Micron-scale Field Emission Model for PIC-DSMC Simulations Based on Nanoscale Surface Characterization

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Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Additional Support: CINT User Facility (DE-AC04-94AL85000)

SAND2021-2866 C

Micron-scale Field Emission Model for PIC-DSMC Simulations Based on Nanoscale Surface Characterization

Vacuum discharge is critical to many modern devices.

- Critical failure mechanism → Want to avoid
- Mode of operation → Want to have predictable behavior

Employ STM and PhotoEmission Electron Microscopy (PEEM) to characterize local (~0.1-10 nm) surface

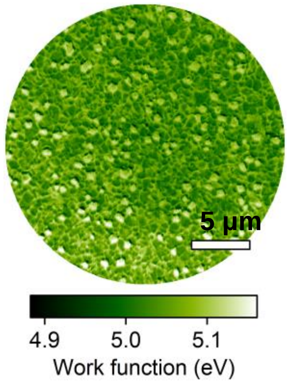
- Utilize a "meso-scale" (0.1-1.0 μm) model of the surface for PIC-DSMC simulation of breakdown
- Field emission is necessary precursor to a breakdown event. No field emission → no breakdown.

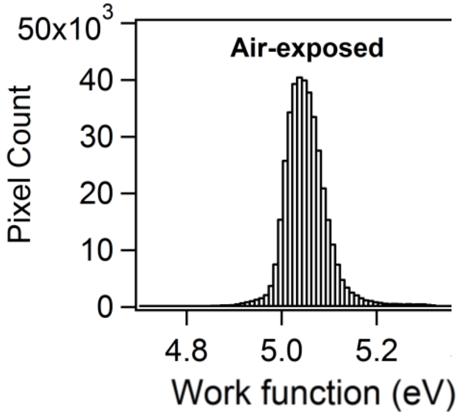
We want to locally characterize the surface to eliminate β as a fit parameter:

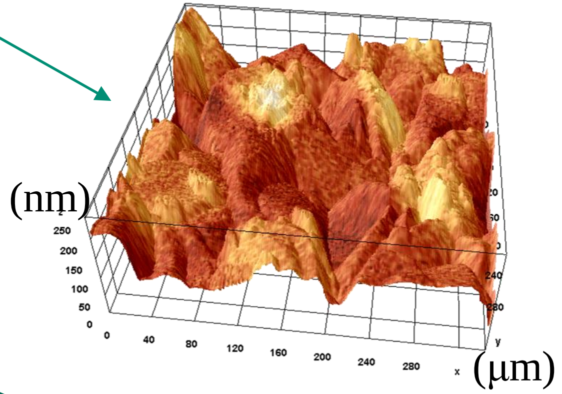
- Create Pt electrode via sputter deposition
- Use PhotoEmission Electron Microscopy (PEEM) to measure work function (ϕ)
- Use Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM) to measure topology (β)
- Generate probability density functions (PDFs) for local work functions and effective topological field enhancement
- Use measured *atomic-scale* distributions for ϕ and β to inform macro-scale model for discharge simulations

Poly-Pt (111) on ZnO/SiO_2/Si

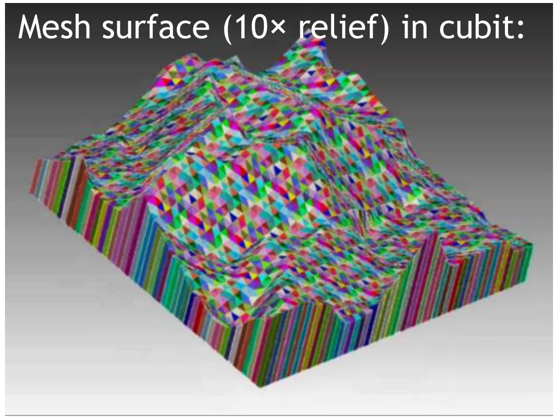
Air-exposed





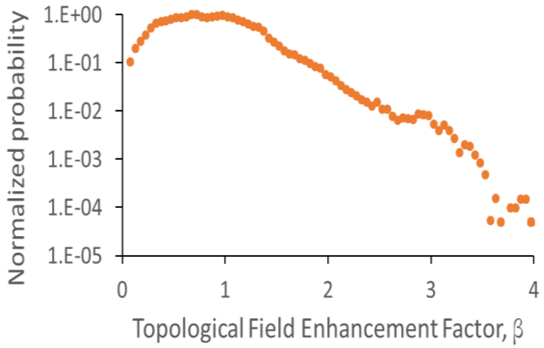


Generate β PDF:



Put into ES code and compute E_{norm} and A_{proj} for every element face in the resolved STM mesh and thereby create ~10nm-scale PDF (weighted by projected area) of β:

$$\beta_i = \frac{E_{norm,i}}{E_{applied}}$$

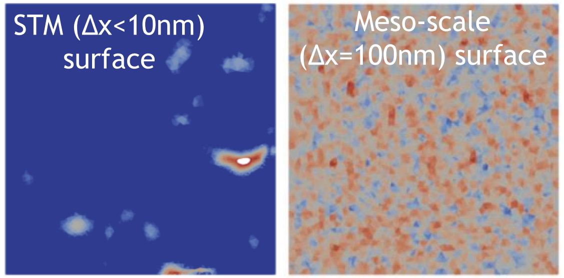


We then sample from the work function and β PDF's for the meso-scale model in our PIC discharge simulations

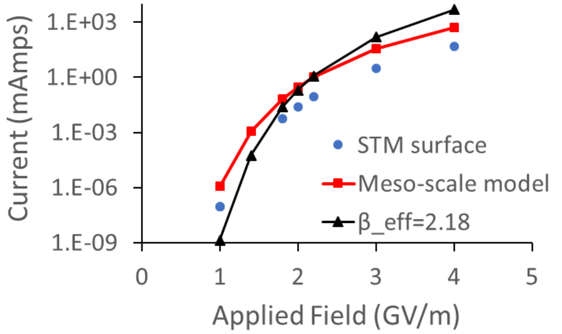
For each meso-scale element we sample appropriate number of nano-scale emitters and only store those that contribute more than 0.1% of i_{total}

- Loop over emitters to get current for a face:

$$I_{face} = \Sigma_{emitters} A_e A_{FN} \frac{(\beta_e E_{norm})^2}{\phi_e t^2(y)} exp\left[-\frac{B_{FN} v(y) \phi_e^{1.5}}{\beta_e E_{norm}}\right]$$



Current density contours (log scale)



By examining field emission at the nanoscale, we have attempted to create a meso-scale physics-based model suitable for predictive (and stochastic) PIC simulation of emission

- Make field emission model where β really is only geometry induced field enhancement.

Surfaces that we characterized are extremely flat: β~1 over 100's of μm^2

Vacuum Arc Initiation Project

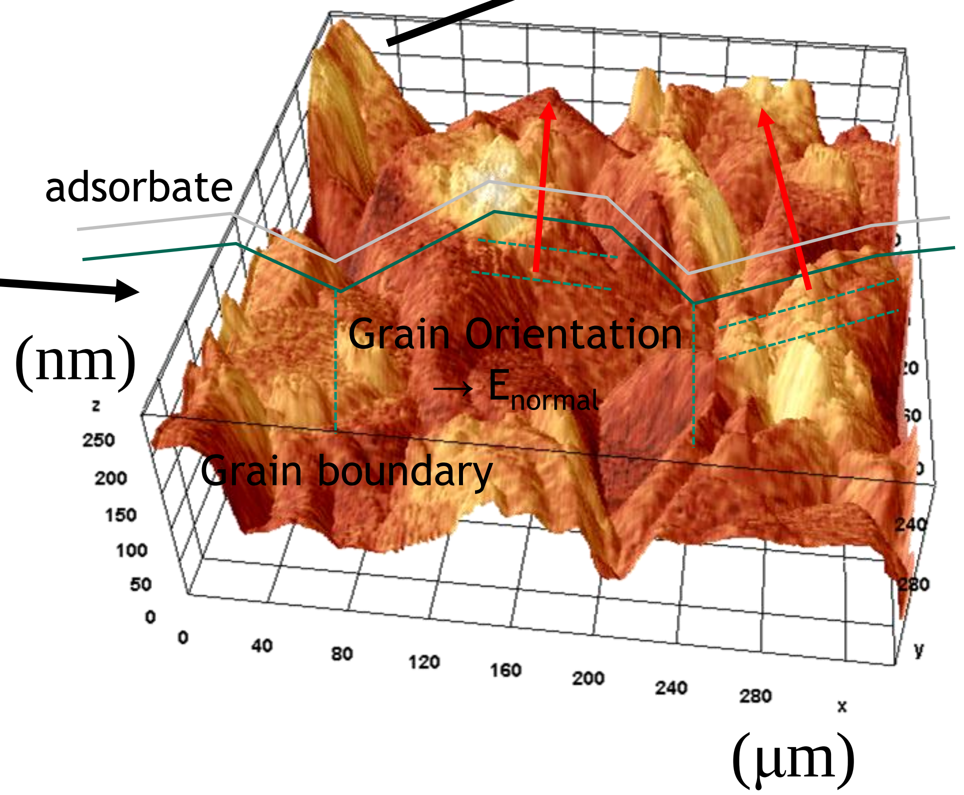
- We are interested in modeling a variety of discharge situations: from streamers at atmospheric pressure to vacuum arcs
- Vacuum discharge is critical to many modern devices.
  - Critical failure mechanism → Want to avoid
  - Mode of operation → Want to have predictable behavior
- We have a project to understand vacuum field emission from well-characterized surfaces to create physics-based models for use in large-scale PIC-DSMC breakdown simulations
  - Field emission is necessary precursor to a breakdown event. No field emission → no breakdown.
  - Employ Scanning Tunneling Microscopy and PhotoEmission Electron Microscopy to characterize surface very locally, and then apply high fields to initiate breakdown. Very locally = ~0.1-10 nm
  - Address the problem of not knowing the state prior to discharge at the location of discharge by characterizing and then discharging.
  - Apply known layers of dielectric (e.g.,TiO2, MgO) to challenge models and begin investigation of role of surface contaminants.
  - Utilize a "meso-scale" (0.1-1.0 μm) model of the surface for PIC-DSMC simulation of breakdown

Why local characterization?

- Fowler-Nordheim field emission:
  - Typical use in macro-scale models is to curve-fit measured j(E) from the as-built electrode
  - Can result in β ~ 10-1000 !!!

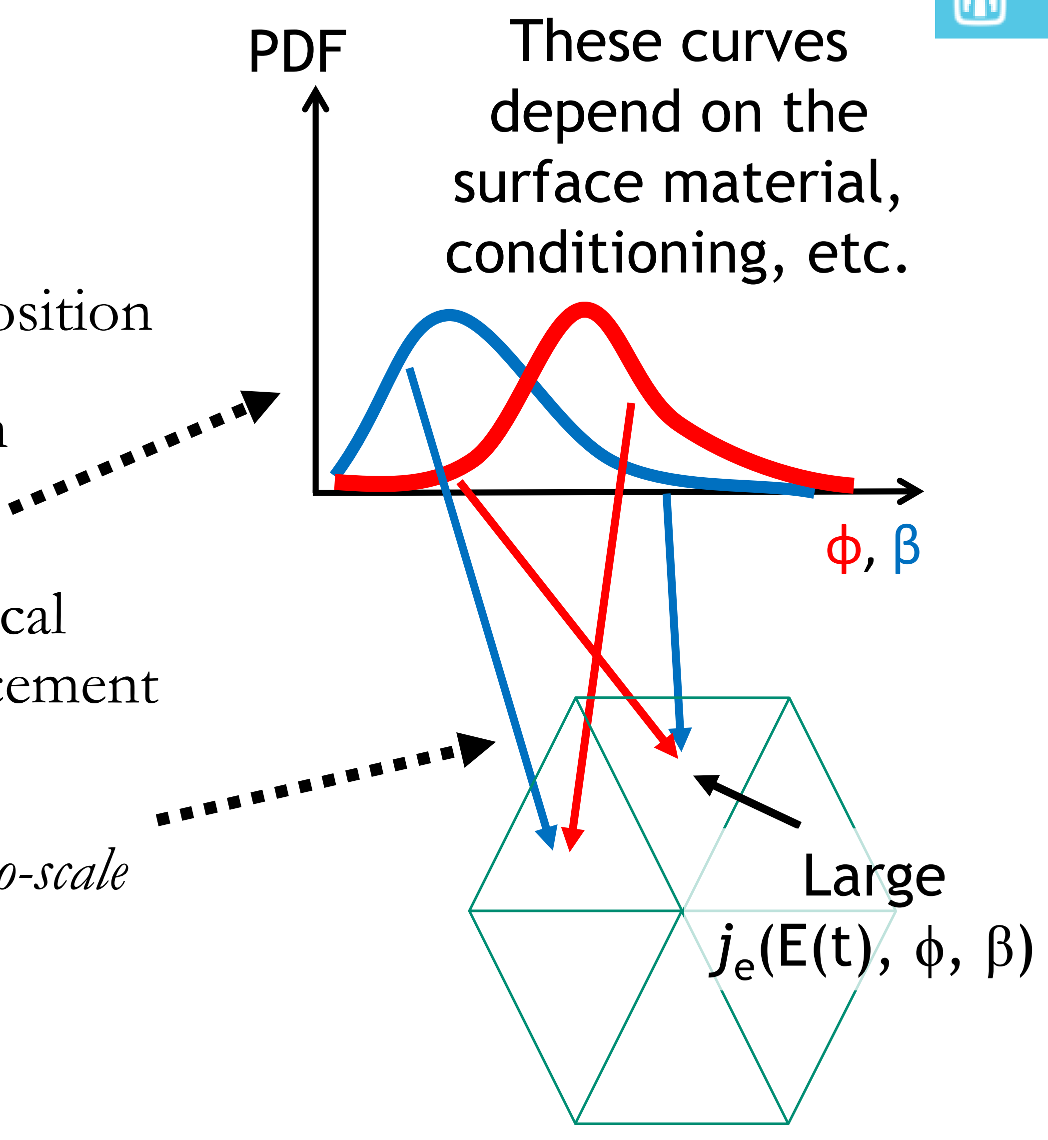
$$i = A_{eff} A_{FN} \frac{(\beta E)^2}{\phi t^2(y)} exp\left[-\frac{B_{FN} v(y) \phi^{3/2}}{\beta E}\right]$$

- We want to locally characterize the surface to eliminate β as a fit parameter
  - Use Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM) to measure topology (β)
  - Use PhotoEmission Electron Microscopy (PEEM) to measure work function (ϕ)
  - Use measured distributions for ϕ and β to inform macro-scale model for discharge simulations



Overview

- Create Pt electrode via sputter deposition
- Controllably contaminate Pt via Atomic Layer Deposition
- Measure work function, local topology, and electron emission for sample
- Generate probability density functions (PDF) for local work functions and effective topological field enhancement
- Incorporate measured *atomic-scale* distributions into discharge simulations by populating time-varying *meso-scale* element-based data from the PDFs
- Compare family of plasma discharge simulations to measured breakdown behavior



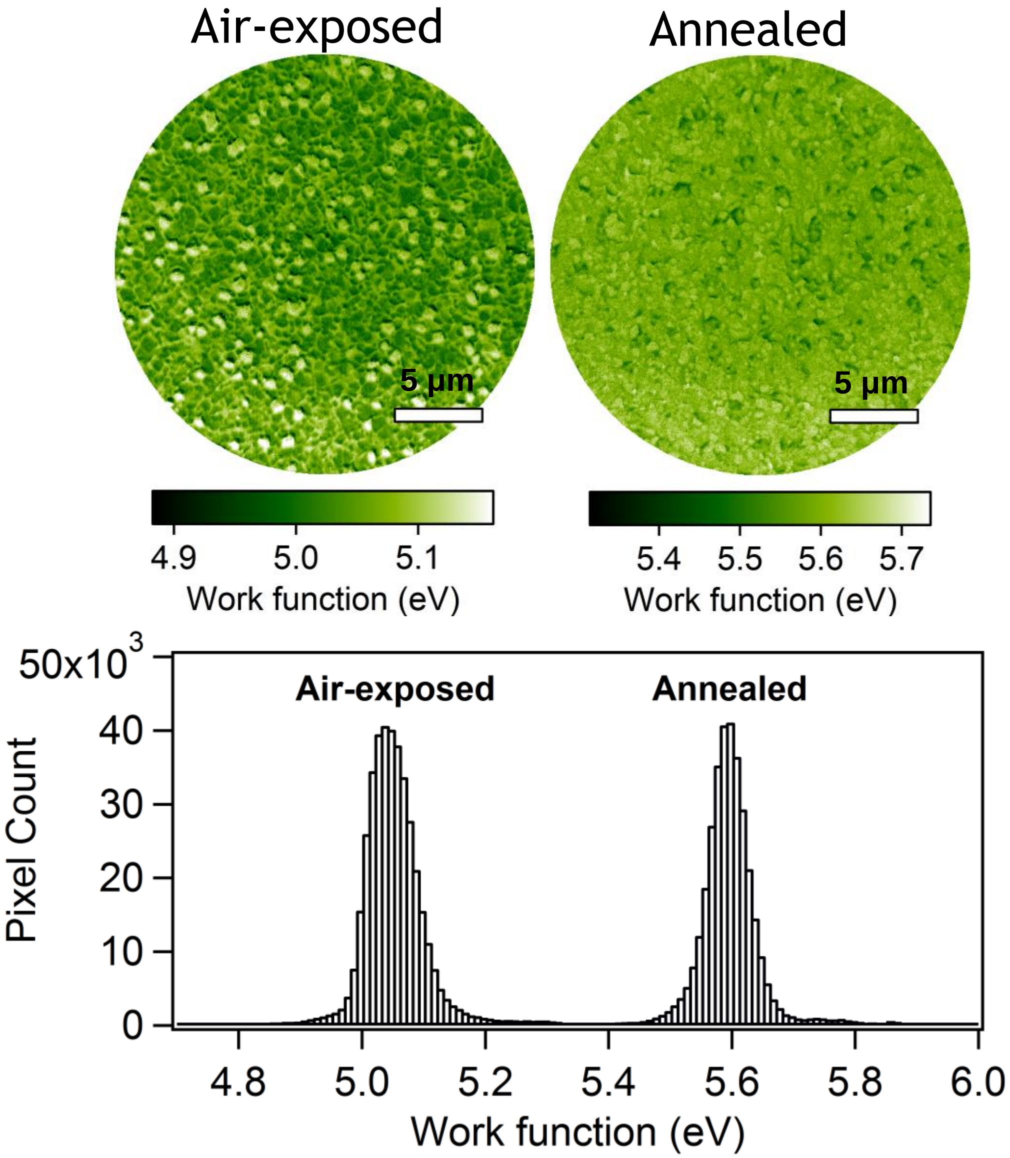
These curves depend on the surface material, conditioning, etc.

surface mesh in the plasma code

PEEM Measurement of Work Function Variation

- Measured spatial variation of local work function using PhotoEmission Electron Microscopy
  - Variation across given Pt surface relatively small – only a few percent
  - However, ϕ is in the exponential and the tail of the distribution can initiate field emission and eventually breakdown
- Significant (~10%) decrease in the work function due to surface contaminants picked up via exposure to air
- Use the ~10nm-scale PDF's in meso-scale model to set element work functions in PIC-DSMC simulations

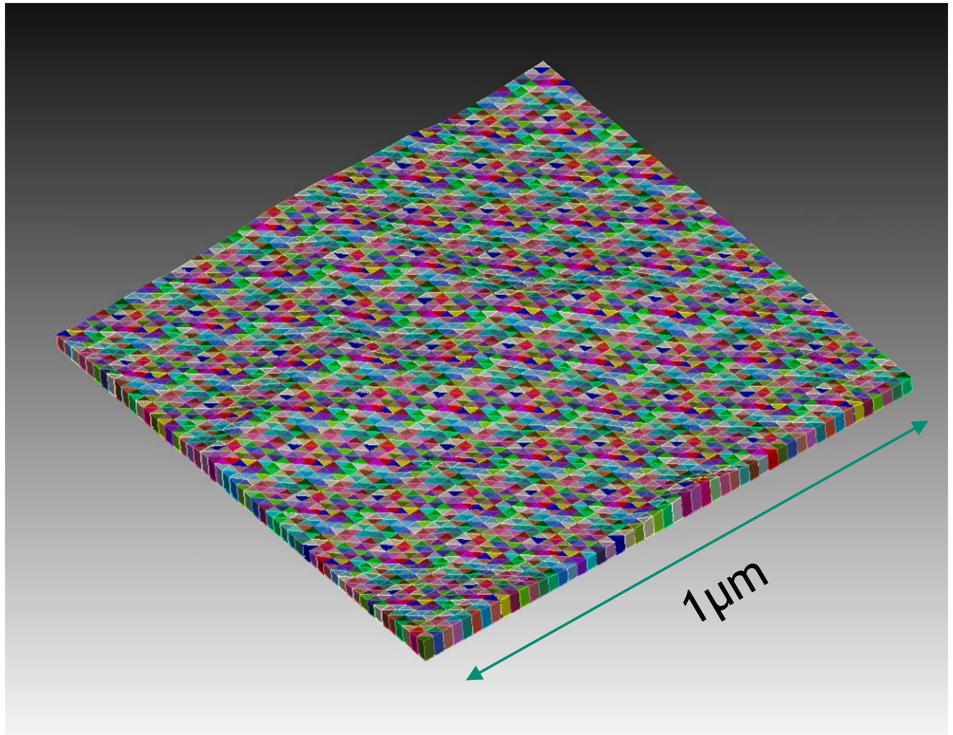
Poly-Pt (111) on ZnO/SiO_2/Si



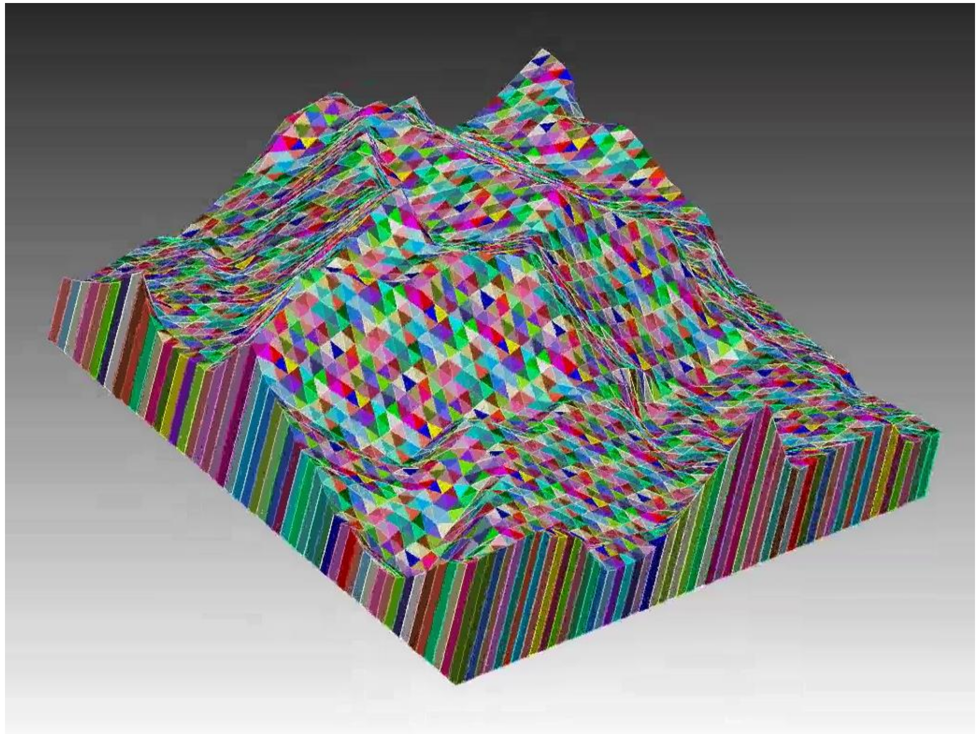
AFM Surface Characterization

- Took the AFM (x,y,z) spatial points (here ~20nm resolution) and map into Cubit meshing software
- Actual surface has virtually no significant topology – we will see later that β~1 everywhere
- To demonstrate significant spatial variation of field emission across the surface we also compute results with the surface relief multiplied by 10×

As-measured surface relief (~ ±15nm)

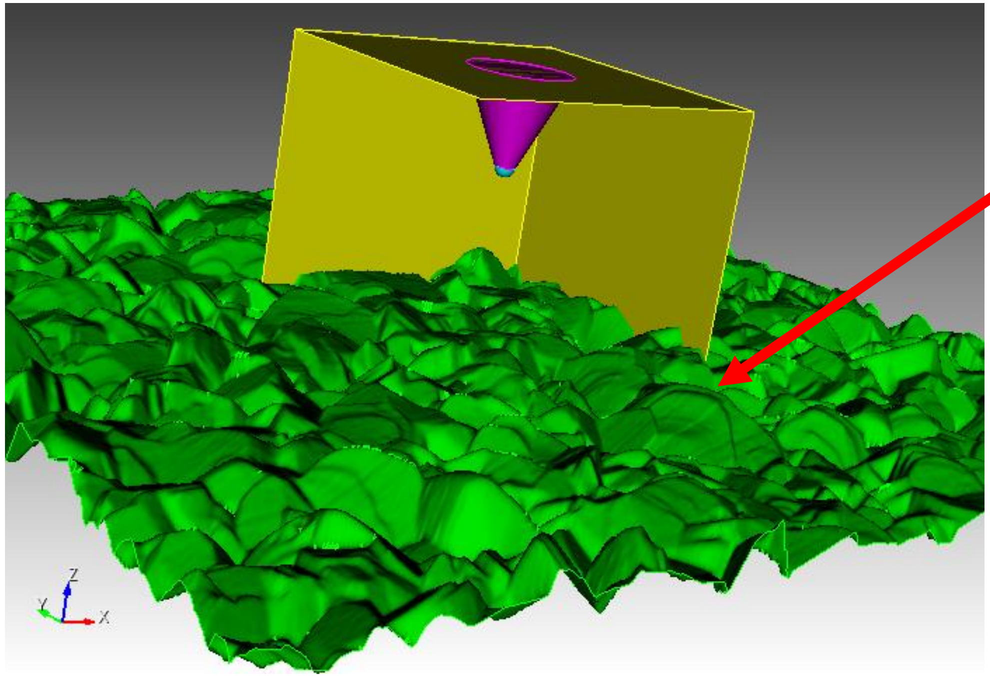


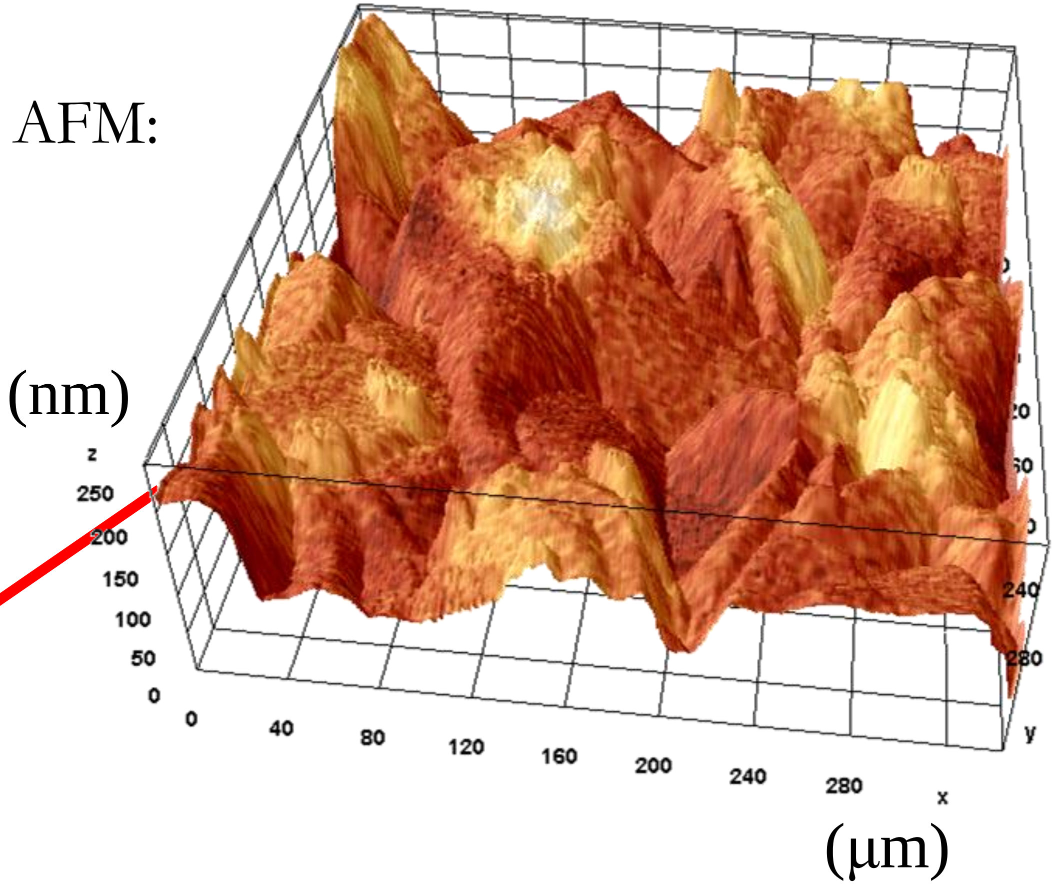
Surface relief increased by 10×



AFM topology → topological atomic-scale β

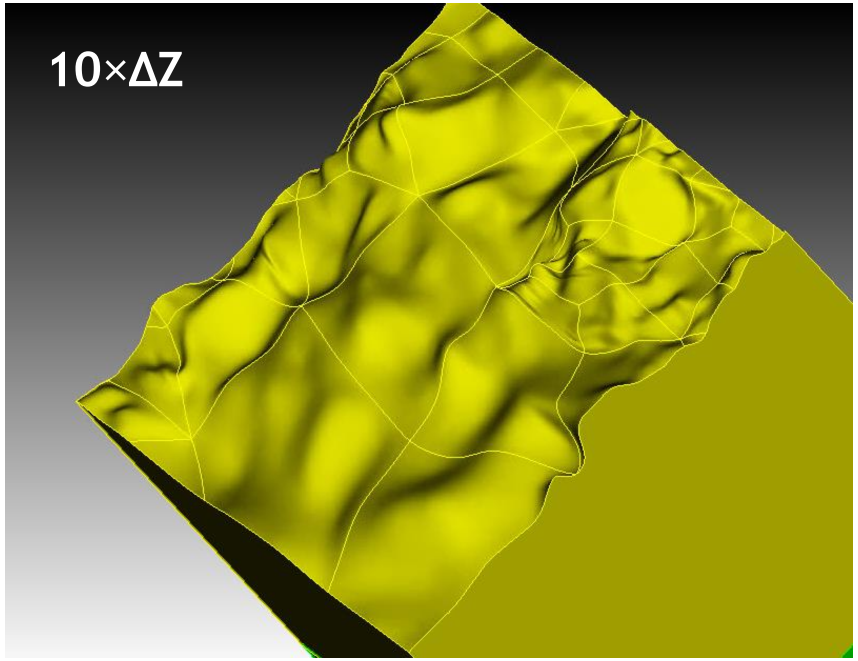
- Measure surface topology before breakdown using AFM:
- Load topology into Cubit and mesh the surface in order to use electrostatic solver
  - Place flat anode ~10μm from as-measured cathode
  - Use ~1 nm elements near cathode to resolve features



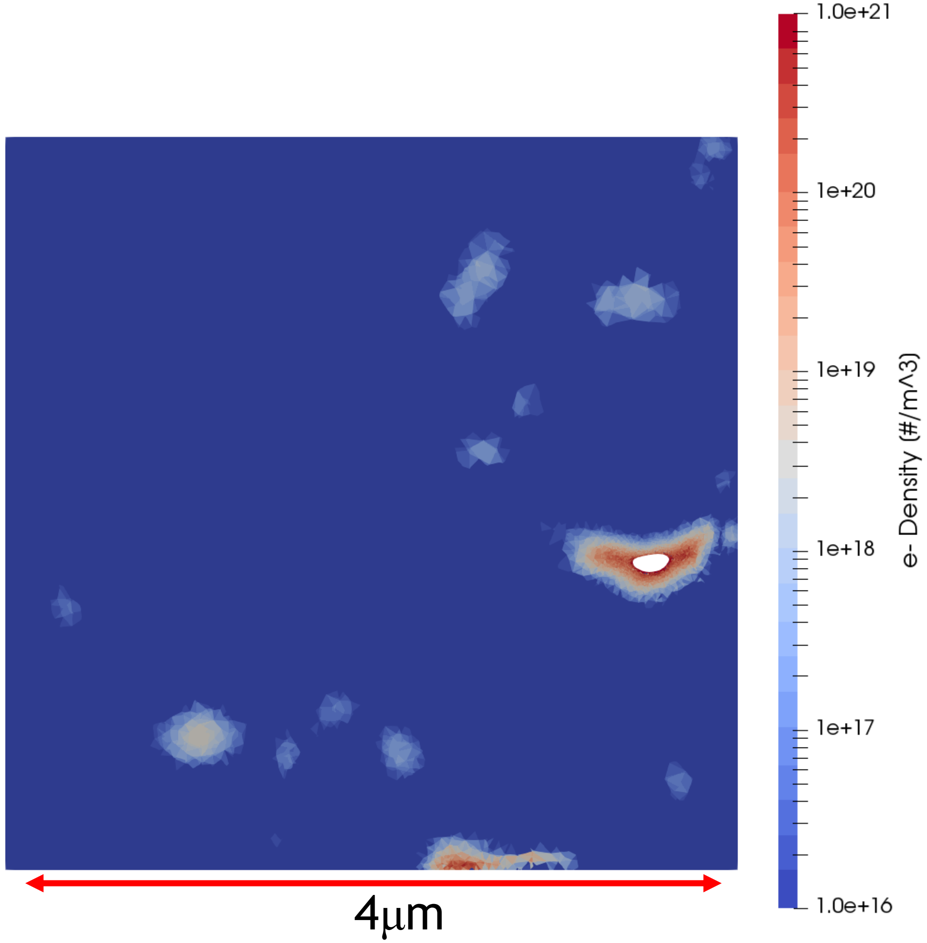


Simulation of Emission from AFM Surface

- With the resolved (Δx<10nm) mesh, simulate the emission from the AFM surface
  - Show contours of e^- density just above the cathode surface
  - Some clipping of the topology is seen for the largest feature
- See several large-scale features that emit, otherwise very little emission

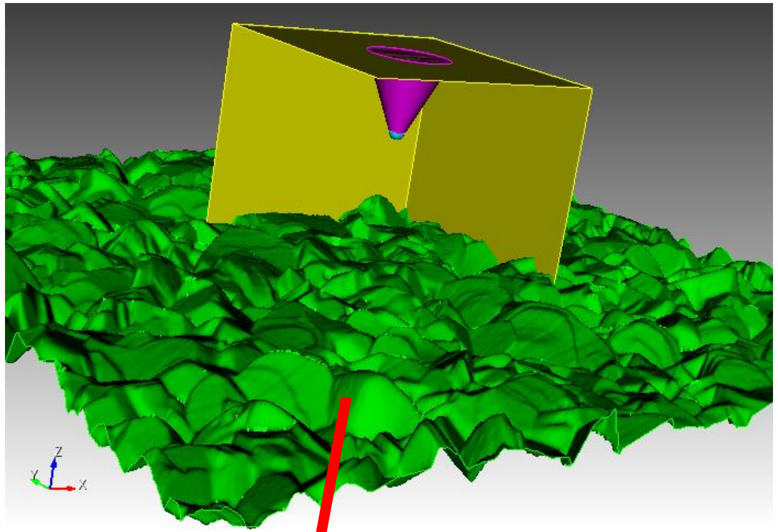


Simulate emission in PIC-code

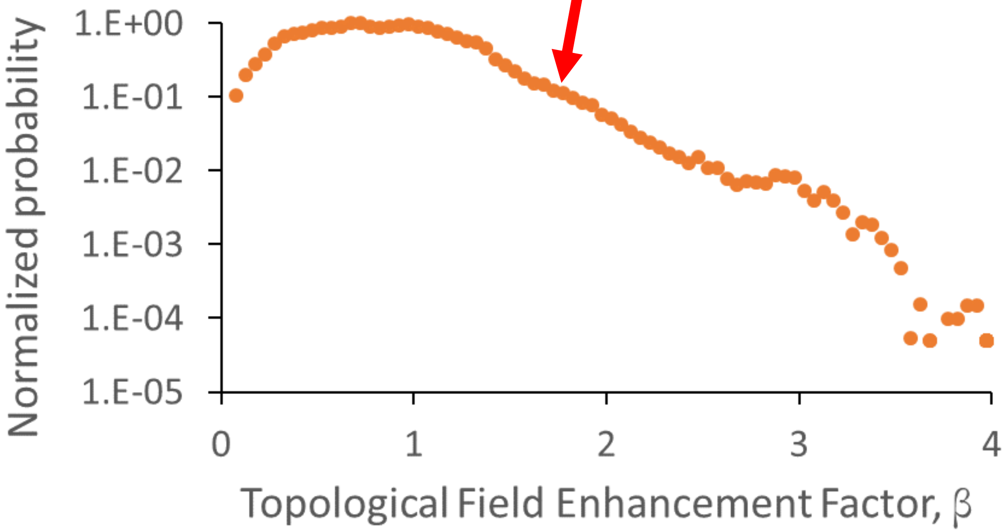


AFM topology → topological atomic-scale β

- Compute E_{norm} and A_{proj} for every element face in the resolved STM mesh
  - <10nm elements; ~600K surface faces
- Get projection factor, $f_{proj} = \dfrac{\sum_{faces} A_{face}}{\sum_{faces} A_{proj,face}}$
  - For present data $f_{proj} \sim 1.15$
- Create ~10nm scale PDF of $\beta = \dfrac{E_{norm}}{E_{applied}}$
- Some elements will have β<1
  - Globally the surface could be tilted
  - Sides of “sharp” atomic features



Electrostatic solve



Meso-scale Model for Surface Variations

- We have measured atomic-scale (1-10nm) PDF's of the work function and topological field enhancement factor

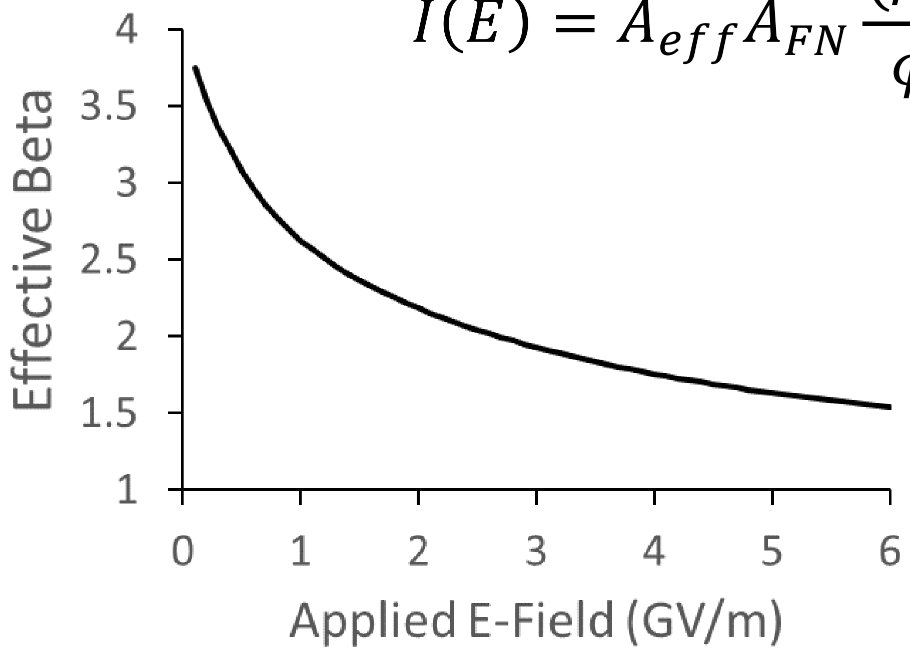
- Must convert these to the meso-scale (0.1-10 μm). Some options:
  1. Just pick the meso-scale β and ϕ from the atomic-scale PDFs
  2. Make an effective β and ϕ to use at the meso-scale
  3. "Brute force" – for each meso-scale element face, pick N local emitters (unique β's and ϕ's)

- The first option obviously has artificially large variation for different surface realizations in simulations. We will not consider it further.
  - Sometimes get an extreme tail value and then field emit based on the meso-scale element's area
  - Other times there will be no tail values picked and no field emission until much higher fields

Meso-scale Model for Surface Variations

- Can we make an effective β (and ϕ) from the data and/or atomic-scale β PDFs?
- Measure/compute the total field emission current versus $E_{applied}$
- Non-linear solve for β_{eff}:

$$I(E) = A_{eff} A_{FN} \frac{\left(\beta_{eff} E\right)^2}{\phi t^2(y)} exp\left[-\frac{B_{FN} v(y) \phi^{3/2}}{\beta_{eff} E}\right]$$



→ **β_{eff} depends on $E_{applied}$!**

- This makes sense: small β regions "turn on" at higher fields and pulls the effective β lower
- The precise functional form depends on the atomic-scale β PDF

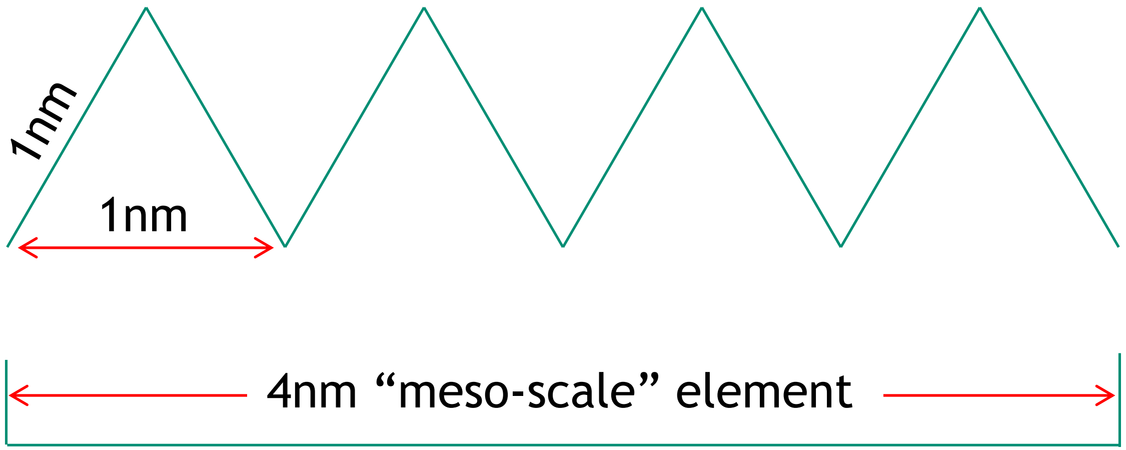
e.g. see: Feng and Verboncoeur, PoP **13**, 073105 (2006)
Jinpu Lin et al., J. Appl. Phys. **121**, 244301 (2017)

Meso-scale Model for Surface Variations

- We are left with “brute force” -- for each meso-scale element face, pick N local emitters (randomly pick unique β’s and ϕ’s) from the atomic-scale measured distributions:

$$N = \frac{A_{element}}{A_{resolved}} f_{proj}$$

- Must scale the number of local emitters to draw:



8 local faces that the β and ϕ PDF created from

$$f_{proj} = \frac{\sum_{faces} A_{face}}{\sum_{faces} A_{proj,face}} = 2$$

Draw 8 local emitters

Meso-scale Model for Surface Variations

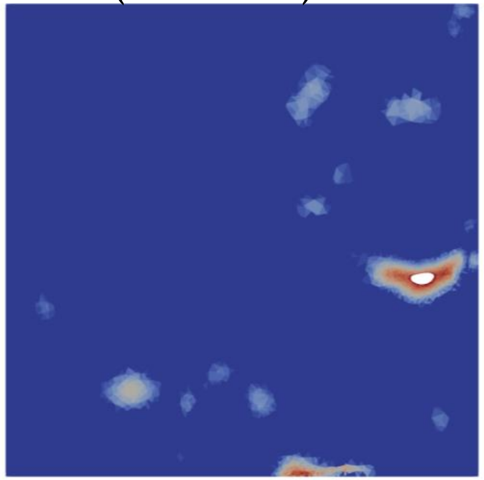
- However, we don’t have to store all N local emitters for each surface element face
  - Field emission is highly non-linear and the majority of emitters (β and ϕ) can be neglected
- Store every atomic-scale emitter (β and ϕ) that appreciably contributes to the current
  - A threshold current contribution of 0.1% results in storing ~0.01% of the atomic-scale emitters
  - 1 μm^2 element has 10^4–10^6 atomic-scale emitters → store <1000 emitters.
- PIC field emission algorithm each Δt:
  - Compute E_{norm} on each surface element face
  - Loop over all ~100 atomic-scale emitters:

$$I_{face} = \sum_{emitters} A_e A_{FN} \frac{(\beta_e E_{norm})^2}{\phi_e t^2(y)} exp\left[-\frac{B_{FN} v(y) \phi_e^{1.5}}{\beta_e E_{norm}}\right]$$

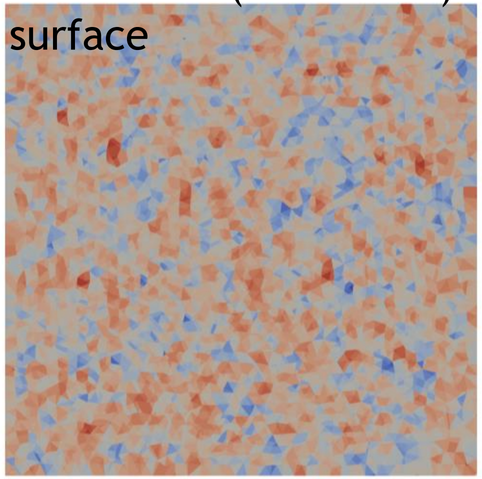
Meso-scale Field Emission Simulations

- Meso-scale model does show stochastic variation in the e- density just above the surface based on the random seed
- Goal is to be able to sample many possible surfaces (e.g. different β's and ϕ's) and compute breakdown probabilities for as-built surfaces
- Contours of electron density just above the cathode show very different spatial variation between the meshed STM surface and the flat, meso-scale surfaces
  - The STM surface was sputtered deposited Pt → large, ~micron-scale features are apparent
  - The current model picks atomic-scale emitter properties (β's and ϕ's) independently for every "meso-scale" surface elements. Clearly not independent for sputtered deposited Pt

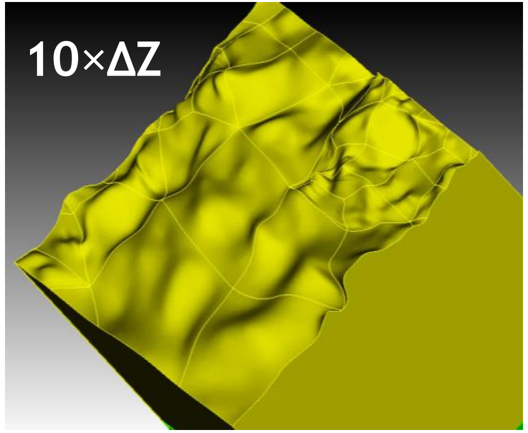
STM (Δx<10nm) surface

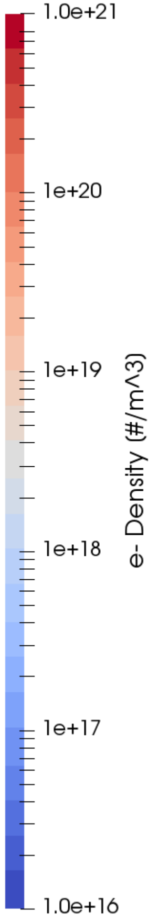


Meso-scale (Δx=100nm) surface



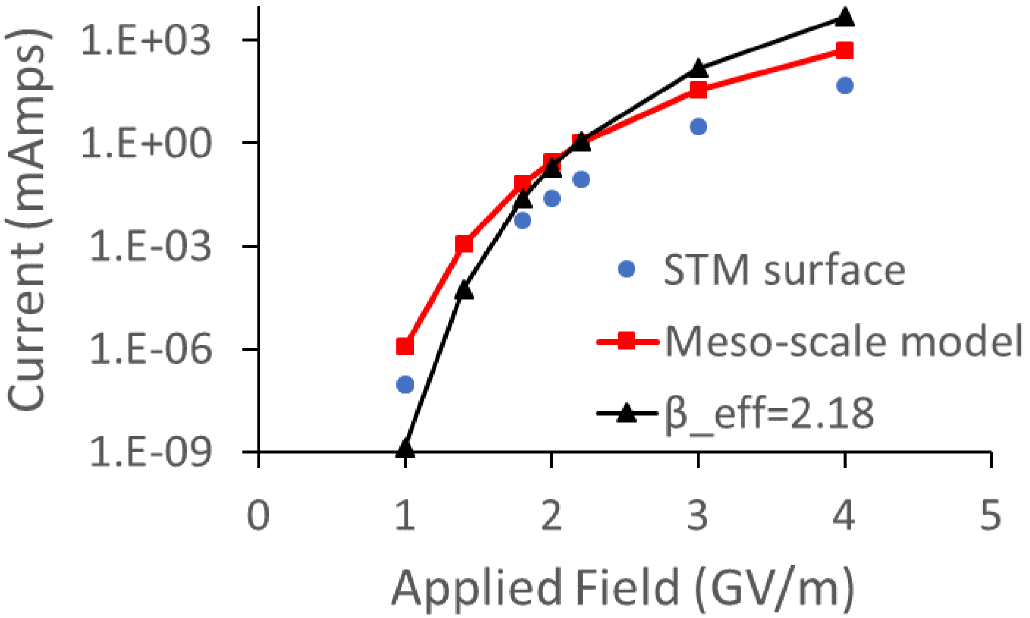
STM surface topology

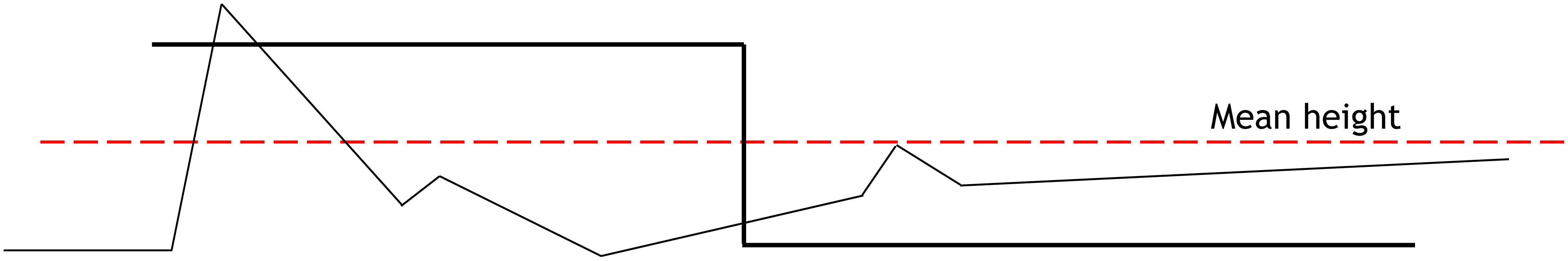




Meso-scale Field Emission Simulations

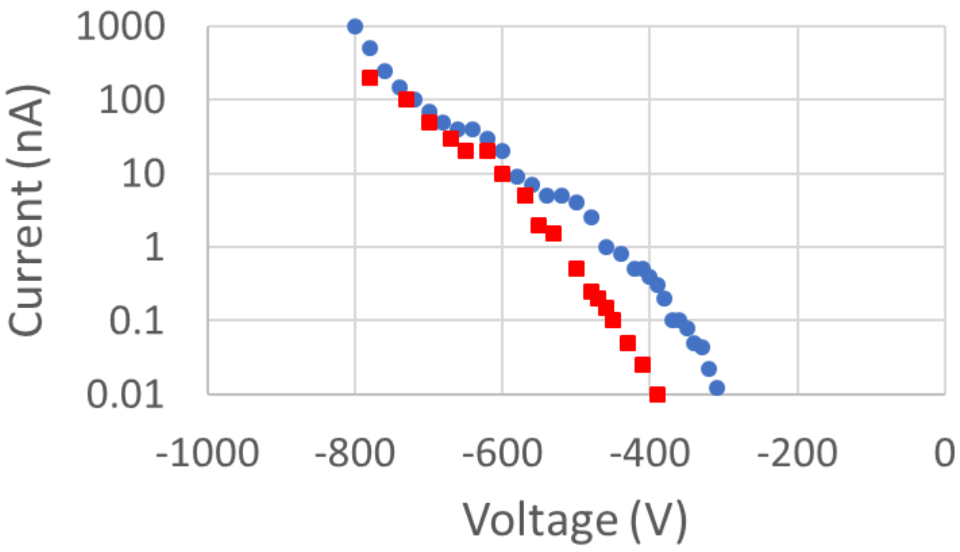
- Compare computed global current versus applied field for the resolved STM surface and meso-scale model surface
  - Stochastic variation in the meso-scale currents small
- The meso-scale model currents have the same trend as the STM surface, but ~12×i_{STM}
  - Difference partially (mostly?) from variation in fields due to changes in gap distance for the STM surface
  - Flat anode placed 10.4μm from the mean STM cathode height





Initial Local STM Breakdown Results

- Took local field emission i-V curves with tip radius < 100nm at a distance of ~200nm
- Relatively feature-less surface with small-β within the region of the tip field footprint
- Breakdown at ~4 GV/m!



- This seems to be evidence that, at least for relatively smooth sputter deposited Pt, we do not have small-β atomic-scale features that grow into large-β features which then allow breakdown to occur at ~10 MV/m.
- Perhaps there is a special feature somewhere on a ~1 cm^2 electrode that results in (or can grow to) a large enough β to get breakdown at ~10 MV/m that was not present on our ~10^{-6} cm^2 sampled area.

Conclusions

- Investigating surfaces at the atomic scale to characterize features relevant to vacuum field emission.
  - Surfaces that we characterized are extremely flat: $\beta\sim1$ over 100's of μm^2
  - Want to clarify β-based field emission so β really is only geometry induced field enhancement.
- By examining field emission at the nanoscale, we have attempted to create a meso-scale physics-based model suitable for predictive (and stochastic) PIC simulation of emission
  - Still have a long way to go – any ideas/suggestions on how to handle the correlation between beta and work function?
- Characterized region, then performed local discharge in STM (spatially constrained surface participation) → Breakdown occurred at ~4 GV/m!
  - Region was flat and uninteresting – the breakdown field is consistent with breakdown from region with a small β

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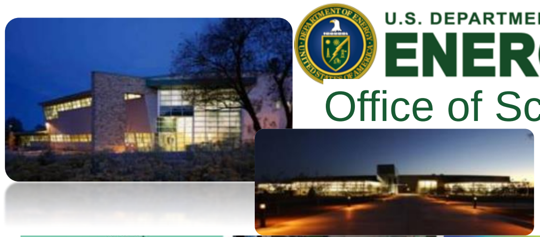

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