# Optimization of Inverse Opal Structures for Applications as Stable Field Emitters

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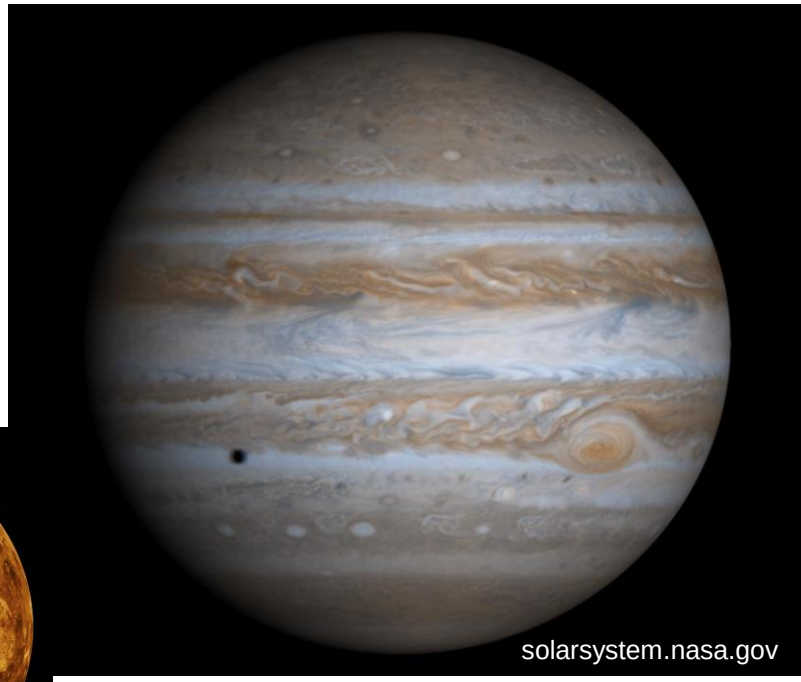
# Motivation/State of the Art

NASA needs electronics that are:

- Miniaturized and lightweight
  - ~$30K to send 1kg to geosynchronous transfer orbit*
- Hot/cold environment compatible
  - Up to 500C (Venus)
- Radiation tolerant (Jupiter)



Solid state technology issues, as compared to vacuum electronics:

- dark current
- failed ohmic contacts
- low signal to noise ratio
- diffusion at high temperature

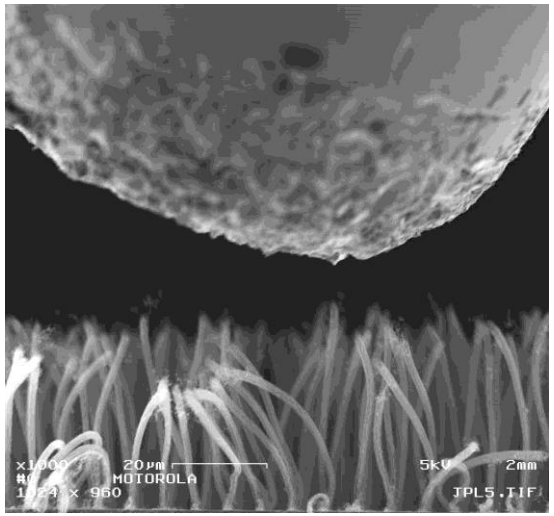
Vacuum Electronics (cold cathodes):

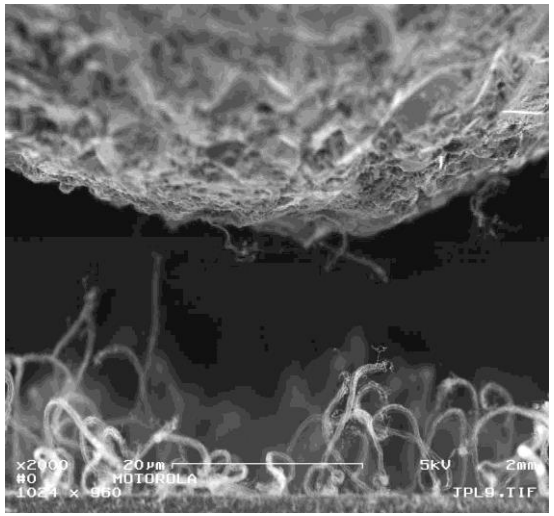
- Spindt Type emitters challenging and expensive to fabricate
- Carbon nanotube (CNT) emitters

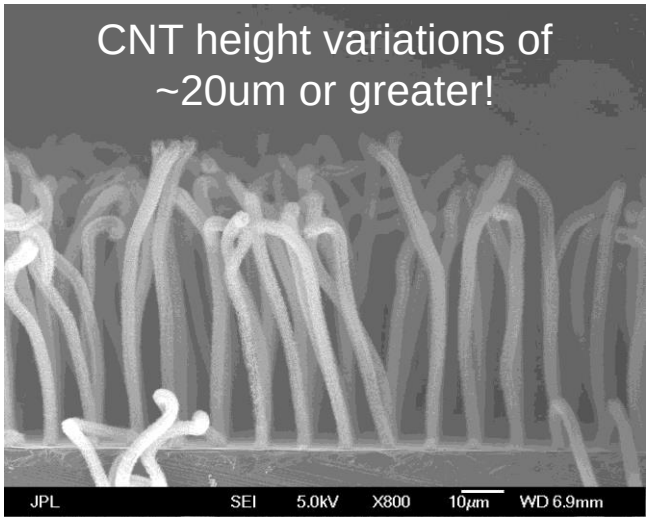
*https://www.nasa.gov/centers/marshall/news/background/facts/astp.html

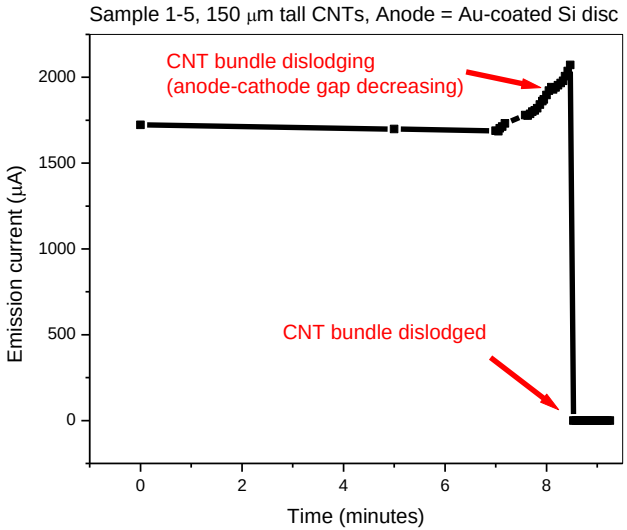
# Vacuum Electronics: CNT cold cathodes

At high currents and voltages, the electrostatic forces can cause the CNTs to deform or dislodge and short the circuit.



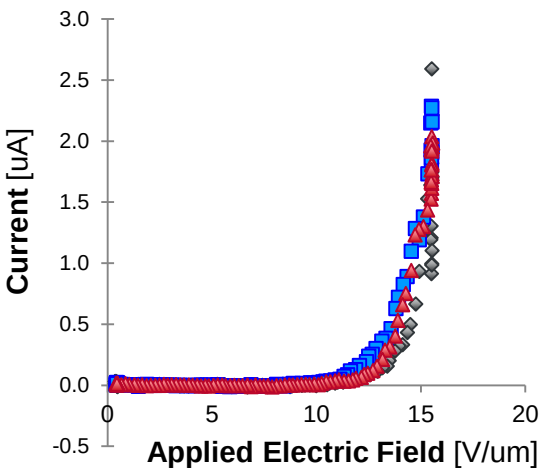



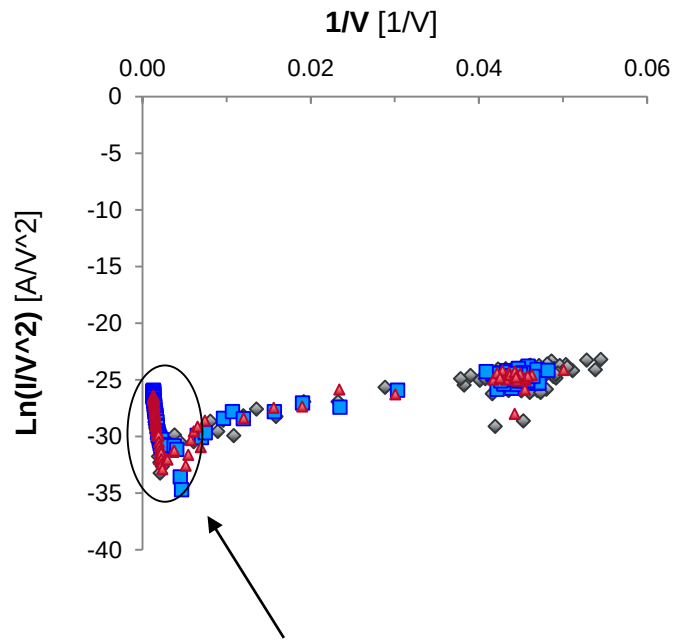
# Field Emission: Fowler-Nordheim Eqn

$$\ln\left(\frac{J}{V^2}\right) = \ln(a) - \frac{b}{V}$$ where $$a = 1.54 \times 10^{-6}\left(\frac{\gamma^2}{\phi \cdot d^2}\right); b = 6.8 \times 10^7\left(\frac{\phi^{3/2} \cdot d}{\gamma}\right)$$

Desired:

- Close cathode/anode distance ($d$)
- Low work function material ($\phi$)
- High enhancement factor ($\gamma$)
  - Aspect ratio
  - Tip sharpness and spacing



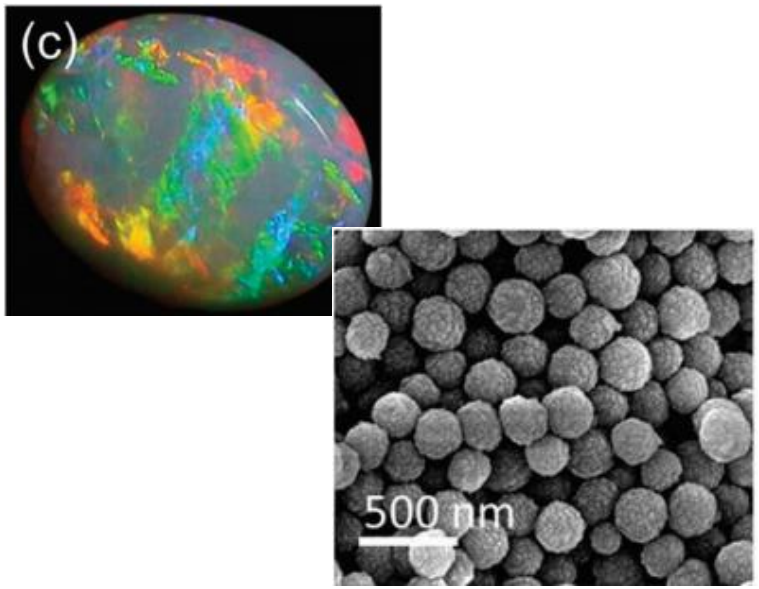




Enhancement Factor ($\gamma$) is calculated by fitting the linear portion of the F-N curve. Higher $\gamma$ are indicative of lower threshold voltages and higher current densities.

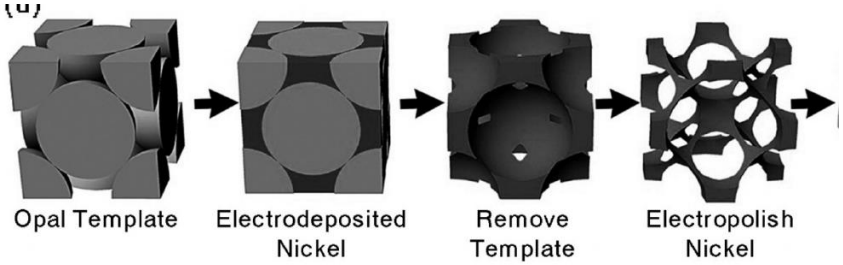
# Inverse Opals as Field Emission Cathodes

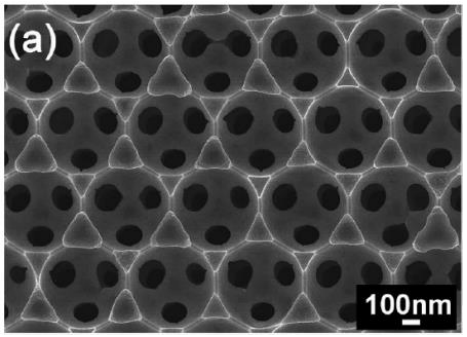
Existing inverse opal applications:

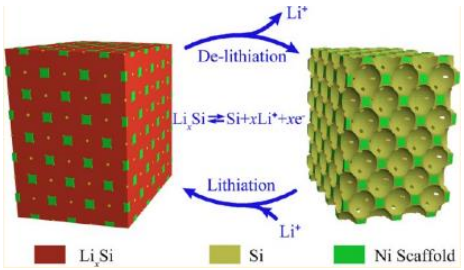
- Photonic crystals
- Electrochemical storage
- Thermophotovoltaics

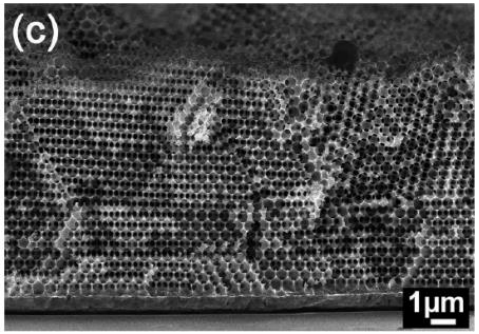



E. Armstrong and C. O'Dwyer, J. Mater. Chem. C, 2015, 3, 6109



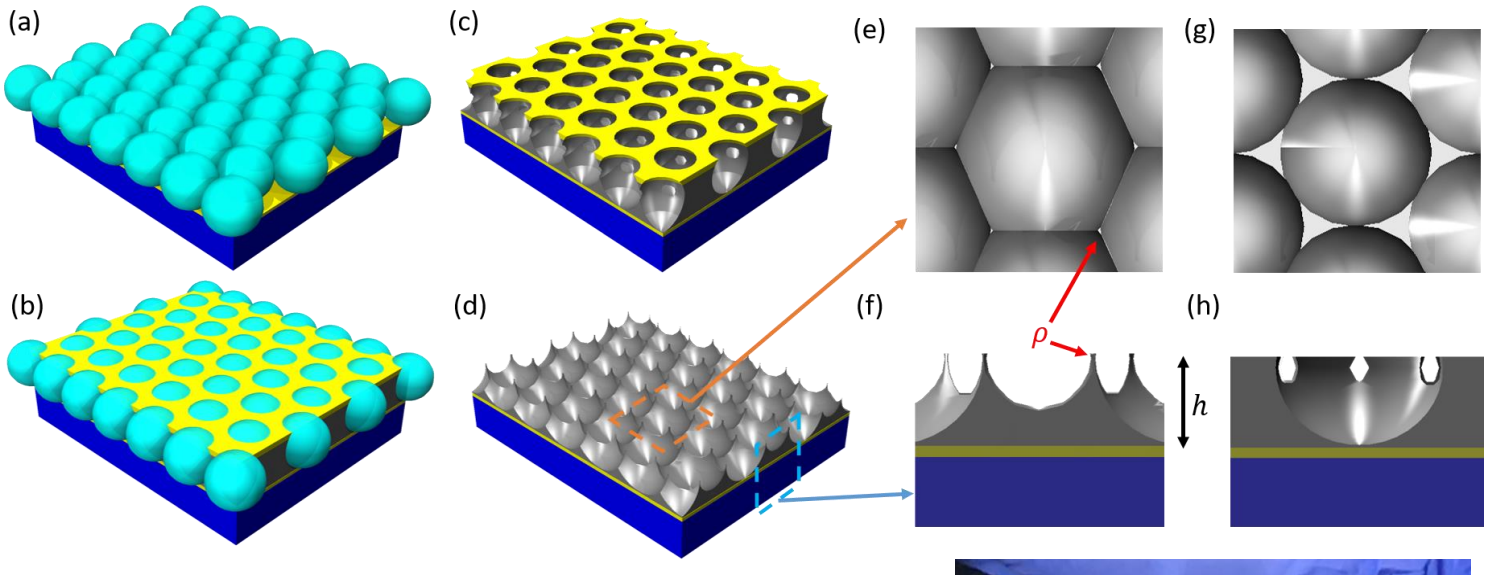



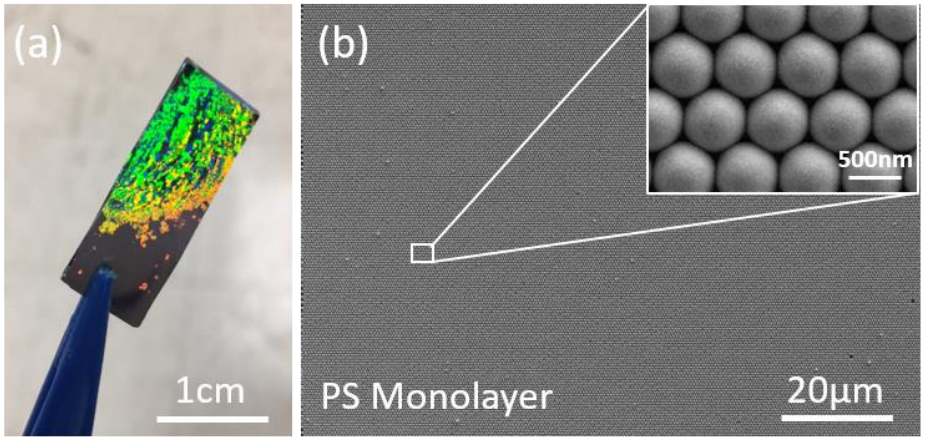

H. Zhang and P. V. Braun, Nano Lett., 2012, 12, 2778–2783

Regardless of sphere size, non-ideal area will always exist in multilayer structures either due to stacking fault or regional non-uniform deposition rate.

# Inverse Opal Fabrication

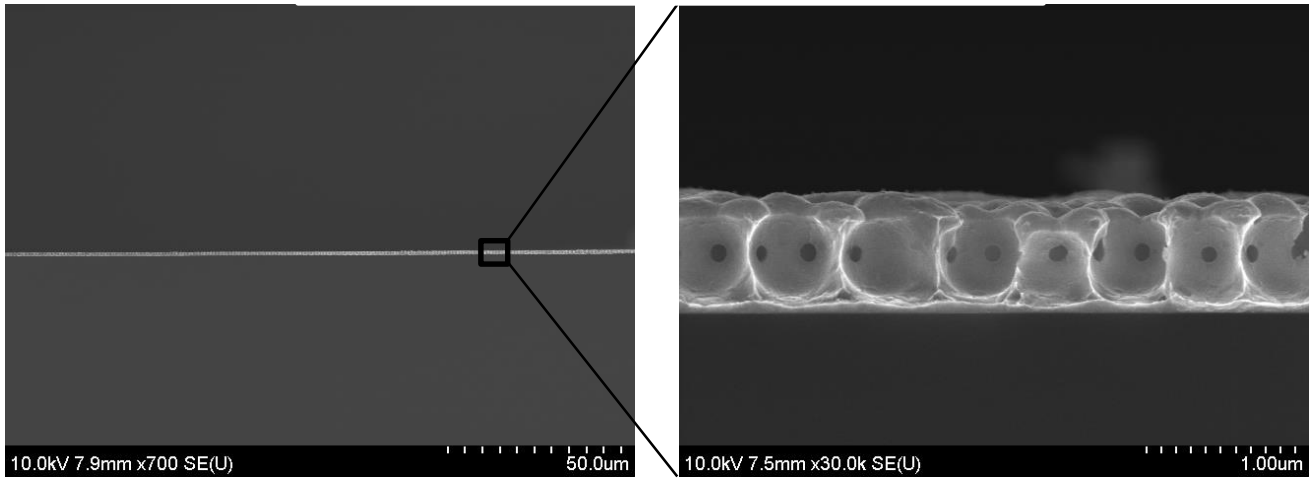



(a) Formation of polystyrene (PS) monolayer on Au coated conductive Si
(b) Electroplate Ni (half sphere height, base to *h*) and Au (to sphere top, *h* to 2*h*) into PS monolayer crystal
(c) Dissolve PS using toluene
(d) Formation of sharp tips using electropolishing

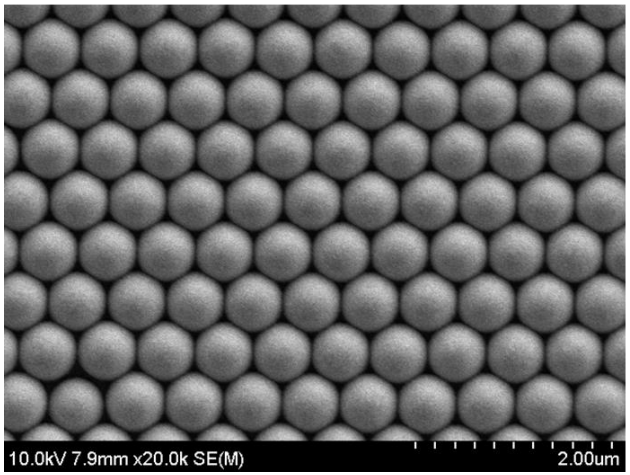


# Inverse Opal Fabrication

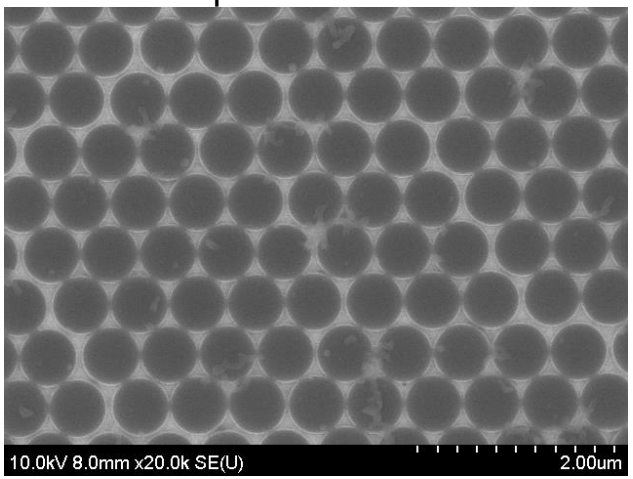
Very Uniform Sample Height



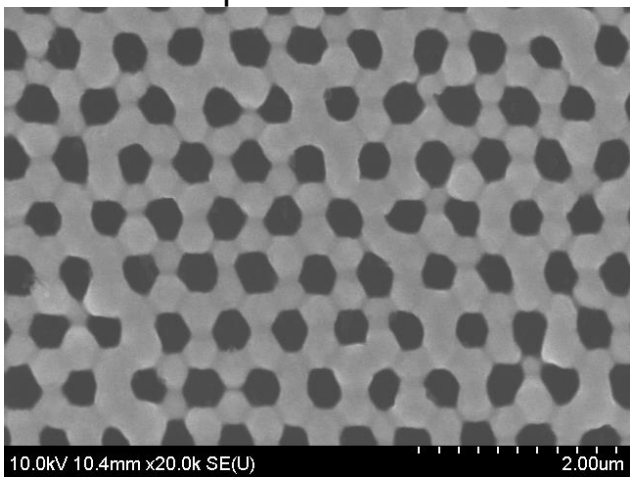

Before Ni



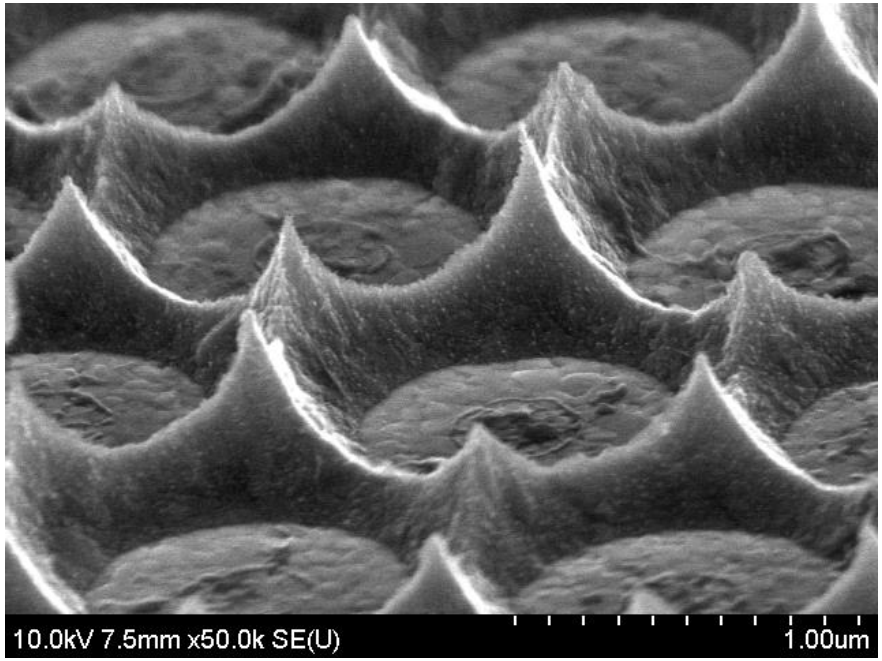

Ni: Deposited to ~40%




Au: Deposited to ~90%

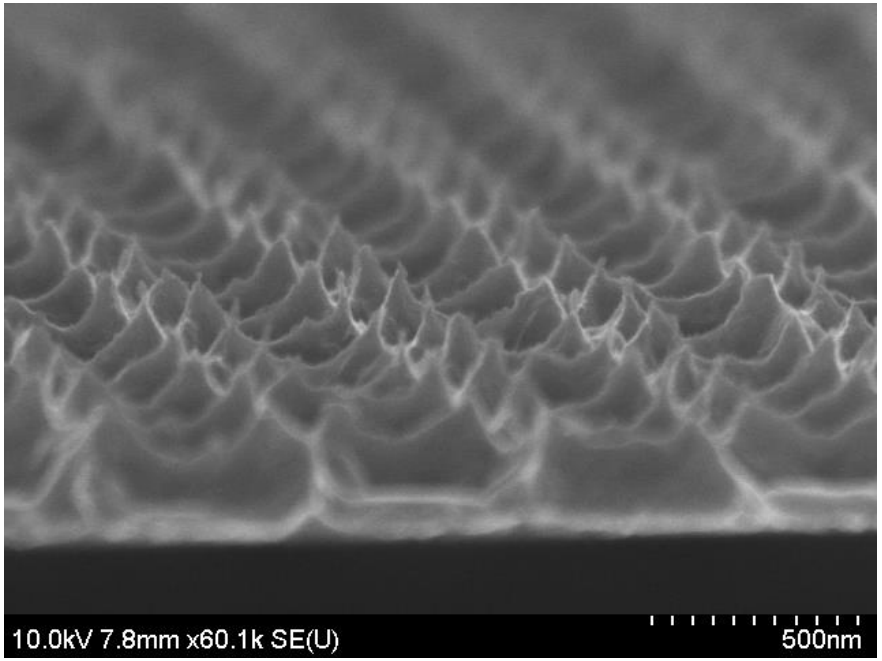


# Inverse Opal Structures (1um and 600nm)

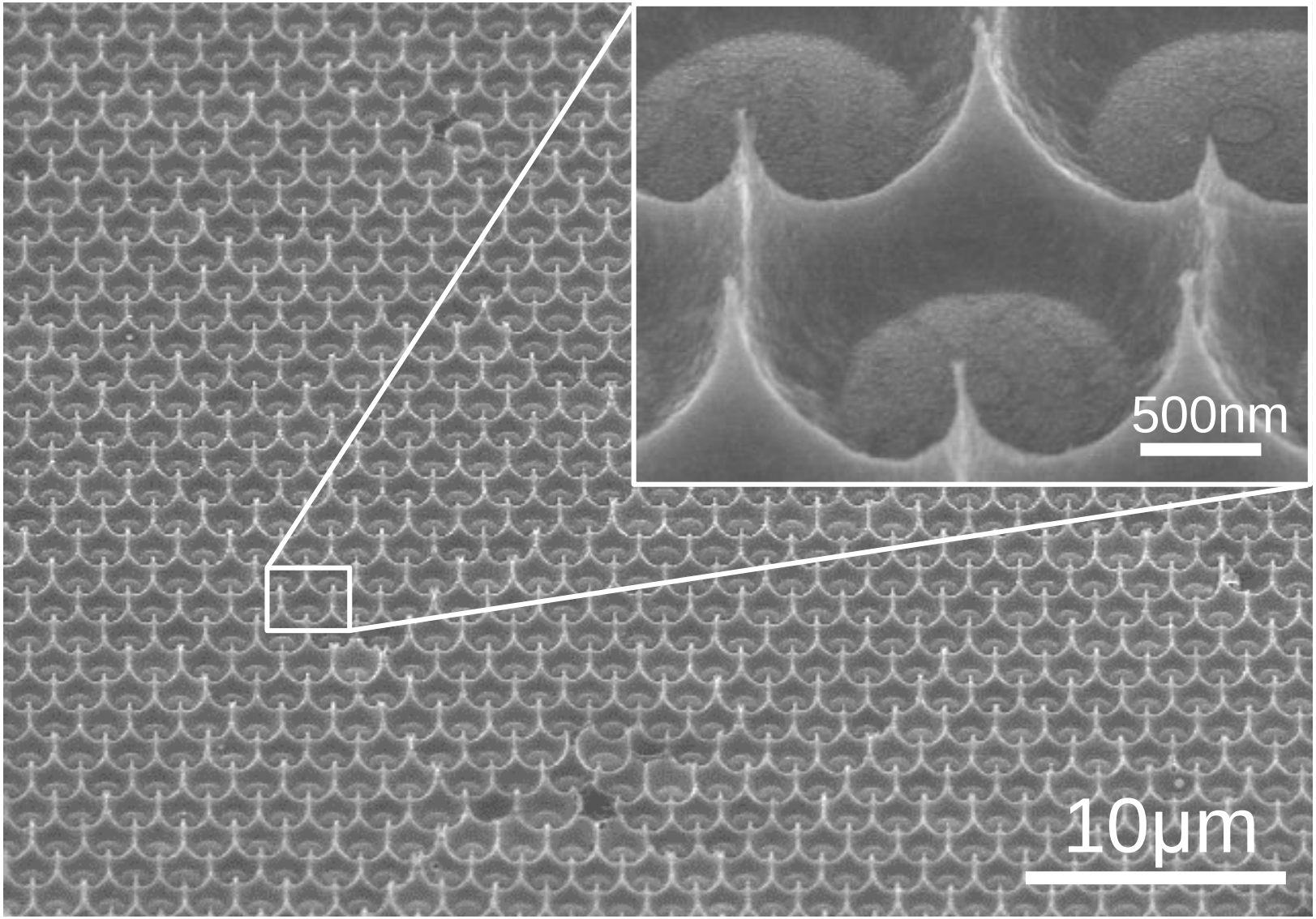



1um inverse opal

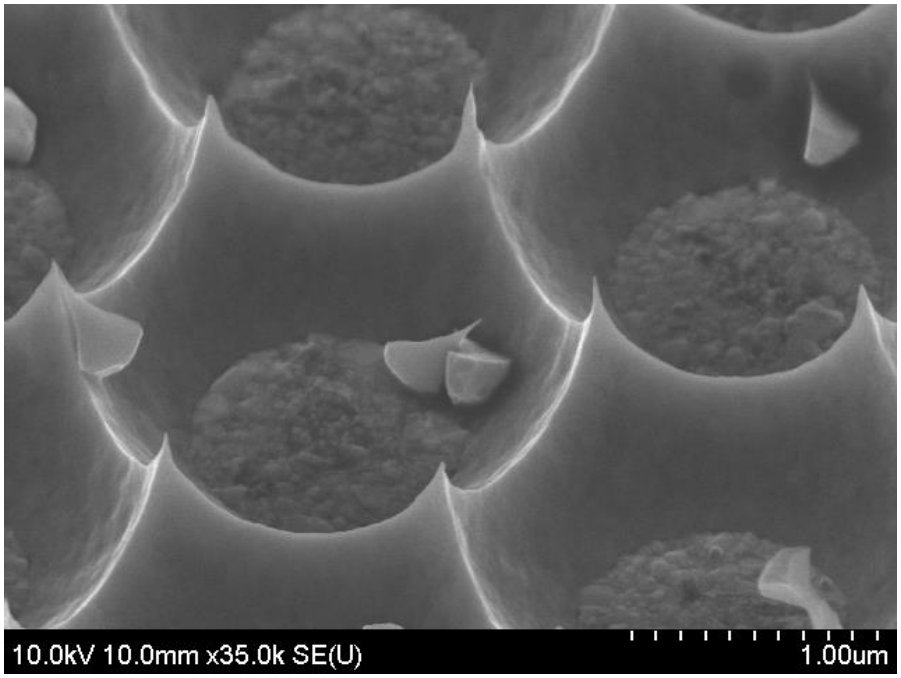
600nm inverse opal

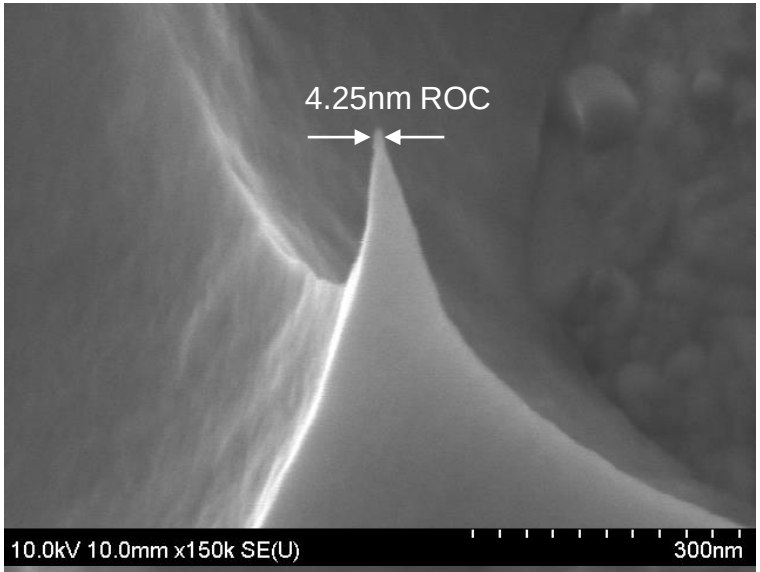


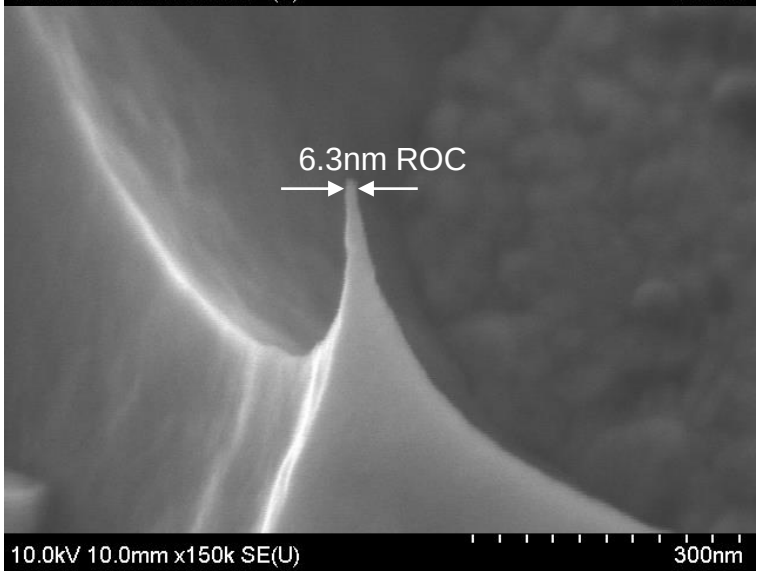
# Inverse Opal Structures (2um)



# Inverse Opal Emitter Tips



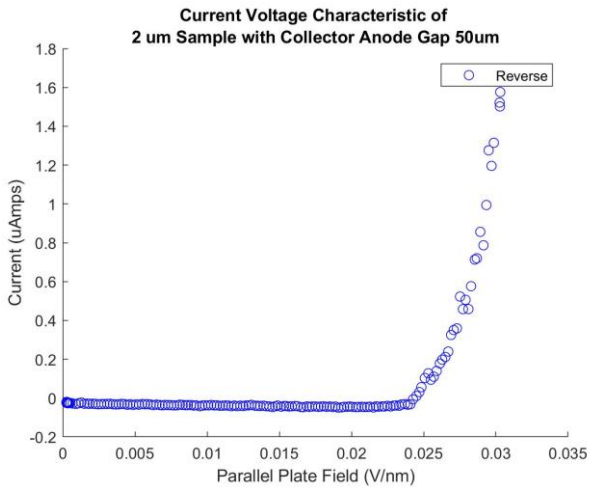



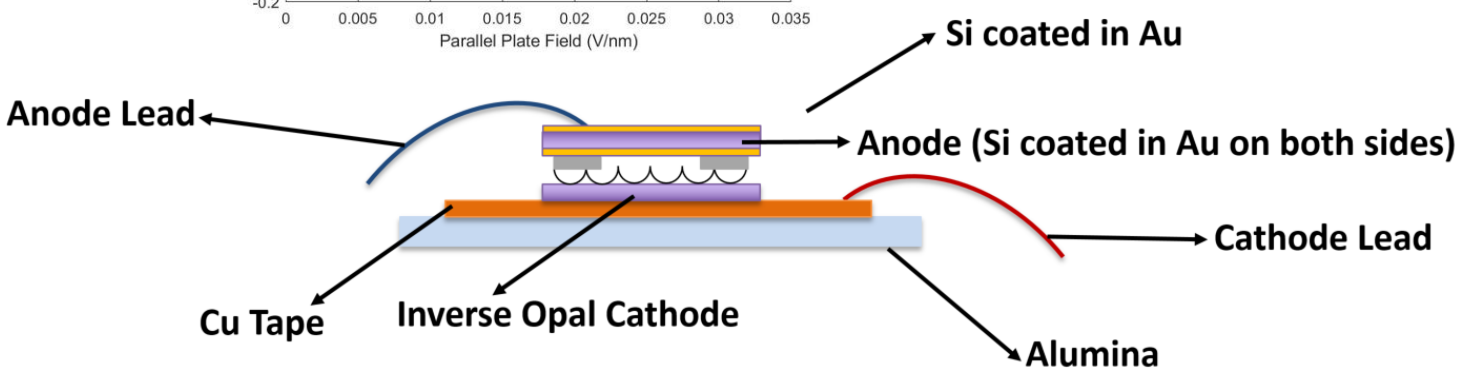
# Field Emission Test Set-up & Test Matrix

- Sweeps consist of increasing the applied electric field from 0 to maximum followed by decreasing back to zero.

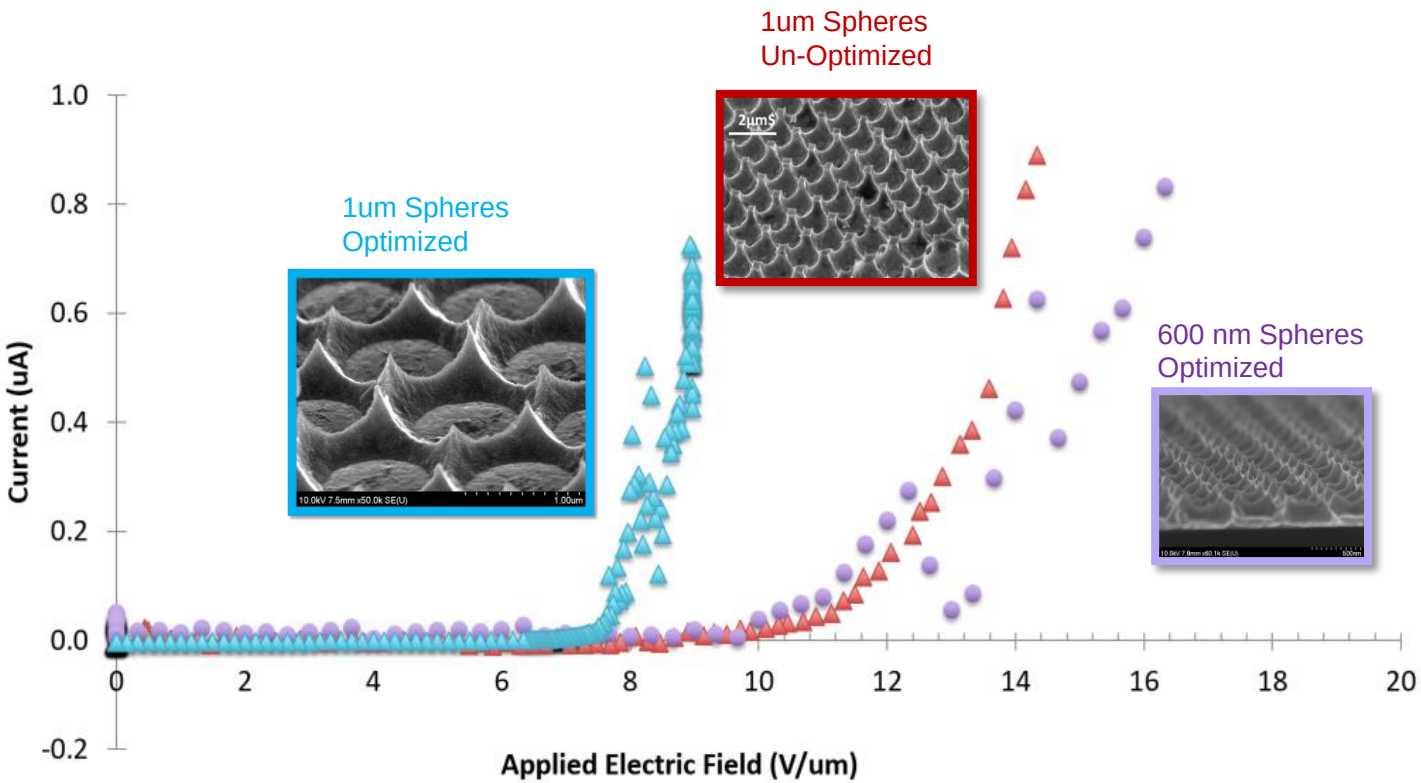
- Forward sweep discarded as it often shows effects of surface contamination.




| Inverse Opal Sphere Size | Anode-Cathode Spacing |
|---|---|
| 600nm | 10um |
| | 30um |
| | 50um |
| 1um | 30um |
| 200um | 50um |
| | 200um |



# I-V Curves for Various Inverse Opal Geometries

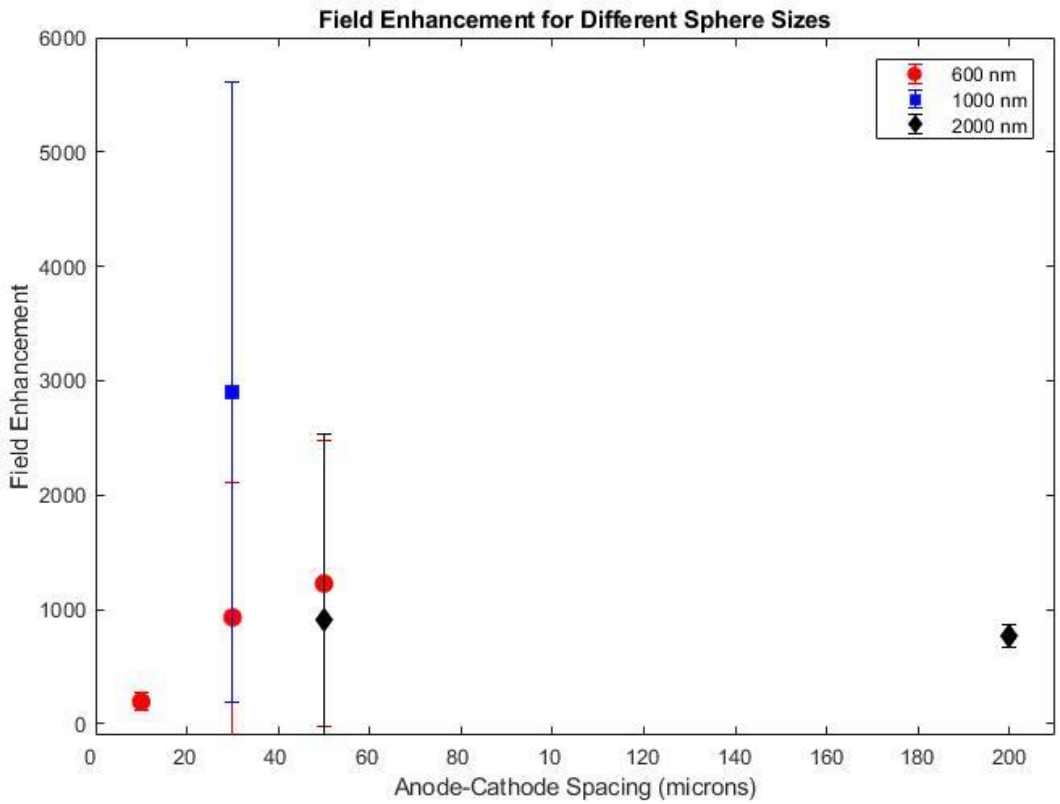



**1 um optimized inverse show ~30% decrease in the threshold field.**

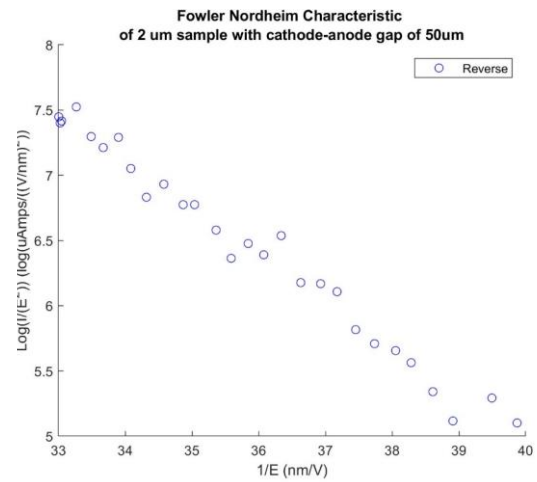
600 nm spheres give a higher density of emitters, but there is no appreciable difference in threshold voltage due to the change in aspect ratio of the tips

# Enhancement Factor for Various Opal Sizes

$$\ln\left(\frac{J}{V^2}\right) = \ln(a) - \frac{b}{V}$$ where $$a = 1.54 \times 10^{-6}\left(\frac{\gamma^2}{\phi \cdot d^2}\right); b = 6.8 \times 10^{7}\left(\frac{\phi^{3/2} \cdot d}{\gamma}\right)$$

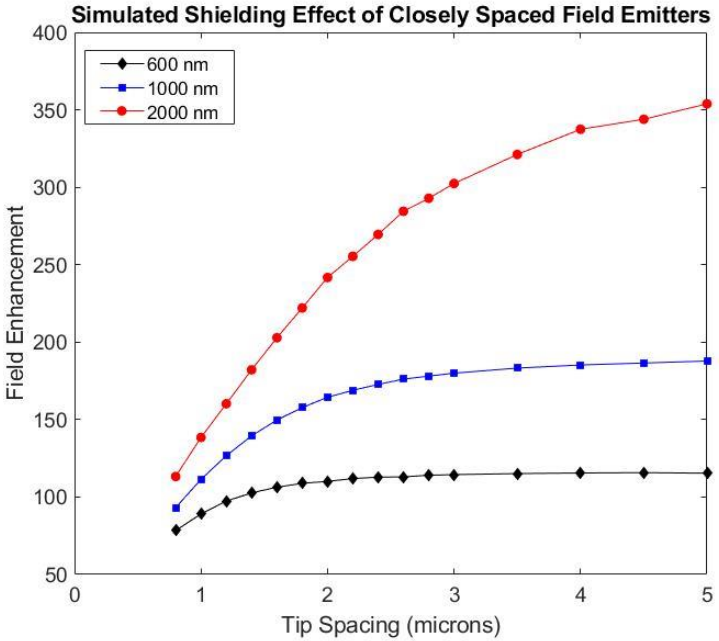


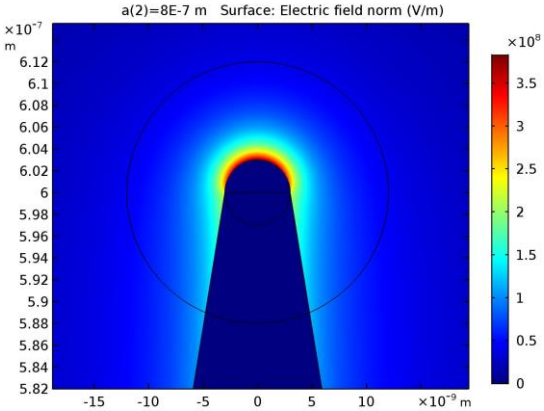

| Sphere Diameter (nm) | Anode-Cathode Spacing (um) | Number of Data Points |
|---|---|---|
| 600 | 10 | 9 |
| | 30 | 3 |
| | 50 | 9 |
| 1000 | 30 | 9 |
| 2000 | 50 | 9 |
| | 200 | 3 |

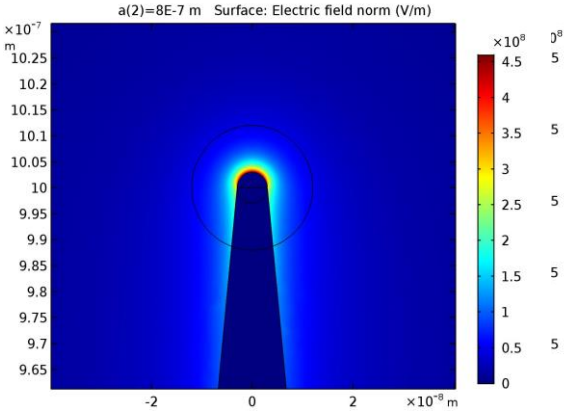


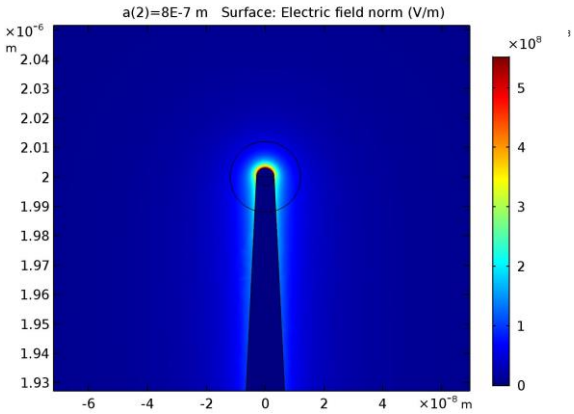
# Shielding observed as inter-tip distance decreases

- 3D COMSOL simulation of opal field emitters
  - Assumptions: periodic boundary conditions, constant cathode-anode gap of 20um
- Explore electrostatic shielding between tips due to
  - Packing density (sphere size)
  - Tip height (600nm, 1um, 2um) and sharpness (constant 3nm radius of curvature)



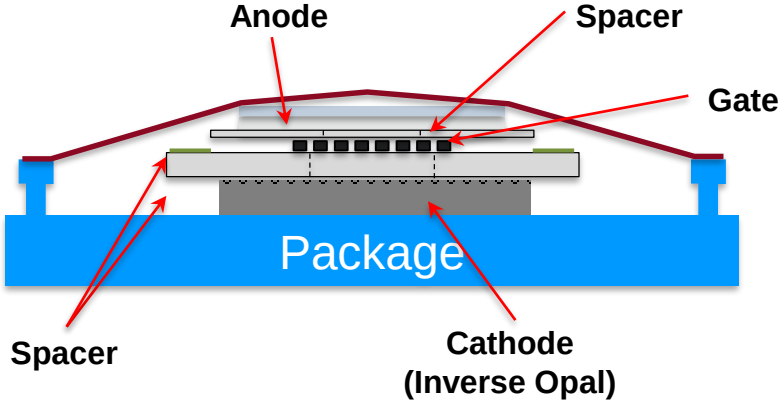



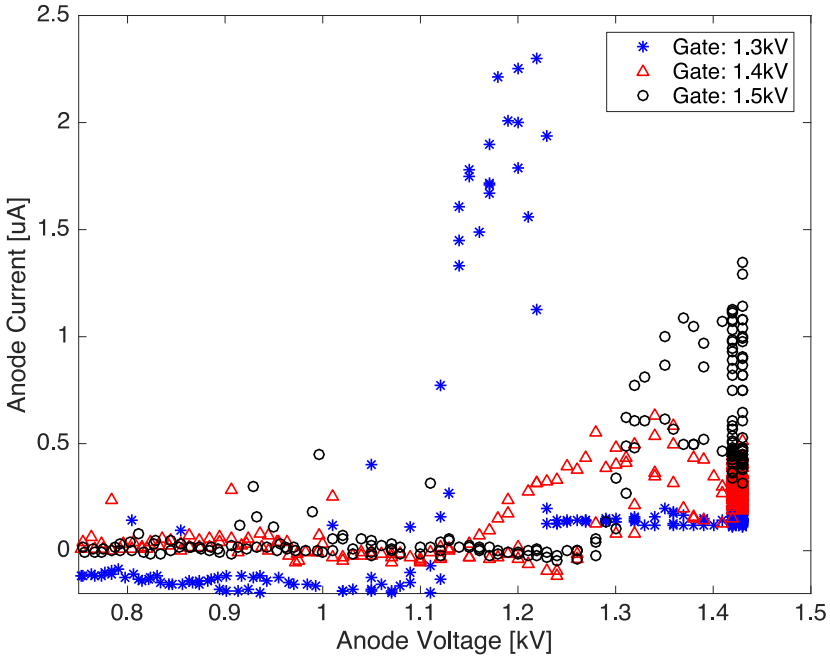



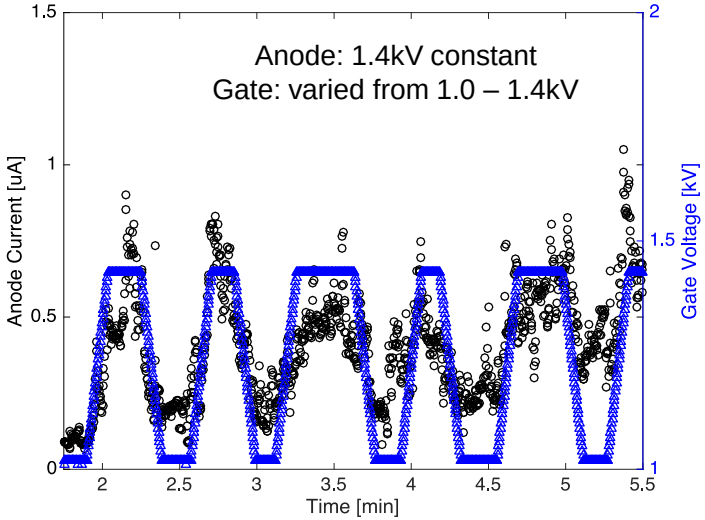



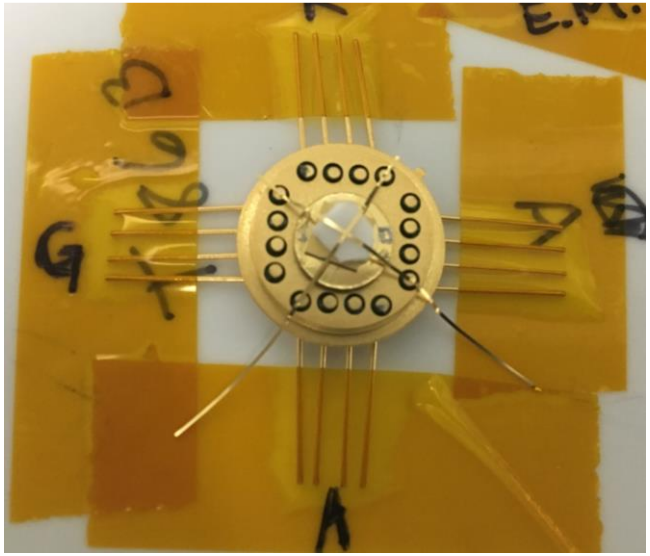
# Inverse Opal Triode

$Gap_{Cathode/Gate}$ = 75um
$Gap_{Gate/Anode}$ = 50um



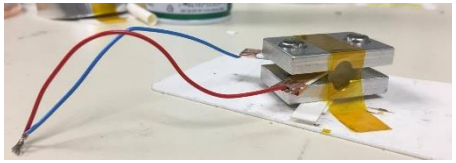



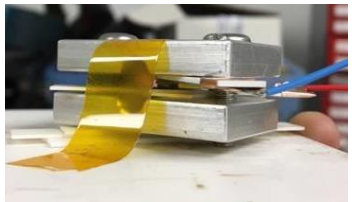



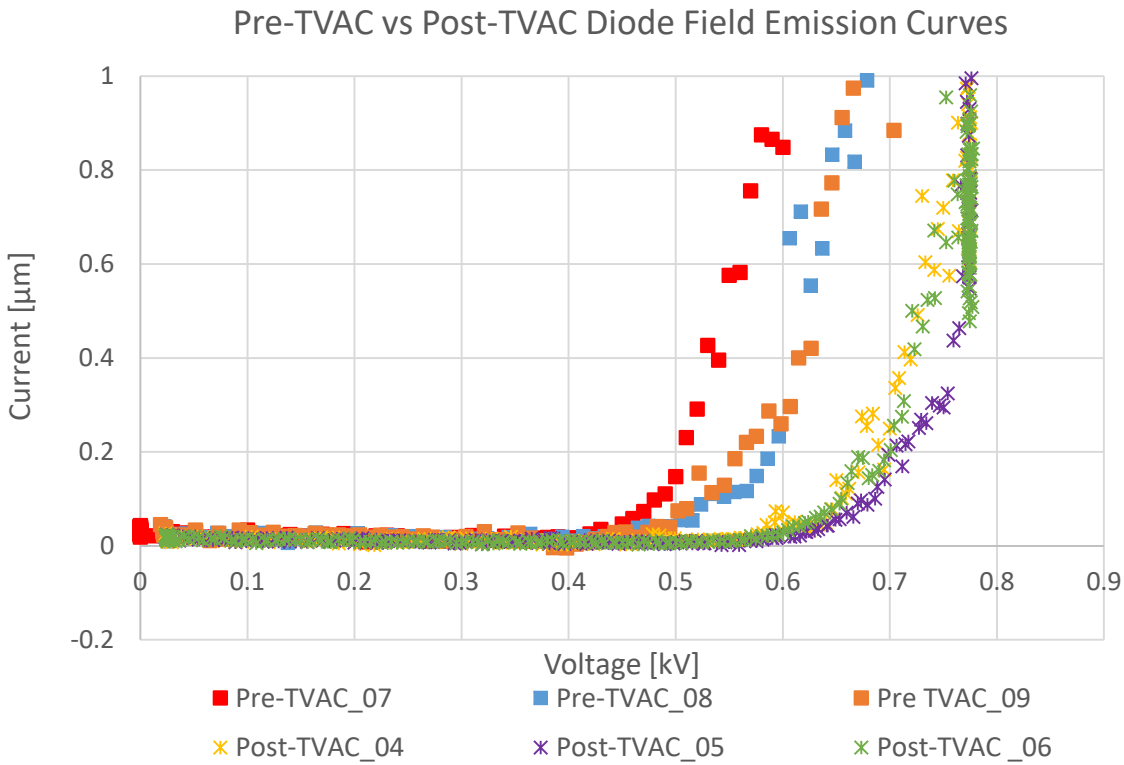



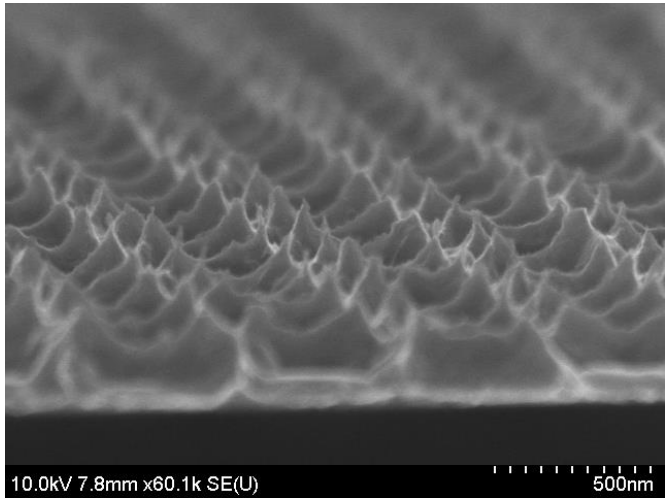
# Thermal Vacuum Testing

- TVAC Test Parameters
  - Max T = 300C for 3 hours
  - Heating rate = 5C/min
- Cathode/Anode gap = 50um

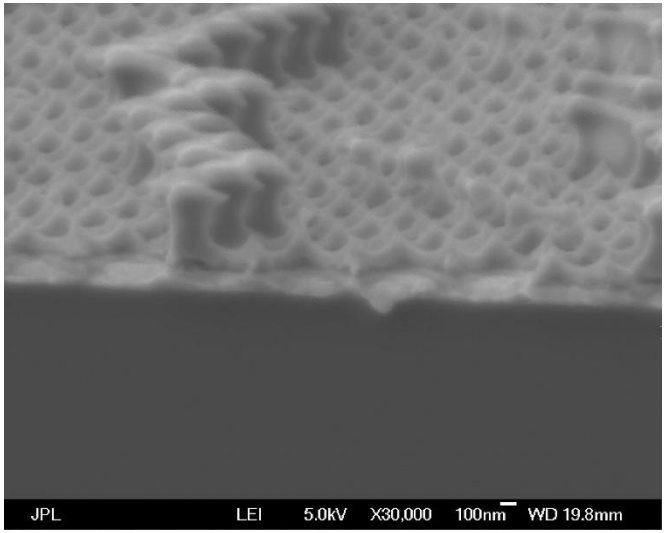






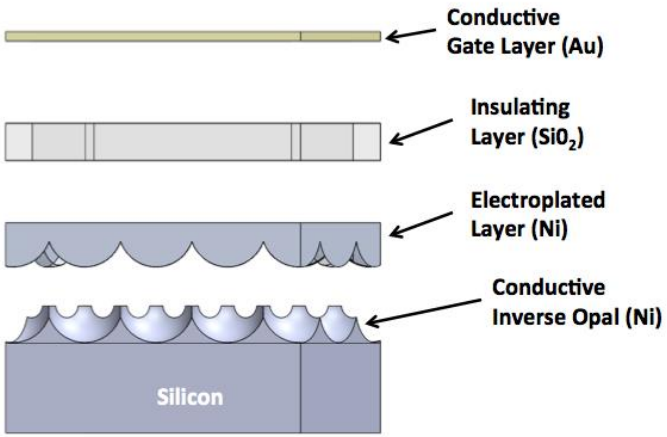

Before TVAC



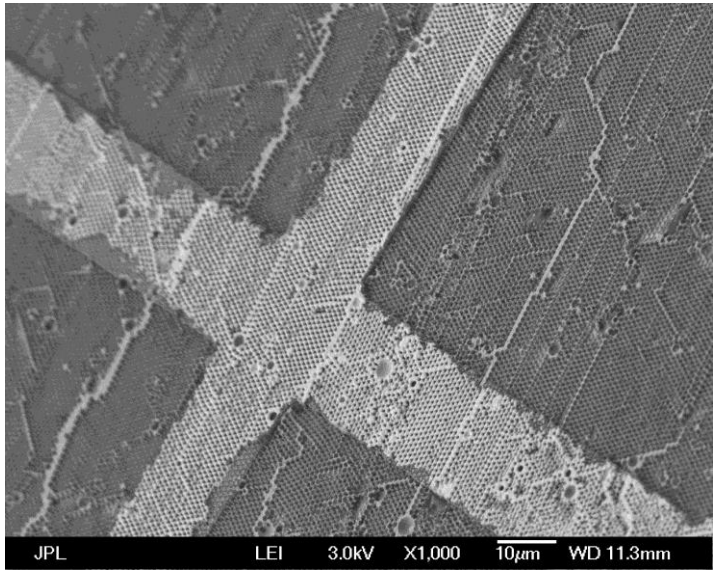

After TVAC

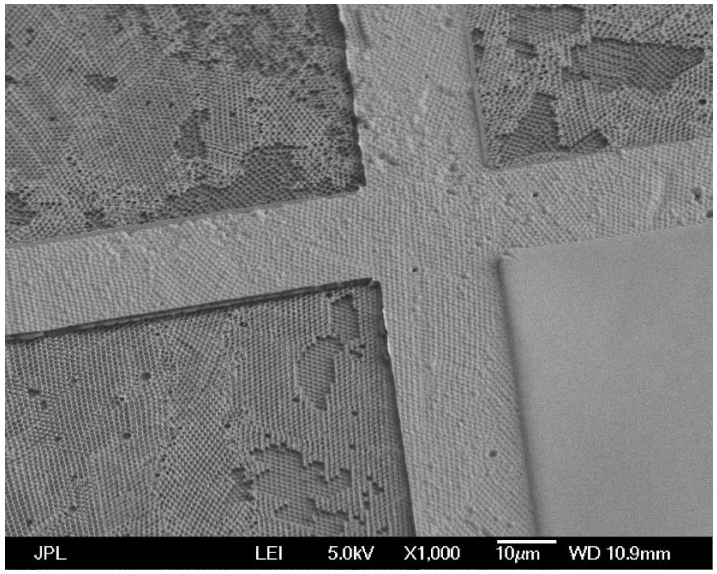
# Photolithographic Gate Integration

- Integrated Cathode/Gate Fabrication:
  - Designed photolithography mask for integrated cathode/gate concept
  - Initial processing done on un-optimized samples



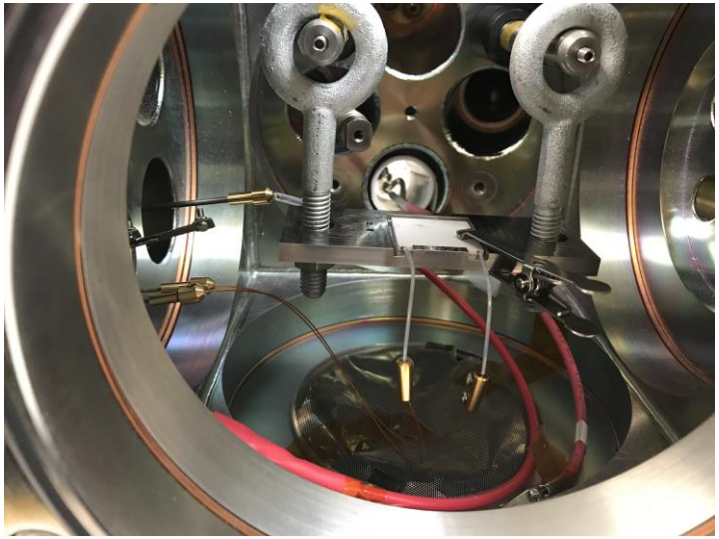

- Observations
  - Process works with Si wafer, issues on Inverse Opal thus far
  - Inverse Opal chip surface is rough, delamination seen. Newer lots appear to be improved



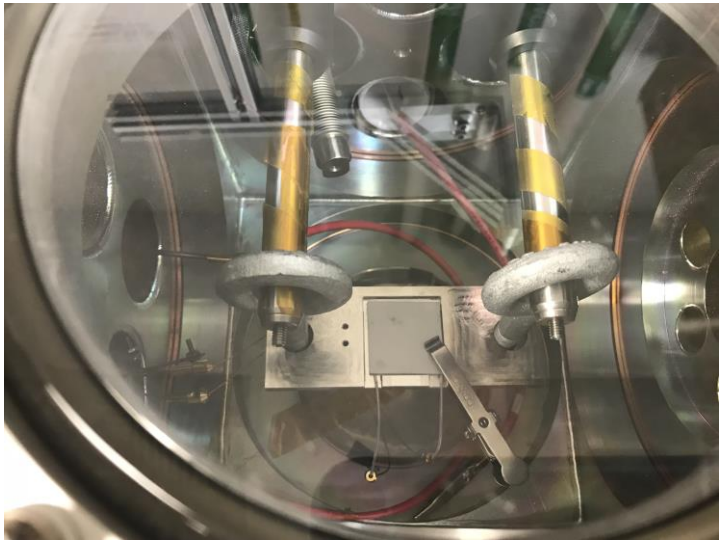
# Summary/Future Work

- Optimized inverse opal geometry for field emission application
- Characterized field emission performance using diodes and triodes
- Proof of concept for high temperature compatibility of inverse opal based field emission devices



Future Work:

- Integrate gate/cathode w/smaller inverse opal cathode areas
- Testing at elevated temperature (300-600C) in diode configuration
- ALD coating of inverse opals
  - Aluminum doped TiC (4.2-4.7eV)
  - ZrNi, ZrO, ZrC (4.6 eV)
  - Amorphous Carbon



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Research & Technology Development program
Microdevices Laboratory: Matthew Dickie
Analysis and Test Laboratory: Ron Ruiz
Valerie Scott

The research described in this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a prime contract with the National Aeronautics and Space Administration (NASA).

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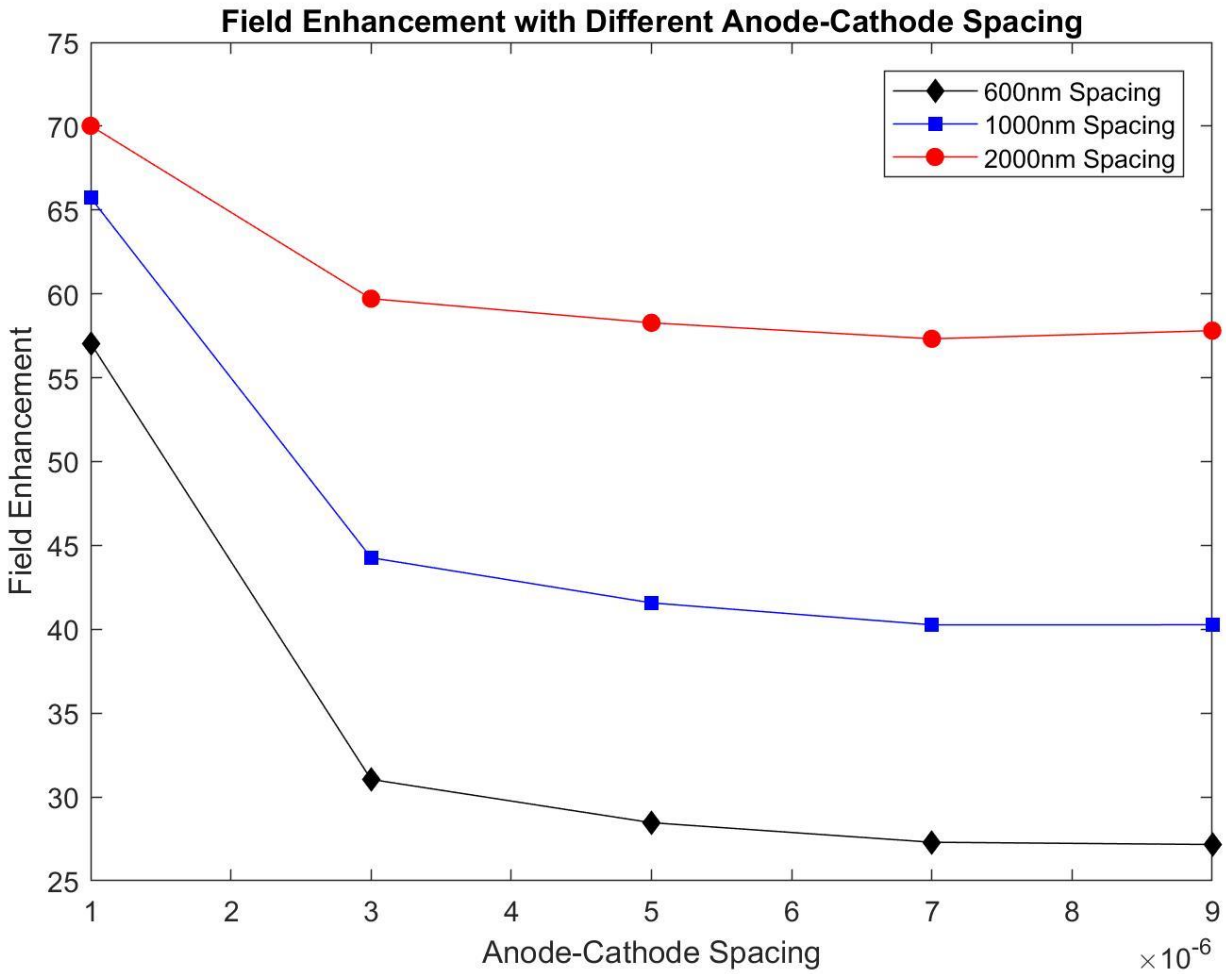
# COMSOL Model: Enhancement Factor as a f(Inverse Opal Geometry)