Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Spin Polarized Photocathodes

Samuel Levenson and Chad Pennington

Cold Copper Collider Workshop

SLAC

February 13, 2024

Acknowledgements

Cornell University

U.S. DEPARTMENT OF ENERGY

NSF National Science Foundation

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

Accelerator Physicists

M.B. Andorf

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Spin-Polarized Electron Beams

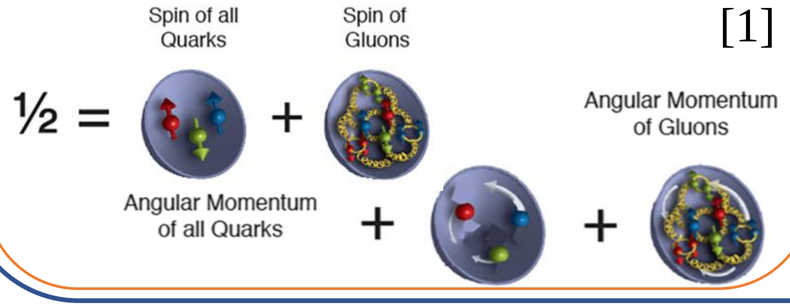
Spin-Polarized Electron Beams

Applications

Nuclear/HEP Physics

- Deep inelastic scattering
- Parity violating experiments
- Higgs Factory

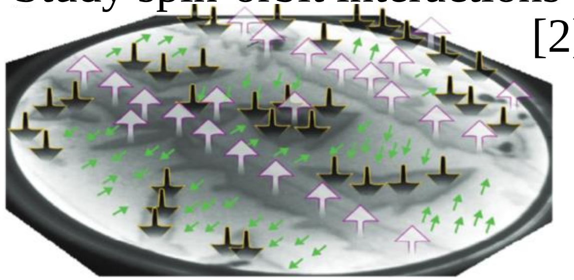
[1]



Electron Microscopy

- Image magnetic structure of surface
- Study spin-orbit interactions

[2]



1. D. Geesaman et al. The 2015 Long Range Plan for Nuclear Science.

2. El Gabaly et al. PRL 96, 147202 (2006)

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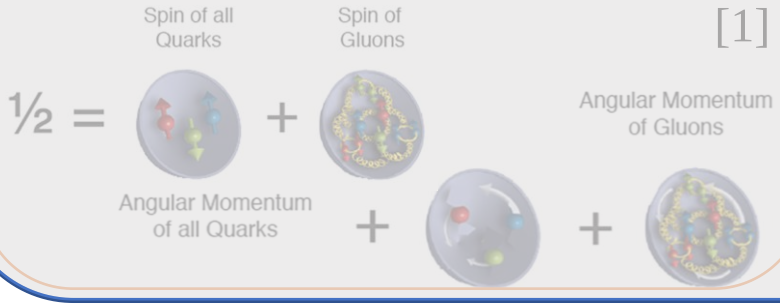

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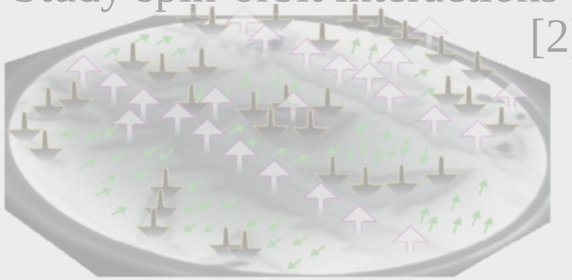

Goals for Sources

- ❑ >90% spin polarization
- ❑ Spin orientation reversibility
- ❑ mA-scale current delivery
- ❑ Low emittance and energy spread
- ❑ Long operational lifetime

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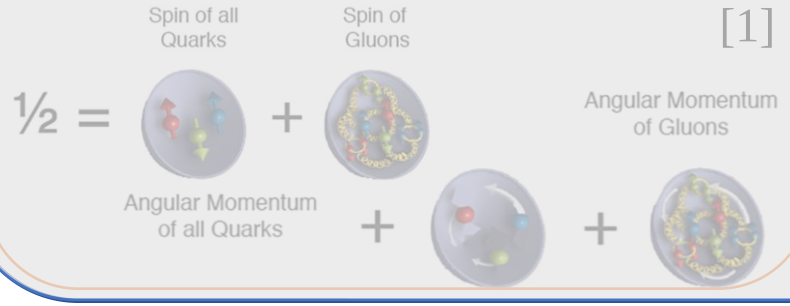

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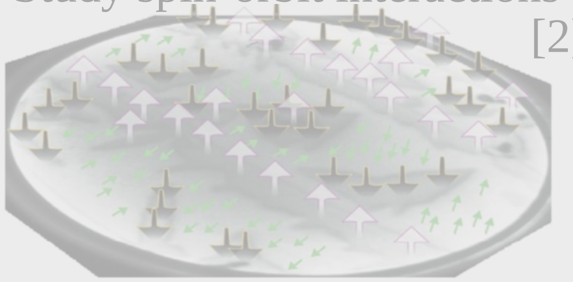

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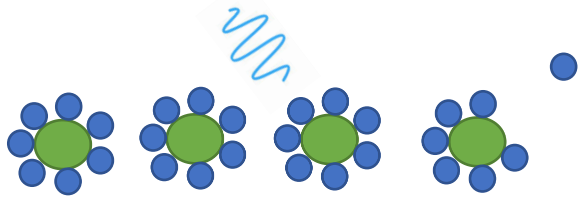

Polarize alkali atoms (PEGGY) or use circularly polarized light (Fano)

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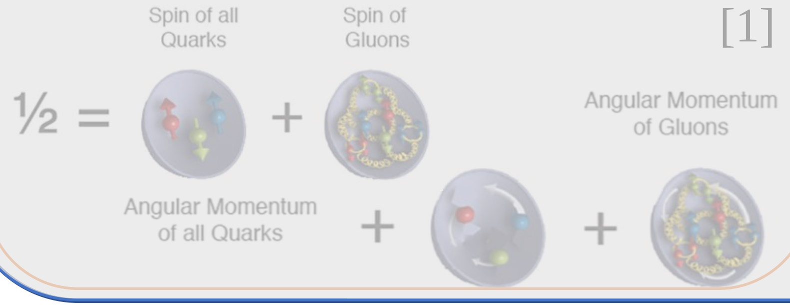

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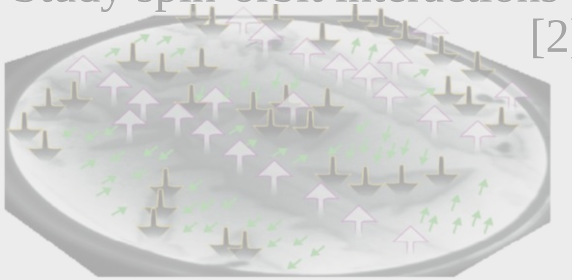

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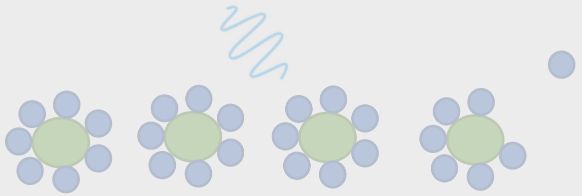

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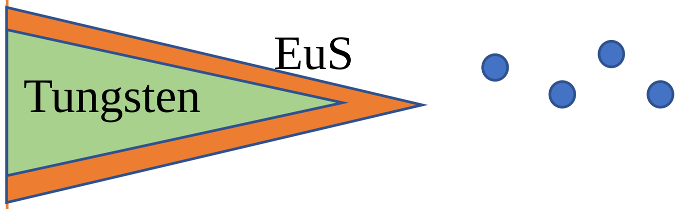
Field Emission/Spin Filter



W tip coated with EuS (spin filter) ferromagnetic thin film

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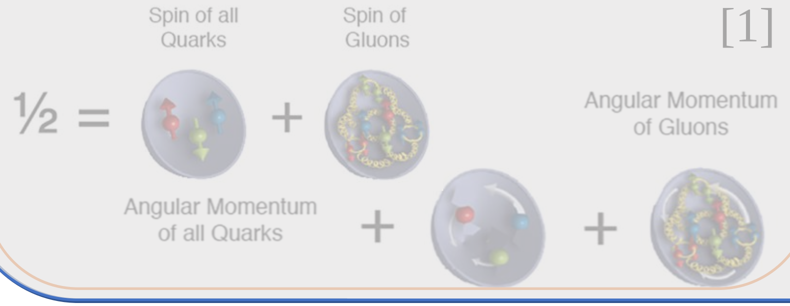

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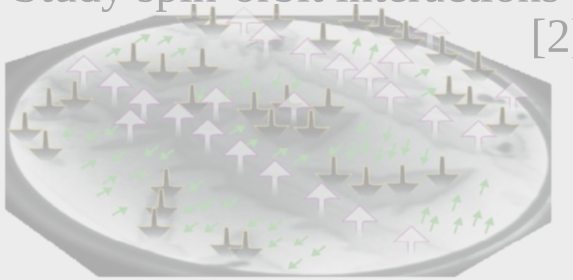

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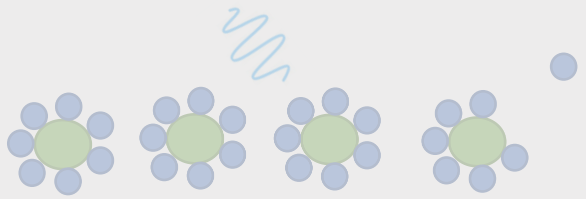

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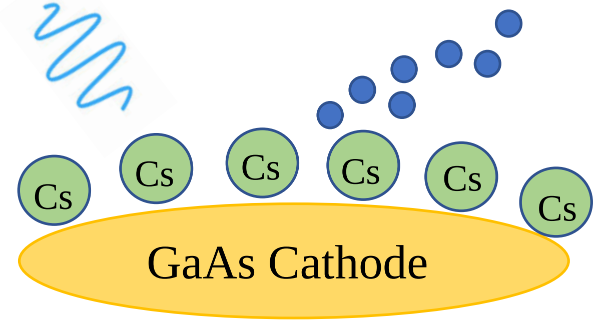
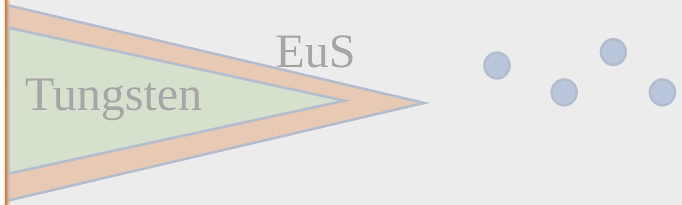
Photocathode



Cs:GaAs photocathode excited with circularly polarized light

Field Emission/Spin Filter



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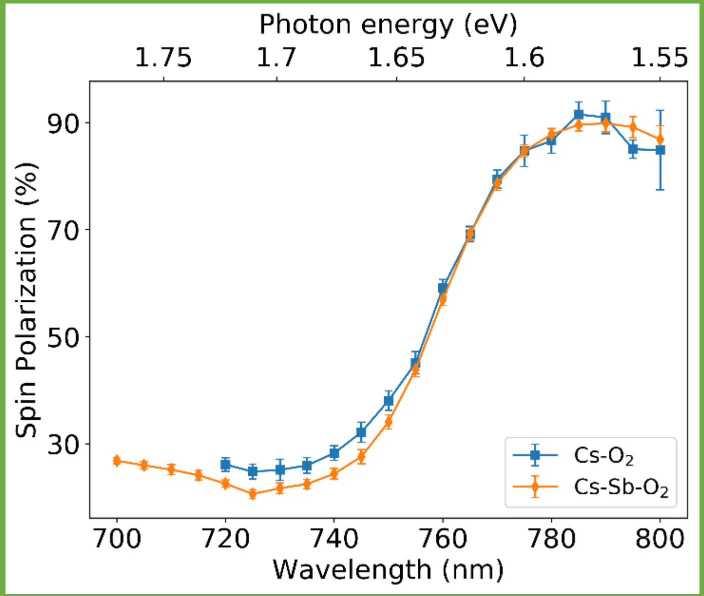
GaAs Photocathodes

- >90% polarizations achievable with strained GaAs
- 52 mA record current (un-polarized)
- <150 meV energy spread
- High quantum efficiencies (QE)
- Commercially available

Strained GaAs has achieved >90% spin polarizations



Journal of Applied Physics. 127, 124901 (2020)

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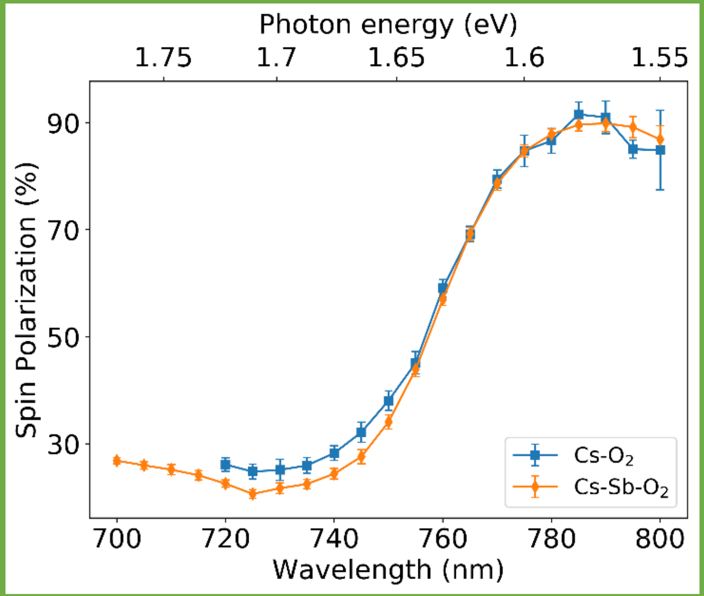

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Since the 1980s, GaAs photocathodes have been the state-of-the-art spin-polarized electron source, used at facilities all over the world.

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✕ Needs Cs layer, making the cathode unstable, sensitive and short-lived

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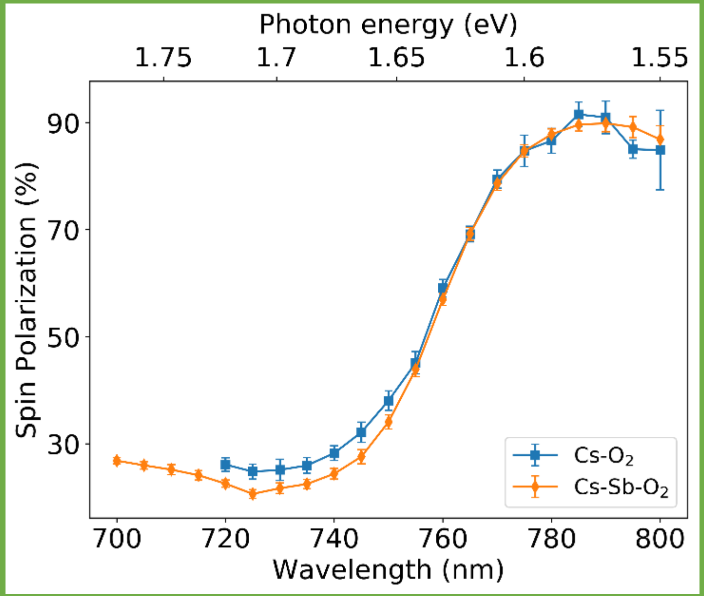

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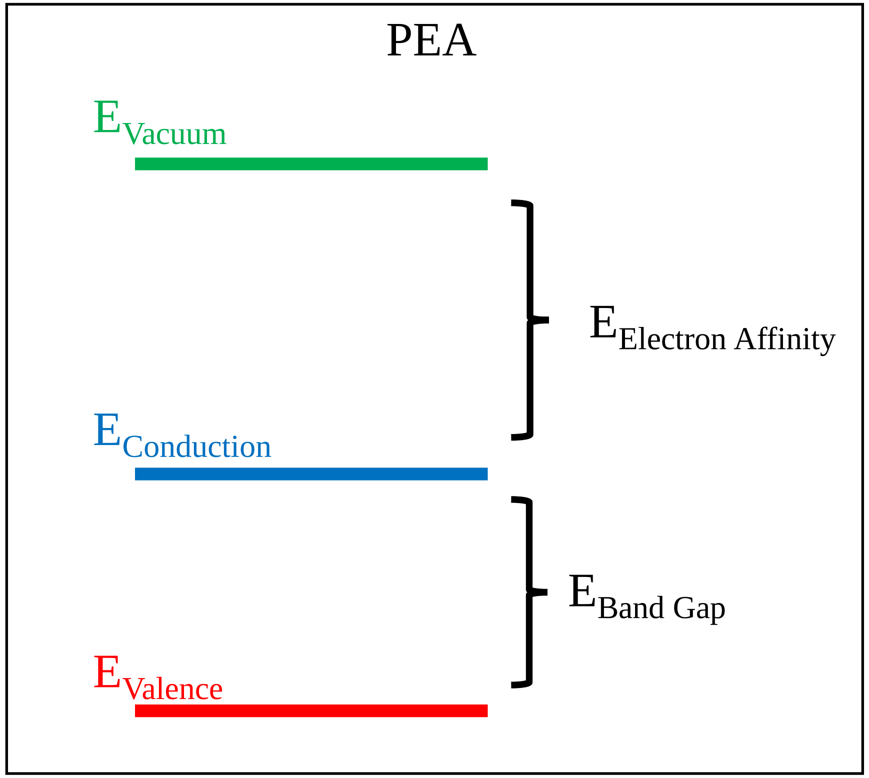
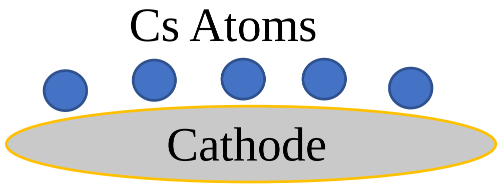
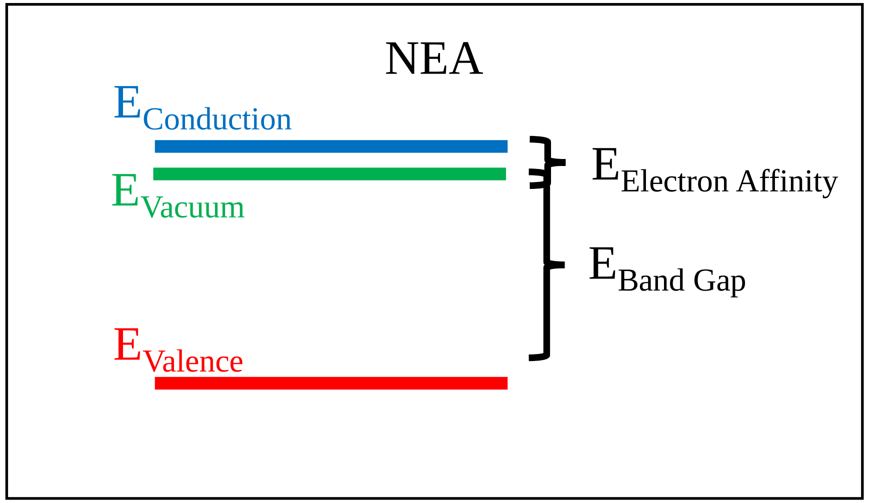
Top of Valence Band Photoemission



Electropositive metal, like cesium, forms a strong dipole layer that lowers the vacuum level

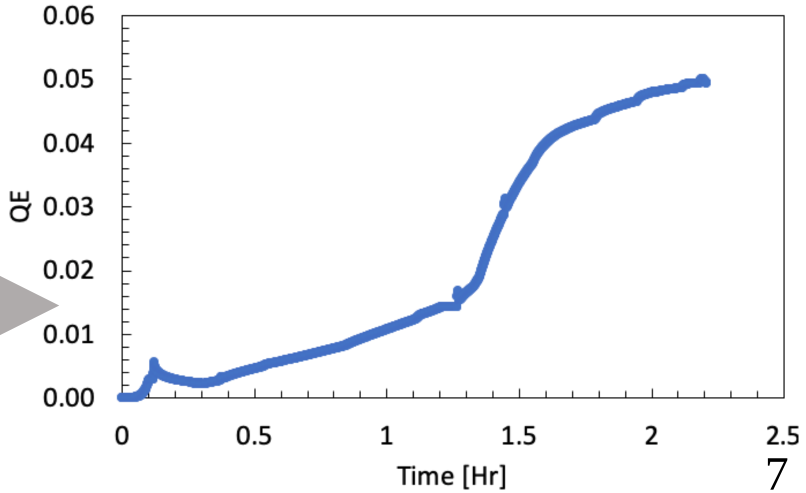




Workfunction $= E_{Band\ Gap} + E_{Electron\ Affinity}$

NEA Cathodes $E_{Band\ Gap}$:
- GaAs* = 1.42 eV
- GaN = 3.2 eV (C), 3.4 eV (H)

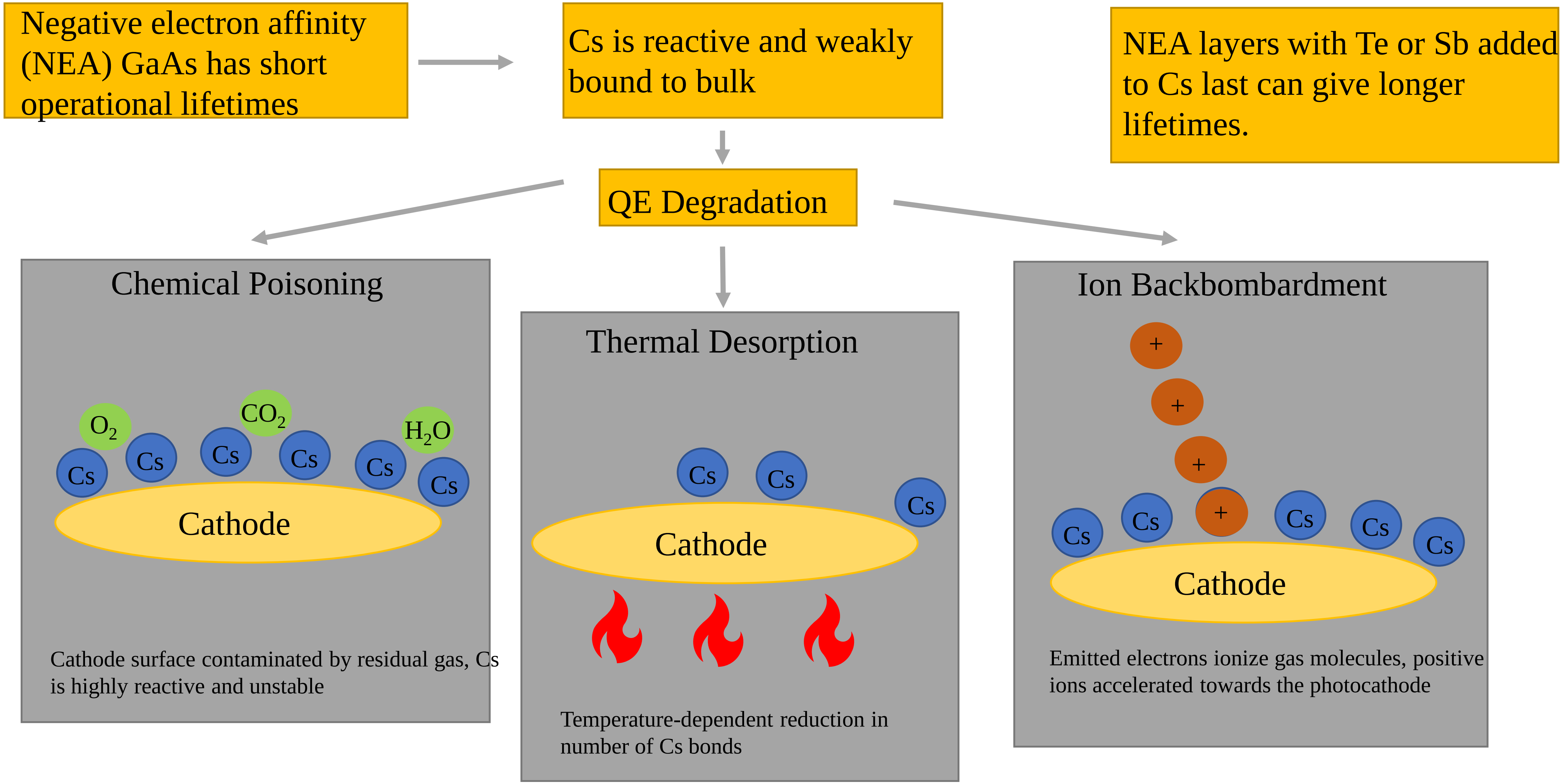
Activation to NEA



$$QE(\lambda) = \frac{\#\ electrons\ out}{\#\ photons\ in}$$

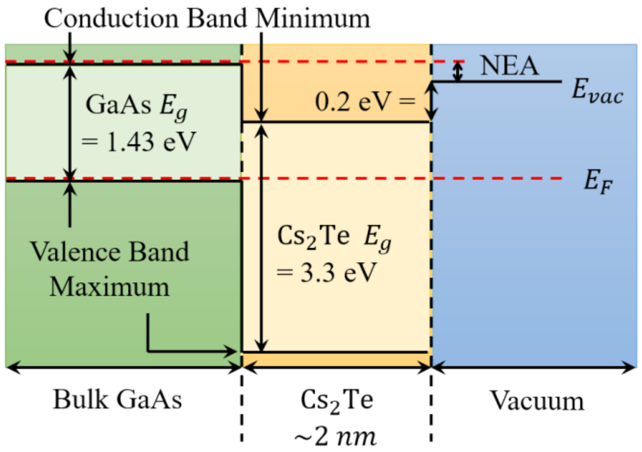
*Also requires O_2 for NEA

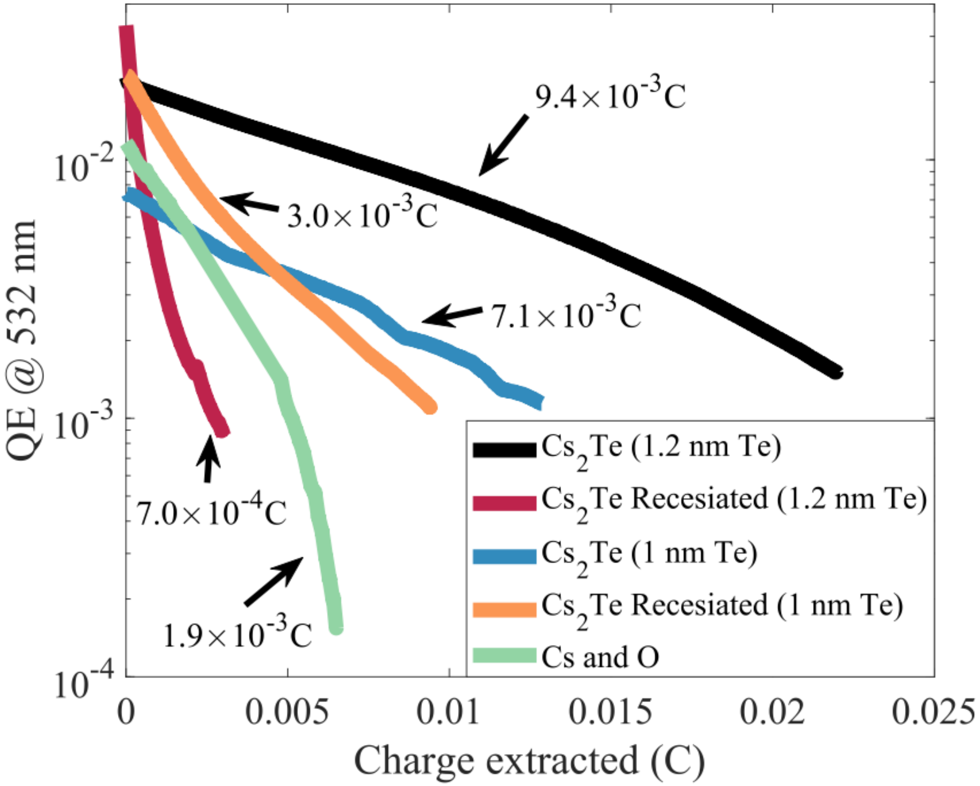
- GaAs requires activation to achieve Negative Electron Affinity (NEA) – polarized electrons can then be emitted from the bottom of the conduction band.
- Depositing a layer of Cs or Cs-O is the traditional method of activation.



Alternative NEA Coatings: Cs-Te

Can use Cs-Te to activate to NEA





GaAs activated with conventional Cs-O, then with Cs_2Te

Cs_2Te activation gave a 5x improvement in charge extraction lifetime as opposed to Cs-O activation

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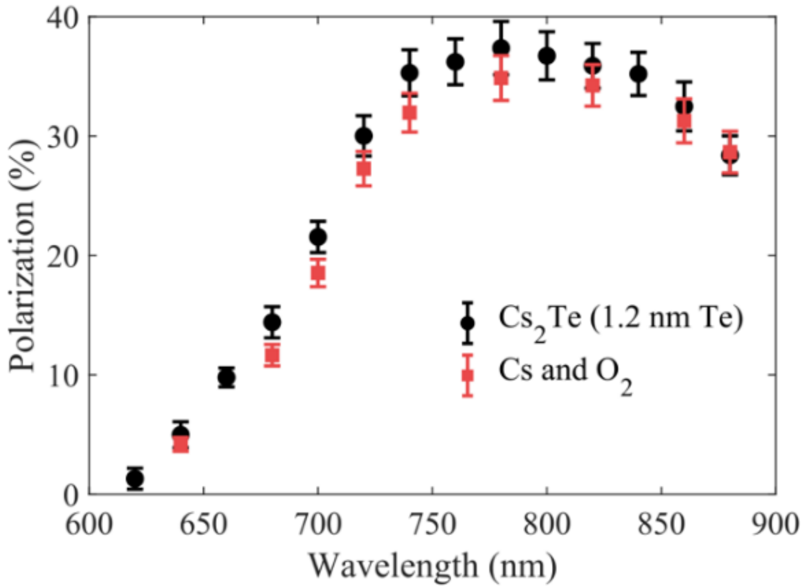
Spin polarization unchanged →



J. K. Bae, L. Cultrera, P. Digiacomo and I. Bazarov, *Appl. Phys. Lett.*, 2018, **112**, 1–6.

Alternative NEA Coatings: Cs-Sb-O

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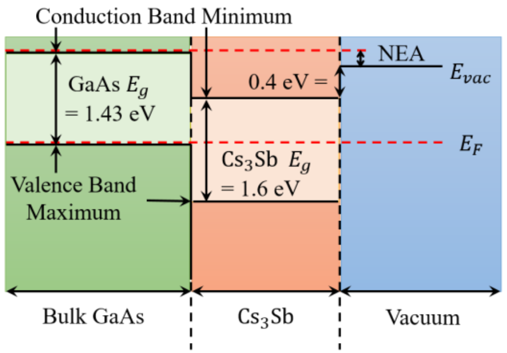
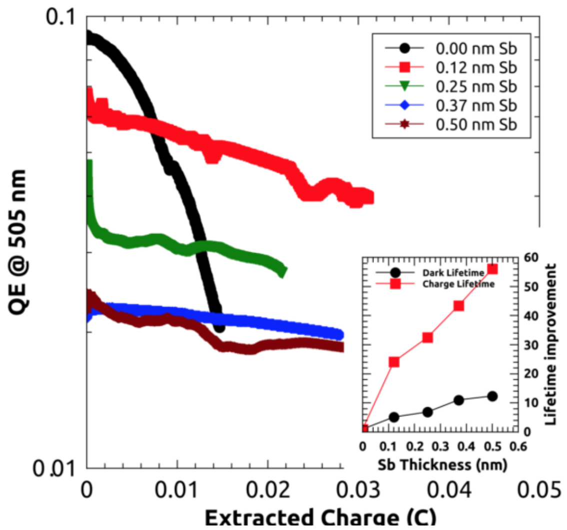
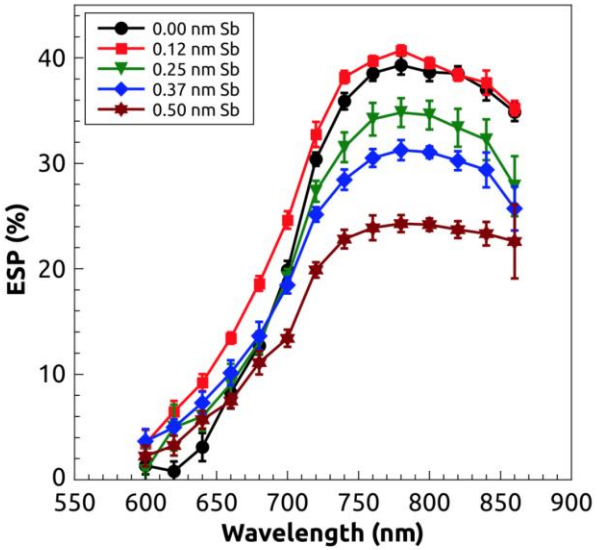




GaAs activated with varying Cs-Sb thicknesses



L. Cultrera, A. Galdi, J. K. Bae, F. Ikponmwen, J. Maxson and I. Bazarov, *Phys. Rev. Accel. Beams*, 2020, **23**, 23401.

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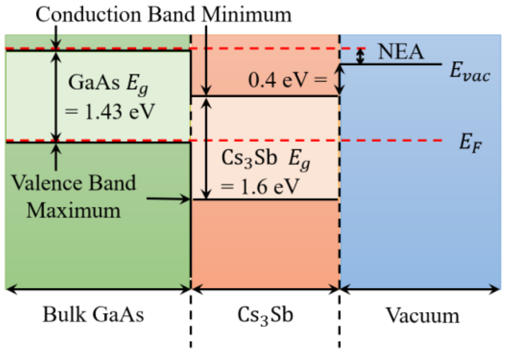

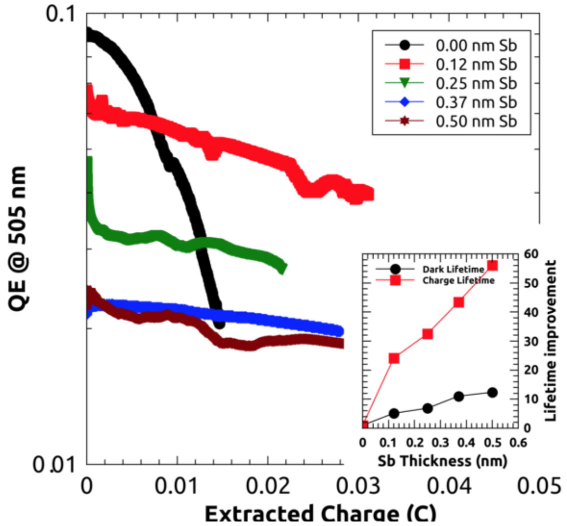

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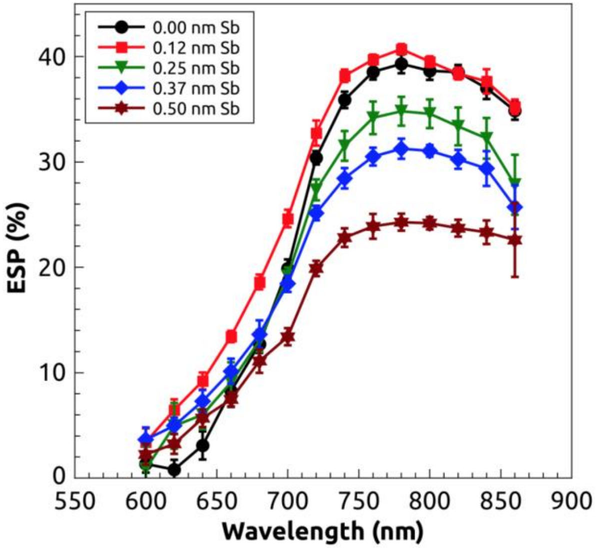

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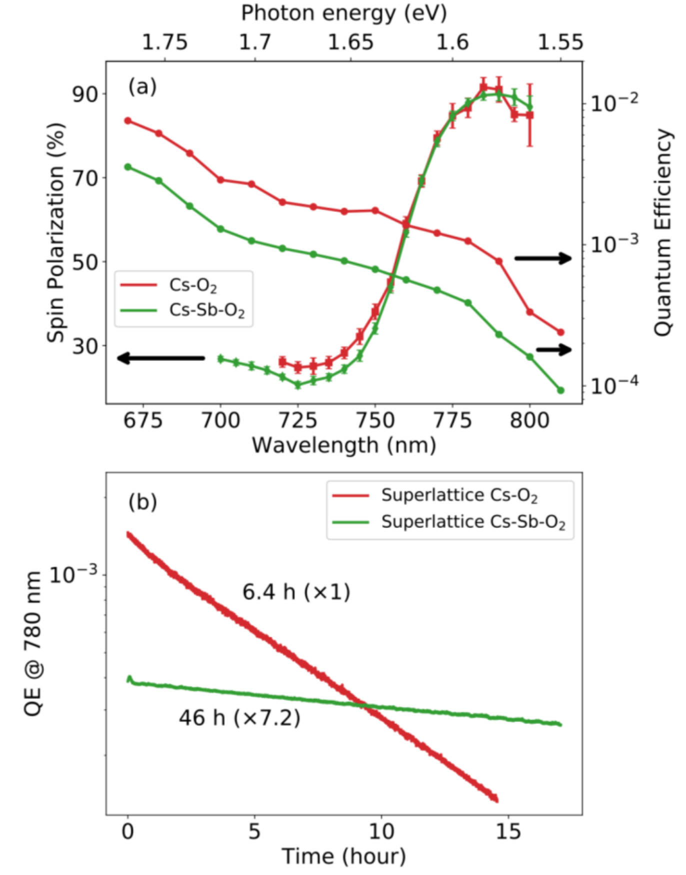
Superlattice GaAs activated with Cs-Sb-O



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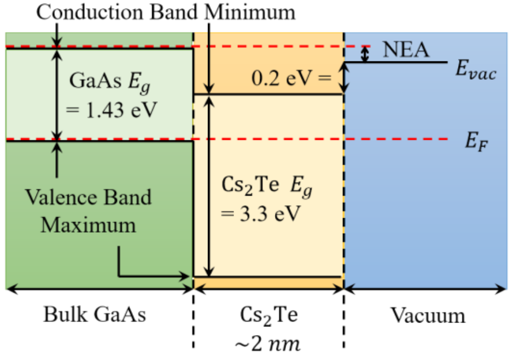

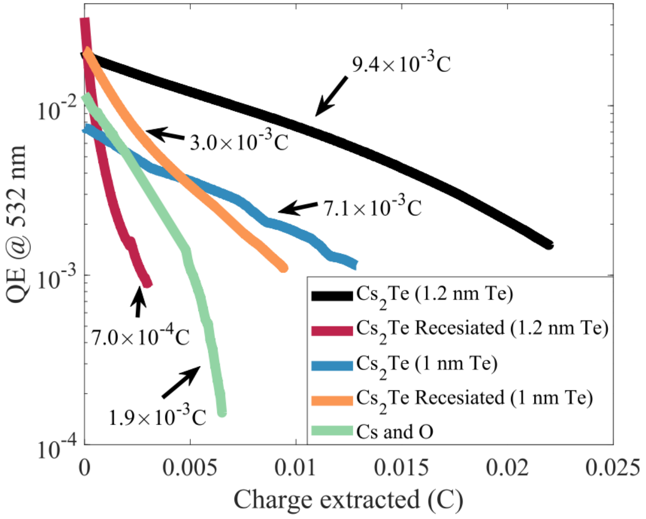

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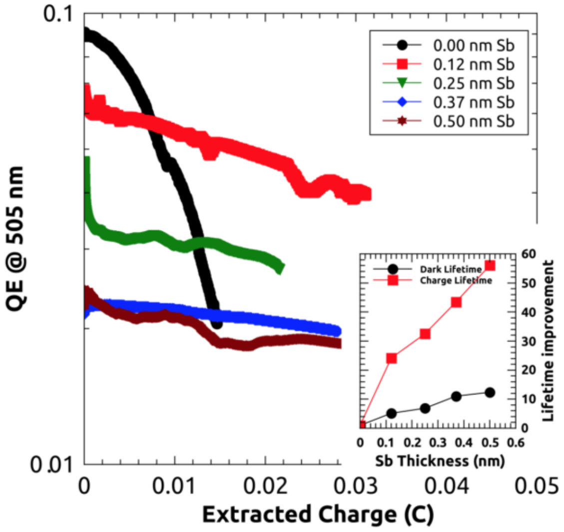

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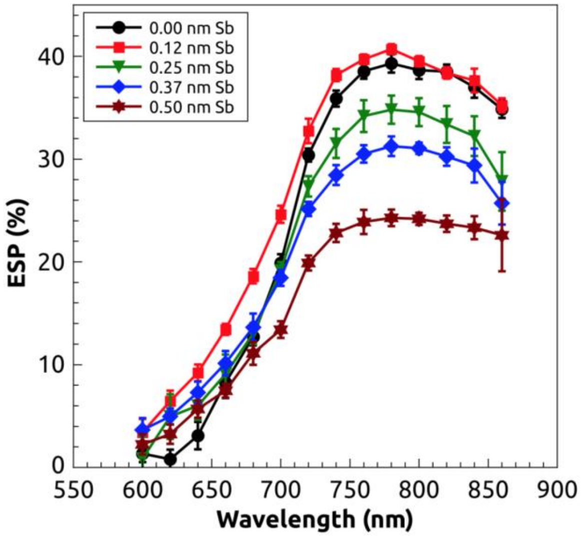

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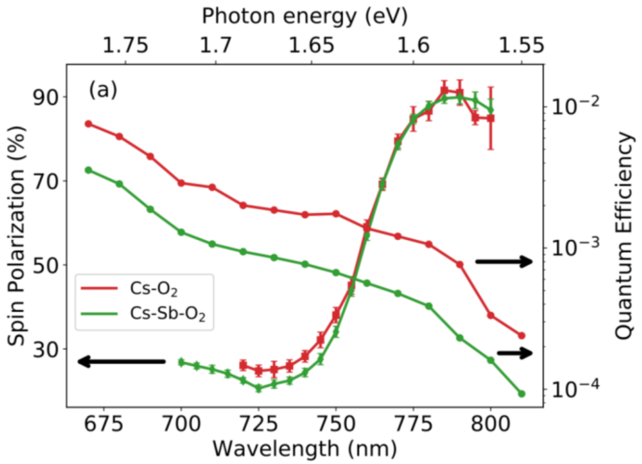

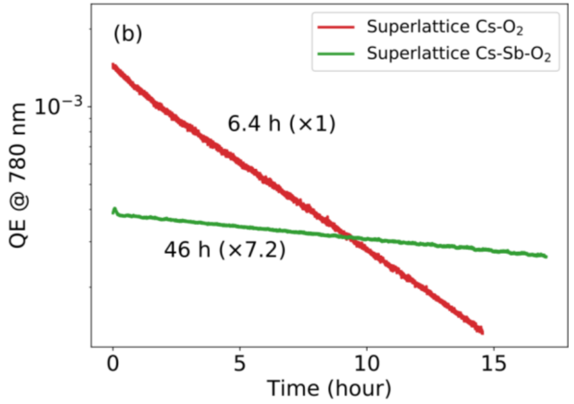

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Beyond GaAs: New Materials

- Is it possible we can find an alternative to GaAs that isn't so sensitive?
- Two examples being studied:

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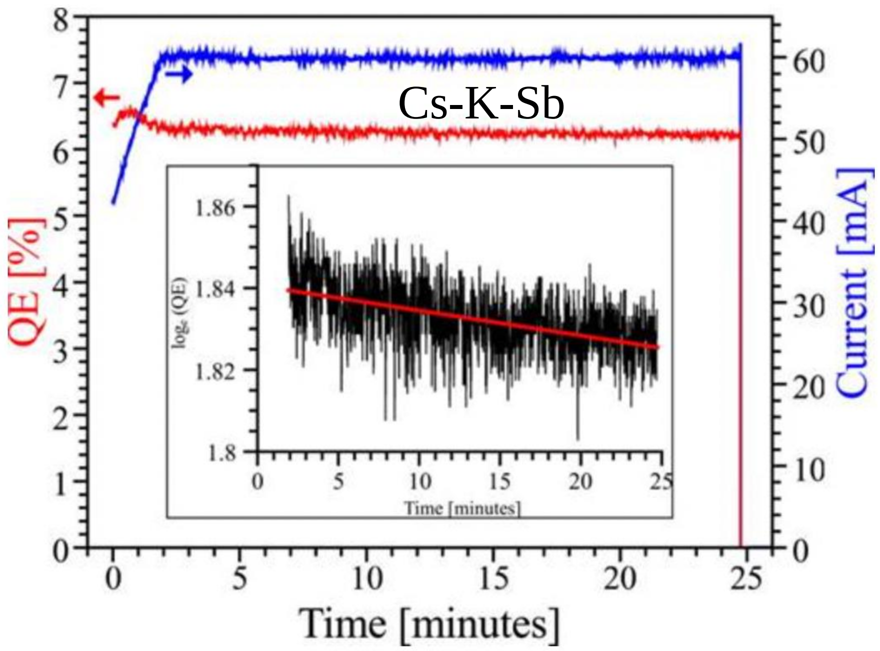
Alkali Antimonides: A family of robust bulk visible light photoemitters



B. Dunham et al. Appl. Phys. Lett. 102, 034105 (2013)

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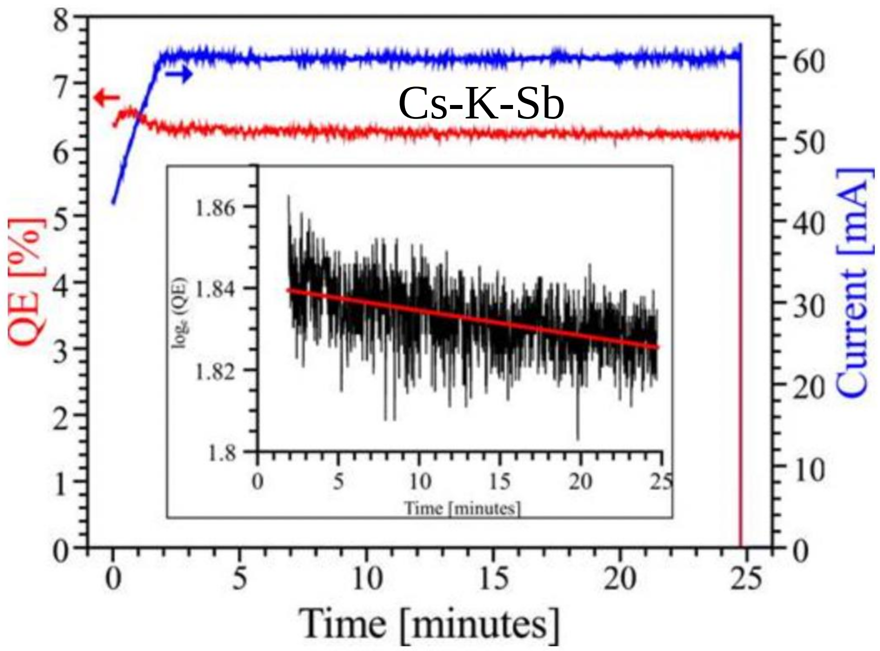
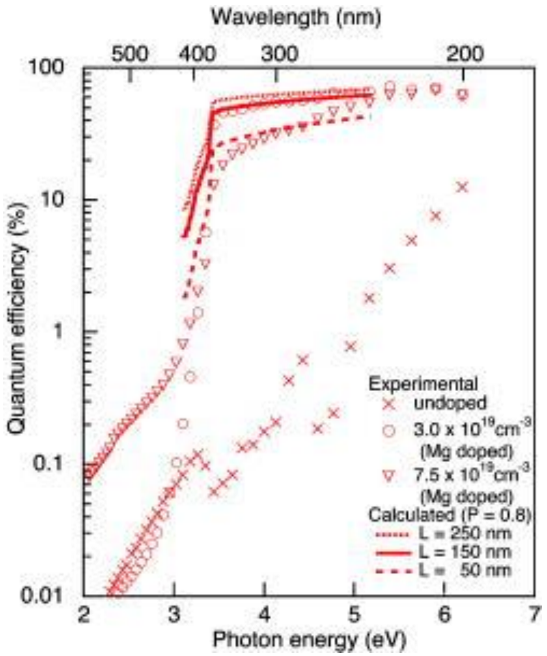


B. Dunham et al. Appl. Phys. Lett. 102, 034105 (2013)

GaN: Wide Bandgap analog of GaAs



S. Uchiyama et al. Appl. Phys. Lett. 86, 103511 (2005)

Alkali Antimonides for polarized photoemission

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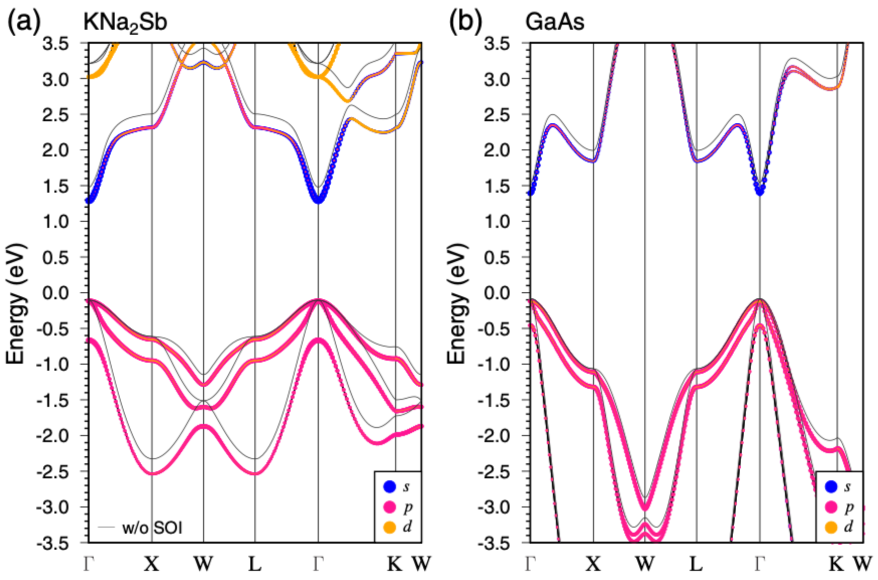
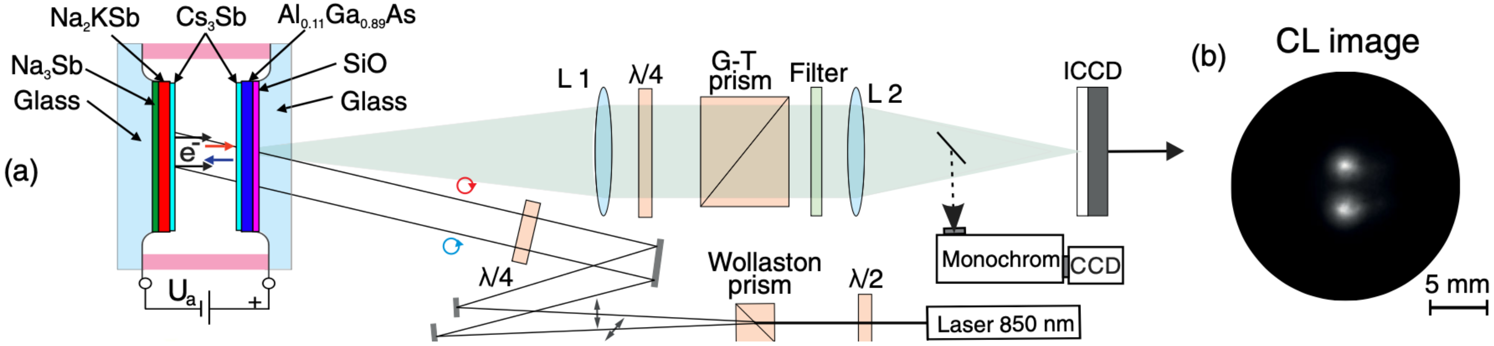
- However, recent measurement suggests polarized photoemission is possible:



Band Structure very similar to GaAs…

PHYSICAL REVIEW LETTERS **129**, 166802 (2022)



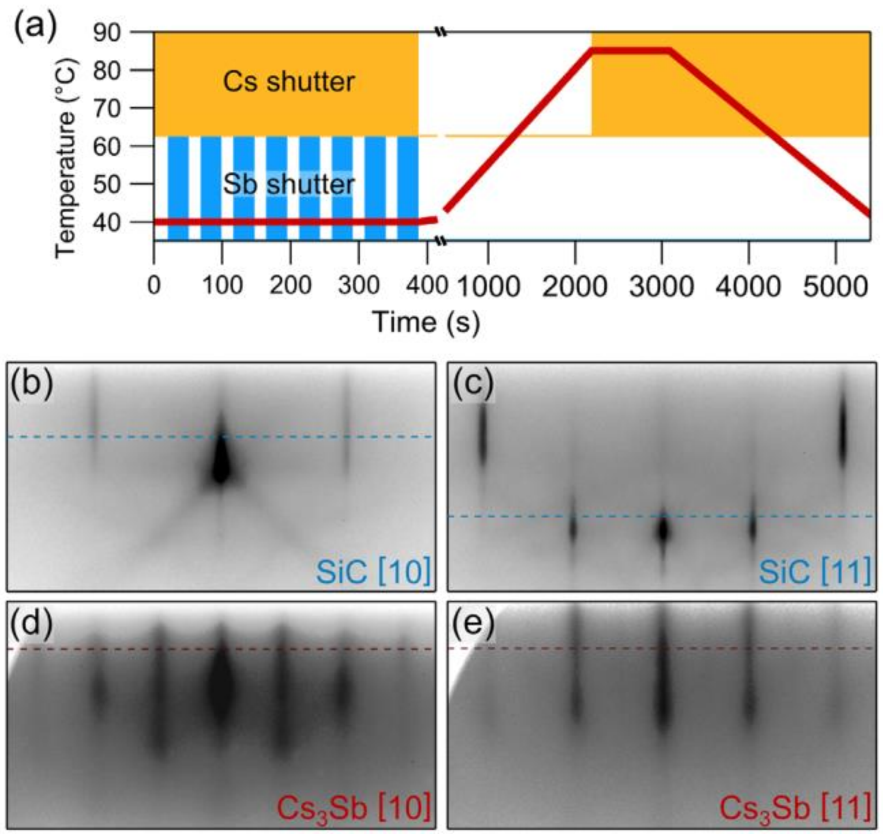
Polarization inferred from degree of circular polarization of cathodoluminescence (CL). Observed similar levels of CL polarization as unstrained GaAs---- polarized electrons!

Very promising result! Future study should include direct polarization measurement (eg. Mott scattering).

Single-Crystal Alkali Antimonides

- Atomically Ordered growth of alkali antimonides: paves the way for nanolayering.

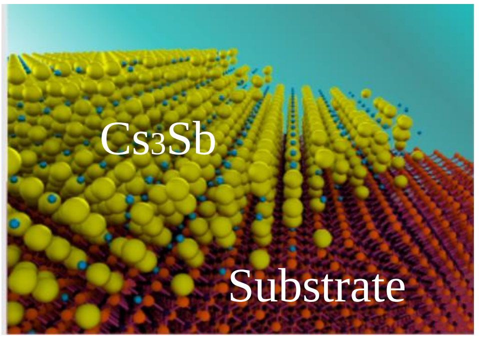
PHYSICAL REVIEW LETTERS **128,** 114801 (2022)

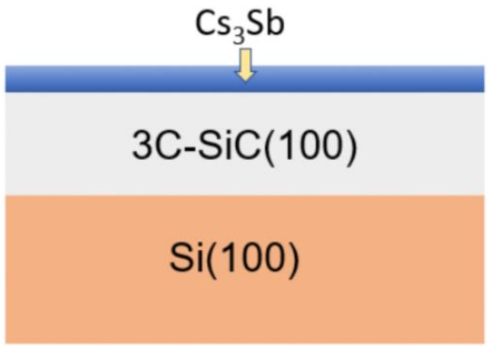


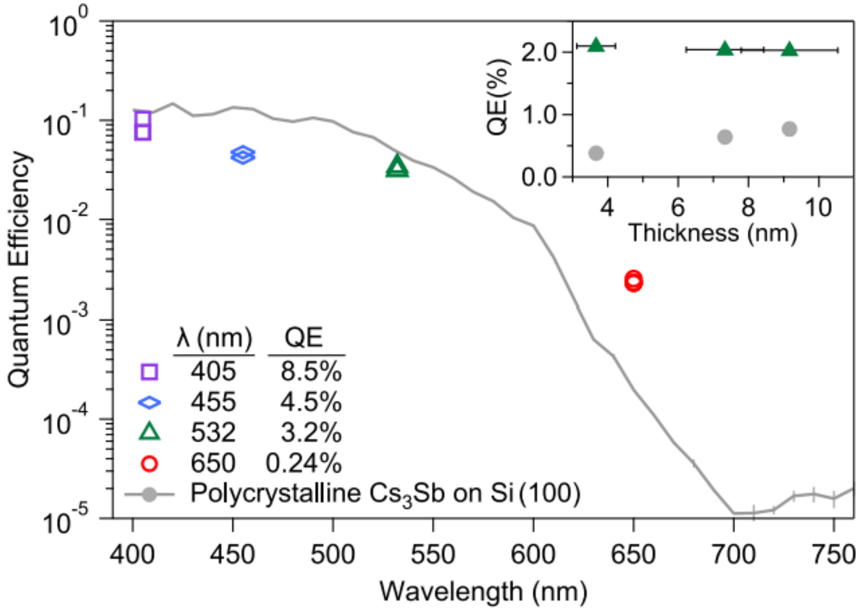
RHEED Images:

Substrate: 3C-SiC->

Photocathode -> Cs_3Sb

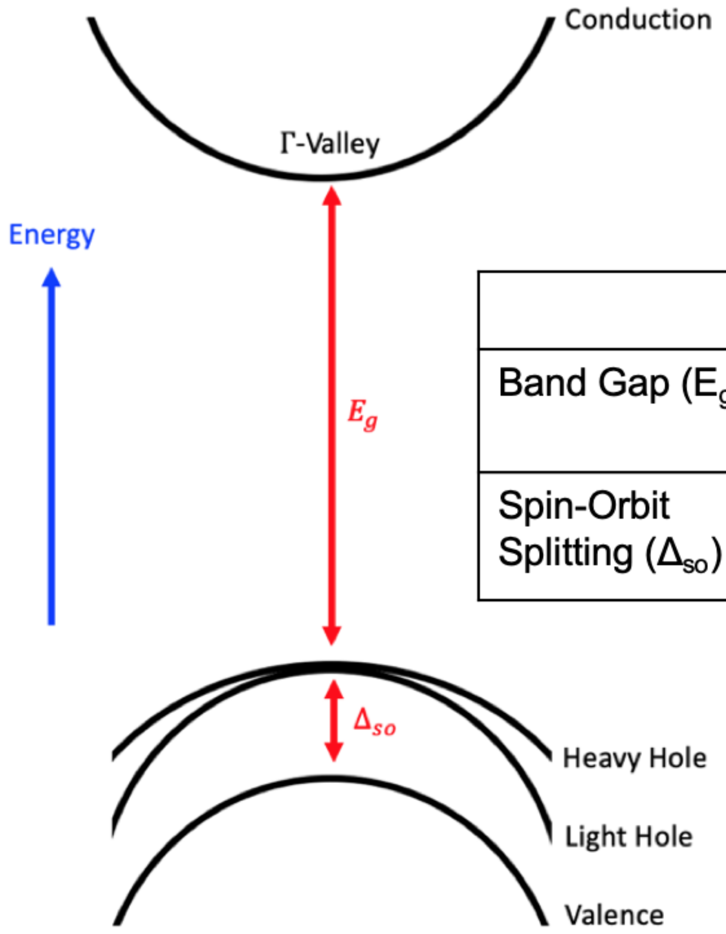




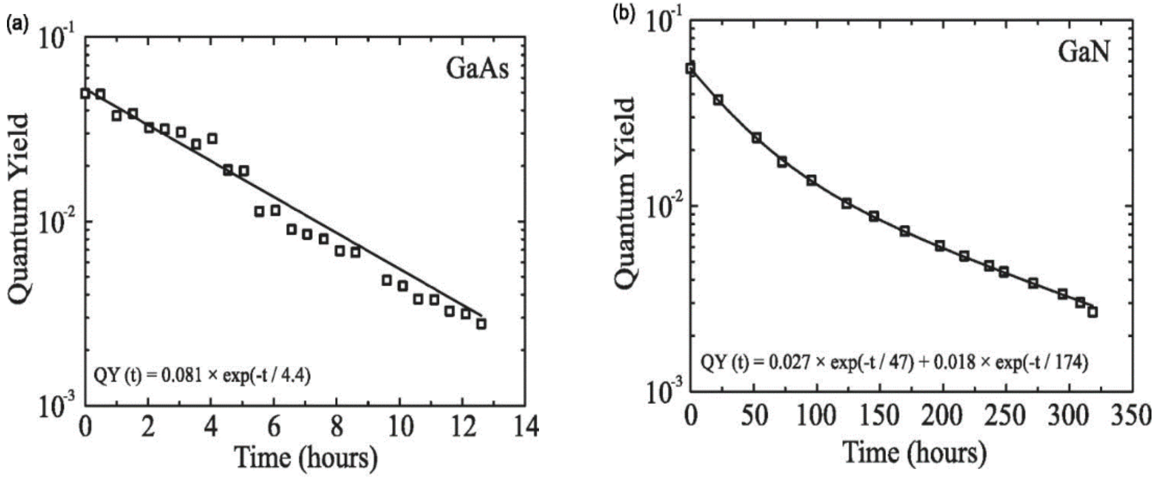


GaN as a Spin-Polarized Source

- ✓ Wurtzite or Zinc-Blende orientation
- ✓ >50% QE achievable with W-pGaN
- ✓ Comparable spin relaxation time to GaAs (~5 ns)
- ✓ Could be strained for high polarization
- ✓ 3.2 eV band gap is conveniently at the second harmonic of Ti:Sapphire
- ✓ Less Cs to get to NEA→ stronger bond to Cs?
- ✓ NEA with Cs only



	Wurtzite	Zinc-Blende
Band Gap (E_g)	3.4 eV	3.2 eV
Spin-Orbit Splitting (Δ_{so})	8 meV	20 meV

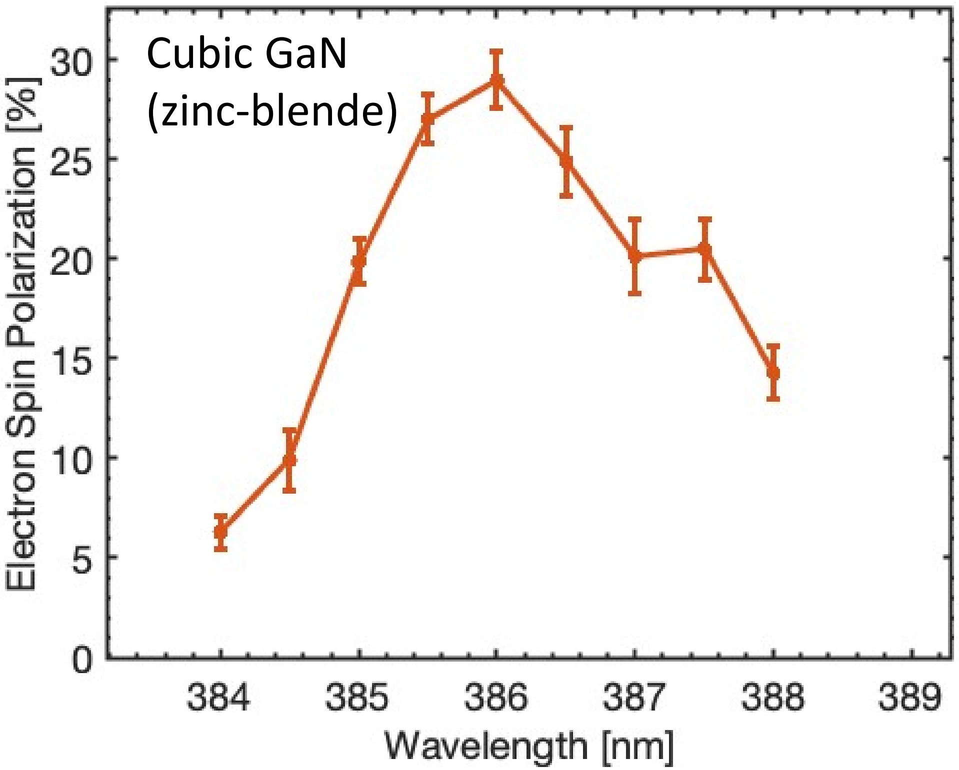


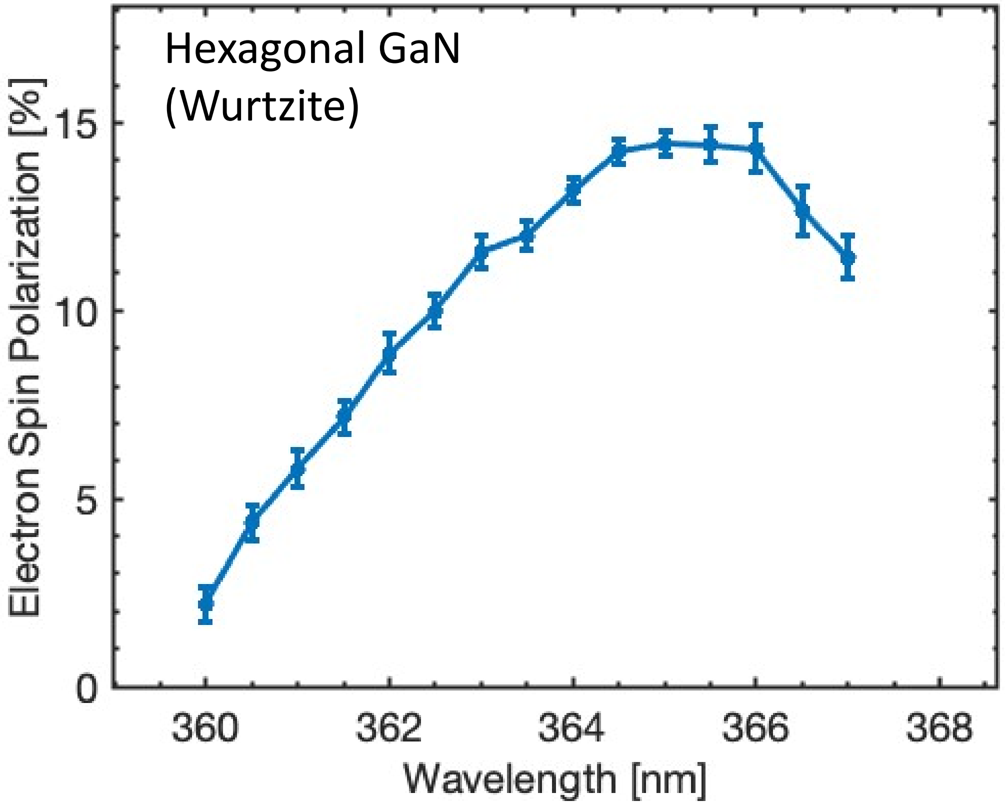
GaAs for comparison: $E_g = 1.42$ eV, $\Delta_{so} = 0.34$ eV

J. Vac. Sci. & Technol. B 32, 06F901 (2014)

First results with GaN

	Cubic	Hexagonal
Band Gap	3.2 eV	3.39 eV
SO Split	20 meV	8 meV
Spin Relaxation Time	2 ns	50 ps





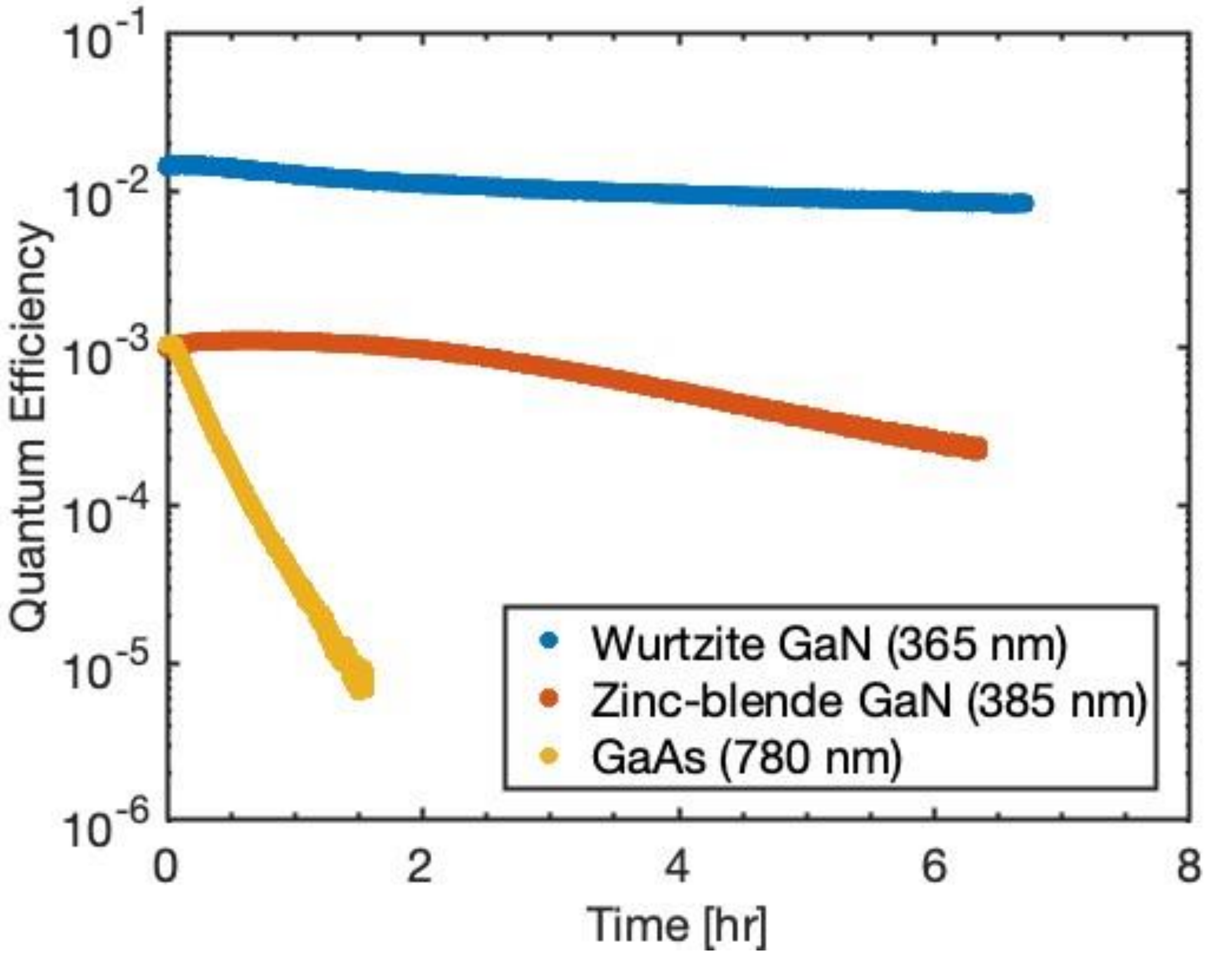
GaN Photocathode Lifetime

Lifetimes monitored at respective photon energy corresponding to emission threshold

GaAs activated in same chamber, monitored at 780 nm for reference

ZB-GaN’s threshold lifetime was 15 times longer than GaAs’s

W-GaN’s threshold lifetime was 38 times longer than GaAs’s

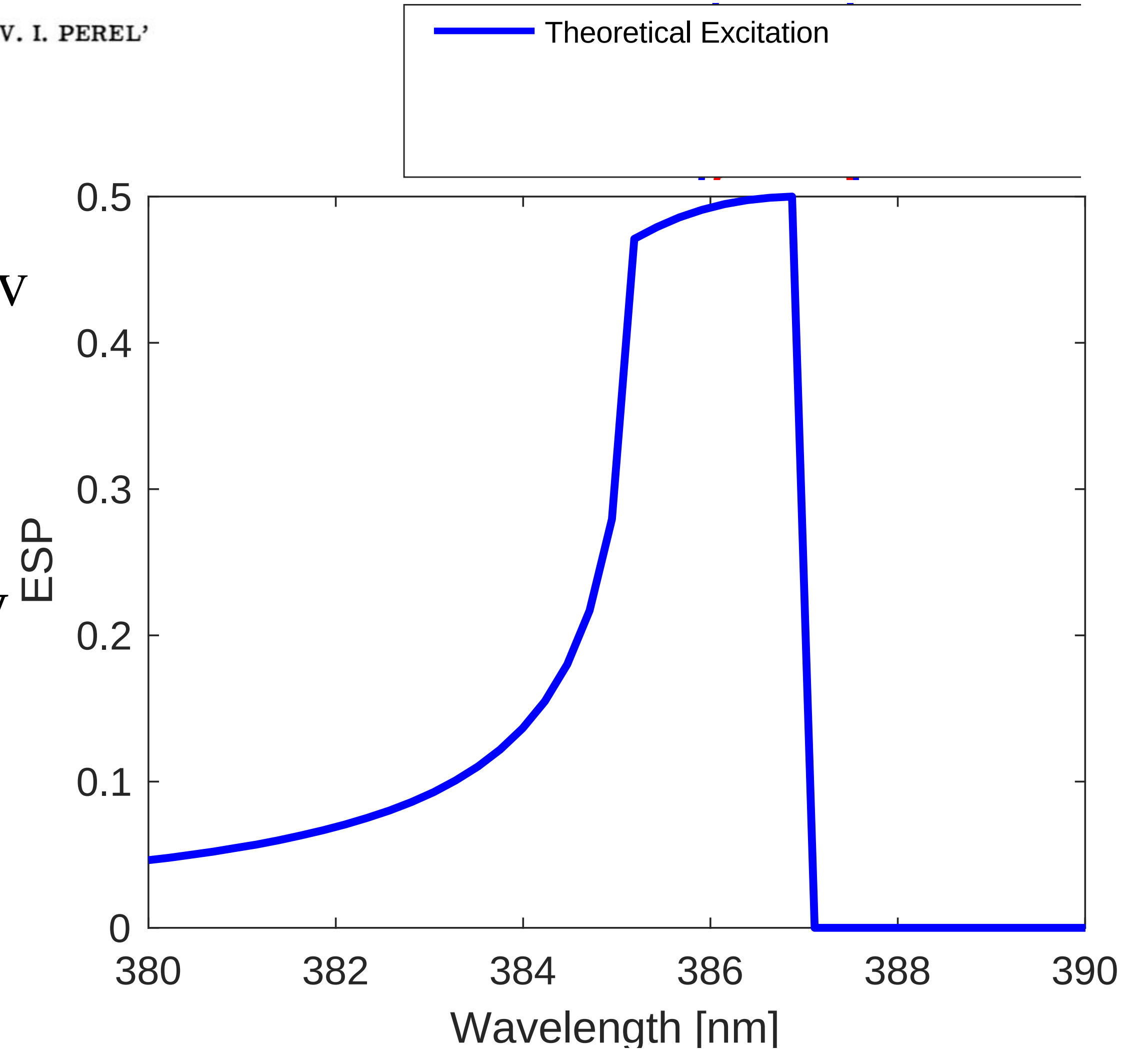


Model

SOVIET PHYSICS JETP VOLUME 33, NUMBER 5 NOVEMBER, 1971

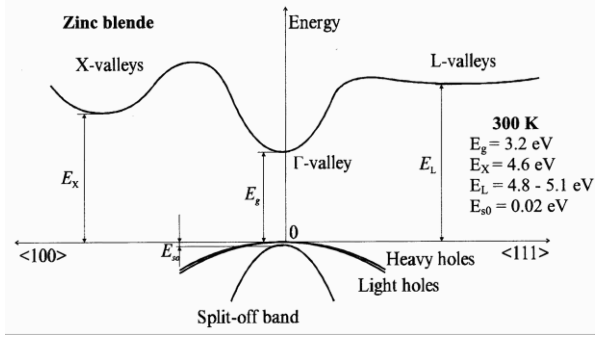
SPIN ORIENTATION OF ELECTRONS ASSOCIATED WITH THE INTERBAND ABSORPTION OF LIGHT IN SEMICONDUCTORS

M. I. D'YAKONOV and V. I. PEREL'



- Initial excited spin polarization from cubic GaN approximated with model by D'yakonov and Perel
- Excited distribution peaks at 50% maximum, as expected
- Mixing of split-off band with light and heavy hole bands

$$P_o = \frac{\sum_n P_o^{(n)} K_n}{\sum_n K_n}$$



Model

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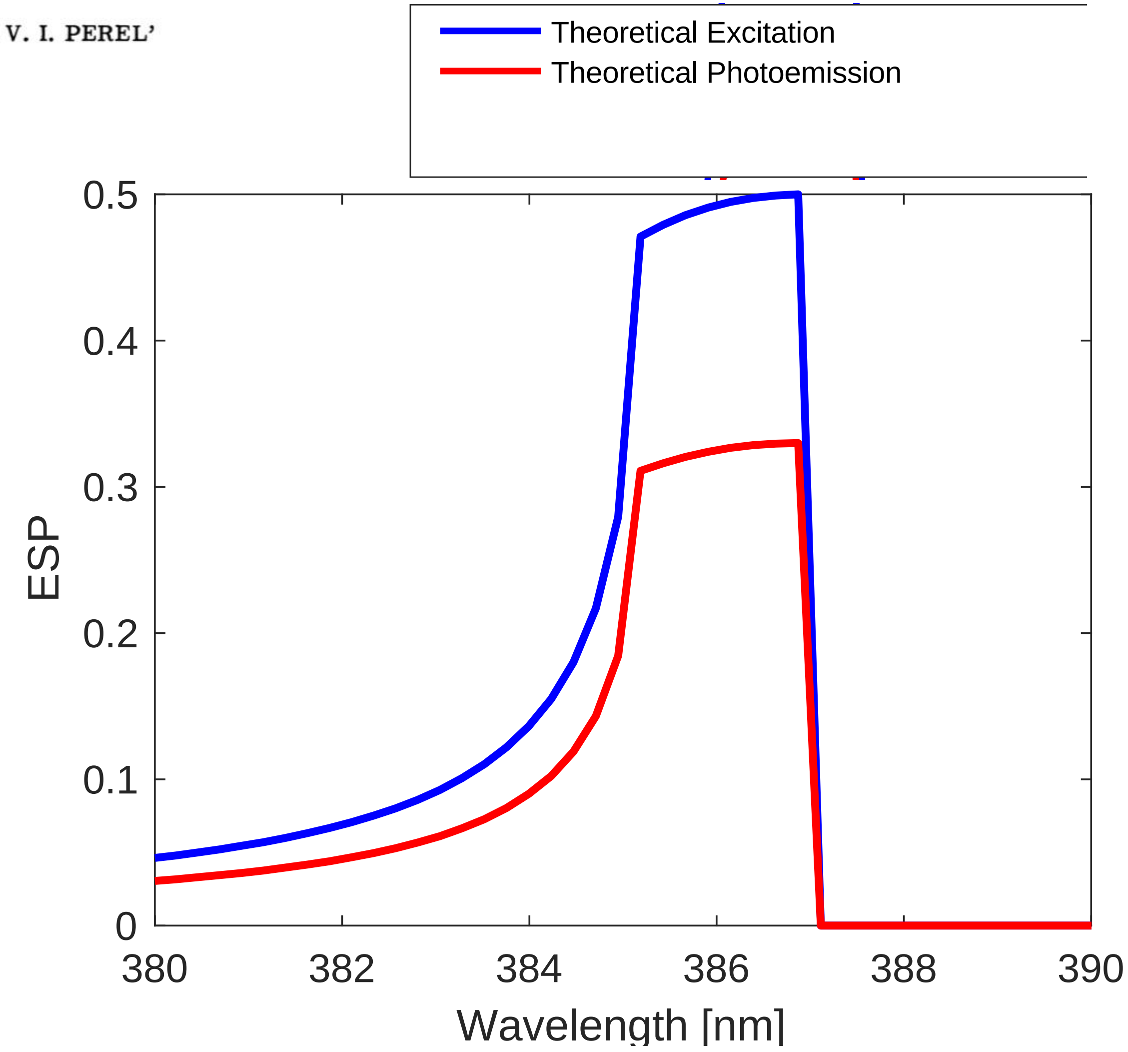
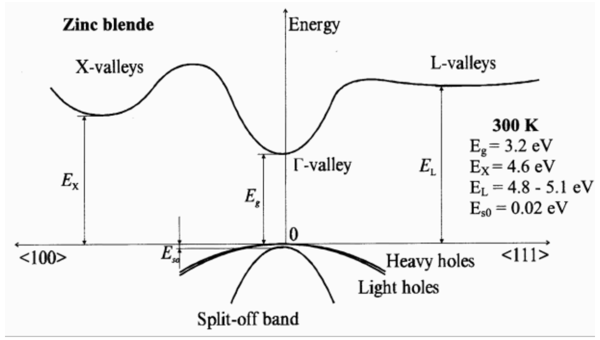
Scale model to approximate de-polarization effects

Peak (measurement maximum) at 33%, on par with that of GaAs

Note that the peak was scaled according to a fit with our data!





Model

$$P_{eff} = \frac{N_{+,eff} - N_{-,eff}}{N_{+,eff} + N_{-,eff}}$$

Since the spin-orbit splitting is so small, need to consider measuring spectrum with incident light spectra

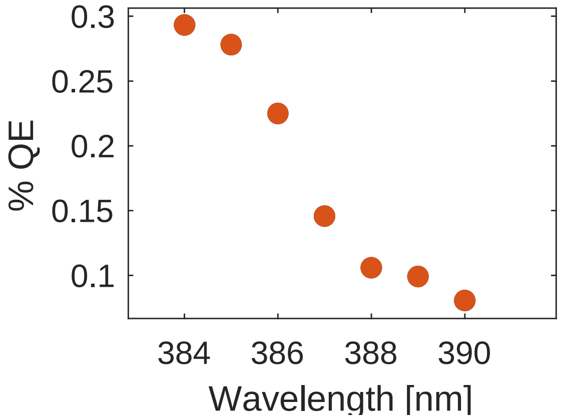
Calculate effective polarization based on the light bandwidth

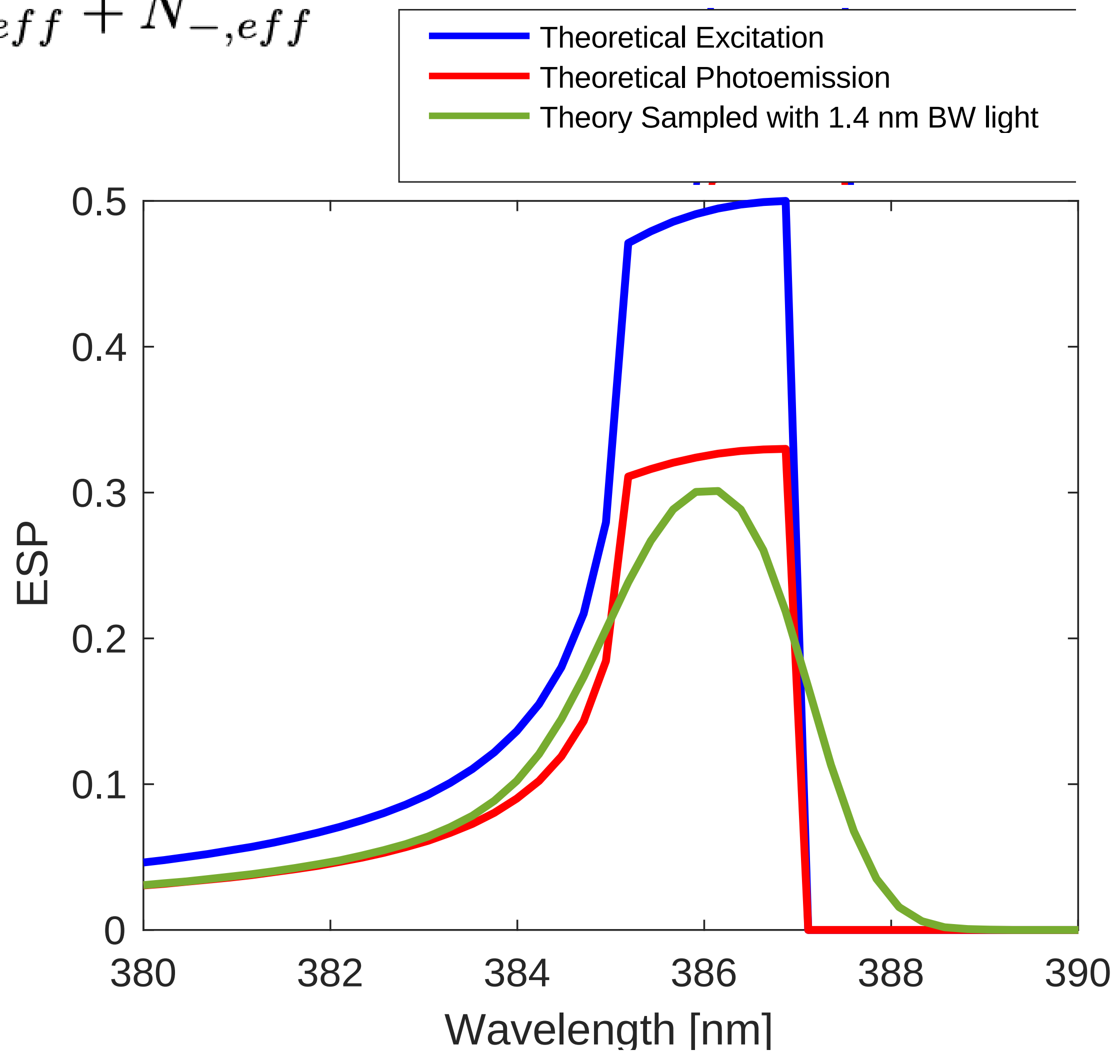
$$N_{\pm}(\lambda, B) = \int I(\lambda', \lambda, B) N_{\pm}(\lambda') QE(\lambda') d\lambda'$$

Gaussian light spectrum with variable bandwidth (B) and center at lambda

$$P_e(\lambda) = \frac{N_+(\lambda) - N_-(\lambda)}{N_+(\lambda) + N_-(\lambda)}$$

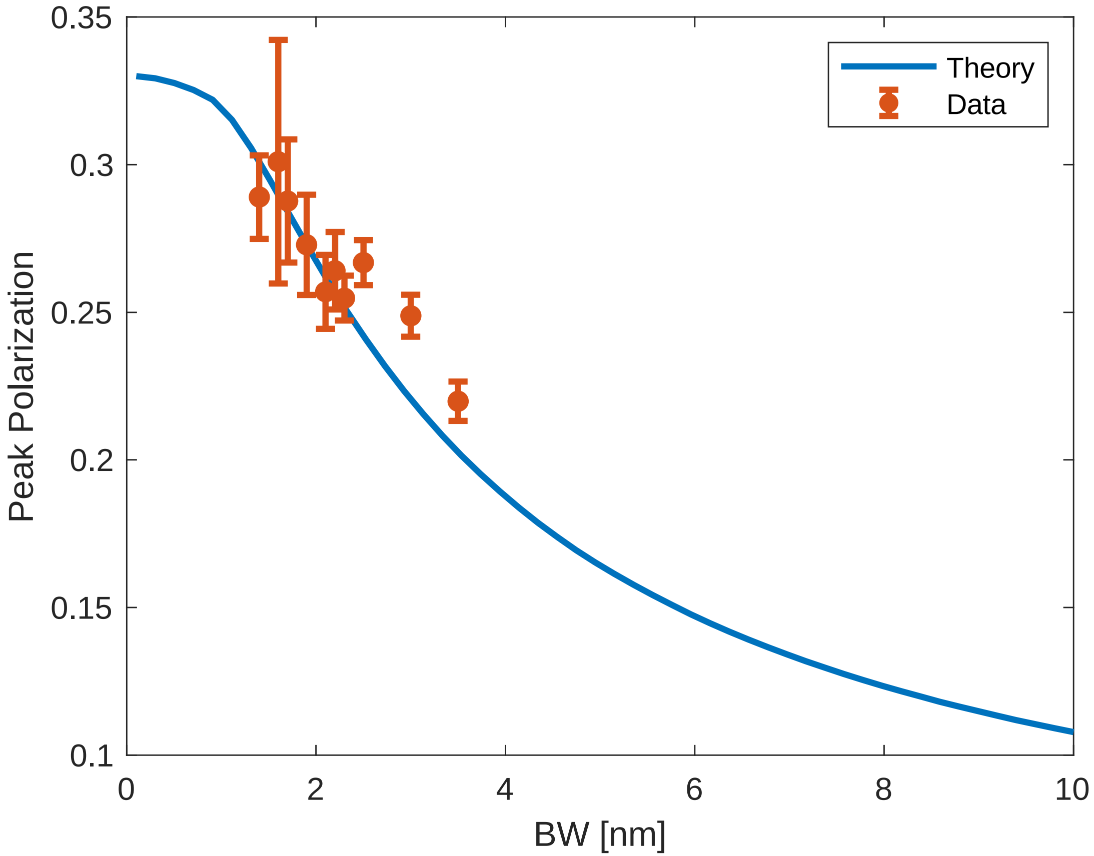
$$N_+ + N_- = 1$$

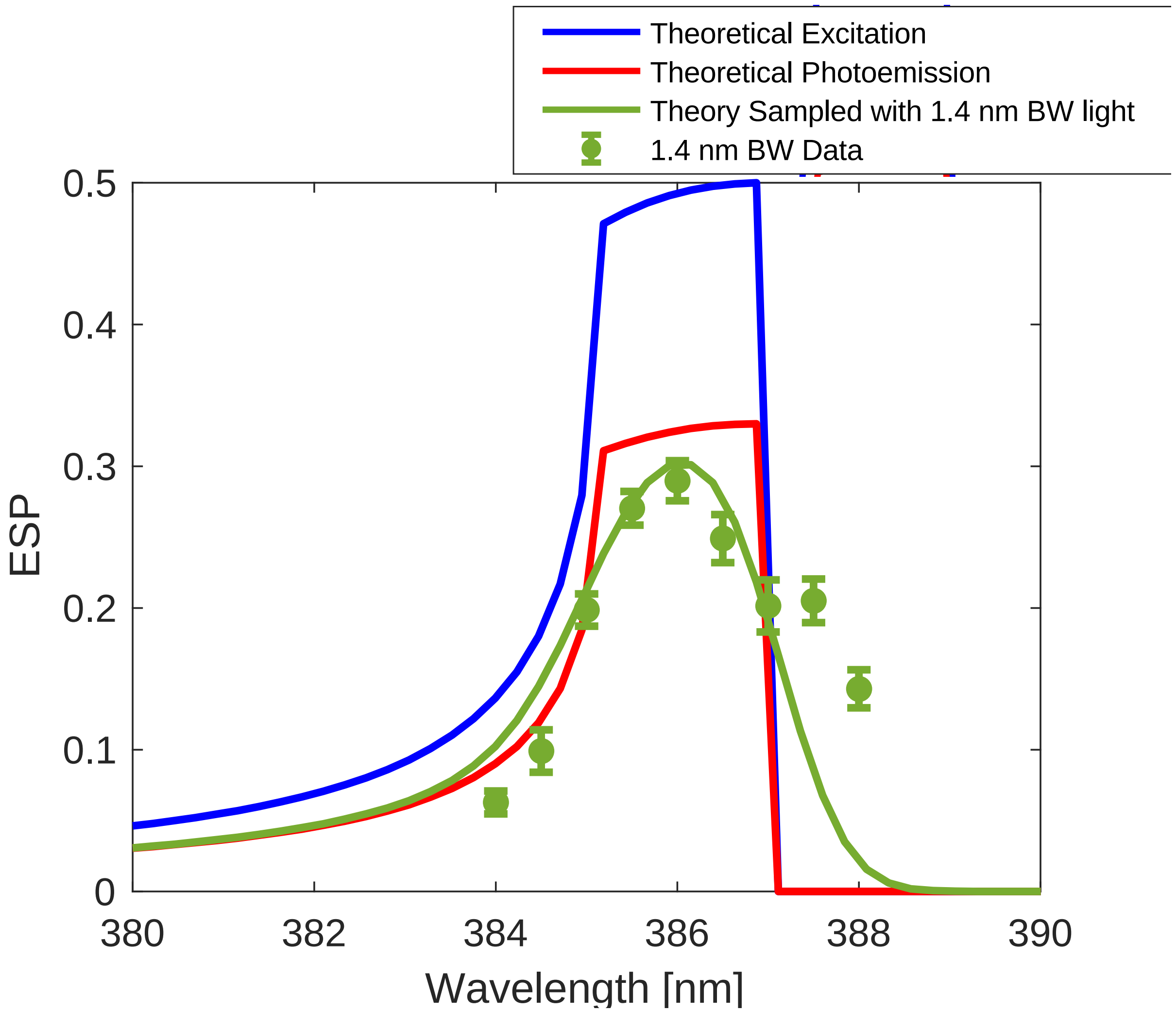




Model

Measurements confirm bandwidth limit





Our 1.4 nm bandwidth measurements may be close to the theoretical maximum.

Conclusion

Many developments in NEA activation layers have produced longer-lasting GaAs photocathodes

→

Advances in new materials (GaN, single crystal alkali antimonides) may provide a path towards more robust spin-polarized sources.

Thank you for your attention!

Cornell University

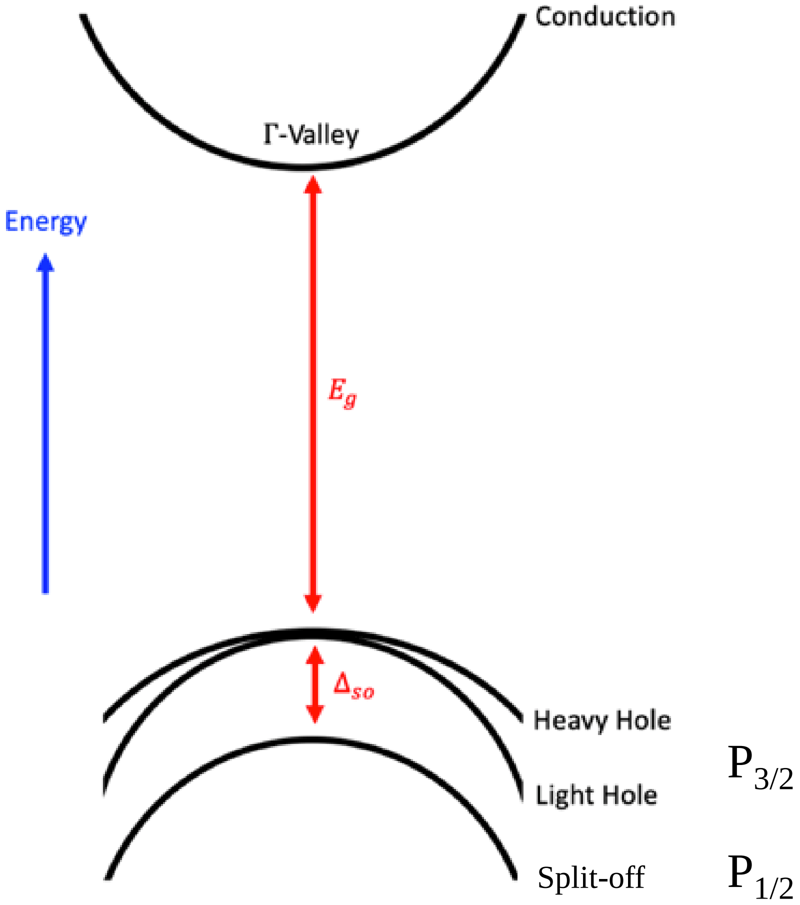
U.S. DEPARTMENT OF ENERGY

National Science Foundation

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

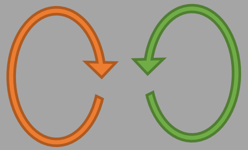
Bonus Slides

Spin Polarized Photoemission

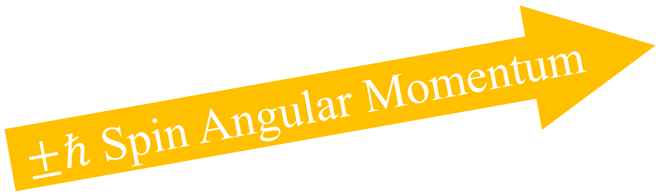


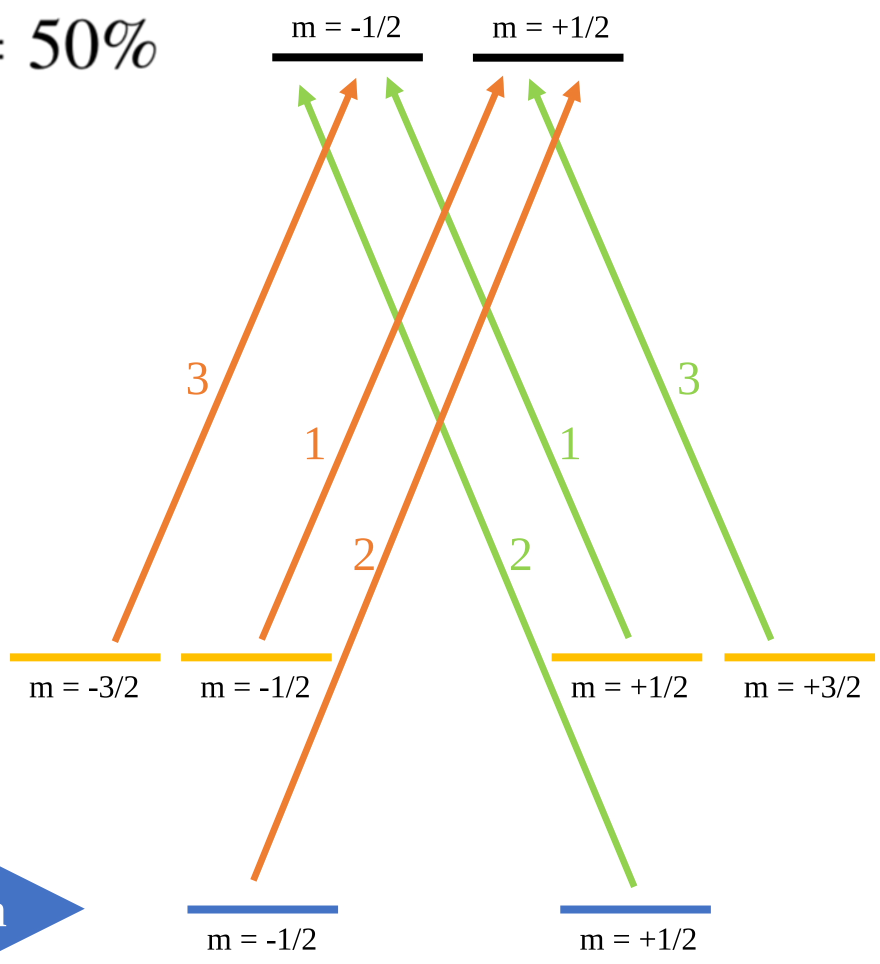
$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{3-1}{3+1} = 50\%$$

$\pm\hbar$ Spin Angular Momentum



Opposite-handed circularly polarized light





+1 in orange

-1 in green

D. T. Pierce & F. Meier. Phys. Rev. B 13, 5484.1976.