Northern Illinois University

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

Modeling, Growth, and Characterization of Advanced Photocathode Materials at Northern Illinois University

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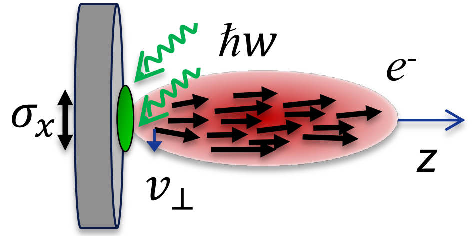
Introduction

High-quality electron beams =

- bright beams $B_{4D} \propto \frac{N_{bunch}}{\epsilon_x \epsilon_y} \propto \frac{(E_z)^k}{MTE}$



Photocathode

$N_{bunch} \propto \sigma_x \sigma_y (E_z)^k$

$1 \le k \le 2$

$\epsilon_{x,y} = \sigma_{x,y}\sqrt{MTE/m_e c^2}$

High-quality photocathodes =

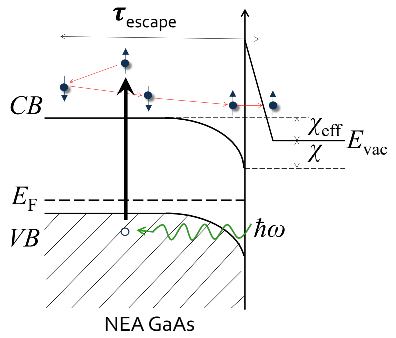
- low mean transverse energy $MTE = \frac{m\langle v_\perp^2 \rangle}{2}$

  MTE ~ k_BT ~ 25 meV at room temperature → MTE ~ few 100s meV

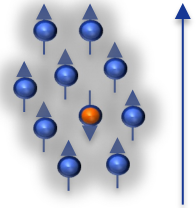
  Factors, limiting MTE:
  - requirements of the high charge density
  - disordered nature of photocathode materials
  - surface roughness and work function variations

- high Quantum Efficiency, $QE = \frac{N_{e^-}}{N_{\hbar w}}$

- prompt response time



- high Electron Spin Polarization, $ESP_0 = \left|\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right|$

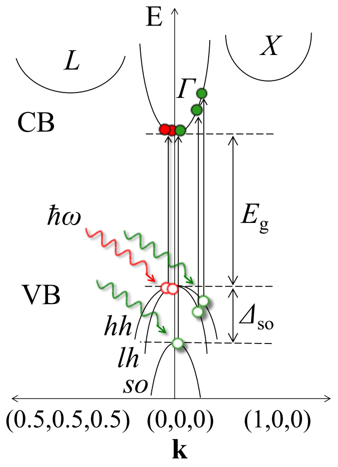


- robustness + long operational lifetime under realistic photoinjector conditions (5-100 MV/m to extract ~ 50-1000 pC/mm^2 of charge densities/bunch)

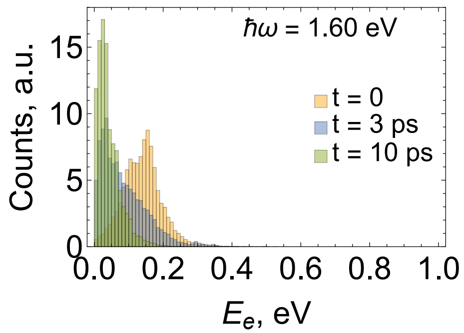
Monte Carlo Modeling of Photoemission from Semiconductors

Advantages of Monte Carlo approach:

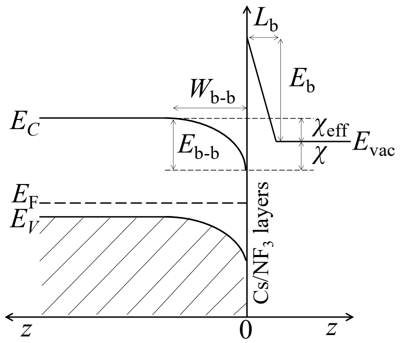
- QE, ESP, MTE, response time = $f(\hbar\omega, p, \chi, T)$.
- Accounts for the subtleties of the material band structure.

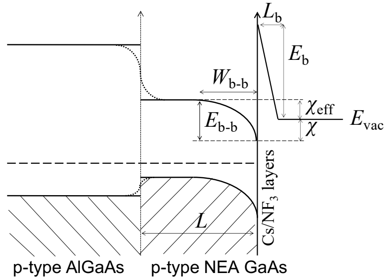


- Does not require *a priori* assumption about the particle distribution functions.



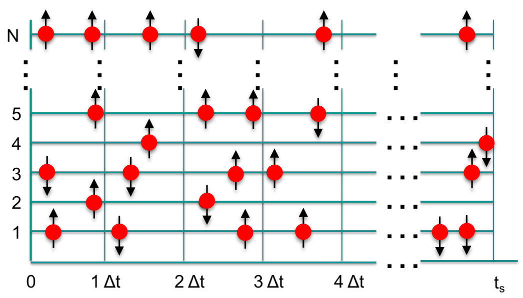
- Can be easily modified to include different scattering mechanisms to model both steady-state and non-equilibrium conditions.
- Accounts for the surface effects.
- Can be applied to both bulk and thin layers.

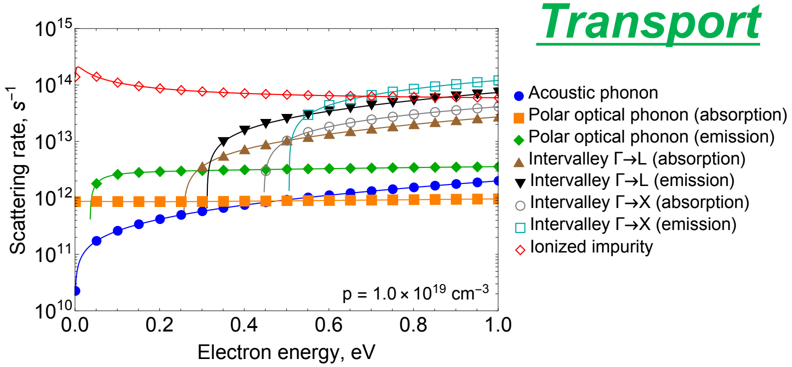


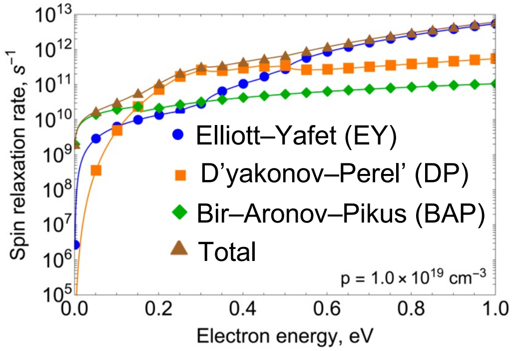


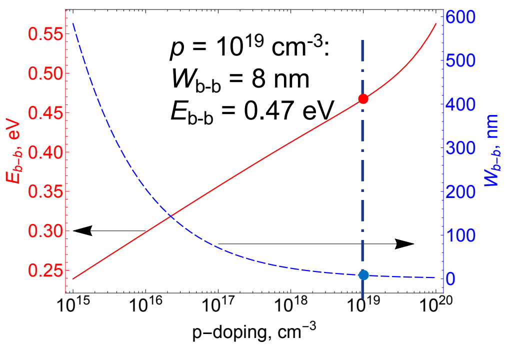
Monte Carlo Modeling of Photoemission from Semiconductors

Transport



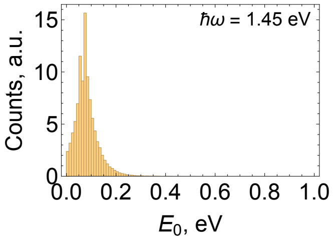




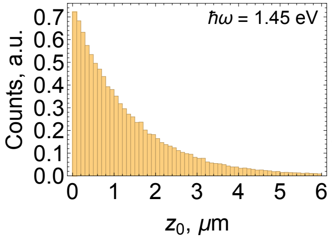


Photoexcitation

Initial energy distribution of photoexcited electrons

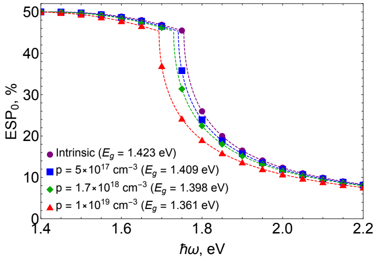


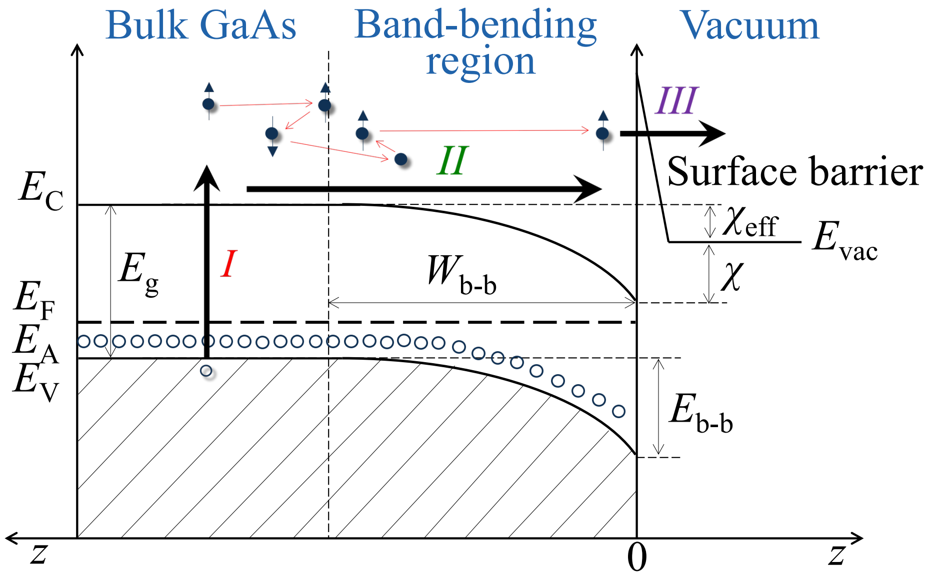
Initial electron distribution in real space



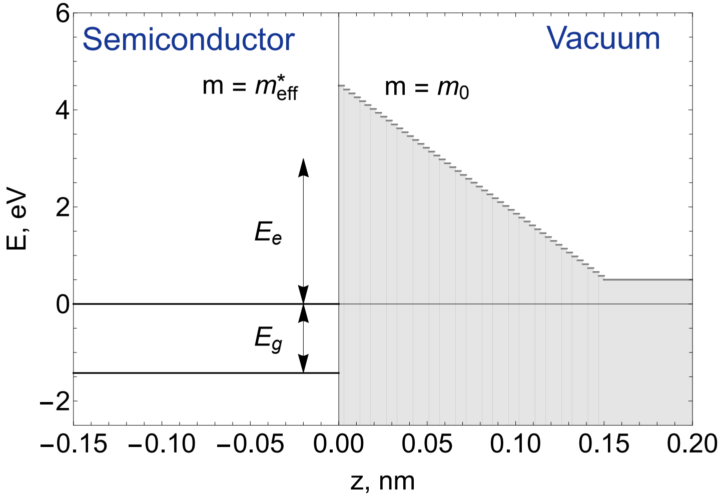
Initial spin orientation of photoexcited electrons

$$ESP_0 = \left|\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right|$$





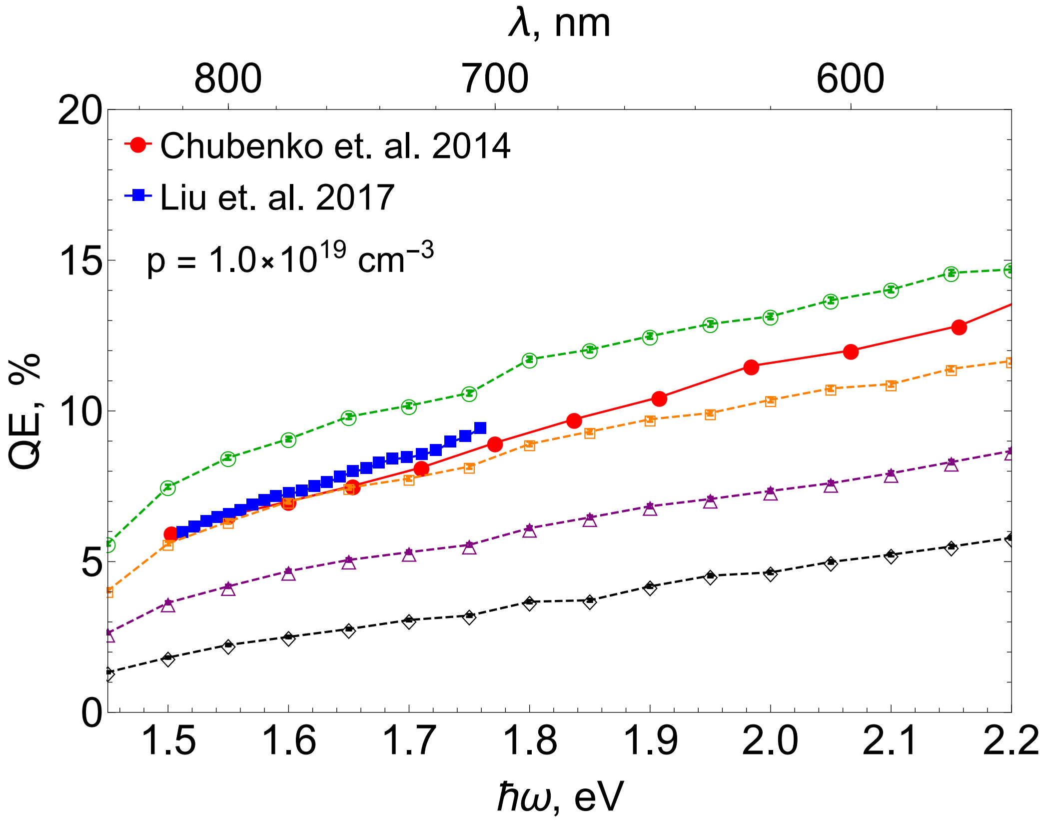
Emission

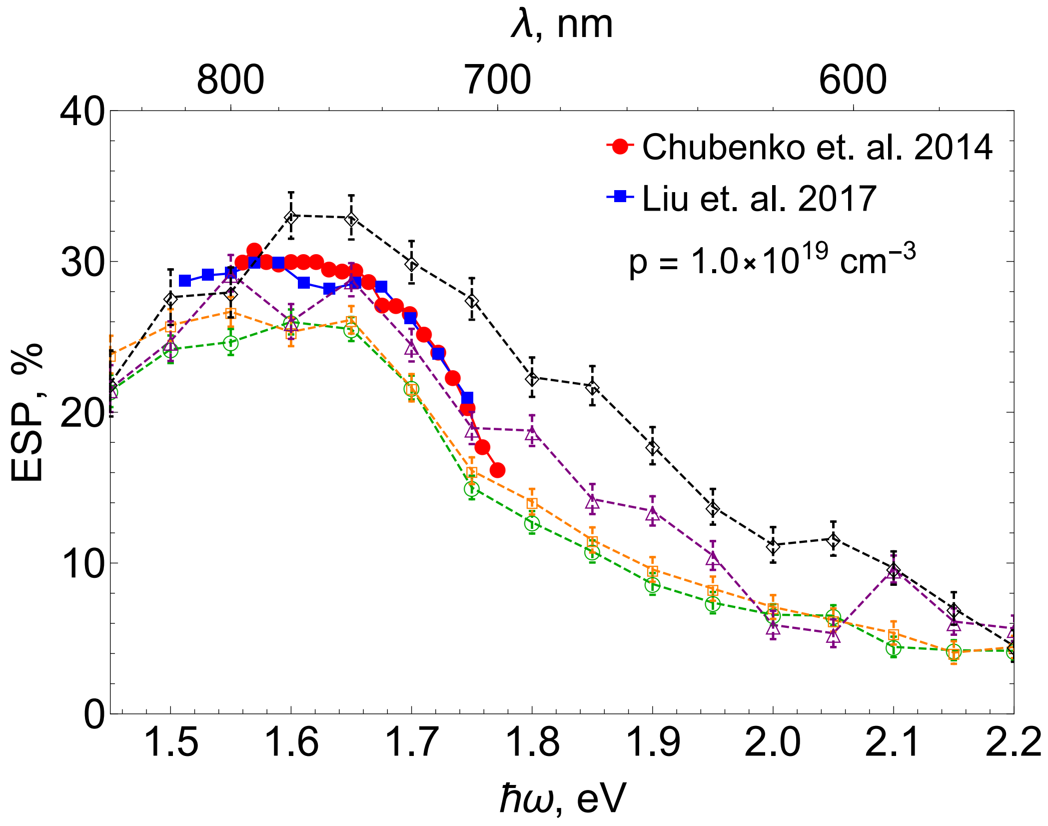


Spin-polarized photoemission from p-type GaAs activated to Negative Electron Affinity (NEA): I – photoexcitation, II – transport, III – emission.

Spin-polarized Photoemission from GaAs

Comparison with experiment: QE and ESP from p-type GaAs for different electron affinity levels

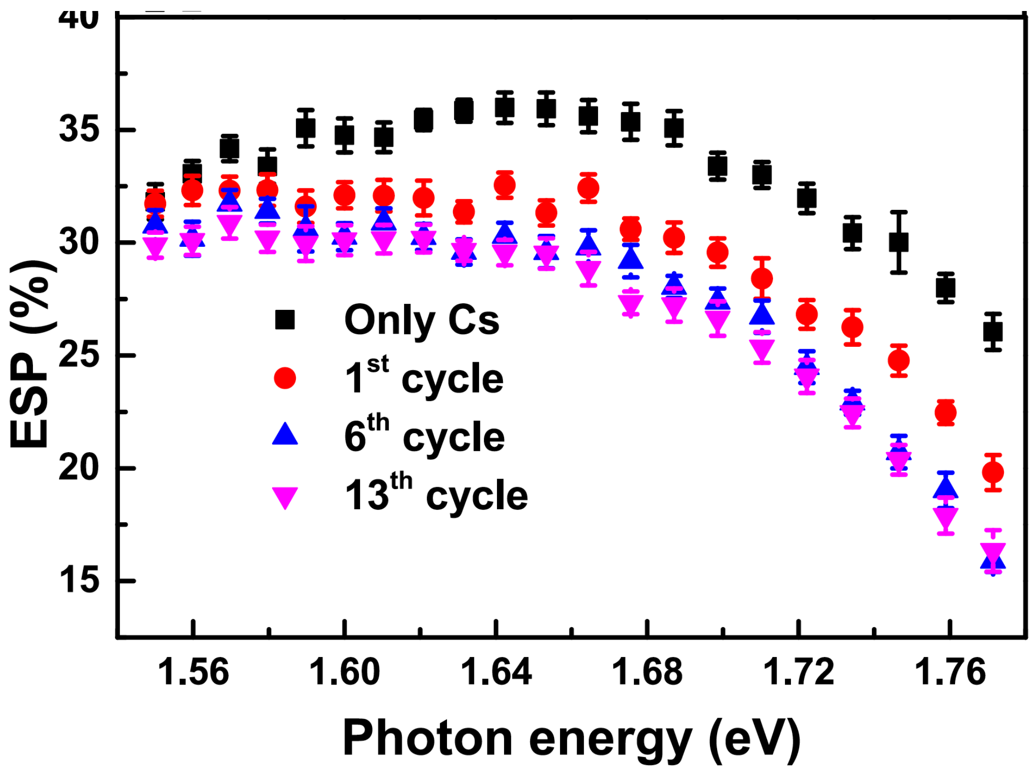


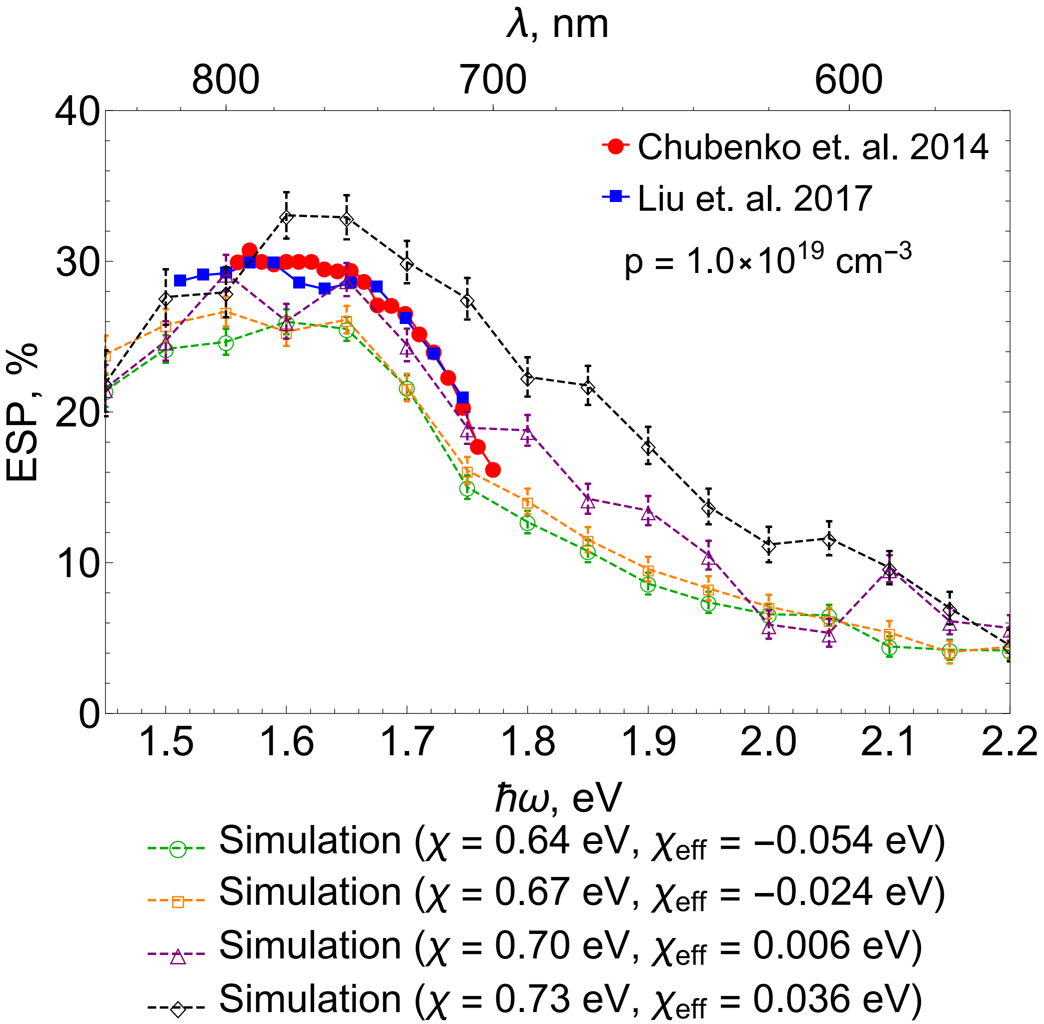


Simulation (χ = 0.64 eV, χ_{eff} = −0.054 eV)
Simulation (χ = 0.67 eV, χ_{eff} = −0.024 eV)
Simulation (χ = 0.70 eV, χ_{eff} = 0.006 eV)
Simulation (χ = 0.73 eV, χ_{eff} = 0.036 eV)

Chubenko et al. J. Appl. Phys. **130**, 063101 (2021)

Introduction

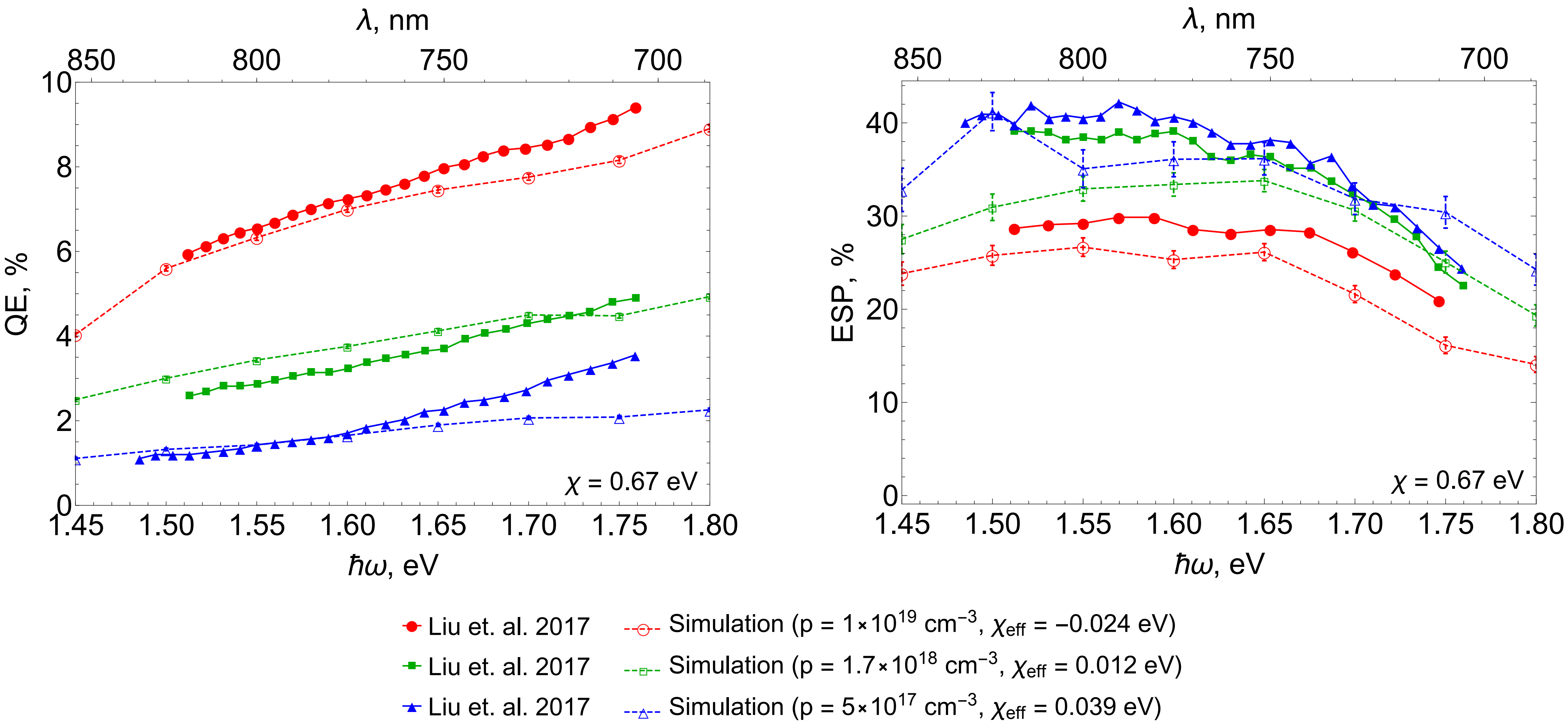




Liu et al. Appl. Phys. **122**, 035703 (2017).

Chubenko et al. J. Appl. Phys. **130**, 063101 (2021)

Comparison with experiment: QE and ESP from p-type GaAs for different doping densities



Chubenko et al. J. Appl. Phys. **130**, 063101 (2021)

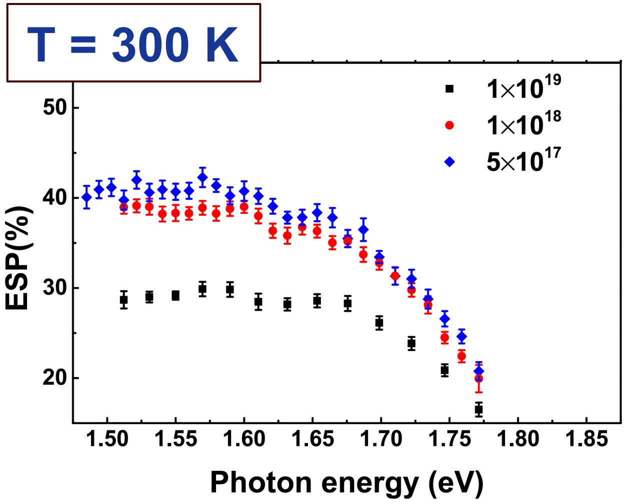
Future applications of Monte Carlo model

- ✓ Effective/fast modeling of spin-polarized photoemission: C + MPI to run in parallel at HPC cluster.
- ✓ Good agreement with available experimental data.
- ✓ Required model parameters from Density Functional Theory (DFT) calculations.

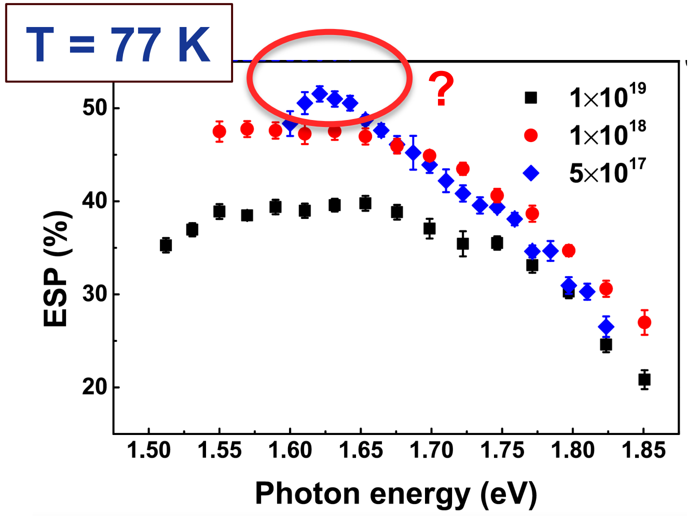
The developed Monte Carlo model establishes a paradigm for future studies of spin-polarized photoemission.

Future applications of Monte Carlo model

$$ESP_0 = 50\%$$



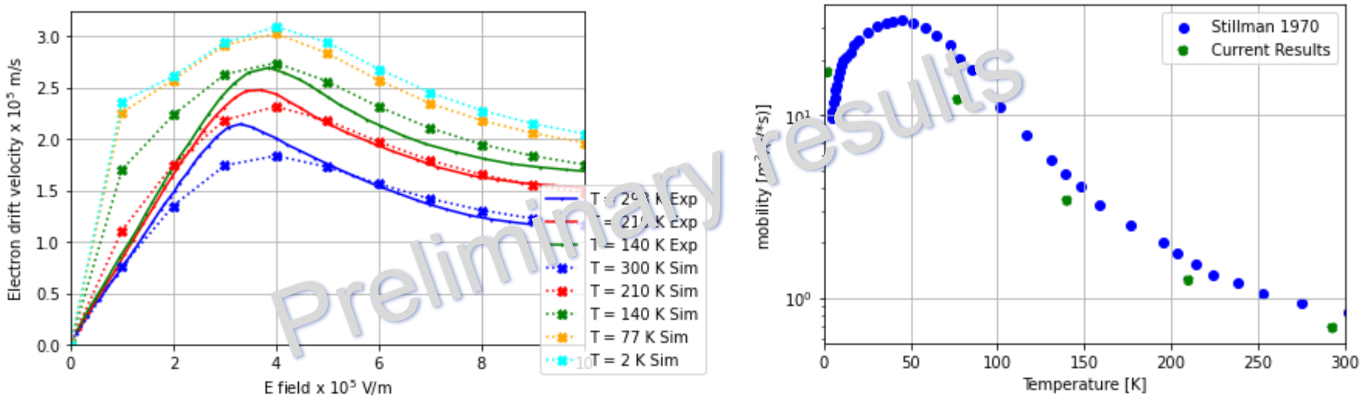
Liu et al. Appl. Phys. 122, 035703 (2017).



T = 2 K

?

Temperature effects on spin-polarized photoemission from bulk GaAs



Callahan et al., Proceedings of IPAC24, https://doi.org/10.18429/JACoW-IPAC2024-WEPC65

Future applications of Monte Carlo model

High-QE, high-ESP from GaAs-based SuperLattices

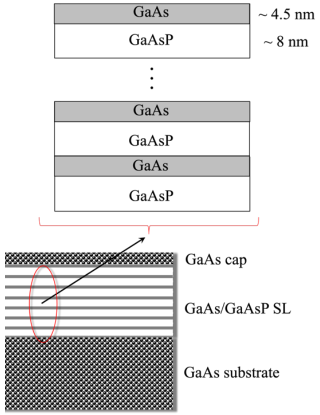


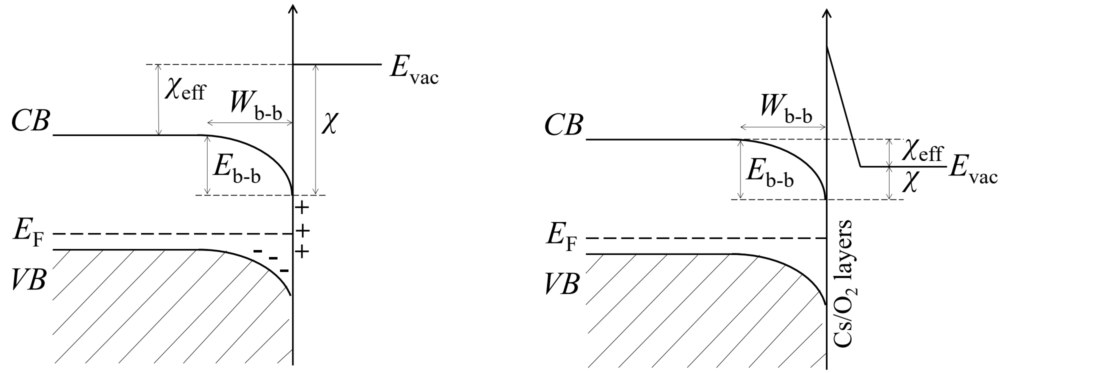
TABLE I. Figure of merit for polarized electron sources.

Cathode	Reference	P (%)	QE (%)	P^2QE (%)
$GaAs\text{-}GaAsP_{0.36}$	SLAC/SVT[15]	86	1.2	0.89
$GaAs\text{-}GaAsP_{0.38}$	Nagoya[20]	92	1.6	1.35
$Al_{0.19}In_{0.2}GaAs\text{-}Al_{0.4}GaAs$	St. Peterburg[18]	92	0.85	0.72
$GaAs\text{-}gaAsP_{0.35}$ (with DBR)	JLab/SVT	84	6.4	4.52

Liu et al. Appl. Phys. Lett. **109**, 252104 (2016)

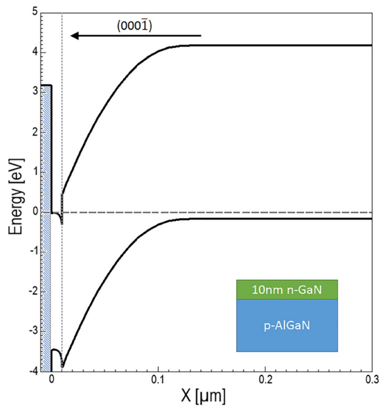
Require traditional Cs-based activation to NEA

p-doped GaAs: **p-doped GaAs activated to NEA:**



Spin-polarized photoemission from materials with inherently low/negative electron affinity levels

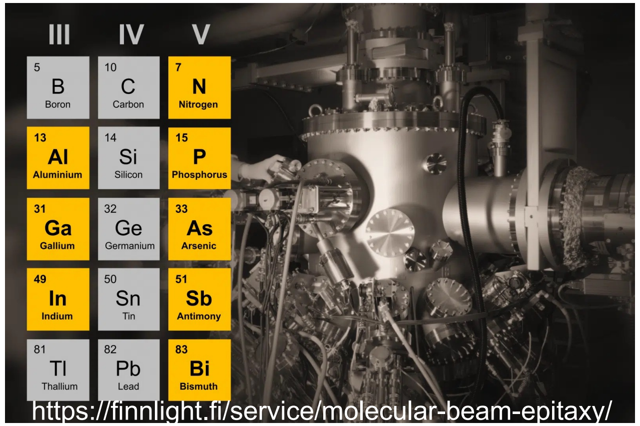
- Polarization band engineering to achieve an effective NEA condition without the use of Cs at the surface of GaN photocathode structures.
- Monte Carlo + DFT to study spin-polarized photoemission from III-Nitride materials.



Marini et al. J. Appl. Phys. 124, 113101 (2018).

Future applications of Monte Carlo model

Highly efficient GaAs-based SL structures are fabricated using an expensive MBE

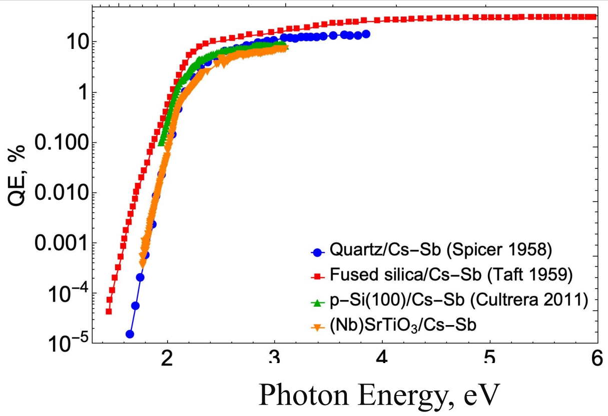


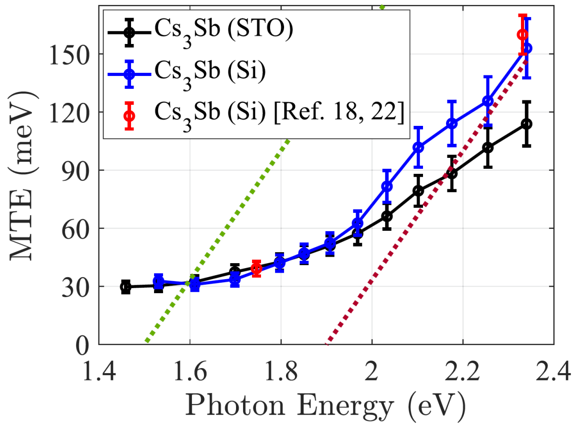
Spin-polarized photoemission from CdTe and other II-VI semiconductors

	GaAs	CdTe
Direct bandgap	yes	yes
Cs-based activation	yes	yes
Surface quality	high	high
p-doped	yes	yes
Spin-orbit coupling	strong	moderate
Cost	MBE, expensive	ALD, cheap
Accessibility	limited	accessible

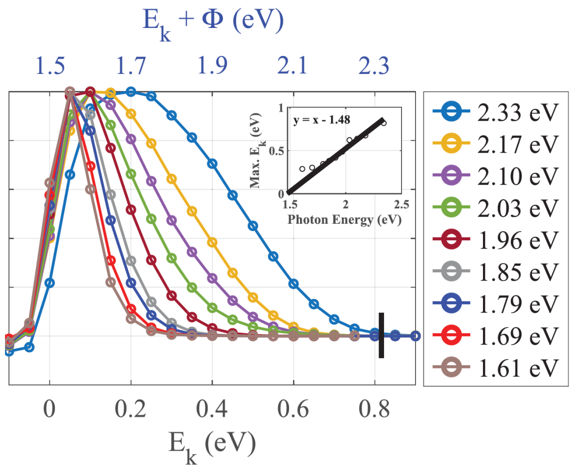
Future applications of Monte Carlo model

Cesium antimonide films: thermal-limit MTE and relatively high QE at photoemission threshold



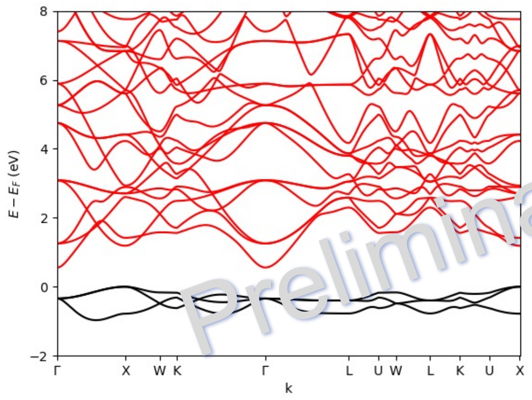


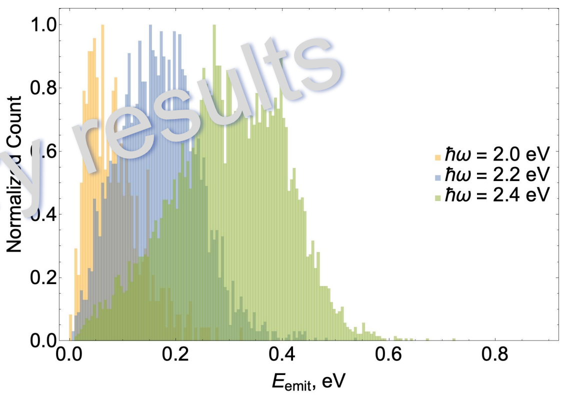
Electron energy loses in thin films



Kachwala et al., Appl. Phys. Lett. **123**, 044106 (2023).

Photoemission from alkali antimonide films (e.g., Cs_3Sb)



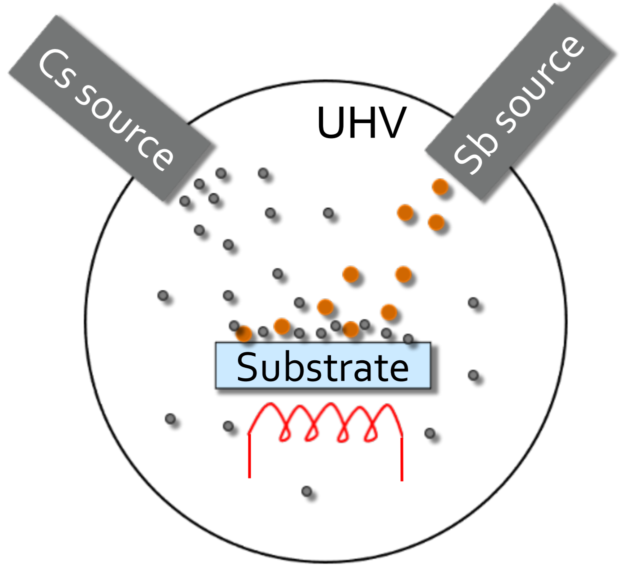


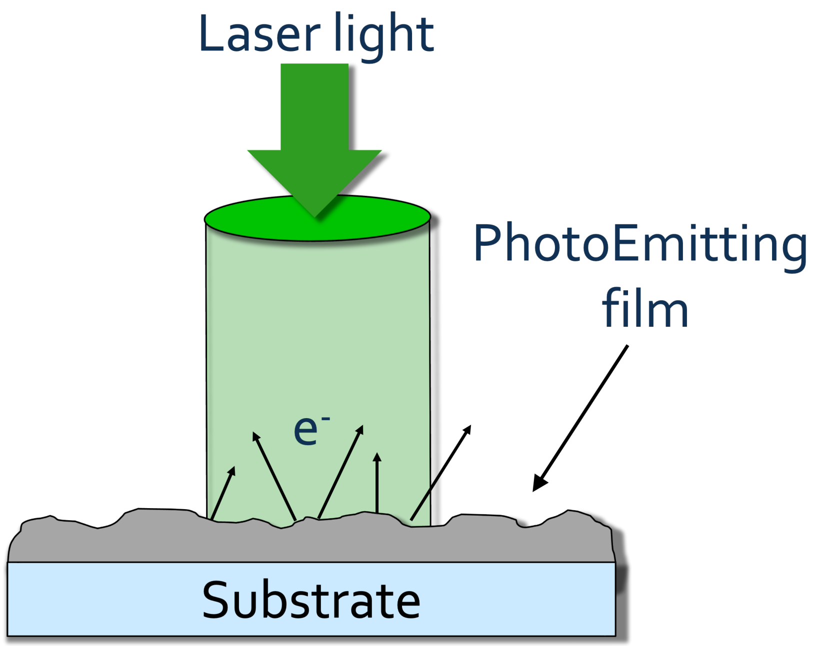
Franklin et al., Proceedings of IPAC24, https://doi.org/10.18429/JACoW-IPAC2024-WEPC66

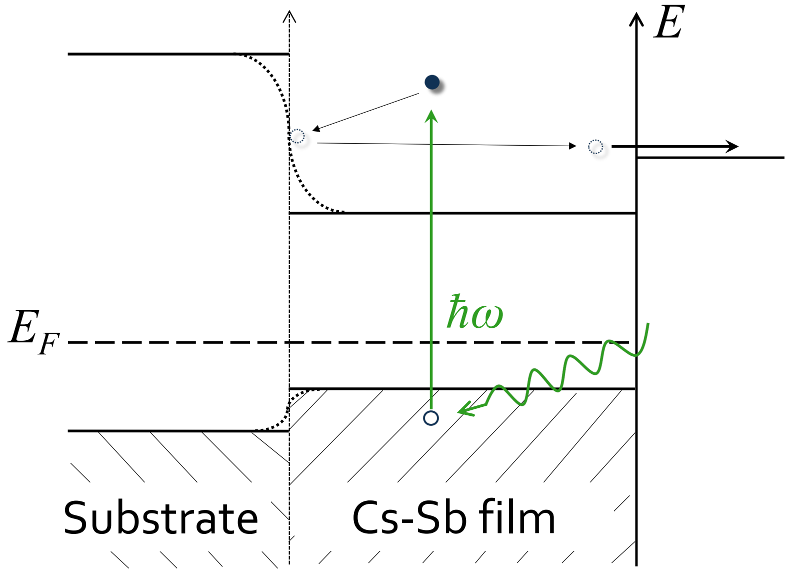
Growth and Characterization of Alkali Antimonide Photocathodes

Cesium-antimonide photocathodes:

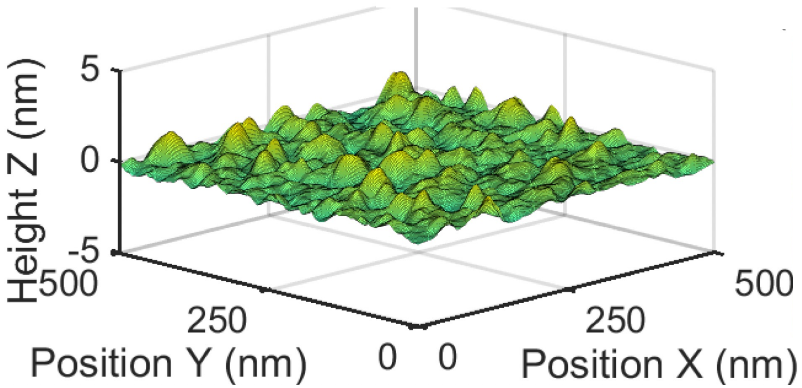
- can be easily deposited through thermal evaporation at moderate temperatures
- photoemit in a visible wavelengths range

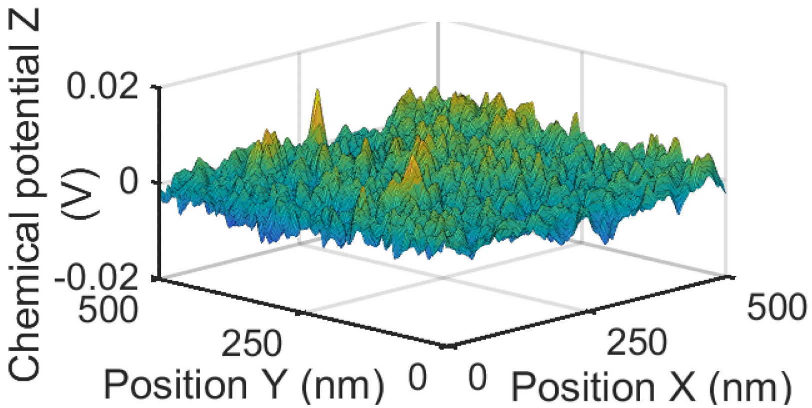


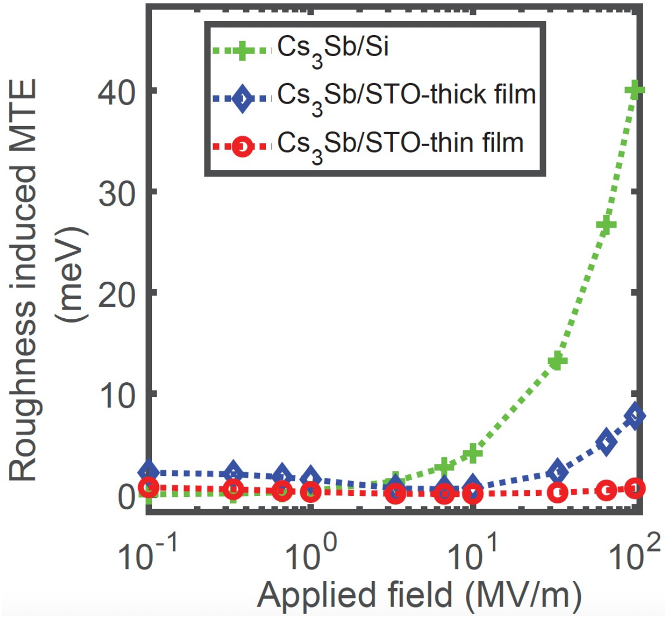




- Surface roughness and work function variation can limit MTE!





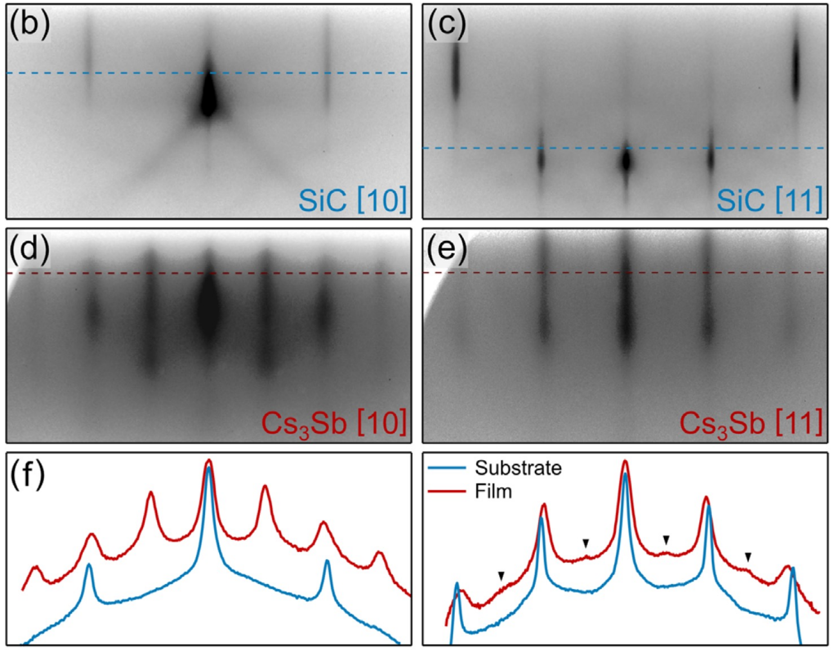


Cesium-antimonide films grown on lattice-matched single crystal strontium titanate (STO) substrates demonstrate roughness-induced MTE < 10 meV even at large applied fields.

Saha, Chubenko et al, Appl. Phys. Lett. **120**, 194102 (2022).

Cesium-antimonide photocathodes

- Disordered crystal structure can limit MTE!



RHEED images of an annealed SiC substrate and a 10 u.c. Cs_3Sb film.

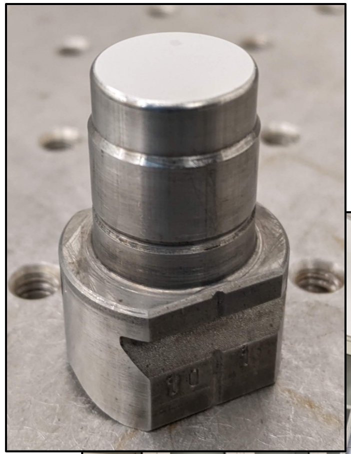
First-to-date demonstration of epitaxial growth of cesium-antimonide films on lattice-matched single crystal SiC substrates.

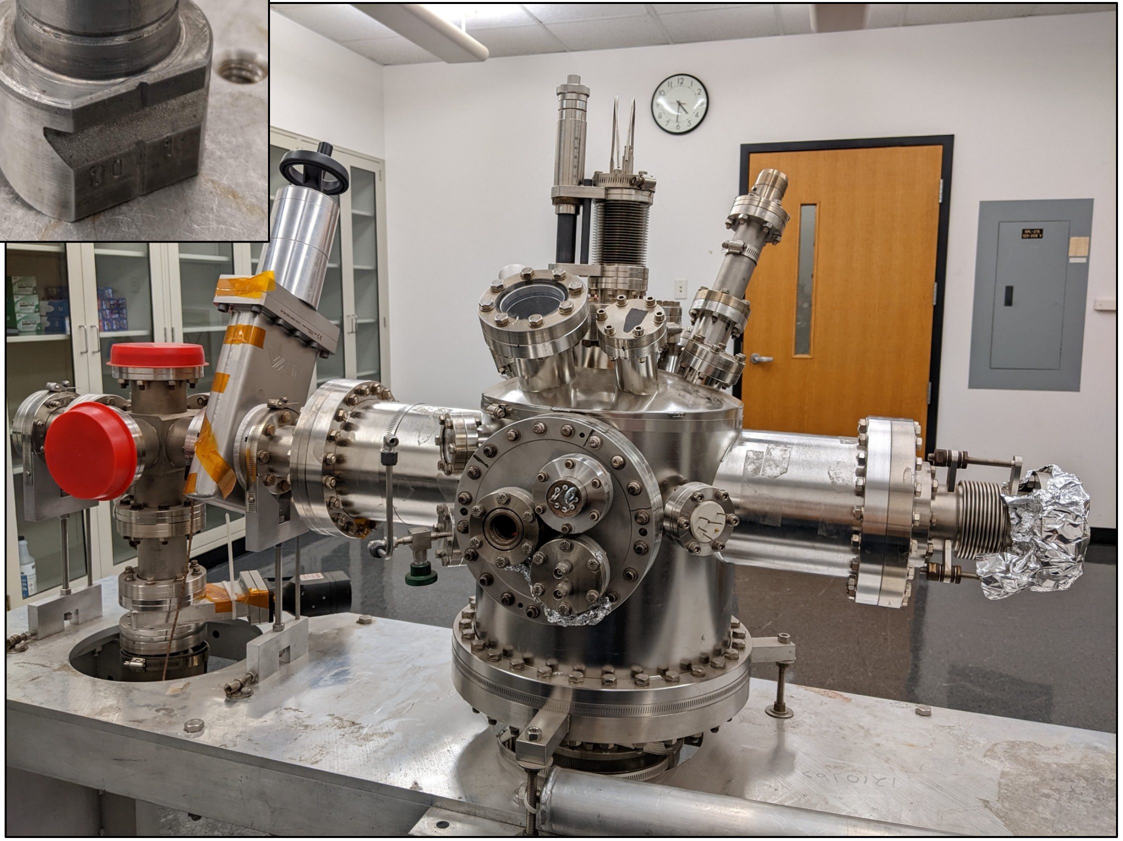
Parzyck et al, Phys. Rev. Lett. **128**, 114801 (2022).

Growth of alkali-antimonide films at NIU

NIU photocathode growth system:

- Was previously used to grow Cs-Te at Fermilab.
- Uses old INFN-type photocathode plug.

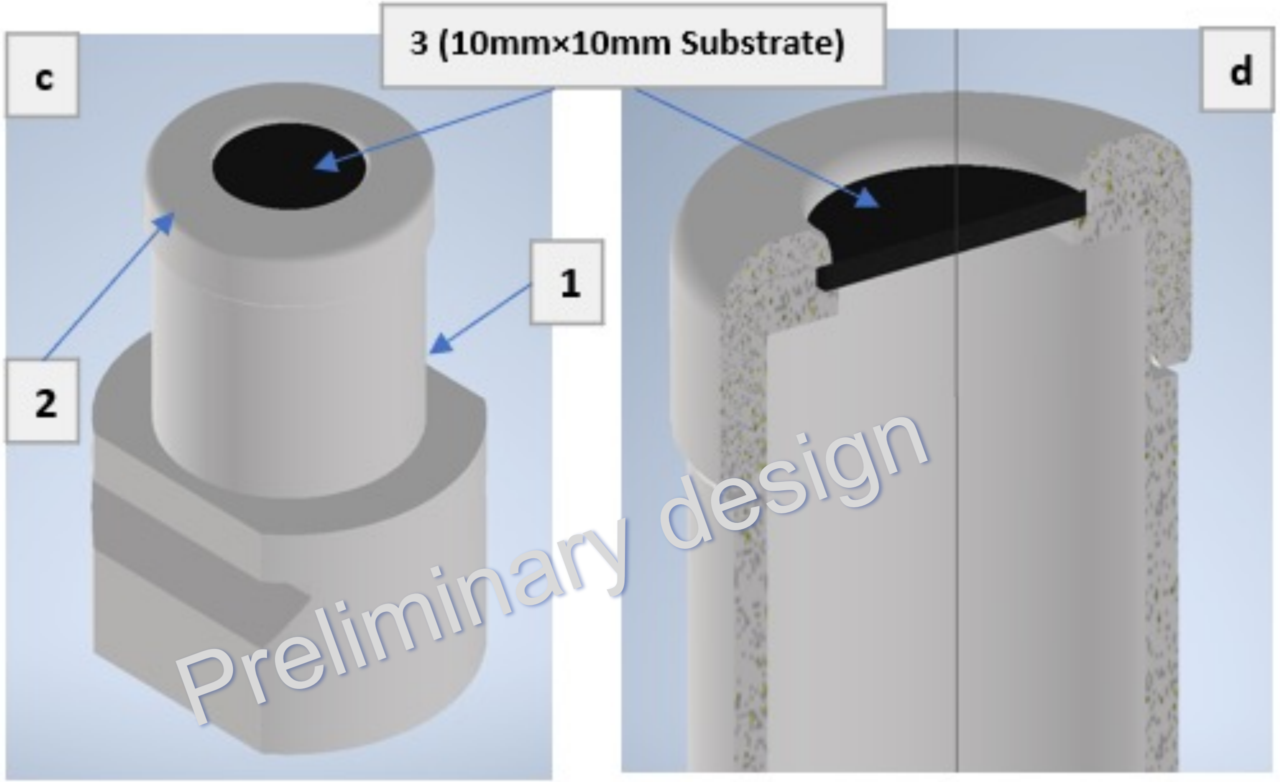




Growth system updates

- Replace SAES strip Cs sources with long-lasting effusion cells (MBE Komponenten) with cesium molybdate pellets (SAES Getters)
- *In situ/operando* characterization with the RHEED system required for the epitaxial growth of cesium antimonide photocathodes

Growth of alkali-antimonide films at NIU



Prototype of the INFN-style plug with substrate insertion capability

Hasan et al., Proceedings of IPAC24, https://doi.org/10.18429/JACoW-IPAC2024-WEPC64

Testing alkali-antimonide photocathodes in accelerators

Alkali-antimonide photocathodes (Cs-Sb, Na-K-Sb):

- Low MTE ✅
- High QE ✅
- Thin films → prompt response time ✅
- Robustness + long operational lifetime under realistic photoinjector conditions ?

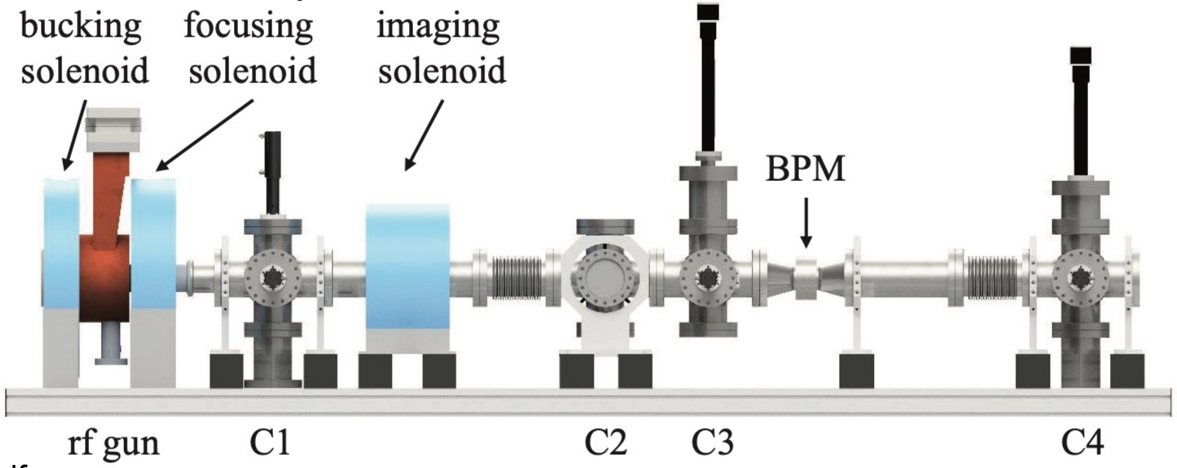
Testing alkali antimonide photocathodes at AWA Facility

Argonne Cathode Teststand (ACT):

- L-band 1.3 GHz single-cell photocathode RF gun
- emittance measurement capability
- includes field emission (FE) imaging system to locate emitters with a resolution of ~20 μm
- currently suitable for testing air-stable materials only
- unique plug design

ACT updates:

- integrate NIU-compatible photocathode plug suitable for testing different photocathode substrates
- develop NIU-compatible load-lock and photocathode transfer systems for testing Cs-containing photocathodes
- update the pump system to achieve ~10^{-10} Torr
- possibility of adding the deflecting cavity for photocathode response time measurements



Shao et al, IPAC 2018 https://accelconf.web.cern.ch/ipac2018/papers/tupml006.pdf

Summary

- A comprehensive R&D photocathode program is currently under development at NIU.
- Located close to two national labs (Argonne and FermiLab).
- Three PhD students are actively working on different aspects of photocathode R&D.

Introduction

Grad students:

- John Callahan (NIU)
- Daniel Franklin (NIU)
- Tariqul Hasan (NIU)
- Joniel O Mendez-Nieves (joins NIU this Fall)

Collaborators:

- Siddharth Karkare (ASU)
- Luca Cultrera (BNL)
- John Power (ANL)
- Scott Doran (ANL)
- Eric Wisniewski (ANL)
- Gongxiaohui Chen (ANL)
- Philippe Piot (ANL)
- Eric Montgomery (Euclid)

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Thank you!