A Synaptic Switch for Neuromorphic Compute

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New Materials and Devices: Framework for Novel Compute (FRANC)

SyNCED: Synapses and Neurons using Correlated Electron Devices

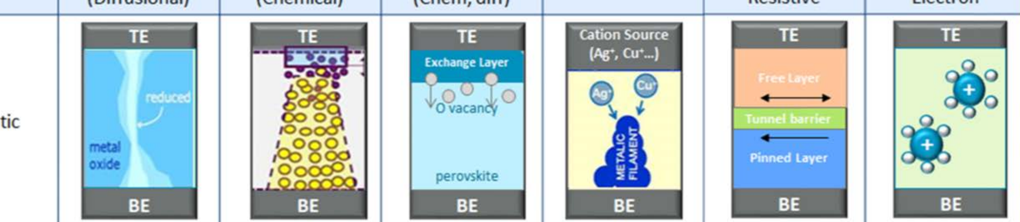
- Development of a correlated electron switch (CES) as a radiation-hard high-temperature tolerant non-volatile logic switch for post-Moore sub 5nm nodes
- CES is capable of replicating the function of a neuron and synapse for neuromorphic compute, which holds the promise to have five orders of magnitude more power efficiency versus current von Neumann compute

Candidate Synaptic Switches

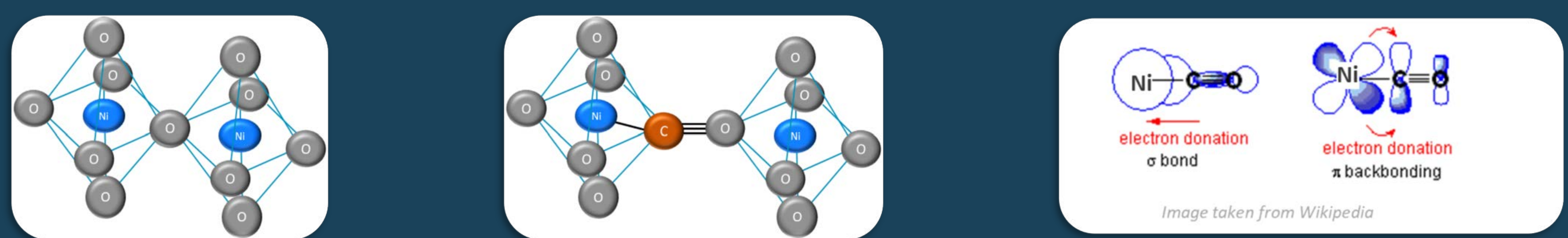
- CMOS is not a good synaptic switch
- It is widely accepted that non-volatile memory (NVM) is the most likely device candidate to be used as a synaptic switch (synapse and/or neuron)
- ReRAM (including CBRAM) devices are electro-mechanical switches which suffer from variability and failure in the low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

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



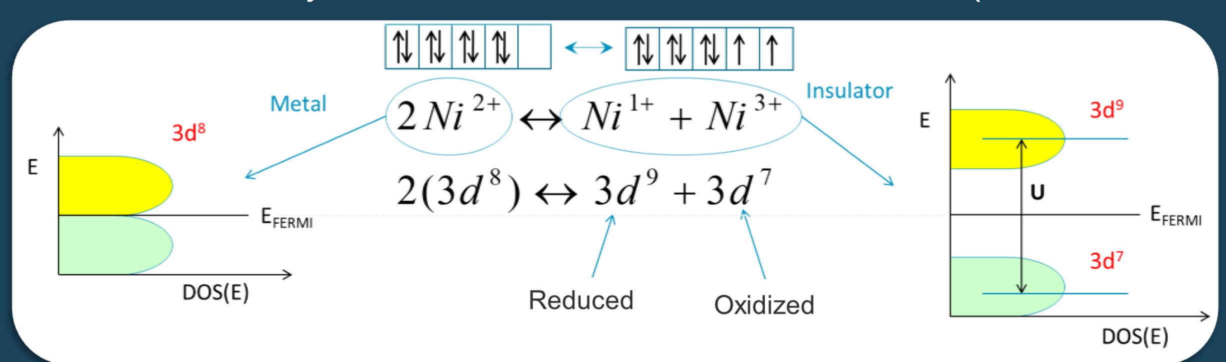
CeRAM Construction



- 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)



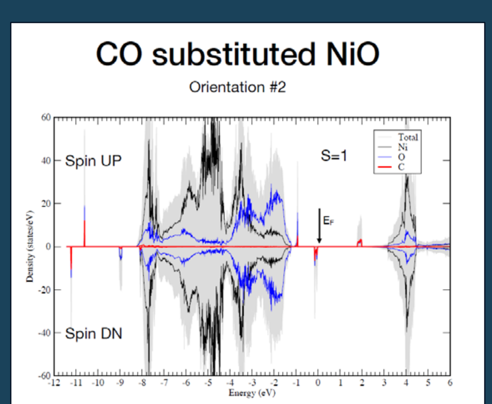
Kinetic — Potential — Chemical

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

- 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

Modeling and Mechanism Determination

DFT + U Simulations to help guide experimental direction



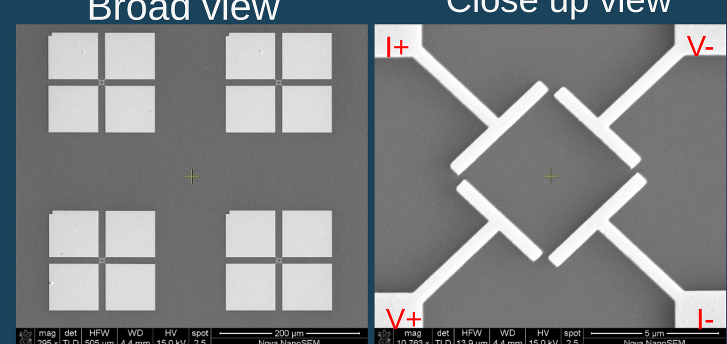
Defect formation energies in eV

	O vacancy	Cation vacancy	CO	C
MgO	6.89	8.33		6.33
NiO	4.27	5.23	6.7 , 7.0	3.23
MnO	4.46			2.71

$$E_f^m = E_d - E_{bulk} + \sum_i n_i(E_i^m + \mu_i)$$

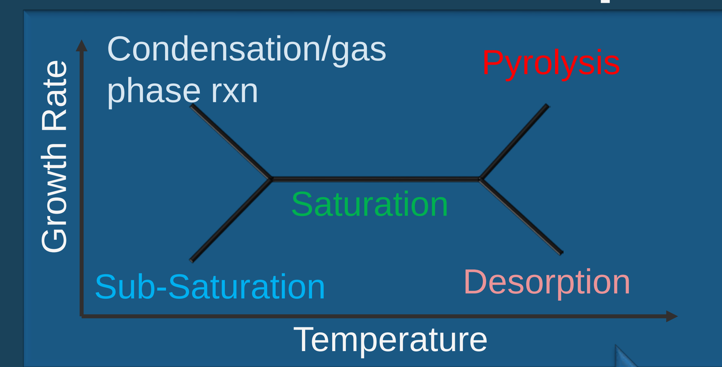
Hall Effect Test Vehicle

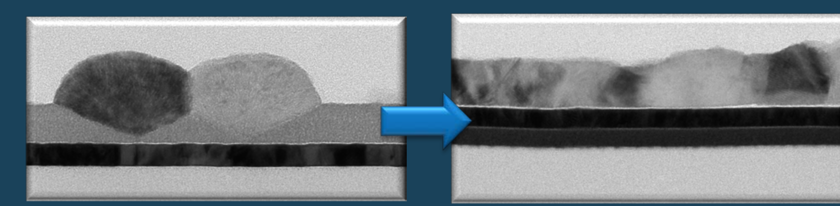
Broad view — Close up view



- 4 wire measurement with pads on surface of NiO
- Ti/Au pads 5nm/100nm thickness
- Opposing sets of current and voltage leads
- 5 µm spacing between opposing contacts

New Material Development



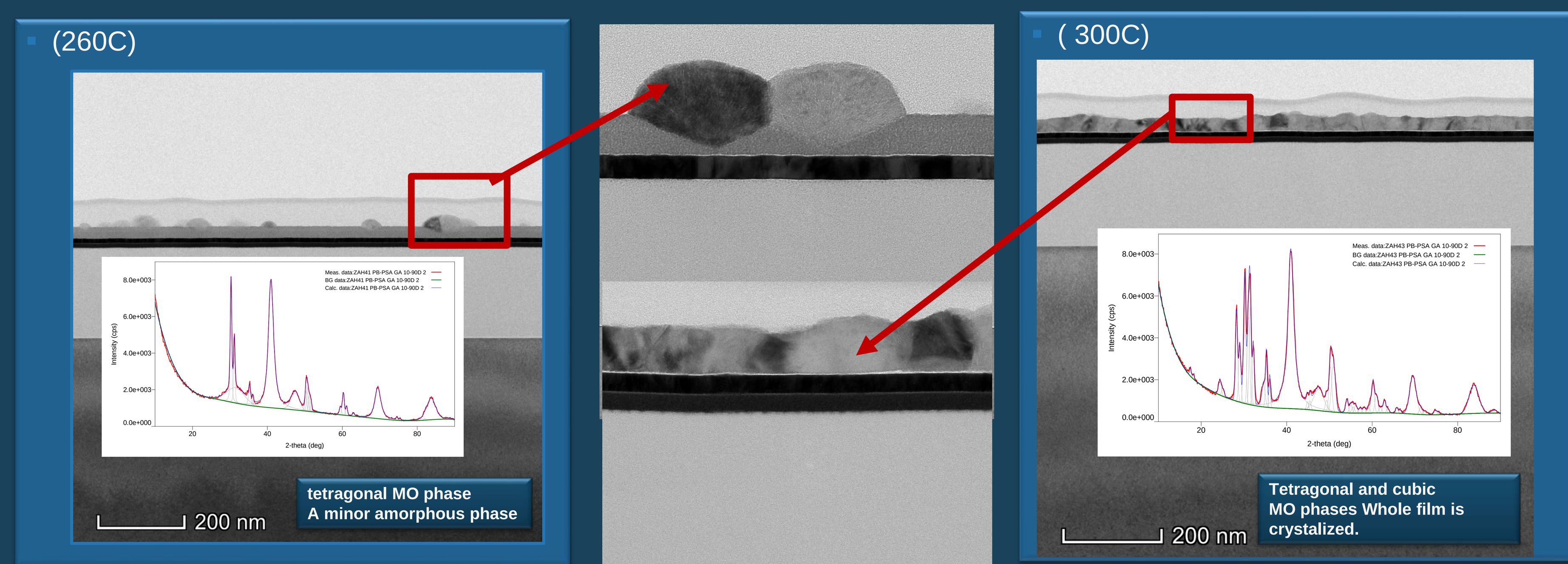


- Vapor Pressure
- Thermal Stability
- Composition

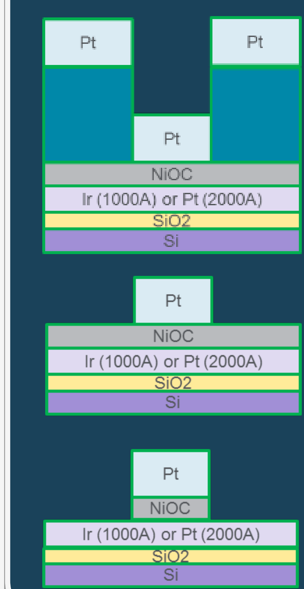
- Precursor Pyrolysis Curve
- Precursor Saturation
- Co-reactant Saturation
- Purge Saturation
- Saturated Temperature Window
- Substrate Interaction

- Explore Sub-Saturated Regimes (Precursor/Co-reactant/Purge)
- Reactivity of co-reactants (different oxidation sources)
- Deposition Method (ALD/CVD/SPD)

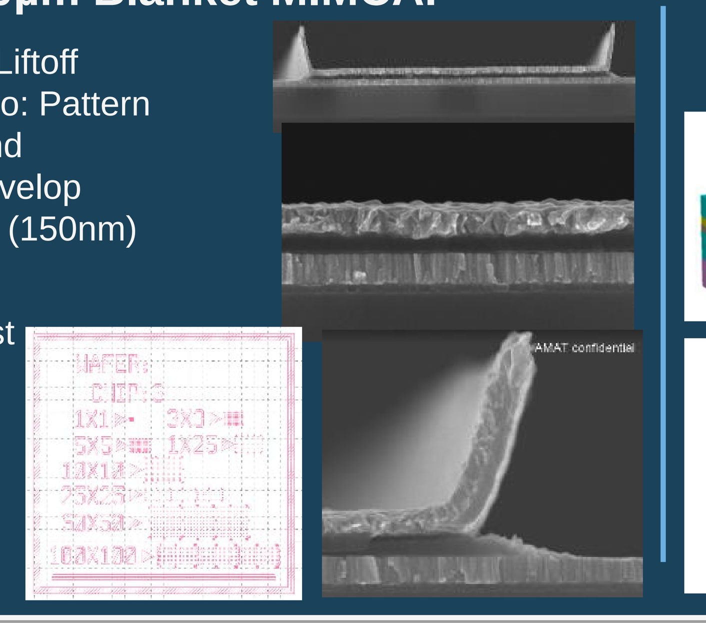
Process repeated for each new precursor and co-reactant



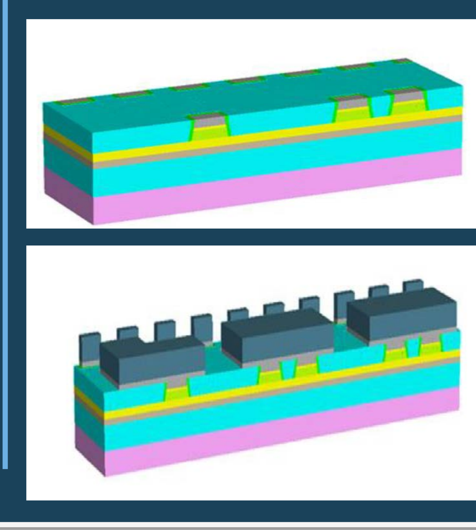
1µm - 100µm Blanket MIMCAP



a) Resist for Liftoff
b) Digital Litho: Pattern transfer and expose/develop
c) Deposit Pt (150nm)
d) Liftoff resist
e) Ar Sputter through MO

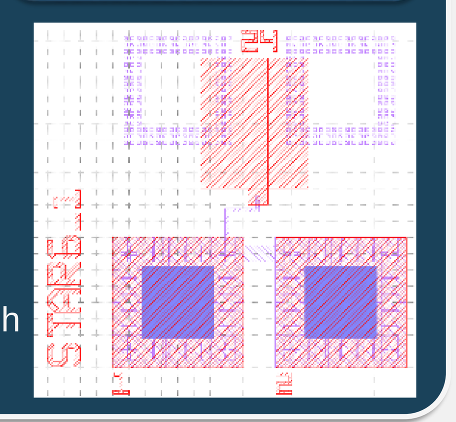


100nm - 500nm Planar MIMCAP

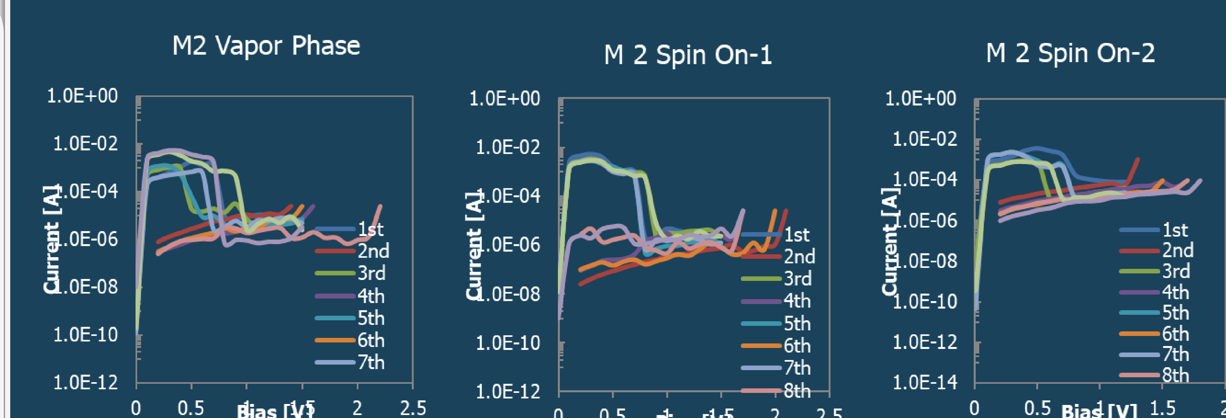


a) Process on 300mm until MO dep is complete
b) Resist for Liftoff
c) Digital Litho: Pattern transfer and expose/develop
d) Deposit Pt (150nm)
e) Liftoff resist
f) Ar Sputter through NiOC

Key Advantages:
- 50 experiments out of every single wafer
- 100 nm pillars limits the device area



Initial E-Test Data for Final Material Selection in Phase 1



Property		Metric	Method	M 1	M 2	M 3	M 4	M 5	M 6	M 7
Device	Jon	3000 - 6000 A/cm2	E- test	4000	1720	12000	9000	5000	768	12000
	Vset	1- 2V	E- test	6V	2V	5V	5V	2V	4V	2V
	Vreset	50% Vset	E- test	0.5V	0.8V	0.9V	0.7V	0.8V	0.7V	0.8V
	Born - on	Yes	E- test	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Non - polar	Yes	E- test	Yes	Yes	Yes	Yes	Yes	No	Yes
Process	C %	1 to 20%C	XPS	6.5%	3.7%	10%	4.3	4.9	2.9%	4.4
	Thickness uniformity	(+/ -) 10% throughout bulk	XPS	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Continuity	No exposed bottom electrode	TEM	Yes	Yes	Yes	No	N/A	Yes	No

Three materials have been selected for "deep dive" device development in Phase 2

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