In Pursuit of the Narrow Cone

Prospects for 2-photon and n-type Photoemission from Al$_x$Ga$_{1-x}$N

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Outline

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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

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

\[ m^* = \sim 0.063 \]
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:

\[ \text{MTE} = 25 \text{meV at long } \lambda \]


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


Cs Atoms move around on surface in disordered layer
Clean GaAs w/ sharp LEED
Cs NEA activation eliminates pattern

L. Boulet
Likely Causes of MTE Growth

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

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**

**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

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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$_x$Ga$_{1-x}$N satisfies this
- Tune x to a convenient value for experimental setup
n-Doped Photoemission

For initial studies, n-doped Al\textsubscript{x}Ga\textsubscript{1-x}N was selected

- Avoids the complication of two photon emission; carriers already in conduction band
- Carrier concentrations expected to be less than with 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. = -1.058x10\textsuperscript{18} cm\textsuperscript{-3}

Samples are transparent!
**Experimental Results**

Sample was introduced to Cornell photocathode characterization system
- LEED showed sharp hexagonal pattern
- Annealed sample at 250°C 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

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 $m^* = 1.2$
bond is located
Increases w/ slope of ~0.06, much less than value for disordered photocathodes

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