ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPML025

LONG LIFETIME SPIN-POLARIZED GaAs PHOTOCATHODE ACTIVATED BY Cs_2Te

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Abstract

High intensity and highly spin-polarized electron source is of great interest to the next generation Electron Ion Colliders. GaAs prepared by the standard activation method, which is the most widely used spin-polarized photocathode, is notorious for its vacuum sensitivity and short operational lifetime. To improve the lifetime of GaAs photocathodes, we activated GaAs by Cs_2Te, a material well known for its robustness. We confirmed the Cs_2Te layer forms negative electron affinity on GaAs with a factor of 5 improvement in lifetime. Furthermore, the new activation method had no adverse effect on spin-polarization. Considering Cs_2Te forms much thicker activation layer (~2 nm) compared to the standard activation layer (~ monolayer), our results trigger a paradigm shift on new activation methods with other robust materials that were avoided for their thickness.

INTRODUCTION

In Accelerator physics community, GaAs is the most widely used material for spin-polarized photocathodes because it can provide high intensity currents under Negative Electron Affinity (NEA) condition. NEA is achieved in GaAs through activation process where the surface is exposed to less than a monolayer of cesium and oxidant (O_2 and NF_3 are commonly used). Then, the activation layer covers the surface with strong dipole moments which lower the vacuum level even below the conduction band minimum (CBM) of the bulk GaAs. Under NEA conditions, electrons that have relaxed to the bottom of the conduction band can still escape into the vacuum. Therefore, NEA is essential to achieve a high Quantum Efficiency (QE).

The physics of spin-polarized photoemission of GaAs originates from the selection rule and the angular momentum conservation. When circularly polarized light, which has the spin angular momentum of $\pm\hbar$, shines the bulk GaAs, the spin angular momentum of excited electrons changes by $\pm\hbar$, which results in spin asymmetry among the excited states. Due to the degenerate heavy-hole and light-hole bands in the $P_{3/2}$ valence band state, a bulk GaAs can provide spin-polarization up to 50%. To overcome this limit, exerting lattice strain on GaAs was studied to break the degeneracy, and successfully showed an enhanced polarization of 90% at a cost of decreased QE of 0.07% [1]. A recent study showed GaAs/GaAsP multi-layer super-lattices with a distributed Bragg reflector structure can have an enhanced QE of 6.4% with a high polarization of 84% [2].

The activation layer of NEA GaAs is known to be extremely vacuum sensitive because the traditional activation layer materials, such as Cs-O_2 and Cs-NF_3, are chemically unstable and weakly bound to the bulk surface. Thus, they require extreme high vacuum (XHV) conditions to operate for long enough time. Several approaches were proposed to prolong the lifetime of GaAs photocathodes. For example, extracting electron charges from a position mm off the electrostatic center of the photocathode was suggested to minimize the ion-back bombardment at the extraction spot [3]. This operating condition can improve alkali antimonide photocathodes as well [4]. In another study, it was shown that the chemical immunity can be enhanced when GaAs is activated by two alkali materials, Cs and Li, simultaneously with NF_3 oxidant agent [5]. These studies suggest a possibility of improving lifetime of GaAs photocathodes by using chemically robust activation layer.

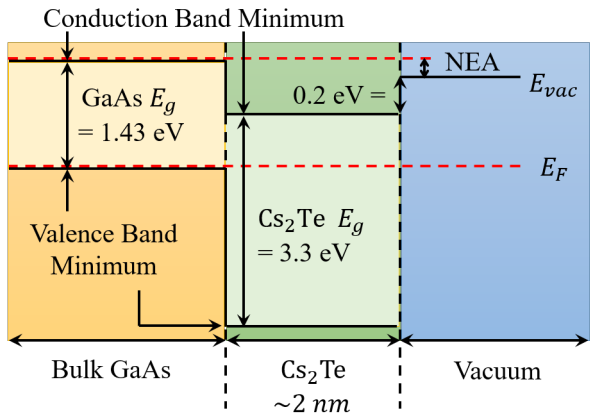

Figure 1: Energy band diagram of GaAs activated with Cs_2Te. The vacuum level is below the conduction band minimum of bulk GaAs, indicating achievement of NEA. GaAs band gap energy photons (1.43 eV) excites electrons only from the bulk valence band minimum because of large band gap (3.3 eV) of Cs_2Te.

Cs_2Te is a robust solar-blind photocathode material well known for its resistance against chemical poisoning and poor vacuum conditions, and it's the most common photocathode material used in normal conducting RF guns for that reason [6]. Recent studies [7] demonstrated GaAs can be activated to NEA with Cs_2Te as shown in Fig. 1.

In this proceeding, achievement of NEA conditions with Cs_2Te activation layers is reported, and GaAs samples activated by Cs_2Te are compared with GaAs activated with standard materials, Cs and O_2, in lifetime and spin-polarization measurements. The measurements demonstrate Cs_2Te can achieve NEA and improve a factor of 5 on charge lifetime without any adverse effects on spin polarization of photoelectrons.

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EXPERIMENT

Sample Preparation

Highly p-doped (Zn 5×10^{18}cm^{-3}) GaAs (100) wafers were prepared by wet etching in a 4% HCL solution for 5 min in the air. Prepared samples were rinsed in deionized water, dried with pure nitrogen, and loaded under vacuum in less than 1 hour. The loaded wafers were heated at about 400°C for 12 hours. This mild heating was deemed sufficient for surface cleaning considering the samples could achieve NEA with only Cs after the heating. Cs_2Te was grown on GaAs under ultra-high vacuum (UHV) by effusion cells equipped with BN crucibles loaded with Cs (99.5% from Strem Chemicals) and Te (99.999% from Sigma-Aldrich). Each effusion cell is geared with a shutter that allows to control the flux towards the substrate. After the heat cleaning, the samples were cooled down to 130°C and negatively biased. Then, a 532 nm diode laser was used to monitor QE of the samples during the process of Cs_2Te growth.

The growth was performed while the sample is being cooled down from 130°C. Initially, the substrate was exposed to a small flux of Cs until the QE increased up to 0.5%, which implies sufficient cleanness of the GaAs surface. Once QE reached 0.5%, the Cs flux was blocked by the shutter and Te evaporation started (see Fig. 2). Te deposition continued until the thickness reached 0.5 nm as estimated by quartz microbalance frequency shift. Then, the shutter of Te was closed, and Cs was deposited until the QE reaches 1%. At 1% QE, simultaneous exposure to Cs and Te added another 0.5 nm of Te to the substrate. Once total 1 nm of Te is deposited on the surface, the samples were cooled down to room temperature while being exposed to a small flux of Cs, reaching a final QE of 1.5 % at 532 nm.

One of the samples was analyzed by Auger electron spectroscopy as shown in Fig. 3. Te and Cs show distinctive peaks in Auger spectrum, which implies the presence of the two elements on GaAs surface. Ga and As peaks are also detected since Cs_2Te layer is only few nm thick.

Spectral Response

Achievement of NEA condition can be verified experimentally by observing photoemission with photons that has GaAs band gap energy (1.43 eV). The spectral response of GaAs activated with Cs_2Te from Fig. 4 confirms NEA formed on the surface.

Lifetime

Operational lifetime, defined as the amount of time a photocathode can satisfy the beam current requirement, is practical but not an appropriate metric to compare performance of multiple photocathodes because it can vary significantly depending on operating environment, such as the current intensity being extracted. In this work, we report in terms of charge lifetime, defined as the amount of charge a photocathode can extract until the QE drops down to $1/e$ of the initial value. Figure 5 reports QE over the amount of charge

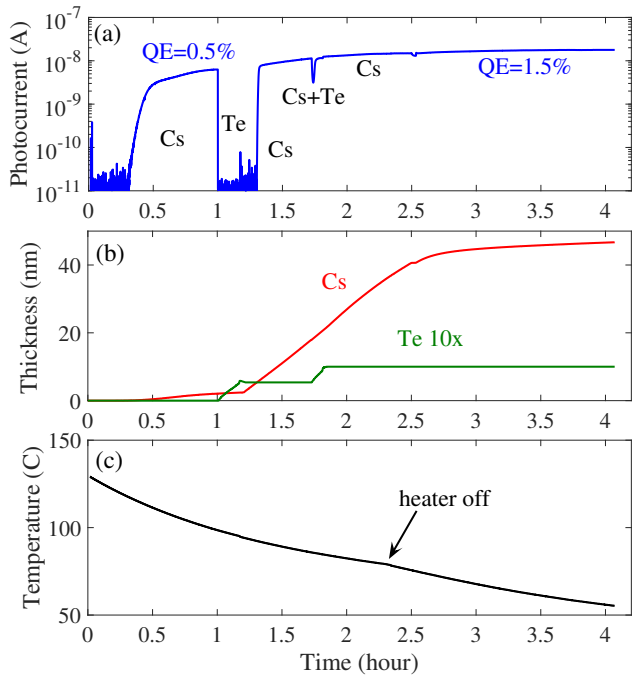

Figure 2: (a) Photocurrent measured over time using a 532 nm laser shining GaAs during the growth of Cs_2Te; (b) Estimated thicknesses of Cs and Te deposition from the quartz microbalance frequency shift; (c) Temperature of GaAs substrate during the Cs_2Te growth.

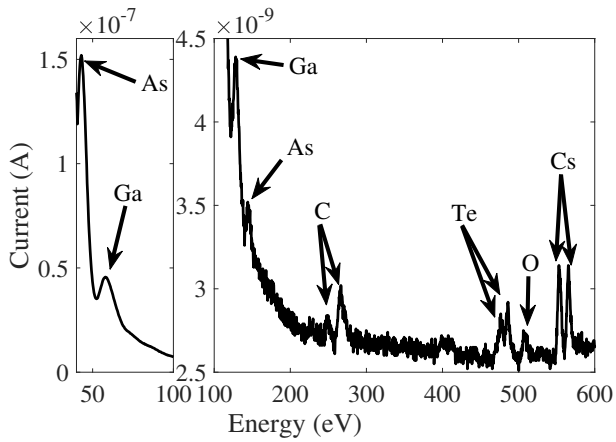

Figure 3: Auger electron spectrum of GaAs activated by Cs_2Te.

extracted for multiple samples with different activation methods under UHV at 532 nm with identical spot size and laser intensity ($\sim 50\mu$W). For GaAs samples activated by Cs_2Te, once the QEs fall below 10^{-3}, the surfaces were recesiated again to restore the QEs, and the QEs were monitored again as a function of extracted charges.

The sample coated with the most thick Cs_2Te layer (1.2 nm Te) showed the largest charge lifetime of 9.4×10^{-3}C, which is a factor of 5 improvement from GaAs activated by Cs and O_2 that has 1.9×10^{-3}C charge lifetime. However, the recesiated samples showed similar charge lifetime with the one activated with conventional method, which implies Cs atoms

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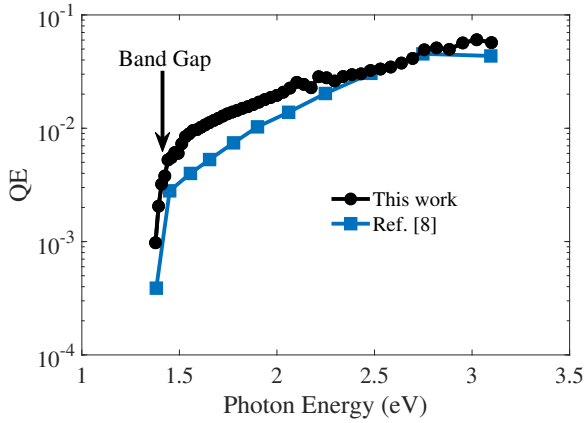

Figure 4: Spectral response of GaAs activated with Cs_2Te in this work compared to the one from Ref. [8].

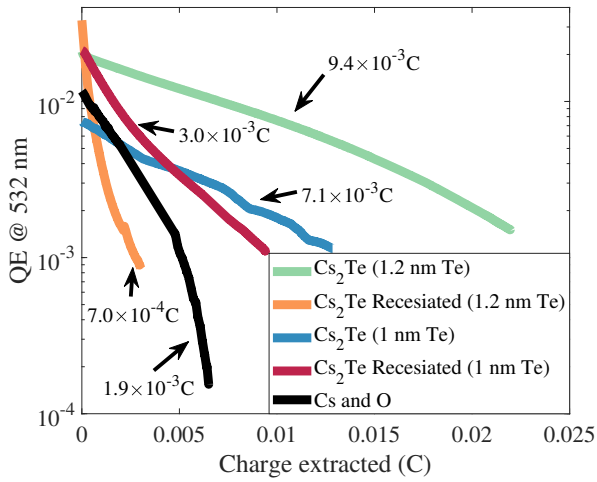

Figure 5: Quantum Efficiency measured at 532 nm as a function of extracted charges for various activation methods of GaAs. The charge lifetimes calculated from exponential fits are written next to each curve.

could not penetrate the Cs_2Te layer but rather deposited on the surface during the recesiation.

Spin Polarization

Spin-polarization of photoelectrons were measured using a Mott Polarimeter that was characterized to have a Sherman function of 0.15 at 20 kV operating voltage with a 1 keV energy loss window. Circularly polarized light was generated using a linear polarizer and a liquid crystal variable wave plate that could switch retardance between $\lambda/4$ and $3\lambda/4$.

Although excited electrons in GaAs have 50% polarization initially, the spin relaxation that occurs during the transportation from the bulk to the surface results in 30-40% spin-polarization measured at room temperature. The spin relaxation mechanisms for GaAs are extensively studied field, and the characteristic relaxation time is known to be in the order of 100 ps at room temperature [9]. On the other hand, the spin relaxation at activation layers is relatively

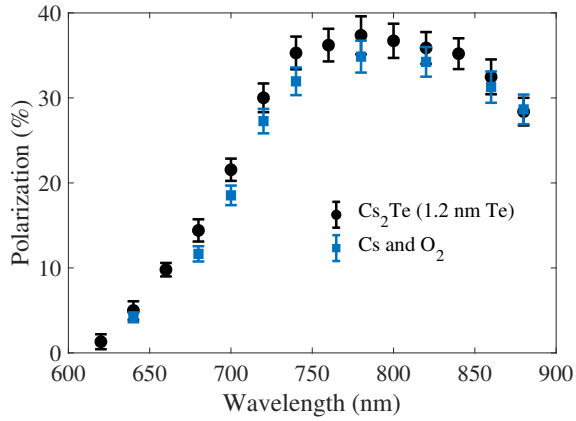

Figure 6: Comparison of photoelectron spin-polarization from GaAs prepared with Cs_2Te activation and standard activation with Cs and O_2.

unknown and considered negligible because conventional activation method only deposit in the order of a monolayer of Cs and O_2. However, for Cs_2Te activation layer, the thickness ($\sim$ 2 nm) may result in another source of significant depolarization. By closely following Ref. [9], we estimate the characteristic spin relaxation time in Cs_2Te to be similar to that of GaAs ($\sim$ 100 ps) and thus, predict the activation layer can be up to a few tens of nm without being a source of significant depolarization. Fig. 6 supports this prediction.

CONCLUSION

In this proceeding, we report on GaAs activated by Cs_2Te and how this new activation method affects the performance as a spin-polarized photocathode. Photoemission was observed at GaAs band gap photon energy, confirming achievement of NEA condition. Compared to the standard activation method with Cs and O_2, the charge lifetime was improved by a factor of 5 without any adverse effect on spin-polarization. Our results with simplified estimates suggest the performance of NEA GaAs can be optimized with even thicker activation layers, thereby shifting the paradigm on activation method of GaAs.

ACKNOWLEDGMENTS

This work was supported by the Department of Energy Grant Nos. DE-SC0016203 and NSF PHY-1461111.

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