Robust electron sources for future accelerator facilities

Jyoti Biswas

Brookhaven National Laboratory
On behalf of the collaborations

May 23, 2023

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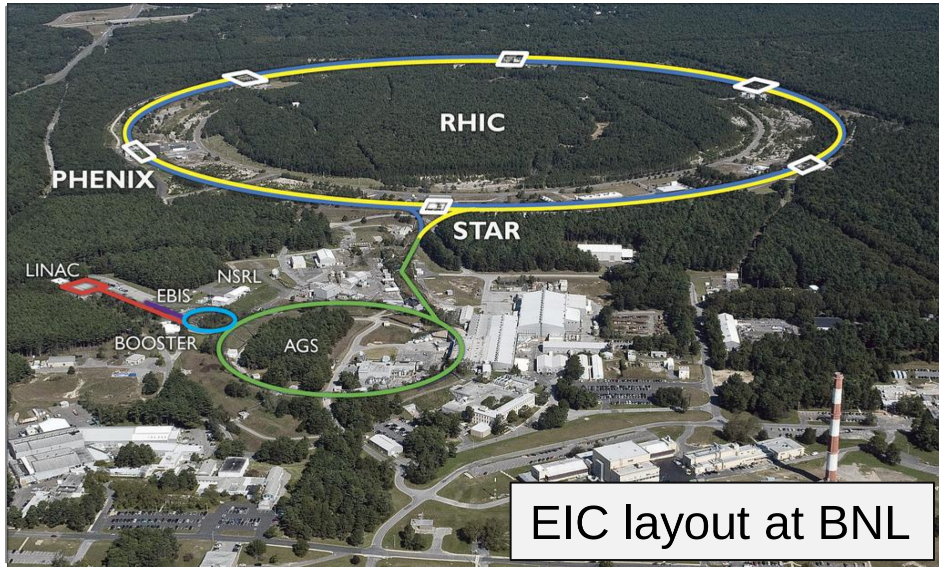
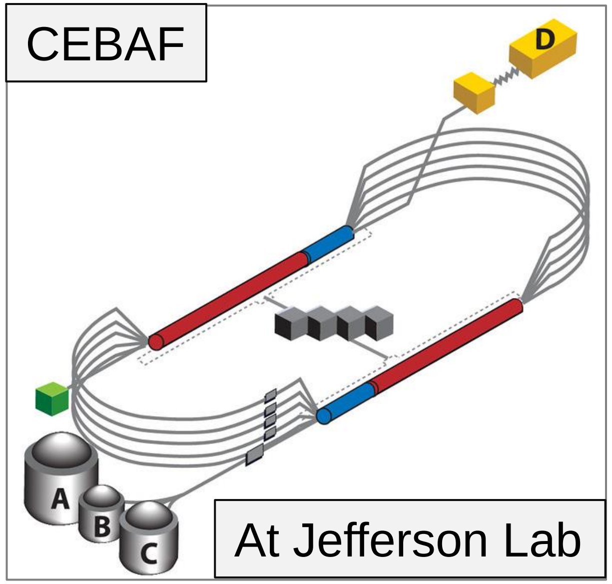
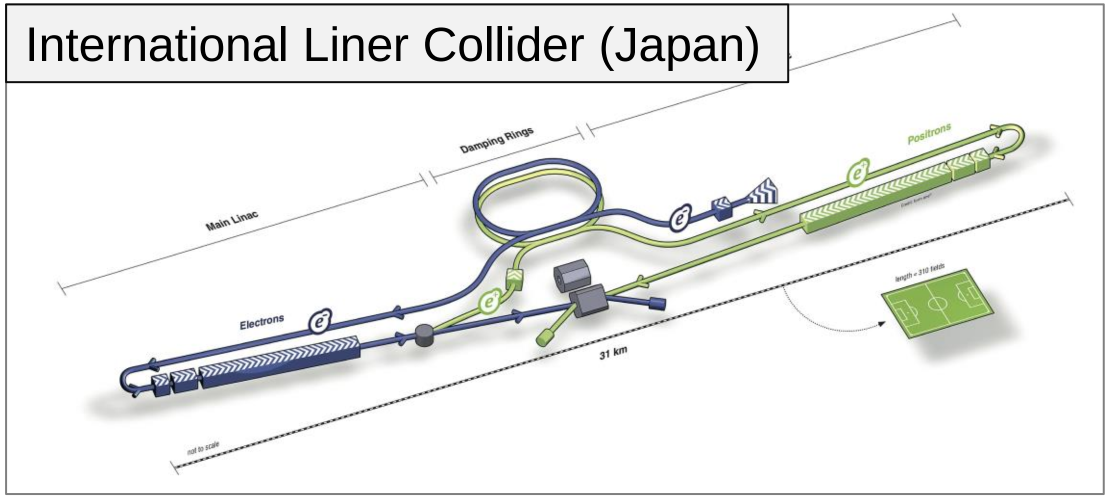
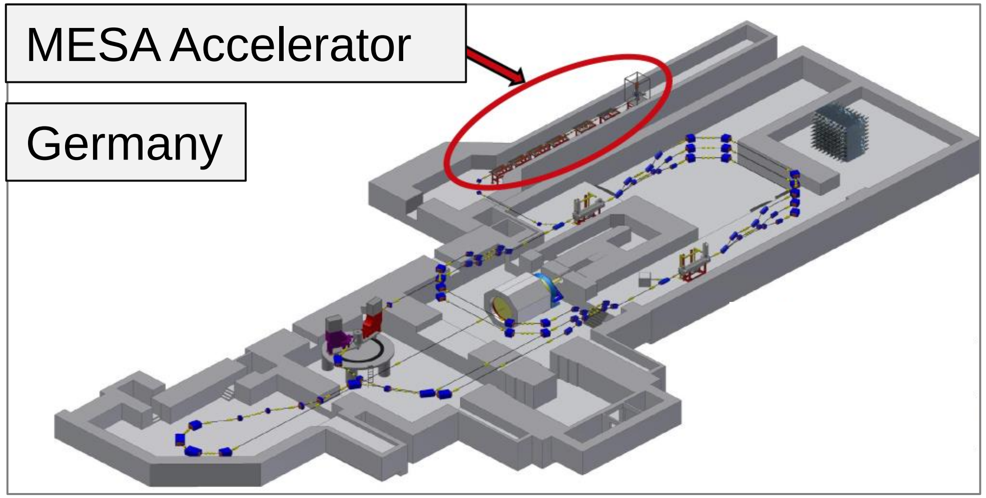
Perspective - Polarized Electron Sources









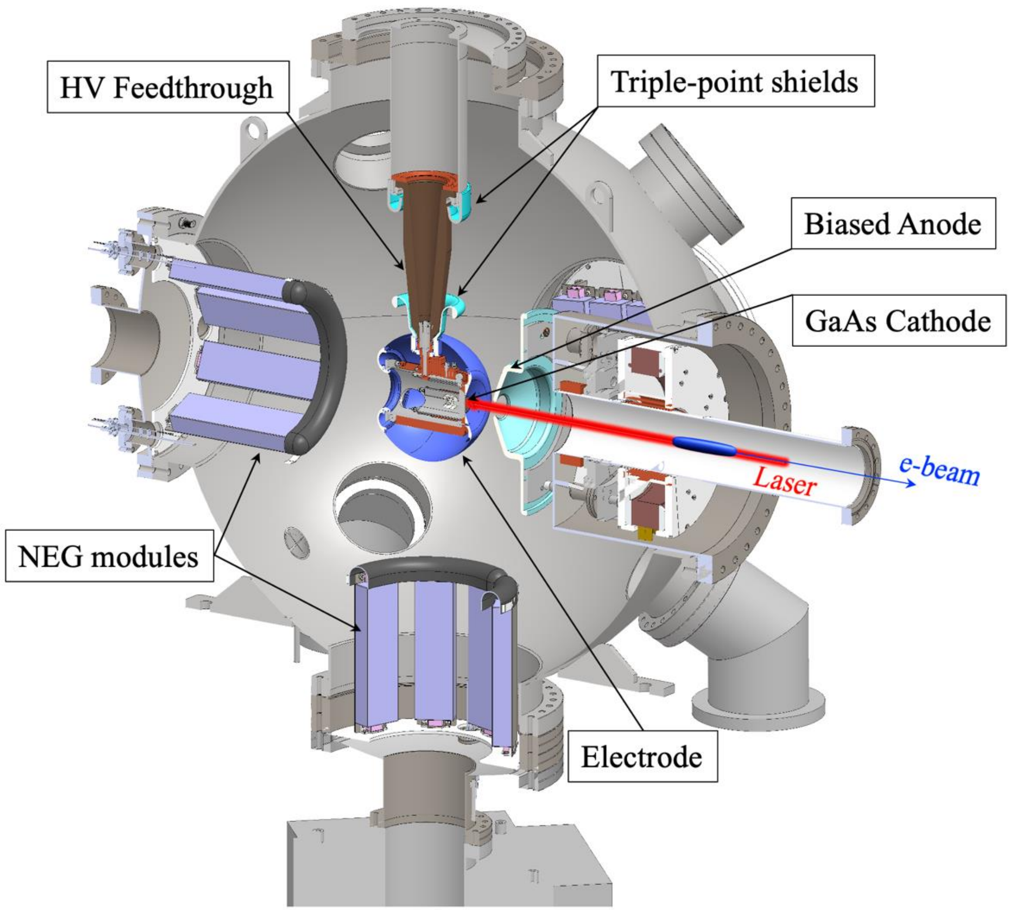
DC - Polarized Electron Sources

Circularly polarized light

DC acceleration

GaAs photocathodes as the source

DC polarized electron gun



BNL EIC Gun

Wang *et al.* Phys. Rev. Accel. Beams 25, 033401 (2022)

Polarized Electron Sources

GaAs-based photocathodes: Essential Attributes

- High Quantum Efficiency (QE)
- Long charge lifetime
- High Electron Spin Polarization (ESP)

I will present our advances on each of these issues!

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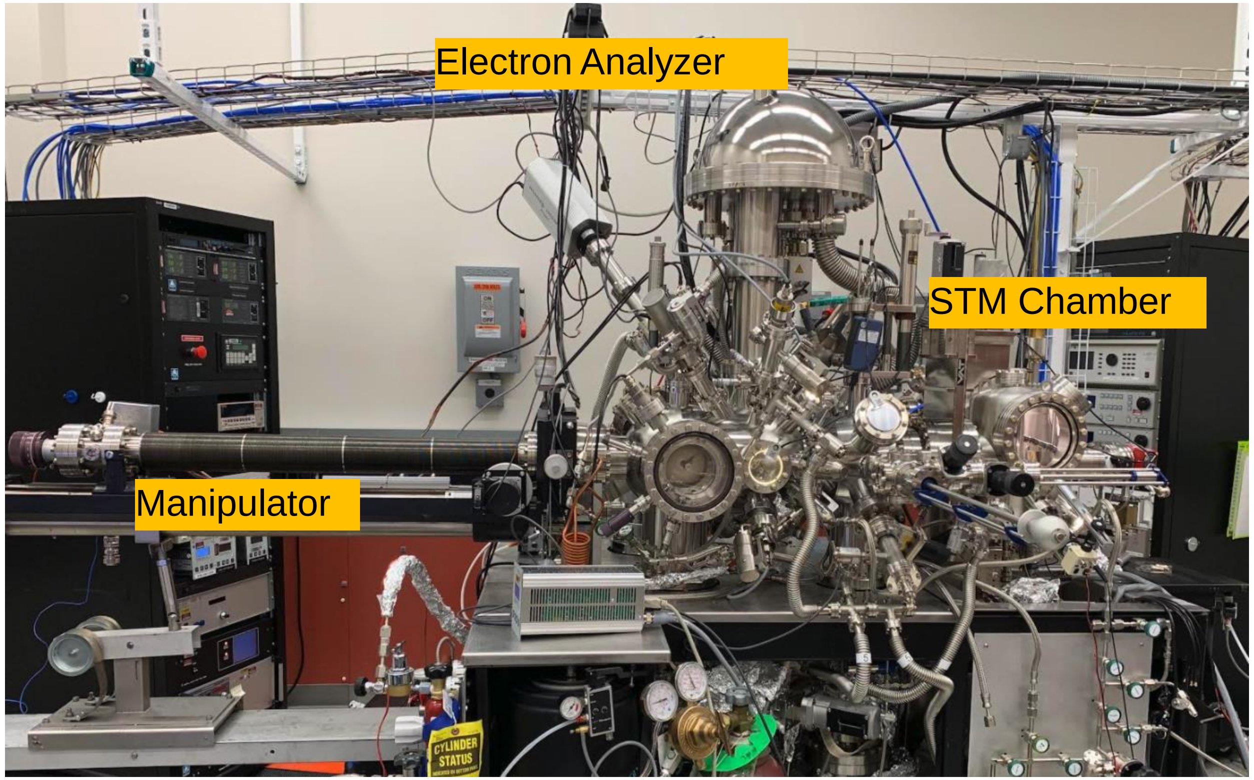
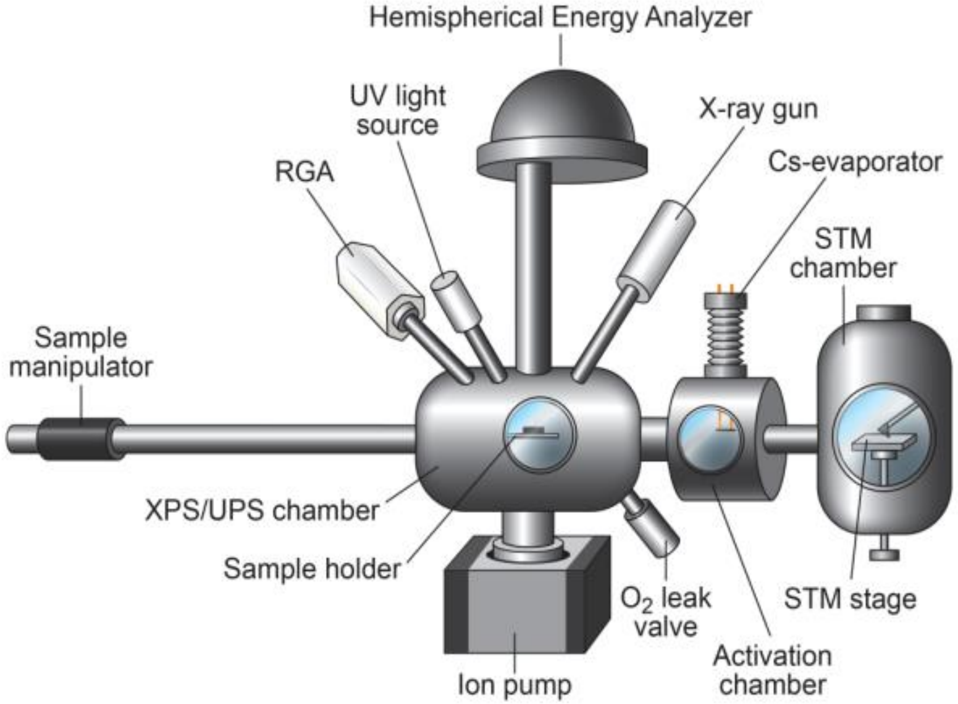
Towards High QE GaAs Photocathode

Substrate Preparation and Characterization



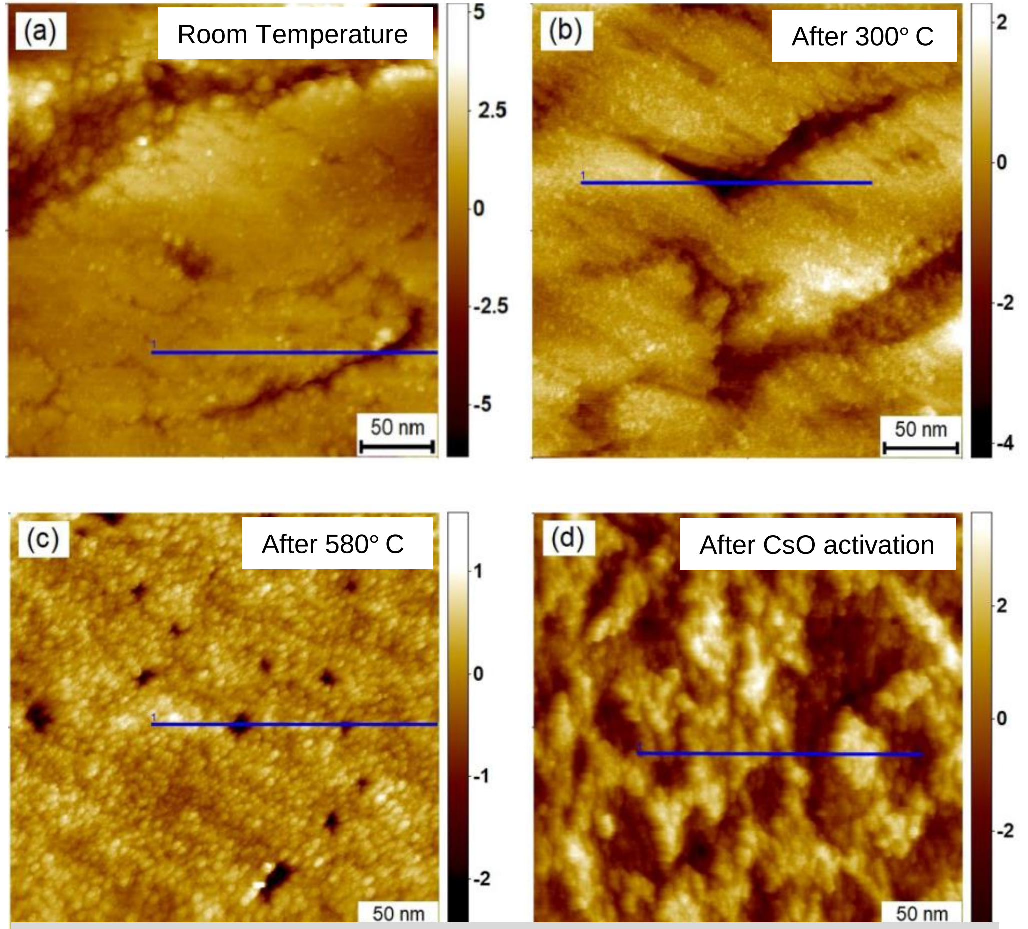
Multiprobe system located in Center for Functional Nanomaterial (CFN) at Brookhaven National Laboratory (BNL).



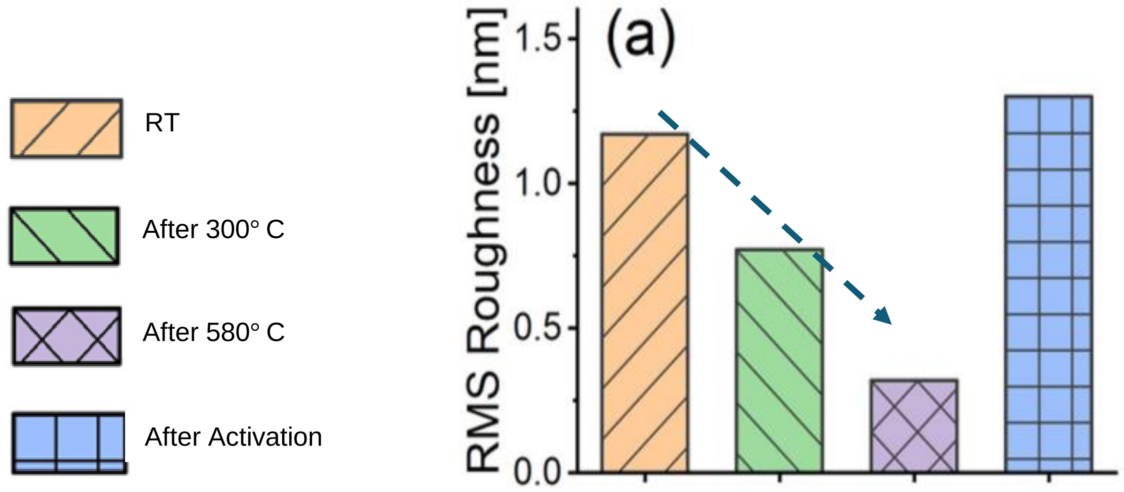
Schematic drawing of the multiprobe system at CFN, BNL

Towards High QE GaAs Photocathode

Substrate Preparation and Characterization - Surface Roughness



STM - GaAs at different temperature, & after activation



RMS roughness at different stage of the activation

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J. Biswas *et al.* J. Appl. Phys. 128, 045308 (2020); https://doi.org/10.1063/5.0008969

Conclusion from Substrate Preparation and Characterization

- ❑ Contrary to common assumption, we found that right amount of heat treatment at UHV decreases the surface RMS roughness.
- ❑ This preparation is optimal for the subsequent growth of thin activation material on it.
- ❑ Reduced field emission and emittance growth.

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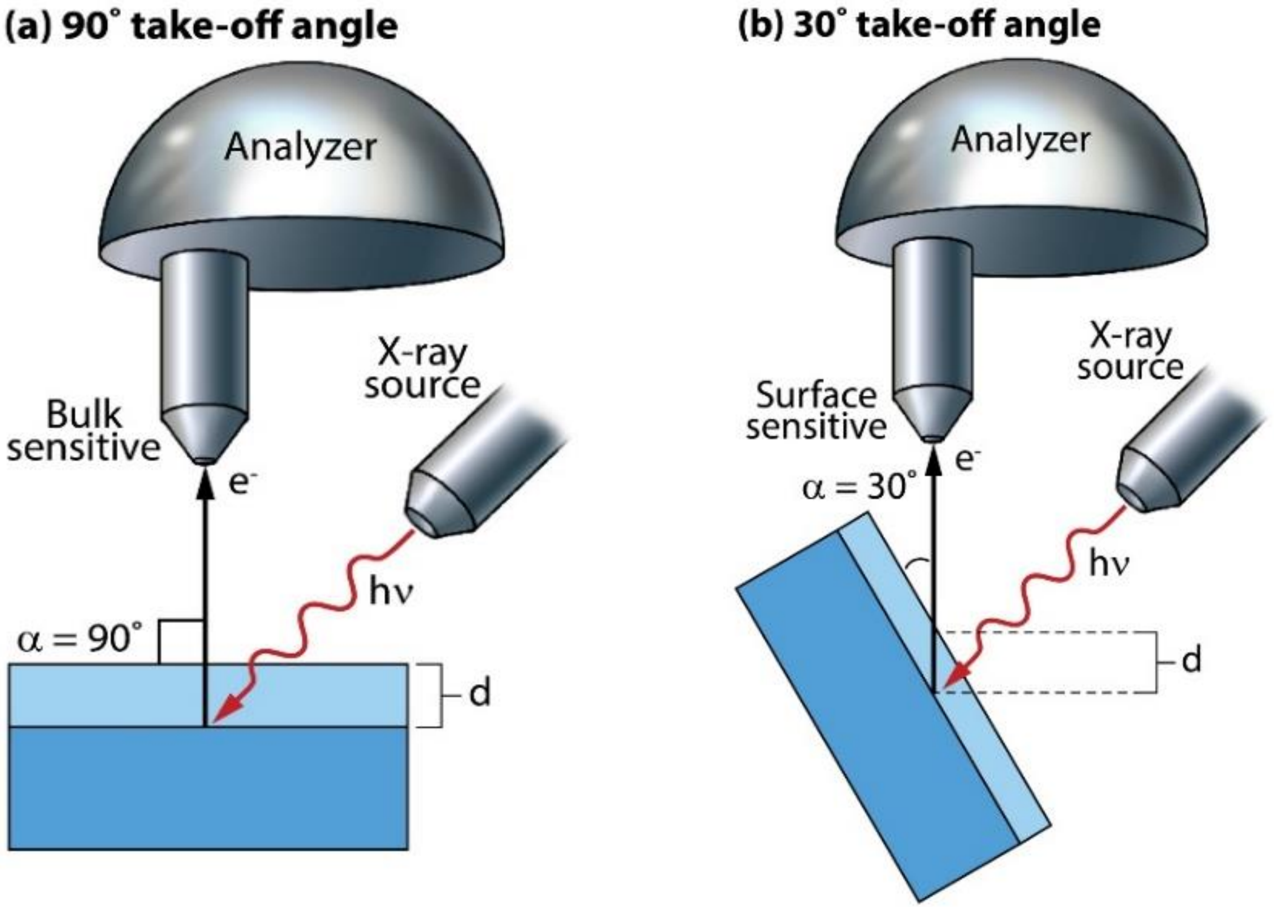
J. Biswas *et al.* J. Appl. Phys. 128, 045308 (2020); https://doi.org/10.1063/5.0008969

Towards High QE GaAs Photocathode

Chemical analysis of CsO/GaAs cathode using AR-XPS/UPS



$\alpha = electron\ take\ off\ angle$

$ID = Information\ depth$

$ID = d\ sin\alpha$

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J. Biswas *et al.* J. Appl. Phys. 128, 045308 (2020); https://doi.org/10.1063/5.0008969

Towards High QE GaAs Photocathode

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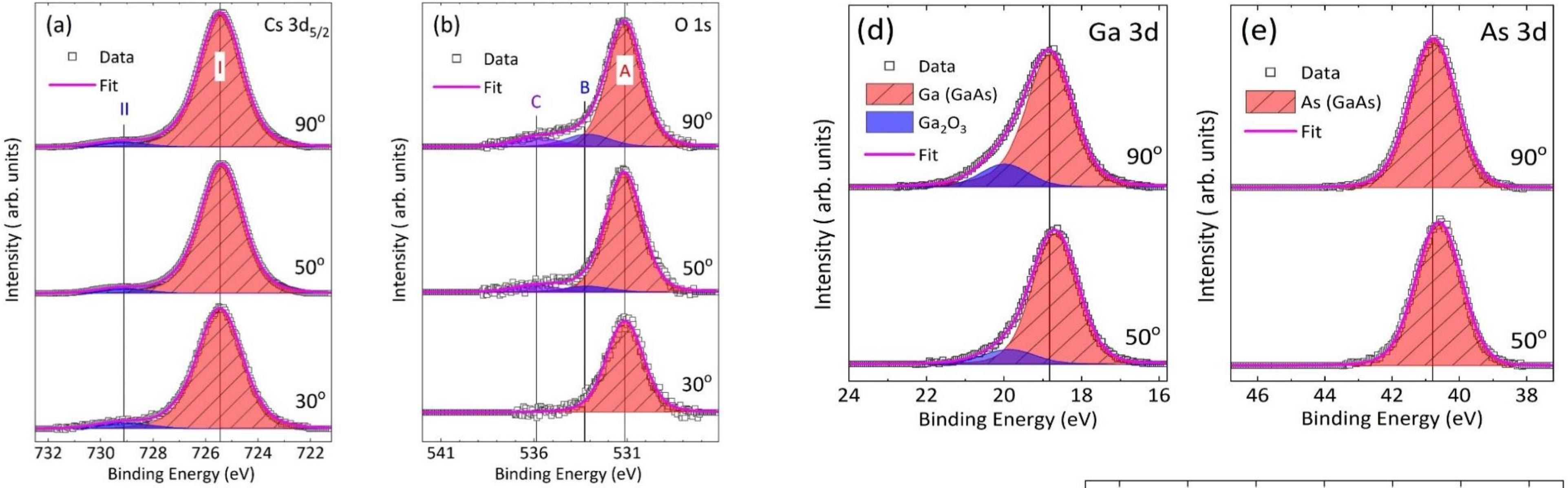
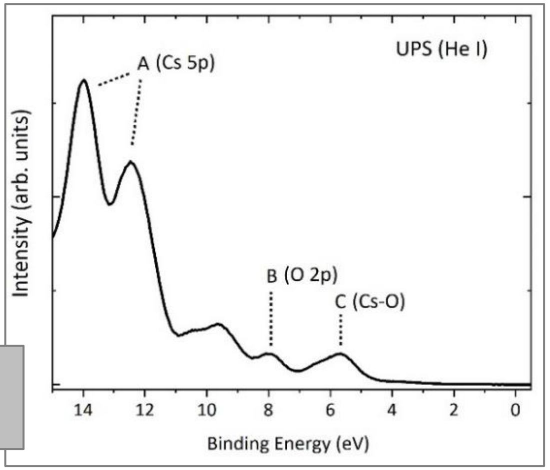
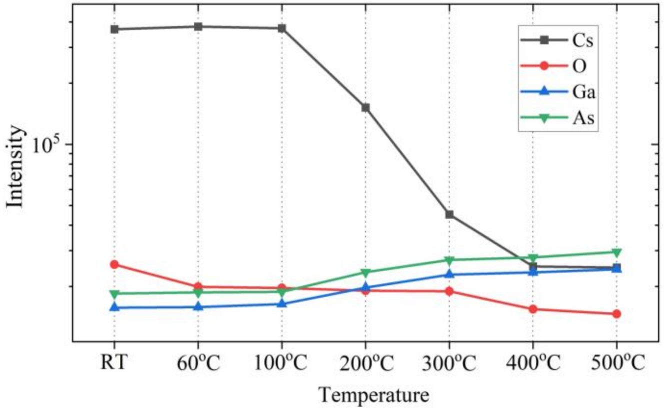




UPS after Cs-O Activation



XPS - Temperature Programmed Reduction

J. Biswas *et al.* J. Appl. Phys. 128, 045308 (2020); https://doi.org/10.1063/5.0008969

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Towards High QE GaAs Photocathode

Conclusion from the chemical analysis of CsO/GaAs

- This is a **first detailed chemical analysis** of Cs-O activation on GaAs.

- We find the ratio of Cs & O on the activation layer, **Cs:O ≈ 2:1**
  - **No formation of previously proposed $\mathbf{Cs_2O}$, or $\boldsymbol{Cs_{11}O_3}$** compound in activation layer.

- XPS confirms that, surface start to lose Cs significantly at ~100°C, whereas **oxygen loss is significant even at 60°C**.
  - Laser illumination induced heating could destroy the cathode if temperature of the sample exceeds 60°C.

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J. Biswas *et al.* J. Appl. Phys. 128, 045308 (2020); https://doi.org/10.1063/5.0008969

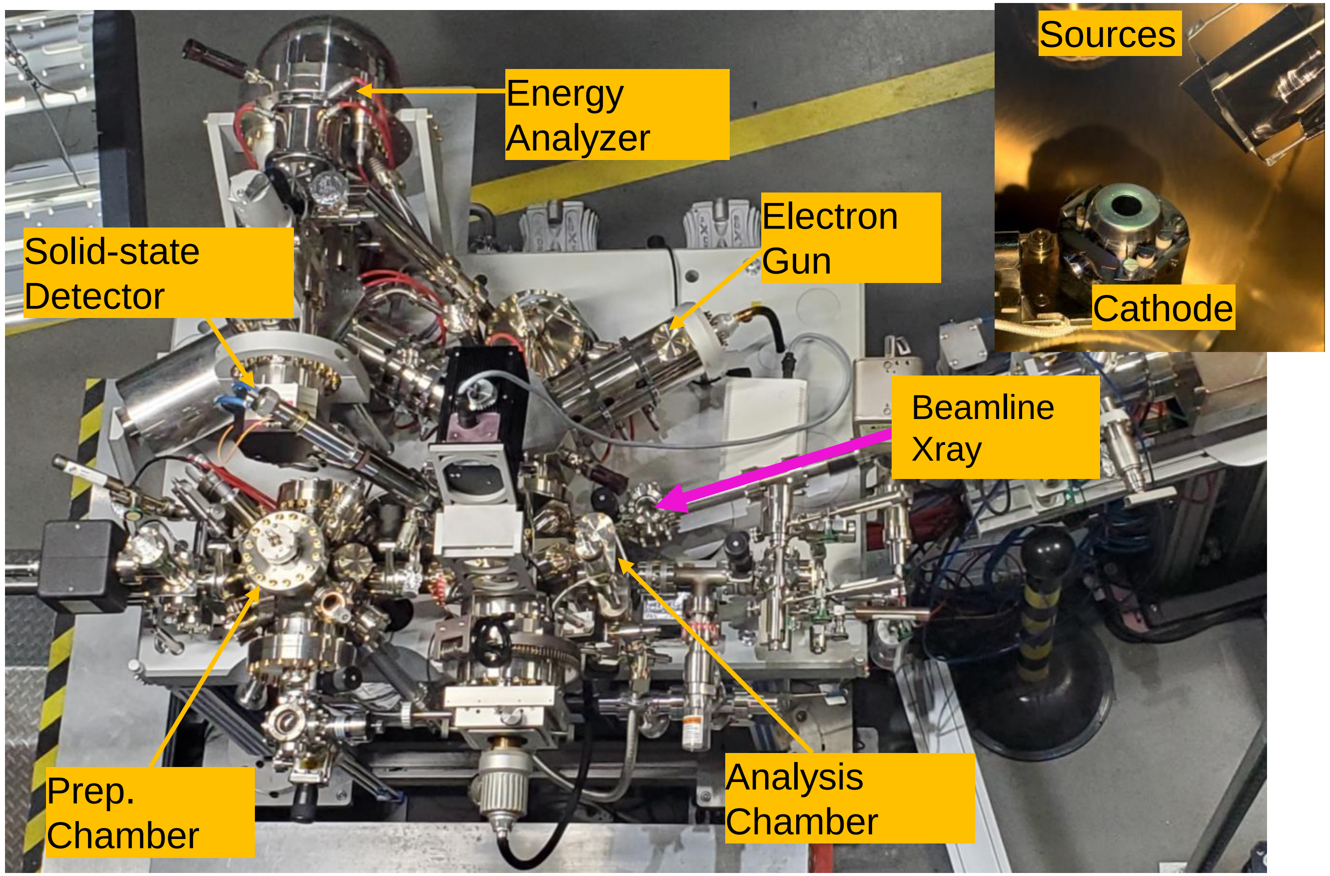
Towards Long Charge lifetime GaAs Photocathode

New Activation Technique using Te, Cs, and O

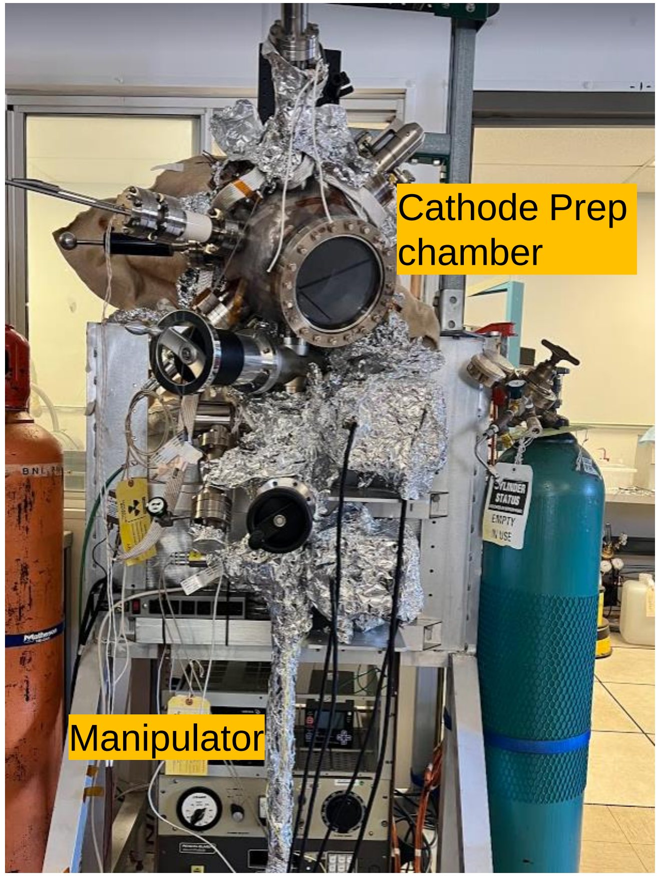
We developed a new technique of activation employing a combination of cesium, tellurium, and oxygen that shows longer charge lifetime.

Towards Long Charge lifetime GaAs Photocathode

New Cs-Te and Cs-Te-O based Activation on GaAs



LEEM/XPEEM beamline located at NSLS II, BNL



Cathode chamber at CAD, BNL

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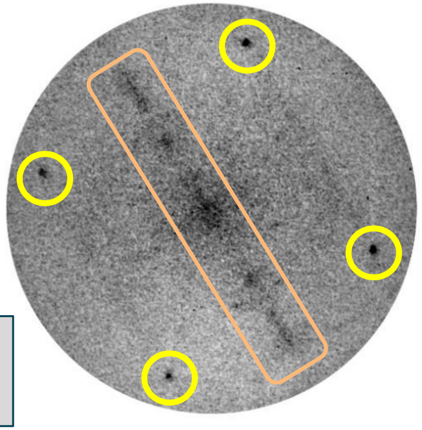
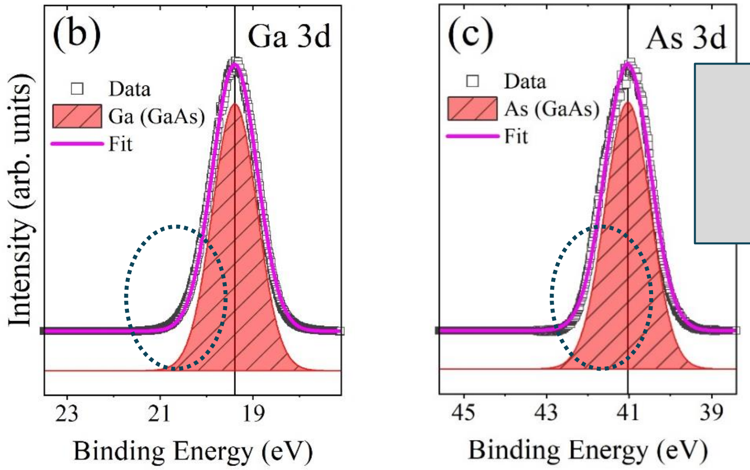
Towards Long Charge lifetime GaAs Photocathode

New Cs-Te and Cs-Te-O based Activation on GaAs



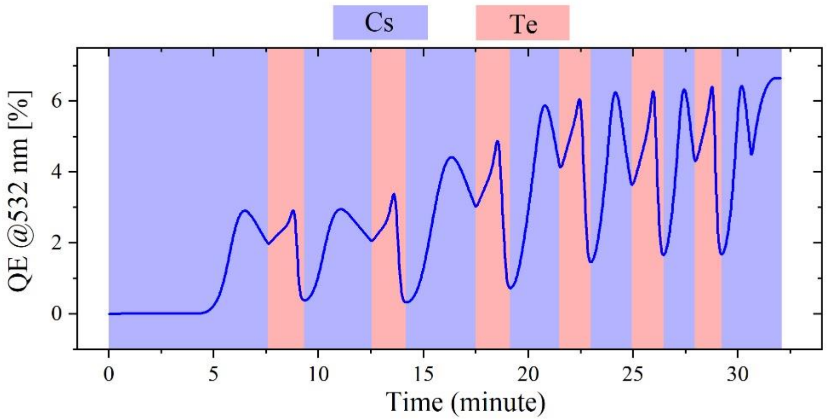
(1x1), & defused (4x6) reconstruction

Oxide desorption – LEED

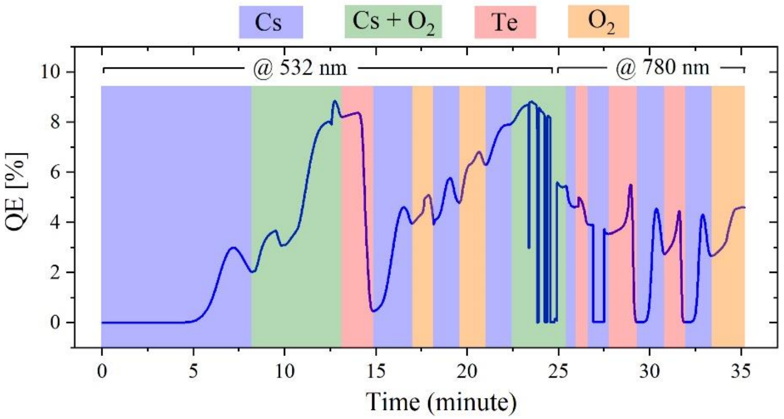


Oxides desorbed completely

Oxide desorption – SR-XPS



Cs-Te activation on GaAs



Cs-Te-O activation on GaAs

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J. Biswas *et al.* AIP Advances 11, 025321 (2021); https://doi.org/10.1063/5.0026839

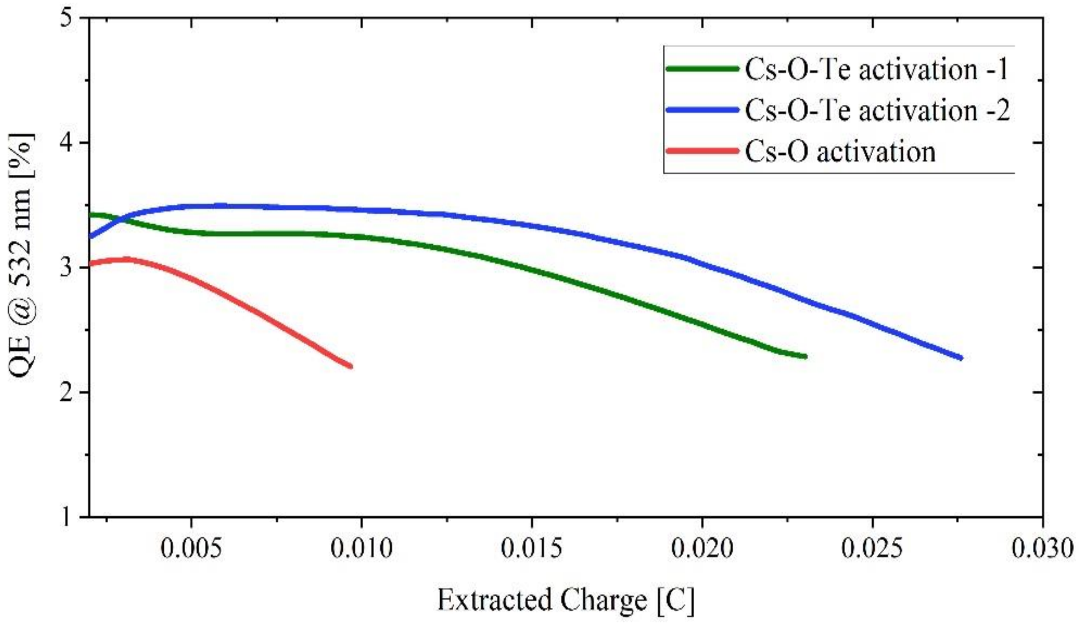
Conclusion from the Cs-Te and Cs-Te-O based Activation

- ❑ In Cs-Te activation QE **at 532 nm: 6.6%**
- ❑ In Cs-Te-O activation QE **at 532 nm: 8.8%;** at **780 nm: 4.5%**

J. Biswas *et al.* AIP Advances 11, 025321 (2021); https://doi.org/10.1063/5.0026839

Towards Long Charge lifetime GaAs Photocathode

Comparing Charge lifetime of Cs-Te-O based Activation



We demonstrated 5-6 times longer charge lifetime in a test chamber as compared to Cs-O/GaAs

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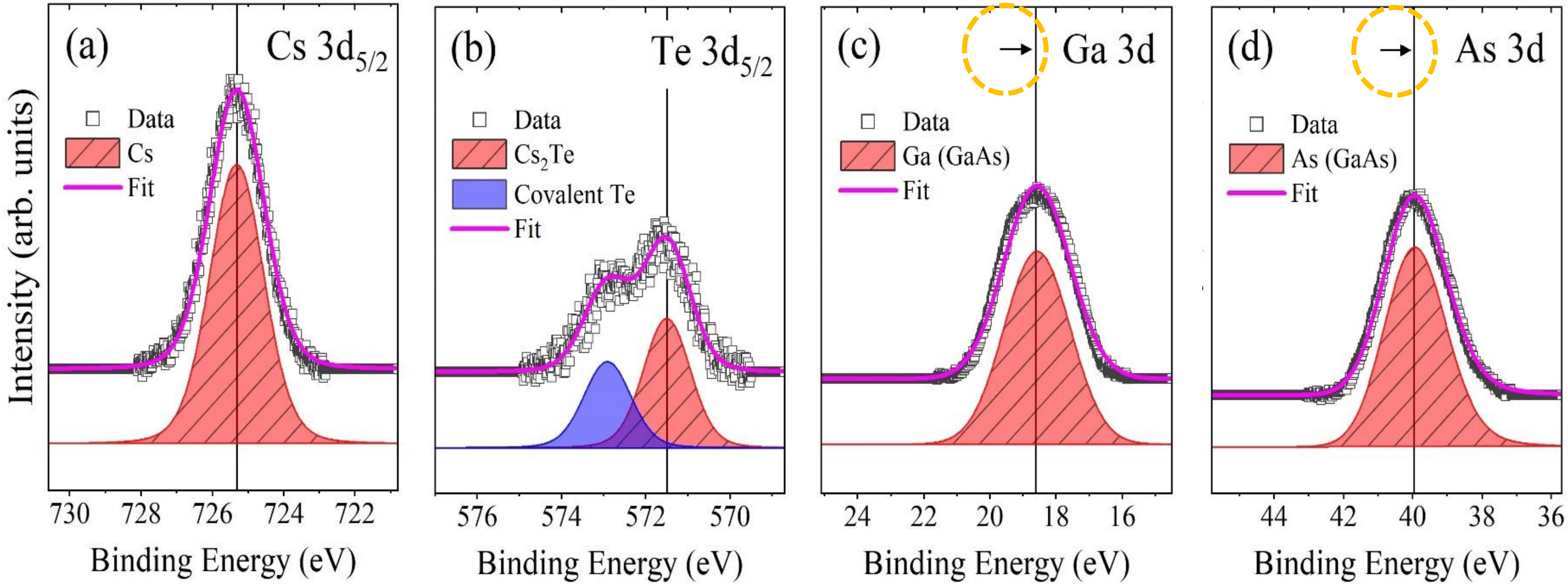
O. Rahman *et al.* , Int. Particle Accelerator Conf. IPAC2019, Melbourne, Australia

Towards Long Charge lifetime GaAs Photocathode

Evaluating Surface Chemical States Cs-Te/GaAs



SR-XPS spectra after GaAs photocathode **activation with Cs-Te**

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J. Biswas *et al.* AIP Advances 11, 025321 (2021); https://doi.org/10.1063/5.0026839

Conclusion from Surface Chemical States Cs-Te/GaAs

- ❑ Successful formation of Cs_2Te, which is robust against poor vacuum
- ❑ Chemical shift of Ga 3d, & As 3d suggest formation of surface dipole, similar to Cs-O activation.
- ❑ Estimated Cs-Te layer thickness $2 \pm 0.2\ nm$

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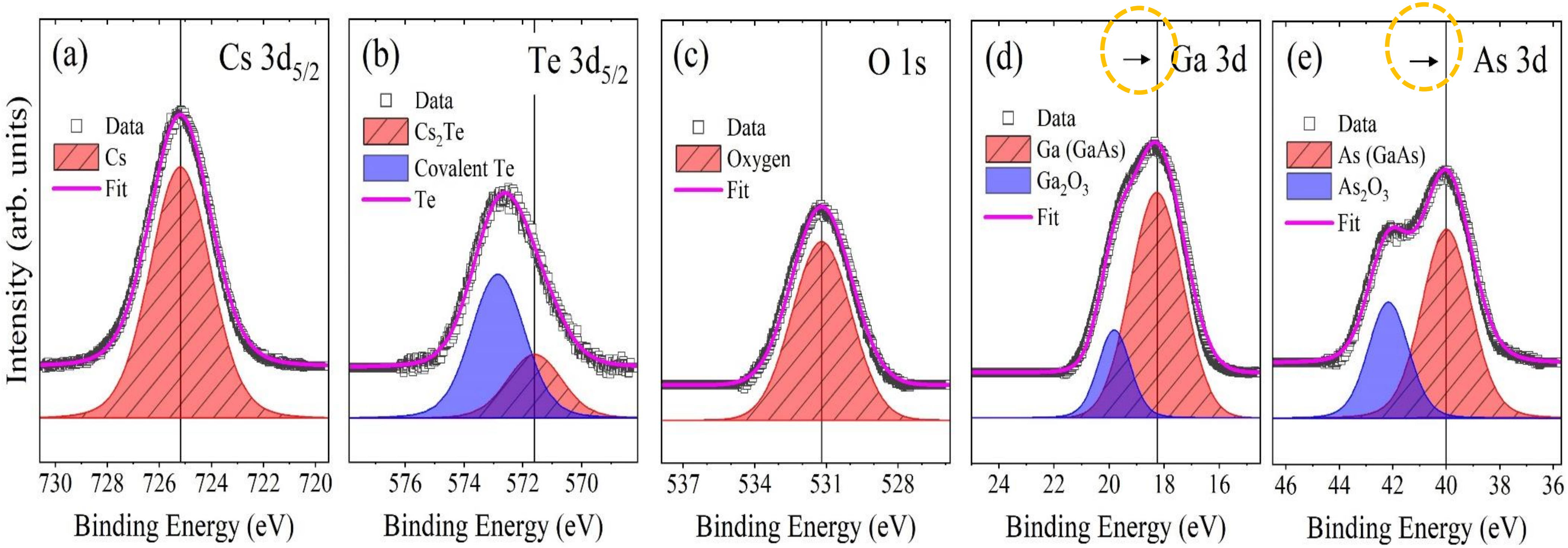
J. Biswas *et al.* AIP Advances 11, 025321 (2021); https://doi.org/10.1063/5.0026839

Towards Long Charge lifetime GaAs Photocathode

Evaluating Surface Chemical States Cs-Te-O/GaAs



SR-XPS spectra after GaAs photocathode **activation with Cs-Te-O**

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J. Biswas *et al.* AIP Advances 11, 025321 (2021); https://doi.org/10.1063/5.0026839

Towards Long Charge lifetime GaAs Photocathode

Conclusion from the Chemical Analysis of Cs-Te-O/GaAs

- ❑ Successful formation of Cs_2Te, which is robust against poor vacuum
- ❑ Large chemical shift of Ga 3d, & As 3d suggest formation of surface dipole similar to CsO/GaAs.
- ❑ Estimated Cs-Te layer thickness $1.6 \pm 0.2\ nm$

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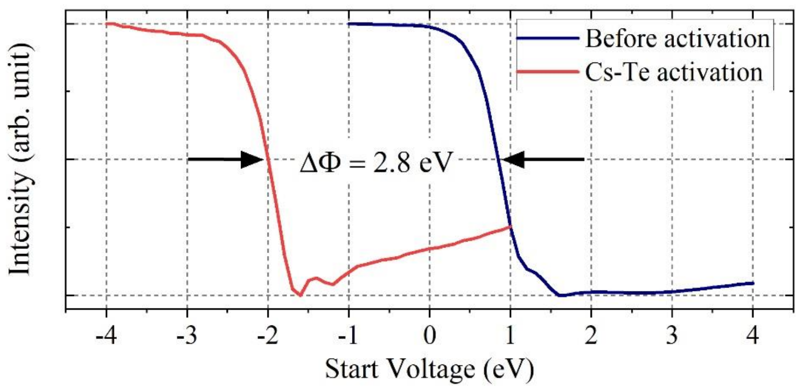
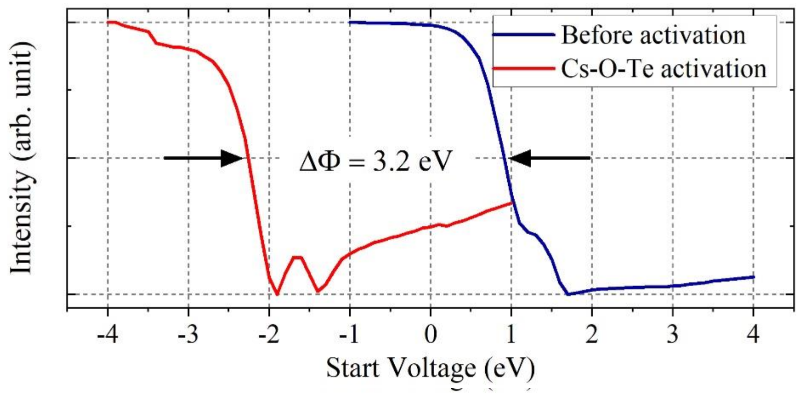
J. Biswas *et al.* AIP Advances 11, 025321 (2021); https://doi.org/10.1063/5.0026839

Towards Long Charge lifetime GaAs Photocathode

Evaluating the Negative Electron Affinity (NEA)



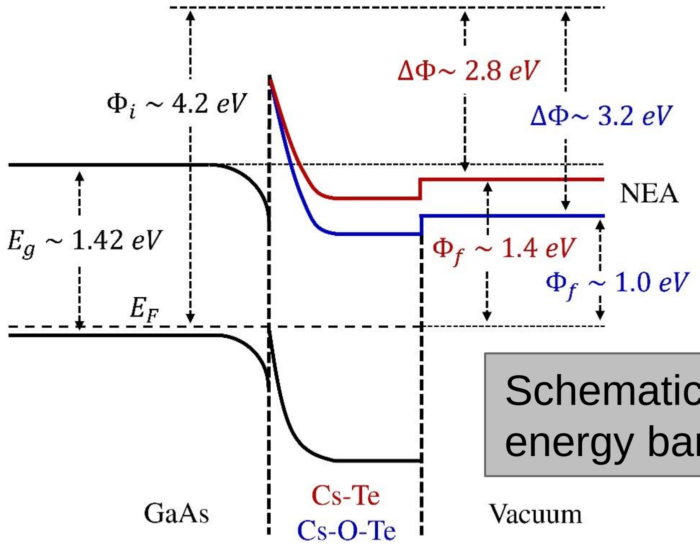
LEEM I/V of Cs-Te activated GaAs



LEEM I/V of Cs-Te-O activated GaAs

Cs-Te/GaAs
Final work function, $\Phi_f = 1.4$ eV
Effective NEA, $\chi_{eff} = -0.02$ eV

Cs-Te-O/GaAs
Final work function, $\Phi_f = 1.0$ eV
Effective NEA, $\chi_{eff} = -0.42$ eV



Schematic drawing of energy band diagram

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J. Biswas *et al.* AIP Advances 11, 025321 (2021); https://doi.org/10.1063/5.0026839

Conclusion from the NEA Measurement

- ❑ On Cs-Te activation the achieves NEA; $\chi_{eff} = -0.02$ eV

- ❑ On Cs-Te-O activation the achieved NEA; $\chi_{eff} = -0.42$ eV
  This is comparable to CsO/GaAs NEA.

NEA is important because the thermalized electrons at the bottom of the conduction band can escape into the vacuum. Thus, QE increases the when larger NEA is achieved.

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J. Biswas *et al.* AIP Advances 11, 025321 (2021); https://doi.org/10.1063/5.0026839

Towards High Electron Spin Polarization (ESP)

Motivation:

- Achieving both high QE and ESP at near bandgap energy is challenging.

- We need a stable supply of SL-GaAs

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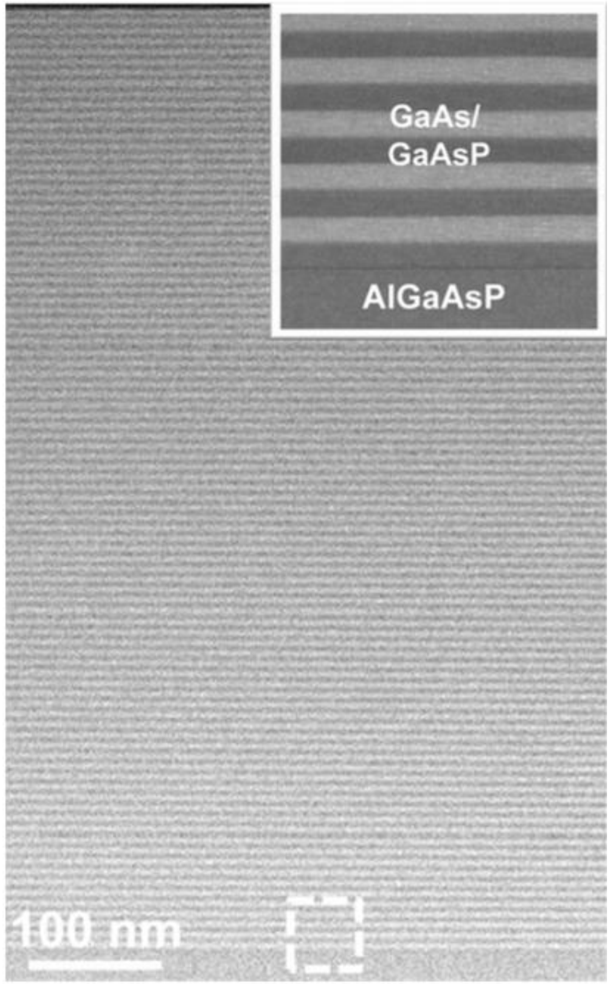
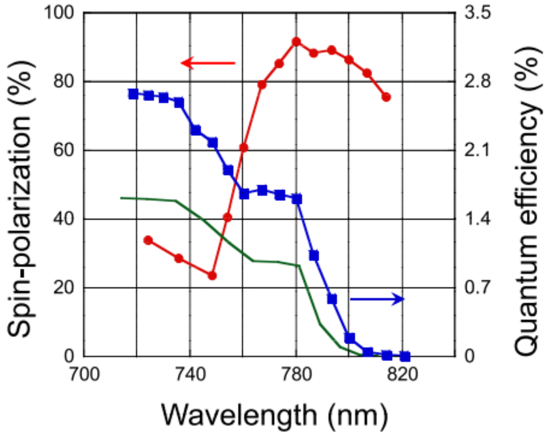
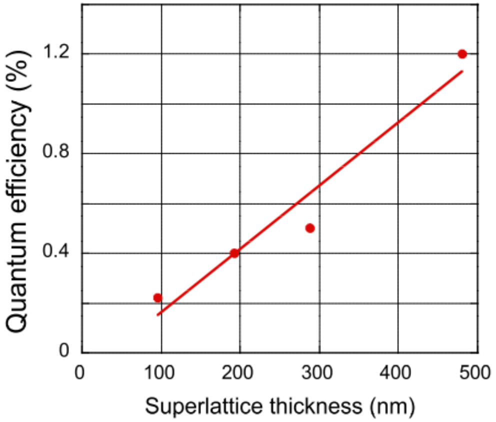
Towards High Electron Spin Polarization (ESP)

Superlattice (SL) GaAs

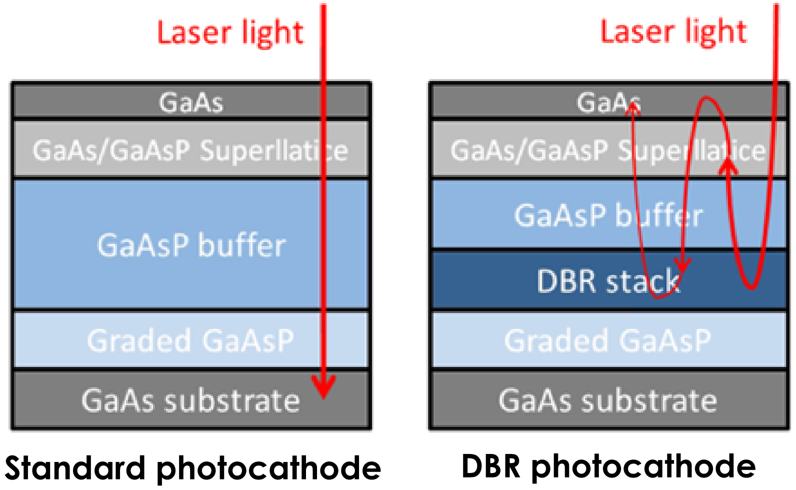


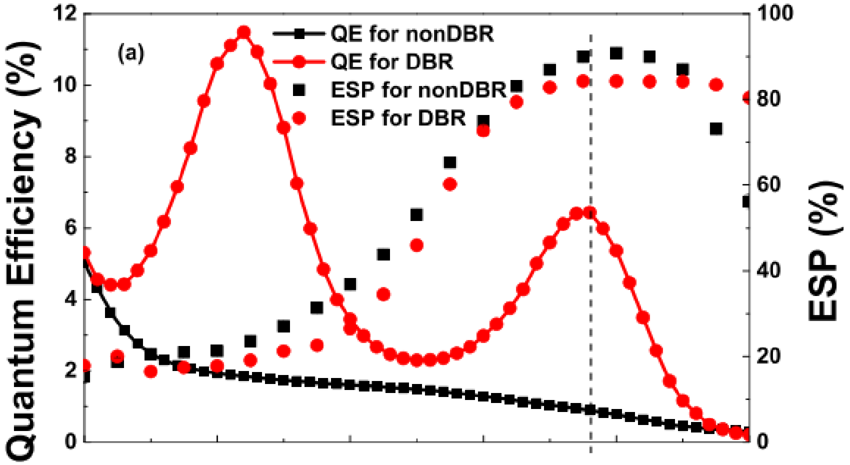




Jin *et el.* Appl. Phys. Lett. **105**, 203509 (2014)

SL – GaAs with Bragg Reflector





Liu *et el.* Appl. Phys. Lett. **109**, 252104 (2016)

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Towards High QE and ESP using SL-DBR

We have been growing SL-DBR and characterizing them

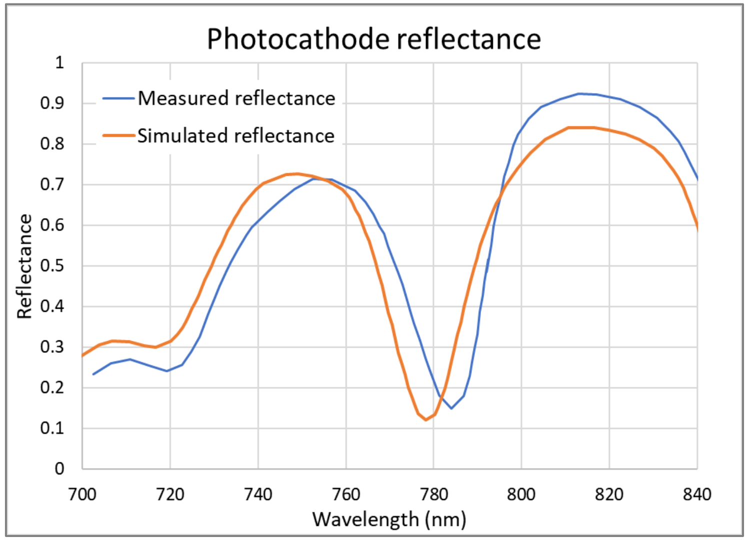
- Details will follow in the Poster session: **WEPA68**

GaAs	5 nm	p = $5x10^{19}$ cm^{-3}
$GaAs_{0.62}P_{0.38}$	4 nm	p = $5x10^{17}$ cm^{-3}
GaAs	4 nm	p = $5x10^{17}$ cm^{-3}
$GaAs_{0.81}P_{0.19}$	300 nm	p = $5x10^{18}$ cm^{-3}
$AlAs_{0.78}P_{0.22}$	65 nm	p = $5x10^{18}$ cm^{-3}
$GaAs_{0.81}P_{0.19}$	55 nm	p = $5x10^{18}$ cm^{-3}
$GaAs_{0.81}P_{0.19}$	2000 nm	p = $5x10^{18}$ cm^{-3}
GaAs->$GaAs_{0.81}P_{0.19}$	2750 nm	p = $5x10^{18}$ cm^{-3}
GaAs buffer	200 nm	p = $5x10^{18}$ cm^{-3}
GaAs substrate		p > $1x10^{18}$ cm^{-3}

30 pairs (GaAs0.62P0.38 / GaAs)

10 pairs (AlAs0.78P0.22 / GaAs0.81P0.19)

85 layers!!!



Good agreement between the design reflectance and the measured one.

The sample **photoemission efficiecny** and the **photoelectron spin polarization** are currently being evaluated at BNL

Achieved over 15% QE and ESP around 75% at near band gap photon energies.

Biswas *et el. AIP Advance (under review)*

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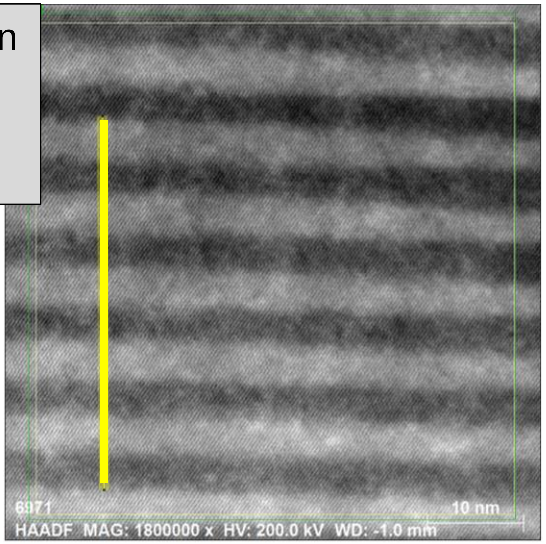
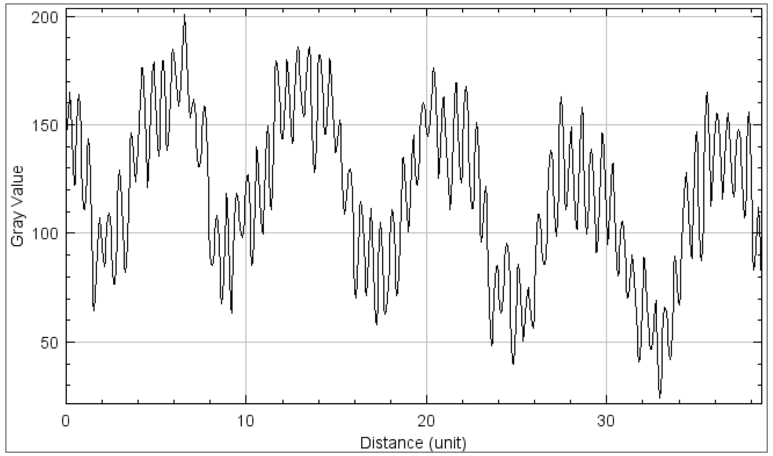
Towards High QE and ESP using SL-DBR

Evaluation of Crystal Quality of SL-DBR GaAs photocathode

Transmission Electron Microscopy (TEM) imaging of SL structure

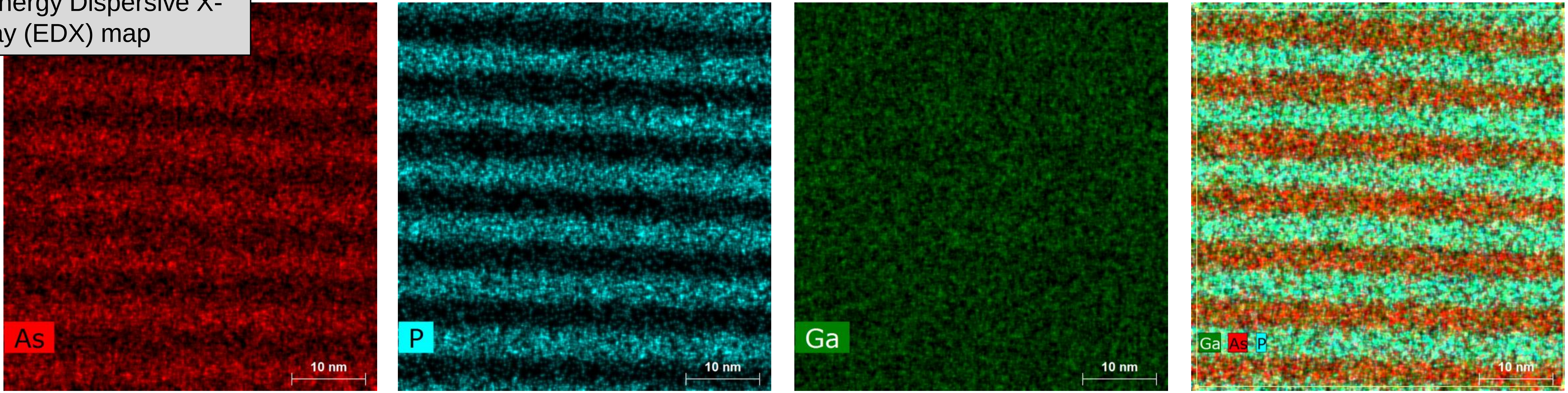


SL pair thickness: 38.8/5 ≈ 7.76 nm



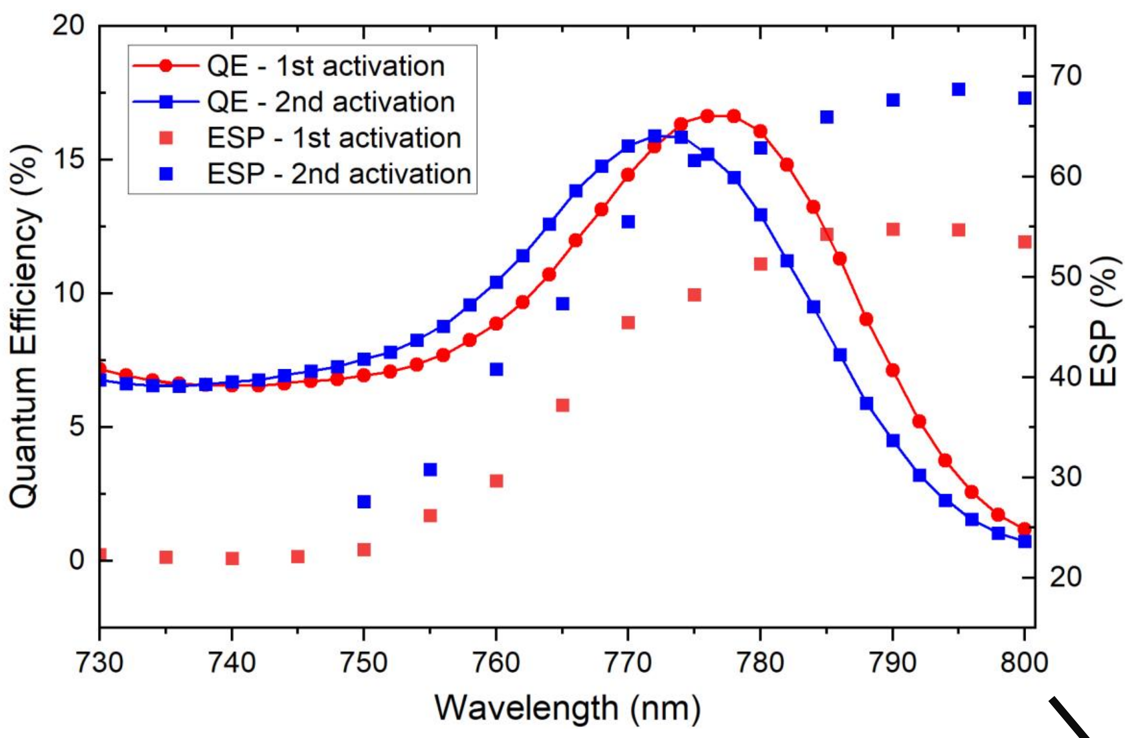
J. Biswas *et el. NAPAC 2022, Paper WEPA68*

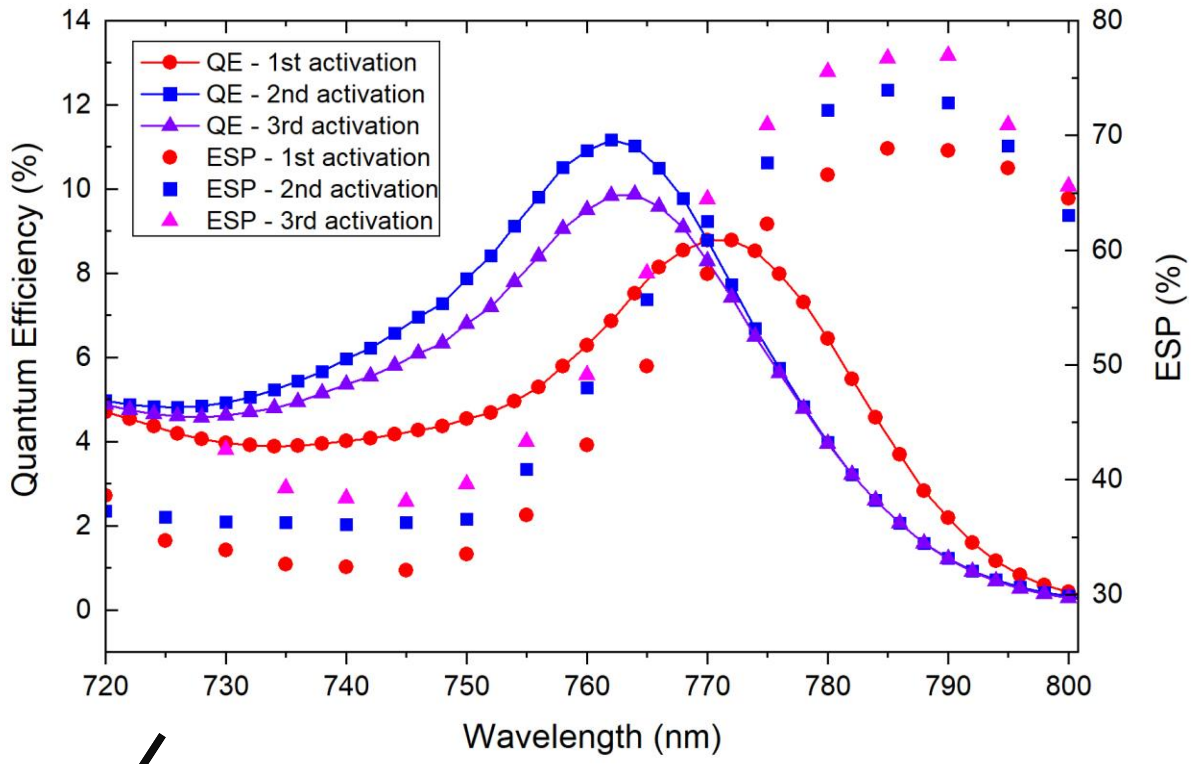
Energy Dispersive X-ray (EDX) map



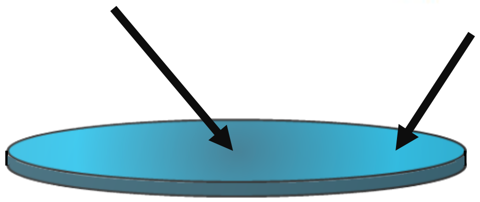
Towards High QE and ESP using SL-DBR

Evaluation of QE and ESP of SL-DBR GaAs photocathode





QE~16% (~776nm)
ESP~70% (@780nm)



QE~10% (~765nm)
ESP~75% (@780nm)

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Possibly due to non uniform heating. We are exploring different experimental condition to make uniform distribution across the wafer.

Biswas *et el. AIP Advance (under review)*

Summary - 1

- In the XPS measurement of the chemical states of CsO/GaAs we demonstrate the chemical states before, and after activation.

- The XPS-TPD measurement established that loss of Cs and O may take place at temperatures as low as 60°C.

- Our newly developed Cs-Te-O based activation on GaAs showed high QE, and 5-6 times longer charge lifetime compared to CsO activation in a test chamber.

- Cs-Te-O based GaAs shows NEA, and chemical states are identified for the first time.

- Let's evaluate the robustness & charge lifetime of Cs-Te-O/GaAs in a gun

- SL / SL-DBR with Cs-Te-O based activation

Summary - 2

- We have been growing SL/SL-DBR GaAs and measuring the QE & ESP, crystal quality at BNL.

- On SL-DBR we obtained QE exceeding 15% and ESP close to 75% at near bandgap photon energy (i.e., $\sim 780\ nm$)

- Further tuning of SL layer, and growth method are ongoing, and activation with Cs-Te-O could lead to even higher QE.

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Thanks for your attentions!

Questions

Acknowledge:
E. Wang, L. Cultrera, W. Liu, O. Rahman, M. Gaowei, J. Skaritka, X. Tong, J. Sadowski, K. Kisslinger, I. Ben-Zvi, T. Rao, S.D. Hawkins, S.R. Lee, J.F. Klem.

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