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ENHANCED ROBUSTNESS OF GaAs-BASED PHOTOCATHODES ACTIVATED BY Cs, Sb, AND O_2

J. Bae*, I. Bazarov, L. Cultrera, A. Galdi, F. Ikponmwen, J. Maxson, Cornell University, Ithaca, USA

Abstract

GaAs-based photocathodes are widely used to produce highly spin polarized electron beams at high currents. Spin polarized photoemission requires activation to achieve Negative Electron Affinity (NEA). The NEA surface is extremely vacuum sensitive, and this results in rapid QE degradation. In this work, we activated GaAs samples with unconventional methods using Cs and Sb. We confirmed NEA activation on GaAs surfaces and more than a order of magnitude enhancement in charge extraction lifetime compared to the standard Cs-O_2 activation without significant loss in spin polarization.

INTRODUCTION

GaAs-based photocathodes are the most popular electron sources for producing highly spin polarized electron beams at high currents in accelerator physics and condensed matter physics. To achieve a high Quantum Efficiency (QE) and high spin polarization, Negative Electron Affinity (NEA) is required, where the vacuum level is below the minimum of the conduction band [1]. Activation of NEA can be achieved by exposing GaAs samples to cesium vapor. Then, the Cs monolayer forms a dipole layer on the surface that lowers the potential barrier of electron extraction [2]. Additionally, oxidants, such as O_2 and NF_3, are commonly used to make the dipole layer stronger for a higher QE.

Activation layers for NEA are notorious for extreme vacuum sensitivity, and this results in rapid degradation of QE during beam operations. Conventional activation layers, such as Cs-O_2 and Cs-NF_3, are monolayers weakly bound to the GaAs surface with high chemical reactivity. Therefore, GaAs photocathodes are typically operated under extreme high vacuum (XHV) conditions, but still suffers from the rapid degradation. Various approaches were suggested to improve this sensitivity. Deflecting the electron beam near the laser spot was proposed to minimize one of the main surface degradation mechanisms, ion-back bombardment, and demonstrated enhanced lifetime in GaAs and alkali antimonide photocathodes [3–6]. In another study, chemical immunity enhancement was achieved by using two alkali materials, Cs and Li, for activation along with NF_3 oxidant [7,8]. Recently, activation with alternative semiconductor layers was proposed to improve the lifetime. In particular, successful NEA activation was demonstrated with Cs_2Te layer without any significant loss in spin polarization and QE while improving the charge extraction lifetime by a factor of 5. [5, 9]

A heterojunction model suggests an alternative semiconductor activation layer on GaAs needs to satisfy two conditions to achieve NEA on the surface (Fig. 1): (i) the energy difference between the Fermi level and vacuum level should be smaller than the band gap of GaAs (1.43 eV), and (ii) the band gap of activation layer should be greater than that of GaAs for transparency of photons used for spin polarized photoemission. Cs_3Sb has a small electron affinity of 0.4 eV and the band gap of 1.6 eV that satisfy the two conditions as illustrated in Fig. 1. In this work, we demonstrate NEA activation on GaAs surface using Cs and Sb vapors. Additionally, we exposed the sample to oxygen during the growth for one of the samples and observed improved performance in QE and lifetime.

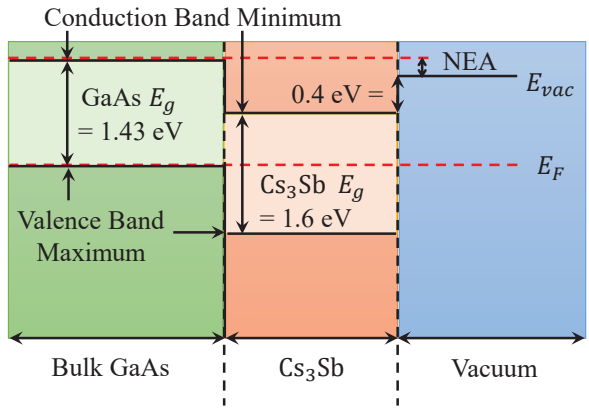

Figure 1: Energy band diagram of GaAs activated with Cs_3Sb based on heterojunction model. An alternative semiconductor activation layer needs to satisfy two conditions mentioned in the text to achieve NEA.

EXPERIMENT

Growth

Highly p-doped (Zn 5×10^{18}cm^{-3}) GaAs (100) wafers were cleaved in air with a diamond scribe. Each sample was solvent cleaned with isopropanol, and rinsed in de-ionized water. Samples are wet-etched with 1% HF solvent for 30 s and rinsed again with de-ionized water before loading under vacuum. The growth chamber has a base pressure of 10^{-9} Torr, and Cs and Sb effusion cells are installed with shutters that control the flux on the sample. Each sample was heat cleaned at ~ 500° for ~ 12 hours and cooled down to 130° for activation with Cs, Sb, and O_2. Samples were grown with three different methods:

1. Cs and O_2 are codeposited at room temperature for a reference sample.

* jb2483@cornell.edu

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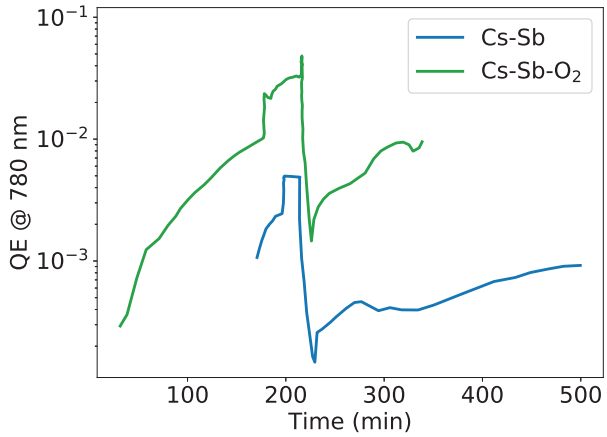

Figure 2: Quantum Efficiency of GaAs photocathodes during the thin film growths. Initial QE at 780 nm is not zero due to cesium vapors in the growth chamber. The sudden increase and decrease of QE are due to the opening of Cs shutter and Sb shutter, respectively. QE gradually increased for both samples while cooling down the sample.

2. One sample was first activated with just Cs and later Cs and Sb are codeposited.

3. Another sample was first activated with Cs and O_2. Then, Cs, Sb, and O_2 are codeposited.

In Fig. 2, we plot the near infrared QE measured during growth. At the beginning, GaAs samples photoemit at 780 nm in the growth chamber due to residual Cs vapors from previous experiments. As Cs effusion cell is heated to a high temperature, the QE at 780 nm starts increasing. The sudden increase for both curves are when the Cs shutter opens. The green curve achieves an order of magnitude higher QE due to the oxygen exposure. The rapid decrease was observed when Sb shutter is opened. Sb shutter was kept opened for 1000 s to deposit 2.5 Å with a flux of 8.3×10^{11} atoms/cm^2/s. Oxygen was leaked into the chamber with a partial pressure of $\sim 5\times10^{-11}$ Torr. The thickness of the film was monitored with quartz crystal microbalance. The Cs shutter was left opened until the samples were cooled down to $\sim 50°$ after closing Sb shutter.

Spectral Response

The spectral response for the three samples are plotted in Fig. 3. The sample activated with just Cs and Sb were photoemitting at the GaAs band gap 1.43 eV very weakly (QE $\sim 4\times10^{-4}$). When oxygen was codeposited during the growth, the QE improved more than a order of magnitude indicating larger NEA is formed on the surface. Although, the reference sample with conventional activation Cs-O_2 showed the highest QE.

Lifetime

Robustness of the samples can be compared by monitoring QE degradation over time while extracting electrons. The

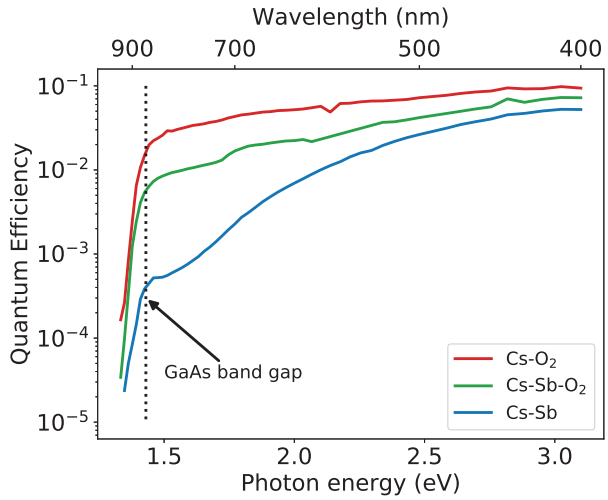

Figure 3: Spectral response of GaAs samples activated by Cs, Sb, and O_2. While all samples indicate NEA activation on the surface by photoemission at the GaAs band gap energy (1.43 eV), quantum efficiency varies depending on the magnitude of NEA.

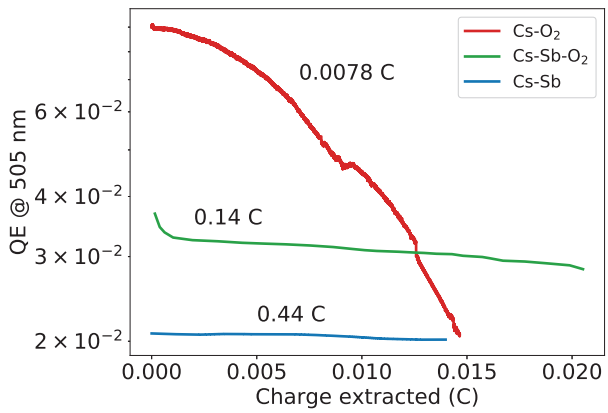

Figure 4: Quantum Efficiency degradation as a function of total charge extracted. 505 nm laser was used to illuminate the sample. The number next to each curve are the charge extraction lifetime calculated by fitting each curve to an exponential function.

charge extraction lifetime is defined as the amount of charge extracted until QE drops by a factor of e [3]. Photocurrent was measured continuously with 505 nm diode laser at $\sim 20\mu$W where sample are biased by 18 V. The QE degradation is plotted in Fig. 4. The numbers next to each curve are charge extraction lifetime obtained by fitting each curve to an exponential function. Conventional Cs-O_2 activation has the highest initial QE, but it rapidly falls below the other two. The charge lifetimes were improved by more than a order of magnitude when Sb was deposited during the activation. The longest lifetime of 0.44 C was achieved for bare Cs-Sb activation, but oxygen was required to achieve a high QE. The oxidized sample showed a factor of ~ 20 improvement in lifetime (0.14 C).

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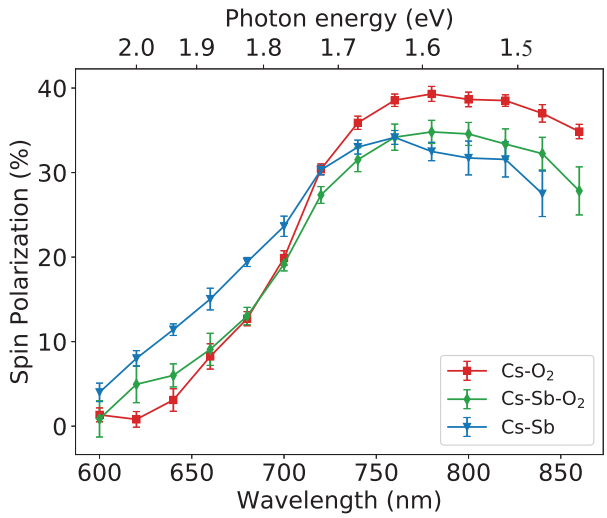

Figure 5: Spin polarization of photoemitted electrons from GaAs activated by Cs, Sb, and O_2.

Spin Polarization

Spin polarization of photoemitted electrons were measured by a Mott polarimeter and plotted in Fig. 5. Monochromatic light was used to produce circularly polarized light directed at normal incidence to the sample surface. Longitudinally spin polarized electrons were bent 90° by electrostatic lenses and Mott scattered with 20 keV at a tungsten target which was characterized to have 0.15 Sherman function with 5% uncertainty [9]. Sb deposited samples showed a lower spin polarization by ~ 5%.

CONCLUSION

Successful activations of GaAs to NEA are demonstrated using Cs and Sb with and without oxygen exposure during growth. The sample grown without oxygen exposure showed the longest charge extraction lifetime of 0.44 C that is a factor of 56 improvement from conventional activation. However, oxygen exposure was required to achieve a comparable near infrared QE with the standard Cs-O_2 activation. The oxidized sample had a factor of 20 larger charge lifetime compared to the reference sample without significant loss in QE and spin polarization.

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REFERENCES

[1] D. Pierce and F. Meier, "Photoemission of spin-polarized electrons from GaAs," *Physical Review B*, vol. 13, no.12, p. 5484, 1976.

[2] 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, pp. 0–9, 2017.

[3] J. Grames, R. Suleiman, P. A. Adderley, J. Clark, J. Hansknecht, D. MacHie, M. Poelker, and M. L. Stutzman, "Charge and fluence lifetime measurements of a dc high voltage GaAs photogun at high average current," *Physical Review Special Topics - Accelerators and Beams*, vol. 14, no. 4, pp. 1–12, 2011.

[4] R. R. Mammei, R. Suleiman, J. Feingold, P. A. Adderley, J. Clark, S. Covert, J. Grames, J. Hansknecht, D. Machie, M. Poelker, T. Rao, J. Smedley, J. Walsh, J. L. McCarter, and M. Ruiz-Osés, "Charge lifetime measurements at high average current using a K2CsSb photocathode inside a dc high voltage photogun," *Physical Review Special Topics - Accelerators and Beams*, vol. 16, no. 3, pp. 1–16, 2013.

[5] O. Rahman, E. Wang, I. Ben-Zvi, J. Biswas, and J. Skaritka, "Increasing charge lifetime in DC polarized electron guns by offsetting the anode," *Physical Review Accelerators and Beams*, vol. 22, no. 3, p. 083401, 2019.

[6] L. Cultrera, J. Maxson, I. Bazarov, S. Belomestnykh, J. Dobbins, B. Dunham, S. Karkare, R. Kaplan, V. Kostroun, Y. Li, X. Liu, F. Löhl, K. Smolenski, Z. Zhao, D. Rice, P. Quigley, M. Tigner, V. Veshcherevich, K. Finkelstein, D. Dale, and B. Pichler, "Photocathode behavior during high current running in the Cornell energy recovery linac photoinjector," *Physical Review Special Topics - Accelerators and Beams*, vol. 14, no. 12, pp. 1–9, 2011.

[7] G. A. Mulhollan and J. C. Bierman, "Enhanced chemical immunity for negative electron affinity GaAs photoemitters," *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films*, vol. 26, no. 5, pp. 1195–1197, 2008.

[8] Y. Sun, R. E. Kirby, T. Maruyama, G. A. Mulhollan, J. C. Bierman, and P. Pianetta, "The surface activation layer of GaAs negative electron affinity photocathode activated by Cs, Li, and NF3," *Applied Physics Letters*, vol. 95, no. 17, 2009.

[9] 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, pp. 1–6, 2018.