Los Alamos NATIONAL LABORATORY

2D Materials As Protection Layer for Bialkali Photocathodes

H. Yamaguchi, N. A. Moody

Los Alamos National Laboratory (LANL)
New Mexico, U.S.A.

YouTube scientific videos on our findings:

https://www.youtube.com/watch?v=S4krKYGUopg&feature=youtu.be

https://www.youtube.com/watch?v=rkusTI_45o0

Addressing decadal R&D priority for cathodes

[1] Hemminger, J.C., *Next Generation Photon Sources for Grand Challenges in Science and Energy.* Office of Science (*http://science.energy.gov/~/media/bes/pdf/reports/files/ngps_rpt.pdf*), *2009.*

[2] Barletta, W.A. et al, *Compact Light Sources.* Department of Energy's Office of Science (*http://science.energy.gov/~/media/bes/pdf/reports/files/CLS.pdf*), *2010.*

[3] Henning, W. and C. Shank, *Accelerators for America's future. Department of Energy's Office of Science* (*www.acceleratorsamerica.org/files/Report.pdf*), *2010.*

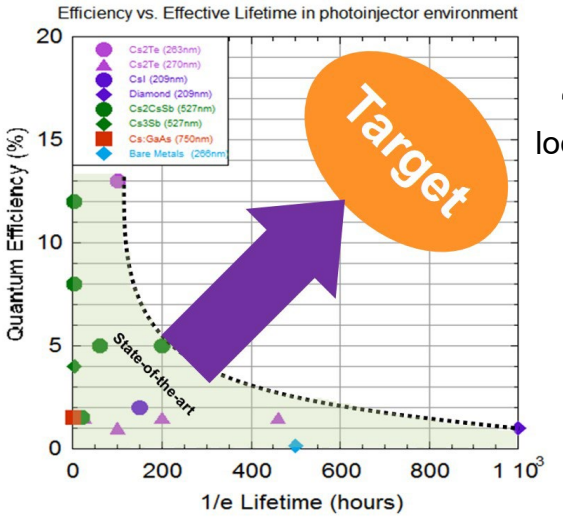
Our project aims to address nationally articulated need (DOE commissioned studies) which call for transformative advances in electron source development: *long lifetime at high efficiency and high brightness*

- "Singular risk area[1]"
- "One of the highest accelerator R&D priorities for the next decade[2,3]"

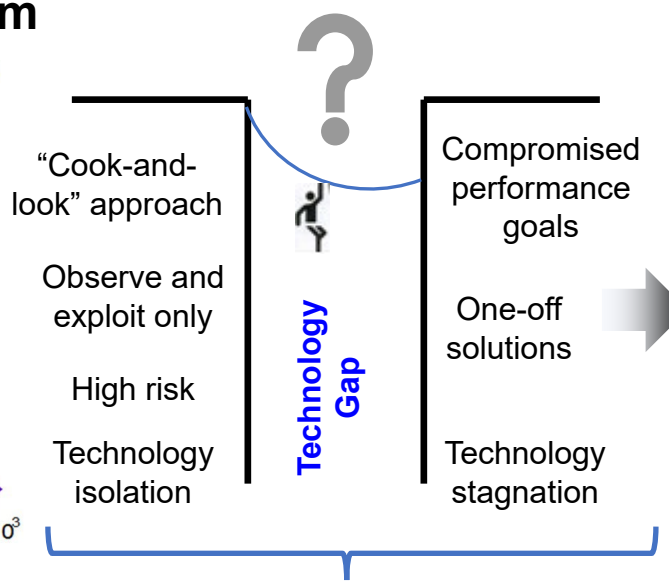
Transformative: enabling discovery science, national security missions

The problem: Performance-Lifetime limitation
Our innovation: Decouple the limitation by 2D materials

Current status & problem



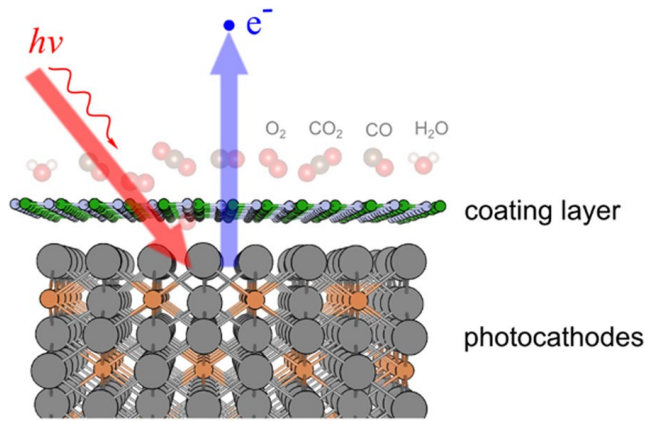
Bridging the technology gap



Present approaches do not depart from historical methods

Our idea

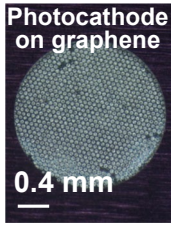
N.A.Moody *US patent 8,823,259* (2014)

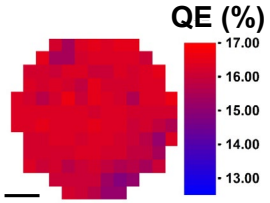


G.Wang, N.A.Moody et al. *Nature Partner Journal 2D Mater. Appl.* (2018)

LANL internal project to DOE funded project

2D materials (U.S.)

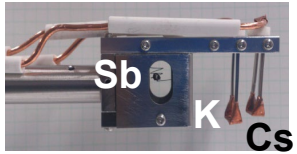


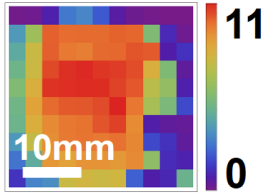


K_2CsSb/Gr in vacuum tube

Bialkali (Japan)

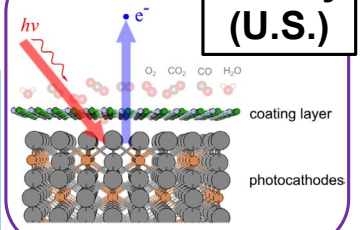
Evaporation sources

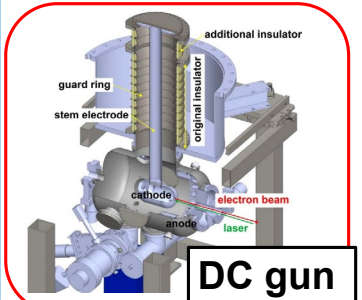




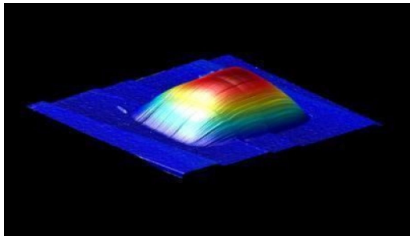
K_2CsSb/Mo in vacuum chamber

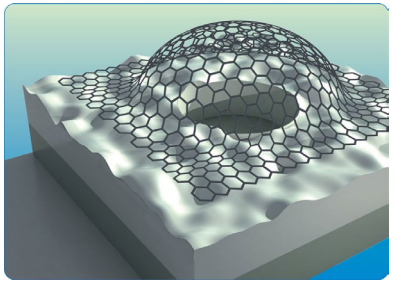
Theory (U.S.)



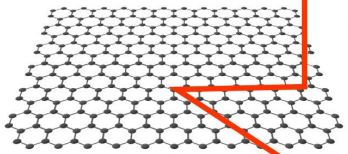


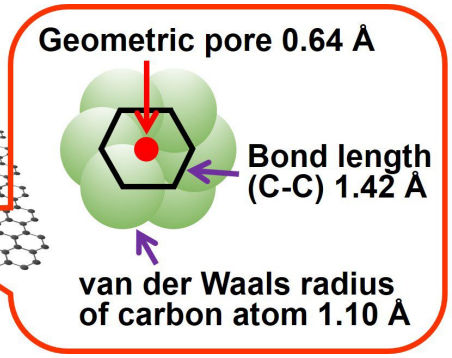
DC gun (Japan)





Discovered in *2004*





Photocathode life enhancement using 2D material protection

- Good anti-corrosion property
- High stability
- Minimal alteration of protecting material surfaces

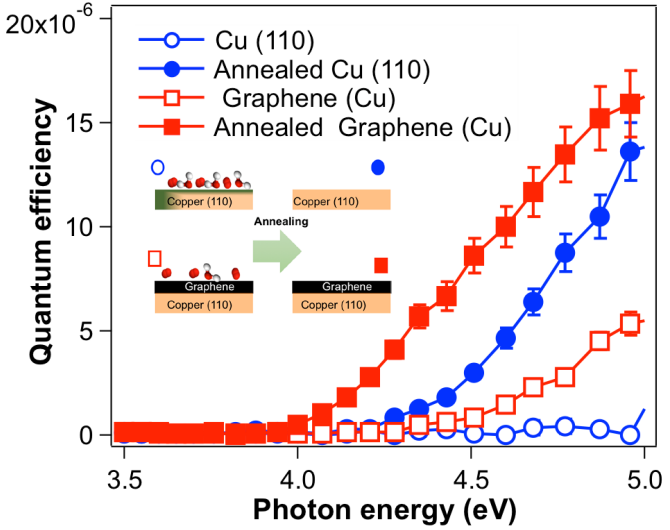
Los Alamos NATIONAL LABORATORY

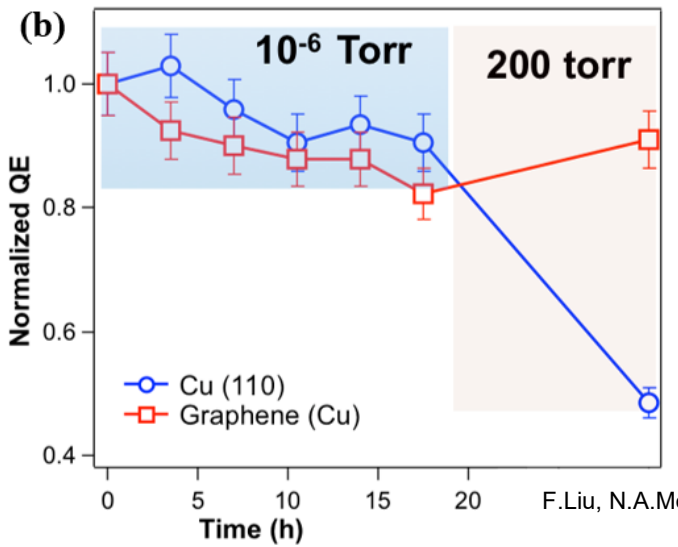
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

U.S. DEPARTMENT OF ENERGY Office of Science

KEK

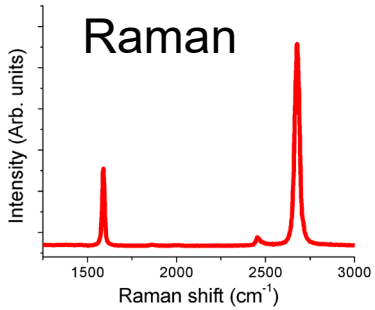
Experimental demonstration of our concept on metal photocathodes

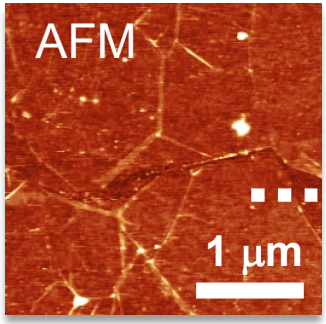


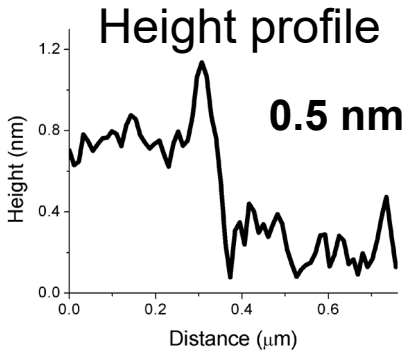


F.Liu, N.A.Moody et al. *Appl. Phys. Lett.* (2017)

- Successful electron transmission through graphene
- 8 orders of magnitude improvement in operating pressure

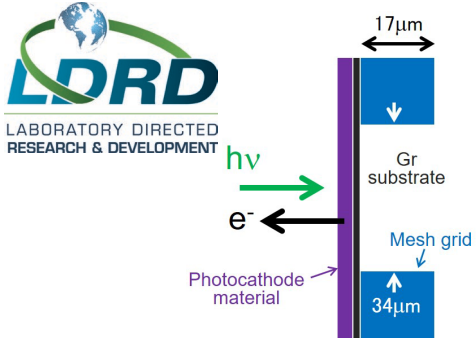




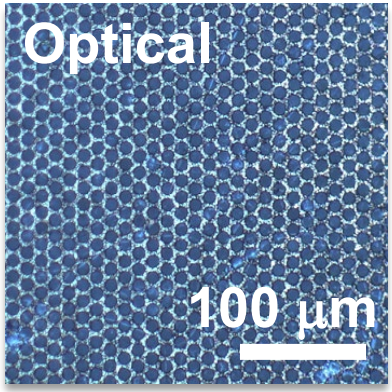


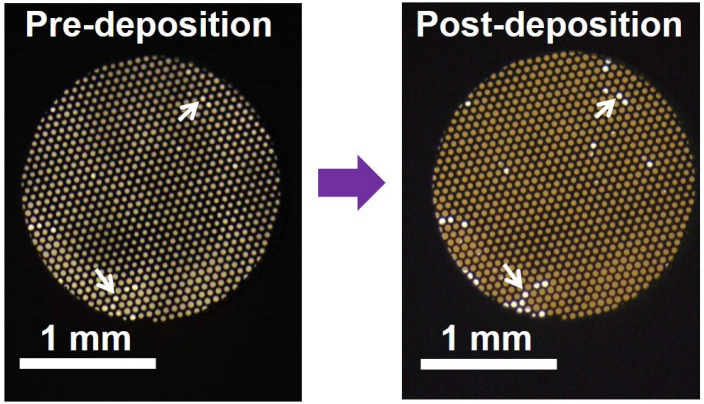
- High crystal quality graphene
- Uniform & atomically thin graphene

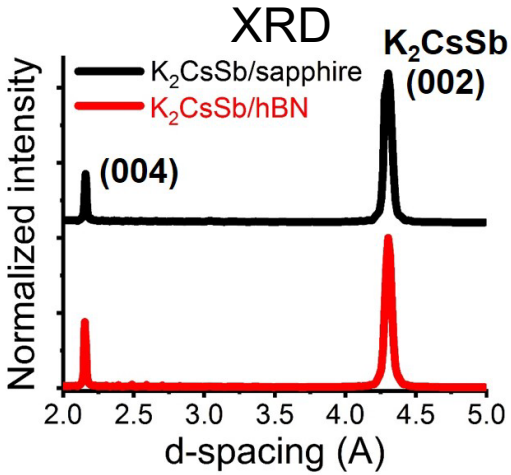
Milestone #1: Demonstration of material compatibility between 2D materials and bialkali photocathodes

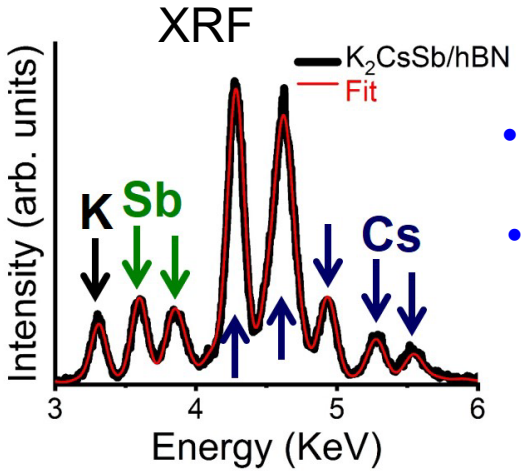


N.A.Moody, H.Yamaguchi et al.
US Patent 10,535,486 (2020)





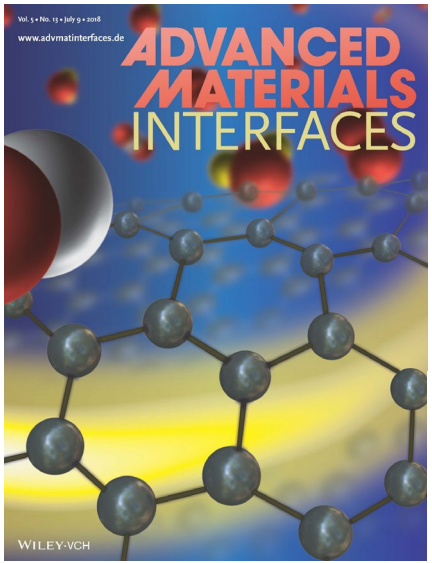




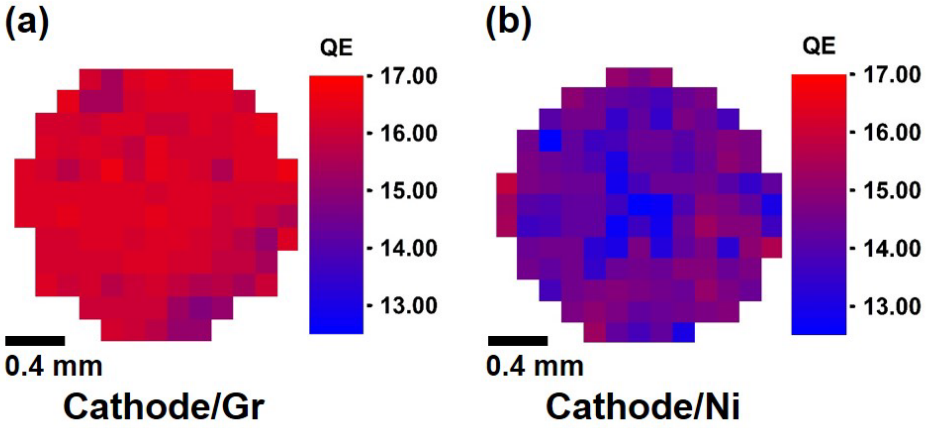
- High crystallinity achieved on 2D material (XRD)
- Nearly ideal stoichiometry of $K_{1.85}Cs_{1.08}Sb$ achieved on 2D material (XRF)

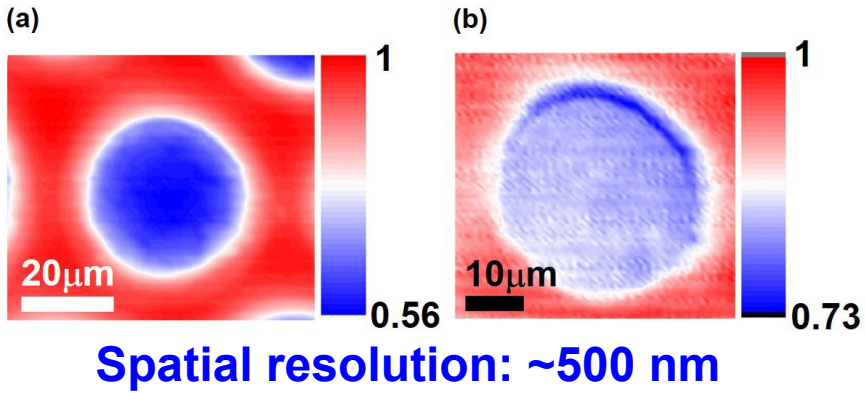
H.Yamaguchi, N.A.Moody et al. phys. stat. solidi (a) (2019)

High spatial resolution maps with high QE and uniformity



Selected as journal cover

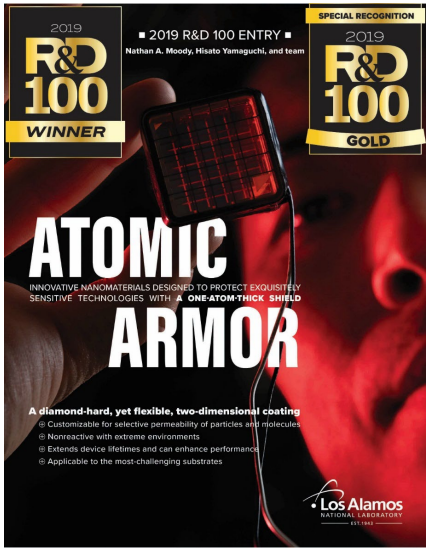


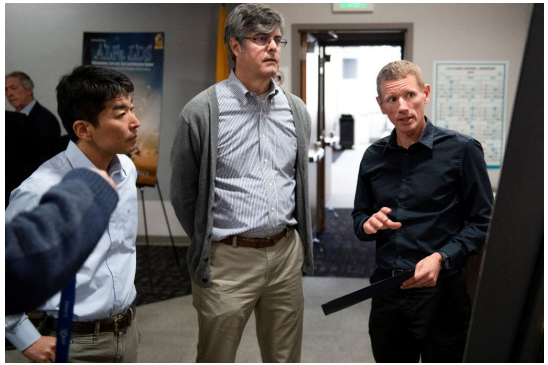


Spatial resolution: ~500 nm

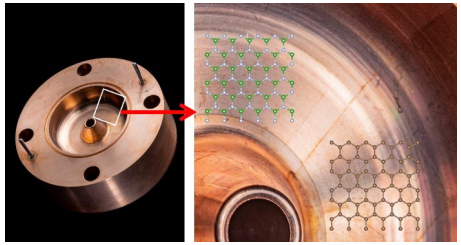
H.Yamaguchi, N.A.Moody et al. *Advanced Materials Interfaces* (2018)

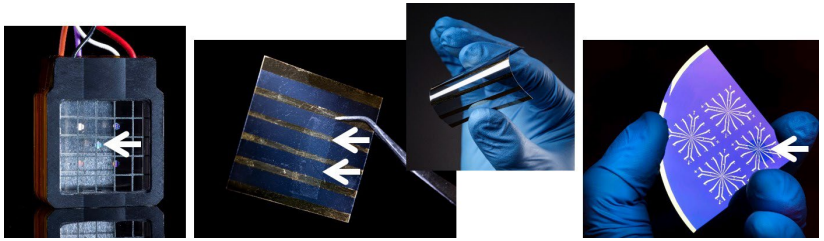
Recognition of our work: R&D 100 Award in 2019

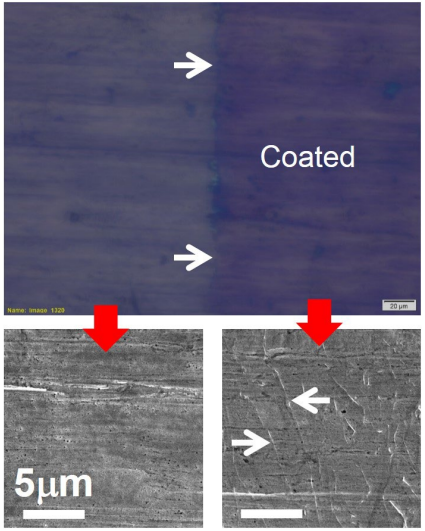




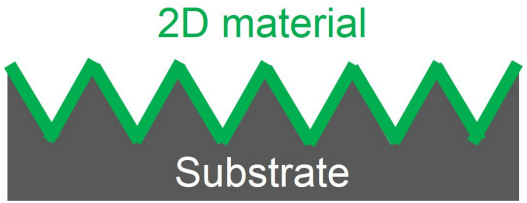
Coating of surfaces with ***macro-scale roughness***







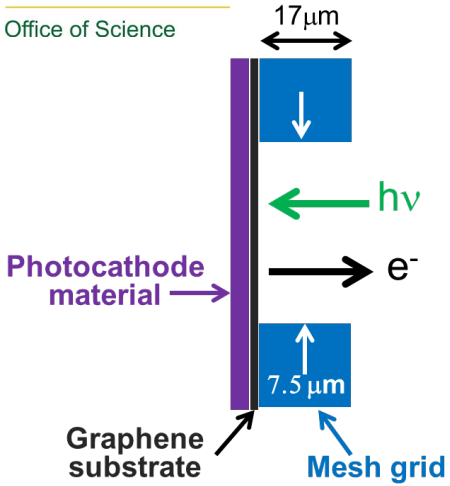
Coating of surfaces with ***micro-scale roughness*** (e.g. rolled stainless steel)



Special recognition Market Disruptor - Products

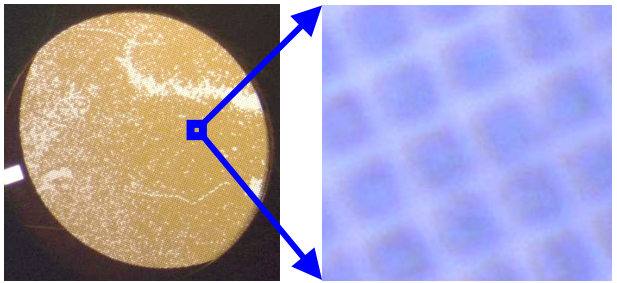
Milestone #2: QE maps of K_2CsSb through graphene coating

U.S. DEPARTMENT OF ENERGY
Office of Science

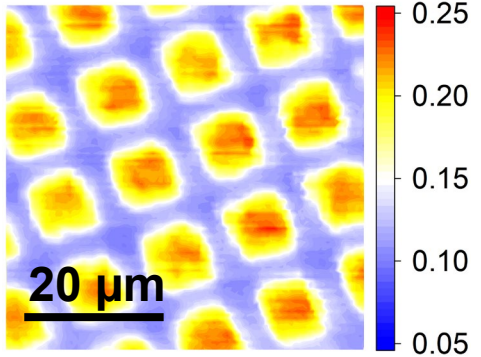


First ever QE of bialkali photocathodes through graphene coating demonstrated

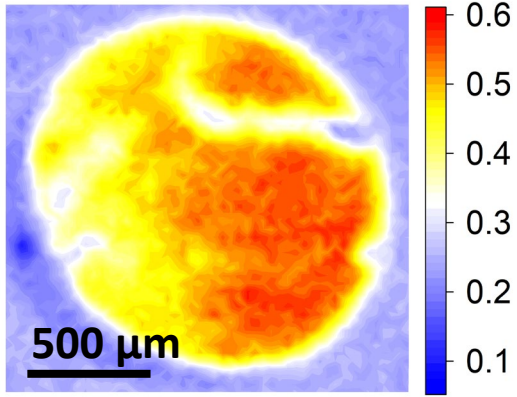
Quantum efficiency (%) map through graphene



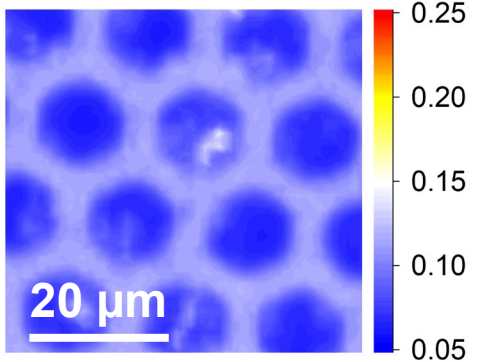
2-layer Gr, 3eV (405 nm)



2-layer Gr, 4.4 eV (280 nm)



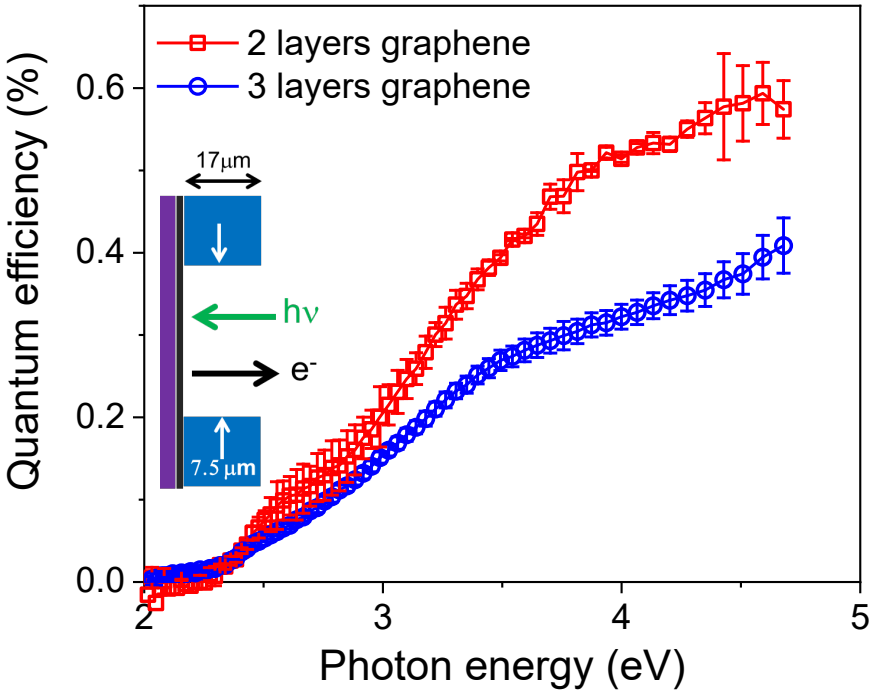
3-layer Gr, 3eV (405 nm)



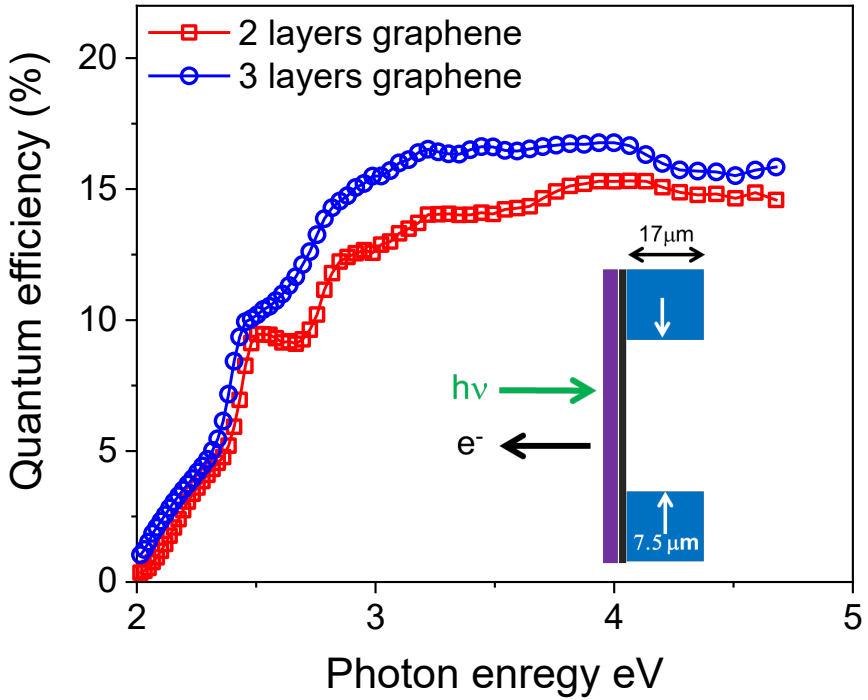
F.Liu, N.A.Moody, H.Yamaguchi et al. *ACS Appl. Mater. Inter.* (2022)

Spectral QE of K_2CsSb photocathodes through graphene coating

QE through graphene coating



QE without graphene coating



Los Alamos NATIONAL LABORATORY

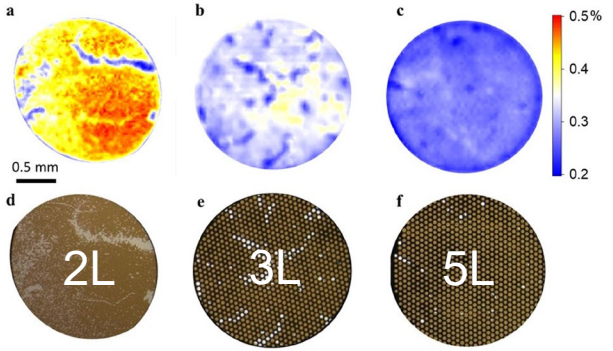
U.S. DEPARTMENT OF ENERGY
Office of Science

F.Liu, N.A.Moody, H.Yamaguchi et al. *ACS Appl. Mater. Inter.* (2022)

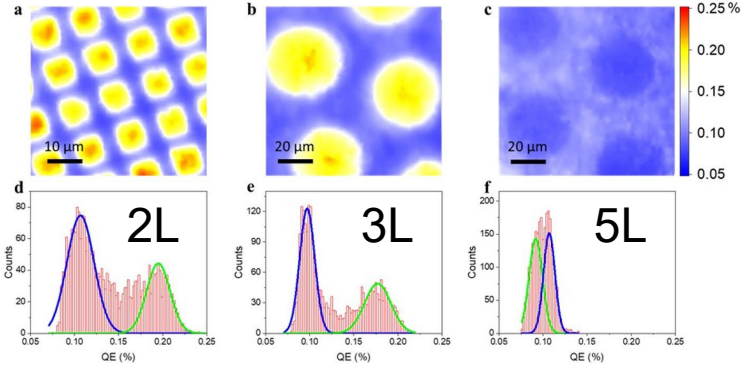
Graphene layer dependence of QE from K_2CsSb photocathodes through graphene coating

QE map through graphene @ 4.4 eV (280 nm)

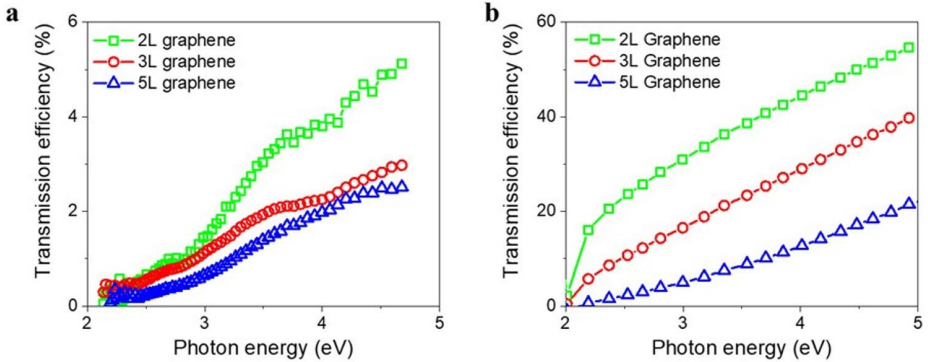
Optical microscope



High resolution maps @ 2.33 eV (532 nm)



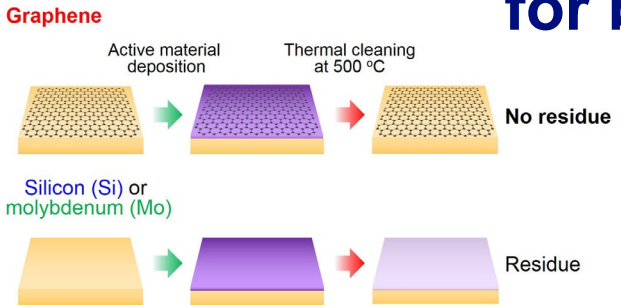
F.Liu, N.A.Moody, H.Yamaguchi et al. *ACS Appl. Mater. Inter.* (2022)



- Our result is 5 % electron transmission through 2 layer graphene @ ~5 eV (left graph)
- Theory predicts ~50 % (left graph) → room for material quality & process improvements

Electron transmission efficiency through graphene

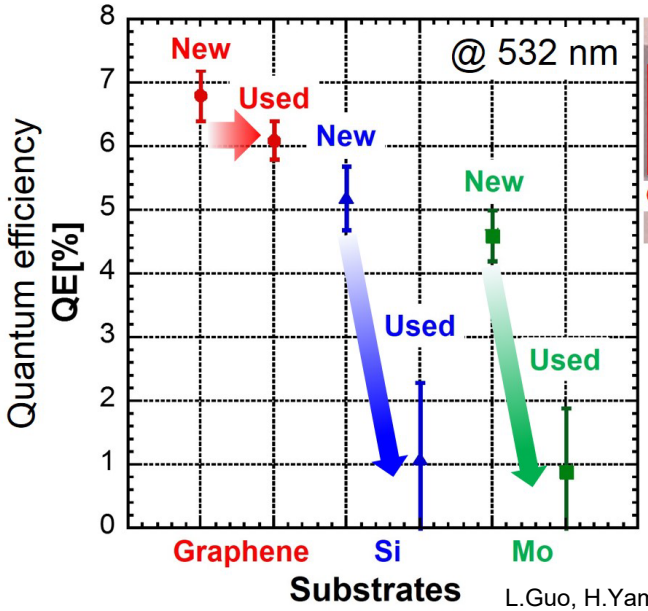
Unexpected finding #1: Graphene as reusable substrate for bialkli photocathodes

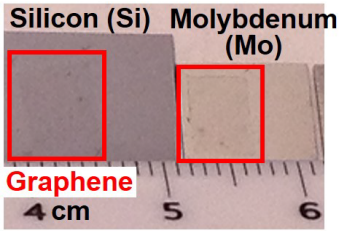


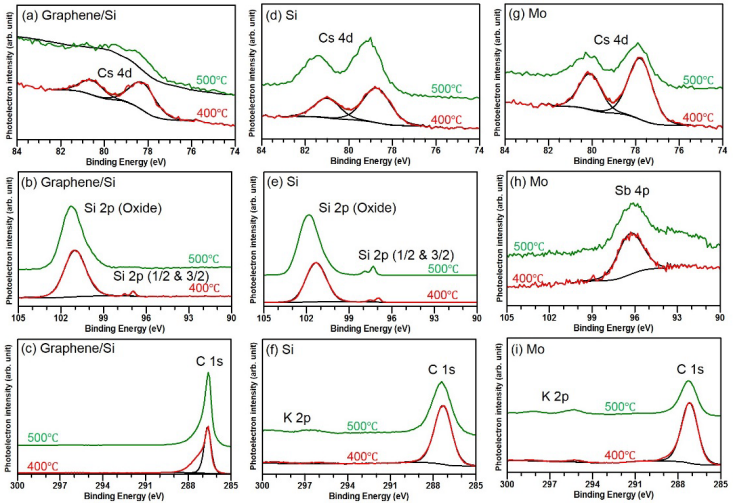
On other substrates

On graphene

News released



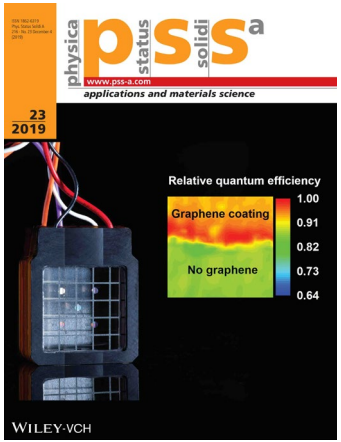




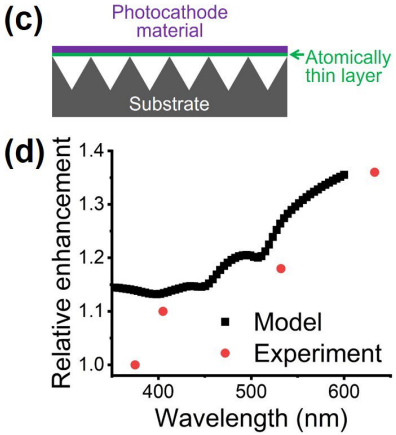
No detectable photocathode residue on graphene by X-ray photoelectron spectroscopy

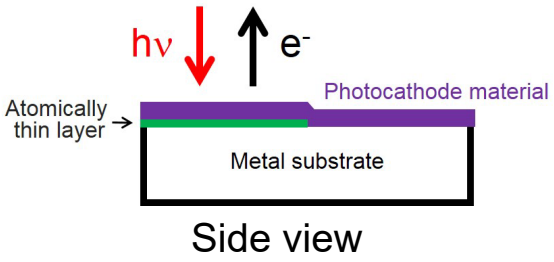
L.Guo, H.Yamaguchi, N.A.Moody et al. *Appl. Phys. Lett.* (2020)

Unexpected finding #2: QE enhancement of bialkali photocathodes by coating metal substrates with graphene

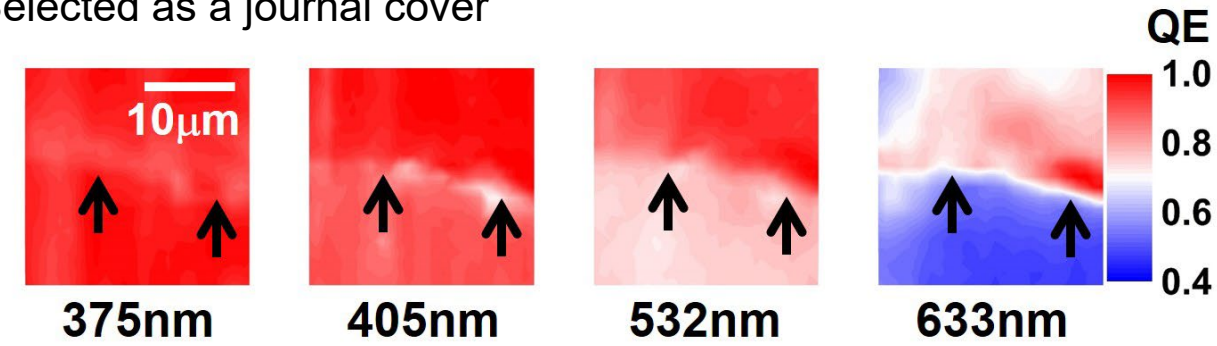


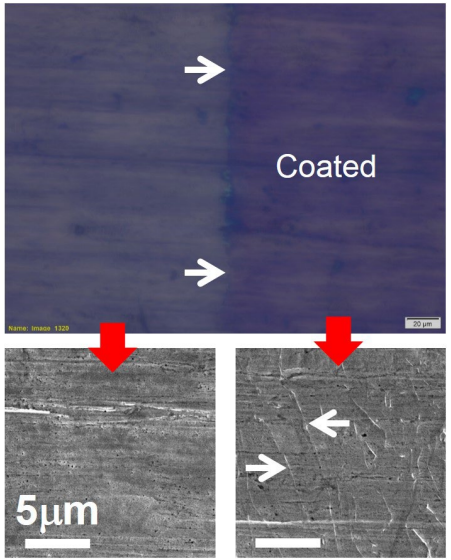
Enhanced mirroring effect





Selected as a journal cover



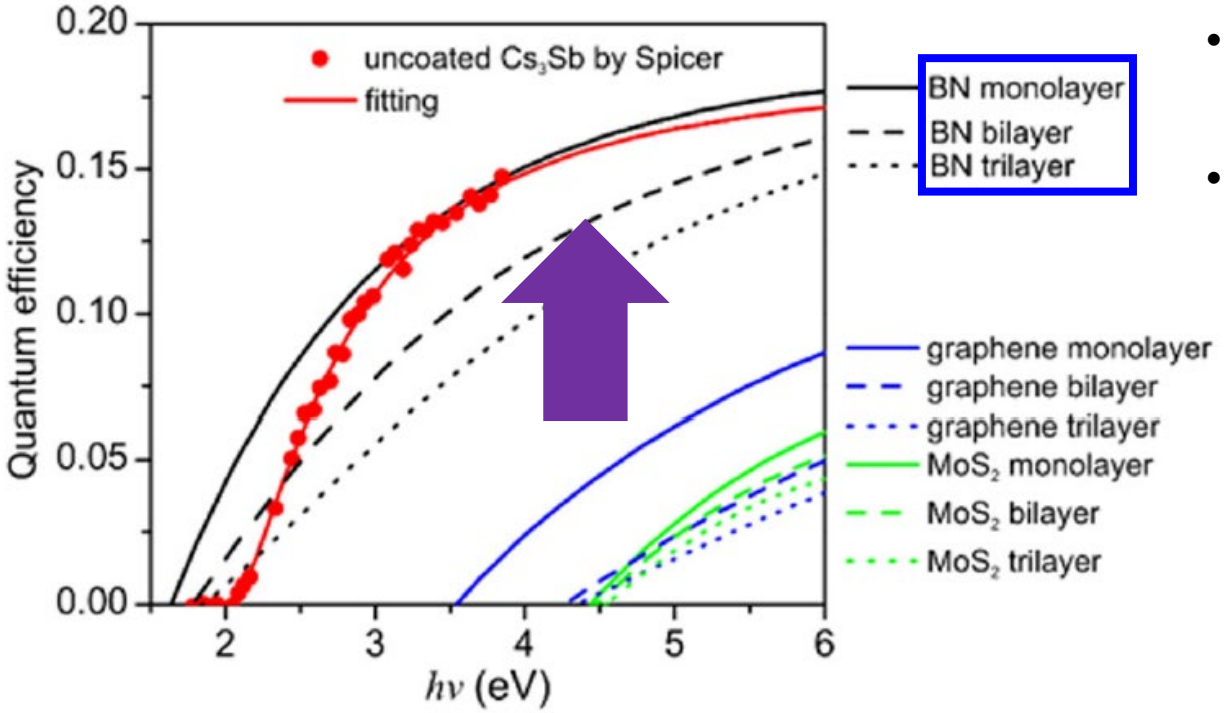


H. Yamaguchi, N.A.Moody et al. phys. stat. Solidi (a) (2019)

LOS ALAMOS NATIONAL LABORATORY

In progress/future plan - 2D material beyond graphene

Theorical prediction by our team



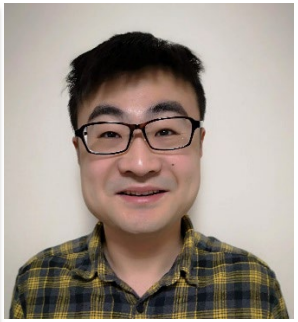
G.Wang, N.A.Moody et al. npj 2D Materials and Applications 17 (2018)

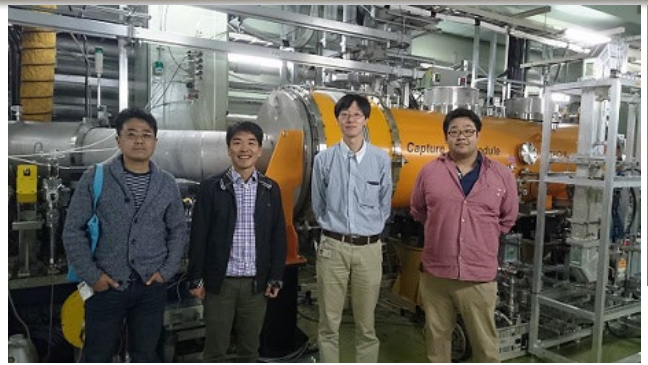
- Test hexagonal boron nitride (hBN) instead of graphene
- Our theory predicts higher QE than graphene while maintaining protection performance

Summary

- Graphene protection of photocathode demonstrated on Cu
  - No degradation of photocurrent due to graphene
  - Protects against pressure up to 200 Torr
- High quality bialkali photocathodes on free-standing graphene substrates
  - QE approaching 17 %
  - 0.5 μm spatial resolution QE map achieved
- QE from alkali photocathodes through graphene
  - ~0.6 % @ 280 nm (4.4 eV) for 2 layers
  - Clear dependence on number of graphene layers
- Graphene as reusable substrate
  - No QE degradation after reuse
  - No photocathode residue detected by XPS
- Graphene as QE enhancer
  - Photocathode QE enhanced simply by coating substrate surfaces with graphene
- In progress/future: 2D materials beyond graphene

Project members





YouTube scientific videos on our findings

https://www.youtube.com/watch?v=S4krKYGUopg&feature=youtu.be

https://www.youtube.com/watch?v=rkusTI_45o0