Symetrix Corporation

Background

- Symetrix has strong history as IP provider
  - *> 25 years of development*
  - *>200 U.S. and foreign patents.*
  - *> $70M in research revenues, royalties and other income from development.*
- Symetrix has licensed various technologies to eleven separate companies.
- Several of these technologies are in high volume production, most notably FeRAM at Panasonic.

Basic Idea of CeRAM
Game Changer – No Filaments

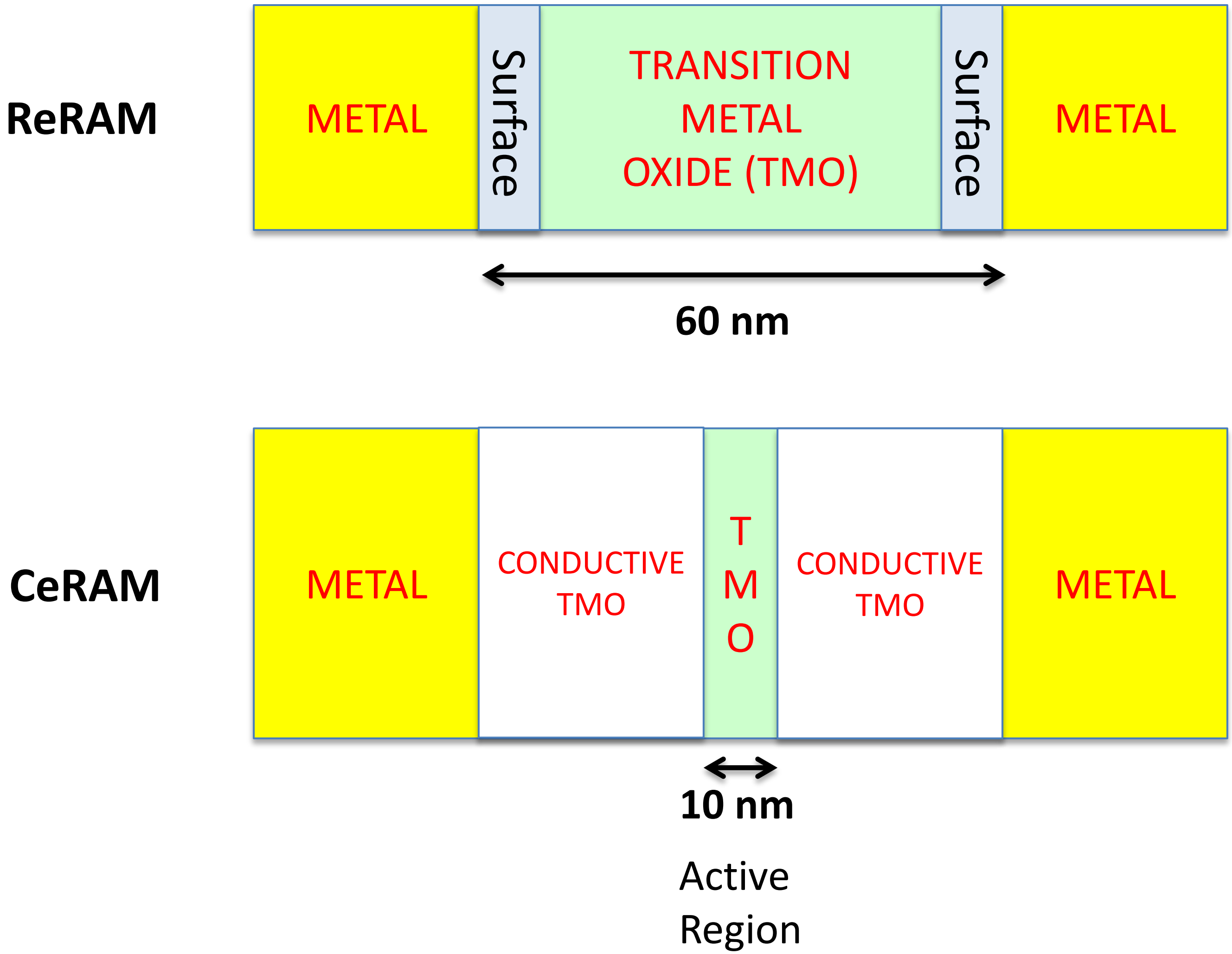
- Control of material properties and proper device architecture are fundamental to this new paradigm. Evidence? No filament formation. (**No electroforming**)
- The CeRAM resistor is designed to exploit materials properties, surface properties, switching mechanism (endurance) and memory mechanism (retention).
- Optimizing CeRAM is a different science than building the perfect filament.

Baseline

The device is like a diode (varistor) to start with:

The surfaces are defect-rich with oxygen vacancies,
transition metal excess, grain boundaries…
And a schottky barier !!

Baseline

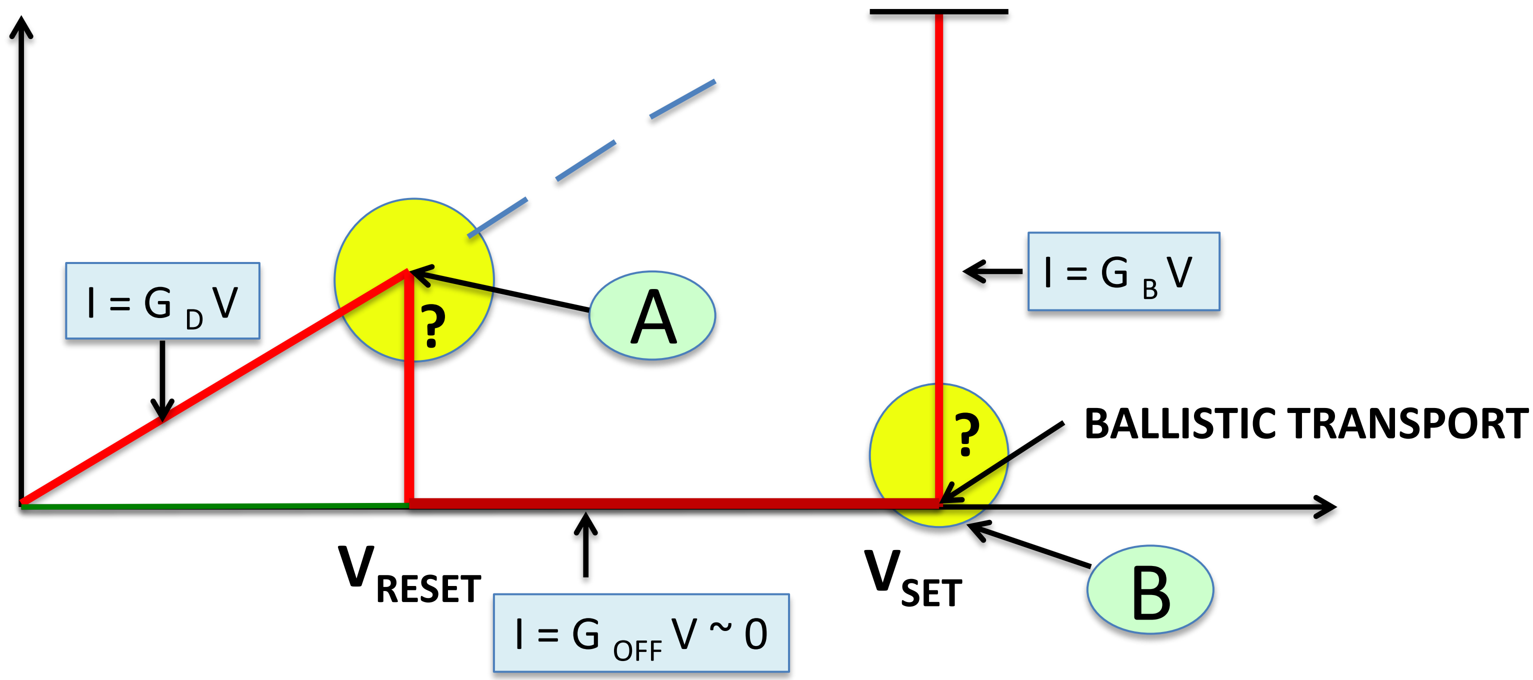


ReRAM
METAL
Surface
TRANSITION METAL OXIDE (TMO)
Surface
METAL
60 nm
CeRAM
METAL
CONDUCTIVE TMO
T M O
CONDUCTIVE TMO
METAL
10 nm
Active Region

Why the Layers?

- **Eliminate space charge** at the interface
- **Doping of TMO** to make it conductive as-deposited (valence stabilization)
- **Differential Doping** to create active region that is "switchable" and repeatable ("pure" phase transition)
- **Isolate and thin the active region** where the "electronic switch" property can be used exclusively----what electronic switching property? (Next slide)

IV Characteristics - Device Physics

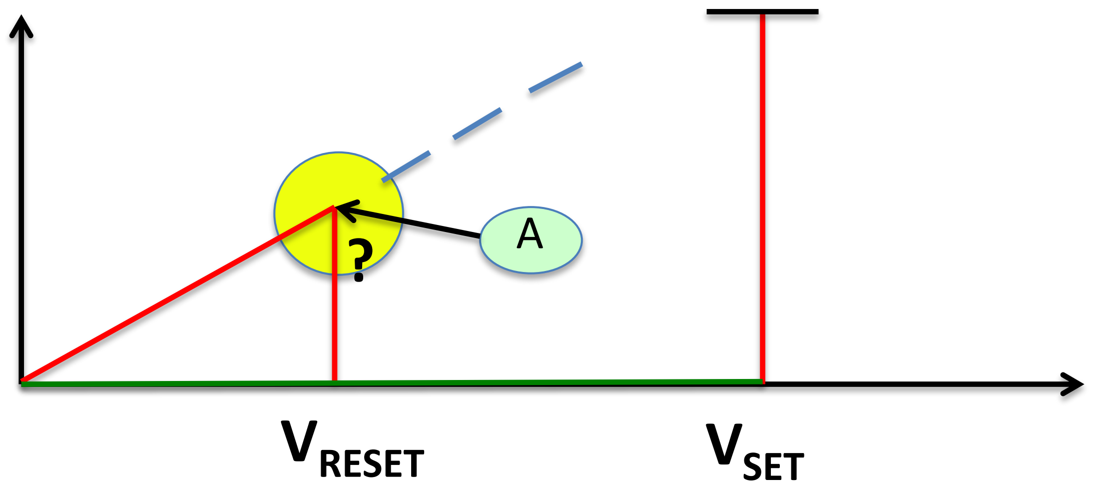


G_D = **DIFFUSIVE TRANSPORT** – *DRUDE*

G_B = **BALLISTIC TRANSPORT** *DUE TO e-e CHARGE GAP CLOSING IN THE TRANSITION METAL ION 3d ORBITALS*

G_{OFF}= **NO TRANSPORT** IN INSULATING PHASE *CONTROLLED BY e-e REPULSION IN 3d ORBITALS*

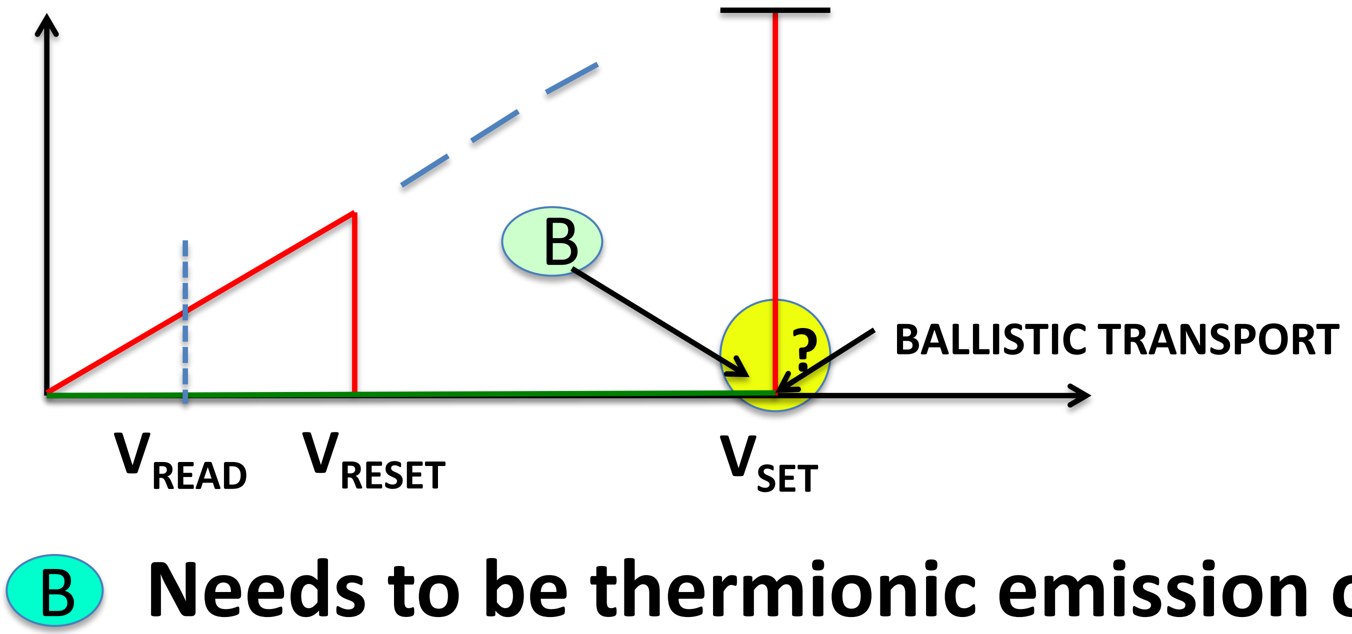
Underlying Physical Mechanism



A Is a quantum phase transition

- Mott, charge transfer (CT) but not Anderson
- Extended band gap is of no consequence here
- Only localized electron matters (in the atom)
- Extremely high speed – 80 femtoseconds

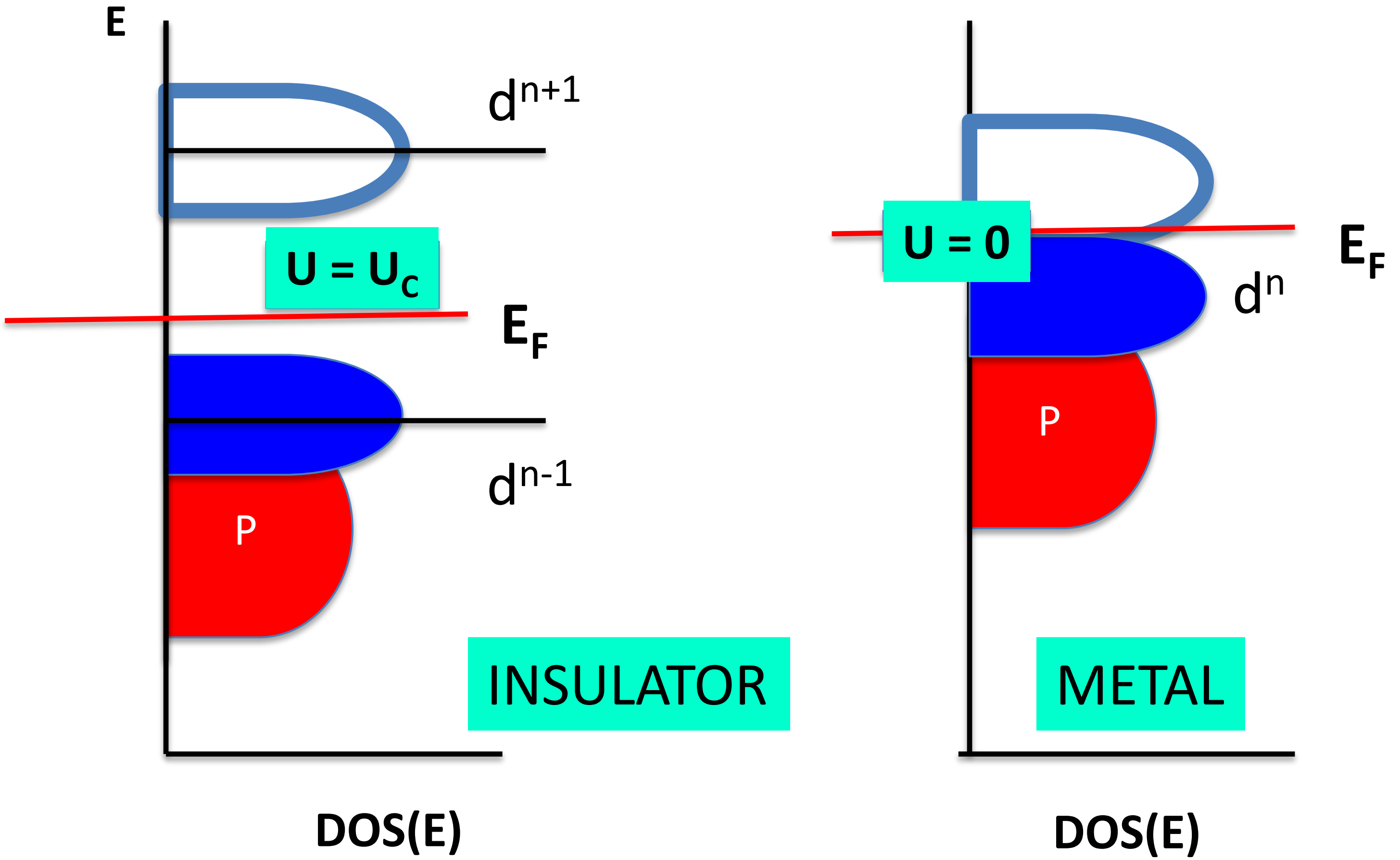
Underlying Physical Mechanism



Needs to be thermionic emission only to be sharp and cohesive so that it matches the charge gap energy (no fluctuations)

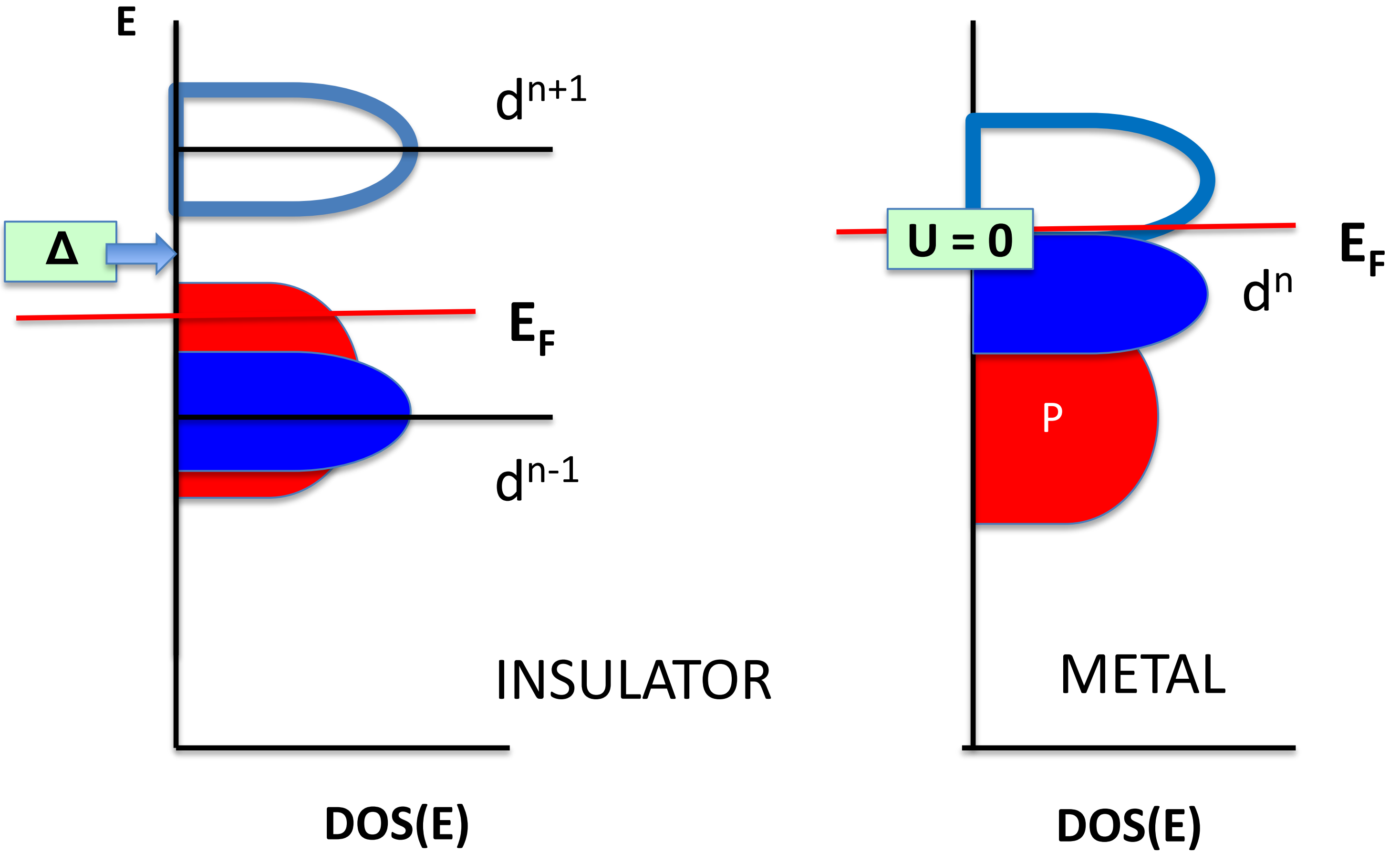
Mott Insulators

MOTT TYPE

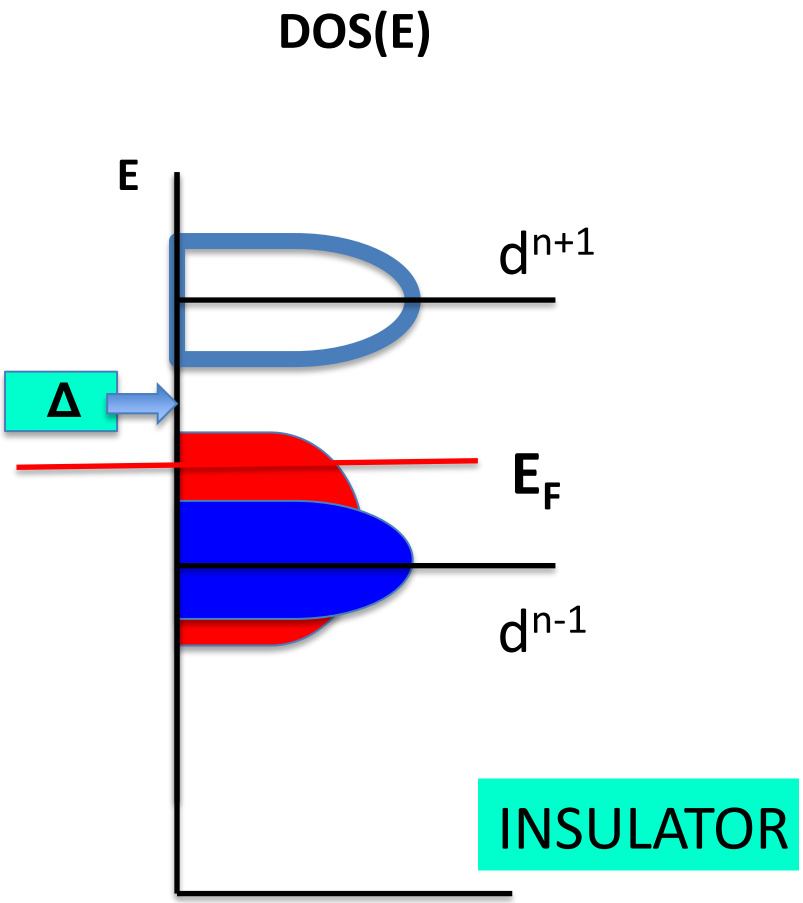


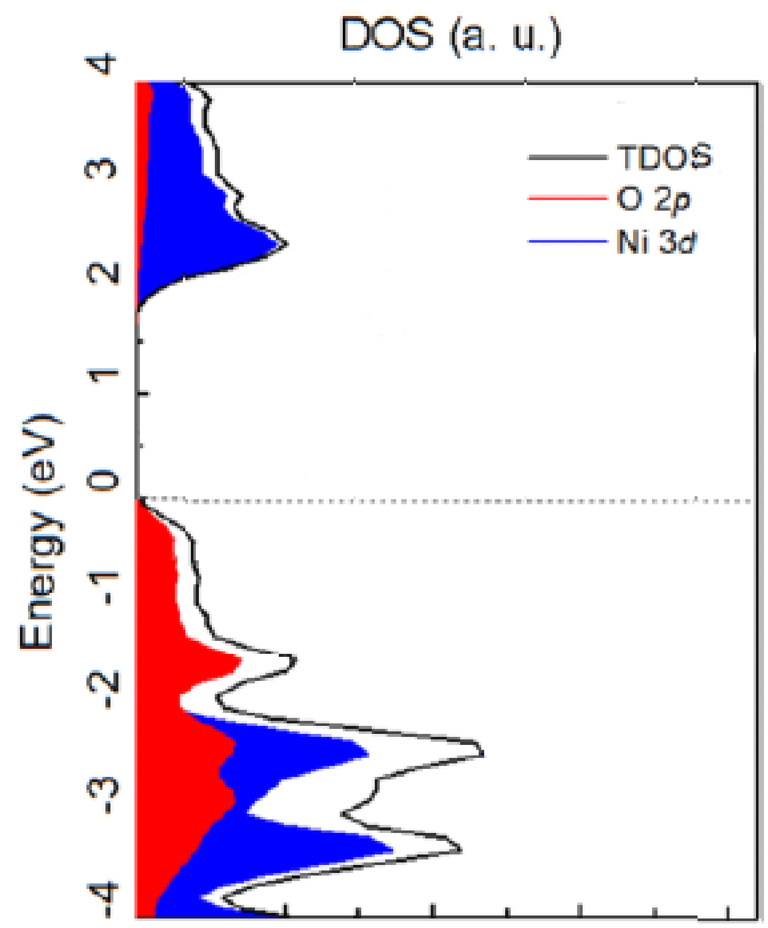
Mott Insulators

CHARGE TRANSFER "MOTT INSULATOR"

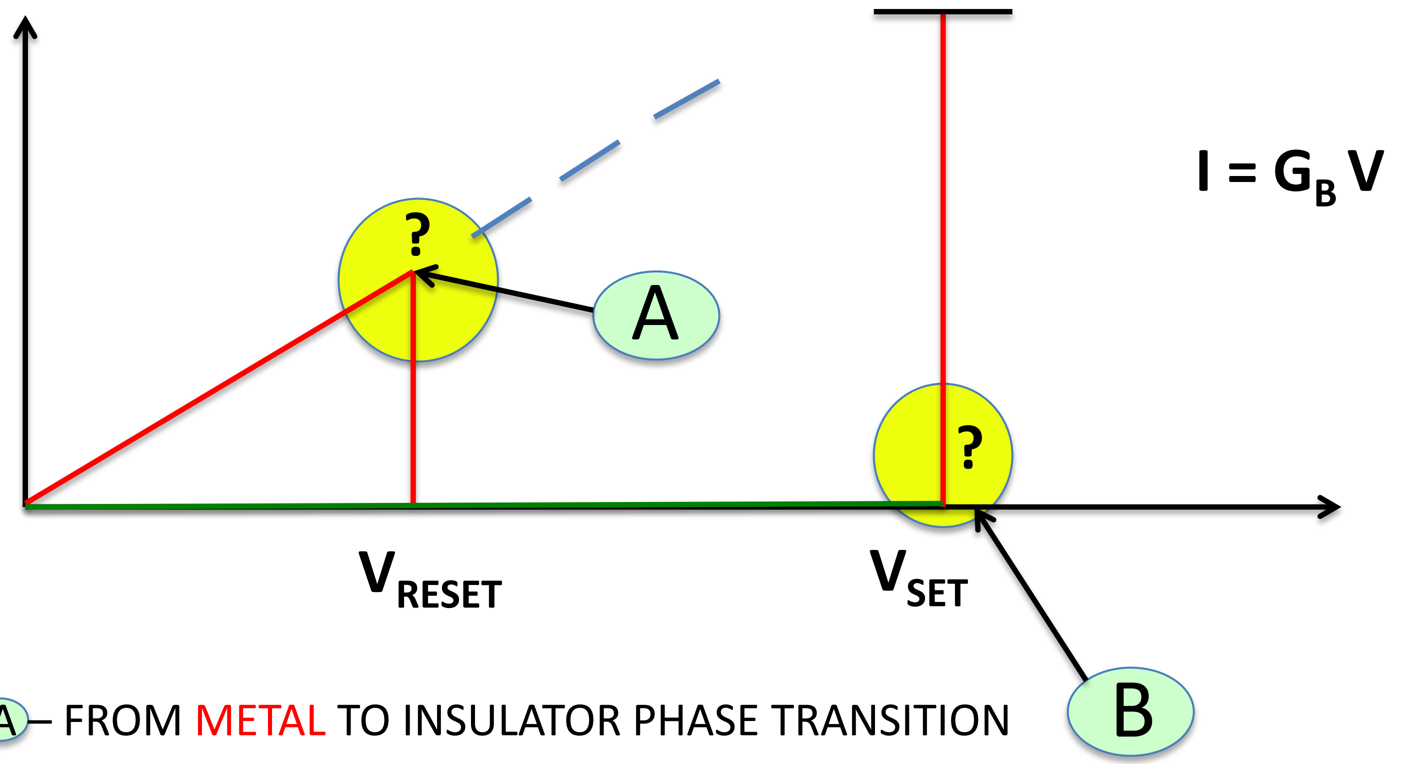


Charge Transfer M Mott Insulator





IV Characteristics - Device Physics



A – FROM METAL TO INSULATOR PHASE TRANSITION

B – FROM INSULATOR TO METAL PHASE TRANSITION

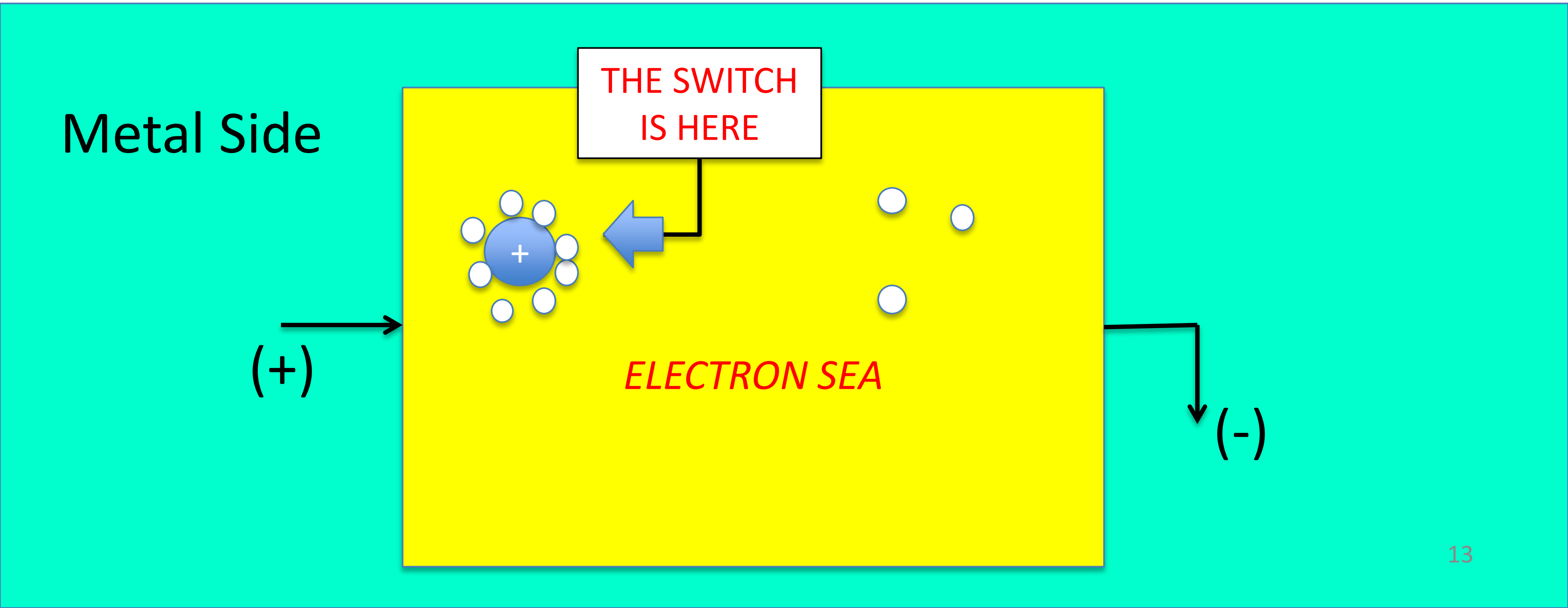
The Switch

- The density of states modulates the screening length

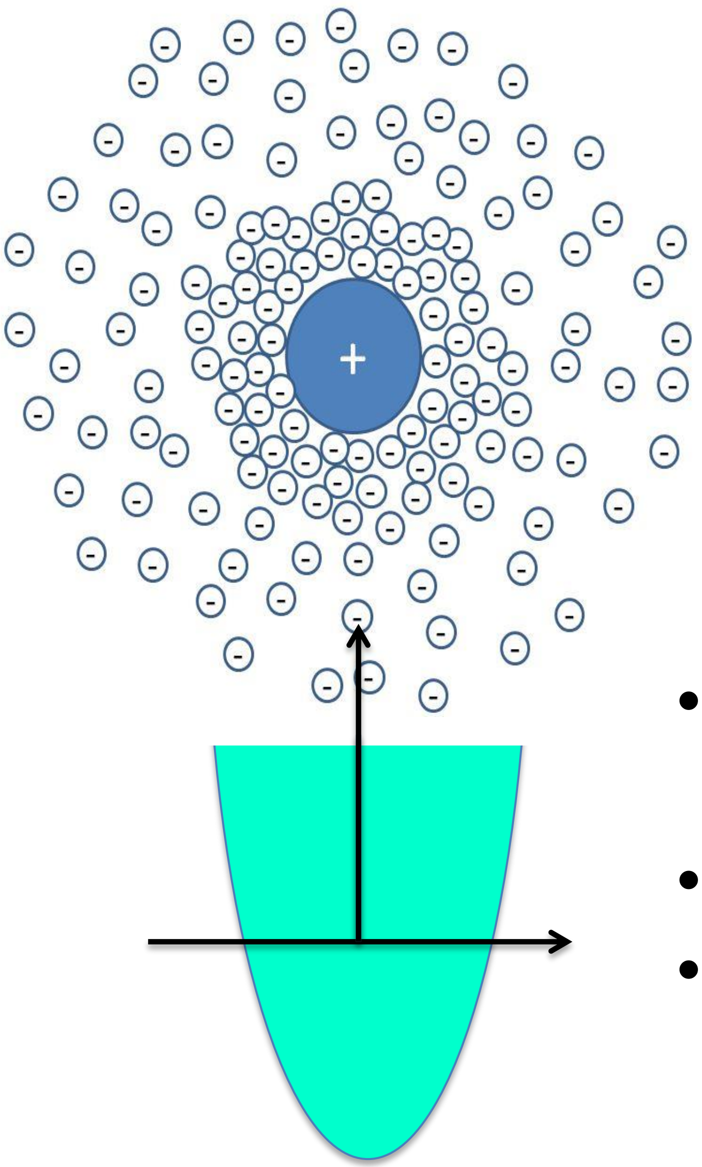
  $$\lambda_{TF} = \varepsilon_0 / e^2 \, DOS(E_F)$$

- The screening length modulates the current

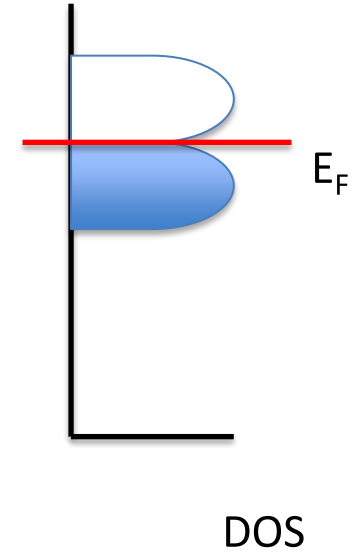
  $$J \approx 1 / \lambda_{TF}$$



Screening

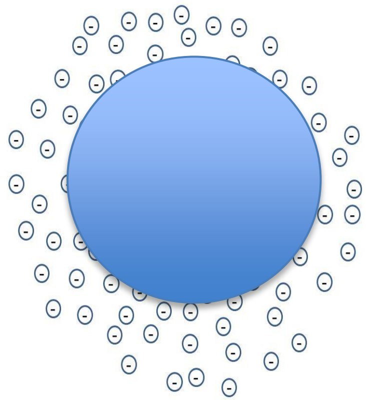


METAL

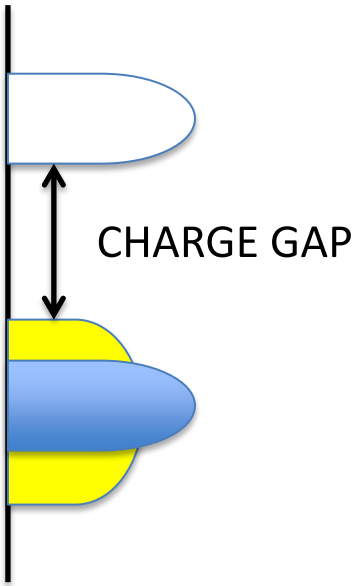


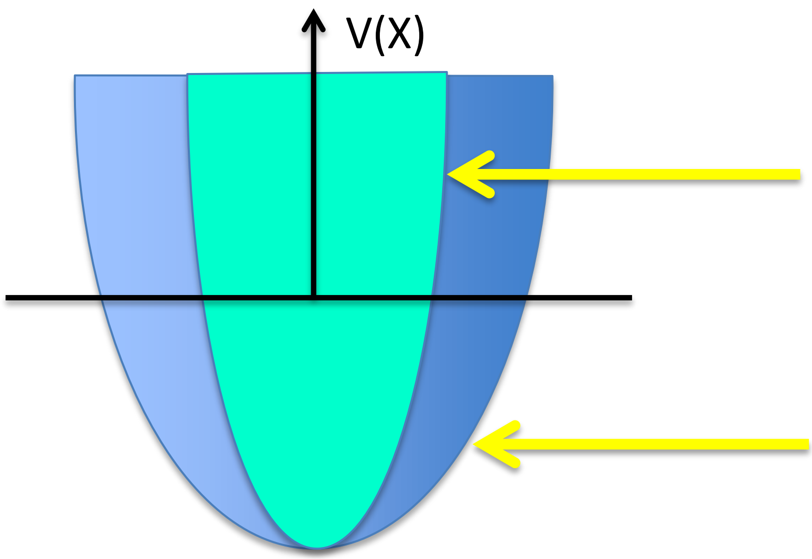
- Valence electrons screen the transition metal atom (ion)
- Narrows the potential well v(x)
- Releases localized electron – closes the gap

Screening



INSULATOR





Releases localized electron. Metal.

Captures and localizes Electron – repulsive u Opens the gap. Insulator.

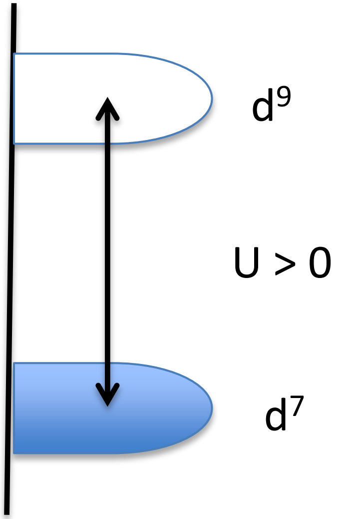
Disproportionation

- A single atom can have oxidation and reduction reaction at the same time
- GAP = I – A   I = ionization energy   A = e^- AFFINITY

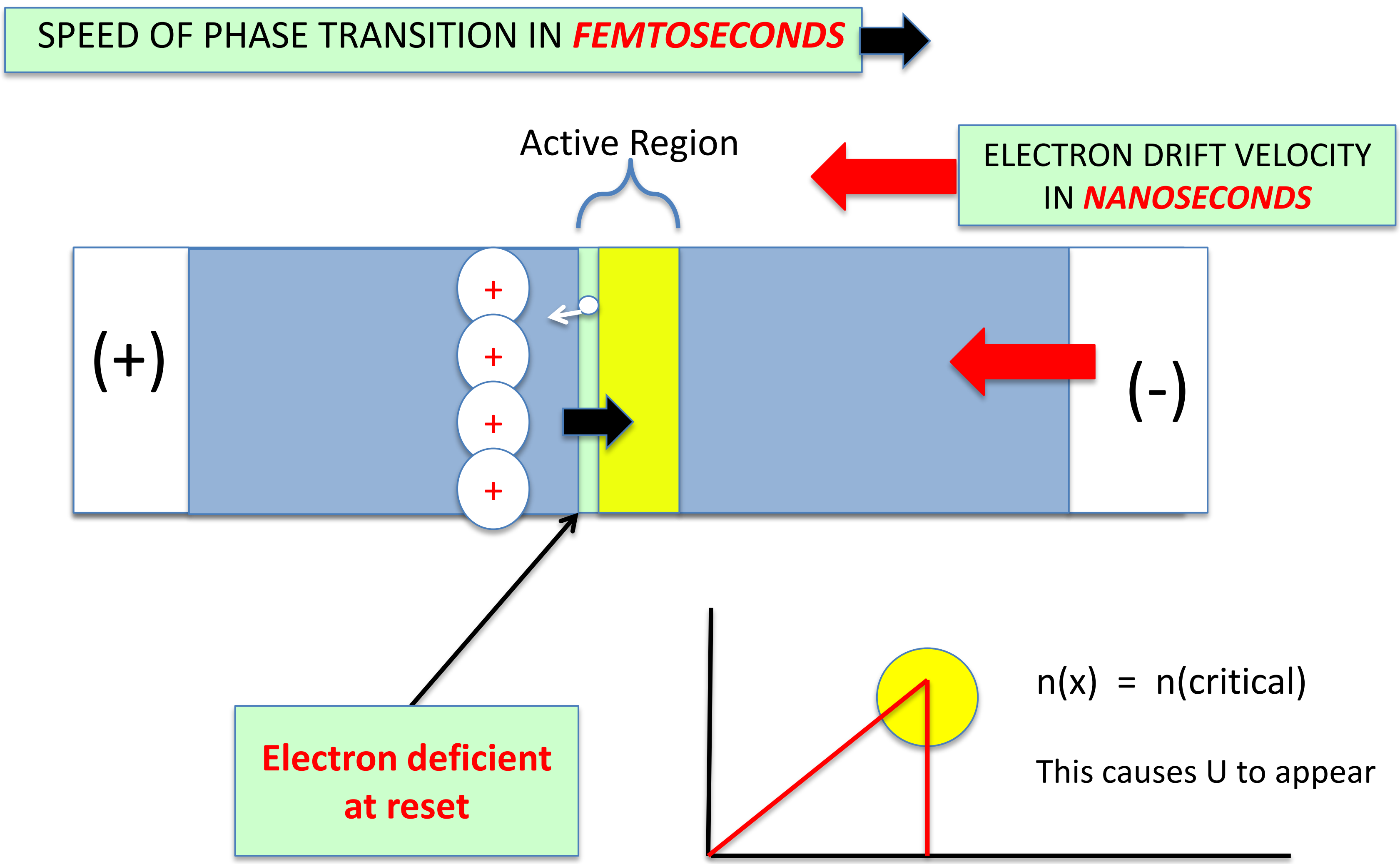
Ni^{+2} + e^- ---- Ni^{+1}

Ni^{+2} + h^+ ---- Ni^{+3}

For Nickel (Oxide) ---- d^8 "splits"
Into d^7 and d^9



Switching


SPEED OF PHASE TRANSITION IN *FEMTOSECONDS*
Active Region
ELECTRON DRIFT VELOCITY IN *NANOSECONDS*
(+)
+
+
+
+
(-)
Electron deficient at reset
n(x) = n(critical)
This causes U to appear

KEY POINTS

- The robustness of device switching requires control of the nickel ion oxidation number, specifically the suppression of Ni^{+4} and Ni^{0} species that inhibit the pure Mott transition:

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

- This is achieved with ligand doping, specifically CO^{-} .
- Co^{-} doping stabilizes the CeRAM resistive element at Ni^{+2} and the NiO film is conductive as-deposited.
- There is no rupturing and reformation of filaments, there is no oxygen diffusion (Memristor), only a pure Mott (charge transfer) phase transition

Technology Highlights

- Low temperature processing ~400c
- Robust retention at 300-400 c - proved
- Reading at 0.2 volts 10^{12} times – proved
- Read memory widens with device scaling
- Variability reduced due to clean surfaces and isolated active region – proved
- Results demonstrated on 0.8μ devices only. Smaller feature sizes have been recently enabled under a program with Univesity of Texas at Dallas.

CeRAM STATUS

- **THEORY**: Confirmed with empirical results → DONE
- **MATERIALS**: Doping any TMO with any extrinsic ligand → PATENTED
- **PROCESS:** Create and isolate thin (5 nm) active region by simple spin-on or ALD → PATENT FILED
- **ARCHITECTURE**: Array only (no pass gate) → PATENTED
- **3-D (STACKING)** With only silicon friendly materials → IN PROCESS
- **FPGA** Architecture → PATENT FILED

Implications

A NEW DEVICE AND THEORETICAL PARADIGM HAS BEEN DEVELOPED FOR RESISTIVE SWITCHING MEMORIES, ONE THAT:

- Eliminates the oxygen diffusion effect (basis of memristor) to allow "pure" Mott-like transition.
- Reduces variability in key parameters (v_{set} & v_{reset}) that has prevented ReRAM commercialization.
- Provides the robustness and repeatability required by future device scaling.
- Offers a path to 3d (stackable) memory architectures.
- May, in time, replace transistors as the fundamental switch in circuits.