In Pursuit of the Narrow Cone

Prospects for 2-photon and n-type Photoemission from $Al_xGa_{1-x}N$

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Outline

MTE of GaAs Photocathodes

Likely Causes of MTE Growth

Pump-Probe Photoemission

n-Doped Photoemission

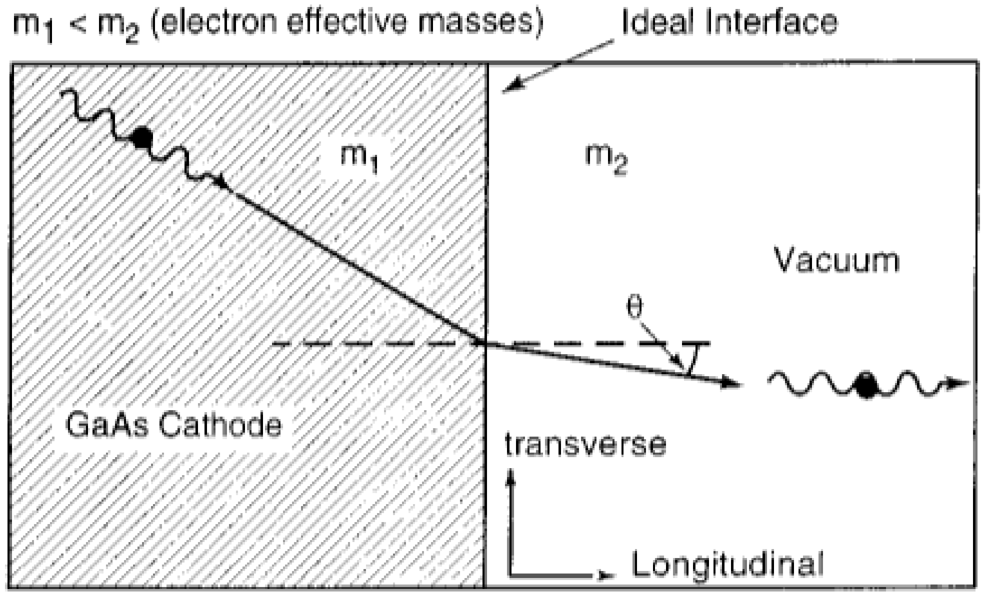
Experimental Results

Future Work

MTE of GaAs Photocathodes

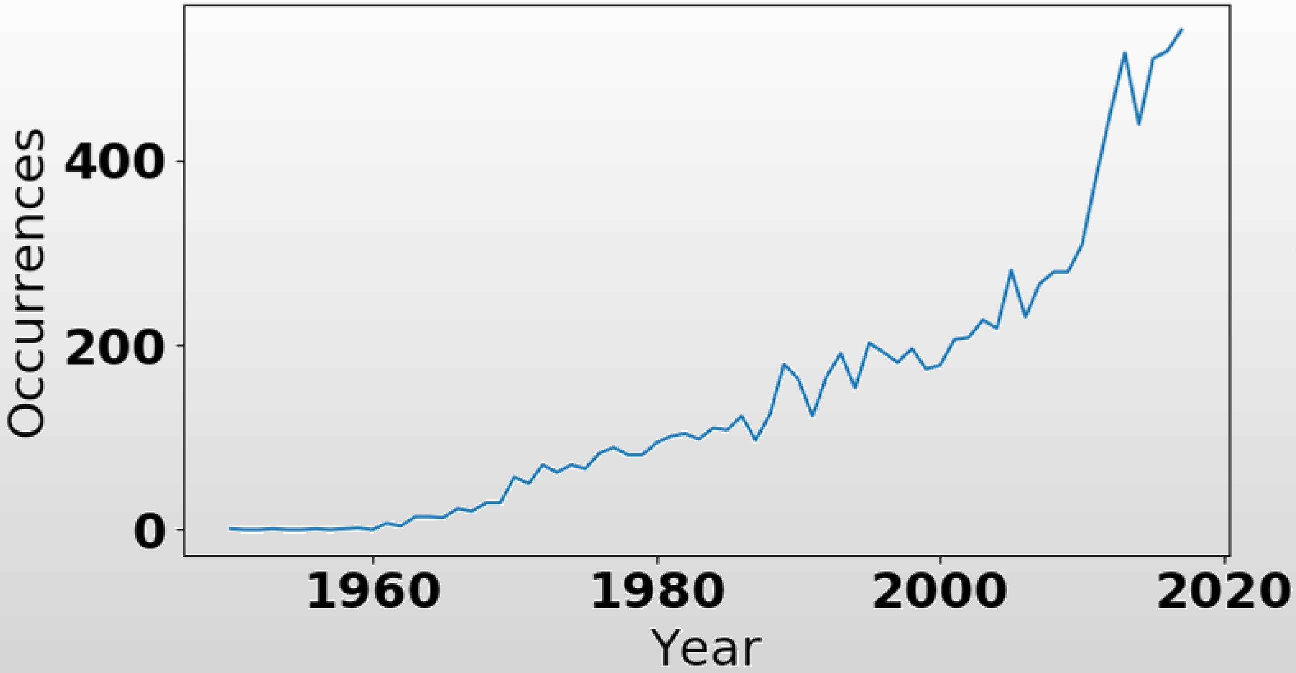
Low effective mass photocathodes like GaAs have been studied for decades

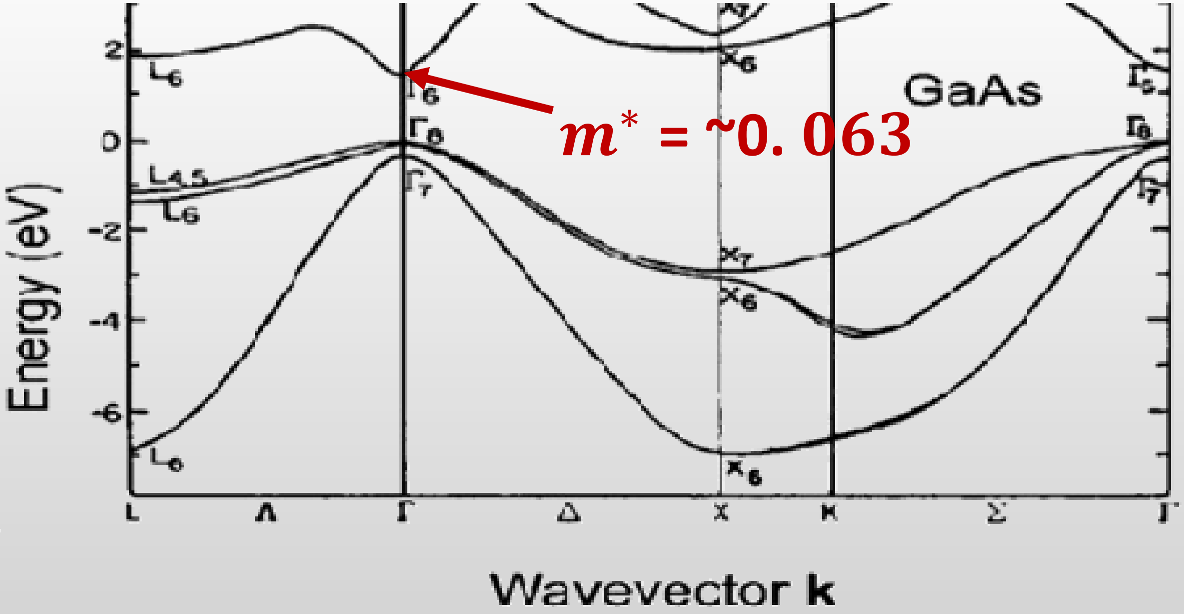
- Conservation of momentum says electrons should diffract as they enter vacuum and give subthermal MTE
- MTE of GaAs should be 1-2meV; outperform best photocathodes of today
- Electrons should come out in “narrow cone” of 15 degrees



Vergara, G., A. Herrera-Gómez, and W. E. Spicer *Journal of applied physics* 80.3 (1996): 1809-1815.

Number of Articles on Google Scholar by Year for ‘NEA GaAs Photocathode’





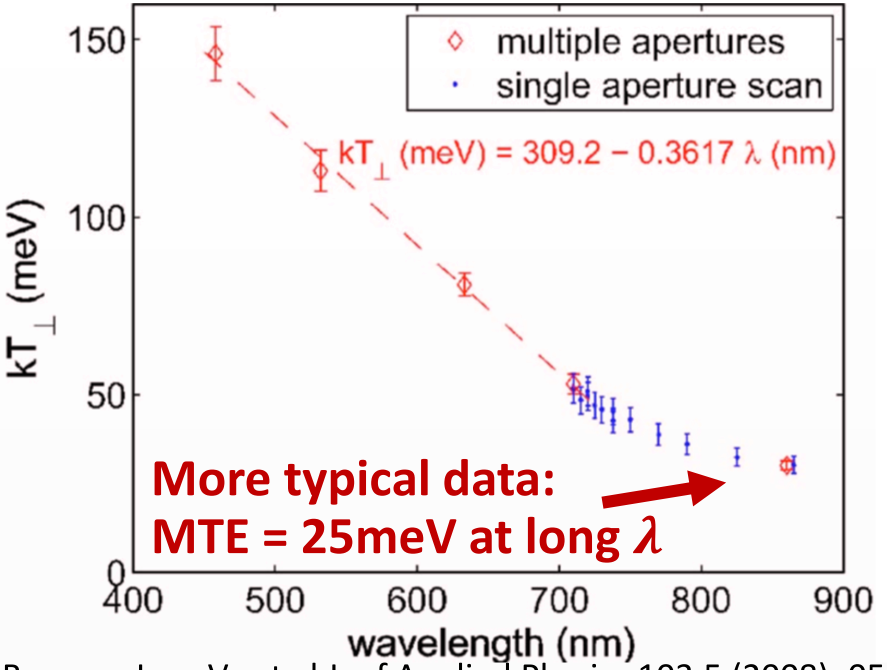
MTE of GaAs Photocathodes

Most researchers report 25meV ($k_B T_{\text{room}}$) MTE near threshold.

- That's over an order of magnitude greater than what's expected!
- Where did the MTE come from?

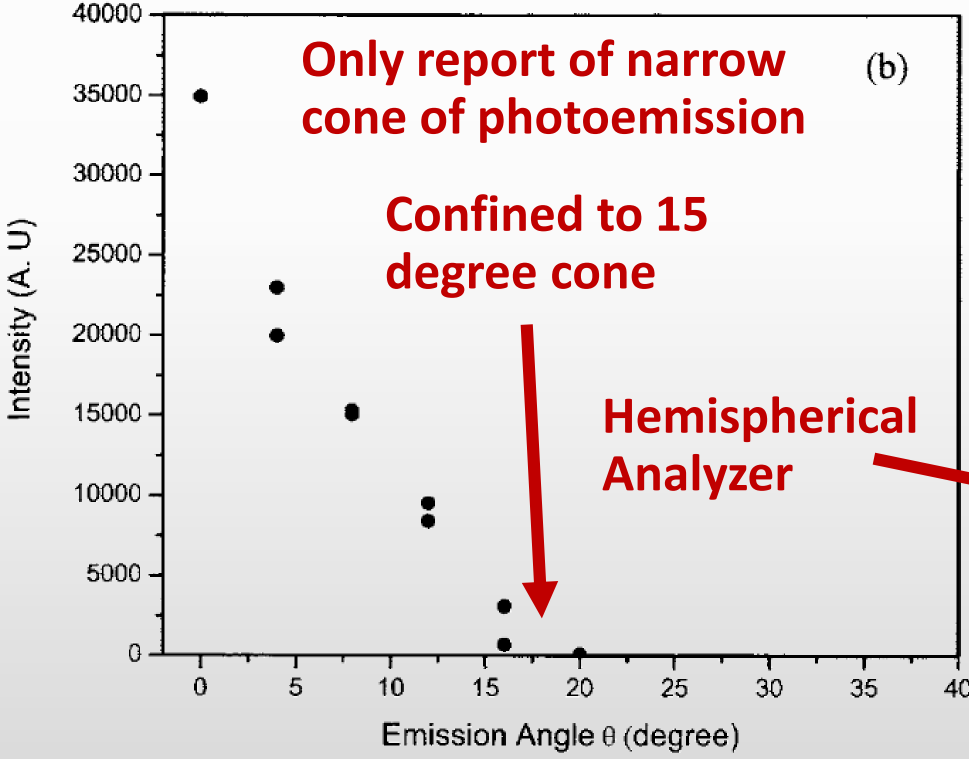
Exception of Z. Liu et al, who claim to see the small effective mass

- Using hemispherical analyzer



More typical data:
MTE = 25meV at long λ

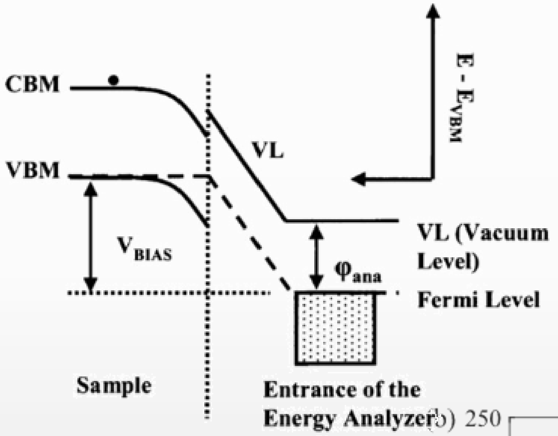
Bazarov, Ivan V., et al J. of Applied Physics 103.5 (2008): 054901.

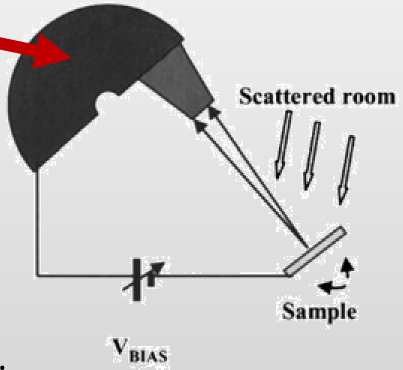


Only report of narrow cone of photoemission

Confined to 15 degree cone

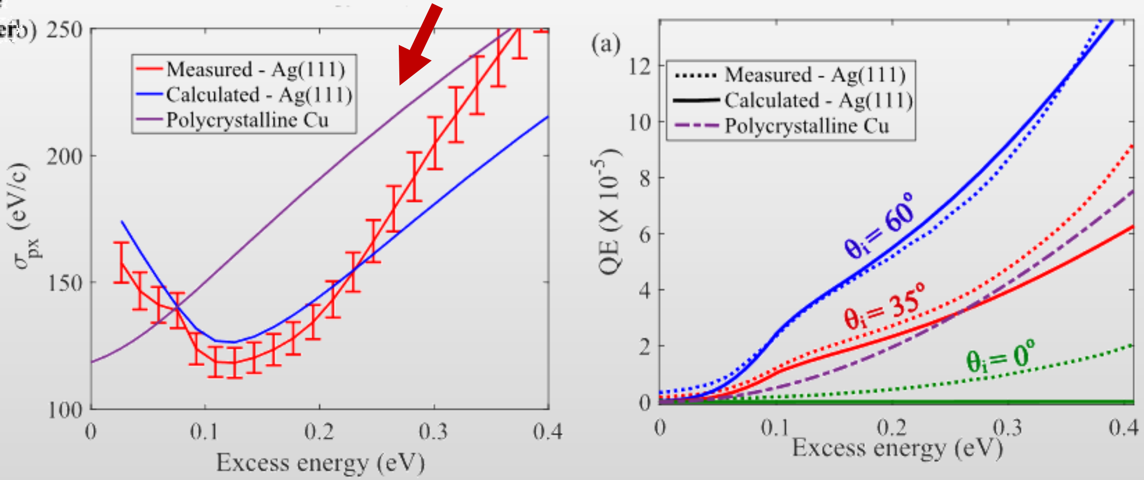
Hemispherical Analyzer





Liu, Zhi, et al. *J. Vac. Sci. & Tech. B* 23.6 (2005): 2758-2762.

NOTE: Transverse momentum is conserved in monocrystalline metals w/ clean surfaces.



Karkare, Siddharth, et al. *Physical review letters* 118.16 (2017): 164802.

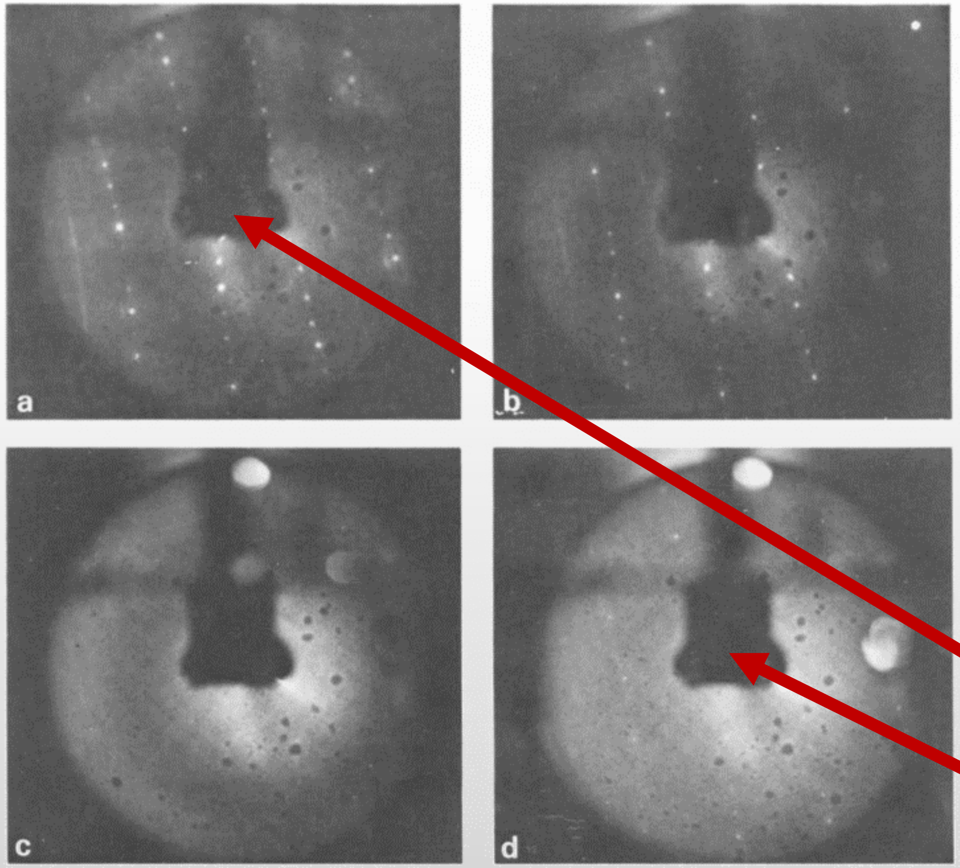
Likely Causes of MTE Growth

Cs NEA activation causes disorder on GaAs surface

- LEED patterns disappear as Cs is added
- STM and DFT shows mobile layer of atoms; changes on nS times scales

Work function can be locally different than average for surface

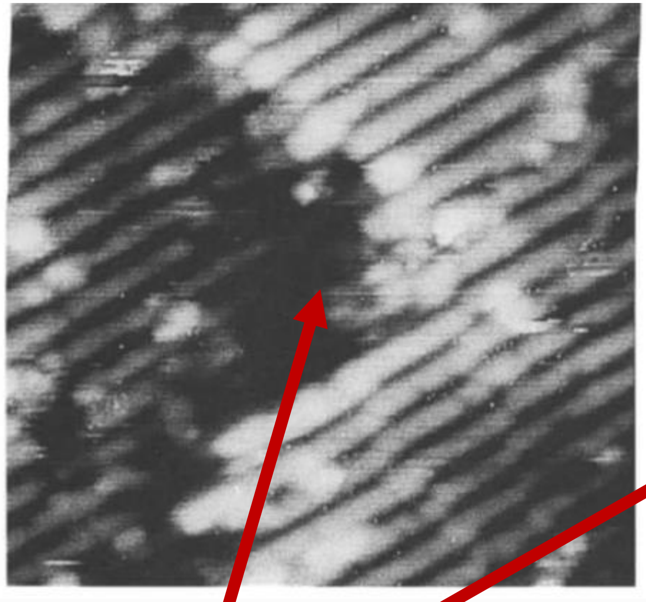
- KPFM data on order of 10-500mV differences for nm patches



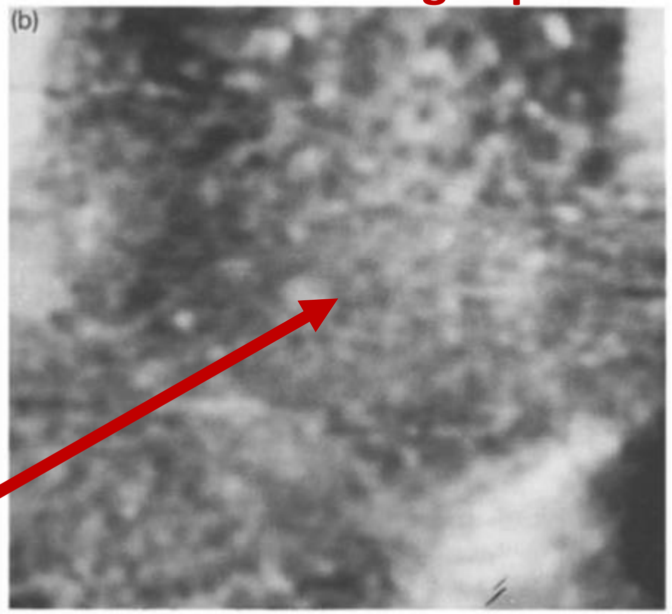
Goldstein, Bernard. Surface Science 47.1 (1975): 143-161.

J. Kim, M.C. Gallagher and R.F. Willis, Appl. Surf. Sci., 67, 286 (1993)

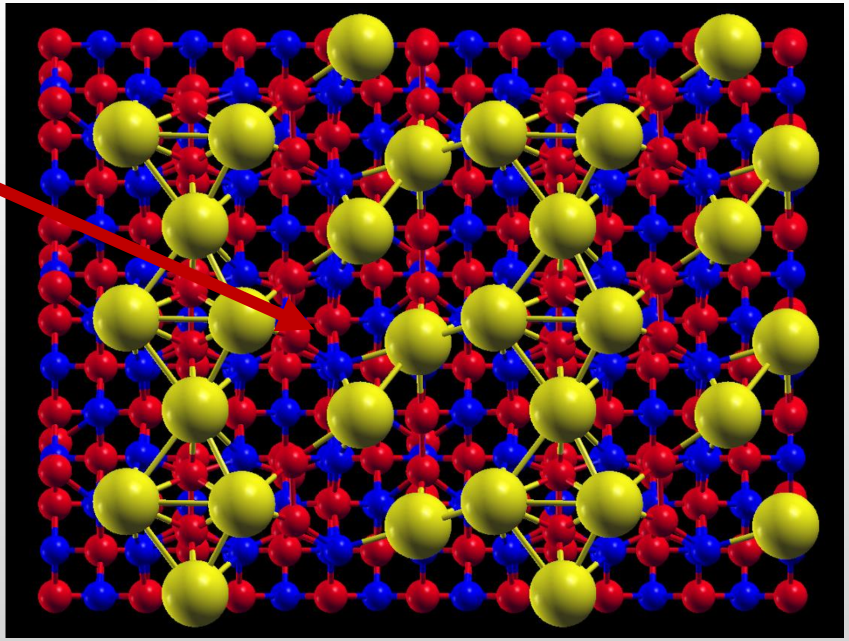
Short Exposure



Long Exposure



Cs Atoms move around on surface in disordered layer



L. Boulet

Clean GaAs w/ sharp LEED

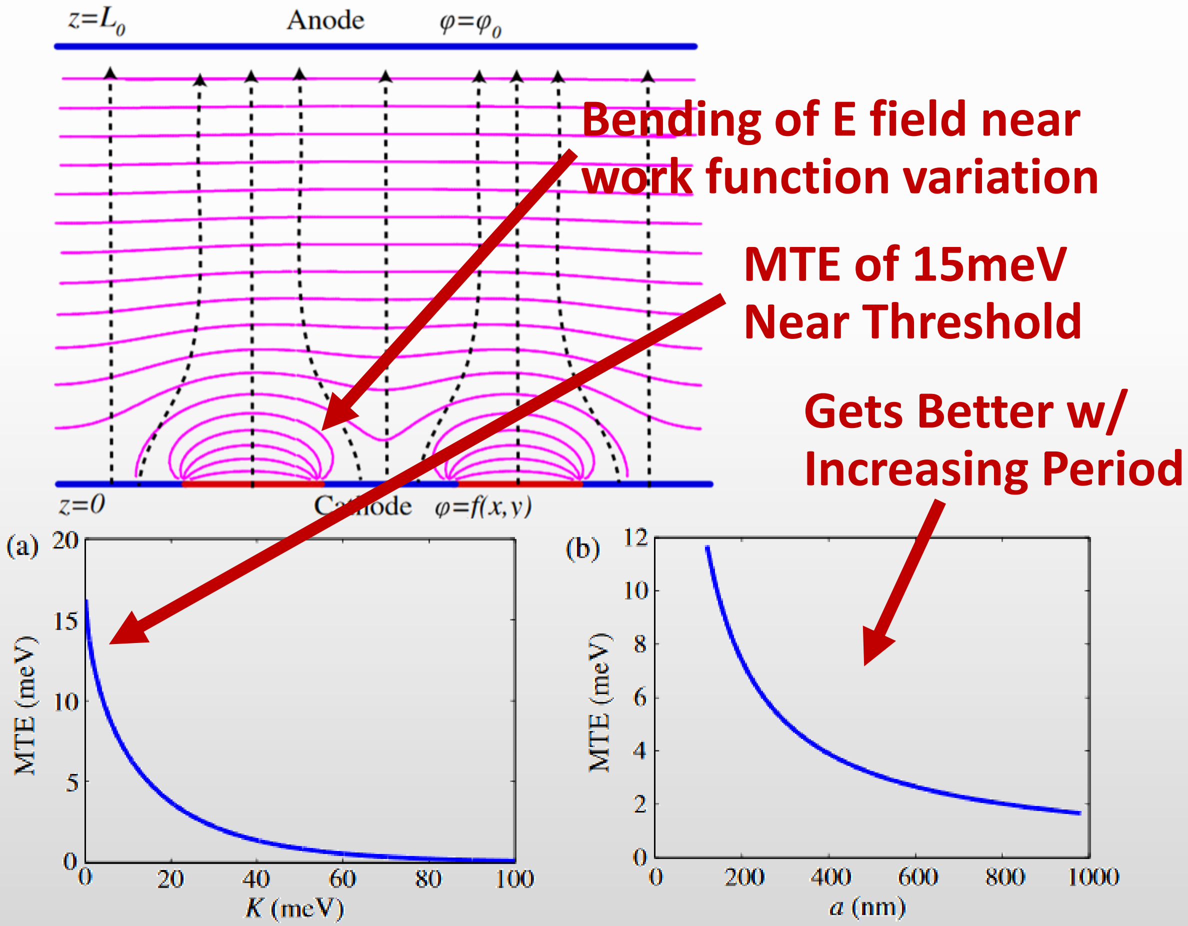
Cs NEA activation eliminates pattern

Likely Causes of MTE Growth

Karkare, Siddharth, and Ivan Bazarov. Applied Physics Letters 98.9 (2011): 094104.

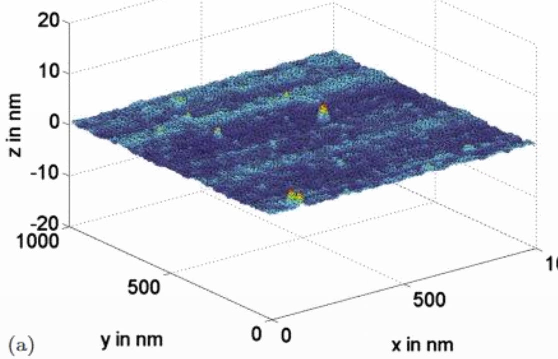
MTE growth can come from work function variation over small scales

- Simulations w/ realistic electron distribution and variation for GaAs show 15meV growth
- Decreases w/ KE; classically, electrons spend less time in bad fields

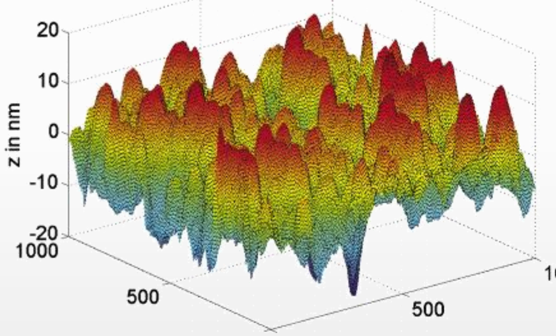


Karkare, Siddharth, and Ivan Bazarov *Physical Review Applied* 4.2 (2015): 024015.

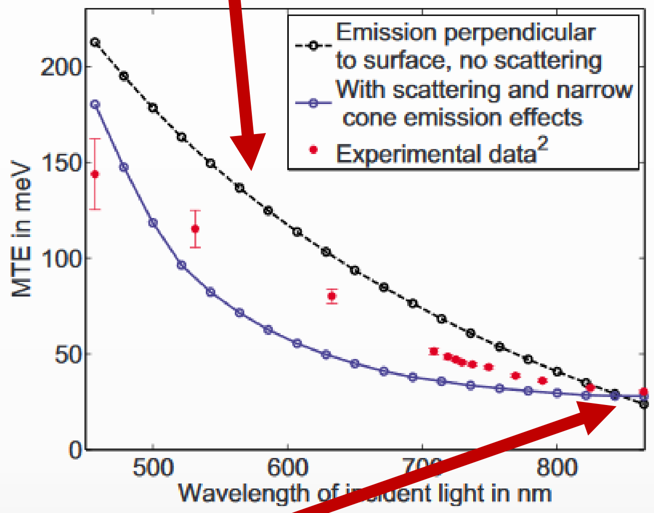
Polished Cathode



After Heat Treatment



Physical Roughness MTE Growth Reproduces Experiment



30meV near threshold

Photocathodes also have nanoscale surface variation

- AFM data shows ~10nm roughness after heat treatment on polished GaAs

Physical roughness can increase MTE

- Around 30meV based on simulation w/ data from AFM on heat treated GaAs
- Scales correctly w/ wavelength, matches nicely w/ experiments

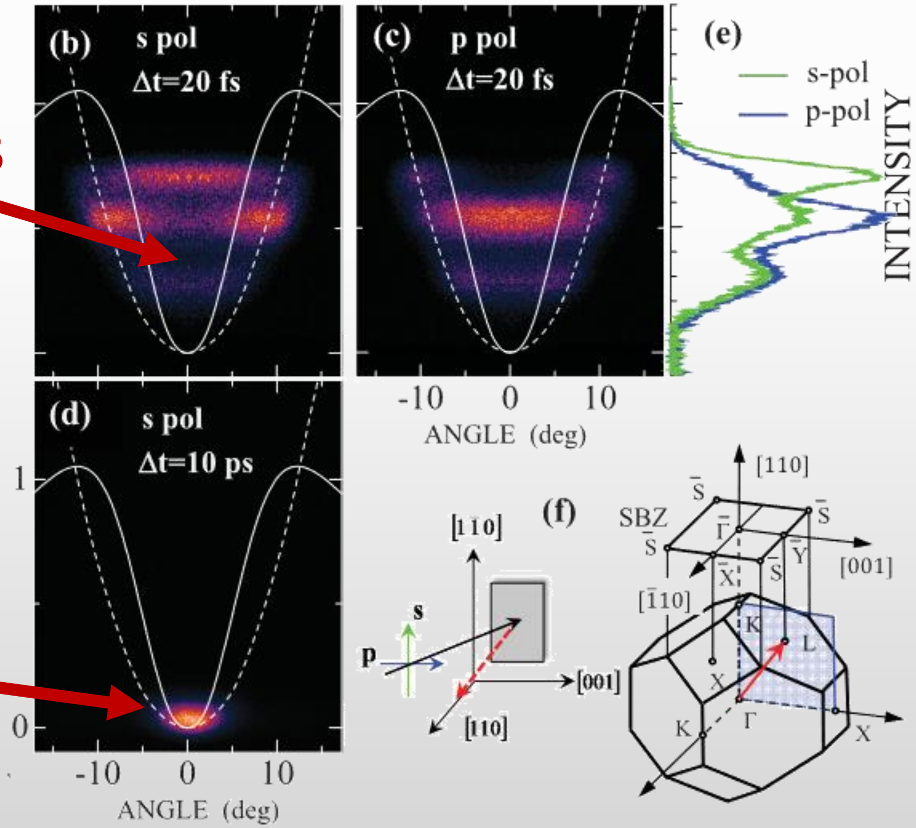
Not the whole story -> Still observe poor MTE on flat cathodes

Pump-Probe Photoemission

- Despite MTE growth effects, people observe momentum conservation all the time
  - Exploited for ARPES -> High enough excess energy to avoid surface effects
- Recent paper observed narrow cone in GaAs w/ time resolved ARPES
  - Can we do the same to generate bright beams?

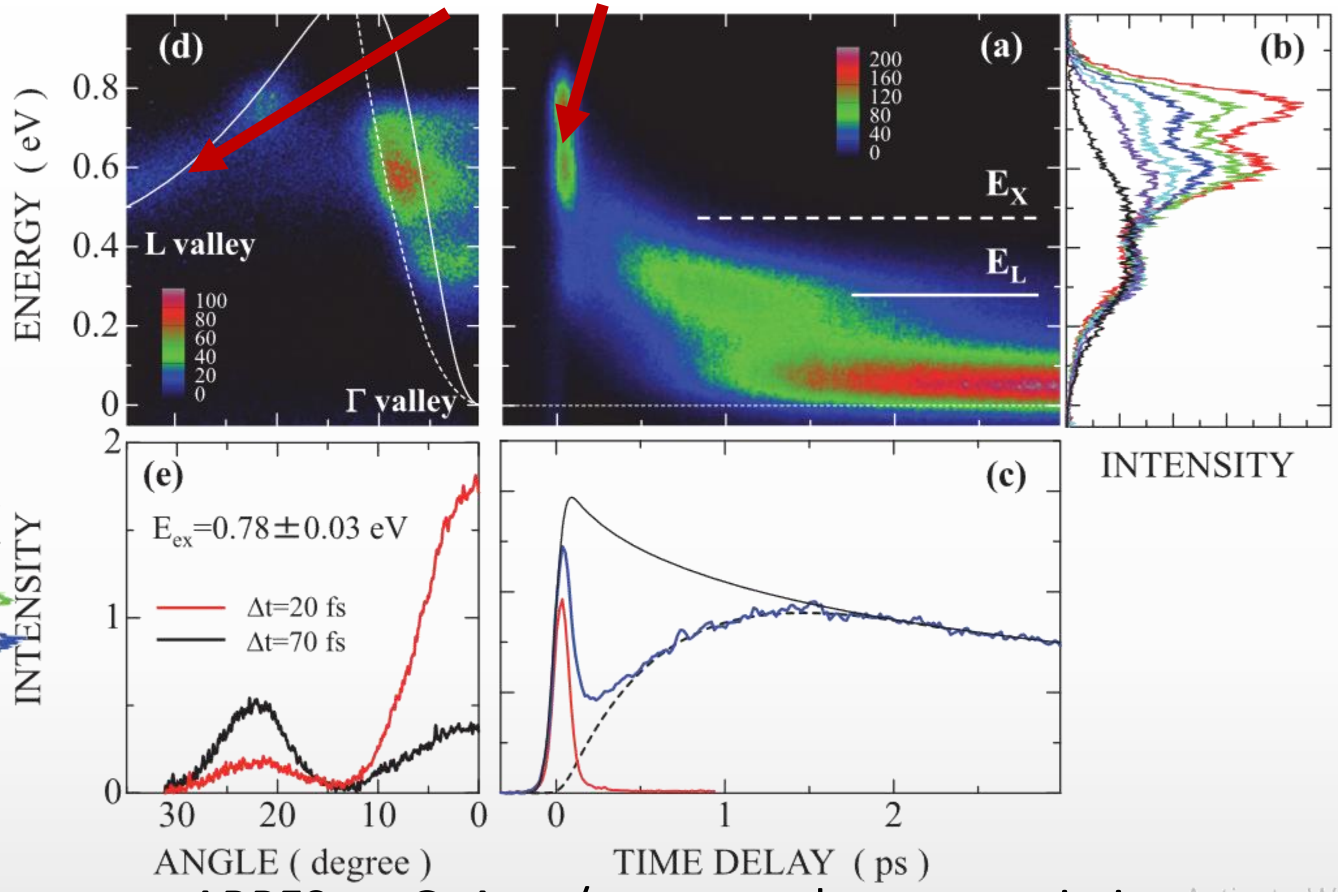
Thermalization to CBM in 10pS

Small Angle of emission = low MTE



Kanasaki, Jun'ichi, Hiroshi Tanimura, and Katsumi Tanimura. Physical review letters 113.23 (2014): 237401.

Scattering to X/L Valley at large photon energy



- ARPES on GaAs w/ pump probe type emission
  - Excite electrons into CB w/ IR->Visible light; eject from sample w/ UV
  - Analysis done w/ hemispherical analyzer to get energy and angle data
- Observed electrons thermalize to conduction band minimum
  - Inter-valley scattering w/ large pump energies

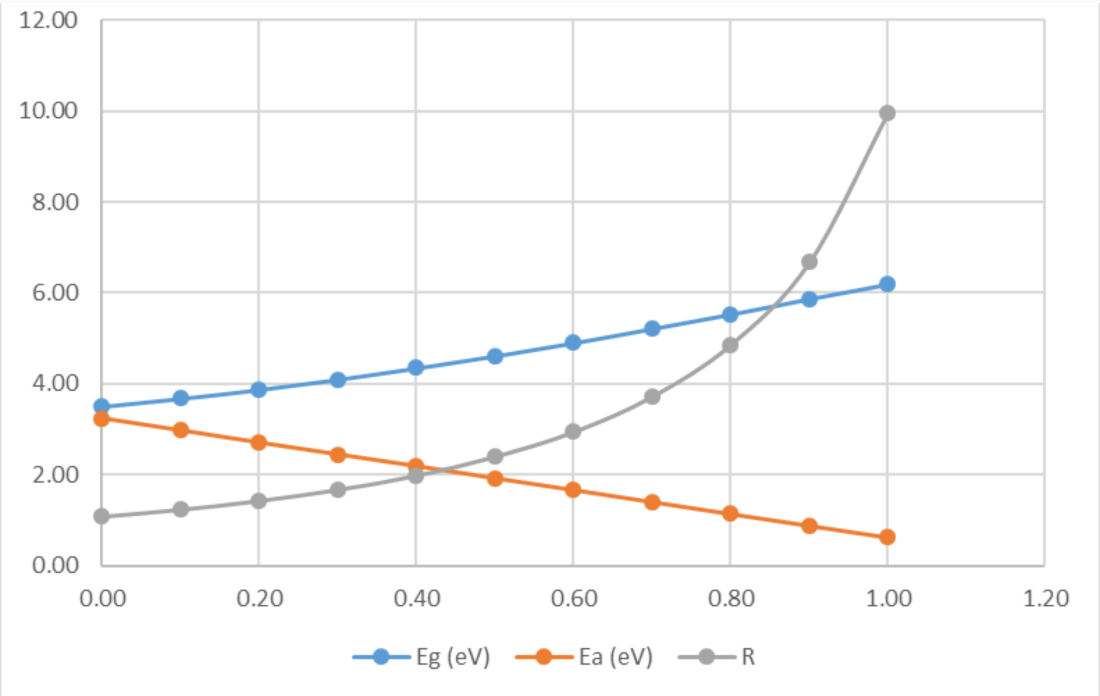
Pump-Probe Photoemission

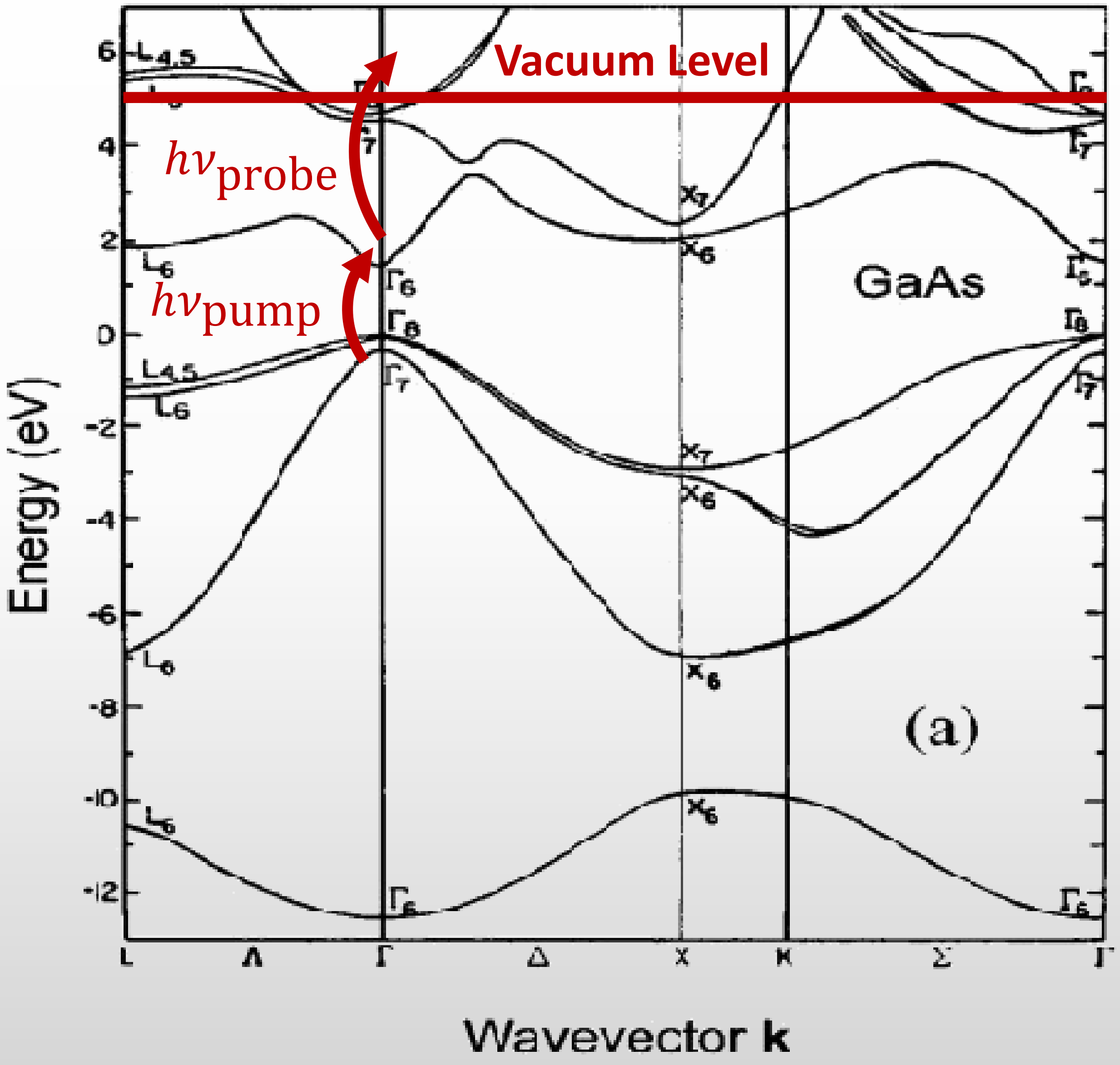
GaAs band structure leads us to believe this won't work

- High enough energy probe photon for two photon emission
- Electron-electron scattering w/ valence band
- In order to avoid these effects, require material w/ $E_{affinity} < E_{gap}$

$Al_xGa_{1-x}N$ satisfies this

- Tune x to a convenient value for experimental setup





n-Doped Photoemission

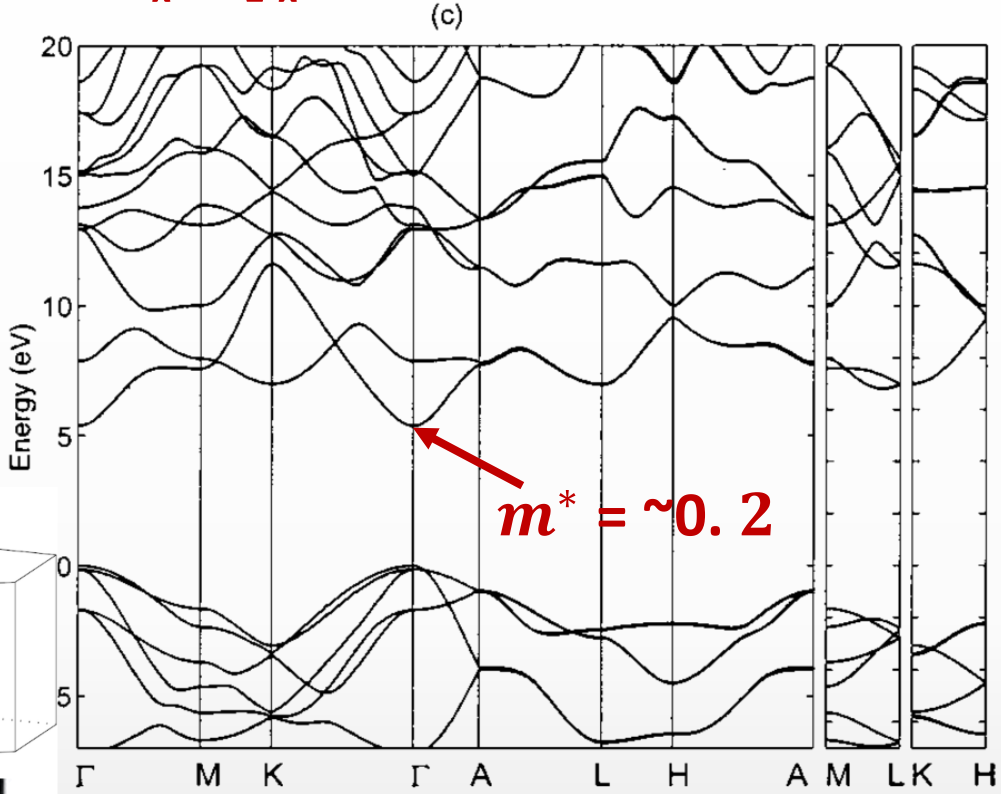
For initial studies, n-doped $Al_xGa_{1-x}N$ was selected

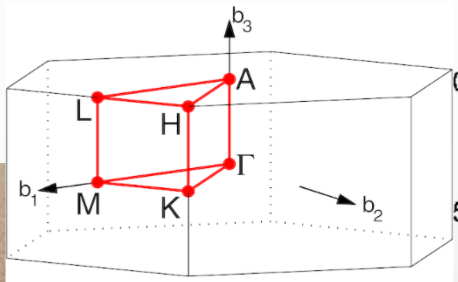
- Avoids the complication of two photon emission; carriers already in conduction band
- Carrier concentrations expected to be less than w/ 2 photon
- Has band bending, unknown how this affects QE/MTE

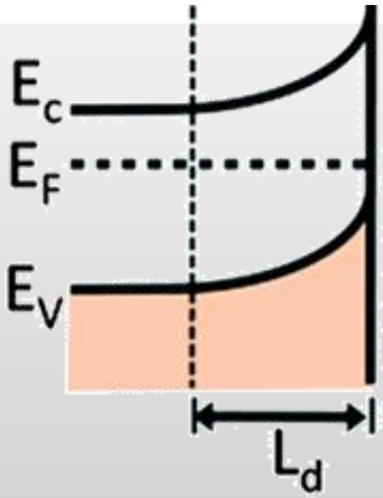
Received epitaxially grow samples from Jena/Xing group at Cornell

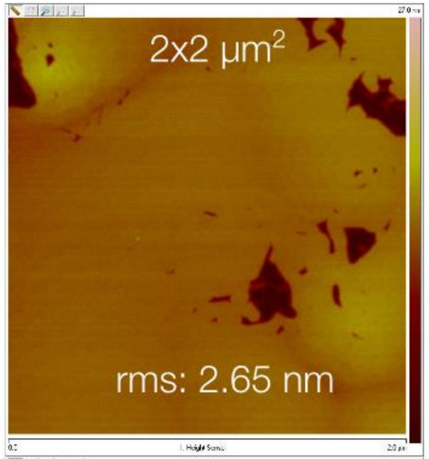
- Grown on top of GaN on Sapphire w/ good surface quality characterized by AFM
- X=0.75, Carrier Conc. = -1.058×10^{18} cm^{-3}
- Samples are transparent!

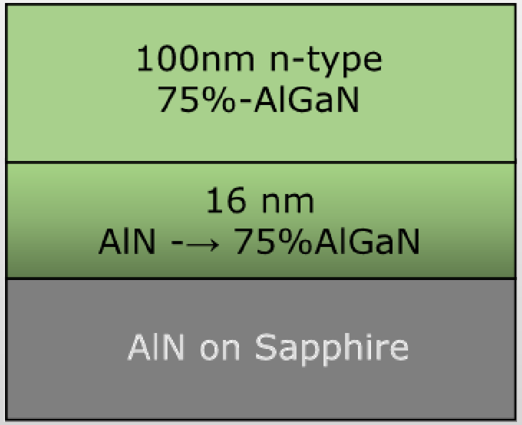
$Al_xGa_{1-x}N$ (x=0.8) Band Structure











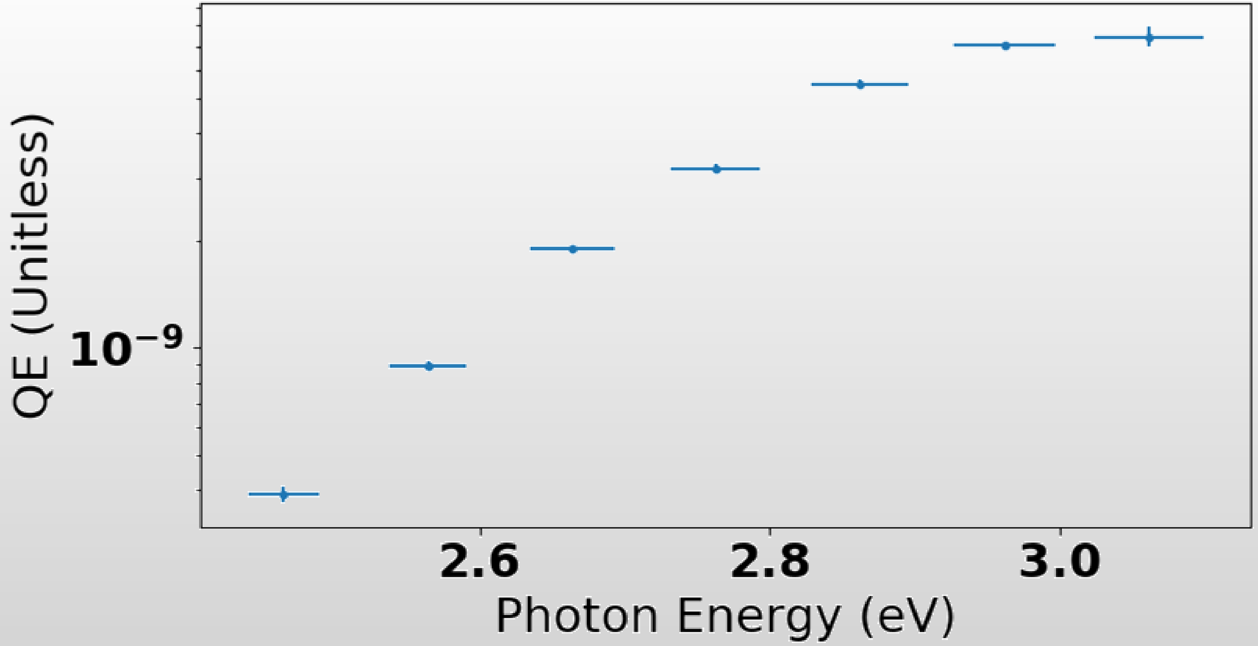
Experimental Results

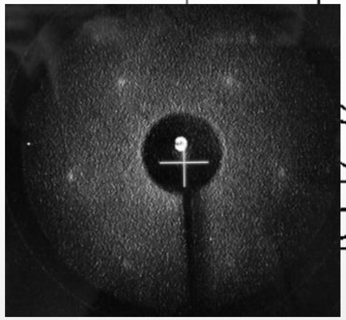
Sample was introduced to Cornell photocathode characterization system

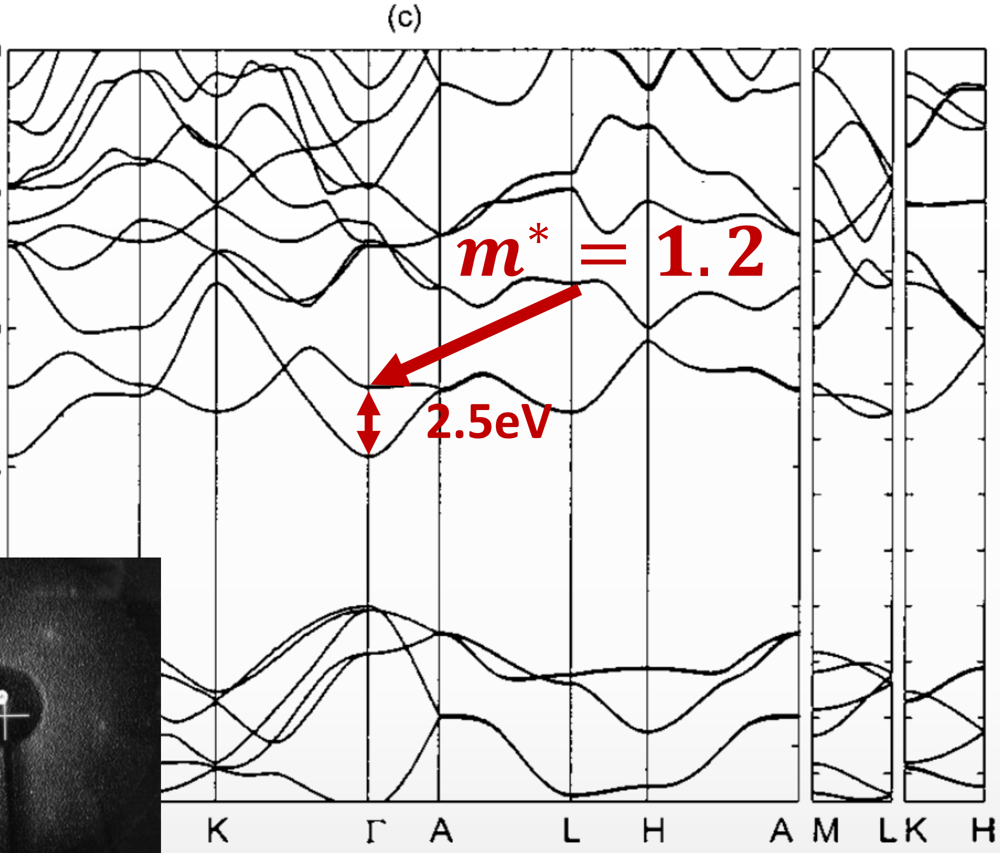
- LEED showed sharp hexagonal pattern
- Annealed sample at 250C for 5 hours

Photocurrent measurement performed on clean sample

- Tunable light from supercontinuum source w/ monochromator (10nm FWHM bandwidth; 10s of pS pulse length); ~1mW/nm power
- Lock-in amplifier + chopper used to measure photocurrent of cathode biased to -18V. (saw less than nA current)
- Not enough current for MTE measurement







This led us to activate the sample by cesiation

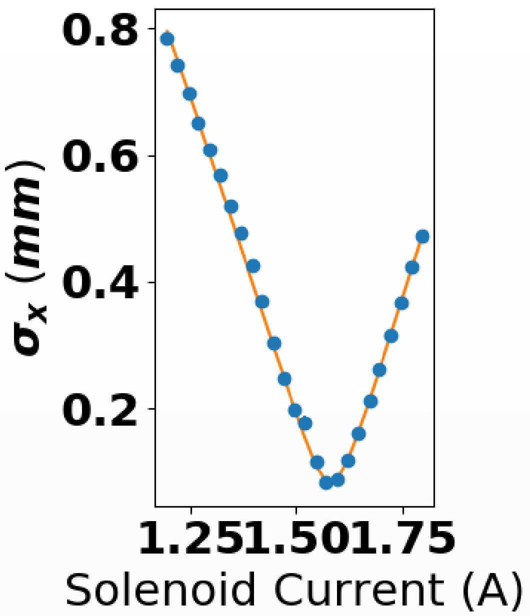
- Hope to get high enough QE to perform MTE measurement
- Could cause issues w/ MTE growth effects as before

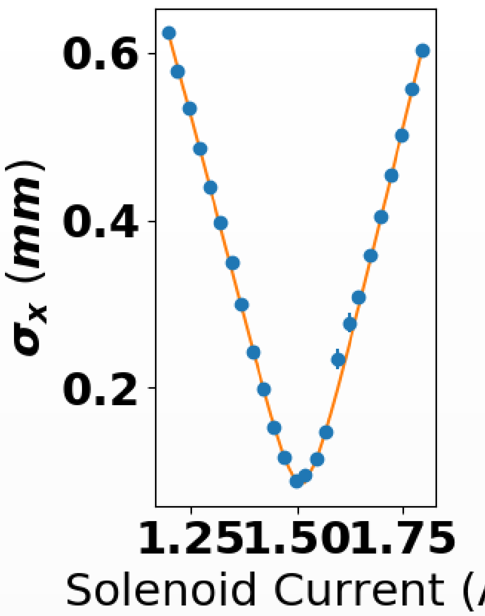
Still good reason to believe good MTE is achievable

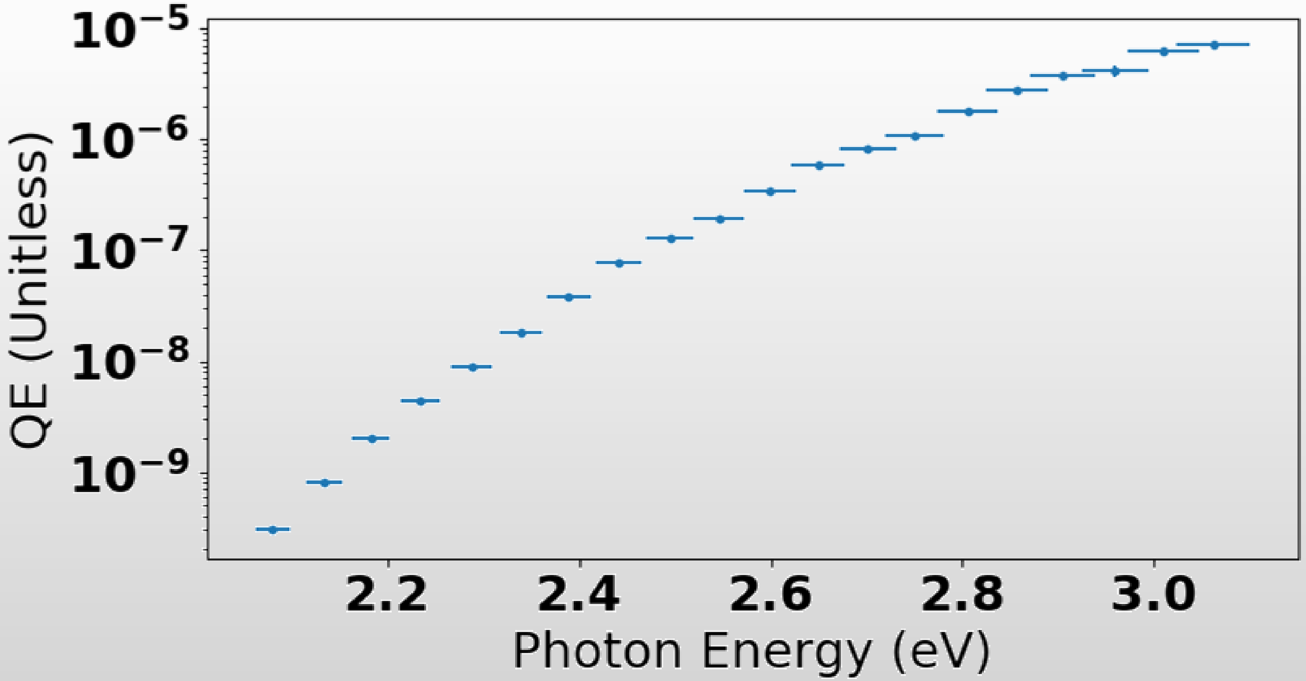
- Many surface effects are diminished at high excess energy
- Emission from conduction band allows us to use large photon energy.
- Still have to watch out for band w/ large m^*

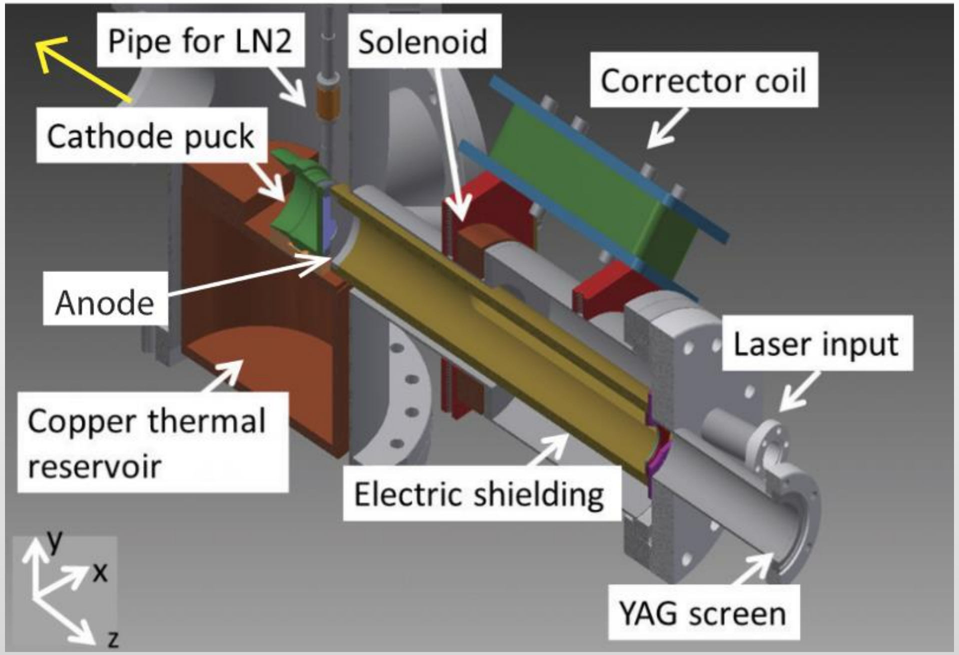
Experimental Results

- Recorded two order of magnitude increase in QE
  - Still have threshold of ~2eV, so we aren't NEA
- Performed MTE measurements at variety of photon energies
  - Same supercontinuum source as before
  - Cornell TE meter at 10Kv, performing solenoid scans
  - Sensitive to beam currents < 1nA near beam waist







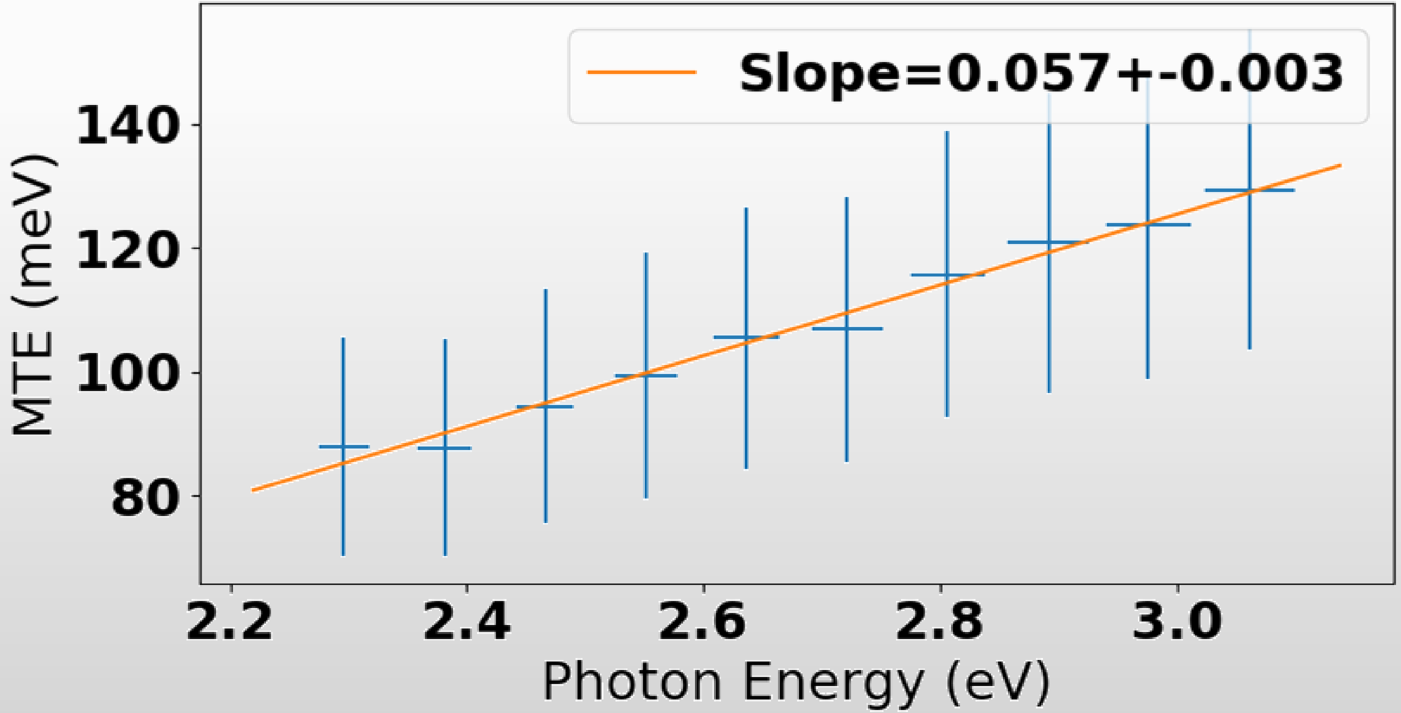


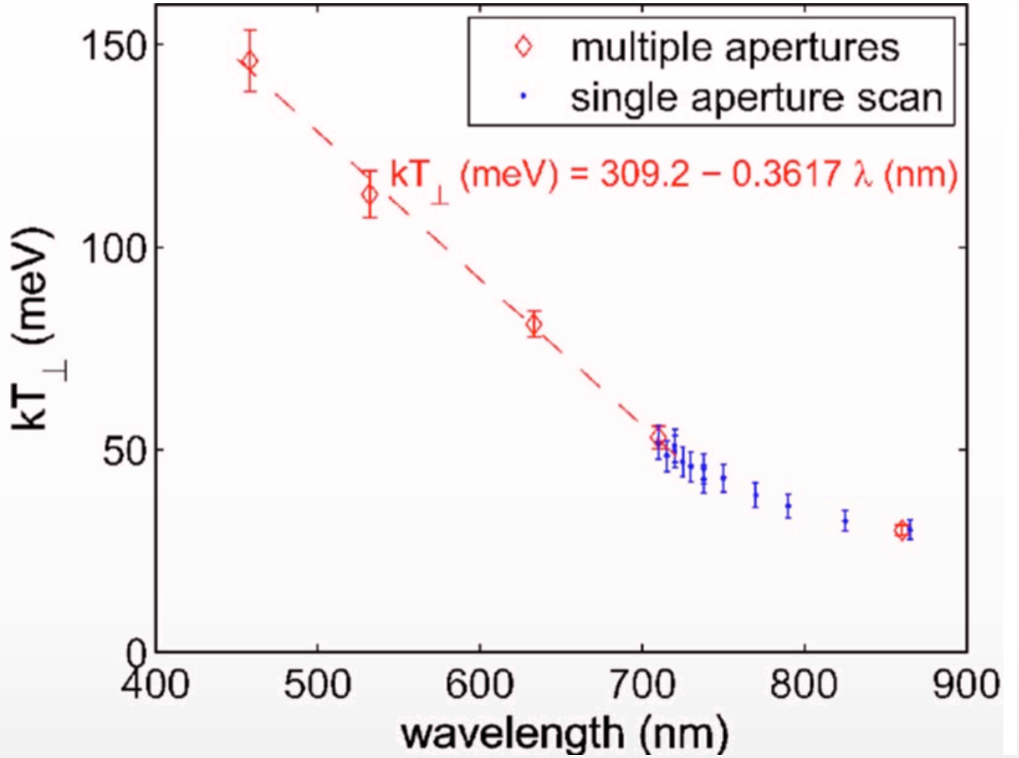
Lee, Hyeri, et al. *Review of Scientific Instruments* 86.7 (2015): 073309.

Experimental Results/Future Work

MTE has some interesting features to it

- Still far above 5meV expected from $m^* = 0.2$
- No jump in MTE at 2.5eV where $m^* = 1.2$ band is located
- Increases w/ slope of ~0.06, much less than value for disordered photocathodes





Bazarov, Ivan V., et al J. of Applied Physics 103.5 (2008): 054901.

Search is not over, still must investigate pump-probe photoemission

- Simulations show an order of magnitude better carrier concentration
- Avoids issues with cesiation of surface
- No band bending as in n-doped samples