SAND2013-5541C

A Comparison of the Radiation Response of TaO_x and TiO_2 Memristors

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This work was supported Sandia's Laboratory Directed Research and Development and the Defense Threat Reduction Agency

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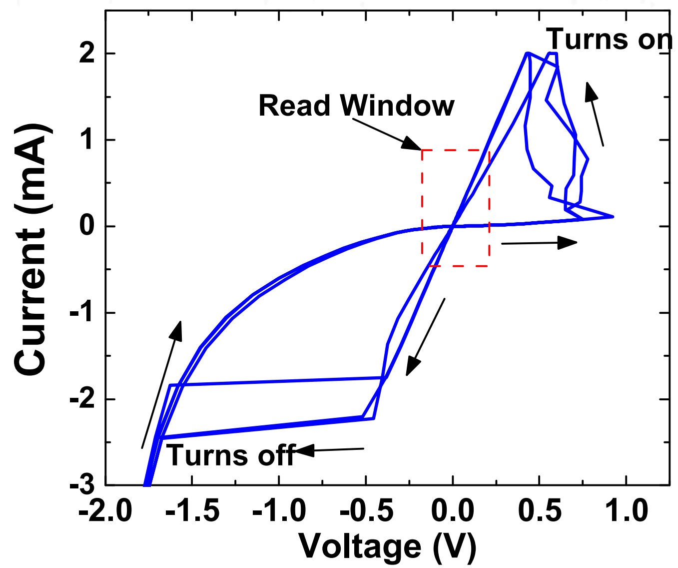
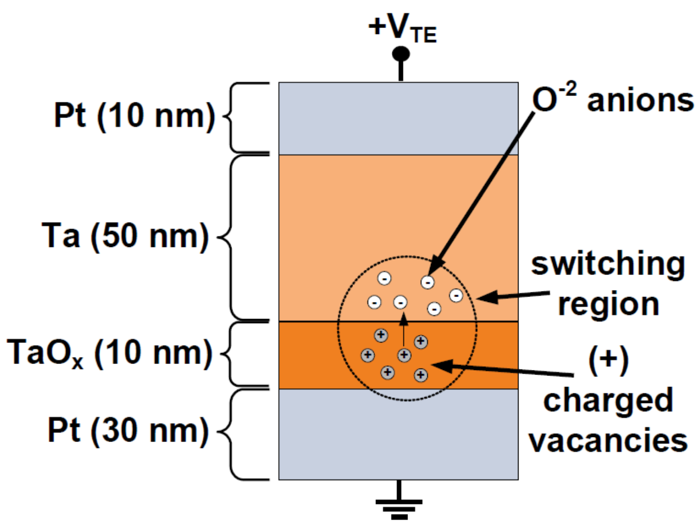
Why Memristors?

- Current nonvolatile memory (NVM) technologies like Flash are expected to be increasingly limited by scaling
- Resistive RAM (ReRAM) is a strong candidate to replace Flash with many promising performance metrics
  - Scalability
  - Endurance
  - Speed
  - Low power
- State of the art is rapidly advancing
- TaO_x and TiO_2 radiation effects
  - High tolerance for both displacement damage and ionization
  - Different responses at high damage levels

Memristor I-V Characteristics

- Resistive RAM (ReRAM) is a memristor
- Applied current and voltage can change resistance state
  - Hysteresis loop
- Low voltages can read state
  - Read window

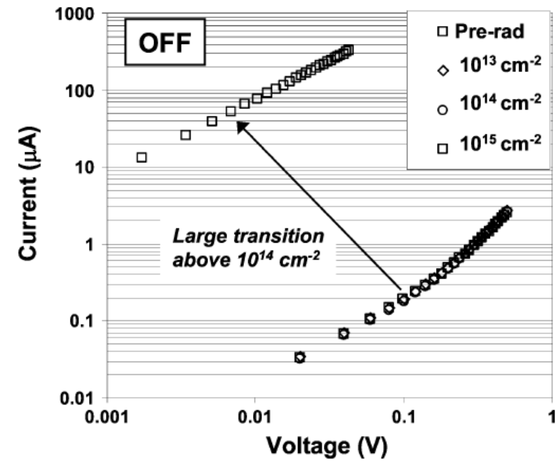




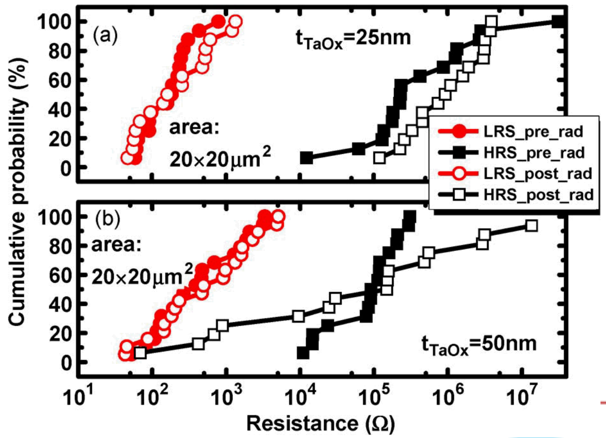
- Resistive switching
  - Oxygen vacancies
- TaO_x
  - Oxygen anions

Previous Radiation Experiments

- TiO_2
  - 45 Mrad(Si) γ-rays and 23 Mrad(Si) Bi ions
  - 1 MeV alpha particles
  - 10^{14} cm^{-2} fluence
- TaO_x
  - Thickness dependence from Peking University
  - Varying responses to TID seen previously by Sandia
  - Heavy ions and displacement damage



Barnaby *et al.*, *Trans Nuclear Sci*, vol. 58, pp. 2838-2844, 2011.

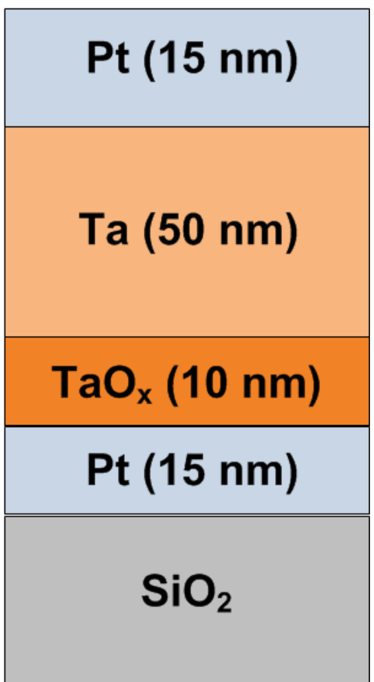


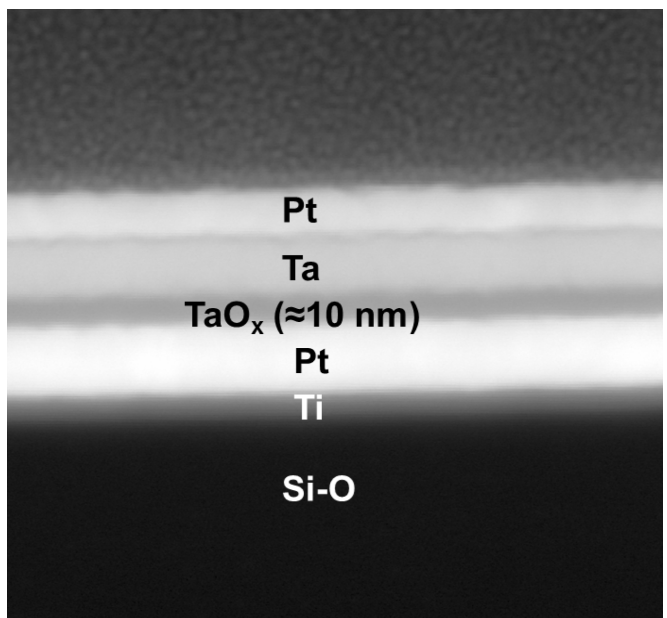
Ion Beam Experiments

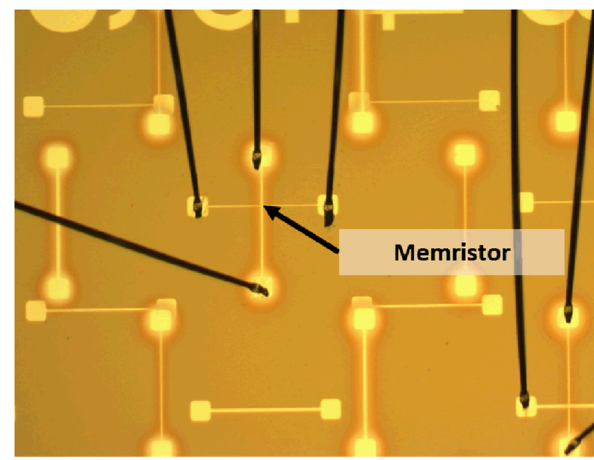
- 800 keV Ta ions and 28 MeV Si ions
  - Displacement damage vs. ionization
- Parts irradiated in vacuum
  - Sequence of runs
  - Full set/reset cycle between runs
  - Read sweeps between shots
- Fluence values have been translated to oxygen vacancy concentration and rad(Si) via SRIM calculations
  - Charge yield is not accounted for

Experimental Details

- All samples use same stack:
  - SiO_2(substrate)/Ti/Pt/TaO_x/Ta/Pt
- Random "dogbone" shadow mask
  - Memristors formed at crossing electrodes

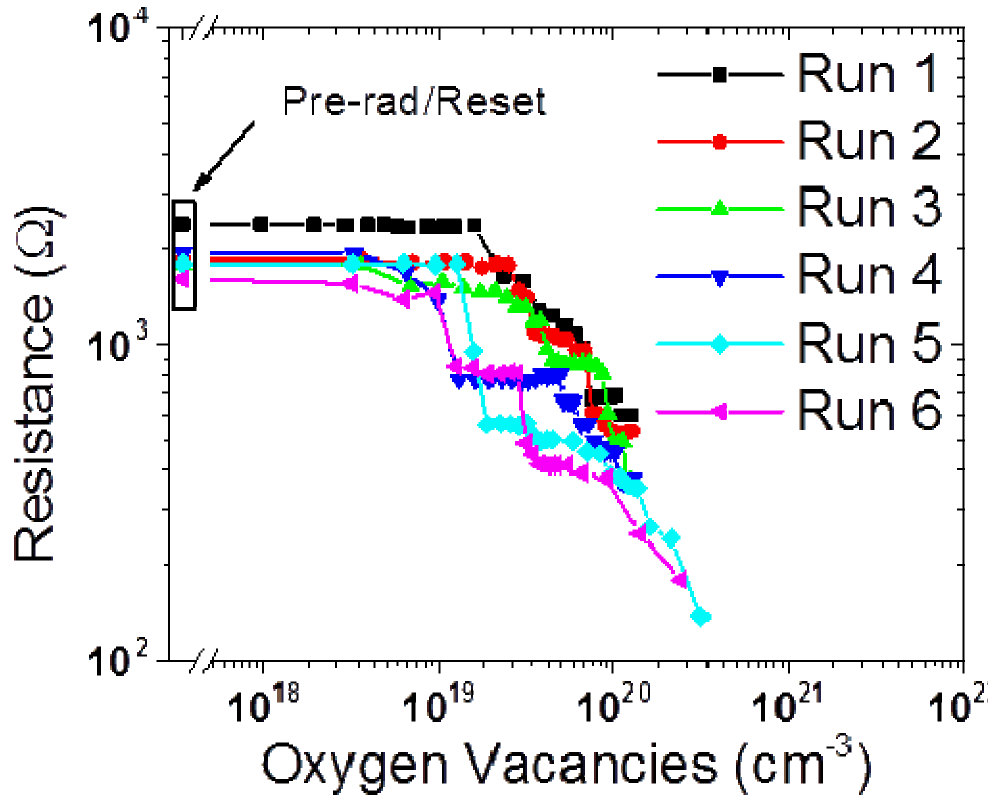






800 keV Ta Irradiation - TaO_x

- Gradual resistance degradation
- Creation of oxygen vacancies
  - Threshold ~10^{19} cm^{-3}
- Reset operation recovers significant portion of resistance loss
  - Cumulative damage



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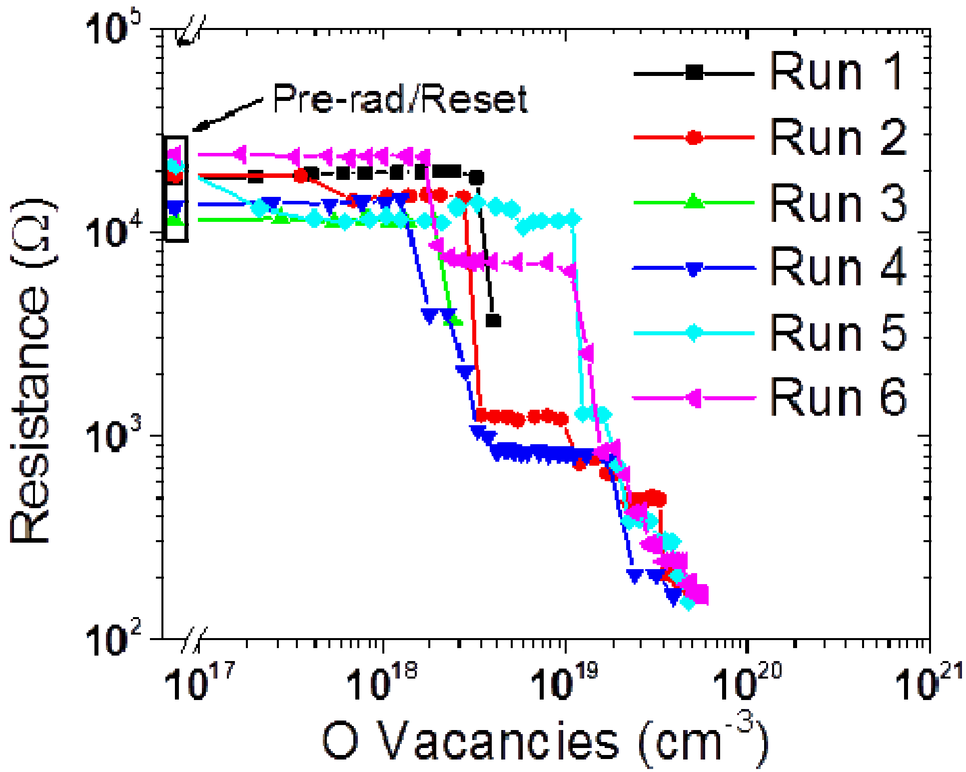
Displacement Damage Accumulation and Annealing

- **Percolation model for resistive switching**
- **Cumulative damage**
  - **Not all oxygen vacancies removed by oxidation/diffusion?**
- **Repeated resetting can return device closer to original state**
  - **Runs 5 and 6**



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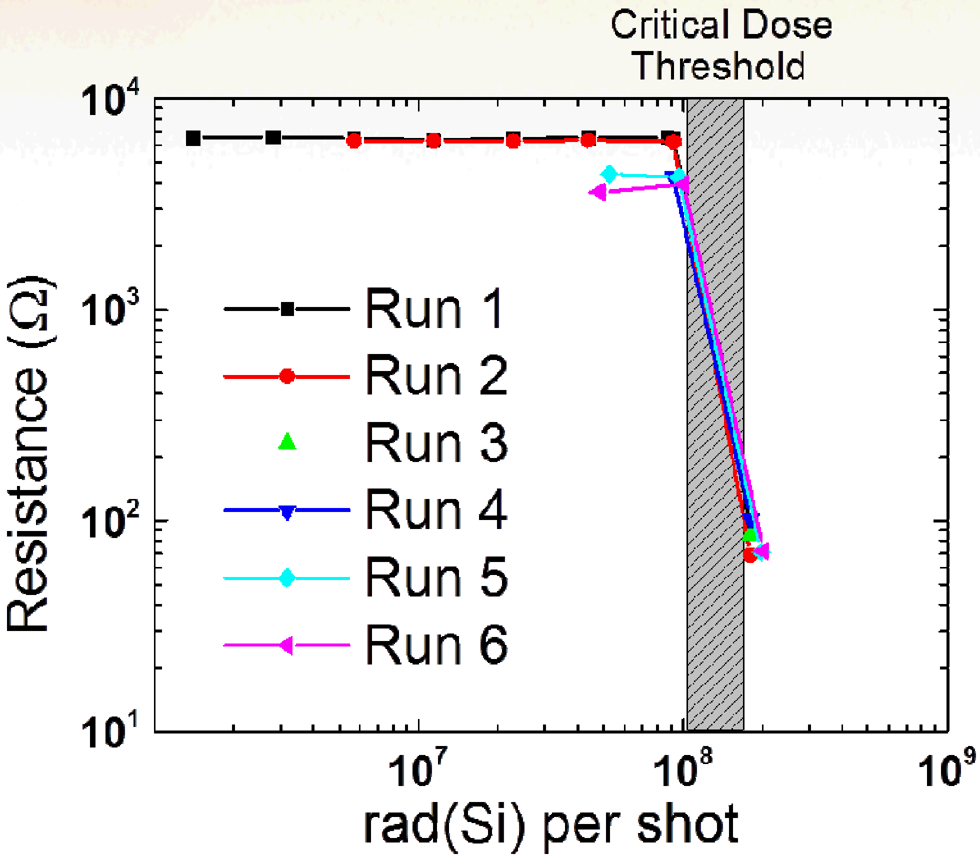
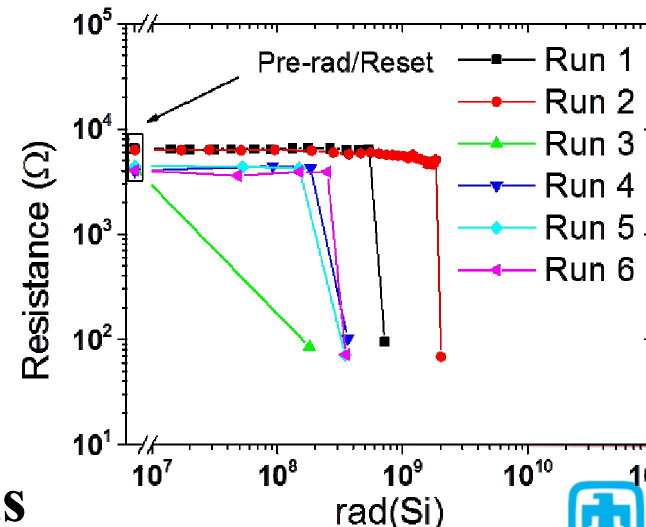
28 MeV Si Irradiation - TaO_x



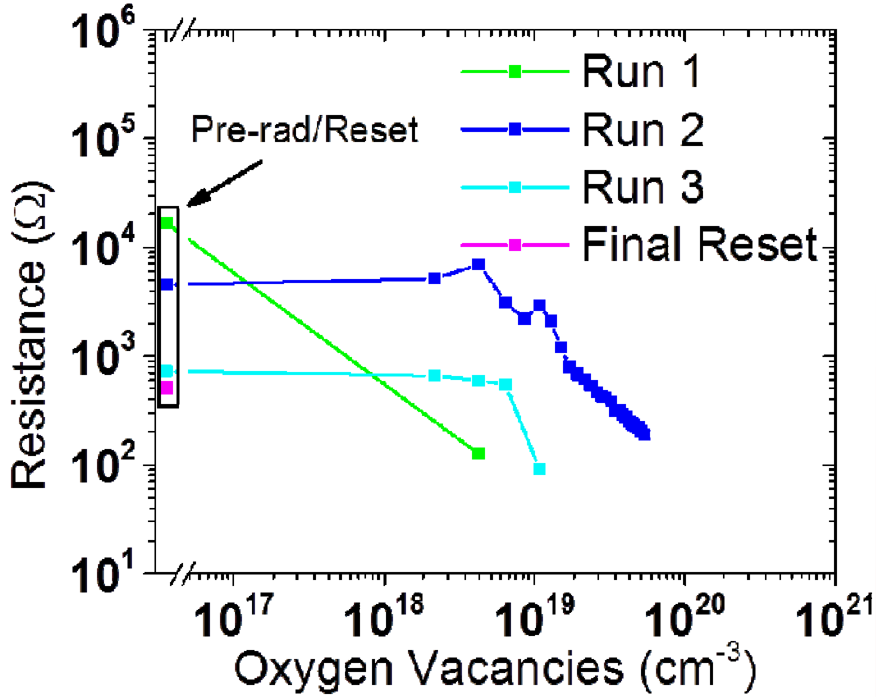
- **Resistance change abrupt and consistent**
  - **Different mechanism**
- **Ionization**
  - **Rad(Si) per shot**
- **Threshold ~200 Mrad(Si)**



- **Critical dose per shot threshold**
  - **Cumulative between reads**

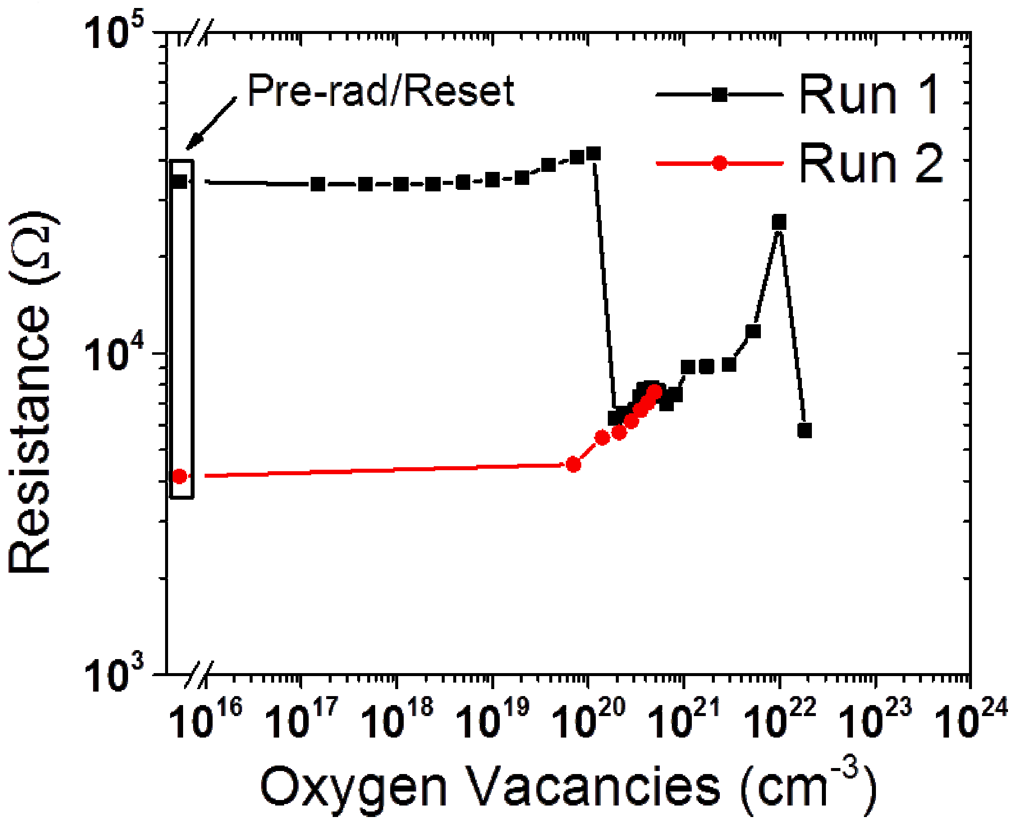
28 MeV Si Irradiation - TaO_x

- 28 MeV primarily causes ionization
  - Displacement damage mechanism still present
- Shots in run two half of critical dose threshold
- O vacancy threshold ~6.5×10^{18} cm^{-3}
  - Consistent with 800 keV Ta
- Dose threshold ~1.8 Grad(Si)
  - 10x larger than 800 keV Ta
  - Charge yield or variation



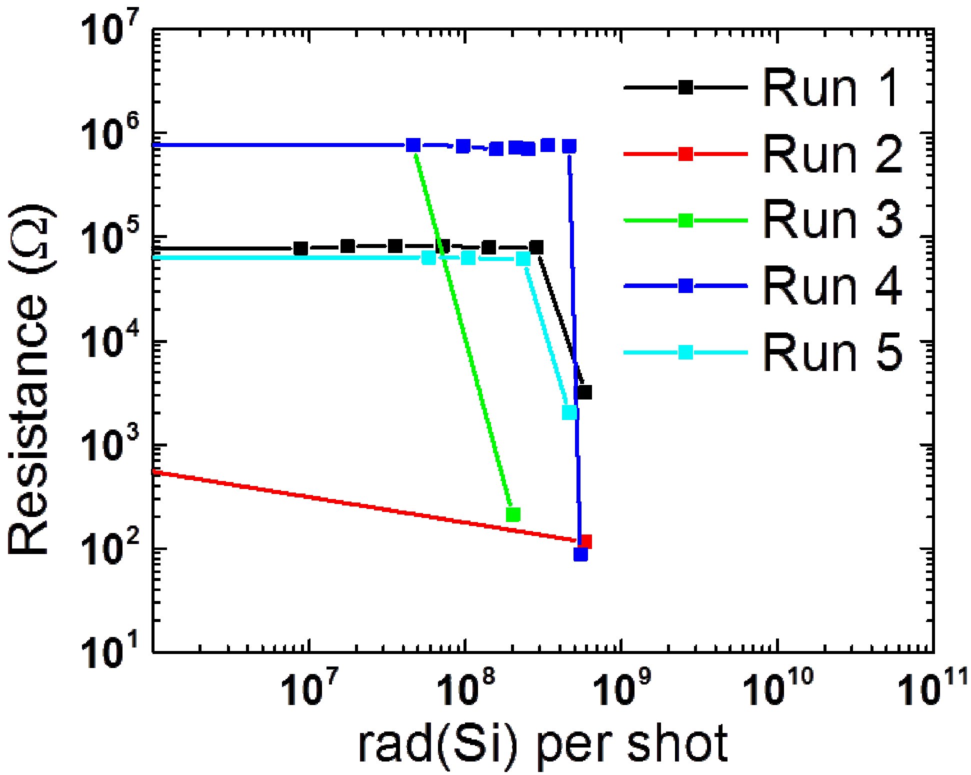
800 keV Ta Irradiation – TiO_2

- Gradual increases in resistance with inconsistent abrupt decreases
  - R_{OFF} doesn't drop to on-state values
- Post-rad behavior inconsistent
  - High variability
  - Degrading R_{OFF}
  - Higher reset current may be needed



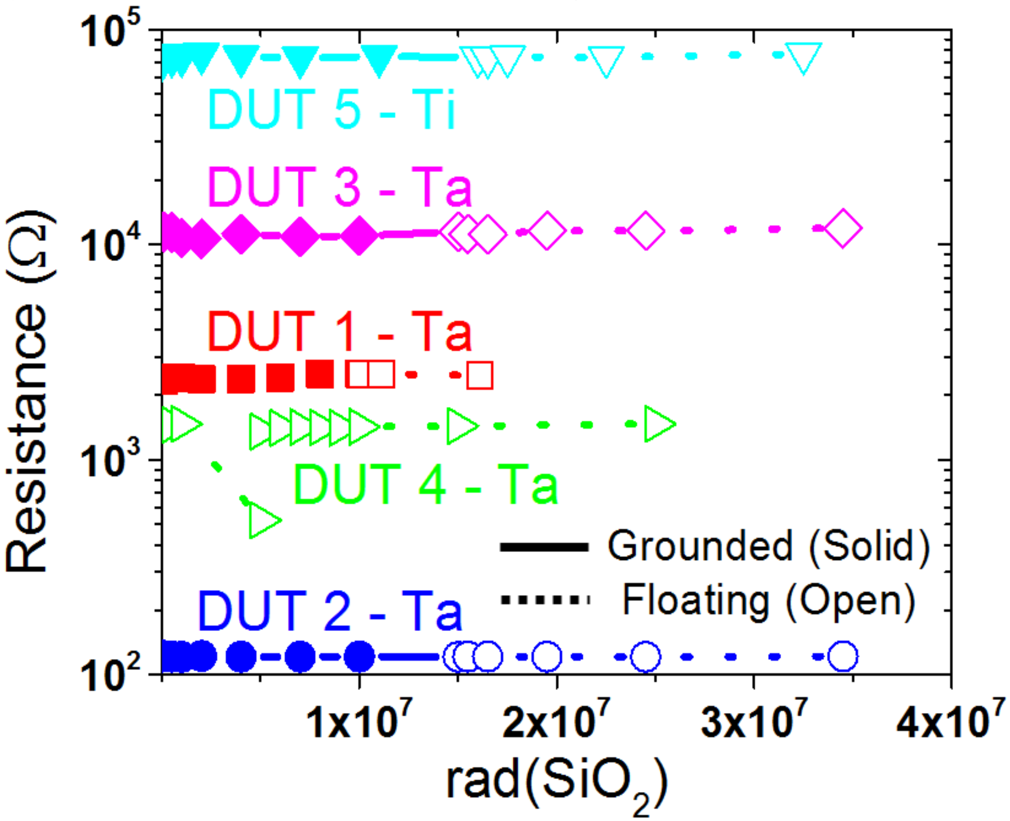
28 MeV Si Irradiation – TiO_2

- Similar critical dose per shot between read sweep threshold behavior
- Variability in resistance to which device switched
- Four upsets occurred at 500 Mrad(Si)
  - One at 250 Mrad(Si)



10 keV X-ray – TaO_x and TiO_2

- **Grounded and floating**
  - Steps up to 10 Mrad(SiO_2)
- **DUT 4 changed resistance at 4 Mrad(SiO_2)**
  - No lasting damage
  - Unrepeatable
- **No other effects on any devices**



Summary and Conclusions

- Both TaO_x and TiO_2 memristors appear to be tolerant to very high levels of radiation
  - 200 Mrad(Si) to 2 Grad(Si) calculated dose from 28 MeV Si ions and at least 10 Mrad(SiO_2) from 10 keV X-rays
  - Fluences of 10^{10} cm^{-2} for 800 keV Ta and 5×10^{12} cm^{-2} for 28 MeV Si
- Displacement damage
  - TaO_x: Gradual resistance decrease above ~10^{19} cm^{-3} oxygen vacancies
  - Post-rad cycling can restore degraded resistance
  - TiO_2: Gradual resistance increases with inconsistent abrupt decreases above ~10^{19} cm^{-3} oxygen vacancies
  - Post-rad cycling can lead to further degradation and high variability

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Summary and Conclusions (cont.)

- **Ionization – TaO_x and TiO_2**
  - **Ionizing dose per shot between read sweep critical threshold**
  - **Threshold can range from 200 Mrad(Si) to 2 Grad(Si) calculated for 28 MeV Si ion irradiation**
  - **Little change from 10 keV X-rays up to 10 Mrad(SiO_2) steps and 35 Mrad(SiO_2) cumulative**
  - **Applying small read voltages may bleed charge and prevent resistance switch**

- **TaO_x and TiO_2 memristor characteristics appear unchanged at high total doses and fluences and show great promise for future radiation-hardened non-volatile memory applications**