Photocathode R&D at Argonne

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Accelerator Systems Division

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Acknowledgements

Ultra-bright cathodes:

Marion White

Linda Spentzouris (IIT)

Richard Rosenberg

Karoly Nemeth (ANL/NIU)

Yuelin Li

Viji Kalyanaraman

For ultrafast detectors:

Klaus Attenkofer

Igor Veryovkin

Robert Wagner

*Zikri Yusof**

Henry Frisch (U Chicago)

**also high-charge injectors*

Thanks to: ***D. Dowell, I. Bazarov, B. Dunham, C. Hernandez-Garcia, R. Legg, H. Padmore, T. Rao, J. Smedley, W. Wan, J. Byrd***

Outline

- Three groups at Argonne are working on photocathode research for different applications
  - **Ultra-bright injectors for light sources**
  - High-charge injectors for HEP
  - Large area, fast detectors for HEP
- Common goals
  - Fundamental cathode R&D
  - Designed properties: "Bandstructure engineering"
  - Cathode fabrication
- Collaborating and sharing resources in areas of overlapping interests

Ultra-Bright Photocathode Physics

- Fundamental cathode emission properties determine lower bound on achievable electron source emittance *
- Intrinsic emittance depends on:
  - Emission momentum distribution
  - Surface roughness, nonuniformity
  - Surface chemistry, impurities (e.g., oxide layers)
  - Grain boundaries
  - Laser profile, energy, polarization
- Interested in fundamental physics of photocathode emission properties

* I.V. Bazarov, B.M. Dunham, C.K. Sinclair, Phys. Rev. Lett. 102, 104801 (2009).

Ultra-Bright Photocathode R&D Plan

Near-term

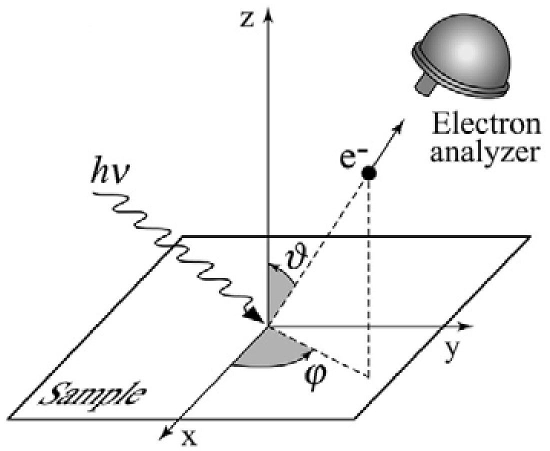
- Characterize emission distribution, correlate with material properties
- Angle-resolved photoemission spectroscopy (ARPES), an important tool in surface science, is also promising as a tool to characterize photocathodes*
- Other tools also applicable: XPS, LEED, SEM, etc
- Study how to optimize material properties to minimize emittance via bandstructure engineering

Far-term

- Fabricate promising cathodes, characterize emittance, refine model
- Test cathodes in APS Injector Test Stand** or other injector test facilities

Physica Scripta T109, 61 (2004)

A. Damascelli



Basic ARPES geometry

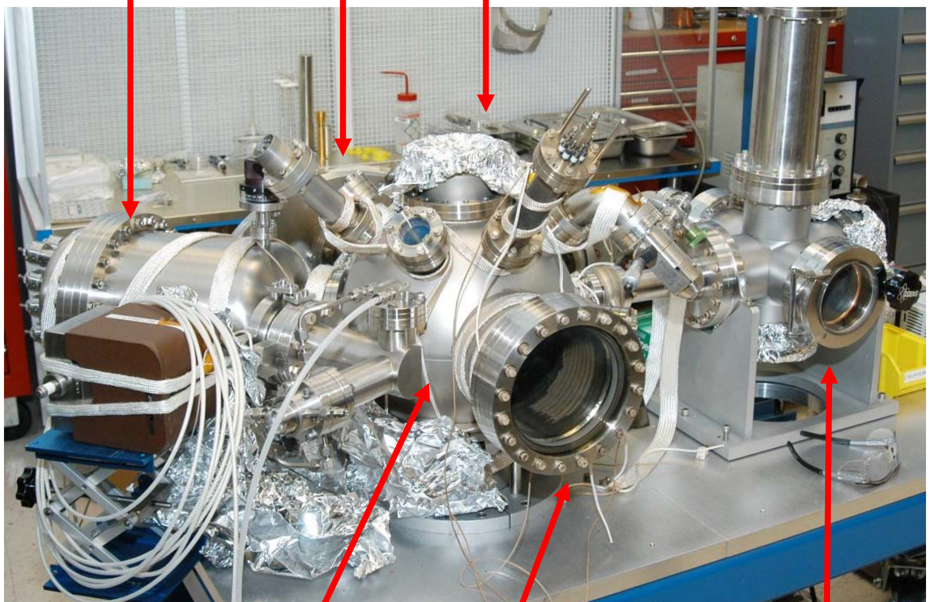
* D. Sertore et al., Proc. 2004 EPAC, 408 (2004);
W. Wan, CHBB Mini-workshop, DESY Zeuthen (2008).
** J.W. Lewellen et all., Proc. 2001 PAC, 2212 (2001);
Proc. 2003 PAC, 2038 (2003).

Photocathode Surface Lab *

XPS system: Monochromatized x-ray source

Spherical electron analyzer

Dual-anode Al, Mg source



Analysis chamber

Sample intro chamber

UV ARPES system: Mounting flange for photon input and TOF detector

Existing UHV surface analysis chamber being upgraded to add ARPES**

- Mu-metal analysis chamber
- XPS to study surface chemistry *in-situ*
- Heat/cool sample (1000C/140K)

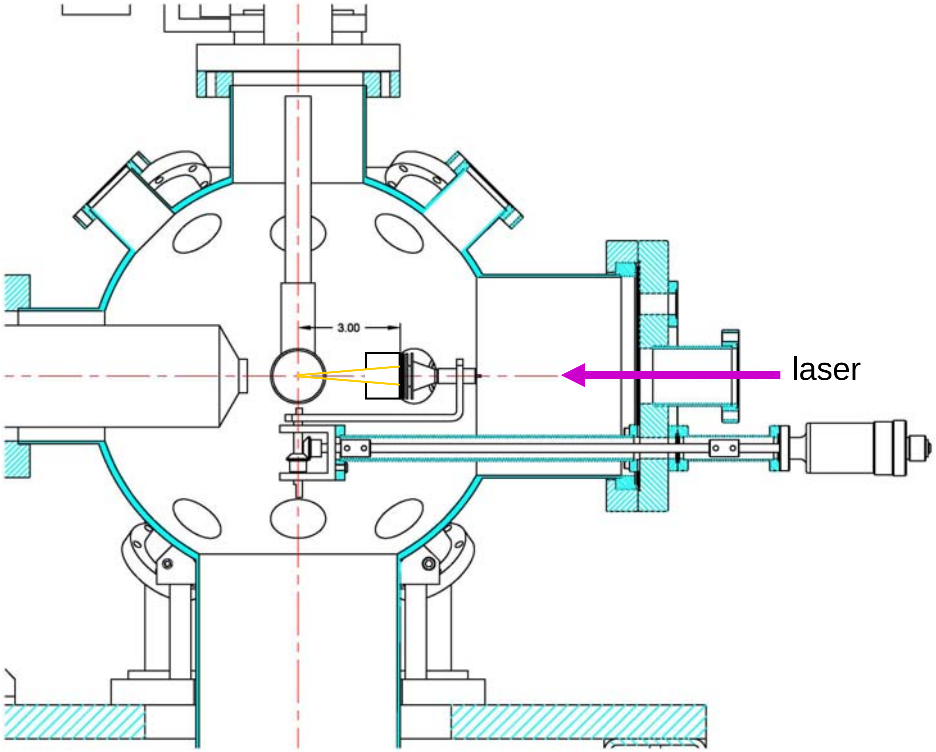
Eventual upgrade (2nd UHV chamber)

- Scanning Auger (AES) and scanning electron microscopy (SEM) (1-2 μm resolution)
- *In-situ* ion sputtering/ vapor deposition

* Courtesy R. Rosenberg (ANL)

** K. Harkay et al., Proc. 2009 PAC (MO6RFP045)

ARPES Chamber *

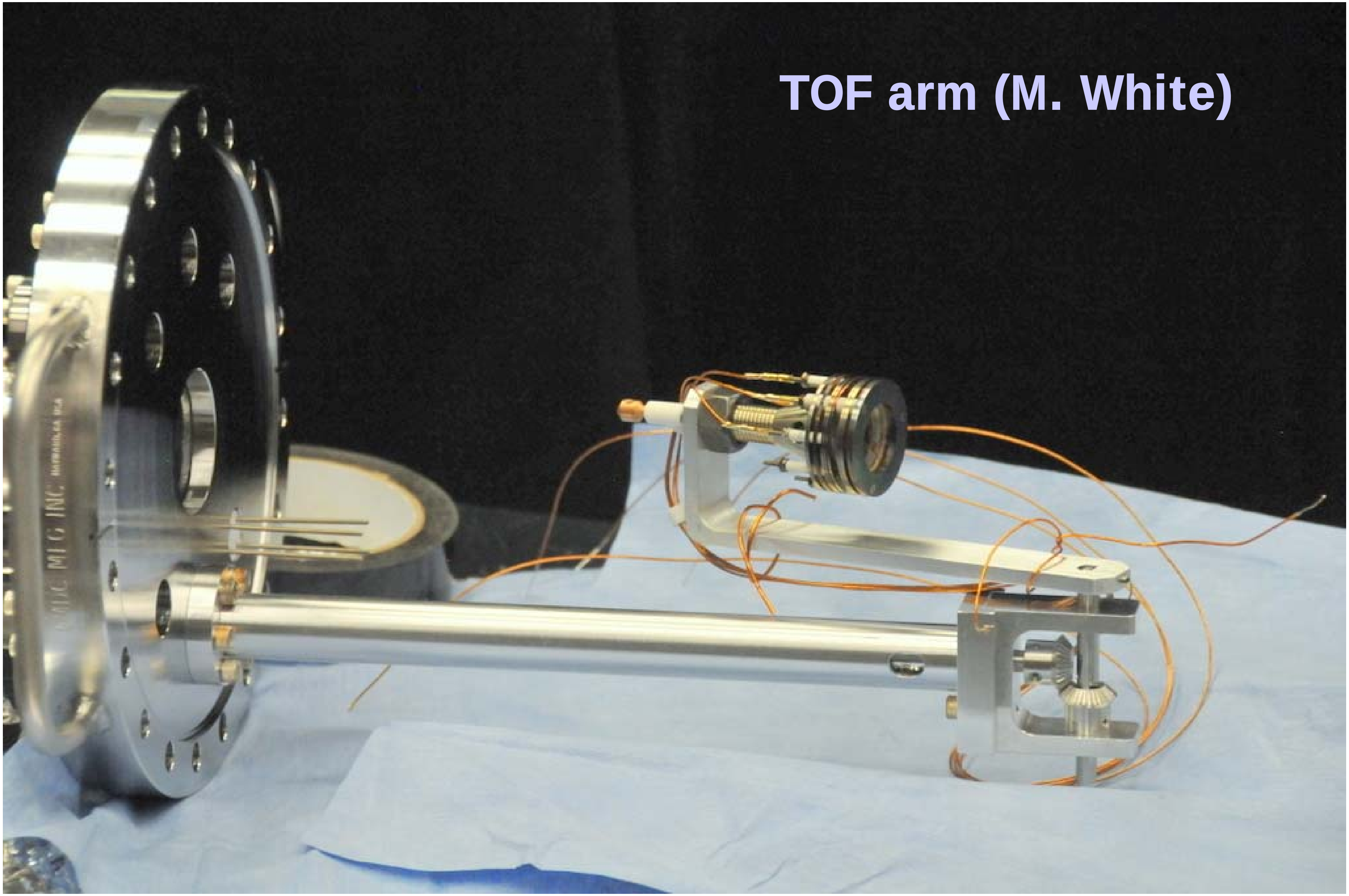


* Design: R. Rosenberg

K. Harkay et al., Proc. 2009 PAC (MO6RFP045)

- Sample holder XYZ θ, sample current
- Vary photon incident angle and polarization
  - Fiber laser, 3-ps pulse (1030, 515, 257 nm)
  - Nd:YAG laser, 3-ns pulse (1064, 540, 355, 266 nm)
  - UV flash lamp (1-μs), spectrometer
- MCP TOF electron detector inside vacuum on a rotating arm
  - Angular acceptance ~6 deg
  - Scan emission angle vs. photon incident angle
- Electron tracking (SIMION) to optimize design (EM fields)
- Eventual upgrades: vacuum load-lock system, fast laser, 2D MCP TOF detector, test fast MCPs

TOF arm (M. White)



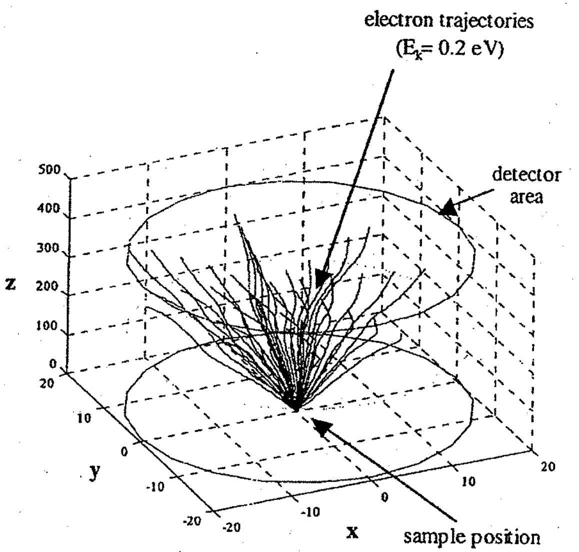
SIMION Commercial electrostatic and magnetic field modeling code
Finite difference technique of over-relaxation to solve Laplace's eqn

Input
- Geometry
  - Physical boundaries
  - Electrodes, Magnetic poles
  - (Can import CAD files)
- Initial electron distribution
  - location, energy, momentum

→

Output
- Electron trajectories
  - including momenta, energies
- Field gradients
- Potentials, magnetic field

Tool for the following studies
- Effect of stray EM fields on distortion of electron distribution*
- Optimization of bias voltage
- Improvement of component design (shape and placement)



L. Spentzouris

* Fig courtesy P. Michelato, L. Monaco, D. Sertore, Rev Sci Instrum 74, 6 (2003)

Emittance: Theoretical Estimate (Padmore, Wan)

At the surface, the emittance is

$$\varepsilon_{x,rms} = x_{rms}\, p_{x,rms} /(m_e c)$$

For uniform emission from a disk,

$$x_{rms} = \frac{1}{2} R$$

For uniform distribution in the transverse momentum space,

$$p_{x,rms} = \frac{1}{2} P_r = \frac{1}{2} \hbar k_{\max}$$

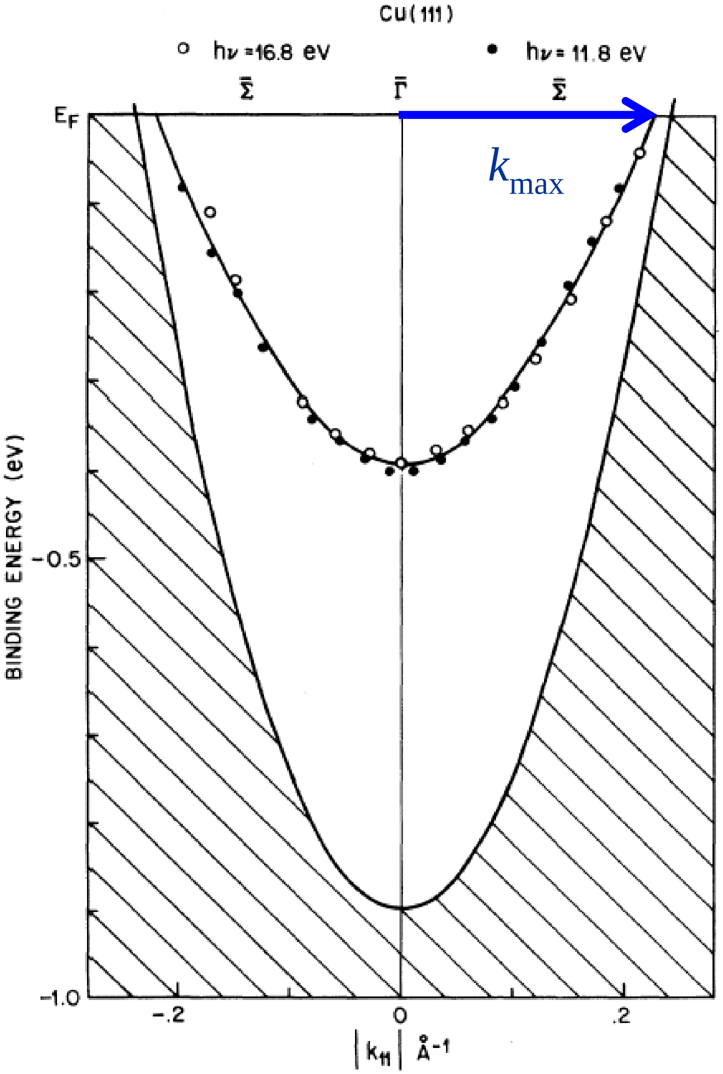
$$\varepsilon_{x,rms} = \frac{1}{4} R \cdot \hbar k_{\max} /(m_e c)$$

For Cu(111), $k_{max} = 0.225 \overset{\circ}{A}^{-1}$; $R = 1$ mm

$$\varepsilon_{x,rms} = 2.2 \times 10^{-7} \text{ m rad}$$

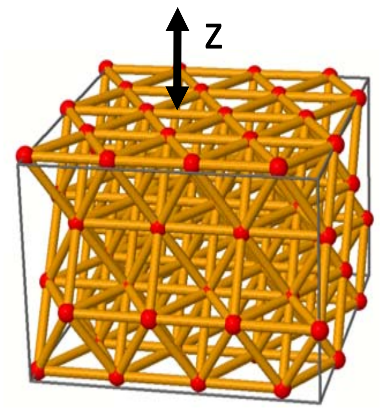
For Ag(111), $k_{max} = 0.125 \overset{\circ}{A}^{-1}$, $R = 1$ mm

$$\varepsilon_{x,rms} = 1.2 \times 10^{-7} \text{ m rad}$$



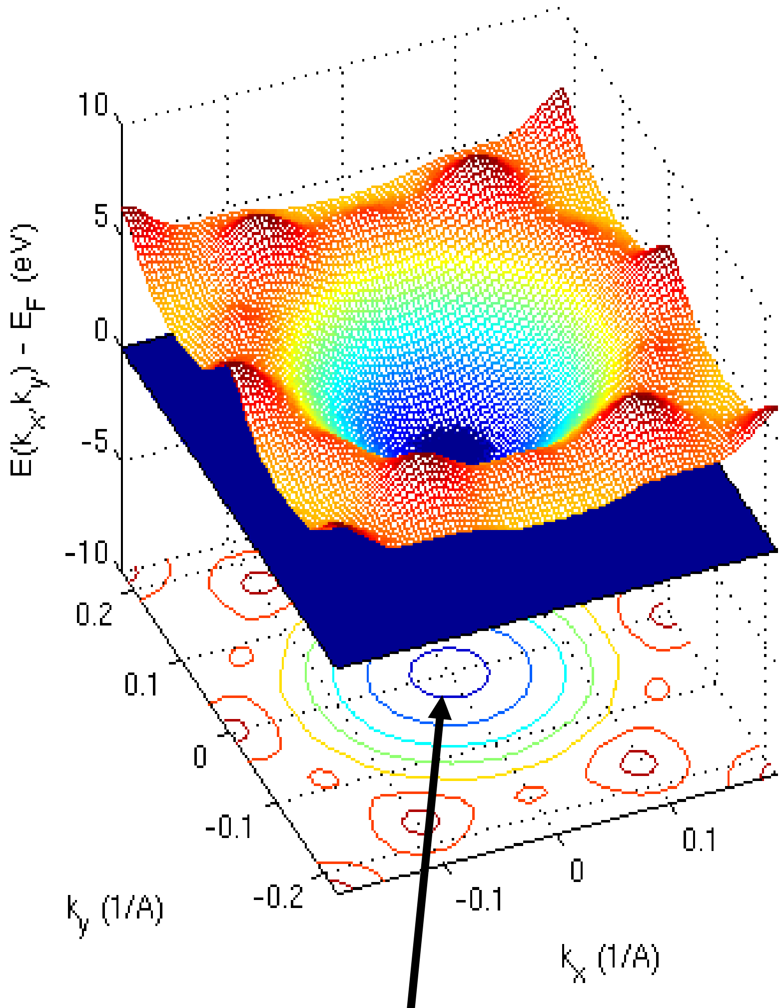
S.D. Kevan, PRL 50, 526 (1983).

Density Functional Theory (DFT) Analysis (K. Nemeth)



Cu (111) surface slab

- Agreement within 10% between calculated (DFT) and experimental values of ϕ and k_{max} for a number of crystals.
- Photoelectrons are emitted from the "Fermi-ponds" -- small diameter indicates possibility of small transverse emittance beams. Conservation of crystal momentum during photoemission is assumed.



"Fermi-pond": cross-section of the surface band with the Fermi energy in the Brillouin zone.

Potential low-transverse-emittance layered structure

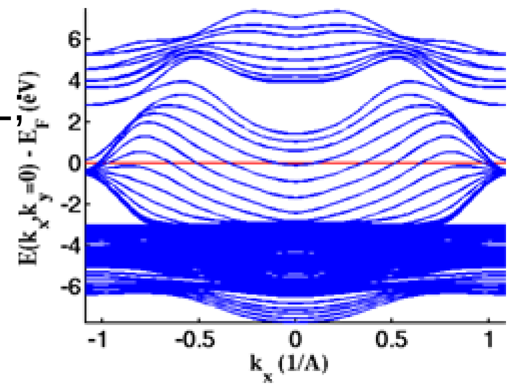
Preliminary idea from surface catalysis systems [L. Giordano et al., J. Chem. Phys. 127, 144713 (2007)].

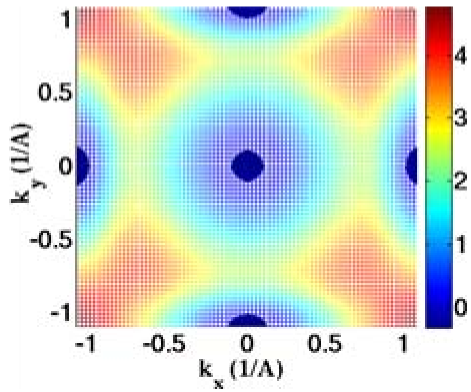
k_x vs. energy bands relative to E_f

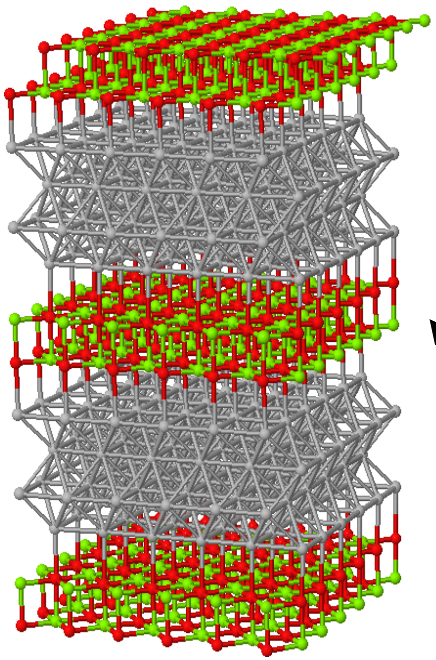
Lowest-energy (relative to E_f) surface bands in k_x vs. k_y space

K. Nemeth et al., PRL 104, 046801 (2010)

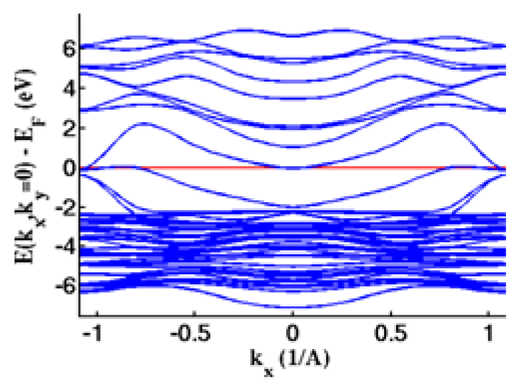
Ag(001)16L; DFT(PBE)
k_{max} 0.1 Å^{-1}

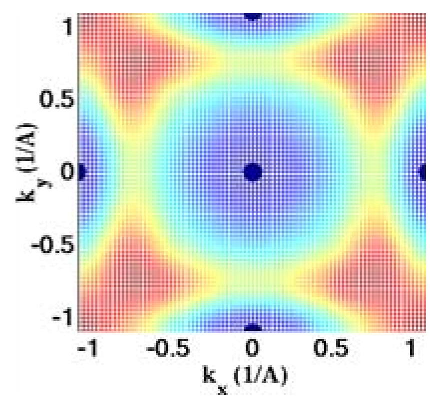






k_{max}
0.05 Å^{-1}

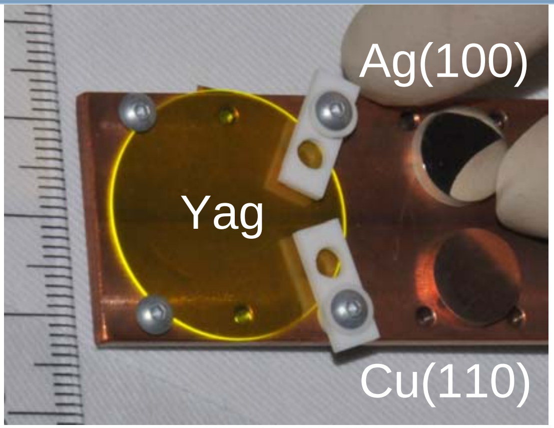




MgO(100)2L-Ag(100)4L-MgO(100)2L; DFT(PW91)
Work function reduced by ~1 eV relative to pure Ag(001)

$\varepsilon_{n,i}/\sigma_x$ = 0.05 mm-mr/mm

Ultra-bright Photocathode R&D Status



Near-term

- UV ARPES chamber assembly underway; first measurements this year on standard metal cathodes.
- Compare intrinsic emittance results with BNL, PITZ (measured in injector); INFN, LBNL (ARPES labs); others
- Preliminary theoretical calculations suggest a design method for ultra-high brightness cathodes. Further study of practical implementation is ongoing.

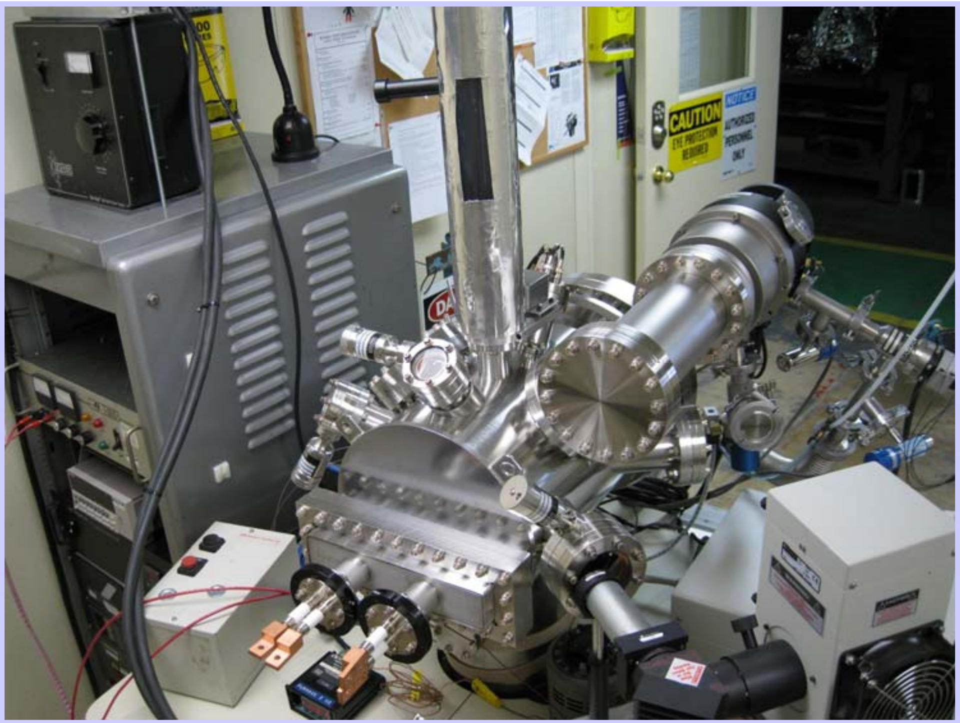
Longer-term

- Develop load-lock system to study Cs_2Te and semiconductors
- Fabricate novel cathodes in collaboration with LAPPD project
- Investigate experimentally (in the lab) novel material designs that predict small emittance
- Test in an rf injector (cathode lifetime, performance)

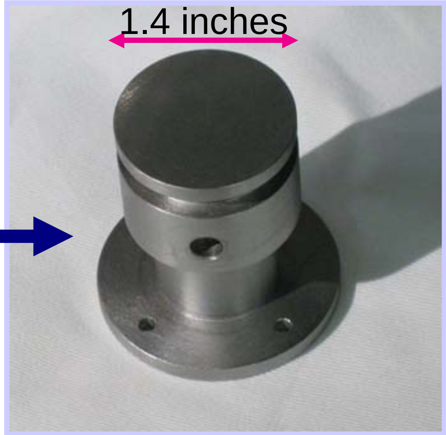
Outline

- Three groups at Argonne are working on photocathode research for different applications
  - Ultra-bright injectors for light sources
  - **High-charge injectors for HEP**
  - **Large area, fast detectors for HEP**
- Common goals
  - Fundamental cathode R&D
  - Designed properties: “Bandstructure engineering”
  - Cathode fabrication
- Collaborating and sharing resources in areas of overlapping interests

Cs_2Te Photocathode – Fabrication and Vacuum Transfer

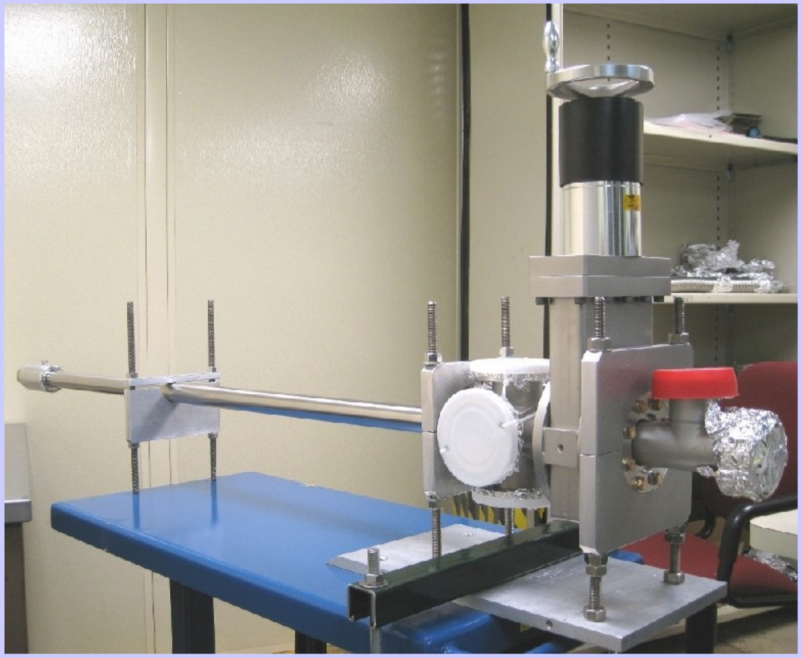


Photocathode plug/substrate (Mo)



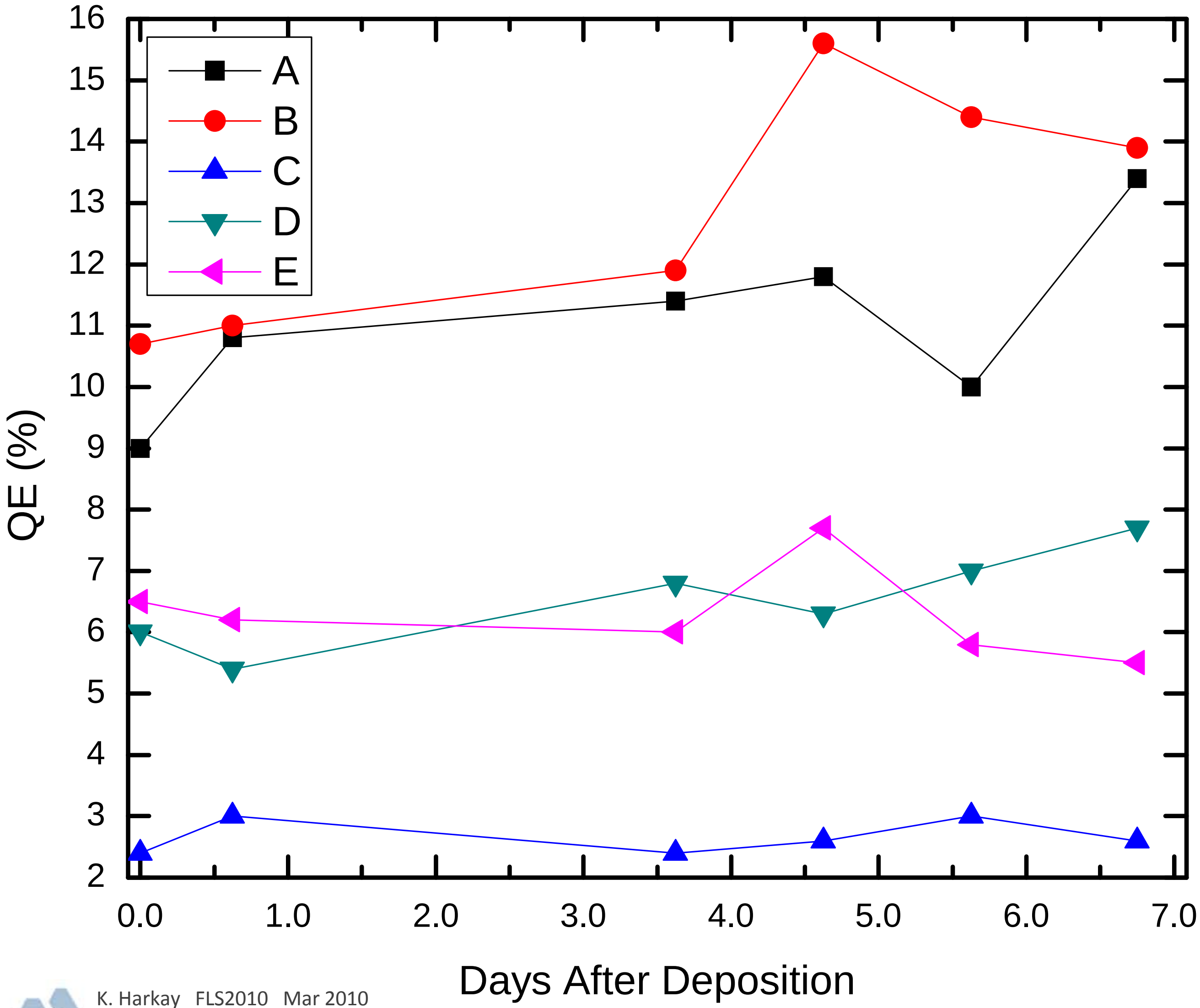
Cs_2Te photocathode deposition system

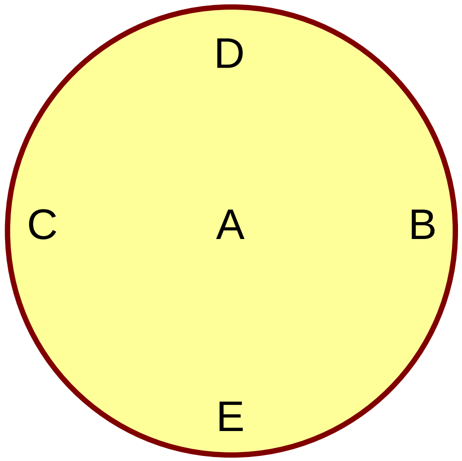
Cs_2Te UHV vacuum transfer system



Slide courtesy Z. Yusof

Summary of Uniformity and Lifetime, Cs_2Te





Slide courtesy Z. Yusof

Large-area psec photodetector array cathode required infrastructure

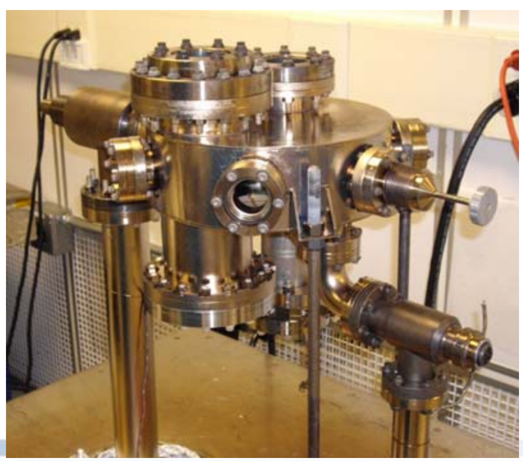
- Use of existing Growth facilities
- Missing link is Growth/Activation Chamber
- ANL strength is characterization & Theory/Simulation
- III-V samples can be transported on air (not activated)
- Multi-Alkali have to be prepared on site (under instruction from SSL?)

UIUC

GaAs-based

Wash U

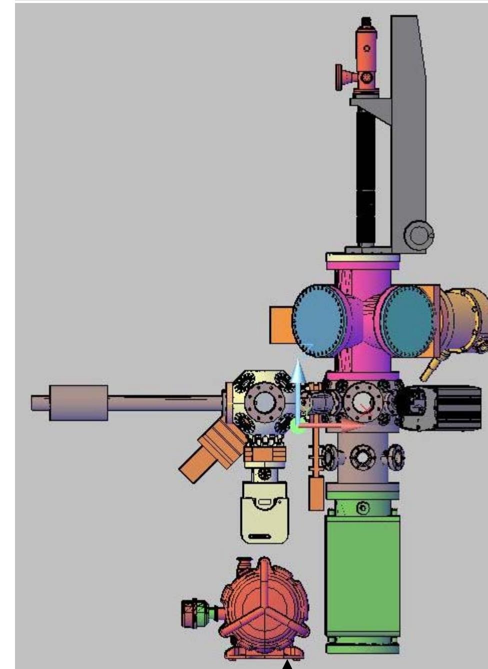
GaN-based



SSL

Multi-Alkali

ANL: Growth/Activation Chamber



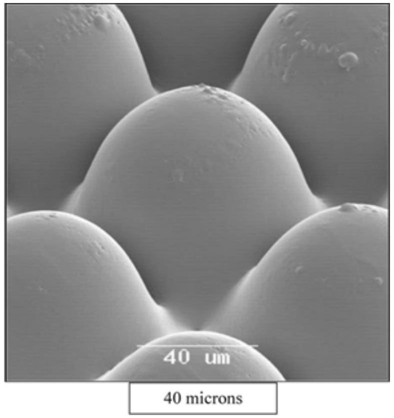
ANL-Characterization & Theory/Simulation

Slide courtesy K. Attenkofer

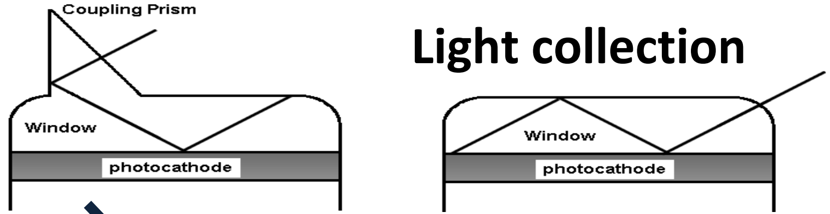
The Goals: What has to be done (LAPPD)

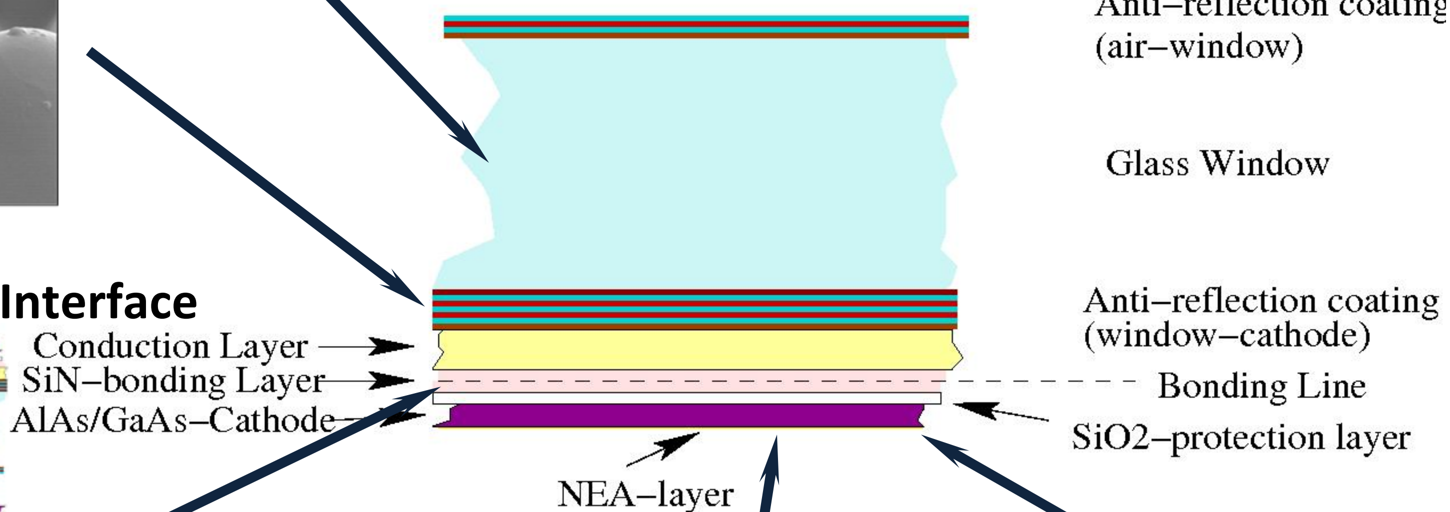
Slide courtesy
K. Attenkofer

Reduction of reflections

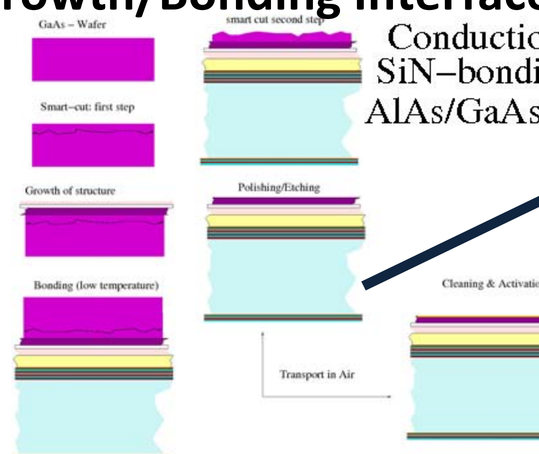


Light collection

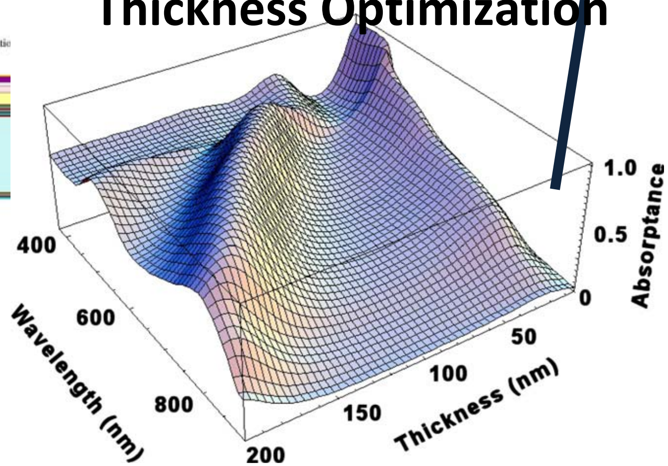




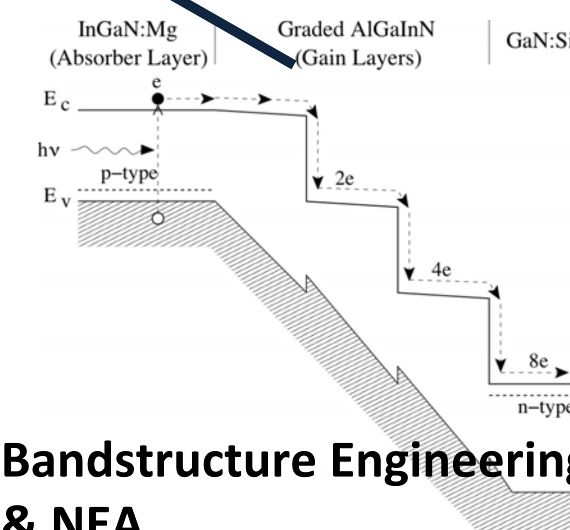
Growth/Bonding Interface



Thickness Optimization



Process compatibility (transfer Process)



Bandstructure Engineering & NEA

Sample transfer design (Rosenberg) for mutually-compatible load-lock design (TBD)

Summary

- Photoemission characterization using UV ARPES, XPS under development; chamber assembly underway
- Potential material design methods being explored theoretically to optimize (minimize) emittance for next-generation x-ray source
- Fabrication of promising designer cathodes to be developed (MBE, CVD, ALD, etc); emittance properties to be characterized (also lifetime, QE, etc)
- Theoretical predictions to be tested experimentally, both in lab and in injector test stand
- Other photocathode efforts at Argonne and elsewhere have complementary goals, opportunity for collaboration!