ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WECOXBS02

High Current Performance of Alkali Antimonide Photocathode in LEReC DC Gun *

M. Gaowei†, E. Wang, J. Cen, A. Fedotov, D. Kayran, R. Lehn, C. J. Liaw, T. Rao, J. Tuozzolo, J. Walsh
Brookhaven National Laboratory, Upton, NY 11973, U.S.A

Abstract

The bi-alkali antimonide photocathode are chosen as the electron source material for the Low Energy RHIC electron Cooling (LEReC) project at RHIC, BNL based on its requirement for high bunch charge and long-time beam operation. This report presents the design and operation of the cathode deposition and transportation systems for the LEReC photocathodes, the cathode performance under the high current operation in the LEReC DC gun, as well as the characterization of the damaged cathodes from the long-time operation. *In situ* x-ray characterization results for the growth recipe of the alkali antimonide photocathodes prepared for the LEReC is also presented and discussed.

INTRODUCTION

The bunched beam electron cooler (LEReC) at the Relativistic Heavy Ion Collider (RHIC) has been built to provide luminosity improvement for Beam Energy Scan II (BES-II) physics program BES-II at RHIC. The photocathode DC gun in the LEReC accelerator is designed to provide an average current of up to 100 mA, with a required quantum efficiency of 2% ~ 10% from the photocathode material. In the LEReC 2018 operation, the photocathode DC gun has generated an average current of 30 mA and operated non-stop for several hours, with cathode lifetime fitted to be ~ 100 hours. [1-4] In this paper we report the *in situ* x-ray characterization results for the growth recipe of the alkali antimonide photocathodes prepared for the LEReC operation. Cathode performance in the 9.3MHz CW operation of LEReC is also reported. Post operation characterization has been performed and results are discussed in the last section of this paper.

CATHODE DEPOSITION

The LEReC cathode deposition has been switched from the effusion cell deposition back to the sequential 3 step deposition using SEAS getter sources since 2018. The deposition procedure we used for the bi-alkali antimonide photocathode was well developed for the ERL and CeC projects. [5] Compared to the CeC system, the LEReC deposition chamber differs slightly in geometry and does not have an active cooling capacity for the substrate. Therefore, the growth procedure in the LEReC deposition chamber has been optimized for this specific application. The detailed design of the LEReC deposition chamber was described in [6].

As was described in [6], the recipe we decided to use for the LEReC cathode is the well-established sequential growth recipe where 10 nm of Sb was deposited onto the substrate at 80 ˚C, followed by K and subsequent Cs deposition. The K step was performed at 135 ˚C to 140 ˚C, while the Cs step is performed between 130 ˚C to 70 ˚C, while the sample heater is turned off and the substrate cools down. Photocurrent generated by green light was monitored for both the K and the Cs step.

The temperature profile of the substrate with respect to the QE evolution through the K and the Cs step are plotted in Fig. 1. The inset photocurrent during the K step has been shown in × 5 scale for better display and the Cs QE was scaled by post QE calibration with a green laser with known power from the characterization chamber. For the LEReC cathode, we decided to seize the K deposition at an early stage, shortly after the QE rise and before its maximum. The Cs growth is stopped after substrate temperature drops below 70 ˚C, which is the known temperature for maintaining the stable stoichiometry of K_2CsSb. [7]

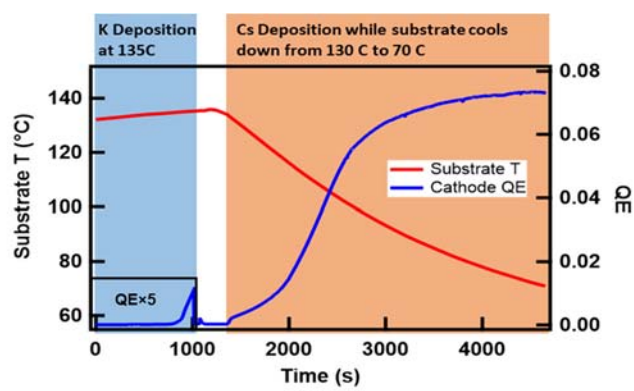

Figure 1: The temperature profile of the substrate with respect to the QE evolution in the Cs step.

The full deposition process takes ~ 2 hrs, while the whole deposition cycle for one cathode is typically 12 hrs, including the substrate heating cleaning, cathode cool down, QE mapping and puck exchange. The production rate for this deposition system is therefore 2 cathodes per day.

In 2018, we have produced 28 cathodes using this system. In 2019, the produced cathodes increased to 38, with an average deposition QE increased from 5.41% to 6.25%. Figure 2 and Table 1 listed all the as measured deposition QE from the LEReC cathodes in 2018 and 2019. The optimized deposition procedure for the LEReC deposition system has yielded ~ 1% higher average QE and an overall

*This work was carried out at Brookhaven Science Associates, LLC under contract DE-SC0012704 with the U.S. DOE.
† mgaowei@bnl.gov

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WECOXBS02

stable output. The QE vitiation within a run is commonly observed due to the variation in the outgassing rates and deposition rates of individual alkali source. Cathode QE measured in the LEReC DC gun is typically 10 % ~ 20% higher than the deposition QE, due to the difference in the QE measuring scheme.

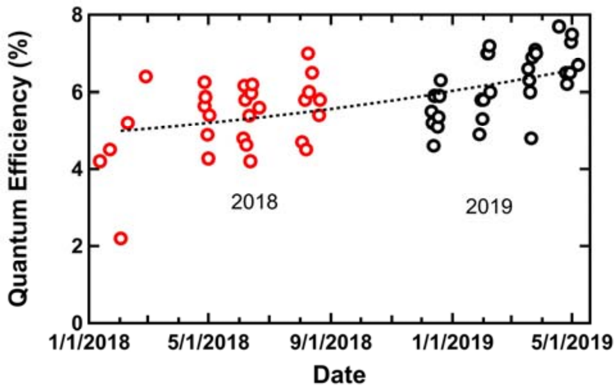

Figure 2: The cathode QE summary of LEReC run 2018 (red circles) and run 2019 (dark circles)

Table 1: The Cathode QE Summary of LEReC Run 2018 and 2019

	Run 2018	Run 2019 (to May)
# of cathodes	28	34
RMS Deposition QE (%)	5.41	6.25 (+0.87)
SDEV of QE (%)	0.97	0.85 (-0.08)

X-RAY CHARACTERIZATION OF LEREC CATHODE

The recipe of LEReC photocathode was duplicated in the UHV characterization chamber at beamline 4-ID, NSLS2, BNL, where real time, *in situ* x-ray characterization was performed to record the structural and chemical evolution of the LEReC photocathode, with detailed post analysis of x-ray fluorescence (XRF) and x-ray diffraction (XRD). In this report, the XRF and the XRD results are presented and discussed.

At beamline 4-ID, the photon energy of the incident x-ray was 11.4 keV (λ = 1.09 Å) with a nominal beam diameter of 50 μm focused at the sample position. The x-ray diffraction pattern was collected via two Dectris Eiger R 1M X-ray cameras mounted in-axis (75 cm away from the sample) and 30 ° off-axis (27 cm away from the sample) with the sample plane, respectively. The XRF signal was collected through a vortex multi-cathode x-ray detector mounted 45 ° with respect to the sample surface normal and ~ 30 cm away from the sample. Note that instead of the Moly puck used in the DC gun, the growth recipe was duplicated on an HF rinsed Si (100) substrate heated to 600 °C and then cool down to 80 °C for deposition. The detailed description of the UHV characterization chamber and illustration of experimental set up can be found in [8-11].

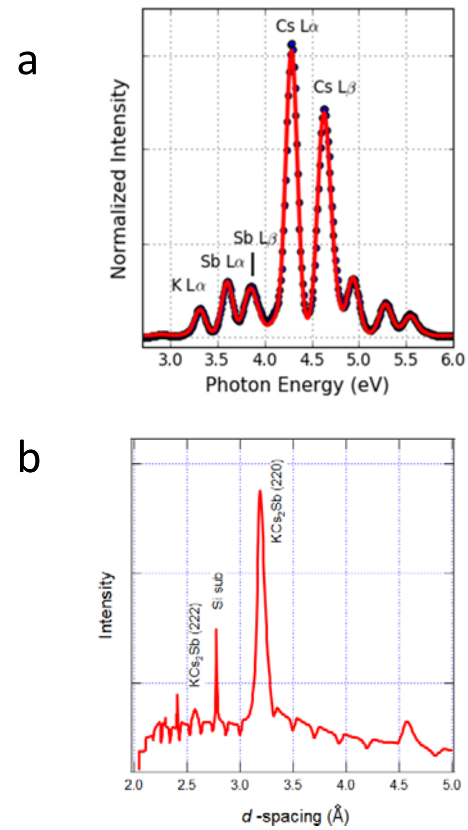

Figure 3: a) XRF spectrum and b) XRD spectrum of K-Cs-Sb cathode prepared with LEReC recipe.

Table 2: Atomic Mass Fraction of LEReC Photocathode

	Atomic Ratio
K/Sb	1.14
Cs/Sb	2.08

After the completion of the photocathode growth as was described in the beginning of this report, a final XRF and XRD was performed to determine the cathode stoichiometry and crystal structure. The fluorescence peaks of the 3 composite elements labeled are shown in Fig. 3a. The fitted atomic mass fraction is listed in Table 2. From the fitting results we can determine that the photocathode film prepared by the LEReC recipe is KCs_2Sb, instead of K_2CsSb, which is commonly obtained with the sequential recipe [12]. Similar cathode stoichiometry was observed by elsewhere. [13]

The *in situ* XRD pattern of the LEReC photocathode is shown in Fig. 3b. The results were compared with simulated powder diffraction patterns calculated using cubic structure and lattice parameters established in [14], namely 8.61 Å for K_2CsSb and 8.88 Å for KCs_2Sb. The dominant peak at d = 3.19 Å is identified as KCs_2Sb (220), which

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WECOXBS02

agrees with the fitted stoichiometry from the fluorescence spectrum. [13] Grain size estimated for this film is ~ 14 nm.

CAHTODE LIFETIME IN CW OPERATION

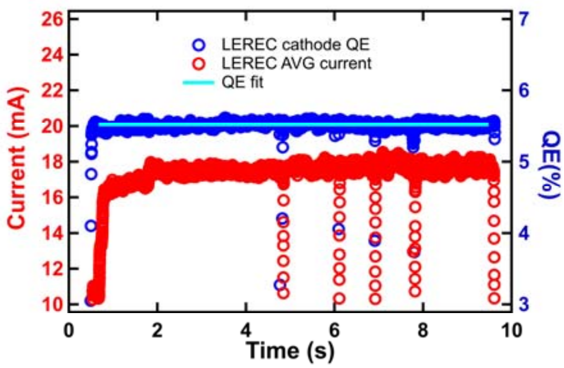

Figure 4: LEReC average beam current (red circles) and cathode QE (blue circles) monitored in CW operation.

In the run of 2019, the LEReC CW operation was kept under 20 mA to ensure better beam performance. Figure 4 shows the recorded average beam current (in red) and the calculated cathode QE (in blue) with the laser power kept ~ 0.7 W. During the 10 hr CW operation with an average beam current at 17 mA, despite multiple MPS trips, there was no QE decay observed for this cathode. The detailed description of the LEReC high current operation was described in [15].

CONCLUSION

The LEReC cathode production system has demonstrated its capability of stably and repeatedly producing high QE and uniform bi-alkali antimonide photocathodes in a timely manner. These cathodes show great lifetime in high current operation. LEReC cathode has been studied by x-ray characterization at synchrotron light source. The Results show that this bi-alkali antimonide photocathode is KCs_2Sb with good crystallinity, which explains the high QE.

ACKNOWLEDGEMENT

Special thanks are given to D. Asner, R. Begay, B. Walsh and many staff from Instrumentation Division, Brookhaven national Lab for their essential support on the LEReC deposition system. Authors would also like to thank K. Decker, C. Degen, J. Ditta, D. Gassner, X. Gu, P. Inacker, J. Jamilkowski, J. Kewisch, M. Minty, M. Mapes, L. Nguyen, M. Paniccia, J. Sanfilippo, L. Smart, S. Seletskiy, K. Sinclair, D. Vonlintig, H. Zhao, Z. Zhao and many staff from Collider-Accelerator Department, Brookhaven National Laboratory for their devoted work on the LEReC project.

The authors would like to acknowledge John Smedley, Anna Alexander and Vitaly Pavlenko from Los Alamos National Laboratory, David Juarez-Lopez from the Cockcroft Institute of Accelerator Science, STFC Daresbury Laboratory and John Sinsheimer from NSLS2 and staff at beamline 4-ID for their valuable assistance in the experiment.

Work was supported by Brookhaven Science Associates, LLC, under Contract No. DE-SC0012704 with the U.S. Department of Energy. The use of National Synchrotron Light Source II at Brookhaven National Laboratory is supported by U.S. Department of Energy (DOE) Office of Science under Contract No. DE-AC02-98CH10886.

REFERENCES

[1] A. Fedotov *et al.,* "Accelerator physics design requirements and challenges of RF based electron cooler LEReC", *Proceedings of the North American Particle Accelerator Conference 2016*, Chicago, IL, USA, 2016. doi:10.18429/JACoW-NAPAC2016-WEA4CO05

[2] E. Wang *et al.*, "Multi-alkali photocathodes production for LEReC DC gun", USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26), 2018. doi:10.2172/1438329, 2018

[3] D. Kayran *et al.*, "First results from commissioning of low energy RHIC electron cooler (LEReC)", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC2019)*, Melbourne, Australia, May 2019, pp. 770-772. doi:10.18429/JACoW-IPAC2019- MOPRB085

[4] A. Fedotov, "Bunched beam electron cooling for Low Energy RHIC operation", *ICFA Beam Dynamics letter*, No. 65, p. 22, December 2014. https://icfa-usa.jlab.org/archive/newsletter.shtml

[5] E. Wang *et al.,* "Enhancement of photoemission from and postprocessing of K_2CsSb photocathode using excimer laser" *Phys. Rev. ST Accel. Beams*, vol. 17, p. 023402, 2014. doi:10.1103/PhysRevSTAB.17.023402

[6] E. Wang *et al.,* "Multi-alkali photocathodes production for LEReC DC gun", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19),* Melbourne, Australia, May 2019. doi:10.18429/JACoW-IPAC2019- MOPRB085

[7] Z. H. Ding *et al.,* "Temperature-dependent quantum efficiency degradation of K-Cs-Sb bialkali antimonide photocathodes grown by a triple-element codeposition method", *Phys. Rev. Accel. Beams*, vol. 20, p. 113401 (2017). doi:10.1103/PhysRevAccelBeams.20.113401

[8] M. Gaowei *et al.,* "Co-deposition of ultra-smooth and high QE cesium telluride photocathodes", *Phys. Rev. Accel. Beams* 22, 073401, (2019). doi:10.1103/PhysRevAccelBeams.22.073401

[9] S. Schubert *et al.,* "Bi-alkali antimonide photocathode growth: An X-ray diffraction study," *Journal of Applied Physics* 120, 035303 (2016). doi:10.1063/1.4959218

[10] Z. Ding *et al.* , "In-situ synchrotron x-ray characterization of K2CsSb photocathode grown by ternary co-evaporation", *Journal of Applied Physics* 121, 055305 (2017); doi:10.1063/1.4975113

[11] H. Yamaguchi *et al.*, "Photocathode: Free-standing bialkali photocathodes using atomically thin substrates," *Adv. Mater. Interfaces*, vol. 5(13), 1870065, (2018). doi:10.1002/admi.201870065

[12] J. Q. Xie *et al.*, "Synchrotron x-ray study of a low roughness and high efficiency K2CsSb photocathode during film growth", *J. Phys. D*, vol. 50, 205303 (2017). doi:10.1088/1361-6463/aa6882

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WECOXBS02

[13] M. Gaowei *et al.*, "Synthesis and x-ray characterization of sputtered bi-alkali antimonide photocathodes", *APL Materials* 5, 116104 (2017). doi:10.1063/1.5010950

[14] A.R.H.F. Ettema *et al.*, "Electronic structure of Cs2KSb and K2CsSb," *Physical Review B*, 66, 115102, (2002). doi:10.1103/PhysRevB.66.115102

[15] X. Gu *et al.*, "Stable operation of a high-voltage high-current DC gun for the bunched beam electron cooler in RHIC," unpublished.