P3 Workshop
Photocathode Physics for Photoinjectors

Development of Air Stable Silicon Photoemitter with Electronically Tunable Negative Electron Affinity

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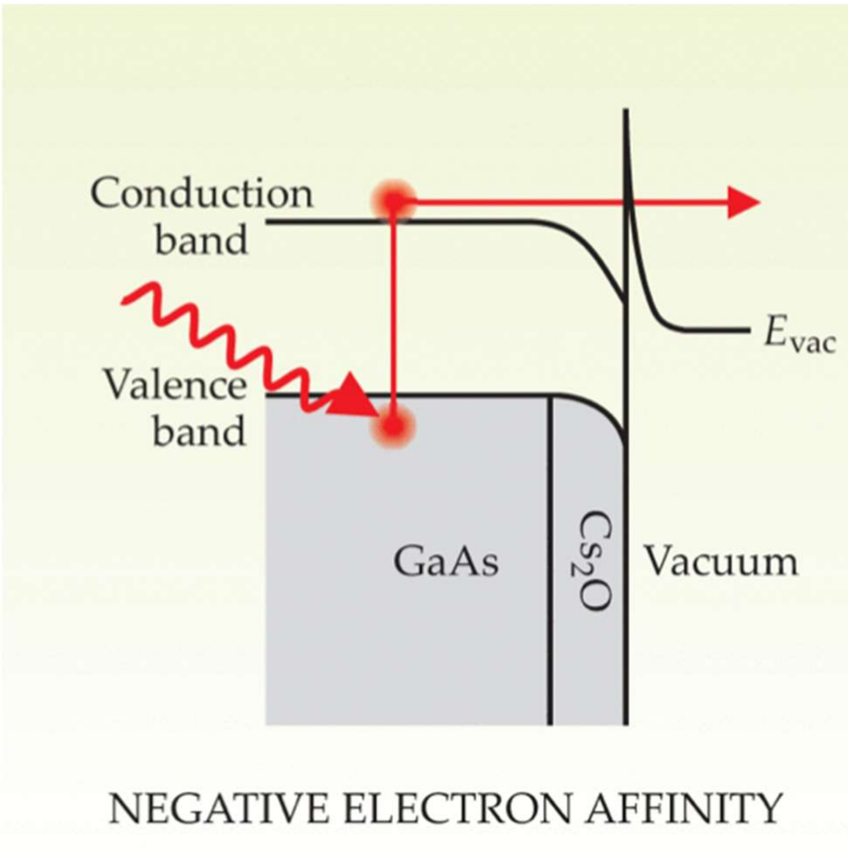
Can we operate a negative electron affinity photocathode without ultrahigh vacuum?

Traditional Negative Electron Affinity Photocathode



Pros:

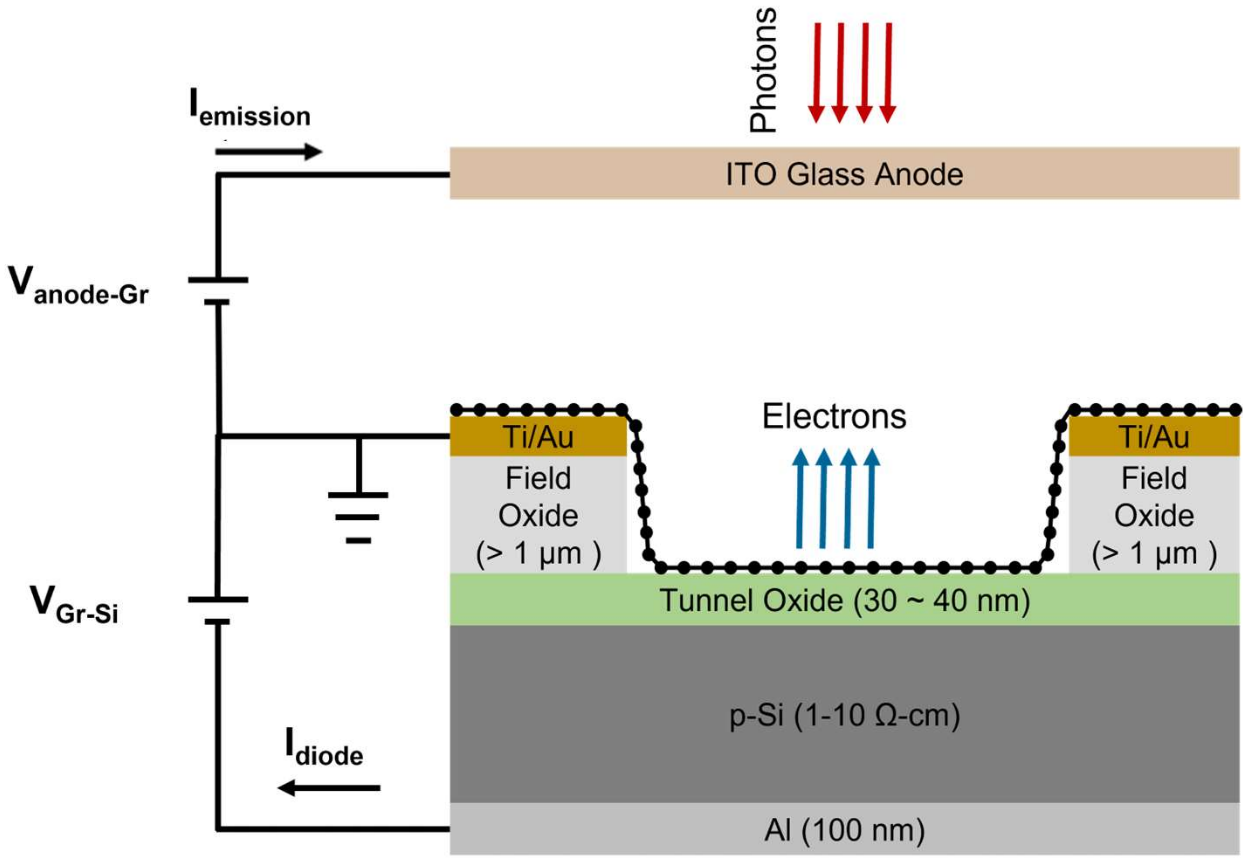
1. High quantum efficiency
2. Visible photon excitation

Cons:

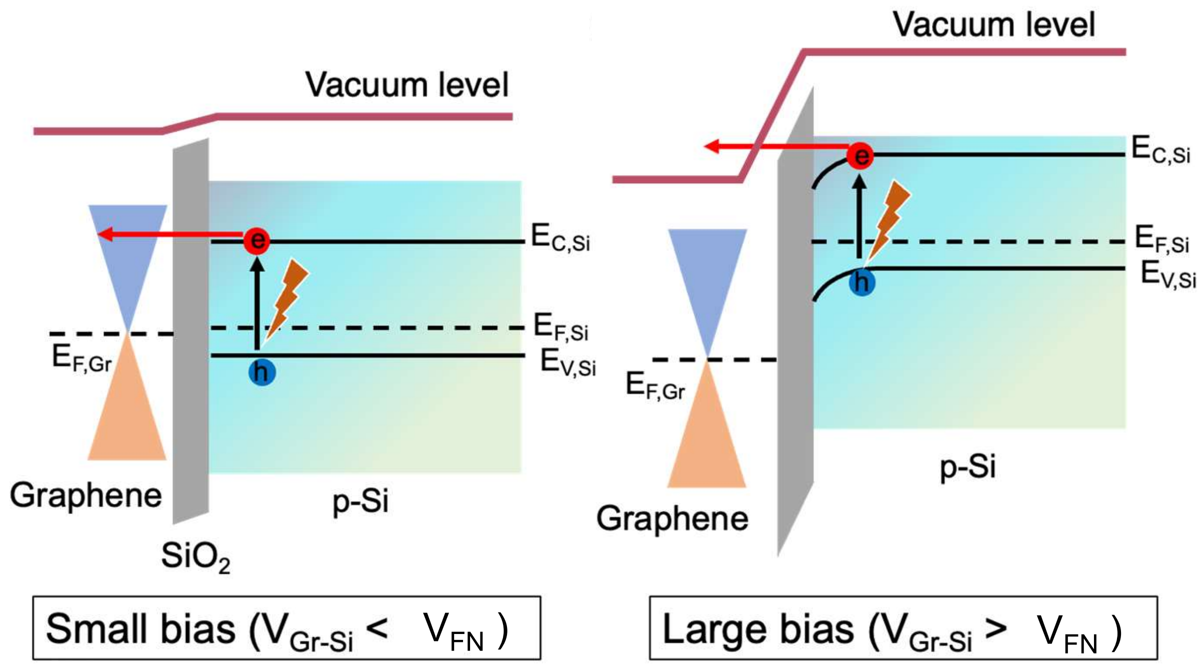
1. Requires ultrahigh vacuum

Hernandez-Garcia, Carlos, Patrick G. O Shea, and Marcy L. Stutzman. "Electron sources for accelerators." Physics today61.2 (2008): 44.

Electronically Tunable NEA Photocathode

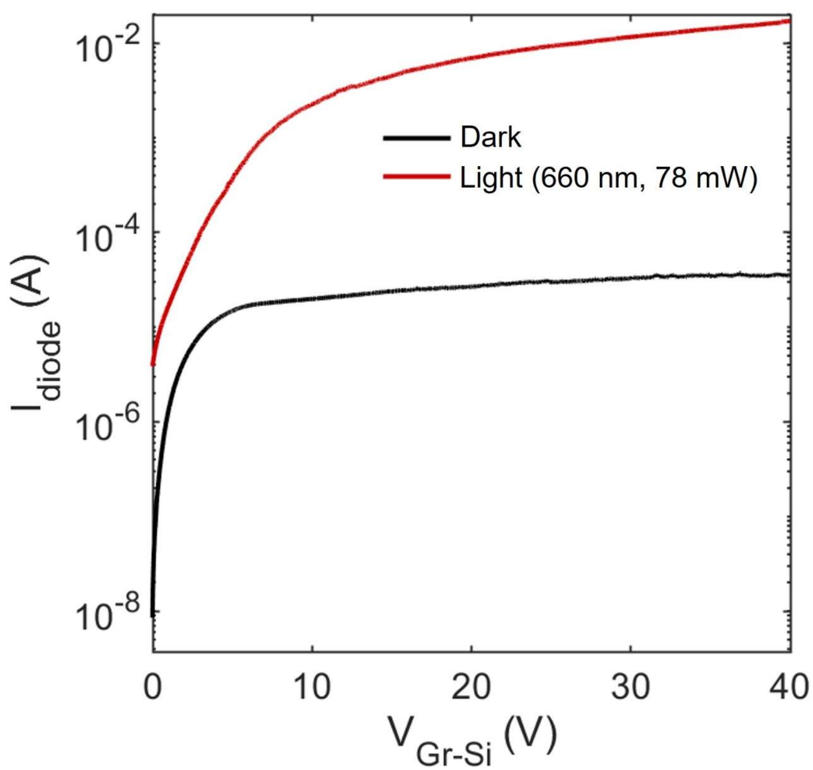


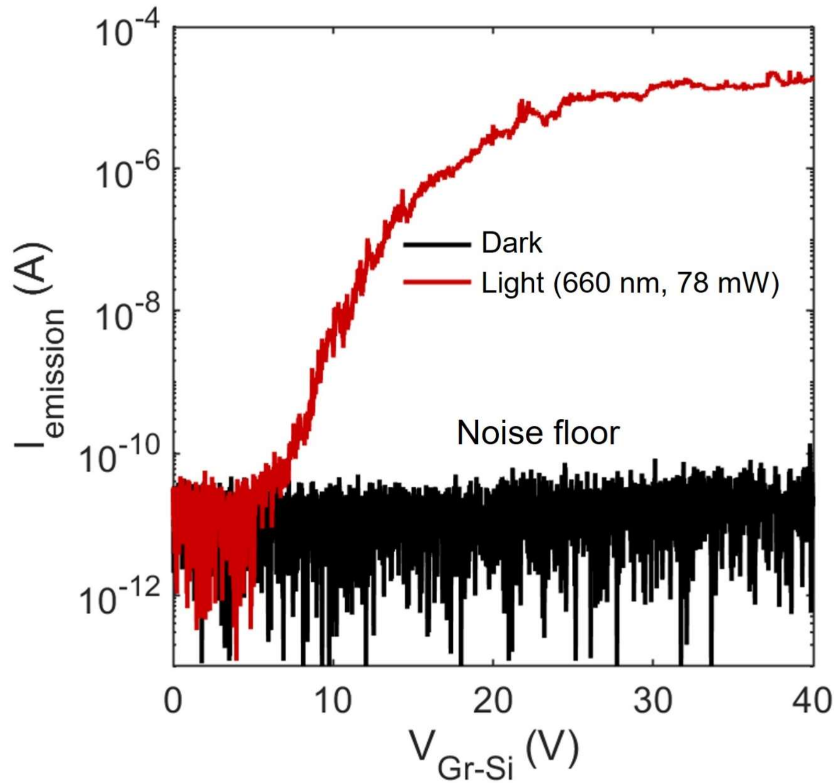
Working Principle



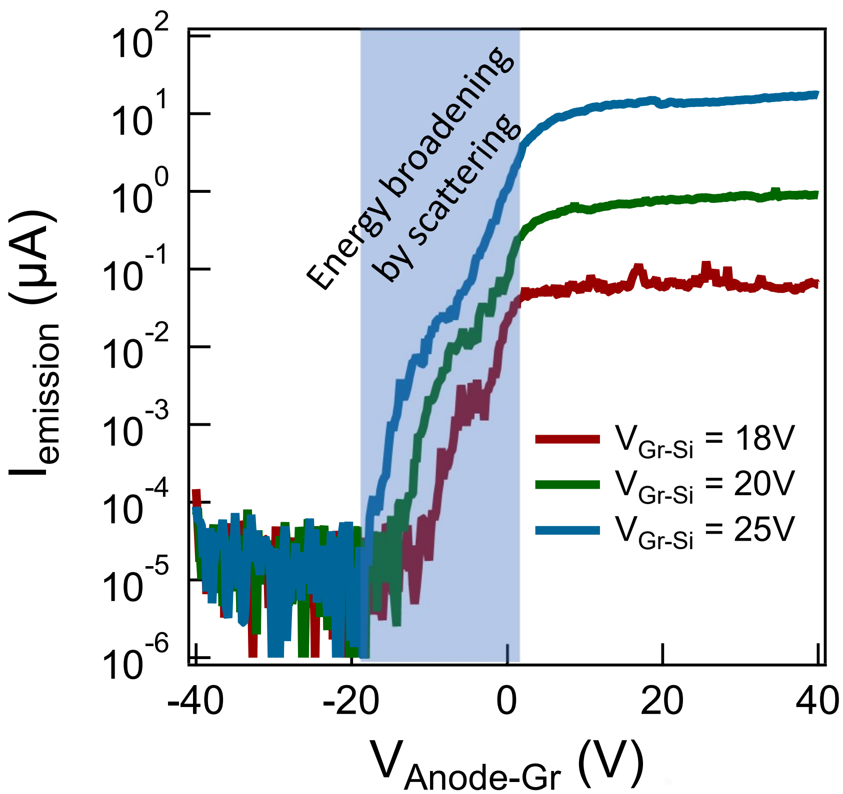
- Voltage is applied between the semiconductor and graphene, generating an electric field which mimics the surface dipole field in an NEA photocathode.
- Photo-excited electrons tunnel through the barrier and introduced into graphene with higher energy than $E_{F,Gr}$

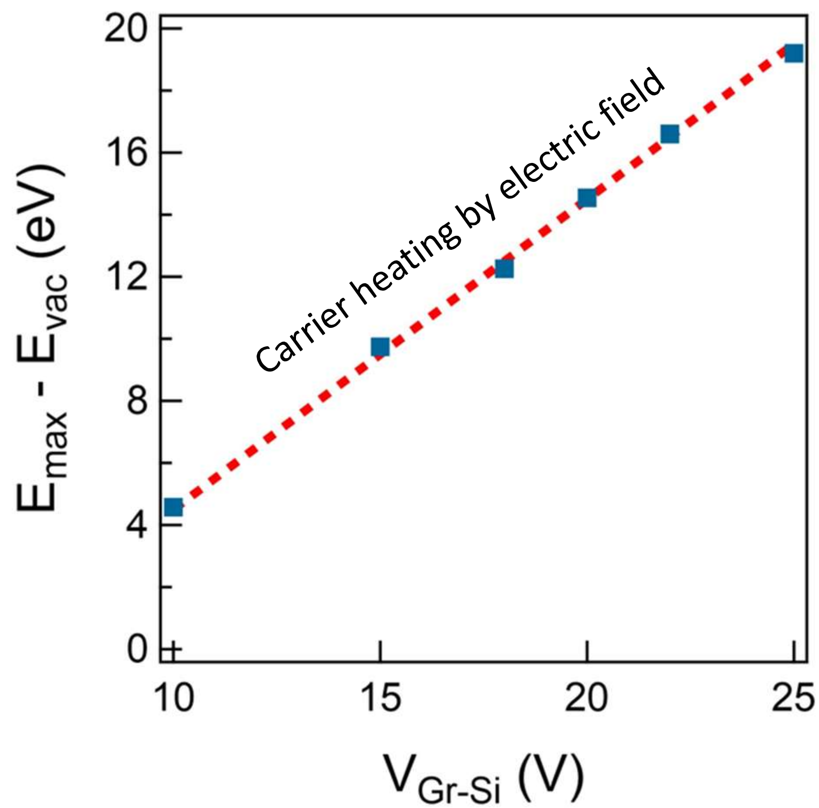
Experimental results: Emission current vs $V_{Gr\text{-}Si}$



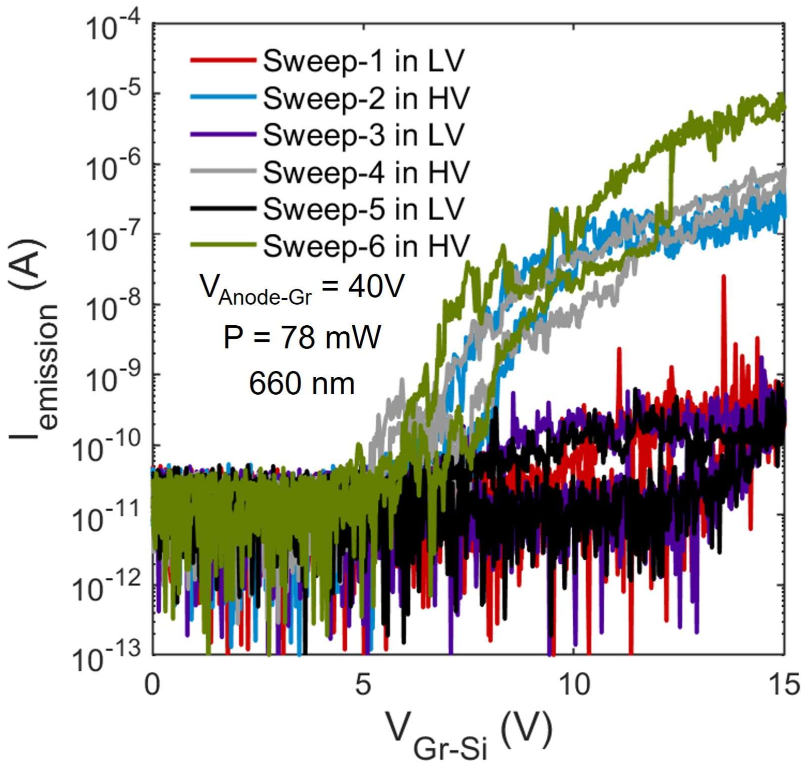


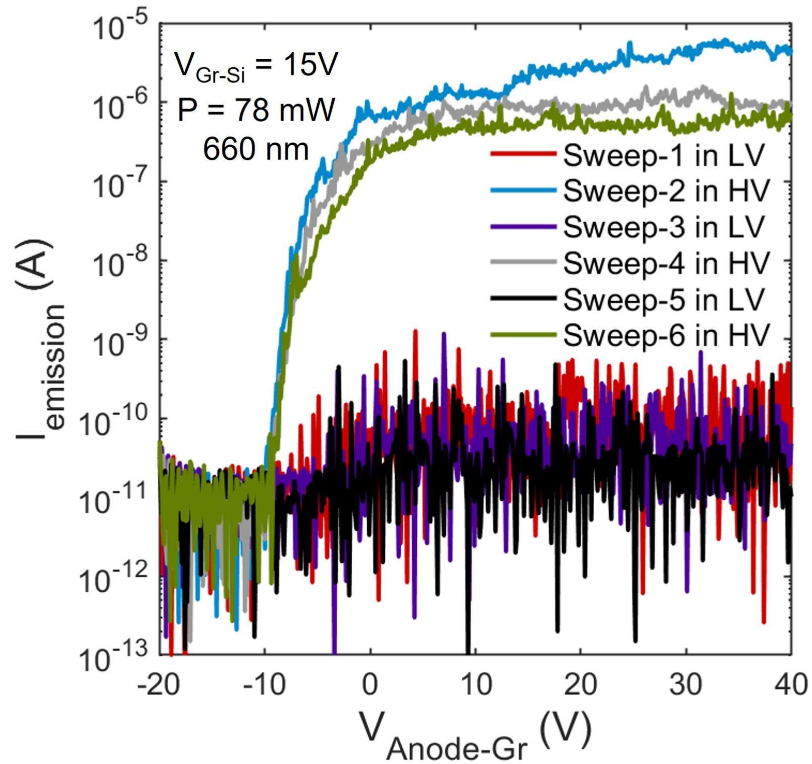
Experimental results: Emission current vs Anode voltage



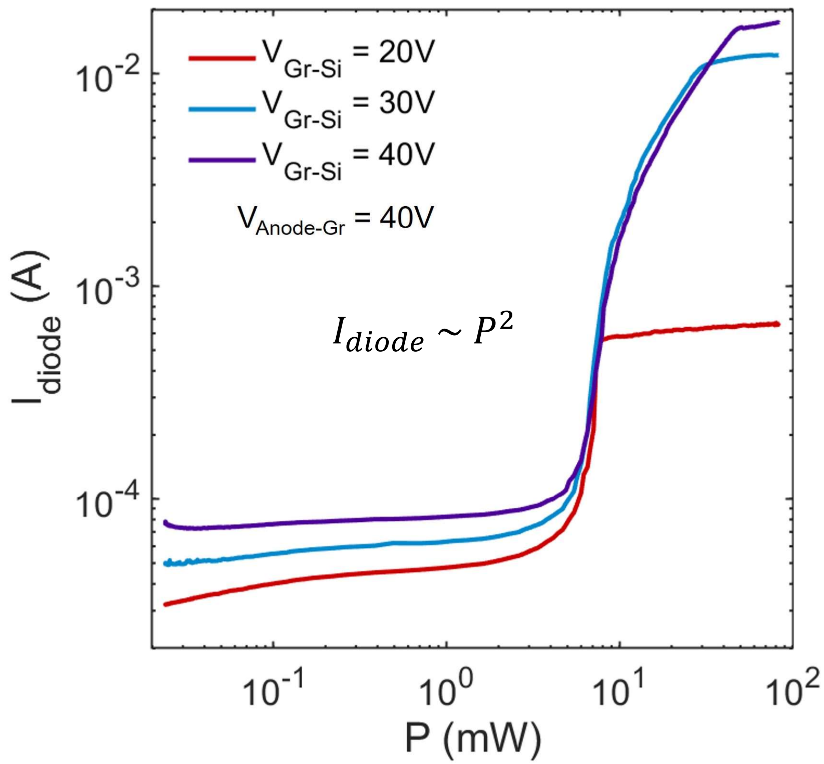


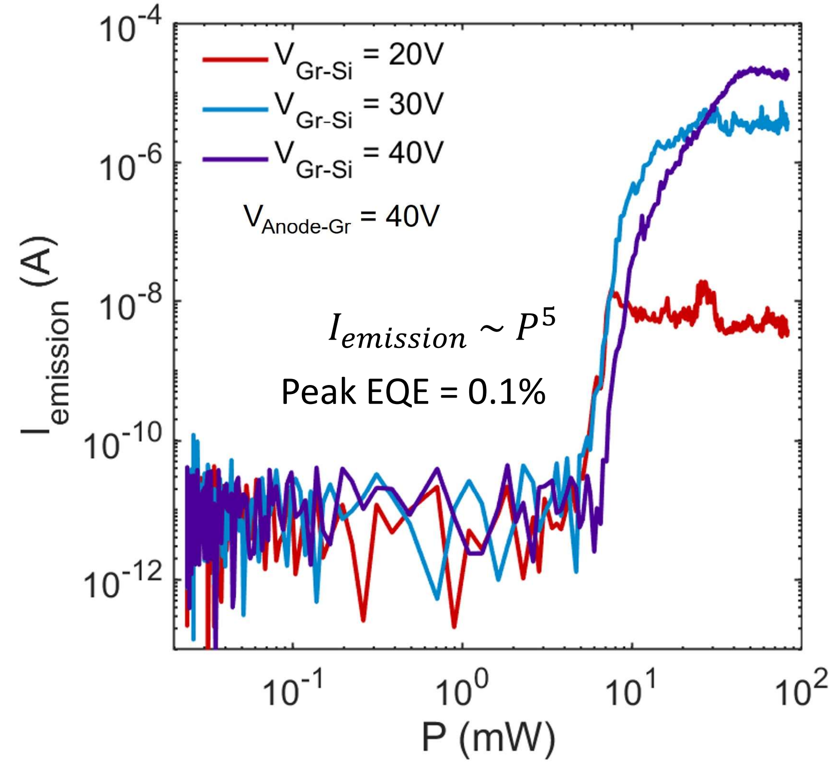
Stability at higher vacuum pressures





Experimental results: Emission current vs Optical power





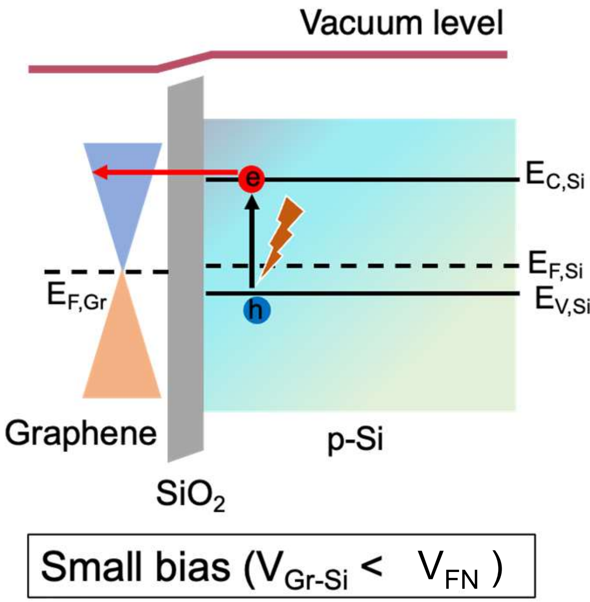
Key emission characteristics

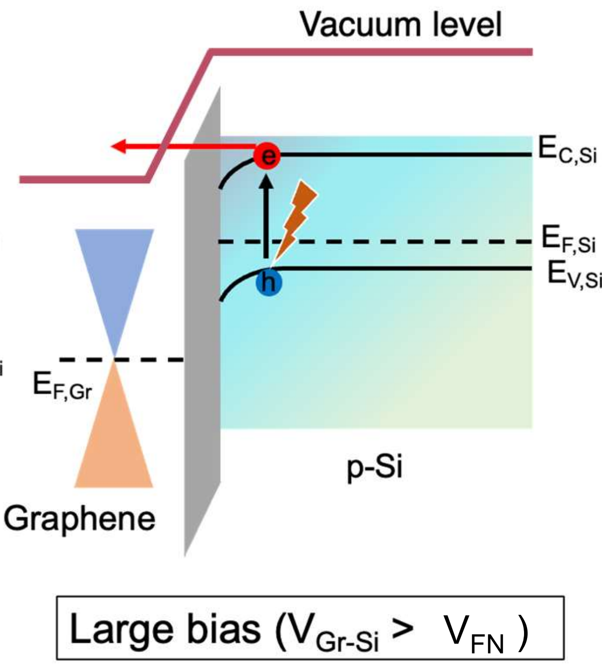
- Existence of a threshold $V_{Gr\text{-}Si}$ to emit electrons
- Energy distribution of emitted electrons is broad
- Emission current shows a highly nonlinear dependence on optical power

Existence of a threshold $V_{Gr\text{-}Si}$

- The electrons tunneling into/through SiO_2 must gain higher energy than the vacuum level (0.9 eV higher than SiO_2 conduction band minima)
- Direct tunneling of electrons through SiO_2 will never allow this
- Electrons must tunnel into SiO_2 conduction band (FN tunneling)
- These electrons must gain at least 0.9 eV energy from electric field

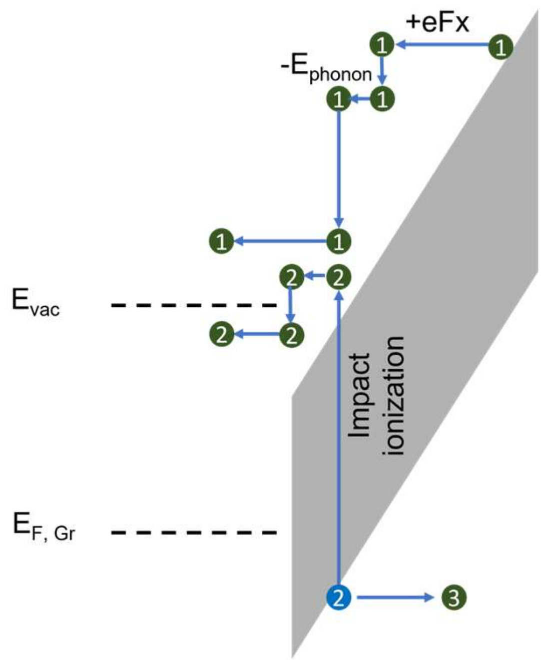
Threshold for applied voltage



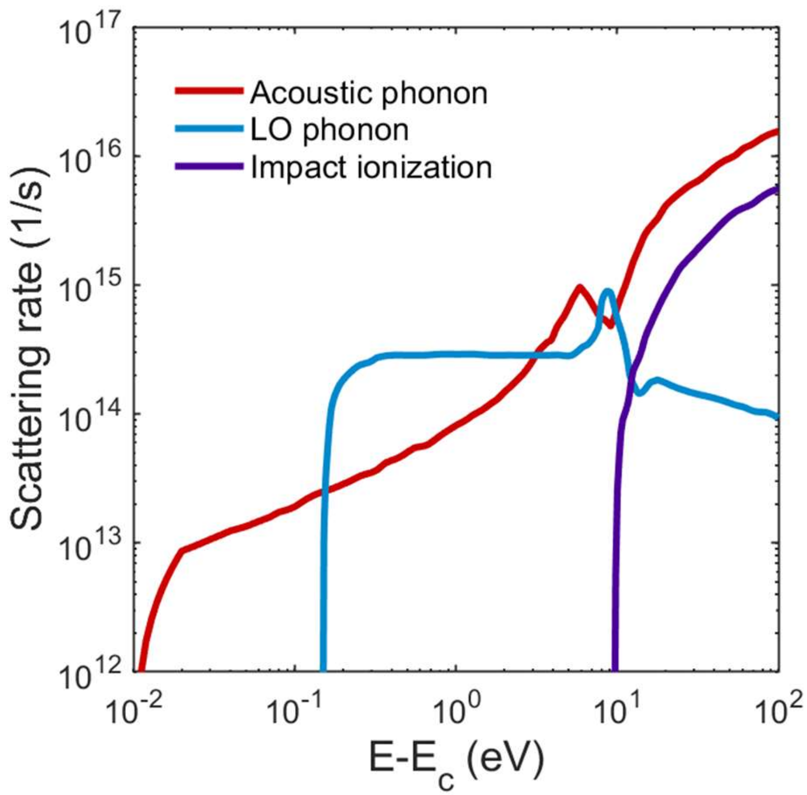


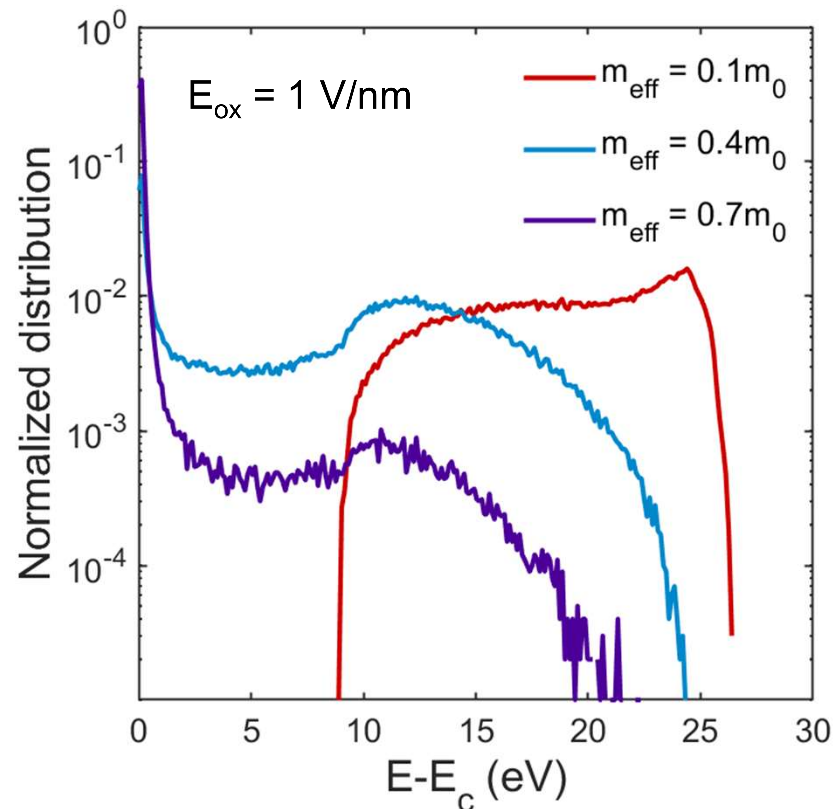
Broad energy distribution

- To have a broad energy distribution, electrons must scatter at SiO_2 conduction band
- Possible scattering mechanisms for SiO_2
  - Longitudinal polar optical phonon scattering
  - Acoustic phonon scattering
  - Impact ionization scattering



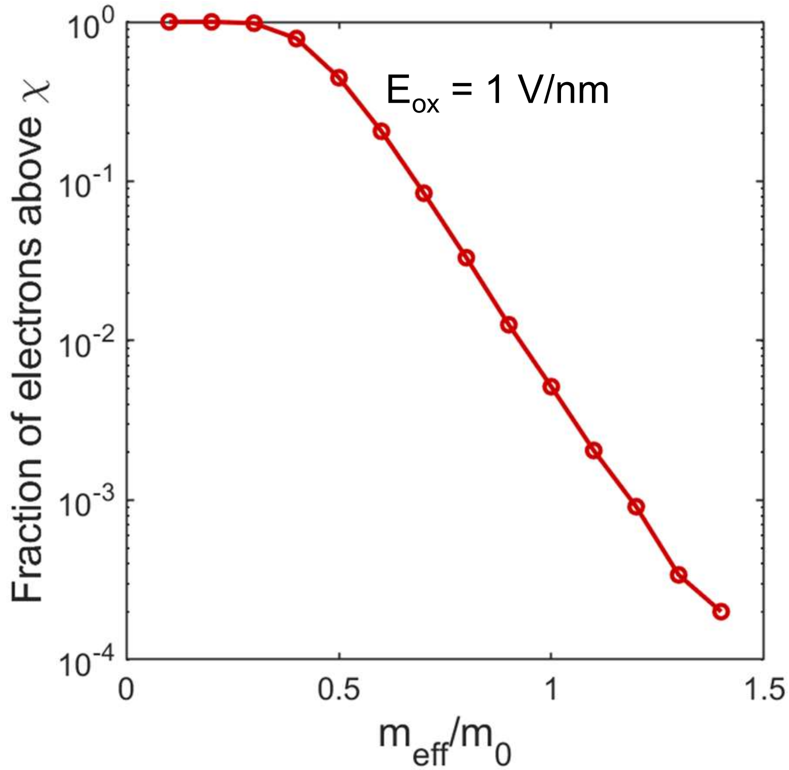
Monte Carlo simulation: Transport at SiO_2

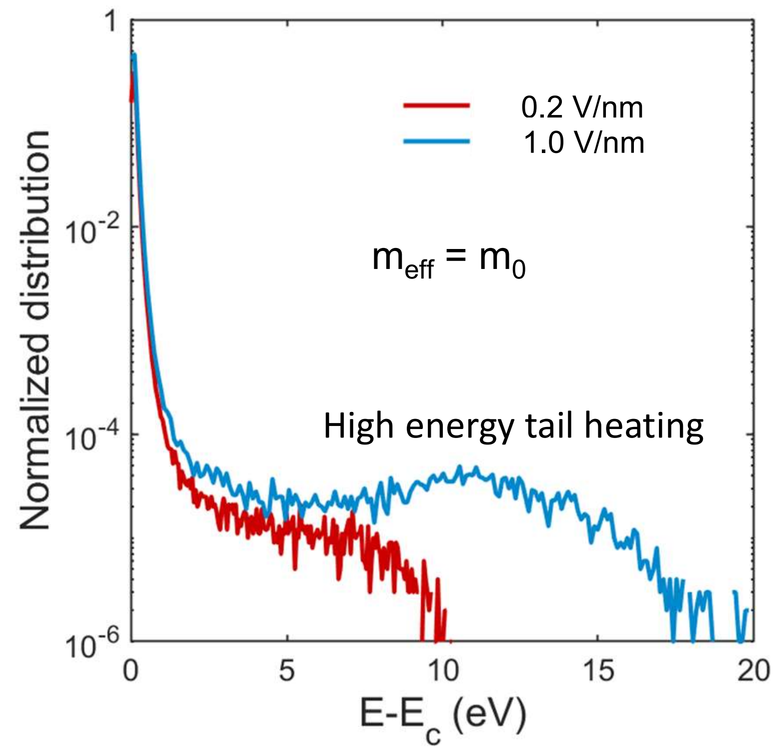




Parabolic band approximation

Monte Carlo simulation: Transport at SiO_2





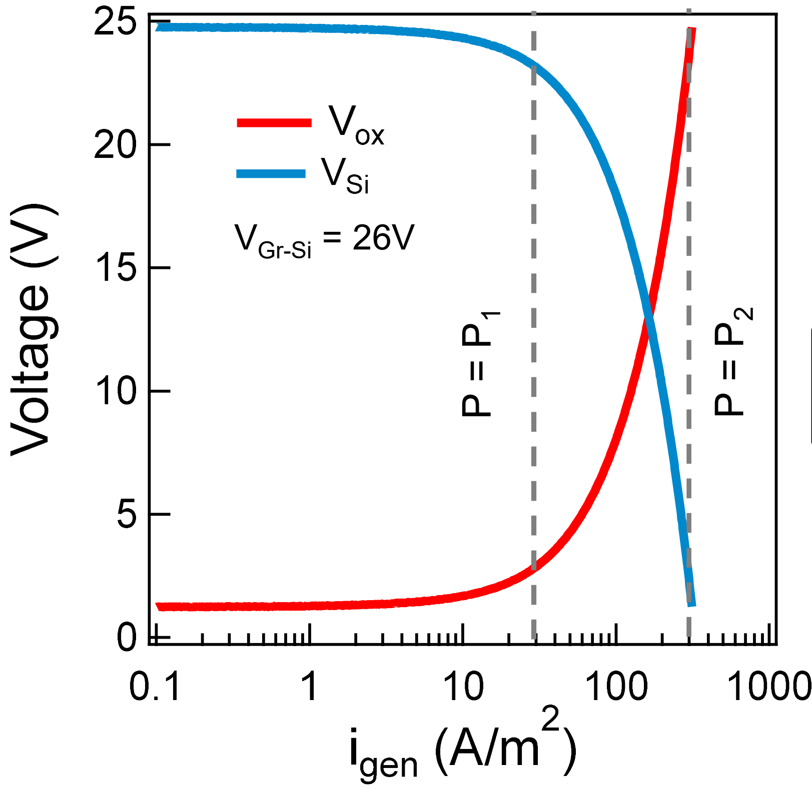
Nonlinear emission current

- Multiphoton absorption is highly unlikely in silicon for the optical power densities we have (10^3-10^4 W/m^2)
- There is no dominant scattering mechanism for SiO_2 that is nonlinear to electron injection rate/optical power
- Optical power must modify the voltage distribution within the device
  - Voltage dropped at depletion region at silicon
  - Voltage dropped at oxide

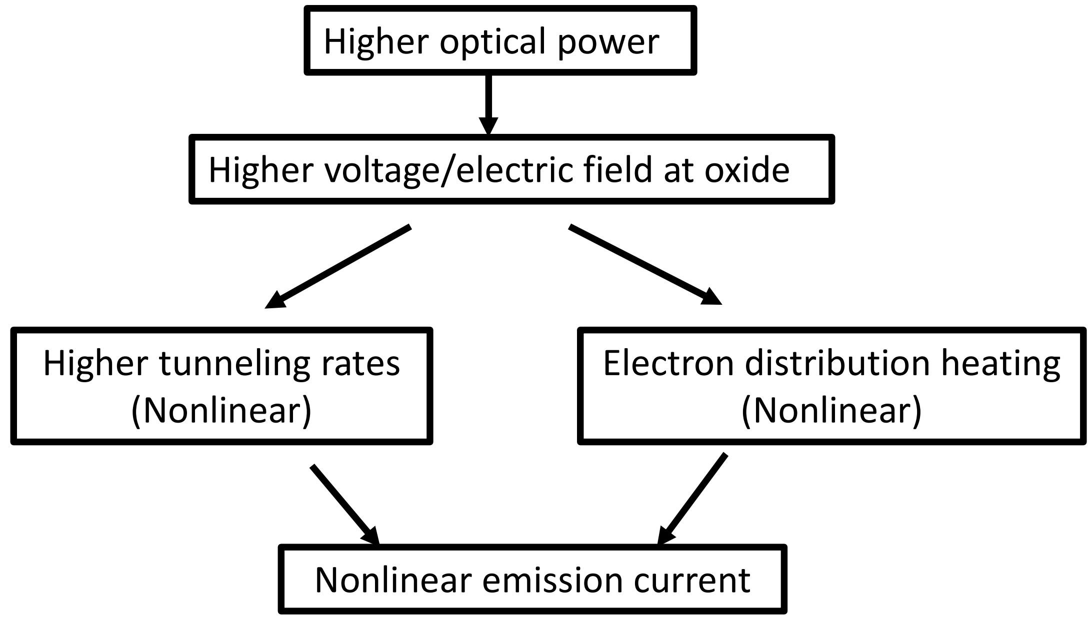
Voltage distribution between oxide and silicon

- Extremely small electron generation rate (dark/low optical power)
  - No inversion layer can be formed at Si/SiO_2 interface
  - Majority voltage is dropped at silicon depletion layer ($V_{Gr\text{-}Si} \approx V_{si} >> V_{ox}$)
- Moderate electron generation rate (moderate optical power)
  - Incomplete generation of inversion layer
  - Appreciable voltage drop across oxide
- High electron generation rate (high optical power)
  - Complete inversion
  - Majority voltage drop across oxide ($V_{Gr\text{-}Si} \approx V_{ox} >> V_{si}$)
- Poisson's equation determines how much voltage drops across different parts of the device ($V_{Gr\text{-}Si} = V_{Si} + V_{ox}$)
- $V_{si} = \frac{1}{2\epsilon_{si}} q N_A {x_{dep}}^2 + \frac{1}{\epsilon_{si}} q\left(g_{dark} + g_{ph}\right) x_{dep} \tau_e$

Voltage redistribution by optical power



Generation current density is proportional to optical power density



Summary

- This is a silicon photocathode
  - Fabrication is easier and cheaper
- NEA surface is controlled by voltage
  - Can be turned on and off
  - Stable at atmospheric conditions
- Photons need to have energy $\geq$ silicon bandgap
  - Visible lasers are enough for emission

Acknowledgements

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- Sponsors: