Focused Helium and Neon Ion Beam Induced Deposition: Examination via a 3D Monte Carlo Simulation

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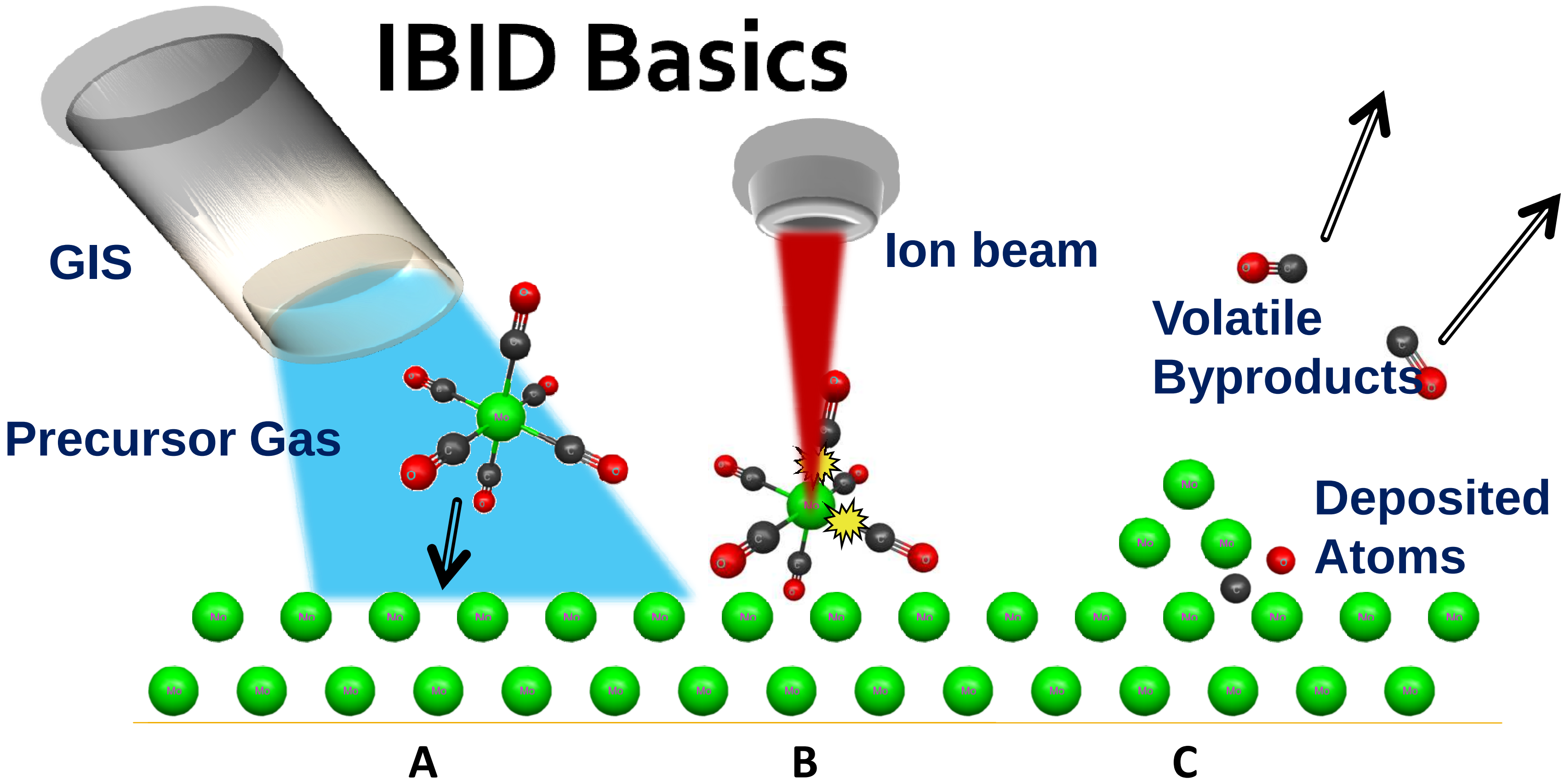
- Delft University of Technology (Paul Alkemade)
- UT/ORNL (Rajendra Timilsina, Carlos Gonzalez, Nick Roberts, Jason Fowlkes)

IBID Basics

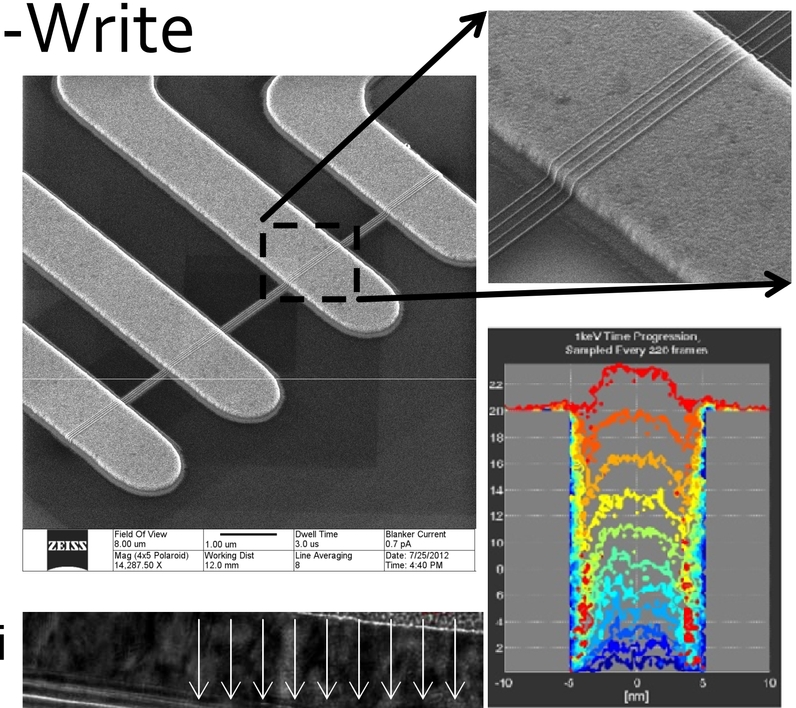


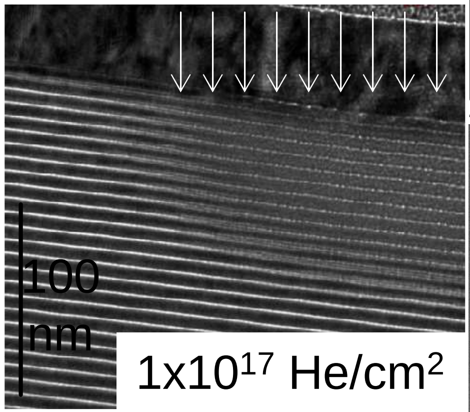
A. Gaseous precursor injected and adsorbs on the substrate
B. Ion beam induced precursor decomposition
C. Target and impurity atoms incorporate into the film, while (some) volatile by-products desorb

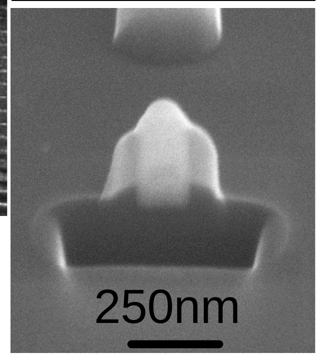
IBID/EBID – Applications/Limitations

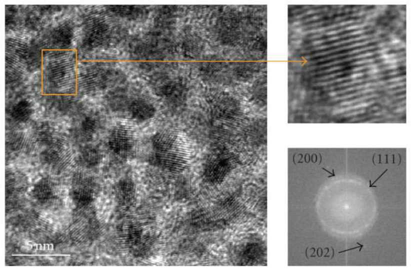
electron (5x10^{-4} amu), He (4 amu), Ne (20 amu), Gallium (70 amu)

- Applications for Nanoscale Direct-Write
  - Circuit Editing
  - Lithography Mask Repair
  - Metrology Preparation
  - Nanoscale Device Prototyping
- Limitations
  - Materials purity
  - Proximity effects
  - Beam induced damage

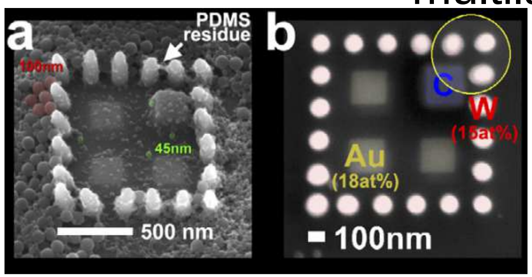






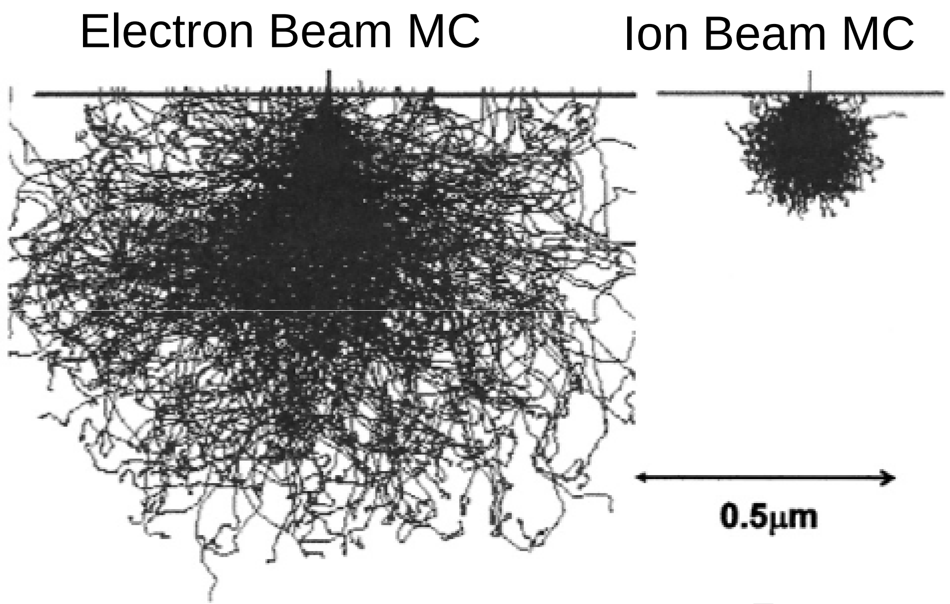


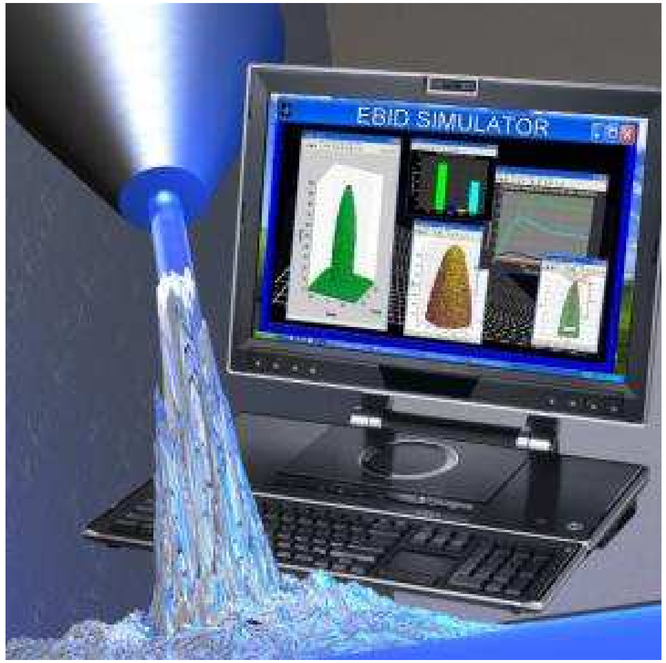
(b) FEBID Pt deposit



EnvizION History

Confluence of IONiSE and EBID Simulation





SRIM TRIM → **IONiSE** → **EnvizION** ← **EBID**

J. F. Ziegler et al
1985-2010
www.SRIM.org

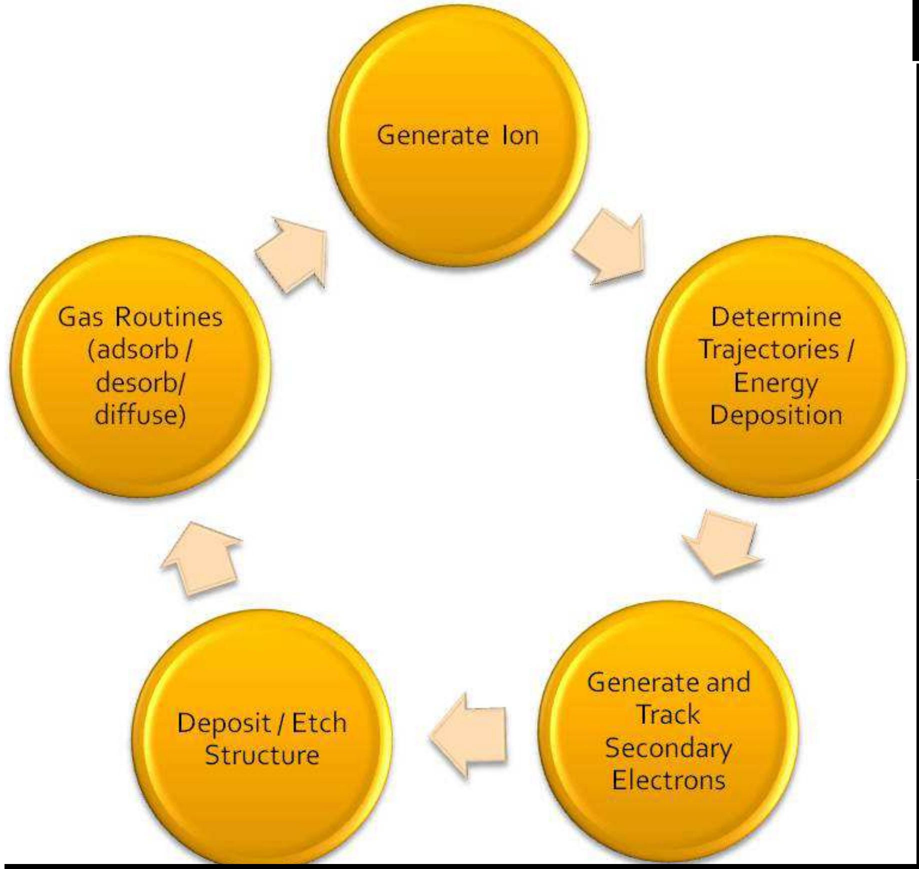
R. Ramachandran and D C Joy
Ultramicroscopy 109 (2009) 748–757

D.A. Smith, D.C. Joy, P.D. Rack, *Monte Carlo Simulation of Helium Ion Beam Induced Deposition*, Nanotechnology Vol. 21 no. 17 pp. 175302 (8pp) (April 2010).

1.Fowlkes J D, et al., *J. Vac. Sci. Technol.* B 23, 2825–32
2.Smith D A, et al. *Nanotechnol.* 18, 265308
3.Smith D A, et al. *Nanotechnol.* 19, 415704
4.Smith D Aet al *Small* 4, 1382–89

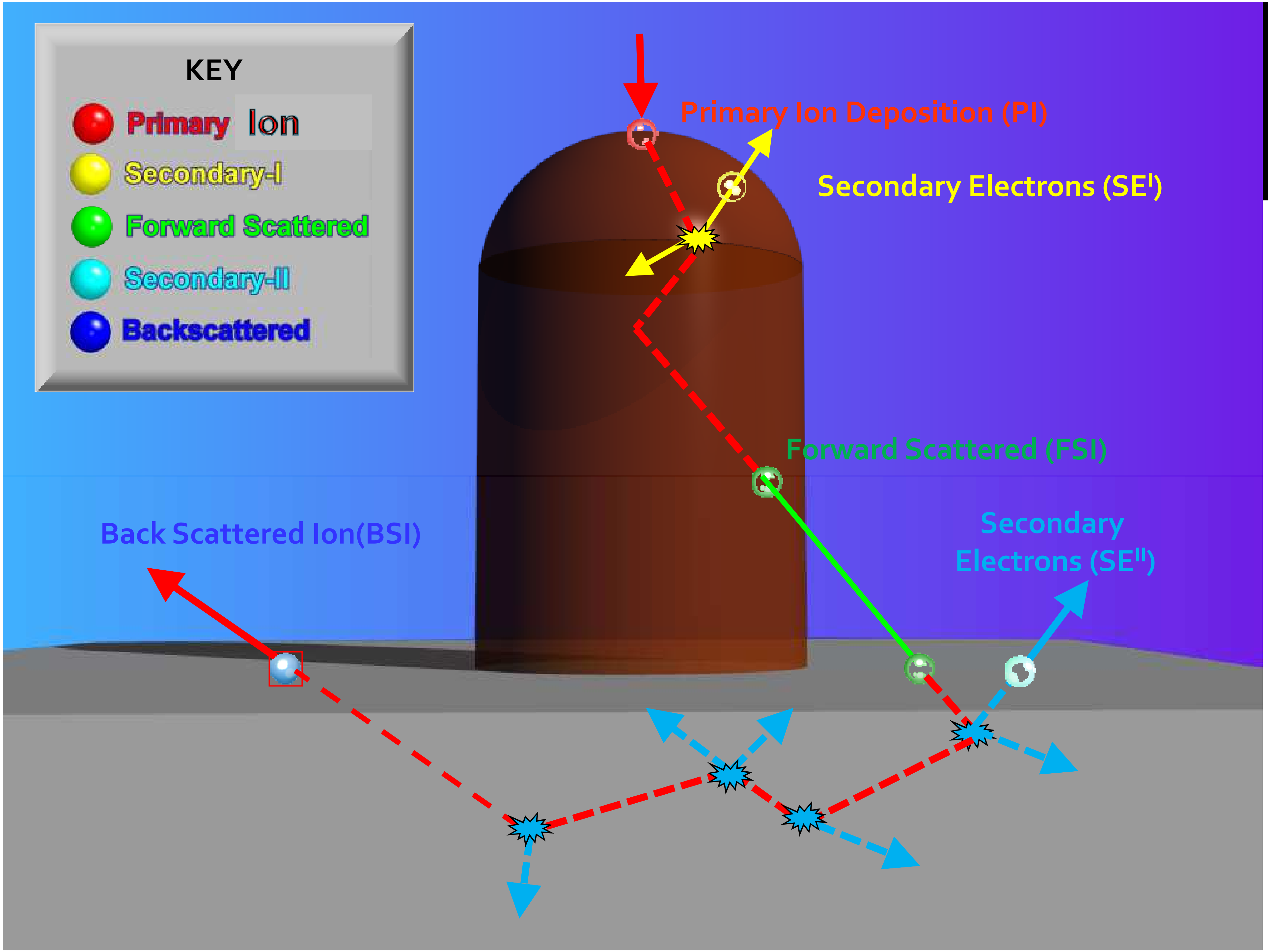
General Program Flow

*D.A. Smith, D.C. Joy, P.D. Rack, Nanotechnology 21 (2010) 175302
*R. Timilsina, D. A. Smith and P. D. Rack, Nanotechnology **24** (2013) 115302



Simulation Attributes

- Three dimensional ion, precursor, and SE routines
- Langmuir adsorption, random walk surface diffusion
- Tracks deposited species
- Light and heavy ions
- Nuclear and electronic energy loss (separate thermal spike model) and new recoil/sputtering

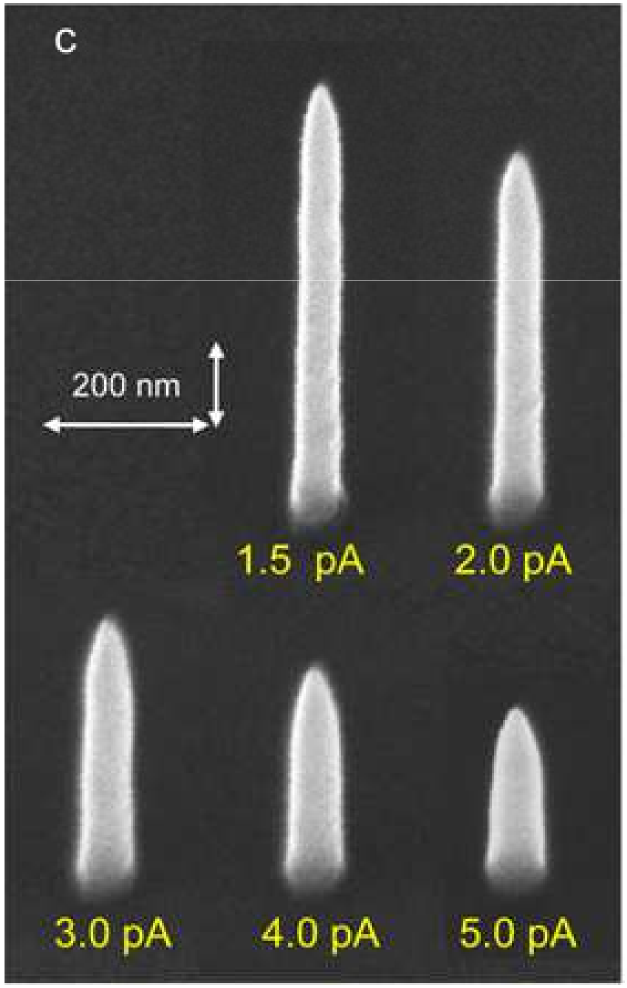


KEY
Primary Ion
Secondary-I
Forward Scattered
Secondary-II
Backscattered
Primary Ion Deposition (PI)
Secondary Electrons (SE^I)
Forward Scattered (FSI)
Back Scattered Ion(BSI)
Secondary Electrons (SE^II)

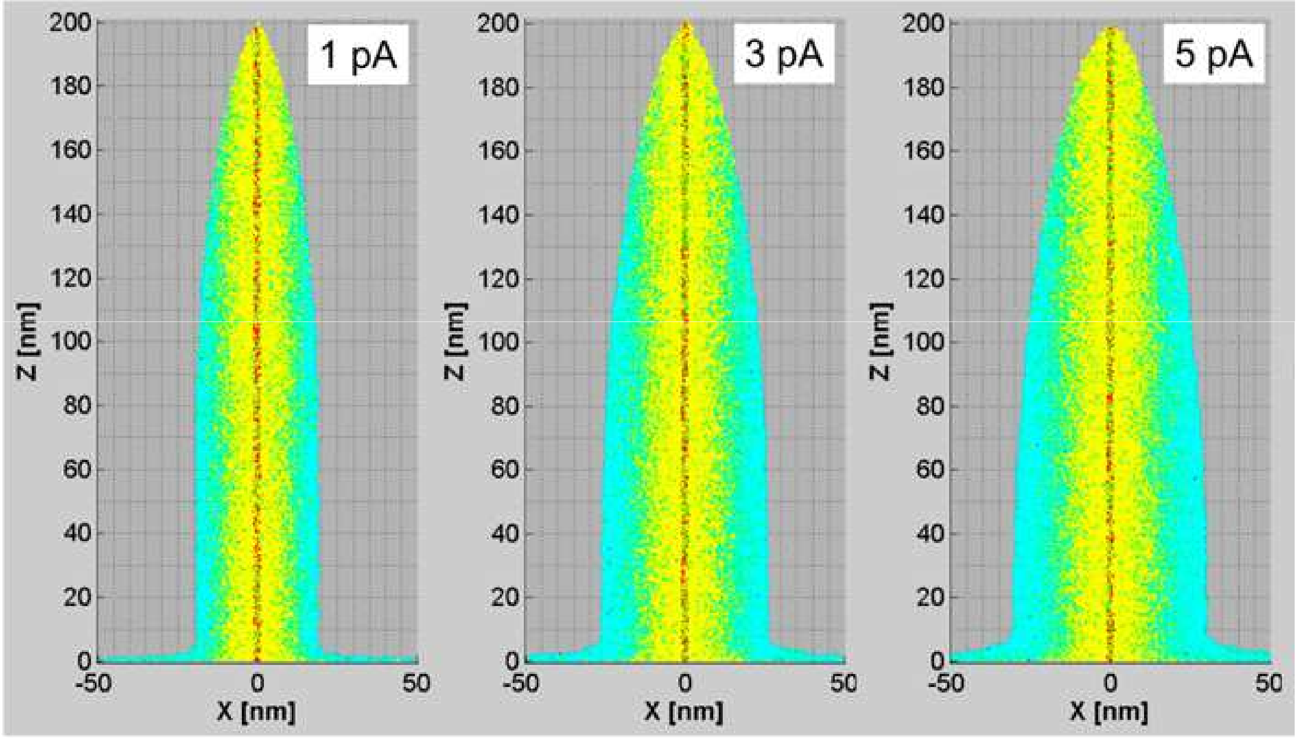
Experiment vs. Simulation

25keV He+ beam, ~ 1.3×10^{-2} *mbar $(CH_3)_3Pt(CpCH_3)$, variable current, constant growth*

Constant Dose (6pC)
↑ i ↓ rate ↑width



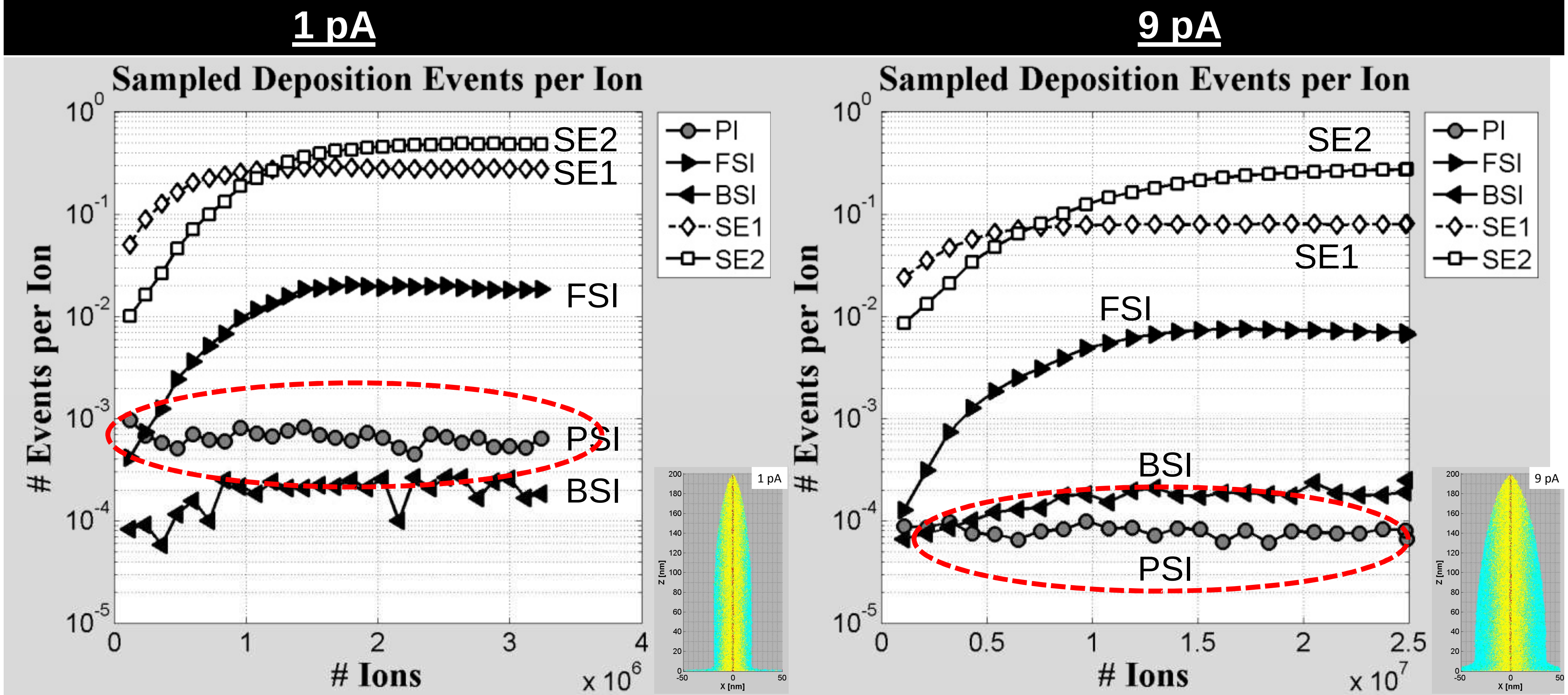
Constant growth height (variable dose) ↑ i ↓ rate ↑width



<u>0.5pC</u> **<u>1.3pC</u>** **<u>2.3pC</u>**

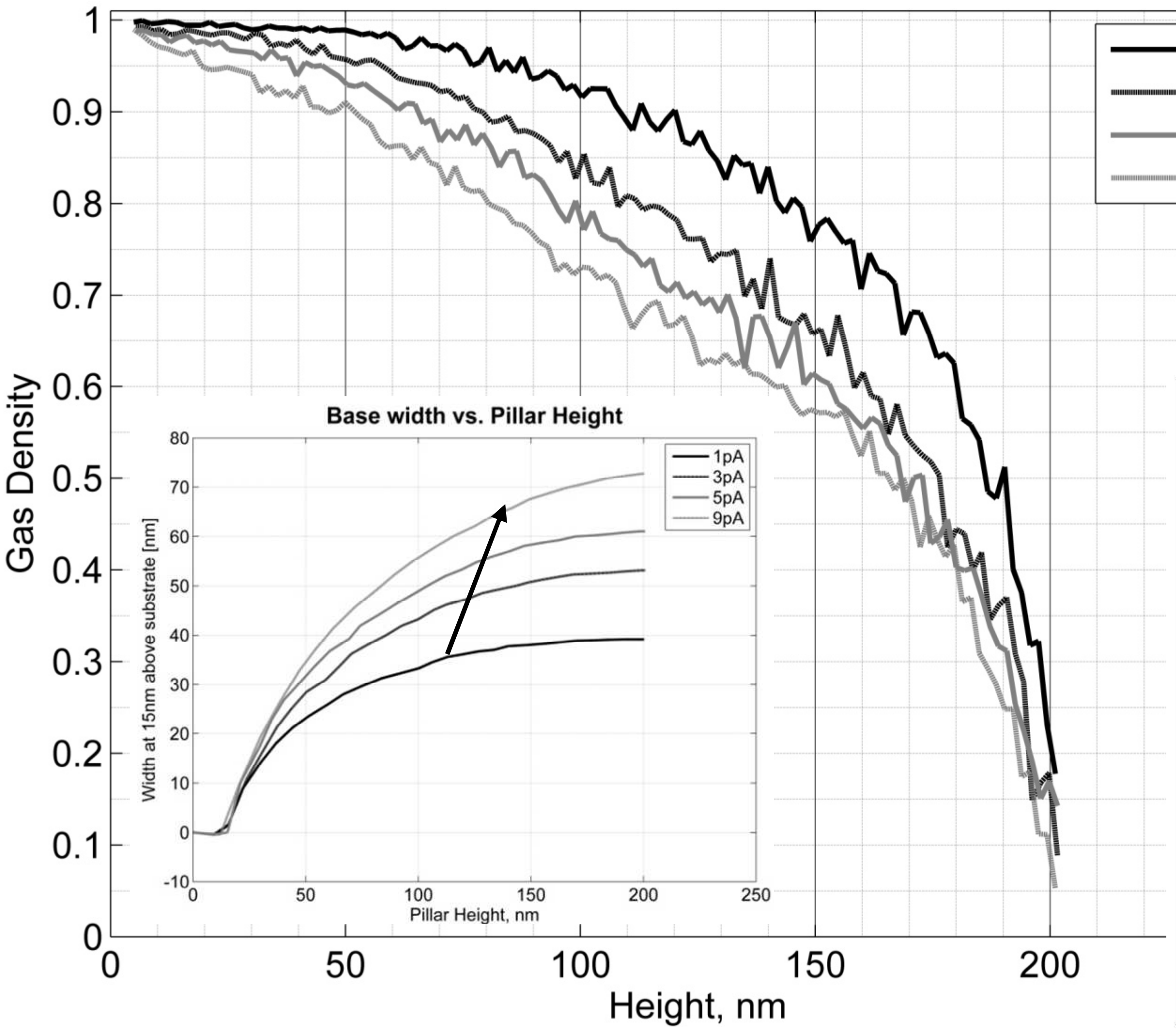
P. Chen, E. van Veldhoven, C. Sanford, H. Salemink, D. Maas, D.A. Smith, P.D. Rack, and P. Alkemade, *Nanopillar growth by focused helium ion beam induced deposition,* Nanotechnology Vol. 21 no. 45, 455302 (1-7) (November 2010).

Current Dependent Growth

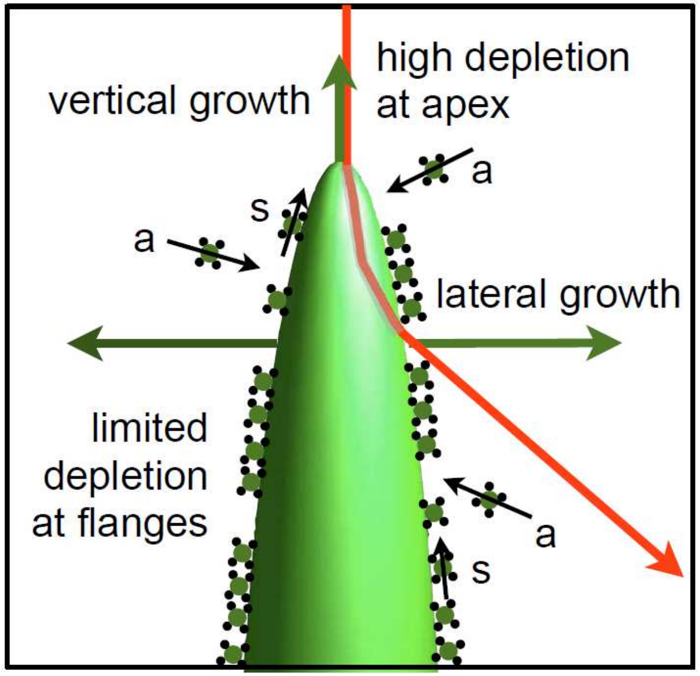


• Higher current reduces overall growth efficiency
• Vertical growth rate (controlled by PSI) is reduced more than the lateral components(SEI, SEII, FSI) → broader pillars.

Current Dependent Growth:
Surface coverage



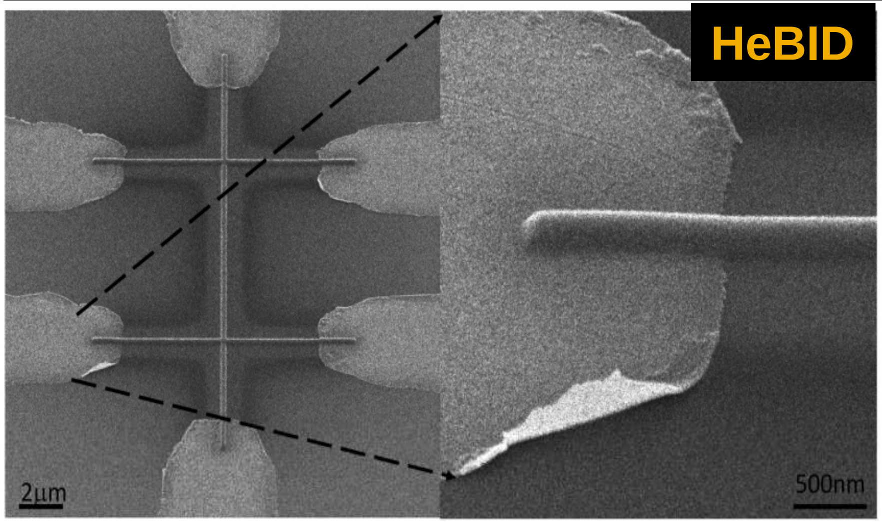
- Gas depletion at the surface reduces vertical growth rate
- Increased gas surface coverage on the side-walls results in higher lateral growth rate probabilities
- Results in more isotropic growth



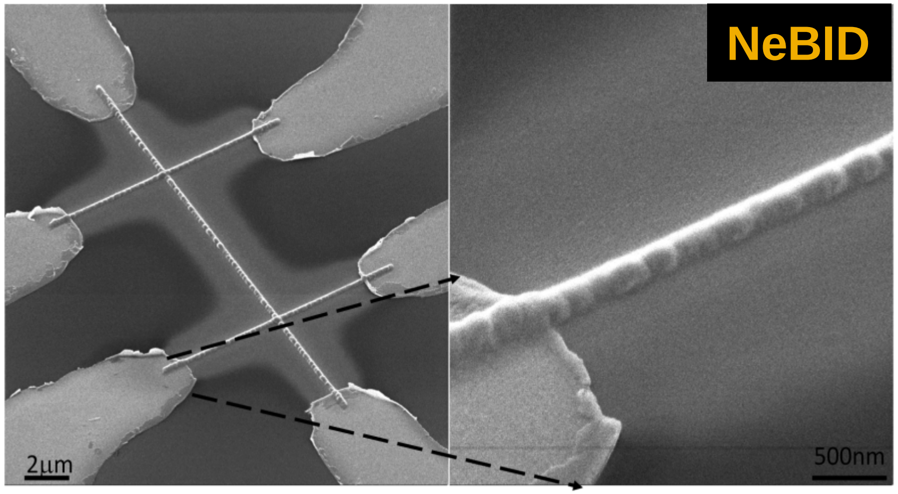
Helium versus Neon Beam Induced Deposition

~ 1×10⁻² mbar $(CH_3)_3Pt(CpCH_3)$, 20 keV, current 10 pA, 1 nm pixel spacing, 10 μs dwell time

Wu et al, Nanotechnology, in press (2013)

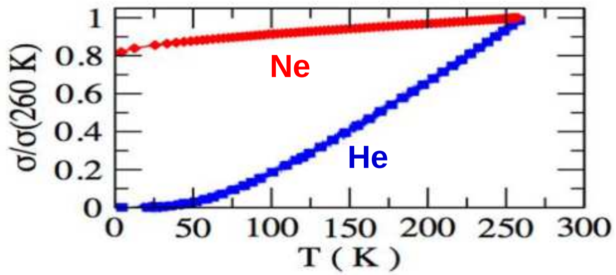


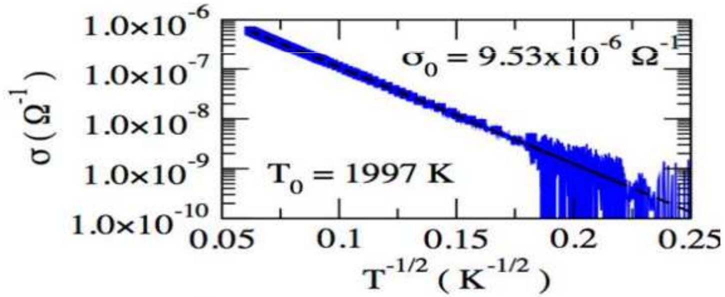
resistivity (~3.5x10⁴ μΩ-cm)

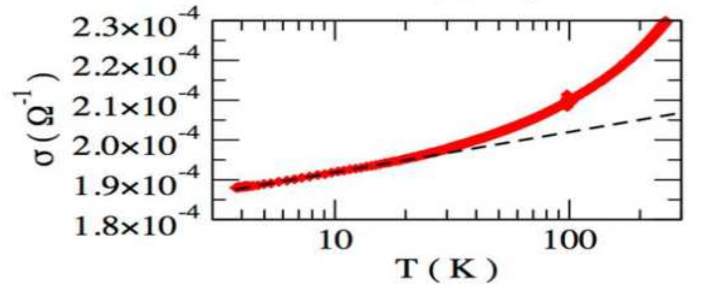


resistivity (~600 μΩ -cm)

Temperature dependent Electrical properties

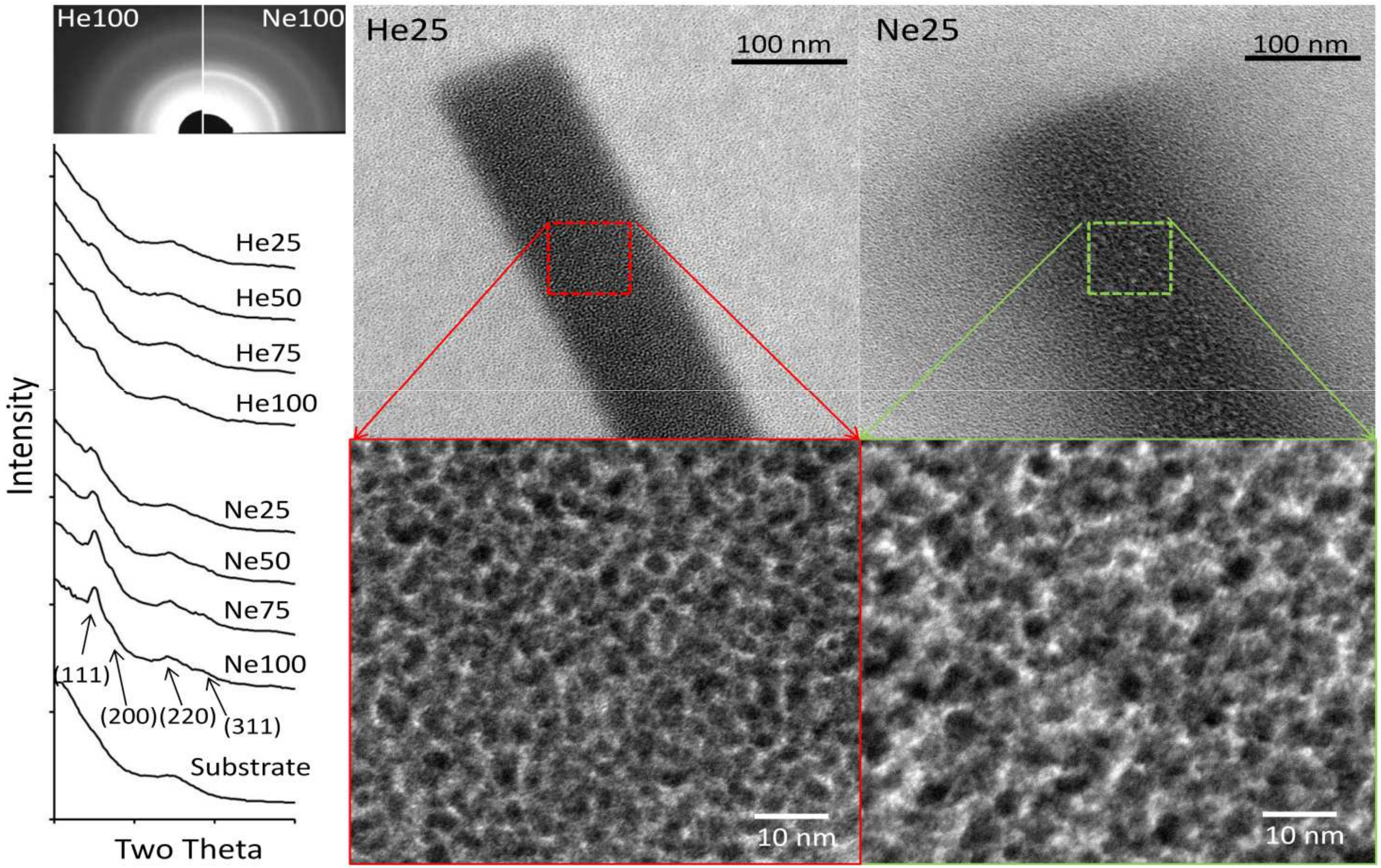






- **NeBID → Lower resistivity**
- **NeBID → Strong tunnel coupling granular metal**
- **HeBID → Weak tunnel coupling granular metal**

TEM Analysis of HeBID and NeBID samples



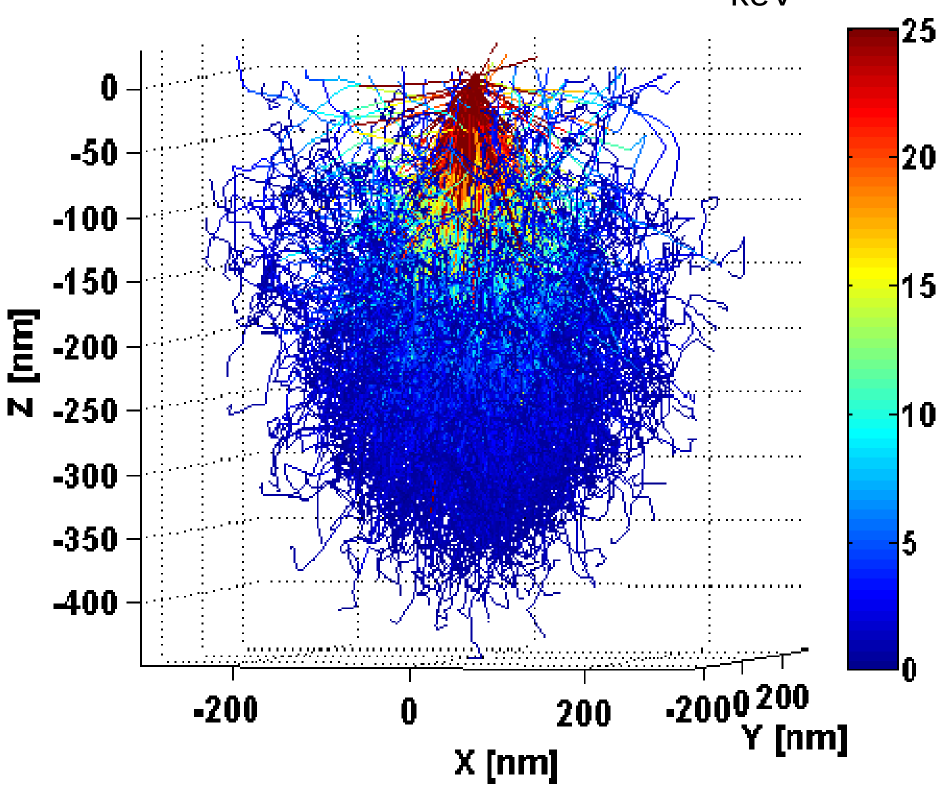
- Slightly larger Platinum grain sizes with more coalescence in NeBID than HeBID
- Diffraction peaks increased with increasing dose in both HeBID and NeBID
- NeBID shows higher diffraction peaks than HeBID

Helium vs Neon ions simulations

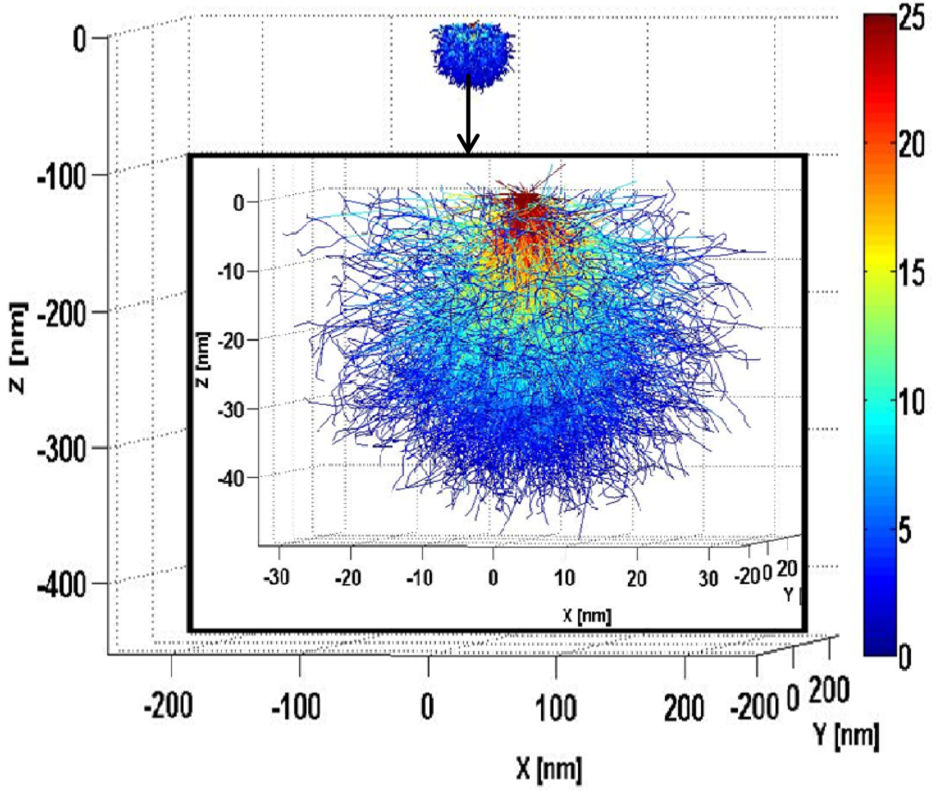
To understand the observed microstructure and resultant electrical properties, we simulate the ion solid interactions

<u>Flat PtC_5 target</u>

<u>Helium at 25 keV</u>

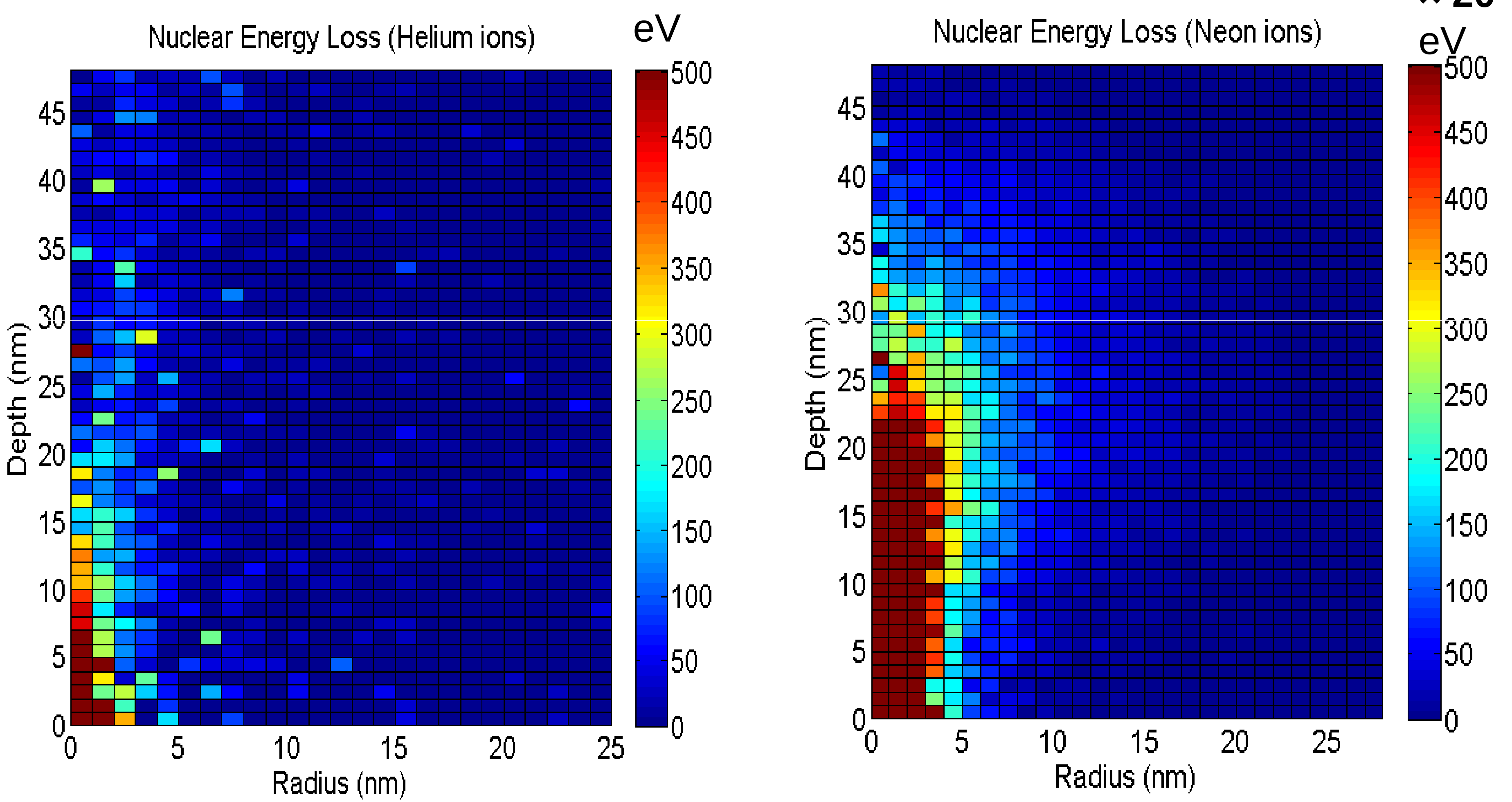


<u>Neon at 25 keV</u>



Nuclear Energy loss per volume (25keV, 100k ions)

*Note different scale



Higher nuclear energy loss for Neon -> the observed coarsening and coalescence and the significantly enhanced electrical conduction

Summary of He vs. Ne IBID

Dubner et al

- Ion beam induced growth rate of dimethyl gold hexafluoroacetylacetonate with various inert ions
- Enhanced growth rates with heavier inert ions and lower energy
- Contribution of both binary collisions and thermal spikes models

Dubner et al, *J. Appl. Phys.* **70** 665 (1991)

Present Work

- Facilitates the enhanced platinum clustering
- Pt mobility coarsens (and coalesces) the Pt grain size
- Dramatically affects the granular metal tunnel coupling and enhances the electrical conduction through the material.

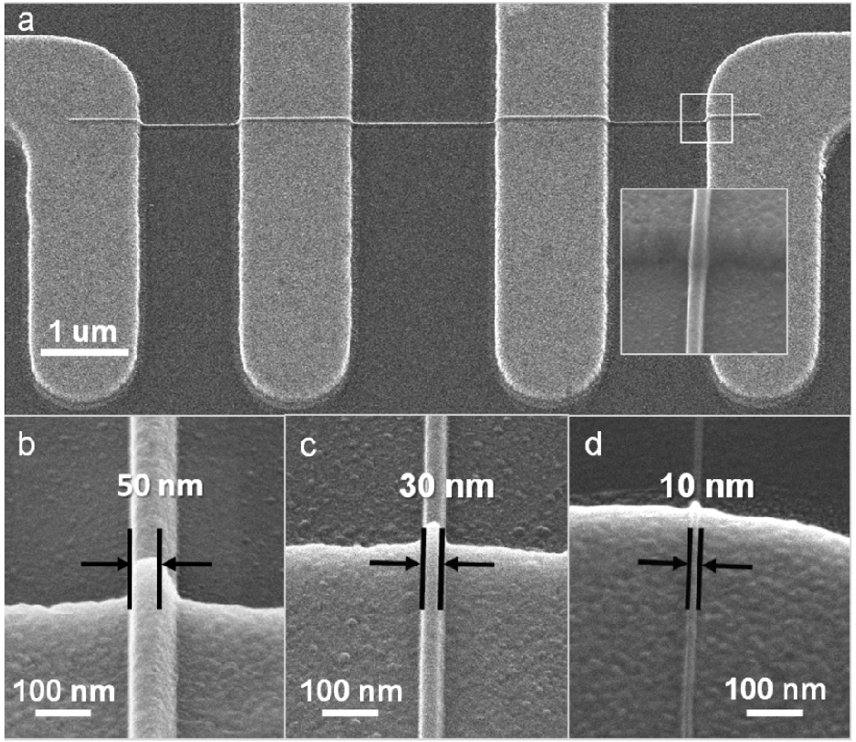
Estimated Temperature rise via thermal spike model

HeBID		NeBID	
1 ps	5 ps	1 ps	5 ps
1450 K	130 K	3860 K	350 K

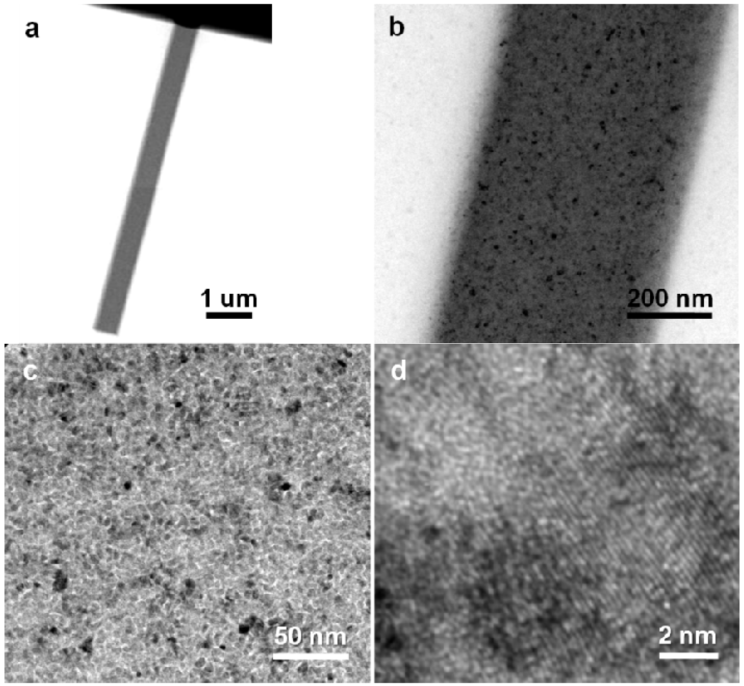
$$\Delta T = \frac{E}{8(\pi\alpha t)^{3/2}\rho C_p}$$

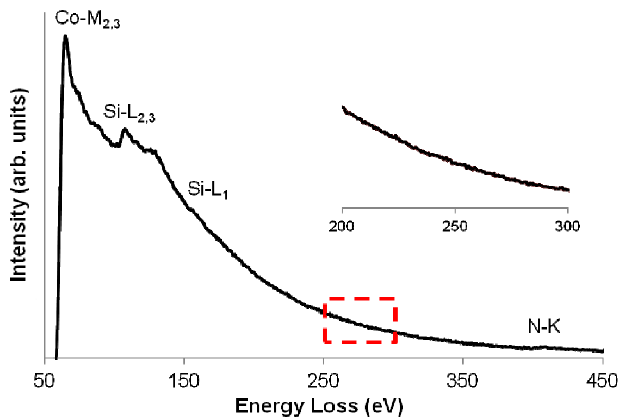
Low Resistivity Cobalt HeBID

Wu et al, Journal of Materials Science: Electronic Materials (submitted)



TEM/EELS





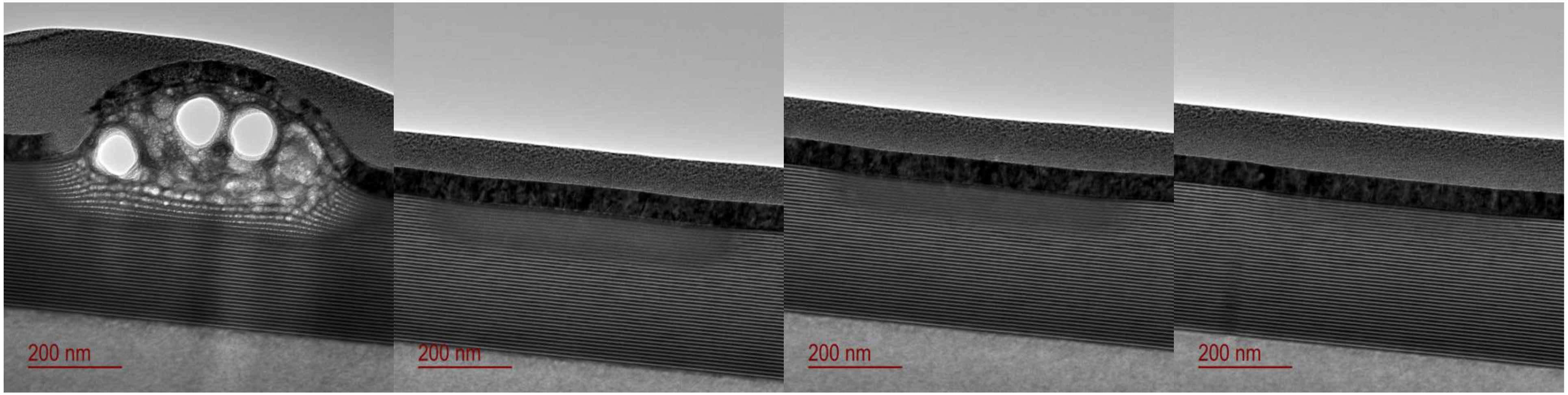
Summary
*Pure hcp cobalt (no detectable Carbon!
*10nm lateral resolution
*good step coverage
*Grain size ~ 6 (±2) nm
*64 μΩ-cm resistivity
*specific contact resistivity of 0.03 μΩ-cm^2

EUV Mask Repair

- Nickel being explored as EUVabsorber material
  - Difficult to etch due to limited volatility of etch products
  - Electron beam induced etching not successful so far
  - Explore focused He and Ne beam induced etching

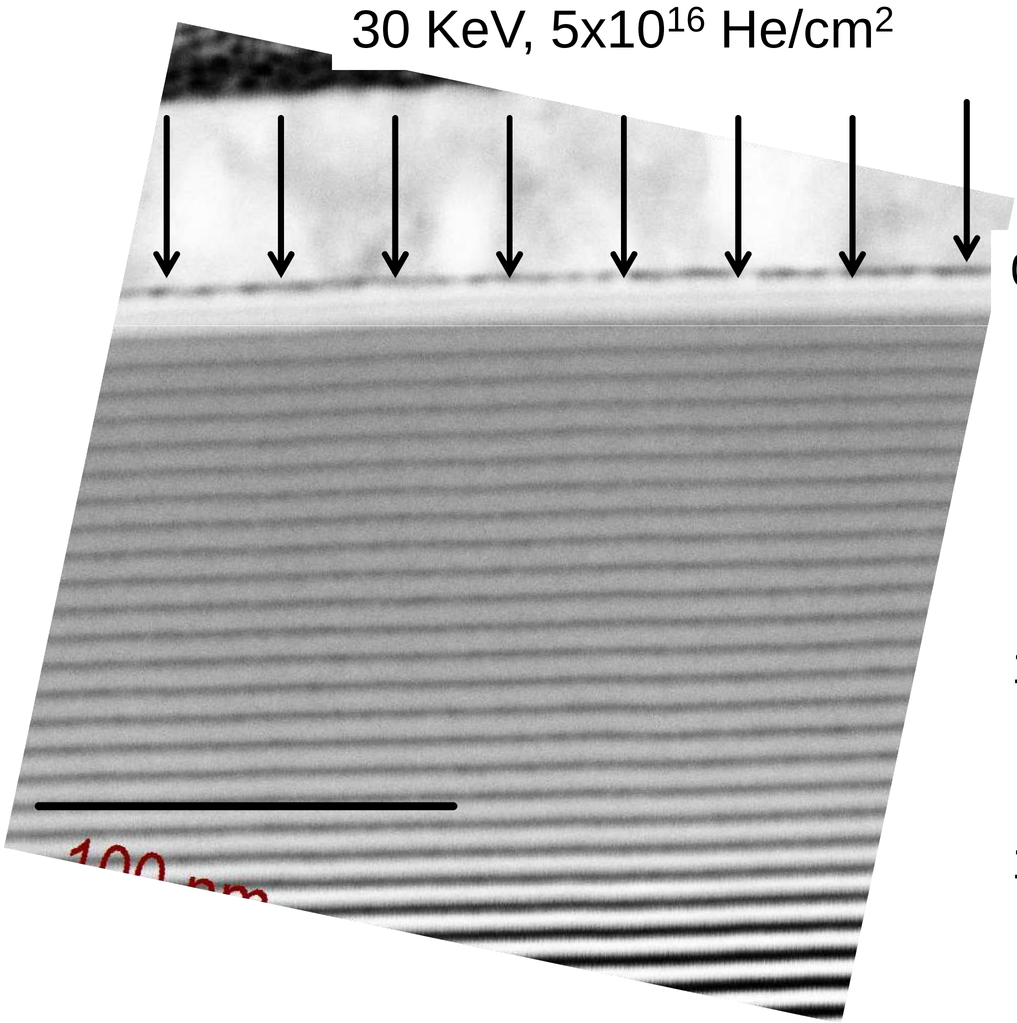
16keV

$1x10^{18}$ He/cm^2 **$1x10^{17}$ He/cm^2** **$5x10^{16}$ He/cm^2** **$1x10^{16}$ He/cm^2**

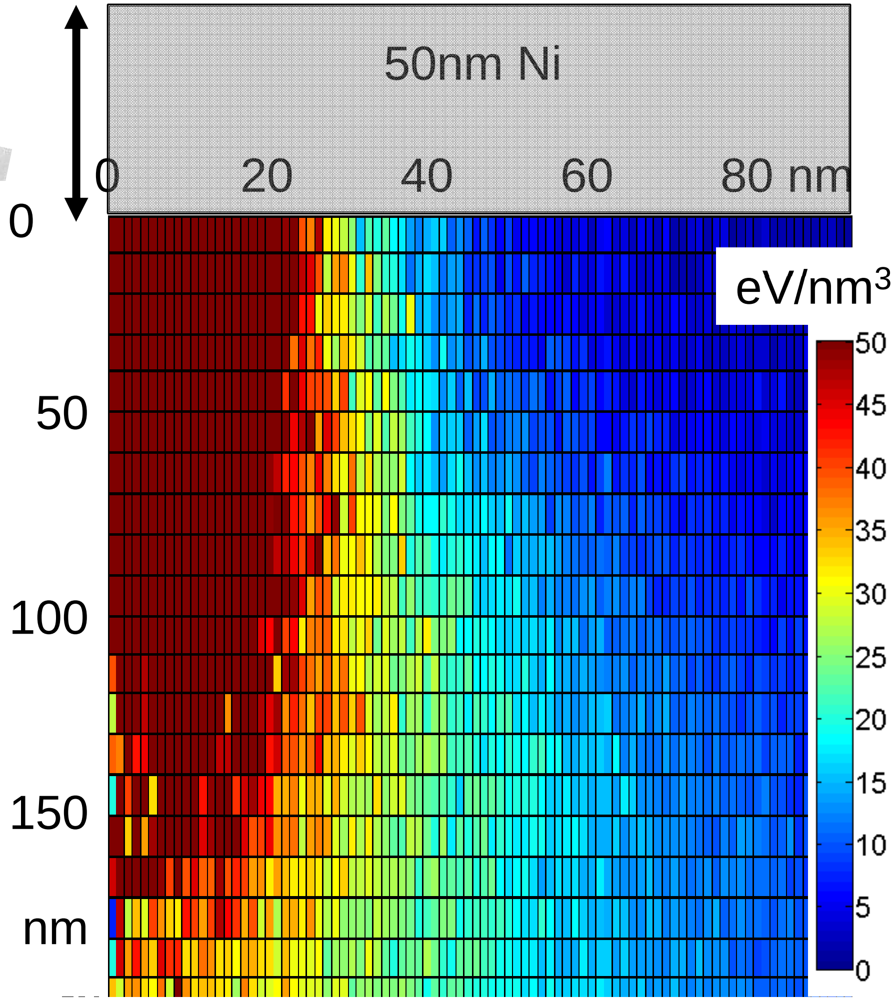


No observable He sputtering (16keV), but significant damage to Mo/Si reflector stack

TEM Analysis vs. Nuclear Energy Loss (30keV)

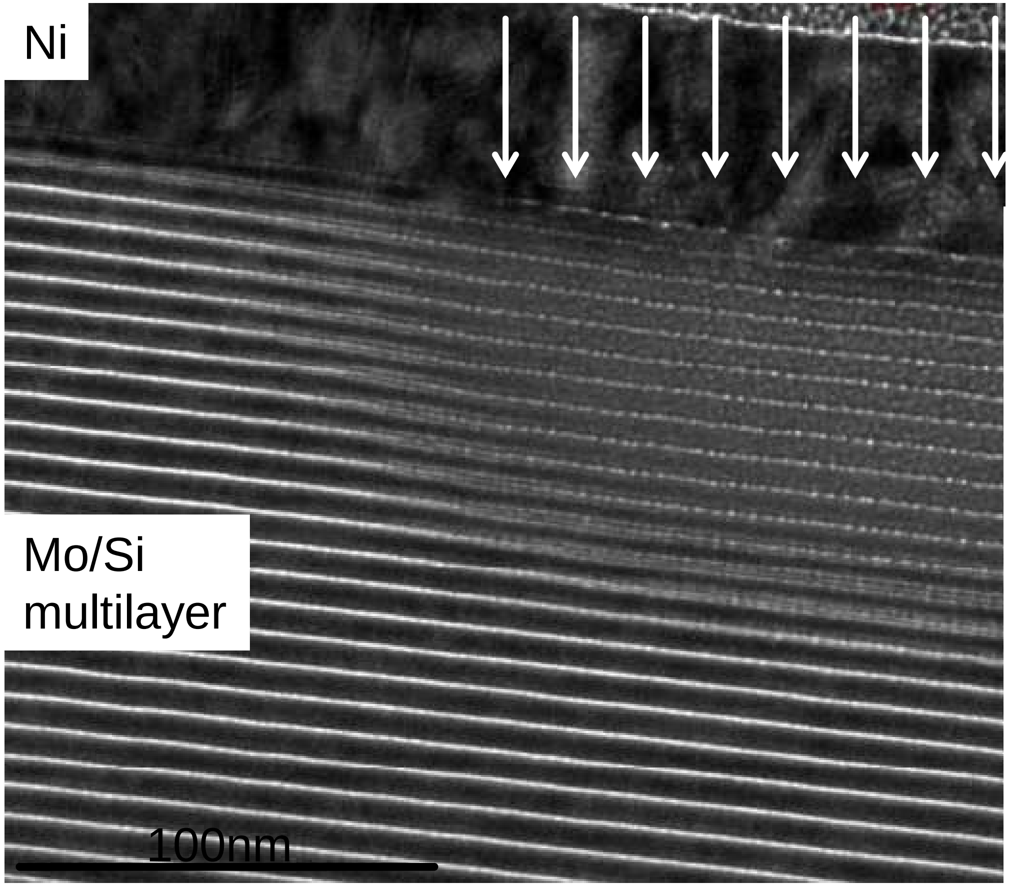


Simulated Nuclear Energy Loss (30keV)

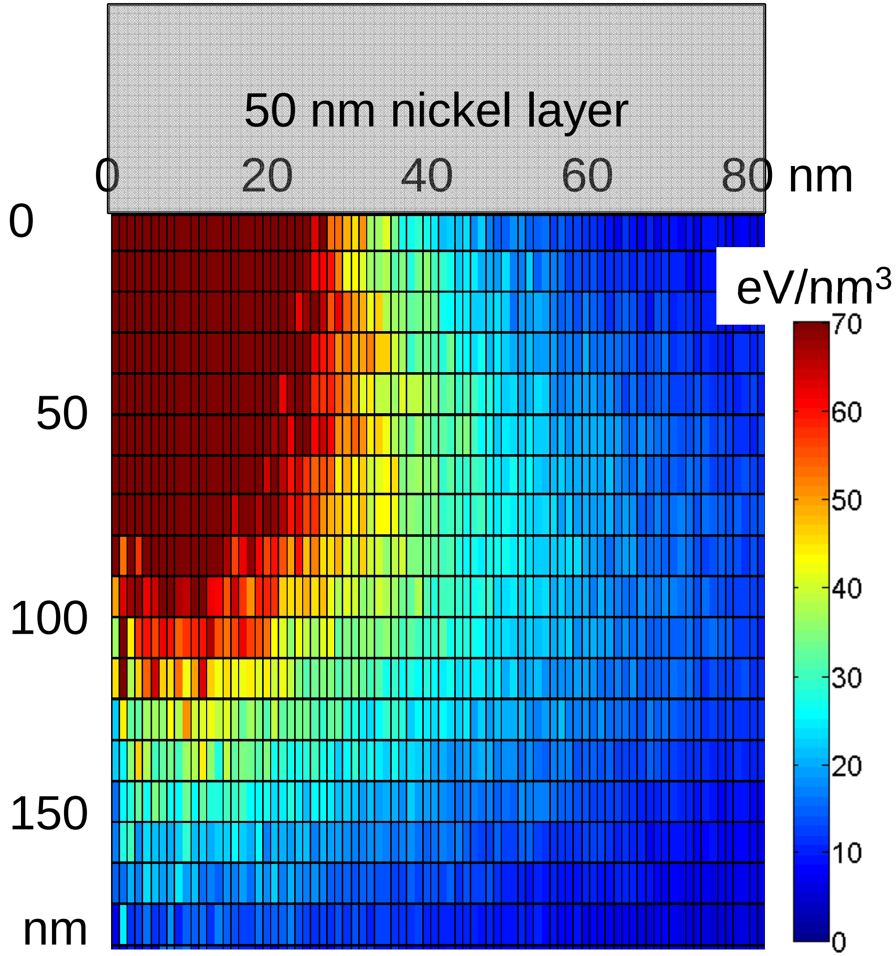


TEM Analysis vs. Nuclear Energy Loss (16keV)

16 KeV, $1x10^{17}$ He/cm^2

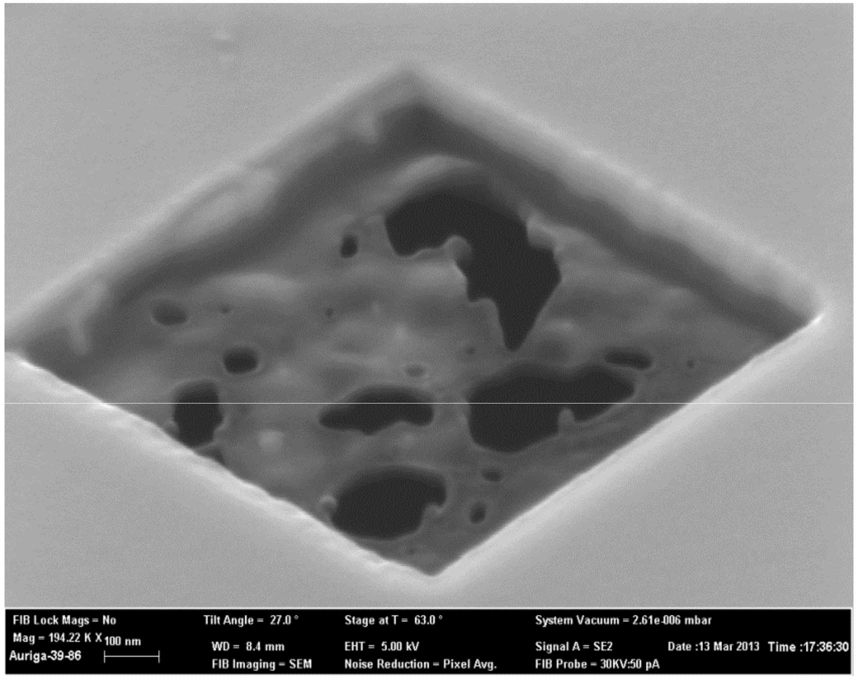


Simulated Nuclear Energy Loss (30keV)



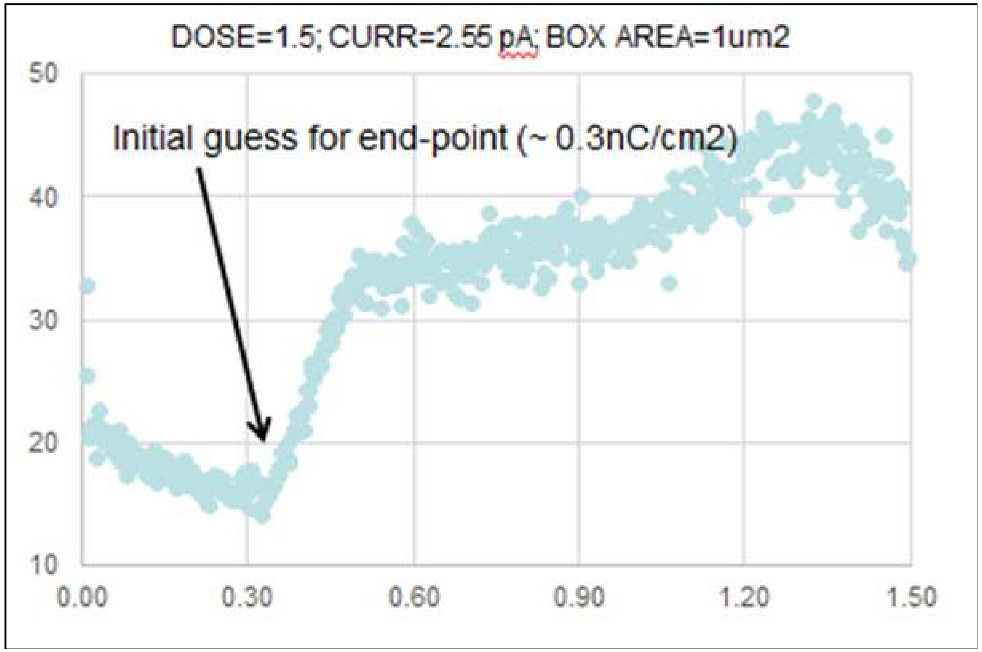
Very Good Agreement between Energy Dependent Damage Depth Threshold

Neon Etch of Nickel Absorber Layer in EUV Masks

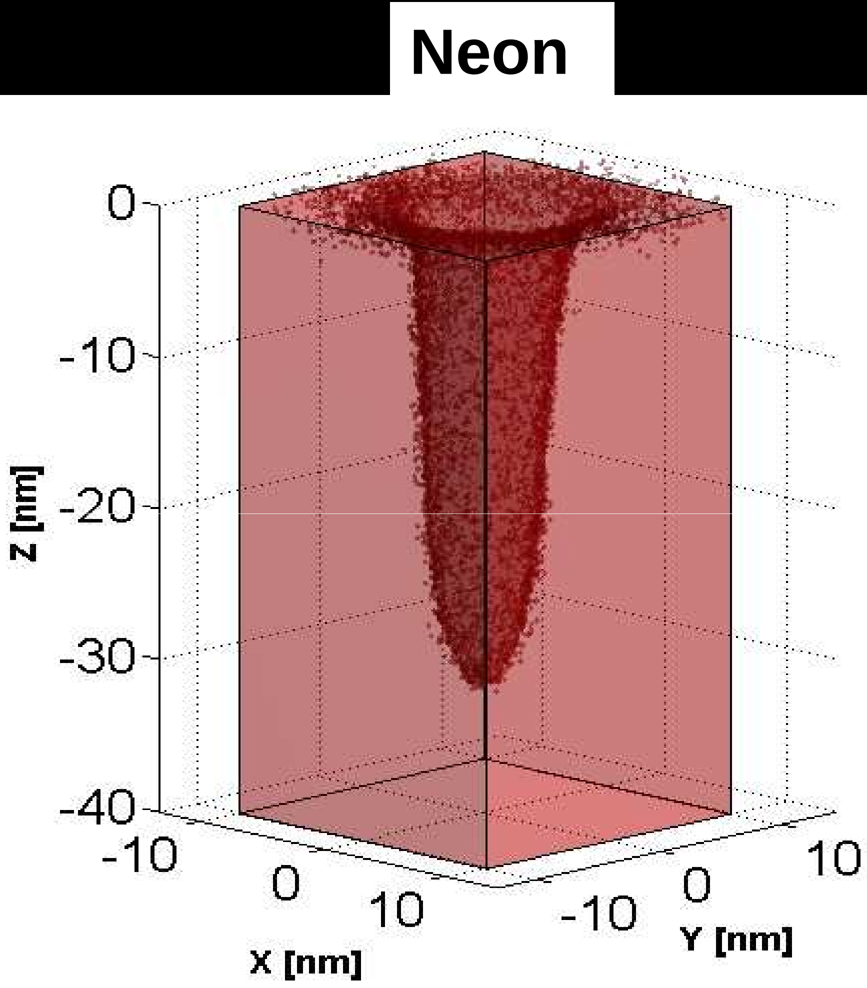


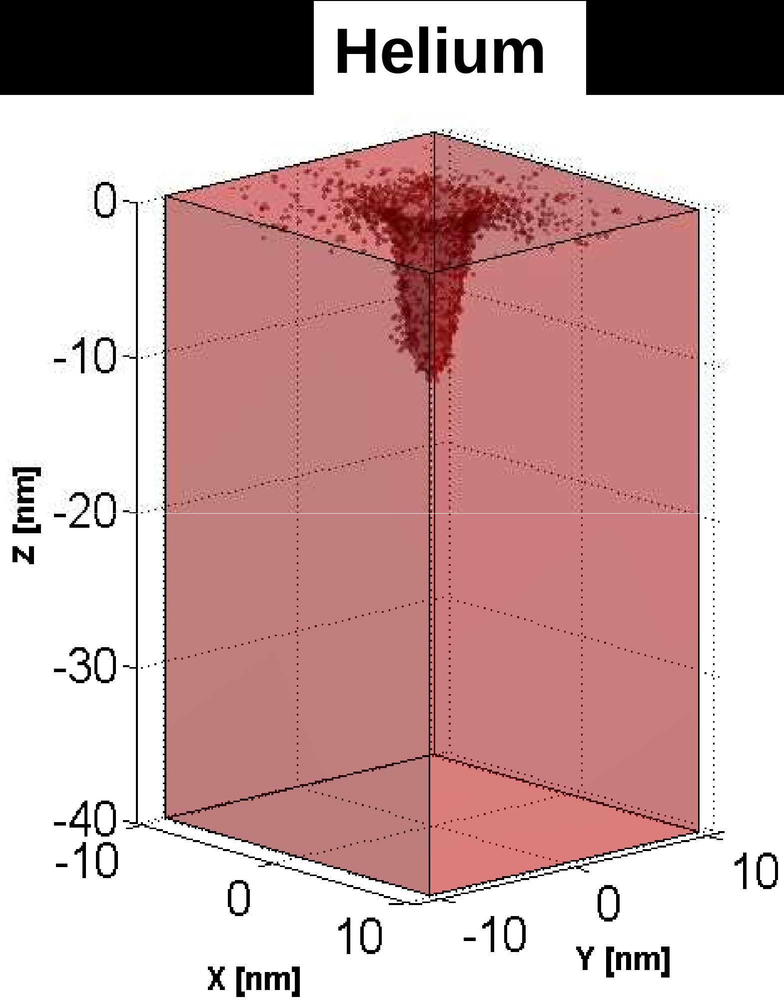
SEM Image of Etching

- 50 nm Nickel
- On 100nm SiO_2
- Substrate = Si
- Dose = 1.5 nC/μm^2
- Beam Current = 2.5 pA
- Size = 1 µm × 1 µm



Monte Carlo Simulation of Nickel Sputtering
Ne versus He

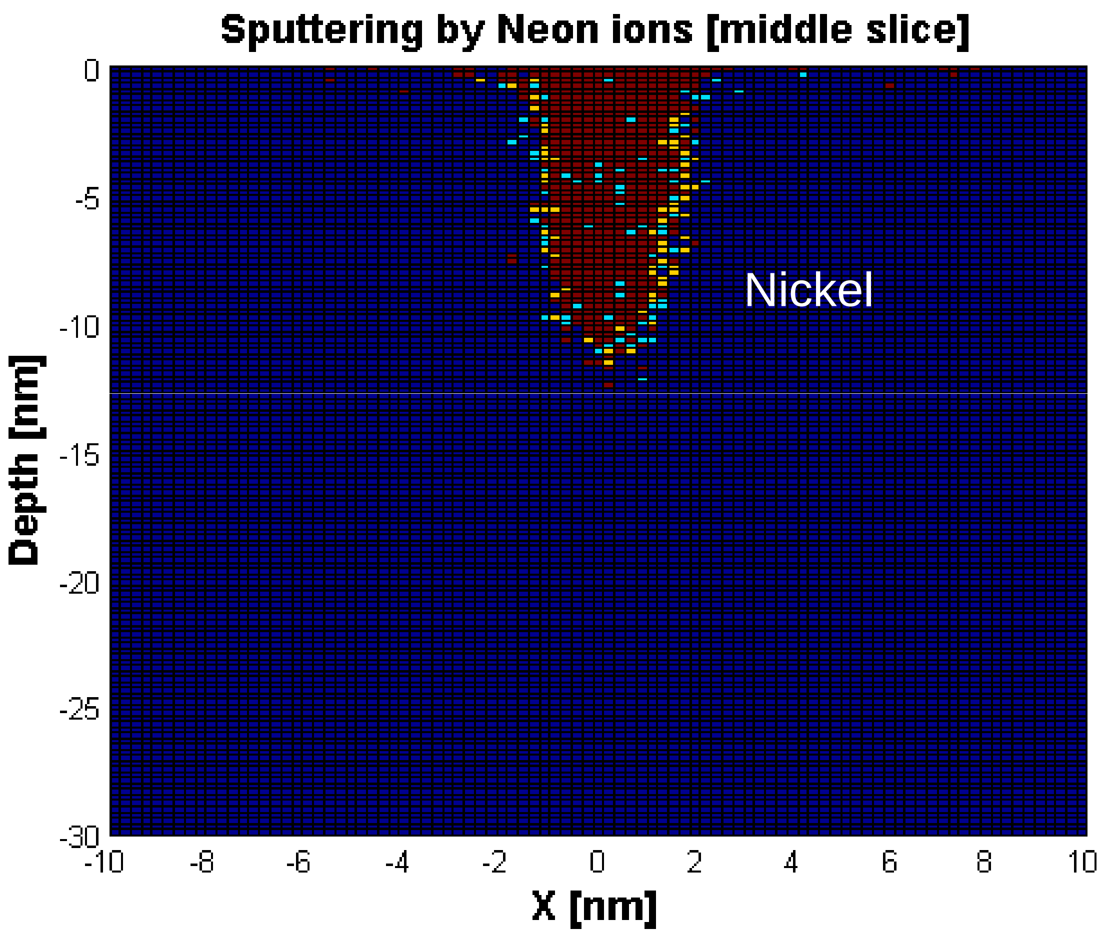




- Surface Binding Energy = 4.4 eV
- Beam Energy = 10 keV

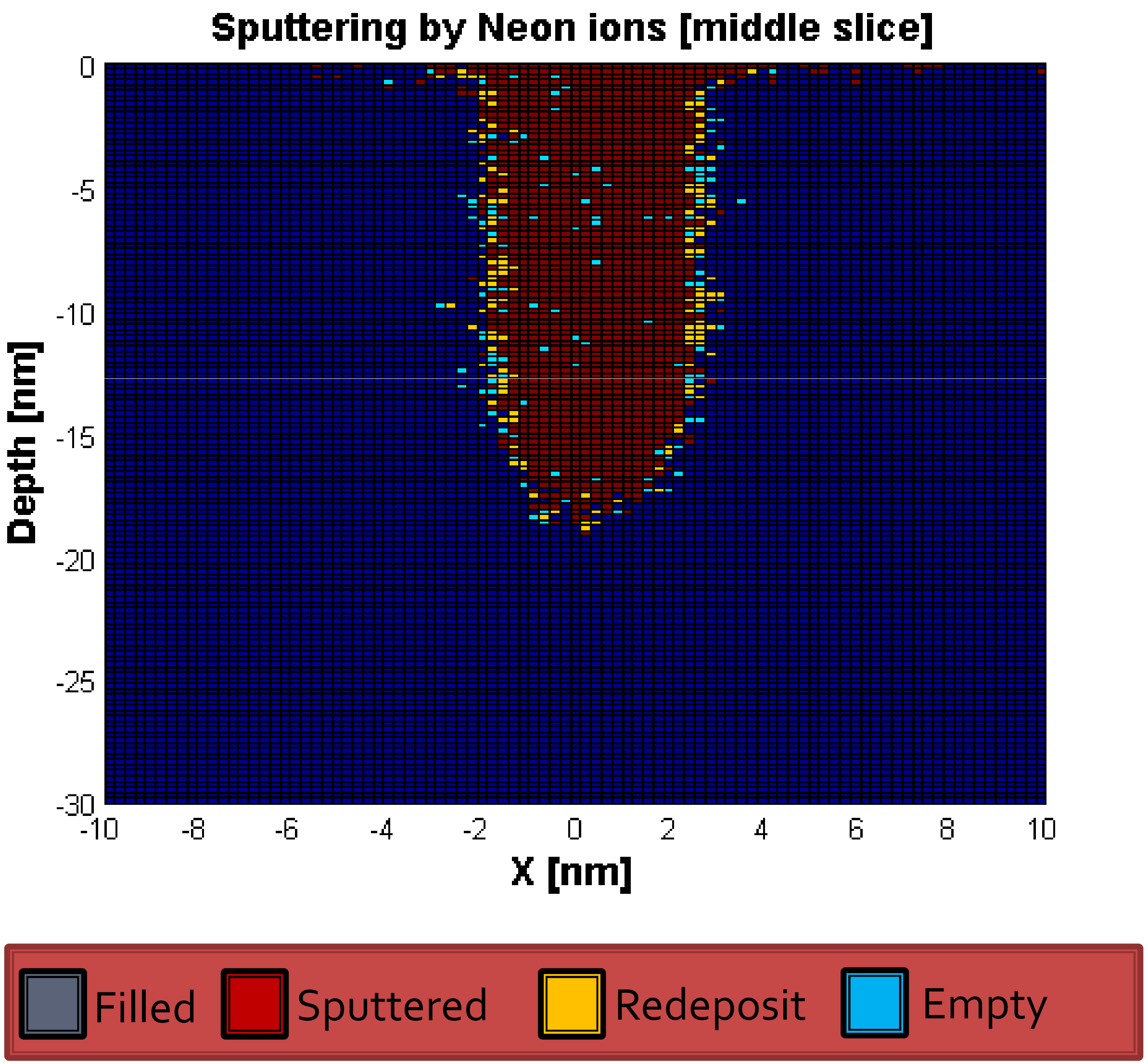
Beam Radius = 0.5 nm
100k ions

Evolution of via etching (10 keV Ne) 10k ions, Beam Radius = 0.5 nm

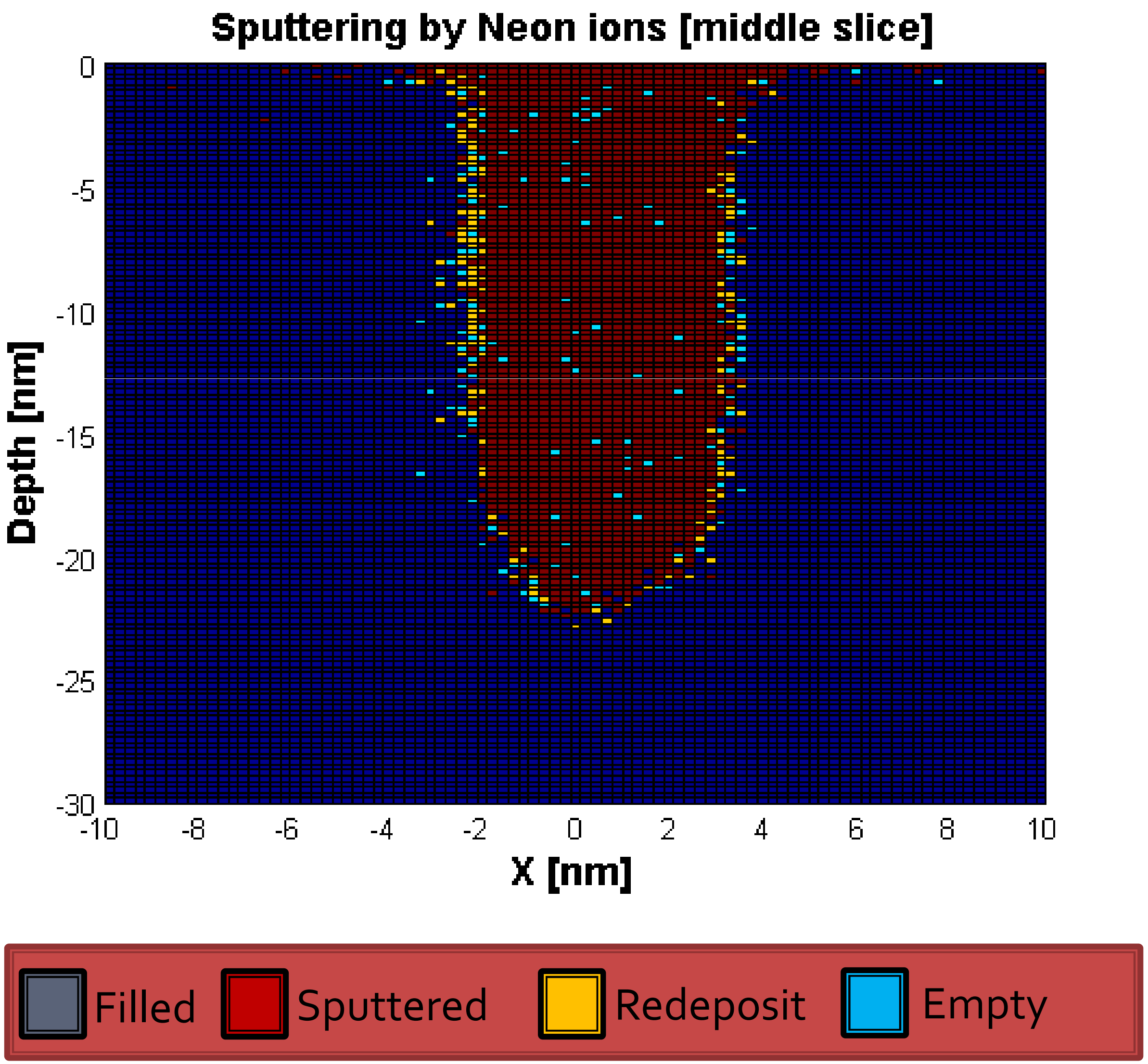


Filled | Sputtered | Redeposit | Empty

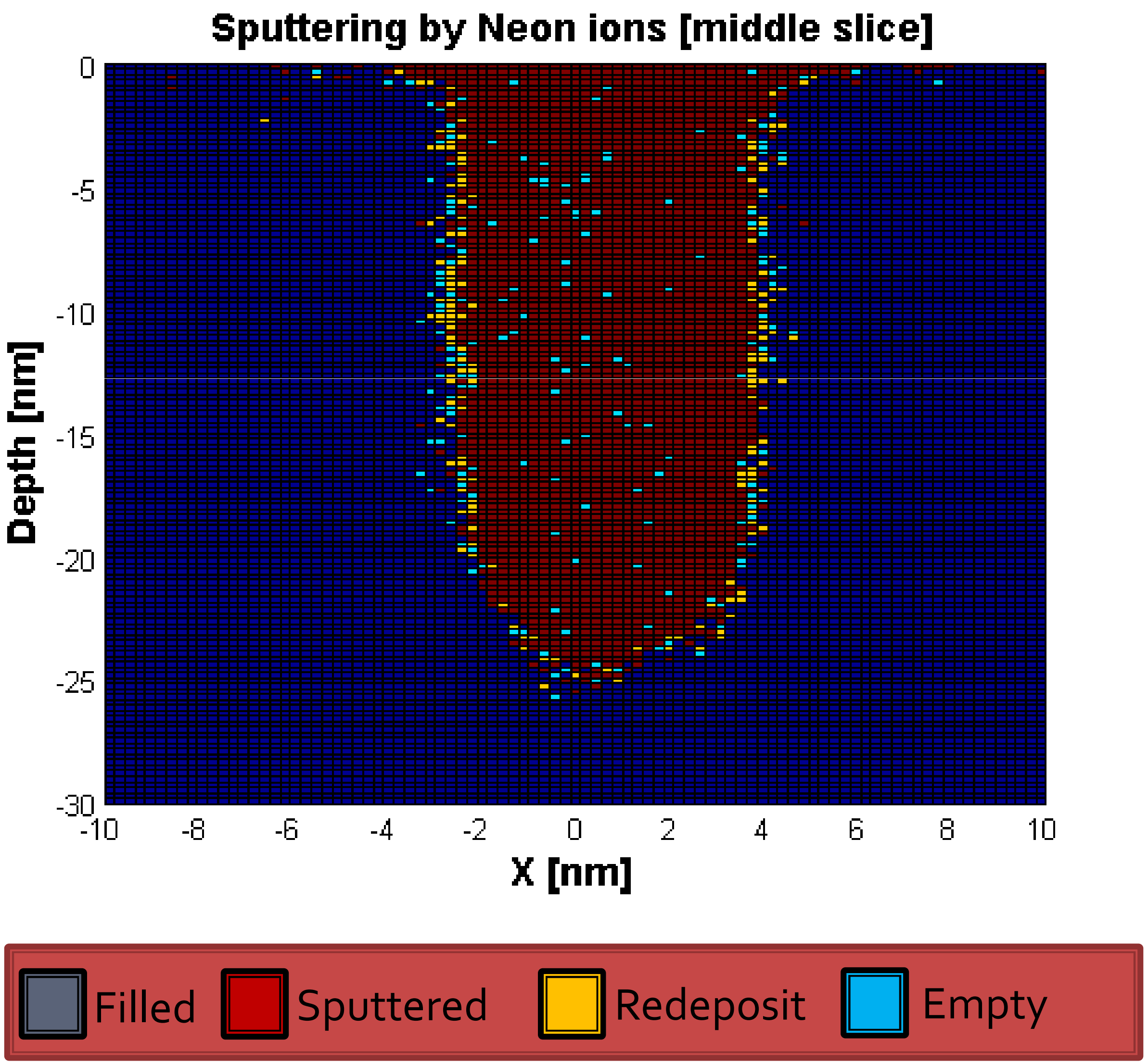
30k ions, Beam Radius = 0.5 nm



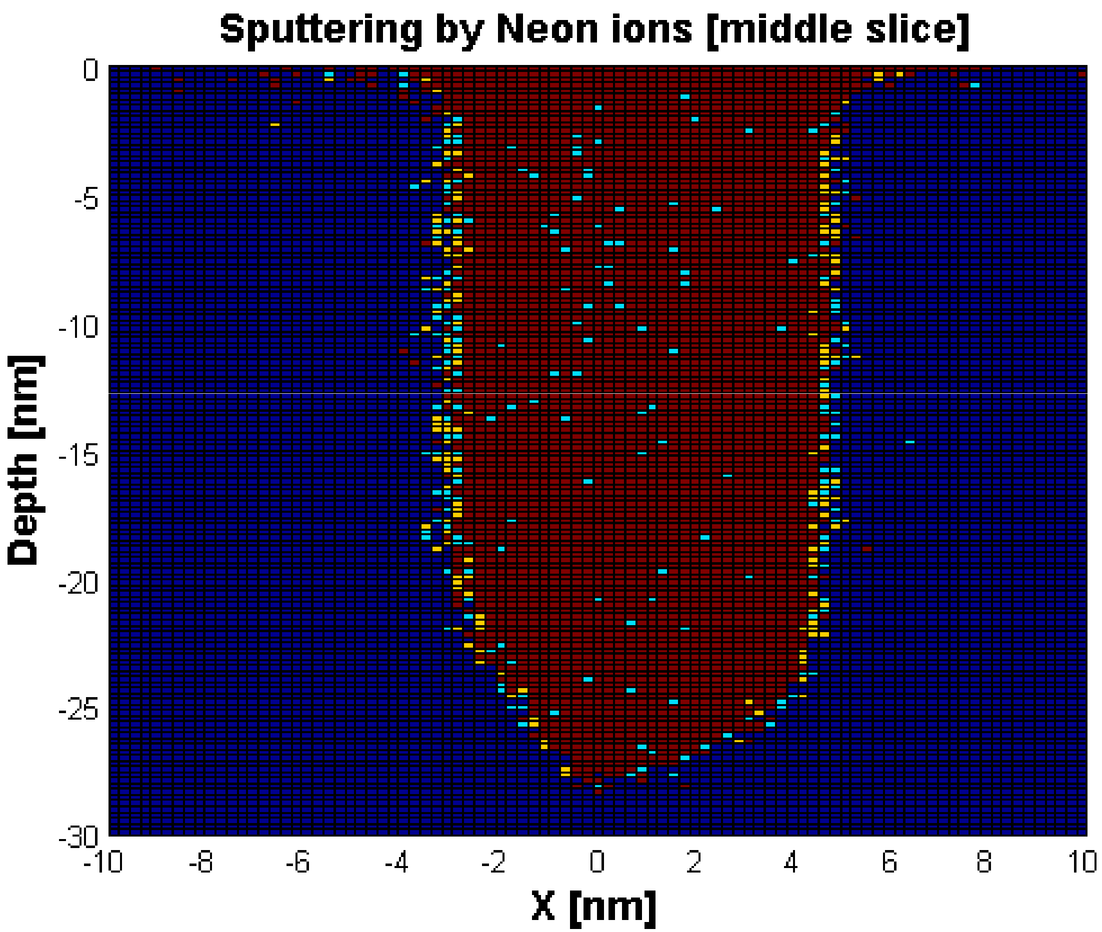
50k ions, Beam Radius = 0.5 nm



70k ions, Beam Radius = 0.5 nm



100k ions, Beam Radius = 0.5 nm



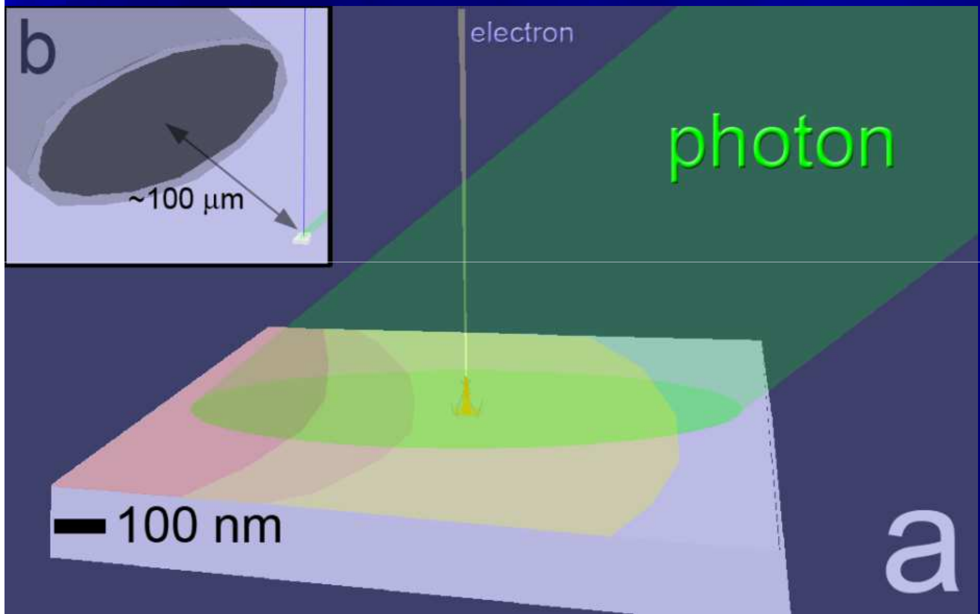
Filled Sputtered Redeposit Empty

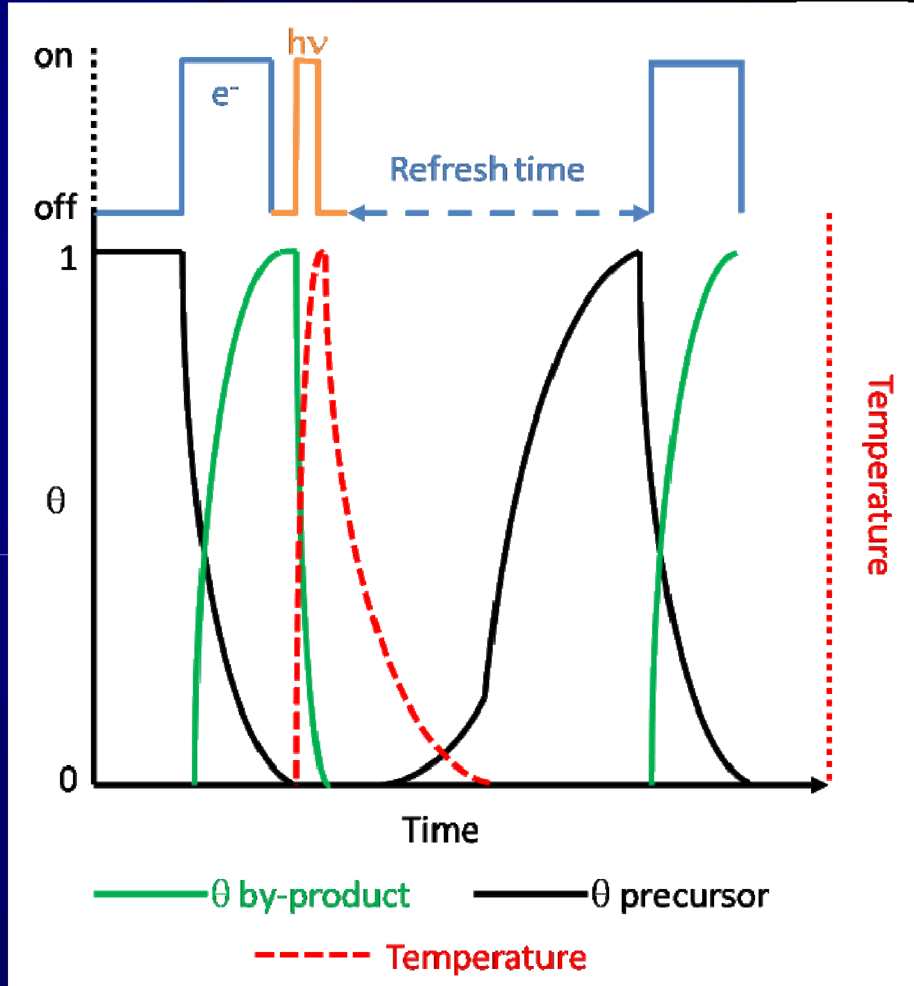
A Peek into the Future

The Three Beam – Electron-Ion-Photon Beam System

Synchronized Laser Assisted EBID/IBID

microscale gas delivery, microscale photon delivery and nanoscale electron delivery



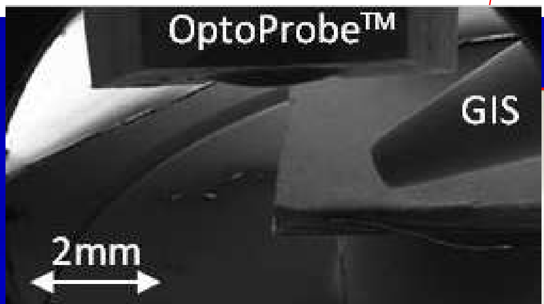


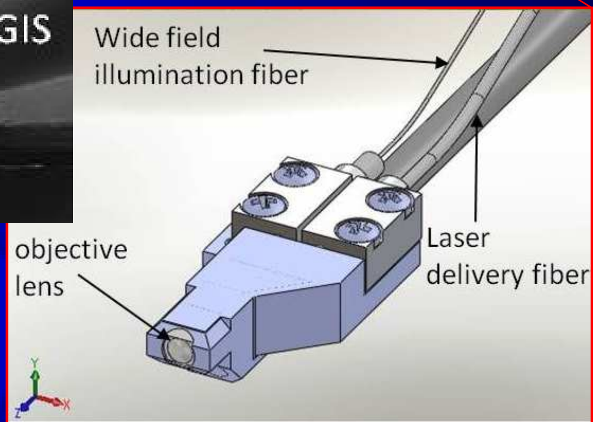
- ns to ms photon pulsing makes it possible to reach a high surface temperature locally with sufficient time for refresh (tens to 100ms)
- Up to ~ 200 kW/cm^2 irradiance

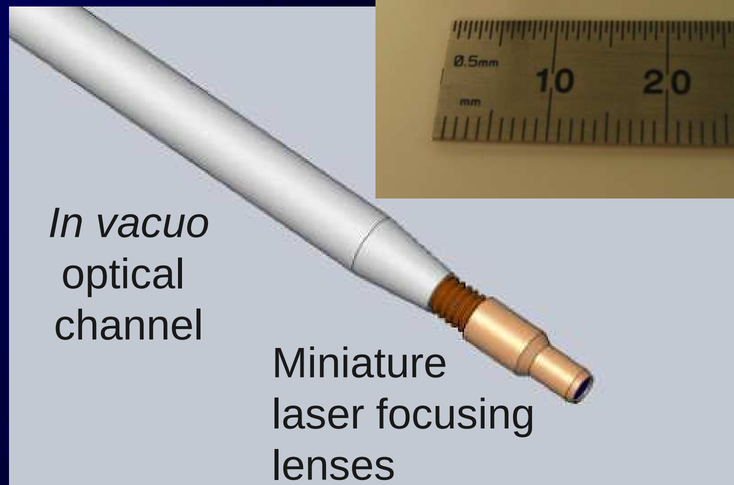
- desorption is stimulated below the thermal decomposition temperature (avoid microscale chemical vapor deposition)

Laser Delivery System (built by Omniprobe®): Laser Assisted EBID

- *In situ* laser processing and optical imaging
- ~50–100 μm minimum laser spot radius using multimode optical fiber and choice of lenses (smaller spots possible using single-mode optics)
- Leverages Omniprobe's nanomanipulator technology (x-y-z manipulation)
- Most LAEBID experiments reported here used laser delivery probes without imaging
- Uses an Oclaro 25W 915nm laser diode coupled to 100μm fiber



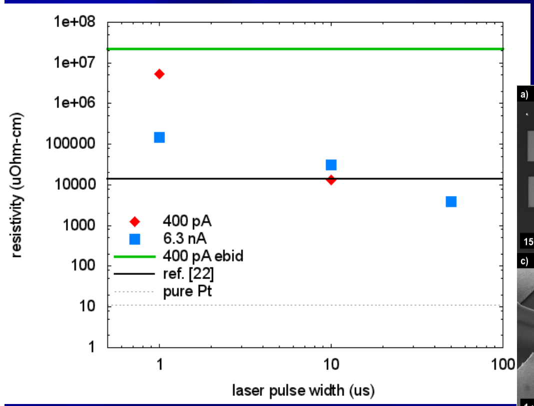


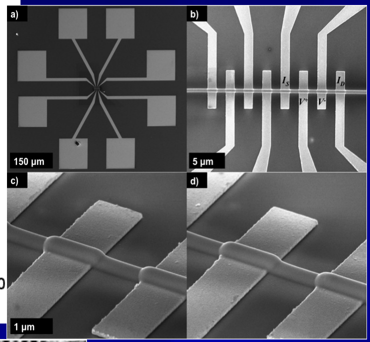


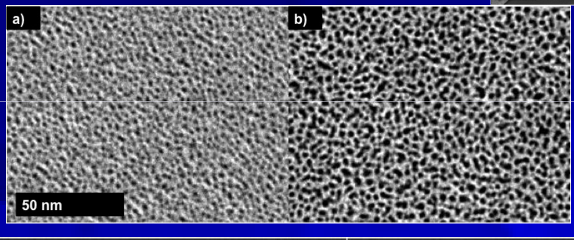
N. A. Roberts et al. J. Vac. Sci. Tech. (2012) 6 041404(1-6)

Recent Results

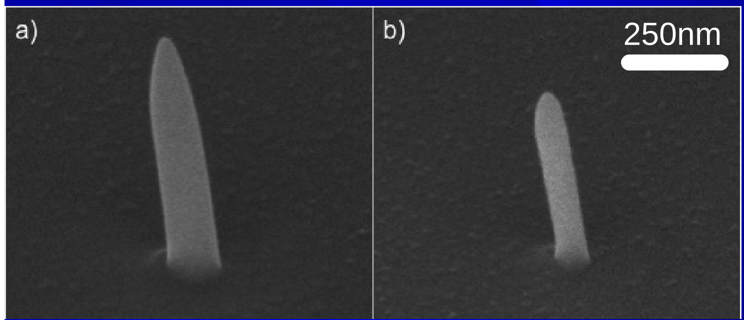
Pt LAEBID from *$(CH_3)_3Pt(CpCH_3)$*





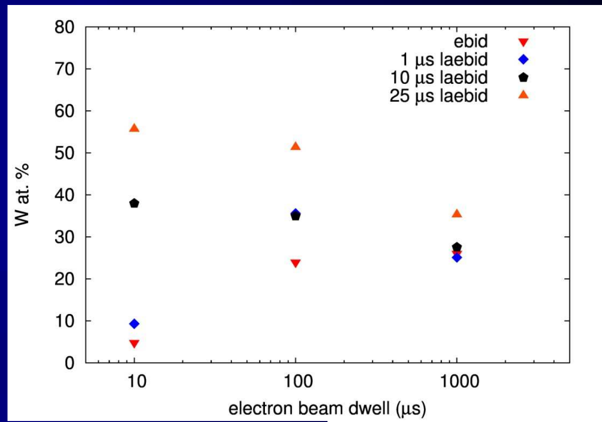


N.A. Roberts et al., Nanoscale, (2013) 5 408-415

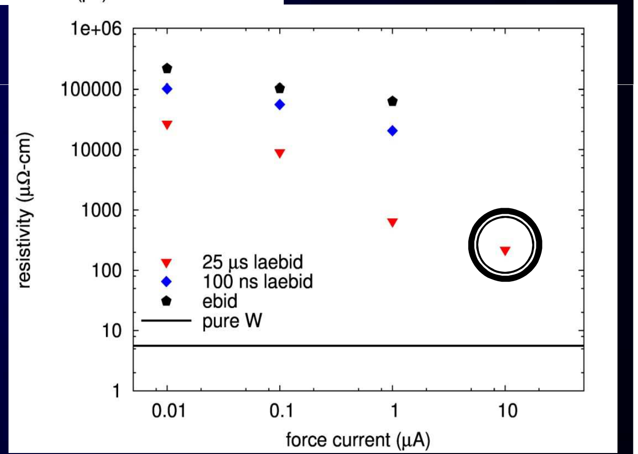


*Enhanced purity (PtC_8 → PtC_2)
*Higher resolution (~ 25 %)
*4 orders of magnitude lower resistivity
*Optimized growth at monolayer synchron.

W LAEBID from *$W(CO)_6$*



N.A. Roberts et al., Angewandte Chemie, To be submitted



*Enhanced purity (10 at% W → 55% W)
*Higher resolution (~ 30%)
*~3 orders of magnitude lower resistivity
*Optimized growth at monolayer synchron.

Summary and Future

- Focused Helium and Neon Beam Induced Processing Promises to Facilitate Advanced Circuit and Mask Repair
- Understanding Fundamental Ion-Precursor-Solid Interactions is Critical for Advanced Nanoscale Fabrication
- We Employ a Combined Experimental and Simulation Approach to Advance the State of the Art Beam Induced Processing
- Laser Assisted Beam Induced Processing Has Promise (couple to He and Ne soon!)
- The Future is Bright!