, several alkali metal dispensers (Cs, Na, K, Sb) and potentially, also instruments typical of surface science investigations. Although this system is thought to be a production unit that supplies cathode to photoinjectors, we can use it to support the R&D activity by producing cathodes with different recipes and techniques, such as co-evaporation of alkali metals.

The potentialities of this system are multiple: it allows the determination of the QE and film reflectance, both during and after the production process. Like the system dedicated to Cs_2Te, the possibility of measuring spatial homogeneity of QE is also maintained. In addition to those, we are planning to add two new characterization devices: an EDX or XRF analyzer and a momentatron. The first will give us information about the film thickness, chemical composition, and surface structure. The second, a TRAnsverse Momentum Measurement device (TRAMM), will let us evaluate the thermal emittance of the electrons emitted by the photocathodes even during production. The key difference of this method, compared to the standard ones, (which are based on electrons being accelerated in high-gradient guns), is that this measurement is performed in a "clean" environment, with accelerating voltages of a few kVs and allows having a prompt response to the changes in the photocathode growing process on the thermal emittance.

Table 3: Comparison of Cathode Parameters of KCsSb and NaKSb(Cs) Photocathodes. All the Thicknesses were Measured by Pre-calibrated QCM

Cathode	Evap. Thickness [nm]	QE @ 514 nm [%]
KCsSb-6	154 ± 2	4.6
NaKSb(Cs)	93 ± 1	3.9

CONCLUSION

The INFN LASA activity on photocathode sensitive to visible light is progressing. A stable recipe is now established for KCsSb photocathodes and further R&D is ongoing to establish a reproducible recipe for NaKSb(Cs) photocathodes. Along with this, exploration on different properties of these photocathodes is continuing. Parallel to this R&D activity, the development of a new dedicated photocathode production system at INFN LASA is in progress.

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