A Synaptic Switch for Neuromorphic Compute

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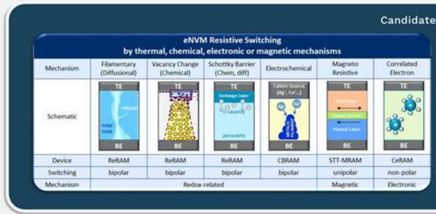
Materials & Integration: Framework for Novel Compute (FRANC)

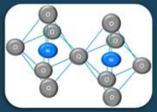
Candidate synaptic switches

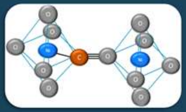


eNVM Resistive Switching by thermal, chemical, electronic or magnetic mechanisms						
Mechanism	Filamentary (Diffusional)	Vacancy Change (Chemical)	Schottky Barrier (Chem, diff)	Electrochemical	Magneto Resistive	Correlated Electron
Schematic						
Device	ReRAM	ReRAM	ReRAM	CBRAM	STT-MRAM	CeRAM
Switching	bipolar	bipolar	bipolar	bipolar	unipolar	non-polar
Mechanism	Redox-related				Magnetic	Electronic

- CMOS is not the ideal synaptic switch
- It is widely accepted that non-volatile memory (NVM) is the most likely device candidate to be used as a synaptic switch (synapse and/or neuron)
- ReRAM (including CBRAM) devices are not electronic but rather electro-mechanical switches which can suffer from variability and endurance
- STT-MRAM is not only stochastic but also suffers from a small difference between on and off states which does not allow for multibit weighting which is required for neuromorphic compute
- CeRAM (correlated electron RAM) is a true quantum mechanical electronic resistive RAM which does not use filaments and electro-mechanical effects to switch
- CeRAM uses the Mott transition in order to switch between low and high resistance states

CeRAM construction





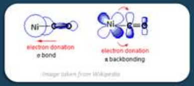
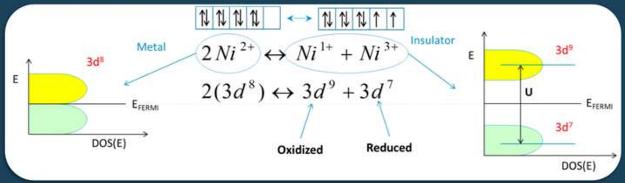


Image taken from Wikipedia

- Carbon doping is used to achieve a stable correlated electron material for the CeRAM device by ensuring that the correct stoichiometry is achieved to allow for the disproportionation reaction (essentially forming a defect free interface and device)
- Carbon doping allows for sigma-bonding donation and pi-bonding backdonation which ensures that the material is p-type as hole conduction is critical for the device operation

CeRAM operation

- The Mott transition is a disproportionation reaction (the same element is oxidized and reduced)
- This is realized by the transfer of electrons between orbitals (CeRAM is an orbital switch with a length scale on the order of the Bohr radius)



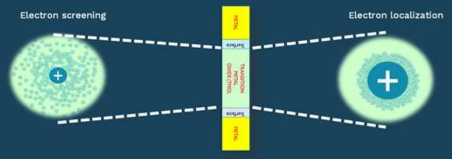
$$2\,Ni^{2+} \leftrightarrow Ni^{1+} + Ni^{3+}$$

$$2(3d^8) \leftrightarrow 3d^9 + 3d^7$$

$$H = \overbrace{-t \sum_{<i,j>\sigma} \left(c_{j\sigma}^{\dagger}\, c_{i\sigma} + h.c.\right)}^{\text{Kinetic}} + \overbrace{U \sum_{j} n_{j\uparrow} n_{j\downarrow}}^{\text{Potential}} - \overbrace{\mu \sum_{j} \left(n_{j\uparrow} + n_{j\downarrow}\right)}^{\text{Chemical}}$$

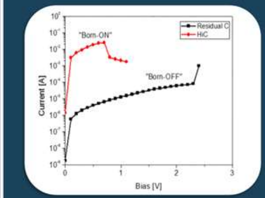
- The full Hamiltonian including the strong Coulomb interaction is used to describe the behavior of CeRAM
- (The strong Coulomb interaction is ignored in semiconductors, we use the single electron approximation)
- The kinetic term (hopping) describes carriers as they move through the lattice
- The potential term results from the strong electron-electron interaction. This interaction causes a large potential U which ultimately becomes the bandgap of the material. This happens when the electrons are strongly localized thereby maximizing U
- The chemical potential is determined by doping and charge injection (both holes and electrons). The doping is set for a target devices while the injection of electrons and/or holes is used to toggle between the high and low resistance states

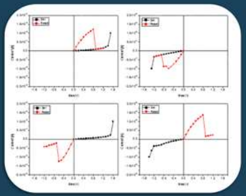
Why is CeRAM "Correlated"

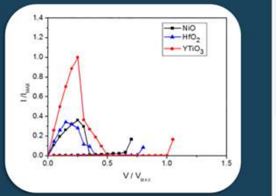


- Electrons are either all screened or all localized, therefore the electrons in the system are correlated (all behave the same)
- When there is strong screening of the metal ion, the electron-electron interaction is reduced which reduces the potential term of the Hamiltonian to zero. As U is the bandgap, the material will have no bandgap and be metal like
- When the electrons are strongly localized, the close proximity of electrons maximizes the Coulomb interaction and therefore the potential energy in the system resulting in the potential U which splits the band; the material will have a bandgap and therefore be insulator like
- Switching between the states is achieved with injection of electrons and/or holes. The injection of electrons in the localized states causes electron screening and therefore a switch to a screened state. Hole injection in the screening state is used to sweep out electrons from the system resulting in decreased screening and eventual localization of the electrons

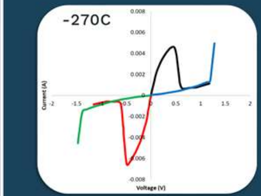
Uniqueness of CeRAM

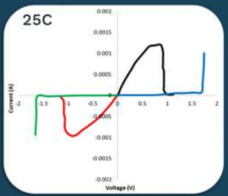


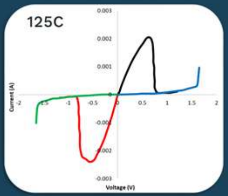




- Without proper carbon concentrations, a standard filamentary "born off" RRAM device is created, where transition to the low resistance state is made at a high voltage that is not compatible with modern logic transistors.
- The CeRAM can be operated fully under 1.2V which makes it easier to design into normal logic circuits, more dense, and lower power than RRAM.
- Device is non-polar meaning it can be set and reset in either Q1/Q3 in any order
- The doping effect is not limited to NiO. It has been demonstrated in several material systems including HfO_2 and $YTiO_3$
- While YTiO is a well known Mott material, HfO is not believed to be a Mott material illustrating the effects of carbon doping on the material system
- The addition of carbon correctly sets the stoichiometry which does not allow defect driven filament formation and allows the HfO_2 to operate as a correlated material by screening and localizing the potential in the system



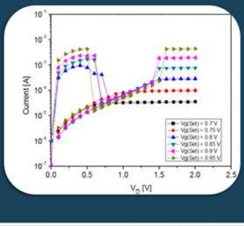




- Switching at a wide range of temperatures has been demonstrated by Symetrix (work performed at NIST in Boulder)
- Retention and possibly switching temperature is expected to exceed 200C
- As CeRAM (Mott transition) are true quantum mechanical transitions, it is expected that CeRAM will not have freeze-out issues and could possibly be rad-hard too
- Additional testing is being planned to reach the mK temperature range to demonstrate use of CeRAM in as a cryostatic memory

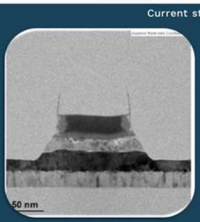
CeRAM as a neuromorphic switch

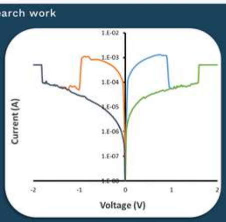
- The requirements for neuromorphic switches are:
  - For the synapse
    - Large high-resistance state
    - Large number of stable/reliable resistance states to store synaptic weights
    - Large OFF/ON resistance ratio
  - For the neuron
    - Sharp set and reset conditions
    - Ability to store accumulated state
    - Ability to change state when certain conditions are met



- Measured CeRAM results indicate that CeRAM would be a good neuromorphic switch:
  - For the synapse
    - Very low leakage compared to on current with at least at least a 100x Ron/Roff ratio
    - Ability to set multiple states
  - For the neuron
    - The Mott transition occurs on the femtosecond scale
    - CeRAM is non-volatile and allows state storage
    - CeRAM needs a critical electric field AND current density which prevents unwanted state changes
    - There is both a large read and write window

Current status of research work





- The device has already been demonstrated by Applied Materials, Arm and Symetrix at 100nm size with NiO
- The device showed born-on, non-polar switching as expected

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