Nanostructured Photoelectron Emitters for Electron Beamlet Array Generation

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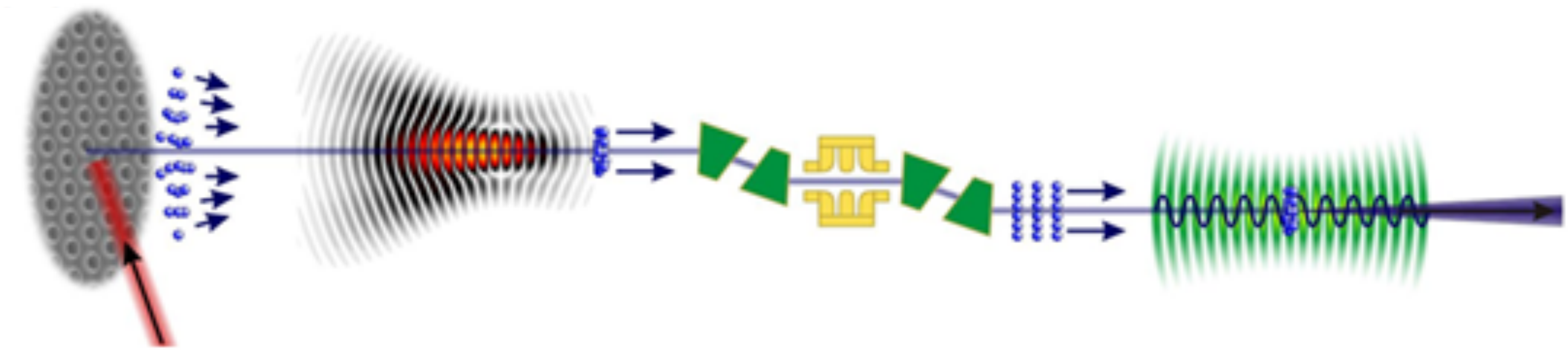
Overview

- Why an electron beamlet array?



Electron Emitter Array

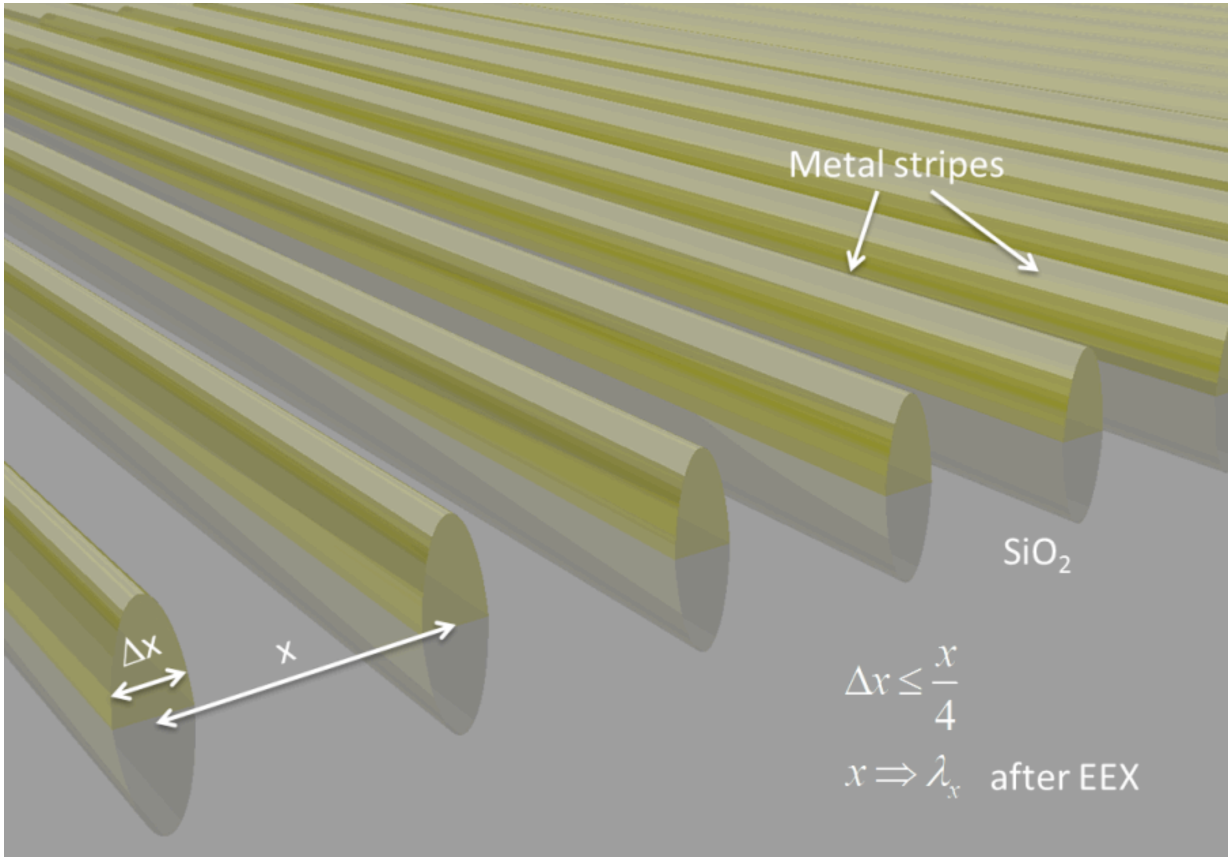
Electron Acceleration

Emittance Exchange

Inverse Compton Scattering

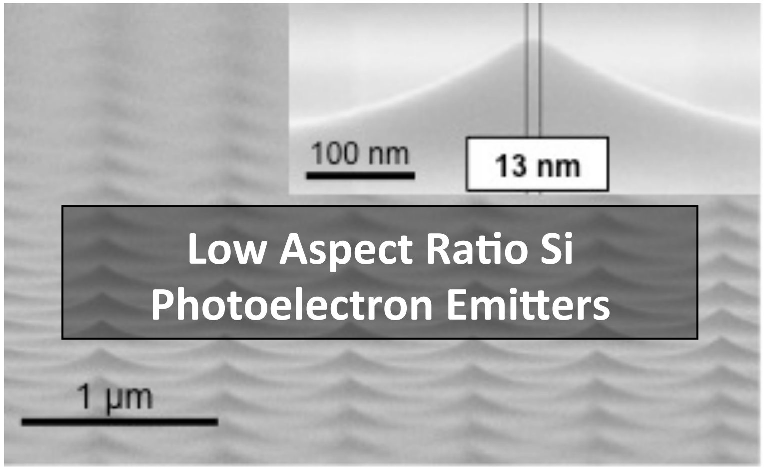
- Coherent electron bunches generate coherent x-rays via ICS

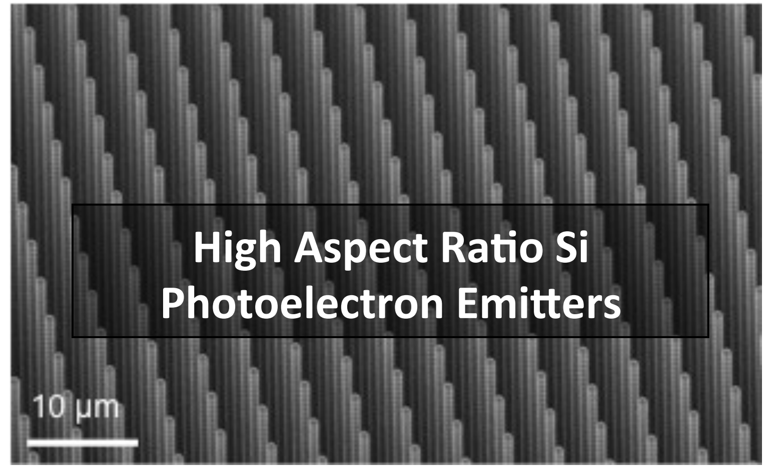
Cathode Requirements

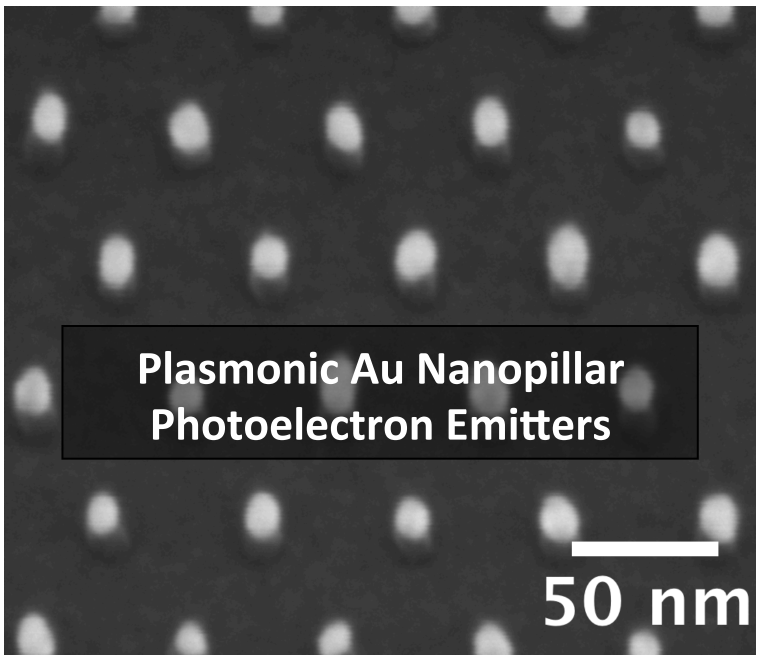


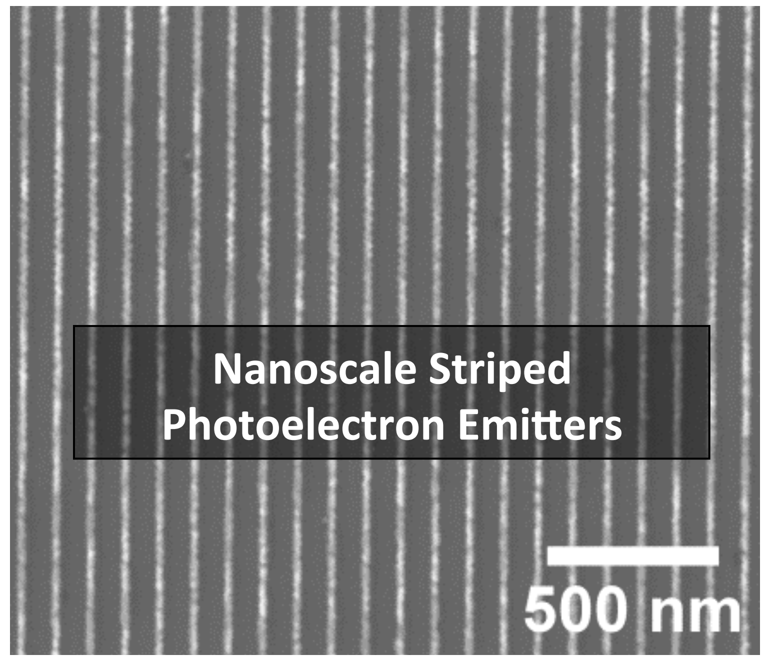
- Emitter pitch (x) demagnified to λ_x in EEX
- Longitudinal electron bunch width $\propto \Delta x$

Nanostructured Cathode Materials







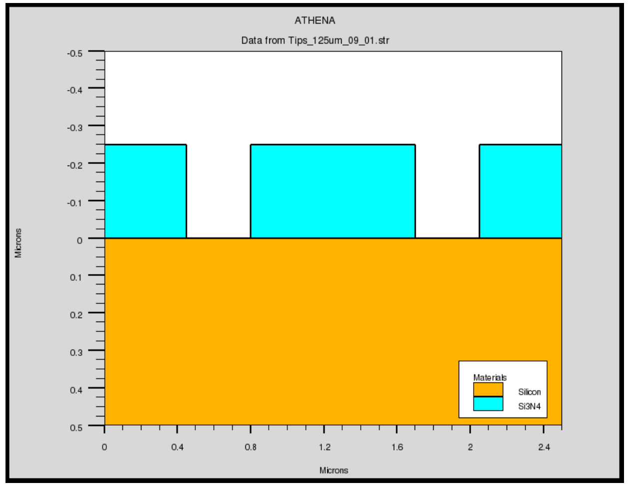


Low Aspect Ratio Si Photoelectron Emitter Array

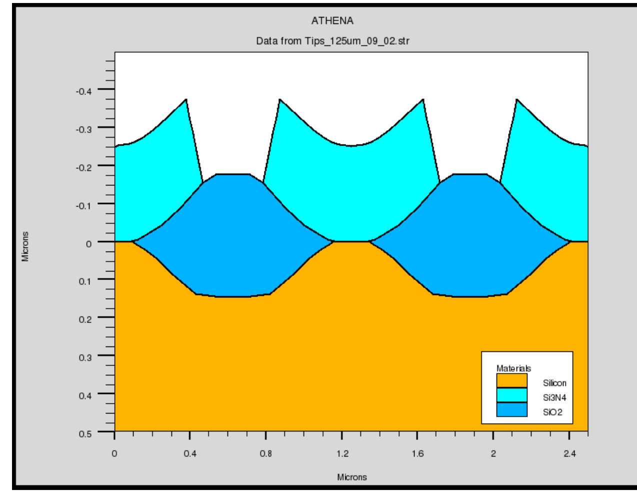
- Goals
  - Highly uniform emitter geometry over entire area of laser spot
  - Uniform charge distribution
  - ~1 pC per laser pulse
- Fabrication
  - Optical lithography and diffusion limited oxidation method
  - Emitter pitch as low as 1.25 μm
  - Highly uniform emitter radii across 150 mm wafer (σ ~1 nm)

Si Tip Array Fabrication

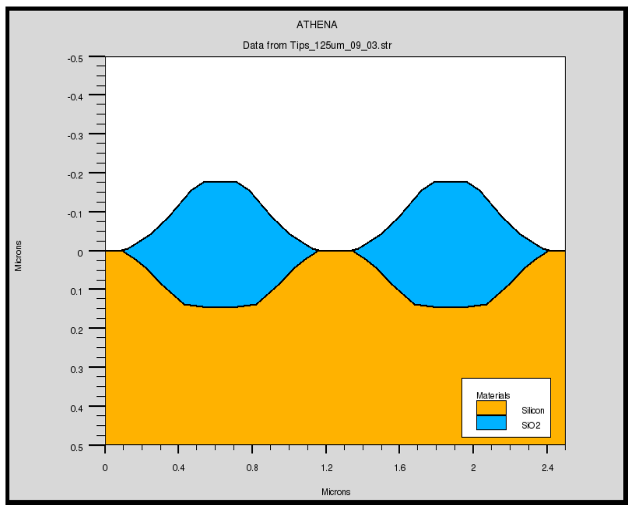
- Stress-limited oxidation
- Uniform oxide thickness across surface
- Tip radii variation limited by spatial variation in lithography
- Tip radii as small as 6-7 nm



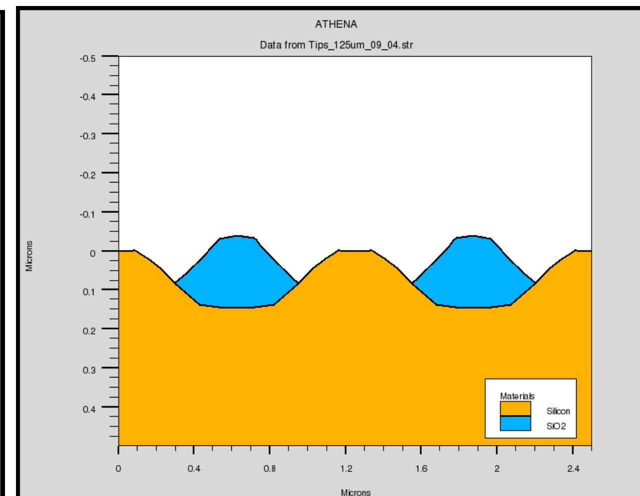
1) Define and Etch Nitride Disks



2) Oxidation of Si

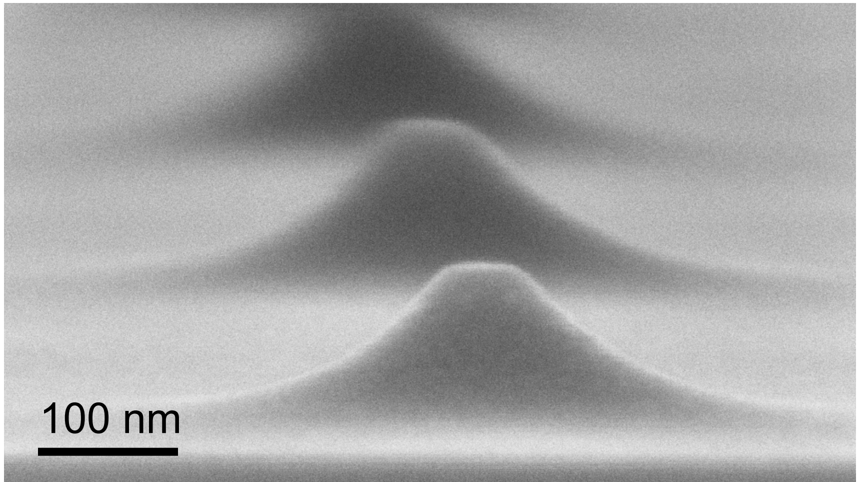


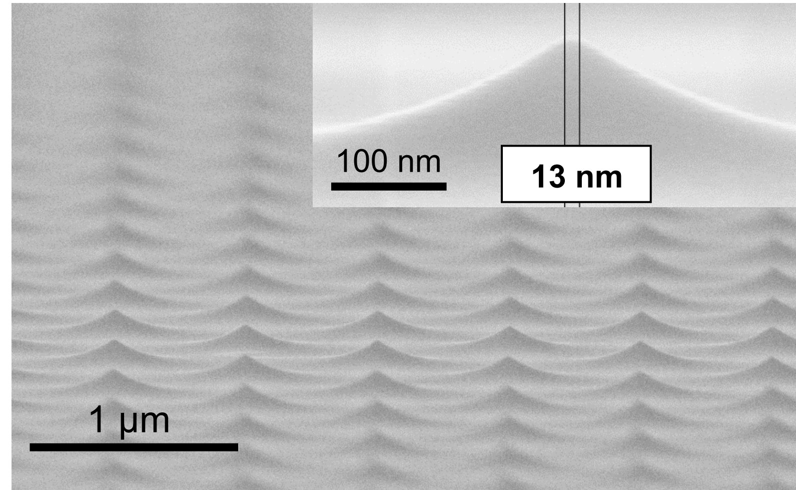
3) Removal of Nitride



4) Etchback Oxide

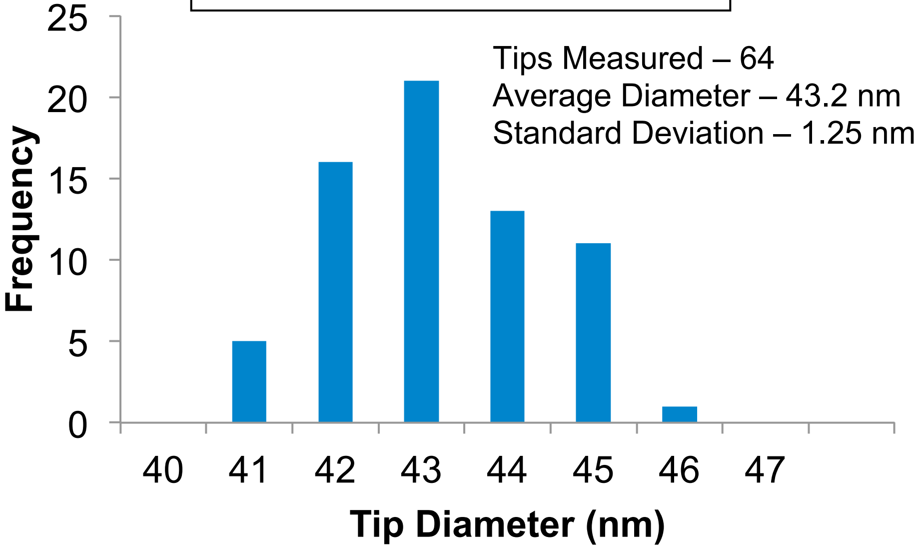
Diameter Variation – Single and Double Oxidation

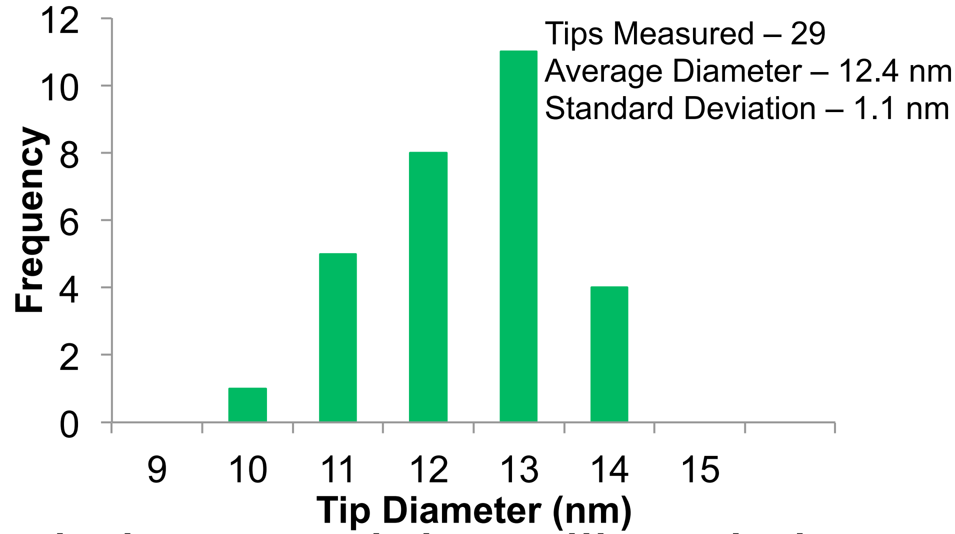




Diameter = 43.2 nm +/- 2.89%

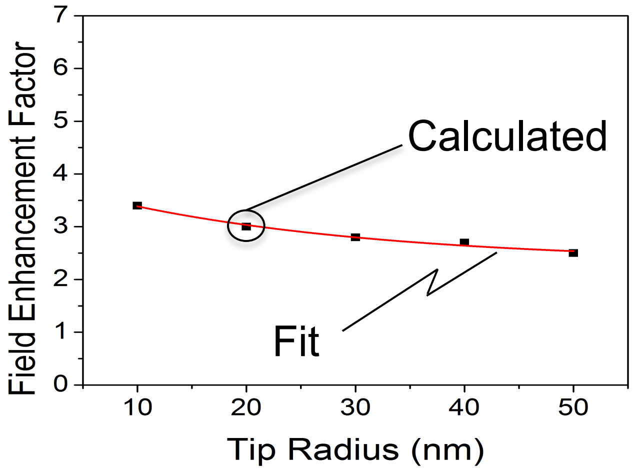
Diameter = 12.4 nm +/- 8.87%

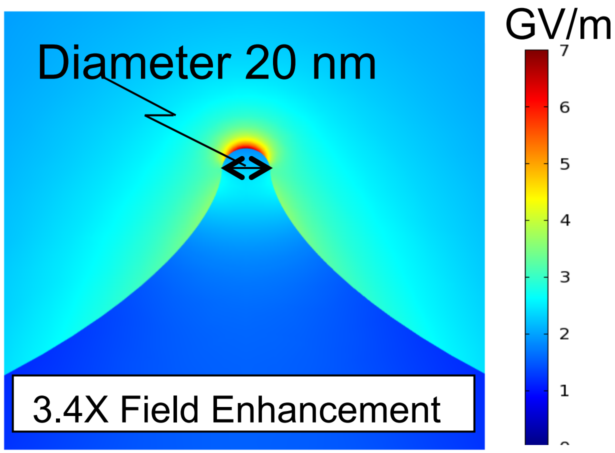




- Stress-limited oxidation results in improved tip radii statistics

Simulation of Local Field Enhancement at Si Tips



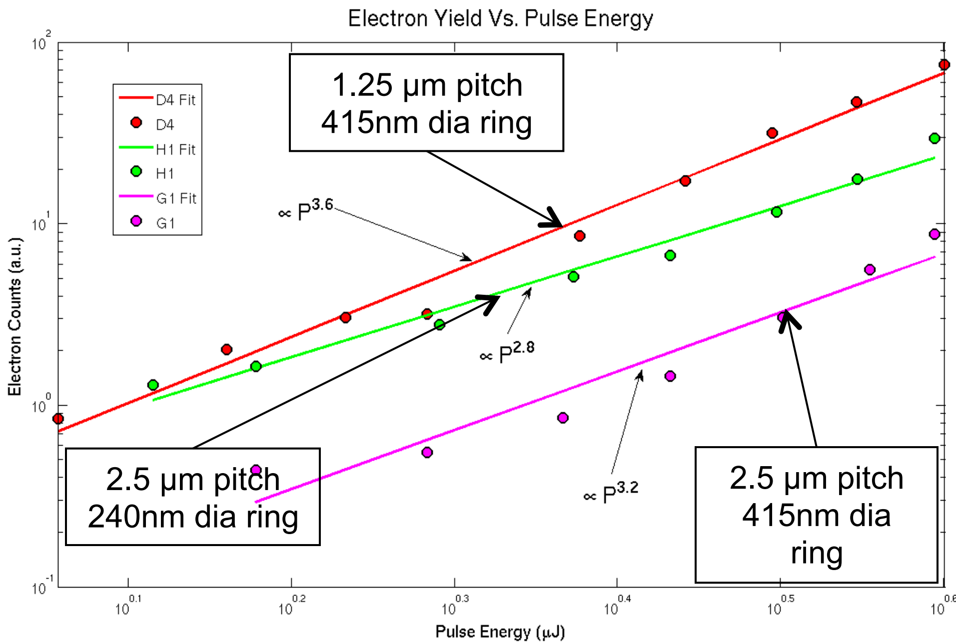


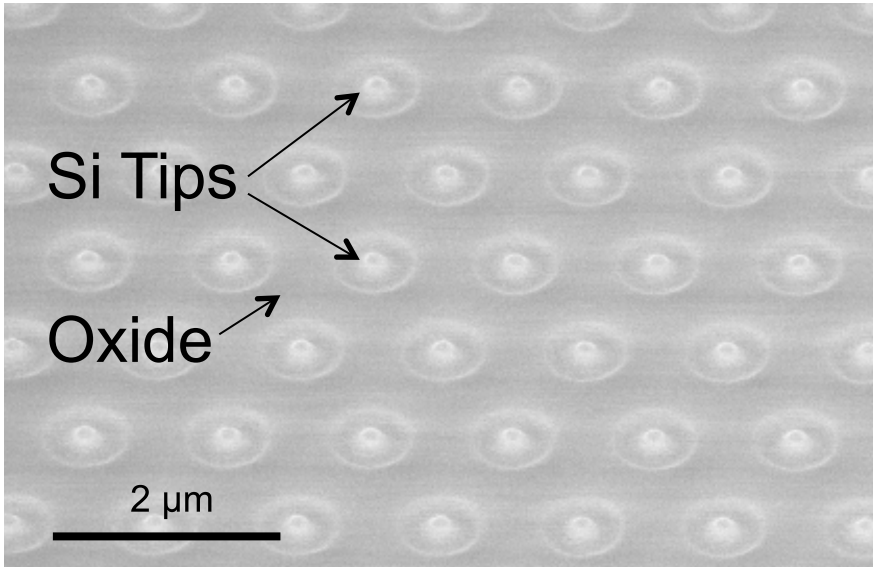
Field Enhancement Simulations Results

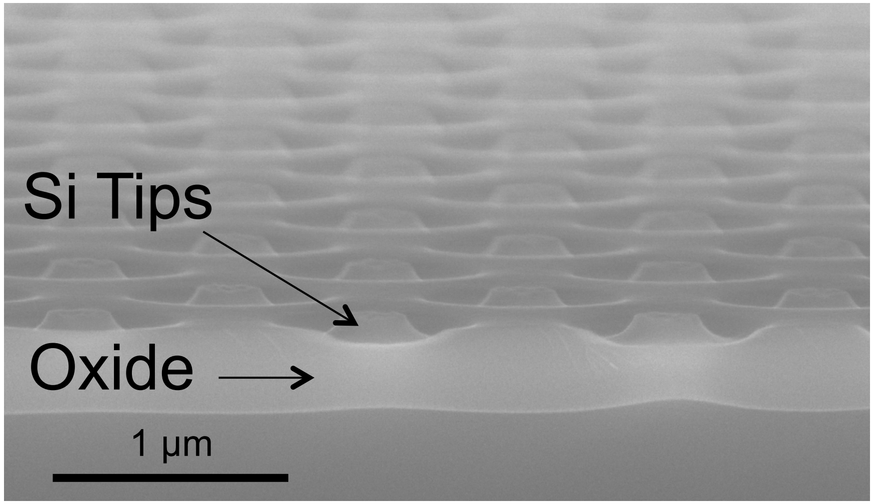
- 2 GVm^{-1}, p-polarized, CW, 800 nm illumination
- Pseudo-linear dependence of field enhancement on tip radius

Simulations conducted by Y. Yang (Berggren Group)

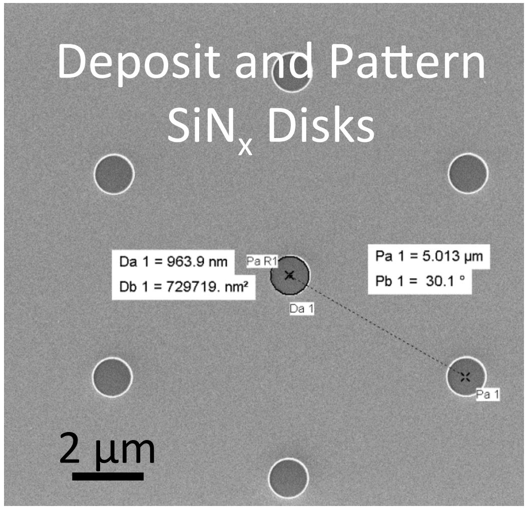
Multi-Photon Photoelectron Emission

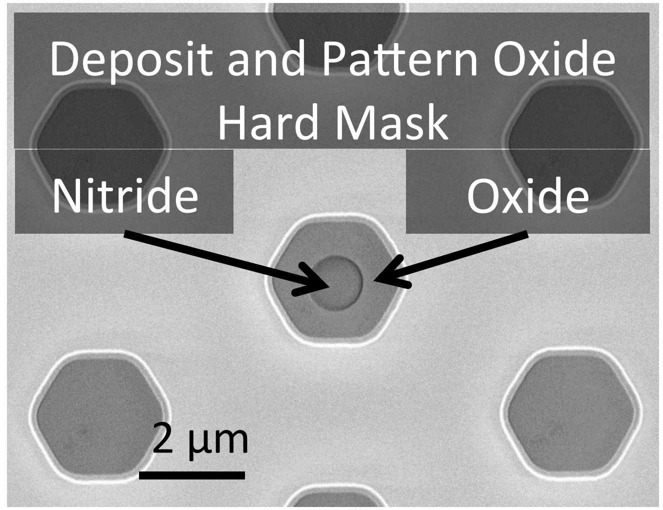


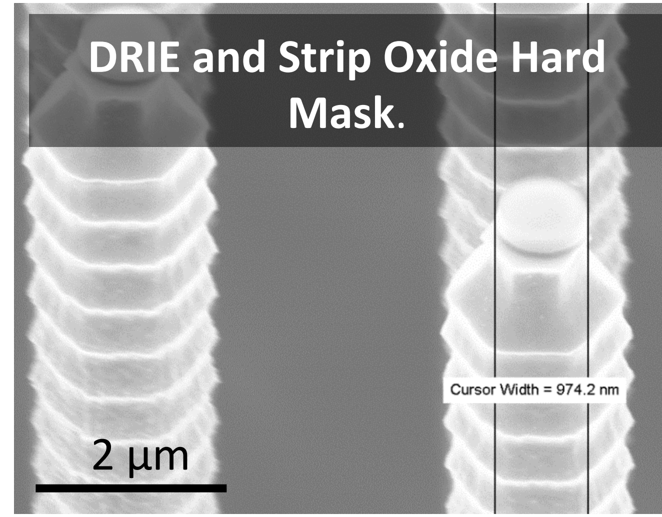


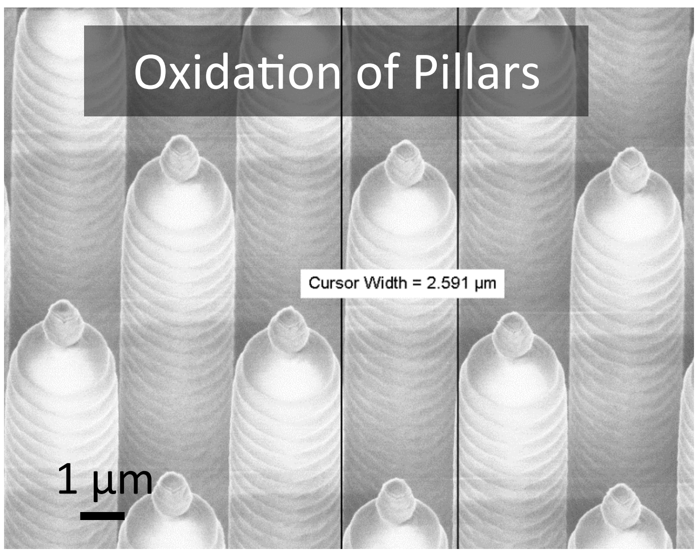


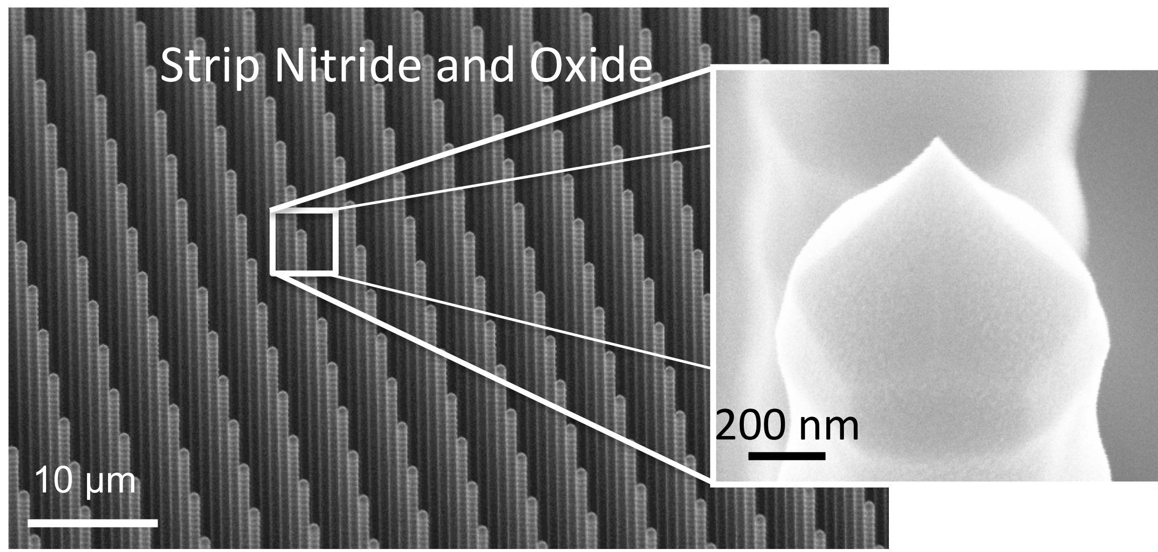
High-Aspect Ratio Si Photoelectron Emitter Arrays





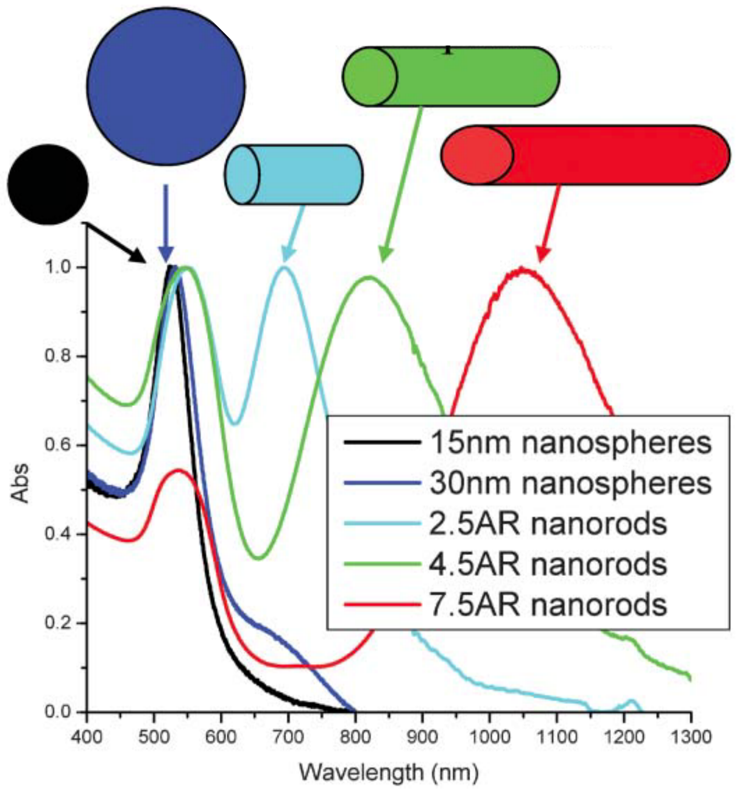






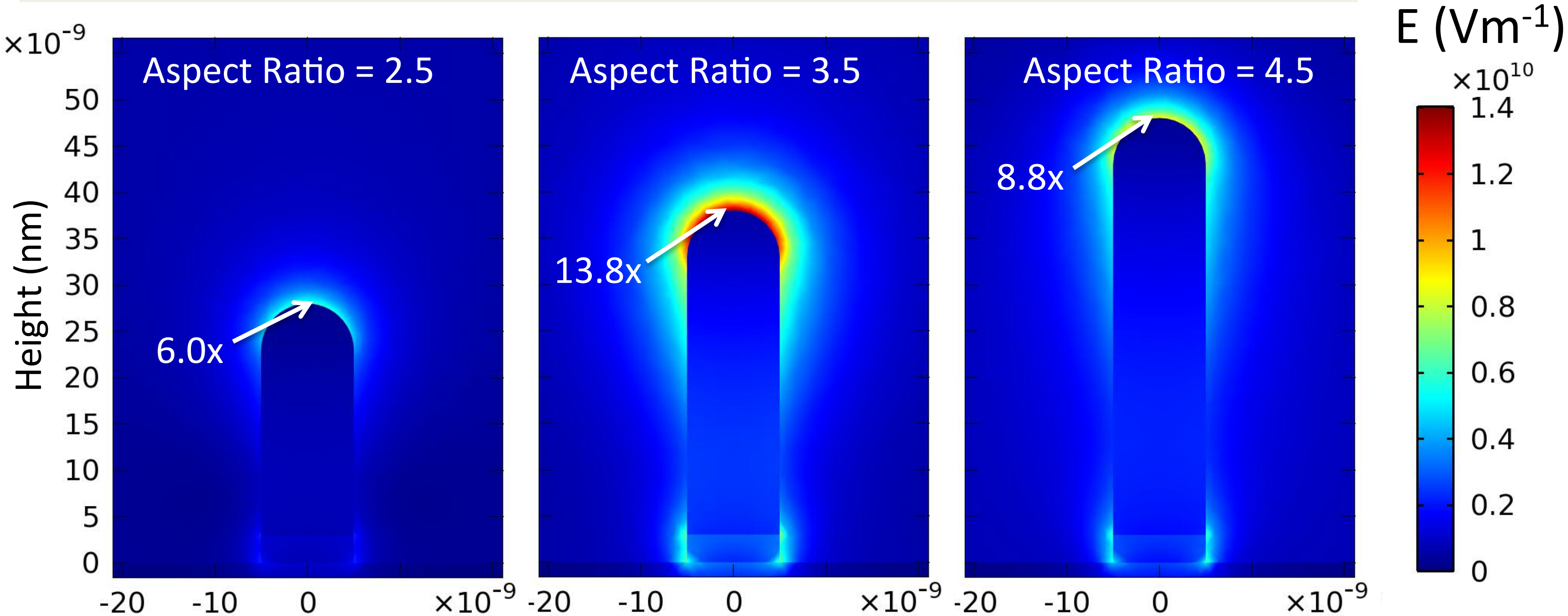
Au Nanopillar Emitter Arrays

- Surface plasmons can strongly enhance local electric fields
- Longitudinal surface plasmon band is geometry dependent in Au
- Light source
  - Ti:Sapphire laser (λ = 800 nm)
- Au pillar geometry tuned to produce longitudinal mode at λ = 800 nm



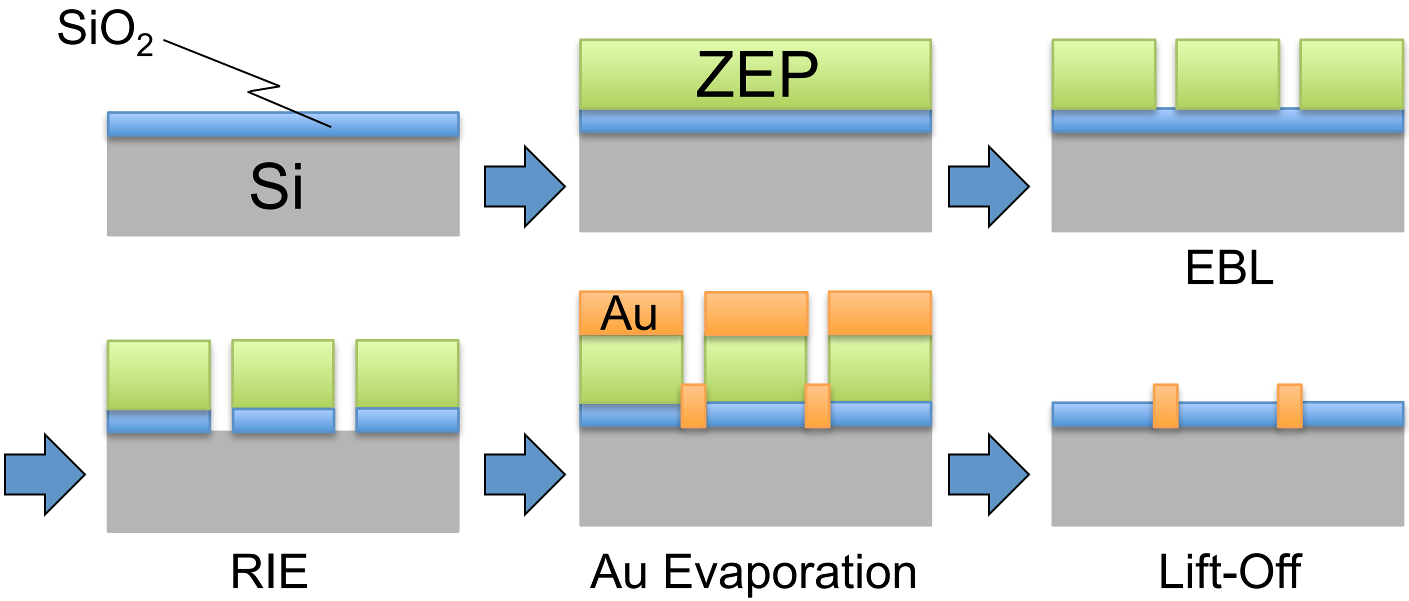
Chem. Soc. Rev., 2006, 35, 209–217

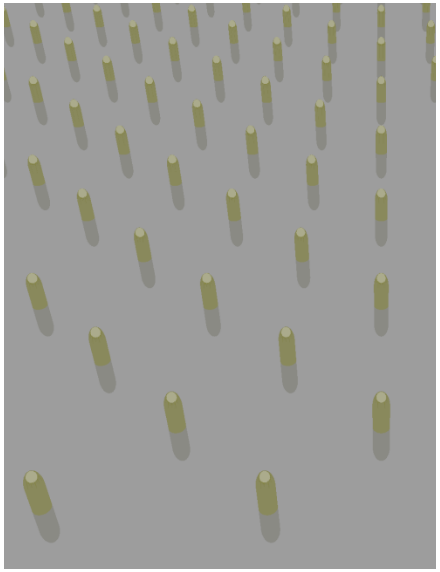
Geometry Dependence



- Simulation of local electric field strength at Au nanopillars
- Coherent 800 nm p-polarized incident plane wave, 1 GVm^{-1}
- Maximum field enhancement for aspect ratio of 3.5
- Au nanopillars with AR = 3.5 have peak longitudinal SP absorbance band at 800nm

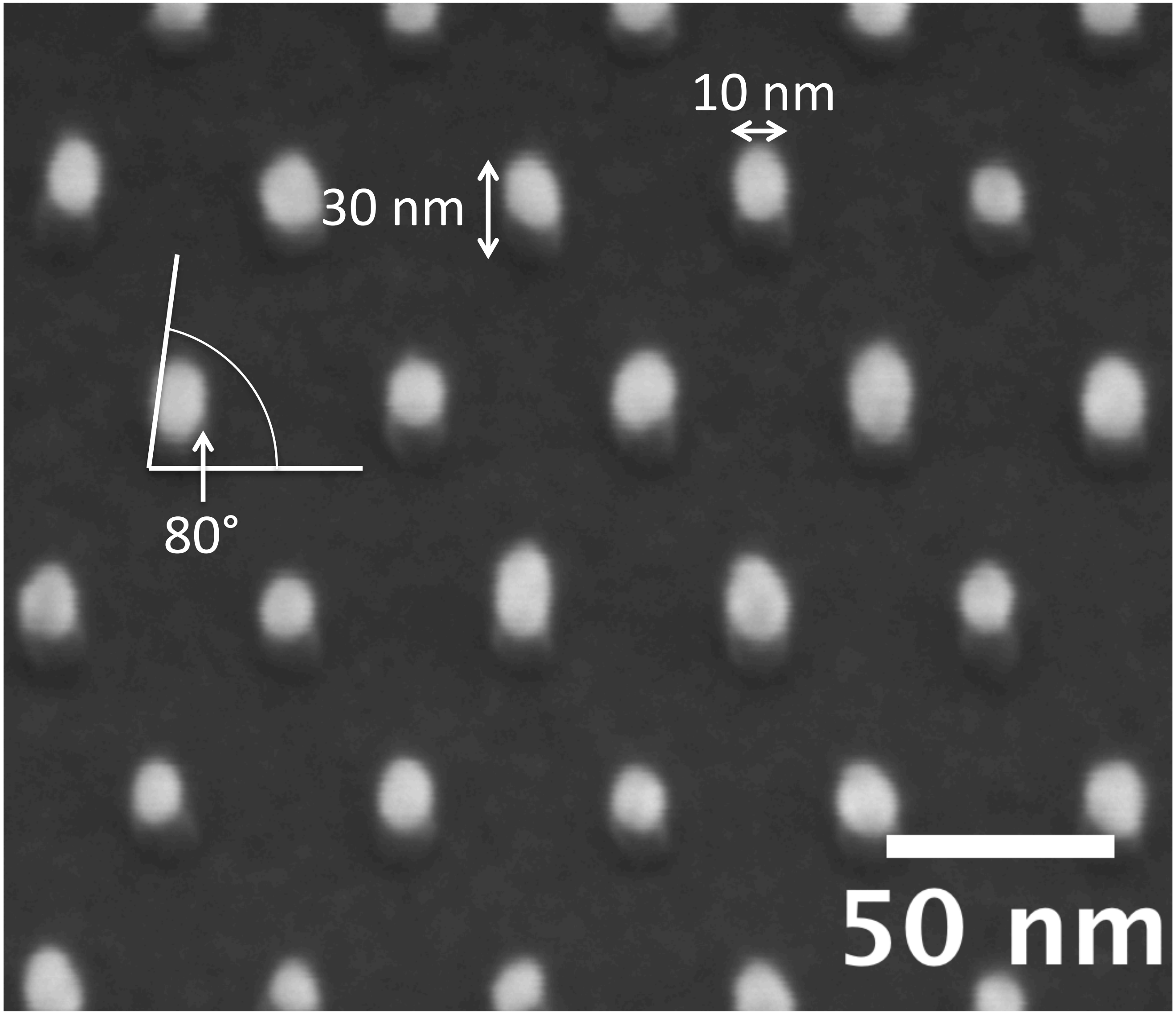
Metal Nanopillar Array Fabrication





- SiO_2 coating to prevent background electron emission
- ZEP resist provides higher etch resistance than PMMA
- Flexible process compatible with other metals *e.g.* Cu strip array fabrication for photocathode development

Au Nanopillar Array Geometry

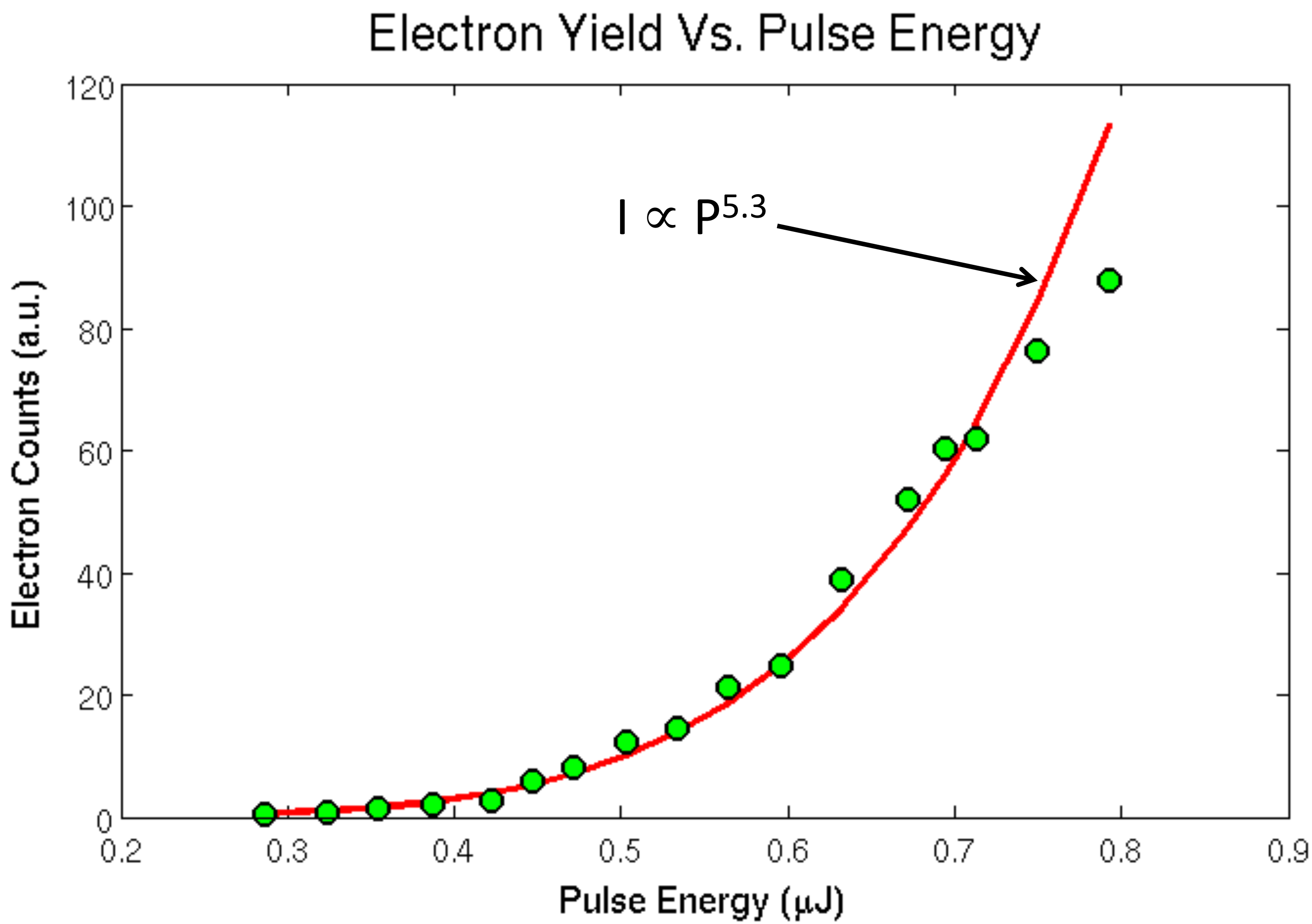


FEI Helios SEM resolution 0.8-0.9 nm

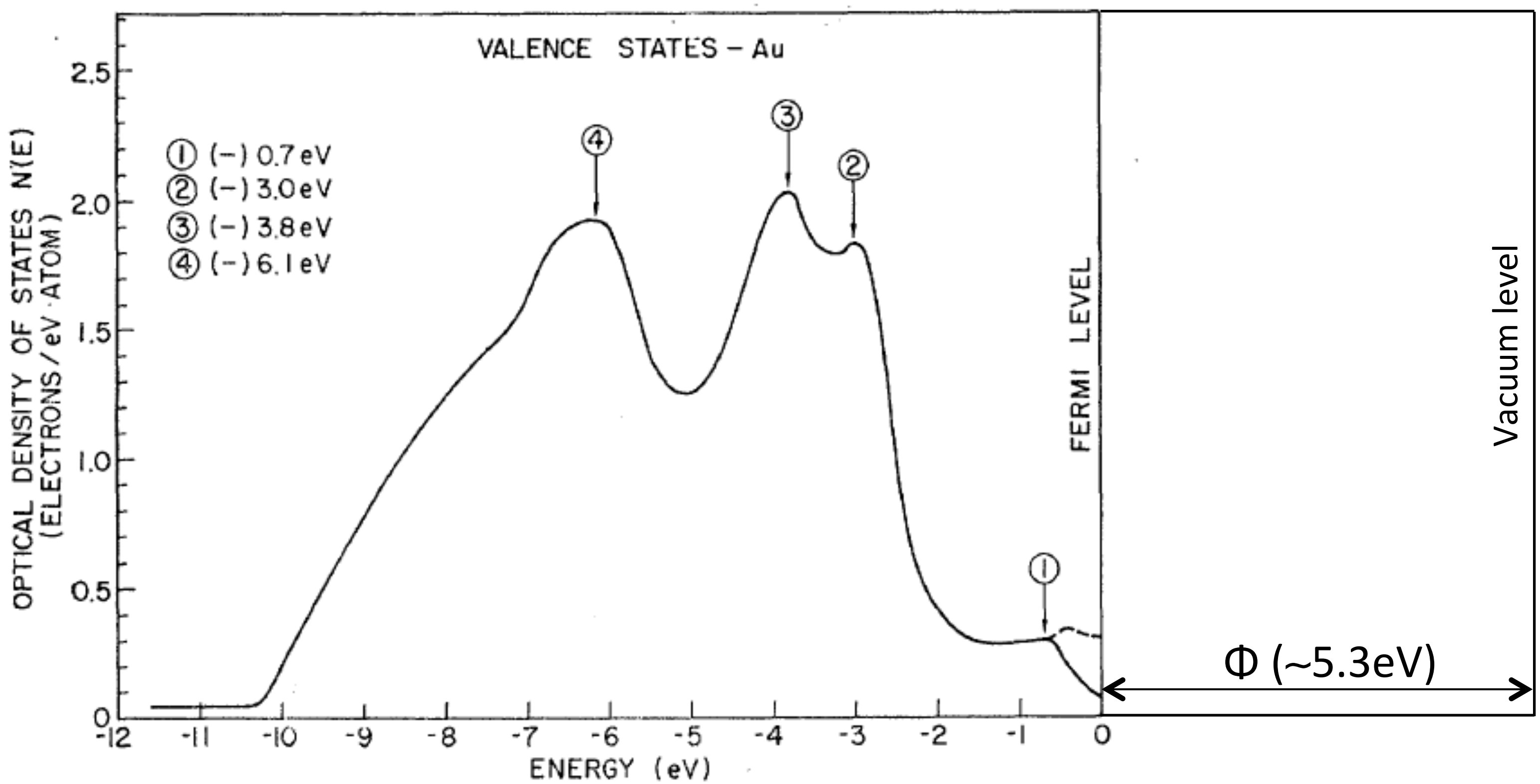
Mean Au pillar tip diameter 10 nm

Standard deviation 1 nm

Electron Emission Spectra



Au d-bands Electron Origin

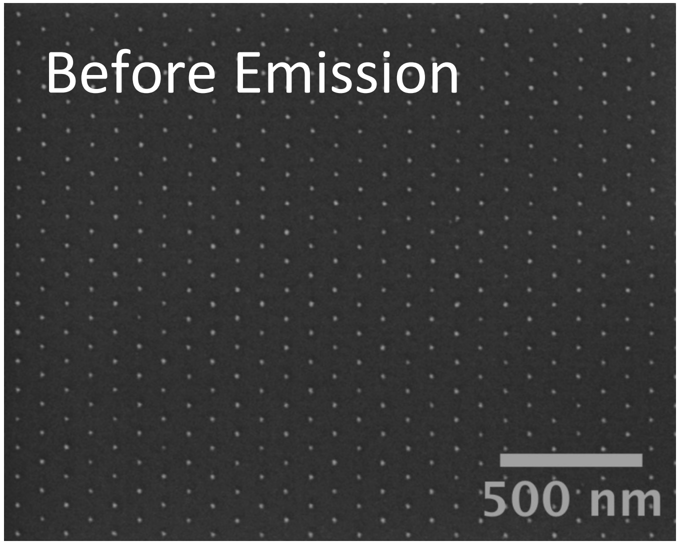


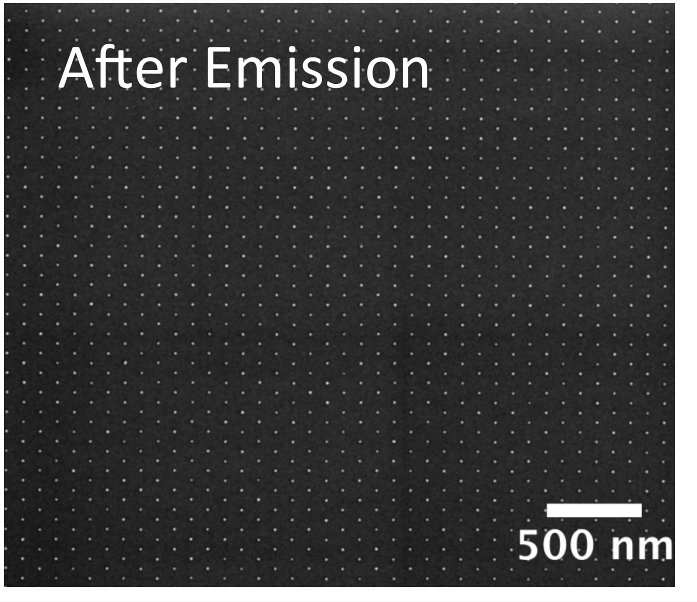
- $I \propto P^{5.3}$ suggests 5-6 photon absorption (7.75-9.3 eV)
- Previously reported by Ropers *et al.*[2] for single tips
- Au d-bands lie 7.5-10 eV below vacuum level

[1]Krolikowski, W. F.; Spicer, W. E. *Phys. Rev. B*, **1970**, *1*, 478
[2]Bormann, R.; Gulde, M.; Weismann, A.; Yalunin, S.V.; Ropers, C. *Phys. Rev. Lett.*, **2010**, *105*, 147601

Laser Ablation?

- SEM imaging before and after emission confirms absence of extensive laser ablation
- Further high-resolution imaging required to investigate
  - Surface melting
  - Au surface desorption
  - Electromigration





Future Work

- Comprehensive characterization of electron emission from various cathode materials
  - Total current yield
  - Emittance from single emitters and arrays thereof
  - Charge uniformity across the emitter array
- Selection of an optimal material and structure to generate coherent x-rays in the range 8-80 keV

Acknowledgements

- James Daley, Vitor Manfrinato, Corey Fucetola and Tim Savas at the Nanostructures Laboratory, MIT