PHOTOCATHODE GROWTH AND CHARACTERIZATION ADVANCES AT CORNELL UNIVERSITY*

L. Cultrera†, A. Bartnik, I. V. Bazarov, B. Dunham, C. Gulliford, H. Lee, R. A. Lipton, T. P. Moore
CLASSE, Cornell University, Ithaca, New York, USA

Abstract

Alkali-antimonides based photocathodes have demonstrated outstanding performance in high brightness electron beam production suitable for a wide range of applications such as FELs, ERLs and UED and for use in photomultiplier devices with picosecond resolution aimed at photon counting application in medicine and High Energy Physics. The photocathode laboratory at Cornell University is dedicated to studying the growth procedures and characterizing the properties in a wide range of photocathodes materials. Different experimental arrangements and alkali metal sources have been successfully explored to date to synthesize photosensitive materials. Recent work on commissioning a new growth chamber equipped with effusion cells loaded with pure metal allowing uniform deposition over large area substrates resulted on successful growth of photocathodes with extended sensitivity in the IR part of the spectrum and high efficiency alkali antimonides containing Rb metal. This and other advances aimed at demonstrating superior photocathodes will be presented.

INTRODUCTION

Semiconductor materials belonging to the alkali antimonides family have been widely used for many decades in photon detection application because of their high efficiency in the visible range of the spectrum [1]. During the lasts few years they have demonstrated their suitability for the generation of high average currents electron beams to drive Energy Recovery Linac (ERL) and with the high brightness required to operate high future X-ray Free Electron Laser (FEL) [2, 3]. Recent studies also proved that for application like Ultrafast Electron Diffaction (UED) requiring very bright electron beams these photocathode can be operated with photon energy near their photoemission threshold at cryogenic temperatures allowing the generation of electron beam with Mean Transverse Energies (MTE) equivalent to sub-room temperature that can potentially enable single shot electron diffraction of large bio molecules [4,5]. Most of the high efficiency photocathode materials have been discovered by trials and their production recipes empirically refined in the course of many years [6]. The renewed interest in these materials has triggered efforts to understand the formation dynamics of these materials in the attempt to improve the smoothness of the alkali antimonides surface with the final aim of mitigating the intrinsic electron beam emittance growth due to the surface roughness [7].

* This work has been funded by the National Science Foundation (Grant No. PHY-1416318) and Department of Energy (Grants No. DE-SC0014338 and No. DE-SC0011643)
† lc572@cornell.edu

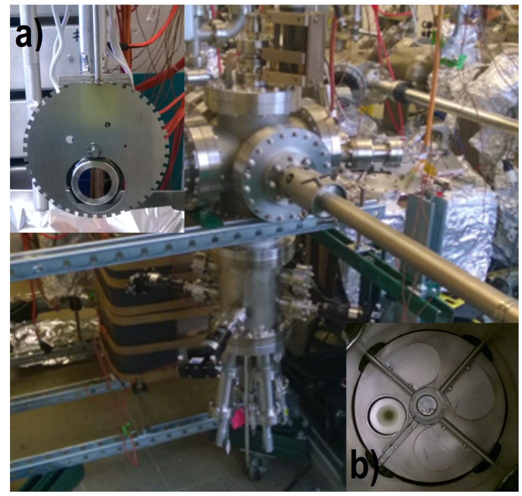

Figure 1: Picture of the new multi alkali antimonides growth chamber which uses a rotating mask (a) to select the exposed area and effusion cells filled with pure elements (b) to generate the vapors used to synthesize the high QE photocathodes.

EXPERIMENTAL SETUP

Despite the large interest in alklai antimonides phtocathodes not all the possible combinations of the elements belonging to the alkali metals and Sb metal have yet been explored. In order to extend the parameters space including the Rb metal as component of the alkali antimonides photocathodes we can shynthesize, to improve the reliability of our growth procedures and to allow for uniform depositions over a large are substrates (> 3 inches diameter, which might be required for growing multiple cathodes during the same run or to grow phtocathodes dedicated to photon detection application) we designed, built and commissioned a new alkali antimonides deposition chamber which is based on effusion cells of the same type used in molecular beam epitaxy reactors (Figure 1). This new growth chamber is now part of the UHV photocathode laboratory installation at Cornell University which consist of a cluster of UHV interconneted chamber dedicated to the growth and characterizations of photocathodes for accelerator and photon detection applications (Figure 2). A rotating mask can be used to select between 4 different apertures allowing for the growth over the whole substrate surface or to select selected apertures (3, 5 or 8 mm diameter) for growing off the geometric center of the substrate (Figure 1). Individual integral shutters pneumatically operated are placed in front of each furnace

ISBN 978-3-95450-147-2

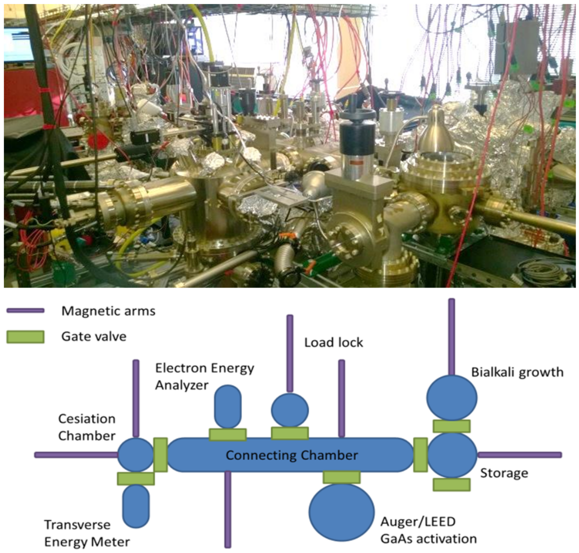

Figure 2: Picture and a schematic representation of the cluster UHV chambers that are part of the installation belonging to the photocathode laboratory at Cornell University.

and used to trigger on or off the evaporating fluxes from the furnaces (Figure 1).

RESULTS

The new UHV chamber was equipped with a rubidium source allowing us to explore the growth of Rb-based photocathodes. We experimented on the photocathode growth in both reflection mode (using stainless steel or silicon substrates) or transmission mode (using glass substrates) using Rb metal.The growth of Rb-K-Sb photocathodes was carried in the UHV growth chamber which was equipped with effusion cells hosting boron nitride crucibles filled with pure metals Rb (99.9% Strem Chemicals Inc.), K (99.95% Strem Chemicals Inc.) and Sb 99.999% (Sigma Aldrich Co.). The growth recipe involved heat cleaning of the substrate at about 550 C for about 24 hours, then sequential depositions of Sb, K and Rb were performed. The evaporation of Sb was performed at about 160 C until the thickness estimated using a quartz crystal microbalance reached a value of 20 nm. Sucessive evaporation of K and Rb were performed while measuring the photocurrent generated from the photocathode illuminated with momochromatic ligth 532 nm from a small lased diode. K evaporation was stopped when a first peak in the photocurrent was detected. At this point evaporation from Rb source was performed and the substrate let to cool down to room temperature. Rb evaporation was terminated once the photocurrent reached a maximum. QE in transmission and reflection mode of operation was measured for the same Rb-K-Sb cathode grown over a glass substrate (Figure 3). The results indicated a non efficient operation in transmission mode for wavelenght shorter than 500 nm. On the other hand a 20% QE was measured at 400 nm in reflection mode. Further investigations will be performed

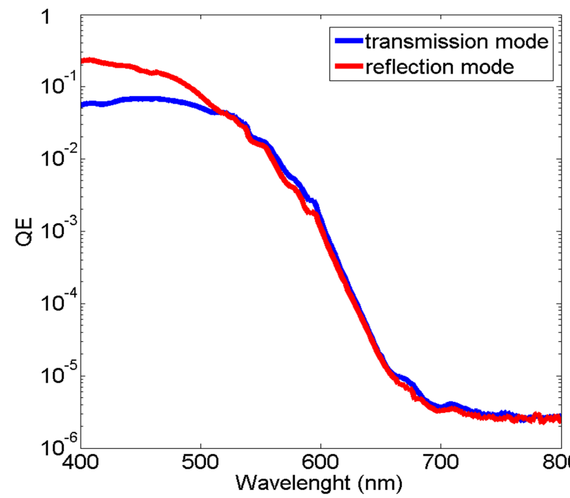

Figure 3: Spectral response of the Rb-K-Sb phtocathode grown over a glass substrates measured for operation in reflection and transmission mode.

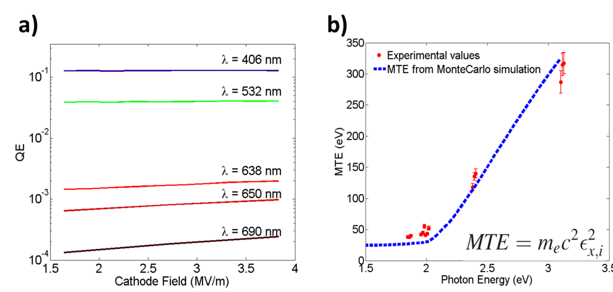

Figure 4: a) QE as measured at different levels of the electric field in the high voltage DC gun and different wavelength of operation; b) Mean Transverse Energy (MTE) as function of the photon energy as measured for 3 different electric field intensity at the surface.

to understand if this behavior is related to a too large initial thickness of the Sb layer. Uniform QEs (4.1±0.2 @ 532 nm) were measured over an area larger than 20x20 mm^2. One of the Rb-K-Sb photocathodes was moved from the growth chamber to the load lock of one of the high voltage DC gun hosted at Cornell University [8]. Here the photocathode was used to generate electron beam using the light provided at different wavelength by a set of small CW lased diode modules oerating at 405, 532, 638, 650, 690 nm. QEs and intrinsic emittance were measured at different electric field intensity (Figure 4). Figure 4 b reports MTEs measured using the solenoid scan technique at 3 different electric field intensity(1.65, 2.75 and 3.85 MVolt/m) for each wavelength experimental data are compared with a MonteCarlo numerical simulation of the electron transport yielding the expected values of electron beam MTEs [9]. Uniform high QE multialkali photocathodes have been grown over large areas (2 inch diameter) with the purpose of extending the spectral response towards the infrared part of the spectrum. In order to achieve the growth of these materials a very thin layer of

ISBN 978-3-95450-147-2

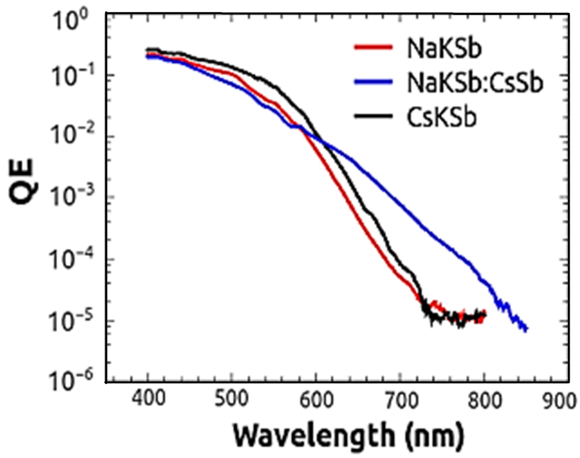

Figure 5: a) Spectral response of the multi-alkali photocathode is compared with the ones of standard bi-alklai photocathodes of the CsKSb and NaKSb type.

Cs_3Sb was grown over the surface of a Na_2KSb photocathode. During the growth of the thin (less than 10 nm) Cs_3Sb layer the photocurrent extracted from the photocathode was measured under illumination with a 780 nm laser [10]. This wavelength is usually beyond the sensitivity range of the high quantum efficiency based bi-alkali antimonides photocathodes we have synthesized with our procedures. Multi-alkali photocathodes on the other hand have shown photoemission at wavelengths as longer as 800 nm (Figure 4) with QEs on the range of few 10^{-5}, comparable with the ones usually achieved from metallic photocathode that require UV laser light to be operated. QEs and intrinsic electron beam emittances have been measured for one of these cathode when operated in one of the high voltage DC gun of Cornell University for a wide range of wavelength using small lased diode modules operating in CW [11]. The results are summarized in figure 6 and indicate that when operated in the infrared part of the spectrum intrinsic emittance close to the one imposed by the thermal energy of electrons into the crystal at room temperature can be achieved. The electric field in the DC gun was set to only 1.65 MVolt/m because of the presence of a single field emitter but the smallest intrinsic emittance was measured to be 0.247±0.006 mm mrad/ mm rms (corresponding to an MTE of 31 meV and to an equivalent electron temperature of 370 K). The extended sensitivity in the infrared part of the spectrum enabled by the growth of a thin Cs_3Sb layer over the surface of a high QE Na_2KSb photocathode makes possible operating these fast photocathodes with laser based on Ti:Sapphire oscillators operated in their fundamental wavelength at about 810 nm. The weak dependence of electron beam MTEs on photon energies lower than 1.6 eV coupled with a QE similar to that of metallic photocathodes make these cathode materials attractive to develop "table top" experimental setups capable of producing ultrashort bright electron beams.

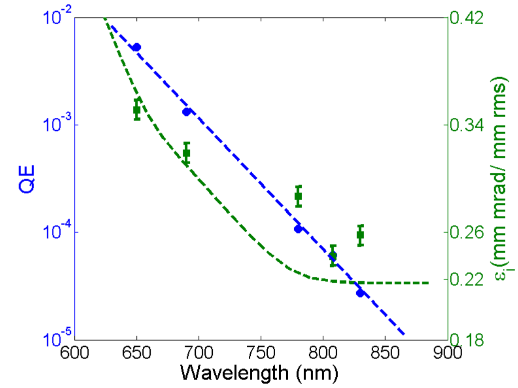

Figure 6: Spectral response of the multi-alkali photocathode is reported along with the intrinsic emittance as measured in the high voltage DC gun at Cornell University: intrinsic emittances close to the limits imposed by the thermal energy of electrons at room temperature have been measured in IR part of the spectrum with QE comparable to the ones of metals commonly used in state of the art photoinjectors.

CONCLUSION

Recent advances in photocathode research at Cornell University have been illustrated. The results obtained are beneficial for further developments of bright electron beams next generation light sources of ultrafast electron diffraction and for application in photon detection.

REFERENCES

[1] Hamamatsu Photonics K. K., *Photomultiplier Tubes: Basics and Applications*, third edition ed., Hamamatsu Photonics K. K. (2007).

[2] L. Cultrera et al., *Appl. Phys. Lett.* **103**, 103504 (2013).

[3] C. Gulliford et al., *Appl. Phys. Lett.* **106**, 094101 (2015).

[4] L. Cultrera et al., *Phys. Rev. ST Accel. Beams* **18**, 113401 (2015).

[5] T. Van Oudheusden et al., *J. Appl. Phys.* **102**, 093501 (2007).

[6] A.H. Sommer, Photoemissive Materials: Preparation, Properties and Use (John Wiley and Sons Inc., 1969).

[7] M. Ruiz-Osés et al., *APL Mater.* **2**, 121101 (2014).

[8] J. Maxson et al., *Rev. Sci. Instrum.* **85**, 093306 (2014).

[9] H. Lee, L. Cultrera, I.V. Bazarov, *Appl. Phys. Lett.* **108**, 124105 (2016).

[10] L. Cultrera, H. Lee and I. Bazarov, *J. Vac. Sci. Technol.* **B 34**, 011202 (2016).

[11] L. Cultrera et al., *Appl. Phys. Lett.* **108**, 134105 (2016).