International Workshop on
Energy Recovery Linacs (ERL22)

Photocathodes for high average current electron beam: state-of-the-art and new perspective

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Cornell University, Oct 3-6, 2022

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Unpolarized photocathodes for ERL facilities

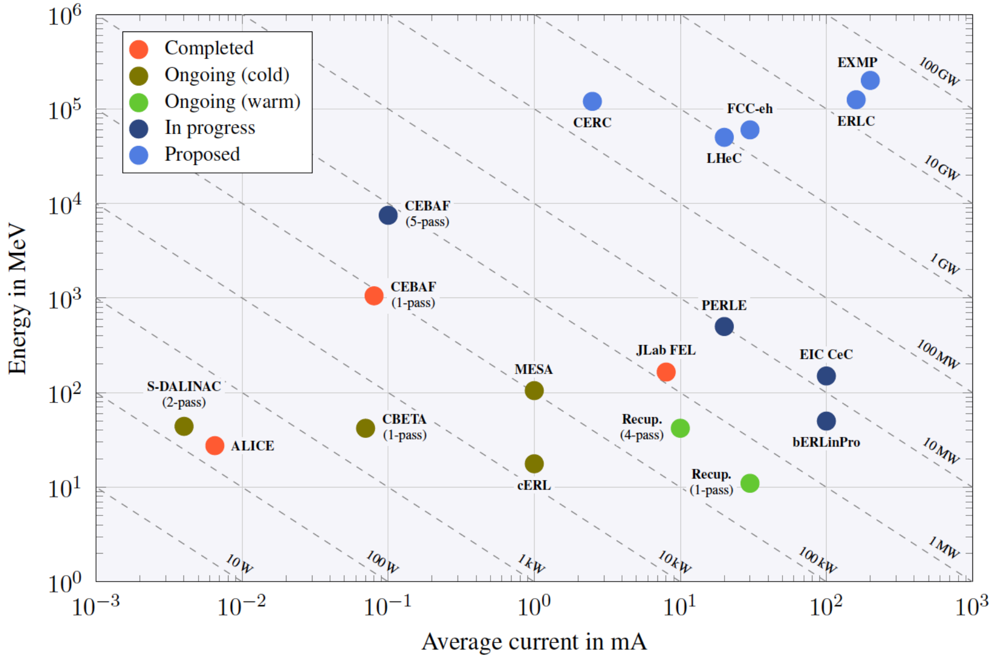
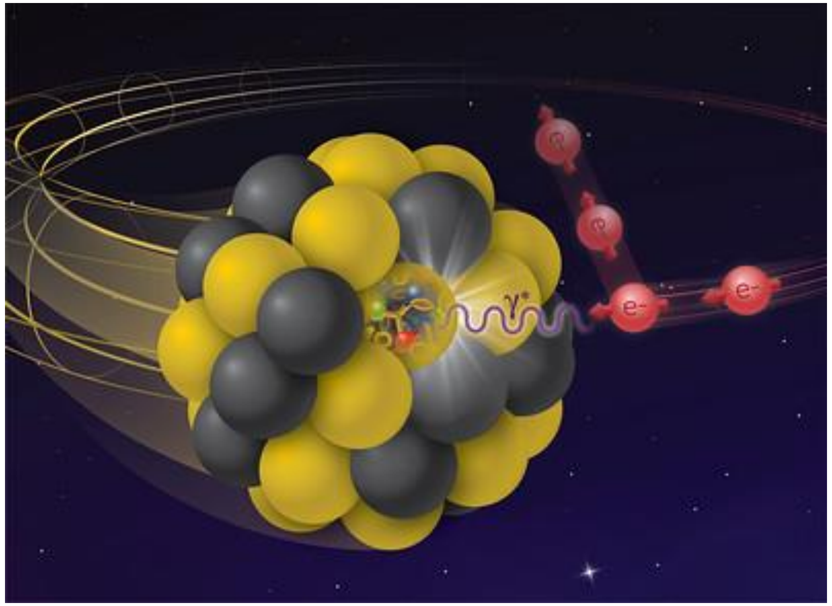


Fig. 6.1: Electron energy E vs. electron source current I for classes of past, present and possible future ERL facilities as are introduced in the text. Dashed diagonal lines represent constant power, $P[\mathrm{kW}] = E[\mathrm{MeV}] \cdot I[\mathrm{mA}]$.

EUROPEAN STRATEGY FOR PARTICLE PHYSICS Accelerator R&D Roadmap, https://doi.org/10.23731/CYRM-2022-001



E-cooling in EIC

- High average current (100 mA)
- High bunch charge (up to 2nC)
- Long lifetime (>3days)
- Reproducible

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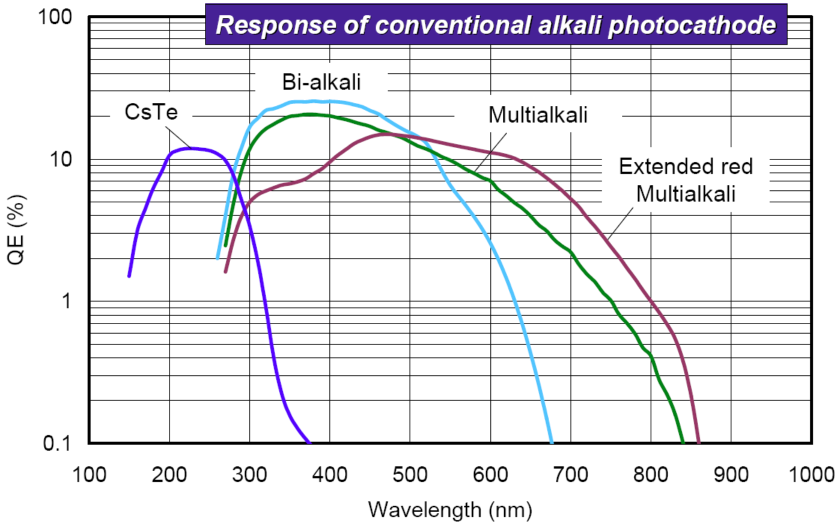
Current state-of-the-art/practice: alkali antimonide photocathode

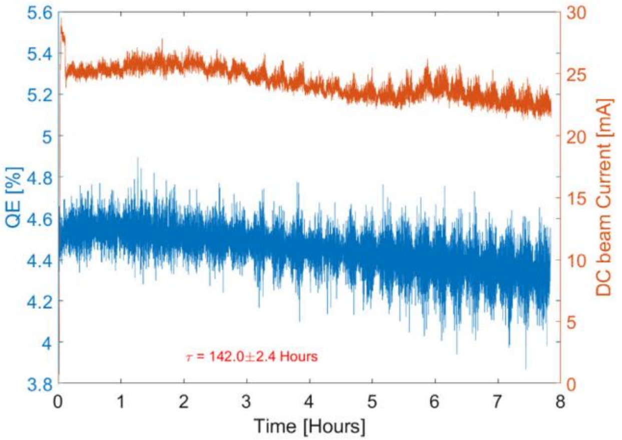
Excellent photocathode for electron cooling: good combination of properties

- High quantum efficiency in visible light range
- Less sensitive to vacuum than GaAs:Cs

Has been demonstrated in practice

- Cornell University: 65 mA, 60 pC bunch charge for 2 days
- LEReC @ BNL: 30mA for days; 15~20 mA for weeks of operation, and 20K C charge lifetime





25 mA;
t = 142 h;
QE > 4%

X. Gu et al., PRAB 23, 013401 (2020)

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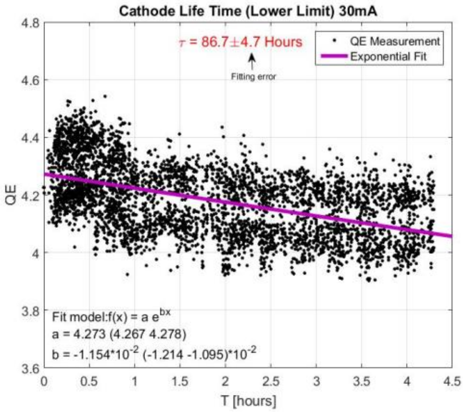
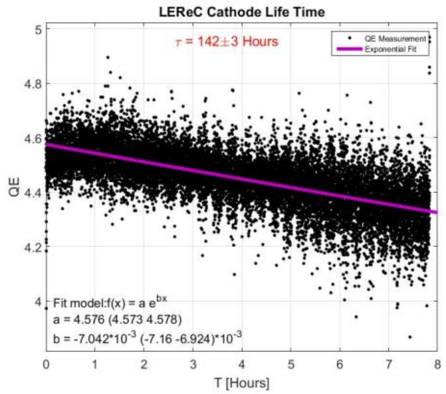
High Current Performance of K-Cs-Sb Photocathode in LEReC DC gun

LEReC Cathode lifetime in the gun

30 mA CW, t = 87 h, QE > 4%



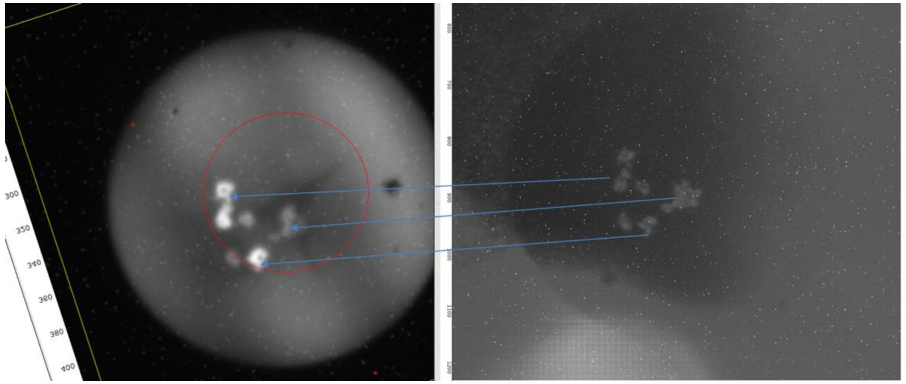
25 mA CW, t = 142 h, QE : >4%

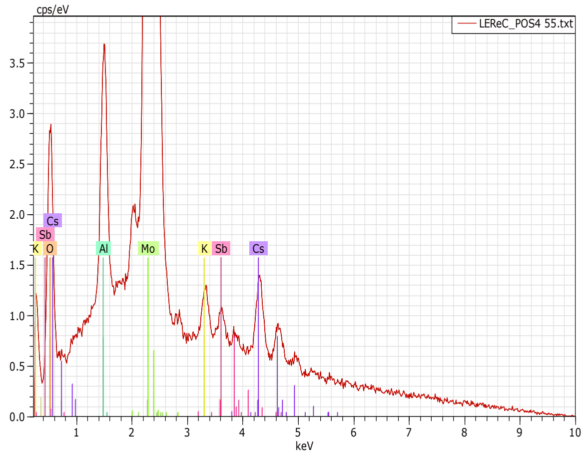


QE decay accompanied with gun trip

QE map

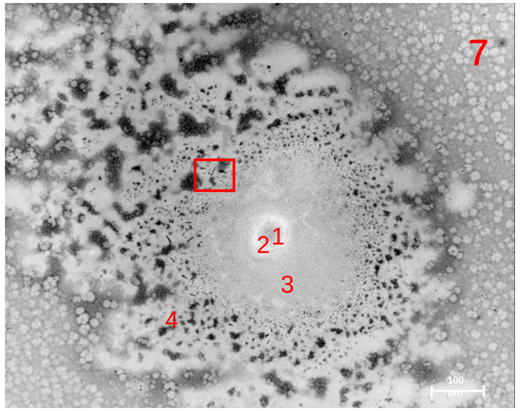
Cathode image





Possible alumina particles form polishing

Post operation SEM

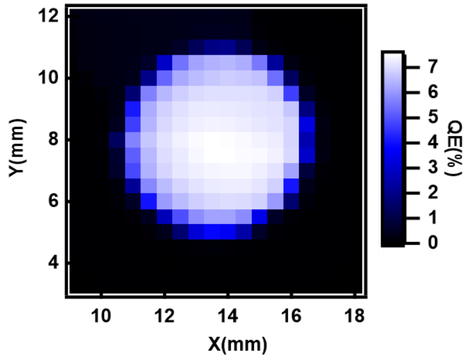


- At the damaged area, Cathode material is least in the center of the spots and most on the rim.
- The crystalized cathode streak on the rim shows higher QE.

Stable high current operation 2018~2019

- Improved cleaning procedure of pucks
- Improved growth procedure for higher QE
- Add the QE uniformity check to cathode preparation procedure.

- Changed the cathode design to off-centered on puck and reduced cathode size
- Improved laser stability by introducing laser intensity feedback
- Applied anode bias to prevent ion back bombardment



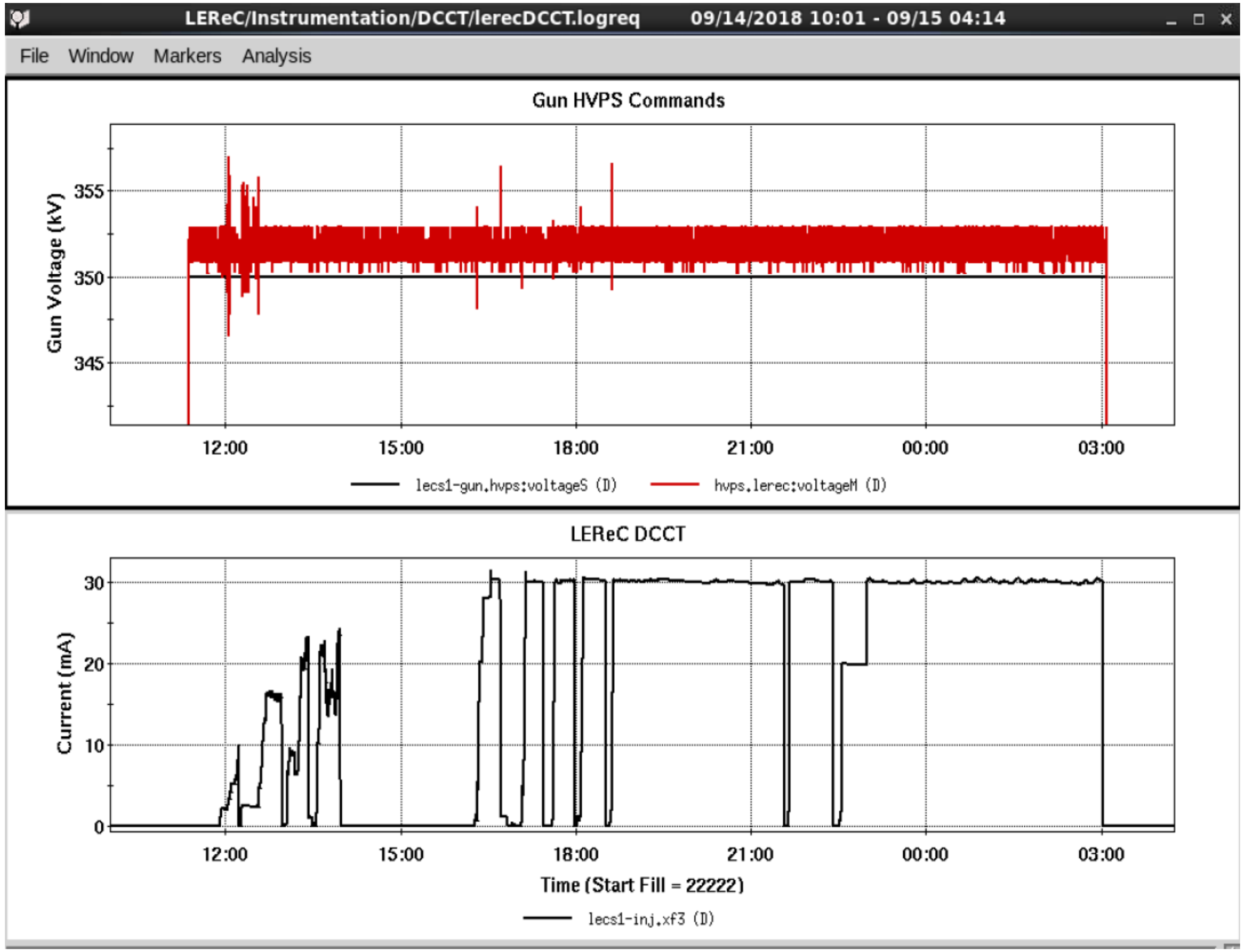
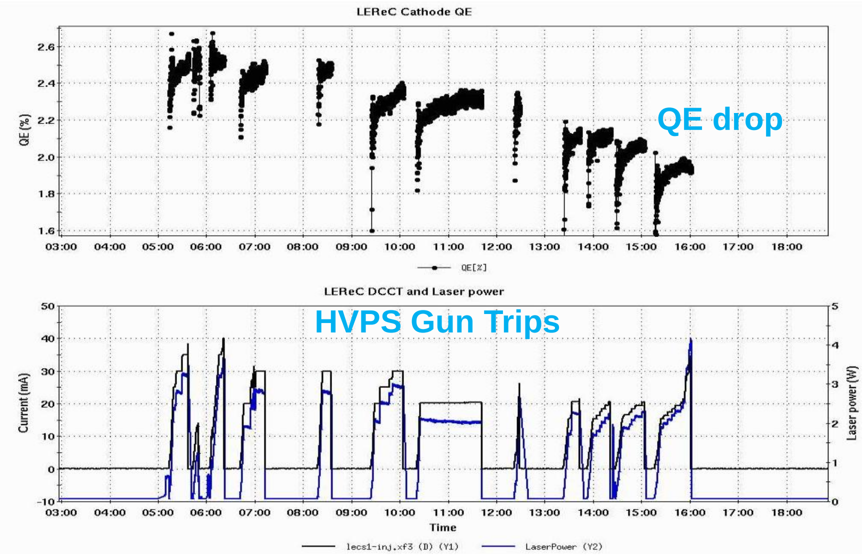
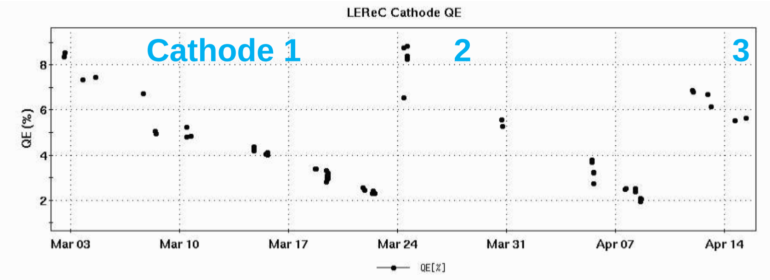


Figure courtesy of: Alexei Fedotov

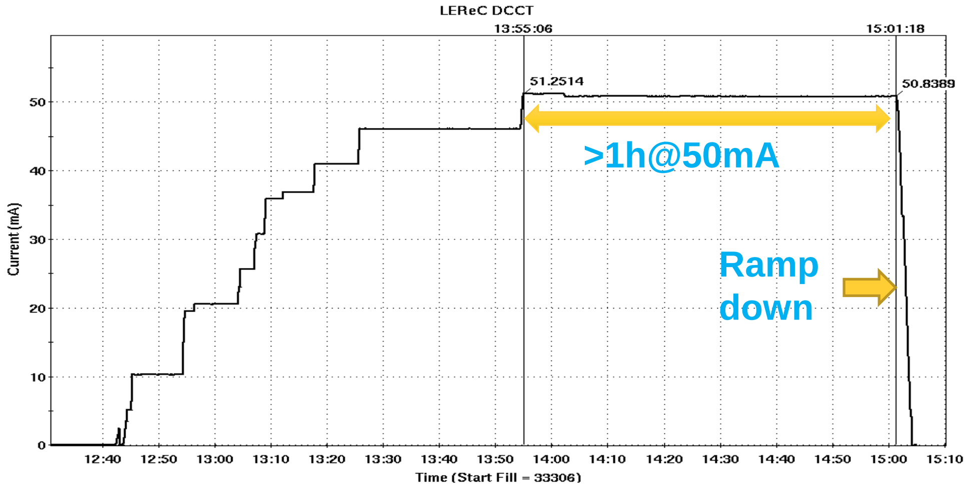
High Current Performance of K-Cs-Sb Photocathode in LEReC DC gun





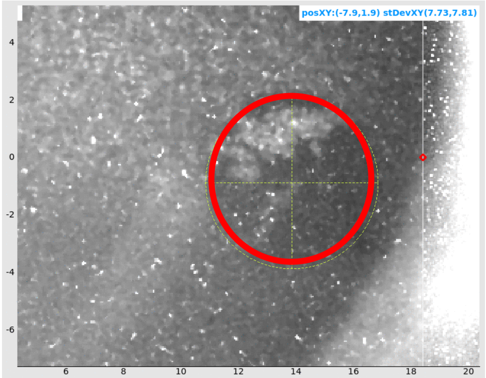
In the run of 2020~2021, the nominal LEREC operation current is 15 to 20 mA. Under these conditions, the typical cathode exchange time is 2~3 weeks.

LEReC high current test: 2022

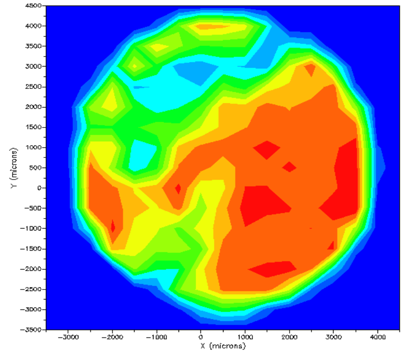


320kV; >1h; 50 mA

Cathode damaged from gun trip



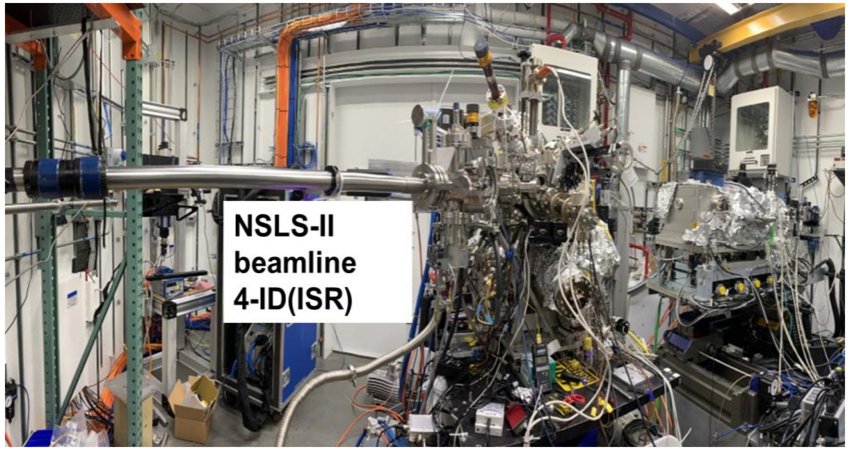
QE map



XiaoFeng Gu, talk on Wednesday

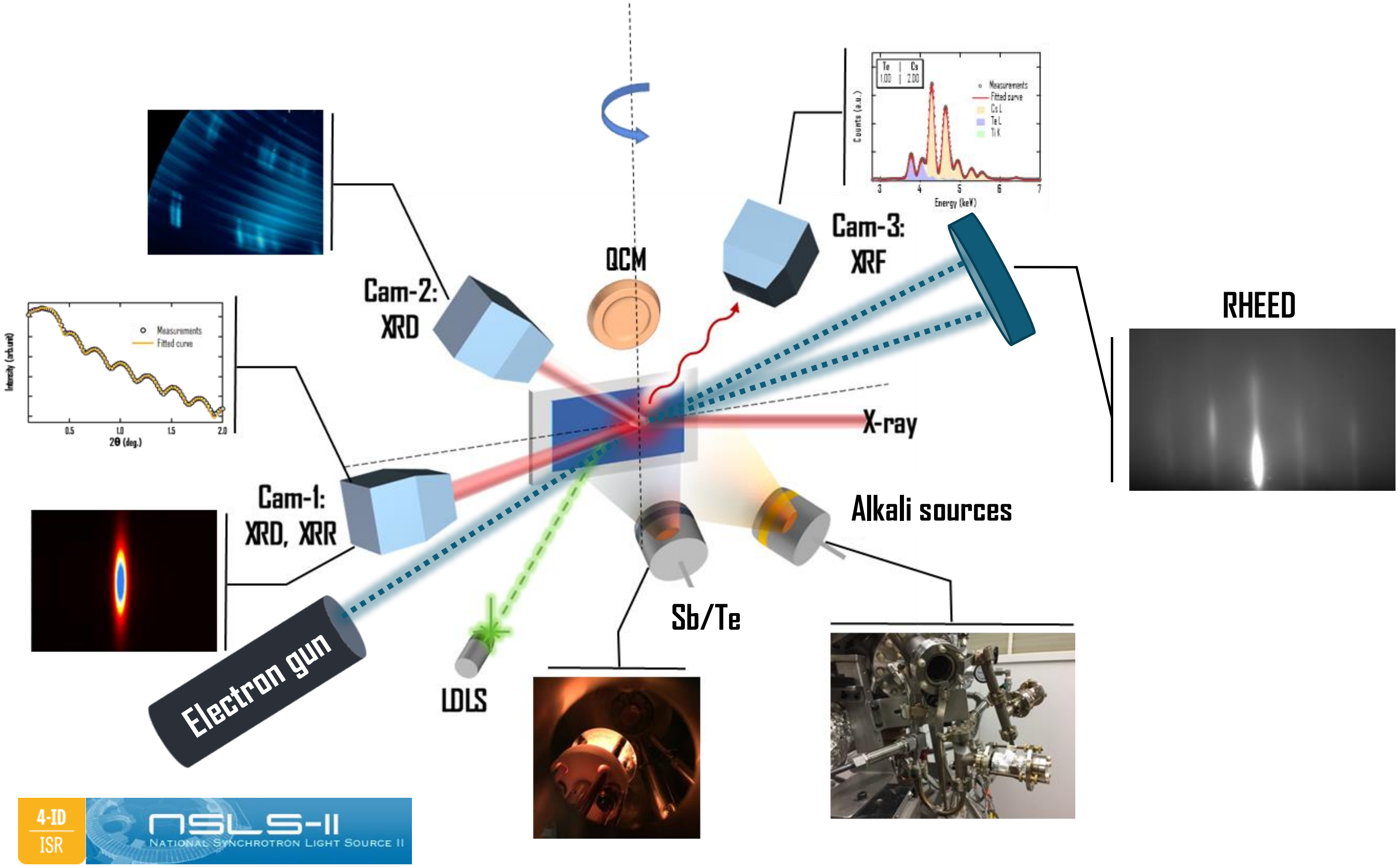
Cathode R&D: Material development

Cathode Material development @ BNL



Evaporators:
- ❑ Thermal Sb/Te
- ❑ Alkali metals
- ❑ PLD Sb/Te

Characterization:
- ❑ QCM
- ❑ XRD
- ❑ XRR
- ❑ XRF
- ❑ QE
- ❑ RHEED



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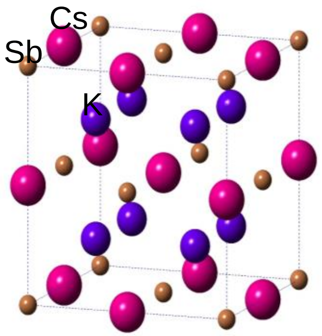
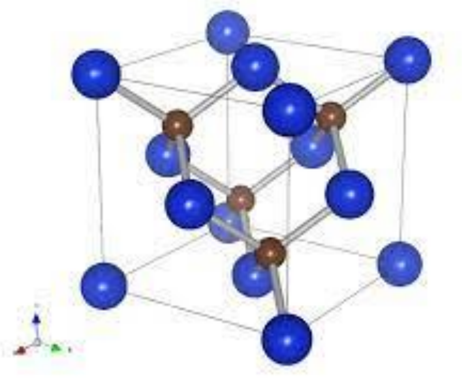
Epitaxial growth of alkali photocathode: Scientific bases



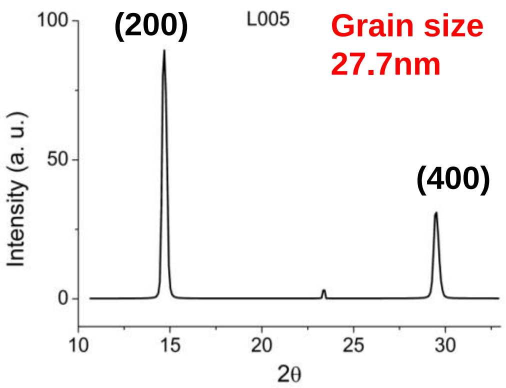


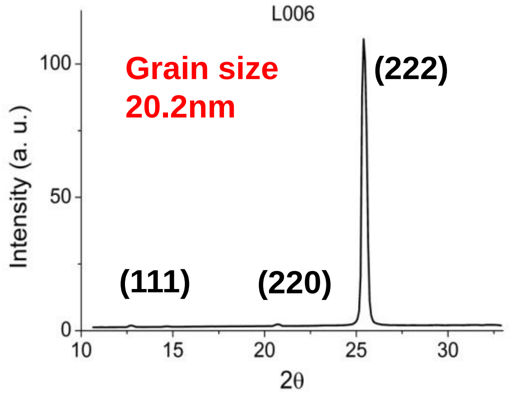
K_2CsSb unit cell

K_2CsSb, Cs_3Sb: b.c.c. crystal structure
Lattice parameter: 8.615 Å, 9.18 Å

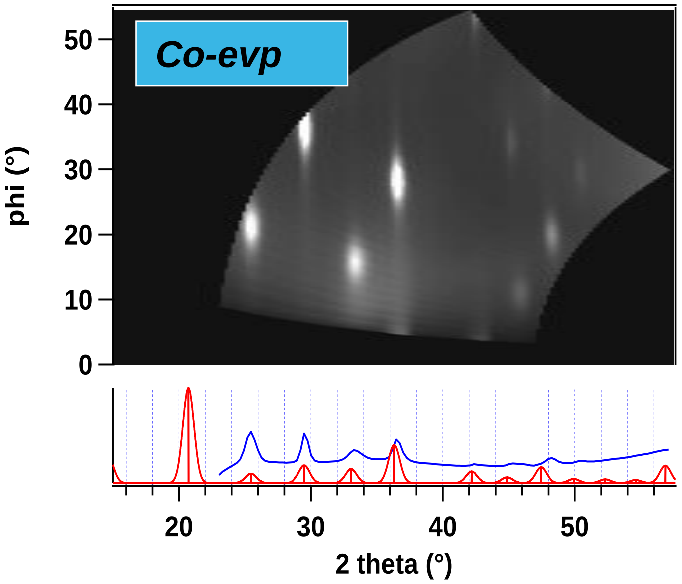
3C-SiC: f.c.c. crystal structure
Lattice parameter: 4.35 Å

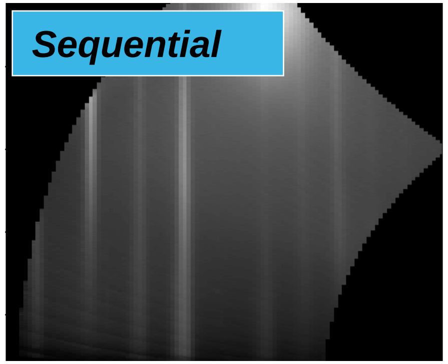
XRD: Camera 1





XRD: Camera 2





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Epitaxial growth of alkali photocathode

A reflection high energy electron diffraction (RHEED) system is a standard in-situ diagnostic that is mainly sensitive to the film surface structure, can provide qualitative information on the growth mode such as island nucleation, texture and crystallinity.

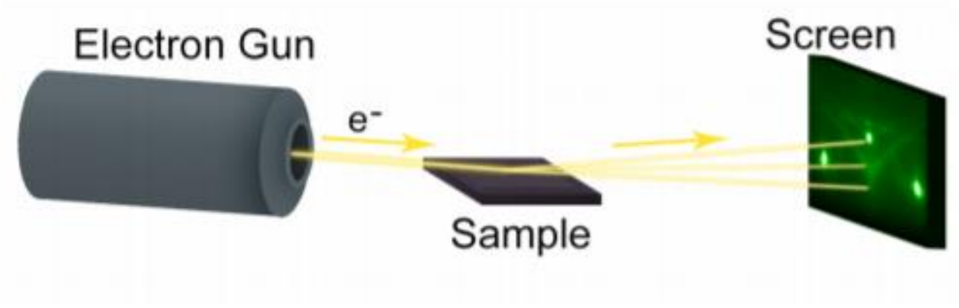
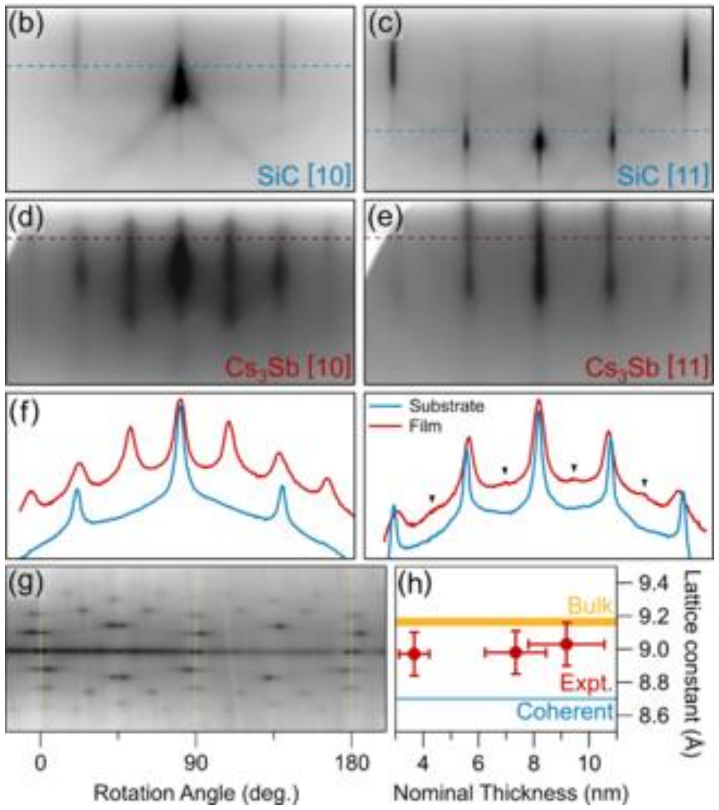


FIG. 1. The simplest RHEED set up includes an electron gun, a sample, and a fluorescence screen across from the gun.

RHEED: Cs_3Sb/3C-SiC

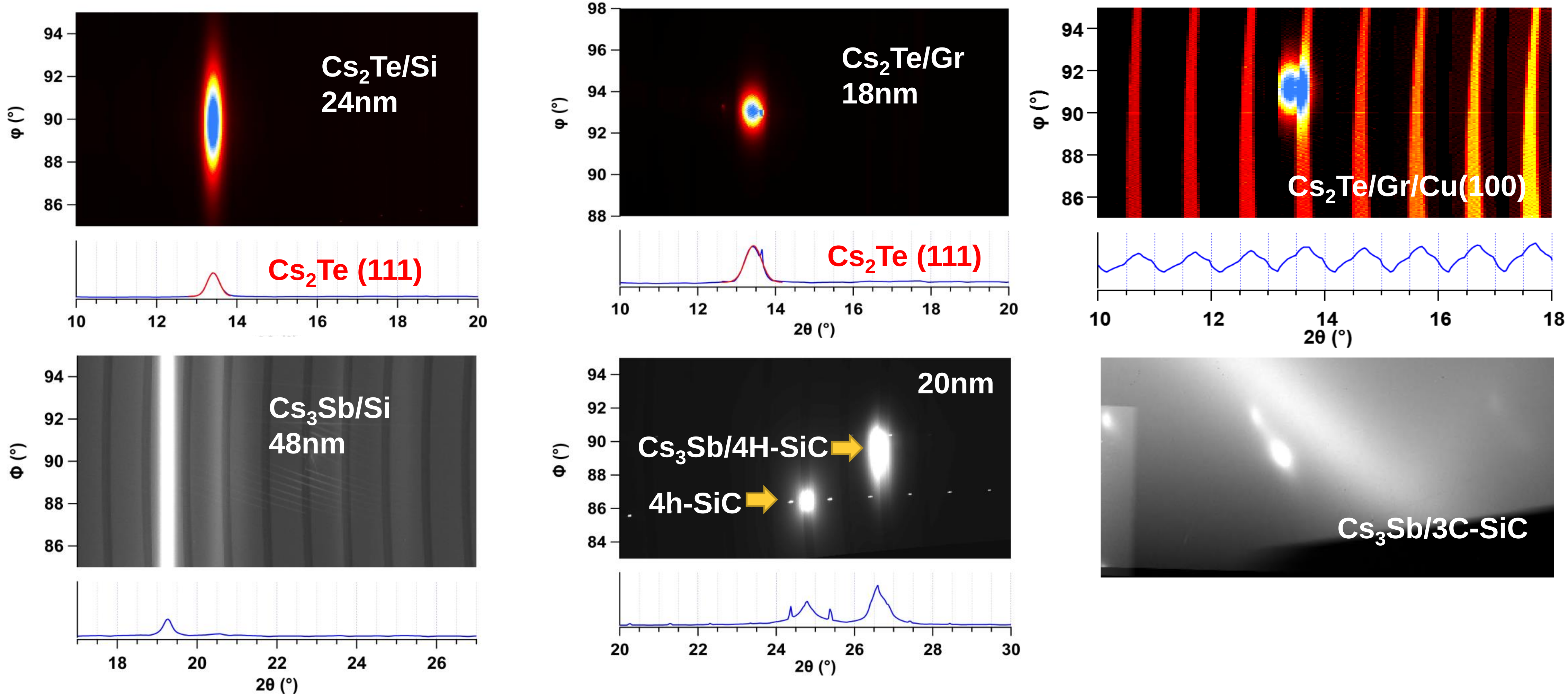


C. T. Parzyck, et al
Phys. Rev. Lett. 128, 114801 – Published 18 March 2022

Reference:
Reflection High-Energy Electron Diffraction, Nassim Derriche et al, 2019
Shuji Hasegawa. Characterization of Materials (Second Edition), chapter Reflection High-Energy Electron Diffraction, pages 1925–1938. 2012.

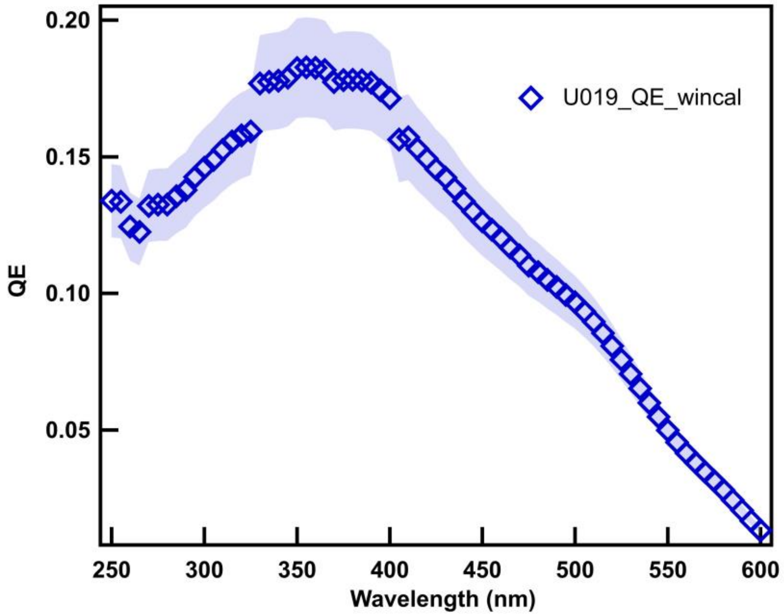
Epitaxial growth of alkali photocathode

X-ray Diffraction

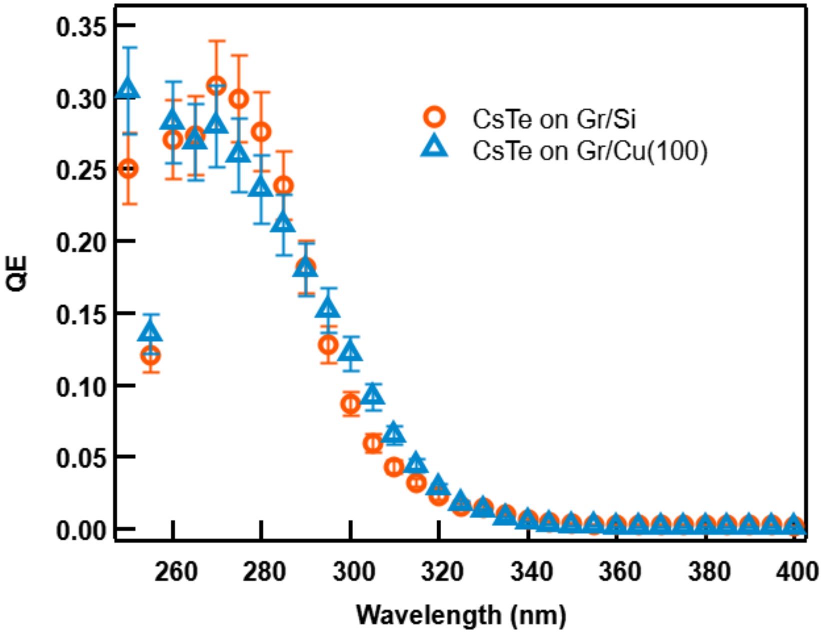


Epitaxial growth of alkali photocathode

Cs_3Sb: 4H-SiC



Cs_2Te: Gr/Si vs Gr/Cu (100)



Spectral Response

- 350 nm (peak): 18.2%
- 530 nm: 7%

- High QE can be achieved on Gr/Si and Gr/Cu substrate

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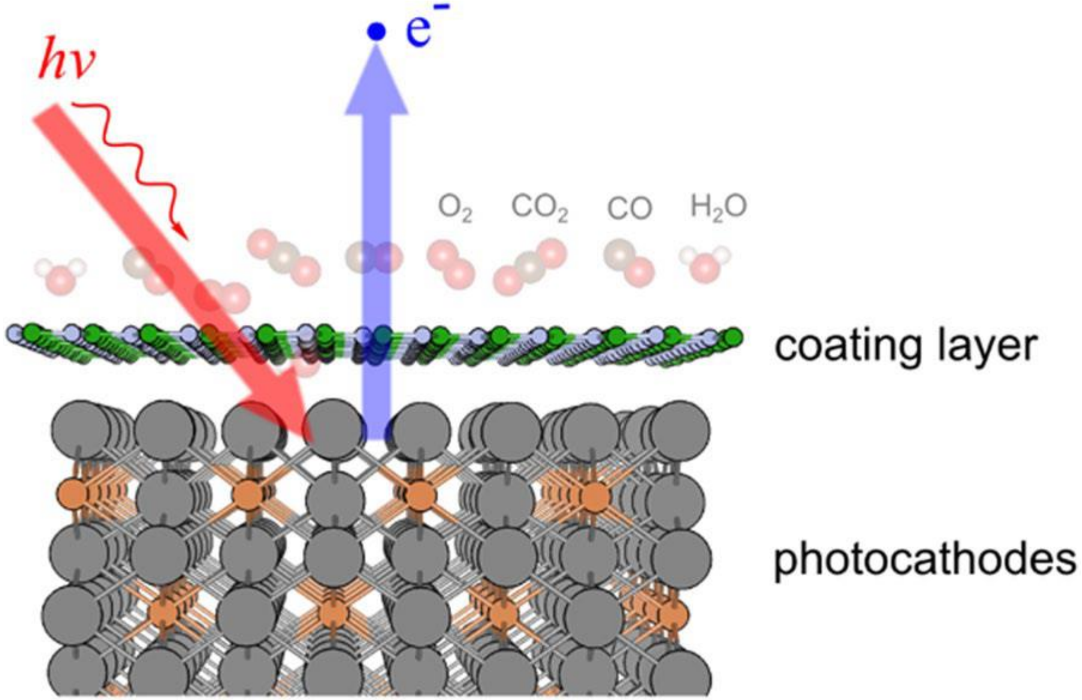
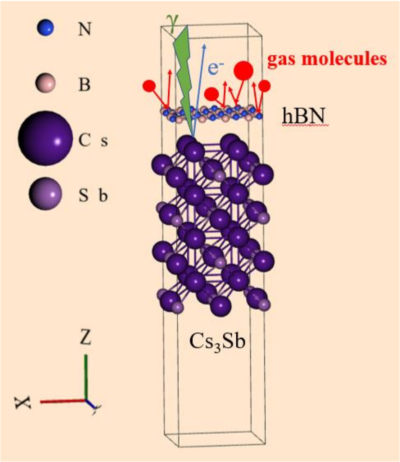
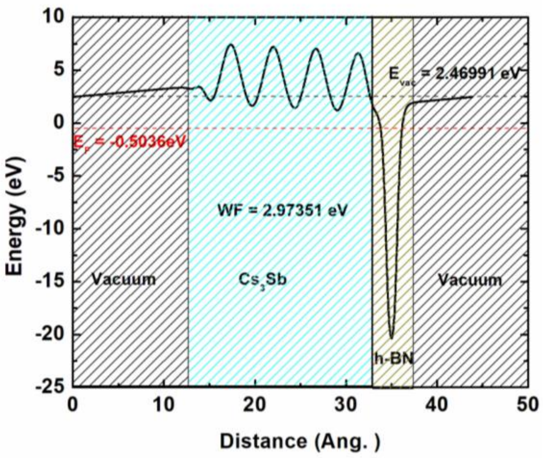
Cathode R&D: protective layer on alkali antimonide

Cs Intercalation of Graphene: 2D protective layer on alkali antimonide

It is a very tempting idea and is supported by various theoretical work. DFT simulations indicate that monolayer of hBN can reduce the workfunction of Cs3Sb.







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

G.Wang et al. *Nature Partner Journal 2D Mater. Appl.*(2018)

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

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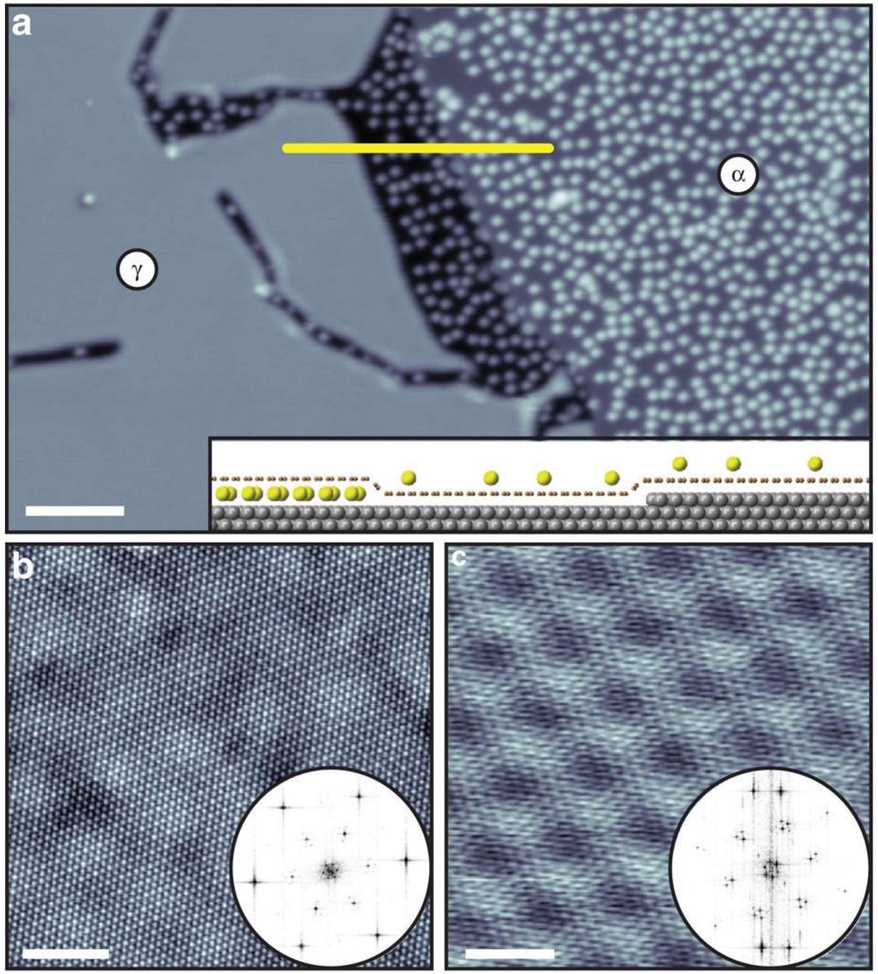
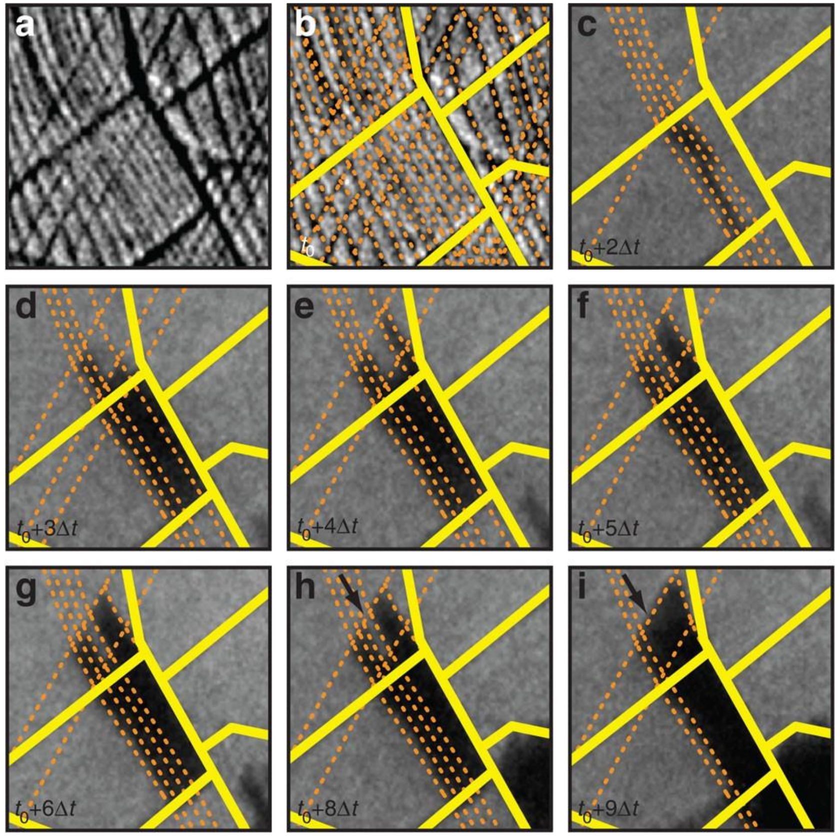
Cs Intercalation of Graphene

The mechanism of Cs intercalation through monolayer graphene





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

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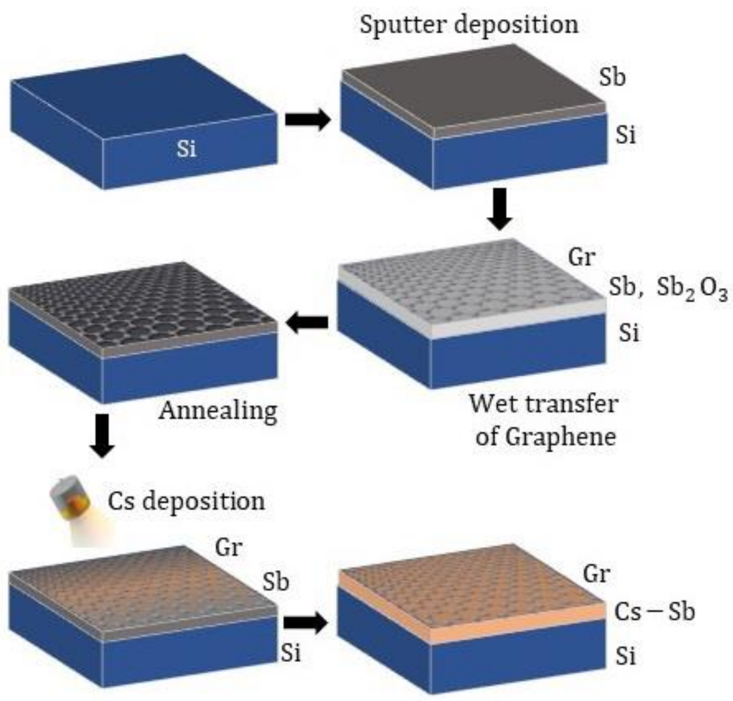
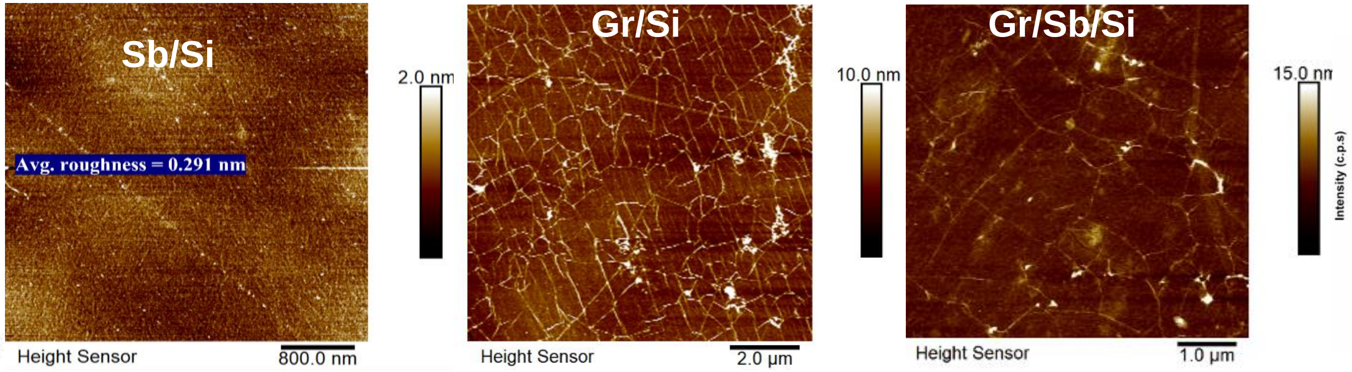
21-ID ESM

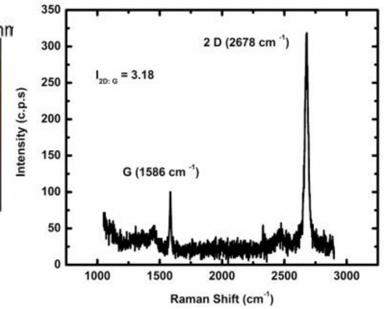
NSLS-II NATIONAL SYNCHROTRON LIGHT SOURCE II

Cs Intercalation of Graphene: Experimental details

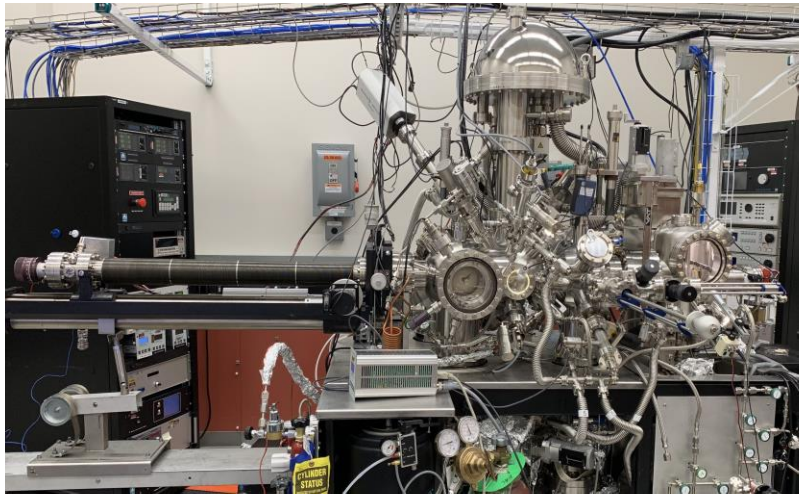




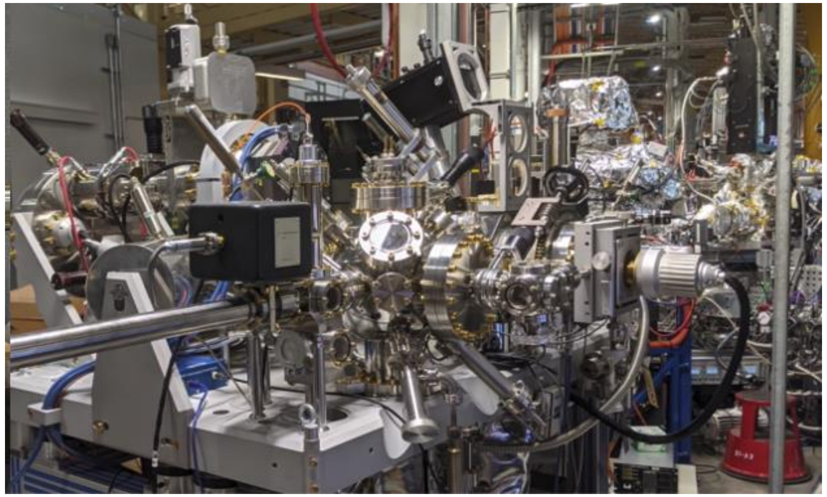
RAMAN SPECTROSCOPY



Multiprobe surface analysis system located at CFN, BNL



Electron spectro microscopy beamline (ESM, 21-ID-2), NSLS-II, BNL



J. Biswas *et al.* (under review), collaboration with Euclid techlabs.

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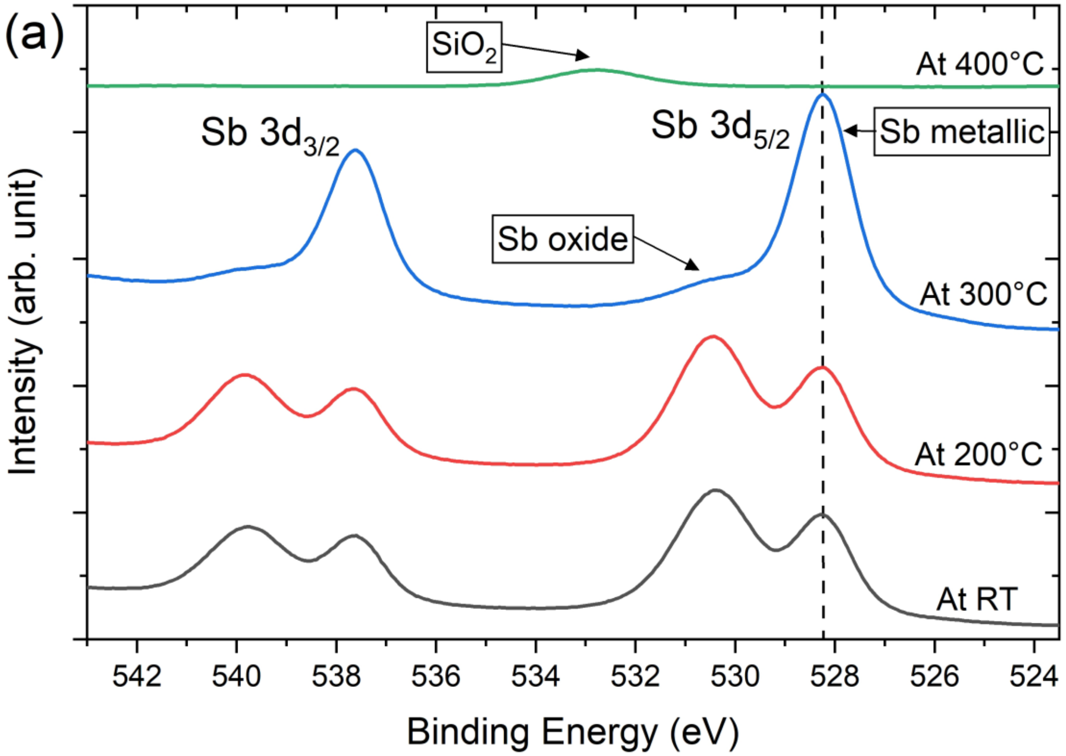
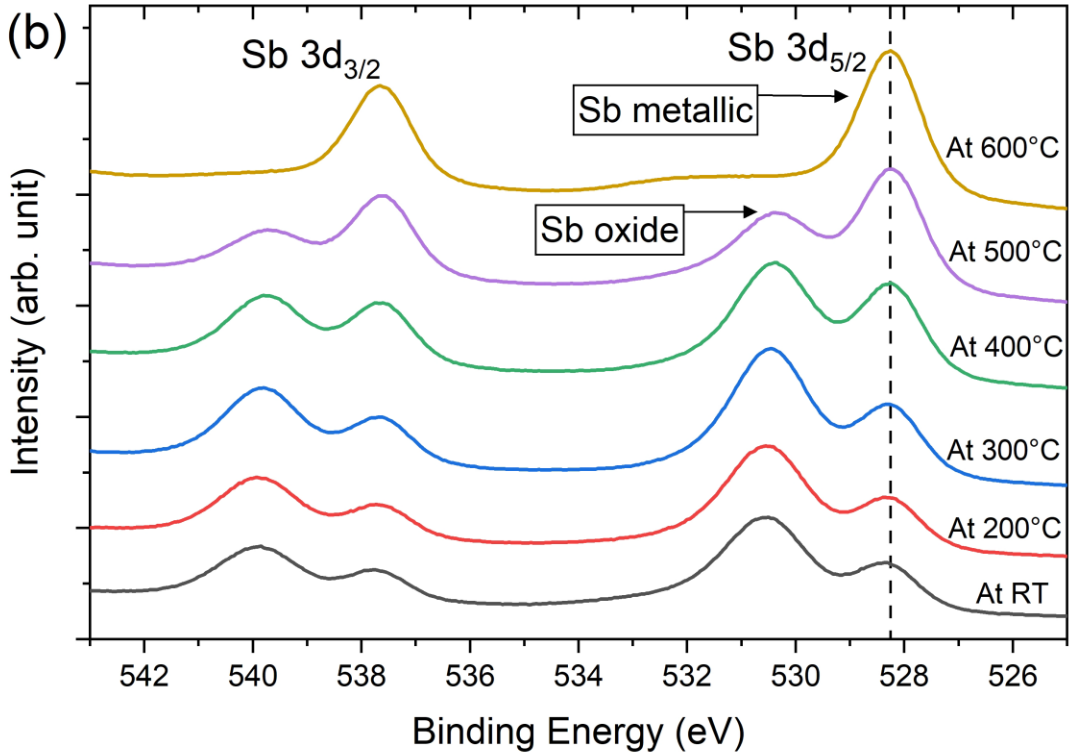
Cs Intercalation of Graphene: Sb desorption under high heat

Ref: 10 nm Sb on Si, No Gr



Sample: 10 nm Sb on Si, Gr encapsulation



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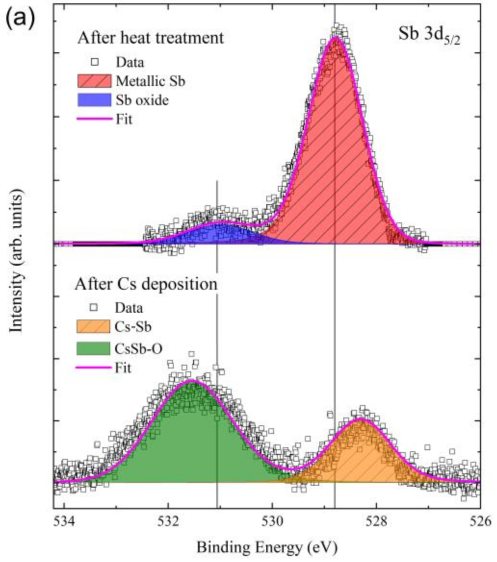
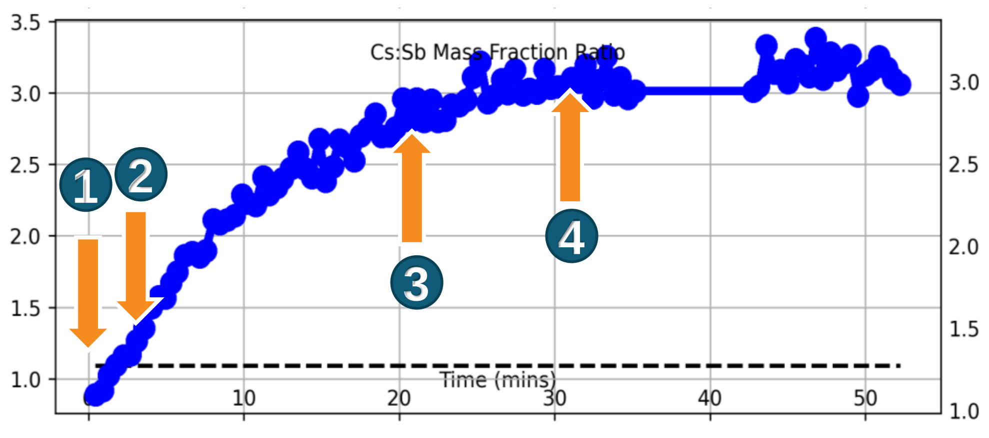
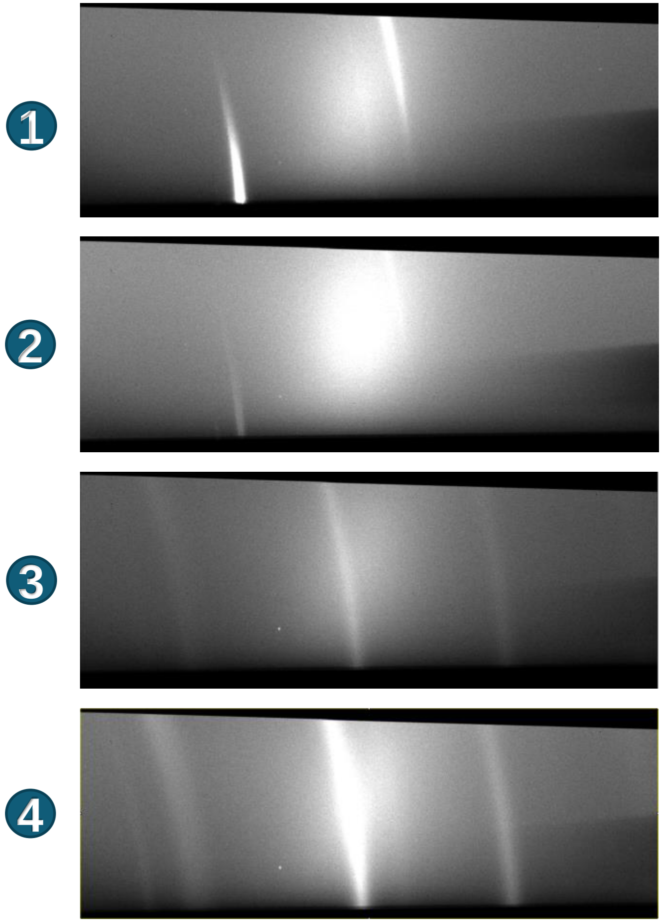
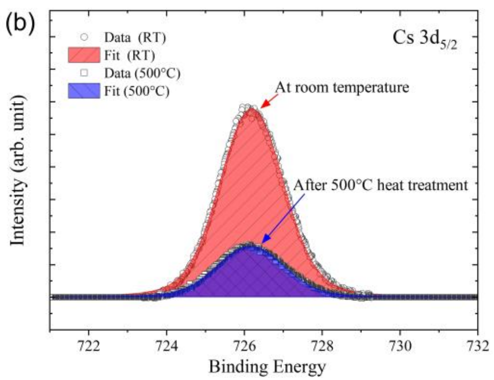
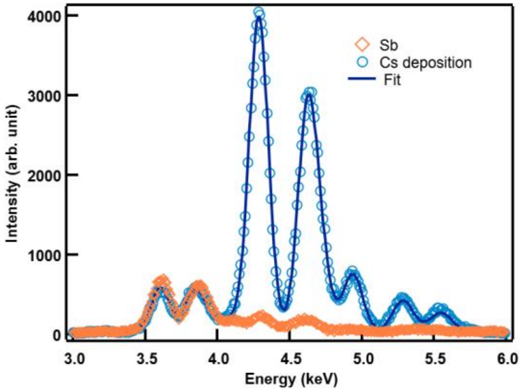
Cs Intercalation of Graphene: Chemical and structural evolution

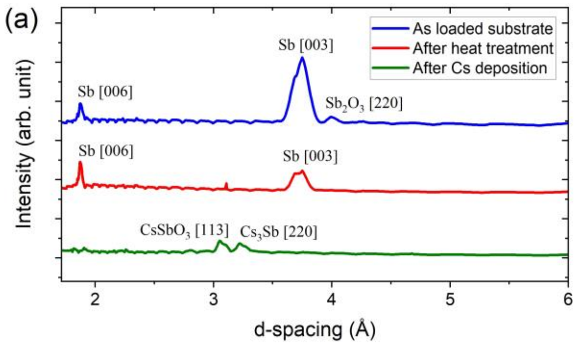












4-ID ISR

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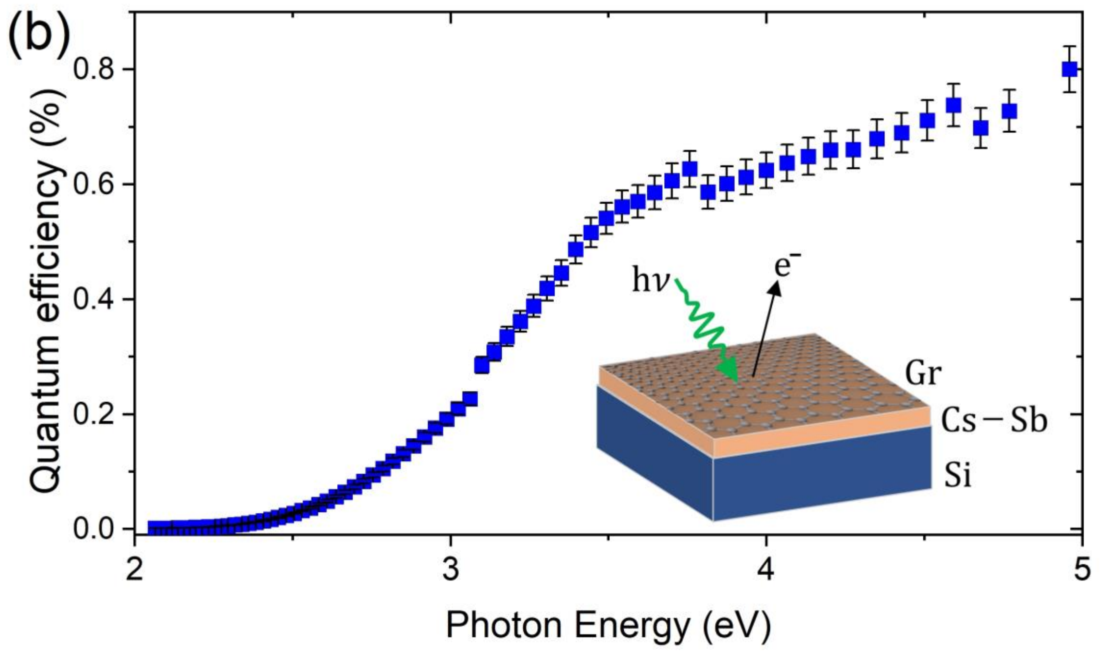
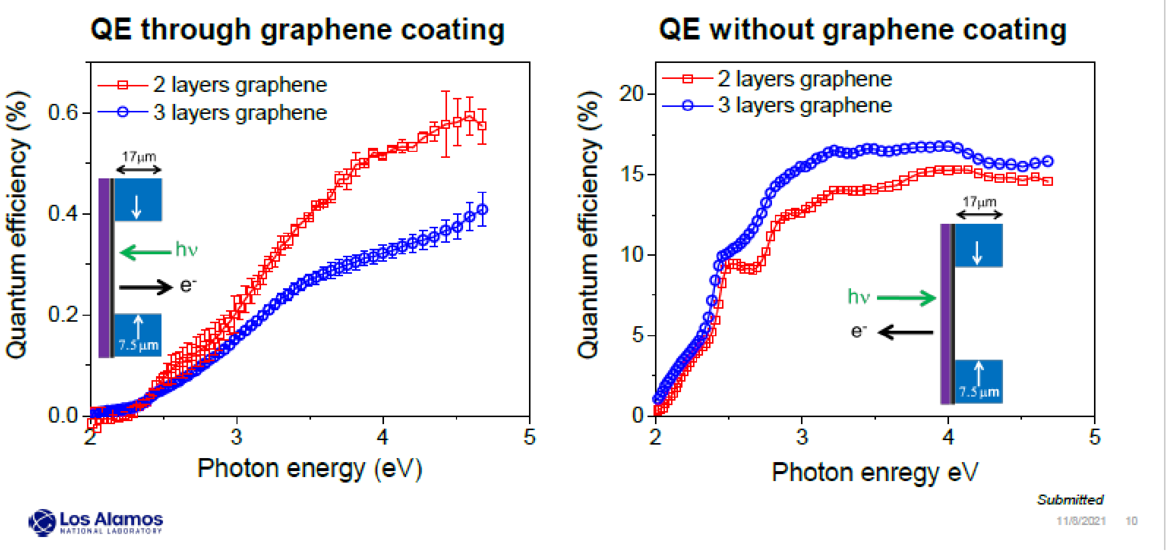
Cs Intercalation of Graphene: Quantum efficiency





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

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Summary

- Attaining high quantum yield, low emittance, and long lifetime from an alkali antimonide photocathode has remained a sustained focus in recent years, due especially to the need for electron beams of high average current for ERL-based electron cooling systems, synchrontron radiation sources, electron ion colliders and other applications.

- At BNL, efforts are made to improve the crytallinity of the alkali based photocathode material to achieve high quantum efficiency.

- Progress is made in the development of the 2D material encapsulated alkali antimonide photocathodes.

Acknowledgements

Work presented are contributed by collaborators from BNL, LANL, SLAC, Cornell U, ASU, and many other institutions.

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