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Fundamental processes in III-V photocathodes; application for high-brightness photoinjectors
• Motivation
• NEA photoemission
• Some practical aspects
• Study cases: GaAs, GaAsP, GaN
• Summary
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 accelerators in active development.

- Essentially removes the average current limitation typical to linacs (i.e. $P_{\text{beam}} \gg P_{\text{wall plug}}$).

- 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**

\[ i(\text{mA}) = \frac{\lambda(\text{nm})}{124} \times P(\text{W}) \times \text{QE(\%)} \]

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

- **Transversely cold (thermalized) electron distribution**
  - Directly sets the solid angle of the emitted electrons; an upper limit on achievable beam brightness
• **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
- Defined as vacuum level $E_{vac}$ relative to the conduction band minimum
- Negative affinity: the vacuum level lies below the CBM $\Rightarrow$ very high QE possible
- NEA:
  - 1) band bending
  - 2) dipole layer
• Alperovich et al., Phys. Rev. B 50 (1994) 5480: clean p-doped GaAs has Fermi level unpinned and shows little band bending
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

Diagram:
- p-doped bulk (neutral)
- + ionized Cs
- bb region
• Majority of Cs atoms become only polarized (not ionized), forming a dipole layer (e- Cs+).

\[ E_{\text{gap}} = 1.42 \text{ eV} \]

Before Cs
\[ \chi = 4 \text{ eV} \]

After Cs
\[ \chi_{\text{eff}} \sim -0.1 \text{ eV} \]
\[ V_{bb} \sim 0.4 \text{ eV} \]
\[ d_{bb} \sim 10 \text{ nm} \]
(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 > $E_{\text{gap}}$ for e–/e– scattering. Thus, electrons excited with $E_{\text{vac}} < \text{KE} < E_{\text{VBM}} + 2E_{\text{gap}}$ have excellent chances of escape
Electron transport processes

CBM thermalization time: 0.1-1 ps
Electron-hole recombination: ~ns
Emission time: \( \propto \frac{1}{(\alpha^2D)} \)
strong wavelength dependence
Energy vs. momentum

Multiple low-phonon emission

Excitation

Radiative recombination

Non-radiative recombination

Defect states

Electron-hole scattering with hh-lh conversion

Intervalley phonon

CB

VB

hh

lh

so

0

\( \Gamma \)

\( \Lambda \)

\( \vec{k} \)

\( \Delta \)
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)

Yo-Yo Activation

JAP 54 (1983) 1413
GaAs: Optimal Cs coverage

laser wavelength: 670 nm

Ugo Weigel, PhD thesis
• $\text{H}_2\text{O}$, $\text{CO}_2$ and $\text{O}_2$ can lead to chemical poisoning of the activated layer

• Low current ($\sim 1 \mu\text{A}$) 1/e lifetimes $\sim 100$ 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
• ~5 hour lifetime (limited by gas backstreaming from the beam dump), i.e. 20 hours 1/e for 5 mA
• 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
\[
\frac{\partial c(h, t)}{\partial t} = D \frac{\partial^2 c(h, t)}{\partial h^2}
\]

subject to:
\[
c(h, t = 0) = c_0 e^{-\alpha h}
\]
\[
c(h = 0, t) = 0
\]

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

\[
I(\kappa) \propto \frac{1}{\sqrt{\pi \kappa}} - \exp(\kappa) \text{erfc}(\sqrt{\kappa})
\]

\[
\kappa \equiv t/\tau, \text{ where } \tau \equiv \alpha^{-2}D^{-1}
\]
response time expected to scale as $\alpha^{-2}$ 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

NEA photocathodes meas.
**GaAsP @ 520 nm**

- Strong QE dependency

- P concentration 45%

- Two valleys: $\Gamma$ (direct) and $X$ (indirect) involved in the process

NEA photocathodes meas.

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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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