Resistive Transition Metal Oxide Memory

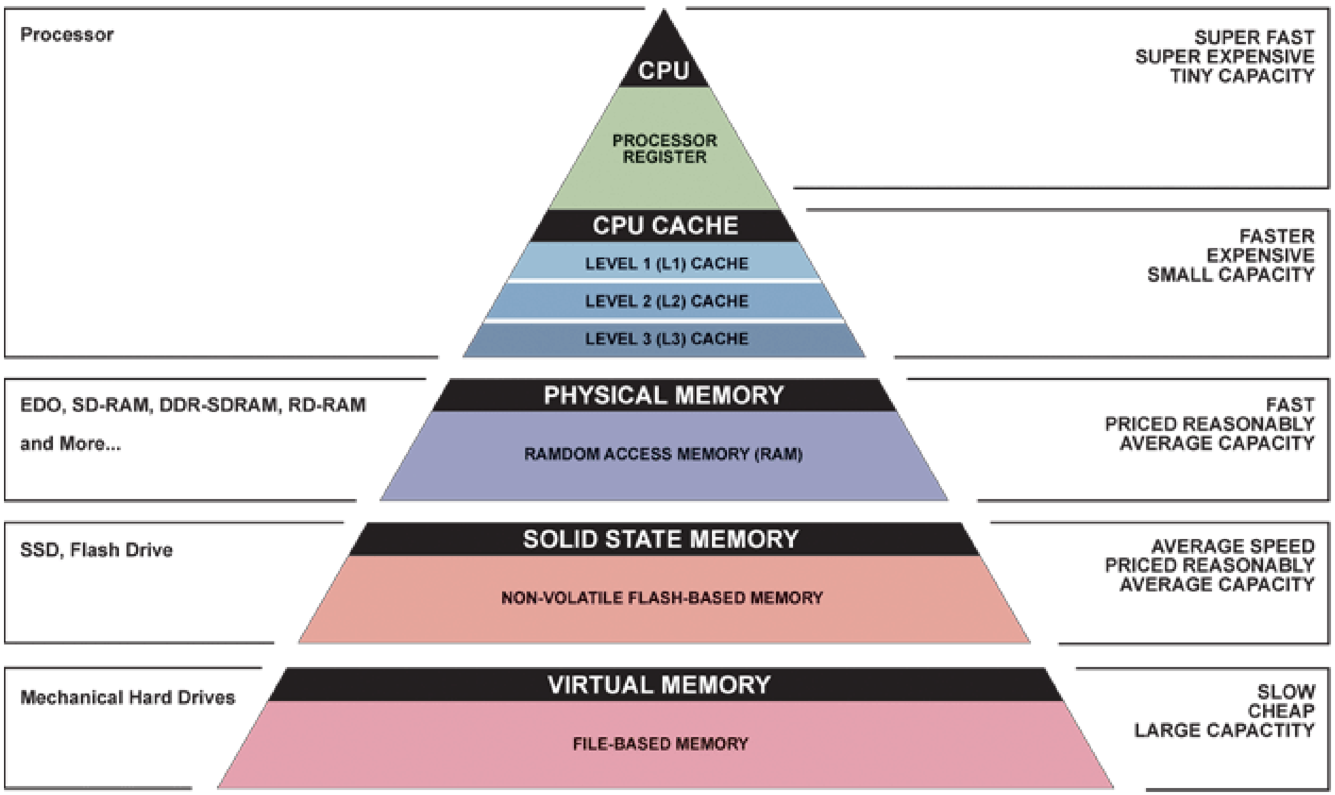
Senior Project
Microelectronic Engineering

Wilkie Olin-Ammentorp, Microelectronic Engineering

Advisor: Santosh Kurinec

Introduction to Memory

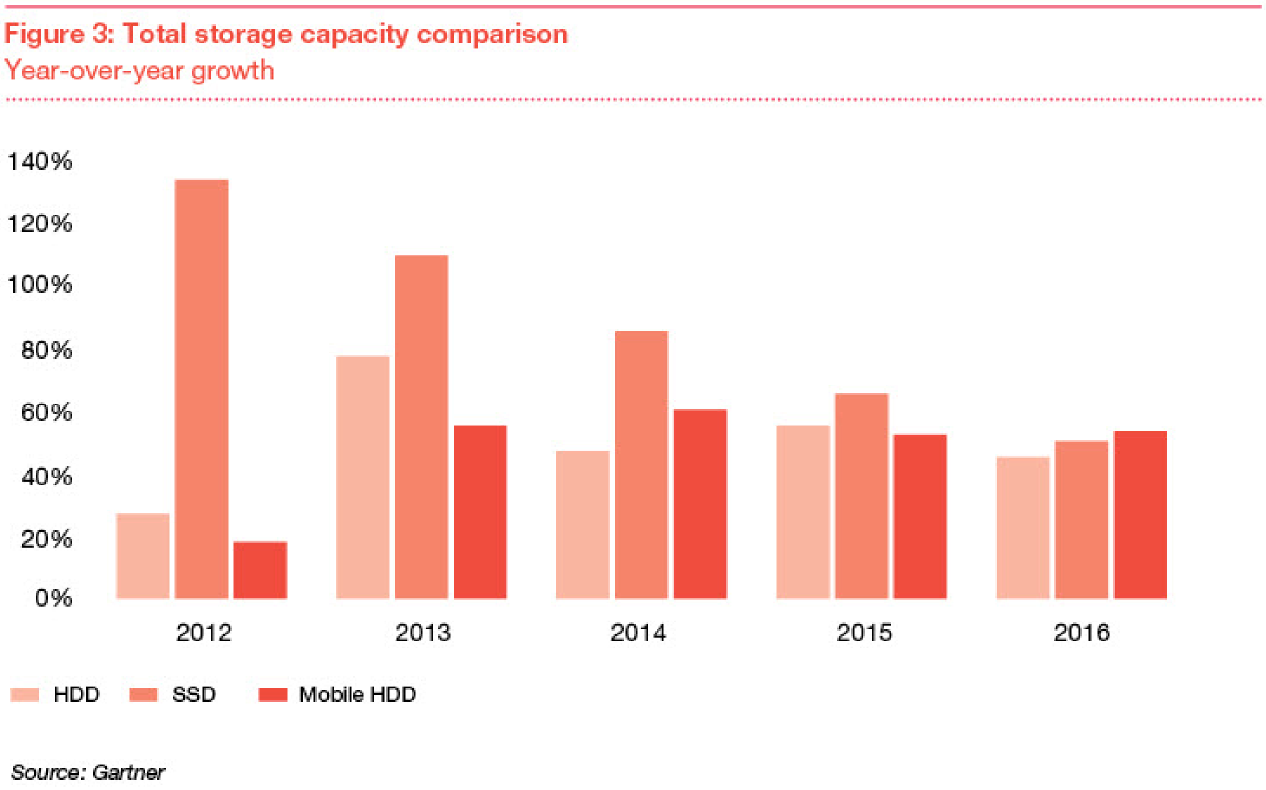
- Many different types of digital memory exist – each has a use based on its latency (how long it takes to access data) and cost.



▲ Simplified Computer Memory Hierarchy
Illustration: Ryan J. Leng

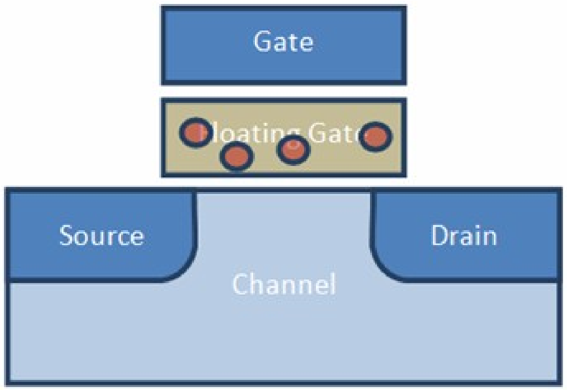
Flash Memory

- Flash memory is a low-latency storage medium which has made massive storage and market gains in the past decade.

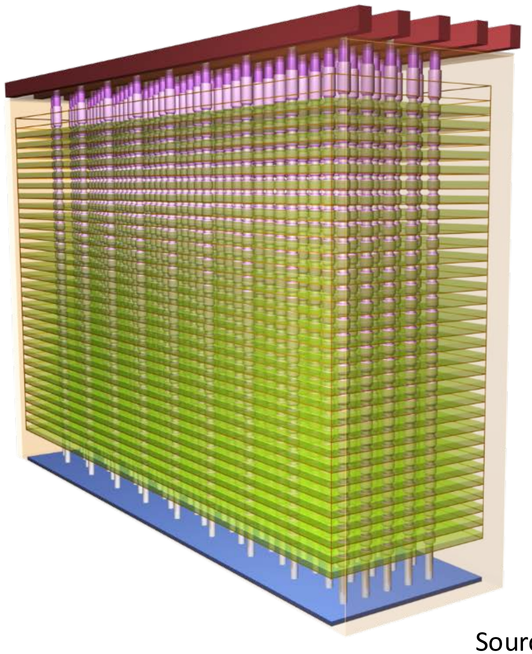


Flash Memory

- Flash memory's high density, low latency, and decreasing cost have made it important in all types of computing.
- However, flash memory has been scaled to its fundamental limits. Further progress depends on using 3D integration to increase density.



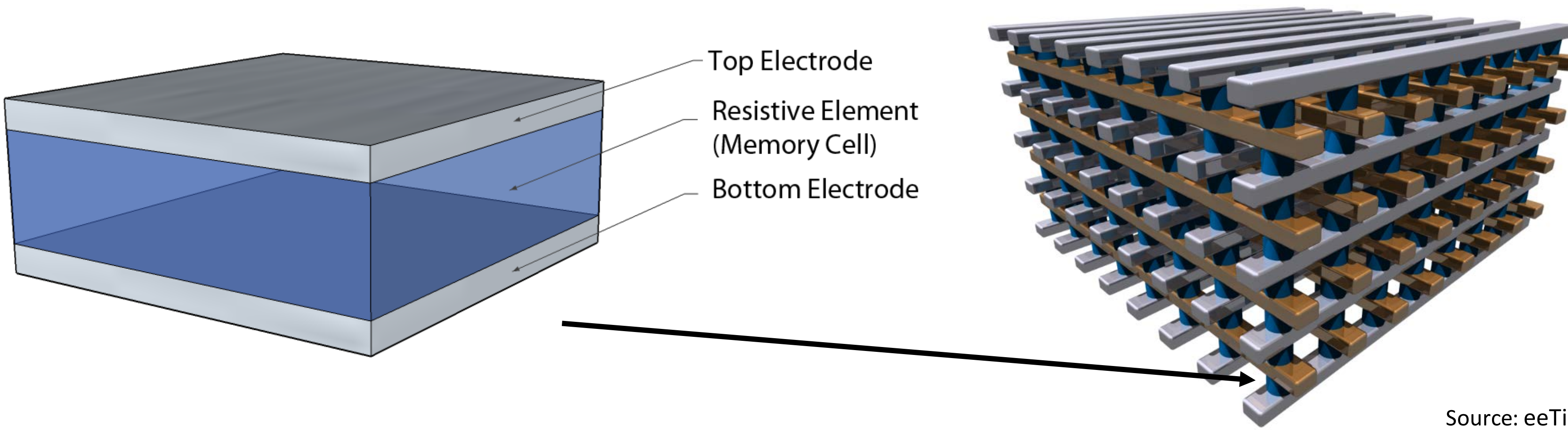
Source: eeTimes



Source: Intel/Micron

Motivation

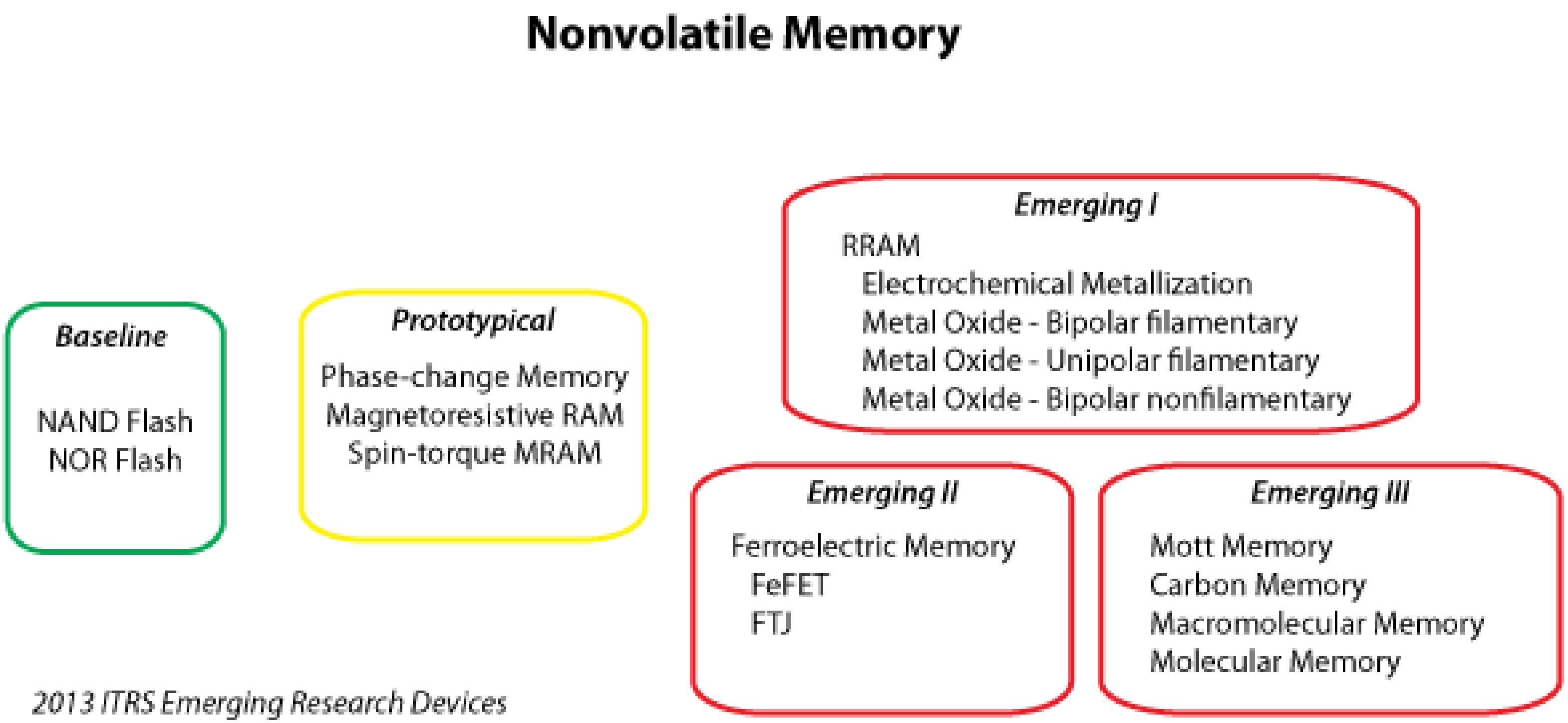
- Novel memory devices must be investigated to continue increasing memory density.
- Resistive random access memory (RRAM) is the leading candidate to replace flash.



Source: eeTimes

RRAM Characteristics

- RRAM is a broad classification which covers many types of memory.
- The commonality between all types is that information is stored by resistance.



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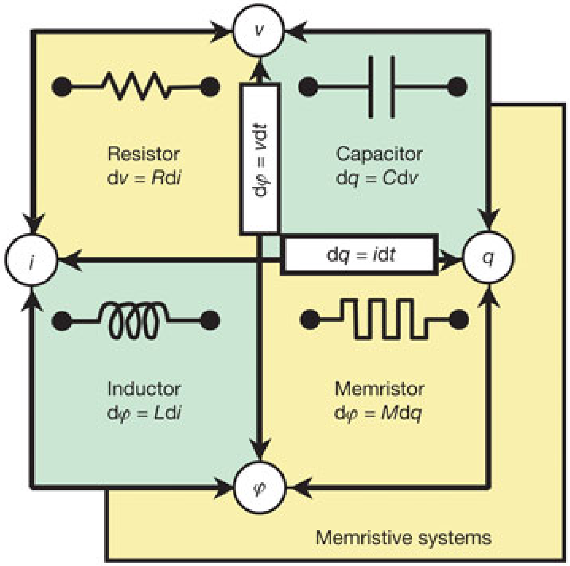
RRAM Characteristics

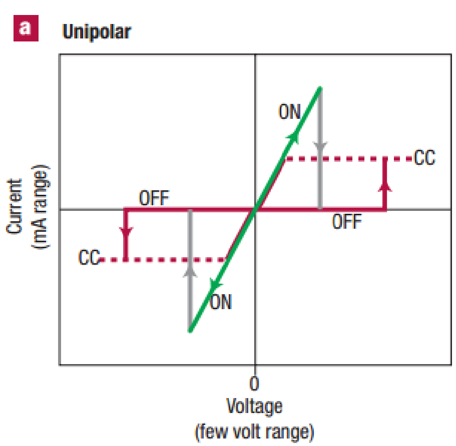
- A passive circuit element which changes resistance depending on how it has been biased was first proposed by Chua in 1971.
- This circuit element was named the “memristor,” a portmanteau of “memory” and “resistor.”
- Each element of an RRAM array can be seen as an individual memristor.

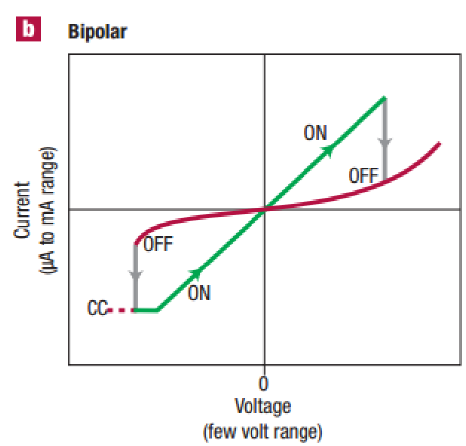


Source: Chua, et al.

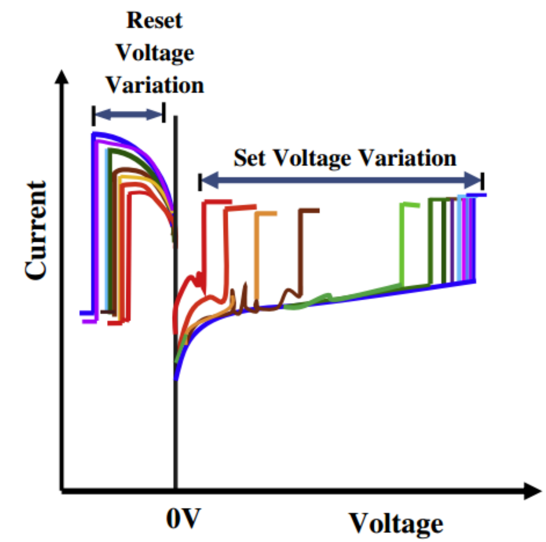
RRAM Characteristics

- As a two-terminal device, the current traveling through the device must be able to either change or read the memory state.
- RRAM can be bipolar, requiring opposite polarity set and reset, or unipolar, requiring a higher current to reset than set.
- One major hurdle in RRAM is making well-behaved devices which form and deform at a set voltage, and give a reliable resistance state.





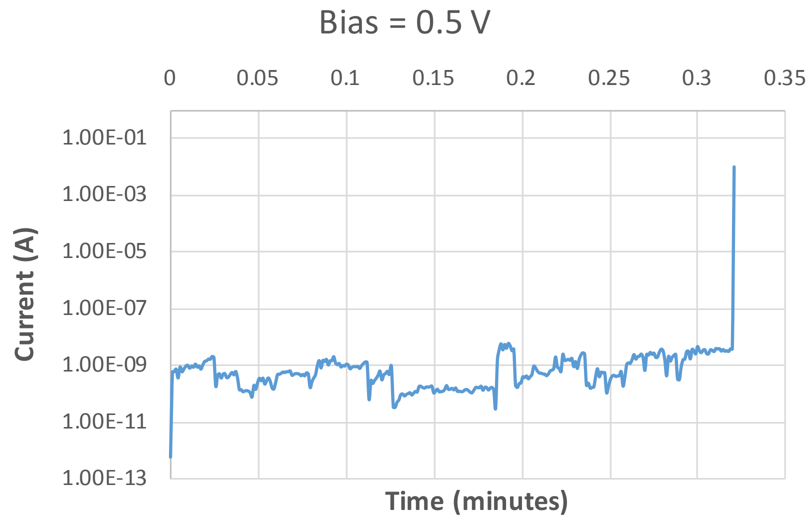
Waser, et al.



Acharyya, et al.

Resistance Changing Materials

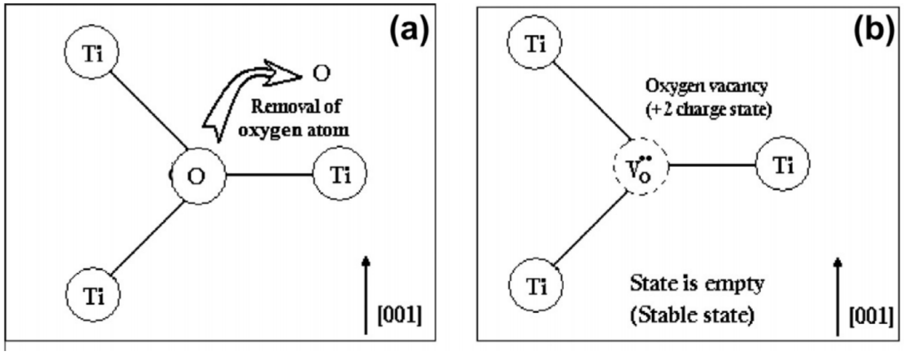
- Many transition metal oxides (TMOs) exhibit a change in resistance after a voltage is applied.



- Charged vacancies or interstitials in these materials induce changes in the valence band of nearby atoms.
- Additional electrons are freed, increasing local conductivity.
- Through controlled generation and migration of conduction-inducing defects, the resistivity of the material can be controlled.

TiO_2 – A Model Material

- Among TMOs, titanium dioxide (TiO_2) is one of the most favored resistance switching materials.
- Characterization efforts have focused greatly on TiO_2 ; its resistance change mechanism is now better understood than in most materials.



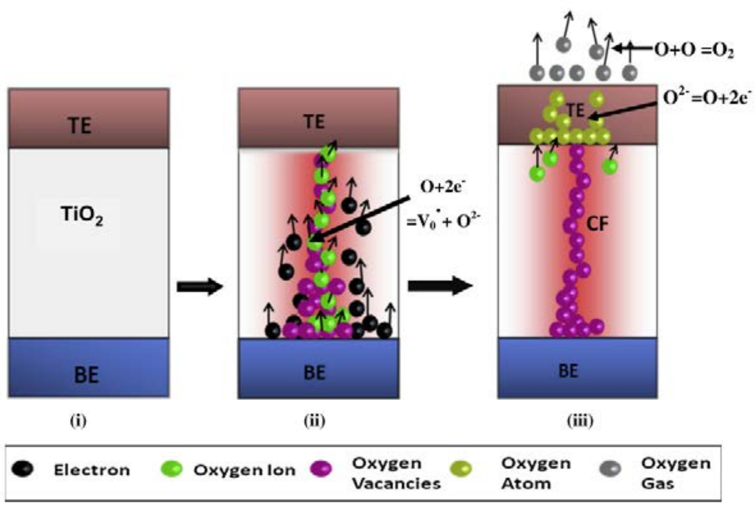
$$O_o \Longleftrightarrow \frac{1}{2}O_2(\text{gas}) + V_o^{\cdot\cdot} + 2e^-$$

Acharyya, et al.

- A reduction-oxidation reaction can cause an oxygen atom to be removed from the lattice.
- This leaves behind a conductive vacancy.
- In bulk, oxygen deficient titanium oxide is called a Magnéli phase.

TiO_2 – A Model Material

- Through a combination of electrical and thermal effects, oxygen vacancies can arrange in the material and form conductive pathways.
- These effects include electric potentials, electric kinetic energy, concentration gradient, and thermal gradients.



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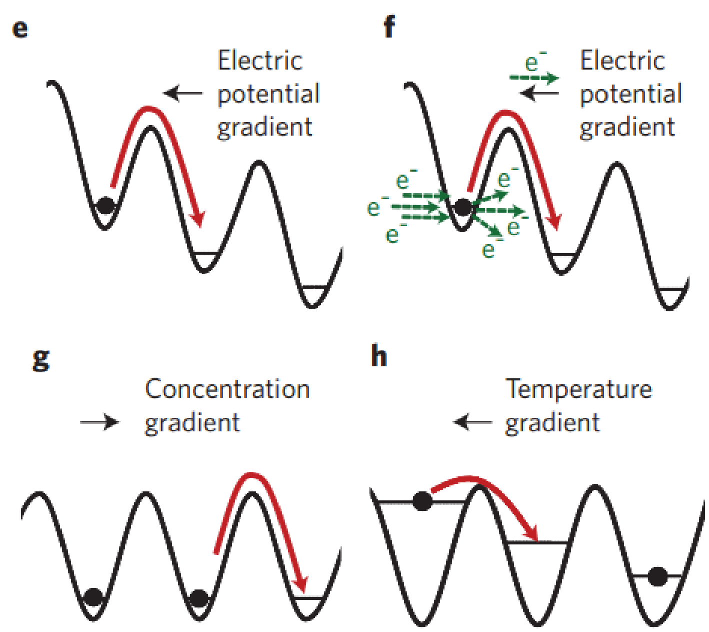
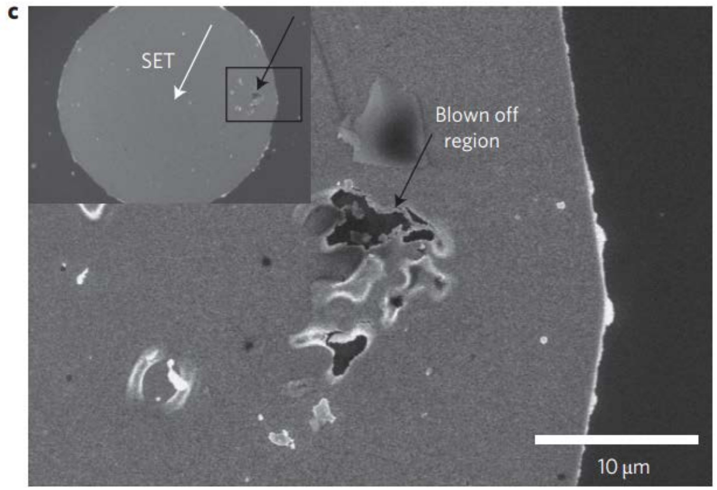


Yang, et al.

TiO_2 – Electroforming

- In order to create conductive vacancies, a TiO_2 film must undergo an initial electroforming stage.
- This electroforming stage requires high fields and generates oxygen, which can destroy electrodes as it outgases.

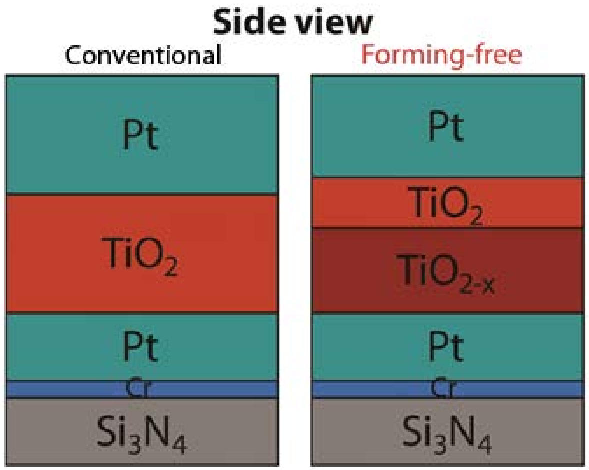


Kwon, et al.

- Designing a structure which does not require electroforming would benefit RRAM's reliability and uniformity.

TiO_2 – Electroforming Free Devices

- To remove the necessity of an electroforming step, more complex film stacks are deposited.

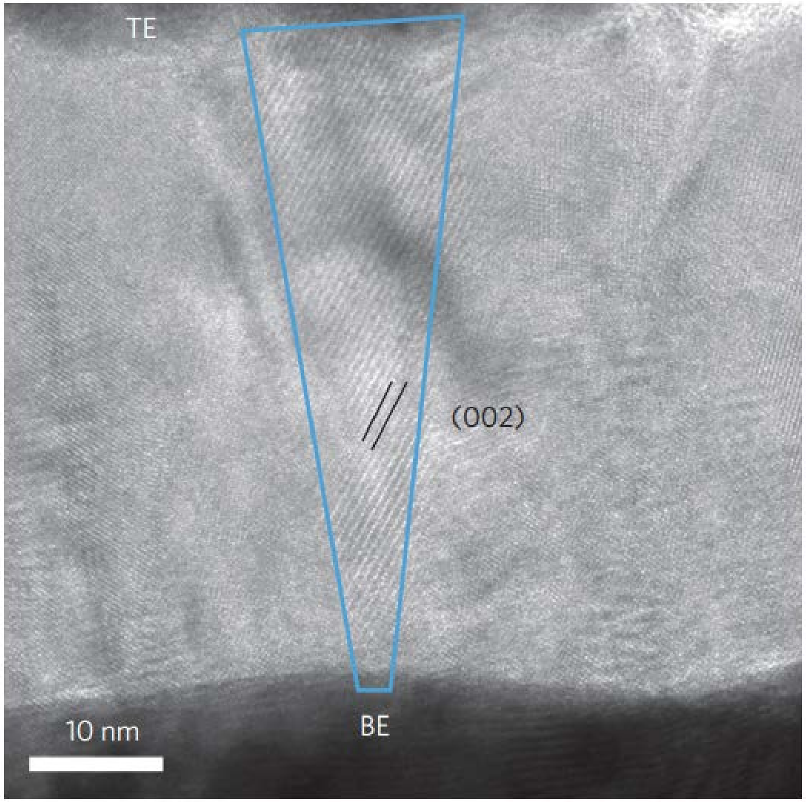


Strachan, et al.

- By including a non-stoichiometric film, the vacancies are already created in most of the film
- These vacancies can then move into the insulating layer to create the conducting filaments.

TiO_2 – Set operation

- When a conductive pathway through the film exists, the device is “set.”
- This is done by using an electrical bias to initiate movement of the vacancies through the film.
- When a certain current level is reached, the set operation stops.



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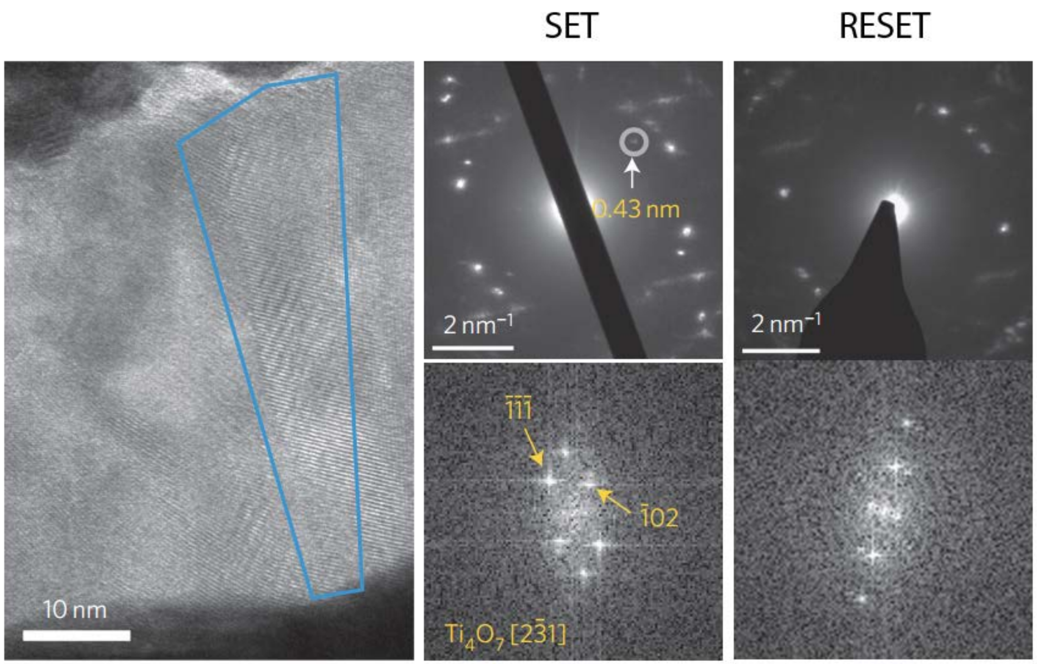
TiO_2 – Reset operation

- To reset to a high resistance state, another current pulse is used to disrupt the conducting filament.
- High current densities ($>10^6$ A/cm^2) in the filament lead to heat, which may be partially responsible for the reset operation.

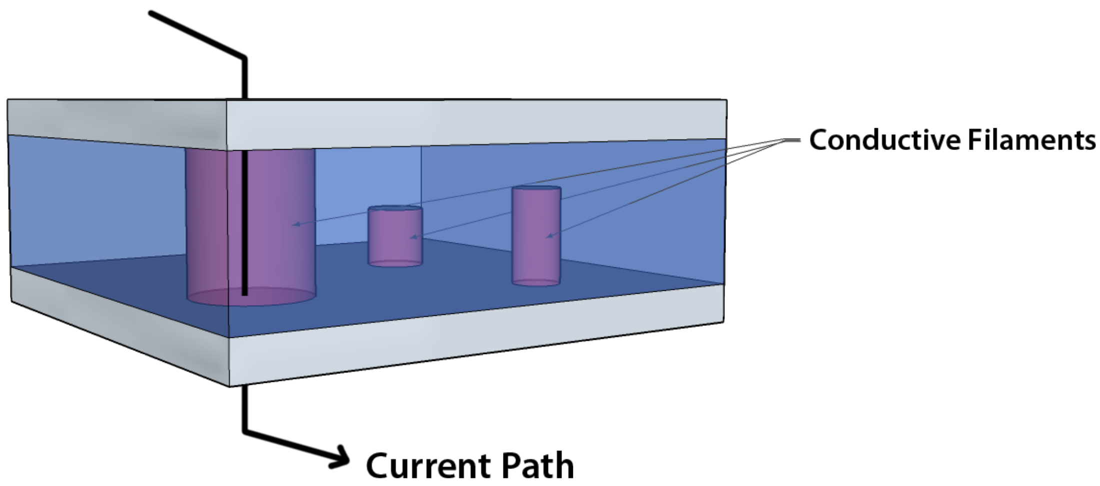


Kwon et al.

Magnéli phase absent

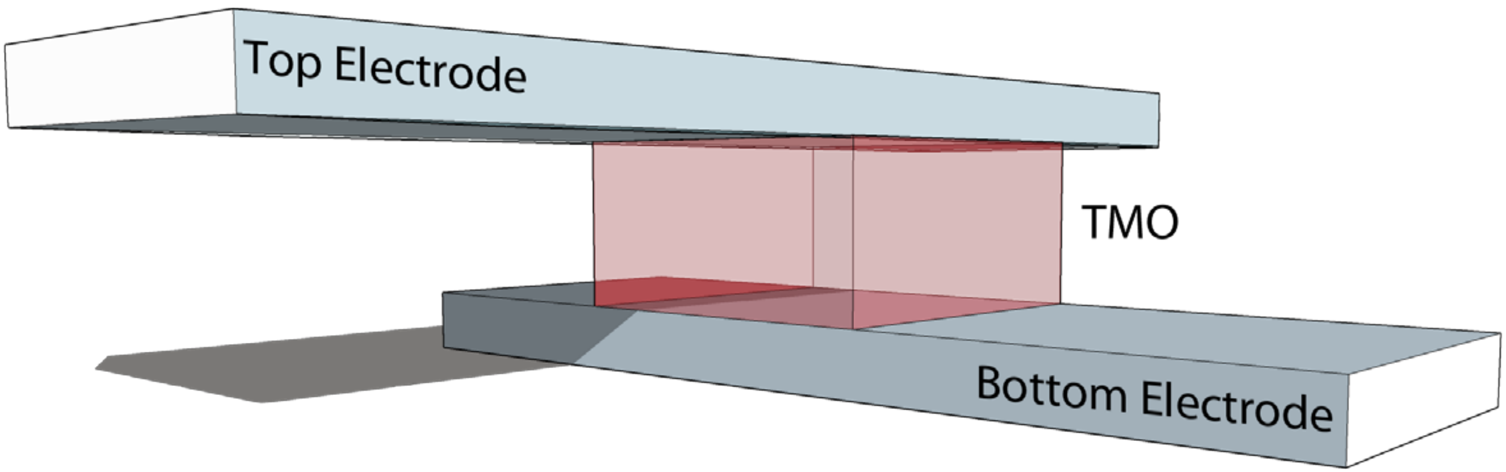
TiO_2 – Variability

- Even in electroforming-free RRAM devices, there is a variation in what set and reset voltages are required.
- Multiple conducting filaments partially form in the insulating film. In each write/erase cycle, a different filament may be conducting the current, leading to variations in resistance.
- Additional impurities can create favorable sites for a filament to form.
- Devices 10 nm wide or less are likely to only contain one filament.



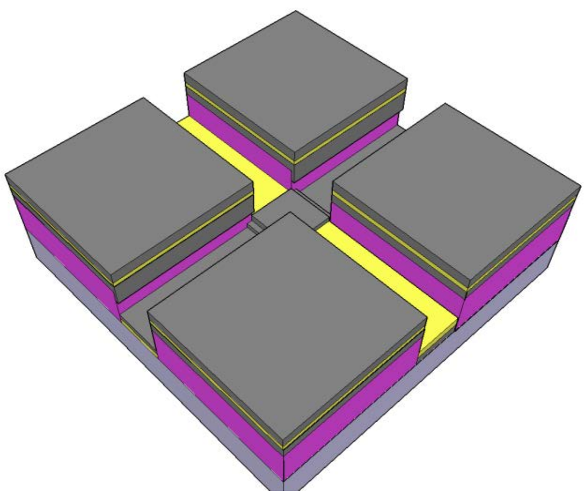
Fabrication - Crossbar Test Structure

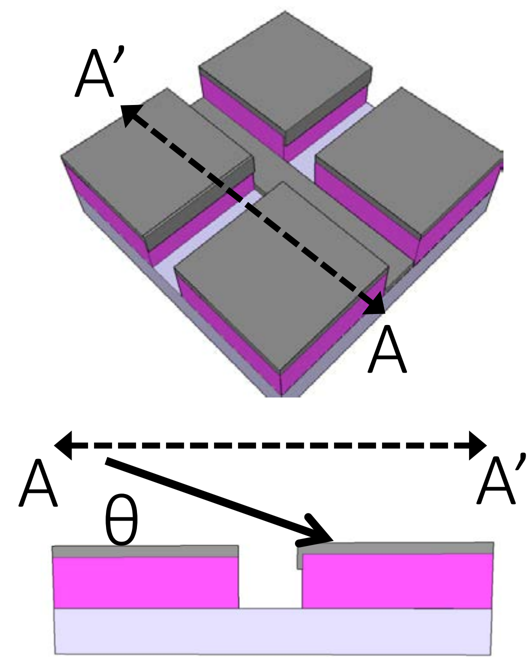
- The simplest test device is a crossbar – a bottom and top electrode, with the film being investigated inbetween them.



RIT RRAM Investigation

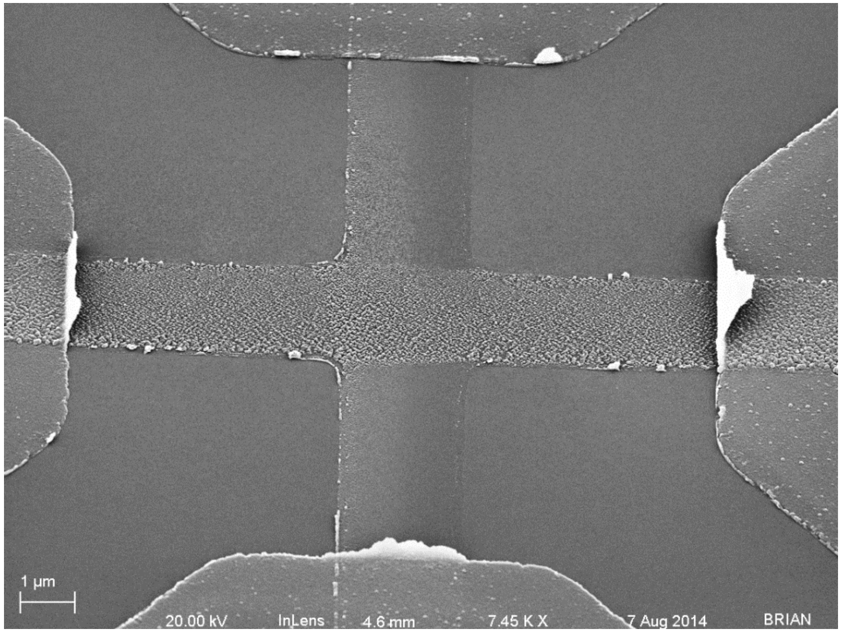
- A process at RIT was needed to fabricate memristive devices.
- Once this process was proved with a simple structure, it could be used to investigate different material combinations.
- Over the last year, a self-aligned process to create memristors was investigated. However, this process was found to be problematic.





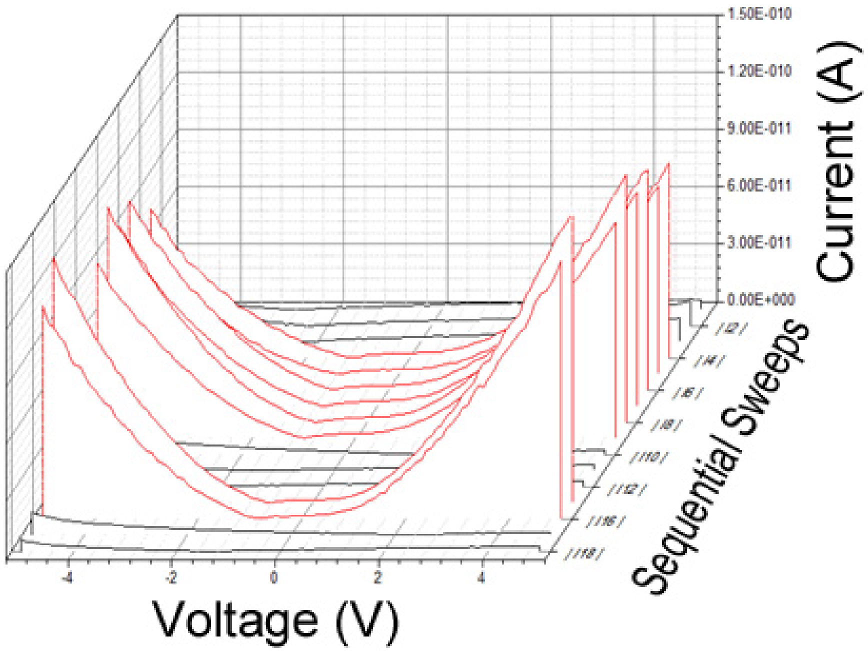
RIT RRAM – Self-Aligned Process

- The self-aligned process left a memristive layer inbetween the bond pad and bottom electrode.
- Grazing-angle deposition yielded films which were very difficult to control in thickness and uniformity.



RIT RRAM – Current-Voltage Characteristic

- Several program/erase cycles were observed.
- A new process was required to create devices which would have better set/reset behavior, carry higher current, and use lower voltages.



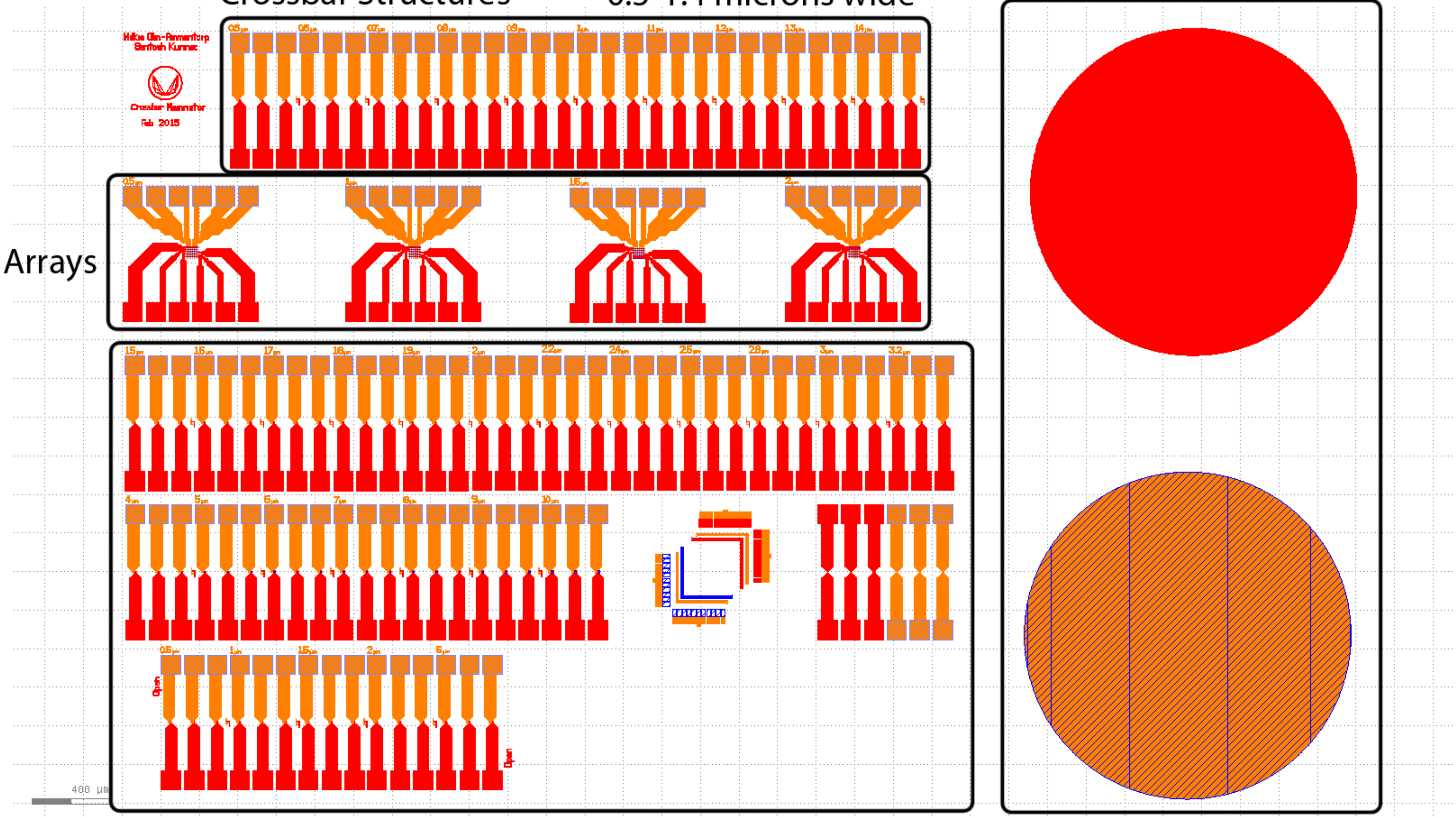
RIT RRAM – New process

- A new process and mask design were created to avoid the previously encountered issues.
- Conventional patterning via lift-off or etch instead of shadow deposition was used.
- An additional insulating layer to prevent unintentional leakage paths was added.
- New process can support many different oxides and metals, deposited with different techniques.

Mask Design

Crossbar Structures 0.5-1.4 microns wide

Crossbar Arrays



Crossbar Structures 1.5-10.0 microns wide

Capacitors

Mentor Graphics Pyxis used to design

Side-profile process summary

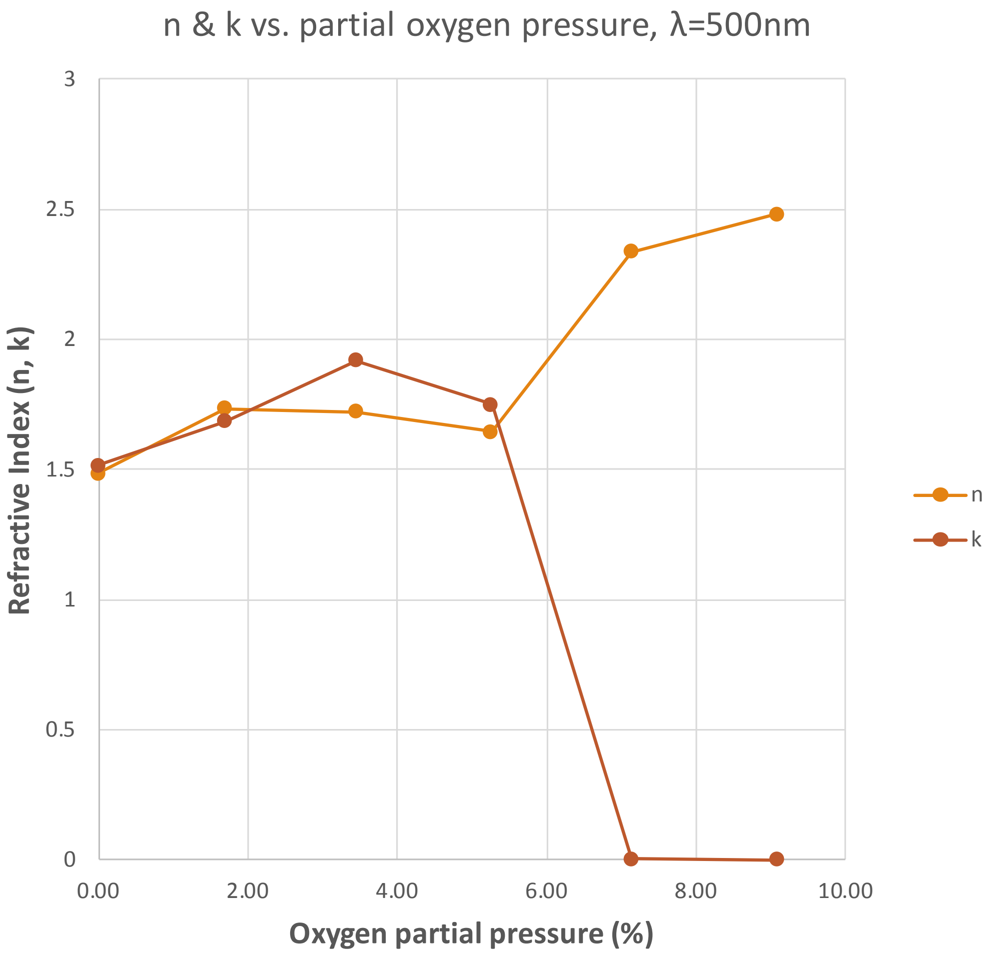
Finished Device

Reactive sputter TMO

- In a normal sputter, a noble gas is used to bombard the target.
- By partially using a reactive species such as oxygen, a different material (such as TiO_2 from Ti) can be deposited.
- An experiment was carried out to determine what partial pressure of oxygen would yield conductive and insulating phases of Ti_xO_{2-x}

O2 partial pressure (mT)	Ar partial pressure (mT)
0	12
0.2	11.8
0.4	11.6
0.6	11.4
0.8	11.2
1	11
Power	300 W
Time	20 second presputter/
	200 second sputter

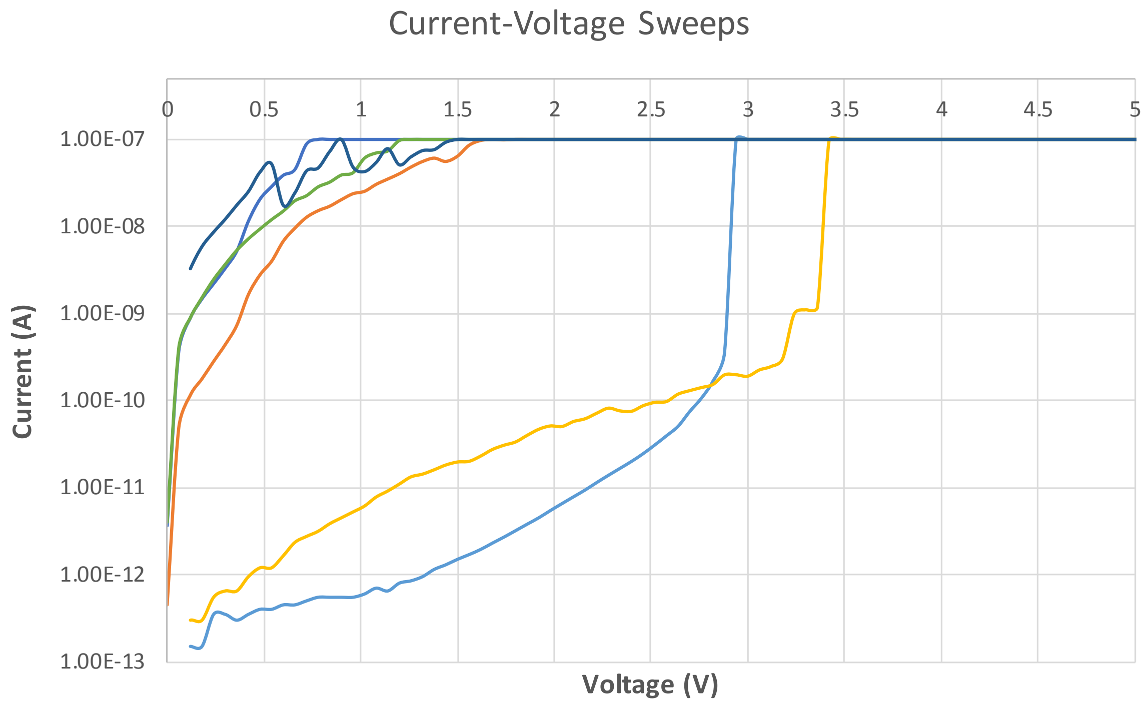
Film Characterization



- Films were characterized by ellipsometry, profilometry, and four-point probe.
- Refractive index of titanium oxides is close to a standard reference (2.592+0i)

Pilot Run Current-Voltage Results

- An pilot run of the new process was carried out to create Al/TiO_x-TiO_2/Al crossbar structures.
- Electrical results show that high and low resistance state are possible.



Future Work

- Work is being extended into a thesis, using different electrode and memristive materials.

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Questions?

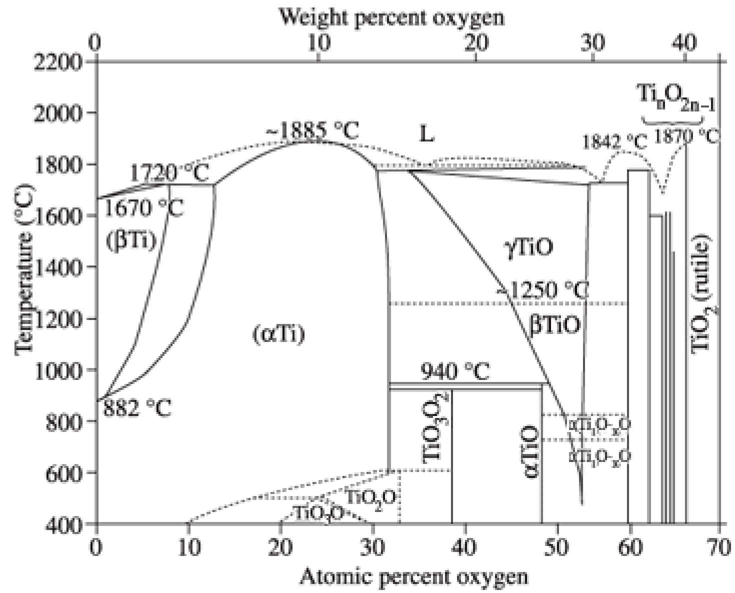

Figure 13. Phase diagram of Ti – O[18].

TiO_2	Rutile	Ambient conditions	Rutile-type Tetragonal
	Anatase	Above 1073 K	Tetragonal (I41/amd)
	Brookite	High pressure phase	Orthorhombic (Pcab)