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Localization of Conductive Filaments in TaOx Memristor using Focused Ion Beam Irradiation

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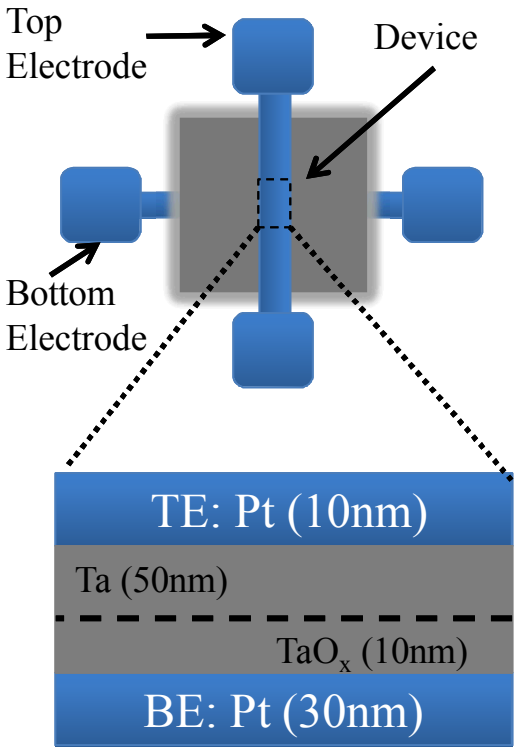
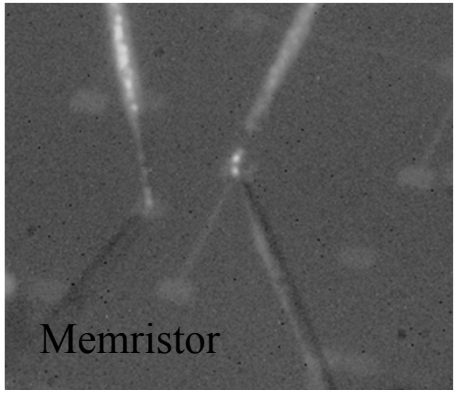
- Introduction to memristors
- Previous characterization results
  - Rad-hard to high levels of displacement damage
- Localization of conductive filaments
  - Tandem accelerator u-beam results
  - Nano-Implanter results
- Future experiments

Memristor Characteristics.

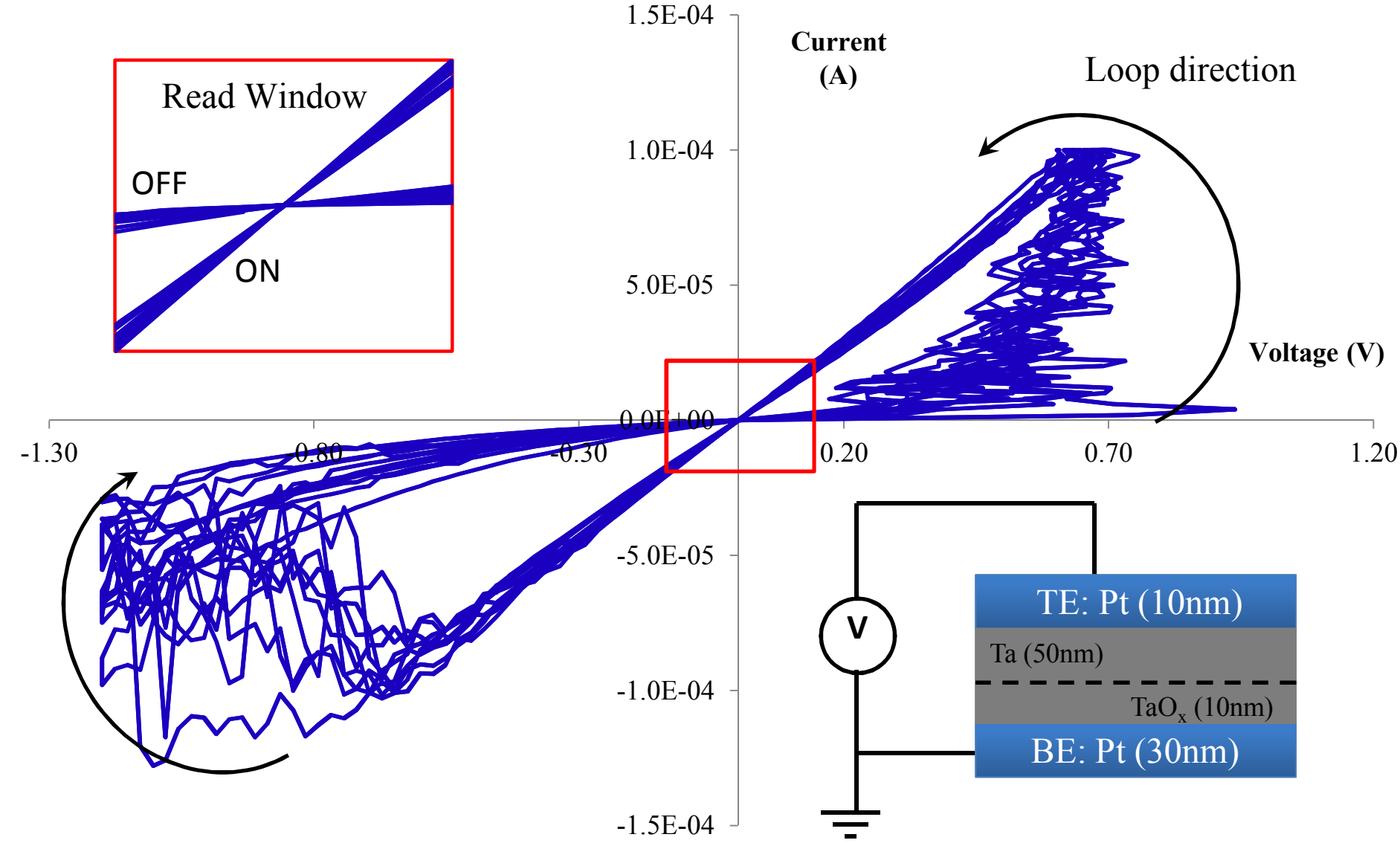
- Memristors arise naturally in nano-scale devices
- A promising candidate to replace flash memory (ITRS)
- Characteristics:
  - High speed, Low voltage, High Density
- Radiation –hard devices
- Electro-Forming and Switching
- Mechanisms dependent on oxygen vacancy motion and concentration
    - Thermal fields
    - Electric fields
- Forming and switching mechanisms not fully understood

Dog-Bone Construction





Memristor Hysteretic IV Curve



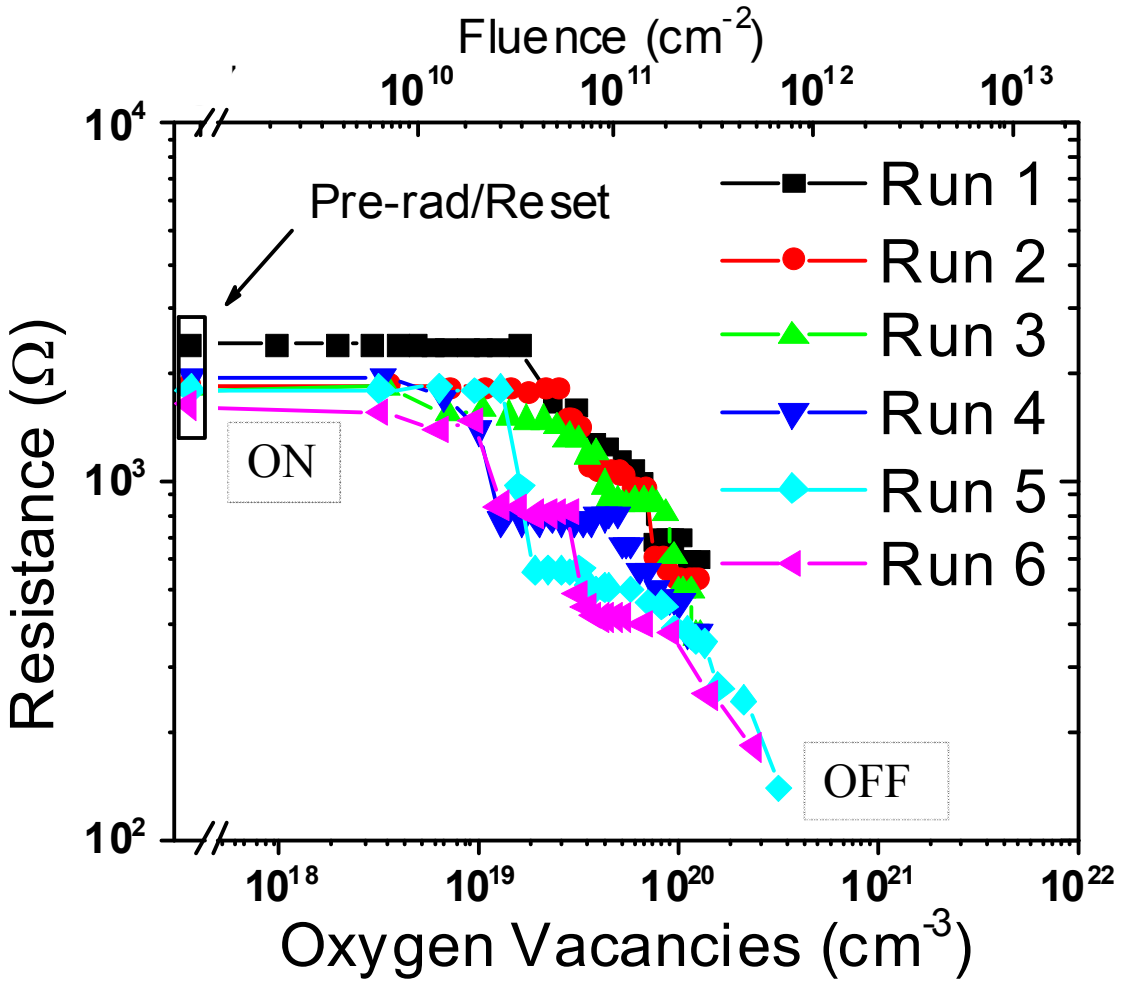
ON-to-OFF State Switching due to Irradiation

- Irradiation with 800 keV Ta @ SNL Tandem μ-One beam line
- Ion fluence indicative of a rad-hard device.
- Stack *insensitive* to ionization
  - 10's to 100's of MeV protons, no remarkable effect
- Stack affected by displacement damage
  - 800keV Si → 5E12
  - 800keV Ta →
- Displacement damage driven ΔR
- Resistance ↓ as ion fluence ↑

Hypothesis:

Oxygen vacancy concentration ↑
device resistivity ↓

Ta_2O_{5-x} : x=0 vs x=3



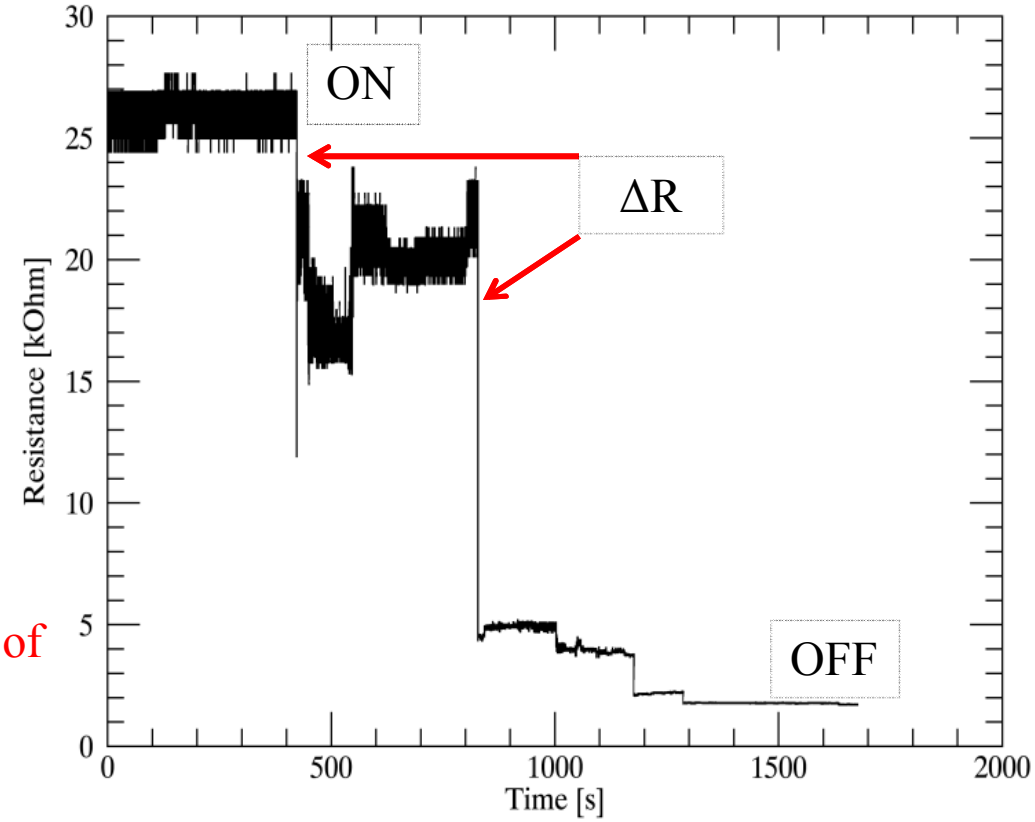
Set → Irradiation → Reset…

Sensitive Area Irradiation: μ-beam raster scan

- 800keV Si irradiation
- Repeated X-Y Scans
- Device dimensions: 10μm X 10μm
- Beam spot size: 0.9 μm
  - ~1 ion per spot
- On-to-Off switching due to a low number of ions

- Effect of total ion fluence vs. effect of targeting sensitive volumes

- Rad-Hard device?
  - High overall fluence → small change
  - Targeted/directed exposure → drastic change

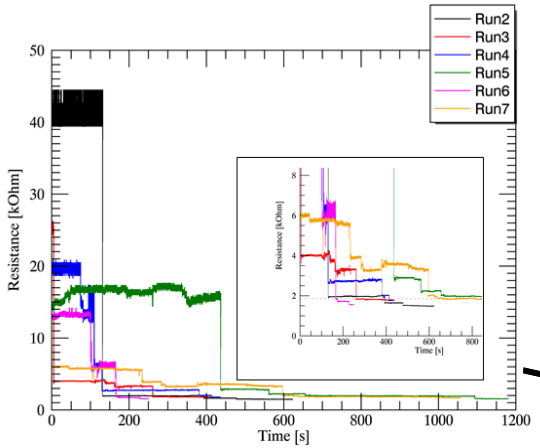


Probability driven exposure of:

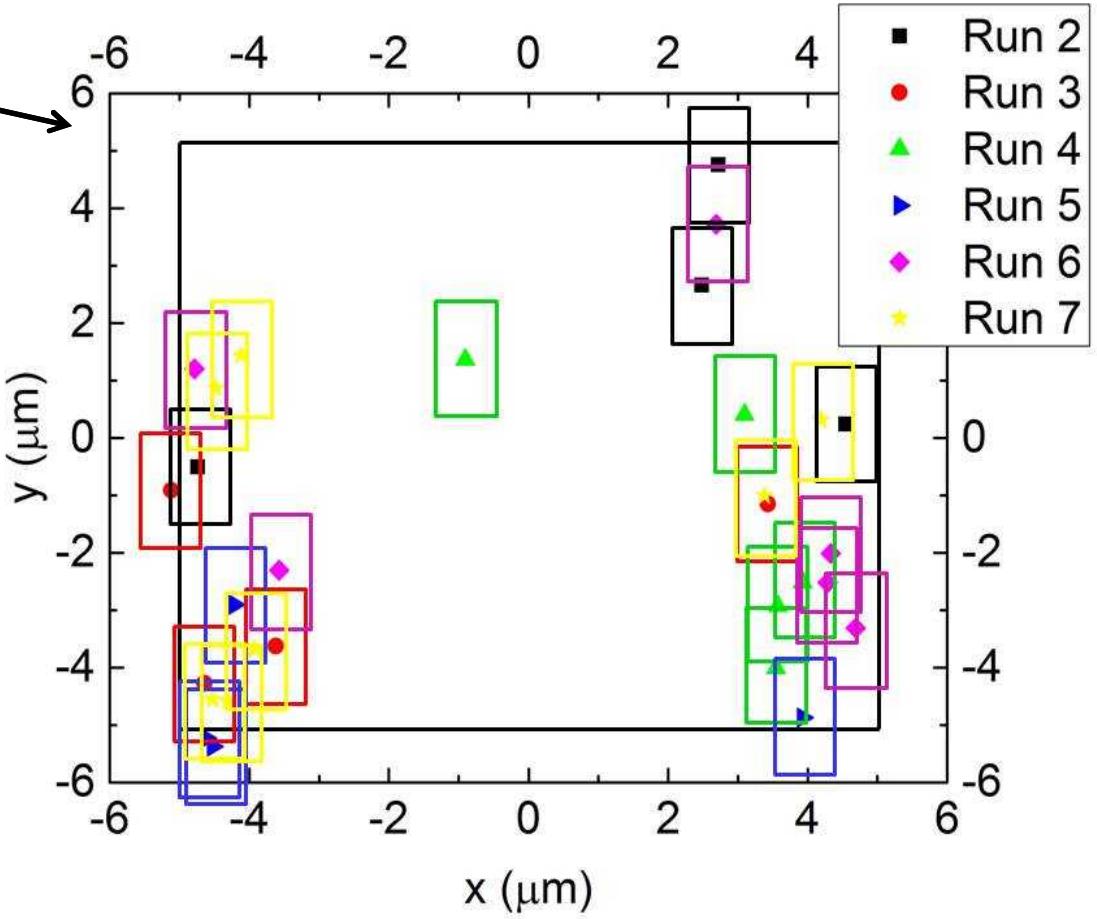
Nano-scale device

Disp. damage sensitive

ΔR Mapping: Conductive Filament Localization



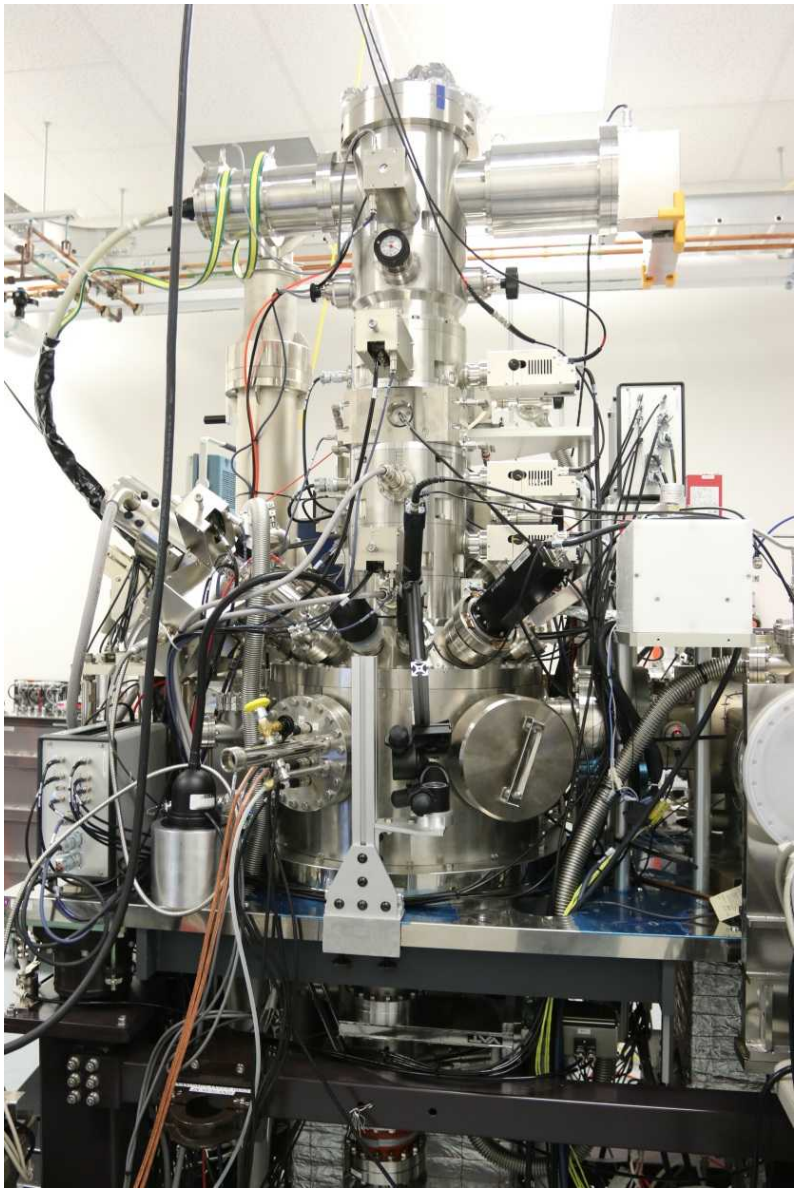
- X-Y scans with 800keV Si Beam
- ΔR → XY map
- ΔR on perimeter of device



- If switching due to conductive filaments…
- Conductive filaments predominately at edges of device
- Elucidating electroforming mechanism
- Limited by spatial resolution of SNL u-One beam line

Nano-scale Ion Implantation

- SNL NanoImplanter (nI)
  - Variable Accelerating Potential: 10-100 kV
  - Fast Blanking and Chopping
    - Down to ~ 1 ion/pulse
  - Liquid Metal Ion Source
    - Ga LMIS
  - Mass-Velocity Filter
  - Liquid Metal Alloy Ion Source
    - AuSiSb
    - and many more…
  - Beam Spot size on target
    - ~10 nm, 100 keV Ga^{+}
    - ~24 nm, 200 keV Si^{++}

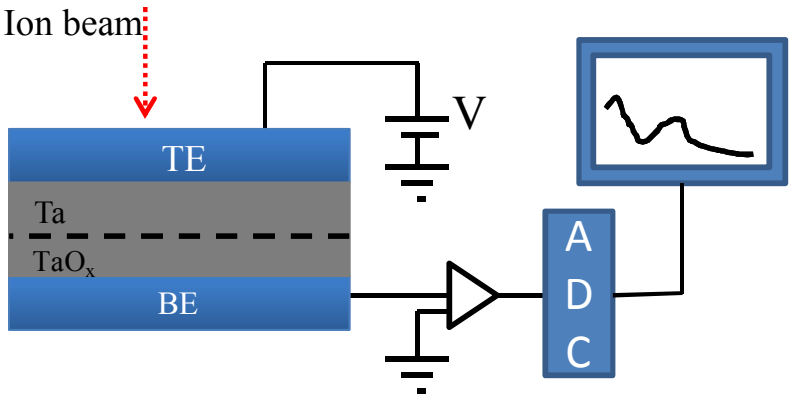


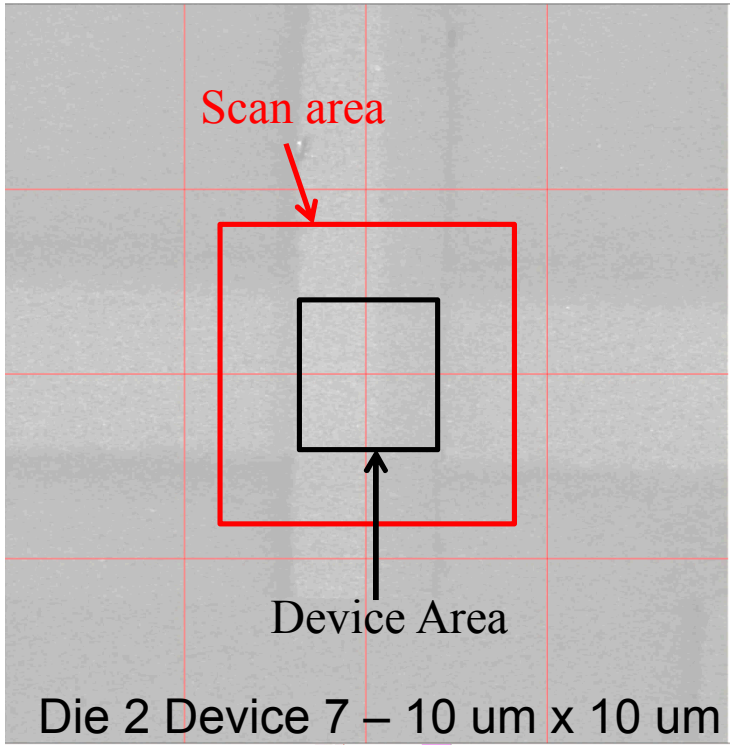
Memristor Irradiation @ nI:

Purpose: Determine location of conductive filaments

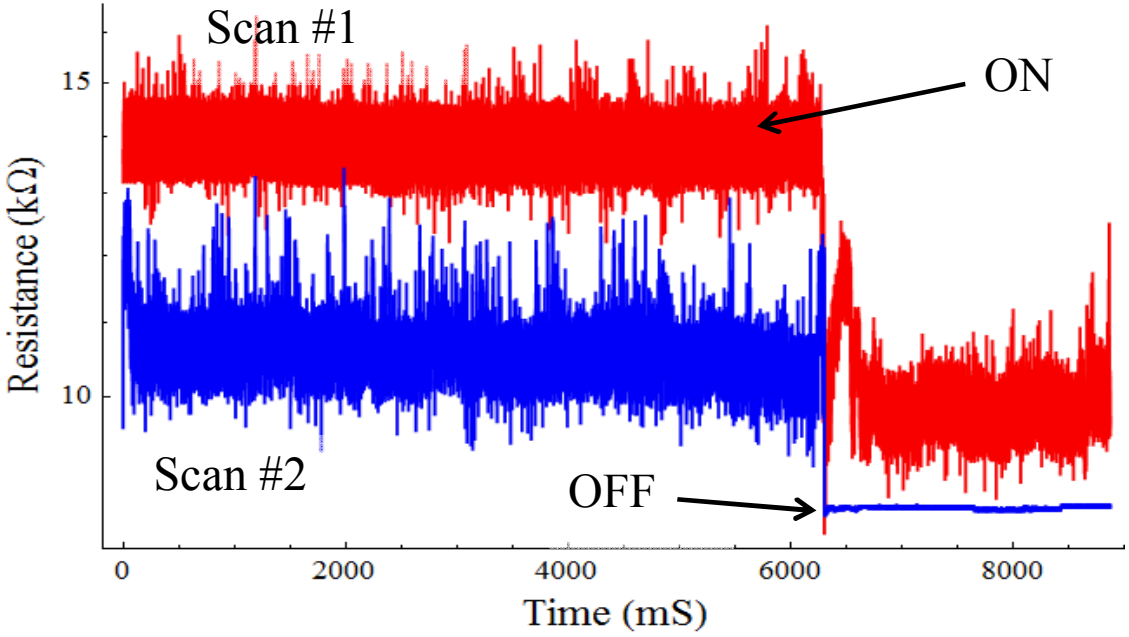
Experiment:

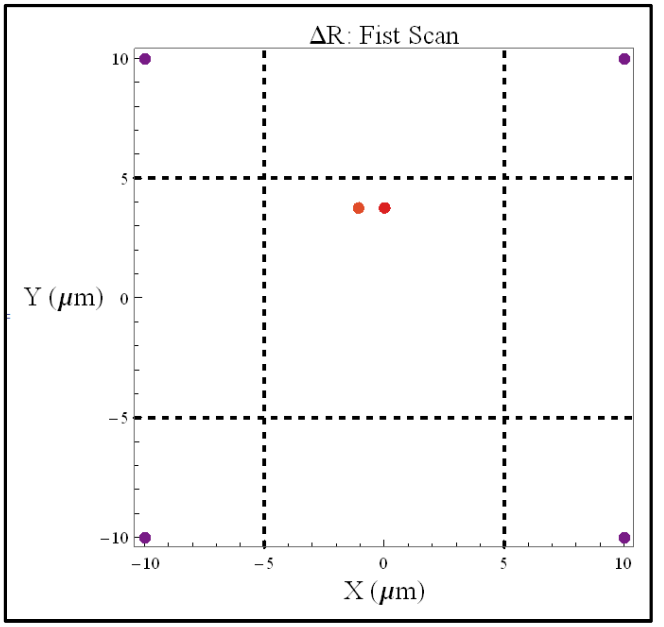
- X-Y Scans: 20 um by 20 um scan area
  - 200 keV Si++
  - Beam current ~1.8 pA
  - Beam spot size ~40 nm
  - Step size 30nm
    - ~30 spots to expose 1um
  - Dwell time of 20 us
    - ~100 ions per spot
- 10um by 10um device area
- Device in the ON state
- Monitor/Record Resistance ΔR(t)
- XY Map of ΔR → ΔR(x,y)

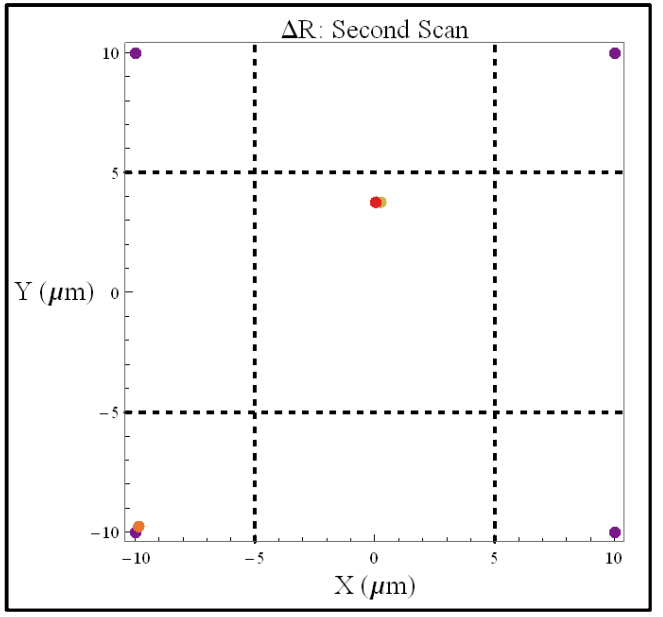




Localization of Areas Sensitive to Irradiation with SNL nI

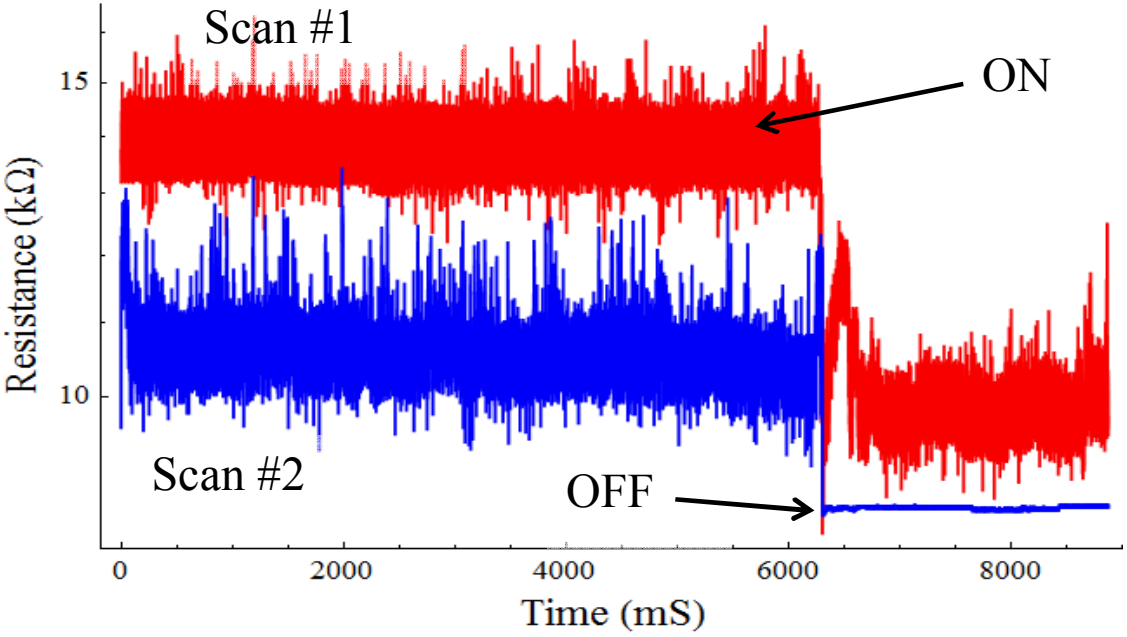


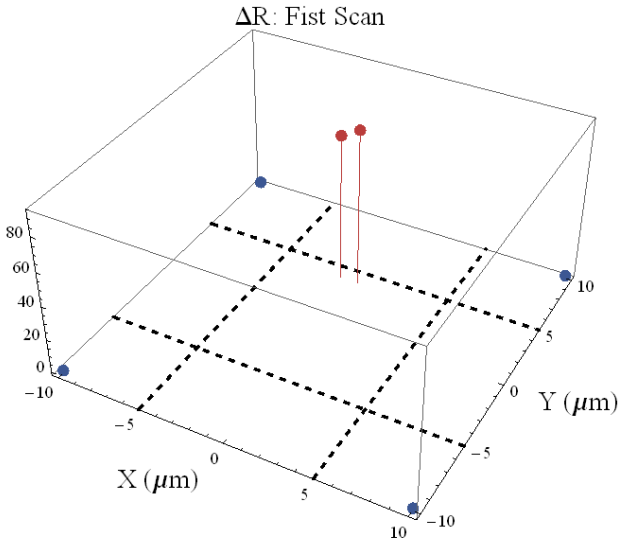


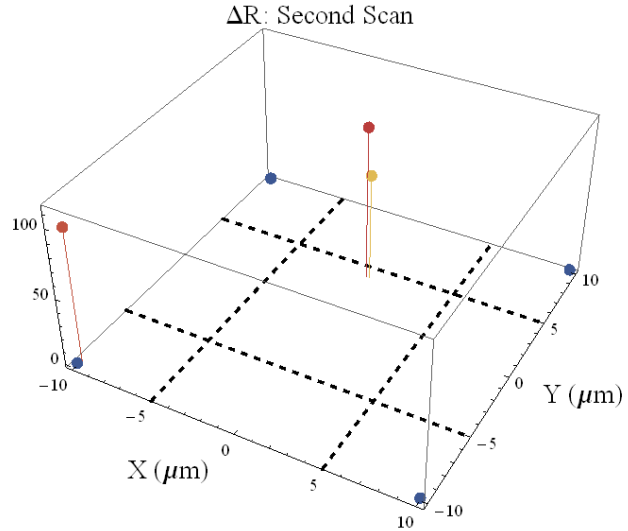


- Sensitive locations irradiated → Resistance ↓
- Conductive channels located (?)
- Limited by delay of signal through electronics
- Use: Slower scan/Faster electronics

Localization of Areas Sensitive to Irradiation with SNL nI







- Sensitive locations irradiated → Resistance ↓
- Conductive channels located (?)
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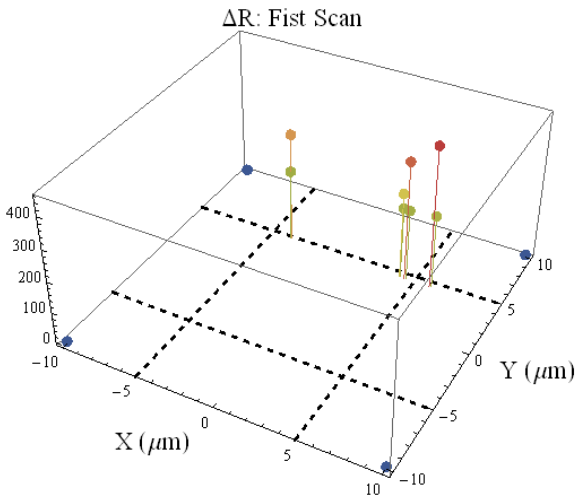
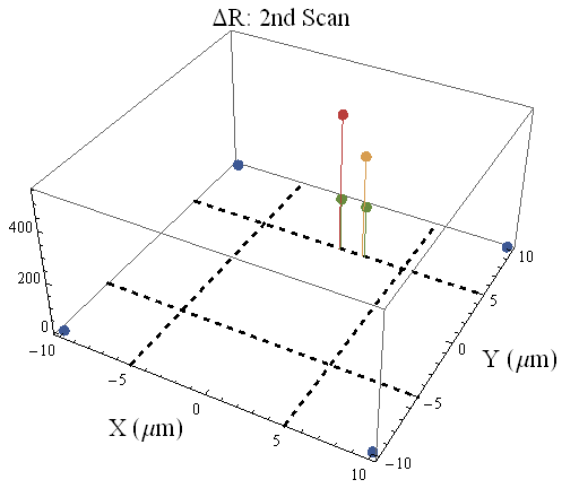
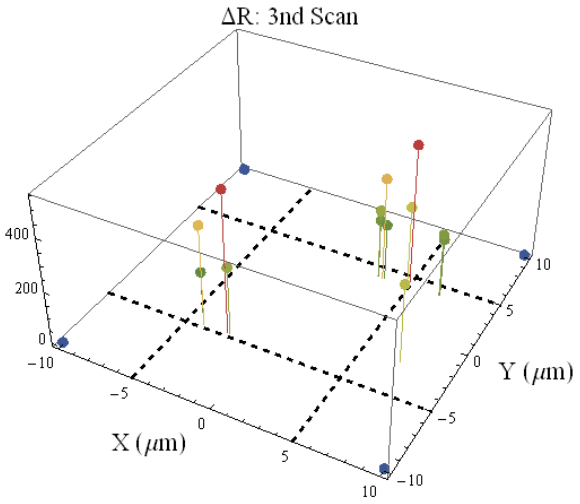
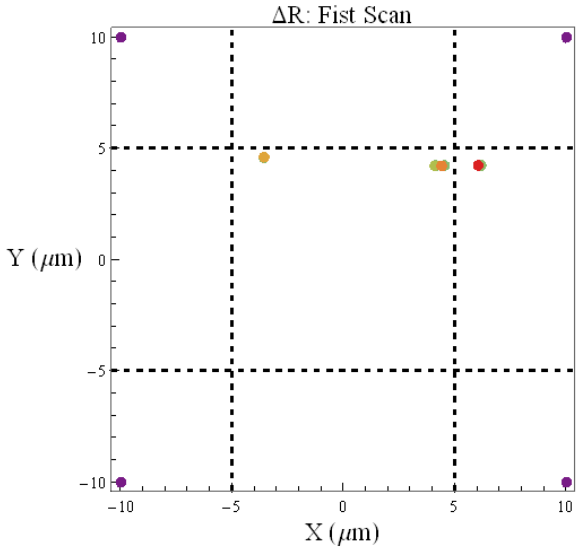
Die 2 Device 7 – 10 um x 10 um

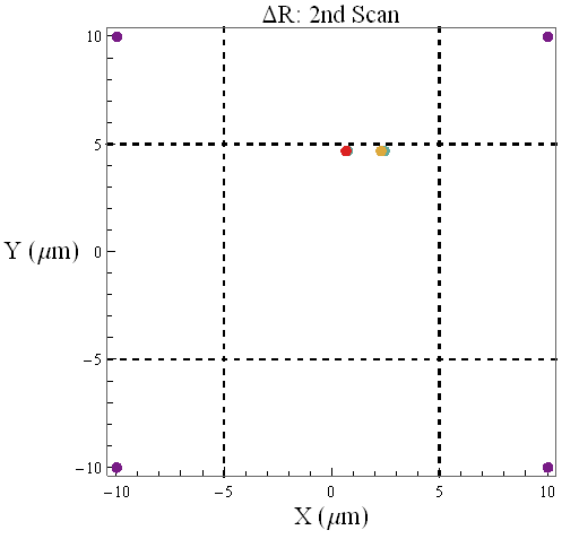
Localization of Areas Sensitive to Irradiation, Cont'd

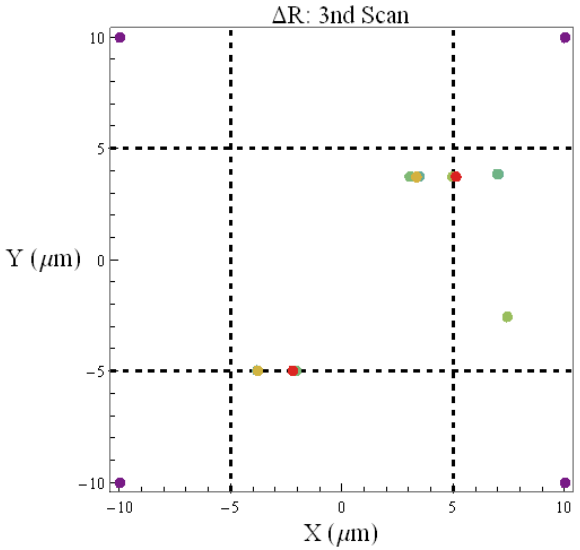






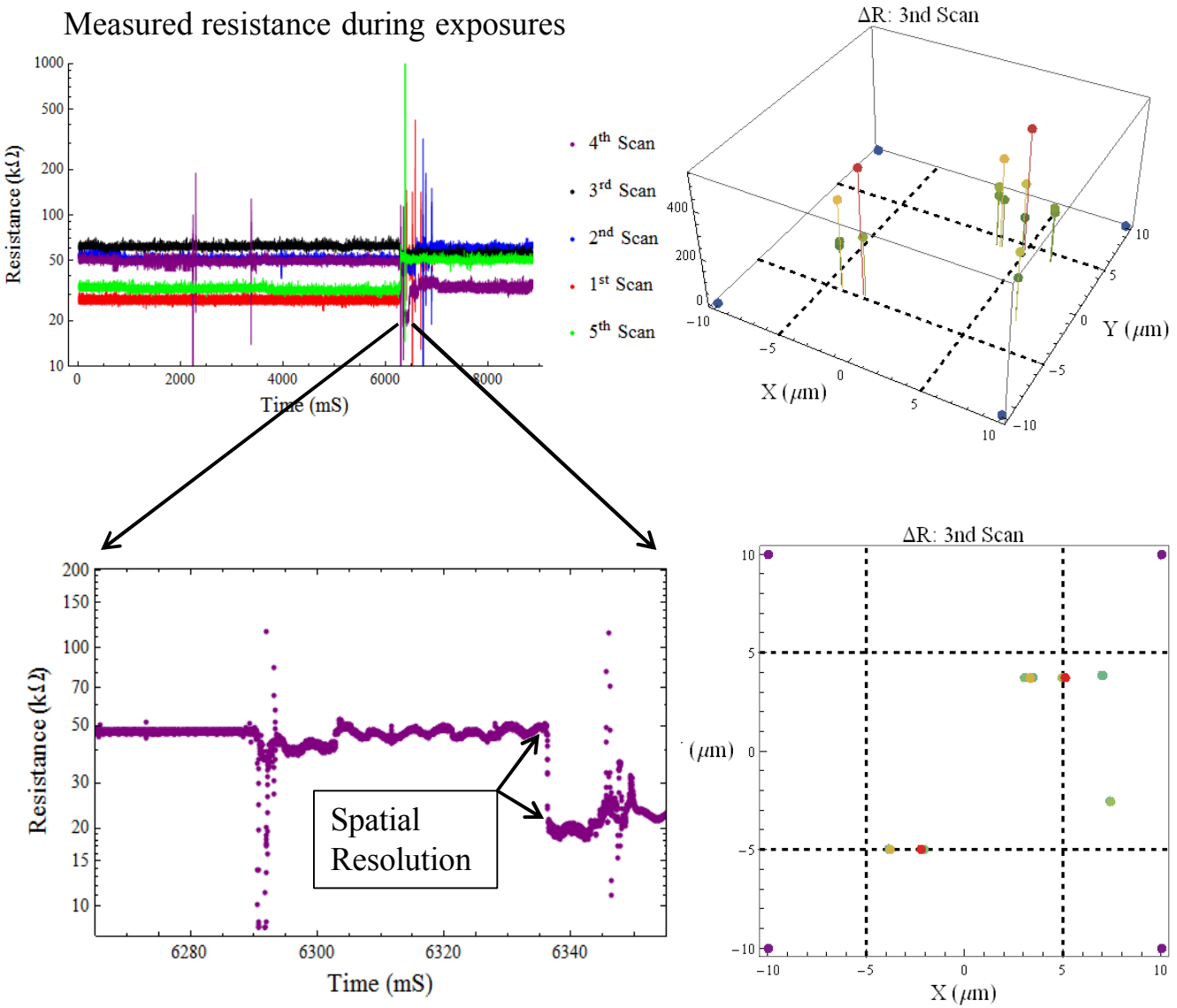






Spatial Resolution and Targeting

- Targeting sensitive location reproducibly
- Irradiation has an effect at the same location
- ~10 Spots per ΔR
  ~300nm resolution
  …room for improvement
- Large spikes observed
  - Possibly due to large number of ions (??)
- XY maps show the preferential edge where ΔR occurs

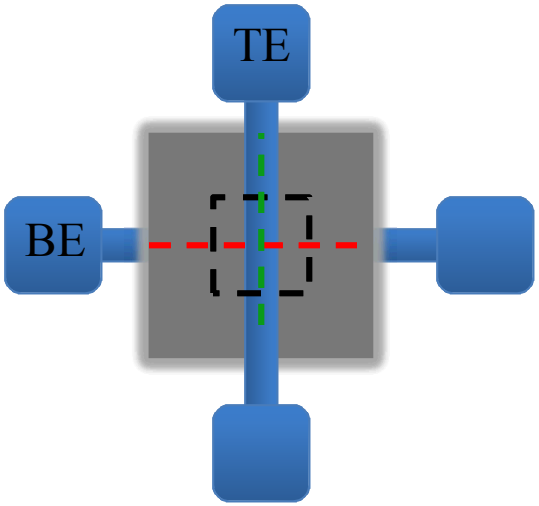


Die 2 Device 7 – 10 um x 10 um

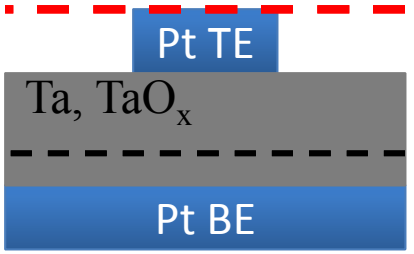
General location of Conductive Filaments

- Conductive filaments at the edges
- Located near regions of strong electric fields
- Further testing
- Conductive channel formation is a random process
- Ideal:

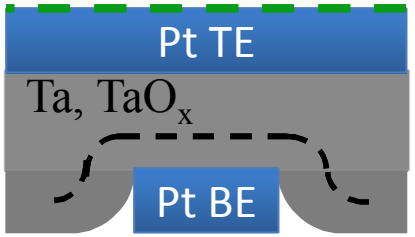
Forming a channel at a predetermined location

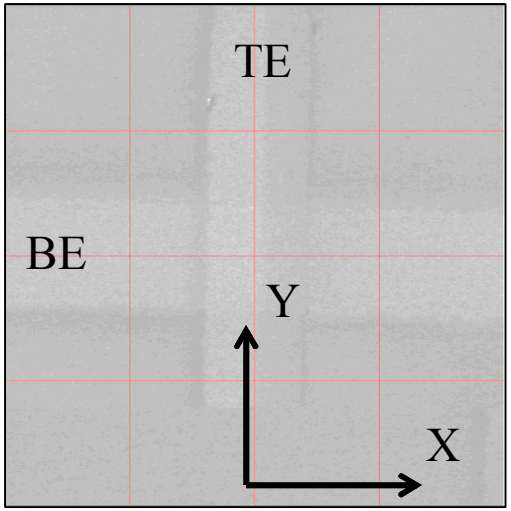


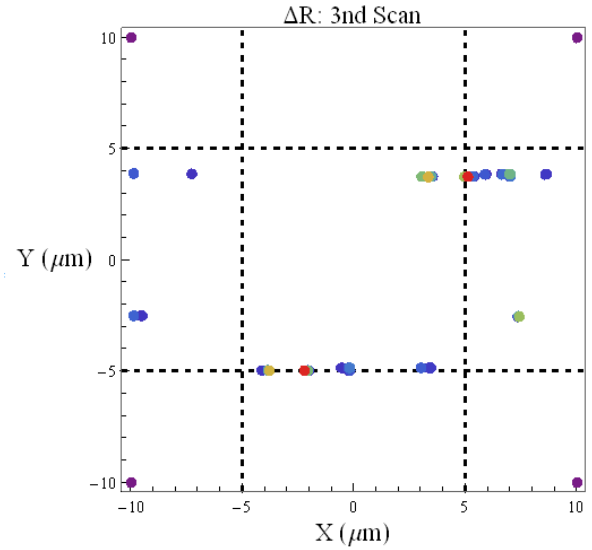
Horizontal cross section



Vertical cross section







Future Experiments…

Immediate:

- determine filament location with nm resolution
- Scan with low number of ions → scan multiple times
- Faster electronics (slower scans)
- Acquire full effect of irradiation before moving to next location
  - Limited by rise time of amplification (Keithley 428 ~10-20 us rise time)
  - Switch to amplifier (Femto TIA 350 ns rise time)

Long Term:

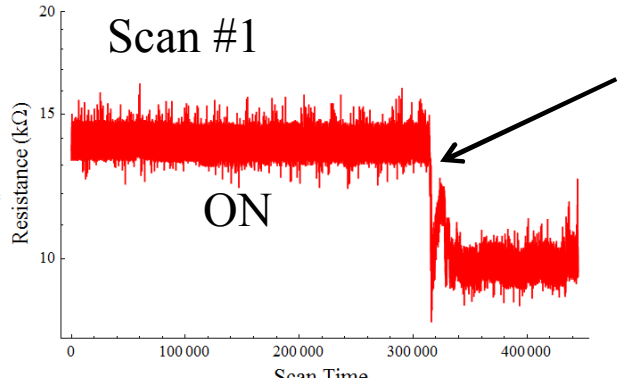
- Explore conductive channel behavior under different modes of irradiation
- Repair, Modify, or Create conductive channels using nI.

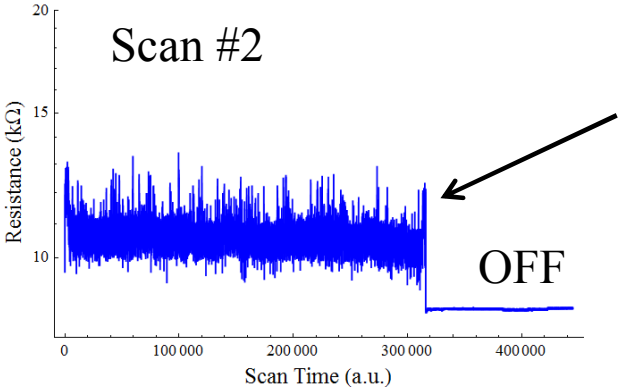
Outline

- Introduction
  - Memristor characteristics and applications
- Previous results
  - Oxygen vacancy percolation
  - 10-100 nm diameter conductive filaments
  - Radiation hard
  - Conductive filament location
- Localization of conductive filaments
  - nano-Implanter (nI) at SNL
  - Filament localization experiment
- Investigate conductive filaments…
  - Rad hard? Total dose vs. channel dose
  - Different modes of irradiation →Channel morphology

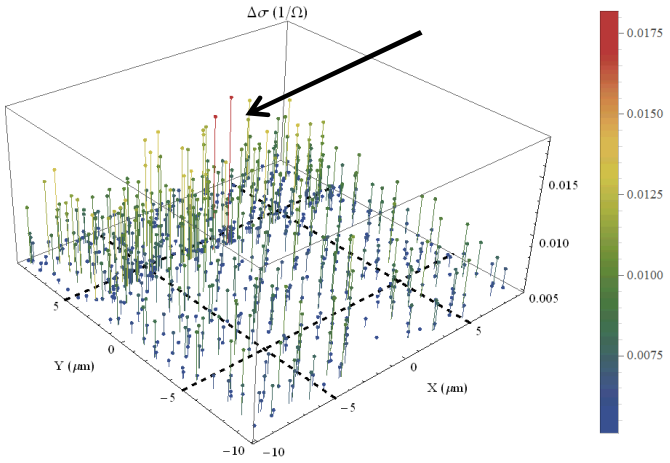
Extra Slides

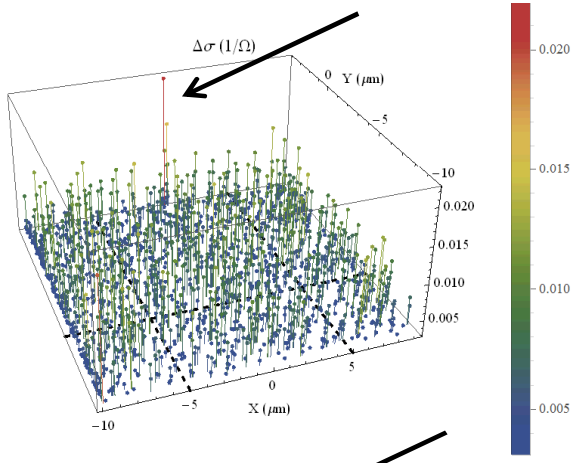
Pin-point location where irradiation affects resistance



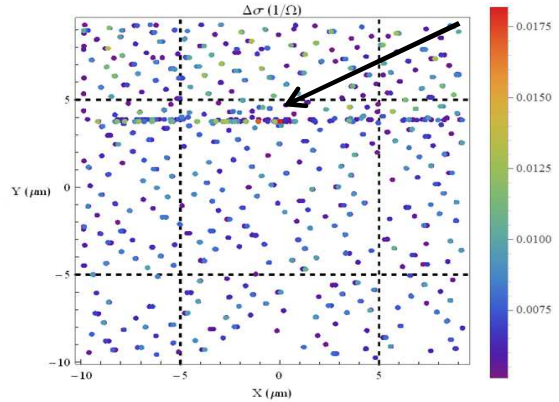


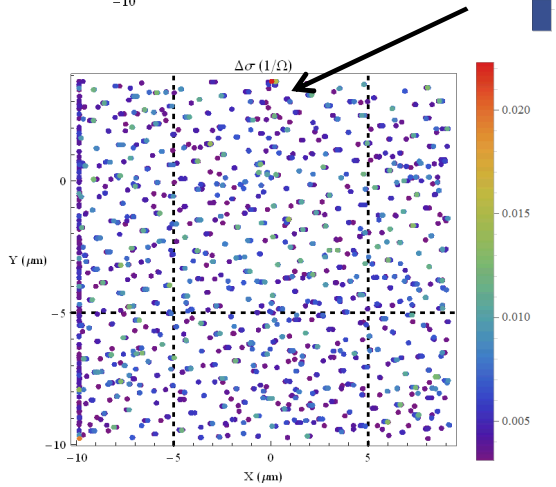
Sensitive locations are irradiated →
↓ Resistance





Locate conductive channels





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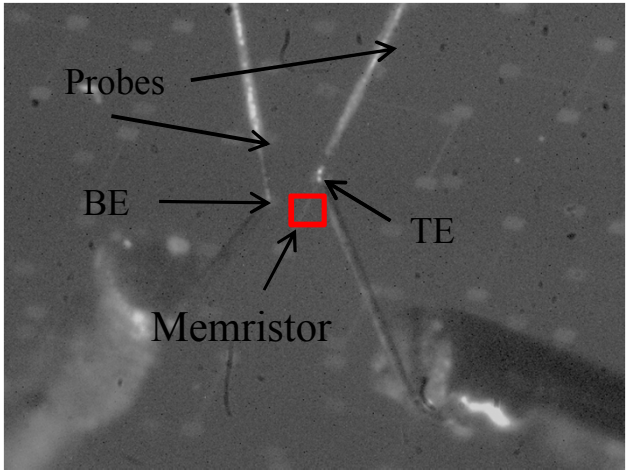
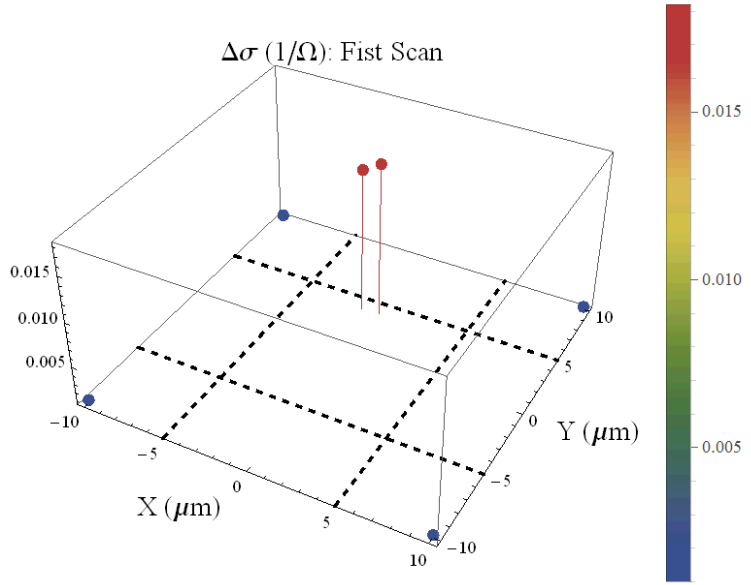
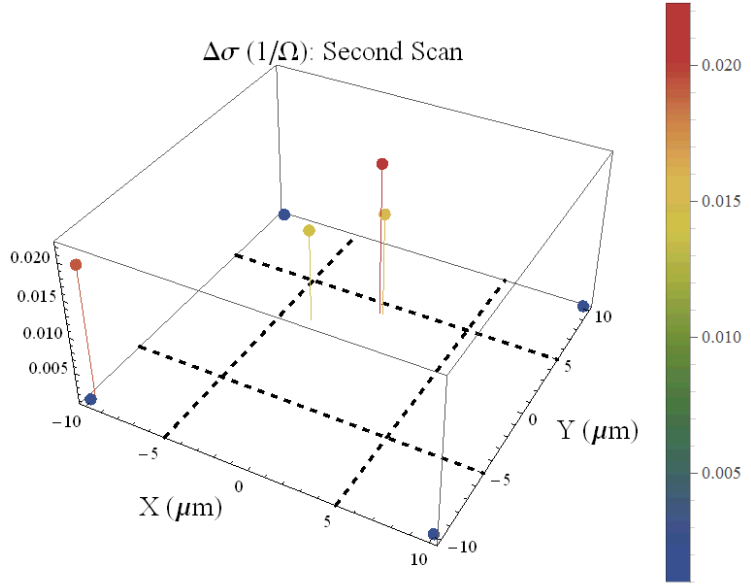
- Ion beam dose at conductive channel vs. total ion dose over device area.



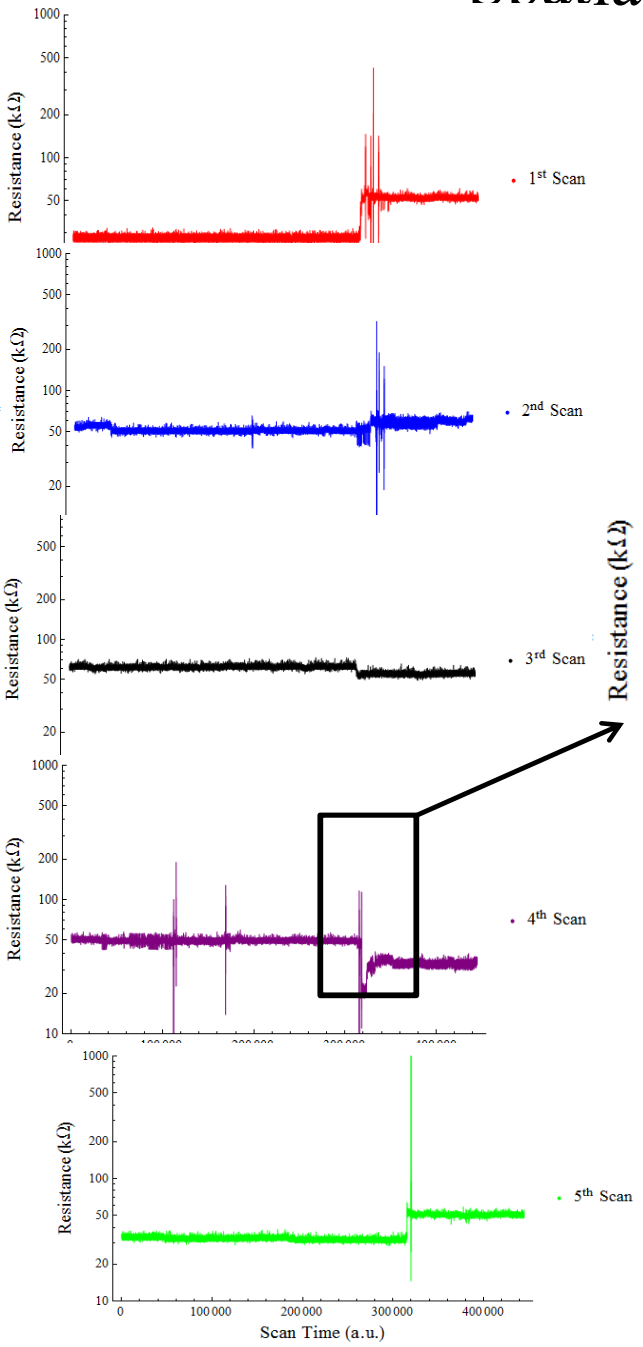

Δσ (1/Ω): Fist Scan
0.015
0.010
0.005
−10
−5
0
5
10
X (μm)
Y (μm)
0.015
0.010
0.005

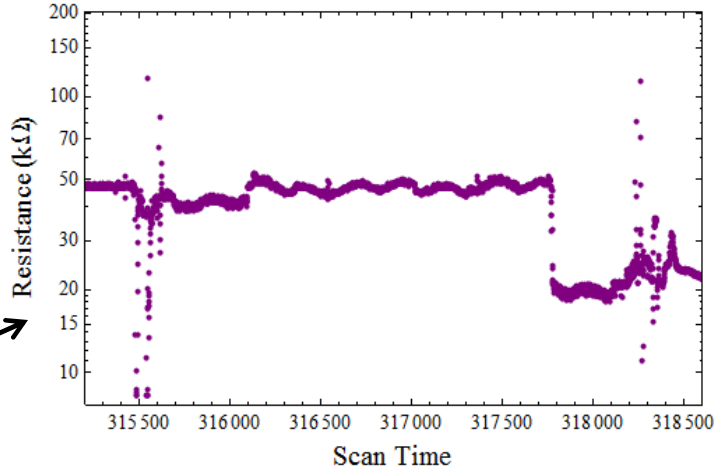

Δσ (1/Ω): Second Scan
0.020
0.015
0.010
0.005
−10
−5
0
5
10
X (μm)
Y (μm)
0.020
0.015
0.010
0.005

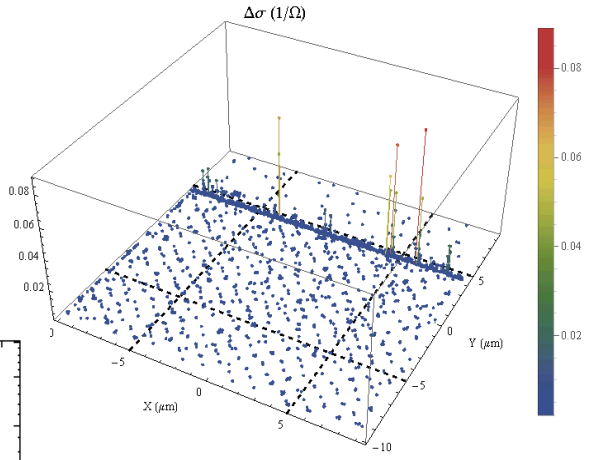
Spatial Resolution thus far Achieved

Irradiation has an effect at the same location

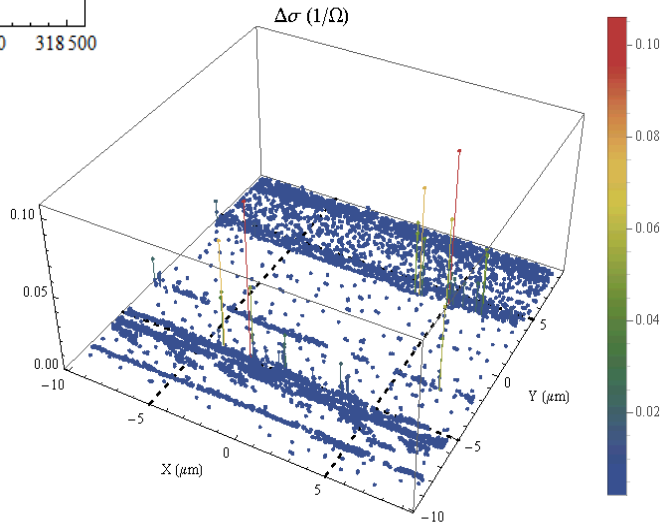
~ 10 Spots per ΔR
→ 300nm resolution

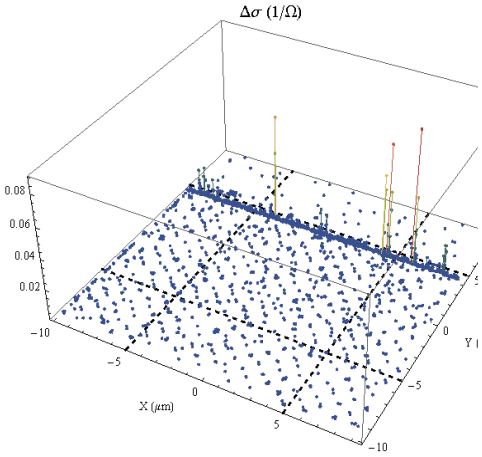


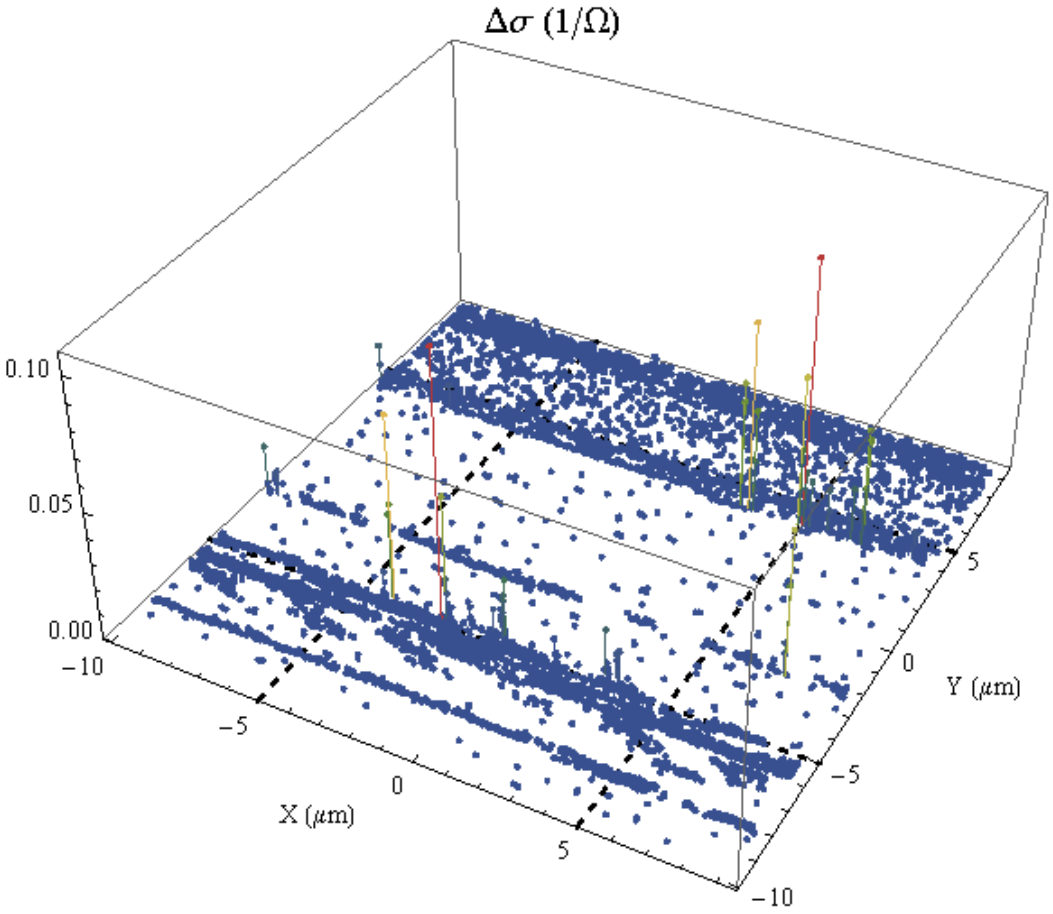


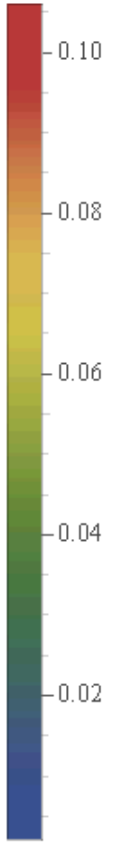


Large spikes observed
→ possibly due to large number of ions??




Δσ (1/Ω)
0.08
0.06
0.04
0.02
−10
−5
0
5
X (μm)
−5
0
−10


Δσ (1/Ω)
0.10
0.05
0.00
−10
−5
0
5
X (μm)
5
0
−5
−10
Y (μm)


0.10
0.08
0.06
0.04
0.02