Treated HfO_2 based RRAM Devices with Ru, TaN, TiN as Top Electrode for In-Memory Computing Hardware

by

Yuvraj Dineshkumar Patel

MS Thesis Defense

Dr. Durgamadhab Misra

(Dissertation Advisor)

Introduction

Resistive Random-Access Memory devices

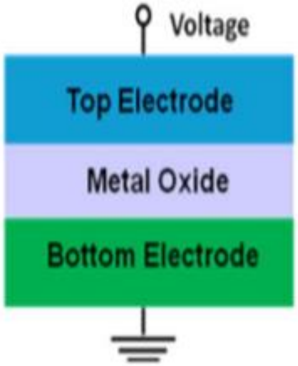
- Scaling down the current CMOS technology node, further from 20 nm technology nodes has not drastically increased the performance. However, the scaling has increased the fabrication cost

- Various new memory technologies are currently being explored which can be combined with the existing CMOS technology for improved performance, lowered fabrication costs, and lower overall power requirement

- Resistive Random-Access Memory (ReRAM or RRAM) are being considered for In-Memory Computing related to inference and learning in artificial intelligence

Introduction

- The RRAM's common structure consists of an insulator sandwich between two metals, in the shape of a metal-insulator-metal capacitor



- The resistance of the insulator that serves as the switching layer is modified when an electric field is applied to the top and bottom metal electrodes, as shown in Figure

Type of RRAM devices

Ferroelectric RAM (FRAM)

- FRAM is made of a ferroelectric capacitor, commonly PZT(Pb(Zr,Ti)O3), which is responsible for switching characteristics. The resistance change happens as a result of the change in polarization introduced by electric fields.

Introduction

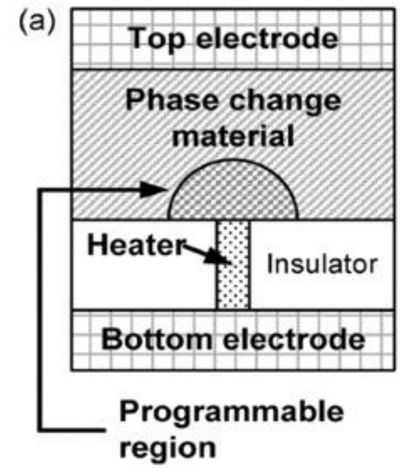
Type of RRAM devices

Magnetoresistive RAM (MRAM)

- Magnetoresistive Random Access Memory, uses 'spin and charge' to store the data. Scalability for this technology, though remains a bottleneck

Phase Chane Memory (PCM)

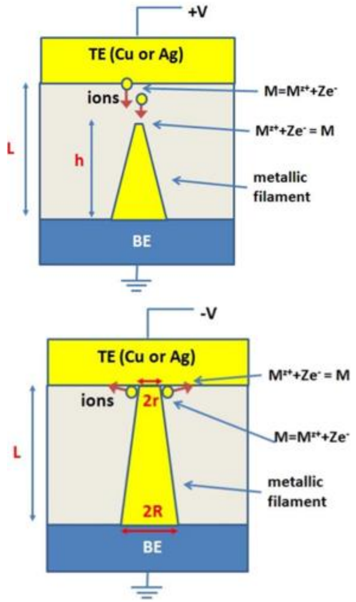
- Phase Change Memory, follows a similar concept to CDs and DVDs for memory storage. PCM defines two stages of transition in resistivity: polycrystalline and amorphous. Low resistivity refers to the polycrystalline phase and high resistivity applies to the amorphous phase



Introduction

Type of RRAM devices

Conductive Bridge RAM (CBRAM)



- Resistive switching in CBRAM occurs due to the forming and breaking of conductive filament (CF) in solid electrolyte. Filament formation and breakage are known to be due to the movement of metal ions.

Transition Metal Oxide-based RAM (OxRAM)

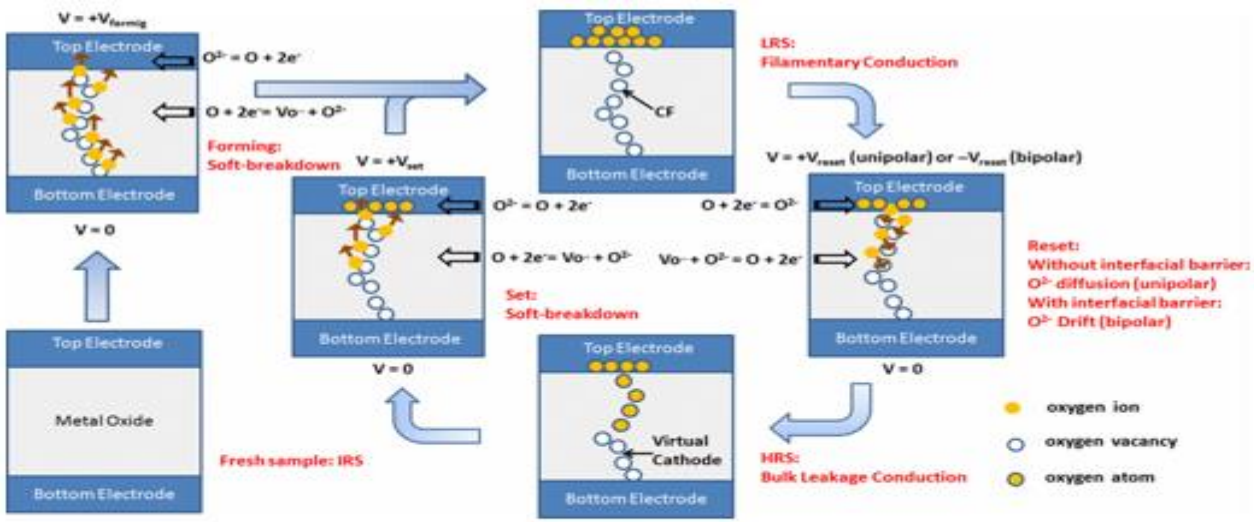
- OxRAM has MIM structure, the insulator is resistive oxide that is normally sandwiched between two metal electrodes.

- The mechanism of switching of the RRAM to execute reversible Low Resistance State ('0') and High Resistance State ('1'), involves initialization of forming process. The switching mechanism involves migration of oxygen ions for resistance change.

Why Transition Metal Oxide RRAM?

- Transition Metal Oxide based RRAM, have shown low power consumption, speed improvement, high endurance and retention rate
- It has shown multilevel storage capabilities, which can enhance memory storage
- It is compatible with current CMOS technology and can be fabricated using same tools

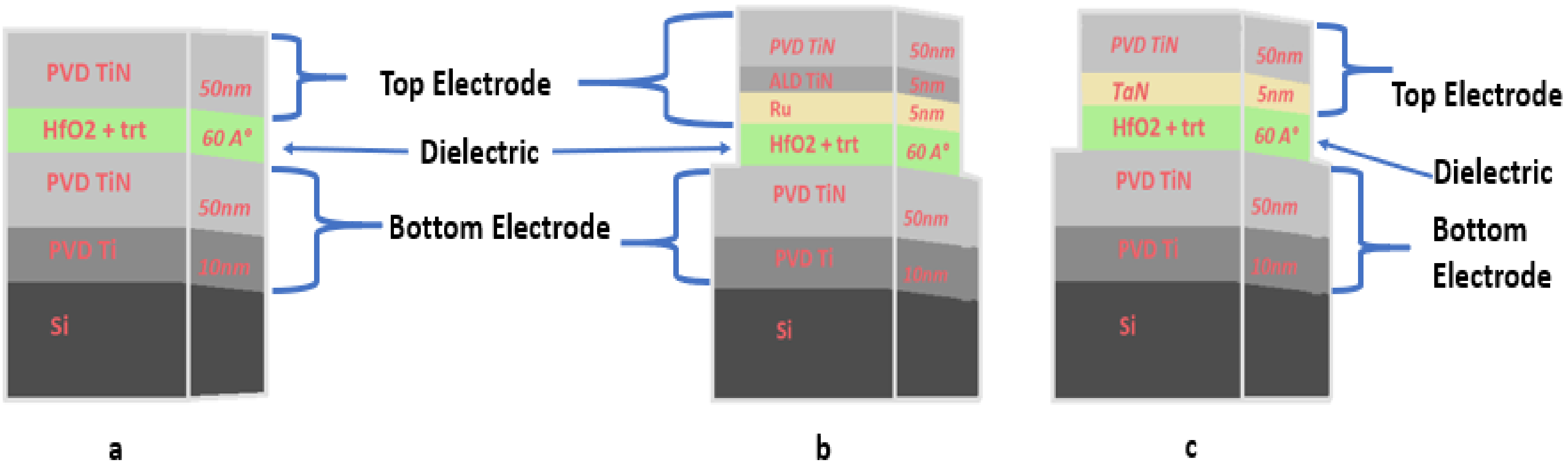
Switching Mechanism



HfO_2 Based RRAM

- Hafnium oxide (HfO_2) is used as switching dielectric in the RRAM. HfO_2 is used as a gate dielectric in in standard CMOS technology.
- Due to presence of free oxygen vacancies in the HfO_2 layer, CF formation process is more controlled
- Non-non-stoichiometric HfO_x has a large number of oxygen vacancies, introduced during the fabrication process or because of the selection of top/bottom electrode.
- The dielectric layer is treated with plasma to introduce more oxygen vacancies.

Structure of the Devices Studied in This Work



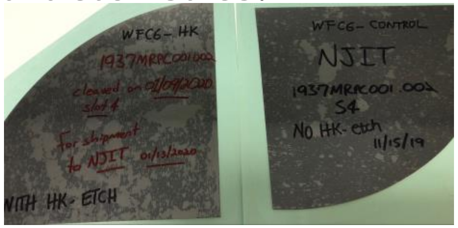
- Three different structures were fabricated for comparison purposes with plasma treated dielectric and different top metal electrode

- Figure (a) shows TiN-Device (b) Ru Device (c) TaN Device

Experimental Details

Fabrication

- The devices were fabricated at Tokyo Electron Limited (TEL) using different deposition techniques. 300 mm wafers were used to deposit the devices and then later diced in to 4 pieces for studying electrical characteristics.



Electrical Characterization of the devices

- A Keysight B1500 semiconductor device parameter analyzer was used to perform the electrical characterization

The Characteristics for Top Metal

TiN/Ti as Top Electrode

• Titanium nitride is less reactive towards oxygen then titanium (Ti). TiN is used as a buffer layer in addition to Ti, it is believed that addition of TiN buffer layer to the Ti layer controls this scavenging of oxygen in a controlled manner

Ru as Top Electrode

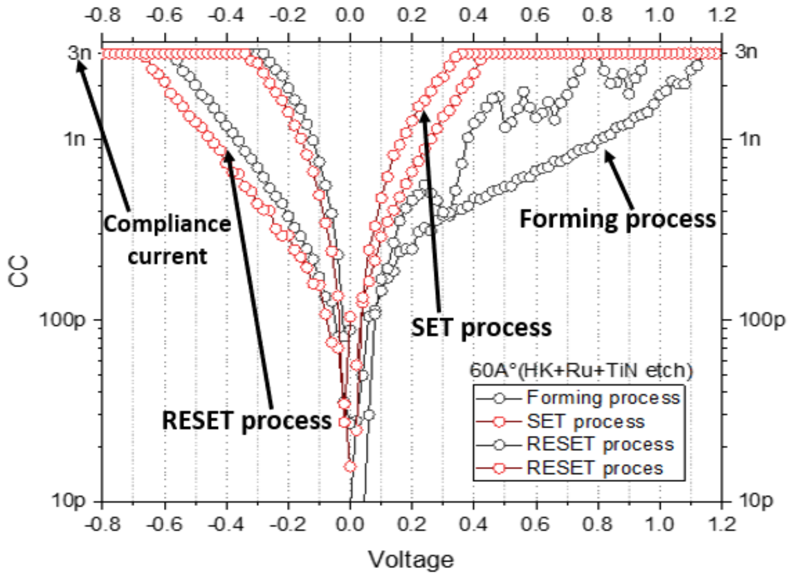
• Ru top metal electrode attracts more oxygen towards metal-dielectric interface, increasing the concentration of oxygen vacancies at the Ru/HfO_2

TaN as Top Electrode

• TaN shows great reactivity toward oxygen and form oxide layer at the interface with HfO_2 because of oxygen scavenging property

Experimental Details

Principle of IV characteristics

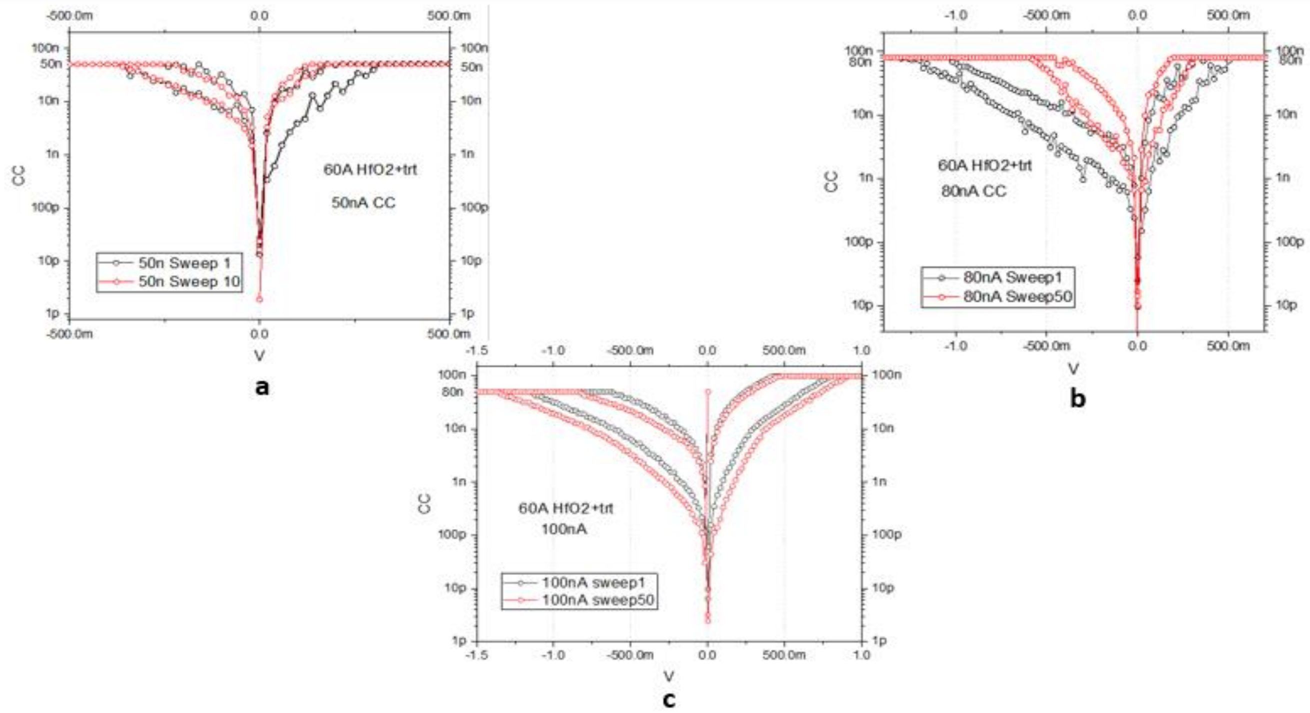


a

- A typical current-voltage (I-V) characteristic of a RRAM cell in log-scale is shown in the figure with initial current sweep and hysteresis behavior which shows the change in resistance and therefore able to write and erase memory

Results of treated devices to enhance oxygen vacancies

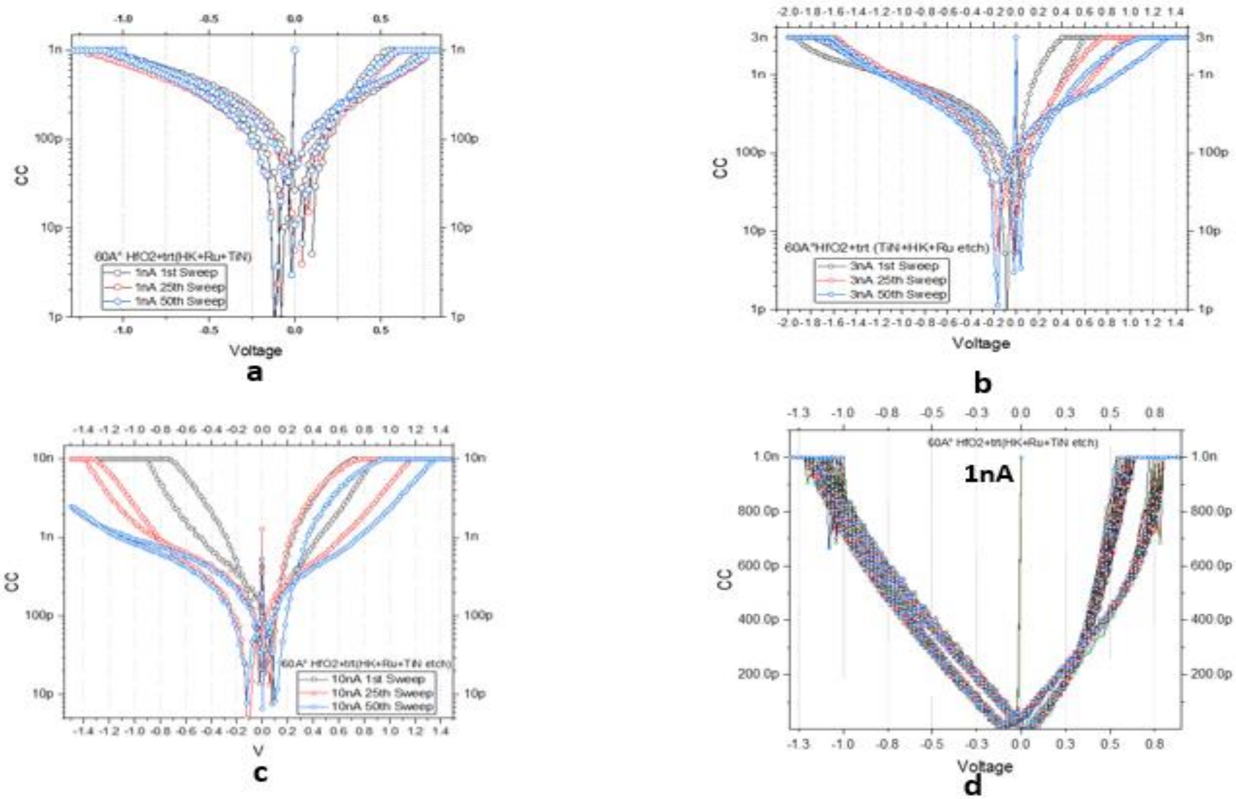
TiN Devices



- After the forming process, the SET voltage was reduced with well enough separated LRS and HRS. However, at lower CC the gap between top metal and ruptured filament was reduced.

Results of treated devices to enhance oxygen vacancies

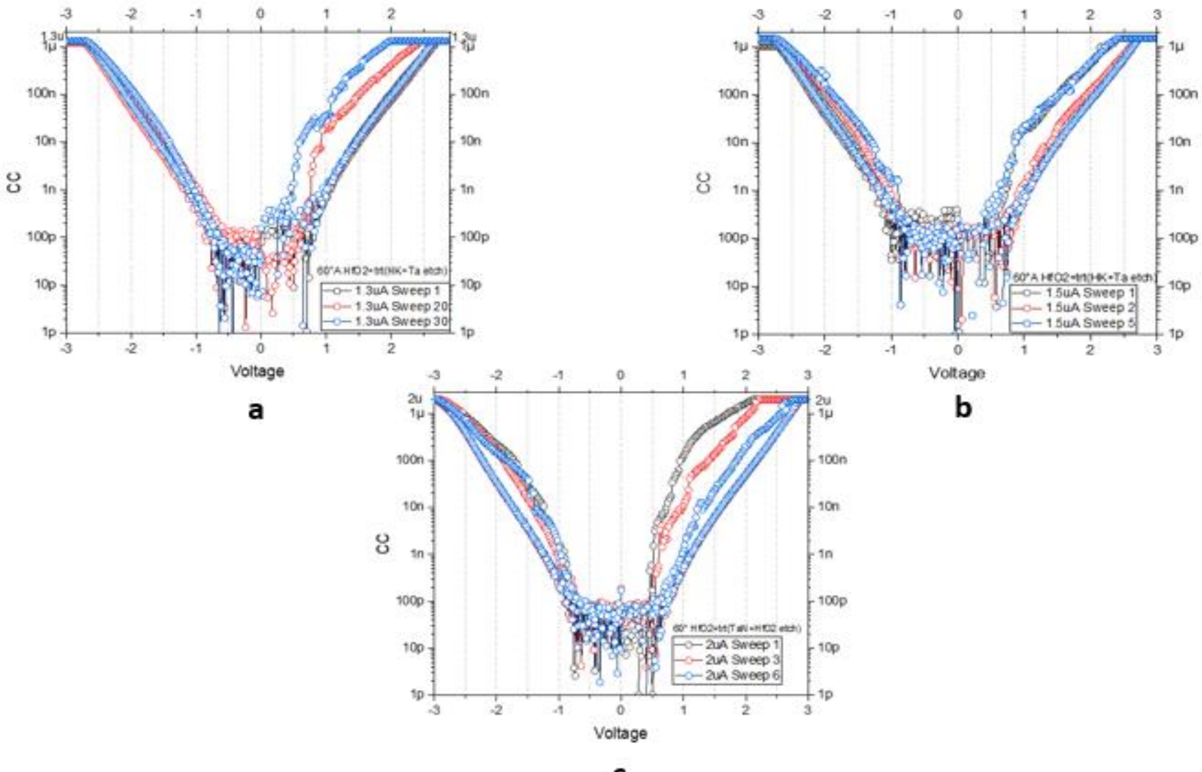
Ru Devices



- The switching CC current was reduced significantly, and the device demonstrated low power consuming characteristics.

Results of treated devices to enhance oxygen vacancies

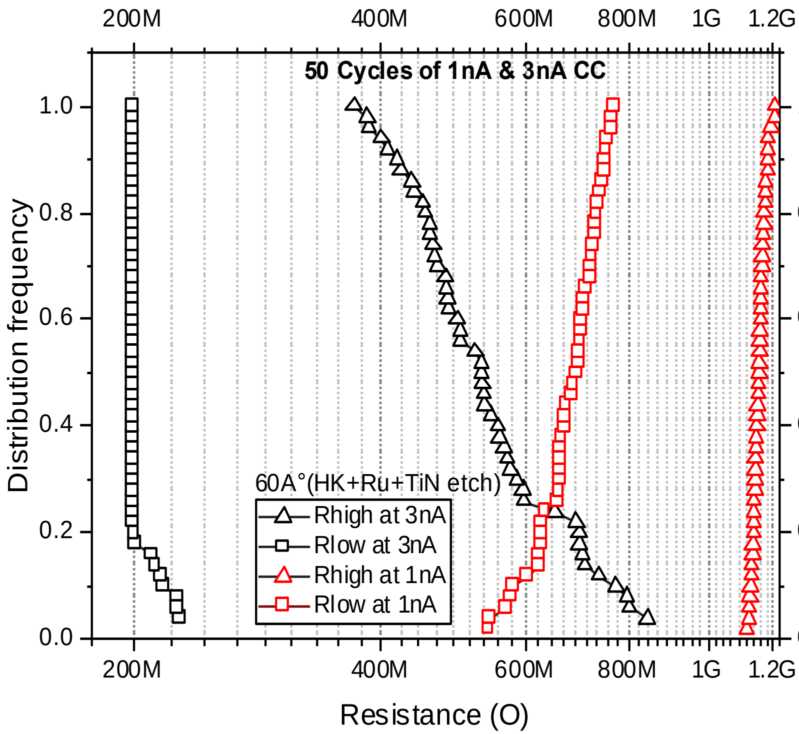
TaN Devices

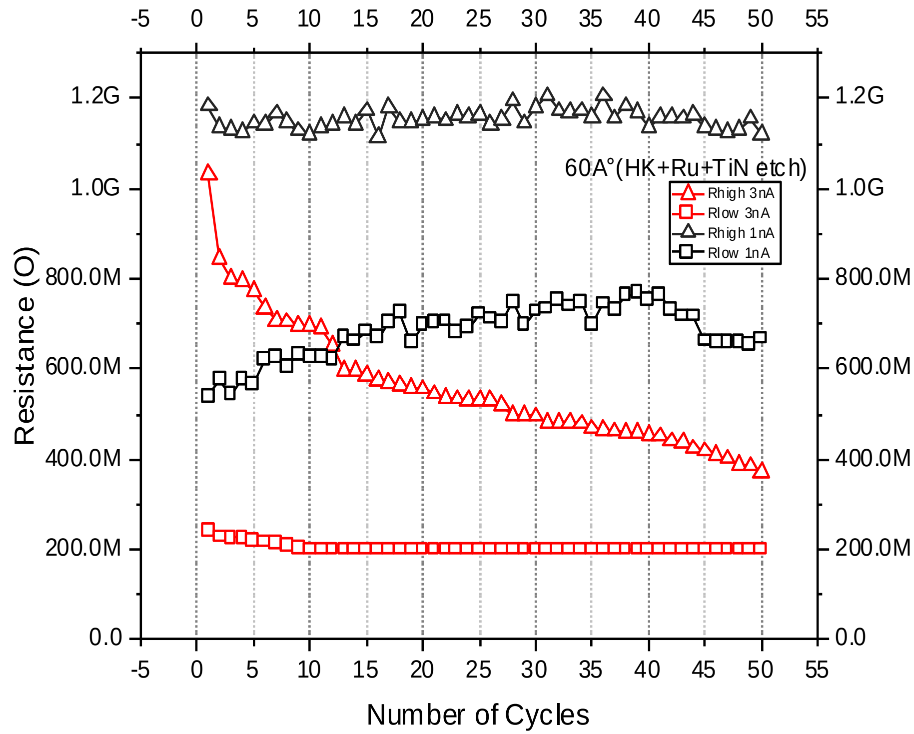


- Higher CC of 1 μA was required for device to form CF and able to toggle between LRS and HRS states. Devices formed a permanent non-reversible CF after switching for few cycles, which shows less stability and endurance rate than previous studied devices.

Results of treated devices to enhance oxygen vacancies

Resistance distribution in Ru Devices

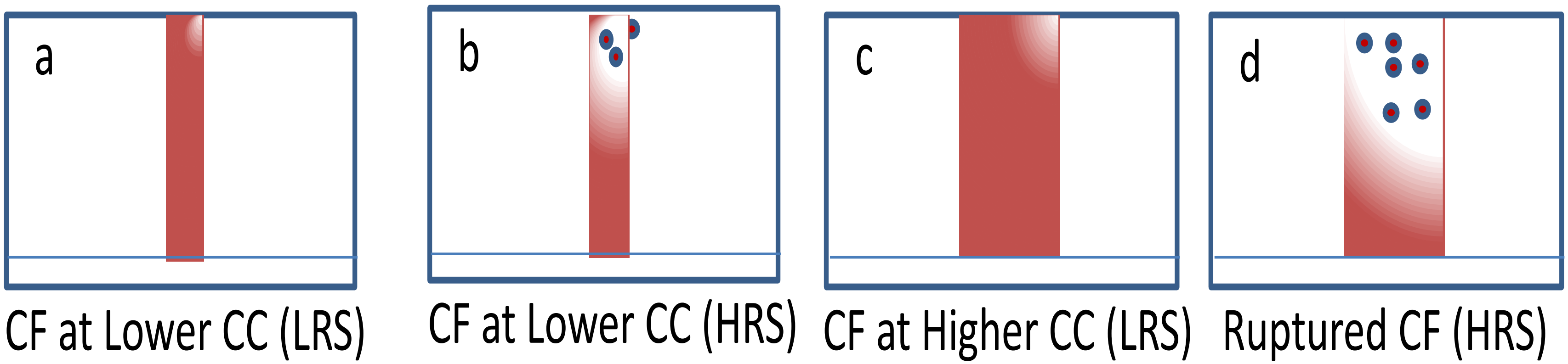




- The resistance distribution of 50 SET-RESET cycles is shown for Ru Devices at 1nA and 3nA CC at 0.54V and 0.6V respectively. Similar trend was observed for 5nA CC.

Results of treated devices to enhance oxygen vacancies

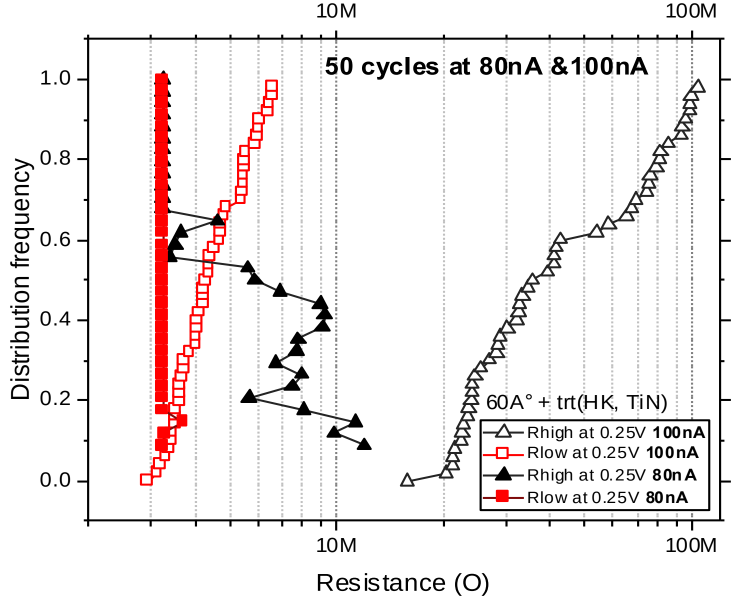
CF formation model in Ru Devices

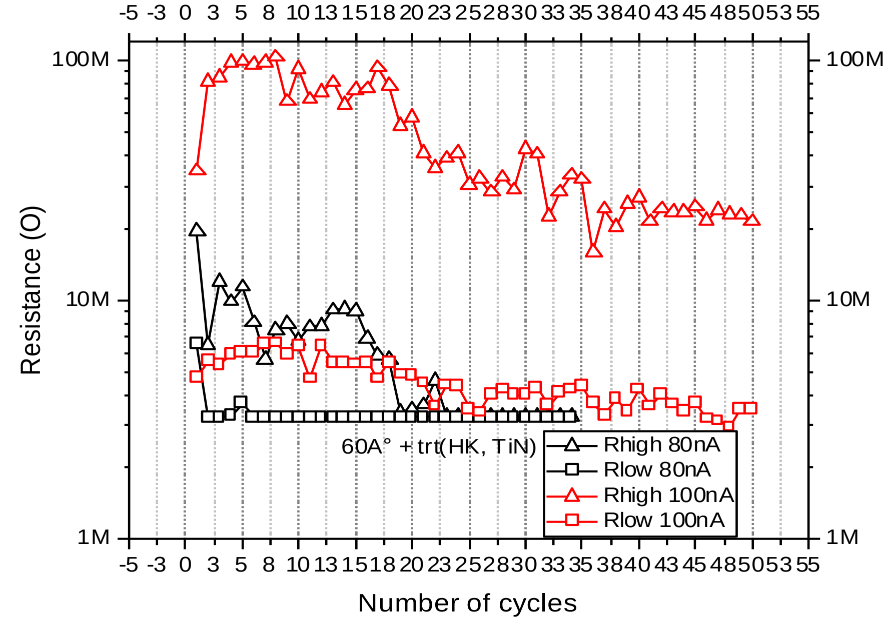


- The variation in the thickness of the filament is related to compliance current.
- At lower compliance current the filament is thinner or only a few established conducting channels across the electrodes. This leads to higher R_{low} as compared to R_{low} for higher CC

Results of treated devices to enhance oxygen vacancies

Resistance distribution in TiN Devices

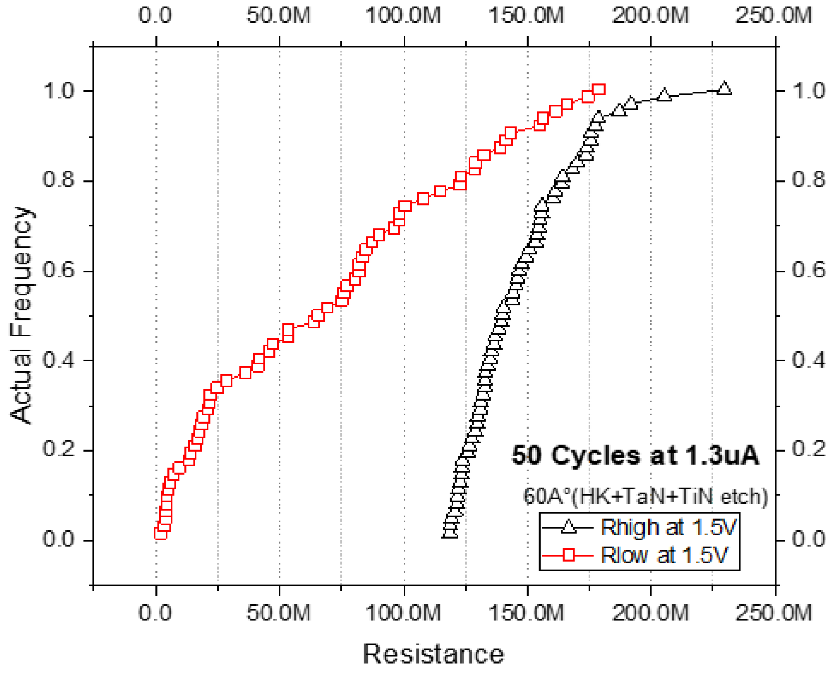




- The cumulative resistance distribution of TiN device for 50 SET-RESET cycles at 80 nA and 100 nA of CC and 0.25V. The resistance spread of HRS is from 20MΩ to 100MΩ, which shows limited MLC capabilities.

Results of treated devices to enhance oxygen vacancies

Resistance distribution in TaN Devices



- The resistance distribution of TaN has a spread for both HRS and LRS, this shows that set voltage is not very controlled

Discussion

- The formation of CF in HfO_2 lattice, with effects of top electrode selection in RRAM is studied in this thesis.
- The thesis studies the role of top metal electrode and dielectric layer in power reduction, which is a deciding factor in today's semiconductor industry.
- More research on the physical and chemical properties of the layers needs to be conducted, with development of a perfect switching model for RRAM that preciously explains all the responsible parameters and constrains.
- Use of Ru, TiN and TaN as the bottom metal needs to be investigated to further understand the effectiveness of these electrode metals

Conclusions and Future works

- The formation of CF in HfO_2 lattice, with effects of top electrode selection in RRAM is studied in this thesis.
- The thesis studies the role of top metal electrode and dielectric layer in power reduction, which is a deciding factor in today's semiconductor industry.
- More research on the physical and chemical properties of the layers needs to be conducted, with development of a perfect switching model for RRAM that preciously explains all the responsible parameters and constrains.
- Use of Ru, TiN and TaN as the bottom metal needs to be investigated to further understand the effectiveness of these electrode metals
- A conference paper is in preparation:

Y. Patel, D. Misra, D. H. Triyoso, K. Tapily, R. D. Clark, S. Consiglio, T. Hakamata, C. S. Wajda, and G. J. Leusink, "Treated HfO2 based RRAM Devices with various Top Electrodes for Power Optimization," ECS Fall Meeting (in Preparation).

Thank you!!