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Radiation Effects on TaO_x ReRAM: A Candidate for Rad-Hard Memory

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Sandia National Laboratories

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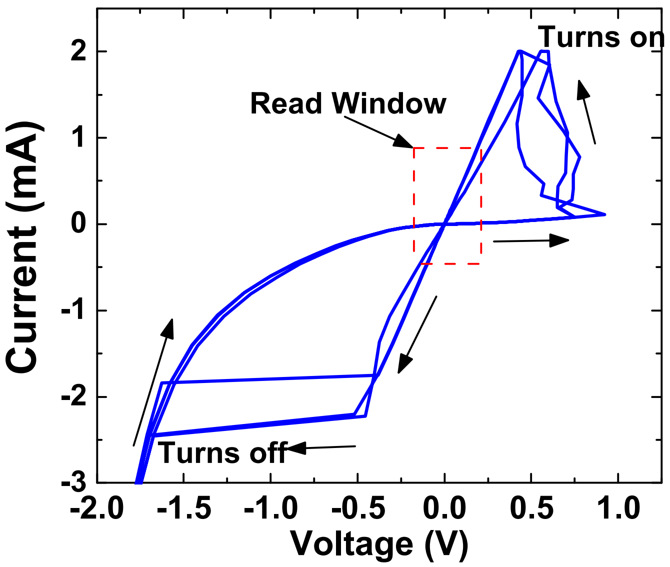
Why Memristors?

- 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
- ReRAM may be a candidate for radiation hardened space electronics applications with promising initial radiation studies

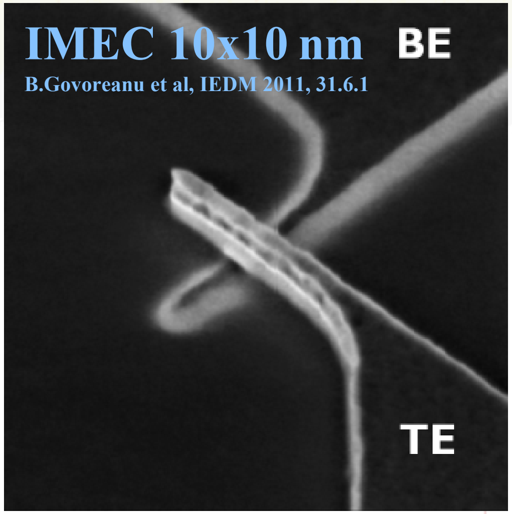
Memristor I-V Characteristics

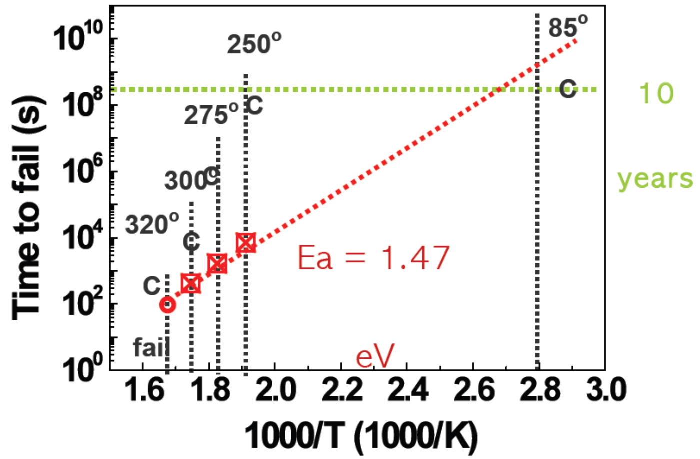
- Resistive RAM (ReRAM) is a memristor
- Applied current and voltage can change resistance state
  - Hysteresis loop
- Low voltages can read state
  - Read window

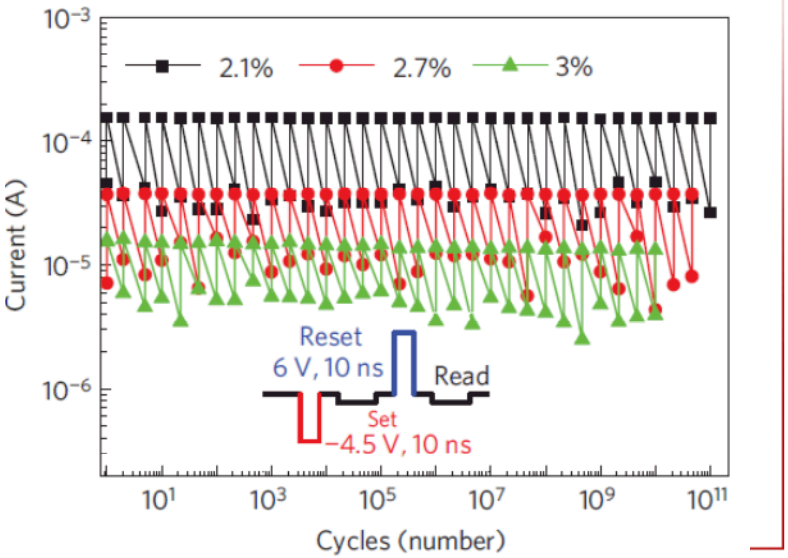


ReRAM Advancements

- **Memristors have shown high performance in key areas**
  - Endurance 10^{12} (Samsung, TaO_x, shown below)
  - Scalability 10x10 nm^2 ($1F^2$), (IMEC HfO_x, right)
  - Switching time < 500 ps (HP Labs, TaO_x)
  - Retention >> 10 y (estimate by HP Labs),
  - Switching energy ~2pJ on and ~6pJ off (HP, TaO_x)
  - Integration with CMOS
- State of the art is rapidly advancing



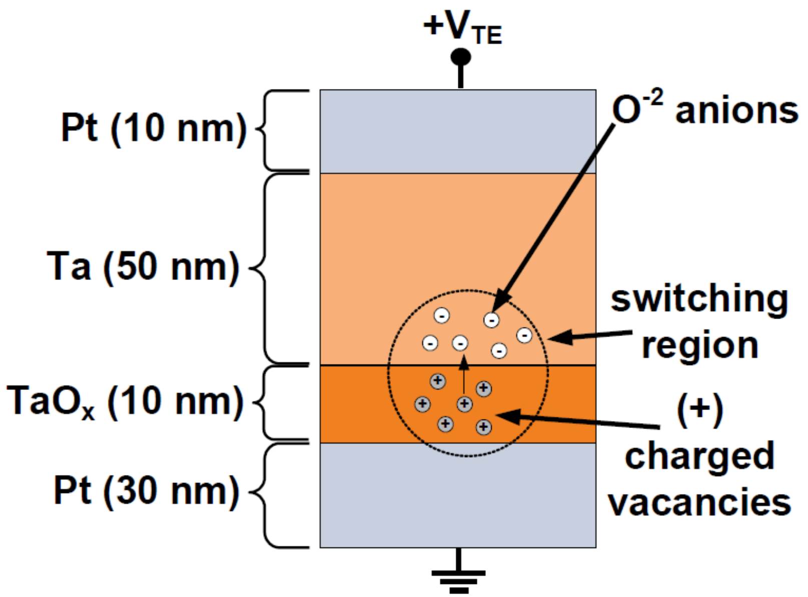




M.-J. Lee, *et al.*, *Nat Mater,* vol. 10, pp. 625-630, 2011.

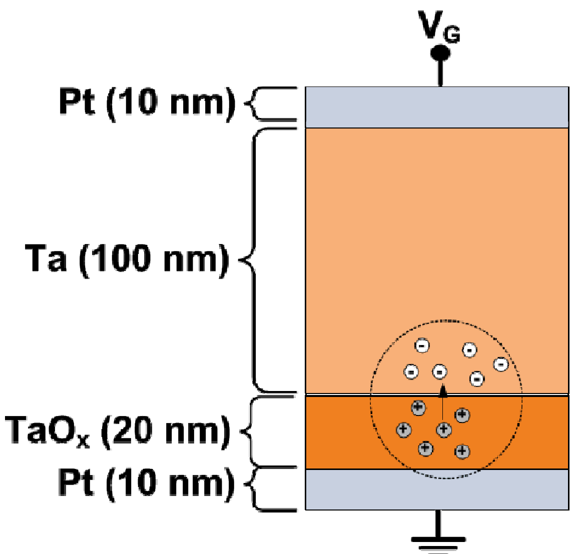
TaO_x Switching

- TaO_x believed to operate due to migration of O^{-2} anions
- Electric and thermal fields cause dissociation and transport of O^{-2}, leaving behind oxygen vacancies, modulating the conductivity of the oxide

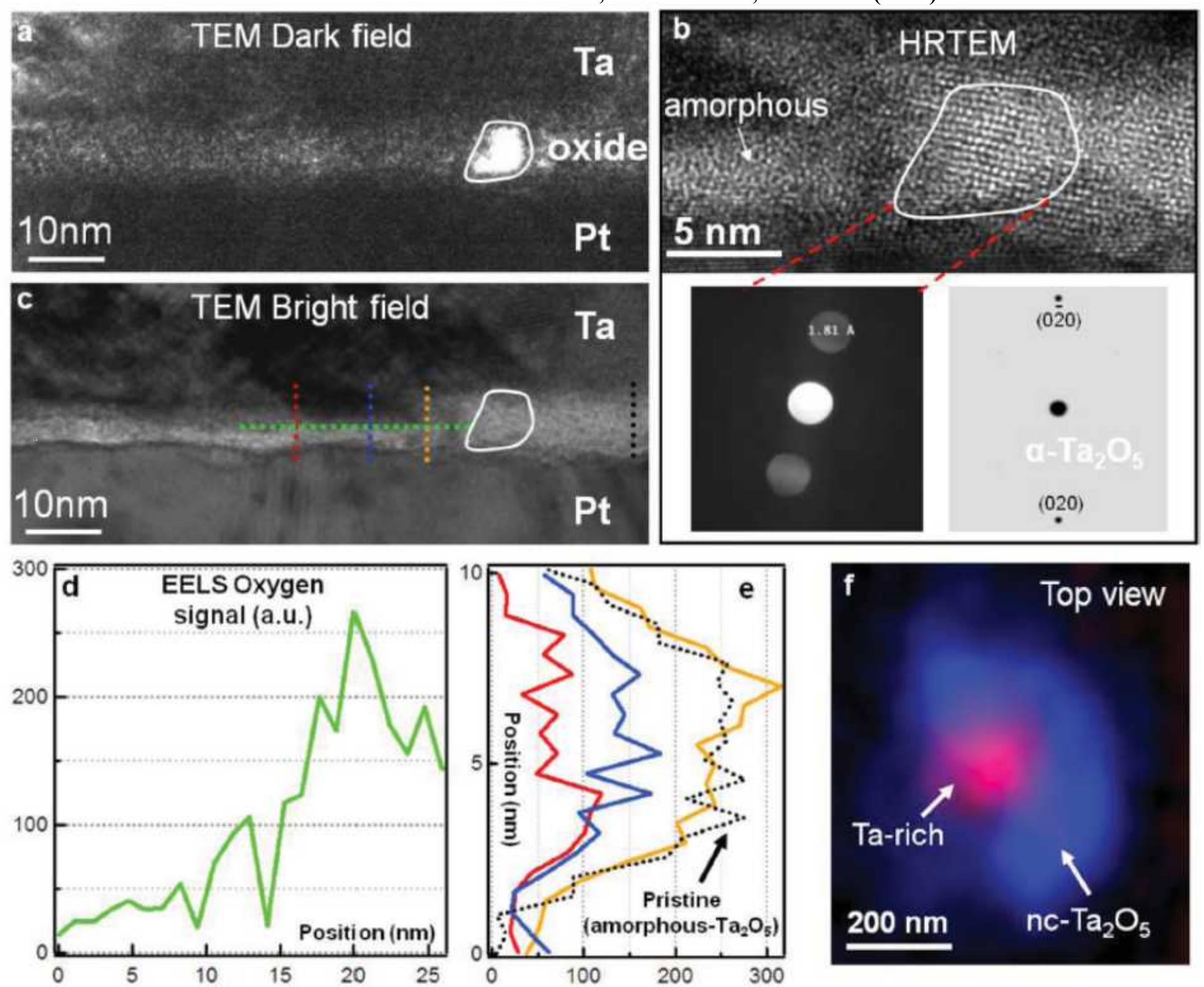


Evidence of Mechanism

- Work by HP Labs

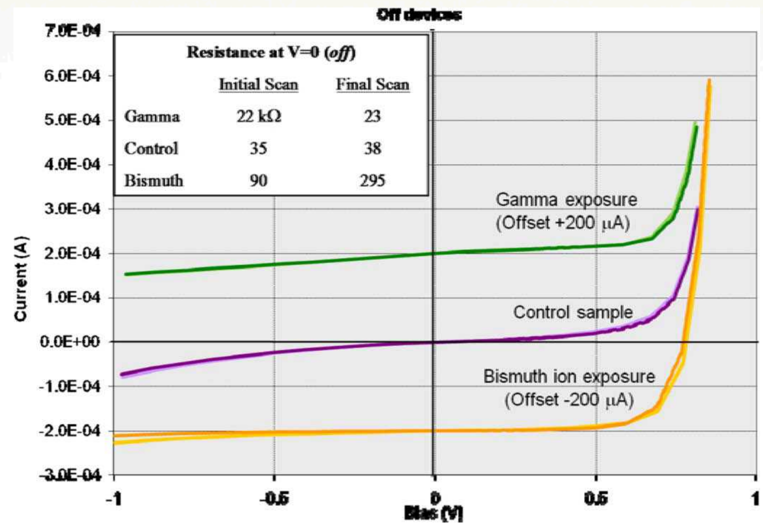


Miao et al, Adv Mater 23, 5633-5640 (2011)

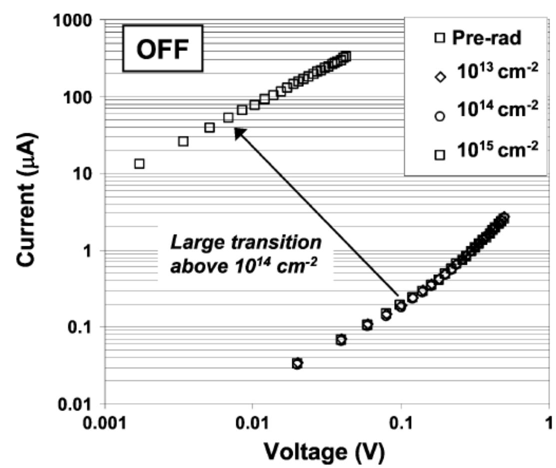


Previous TiO_2 Radiation Experiments

- 45 Mrad(Si) γ-rays and 23 Mrad(Si) Bi ions
  - No degradation
- 1 MeV alpha particles
  - Significant changes to resistance above fluences of 10^{14} cm^{-2}
  - Oxygen vacancy creation
  - Switching functionality remained



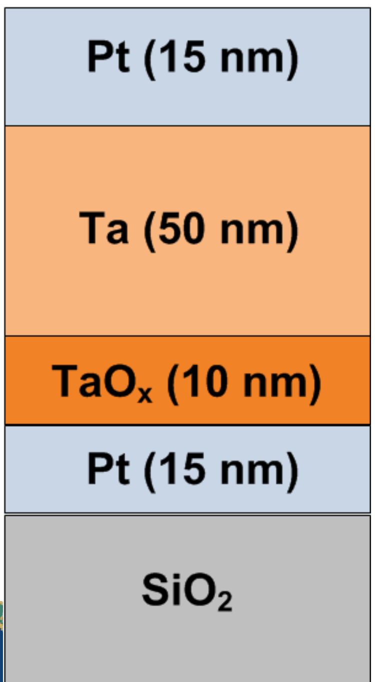
Tong *et al.*, *Trans Nuclear Sci,* vol. 57, pp. 1640-1643, 2010.

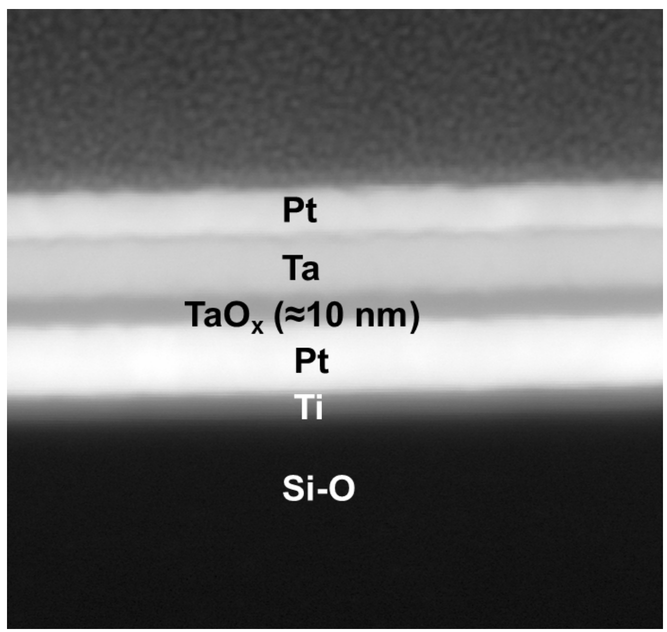


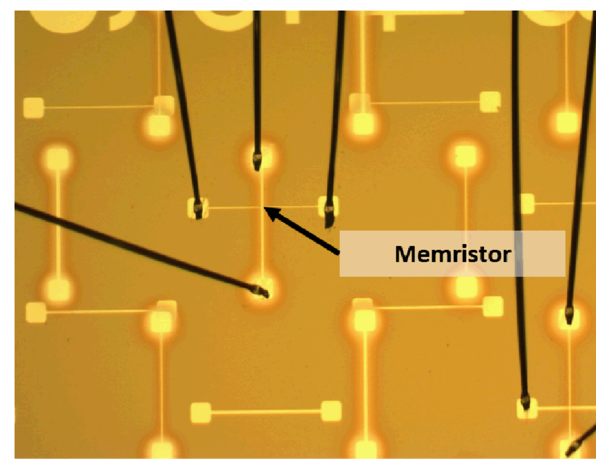
Barnaby *et al.*, *Trans Nuclear Sci,* vol. 58, pp. 2838-2844, 2011.

Experimental Details

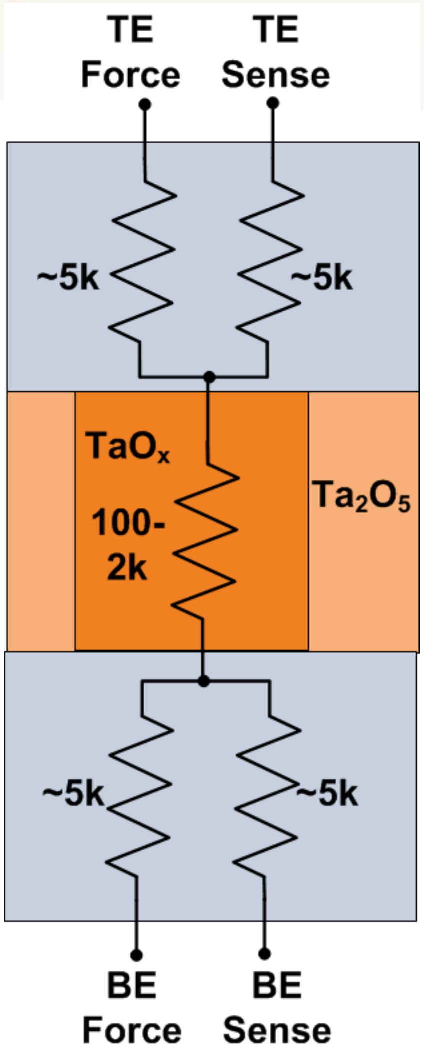
- All samples use same stack:
  - Si/SiO_2(substrate)/$Ti/TaO_x/Ta/Pt$
- Random "dogbone" shadow mask



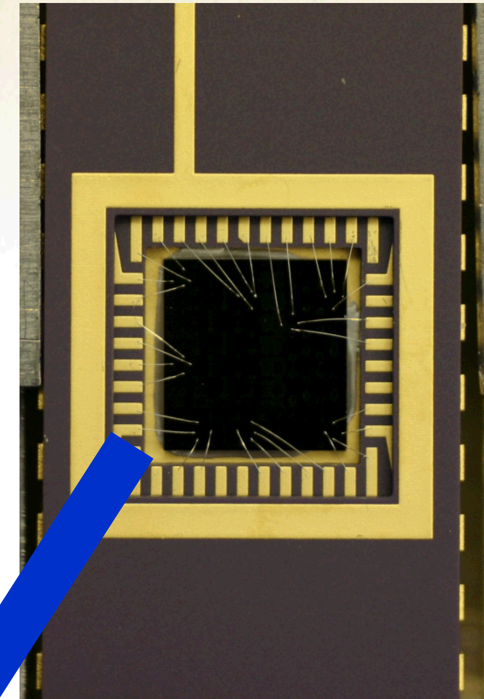


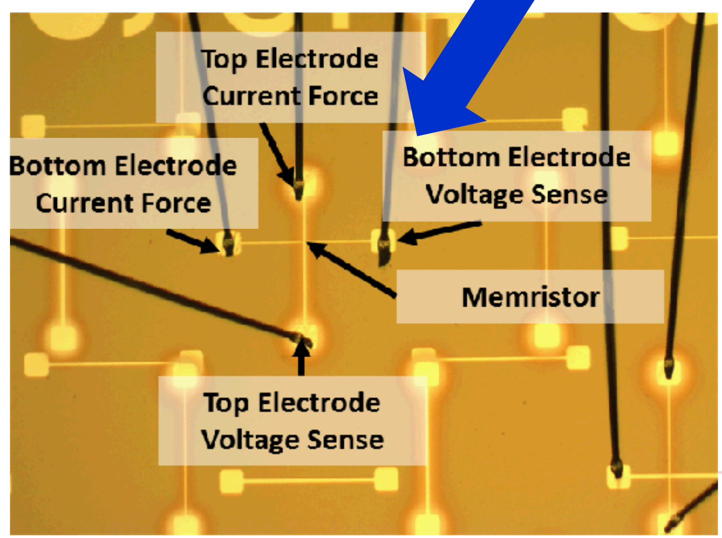


Electrical Connection



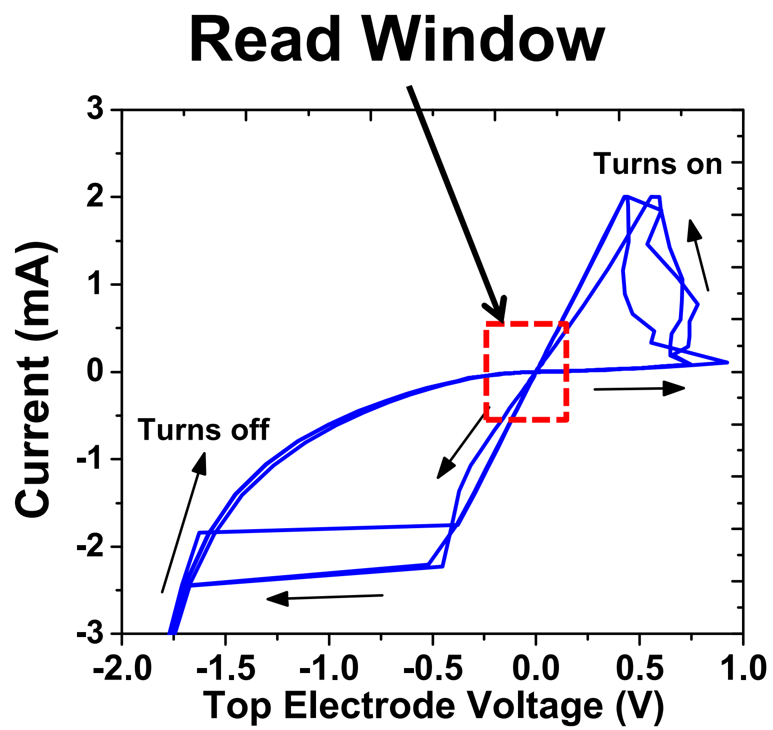
- **Four point measurement technique used to compensate for high contact resistance**





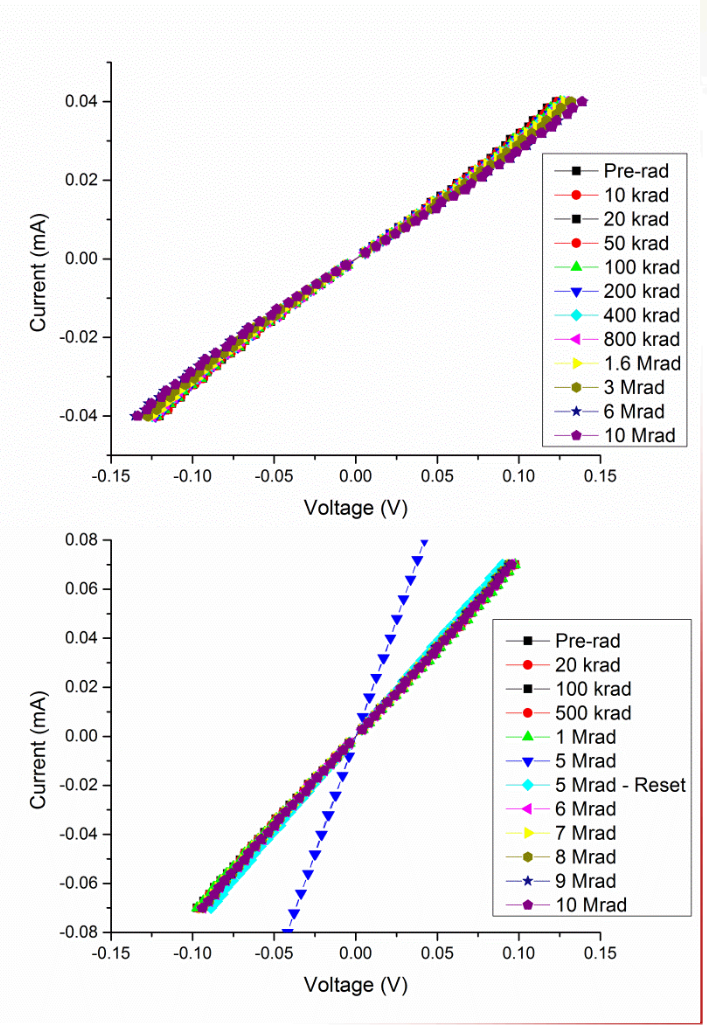
Electrical Characterization

- Devices initially cycled several times
- <u>Write Voltages:</u>
  - Set (on): 800 mV
  - Reset (off): -1.5 V
- <u>Typical Resistances:</u>
  - $R_{ON} \approx$ 30-150 Ω
  - $R_{OFF} \approx$ 300-5k Ω
- Grounded during irradiation
- Read after each shot
- Cycle after series of shots



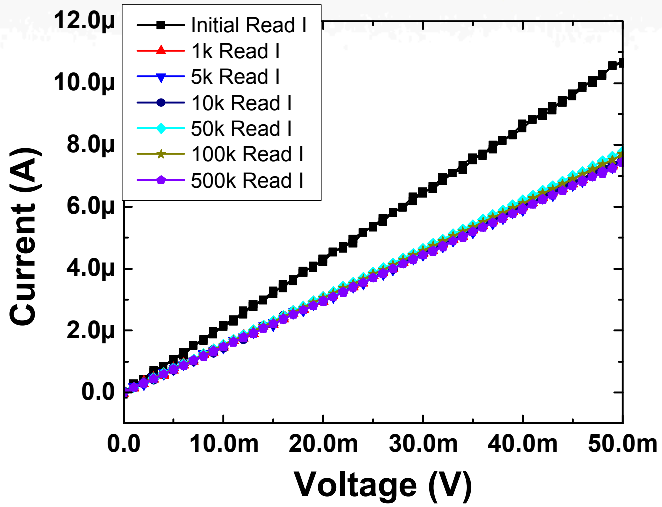
Initial Results: X-ray

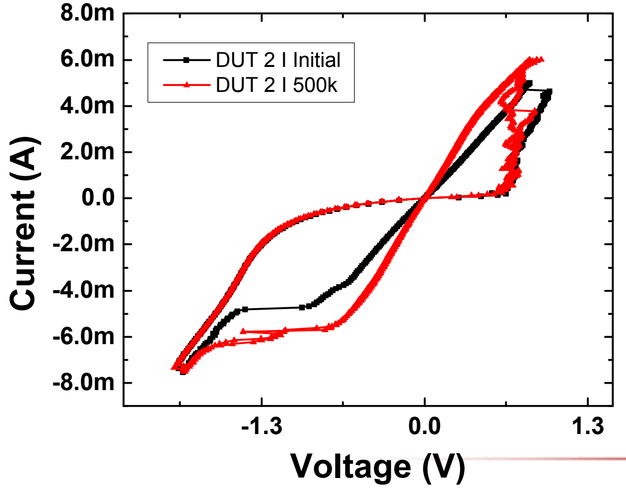
- Aracor 4100 10 keV X-ray System
- All pins grounded during irradiation
- Measured in situ
- One device shows no change up to 10 Mrad(Si)
- One device shows a change in resistance at 5 Mrad(Si)
- Reset restored resistance, no lasting damage
- No change after another 5 Mrad(Si)



γ-rays

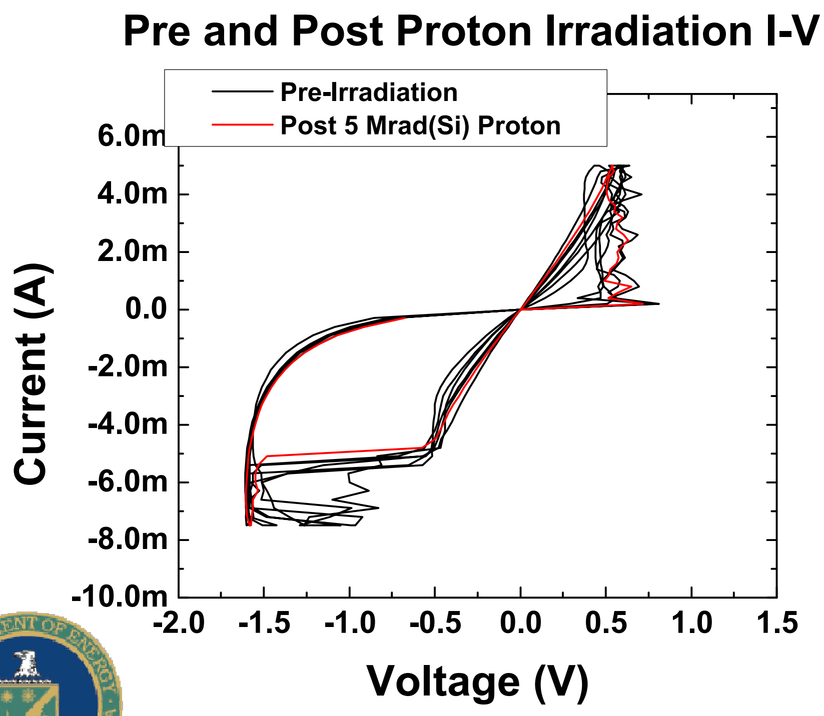
- Sandia Cobalt-60 Radiation Source, 53 rad(SiO_2)/s
- In situ electrical testing, all pins grounded during irradiation
- R_{OFF} measured between shots, full curve after 500 krad(SiO_2)
- No significant change in R_{OFF} due to irradiation

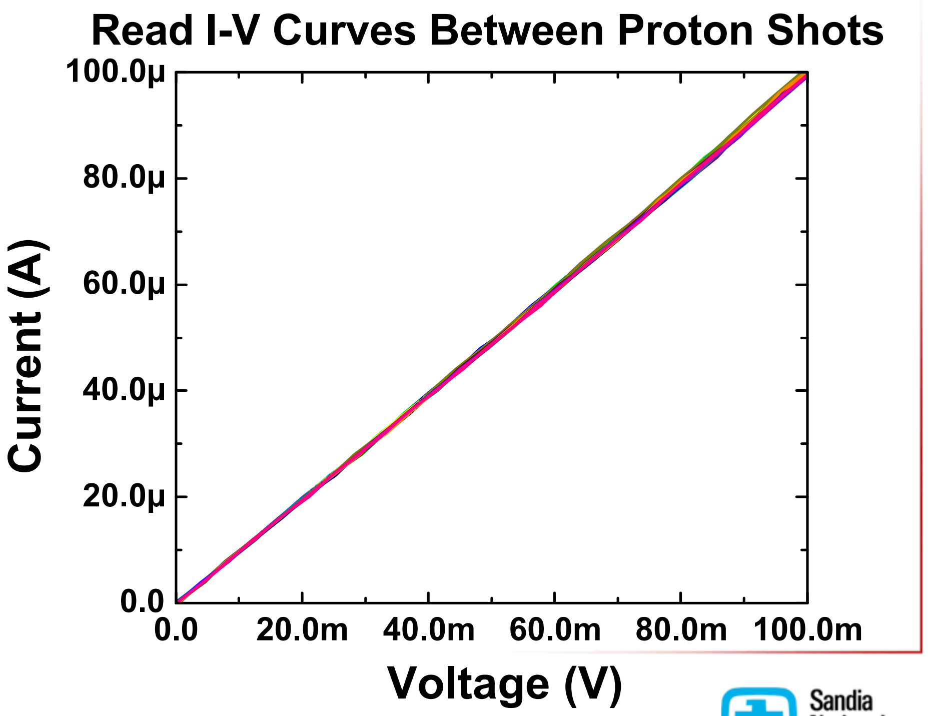




4.5 MeV Protons

- 4.5 MeV proton irradiation at Sandia's IBL
- In situ electrical testing in 10^{-5} torr vacuum
- 1 μm beam rastered across 25x25 μm area
- Little change up to 5 Mrad(SiO_2)





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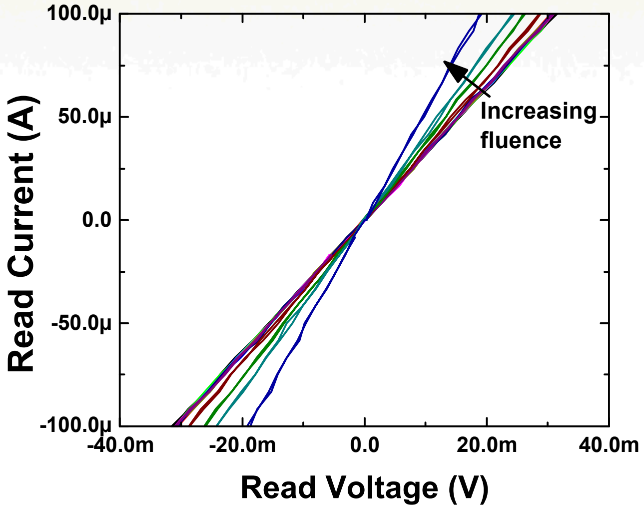
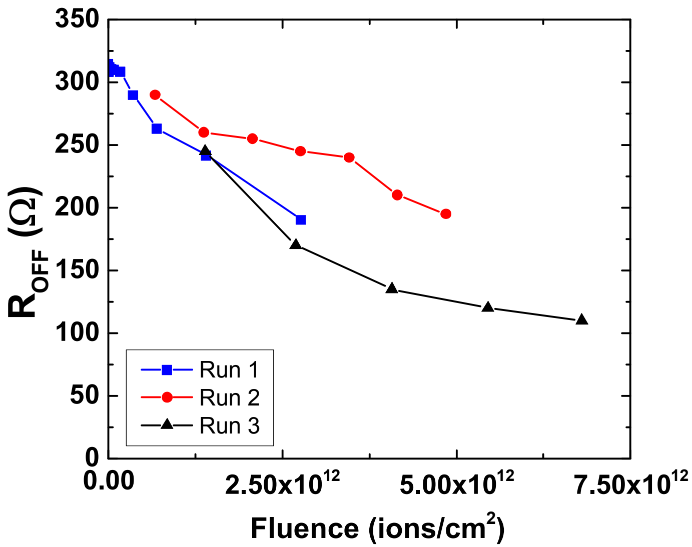
800 keV Silicon

- 800 keV Si beam at Sandia's Ion Beam Laboratory
- All contacts grounded during irradiation
- R_{OFF} gradually decreased with increasing fluence

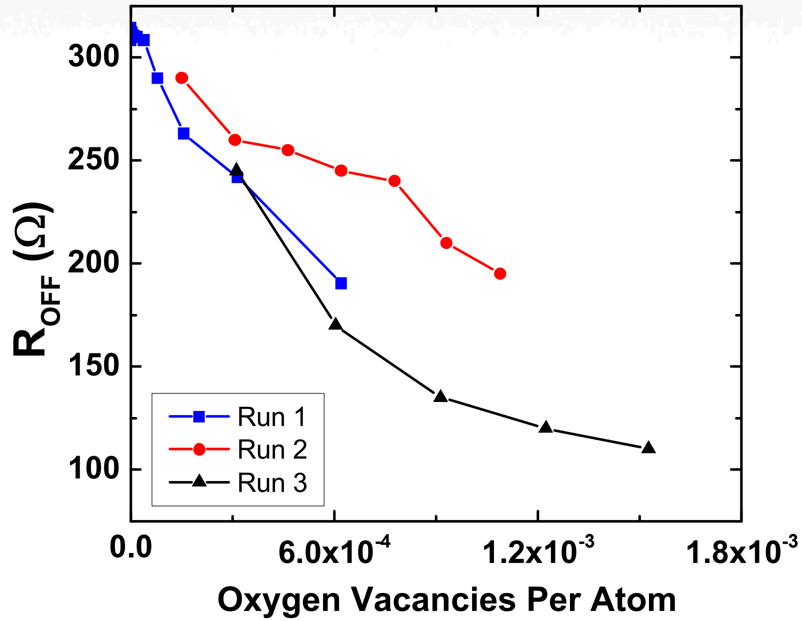


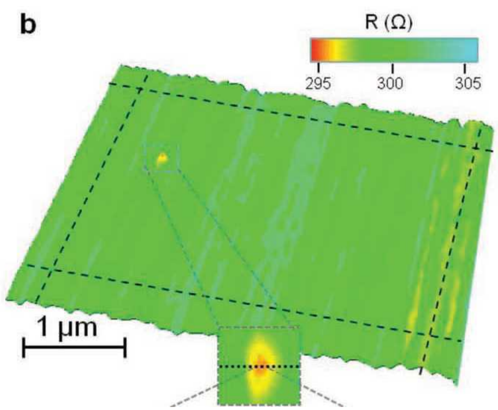


- The amount of decrease varied between runs
- Device with high R_{OFF}/R_{ON} was not affected by similar fluence

800 keV Silicon

- Drop in resistance expected from TaO_x switching theory
  - Oxygen vacancy creation
  - Different initial concentration for different ratios
- Inconsistent changes in resistance between shots of equal fluence
  - Sensitive region may be small (100 nm diameter)





F. Miao, *et al.*, Adv. Mater, vol. 23, pp. 5633-5640, 2011.

Ionization Damage

- TaO_x memristors showed little response to Co^{60} gamma rays to 5 Mrad(SiO_2) or 4.5 MeV protons to 2.5 Mrad(SiO_2)
- Little response due to 10 keV x-rays up to 10 Mrad(SiO_2)
  - One change in resistance observed in one part at 5 Mrad(SiO_2)
  - Part was reset and showed no signs of lasting damage
- Another TaO_x design saw an effect of Co^{60} gamma rays
  - More pronounced in thicker devices (25 nm vs. 50 nm)
  - Devices tested by Sandia had a 10 nm oxide thickness

Displacement Damage

- Irradiation with Silicon ions caused a gradual decrease in R_{OFF} for TaO_x memristors
- Decrease in R_{OFF} likely due to the creation of oxygen vacancies through displacement damage
  - Increase in oxygen vacancies expected to lower resistance
- Fluence required may vary with device parameters like the size of the channel or initial stoichiometry
  - R_{ON}/R_{OFF} ratio

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Summary and Conclusion

- Effect of several types of irradiation on TaO_x memristive memories evaluated
  - Little effect due to 10 keV X-rays, one change in R_{OFF} seen
  - Virtually no change after 500 krad(SiO_2) Co^{60} γ-rays
  - Virtually no change after 5 Mrad(SiO_2) 4.5 MeV protons
  - R_{OFF} resistance altered by 800 keV silicon ions
- Initial results are promising
  - Little change from TID so far and resistance degradation observed after fluences of 10^{12} cm^{-2} for Si ions
- Further investigation is needed to determine if TaO_x memristive memory is a suitable candidate for rad-hard electronics
  - Ionization vs. displacement damage
  - Understand origin of device variation
  - Dependence on device parameters like oxide thickness

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