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INVESTIGATION OF K_2CsSb PHOTOCATHODES *

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Abstract

The interest in multi alkali antimonide photocathodes, e.g. K_2CsSb, for future ERL projects like BERlinPRO (Berlin Energy Recovery Linac Prototype) and MESA (Mainz Energy-Recovering Superconducting Accelerator) has grown in recent years. In particular for the case of RF-sources the investigation of the time response is of great importance.

In Mainz we are able to synthesize these kinds of photocathodes and investigate their pulse response at 1 picosecond level using a radio frequency streak method. We present on the one hand the cathode plant which is used for synthesizing the multi alkali antimonide photocathodes and on the other hand first measurements showing pulse responses of K_2CsSb at $\lambda = 400$ nm laser wavelength. Furthermore, an analyzing chamber has been installed, which allows investigation of lifetime under laser heating and in-situ measurements of the work function using a UHV Kelvin Probe.

INTRODUCTION

High average brightness beam applications all need a photocathode with high QE, long lifetime, low emittance and fast response. If no spin polarization is needed, these figures of merit all may be fulfilled by the group of (multi) alkali antimonide cathodes [1].

Having PEA (Positive Electron Affinity) conditions, the nature of these cathodes promises to have a faster response time ($10^{-13} < \tau < 10^{-12}$ s) than NEA (Negative Electron Affinity) cathodes like Cs(O):GaAs because the average electron energy is thermalized quickly below the energy threshold for photoemission [2]. Besides the commonly investigated FWHM or RMS pulse response, we present measurements of the longitudinal tail of these cathodes. Such tails could be generated for instance by temporal trapping in localized electronic states inside the cathode, which may lead to a delayed response albeit at very low intensity levels. High current machines have to minimize this effect to be able to run without damage or high radioactivity.

Fast response for alkali antimonides has been shown to be compatible with < 1 ps response of a Cs_3Sb cathode at an instrumental resolution of $\sigma = 2$ ps [3]. Our results below will confirm this for a K_2CsSb cathode at a improved resolution of $\sigma \approx 1$ ps. Monte Carlo simulations indicate a sub-ps response [4].

Time response measurements have been carried out at the MAMI (Mainzer Mikroton) test source PKAT (Polarisierte Kanone Test) successfully for a long time [5], [6]. During the last years, we have improved the ability for measuring long tails of the initial bunch at a high dynamic range [7].

It is difficult to manage the purchase and transport of alkali antimonides under vacuum if a commercial vendor is part of the process. We have therefore decided to synthesize the cathodes in our own lab, a similar decision has also been made by others groups, e.g. [8], [9]. Therefore, a separate cathode preparation chamber, the cathode plant, has been commissioned in Mainz with the goal to qualify cathodes for our ERL project MESA.

Since the generation of 10 mA average currents needs considerable laser intensities, we have additionally investigated the effects of laser induced cathode heating.

EXPERIMENTAL SET-UP

Photocathode Plant

UHV is essential for the cathode growing process. Semiconductor photocathodes are very sensitive tow water and oxygen; therefore, we use an combination of IGP (GammaVacuum TiTan300T) and a NEG Pump (SAES CapaciTorr). Baking out is limited to 150 °C due to the used AlfaVakuo (formerly Alvatec) dispensers, which contain an indium sealing protecting the alkali alloy from handling in air. As residual gas should not contaminate the alloy during baking, the indium sealing must not melt.

An RGA (Dycor LC-D 200) and a Bayard-Alpert gauge (Vacom Atmion) control the pressure conditions. Vacuum in the low $p = 1 \times 10^{-10}$ mbar range can be achieved with H_2 as the dominating gas. During potassium evaporation the pressure rises to 5×10^{-8} mbar, $p(H_2O)$ and $p(O_2)$ are in the 5×10^{-11} mbar region. Vacuum conditions for cesium and antimony steps are even better.

Partial pressure of antimony and the alkalis cannot be detected with the RGA during evaporation. Therefore, a thickness monitor (LewVac) is essential for providing information about the metal flux.

In the present set-up, further information on the status of the growth process can only be inferred from the photo electron yield. Due to budget restrictions, equipment yielding structural information of the deposited layer like XPS has not been purchased so far.

Figure 1 shows a schematic inner view of the preparation chamber. K_2CsSb photocathodes are synthesized by sequential deposition mainly after the classical recipe of Sommer [10] beginning with a thin antimony film on a metal substrate reacting with K and Cs vapor at an elevated temperature.

The substrate is positioned in a MAMI standard cathode holder (puck). Its position can be changed by a UHV manipulator. The crystal wheel allows storage of eight different pucks, in practice up to four pucks are used.

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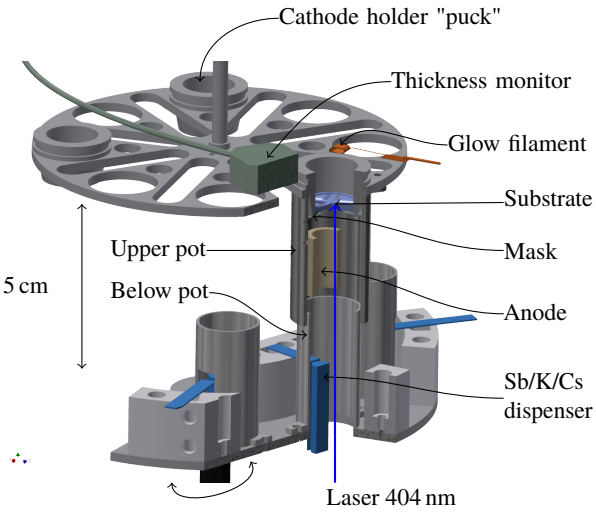

Figure 1: Schematic inner view of the cathode plant. The two stacked pots should prevent a coating of the whole chamber.

A glow filament (OSRAM 64663 HLX) heats the substrate from a distance of ≈ 15 mm.

We have used SUS (Steel Special Use Stainless), Mo, Cu, GaAs as substrate materials so far, achieving highest QE with SUS. At a distance of ≈ 5 cm V-shaped AlfaSources are mounted, the needed flux is adjusted and controlled via thickness monitor.

QE is measured in reflective mode using a blue laser diode (Thorlabs CPS405, $P = 4.7$ mW) illuminating through a window below the glow filament position.

The typical procedure is

- cleaning the substrate with high temperature (> 300 °C) at least 1 h
- deposition of 10 nm – 20 nm Sb
- deposition of K until QE reaches a plateau
- deposition of Cs until QE reaches a plateau

Spectral Response

Using a cold (Thorlabs LEDWE-15) and a warm white LED (CREE XP-L U2) with bandpass filter allows a cheap, fast and easy set-up for a spectral response measurement. QE for the major values of the interesting wavelength spectrum (450-650 nm) can be determined, see Fig. 4. Using an iris and two lenses (concave and convex), the beam spot can be focused to a diameter of 3 mm achieving power values (9- 35 µW) which are sufficient to get a photo electron yield.

Lifetime Measurements

Two lifetime conditions have been investigated: The first one is the vacuum lifetime, which is expected to be months or even years if vacuum conditions are stable and no charge is extracted from the cathode. For the second condition, one has to consider that the MESA source will be operated with currents exceeding 10 mA, which requires laser intensities of the order 1 W. Cathode lifetime must not be shortened by this intensity. Otherwise, the decrease of lifetime will be accelerated due to the necessity of increasing the laser power to keep the current constant. This would quickly lead to the collapse of QE. We therefore have investigated the lifetime under relevant laser powers.

For these investigations, an additional UHV analyzing chamber has been added to the cathode plant. Additionally an EPICS based control system has been commissioned. It controls the experiment in the following way: A large heating laser power is applied only when the cathode is grounded, i.e. no electron current is produced during the irradiation. Periodically, the heating laser is reduced in intensity and the cathode is biased, which allows to observe the development of QE over many hours/days.

A schema of the set-up is presented in Fig. 2. The used

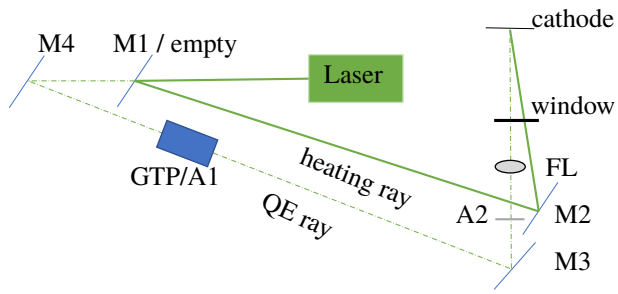

Figure 2: Schema of lifetime measurement under laser heating. M1-M4: mirrors, A1-A2: attenuator, FL: focusing lense.

diode pumped solid state laser (Roithner RLTMGL) is capable of up to 2 W heating power at $\lambda = 532$ nm. The heating ray passes two mirrors (M1, M2) before entering the vacuum window. The laser beam was directed towards the cathode without the need of focusing elements, which resulted in a diameter of ≈ 3 mm on the cathode.

Sitting on a dual-position slider, M1 can be swapped with an empty position, allowing the beam to be used for QE measurements. To ensure low power, a Glan-Thomson polarizer (GTP) is used as an attenuator, where only the extraordinary ray is transmitted and passes an optional additional attenuator A2.

Lifetime τ is defined as the time when QE is reduced to a factor 1/e of the initial value QE_0. One can identify τ as the reciprocal value of the exponential decay constant λ

$$QE(t) = QE_0 \times e^{-\lambda t} = QE_0 \times e^{\frac{-t}{\tau}} \quad (1)$$

By fitting the parameter τ, the lifetime can be determined.

Time Response Measurements

Usually, the transport from the cathode plant to PKAT takes about 1 hour. We use a load lock, which is baked

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out at 120 °C for 2 days and a four-way cross as transport chamber pumped by an IGP (GammaVacuum Ti-Tan45S) and a NEG module (GammaVacuum N50) to below $p = 1 \times 10^{-11}$ mbar. Before the cathode can be moved to the actual source, it has to pass a GaAs preparation chamber.

Figure 3 illustrates the measurement principle at PKAT, a detailed description of the apparatus is given in earlier publications [5], [7].

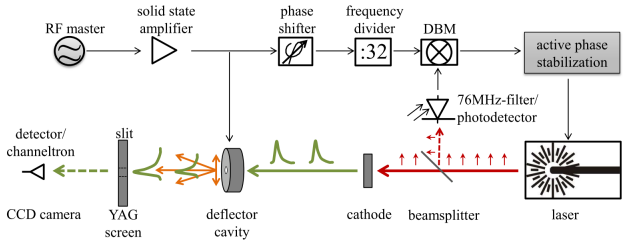

Figure 3: Schema of the time response measurements at PKAT. [11]

Here, only the basic ideas are presented: The radio frequency streak method is based on deflecting the temporal (longitudinal) bunch into a transverse one using a deflecting cavity. Femtosecond laser pulses are produced in phase with the RF (2.449 GHz) and generate electron bunches with a repetition rate of 76 MHz (32nd subharmonic of RF). Since laser and cavity are synchronized, shifting the phase of the laser allows to record the bunch profile sequentially by a channeltron after passing a slit or directly on a YAG screen. The detected intensity distribution represents a convolution of the real response of the cathode with the resolution of the apparatus and other effects, e.g. transit time spread. The experimental resolution is estimated to be 1-2 ps. One key to high resolution is to have a very small beam spot at the slit, since this is one of the biggest contributions to the measured signal. We have achieved an effective contribution of 0.431 ps (see Fig. 7) of the beam size to the time resolution.

RESULTS AND DISCUSSION

Cathodes Properties

Many cathode preparations with QE above 10 %, some above 20 % have been achieved. Nevertheless, we are still improving reproducibility since the production is not yet ideal. On the one hand, for a long time the substrate temperature during preparation was not clear due to a lack of glow filament calibration. On the other hand, though they have some advantages over SAES dispensers like a larger capacity, AlfaSources dispensers are known for reproducibility issues [8]. Glow filament calibration has been carried out. We expect more reproducibility in the future. Figure 4 shows QE measurements at different wavelengths for three cathode samples along with values from Sommer [10].

We have used two cathodes (grown on Mo and SUS) for time response and one (grown on SUS) for lifetime measurements.

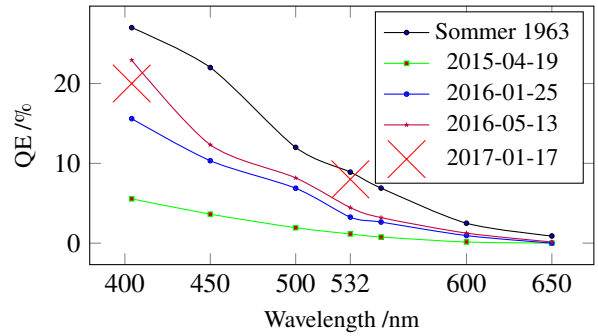

Figure 4: Spectral analysis for three example cathodes are shown. QE for cathode #2017-01-17 reached 9 % at $\lambda = 532$ nm. Lines are to guide the eye only.

Cathode #2017-01-17 was measured with nearly $QE = 9$ % for green light. This is comparable to results obtained by other groups [4].

Lifetime

All produced cathodes were stable at the cathode plant chamber pressure. Some cathodes even improved QE during storage indicating reorganization of the crystal structure over time, e.g. QE of cathode #2016-01-25 rose in a few weeks from $QE = 16$ % up to $QE = 20$ %. Vacuum lifetime for K_2CsSb can be extrapolated to months, even years.

Nevertheless, alkali antimonides are known to decrease in QE after transport using a baked out load lock system [9], which we can also confirm.

The lifetime under laser heating was expected not to be very high for the investigated cathode since the thermal conductivity of the cathode holding system has not been optimized for this application. Assuming 25 % reflection at green light for K_2CsSb [12], a considerable fraction of laser power is absorbed by the thin cathode layer (< 100 nm). Transmitted laser power can be reflected or absorbed by the substrate. Due the to low thermal conductivity of SUS, the heat would not dissipate as effectively as for instance with Mo as substrate, as simulations in [13] indicate.

Figure 5 illustrates the QE decay for $P_{\mathrm{Heat}} = 300$ mW, a fit to the data obtains a lifetime of $\tau \approx 31$ h.

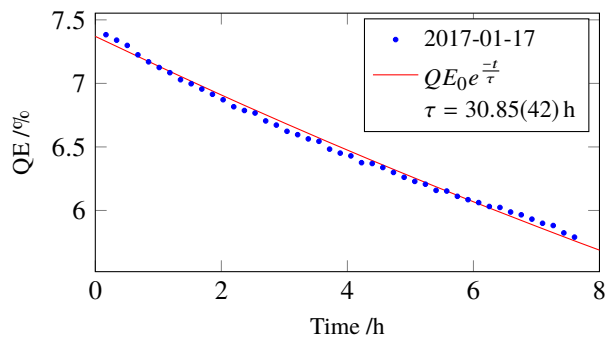

Figure 5: Representative lifetime measurement under laser heating with $P_{\mathrm{heat}} = 300$ mW.

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The intensity used in this experiment can be considered typical for 10 mA operation at MESA with a blue laser since a $QE = 10\,\%$ cathode would yield $33\,\mathrm{mA\,W^{-1}}$. The corresponding lifetime is not sufficient to sustain long-term experiments. Notice that for laser powers up to $\approx 200\,\mathrm{mW}$ QE even improved for a while, which indicates a faster reorganization at elevated temperature until crystal defects begin to dominate and lower the performance of the cathode.

As Fig. 6 indicates, increased laser power is reducing lifetime of the cathode. At 500 mW, the K_2CsSb would survive only a few hours.

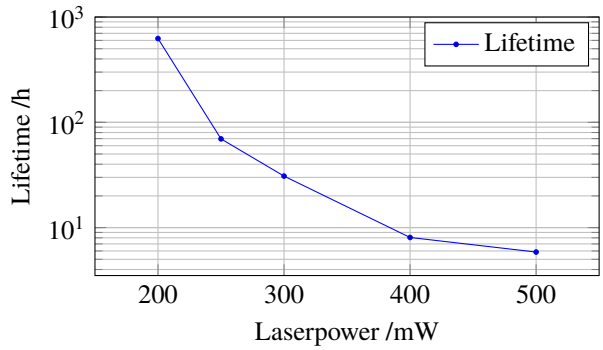

Figure 6: Lifetime measurements for cathode #2017-01-17. Lifetime drops significantly with higher laser power. Line is to guide the eye only

The results show mainly two things:

- a high QE cathode is indispensable, the higher the QE the lower the laser power
- though non thermal effects like non-linear photochemistry could also explain the observations, the most probable explanation seems to be thermal decomposition of the photocathode. It therefore seems necessary to achieve a better thermal conductivity.

Time Response

Time response measurements of two K_2CsSb cathodes have been performed so far. We measured a massive QE decrease (down to 0.0001 %) for the first cathode due to a vacuum incident after opening the valve to the GaAs preparation chamber, where the pressure rose to 1×10^{-6} mbar for about 30 s. It is remarkable that in spite of the very serious reduction of the QE, the pulse response was roughly similar to the cathode investigated later. Due to unknown crystal properties, time response results of this cathode will not be discussed here.

We were able to successfully measure the time response of another K_2CsSb cathode, though QE dropped also this time (1 % at $\lambda = 405$ nm) after transport, probably due to a small leakage of the oxygen valve at the GaAs preparation chamber. Notice that time response experiments are limited to a small bunch charge (< 0.1 fC) due to space charge effects, so a high QE cathode is not needed necessarily.

Two measurements of the same cathode are presented in Fig. 7.

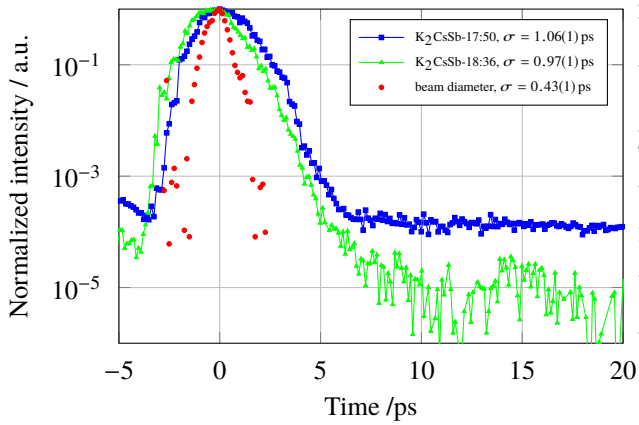

Figure 7: Time response and longitudinal halo of K_2CsSb. The blue curve represents the measurement with the largest halo observed. The green curve is the typical measurement with a very small halo. The red curve represents the transverse beam diameter, which contributes $\sigma \approx 0.43$ ps to the time resolution.

The result show a very fast response of $\sigma = 970$ fs for K_2CsSb, which is within the resolution of our apparatus. Thus, the upper limit of 1 ps can be confirmed.

Time response is faster than the NEA photocathode Cs:GaAs, and also the longitudinal halo is about a factor 3-10 lower than we have found for CsO:GaAs, making this photocathode favorable for RF sources. See also [11].

The fluctuations given in Fig. 7 (green curve) for the time > 10 ps are assigned to background of the channeltron. Artifacts of laser reflections e.g. at the vacuum window are responsible for the remaining signal.

CONCLUSION AND OUTLOOK

In conclusion, K_2CsSb shows the expected potential for a high QE cathode with sub-picosecond response time and a very low longitudinal halo, qualities which are very important for SRF/RF electron sources. Lifetime under laser heating is relatively short on a SUS substrate, probably indicating fast chemical reactions taking place at elevated temperature which damage the optimal conditions for the photo electron yield. In the near future, we will try better thermal arrangements with the goal to improve the lifetime under high intensity laser irradiation.

Furthermore, it is planned to install a Kelvin Probe (McAllister KP6500) at the analyzing chamber to measure the work function in-situ. This tool will also give information about changes of the surface conditions.

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