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Effects of Ionizing Radiation and Heavy Ions on TaO_x-based Memristive Devices

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Motivation

- **To evaluate the effects of ionizing radiation on tantalum oxide (TaO_x) memristors being considered for use in next-generation memristive devices**
- **Data obtained from ^{60}Co gamma ray and 10 keV X-ray ionizing radiation experiments**

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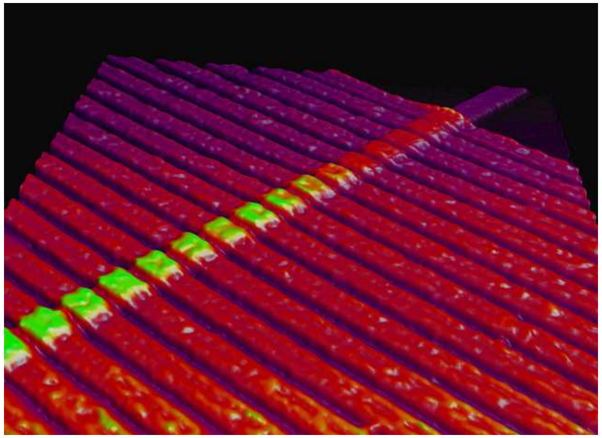

Possible Flash replacement: ReRAM/ RRAM/REDOX Memory

Enable discovery of a radiation-hardened storage class memory technology to replace SRAM, DRAM, and flash in future radiation-hardened applications

Topics of Discussion

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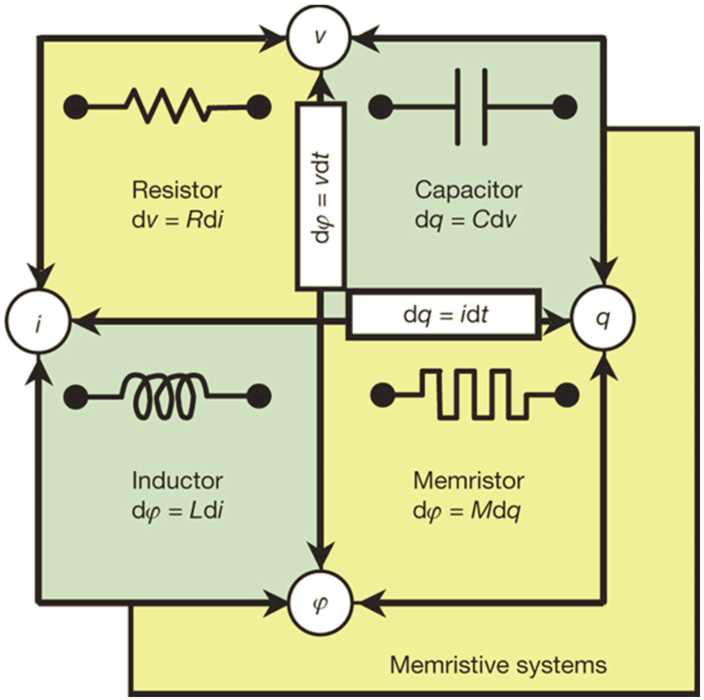
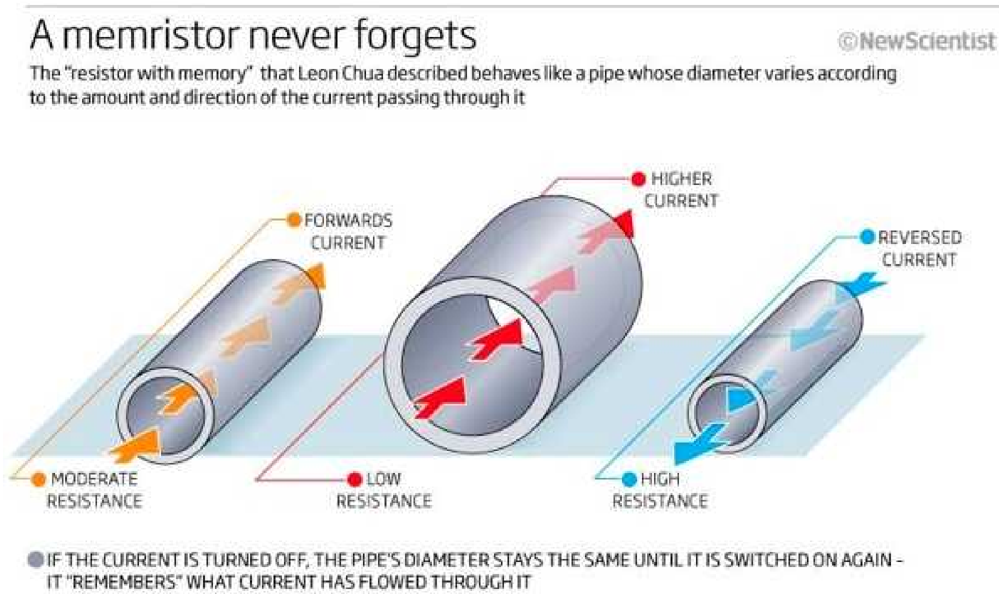
- **Background**
  - **What are memristors and why do we care**
- **Experimental Results and Discussion**
  - **In-situ Transmission Electron Micrograph (TEM) studies**
  - **Total ionizing dose (TID) response**
- **Modeling Efforts**
- **Summary and Future Work**

Concept of Memristors

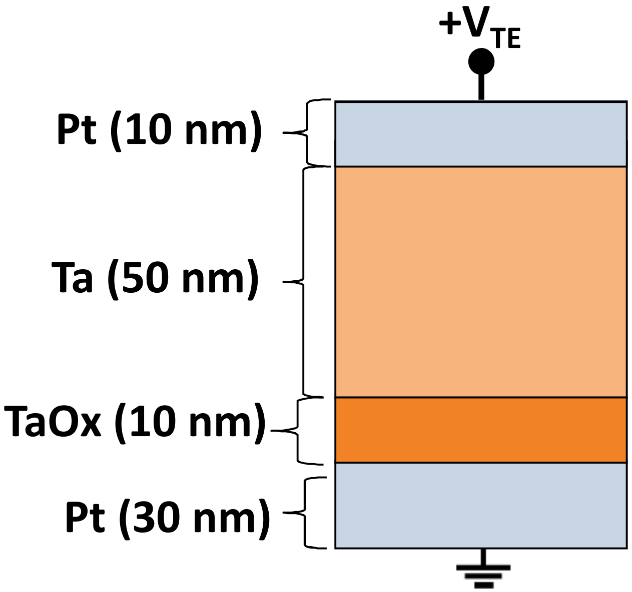


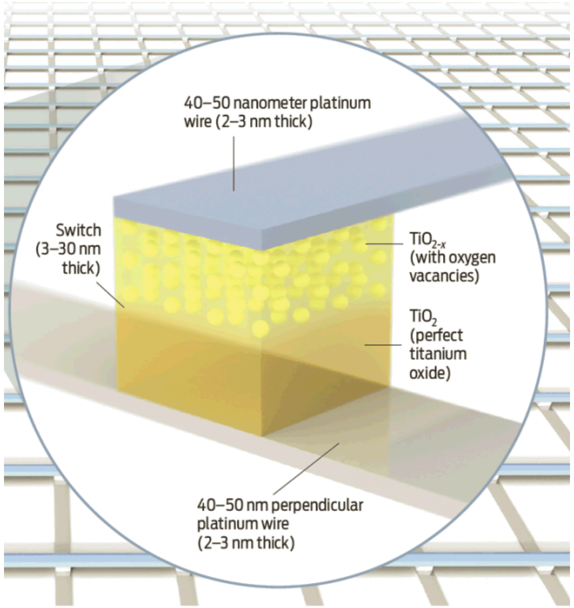
Strukov et al, Nature 459, 1154, 2009



- **Theoretical concept formed by Leon Chua in 1971**
- **4th fundamental passive circuit element**
- **Memristors are built on an observed effect that is very useful but not well understood at this time (active area of research)**

What is a Memristor?

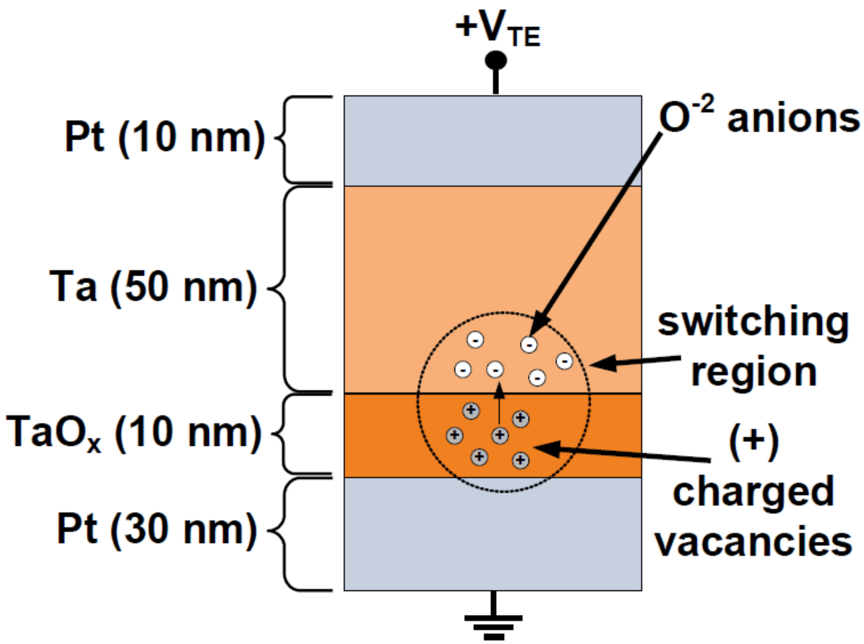


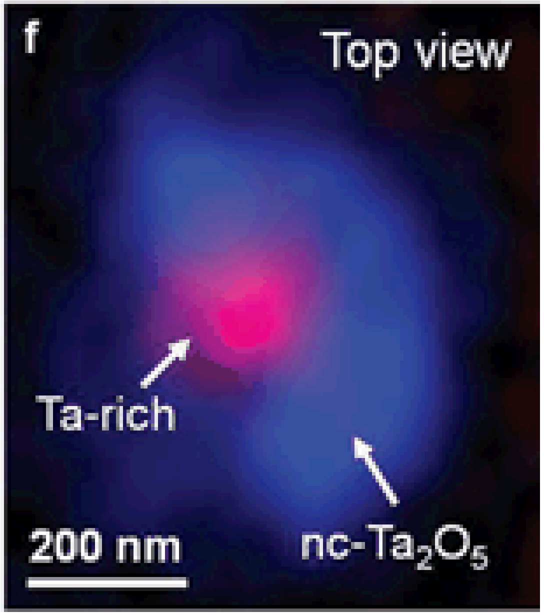


Williams, IEEE Spectrum, 2008

- **Memristors are 2 terminal metal-insulator-metal devices**
  - **Memristors can be fabricated with a variety of different transition metal oxides (TMO) including TaO_x, TiO_2, HfO_x (and others)**
  - **There are also other types of memristive devices (e.g., ChG-based CBRAM)**

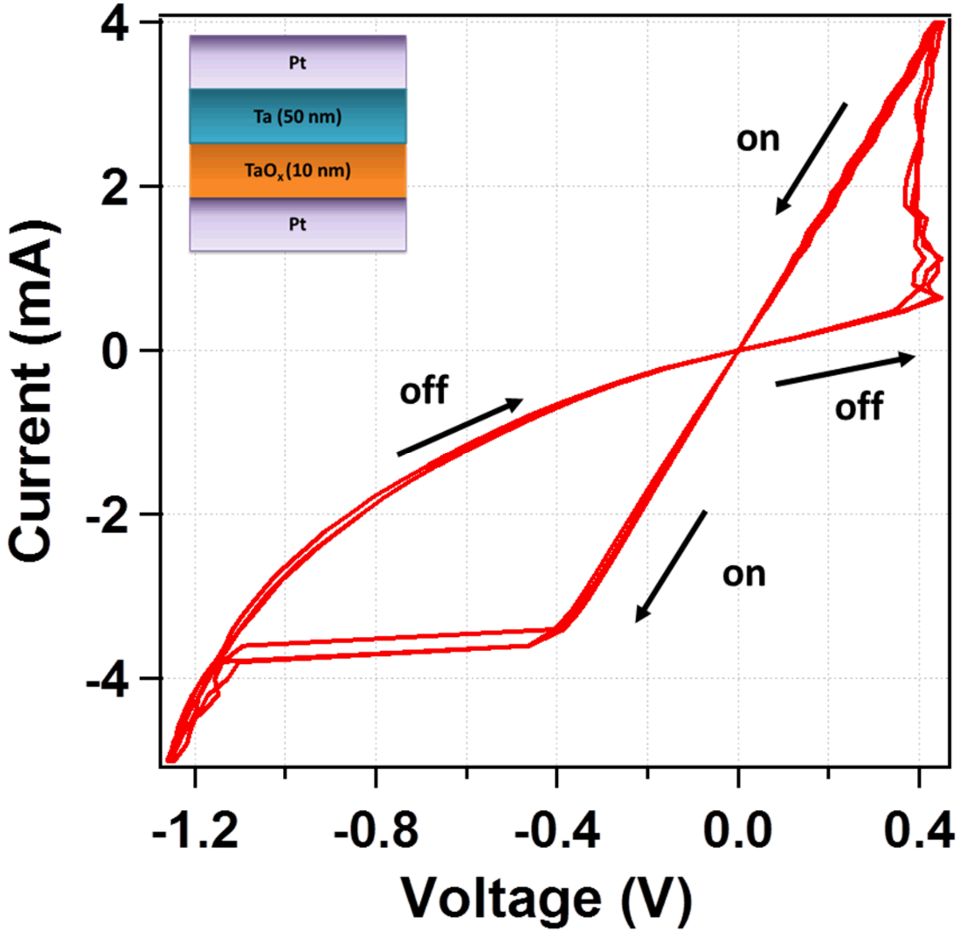
Theory of How a Memristor Works





- Theory: Switching mechanism involves redox reactions and migration of O^{-2} anions
  - Electric and thermal fields cause dissociation and transport of O^{-2} anions, leaving behind oxygen vacancies
- Processes lead to formation of Ta-rich conducting filament of a certain radius

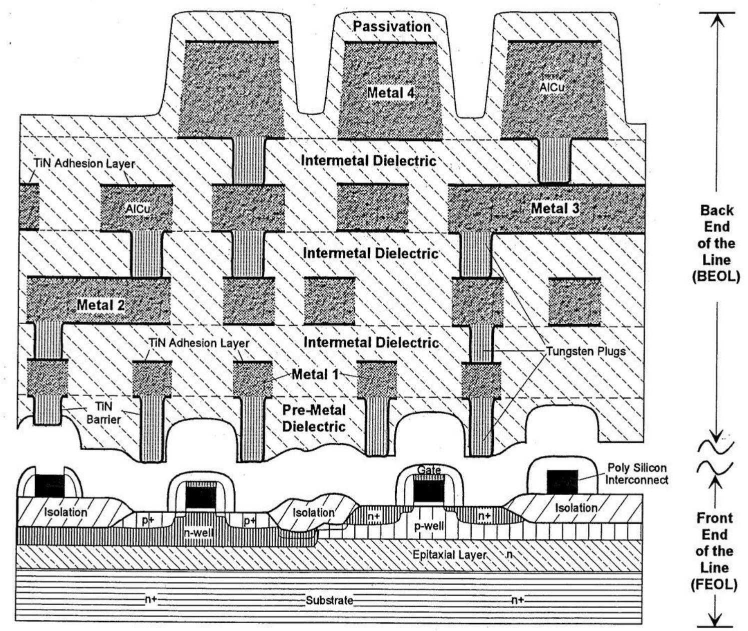
I-V Characteristics



- Characteristic hysteresis response
- Memristors characterized by a low resistance on-state and high resistance off-state
- Resistance depends on applied bias and bias history

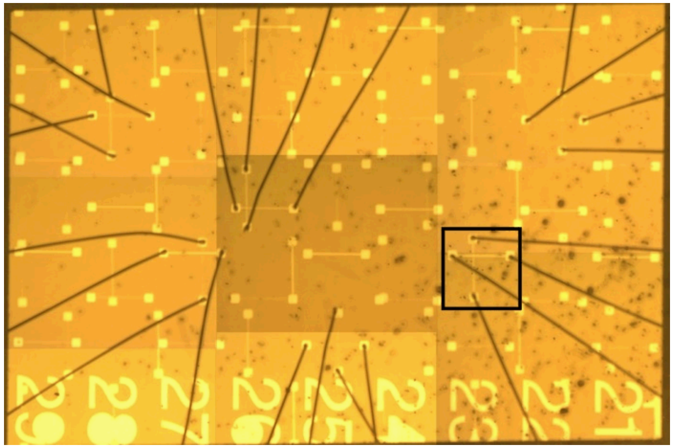
Why Do We Care About Memristors

- **Push to discover a universal or storage class memory to replace Flash/DRAM/SRAM (Radiation Effects community would like a rad-hard nonvolatile memory)**
- **ITRS has identified Resistive RAM (also known as redox or memristive or ReRAM) as one of the most promising future memory technologies**
  - **High endurance (> 10^{12} cycles)**
  - **Long retention (>10 years at 85°C)**
  - **Low switching energy (~2 pJ on and ~6 pJ off)**
  - **High speed (<500 ps)**
  - **Scalable and easy integration with CMOS (back-end-of-line)**

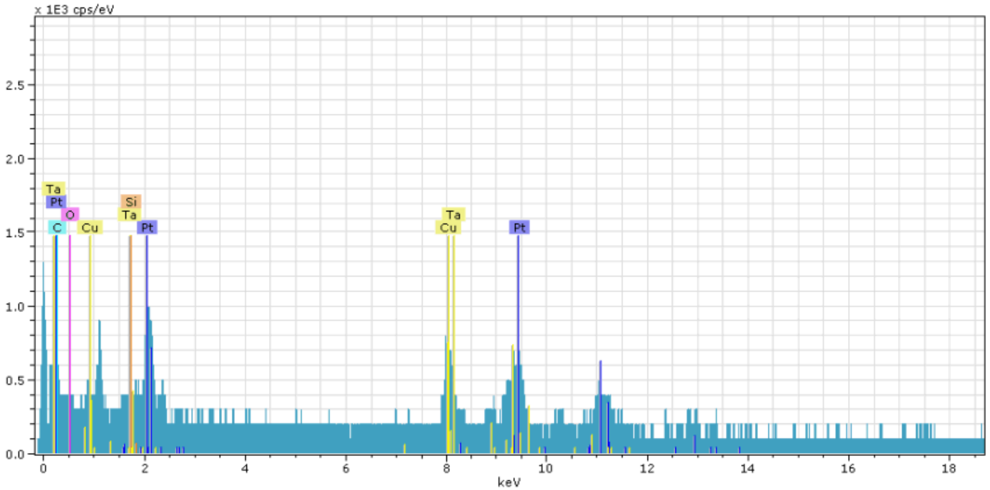


TEM image of Sample MZ-2

Dog-bone structures on die



EDS Chemical mapping to ID layers



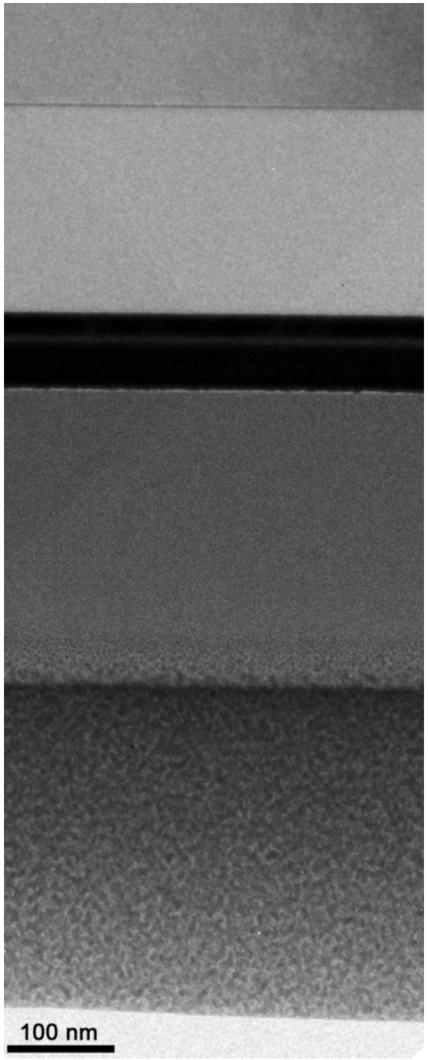
Si

SiOx

Memristor

Electron beam deposited Pt

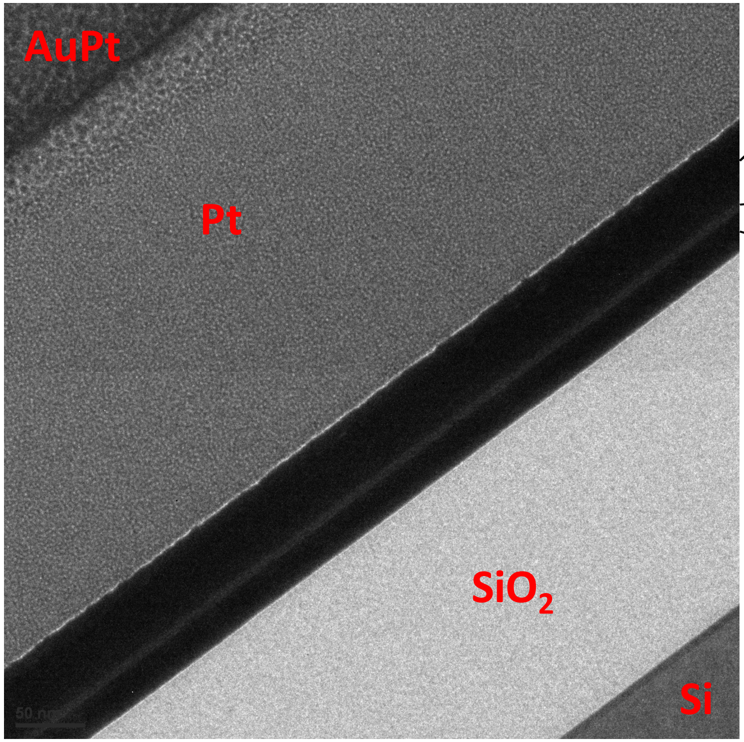
Ion beam deposited Pt



TEM images from IBL

AuPt from FIB lift out

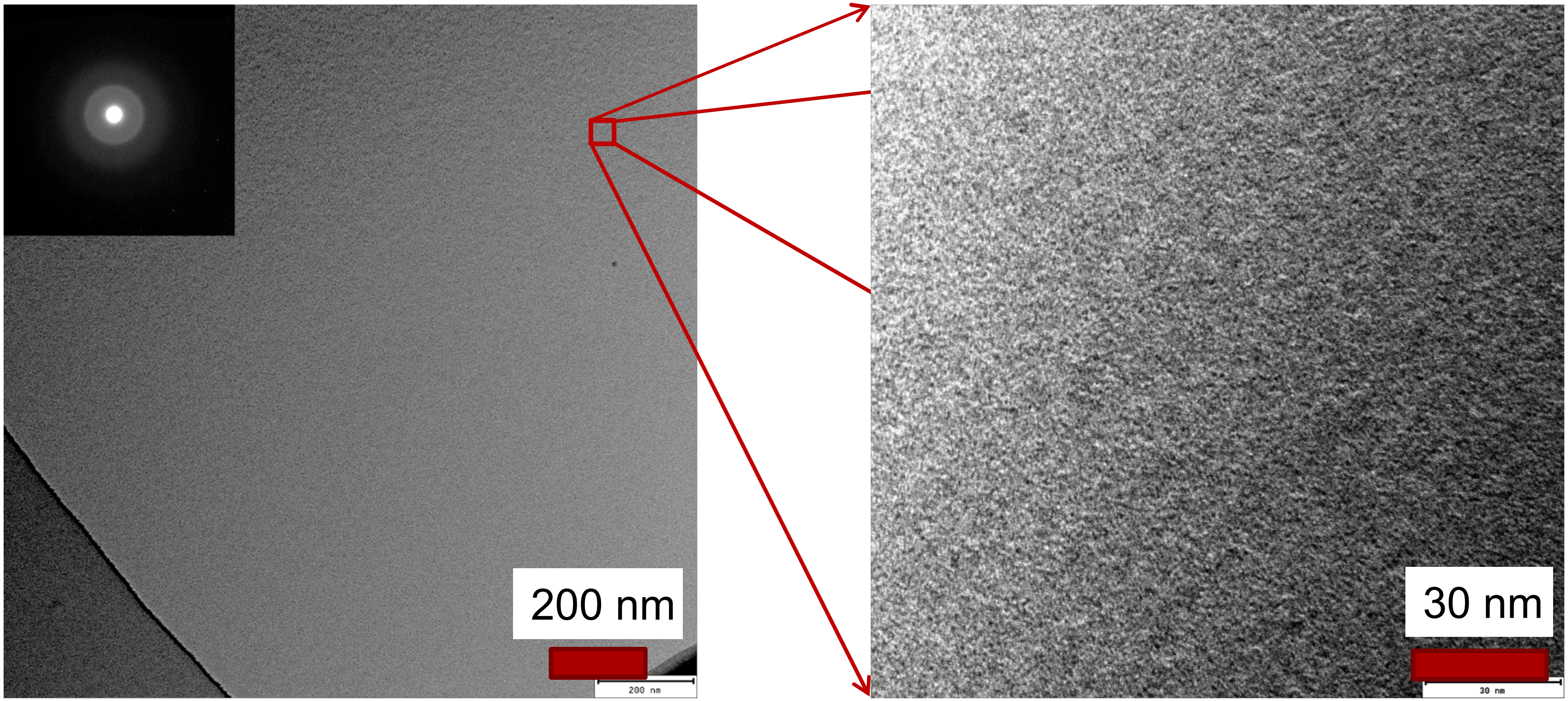
Electron beam deposited Pt



Cannot differentiate between Pt and Ta on TEM images

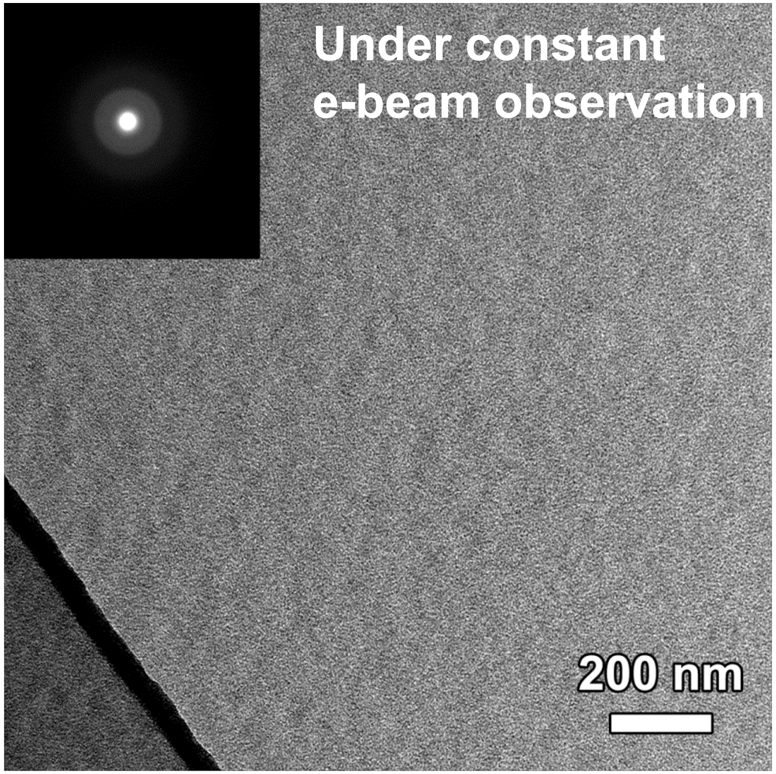
Experiments obtaining TEM images of the devices while being exposed to alpha particles in progress

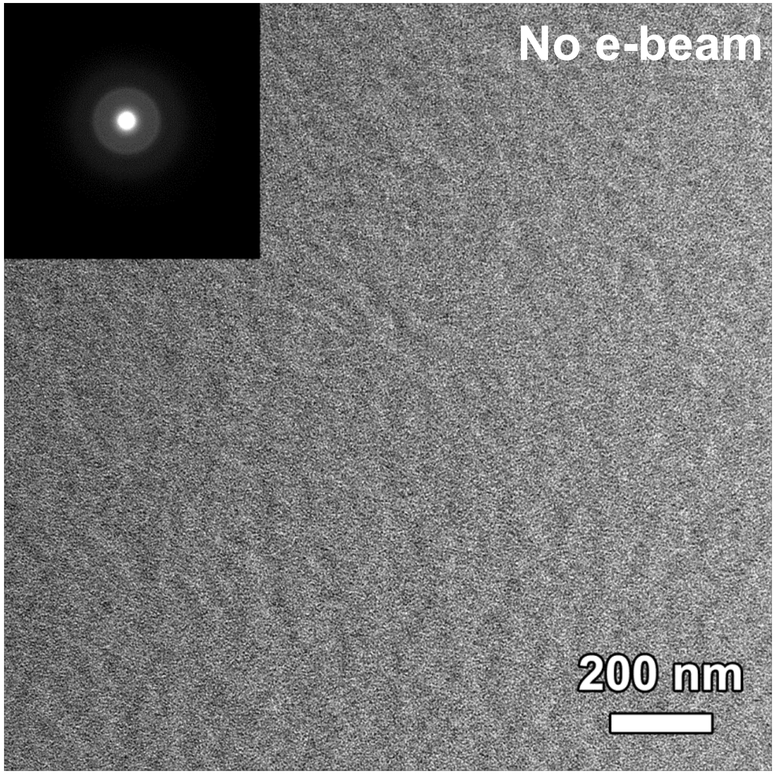
As-received 15nm Amorphous TaO_x



- **Uniform, essentially amorphous structure**
- **Top left is an electron diffraction image**

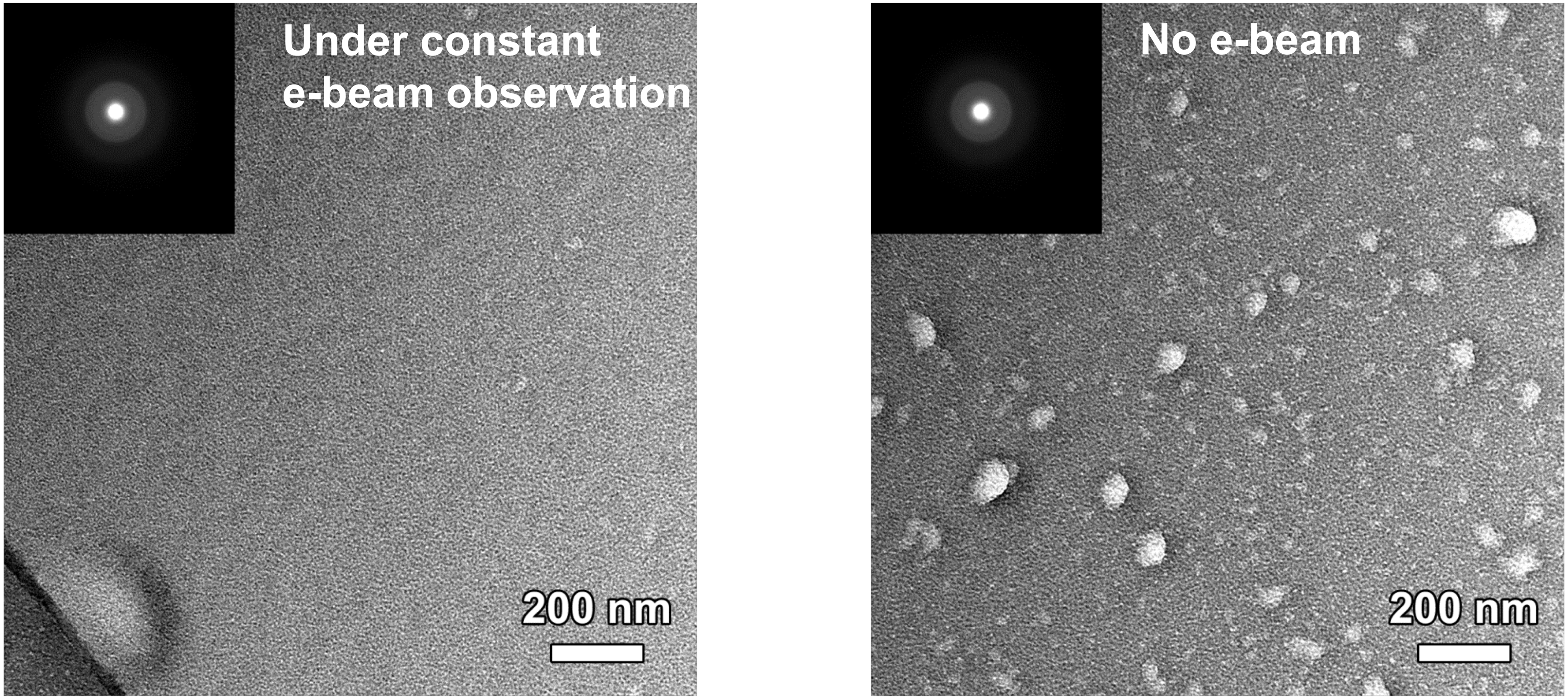
After 2.8×10^{15} He^+/cm^2





- Some ordering apparent
- Possibly more ordering in area not under the e-beam

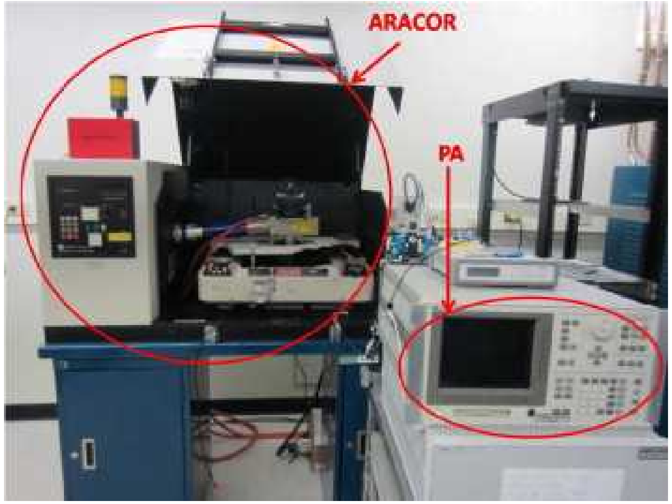
After 8×10^{16} He^+/cm^2

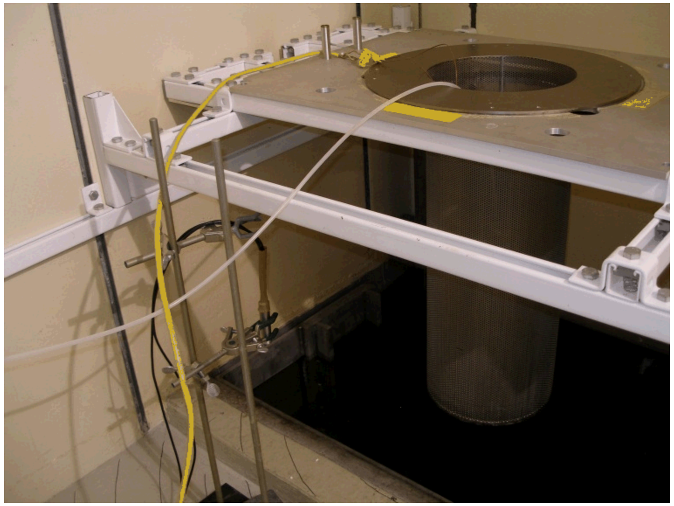


- **Increased ordering with increasing ion fluence; no dramatic recrystallization**
- **More bubbles without constant e-beam (local heating/annealing?)**

Total Ionizing Dose Experiments

- **Aracor 4100 10 keV X-ray system and Gamma Irradiation Facility (Co-60)**
  - **Impact of electron-hole pairs created in insulator**
- **Device terminals grounded, biased, or floating during irradiation**
- **Bias configuration impacts the ionizing radiation response**





Electrical Characterization

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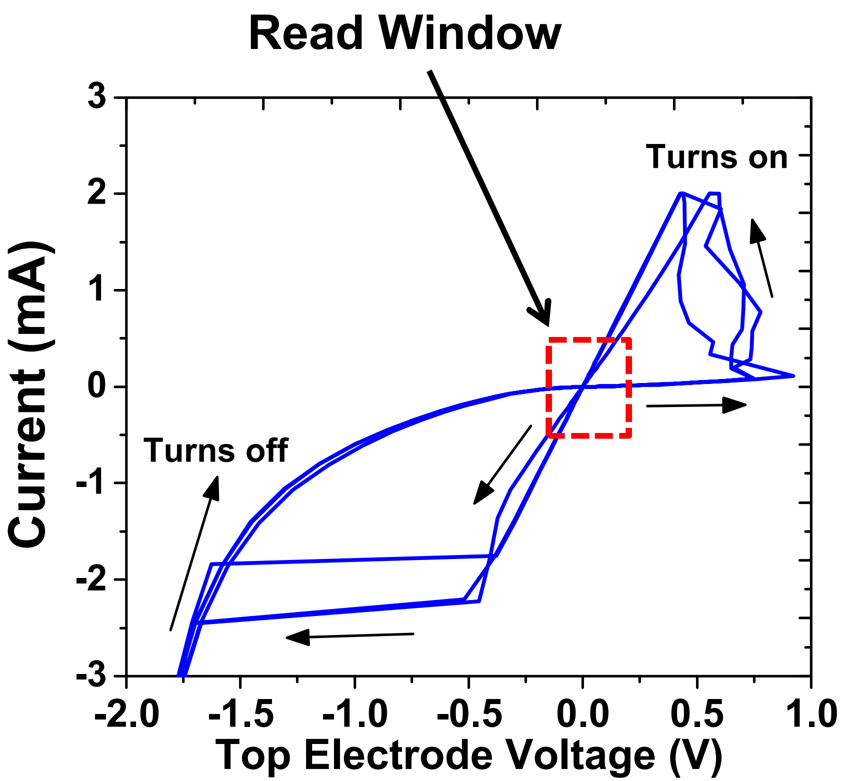
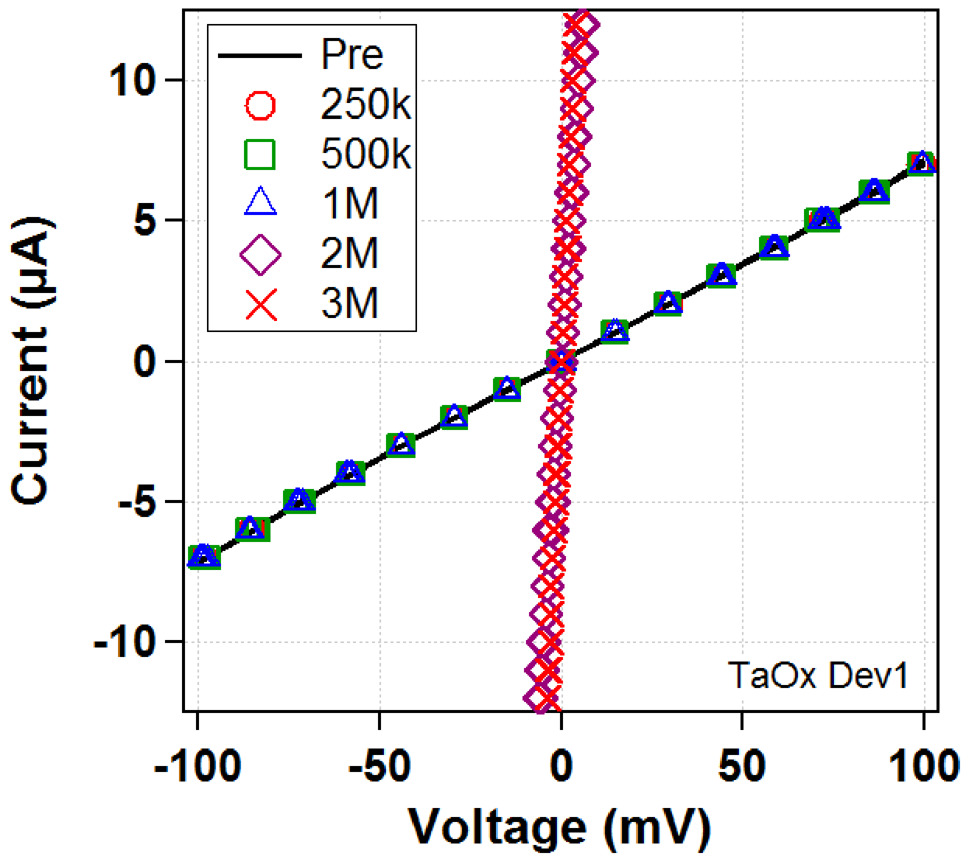


- Devices cycled several times prior to rad test
- <u>Write Voltages:</u>
  - Set (on): ~800 mV
  - Reset (off): ~-1.5 V
- <u>Typical Resistances:</u>
  - $R_{ON} \approx$ 30-150 Ω
  - $R_{OFF} \approx$ 300-100k Ω
- Floating, Grounded, or biased during irradiation
- Read after each shot
- Full sweeps after series of shots

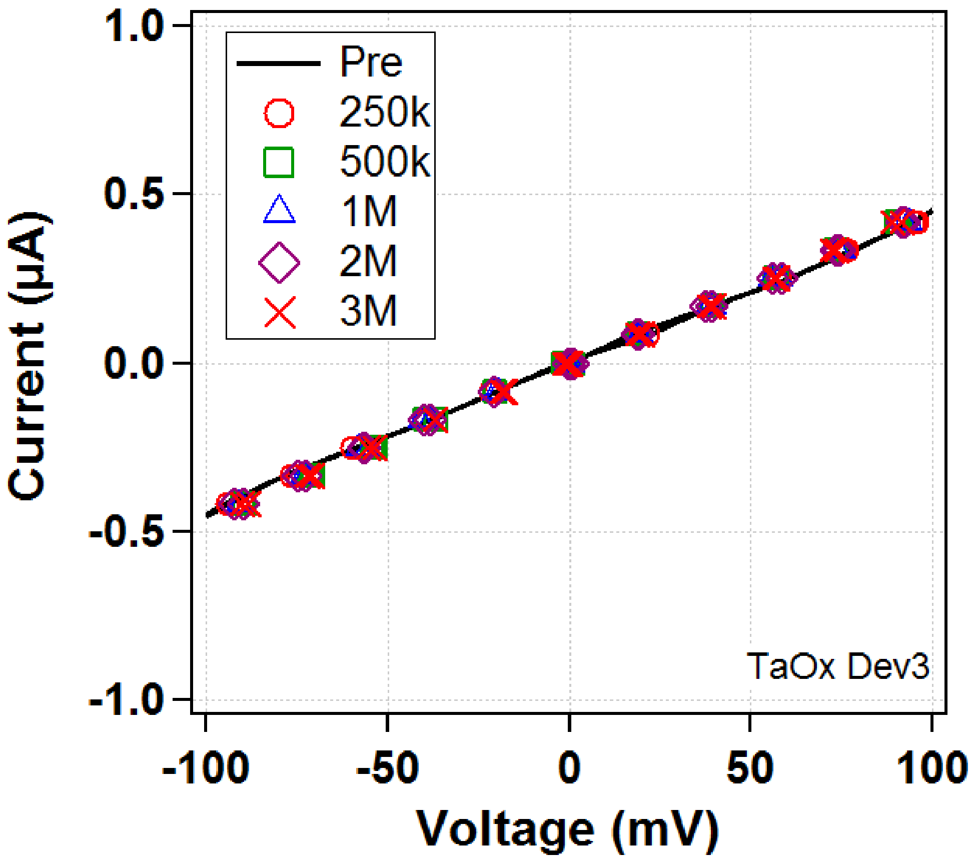
Co-60 γ-ray Response: Grounded



- All terminals grounded during irradiation
- The device was still functional following 3 Mrad(CaF_2)
- Recent ionization experiments at IBL confirmed that resistance will change after a critical charge is surpassed
- No apparent stress from radiation-induced switching

Device #1 consistently changed from high resistance off-state to low resistance on-state after a 1 Mrad(CaF_2) step stress

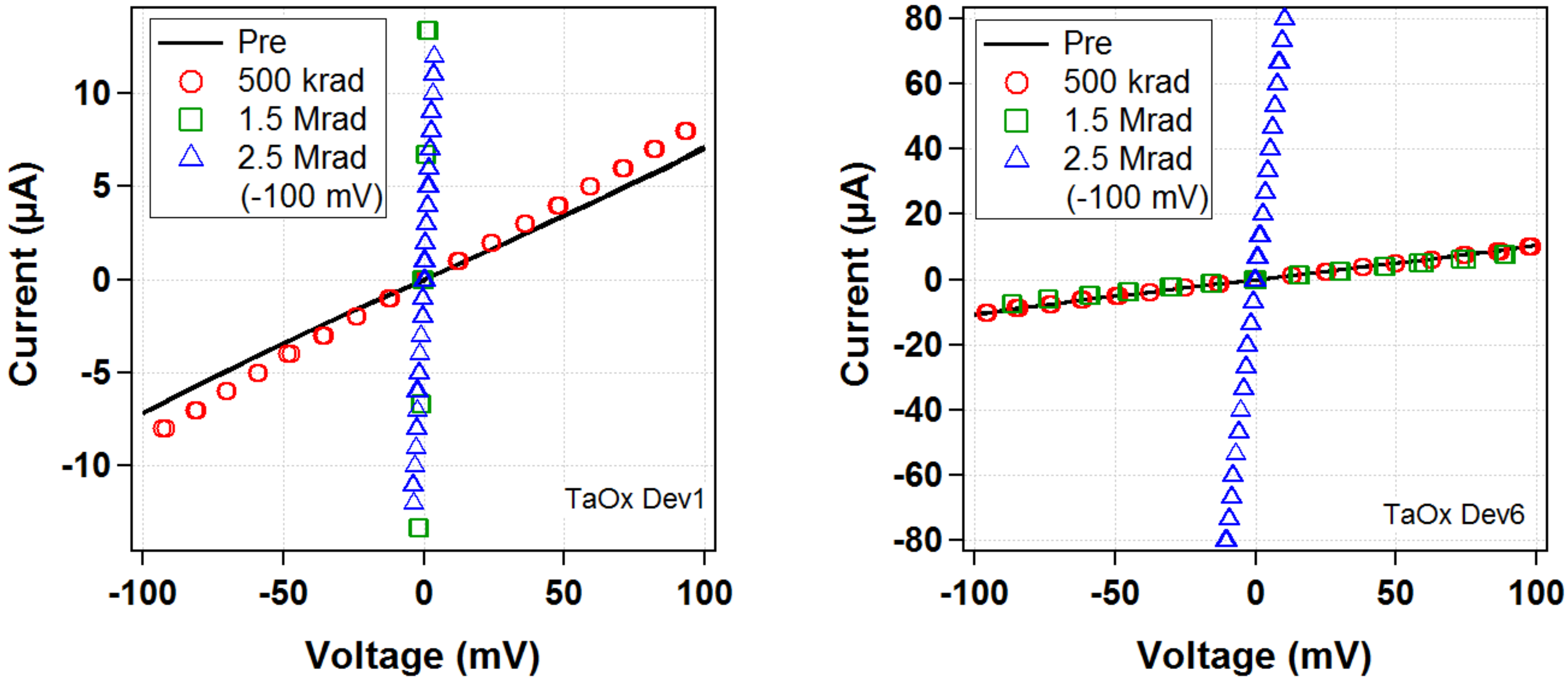
Co-60 γ-ray Response: Grounded



- All terminals grounded during irradiation
- Device #3 and #6 did not exhibit significant resistance changes
- R_{ON}= 100-200Ω
- $R_{OFF,3}$= 185kΩ; $R_{OFF,6}$= 6kΩ
- Both devices still functional following 3 Mrad(CaF_2)

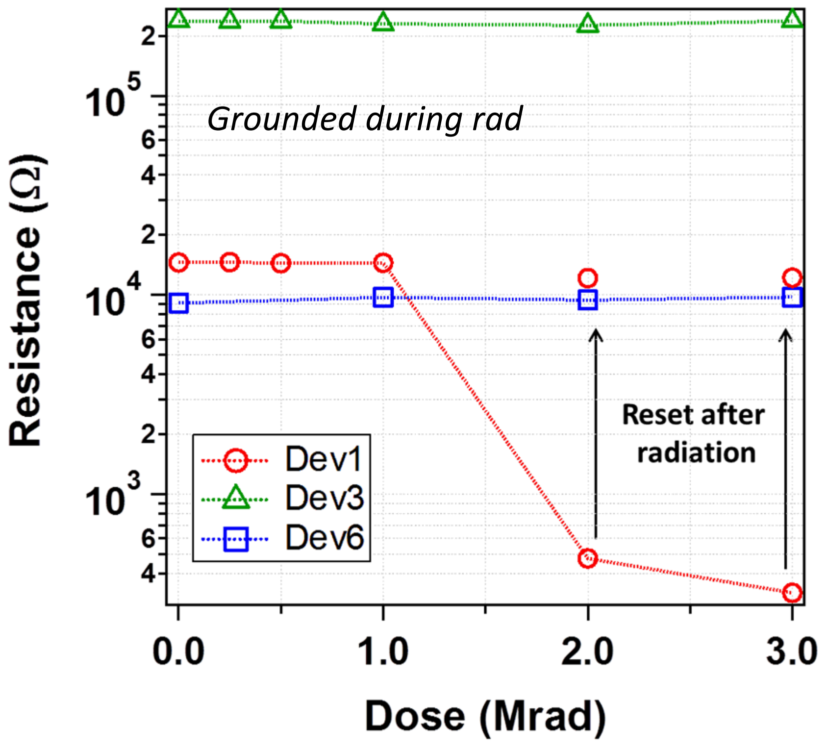
Investigating how device parameters such as thickness, R_{on}/R_{off} ratio, and electroforming impact the TID response

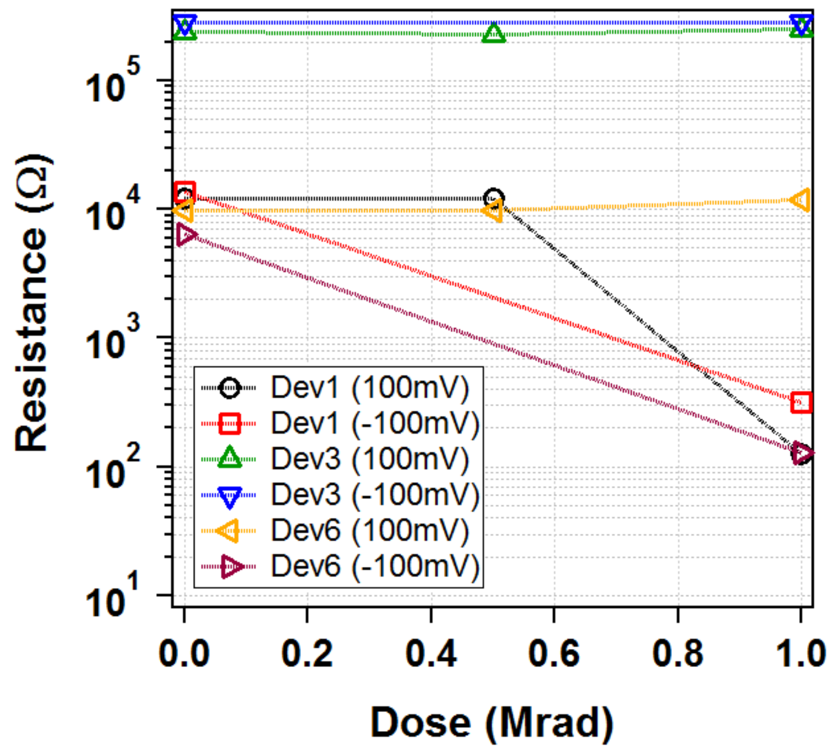
Biased Response



- 1 Hz, ± 100 mV square wave bias applied during irradiation
- Two devices switched resistance states after a 1 Mrad(CaF_2) step stress exposure when the applied bias was -100 mV
- Only Device #1 switched to a low resistance on-state when the applied bias was +100 mV during irradiation

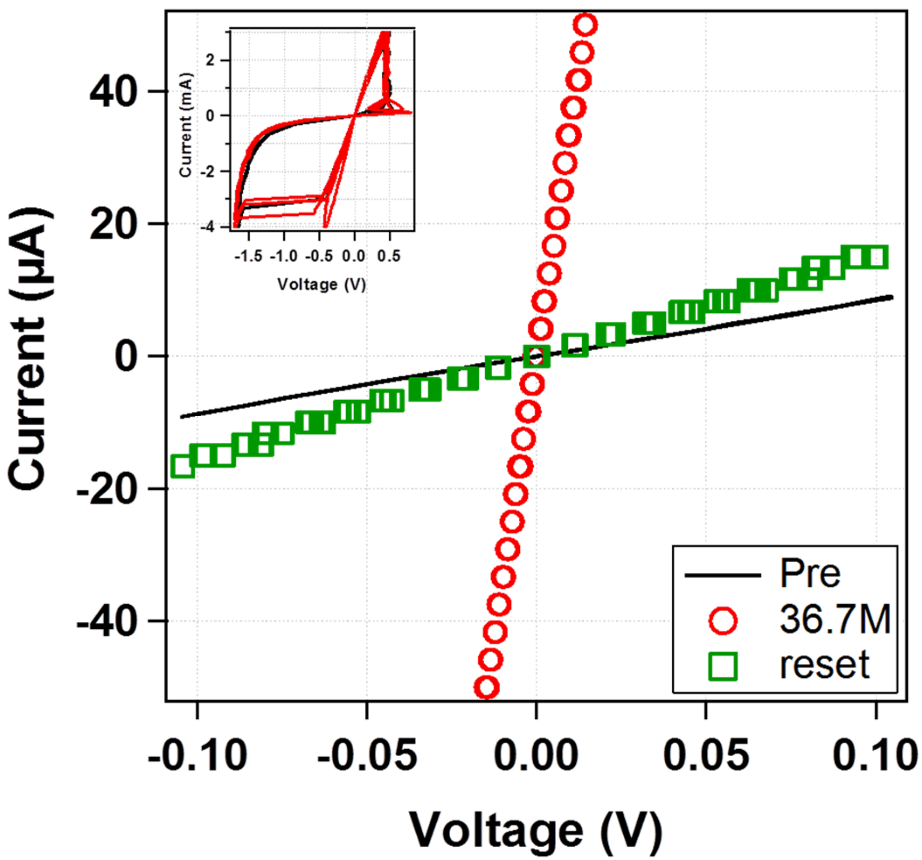
Resistance vs. Dose Rate





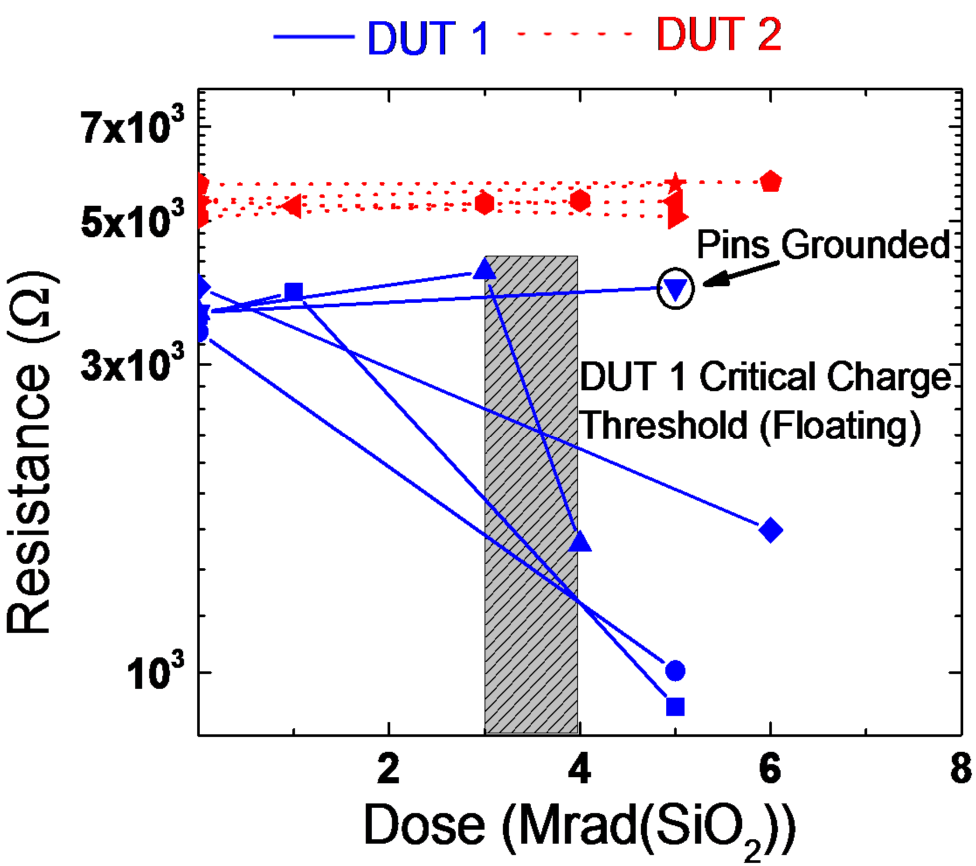
- **Resistance values calculated at a voltage of ~50 mV; x-axis represents the cumulative dose (left) or step stress exposure (right)**
- **In-situ read measurements performed immediately after radiation**
- **Data indicate that it is possible for devices to switch from off-state to on-state after step stress threshold has been surpassed**

High Dose Response



- Pre- and post-irradiation read sweeps for single device after 36.7 Mrad(CaF_2)
- 1 Hz, 100 mV square wave bias applied during irradiation
- Device still functional following exposure
- The Vortec cooler was not able to keep the ambient environment at room temperature during irradiation (reached approximately 50 °C)

10 keV X-ray Response



- Devices exposed to Si ions prior to X-ray exposure (may impact response)
- Minimal change in off-state resistance for DUT2
- DUT1 response dependent on TID level and bias condition
- DUT1 enters an intermediate state and not a low resistance on-state
- Devices functional following irradiation

Summary

- TaO_x memristors show excellent promise as a next-generation technology to be used in a rad-hard non-volatile memory
- Investigated response of TaO_x memristive devices in several radiation environments
  - TID: Varied response after a step stress of 1 Mrad (CaF_2); all devices still functional following 43 Mrad (CaF_2)
  - Heavy ions appear to create ordering and bubbling on surface
- Better understanding of variability in radiation response needed to determine if TaO_x (or another material) memristors are suitable for rad-hard electronics
  - Also need to better understand origin of variation in normal operation