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ALTERNATIVE NEGATIVE ELECTRON AFFINITY ACTIVATION STUDIES AT HERACLES

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Abstract

A new growth chamber at the High ElectRon Average Current for Lifetime ExperimentS (HERACLES) beamline at Cornell has been installed enabling Negative Electron Affinity (NEA) activations of GaAs using Cs-Sb-O and Cs-Te-O recipes. These activation recipes have been shown to be more robust against vacuum poisoning when measured at low voltages and currents. In this proceeding we present initial charge lifetime measurements of these recipes when operated in a high voltage, high current electron gun.

INTRODUCTION

Many particle accelerator applications rely on the generation of high-average current bright electron beams from a photoinjector. Electron-based strong hadron cooling techniques, particularly those envisioned for the LHeC [1] and the EIC energy recovery linac (ERL) [2], may demand average currents as high as 100 mA, while high current ERLs designed for EUV lithography could require a 10 mA beam current [3] and up to 100 mA for medical isotope production [4]. High average current spin-polarized electron production is highly sought after across various nuclear and high energy physics applications [5–8] and electron microscopy technologies [9–11].

For high current applications, semiconductor-based photocathodes are a solution to these demands. They boast high quantum efficiencies (QEs) with visible or Near Infrared (NIR) photons, leveraging the availability of commercial, high-power laser systems. However, NEA semiconductor based photocathodes are sensitive to vacuum conditions, leading to accelerated degradation compared to metal photocathodes [12, 13]. Within semiconductors, the only photocathode used for spin-polarized applications has been negative electron affinity (NEA) GaAs [14, 15]. While GaAs can achieve high QEs and spin polarizations (>90% with strained structures [16]), it has a characteristically short operational lifetime due to the NEA layer's (Cs and O_2) extreme sensitivity to residual gasses (chemical poisoning) and weak adhesion to the GaAs surface. Alternative NEA activation layers (Cs_3Sb, CsTe) have demonstrated improved robustness in chemical poisoning with respect to dark lifetime [17–21]. High current operation of a GaAs photocathode in RF guns is challenging due to the typically higher vacuum levels compared to DC guns. However, they have been successfully used in DC guns for a variety of applications [5, 6, 22]. At Cornell, operation as high as 52 mA was achieved with a GaAs photocathode for a short time [23].

During high current operation, there are other effects that contribute to the degradation of the photocathode QE. Ion back-bombardment occurs when the electron beam ionizes residual gases in the vacuum, causing positively charged ions to accelerate towards the cathode and degrade its performance [22, 24, 25]. As the QE degrades, higher laser intensities are required to maintain beam current levels, which in turn causes a thermal desorption of the NEA layer [26, 27]. While ion back-bombardment is considered the most significant contributor to QE decline in high current environments, strategies such as limiting the photocathode active area, increasing the laser spot size, placing the active area away from the electrostatic center [22], and applying a positive bias to the anode [28] have shown efficacy in mitigating this effect. Nonetheless, ion back-bombardment remains an issue, particularly for ions generated inside the cathode-anode gap, near the photocathode.

HERACLES Beamline

The High ElectRon Average Current for Lifetime ExperimentS (HERACLES) beamline at Cornell University, is dedicated to studying the operational lifetime effects of these photocathodes [29]. Operating at 200 keV with up to 10 mA average beam current, HERACLES focuses on investigating the resilience of photocathodes during high current operations. One of the major research thrusts in HERACLES is testing the robustness of alternative NEA activation techniques for GaAs, such as Cs-Sb-O and Cs-Te-O based recipes. As reported in [17–21], activating GaAs to NEA with Cs-Sb-O and Cs-Te-O have been effective ways to improve the dark lifetime of the photocathode when measured in a low current environment where ion back-bombardment and thermal desorption are negligible.

In HERACLES, we aim to perform the first ever systematic study of charge lifetime obtained with these alternative activation recipes (compared to the traditional Cs-O approach). The charge lifetime will be measured as a function of critical activation parameters such as Sb or Te thickness. An initial study performed in HERACLES compared the high current performance of GaAs photocathodes activated using Cs-O and Cs-Sb-O while operated at 488 nm [30]. No large enhancement in lifetime was observed; however, it is important to note that in this study the photocathodes activated with Sb had to be grown in a separate chamber from the gun and transferred with a vacuum suitcase post-growth. This process required nearly 24 hours and the cathode being

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exposed to higher vacuum levels, leading to QE loss due to chemical poisoning before operational lifetime measurements could begin. In contrast, photocathodes activated solely with Cs-O could be grown in a chamber connected to the gun and promptly transferred with minimal QE degradation.

To make a more accurate comparison of GaAs charge lifetimes activated with the traditional Cs-O approach or the alternative activation recipes based on Cs-Sb-O and Cs-Te-O, in HERACLES we have installed a new growth chamber capable of performing all three activation types. In this paper, we report the installation of this new growth chamber, along with successful growth and dark lifetime measurements and further report on preliminary high current lifetime measurements of Cs-O and Cs-Sb-O NEA activated GaAs photocathodes in HERACLES.

GROWTH CHAMBER

The new growth chamber is attached to the auxiliary vacuum chambers in HERACLES and is equipped with all the necessary instrumentation required to perform GaAs NEA activations with Cs-Sb-O and Cs-Te-O. Bulk GaAs photocathodes may be mounted on a puck and inserted into the growth chamber for NEA activation. The puck is held and manipulated with a jaw that can be opened, closed and rotated with a dual-axis rotary actuator. The jaw is electrically isolated and can be biased for QE measurements during activation. The chamber has 3 water-cooled evaporative effusion cells with shutters from Dr. Eberl MBE-Komponenten with respective crucibles of Sb, Te and a Cs sources. The raw Sb was purchased from Alpha, Inc and Te pellet sources were purchased from United Mineral Corp. The Cs source is an amalgam of Cs and indium, as the incorporation of indium raises evaporation temperature of the material such that the chamber may be baked to achieve low pressures (ordinary Cs evaporates at around 90 °C, whereas our amalgam evaporates around 180 °C) and is also air stable, simplifying chamber maintenance.

The growth chamber is further outfitted with a substrate heater, quartz microbalance (QMB) to monitor deposition thickness, and leak valve for controlled oxygen flow during growths. After assembly and bake, a base pressure of 1e-10 Torr was achieved, as indicated by a cold cathode gauge (CCG). Pumping is provided by two combination NEG-ion pumps.

RESULTS

Growths

After the construction of the growth chamber, the deposition fluxes of the element sources were calibrated with the QMB. Before high current measurements, preliminary GaAs photocathode activations were performed in the growth chamber, and dark lifetimes were measured for a standard Cs-O activation and a Cs-Sb-O activation. Zn-doped (9×10^{18} cm^{-3} carrier concentration) single crystal (100) GaAs wafers were procured from AXT-Tongmei, Inc. To remove surface oxides, a chemical etching procedure consisting of a de-ionized (DI) water rinse, a 30 second immersion in a 1% HF solution, and a final rinse with DI water was performed. The sample was then mounted and indium soldered onto a stainless steel puck and inserted into the growth chamber through a vacuum load-lock. Photocathodes were annealed at 600 °C for 72 hours prior to NEA activation.

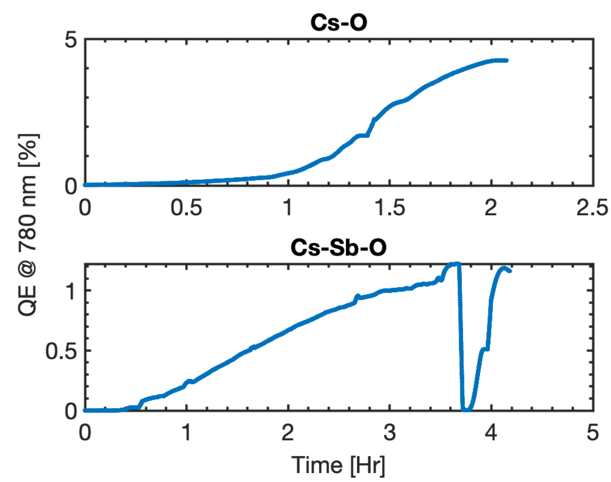

Figure 1: Example NEA activations of GaAs photocathodes with either a Cs-O co-deposition layer or a Cs-Sb-O layer.

For Cs-O NEA activations (see Fig. 1), the Cs-In effusion cell was heated to 195 °C and Cs was evaporated onto the GaAs surface. Throughout the growth, the photocathode QE was monitored with a 10 µW 780 nm laser. Cs deposition continued until a peak QE was achieved. At this point, the oxygen leak valve was opened slightly to co-deposit Cs and O. Deposition stopped when the final peak QE was achieved.

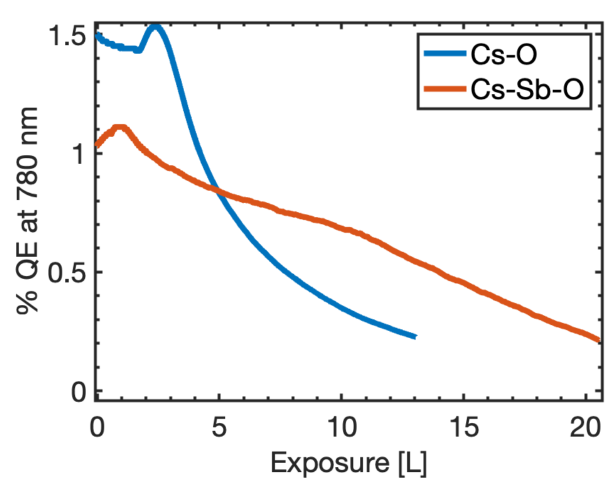

Figure 2: Dark lifetimes of GaAs photocathodes activated to NEA with Cs-O and Cs-Sb-O. As expected, the Cs-Sb-O's dark lifetime was a factor of 2 larger than that of the Cs-O activation.

For Cs-Sb-O activations (see Fig. 1), a Cs-O activation was

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performed until the QE peaked. Once peaked, the Cs shutter and oxygen leak valve were closed and the shutter of the Sb effusion cell (heated to 350 °C) was opened resulting in a steep decrease in QE. After the desired Sb thickness was achieved, the Sb cell shutter was closed and the source was cooled. Another Cs-O co-deposition was performed until the QE peaked again. After successful growths, dark lifetime measurements were performed with the two activation methods on a fresh GaAs sample. As shown in Fig. 2, the GaAs photocathode activated with 0.1 nm of Sb has a dark lifetime of about twice as long as the ordinary Cs-O GaAs.

High Current Runs

Having confirmed the Sb-based activation resulted in a longer dark lifetime, we are now beginning to perform high current charge lifetime measurements in HERACLES. In Fig. 3, we show preliminary data obtained with the two growth methods. The Cs-O activated GaAs photocathode was run with 0.5 mA and the Cs-Sb-O activated GaAs photocathode (0.2 nm of Sb) was run with 1 mA. A Millenia 532 nm laser was used during beam operation. For each charge lifetime run, the beam trajectory and shape is observed on BeO viewscreens at a low current (typically 100 nA). Magnetic correctors are used to optimize the beam trajectory and minimize beam distortions. During operation at high current, additional adjustments to the correctors are made to minimize the beamline pressure which is typically $\approx 8 \times 10^{-11}$ Torr at 1 mA beam current and $\approx 4 \times 10^{-11}$ Torr at 500 µA.

As can be seen in Fig. 3, the Cs-O growth degrades by about 13% during the first 3 C of beam extraction while the Cs-Sb-O remains significantly flatter. Although preliminary, this may indicate Cs-Sb-O to be more robust even when operated at high current. In HERACLES, we plan to perform numerous additional runs to determine the efficacy of Cs-Sb-O activations.

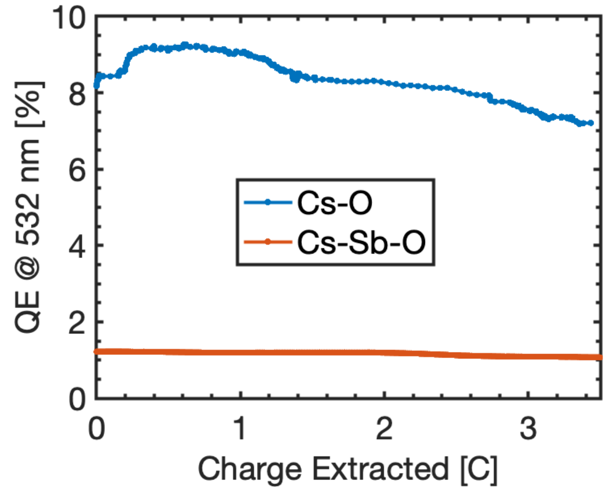

Figure 3: Charge extraction lifetimes of GaAs photocathodes during high current operation. The Cs-O activated GaAs was run at 0.5 mA and when exponentially fitted, displayed a 1/e = 16.3 C. The Cs-Sb-O photocathode was operated at 1 mA and displayed a 1/e = 25.4 C.

CONCLUSION

A new growth chamber has been recently added to the HERACLES beamline. This new addition facilitates the activation of GaAs through Negative Electron Affinity (NEA) using specialized recipes involving Cs-Sb-O and Cs-Te-O compounds. These activation techniques have demonstrated heightened resilience against vacuum degradation. The first GaAs NEA activations and their high-current lifetimes have been reported.

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