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Fundamental processes in III-V photocathodes; application for high-brightness photoinjectors

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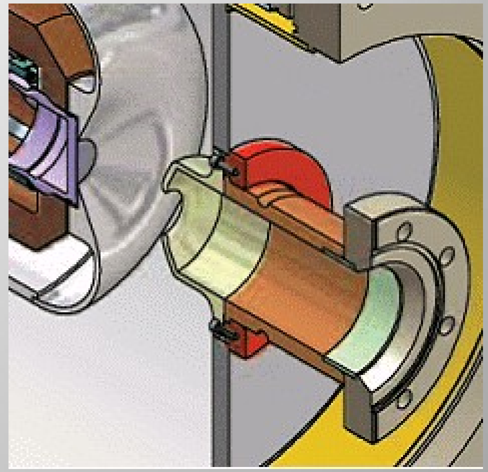
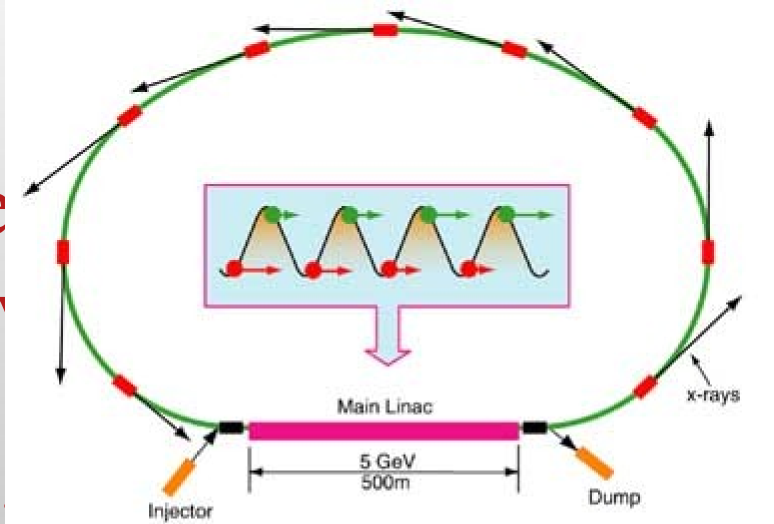
Why are we interested?



- Photoinjectors: a photocathode in high electric field (>> MV/m), either DC or RF
- Relativistic electrons can be further accelerated in a linac (linear accelerator) without degradation of beam brightness:
  - CW ultra-bright x-ray sources; high power FELs
  - Electron-ion colliders and ion coolers
  - Ultrafast electron diffraction, etc.

Energy recovery linac



- *Energy recovery linac*: a new class of accele in acti
- Essentially removes the average current limitation typical to linacs (i.e. $P_{\text{beam}} >> P_{\text{wall plug}}$)
- Average currents 10’s to 100’s of mA can be efficiently accelerated (and de-accelerated)

Cathode figures of merit

- QE and photon excitation wavelength

$$i(\mathrm{mA}) = \frac{\lambda(\mathrm{nm})}{124} \times P(\mathrm{W}) \times \mathrm{QE}(\%)$$

  - E.g. 1W of 775 nm (Er-fiber λ/2) ⇒ 6.2 mA/%
    520 nm (Yb-fiber λ/2) ⇒ 4.2 mA/%
    266 nm (Nd-glass λ/4) ⇒ 2.1 mA/%

- Transversely cold (thermalized) electron distribution
  - Directly sets the solid angle of the emitted electrons; an upper limit on achievable beam brightness

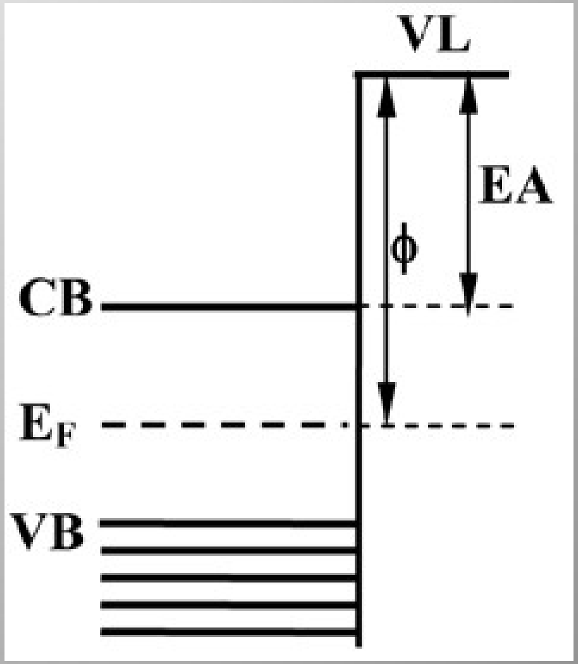
Figures of merit (contd.)

- Prompt response time
  - A picosecond response is essential to take advantage of the space charge control via laser pulse shaping
- Long lifetime and robustness
  - Extraction of many 100's to 1000's of C between activations are necessary to make the accelerator practical

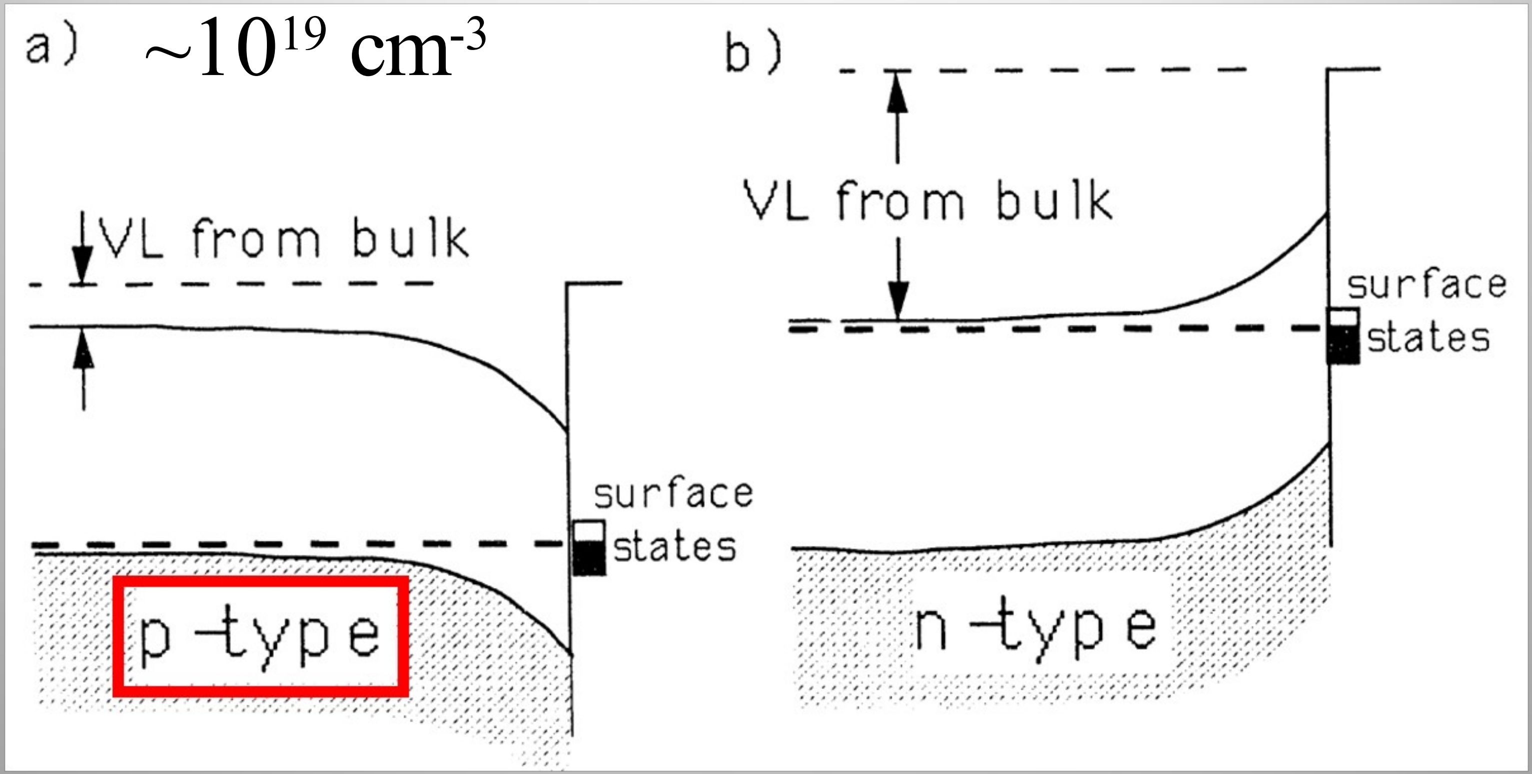
Negative electron affinity

- Defined as vacuum level E_{vac} relative to the conduction band minimum
- Negative affinity: the vacuum level lies below the CBM

  ⇒ very high QE possible
- NEA:
  - 1) band bending
  - 2) dipole layer



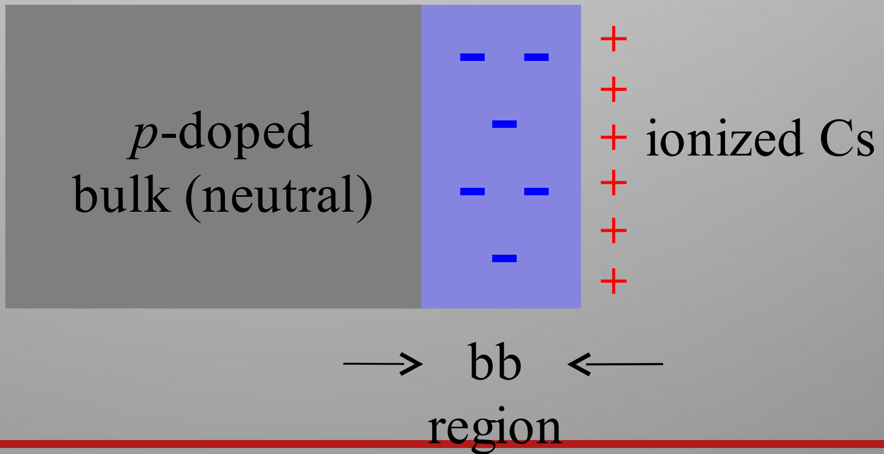
Strong p-doping



- Alperovich et al., Phys. Rev. B **50** (1994) 5480: clean p-doped GaAs has Fermi level unpinned and shows little band bending

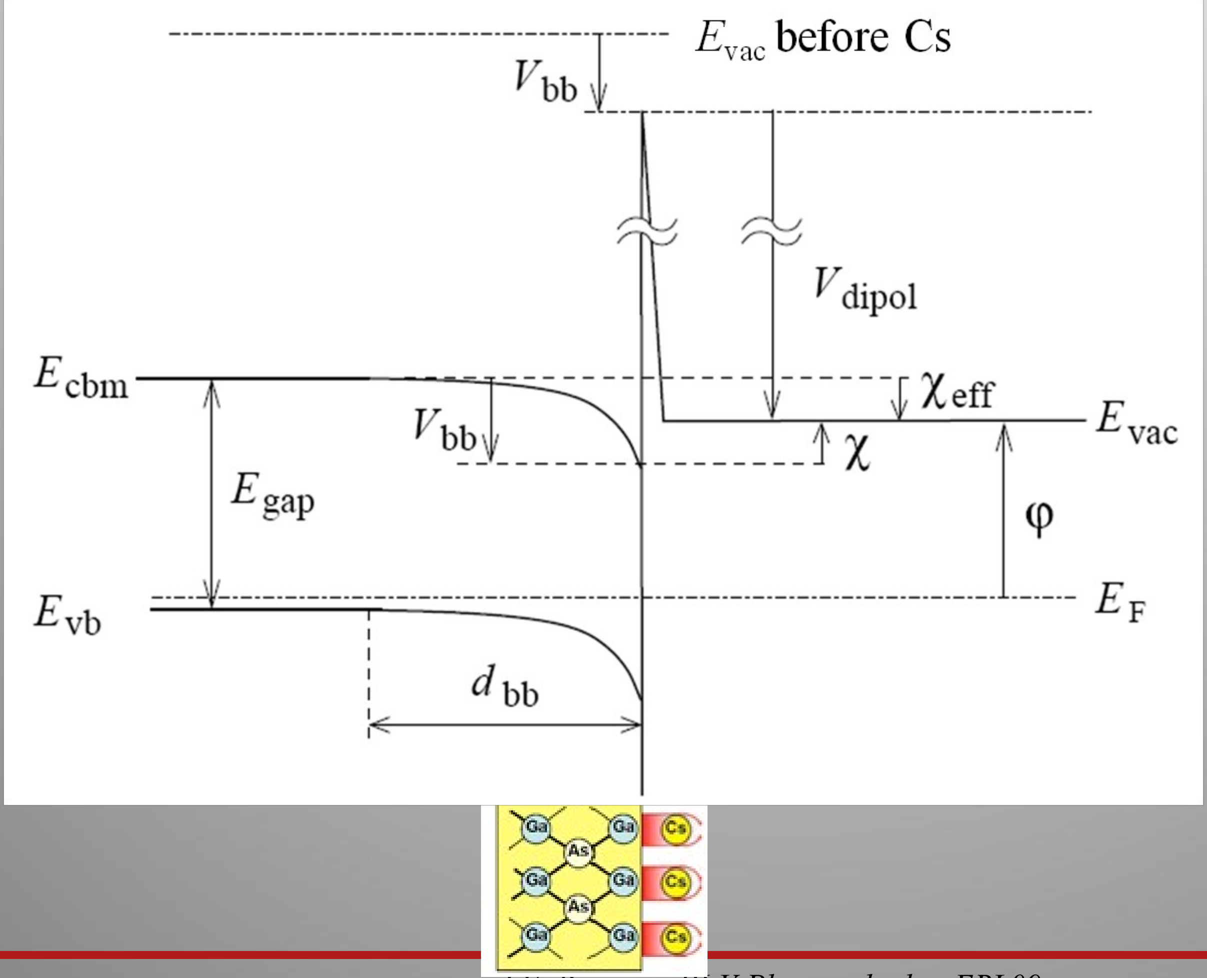
NEA: Cs ~monolayer

- Cs was found to play a larger role for NEA instead: 1) band bending through donor surface states, and 2) dipole surface layer from polarized Cs adatoms
  - Cs-induced donor-like surface states contribute their electrons to the bulk
  - Hole depleted region (negatively charged acceptors) lead to band bending region



NEA: ~Cs monolayer (contd.)

- Majority of Cs atoms become only polarized (not ionized), forming a dipole layer (e- Cs+)



GaAs

$E_{gap} = 1.42$ eV

Before Cs

$\chi = 4$ eV

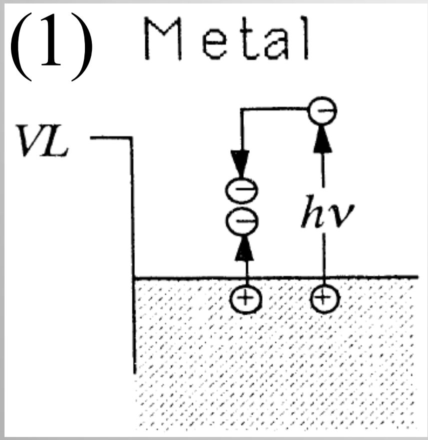
After Cs

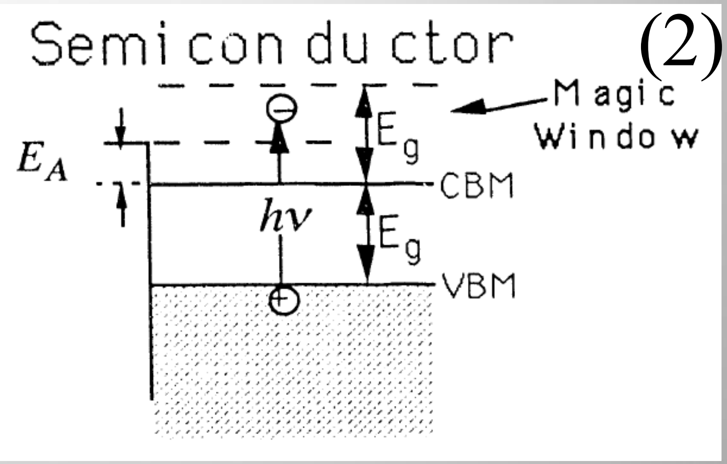
$\chi_{eff} \sim -0.1$ eV

$V_{bb} \sim 0.4$ eV

$d_{bb} \sim 10$ nm

Spicer's magic window



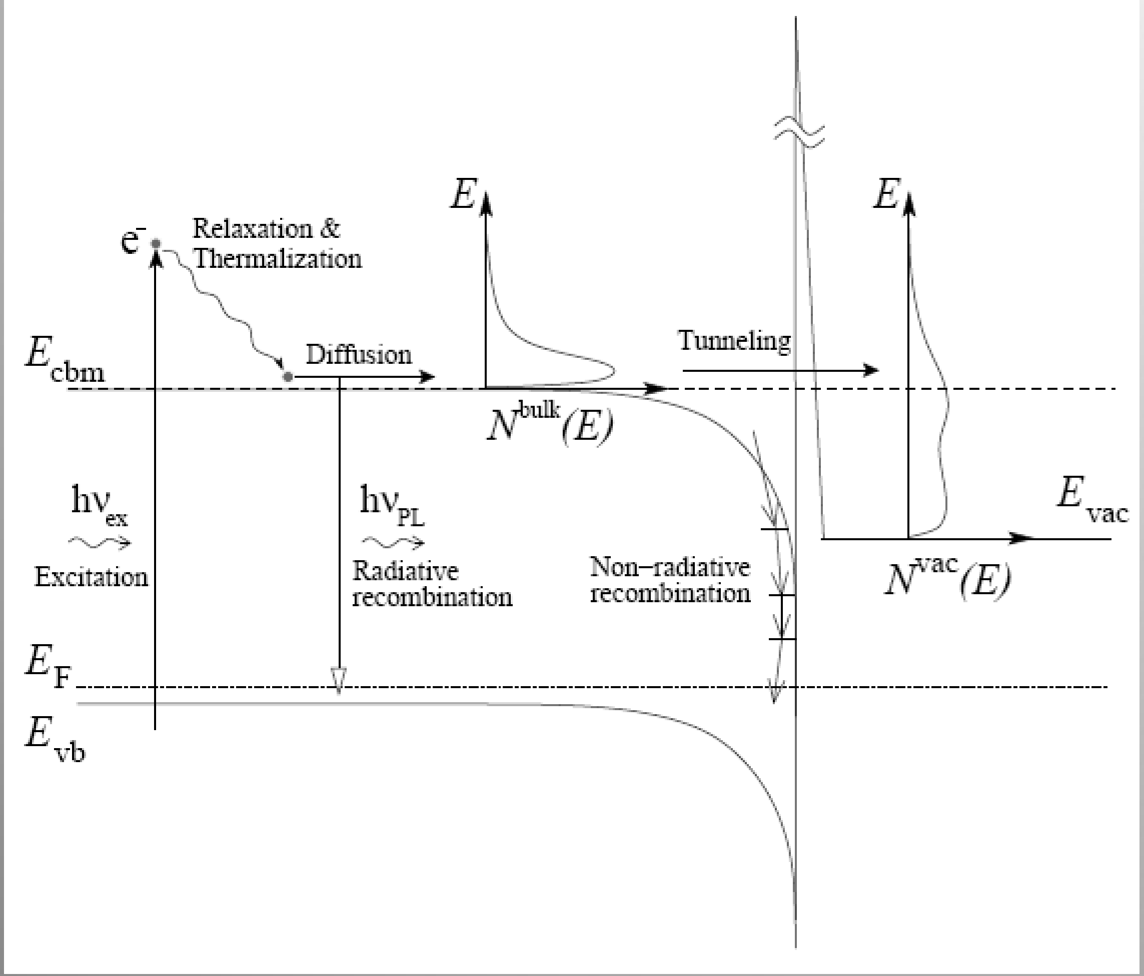


(1) *electron-electron* scattering: typical of metals, large energy loss per collision

(2) *electron-phonon* scattering: slowly depletes excessive energy of excited electron (LO phonons in GaAs ~ 35 meV)

"*Magic window*": in semiconductors, one needs excess KE > E_{gap} for e–/e– scattering. Thus, electrons excited with $E_{vac} < KE < E_{VBM} + 2E_{gap}$ have excellent chances of escape

Electron transport processes

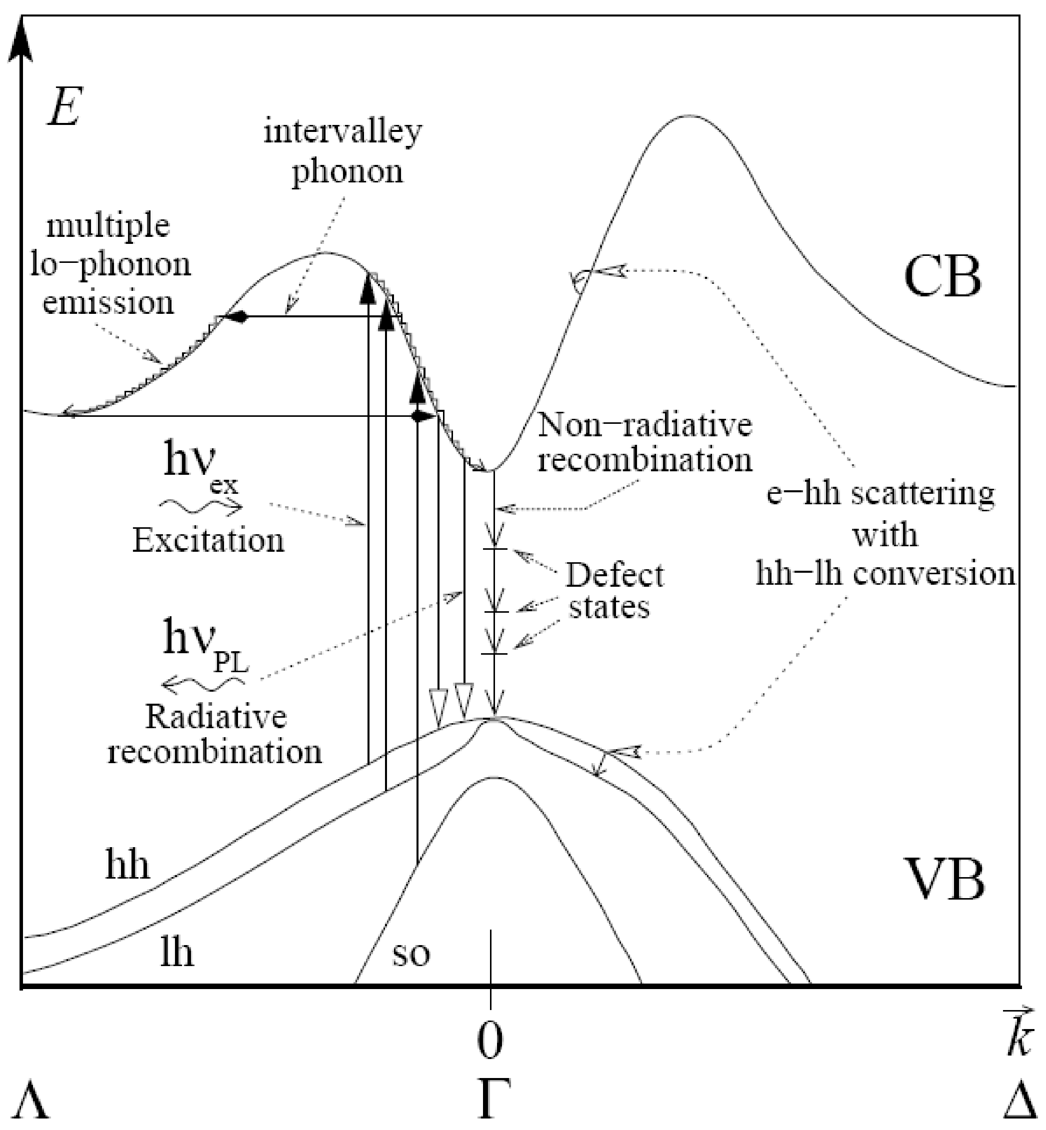


CBM thermalization time: 0.1-1ps

Electron-hole recombination: ~ns

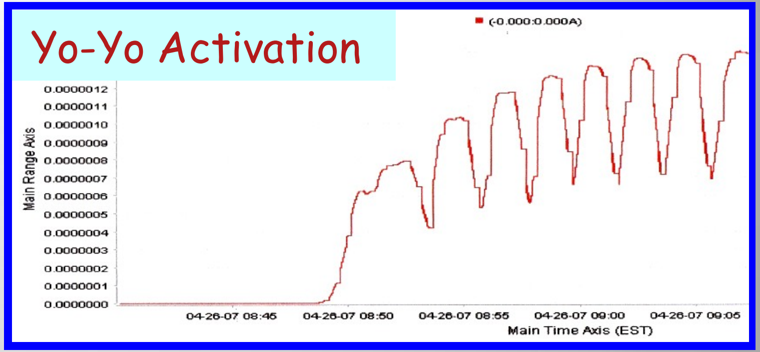
Emission time:
$\propto 1/(\alpha^2 D)$
strong wavelength dependence

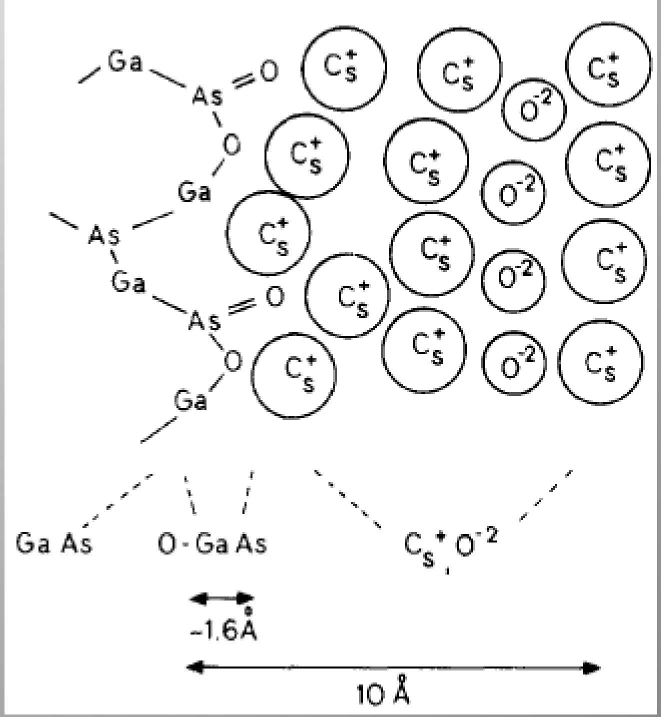
Energy vs. momentum



Role of fluorine/oxygen

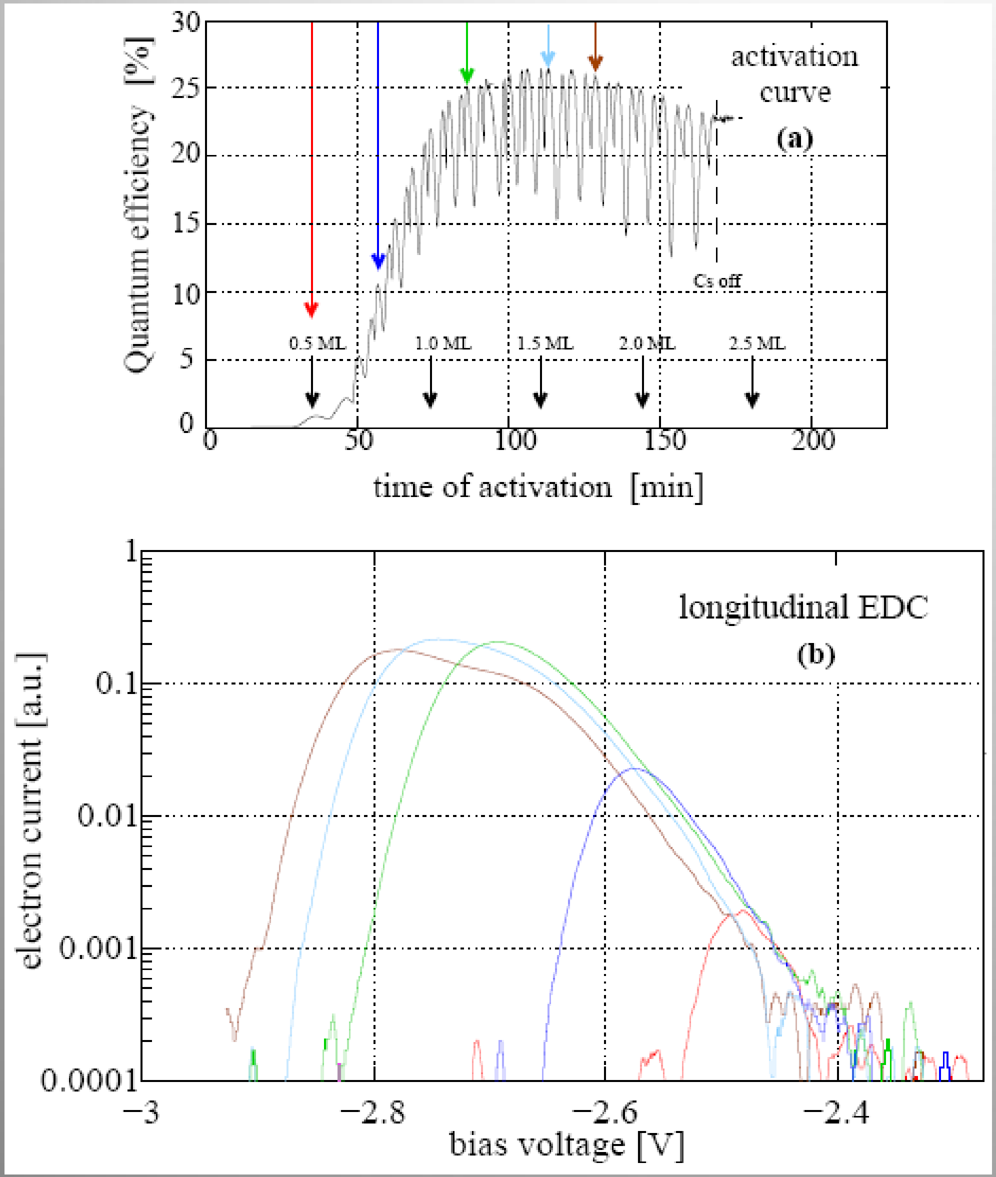
- Routine “yo-yo” activation employs O_2 or NF_3
- Further reduction of affinity consistent with a double dipole model
- Stabilizes Cs on the surface; no lifetime or otherwise apparent advantage for either gas
- Bonded unstable nitrogen is found on Cs-NF_3 activated surfaces (APL 92, 241107)





JAP 54 (1983) 1413

GaAs: Optimal Cs coverage



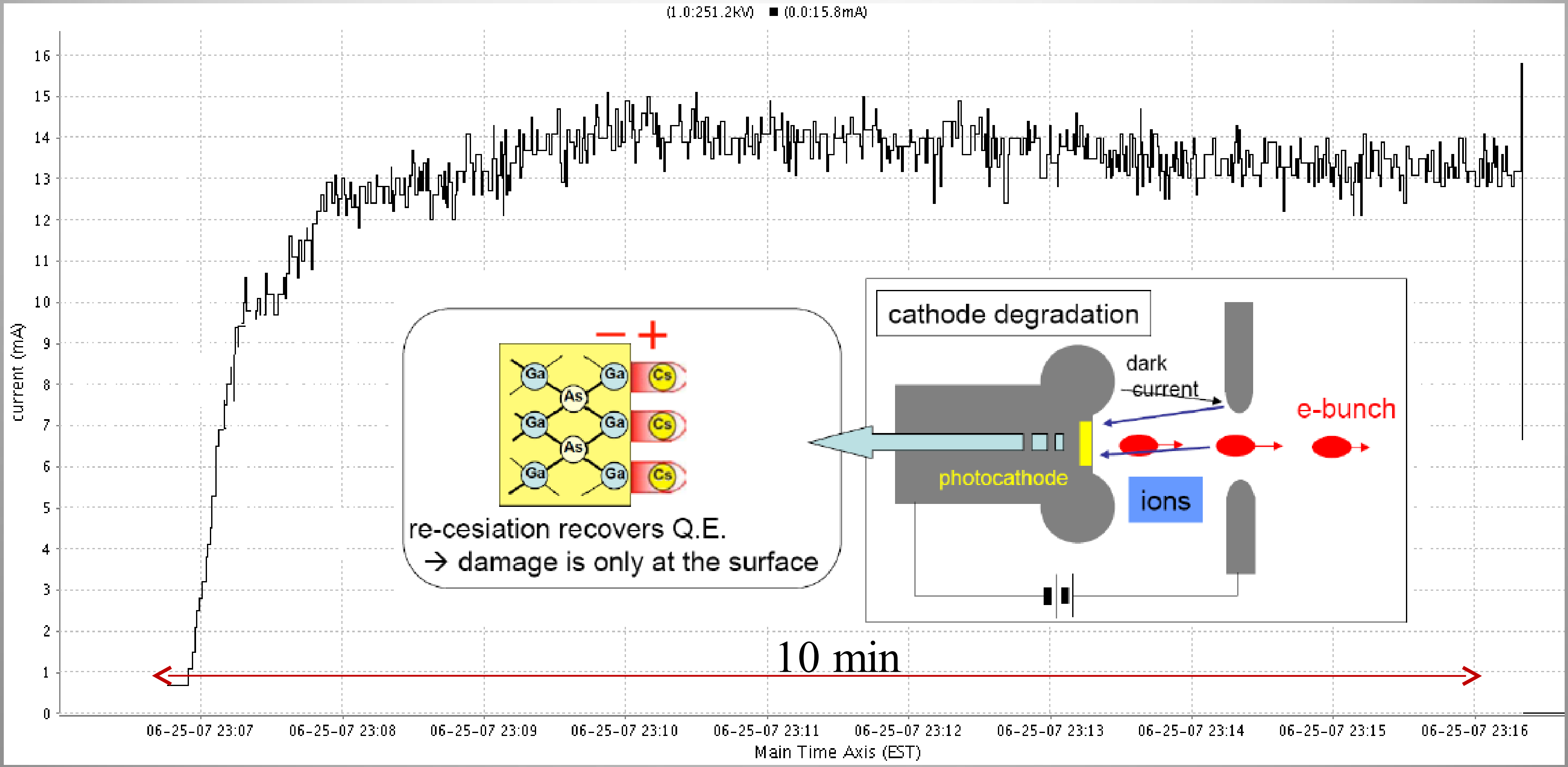
laser wavelength: 670 nm

Ugo Weigel, PhD thesis

Lifetime matters

- H_2O, CO_2 and O_2 can lead to chemical poisoning of the activated layer
- Low current (~ 1μA) 1/e lifetimes ~ 100 hours typical in our prep chambers
- 3-5 times better in the DC gun (low 10^{-12} Torr vacuum)
- High average current (mA's) lifetime limited by ion backbombardment

14 mA



re-cesiation recovers Q.E.
→ damage is only at the surface

cathode degradation

10 min

- ~5 hour lifetime (limited by gas backstreaming from the beam dump), i.e. 20 hours 1/e for 5 mA

Study cases

- Our group has been evaluating III-V photocathodes
  - Transverse energy of electrons (thermal emittance)
  - Measure the photoemission response time
- Materials studied so far
  - GaAs @ 450-850nm: JAP 103, 054901; PRST-AB 11, 040702
  - GaAsP @ 450-640nm: Ibid
  - GaN @ 260nm: JAP 105, 083715

Diffusion model

$$\frac{\partial c(h,t)}{\partial t} = D\frac{\partial^2 c(h,t)}{\partial h^2}$$

subject to:

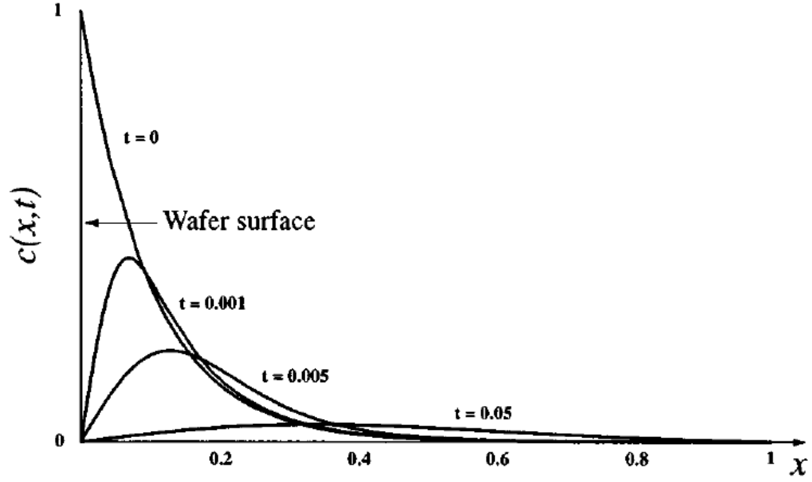
$$c(h, t=0) = c_0 e^{-\alpha h}$$

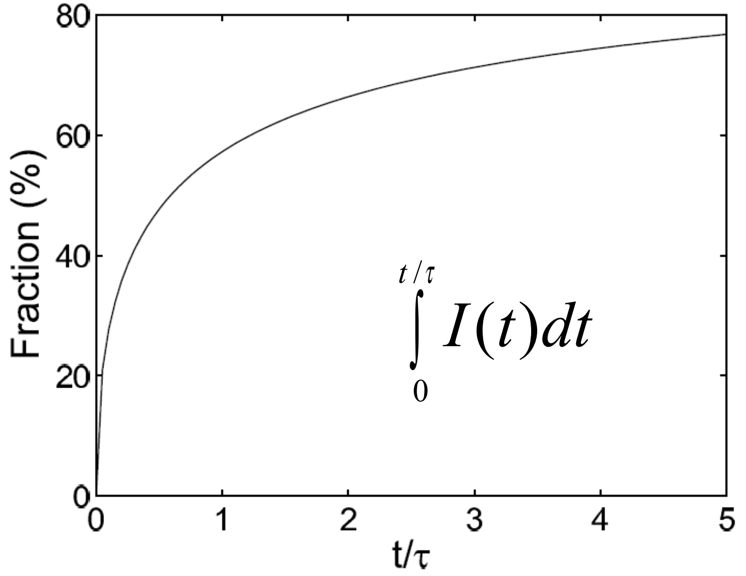
$$c(h=0, t) = 0$$

$$I(t) \propto \frac{\partial}{\partial t}\int_0^\infty c(h,t)dh.$$

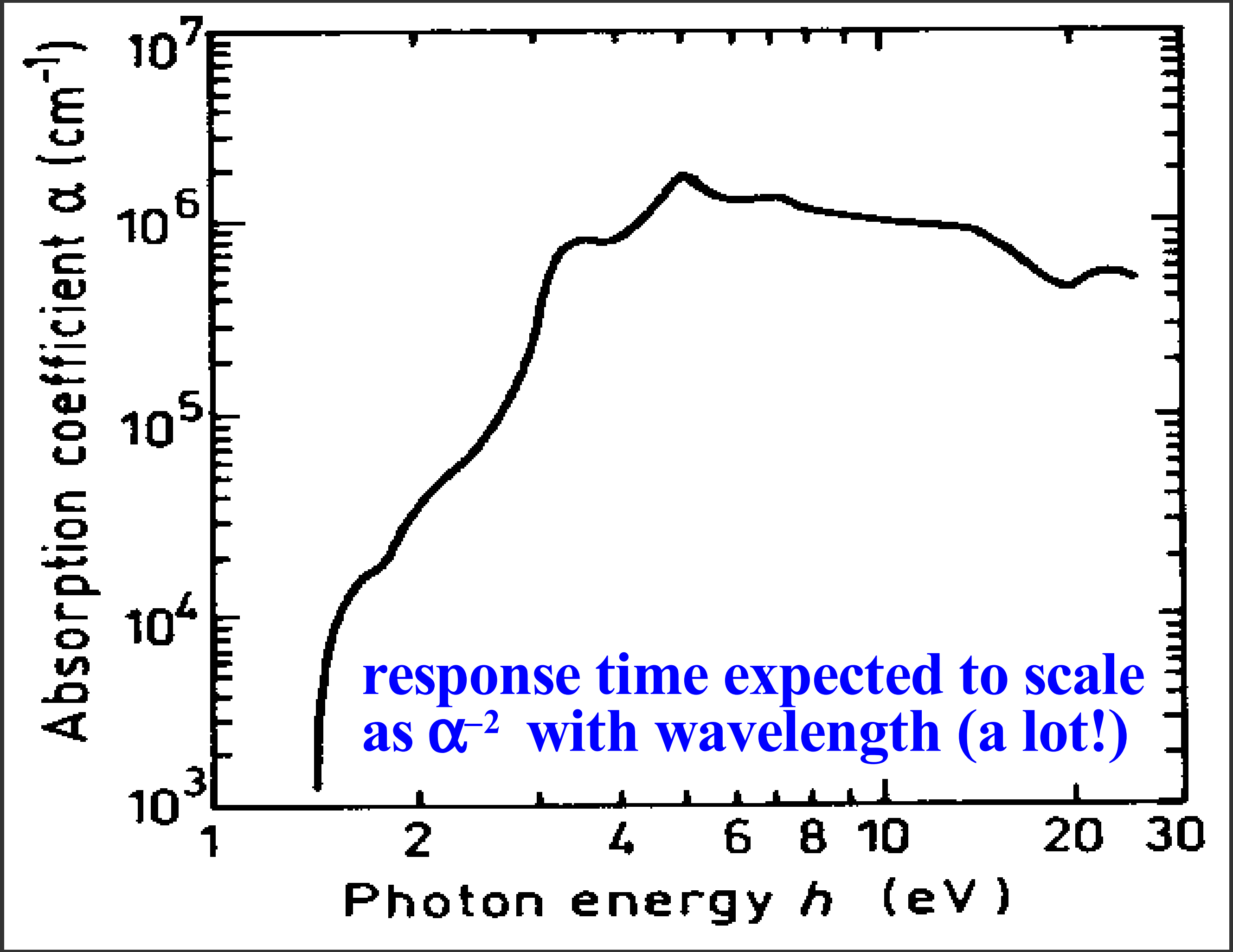
$$I(\kappa) \propto \frac{1}{\sqrt{\pi\kappa}} - \exp(\kappa)\,\mathrm{erfc}(\sqrt{\kappa})$$

$$\kappa \equiv t/\tau, \text{ where } \tau \equiv \alpha^{-2}D^{-1}$$





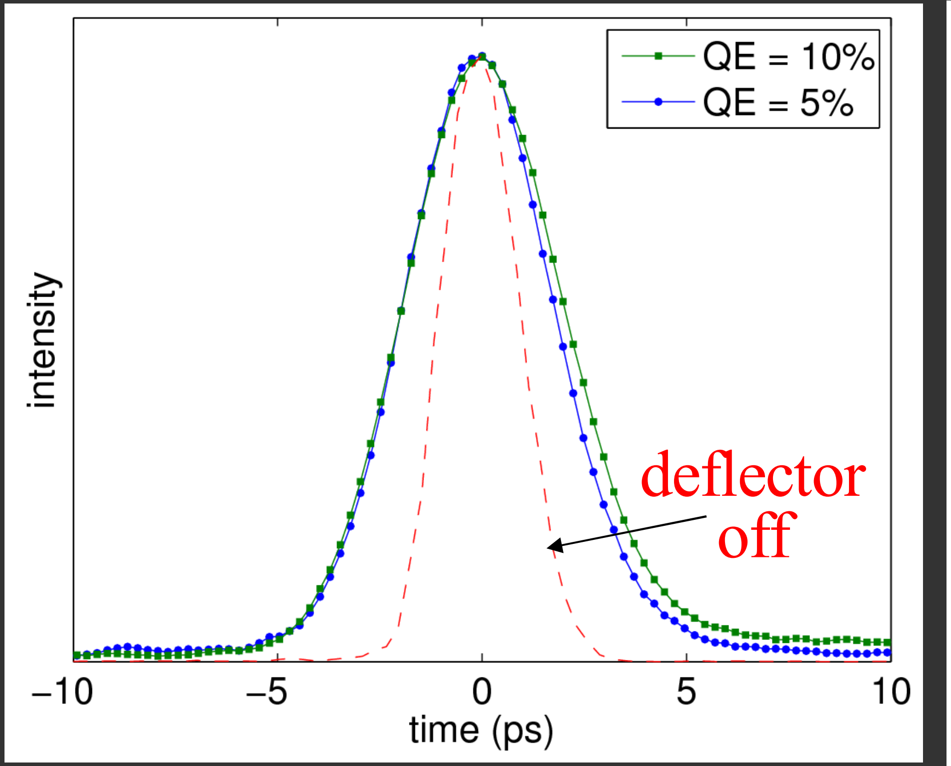
GaAs absorption



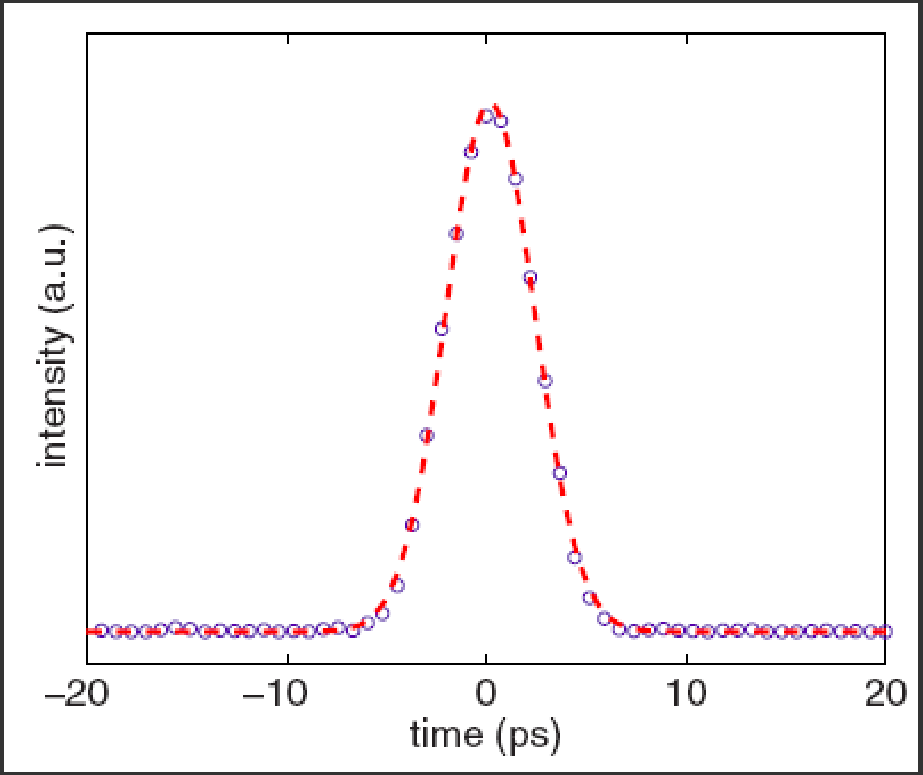
response time expected to scale as α^{-2} with wavelength (a lot!)

Prompt emitters

GaAs @ 520 nm



GaN @ 260 nm



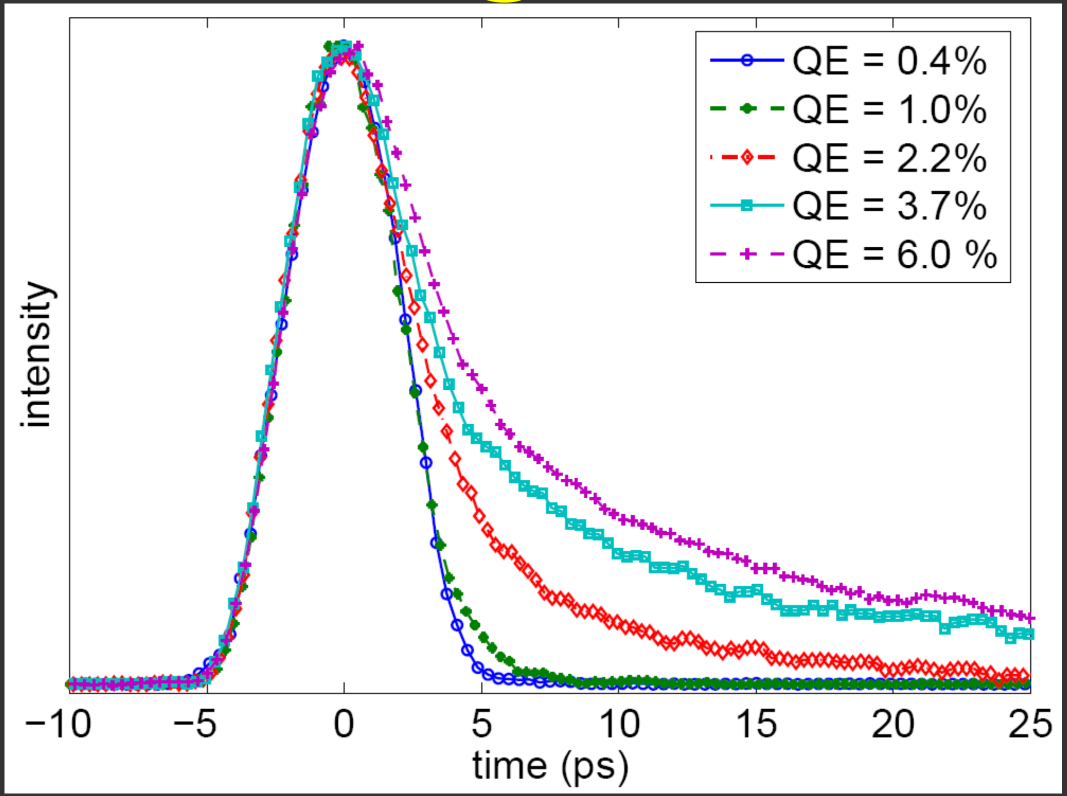
Measurements done by transverse deflecting RF cavity

Limited by 1.8 ps rms resolution dominated by laser to RF synchronization

Cornell University

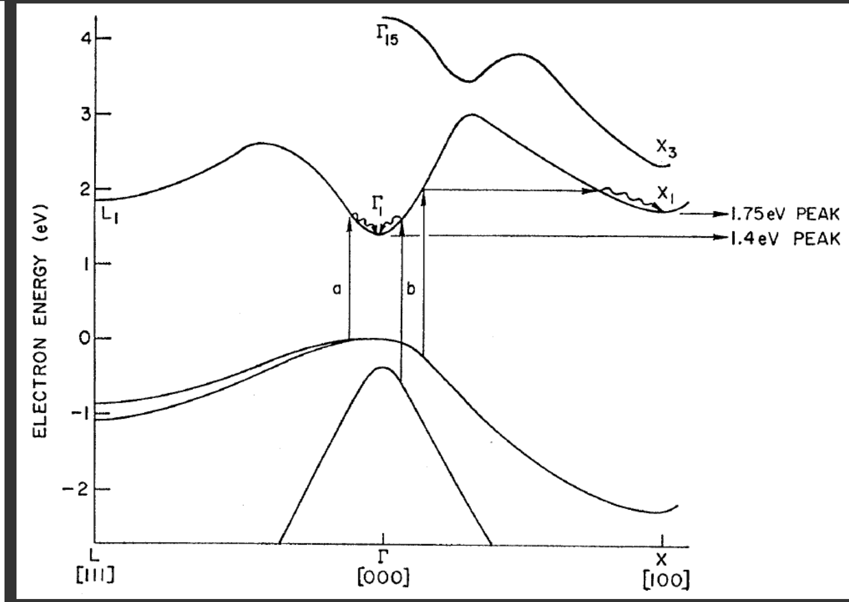
Diffusion tail

GaAsP @ 520 nm



Strong QE dependency

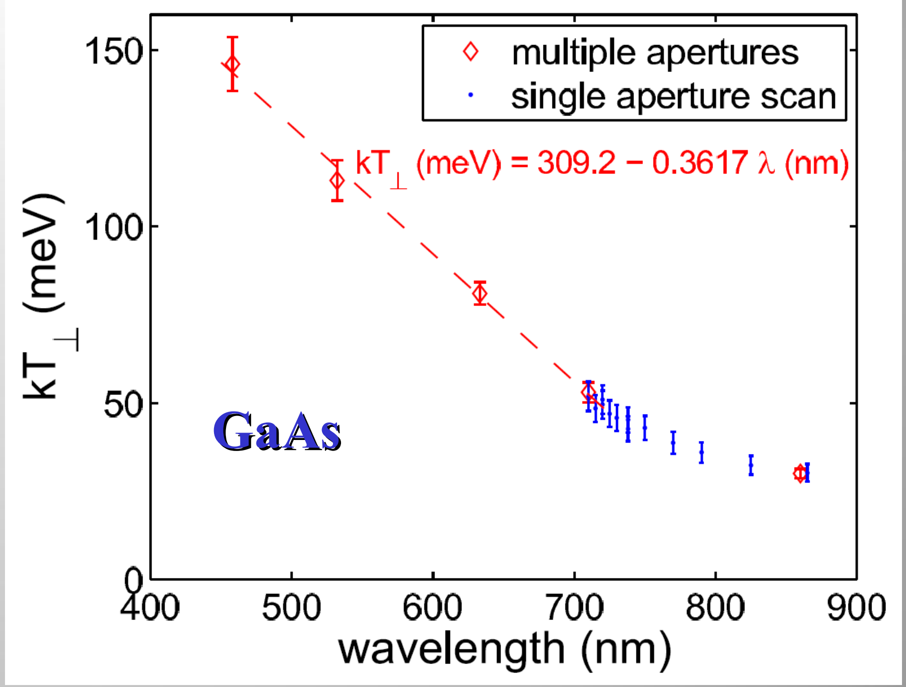
P concentration 45%



Two valleys: Γ (direct) and X (indirect) involved in the process

Transverse energy distributions

- No surprises for bulk GaAs: cold electrons with a near band-gap excitation



- Surprisingly large transverse energy spread for GaN and GaAsP:
  - GaAsP: $kT_\perp$ = 130-240 meV for photons 0-780 meV photons above the band-gap
  - GaN: $kT_\perp$ = 0.9 eV for photons with 1.4 eV above the band-gap

Summary

- Transverse energy of photoelectrons remain poorly understood for III-V semiconductors (other than GaAs)
- More carefully controlled experimental data on transverse energy distributions/time response needed
- Predictive codes and models need to be developed and benchmarked with experiments
- This will allow photocathode engineering with the desired characteristics such as cold electrons with a ps response

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