

OPTIMIZING ACTIVATION RECIPE WITH Cs, Te, O FOR GaAs-BASED PHOTOCATHODES

J. Bae*, M. Andorf, I. Bazarov, J. Maxson, Cornell University, Ithaca, USA
L. Cultrera, Brookhaven National Laboratory, Upton, USA
A. Galdi, University of Salerno, Fisciano (SA), Italy

Abstract

GaAs-based photocathodes are the most popular electron sources for producing highly spin-polarized electron beams in accelerator physics and condensed matter physics. Spin-polarized photoemission requires activation to achieve Negative Electron Affinity (NEA). Conventional NEA surfaces such as Cs-O/NF₃ are extremely vacuum sensitive, and this results in rapid QE degradation. In this work, we activated GaAs with various recipes using Cs, Te, and oxygen. We demonstrate NEA activation on GaAs surfaces. Among Cs-Te activated samples, the oxidized sample showed the highest QE and longest lifetime at 780 nm.

INTRODUCTION

GaAs-based photocathodes are considered state-of-the-art for producing highly spin-polarized electron beams for accelerator and microscopy applications. Negative Electron Affinity (NEA) activated surfaces are required to extract highly spin-polarized electron beams from GaAs-based photocathodes. Activation to NEA is traditionally achieved by exposing the GaAs sample surface to cesium vapor. The deposited cesium layer forms a dipole moment that brings the vacuum level below the bulk conduction band minimum [1]. If an oxidant is included, a stronger, double-dipole layer is formed, that can further enhance the NEA [2].

NEA layers on the surface of GaAs-based photocathodes are notorious for the extreme vacuum sensitivity, and this results in rapid degradation of QE during beam operations. Conventional activation layers, such as Cs-O₂ and Cs-NF₃, are monolayers weakly bound to the GaAs surface with high chemical reactivity. Therefore, GaAs photocathodes are typically operated under extreme high vacuum (XHV) conditions and, even so, still suffer from rapid degradation [3]. Recently, activation with alternative semiconductor layers was proposed to improve the robustness [4]. It has been shown that when Te element is used for activation along with Cs vapors, the robustness of the NEA layer can be improved without negatively affecting spin polarization [5]. Variations of this approach were studied by multiple labs. Cs-K-Te activation was demonstrated to improve lifetime by more than an order of magnitude [6]. Similar to the standard activation method with Cs and oxidants, it has been shown that usage of oxygen during unconventional activation with Te or Sb can increase the QE (Quantum Efficiency) while preserving improved lifetime of GaAs photocathodes. Cs-Sb-O activation improved the photocathode lifetime at 780

nm by a factor of 7 [7, 8]. Lastly, Cs-Te-O activation at room temperature also showed an improved lifetime at 532 nm compared to the standard activation method [9]. In this work, we tested various NEA activation recipes with Cs, Te and O to understand the impact on QE and lifetime at low voltage. The activation temperature, usage of oxygen and thickness of the Te layer were varied.

EXPERIMENT

NEA Activation

Highly *p*-doped ($Zn\ 5 \times 10^{18}\ \text{cm}^{-3}$) GaAs (100) wafers were cleaved in air with a diamond scribe. Prepared samples were solvent cleaned with isopropanol and rinsed in de-ionized water. Wet-etching was performed with 1% HF solvent for 30 s and samples were rinsed again with de-ionized water before loading under vacuum. The activation chamber has a base pressure of 10^{-9} Torr, and Cs and Te effusion cells are installed with shutters that control the flux on the sample. Each sample was heat cleaned at $\sim 500\ ^\circ\text{C}$ for ~ 12 hours. Five samples were grown:

1. Sample #0 was activated with the standard method using Cs and oxygen.
2. Sample #1 was activated with Cs-Te at 120 °C. 1.3 nm of Te was deposited.
3. Sample #2 was activated with Cs-Te-O at 120 °C. 1.3 nm of Te was deposited.
4. Sample #3 was activated with Cs-Te at room temperature. 1.3 nm of Te was deposited.
5. Sample #4 was activated with Cs-Te at 120 °C. 2.5 nm of Te was deposited.

Sample #1 was activated with the same recipe from our previous work [5], and Sample #2-4 are departures from this recipe. Compared to Sample #1, oxygen was additionally used for Sample # 2, the activation temperature was lowered to room temperature for Sample # 3, and twice the amount of Te was deposited for Sample #4.

In Fig. 1, we monitored the infrared QE during the activation process of Sample #1. Initially, the sample is seen to photoemit at 780 nm due to residual Cs vapors in the growth chamber. The sample is activated with only Cs until QE reaches a plateau. Then, the shutter in front of Te effusion cell is opened for deposition. QE immediately drops below a noise level. Deposited Te thickness was monitored by a quartz crystal microbalance during Cs-Te codeposition. Te

* jb2483@cornell.edu

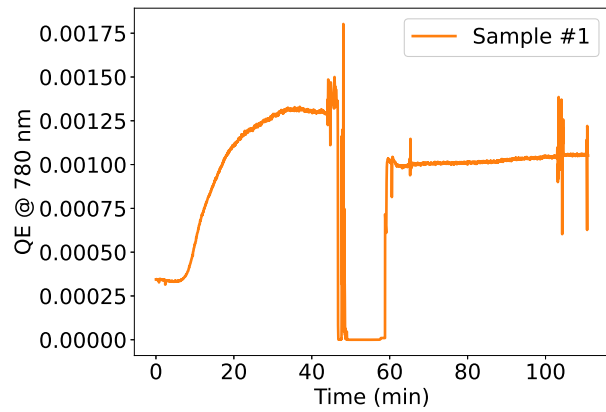


Figure 1: Quantum Efficiency of GaAs photocathodes during Cs-Te activation (Sample #1). Initial QE at 780 nm is not zero due to cesium vapors in the growth chamber. The sudden increase and decrease of QE are due to the opening of Cs shutter and Te shutter, respectively. Sample #2-4 were activated in similar sequences.

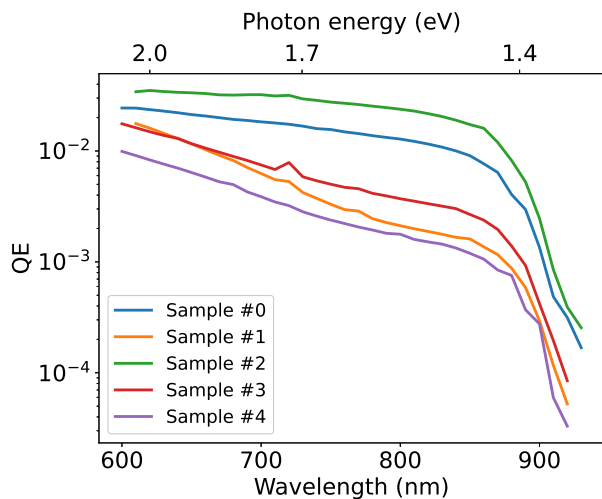


Figure 2: Spectral response of GaAs samples activated by Cs, Te, and oxygen. Nonzero QE at the GaAs bandgap photon energy (1.43 eV) indicates NEA achieved on all samples.

shutter was kept open for 7 minutes to deposit 1.3 nm with a flux of 9×10^{12} atoms/cm²/s. Once Te deposition was done, the sample was exposed to Cs vapor until QE recovered and reached a plateau again. The heater was turned off soon after the Te shutter was closed. In the case of Sample #2, GaAs was initially activated by Cs-O codeposition, and oxygen was leaked during Te deposition as well. The QE before opening the Te shutter and final QE were both about an order of magnitude higher compared to Sample #1. For Sample #3, the same recipe was applied at room temperature, and Te was deposited for 14 minutes for Sample #4.

Spectral Response

The spectral response for the five samples are plotted in Fig. 2. All the samples photoemitted at the GaAs bandgap

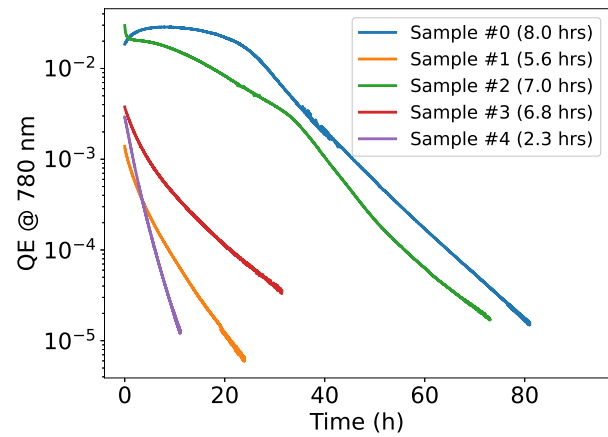


Figure 3: Quantum Efficiency degradation as a function of time. 780 nm diode laser was used to illuminate the samples. The numbers in the legend are the photocathode lifetimes calculated by fitting each curve to an exponential function.

photon energy (1.43 eV) implying NEA was achieved on all samples. Among the samples, Cs-Te-O activated sample (Sample #2) achieved higher QEs compared to the standard Cs-O activation. Changing the activation temperature (Sample #3) or a thicker NEA layer (Sample #4) didn't result in much difference as opposed to usage of oxygen (Sample #2).

Lifetime

The robustness of the samples can be compared by monitoring QE degradation over time while extracting electrons. The photocathode lifetime is defined as the time QE takes to fall by a factor of $1/e$. The samples were biased at -18 V and the photocurrent was monitored continuously with a 780 nm diode laser with $\sim 40 \mu\text{W}$ of power. The QE degradation over time is plotted in Fig. 3. The numbers in the legend correspond to the estimated lifetime from exponential fits. In our previous work [5], we demonstrated a factor of 5 improvement in lifetime at 532 nm. However, when 780 nm diode laser is used for monitoring QE degradation, we measured similar lifetime for Sample #1 compared to the sample activated with the standard method (Sample #0). Cs-Te-O activated Sample #2 had the highest initial QE but quickly dropped at the beginning. All samples had similar lifetimes except Sample #4, which had twice the amount of Te deposition compared to the rest. This was the opposite of what we observed with Cs-Sb-O activation layer, where we saw an increase in lifetime with a thicker layer [8]. The oxidized sample (Sample #2) demonstrated the highest QE and longest lifetime among Cs-Te samples.

CONCLUSION

NEA activation recipes using Cs, Te, and oxygen were studied. As opposed to the lifetime at 532 nm, Cs-Te activations had a comparable lifetime at 780 nm with the standard Cs-O activation. Among Cs-Te activated samples, the oxi-

dized sample showed the highest QE and longest lifetime at 780 nm.

ACKNOWLEDGMENT

This work was supported by DOE under award DE-SC0021039.

REFERENCES

- [1] D. T. Pierce and F. Meier, "Photoemission of spin-polarized electrons from gaas," *Phys. Rev. B*, vol. 13, pp. 5484–5500, 12 1976, doi:10.1103/PhysRevB.13.5484
- [2] C. Y. Su, W. E. Spicer, and I. Lindau, "Photoelectron spectroscopic determination of the structure of (Cs,O) activated GaAs (110) surfaces," *Journal of Applied Physics*, vol. 54, no. 3, pp. 1413–1422, 1983, doi:10.1063/1.332166
- [3] W. Liu, M. Poelker, X. Peng, S. Zhang, and M. Stutzman, "A comprehensive evaluation of factors that influence the spin polarization of electrons emitted from bulk GaAs photocathodes," *Journal of Applied Physics*, vol. 122, no. 3, p. 035703, 2017, doi:10.1063/1.4994306
- [4] K. Uchida, M. Kuriki, Y. Seimiya, R. Kaku, K. Miyoshi, and N. Yamamoto, "A STUDY ON ROBUSTNESS OF NEA-GAAS PHOTOCATHODE," *Proceedings of IPAC2014*, pp. 664–666, 2014, doi:10.18429/JACoW-IPAC2014-MOPRI032
- [5] J. K. Bae, L. Cultrera, P. DiGiacomo, and I. Bazarov, "Rugged spin-polarized electron sources based on negative electron affinity GaAs photocathode with robust Cs₂Te coating," *Applied Physics Letters*, vol. 112, no. 15, p. 154101, 2018, doi:10.1063/1.5026701
- [6] M. Kuriki and K. Masaki, "Negative Electron affinity GaAs Cathode Activation with CsKTe Thin Film," *Journal of Physics: Conference Series*, vol. 1350, no. 1, p. 012047, 2019, doi:10.1088/1742-6596/1350/1/012047
- [7] J. K. Bae, A. Galdi, L. Cultrera, F. Ikponmwen, J. Maxson, and I. Bazarov, "Improved lifetime of a high spin polarization superlattice photocathode," *Journal of Applied Physics*, vol. 127, no. 12, p. 124901, 2020, doi:10.1063/1.5139674
- [8] L. Cultrera, A. Galdi, J. K. Bae, F. Ikponmwen, J. Maxson, and I. Bazarov, "Long lifetime polarized electron beam production from negative electron affinity GaAs activated with Sb-Cs-O: Trade-offs between efficiency, spin polarization, and lifetime," *Physical Review Accelerators and Beams*, vol. 23, no. 2, p. 023401, 2020, doi:10.1103/PhysRevAccelBeams.23.023401
- [9] O. Rahman, J. Biswas, M. Gaowei, W. Liu, and E. Wang, "New Activation Techniques for Higher Charge Lifetime from GaAs Photocathodes," *Proceedings of the 10th Int. Particle Accelerator Conf.*, vol. IPAC2019, 2019, doi:10.18429/JACoW-IPAC2019-TUPTS102