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NEXT GENERATION ROBUST POLARIZATION PHOTOCATHODES FOR EIC

Final Technical Report

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Disclaimer

Abstract

Cornell group developed and characterized robust photocathodes dedicated to generation of spin-polarized electrons by employing a thin protective activation layer of a robust material in place of the conventional cesiation, which is extremely prone to the damage by ions and chemical poisoning. Various thicknesses of Cs2Te and of other materilas on III-V semiconductors were studied to understand their effect on the cathode longevity and the polarization state. These photocathodes, as well as new alternative materials, will be eventually tested with high beam current for their operational (lifetime) performance in the Cornell HV DC guns, including a brand-new photoemission high voltage gun that features a cryogenically cooled photocathode holder.

The research conducted opens a new and robust way to reach the negative electron affinity for a large class of photocathodes specifically designed to maximize their accelerator performance. It particular, it benefits the future EIC by improving the lifetime available from spin-polarized electron photoemission sources.

Introduction

According to the 2015 Long Range Plan for Nuclear Science "a high-energy high-luminosity polarized EIC [is recommended] as the highest priority for new facility construction following the completion of FRIB" to address fundamental questions about the role of gluons in nuclear interactions [1].

In the fall of 2016, a NP Community Panel was charged by the DOE - Office of Nuclear Physics to provide guidance on the current status of accelerator R&D efforts and the priorities for future accelerator R&D that will enable an EIC pre-conceptual design. The outcome of the meeting is a report produced by the panel members aiming at evaluating the current status of accelerator R&D, proposed EIC concepts and their technical feasibility, and providing a list of R&D priorities for each EIC concept **Error! Reference source not found.**.

Three different schemes to develop and realize an EIC have been proposed in the US. Two of the designs are currently being developed at BNL and are based on reusing the RHIC infrastructure to provide the ion beam **Error! Reference source not found.**. In one of the options, the so called Linac-Ring, the high energy spin-polarized electron beam will be provided by accelerating electron bunches generated from a photocathode using an Energy Recovery Linac (ERL) loop. Among the critical challenges to achieving the necessary performance is the fact that eRHIC is envisioned to operate with the beam characteristics still beyond the current state-of-the-art by requiring "a polarized electron gun delivering a current of 50 mA" **Error! Reference source not found.**. Such an average current of polarized electrons is at least one order of magnitude higher than what can be achieved with the current state-of-the-art of the photocathode and gun technologies. For this reason, "two efforts are underway to demonstrate the feasibility of producing a 50-mA polarized electron beam. One is based on a single large GaAs cathode and the other employs multiple GaAs cathodes that are used one at a time and the electron bunches are then combined with a rotating dipole field into a continuous electron beam" [3]. Yet, neither of

the above-mentioned approaches seeks to address the actual challenge of improving the polarized photocathodes themselves by employing new types of materials and activation strategies consistent with improved longevity, high degree of polarization, and high quantum efficiency (QE).

We investigated the properties of Cesium Telluride and other materilas as alternative rugged layer to perform the activation to NEA of III-V based photocathodes and characterized their photoemission properties in terms of their quantum efficiency and operational lifetime. This new class of photocathode materials has been evaluated specifically for the generation of highly polarized electron beams. Our experimental apparatus was indeed upgraded with a Mott polarimeter and with a cryogenically cooled photocathode holder. Theses upgrades allowed us to measure the polarization of the electron beam as produced by this new class of photocathodes and prepared us for future studies on materials requiring low temperatures to fully leverage their potential as polarized electron sources for next generation accelerators. These studies will prepare us for subsequent high current tests using Cornell HV DC guns: the high current (up to 100 mA) 400 kV and the cryogenically cooled 200 kV gun (several mA scale) recently built at Cornell University. A large part of the work we performed was dedicated in resurrecting the Mott polarimeter and on

Mott Polarimeter integration in the photocathode lab

In order to achieve the capability of performing measurements of the spin polarization of the electron beam our group received in loan from Thomas Jefferson National Laboratory a low energy Mott polarimeter that was built and operated in the early ’90s at SLAC and used to perform investigations on the strained GaAs and superlattices structures.

The instrument was moved to JLab where it was sitting not used in an unknown working status. Only selected components of the whole apparatus were shipped to Cornell. Figure 1 shows a picture of the Mott polarimeter components as they were received at Cornell University.

Figure 1. The Mott polarimeter vacuum chamber (left) and control electronics (right) as delivered from Jlab to Cornell University.

We tested all the electronics that have been shipped to us and found that some of the equipment (in particular the voltage supplies for the 90 degrees electrostatic bend required to steer the electron beam on the Mott analyzer) needed maintenance.

We also performed a full reverse engineering of the system in order to identify some of the hardware changes that were not documented. We then reproduced the linear optics model of the electrostatic bend and verified the required electrostatic potential to transport the electron beam through it. Based on our simulation we improved the electron transport to the Mott target by a factor 3 (see Figure 2).

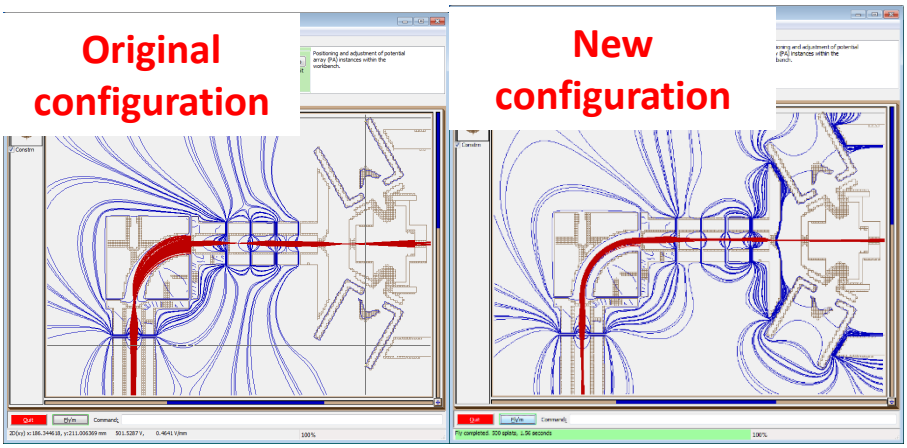

Figure 2. Using an electrostatic solver SIMION the transport of electron from the cathode to the Mott target was simulated and improved achieving an overall efficiency of 25% (ratio of extracted current from the cathode and current reaching the Mott target).

The vacuum chamber hosting the bend was then set on a frame and a Ce:YAG scintillator screen was been placed at the exit of the electrostatic bend to verify we can properly transport the beam before installing the Mott detector.

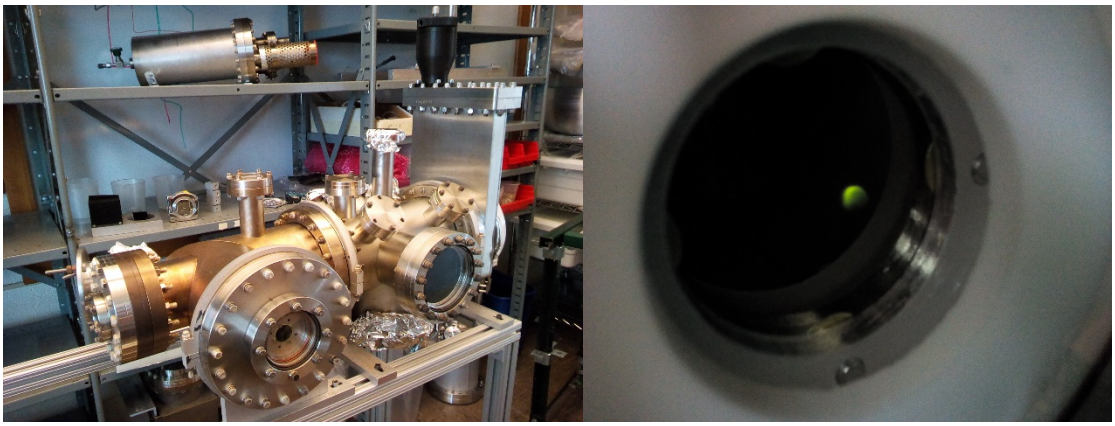

Figure 3. Left: The vacuum chamber hosting the electrostatic bend is shown before being connected to the photocathode lab installation. A flange with a Ce:YAG screen was placed at the Mott detector location to verify a proper electron beam transport. Right: The electron beam successfully transported to the YAG screen as indicated by the fluorescence of the screen.

Once the electron transport from the cathode to the screen was verified, we installed the Mott detector and we measured the signals of the backscattered electrons at the two electron multipliers. Figure 4 shows some pictures of the setup as it is installed in the photocathode laboratory.

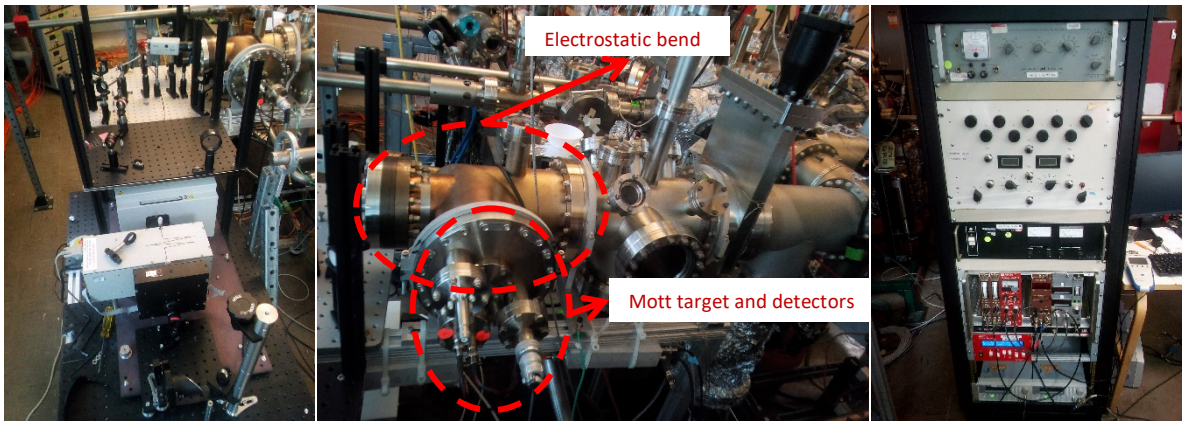

Figure 4. Left: the optical setup (lamp, monochromator and optics to generate and transport circularly polarized light to the photocathode hosted into the UHV chamber. Center: outside view of the UHV chambers hosting the cathode holder, the electrostatic bend and the Mott detector. Right: the rack hosting the electronics units.

Initial experiments were performed using a Cesium Antimonide photocathode: leveraging its long lifetime the system was recommissioned and even in the absence of any asymmetry due to a spin polarization we start measuring count rates at the two channeltrons. Figure 5 shows an example of the count rates measured on the two channeltrons as function of the Energy Loss Window in the Mott detector.

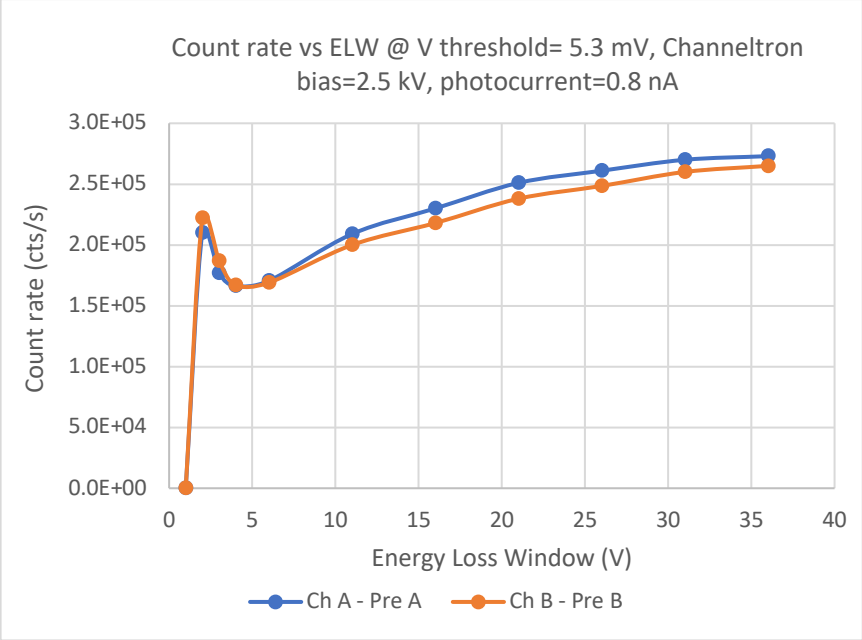

Figure 5. Plot of the counting rates measured on the two channeltrons as function of the Energy Loss Window amplitude.

The Mott chamber was also equipped with a sample holder capable of cryogenic temperatures. To this purpose a cryogenic pump (CTI model CT-100) was modified to be operated as cryostat. A suitable sample holder was designed that, using a sapphire rod, allow the cathodes to be thermally connected to the cryostat and cooled down to about 20 K and at the same time, they can be electrically biased for generating the electron beam used to analyze the spin polarization.

Figure 6 shows a schematics and a picture of the sample holder. We aim in the future to use the cryogenic sample holder to study the depolarization processes and their dependence with temperature to leverage also this operational condition to design electron sources that can provide large degrees of electron spin polarization.

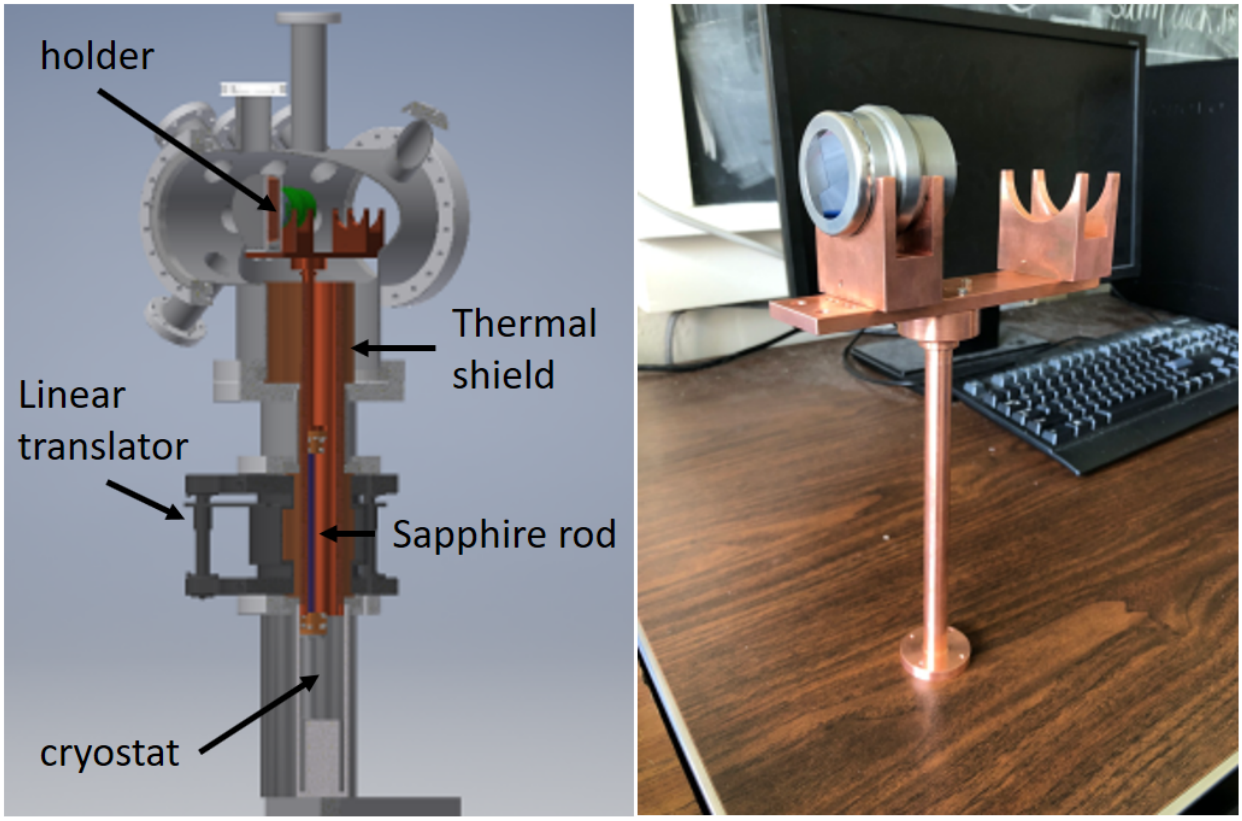

Figure 6. On the left the schematics of the sample holder capable of cryocooling the photocathodes in the Mott analyzer setup.

Cesium Telluride coatings

In order to experiment on the growth of Cesium Telluride over GaAs our photocathode growth chamber was equipped with an effusion cells filled with high purity 99.999% Tellurium pellets. Several growth experiments were performed aimed at obtaining photocathodes with negative electron affinity by means of thin films of Cesium Telluride.

Several different specimens were prepared from the same highly p-doped (Zn 5×10^{18} cm^{-3}) GaAs (100) wafer. In order to remove the native oxide layer, a wet etch was performed in a 4% HCl solution for 5 min under the hood in the air. Then, samples were rinsed in deionized water, dried using pure nitrogen, connected to the sample holder, and loaded under vacuum in less than 1 h. A mild sample heating at about 400 °C for 12 h was deemed sufficient to yield a surface clean enough to perform our experiments. This was inferred from observing that after heating, the samples could be activated to NEA using only Cs (photoemission observed with ~1.43 eV photons).

After the heat cleaning, the temperature of the samples was lowered to approximately 130 °C, and the light of a small diode laser operating at 532 nm was used to illuminate the negatively biased photocathode surface. The Cs_2Te growth on GaAs was performed while continuously cooling down the sample from the initial temperature of about 130 °C [see Figure 6(c)]. Initially [see Figures 7(a) and 7(b)], only a small flux of Cs was evaporated until the photocurrent is saturated for an equivalent QE of about 0.5%, which demonstrates sufficient cleanliness of the GaAs surface. At this point, the shutter for Cs was closed and the one for Te was opened. A sharp decrease in the photocurrent was observed, followed by deposition of 0.5 nm thick Te layer as estimated from the quartz microbalance frequency shift [Figure 7(b)]. Another Cs deposition followed. The photocurrent increased again until an equivalent QE of about 1% was reached. Subsequent simultaneous evaporation of Cs and Te (which adds the equivalent of another 0.5 nm of Te) did not improve QE much further [Figures 7(a) and 7(b)]. Upon final cooling down, the samples were exposed to a very small flux of Cs reaching a typical final QE of about 1.5% at 532 nm.

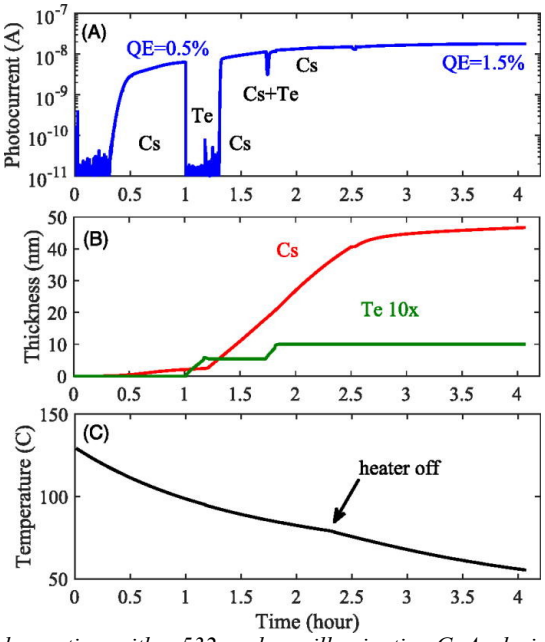

Figure 7. (a) Photocurrent measured over time with a 532 nm laser illuminating GaAs during alternating exposure to Cs and Te evaporation; (b) estimated thicknesses of Cs and Te from the quartz microbalance frequency shift; (c) GaAs substrate temperature during the growth of Cs_2Te.

After the growth the photocathode shows sensitivity to photons as large as the GaAs band gap value of 1.4 eV as shown in the spectral response reported in Figure 8.

One important aspect of the cesium telluride coating is that we expected a longer operational lifetime due to its known robustness as photocathode material. In order to compare the ruggedness of the GaAs samples with cesium telluride coating the QE of the photocathodes was measured as function of the extracted charge and compared with the one of samples activated with Cs and oxygen (see Figure 9). We observed that lifetimes larger by a factor 5 are achieved with the cesium telluride coating under similar condition. We also looked into the possibility of rejuvenating the coating applying additional Cs once the QE has decreased significantly. We

observed that the QE can indeed be restored by exposure to Cs vapors but the measured lifetime is shorter than the ones achieved with a fresh coating. It is suspected that the Cs evaporated at room temperature to rejuvenate the activating layer does not penetrate deeply into the cesium telluride but rather stays at surface of it, being weekly bonded to the surface is again easily lost during operation.

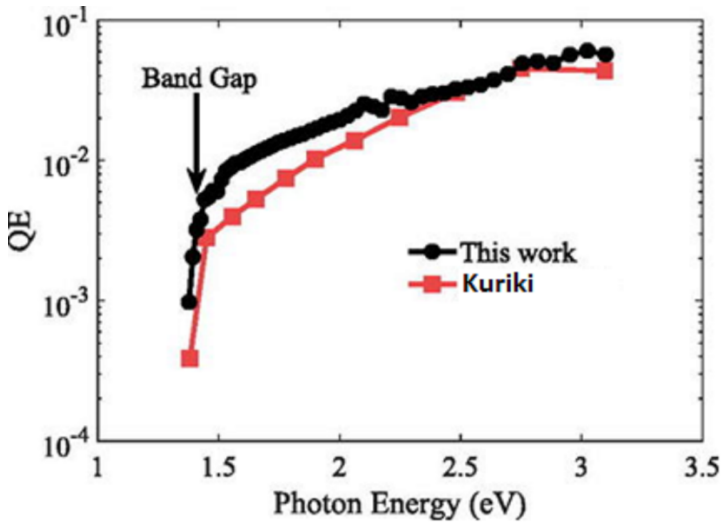

Figure 8. Typical spectral response of our GaAs-Cs_2Te as compared to the one from M. Kuriki, S. Kashiwagi, Y. Seimiya, and K. Uchida, in Proceedings of IPAC2015, Richmond, VA, USA, 2015.

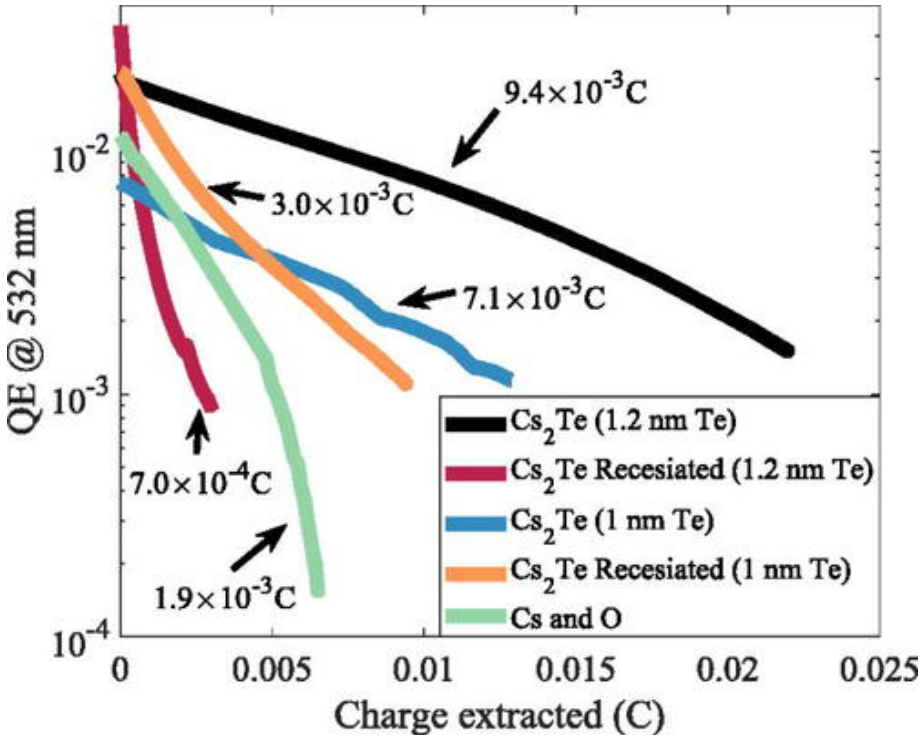

Figure 9. Quantum efficiency of GaAs with various surface conditions at 532 nm wavelength as a function of extracted charges. The number next to each curve is the charge lifetime obtained from an exponential fit.

The last and most important characteristics that we were committed to measure was the spin polarization of the electrons emitted when the GaAs is activated with cesium telluride. We perform this measurement using the same GaAs sample that was activated one first time to NEA using Cs and oxygen and later using cesium telluride. The results reported in figure 10 indicate that there is no additional depolarization induced by the cesium telluride activating coating.

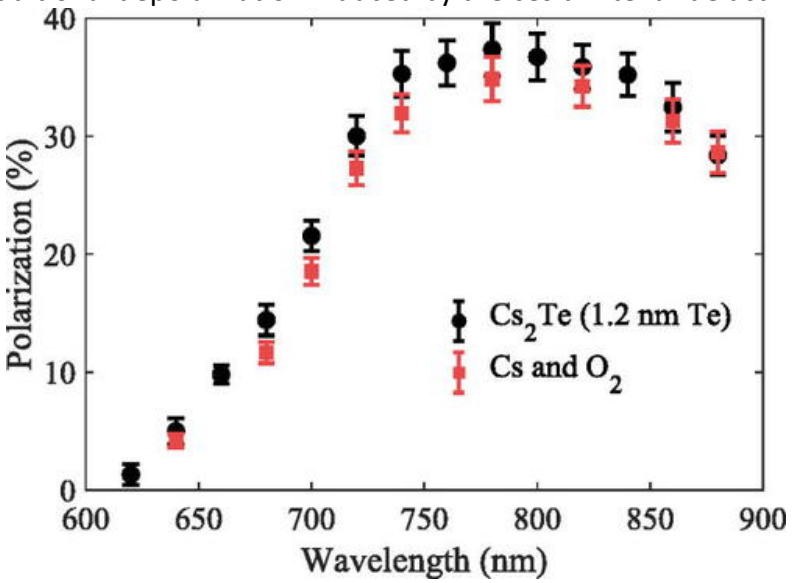

Figure 10. Spin polarization measured from GaAs samples activated by Cs_2Te and Cs and O2 as a function of the laser wavelength.

A new rugged NEA coating transparent to spin polarization

In search of alternative ways to activate GaAs to negative electron affinity we attempted the activation of bulk GaAs samples with another material that based on band gap and electron affinity values we believed could, as the cesium telluride, be capable of activating the surface of GaAs to NEA.

While the results we obtained are still to be considered preliminary some really exciting findings indicate that the outcome of this research can help solving the long-standing issue of the operating lifetime of GaAs photocathodes.

Before illustrating some of our findings it's important noting that the results are not yet complete: especially from the point of view of the synthesis of these samples it has to be noted that some of the sample preparation parameters, like the growth rates and final thickness of the coating have yet to be verified and accurately measured. Indeed, we found that some of the parameters that appears to be critical for synthesizing samples with the largest efficiency can hardly be measured with our experimental setup because at the limits of the sensitivity of some of our instruments.

Nevertheless, we performed several attempts at activating the GaAs with what we believe being a rugged coating. On the overall while the results are still scattered in the growth parameter

space they clearly pointed out that: this materials can produce Negative Electron Affinity on the surface of the GaAs, it looks to be not affecting the electron spin polarization of the photoelectron, and, while is it possible that it can yield a slightly lower QE than the activation with Cs and oxygen or NF3, the benefit in terms of the ruggedness are or far more vastly importance for practical application in accelerator technology.

Also, our preliminary findings clearly indicate that in order to achieve the highest QE the surface of the sample has to be clean of contaminants: only the samples that were achieving the highest sensitivity upon exposure to Cs vapors were also showing the highest sensitivity once coated with the activating coating.

Depending on the experimental condition used and on the initial cleanliness of the surface we obtained GaAs samples with NEA surfaces (which is deduced to be so by looking at a sharp drop in the spectral response when the energy of the photons approaches the 1.4 eV value) with QE in the order of few % in the green at 532 nm and QE at 780 nm spanning one order of magnitudes from $1x10^{-3}$ up to 0.02 (Figure 11).

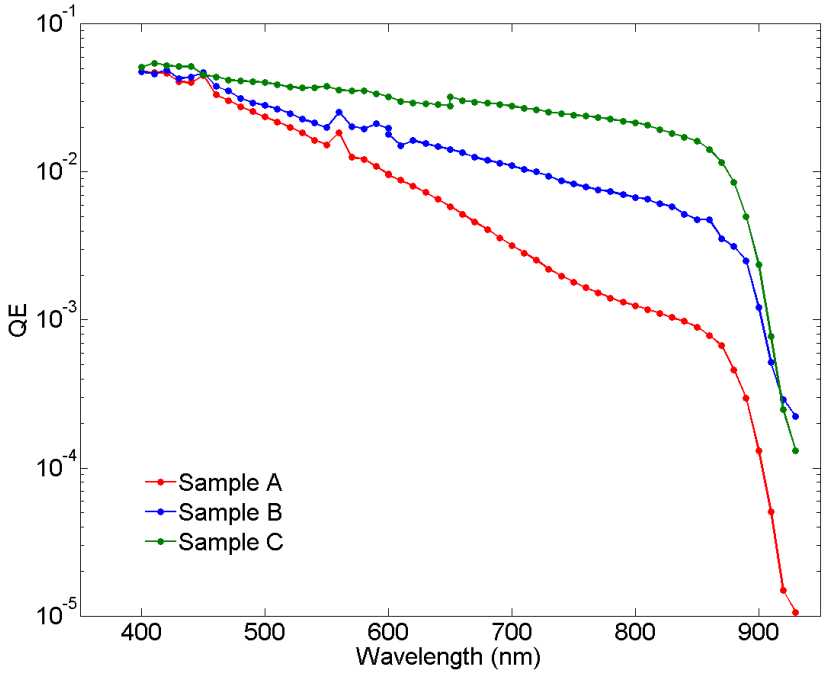

Figure 11. Spectral response of different bulk GaAs activated to NEA using a rugged protective coating. In the IR part of the spectrum large fluctuations of the QE are measured. Up to 2% QE have been obtained at 780 nm.

The electron spin polarization of the samples activated to NEA with this material have been measured as function of the wavelength of the exciting photons and the results are compared to the ones obtained from a GaAs sample activated to NEA using Cs and oxygen (Figure 12). The results obtained indicate that, apart from small changes (in the order of few percent) that can be attributed to small variations in doping densities from sample to sample, the polarization of the electron beams is unaffected by the activation with this new material.

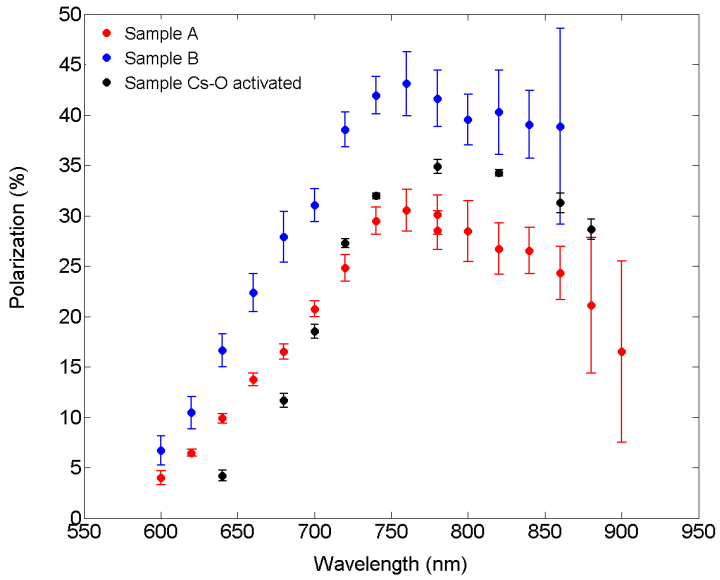

Figure 12. The electron spin polarization measured on sample A and B are compared with the electron spin polarization of a GaAs activated with CS and oxygen.

Selected samples were studied in order to estimate their robustness under prolonged operation. In figure C we report the lifetime measurements in terms of QE vs extracted charge from GaAs activated with different methods (Cs, Cesium Telluride and this new protective coating). Experiment were performed under similar condition of vacuum levels (better than $1x10^{-10}$ Torr) and similar laser irradiation (about $30x10^{-6}$ W at 532 nm) We found that the new coating is more robust of the Cs only and Cesium Telluride allowing a charge lifetime value which is a factor about 80 times better than the GaAs activated with Cs only (in the case of a specimen activated with Cs and O, not reported in the Figure 13, the factor is about 50).

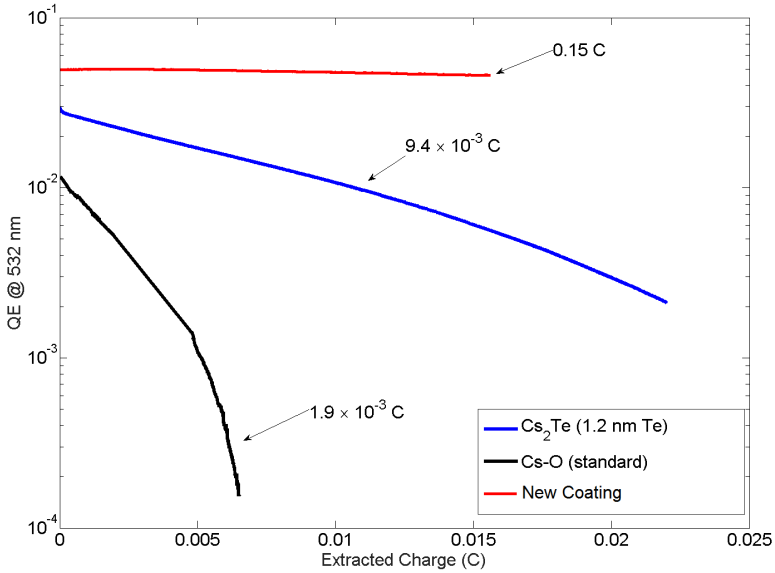

Figure 13. Charge lifetime as measured for bulk GaAs activated to NEA using only Cs, Cesium Telluride and the rugged protective coating. Charge lifetime up to 80 larger are obtained from the sample activated with the new protective coating.

Conclusions

We have presented our accomplishments made possible within the DOE award DE-SC0016203 to develop the next generation robust polarization photocathodes for EIC. Further details can be found in the following publications (acknowledging the DOE DE-SC0016203 funding):

- L. Cultrera, A. Bartnik, I. V. Bazarov, C. Gulliford, P. Gupta, H. Lee, S. A. McBride, T. P. Moore, "Cornell laboratory for high intensity, ultra-bright and polarized electron beams", Proceedings of the 2017, p. 551-3, Copenhagen, Denmark
- J. Bae, I. Bazarov, L. Cultrera, P. DiGiacomo, "Long lifetime spin-polarized GaAs photocathode activated by Cs2Te", Proceedings of the 2018 IPAC, p. 1589-92, Vancouver, BC, Canada
- L. Cultrera, J. K. Bae, A. Bartnik, I. V. Bazarov, R. Doane, A. Galdi, C. Gulliford, W. H. Li, J. M. Maxson, S. A. McBride, T. P. Moore, C. M. Pierce, C. Xu, "Photocathodes R&D for High Brightness and Highly Polarized Electron Beams at Cornell University", Proceedings of the 2018 IPAC, p. 1601-4, Vancouver, BC, Canada
- Jai Kwan Bae, Luca Cultrera, Philip DiGiacomo, and Ivan Bazarov, "Rugged spin-polarized electron sources based on negative electron affinity GaAs photocathode with robust Cs2Te coating", Appl. Phys. Lett. 112 (2018) 154101 https://doi.org/10.1063/1.5026701

Summary

We have demonstrated thin but robust protective activation layers in place of the conventional cesiation. Significant lifetime improvements from spin-polarized photocathodes have been achieved without adversely affecting the state of spin-polarization. This research opens a new and robust way to reach the negative electron affinity for a large class of photocathodes specifically designed to maximize their accelerator performance. It particular, it benefits the future EIC by improving the lifetime available from spin-polarized electron photoemission sources.

References

[1] http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf The 2015 Long Range Plan for Nuclear Science

[2] "NP Community Panel Report on Electron Ion Collider (EIC) Accelerator R&D", Online resource (2017) https://science.energy.gov/np/community-resources/reports/

[3] A. Accardi, J. L. Albacete, M. Anselmino, N. Armesto, E. C. Aschenauer, A. Bacchetta, D. Boer, W. Brooks et al., arXiv:1212.1701