Characterizing Ordered Alkali Antimonides for High Brightness Electron Guns

Chad Pennington

Cornell University , Department of Physics + CLASSE

CBB Annual Meeting, July 20, 2023

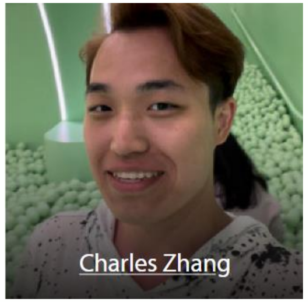
NSF

The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

CORNELL UNIVERSITY FOUNDED A.D. 1865

Acknowledgements

Maxson Group



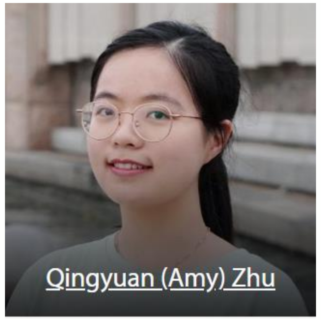
Now at U. Salerno

Musumeci Group

Hines Group

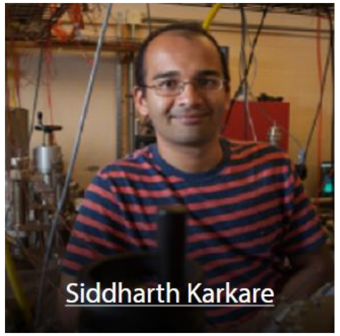
Will DeBenedetti, Postdoc, LANL

Jan Balajka, Postdoc, TU Wien



Shen Group

Karkare Group



Brookhaven National Lab: Mengjia Gaowei, Kenneth Evans-Lutterodt
SLAC: John Smedley

What makes a great photocathode?

1.) Brightness: a figure for the quality of the electron beam.

$$B_n = \frac{2m_e c^2 I}{\sigma_x^2 MTE}$$

Beam current: quantum efficiency, laser fluence

Mean transverse energy: Intrinsic momentum spread + roughness + laser heating + ...

2.) Lifetime: how long the photocathode maintains efficiency during operation.

- In modern accelerators, beam brightness is limited at the photocathode.
- Alkali Antimonides (Cs_3Sb, K_2CsSb, Na_2KSb etc.) are excellent photocathode materials. Question: can we improve them?

Epitaxy and why it matters

- Answer: We can.
- Cs_3Sb is conventionally grown polycrystalline with random long-range order.

Epitaxy is the alignment of crystal layers with respect to an underlying crystal seed layer.

Material ordering eliminates defects that contribute to electron momentum spread (roughness, grain boundaries)

We lattice-match Cs_3Sb films with the crystal substrate (e.g. 3C-SiC(100)) via Molecular Beam Epitaxy (MBE)

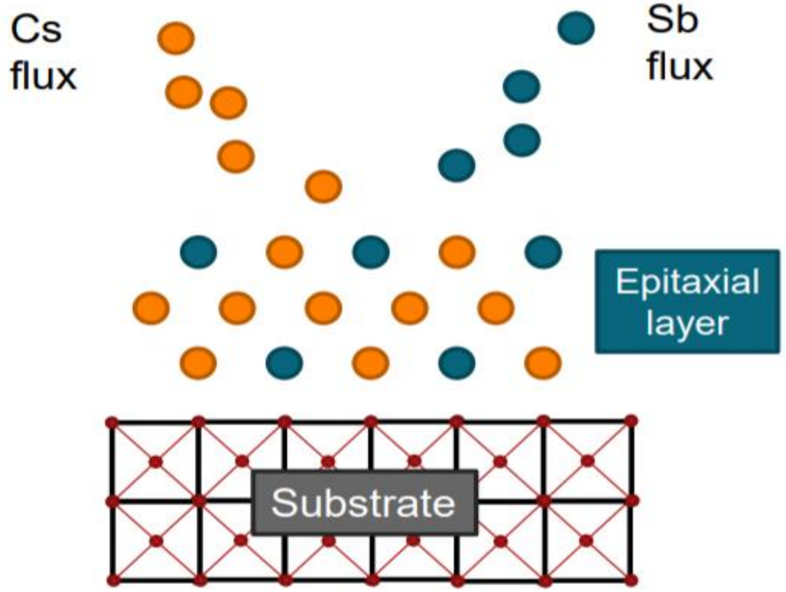
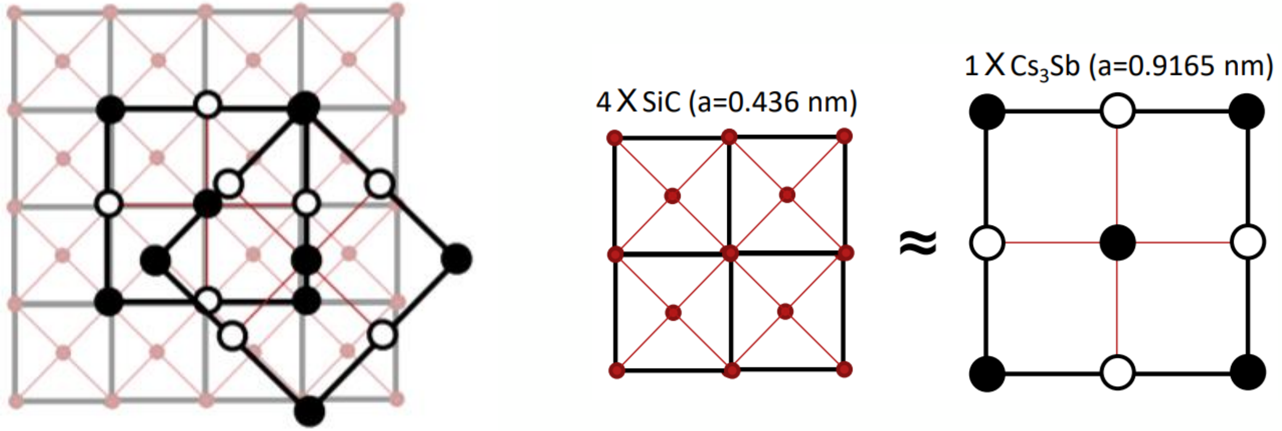


Figure courtesy of Alice Galdi

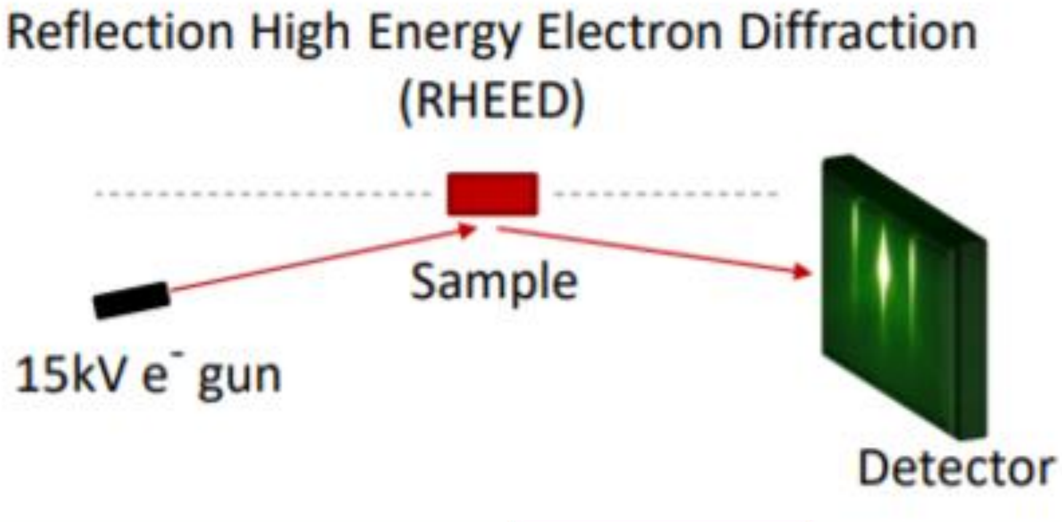


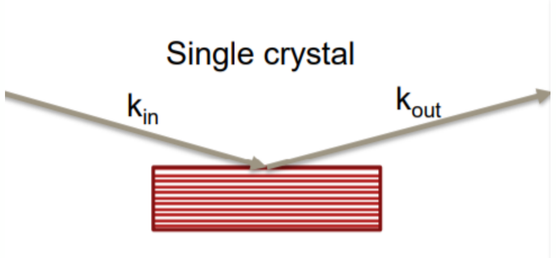
Single-crystal alkali antimonide photocathode: High efficiency in the ultra-thin limit

C. T. Parzyck, A. Galdi, J. K. Nangoi, W. J. I. DeBenedetti, J. Balajka, B. D. Faeth, H. Paik, C. Hu, T. A. Arias, M. A. Hines, D. G. Schlom, K. M. Shen, and J. M. Maxson

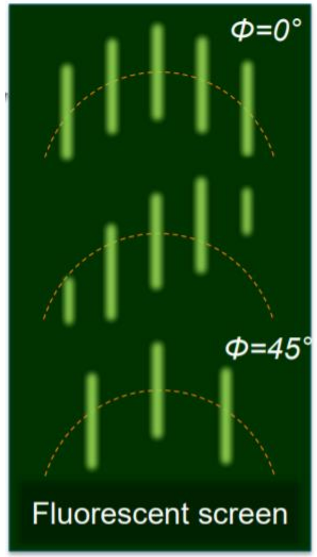
Accepted 2 February 2022

RHEED: a tool for determining epitaxy

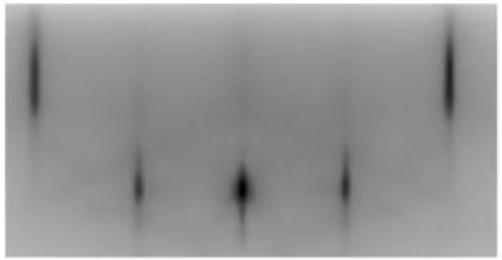




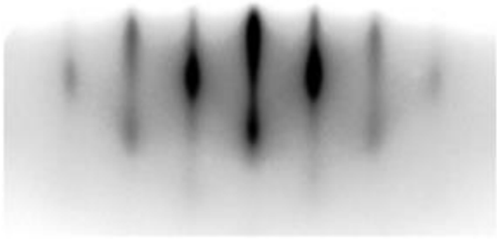
By rotating the sample around its surface normal, we intersect different sets of reciprocal space rods



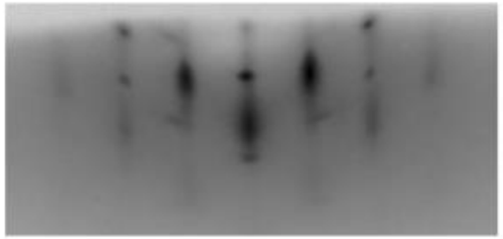
- RHEED identifies the surface structure through grazing incidence over the first few atomic layers of the sample.



Single crystal
High coherence

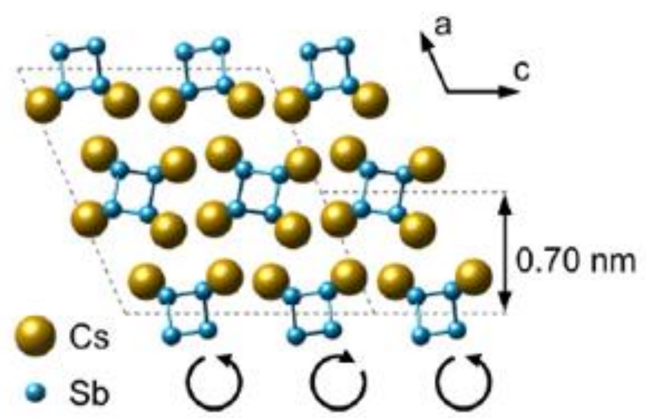


Film
Reduced coherence
Roughened surface



Film
Polycrystalline
domains/impurities

A new stoichiometric phase: Cs_1Sb_1



Azimuthally independent streaks in RHEED

fiber-textured surface

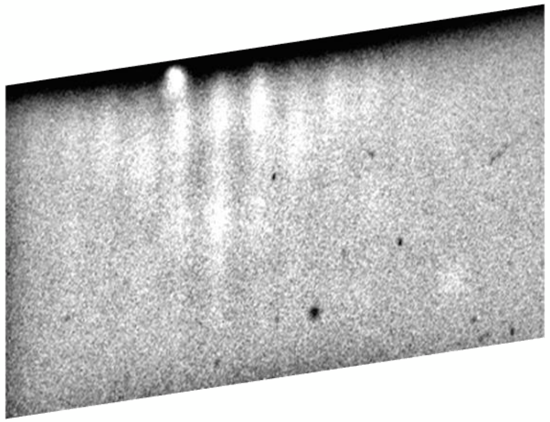
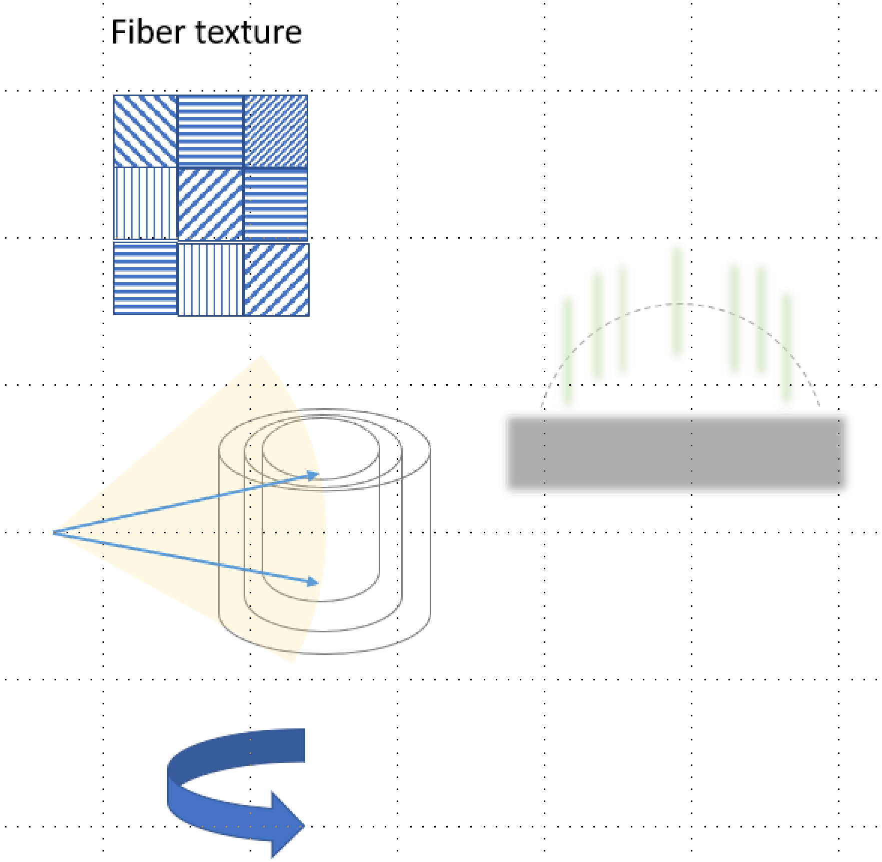
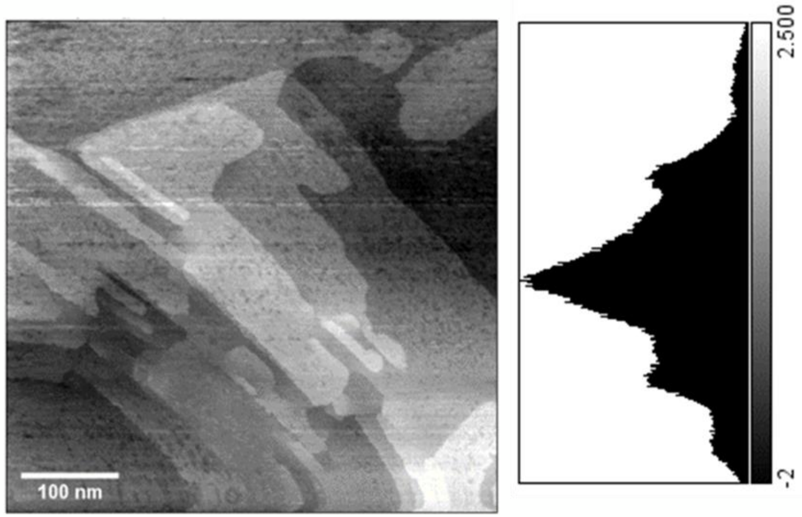


Image band pass filtered for contrast





Scanning Tunneling Microscopy (STM)

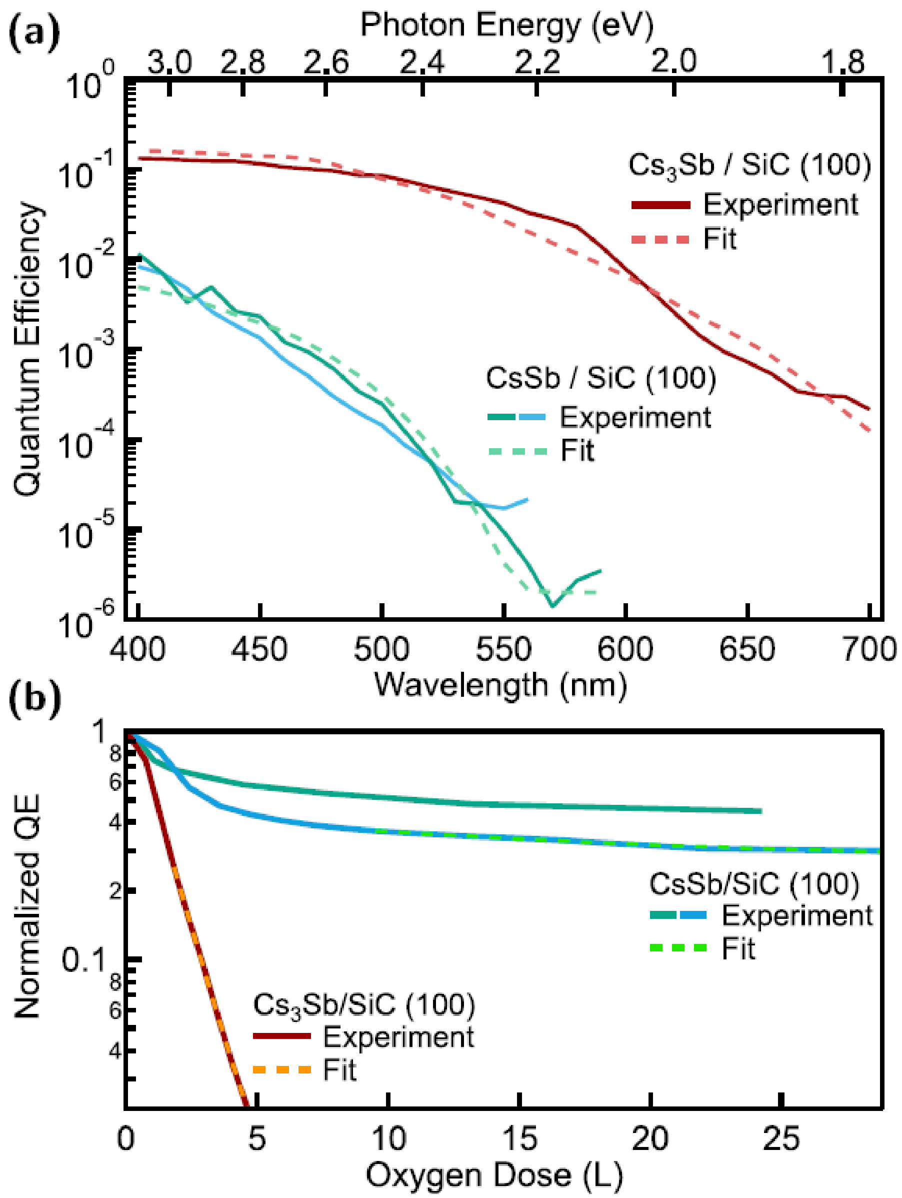
- Surface roughness ~0.6 nm.

-Multimodal histogram indicates flat steps along surface.

STM results courtesy of Hines Lab

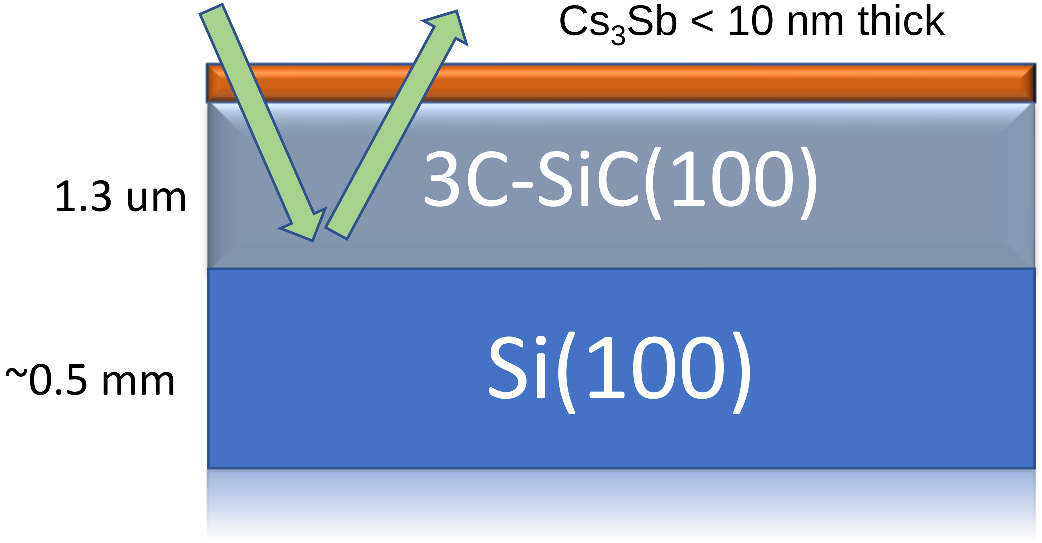
[2] C.T. Parzyck, C.A. Pennington et al, “Atomically smooth films of CsSb: a chemically robust visible light photocathode” arXiv:2305.19553

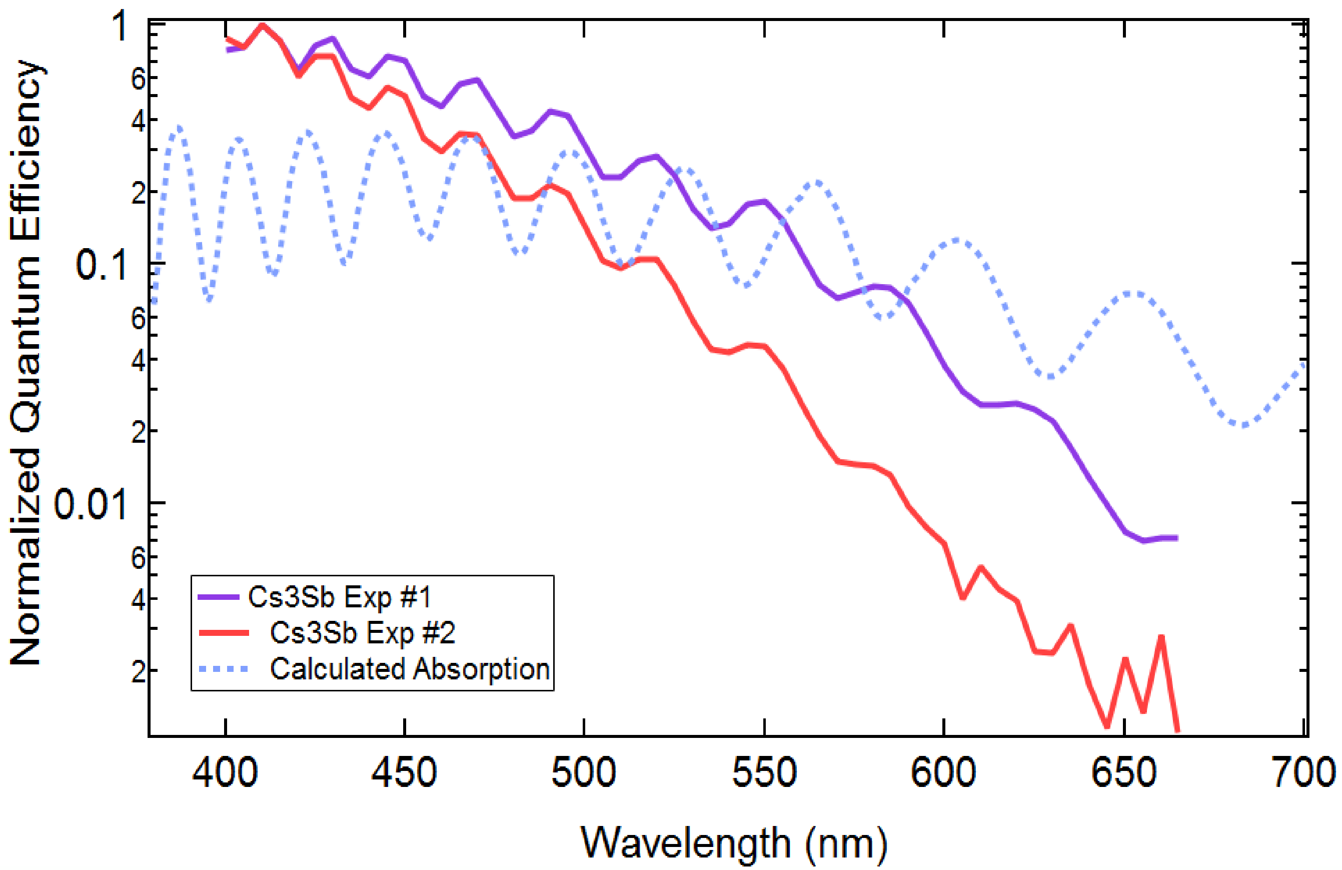
CsSb compared to Cs_3Sb



- Estimated work functions of CsSb and Cs_3Sb to be 2.18 eV and 1.63 eV respectively using a modified Dowell-Schmerge model for semiconductors. [2]
- CsSb has a photoemission threshold near 570 nm (green-ish light).
- Cs_3Sb has the higher quantum efficiency in the visible range. CsSb is exceptionally more robust to oxidation, with the ratio of the decay constants being over an order of magnitude.
- Comparable roughness depending on growth technique.

Optical interference in the cathode substrate





- Optical interference modulates the QE by a factor of two with ~20 nm period.
- Film thickness can be chosen to maximize QE at desired laser wavelength.
- Further engineering potential – distributed Bragg reflectors (DBRs).

•Enhanced photocathode performance through optimization of film thickness and substrate
Journal of Vacuum Science & Technology B **35**, 022202 (2017); https://doi.org/10.1116/1.4976527

Growing Cathodes: Digitally.

- Pulsed Laser Deposition(PLD)
  - 266 nm pulsed excimer laser vaporizes Sb target, condensing on substrate.
  - Consistent rep rate and laser fluence leads to extremely stable and controlled deposition rates.

Growth Controls:

- $T_{substrate}$
- Flux rate

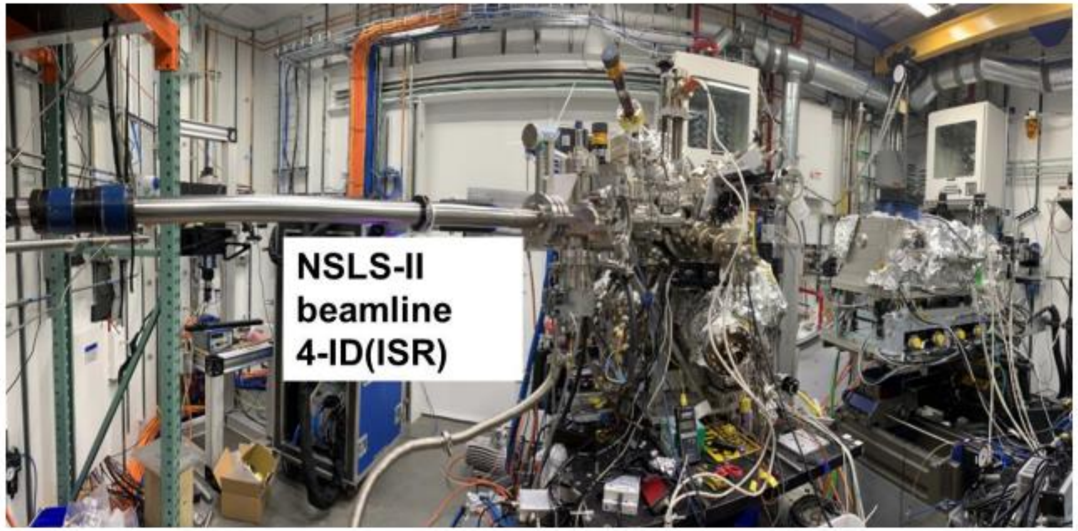
Characterization:

- RHEED – surface structure
- XRD – bulk structure
- XRR – thickness and roughness (rms)
- XRF - stoichiometry
- QE

- Does PLD vaporize atomic Sb or molecular Sb_4?

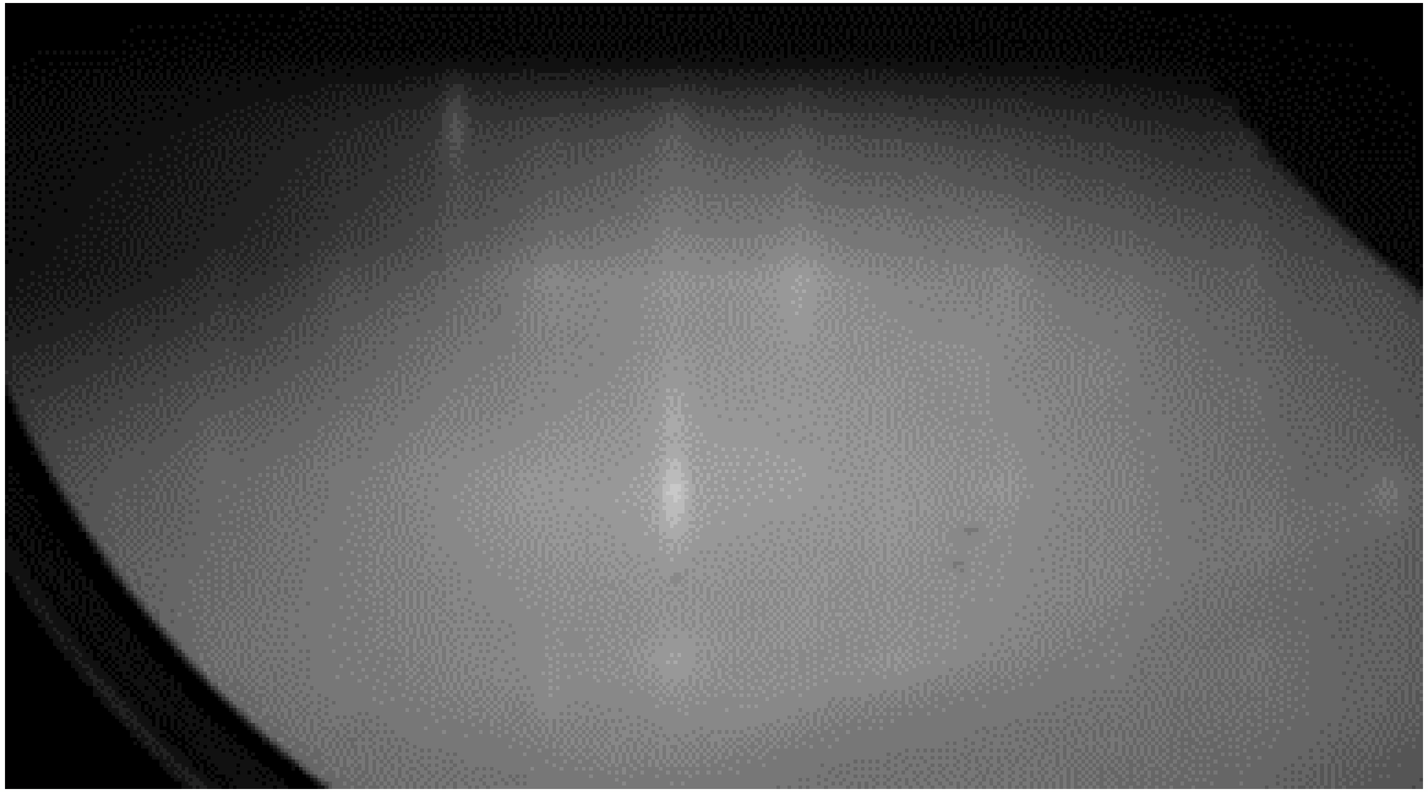
BROOKHAVEN NATIONAL LABORATORY

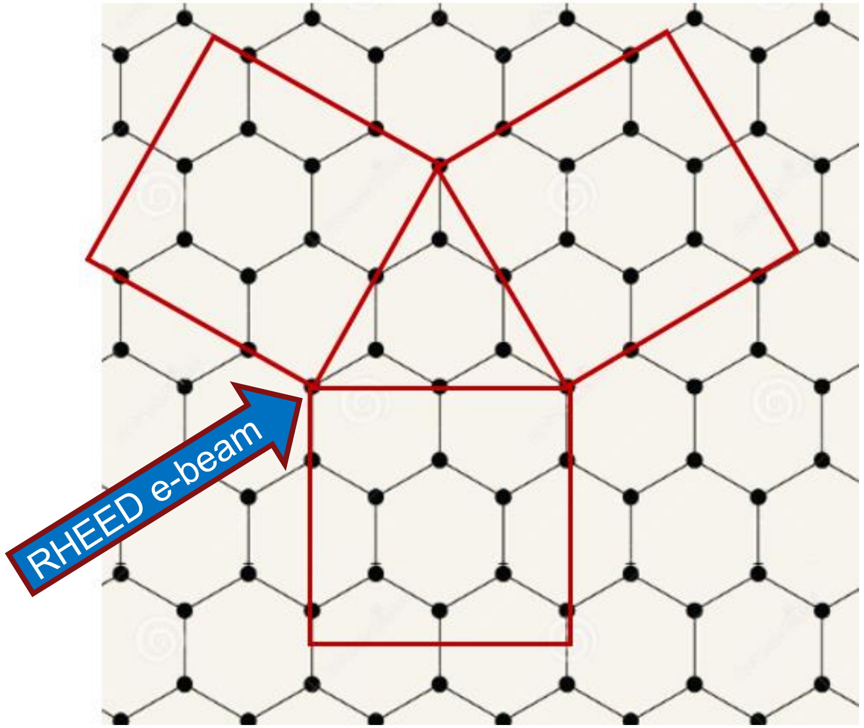
NSLS-II NATIONAL SYNCHROTRON LIGHT SOURCE II



CsK_2Sb with epitaxial domains

Preliminary Data





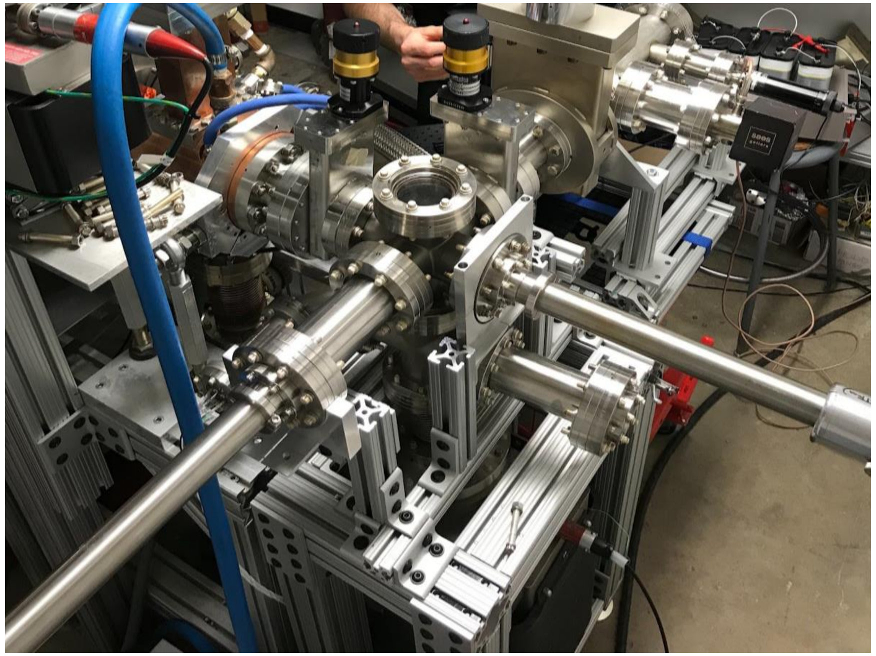
- K_2CsSb lattice constant: ~8.61 Angs
- Graphene lattice constant: ~2.46 Angs

➢ The first epitaxial, bi-alkali antimonide photocathode confirmed with RHEED.

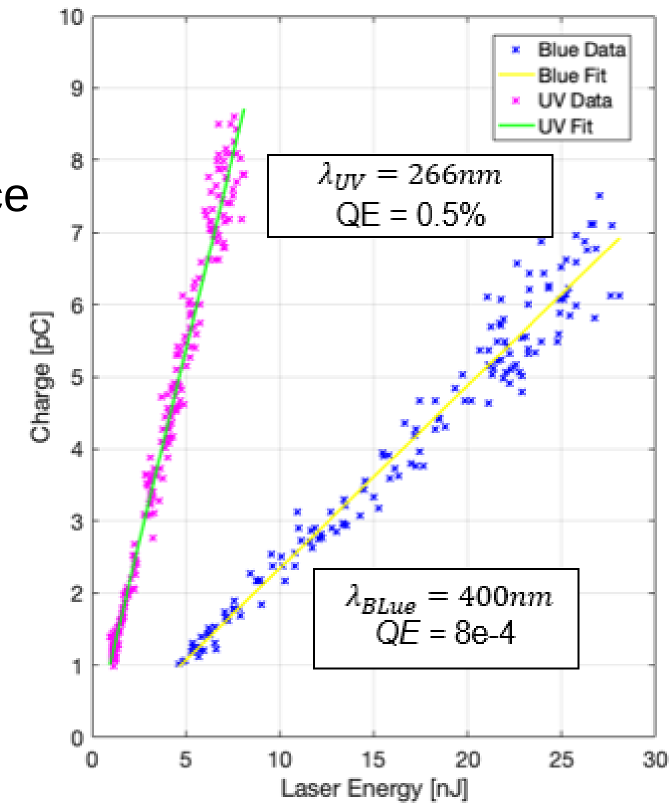
Alkali antimonides at high gradients

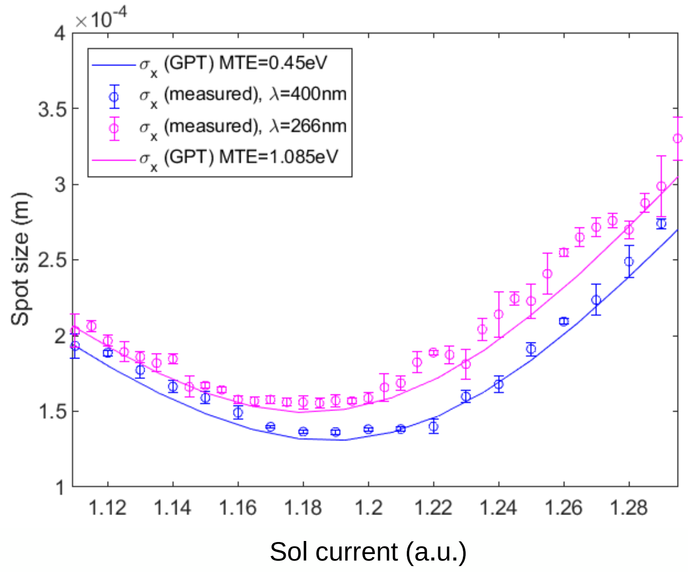
Na-K-Sb grown on molybdenum plug surface

INFN/DESY/LBNL cathode plug



UCLA Pegasus loadlock





Next steps and future directions:
- Test percent-level QE cathodes at high gradients (planned for summer 2023).
- Put a semiconductor substrate (e.g. SiC) on the INFN plug to test ordered AA cathodes at high gradients.

Conclusions and Future Directions

- Improved crystalline order of alkali antimonides is a promising path to higher brightness photocathodes.

- The Cs_1Sb_1 photocathode has superb resistance to oxidation, low roughness, and a photoemission threshold in the visible range.

- MTE measurements of novel cathodes are underway at Cornell (See Charles Zhang’s poster tomorrow!).

- Implement semiconductor substrates (e.g. SiC) on the INFN plug 

Thank you for your attention.

Any questions?

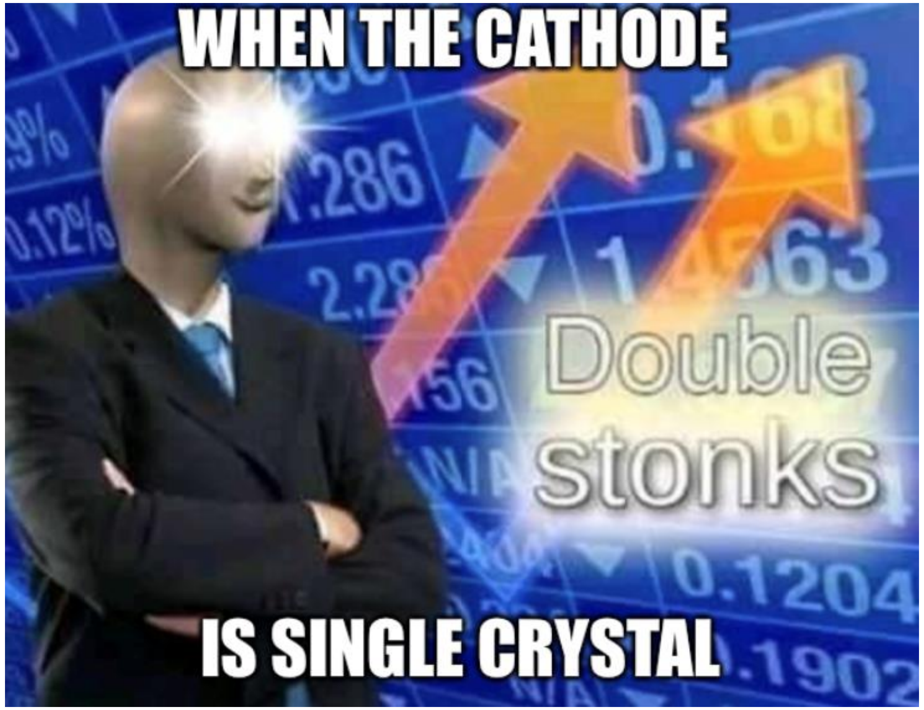


Image courtesy of Samuel J. Levenson

The Center for
BRIGHT
BEAMS
A National Science Foundation
Science & Technology Center

NSF

Backup Slides

- Exploiting optical interference effects via distributed Bragg reflectors (DBRs) could be an exciting way to enhance QE.