25th International Symposium on Spin Physics

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Surface protection photocathode for spin electron source

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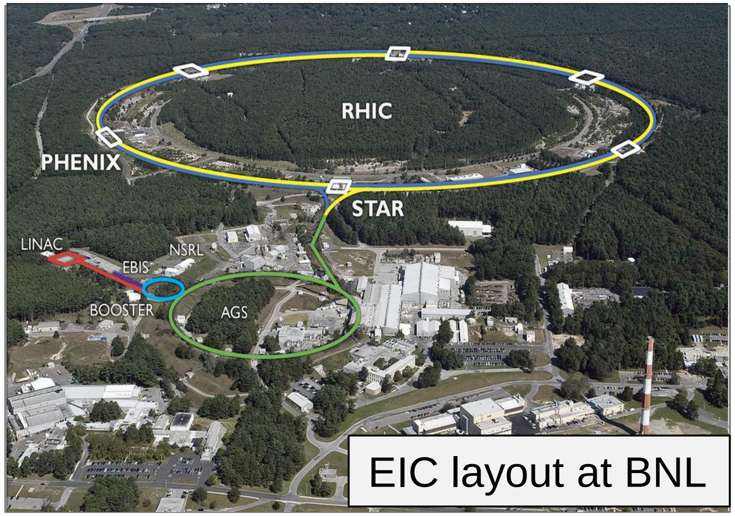
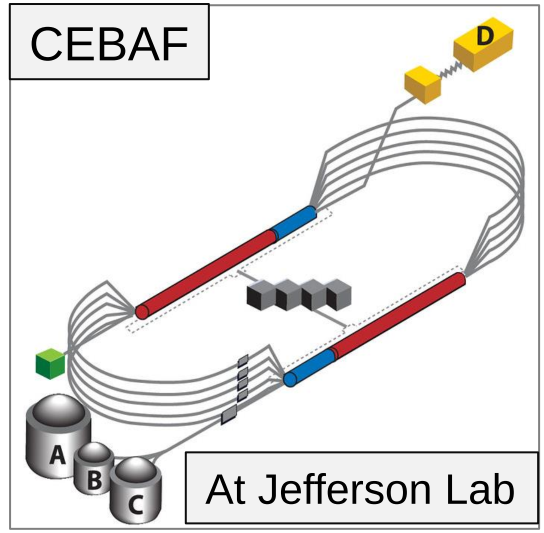
@BrookhavenLab

Perspective - Polarized Electron Sources

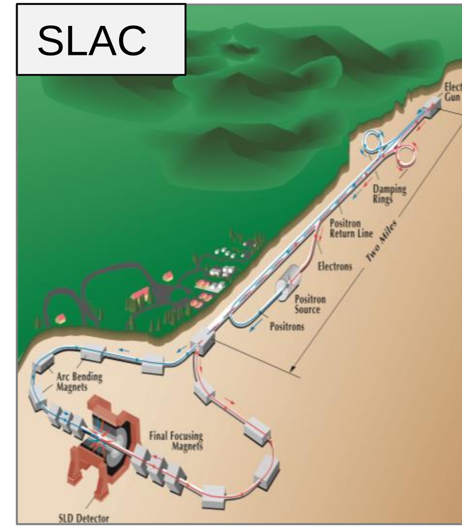


EIC layout at BNL

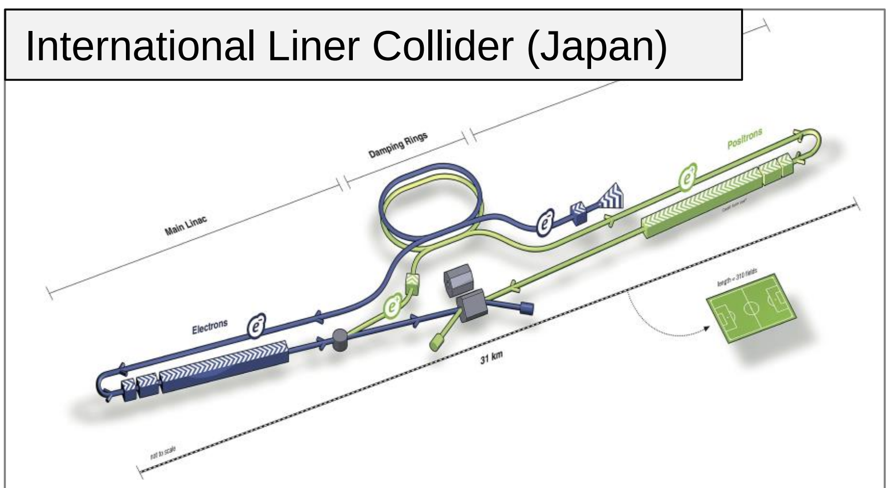


CEBAF

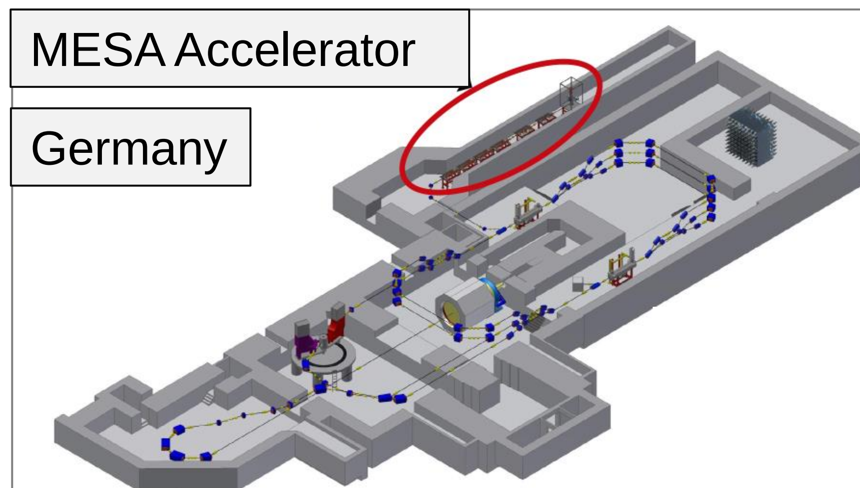
At Jefferson Lab



SLAC



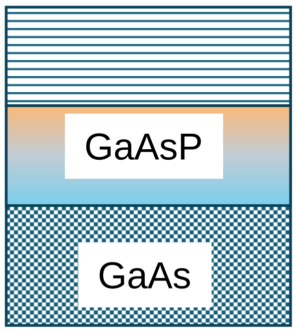
International Liner Collider (Japan)


MESA Accelerator

Germany

Polarized Electron Sources

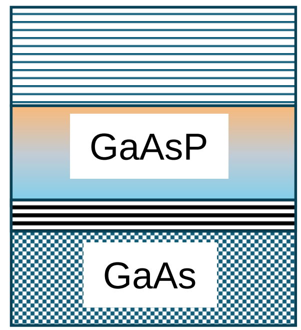
Chapter 1: Based on GaAs photocathodes



Superlattice GaAs

ESP~92% (@780nm)

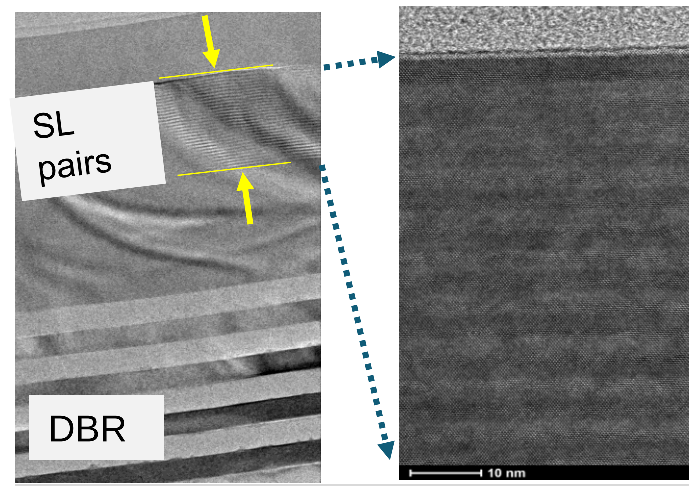
QE~0.6% (@780nm)



Superlattice DBR GaAs

ESP~84% (@780nm)

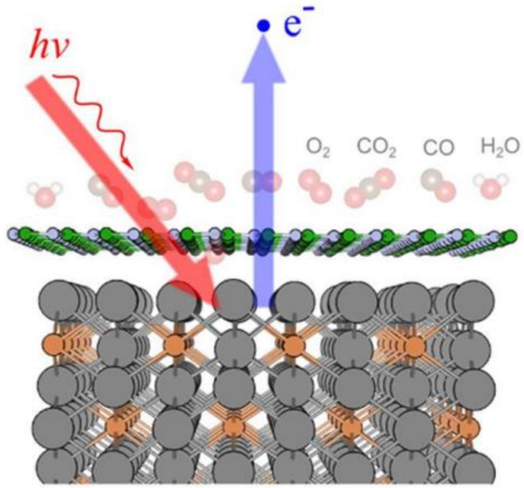
QE~6% (@780nm)



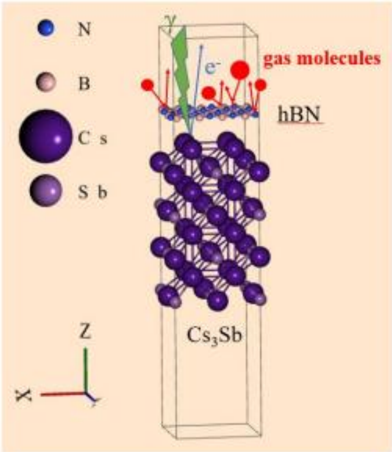
TEM cross section image of SL-DBR

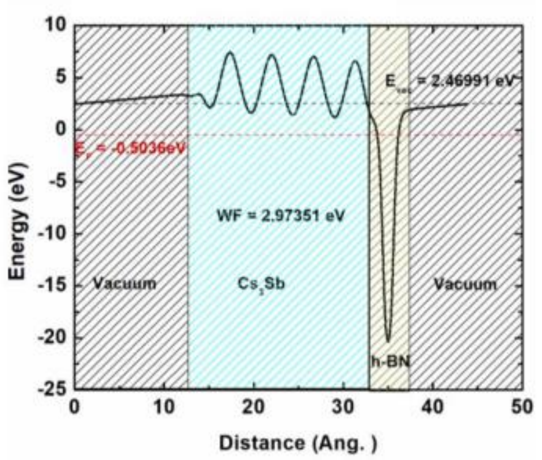
- ❑ Problems associated with GaAs photocathodes
  - ➢ Needs low 10^{-11} or 10^{-12} Torr Vacuum.
  - ➢ Laser induced heating could damage the activation.
  - ➢ Cathode transfer form facility to faculty is challenging.

Protective layer on Spin Electron Source



G.Wang and N.Moody et al.
npj 2D Materials and Applications 17 (2018
doi:10.1038/s41699-018-0062-6





Material	Cs_3Sb	Cs_3Sb/Graphene	Cs_3Sb/h-BN
Work Function	3.24136 eV	4.05628 eV	2.97351 eV

Credit : Work performed by Shashi Poddar, and Ao Liu from at Euclid Techlabs, LLC.

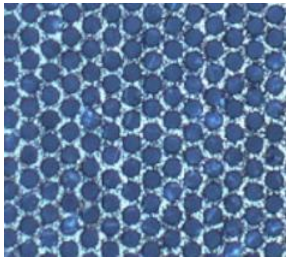
In terms of work function reduction, monolayer hBN is an ideal choice, but finding a large area island free hBN is currently not feasible.

We kept our R&D work to graphene-based protection layer

Challenges: transferring graphene onto GaAs

- ❑ GaAs based photocathodes requires low 10^{-11} *or* 10^{-12} Torr Vacuum.
  - ➢ Vacuum transfer of graphen3 is still not feasible

- ❑ Alkali antimonide based photocathode can be grown onto graphene with TEM supported grid. (R&D at LANL)



  - ➢ This technique is not suitable for high gradient photo gun
  - ➢ Also, not suitable for GaAs photocathodes

We proposed use of intercalation of graphene to make photocathode material underneath the 2D material (i.e., graphene)

Cs Intercalation of Graphene

The mechanism of Cs intercalation through monolayer graphene

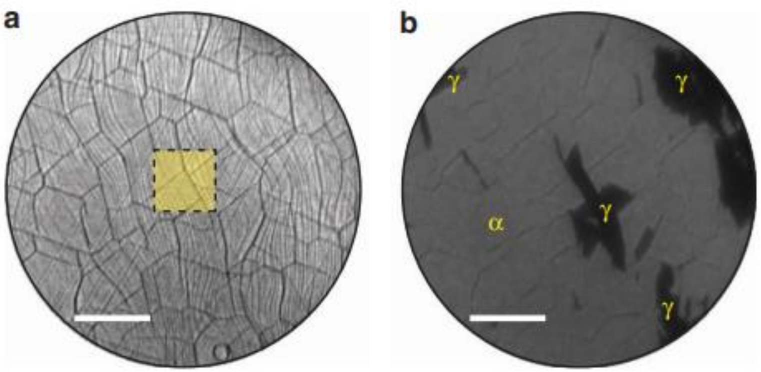


Figure 1 | LEEM and LEED characterization. (**a**) LEEM topograph of an uniform e-Gr ML on Ir(111) showing characteristic surface features: graphene wrinkles and substrate steps. The yellow square indicates the area analysed for the dynamics of intercalation (cf. Fig. 5). (**b**) Same area as in **a** but after deposition of 0.2 ML of Cs. A moderate decrease (α-phase, marked as α) and a strong decrease (γ-phase, marked as γ) in reflectivity are visible. Scale bars in **a**,**b** correspond to 3 μm.

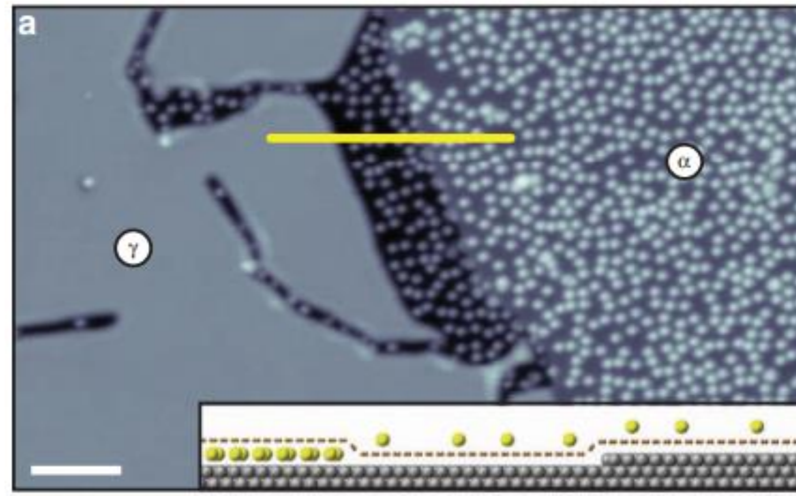
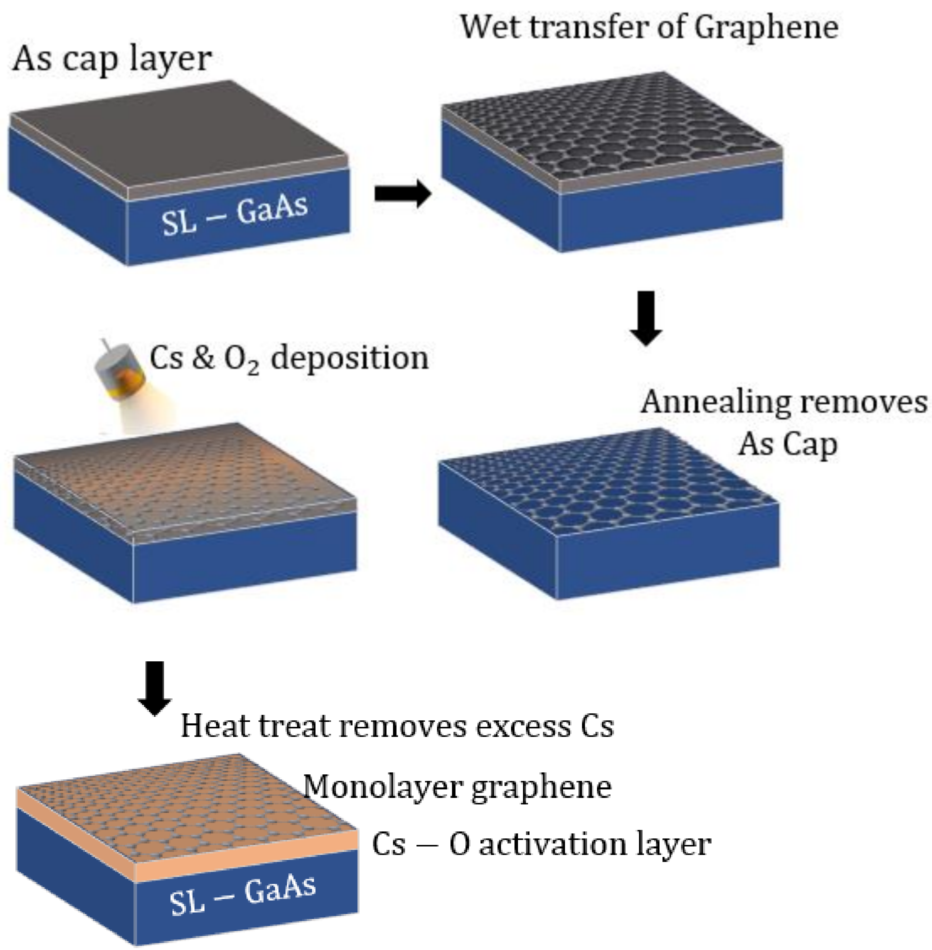


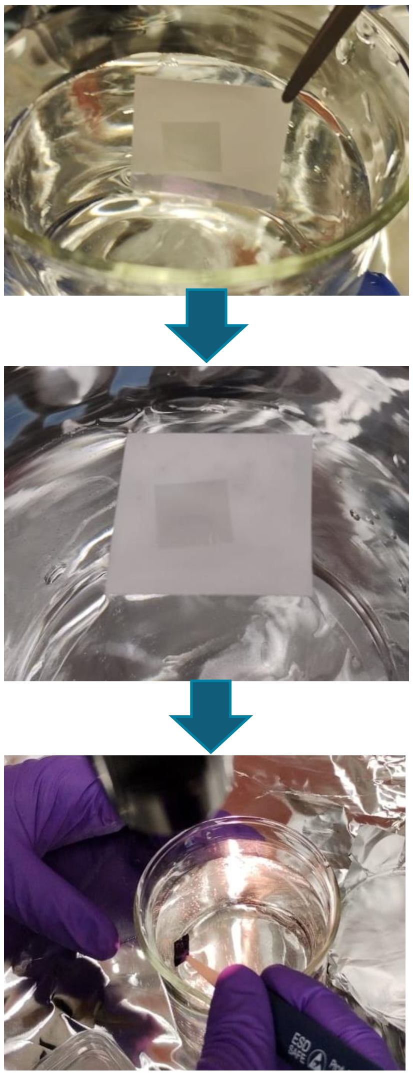
Figure 3 | STM characterization. (**a**) An STM topograph showing two characteristic areas found after the deposition of 0.5 ML of Cs: the adatom α-phase (marked as α) and the intercalated γ-phase (marked as γ). The inset shows a schematic illustration of the topographic profile across different regions of the STM image indicated by a yellow horizontal line. White scale bar corresponds to 10 nm.

Petrović, M., Šrut Rakić, I., Runte, S. et al.
The mechanism of caesium intercalation of graphene.
Nature Communications 4, 2772 (2013). https://doi.org/10.1038/ncomms3772

Transfer of Graphene onto GaAs

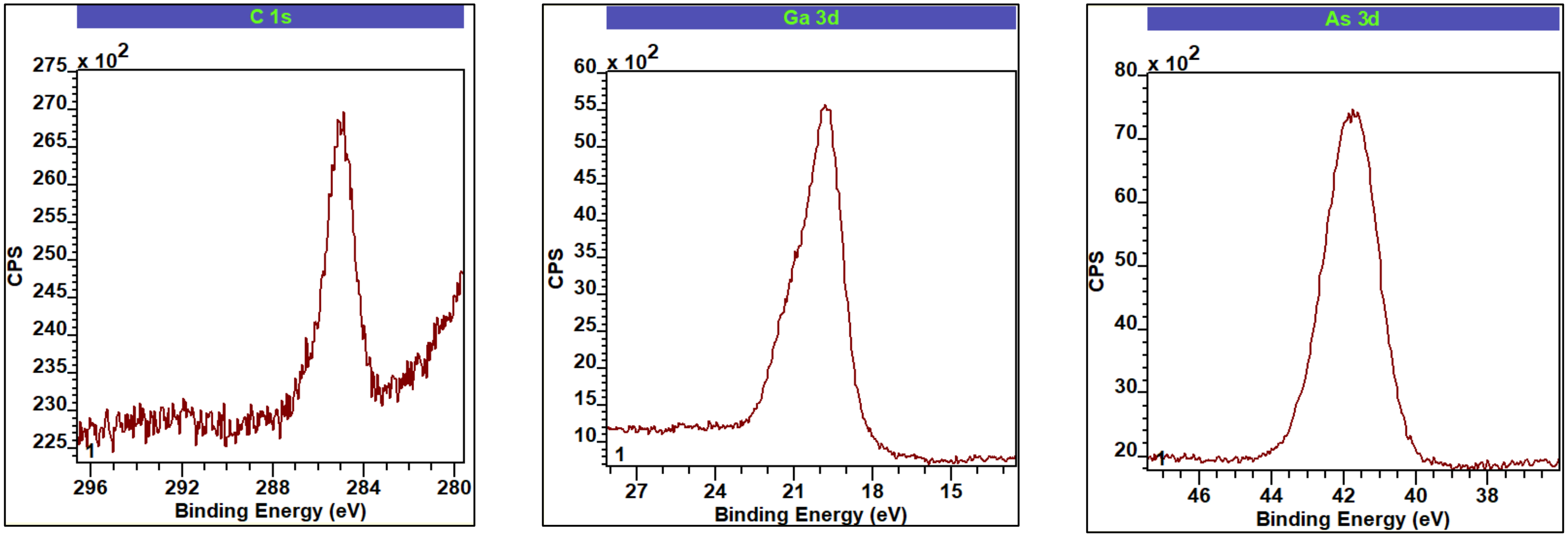


Schematic of the graphene transfer on GaAs



Inspired by our previous work on Cesium intercalation of graphene: Biswas et al. APL Mater. 10, 111115 (2022)

Removing cap layer or oxides through graphene

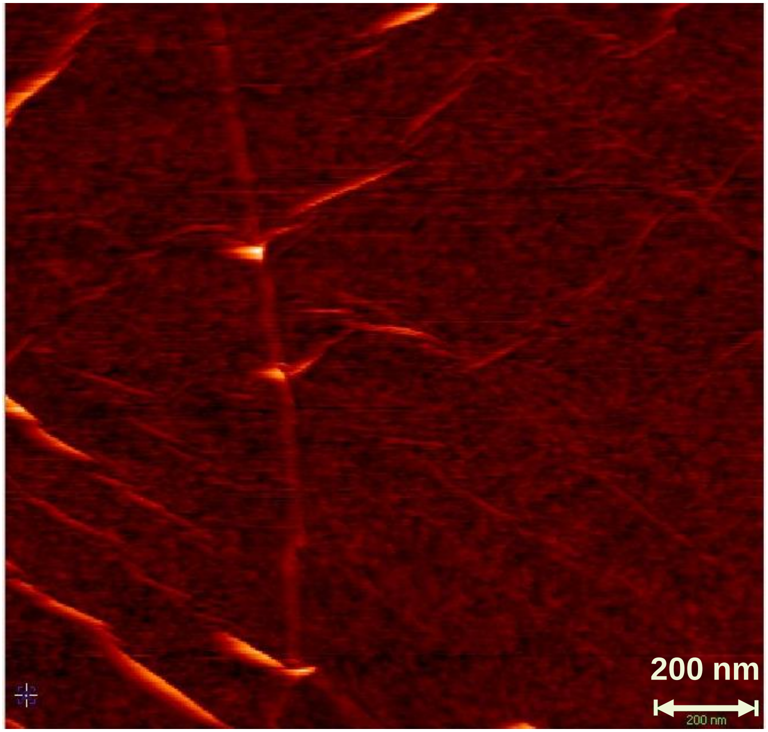


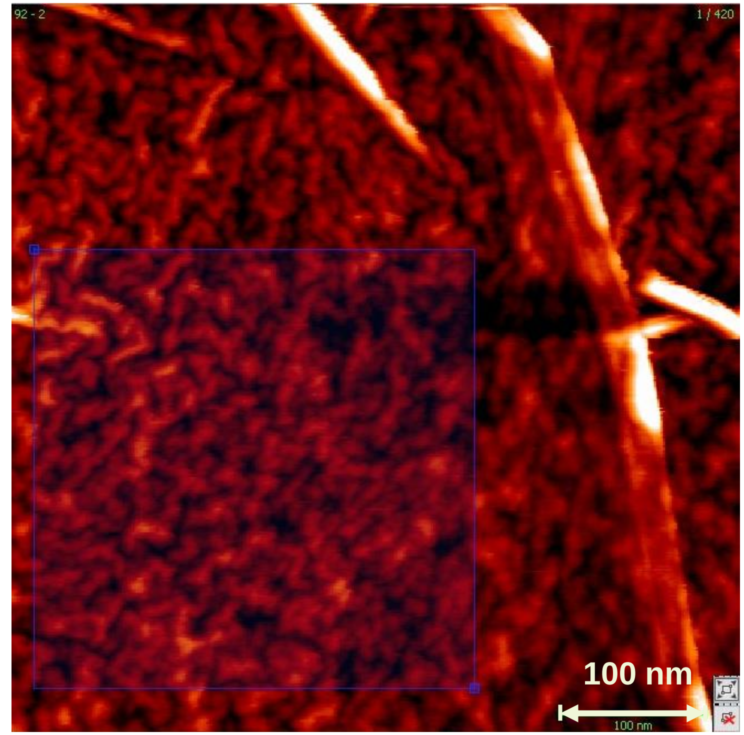
X-ray photoelectron spectroscopy after 550°C heat cleaning of SL-GaAs with a monolayer graphene on top

- Similar features with heat treatment of 450°C of SL-GaAs that has As Cap

- For SL-DBR that has no cap layer, it takes around 550°C to completely get rid of oxides. At 450°C it can eliminate As oxides, however, Ga oxides still remains after 450°C.

Verifying uniformity of graphene on SL-GaAs



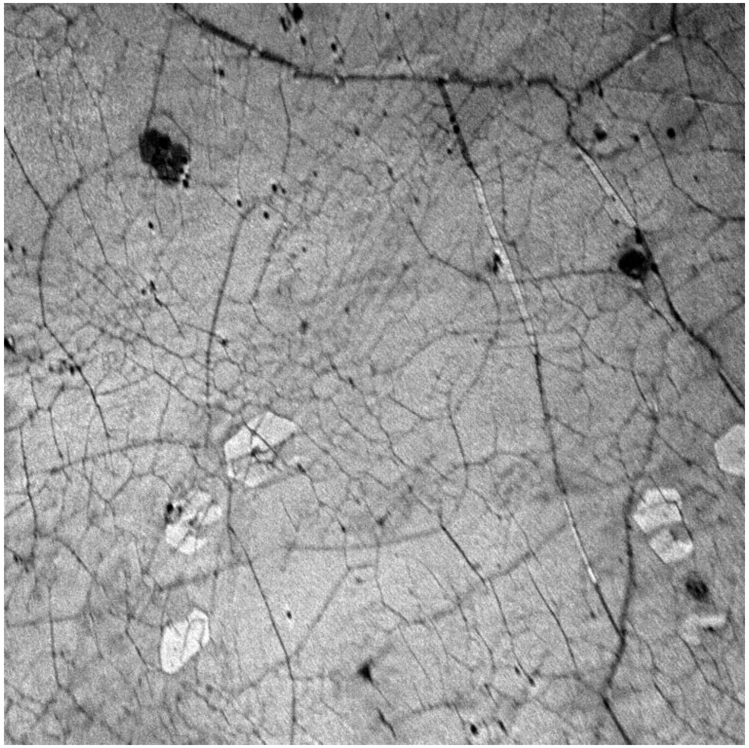


Filled state Scanning Tunnelling Microscopy (STM) image of graphene covered SL-GaAs after 550°C heat treatment to remove As cap. Graphene wrinkles are visible.

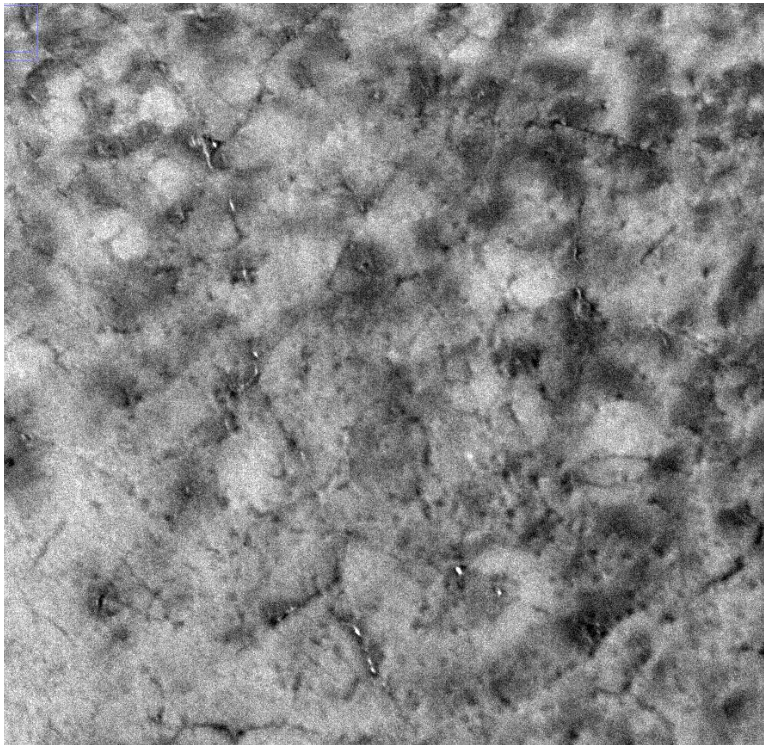
- Successful transfer of graphene on SL-GaAs that can withstand 550°C heat treatment

- Was successful in removing As cap layer from SL-GaAs without damaging the monolayer graphene protection layer.

Characterizing GaAs-CsO/graphene on LEEM



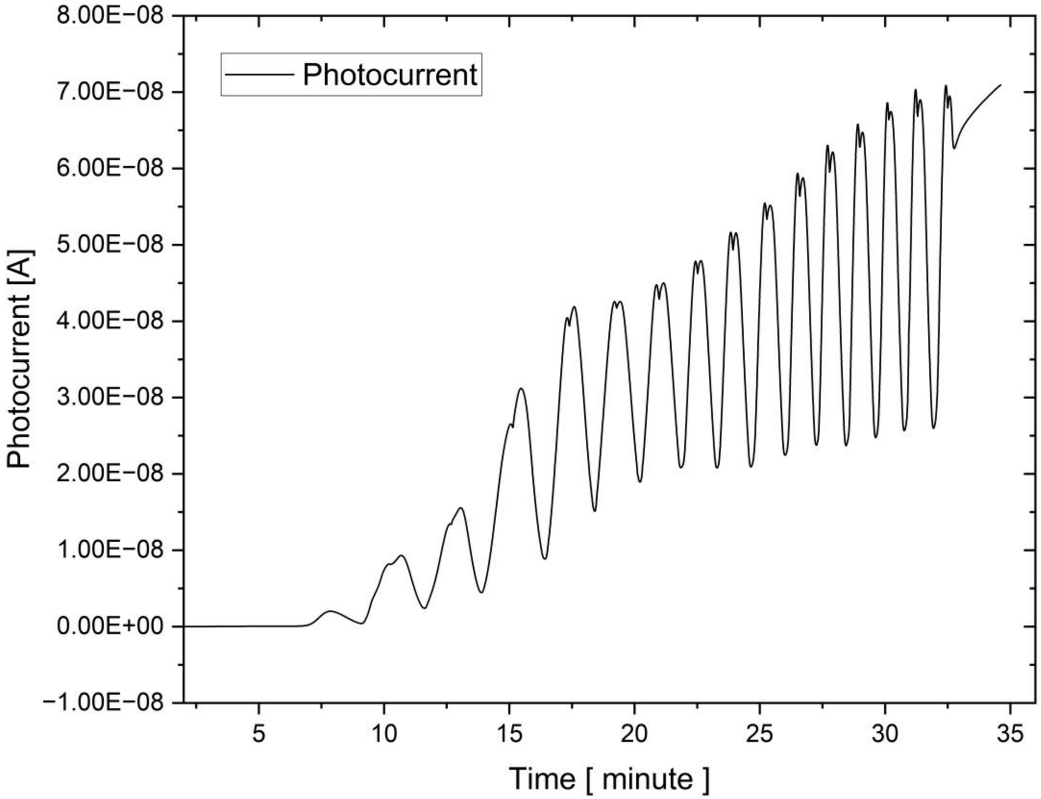
LEEM image before activation



LEEM image after activation

- LEEM indicates intercalation happened.
- Work function reduction of 3 eV observed, which close to work function shift of 3.2 eV on typical CsO activation on GaAs

SL-GaAs activation with graphene on top



$QE\ @532\ nm \approx 0.70\ \%$

Monolayer graphene protection layer was deposited on SL-GaAs with an As cap. Heat treatment of 550°C was used to eliminate As cap layer through the graphene. And deposition of Cs and oxygen was performed using yo-yo method.

- Successful growth of SL-GaAs with CsO activation layer underneath the graphene.
- Similar activation of bulk GaAs was performed. We obtained better results on SL-GaAs with a cap layer.
- Removal of cap layer creates better sites for intercalation of Cs.

Characterizing SL-GaAs-CsO/graphene

QE: 0.7%	QE> 0.55%		QE> 0.014%
Intercalation & Activation	Excess top Cs goes away	Cs start to lose underneath of graphene	Still Cs left underneath of graphene
45°C	>100°C	>250°C	>500°C

We activated the cathode, heat treated sample around 500°C, took it out into the air, and put it back in the vacuum system, that cathode still had 0.01% QE

- ✓ Graphene protection layer makes the GaAs cathode less susceptible to heating.

- ✓ Can sustain coarse vacuum environment with the protection layer. Meaning vacuum transfer of activated GaAs is a possibility.

Polarized Electron Sources

Chapter 2: Based on Alkali Antimonide photocathodes

PHYSICAL REVIEW LETTERS **129**, 166802 (2022)

Editors' Suggestion

New Spin-Polarized Electron Source Based on Alkali Antimonide Photocathode

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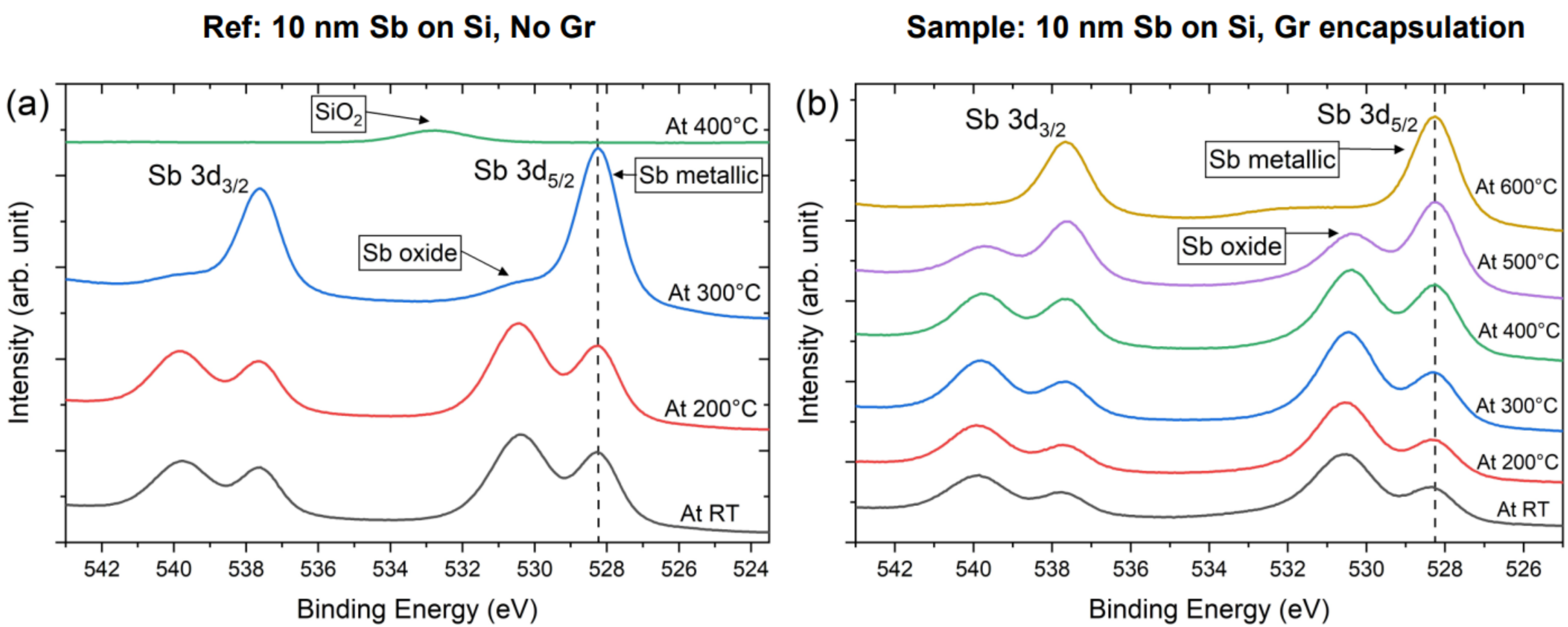
Leads to our work on graphene protection

layer on alkali antimonide photocathodes for polarized electron,

using similar intercalation techniques

Alkali Antimonide with graphene protection layer

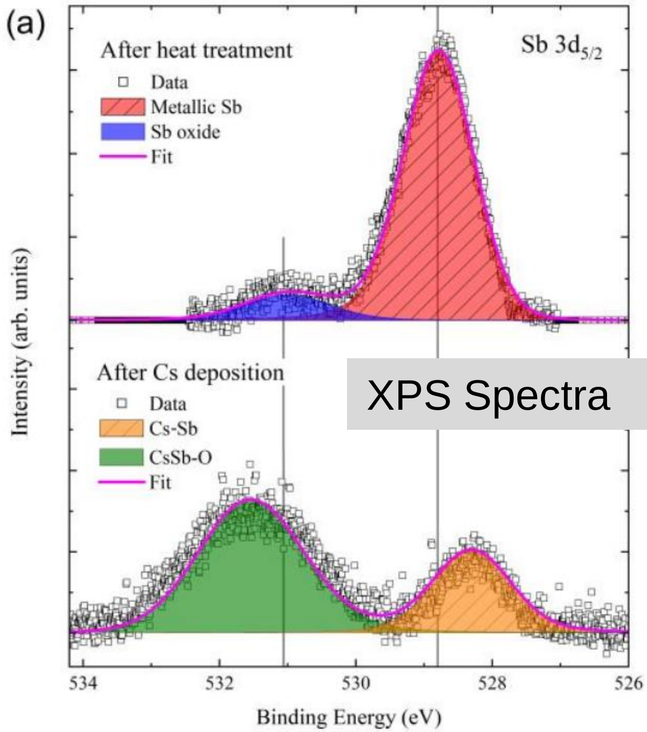
Sb desorption under high heat: XPS Spectra



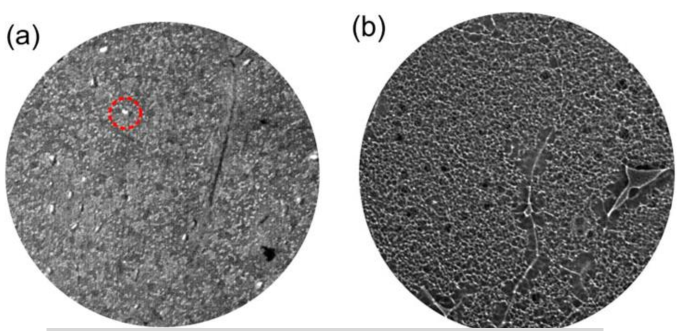
Monolayer graphene lets oxide removal due to high temperature heat treatment, while retains metallic antimony

Biswas et al. APL Materials. 10, 111115 (2022)

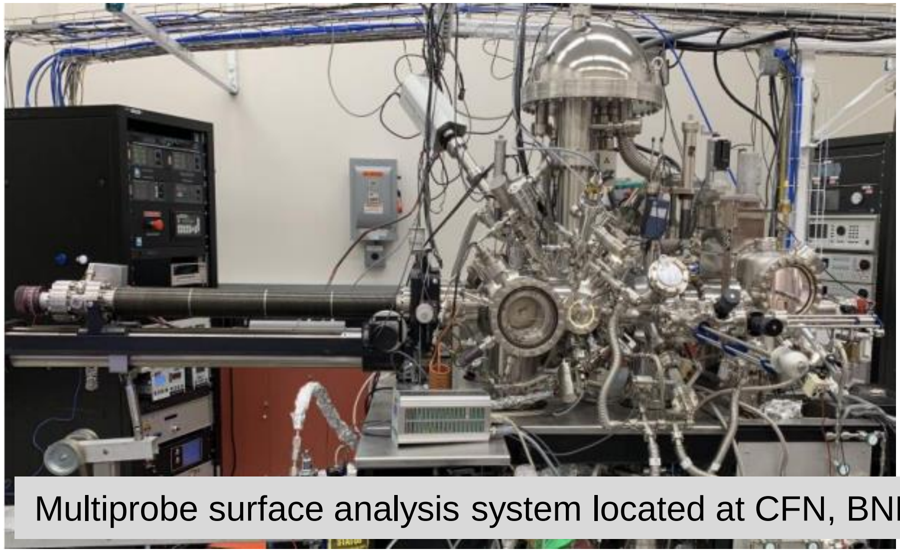
Alkali Antimonide with graphene protection layer



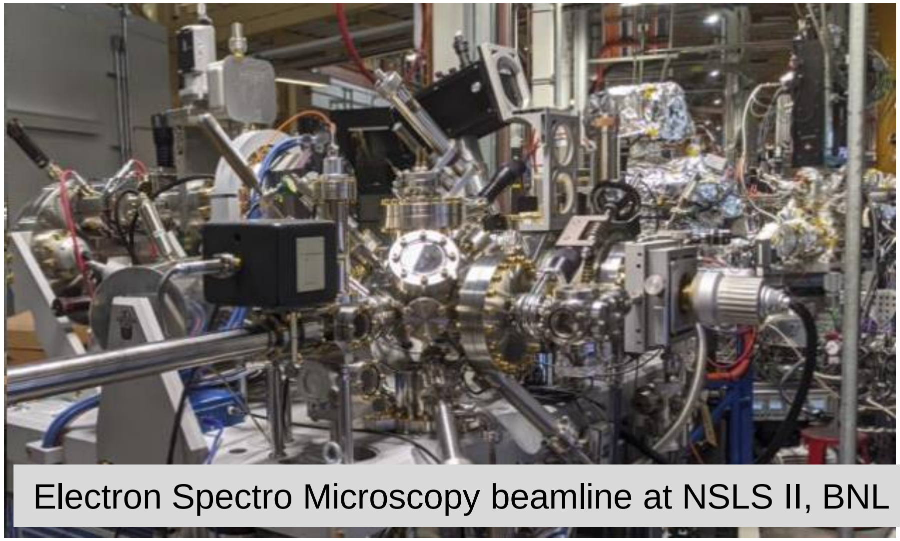
XPS Spectra



LEEM before & after activation



Multiprobe surface analysis system located at CFN, BNL

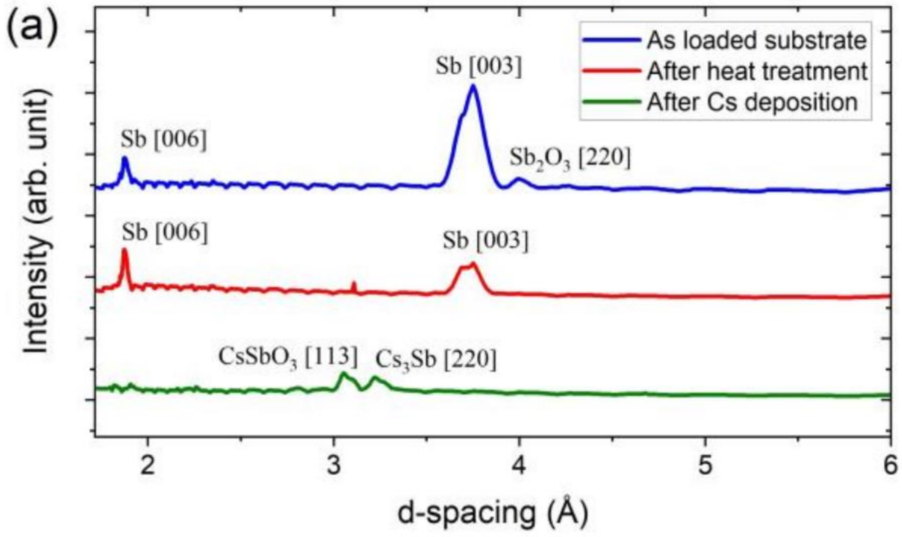


Electron Spectro Microscopy beamline at NSLS II, BNL

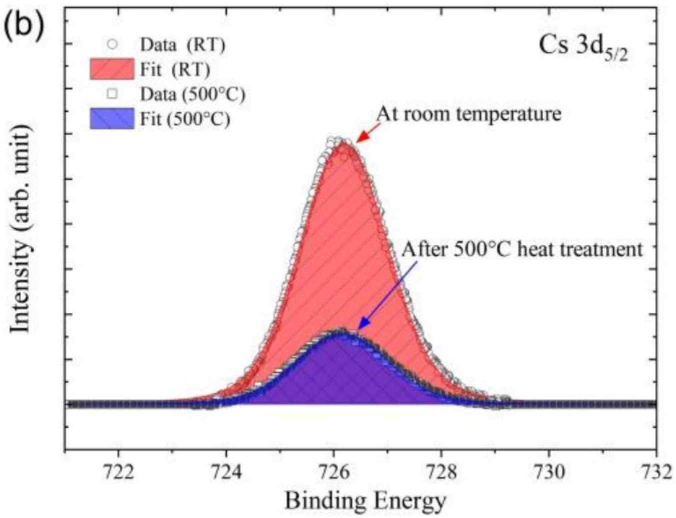
Biswas et al. APL Materials. 10, 111115 (2022)

Alkali Antimonide with graphene protection layer

XRD Spectra



XPS Spectra

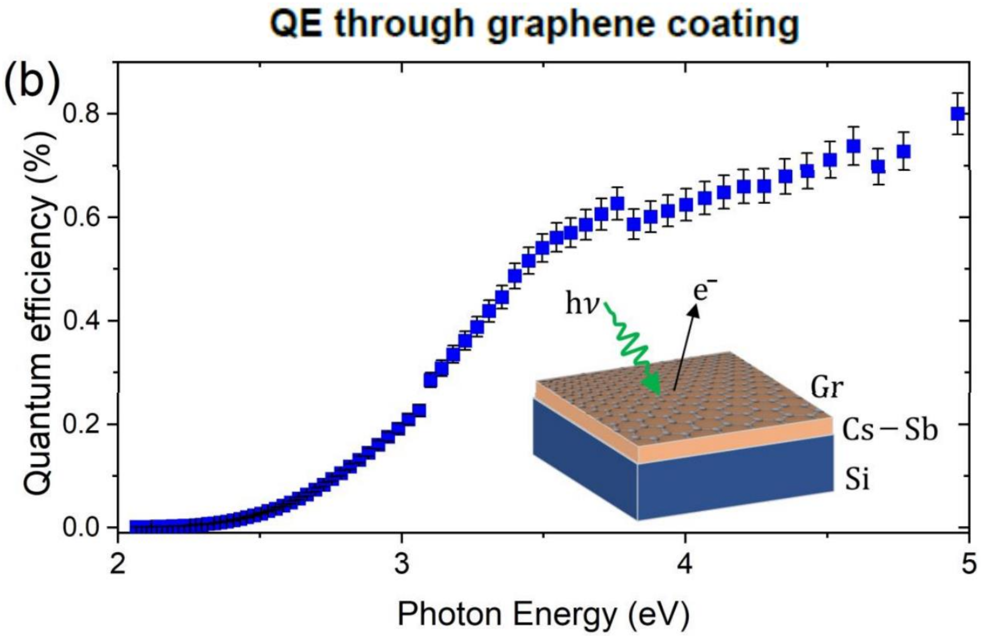


- XPS, LEEM and XRD confirms formation of Cs_3Sb underneath of graphene

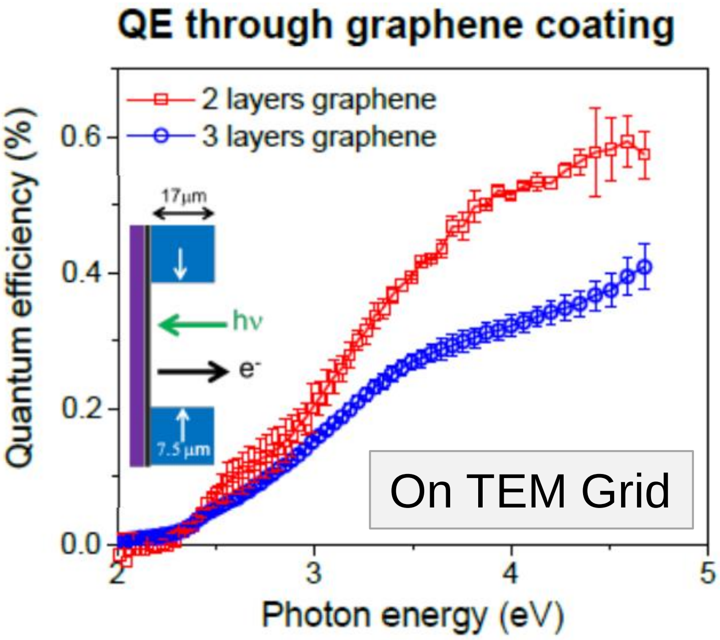
- XPS shows heating at even 500°C remains significant amount of Cs under the graphene. More protection on Alkali Antimonide compared with CsO GaAs based cathodes.

Biswas et al. APL Materials. 10, 111115 (2022)

Alkali Antimonide with graphene protection layer



Biswas et al. APL Materials. 10, 111115 (2022)



F.Liu et al. ACS Appl. Mater. Inter.(2022)

- Our alkali antimonide cathodes with made with Cs intercalation of graphene shows slight improvement on the QE.

Summary

- Method of Intercalation was used to grow **GaAs/CsO photocathode** with **monolayer graphene protection layer** on top.
- LEEM verifies comparable work function reduction similar to CsO activation on GaAs.
- Initial result shows, graphene protection layer makes the cathode **less susceptible to heating.**
- Can sustain coarse vacuum environment with the protection layer. Meaning vacuum transfer of activated GaAs is a possibility.

- Method of Intercalation was used to grow **Alkali Antimonide photocathode** with **monolayer graphene protection layer** on top.
- Intercalation based alkali antimonide cathodes with graphene protection shows comparable spectral response as reported by others.
- Graphene on alkali-based photocathode **add more protection compared to the protection on GaAs** based cathodes.

- Research underway to explore other 2D material such as hBN.

Acknowledge:

Thanks to E. Wang, L. Cultrera, W. Liu, O. Rahman, M. Gaowei, K. Mondal, J. Skaritka, X. Tong, J. Sadowski, K. Kisslinger, T. Rao, Ao Liu, Shashi Poddar, John Smedley, Liliana Stan

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Thanks for your attentions!

Questions