GROWTH AND CHARACTERIZATION OF BIALKALI PHOTOCATHODES FOR CORNELL ERL INJECTOR*

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Abstract

The requirements for high quantum efficiency in the visible spectral range and an increased lifetime as compared to cesiated GaAs can be met by multi-alkali photocathodes, either CsKSb or NaKSb. In this paper we detail the procedures that allow the growth of these thin films suitable for the ERL photoinjector operating at Cornell University. Quantum efficiency, spectral response, and surface characterization of deposited samples are presented. A load-locked multi-alkali cathode growth system is also described.

INTRODUCTION

The photoinjector for the ERL prototype being developed at Cornell University is foreseen to provide a high average current up to 100 mA [1]. In order to limit the power needed for the driving laser beam to a reasonable range (~10 Watts average) such a photoinjector will require photocathode materials that provide electrons with a quantum yield of several % when illuminated with visible light [2].

GaAs with a negative affinity terminated surface could satisfy those needs providing electrons with a Quantum Yield (QE) exceeding 10% at 532 nm with a sufficiently prompt response (below 1 ps) and with thermal emittance as low as 0.4 μm/mm-rms [3].

GaAs suffers from a limited lifetime due to the extreme sensitivity of the activation layer to the back bombardment due to ions generated by electron beam impact with residual gas molecules, which are accelerated towards the cathode itself [4]. Even with long and complex optimization the charge extracted from a GaAs photocathode from a single laser spot does not exceed about 600 Coulomb (1/e lifetime) at a current levesl of 5-10 mA [5]. Even though the surface can be readily re-cesiated to restore its Negative Electron Affinity (NEA) condition or a new laser spot can be chosen to prolong the cathode's lifetime, more robust photocathodes are highly desirable for uninterrupted high average current operation.

Photomultiplier industries routinely produce photosensitive layers based on multialkali antimonide semiconducting materials that provide quantum efficiencies exceeding 10% when illuminated with green light [6].

The Boeing normal conducting RF gun operating with CsKSb (typ. QE 8% at 527 nm) photocathode demonstrated operation at 32 mA average current (setting the average current world record for photoinjectors) but the lifetime of the photocathode was limited to few hours due to the poor vacuum conditions in the normal conducting RF gun [7].

The DC gun operated at Cornell for the ERL injector prototype provides an extremely low vacuum level in the range of 10^{-10} Pa [8] suitable for operating multialkali photocathode with an expected lifetime of hundreds of hours [9].

With the aim of testing these multialkali antimonide cathodes in the DC gun, a UHV deposition chamber has been designed, built, and operated in conjunction with a vacuum suitcase allowing growing CsKSb photocathodes and easy transfer of them into the DC gun by keeping them always under vacuum levels never exceeding $1x10^{-9}$ mbar.

EXPERIMENT

Deposition UHV Chamber

Figure 1 shows the UHV chamber for growing multialkali antimonide photocathodes. The chamber allows the puck with the substrate for photocathode deposition to be inserted through the vacuum suitcase without breaking the vacuum and thus avoiding a bake of the chamber before deposition. The deposition chamber is kept at UHV with a 500 l/s ion pump (Varian model VacIon Plus 300) and is equipped with: a Residual Gas Analyzer (RGA) mass spectrometer to constantly monitor the residual gas composition (SRS model RGA200); a cold cathode ion gauge (MKS model 421, controlled with MKS model 943); Quartz microbalance thickness monitor (INFICON model SQM160); puck (cathode holder) and substrate heater (built using an Heatlabs model 101135); K type thermocouple spot-welded to the puck saddle to measure the substrate temperature. A water cooled cold finger is used to quickly cool down the puck/substrate assembly. A ring shaped electrode (biased up to 100 V) is in front of the cathode to collect the photocurrent when a light source is directed at the cathode surface. With the light source modulated with a chopper, the emission current is measured using a lock-in amplifier (SRS model 830);

Alkali Sources

In order to conduct an intensive R&D program on growth and characterization of multialkali photocathodes we choose for our experiment ALVATEC alkali metal sources mainly due to their high capacity in terms of stored alkali metals. Moreover during the release of alkali vapors, which is achieved by heating a bismuth-alkali alloy, the outgassing during the process is much lower

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compared with commonly used metal chromate based dispensers.

A drawback of these ALVATEC sources is that once the indium seal that prevents air exposure is broken during the first activation they have to be stored under vacuum. In order to prevent cross-contamination and to avoid air exposure of the sources each alkali source assembly is engineered with a long bellows and a gate valve allowing dispensers to be isolated from the main chamber and with its vacuum maintained by a 20 l/s ion pump.

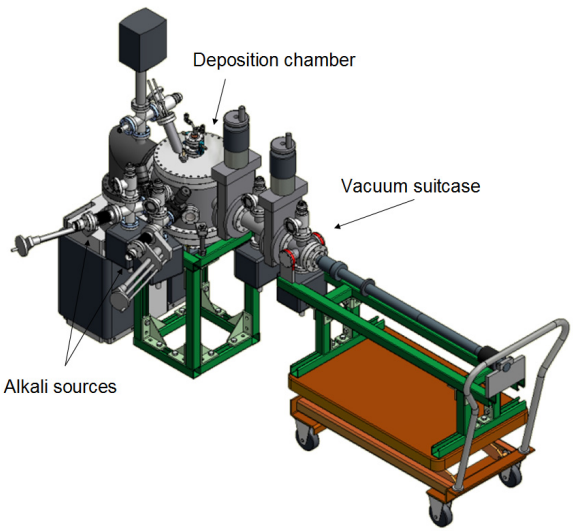

Figure 1: 3D drawing of the assembled UHV deposition chamber and vacuum suit.

Substrate and Puck

The 35 mm diameter substrates used for the growth of multialkali photocathodes were cut from 100 mm Si(100) heavily boron p-doped wafers with a resistivity of .001-.005 Ω-cm rinsed in 2% hydrofluoric acid solution for 2 minutes to remove the oxide layer. The cleaned substrate is then indium soldered to a molybdenum puck and secured in place by a crimped soft tantalum cup.

Load Lock Vacuum Suitcase

The load lock vacuum suitcase (fig. 1) consists of a magnetic translator arm connected to a small vacuum cross equipped with a cold cathode gauge and a small ion pump. An all metal gate valve is used to isolate the suitcase containing cathode during the transfer from deposition chamber to the load lock chamber of the photoinjector gun. The matching between the vacuum suitcase and either the deposition chamber or the load lock of the photoinjector is provided by a bridging vacuum cross equipped with a small ion pump that is connected to the entrance gate valve of the two systems.

Light Sources

The light sources used for measuring the QE of the cathode are a small solid state laser emitting 0.7 mW at 532 nm and a 200 W enhanced metal arc lamp (Newport model 66456) coupled to a monochromator (Cornerstone 130) and silver plated concave mirror to illuminate the surface of the cathode with wavelength ranging from IR to UV. The light power is measured using a powermeter (Newport model 842-PE) coupled with a UV enhanced Silicon photodetector (Newport model 918D-UV-OD3).

Control Software

All the instruments connected to the deposition chamber are remotely controlled with Labview software via RS232 commands. The use of this software provides constant recording of the status of each device allowing us to monitor the deposition process and easily reproduce experimental conditions in the future.

Deposition Procedure

The growth of the CsKSb photocathode follows this procedure:

- The substrate is heated to 600˚C to remove the hydrogen passivation from the Si surface
- Temperature is lowered to approximately 80 ˚C and then evaporation of 10 nm of antimony is performed
- Evaporation of the K is carried out while the substrate is slowly cooling down and the quantum yield is constantly measured until a peak on the photocurrent is reached
- When the substrate temperature falls below 40˚C Cs evaporation starts until the photocurrent reaches a maximum
- The substrate is allowed to cool down to room temperature.

With this procedure we have grown CsKSb photocathode with stable QE in the range of 1-5% at 532 nm (fig. 2).

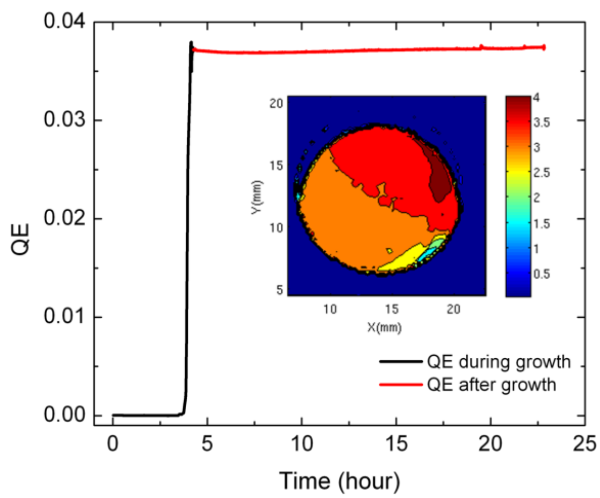

Figure 2: Quantum efficiency recorded at 532 nm during the growth procedure and after the growth. The QE is stable for 20 hours in a vacuum of few 10^{-8} Pa. The inset shows the QE map at 532 nm recorded 3 weeks after the storage in the load lock of the DC photoinjector gun.

Results and Discussion

The spectral response of a typical CsKSb photocathode grown as described in the previous section is shown in figure 3. This graph reports the QE measured at 532 nm being 3.7% while the yield at the operating laser wavelength of the ERL photoinjector, 520 nm, reaches 5.3 %.

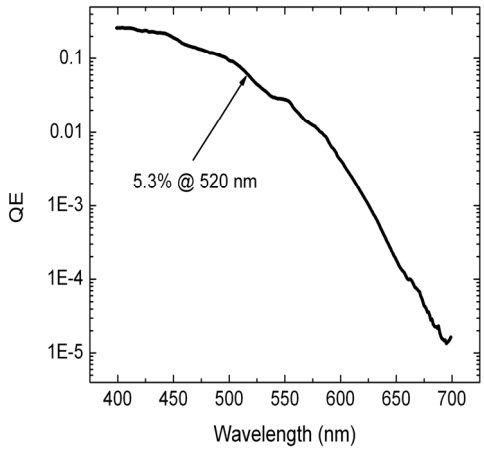

Figure 3: Quantum efficiency versus photon wavelength measured in the range 700-400 nm. The QE at the ERL injector drive laser wavelength is 5.3%.

The QE map reported on the inset of figure 2 shows that, despite the design of the metal evaporating sources pointing towards the centre of the substrate, the resulting cathode displays non-uniform emission properties. We believe that this could be due to a non-uniform flux of chemical species coming from the sources or to an imperfect alignment of the sources within the UHV growth chamber. All sources have been chosen to have the shape of a small diameter (~5 mm) pipe pointing towards the centre of the Si substrate with small angles with respect to puck axis (15° for Cs and K, 10° for Sb) with a distance between substrate surface and the end of each pipe of about 5 cm. This particular geometry, somewhat similar to the one used in molecular beam epitaxy, was chosen in order to maximize the flux of evaporated species on the substrate. But due to the limited distance between the sources and the substrate the non uniformity of the flux is enhanced in the photoelectron yield as seen in the QE map.

AFM surface analyses have been carried out on one the photocathodes to retrieve information on surface morphology and in particular surface roughness, since this parameter strongly affects the achievable photocathode performance by increasing the thermal emittance [10]. Nevertheless it should be mentioned that AFM measurements have been carried out after exposing the photocathode to open air. Due to the strong reactivity of CsKSb the morphology could have been affected by chemical reactions resulting in differences from that obtained after the growth. The AFM surface map (Fig. 4) shows that the photocathode surface is structured on nanometre scale with an rms value of the thickness variation of about 35 nm and spatial modulation on the film plane with about twice of this value. According to numerical models the increase in thermal emittance due to surface roughening should be about 30% [10].

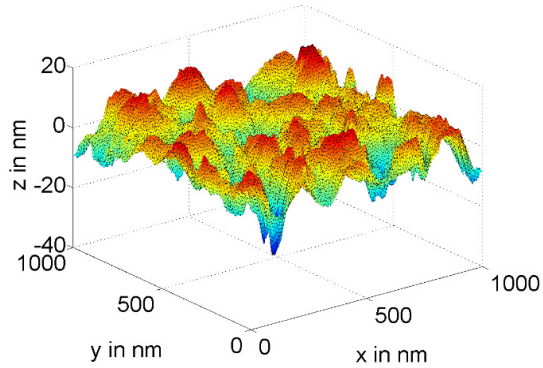

Figure 4: AFM surface map of a CsKSb growth for surface analyses purpose using similar condition to those of the ones used in DC gun.

One of the samples, accidentally grown about 5 mm off-centre with respect to the puck symmetry axis, was used to extract high average current from the injector in order to evaluate the lifetime of this photocathode material. This preliminary test gave promising results. Using this photocathode an average current of 20 mA has been delivered from the photoinjector for 8 hours. Minimal QE degradation has been observed. Detailed lifetime studies are underway.

CONCLUSIONS

Multialkali antimonide photocathodes could represent a valid alternative to GaAs for use in photoinjectors that do not require extremely low thermal emittance. Initial results of the R&D program on multialkali photocathodes being pursued at Cornell University for the ERL project illustrate the promise of these photocathodes for ERL application.

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