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Overview of the Radiation Response of Anion-Based Memristive Devices

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Topics of Discussion

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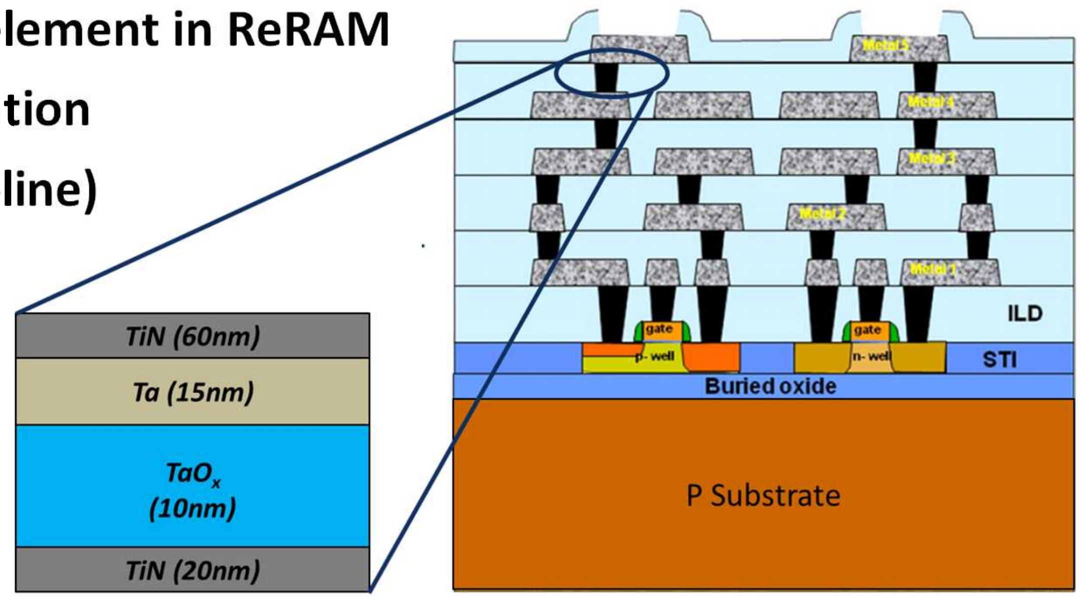
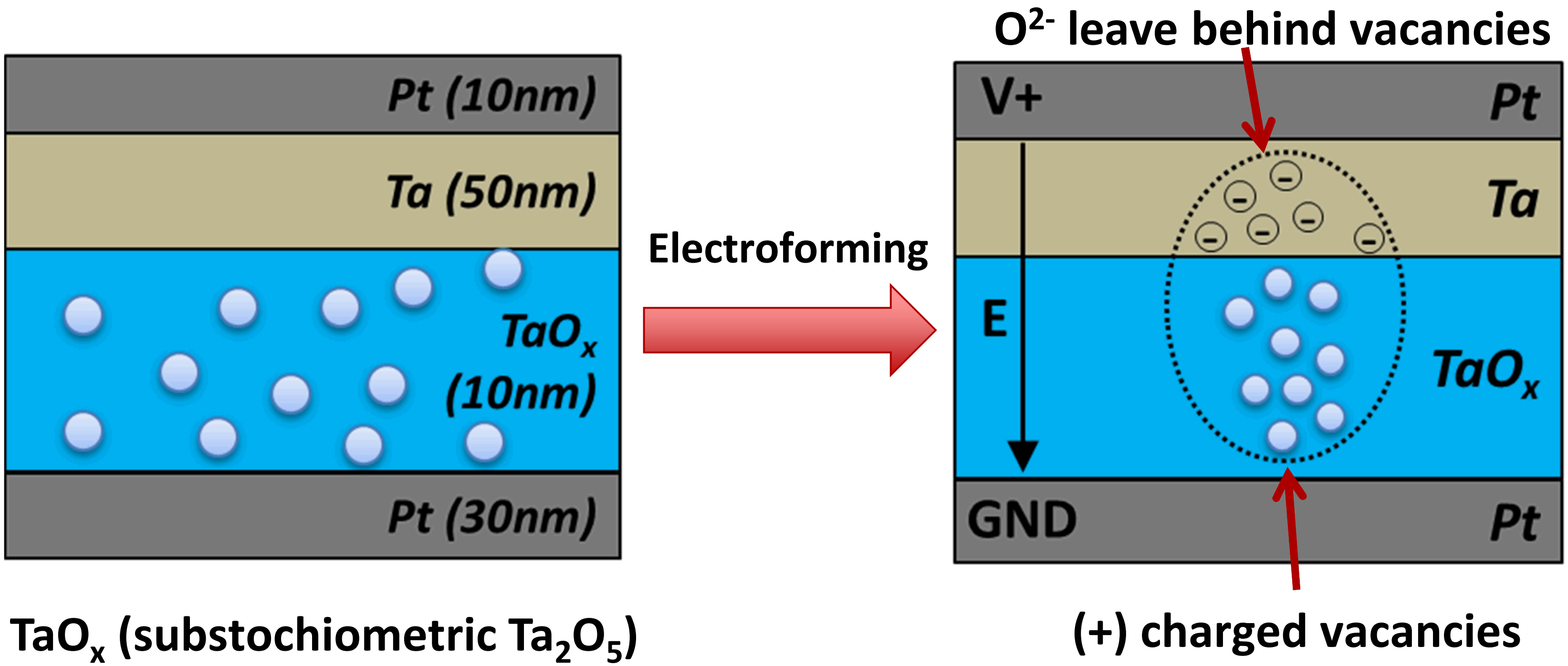
- **Background**
  - **Why do we care about memristors**
  - **Theory of operation for anion-based memristors**
- **Experimental Results and Discussion (focus will be on TaO_x memristors)**
  - **Transient Radiation Effects (i.e., Dose Rate)**
  - **Total Ionizing Dose vs Dose Rate**
- **Summary and Future Work**

Why Do We Care About Memristors

- **COTS nonvolatile memory (NVM) technologies commonly used to store mission critical information in space and aerospace systems**
- **Enable discovery of a technology to replace Flash as we reach Si scaling limits (rad-hard NVM important to rad community)**
- **ITRS has identified Resistive RAM (also known as redox or memristive or ReRAM) as one of the most promising future memory technologies**
  - **Memristors are storage element in ReRAM**
  - **Scalable and easy integration with CMOS (back-end-of-line)**
  - **High endurance**
  - **Long retention**
  - **Low switching energy**
  - **High speed**



How a TaO_x Memristor Works



TaO_x (substochiometric Ta_2O_5)

- Memristors are two terminal metal-insulator-metal devices characterized by a low resistance on-state and high resistance off-state
- Switching mechanism involves redox reactions and transport of oxygen anions
  - Electric and thermal fields cause dissociation and transport of oxygen anions, leaving behind positively charged oxygen vacancies
- Processes lead to formation of Ta-rich conducting filament of a certain radius

How a TaO_x Memristor Works

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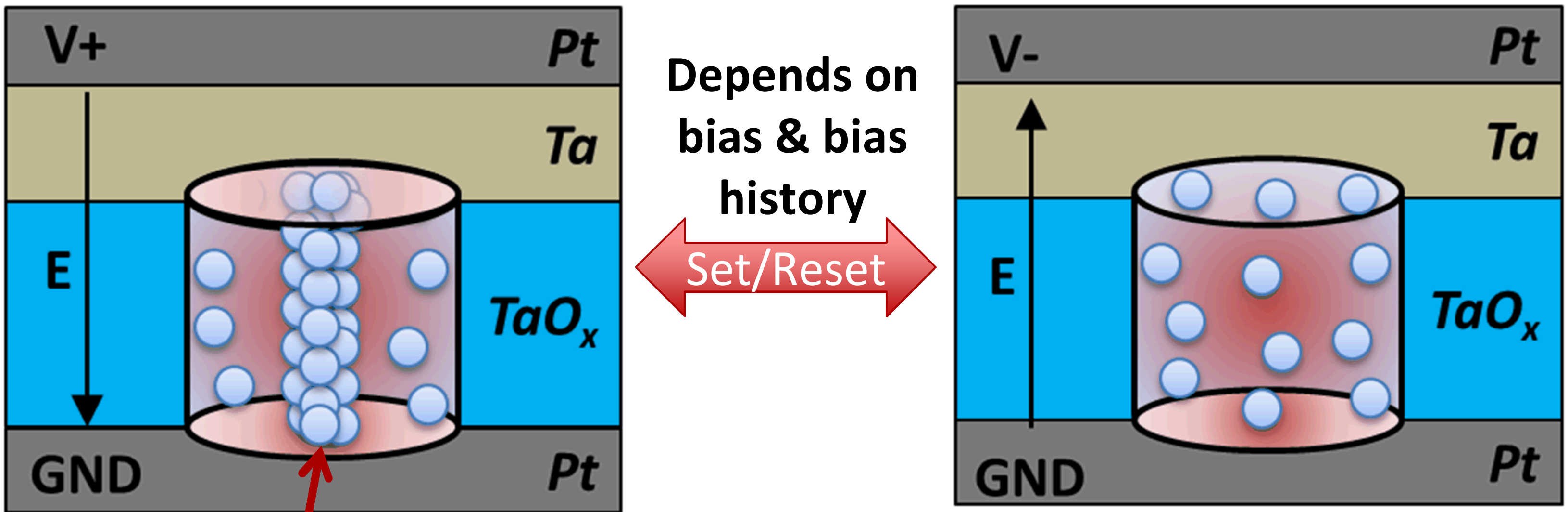

Filament formation in insulator
Low resistance on-state

No filament
High resistance off-state

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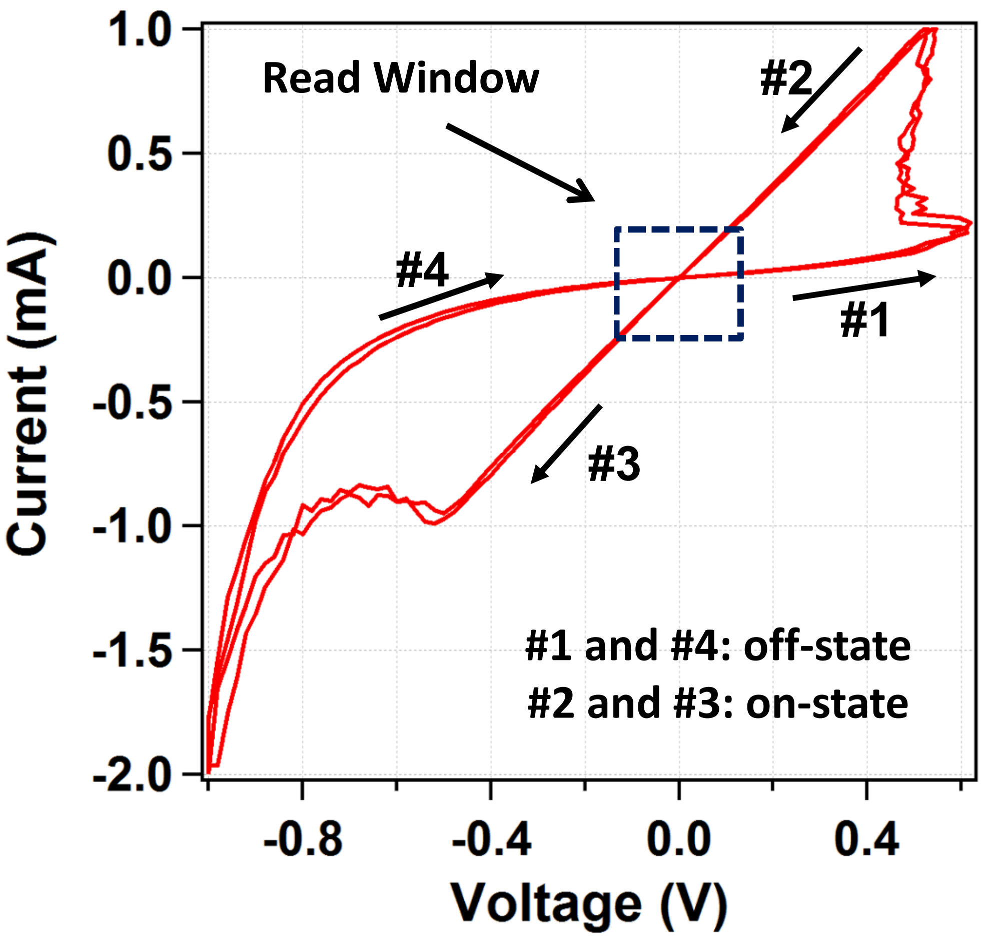
Electrical Characteristics



- Applied current and voltage can change resistance state
  - Hysteresis loop
- In memory applications, pulsing technique will be used to set/reset
- Lower "read" voltage pulses are applied to the device to measure the resistance level
- A read operation does not change the resistance state of the device

Radiation Effects Overview

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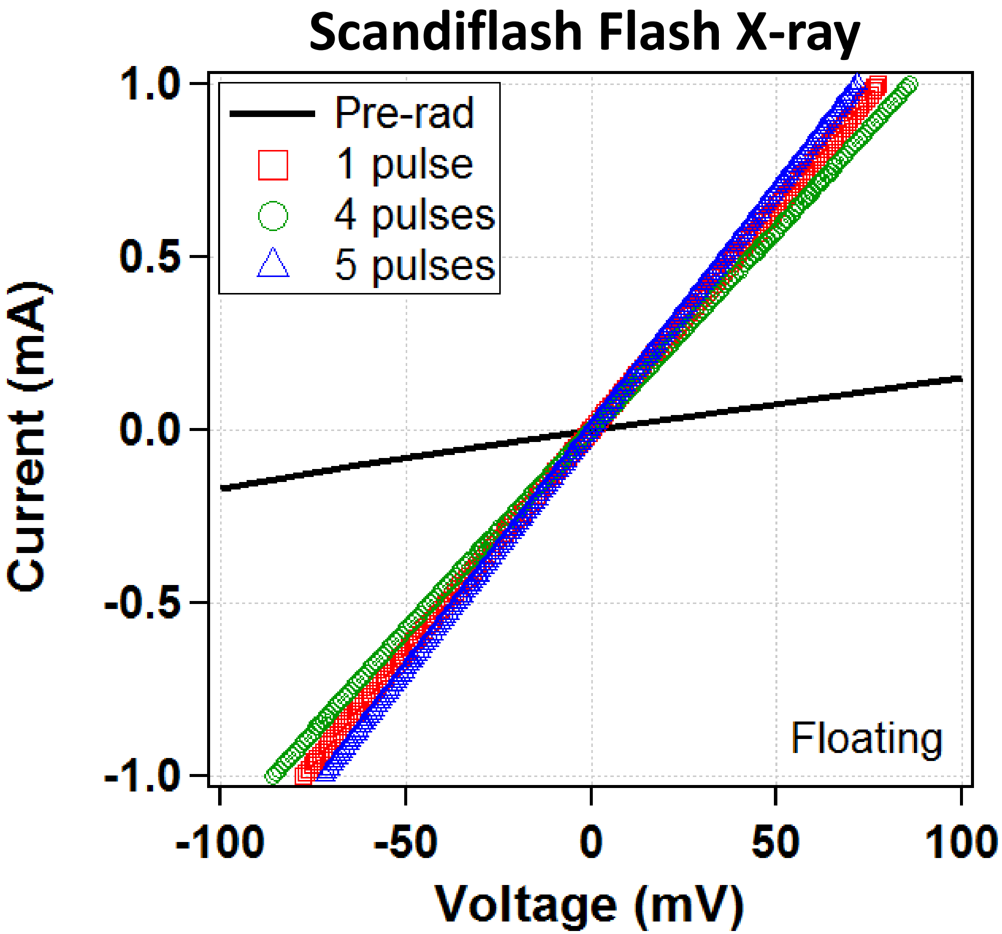
- **Transient Radiation Effects**
  - Scandiflash Flash X-ray source used to investigate susceptibility of on-state and off-state to dose rate upset (static experiments)
  - Also examined impact of bias configuration (floating or grounded)
  - Active measurements obtained on memristive devices using a LINAC for varying dose rates and pulse widths
- **TID Effects**
  - TID studies performed using a LINAC other electron beam sources
  - Co-60 and 10 keV X-ray TID experiments performed at lower dose rates (in paper)
- **Displacement Damage Effects (in paper)**
  - Heavy ion experiments performed at IBL

Dose Rate Response: Floating



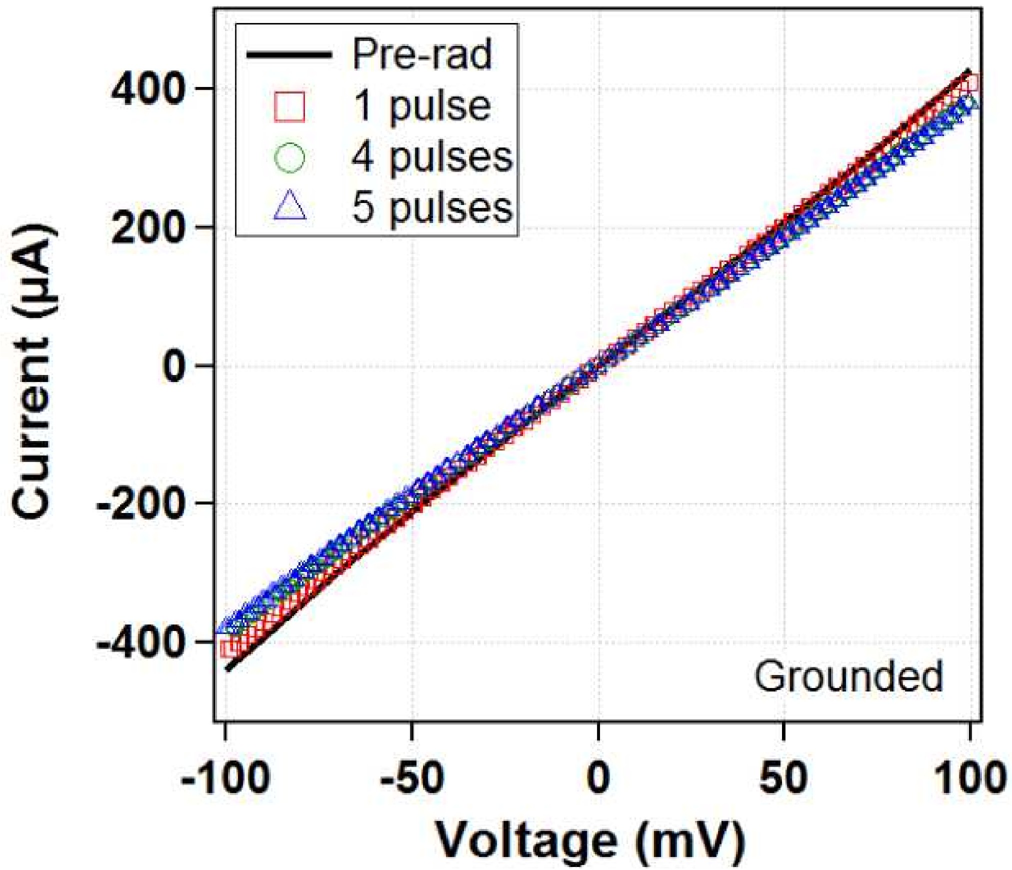
- Investigated susceptibility of on-state and off-state to dose rate upset
- Device terminals floating during irradiation
- Dose rate ~3 x 10^8 rad(Si)/s; pulse width ~35ns; 600 keV endpoint energy
- All devices still functional following irradiation

When floating, two of the four devices switched from off-state to on-state

(after McLain, et al., IEEE TNS 2014)

Dose Rate Response: Grounded

Scandiflash Flash X-ray

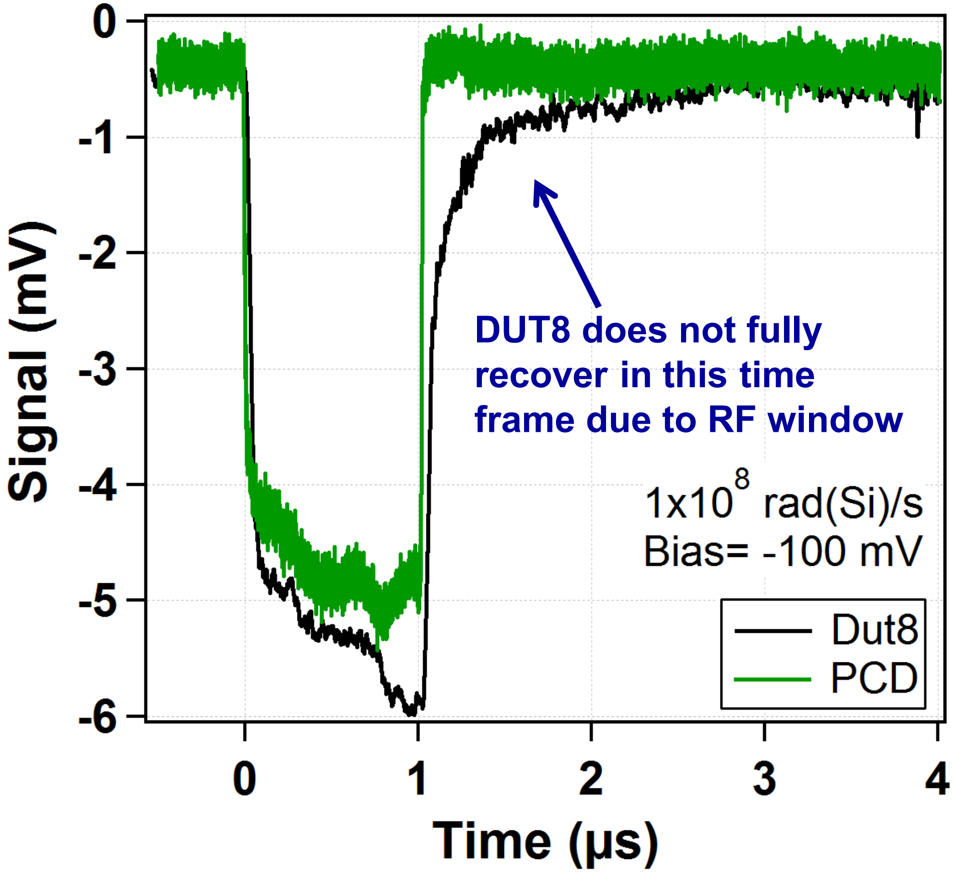


- All terminals shorted to ground during irradiation
- Dose rate ~3 x 10^8 rad(Si)/s
- No devices had resistance changes (off-state or on-state) when grounded
- Similar results obtained when all terminals shorted but left floating

Circuit configuration appears to have significant impact on rad response

(after McLain, et al., IEEE TNS 2014)

Transient Dose Rate Response



- Voltage divider between memristor and 50 Ω on scope
- Device recovered to pre-rad level after 1 µs exposure
- PCD normalized to fit on plot
- Not all devices exhibited a measureable transient signal
- Dose rate: $1x10^8$ rad(Si)/s

Exploring impact of radiation-induced transient spikes on the operation

(after McLain, et al., IEEE TNS 2014)

Transient Dose Rate Response

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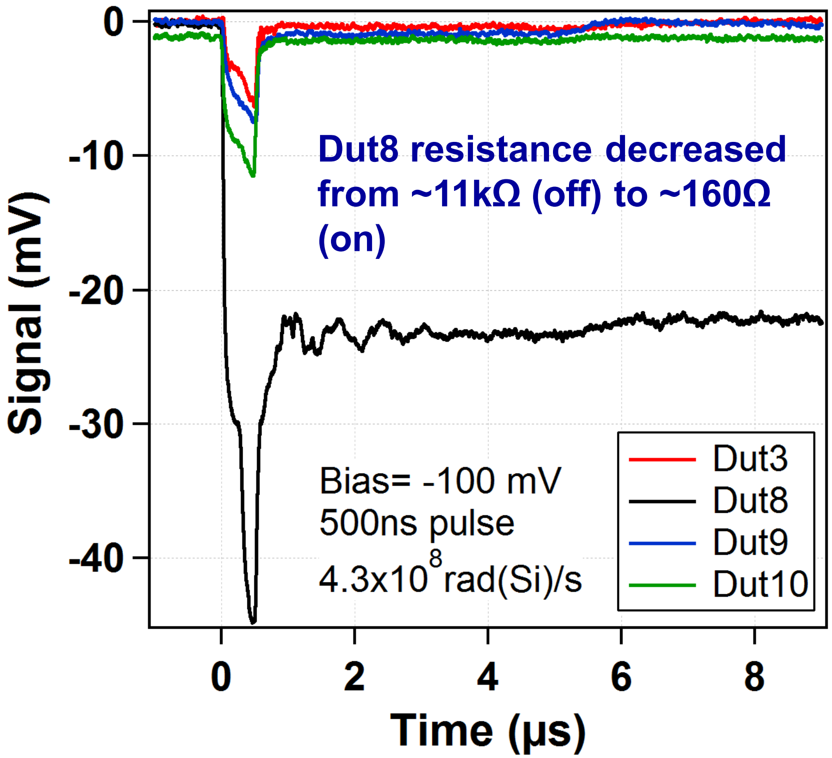
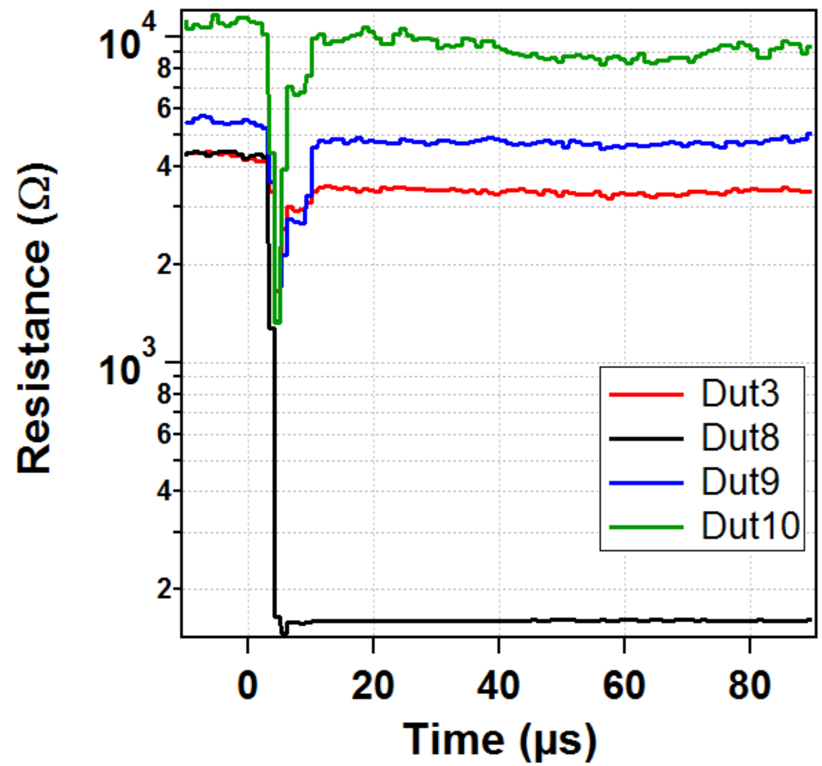
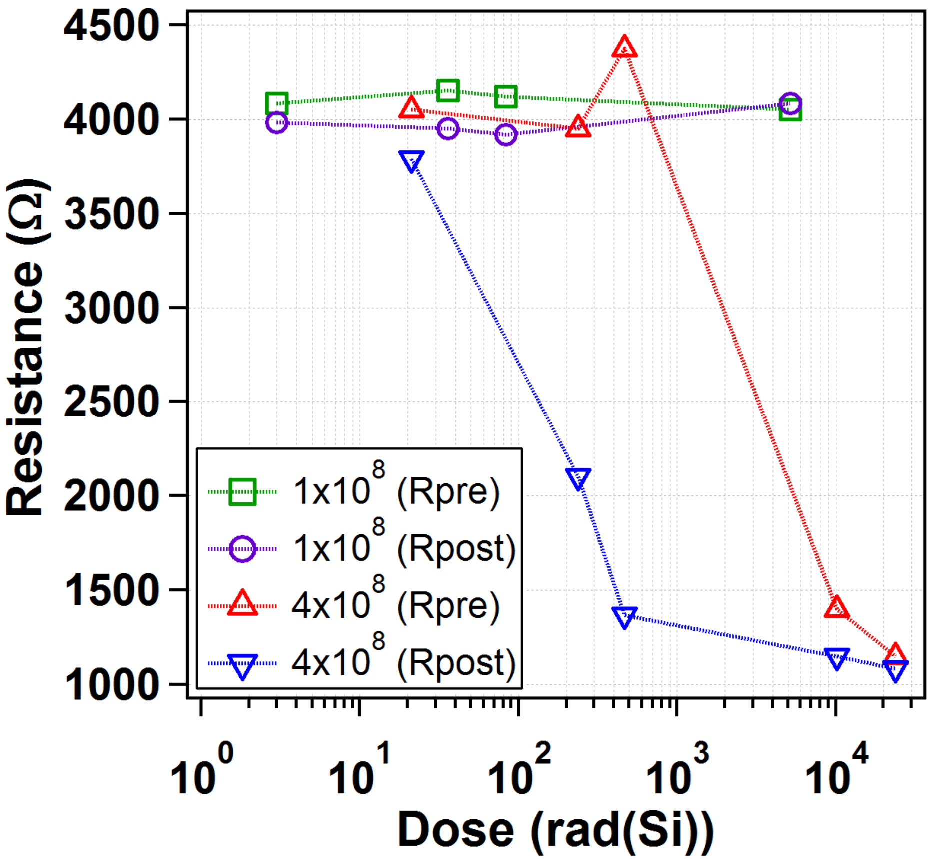




Radiation-induced switching and resistance changes were observed in some devices at a nominal dose rate of 4.0×10^8 rad(Si)/s but not below

(after McLain, et al., IEEE TNS 2014)

Dose versus Dose Rate Effects



- **Pre- and post-exposure resistance versus dose for a single device at different dose rates**
- **At higher dose levels, but lower dose rates, the DUT did not switch states**
- **At lower dose levels, but higher dose rates, the DUT switched states**

Suggests that the dose rate (i.e., rate of energy deposition) is the cause of the resistance changes and not the dose

Summary

- <u>Transient Radiation Effects</u>
  - At higher dose rates, it is possible for the devices to switch from a high resistance off-state to a low resistance on-state
  - Dose rate (i.e., rate of energy deposition) appears to be the cause of the resistance changes and not the dose in the LINAC experiments
  - Devices more sensitive to rad-induced switching when floating
- <u>Total Ionizing Dose Effects</u>
  - Experiments have shown that the devices will switch states after a critical charge is surpassed (much higher than most applications)
  - Devices more sensitive to rad-induced switching when floating
  - If read measurement performed prior to reaching dose threshold, the devices 'reset' back to a pre-irradiation state
- <u>Displacement Damage Effects</u>
  - Technology shows a high threshold to displacement damage
  - Data indicate that there are cumulative effects

Future Work

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- TaO_x memristors show excellent promise as a next-generation technology to be used in a rad-hard NVM
- Better understanding of variability in radiation (and normal) response necessary before integration into actual application
- Explore possible reasons for the enhanced susceptibility:
  - Volume of memristive layer and thinning of active layer at the edges
  - Electroforming step stresses devices differently which impacts filament formation, vacancy density, reliability

Backup

Motivation

- **To evaluate the effects radiation (TID, displacement damage, and transient radiation effects) on next-generation anion-based memristive devices**
- **The primary focus will be on tantalum oxide (TaO_x) memristors (paper also discusses TiO_2 and HfO_x)**

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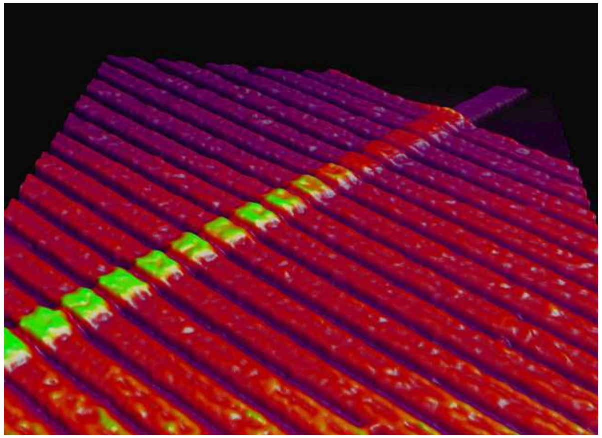
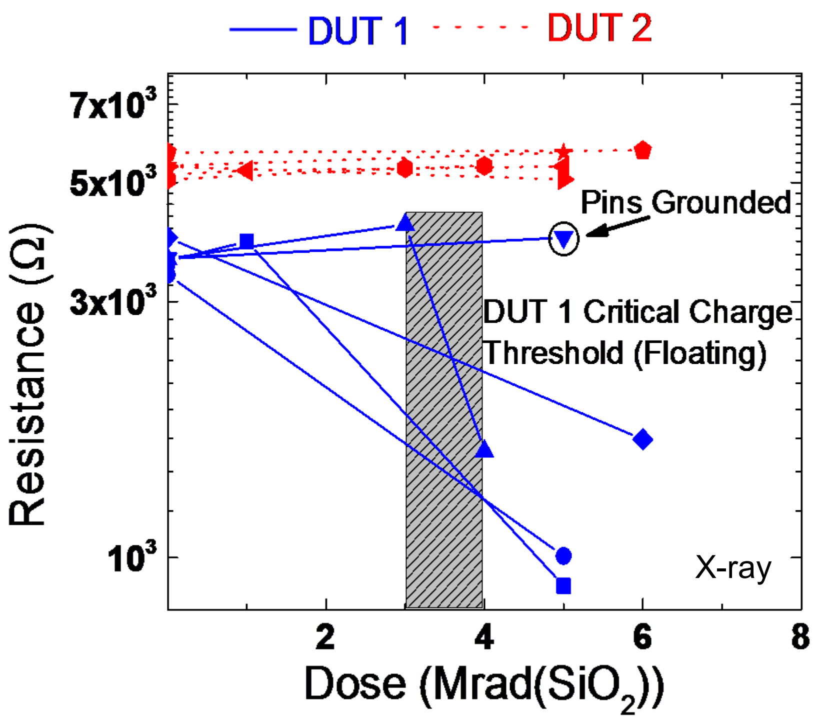
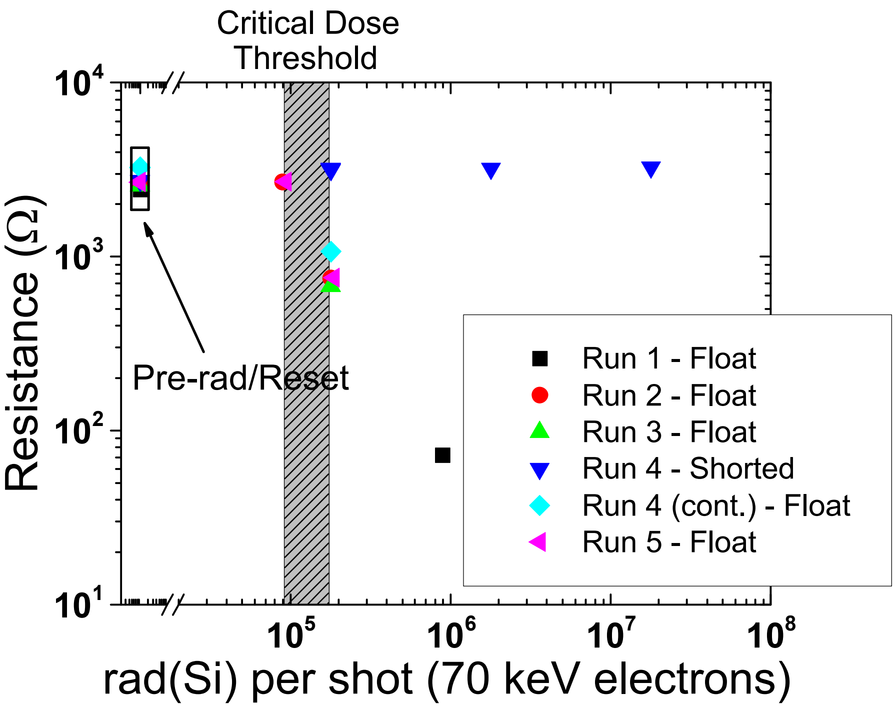


Possible Flash replacement: ReRAM/ RRAM/REDOX Memory

Enable discovery of a radiation-hardened nonvolatile memory (NVM) technology to replace Flash as Si based technologies reach scaling limits

Critical Dose Threshold

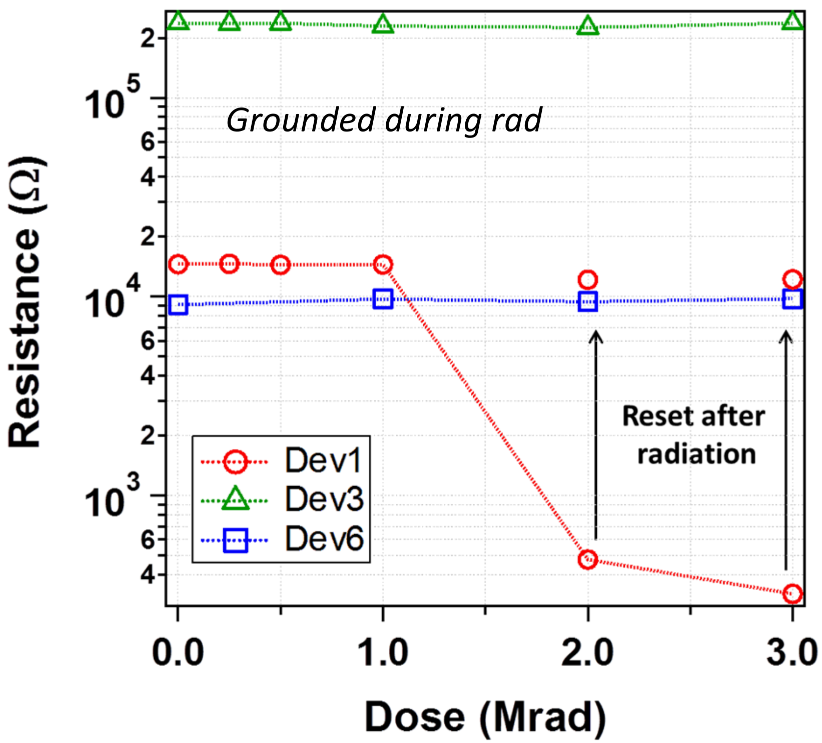


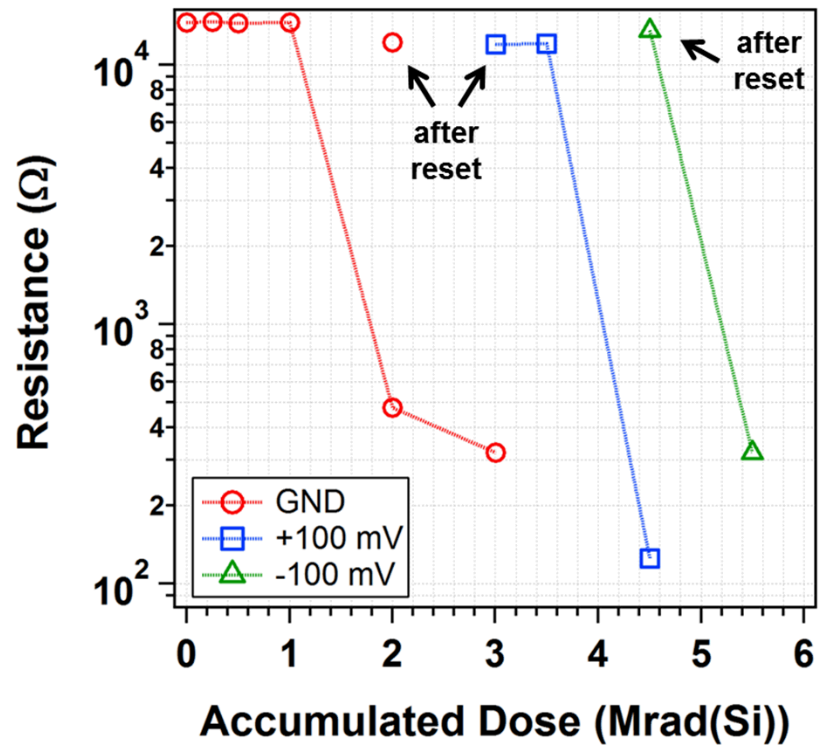


Radiation-induced switching and resistance changes were observed in the floating devices after a critical dose threshold is surpassed

(after Hughart, et al., IEEE TNS 2014 and IEEE Aerospace 2014)

Resistance vs. γ-ray TID





- **Data indicate that it is possible for devices to switch from off-state to on-state after step stress threshold has been surpassed (need to understand variation)**
- **Ionization experiments at IBL showed resistance change after a critical charge is surpassed**

800 keV Ta (Displacement Damage)

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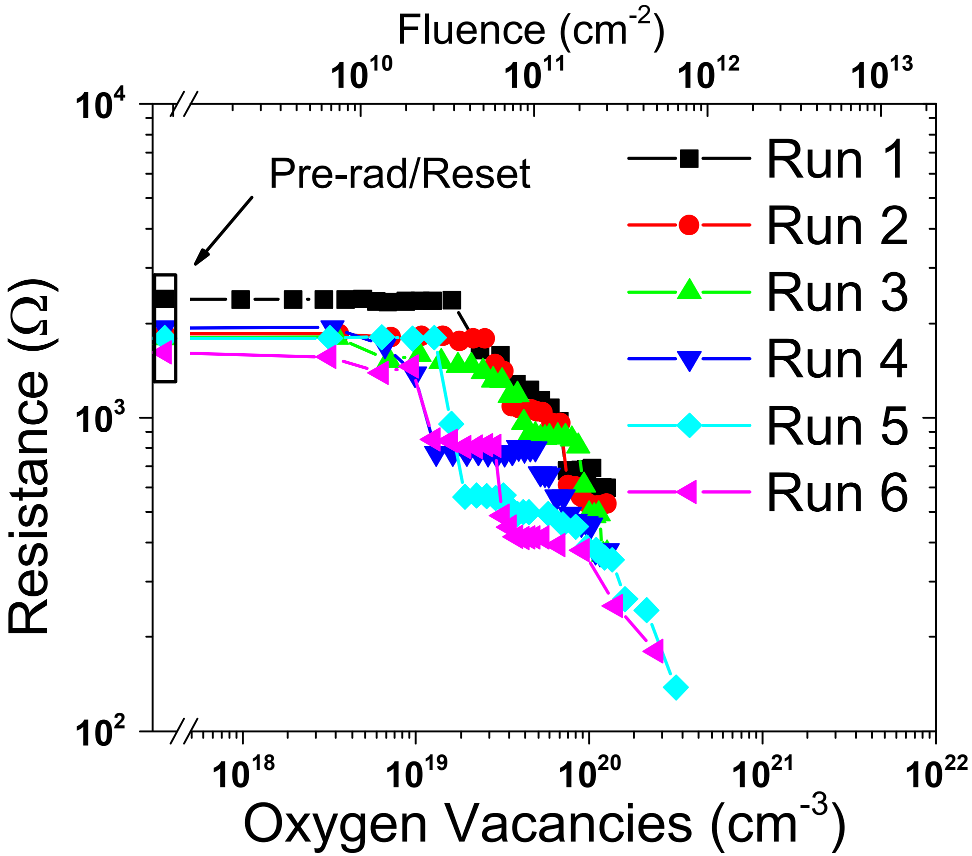

- **Gradual resistance degradation due to displacement damage**
- **Resistance changes not observed until ~10^{19} cm^{-3} vacancies created**
- **Reset operation recovers device but not to original state (cumulative damage)**

Cumulative damage likely due to the fact that not all of the added O vacancies are removed by oxidation/diffusion

(after Hughart, et al., IEEE TNS 2014)