ERL22 Electron Sources Workgroup

4 October, 2022

2D materials as protective coatings for photocathodes

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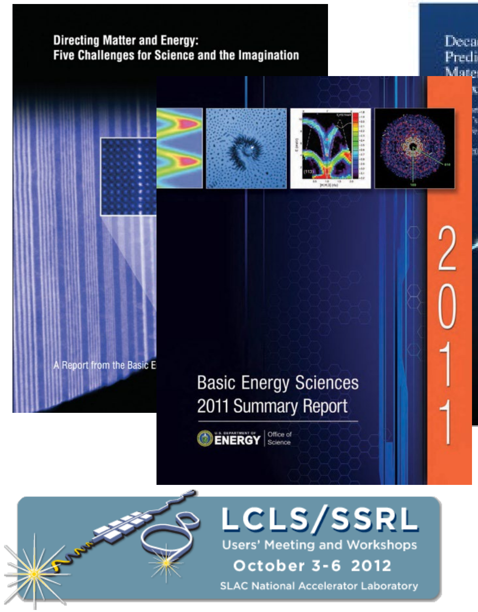
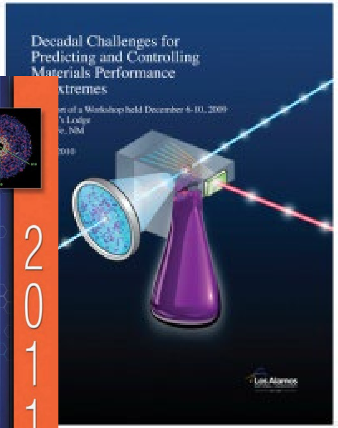
YouTube scientific videos on our findings:

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

https://www.youtube.com/watch?v=rkusTl_45o0

Addressing decadal R&D priority for cathodes





Our effort 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

[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.*

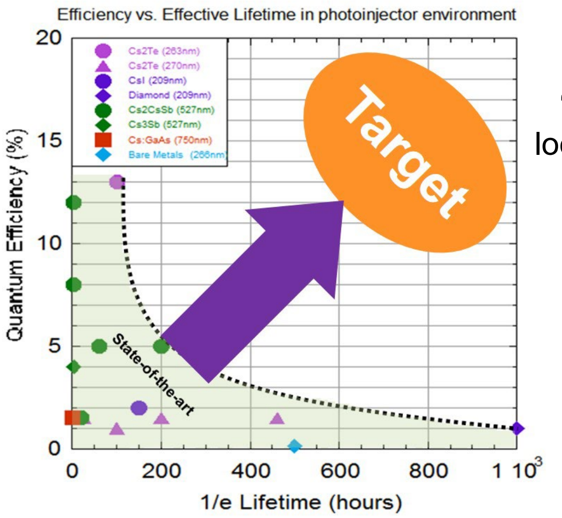
[2] Barletta, W.A. et al, *Compact Light Sources*. Department of Energy's Office of Science (*http://science.energy.gov/~/media/bes/pdf/reports/files/CLS.pdf*), *2010.*

[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.*

Los Alamos NATIONAL LABORATORY

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

Current status & problem



Bridging the technology gap

?

“Cook-and-look” approach

Observe and exploit only

High risk

Technology isolation

Technology Gap

Compromised performance goals

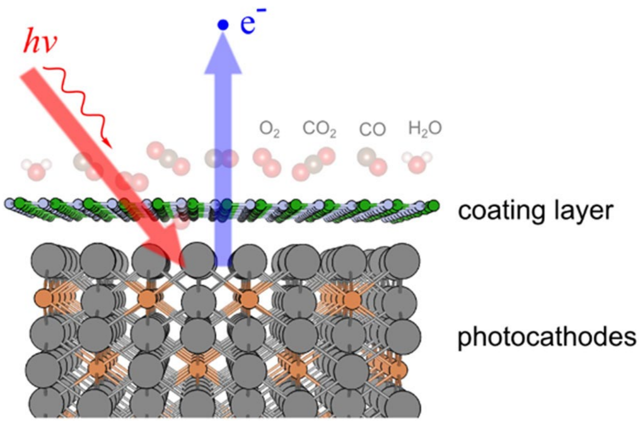
One-off solutions

Technology stagnation

Past approaches

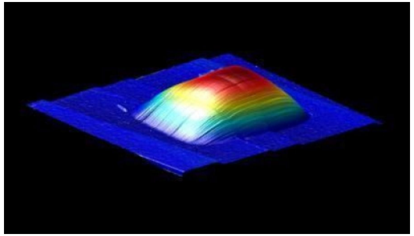
Our idea

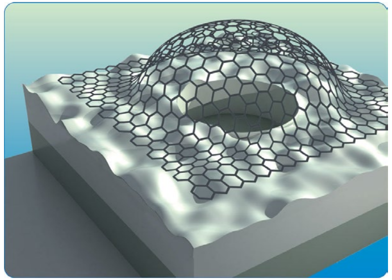
N.A.Moody *US patent 8,823,259* (2014)



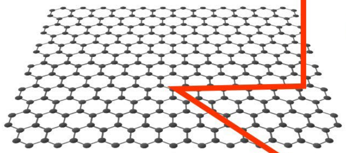
G.Wang, N.A.Moody et al. *Nature Partner Journal 2D Mater. Appl.* (2018)

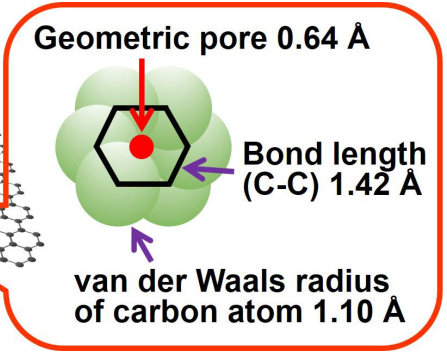
Why 2D materials & our team expertise





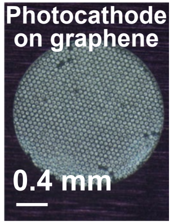
Discovered in *2004*

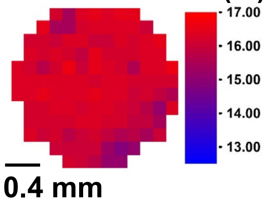




- **Impermeable to gases**
- **Allows electron transmission**
- **High material stability**

2D materials (U.S.)

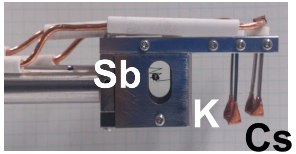


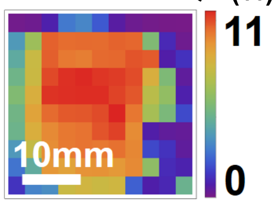


K_2CsSb/Gr in vacuum tube

Bialkali (Japan)

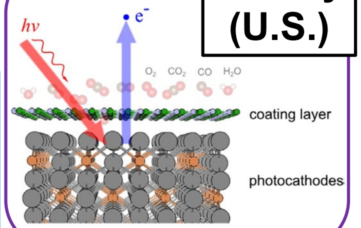
Evaporation sources

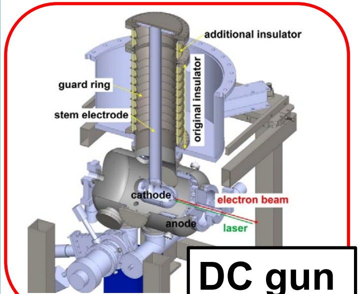




K_2CsSb/Mo in vacuum chamber

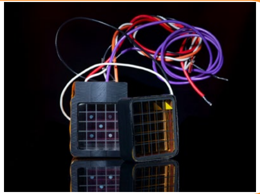
Theory (U.S.)





DC gun (Japan)

Bialkali in vacuum tubes (U.S.)



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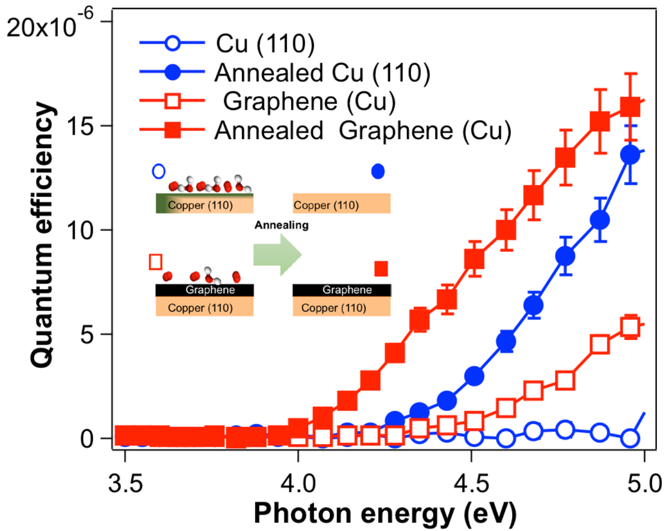
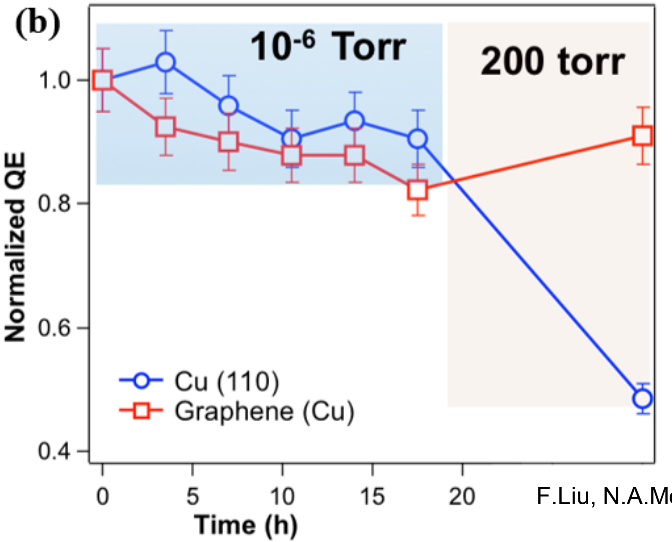
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT
U.S. DEPARTMENT OF ENERGY Office of Science
KEK

US-Japan team working together under DOE-KEK funding

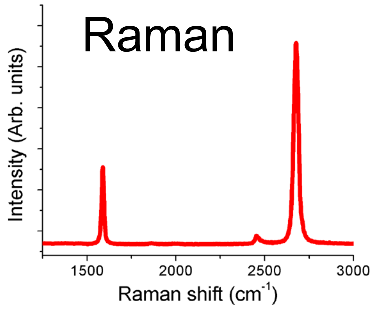
Experimental demonstration of our concept on metal photocathodes

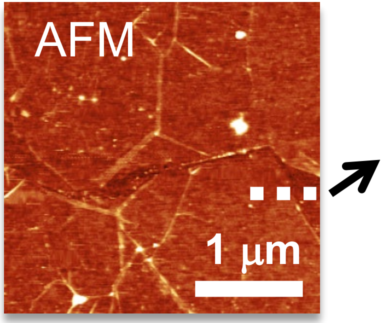


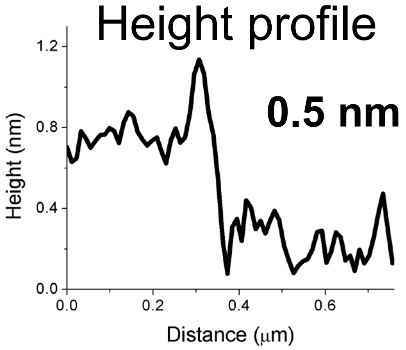


- Successful electron transmission through graphene
- 8 orders of magnitude improvement in operating pressure

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



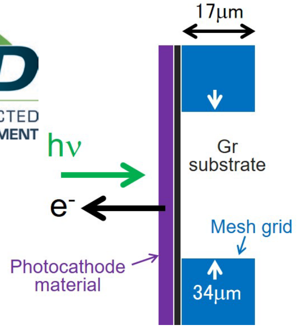




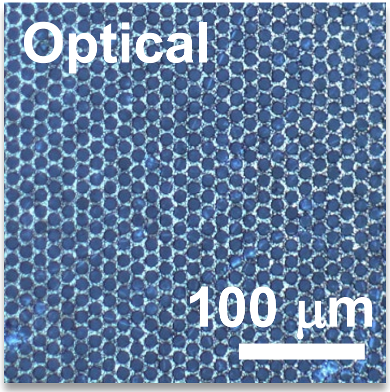
- High crystal quality graphene
- Uniform & atomically thin graphene

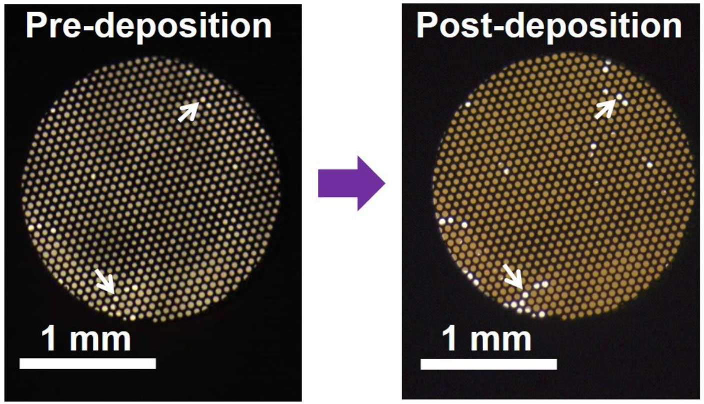
Milestone #1: Demonstration of material compatibility between 2D materials and bialkali photocathodes

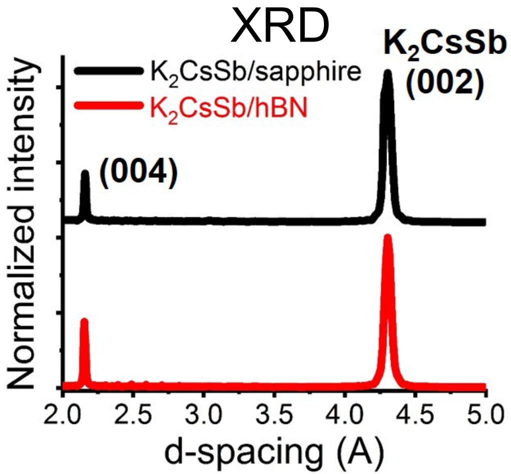
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

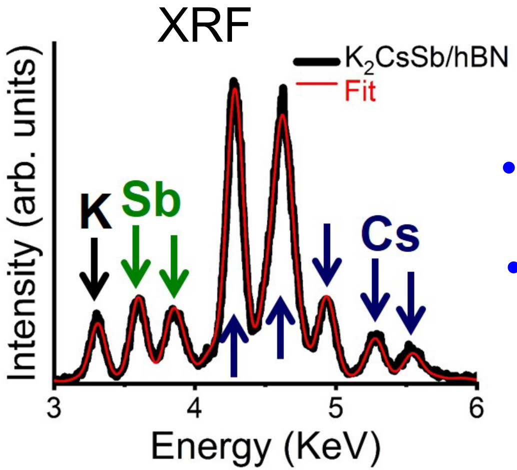


N.A.Moody, H.Yamaguchi et al.
US Patent 10,535,486 (2020)







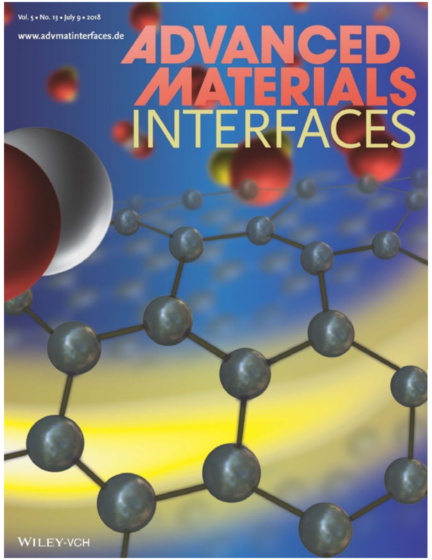


In collaboration with M.Gaowei (BNL) & J.Smedley (SLAC)

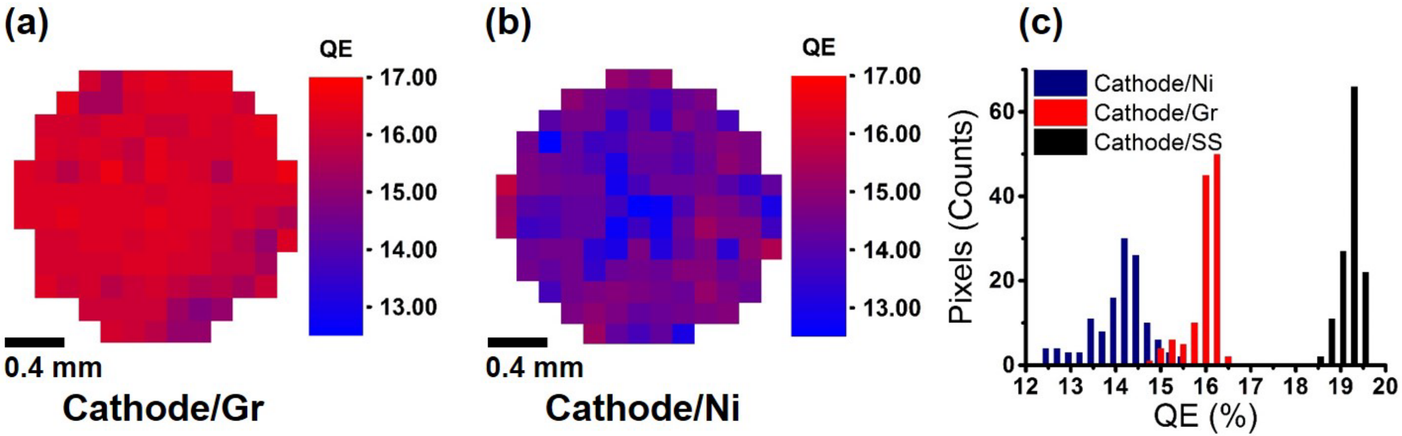
- High crystallinity achieved on 2D material (XRD)
- Nearly ideal stoichiometry of $K_{1.85}Cs_{1.08}Sb$ achieved on 2D material (XRF)

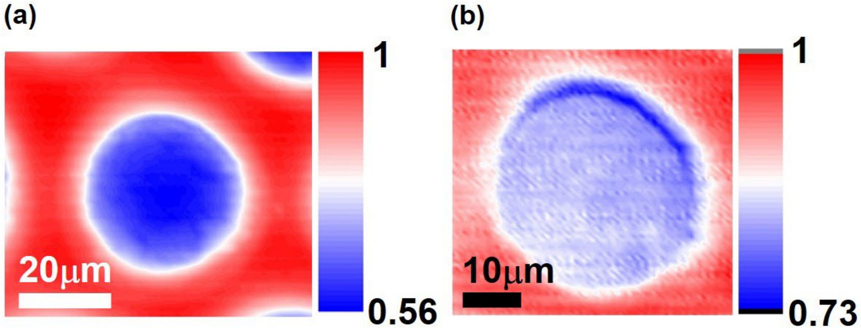
H.Yamaguchi, M.Gaowei, J.Smedley, N.A.Moody et al. phys. stat. solidi (a) (2019)

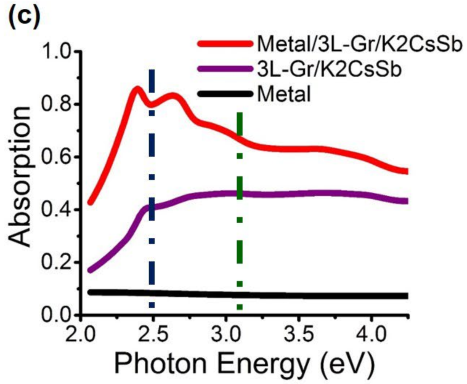
High spatial resolution maps with high QE and uniformity



Selected as journal cover



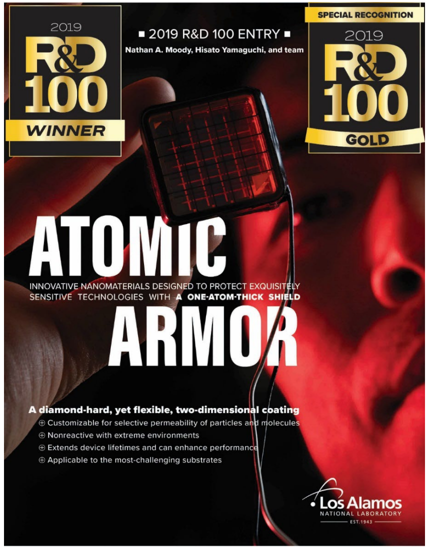


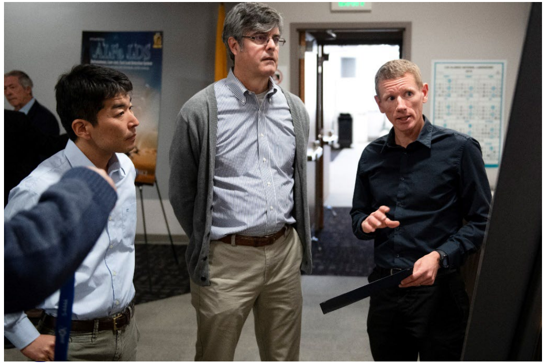


Spatial resolution: ~500 nm

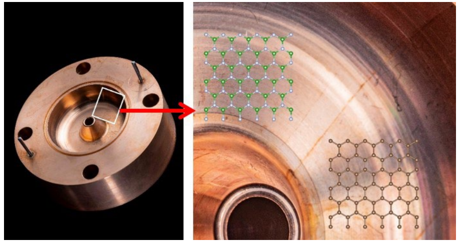
H.Yamaguchi, N.A.Moody et al. *Advanced Materials Interfaces* (2018)

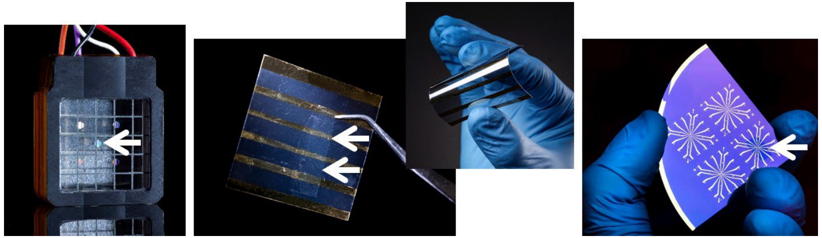
Recognition of our work: R&D 100 Award in 2019

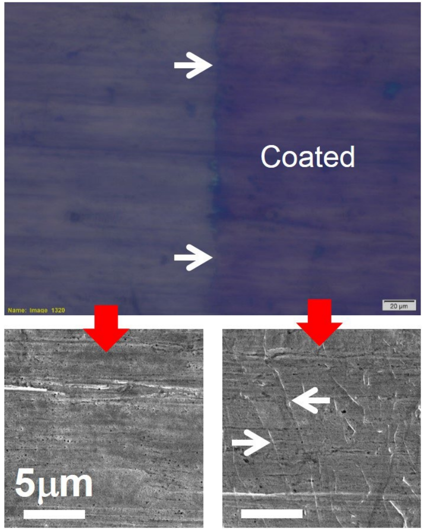




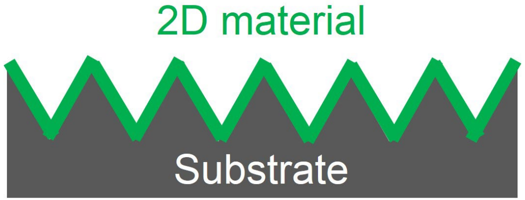
Coating of surfaces with ***macro-scale roughness***





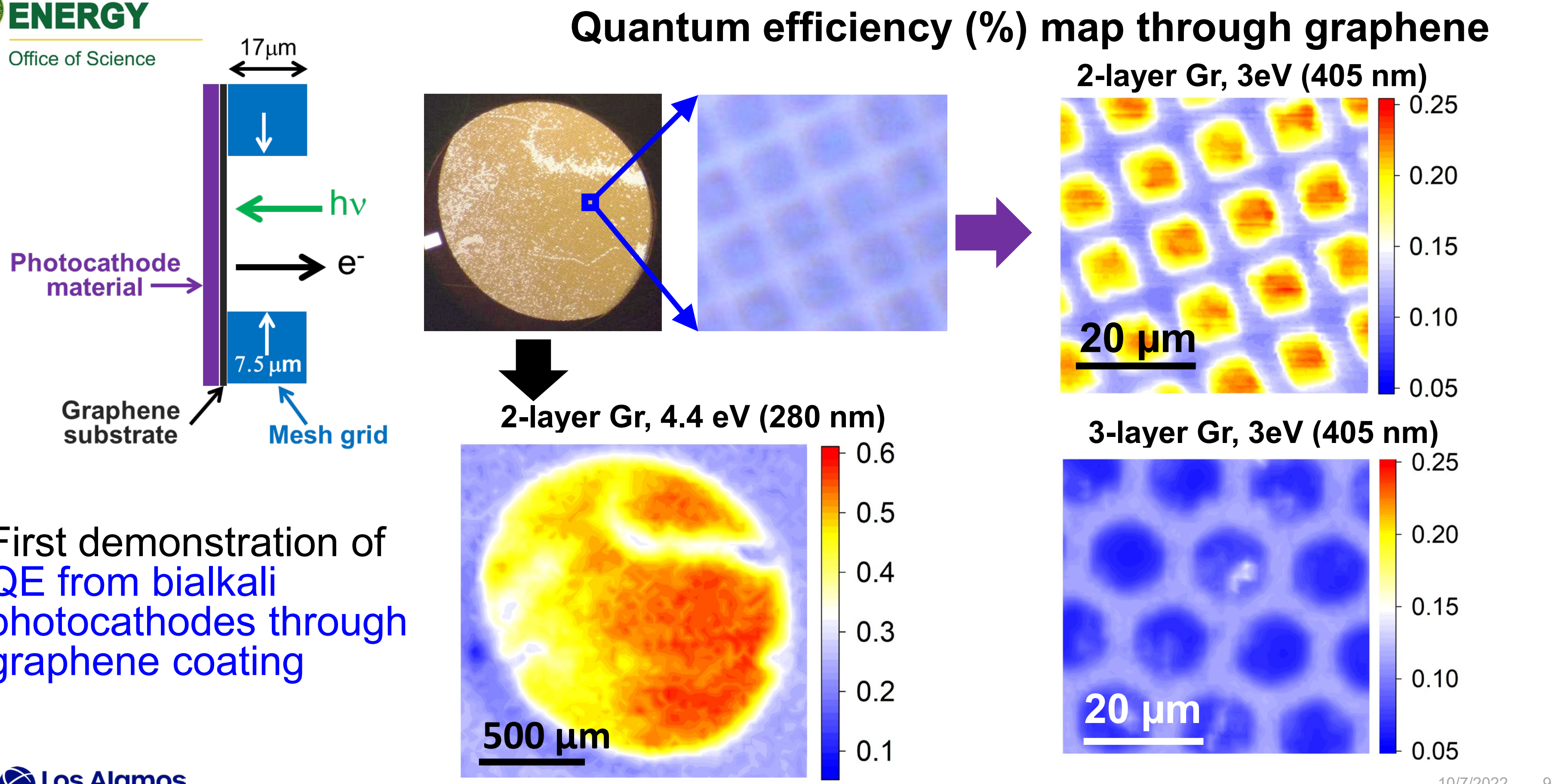


Coating of surfaces with ***micro-scale roughness*** (e.g. rolled stainless steel)



Special recognition Market Disruptor - Products

Milestone #2: QE maps of K_2CsSb through graphene coating

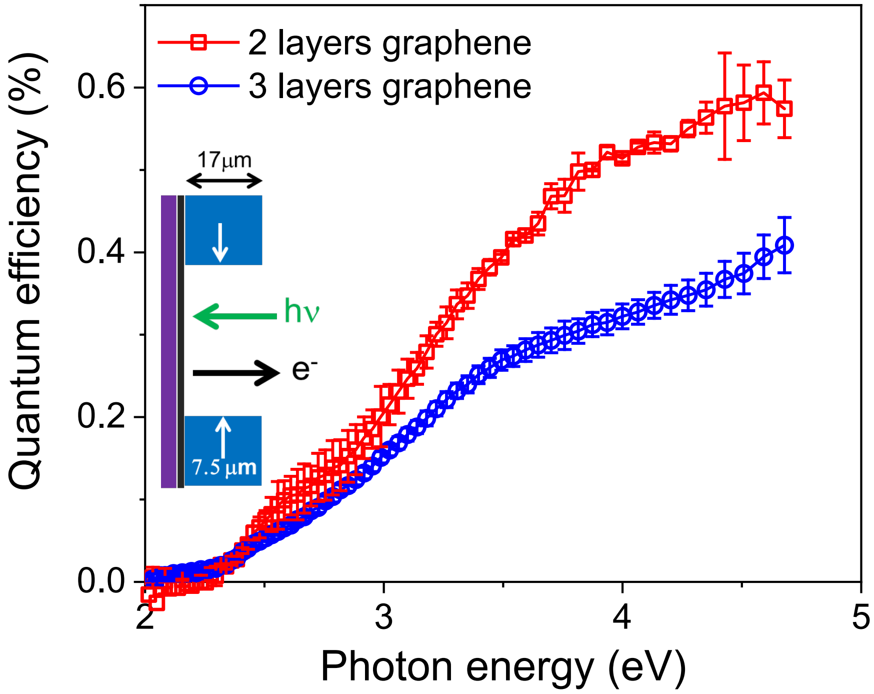


First demonstration of **QE from bialkali photocathodes through graphene coating**

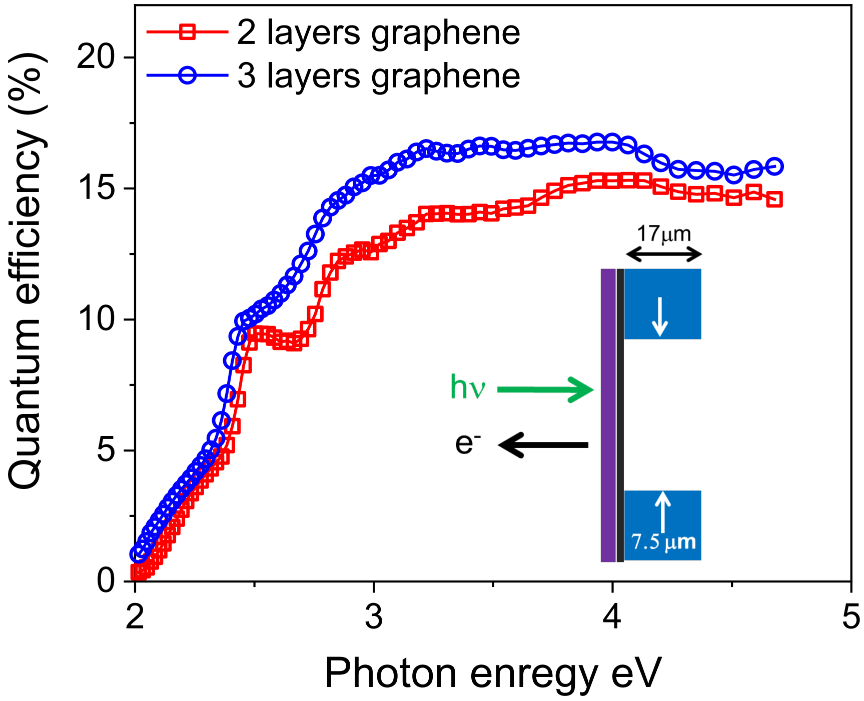
F.Liu, N.A.Moody, H.Yamaguchi et al. *ACS Appl. Mater. Inter.* (2022)

Spectral QE of K_2CsSb photocathodes through graphene coating

QE through graphene coating



QE without graphene coating

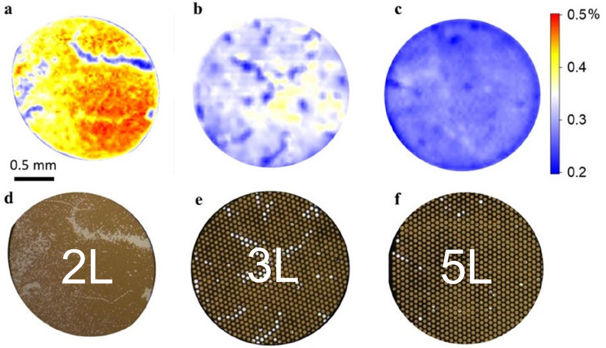


F.Liu, N.A.Moody, H.Yamaguchi et al. *ACS Appl. Mater. Inter.* (2022)

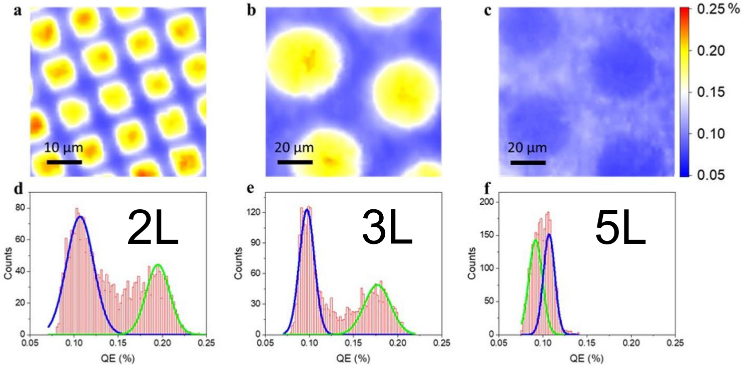
Graphene layer dependence of QE from K_2CsSb photocathodes through graphene coating

QE map through graphene @ 4.4 eV (280 nm)

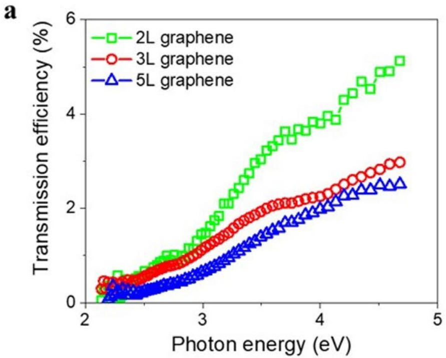
Optical microscope

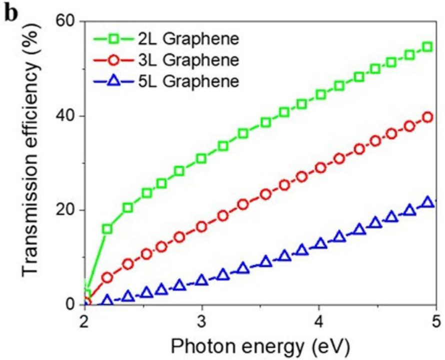


High resolution maps @ 2.33 eV (532 nm)



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



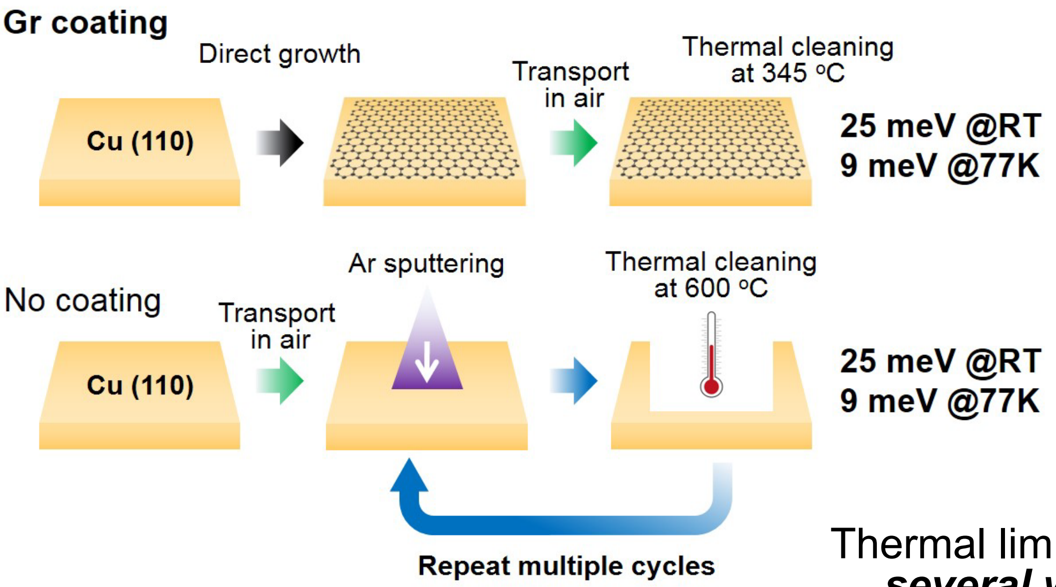


- Our result is 5 % electron transmission through 2 layer graphene @ ~5 eV (left graph)
- Theory predicts ~50 % (left graph) → room for material quality & process improvements

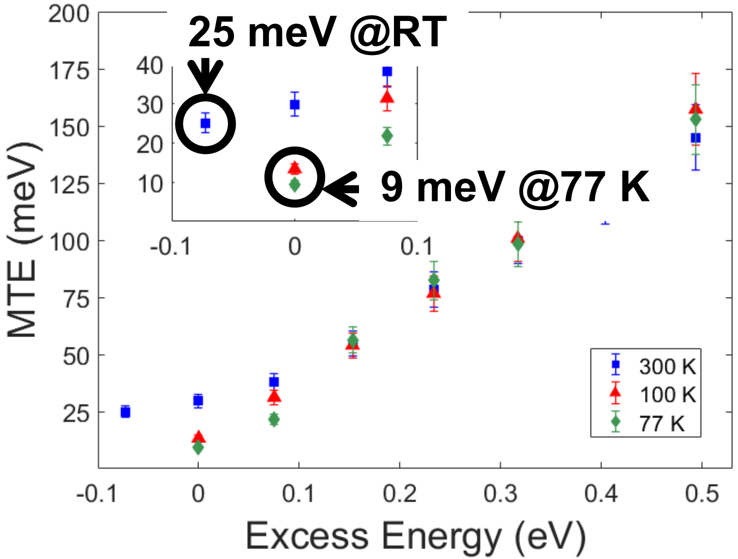
Electron transmission efficiency through graphene

Effect of graphene on emittance of metal photocathode

In collaboration with S.Karkare (ASU)



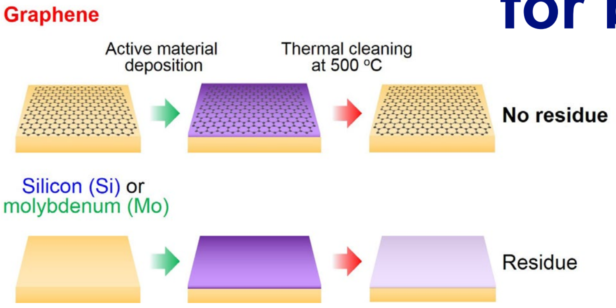
C.Knill, H.Yamaguchi, N.A.Moody, S.Karkare et al. *submitted*



Thermal limit of 25 meV @RT preserved for at least ***several weeks for graphene coated sample***

MTE for non coated Cu (110) starts increasing much sooner, possibly in a ***few hours***

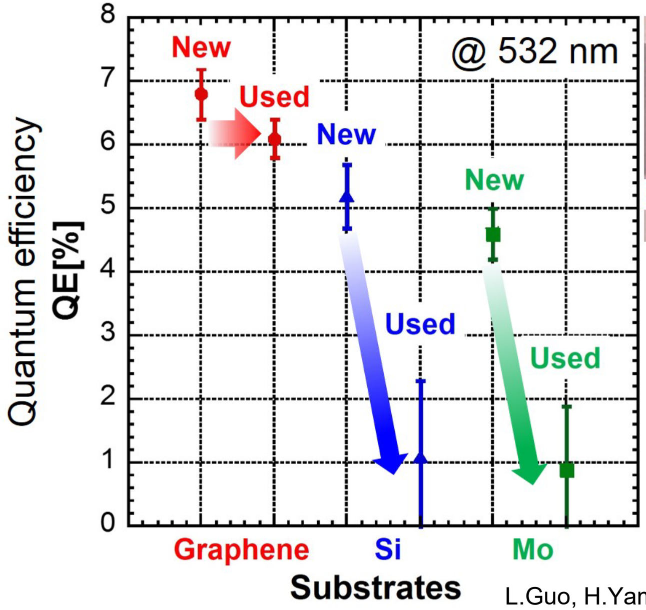
Unexpected finding #1: Graphene as reusable substrate for bialkli photocathodes

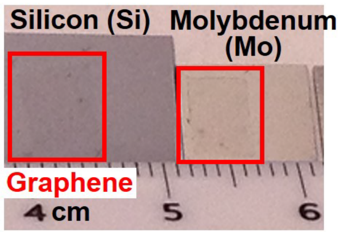


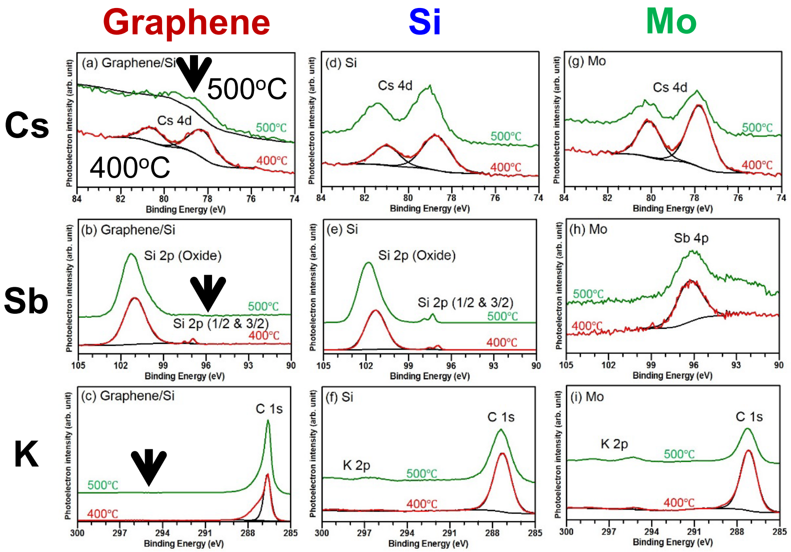
On other substrates

On graphene

News released



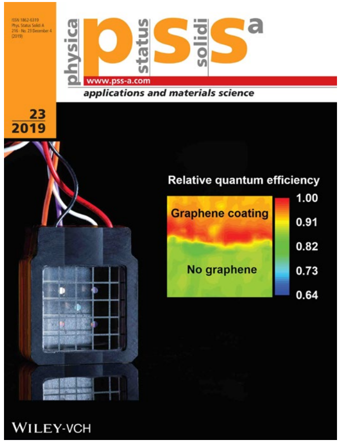




No detectable photocathode residue on graphene by X-ray photoelectron spectroscopy

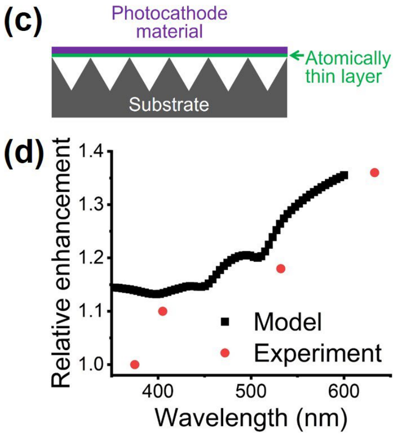
L.Guo, H.Yamaguchi, N.A.Moody et al. *Appl. Phys. Lett.* (2020)

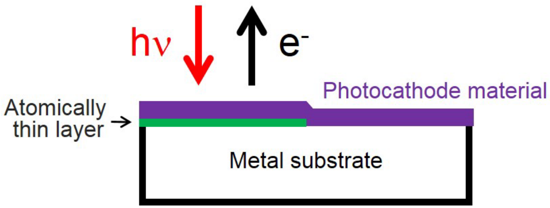
Unexpected finding #2: QE enhancement of bialkali photocathodes by coating metal substrates with graphene



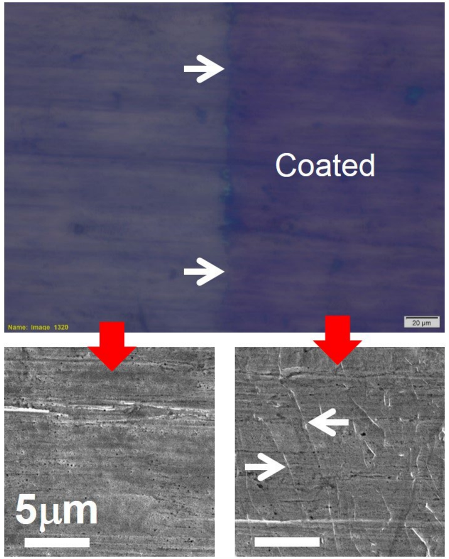
Selected as a journal cover

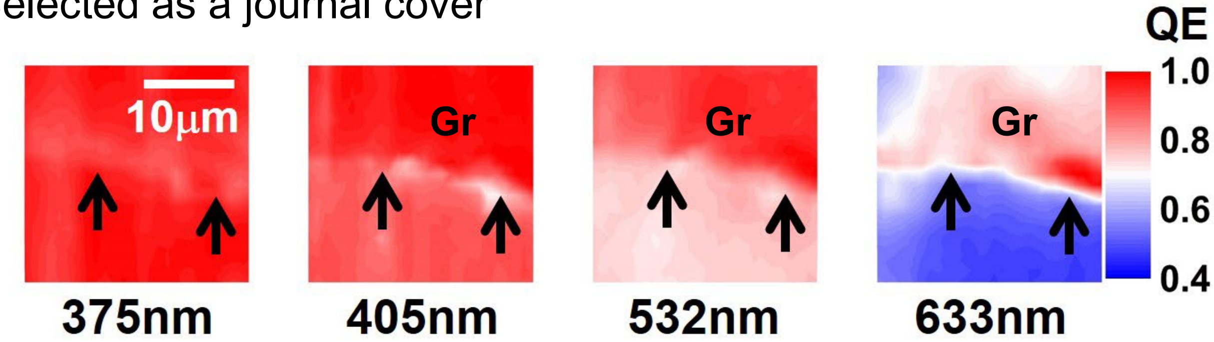
Enhanced mirroring effect





Side view





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

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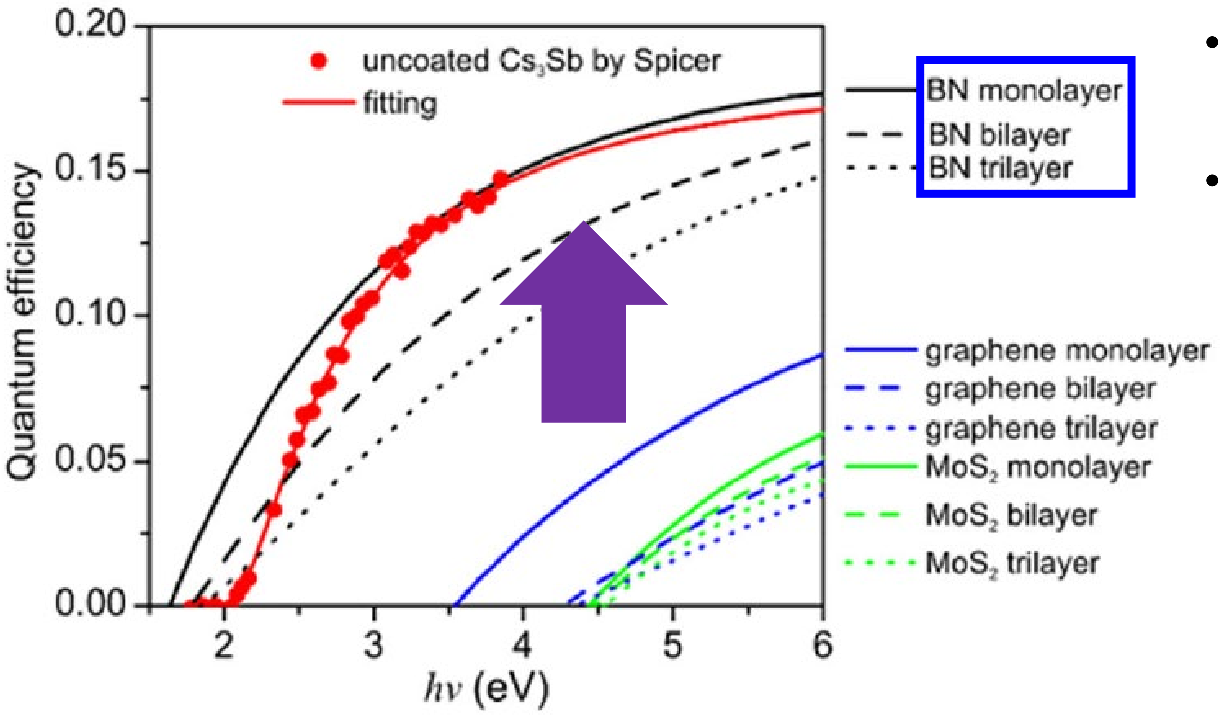
In progress/future plan - 2D material beyond graphene

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 protection of Cu photocathodes while maintaining MTE
  - No MTE increase due to graphene
  - Thermal limit MTE maintained for several weeks
- In progress/future: 2D materials beyond graphene

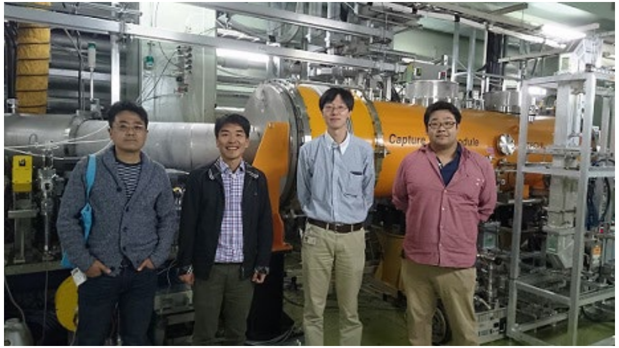
Collaborators

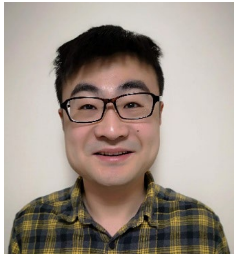
External

Jeff DeFazio (Photonis)
Kevin Jensen (NRL)
Mengjia Gaowei (BNL)
John Smedley (SLAC)
Lei Guo (Nagoya Univ., Japan)
Masahiro Yamamoto (KEK, Japan)
Siddharth Karkare (ASU)

Internal

Nathan Moody
Fangze Liu (formerly LANL)
Gaoxue Wang
Enrique Batista
Ping Yang





Funding