NGC 2017

Fundamentals of Oxide Resistive Random Access Memory (RRAM)

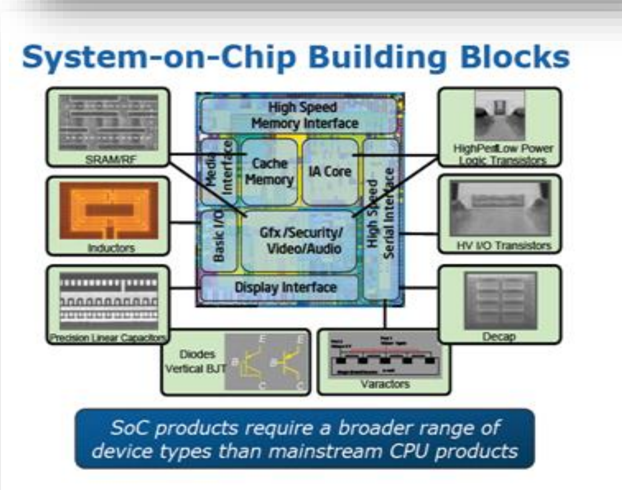
David Gilmer

Memory Technology Trends: New Drivers

How Is the Industry Changing?
1) Mobile Trend

How is the Industry Changing?
2) Data center trend

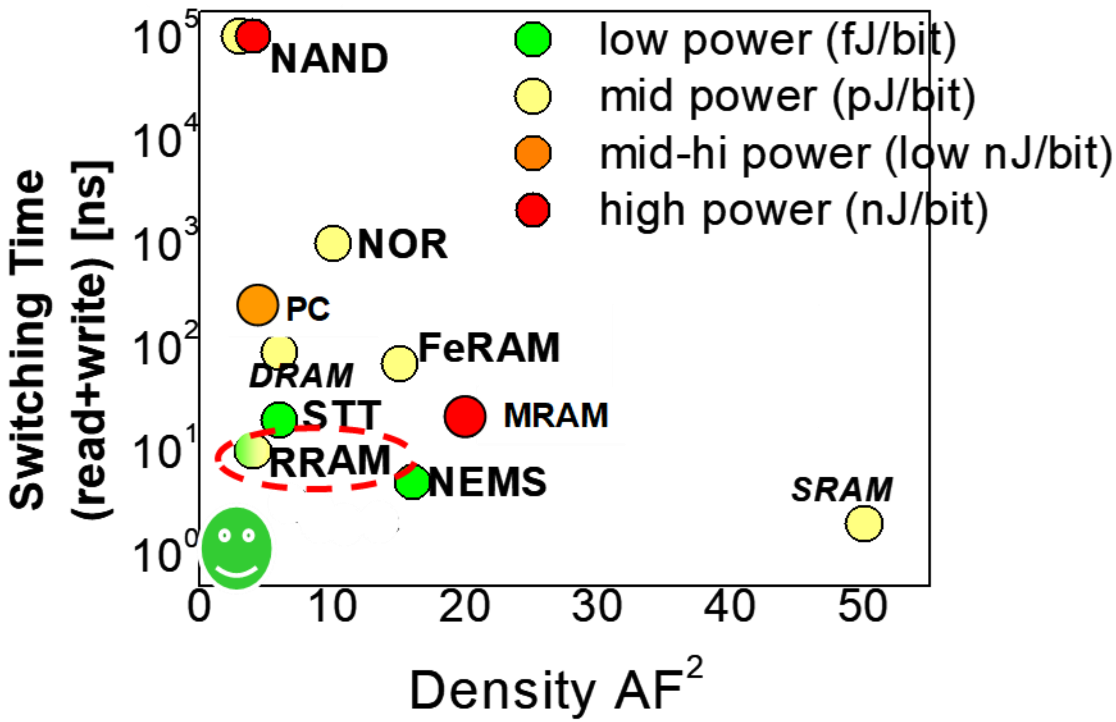
How is the Industry Changing?
3) SOC Trend



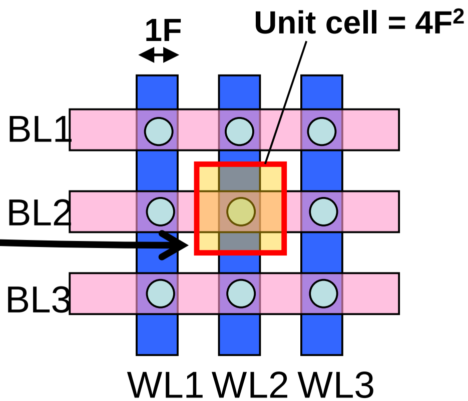
Future may have different needs:

1. Mobile: smaller, lower power, working memory than SRAM & lower power storage than NAND
2. Data Center: faster storage than HDD
3. SOC: smaller, lower power working memory than SRAM & embedded memory

Benchmarking Sub 2Xnm Memory Candidates



F= minimum litho CD
A=multiplier of min CD (cell size)



Goals:

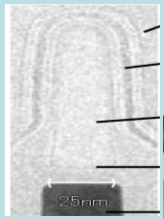
- MLC like NAND
- Cost structure like NAND
- Function, reliability like NAND
- Density > NAND
- Speed > NAND.

[1] W. Y. Choi, and T.-J. King Liu IEDM p. 603 (2007).
[2] A. Driskill-Smith, Y. Huai Future Fab p. 28 (2007).
[3] J. E. Green Nature v. 445 p. 414 (2007).
[4] B. Yu IEEE Trans on Nanotech 7, p. 496 (2008).
[5] Kryder, et. al. IEEE TRANS ON MAGNETICS, 45, NO. 10, (2009)

From: Trapping Electrons…*To*: Moving Atoms

34nm Floating gate

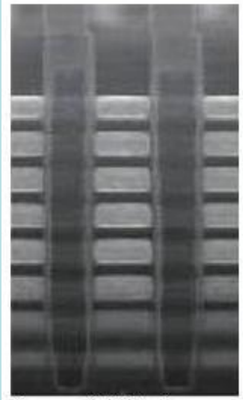
Micron Technologies
http://blogs.zdnet.com/
Aug. 2009



SAMSUNG
2009

25nm

Toshiba T. Kamigaichi,
EDM 2008.

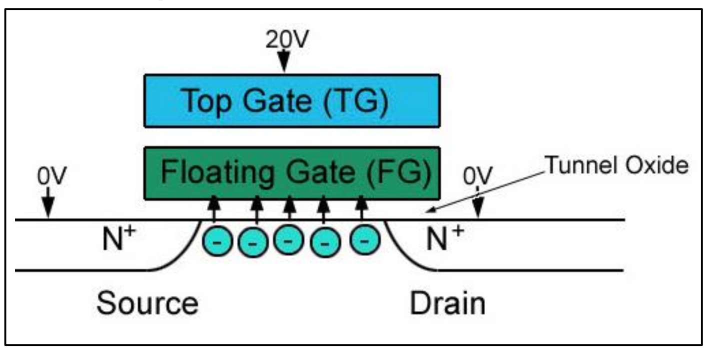


Samsung TCAT stack.
(2009 Symposium on VLSI Technology)

Incumbents :
Flash (NAND)
Increasingly difficult scaling

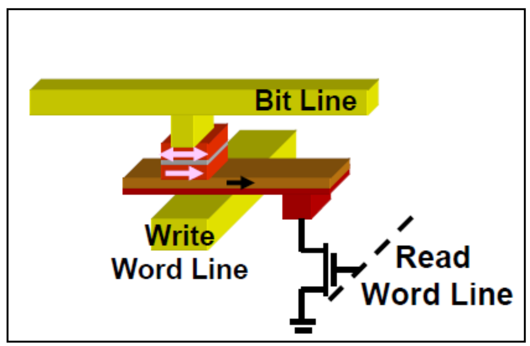
Alternative
Storage
Mechanisms

Trap electrons…



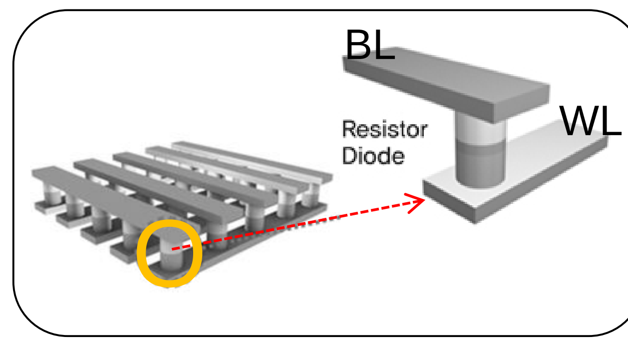
Incumbents
*Hard to maintain charge
When aggressively scaled

…Changing e⁻ Spins



MRAM, STT-RAM
*Hard to maintain polarization
When aggressively scaled

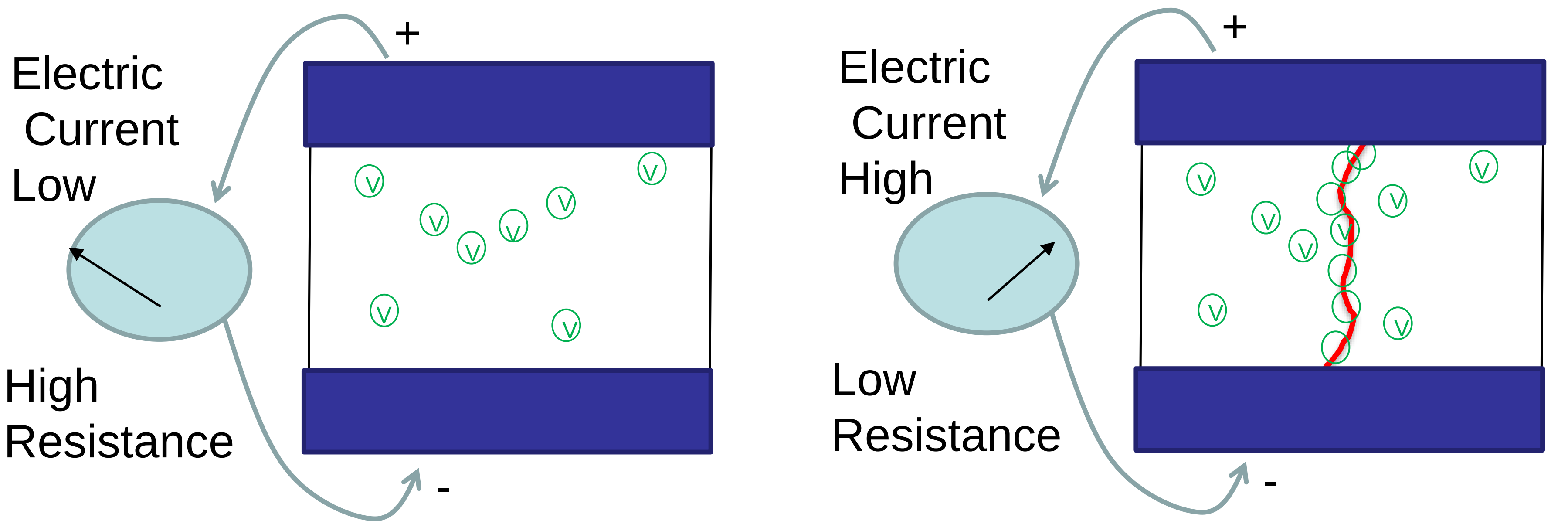
…To Moving Atoms:



→RRAM
[high density, low power,
"immune" to scaling issues]

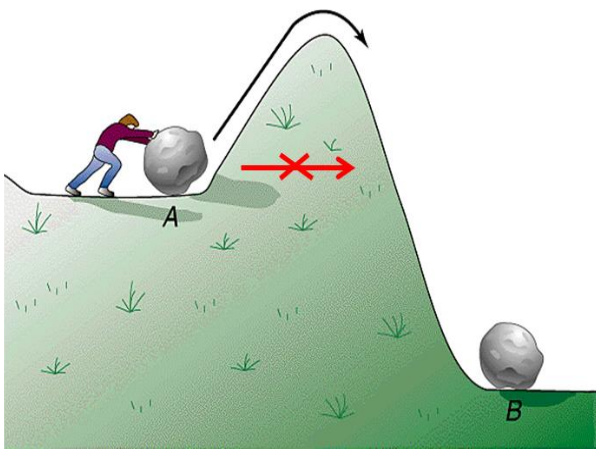
What is Resistive Random Access Memory? (RRAM)

- For any memory system to work, it needs at least two different detectable states
- RRAM detectable memory states are “high” or “low” resistance…. <u>A resistance change memory</u>

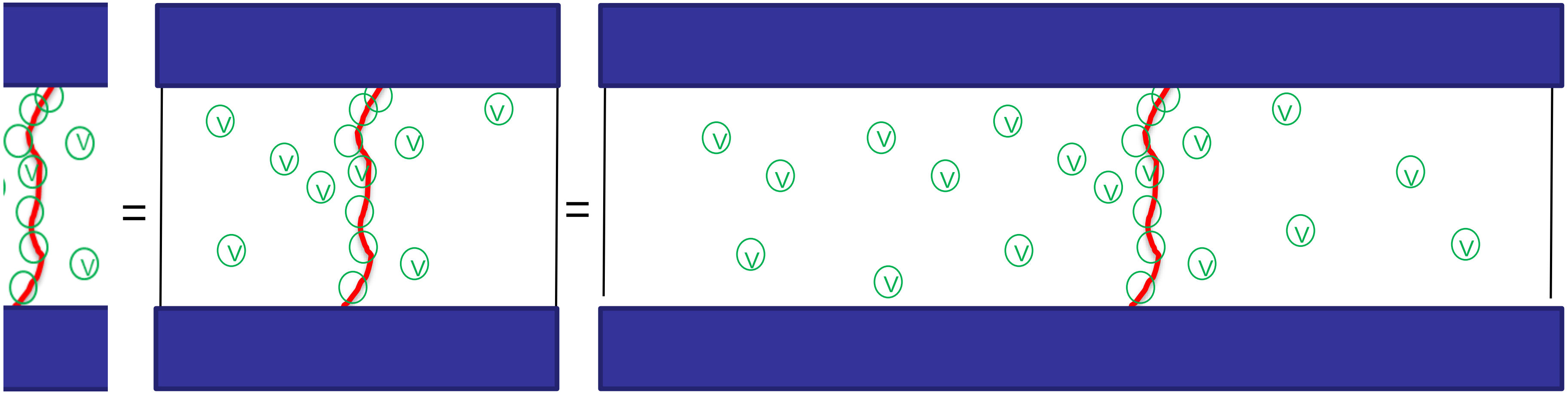


Why metal-oxide filament-based RRAM?

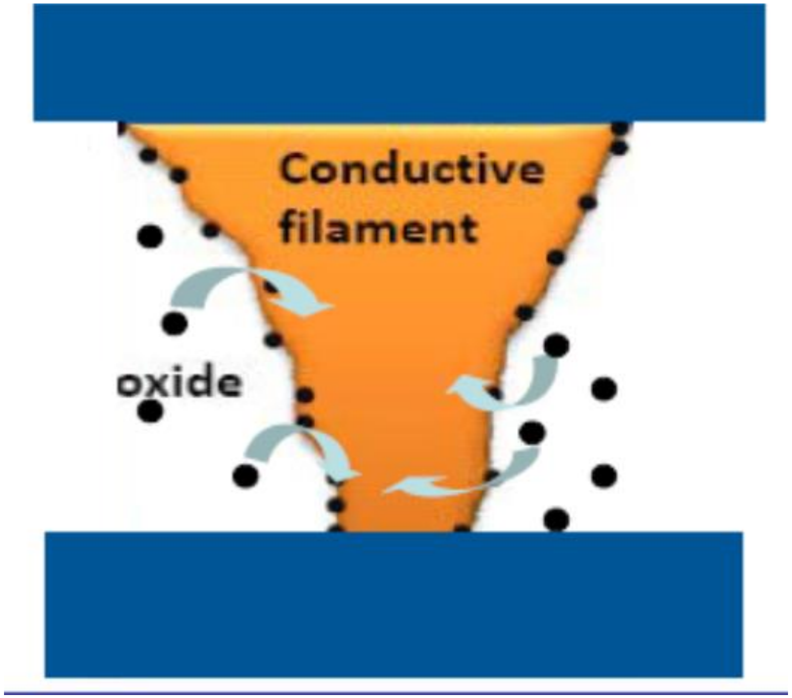
-- The advantage of moving atoms (vs electrons) --



- **Advantages:**
  - **Scaling:** limited by filament dimensions (<10nm)
  - **Retention:** high barrier (chemical bond change)
  - **Speed:** atom movement over short distance
  - **Energy:** changes in small dielectric volume
  - Many **simple systems** and **fab-friendly** materials
  - Ease of **integration**



Challenge for filament-based RRAM



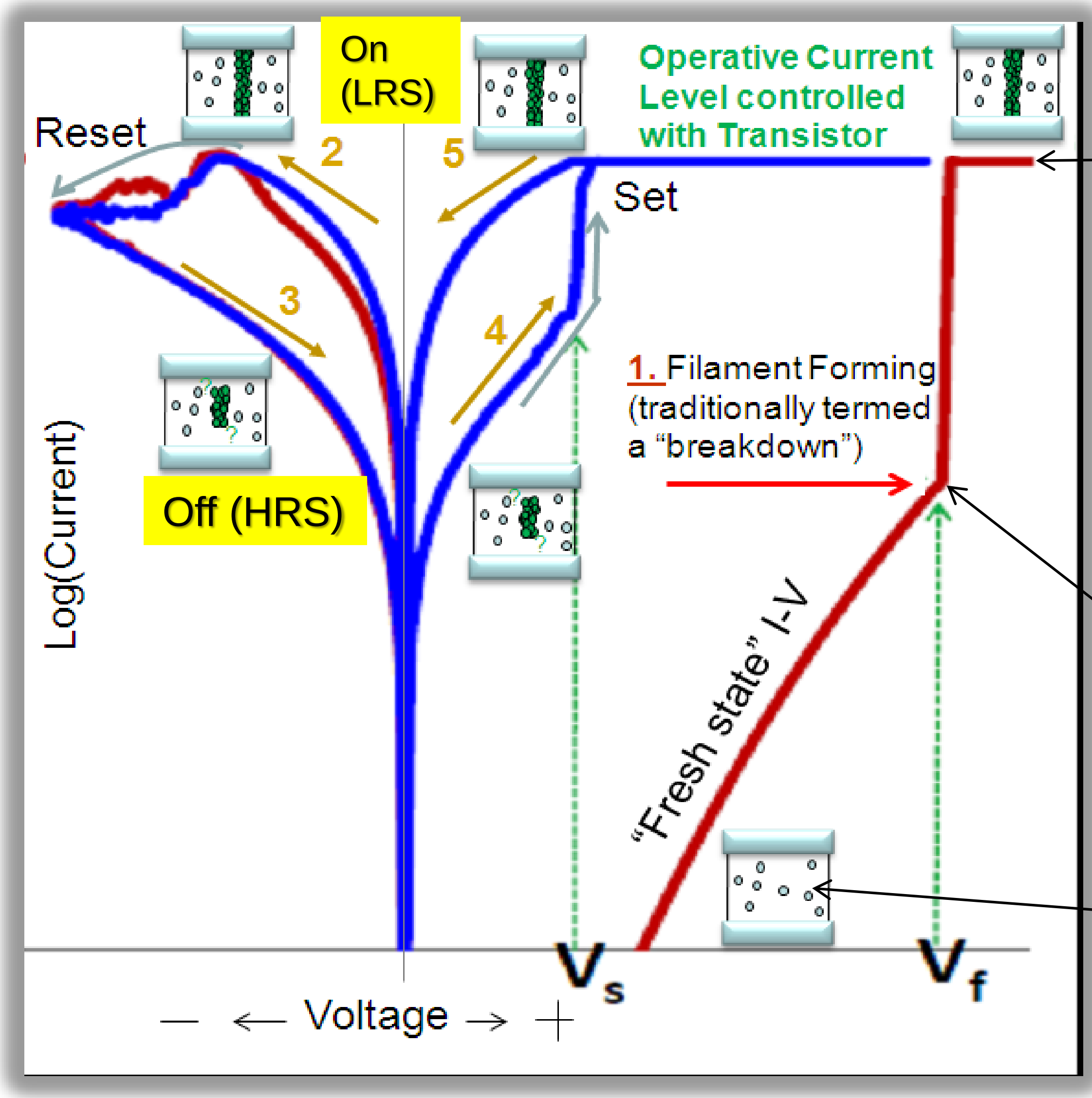
*Filament forming is a random process

→Control conductive filament

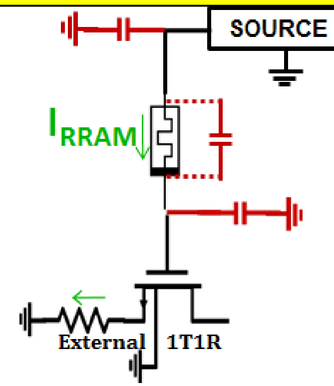
→Uniformity

<u>Key</u>→ Understand operating mechanisms

Features of filamental Bipolar RRAM



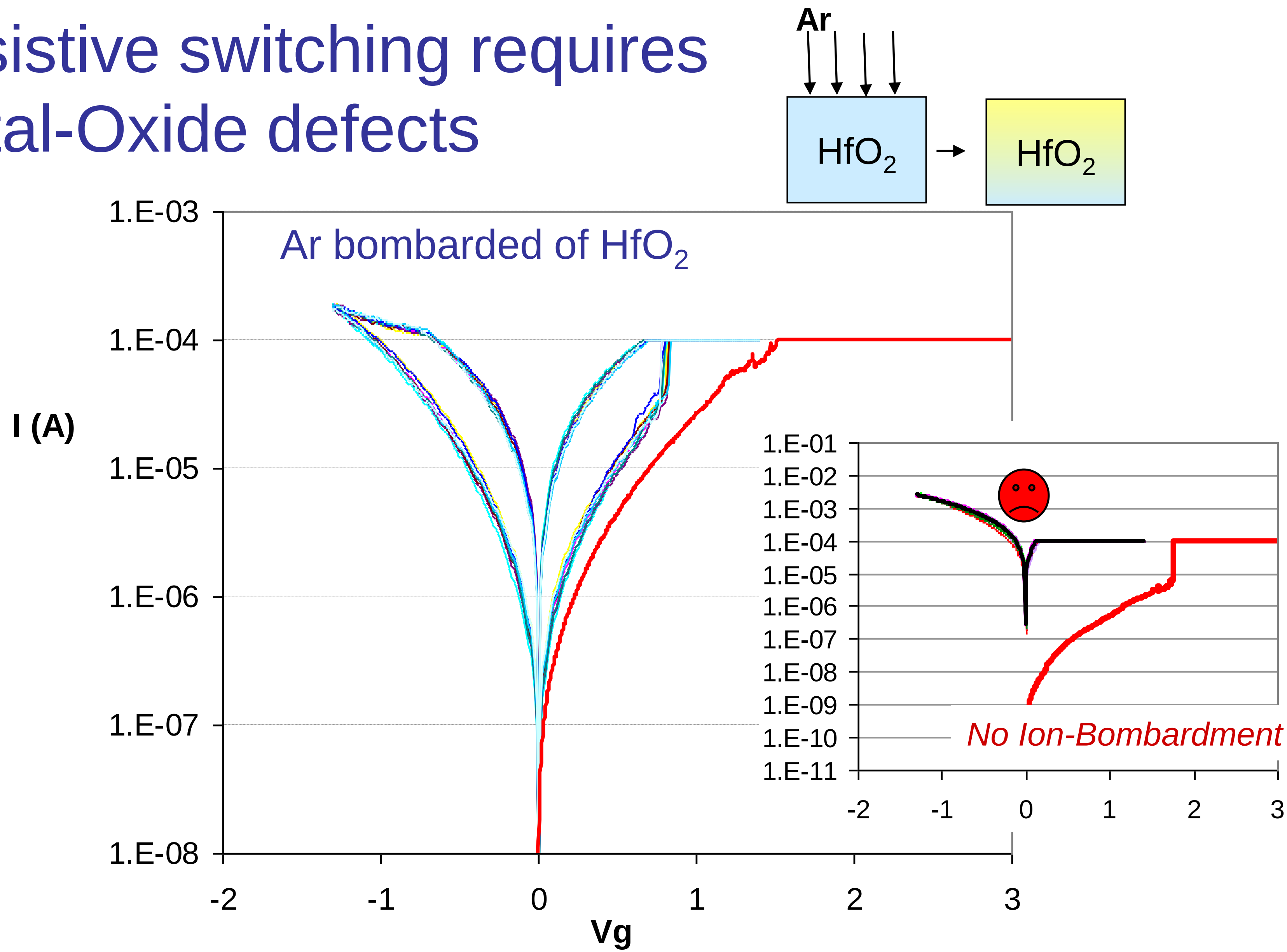
I-compliance: limit with internal FET for low parasitics, overshoot



Filament formation is key to well behaved switching

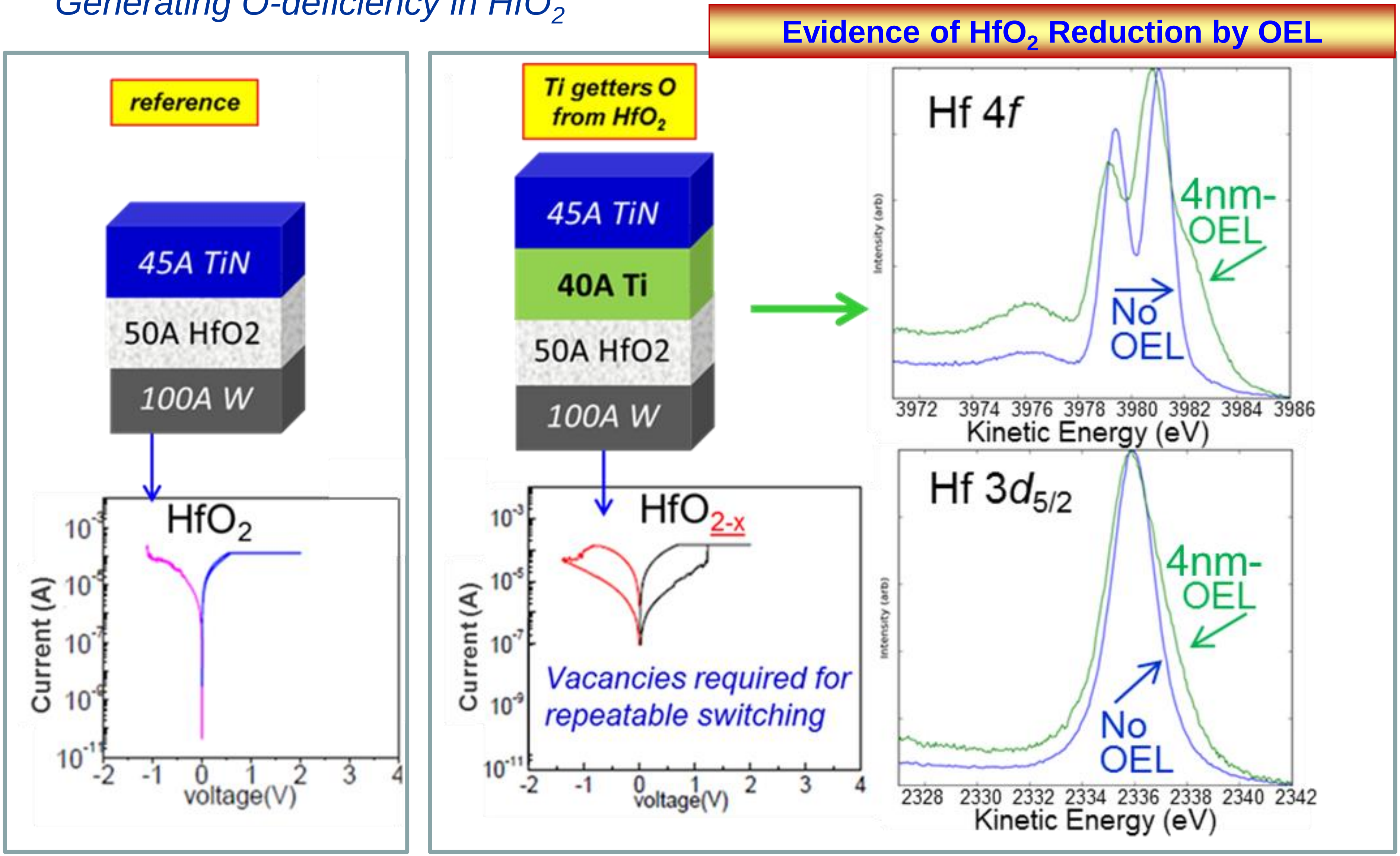
Dielectric Fresh State: starting defect profile important

Resistive switching requires Metal-Oxide defects



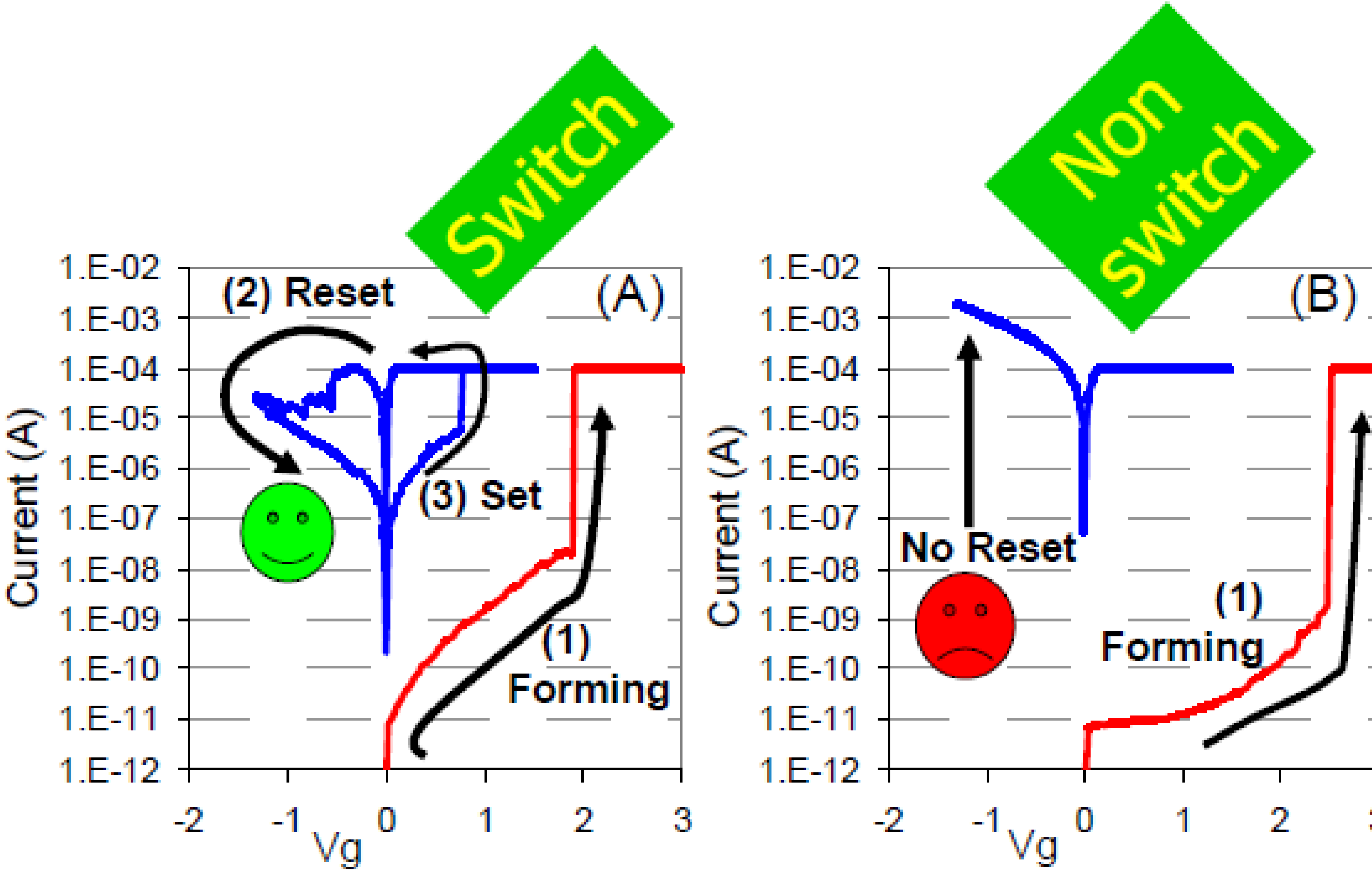
Oxygen gettering for sub-stoichiometry

"Oxygen exchange layer (OEL) for Generating O-deficiency in HfO_2"



*National Synchrotron Light Source (NSLS) at (BNL)

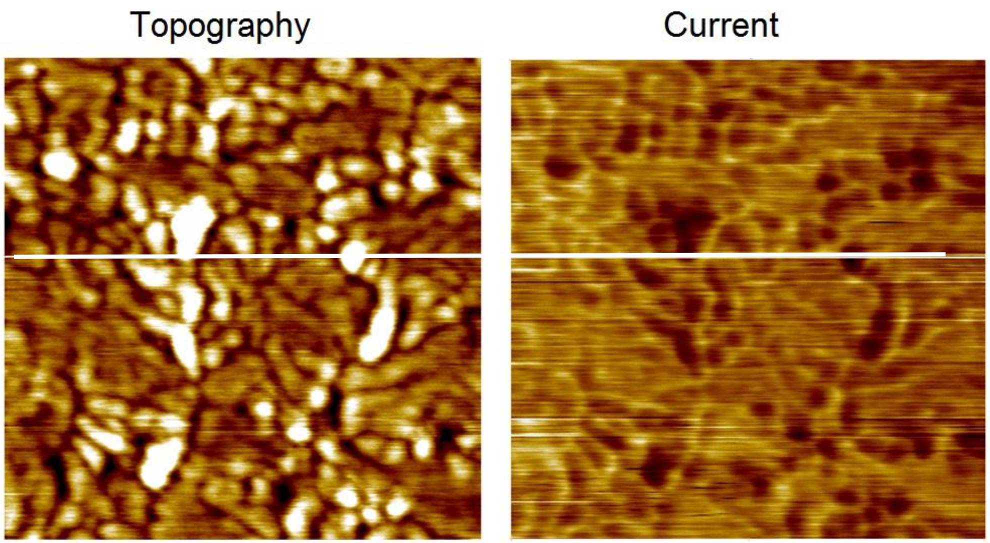
Suitable MeOx dielectrics for RRAM

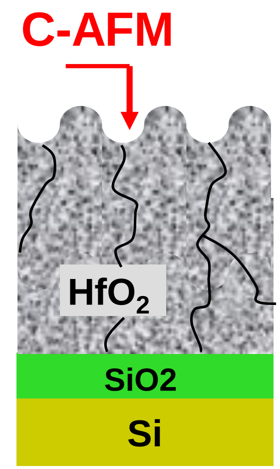


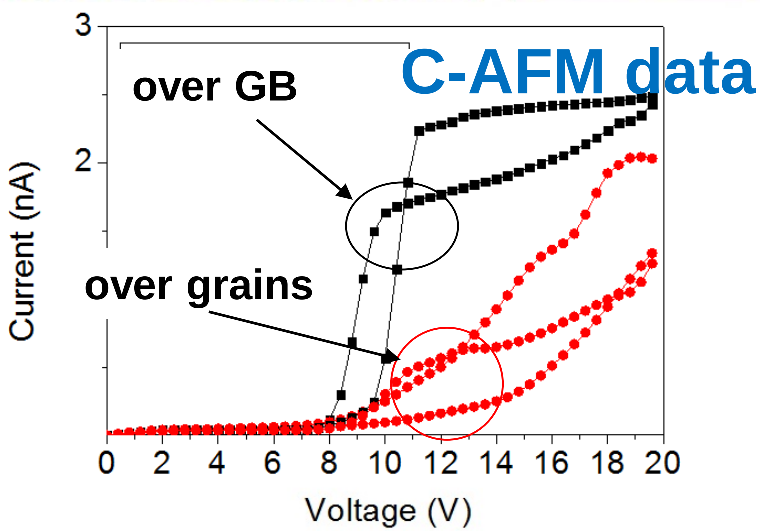
(Sub-stoichiometric) (Perfect-stoichiometric)

Oxygen vacancy control important for MeOx RRAM operation.

Filament Mechanism: Grain boundaries are weak point; likely location for filaments





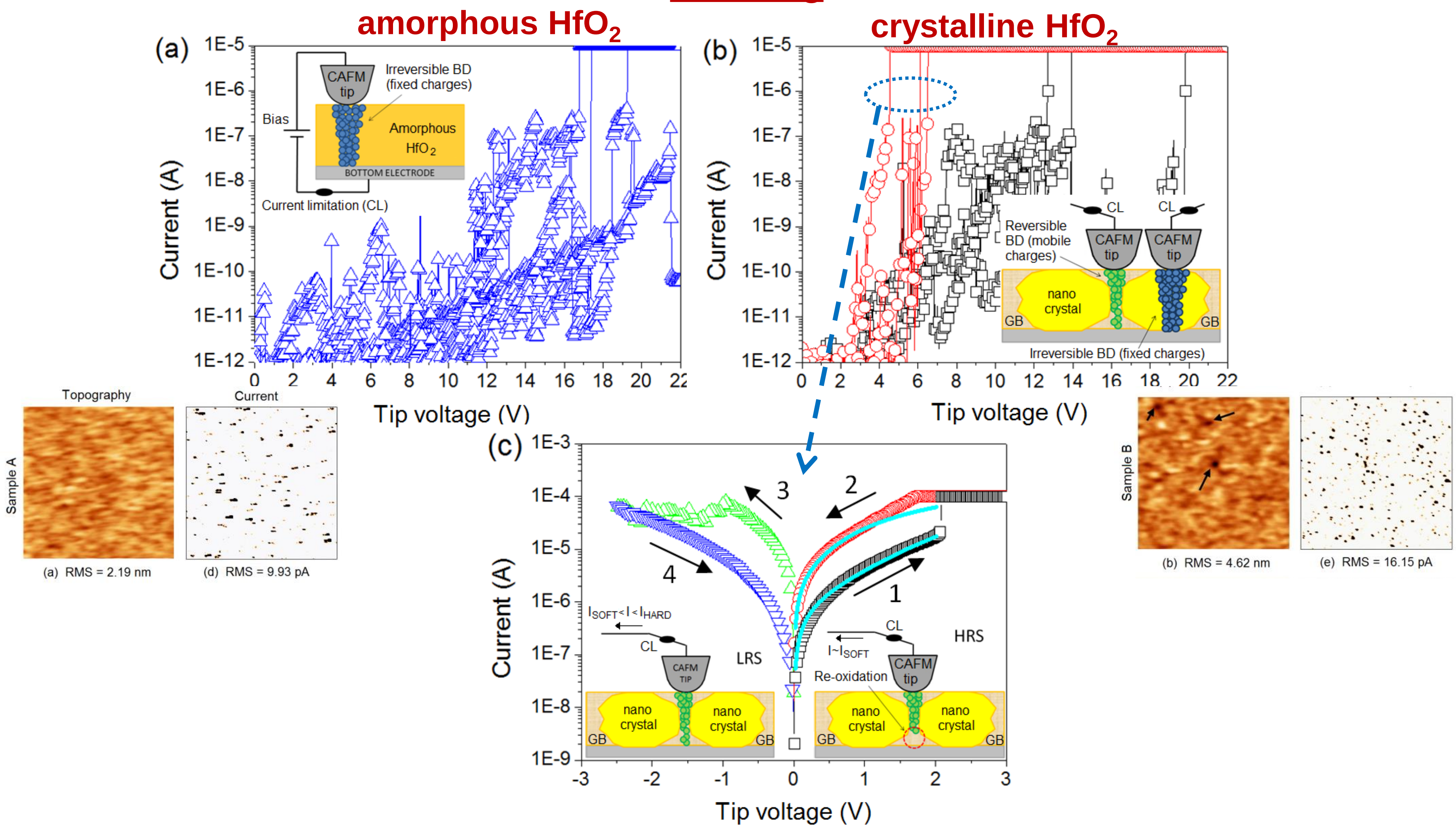


- Different conduction mechanisms along GB and Grains due to accumulated defects at GB's

**YEW, K. S. et al., Proceedings of the International Conference on Solid State Devices and Materials (SSDM), Japan, 2009.*

Switching at grain boundaries induced by AFM tip

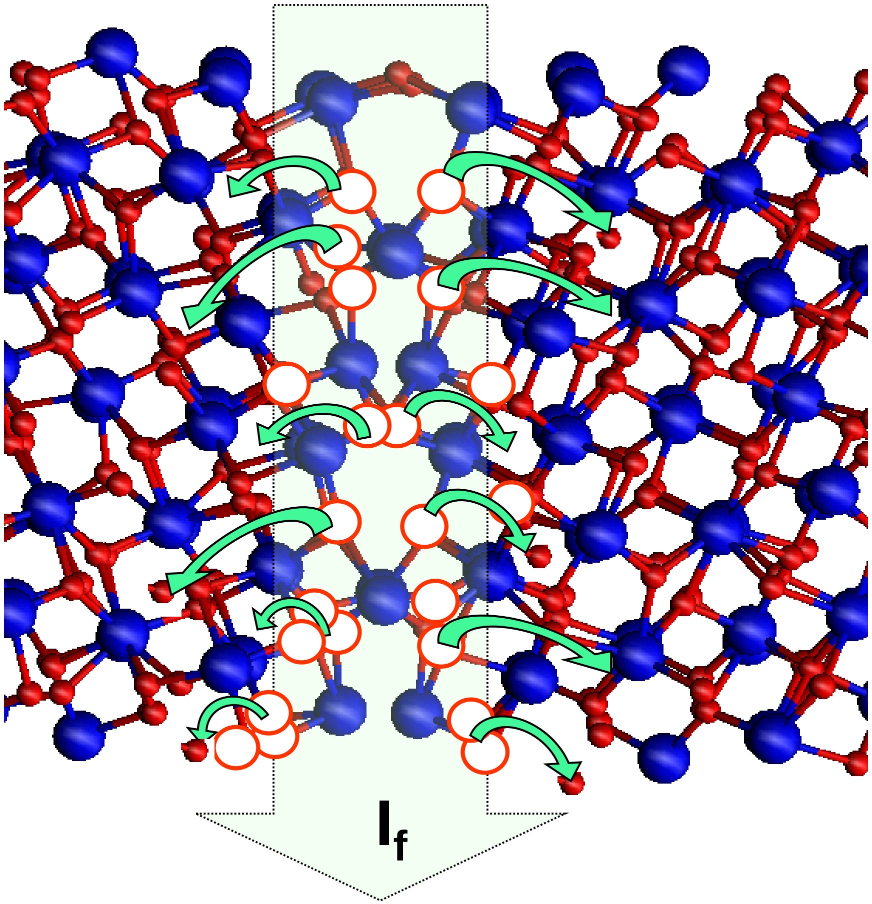
Forming



Switching observed only on GBs → oxygen deficient regions

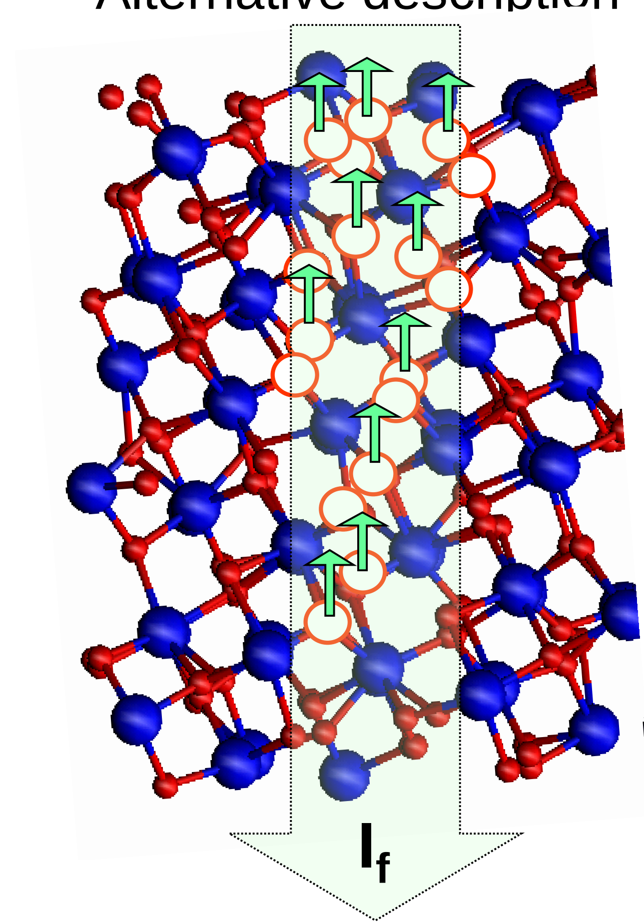
Lanza et al., Appl. Phys. Lett. 101, 193502 (2012)

Metal-Oxide RRAM Material Model;
→Form a Conductive Filament



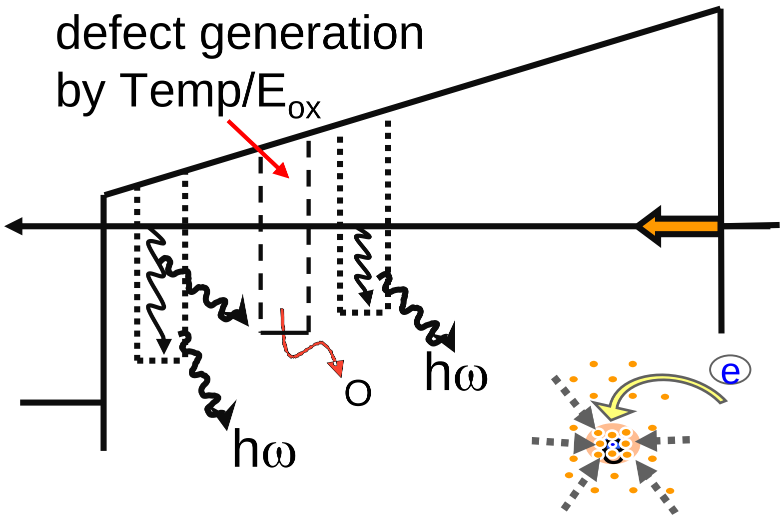
- Bond breakage followed by oxygen out-diffusion

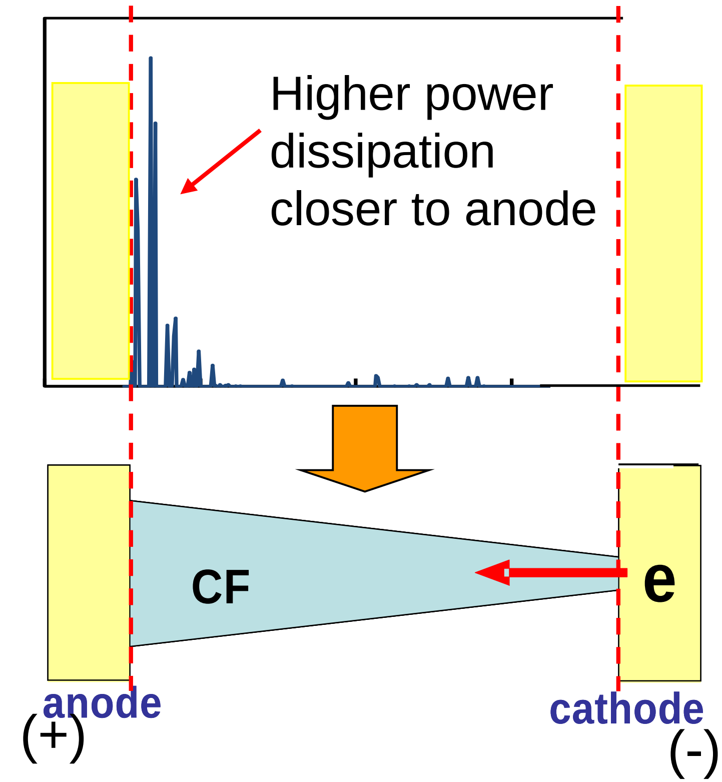
Alternative description



- Vacancy diffusion

Forming process and filament geometry





Trap generation rate:

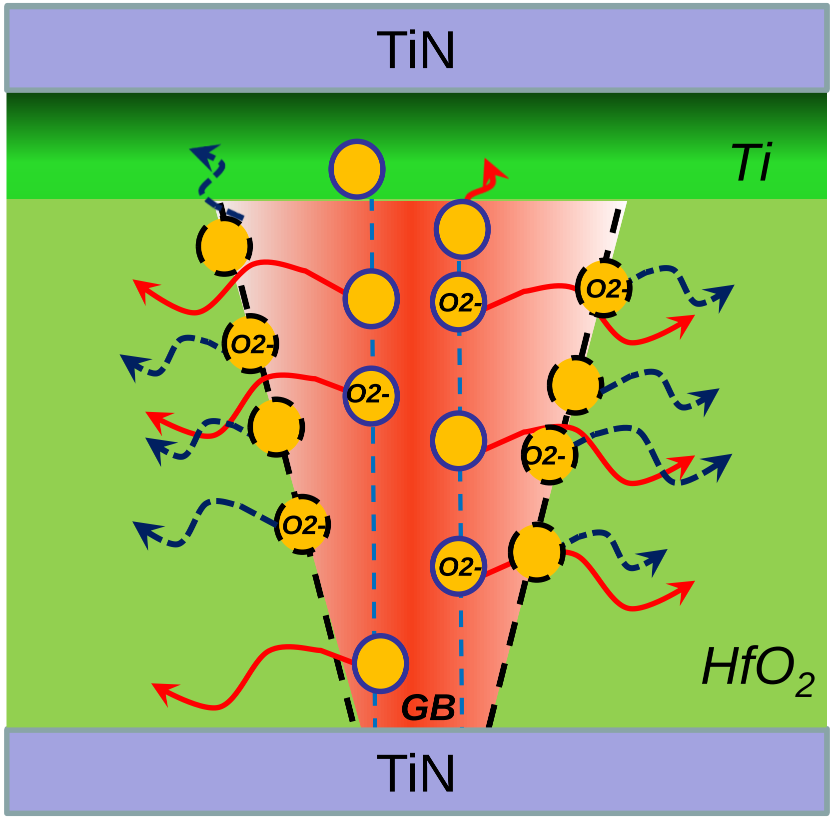
$$G(T,E) \;\alpha\; \exp\left(-\frac{E_{act}-\beta\,E_{ox}}{kT}\right)$$

Heat dissipation increases deeper in the oxide
→ <u>larger O-deficient region near the forming anode</u>

<u>Cone-shaped filament</u>

*G. Bersuker et al, IEDM 2010;   G. Bersuker et al, JAP 2011

Filament growth model



- Initial: *O-vacancies along grain boundary*

- Two-step process for each O atom removal during filament growth:

1) *Breakage of Hf-O bond*
2) *Diffusion of released O ion*

Breakage of Hf-O bonds by thermo-electrical stress:

$$G(x,y,z) = G_0 \exp\left(-\frac{E_A - \beta\, E_{ox}(x,y,z)}{kT(x,y,z)} \right)$$

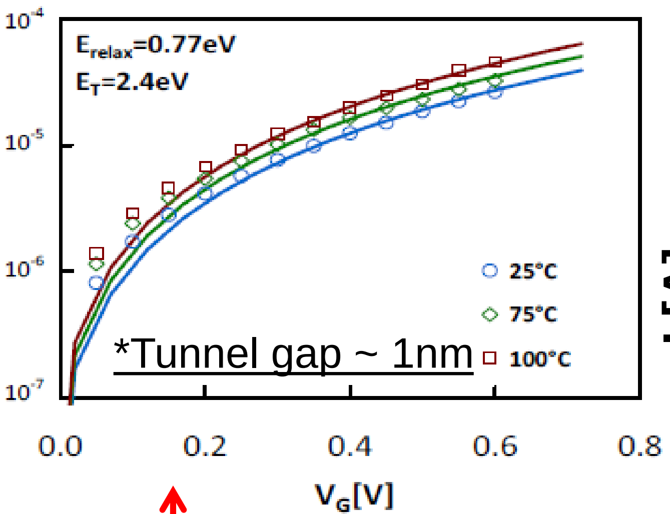
G. Bersuker, ME 2001; J. McPherson, APL 2003

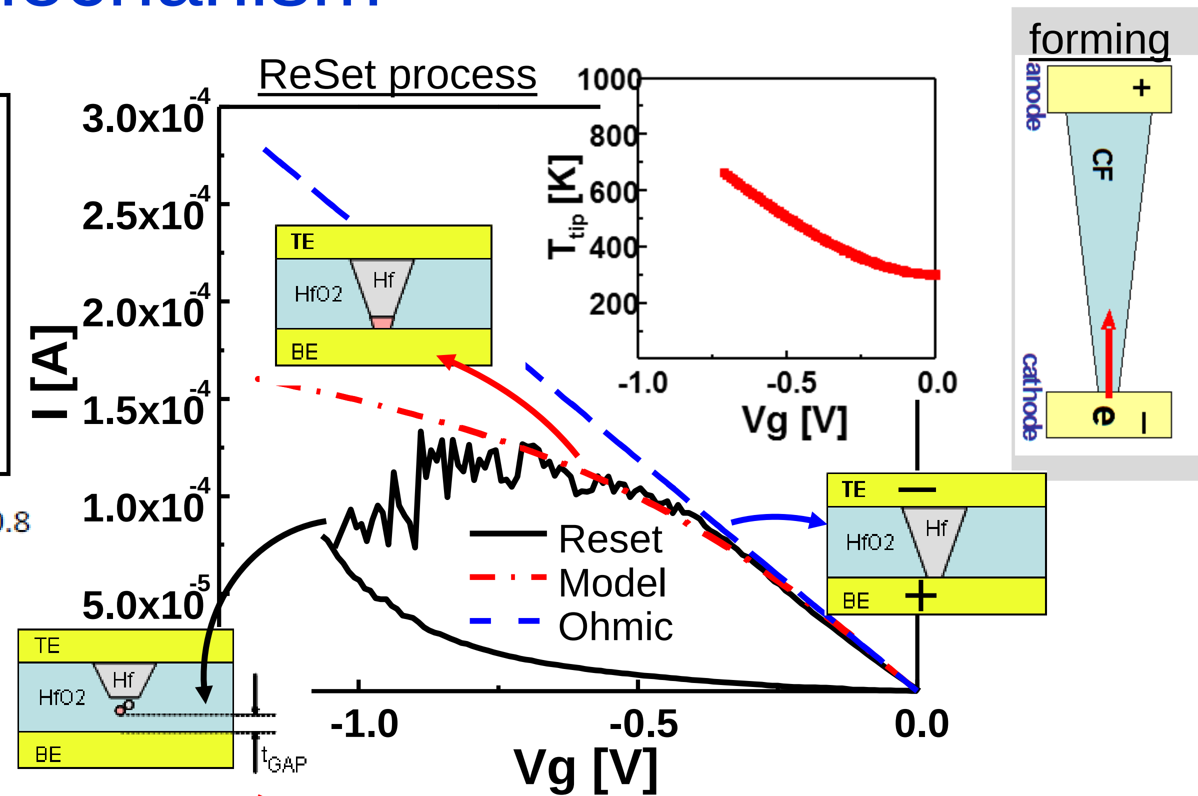
O-ion diffusion by E-field assisted substitutional hopping, :

$$\boldsymbol{D = \upsilon * e^{-\left(\frac{E_D - Q\frac{\lambda}{2}[F_{ext}]}{K_b T}\right)}}$$

Bersuker & Gilmer, CH.9; Metal oxide "RRAM" technology in; "Advances in Non-Volatile Memory and Storage Technology" 2014, Pages 288–340

Filament reset mechanism





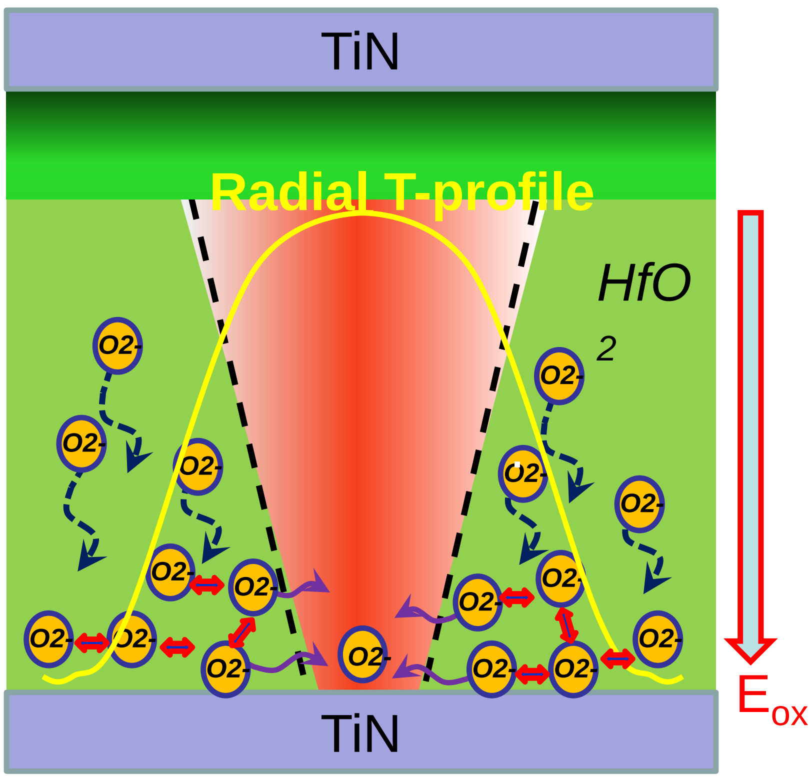
*Need ~1nm
Tunnel barrier to fit

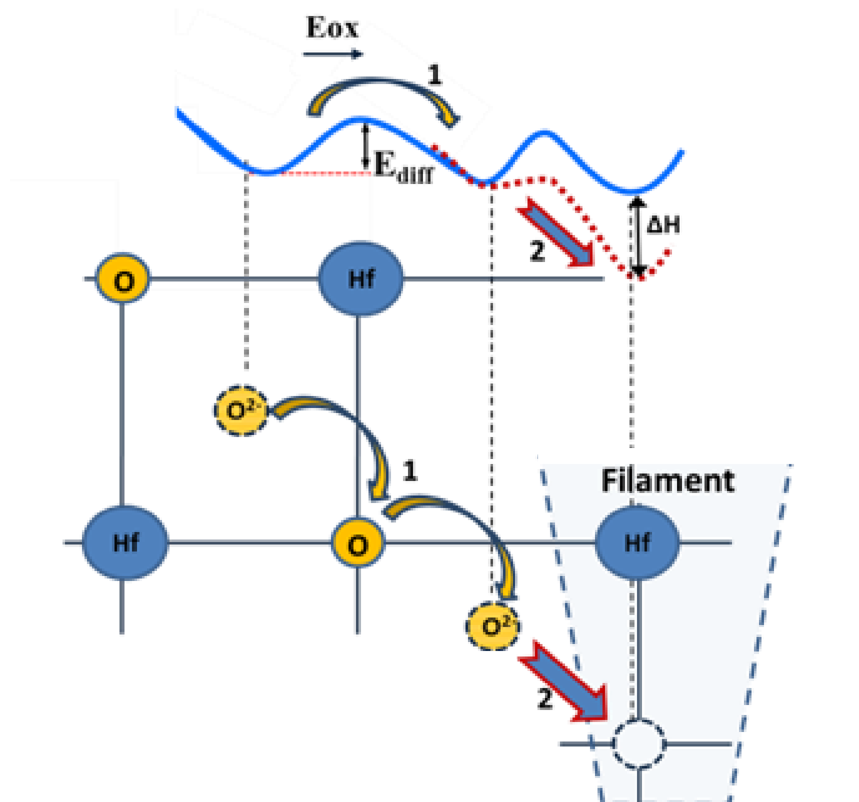
- Most voltage drops across the narrow filament tip
- Current deviates from Ohmic initially due to Resistance↑ from Temp↑
- Reset occurs when temp sufficient for oxidation and oxygen is available
- Asymmetric structure and switching supports model

*G. Bersuker et al, IEDM 2010; G. Bersuker et al, JAP 2011

Reset process

Re-oxidation of the filament tip driven by O-ion Coulomb repulsion and density gradient





O(2-) hopping between interstitial positions and Hf oxidation at oxide/filament interface

Bersuker & Gilmer, CH.9; Metal oxide "RRAM" technology in; "Advances in Non-Volatile Memory and Storage Technology" 2014, Pages 288–340

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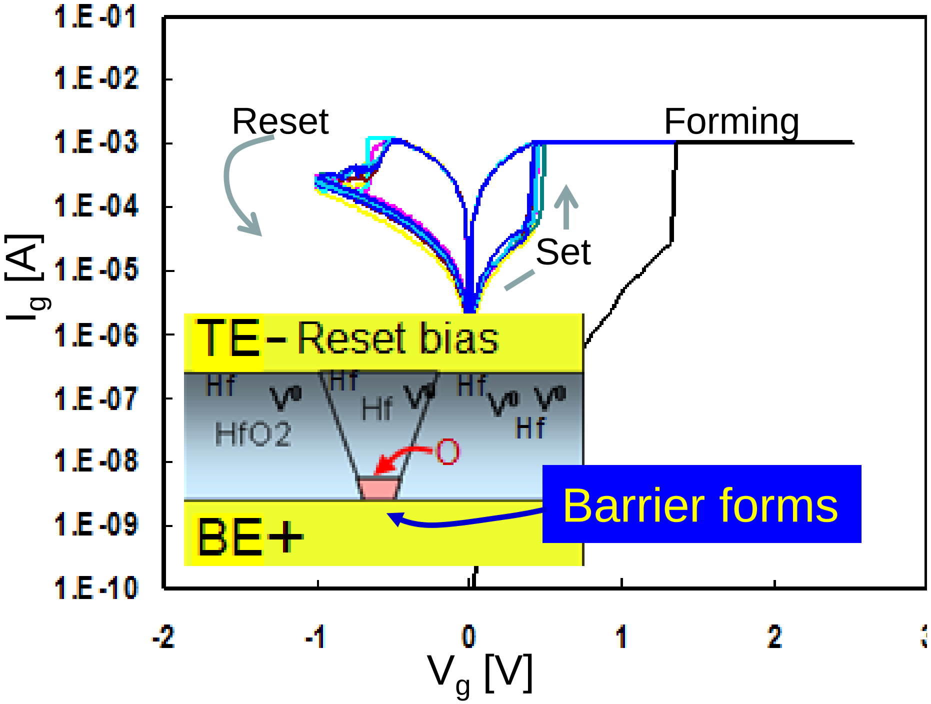
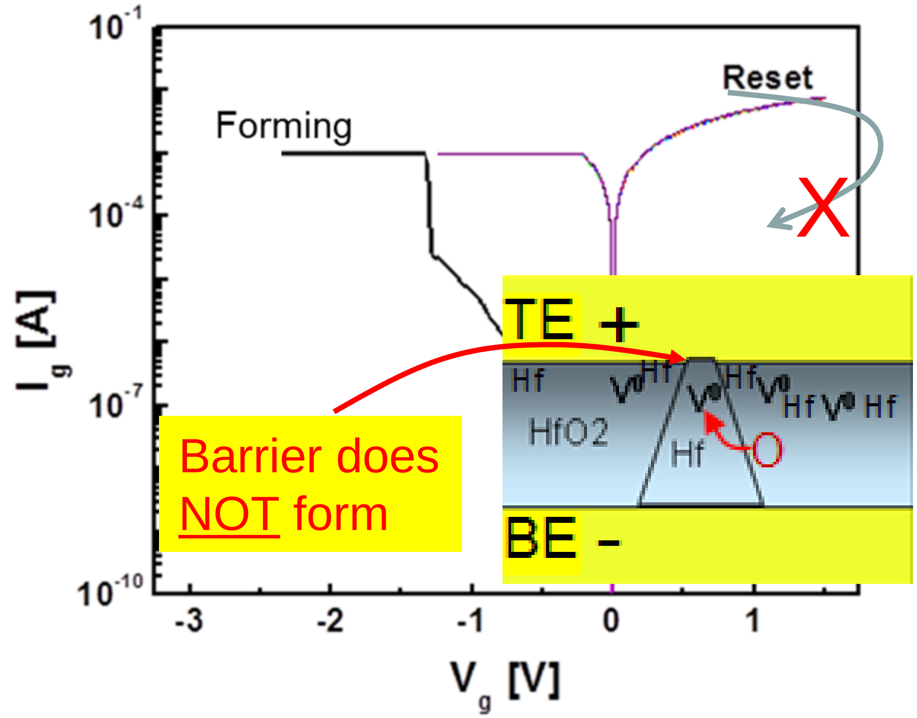
Reset has Polarity Dependency!!

Bias to TE
Positive forming/set, negative reset



Bias to TE
Negative forming/set, positive reset



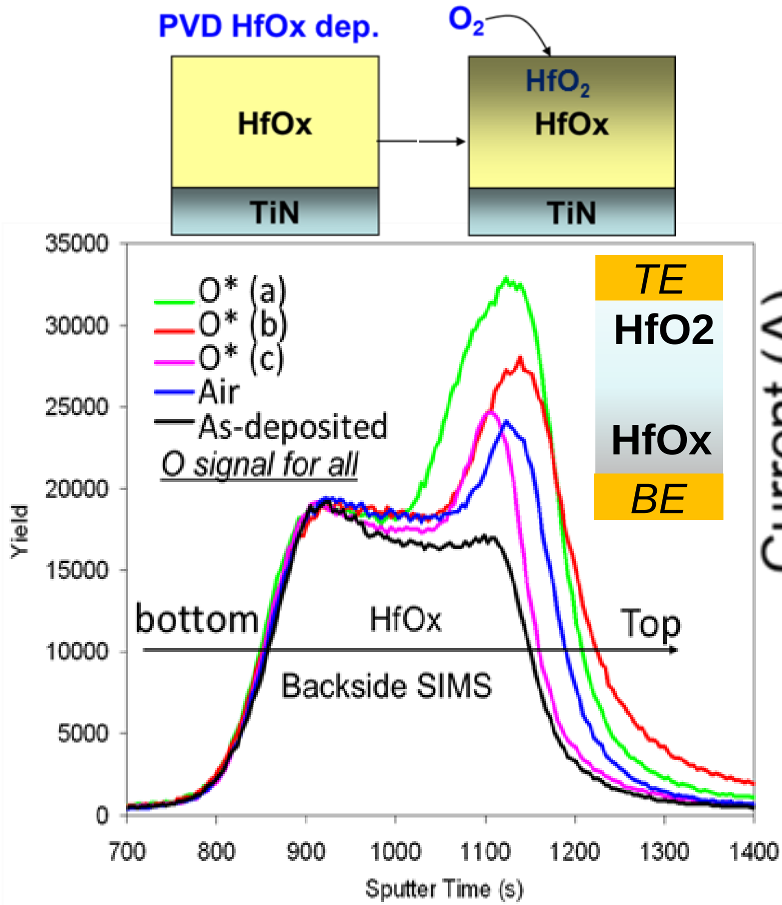
Asymmetric defect/vacancy profile "metal-OEL"/HfO_{2-x} dielectrics ;

Oxygen Rich near the reset anode →barrier forms→ Reset

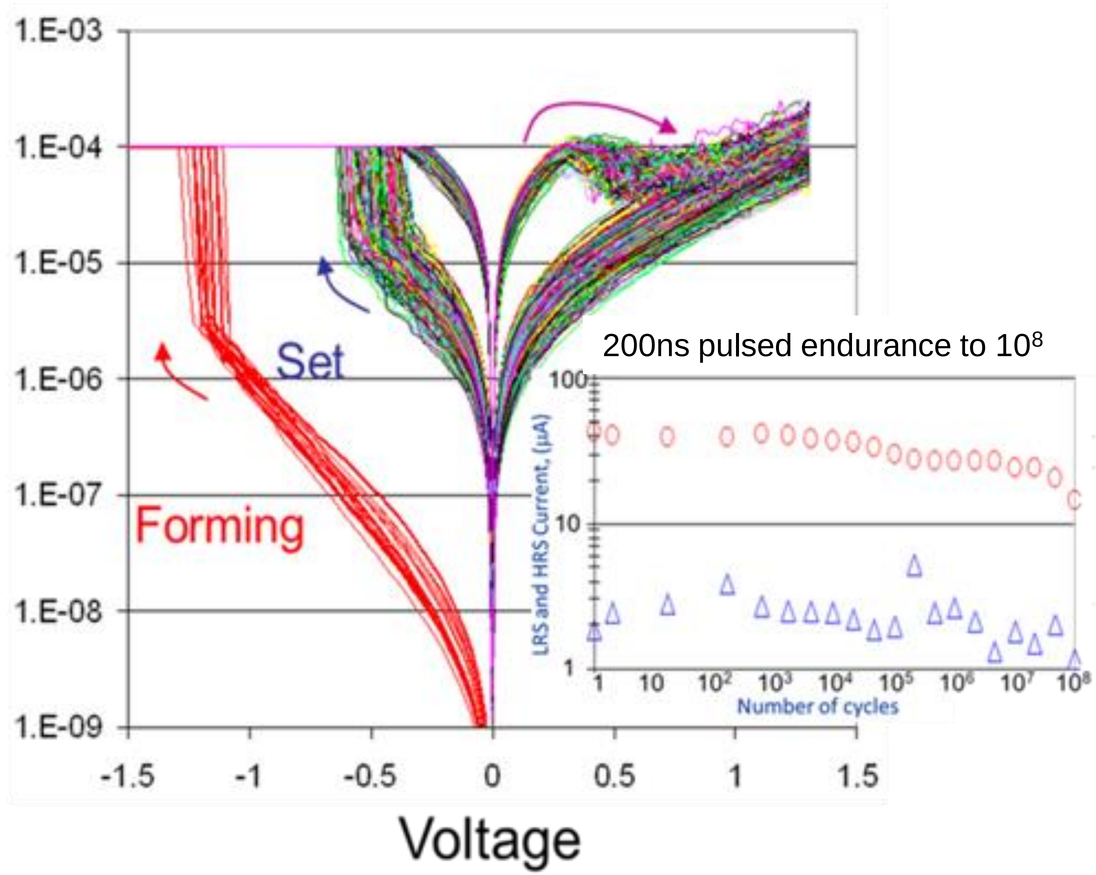
Oxygen Poor near the reset anode →prevents barrier → No reset

*D. Gilmer, et al, IMW 2012

Oxidation for Asymmetric Defect Profile



Relative O% profile for various asymmetric O-vacancy HfOx

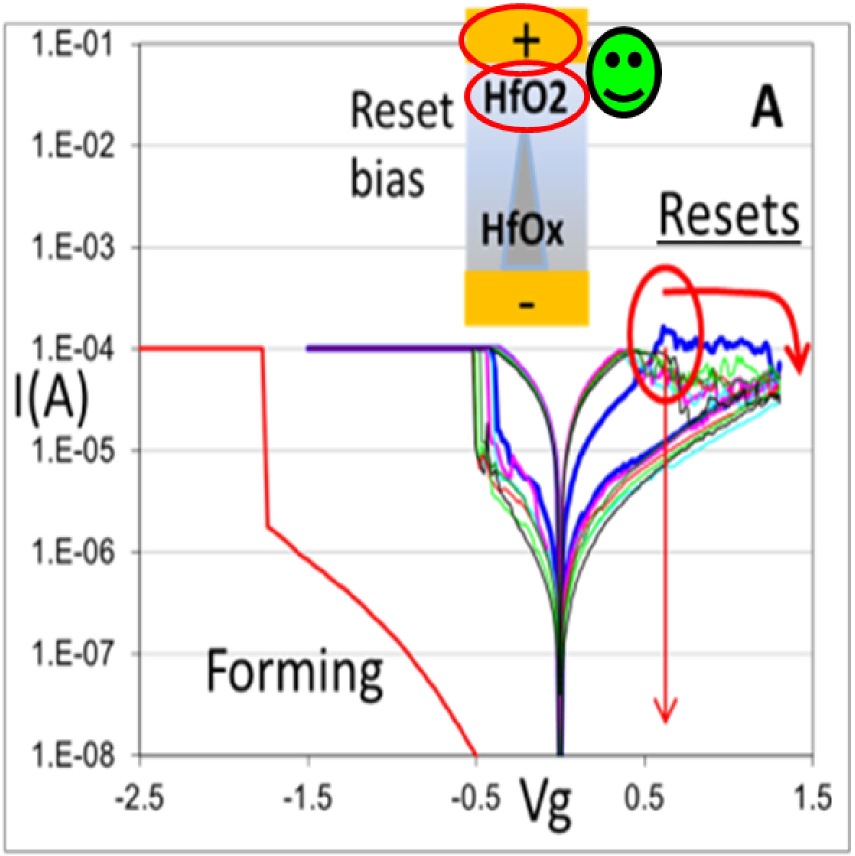


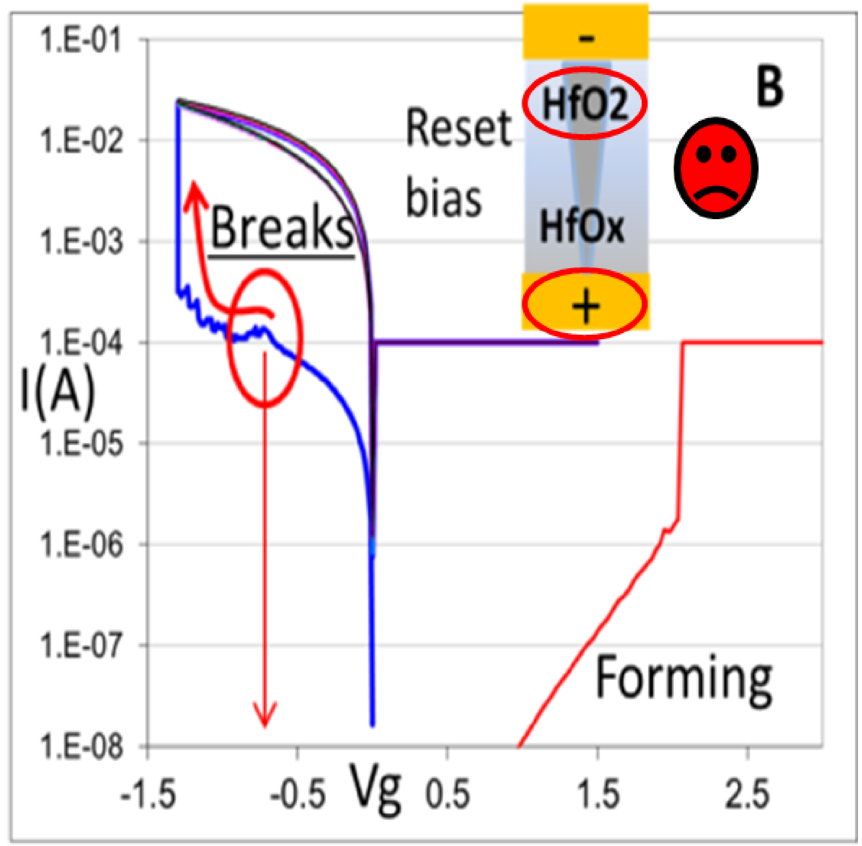
DC switching showing 100% yield for a 10-cycle set/rest dc sweep for 35 die (350 total sweeps) [Inset; characteristic endurance]

- Operating the Asymmetric O-vacancy stack in preferred polarity = 100% yield
- Operating the Asymmetric O-vacancy stack in NON-preferred polarity = 0% yield

*D. Gilmer, et al, IMW 2012

Reset Anode against “Good” vs “Bad” dielectic

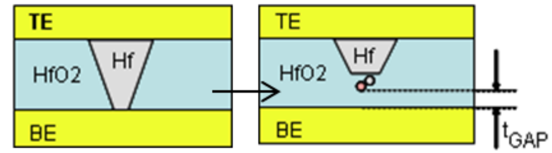




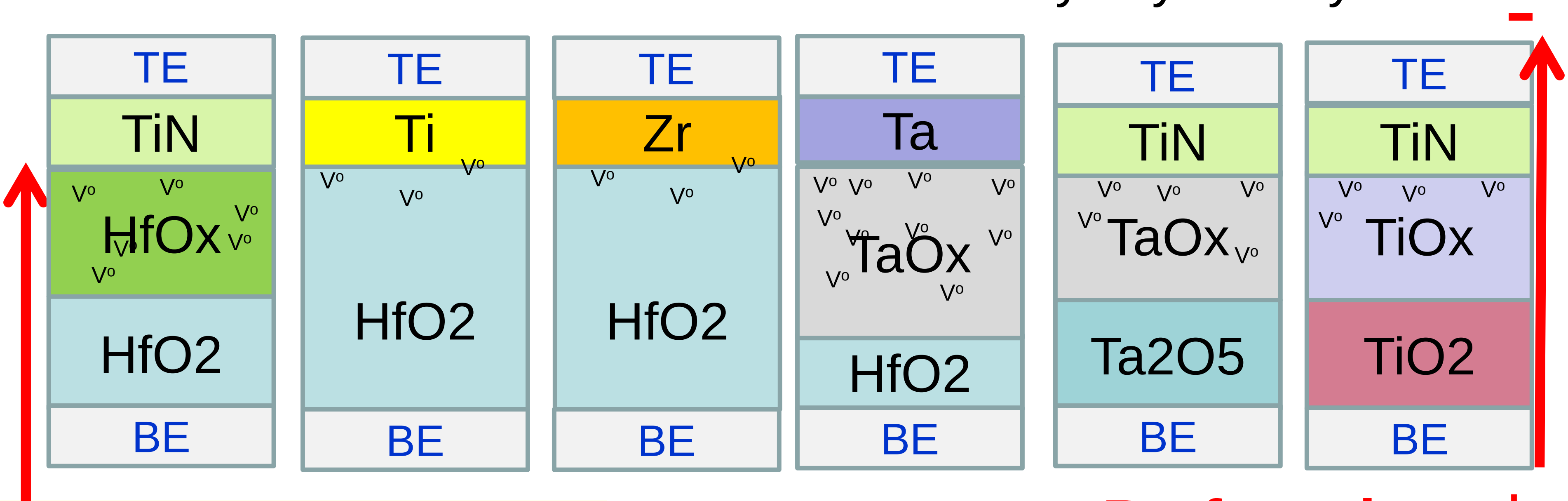
- Even non-preferred bias polarity has similar current deviation near reaching the forming compliance during reset sweep….
→However, the non-preferred biasing does not reset, it breaks

*D. Gilmer, et al, IMW 2012

Asymmetric Defect Profile observed for Best Behaved Bipolar RRAM



Various RRAM stacks with O-vacancy asymmetry



Increasing O-VACANCY Gradient

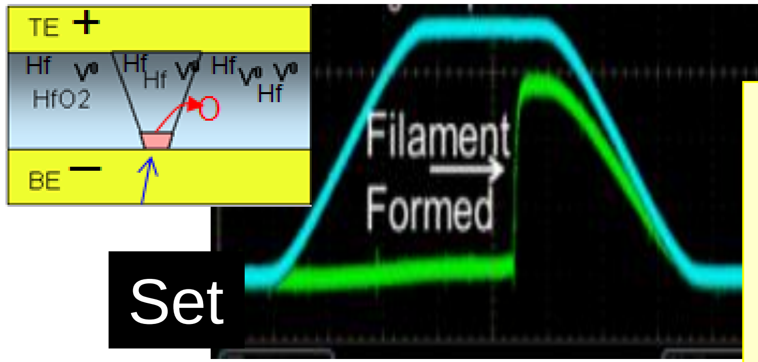
Preferred Reset Polarity!

- O-vacancy asymmetric stacks → Preferred Reset polarity with the <u>“Good” dielectric against the Reset Anode (+)</u>
- Opposites attract….O^- → (+); V^{00} → (-); M^+ → (-)

*D. Gilmer, et al, IMW 2012

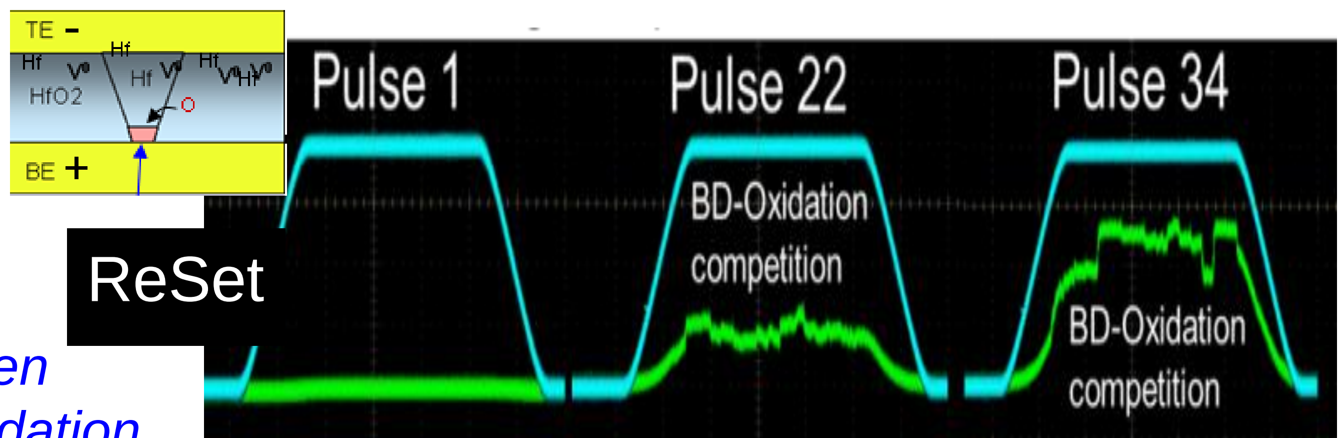
Symmetrical Bias does not similarly break the tunnel barrier →Due to Asymmetric defect profile

- Asymmetry and Preferred Set Bias →
  *Immediate and singular resistance change→
  Barrier breakdown

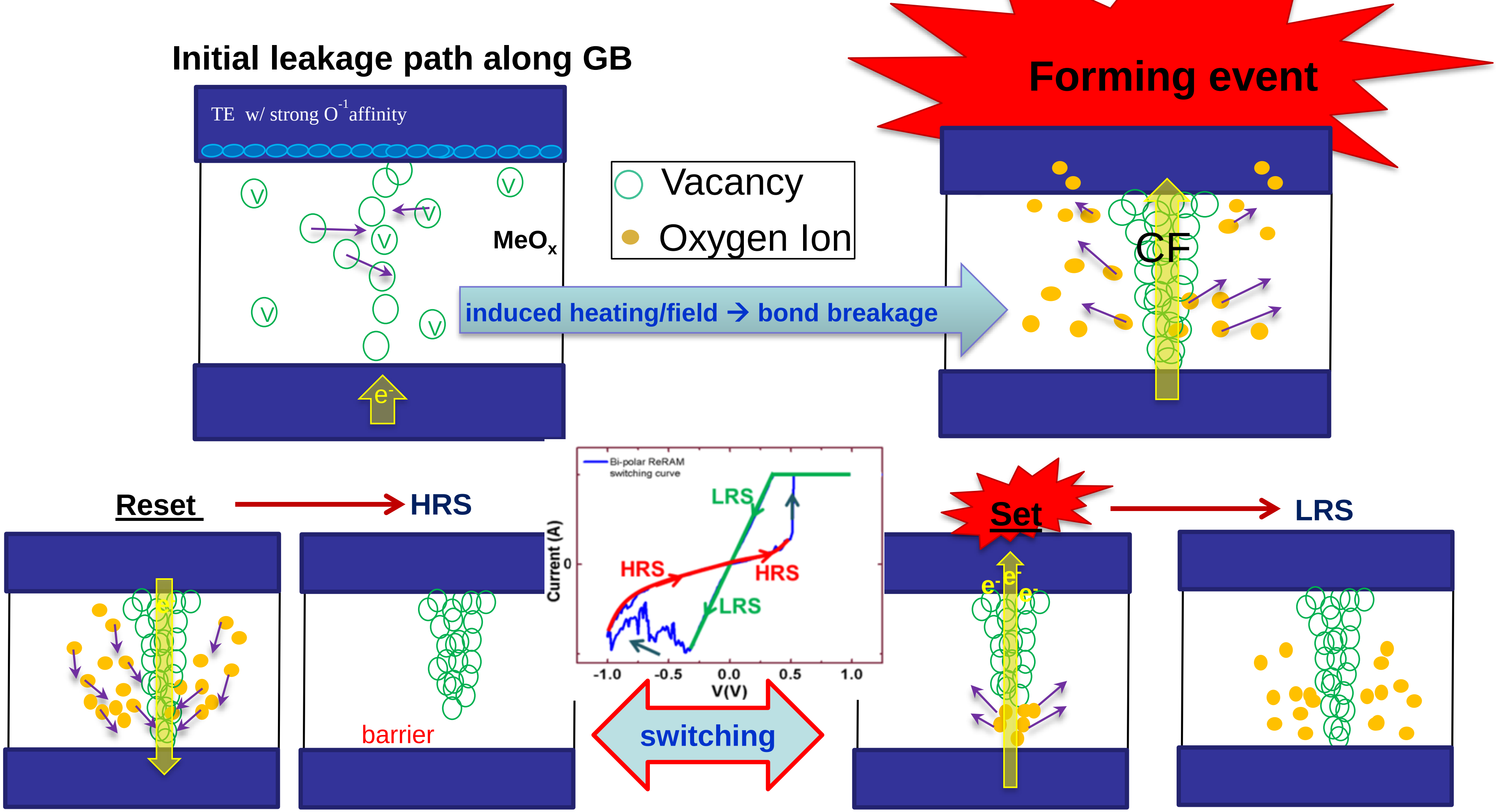


Oscilliscope monitored 80us pulsed Set and pulsed Reset

- Asymmetry and Preferred ReSet Bias →
  *Slower to change, 'fluctuating'→
  Competition between breakdown and oxidation



RRAM operations: From grain boundaries to conductive filament



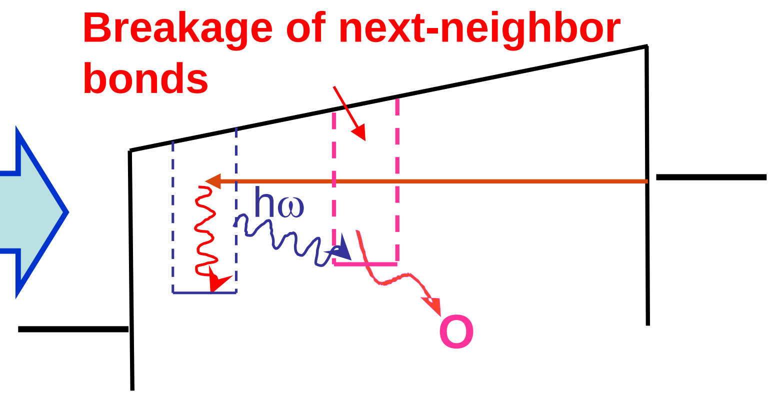
Model-based simulations reproduce the entire forming-switching phenomenon

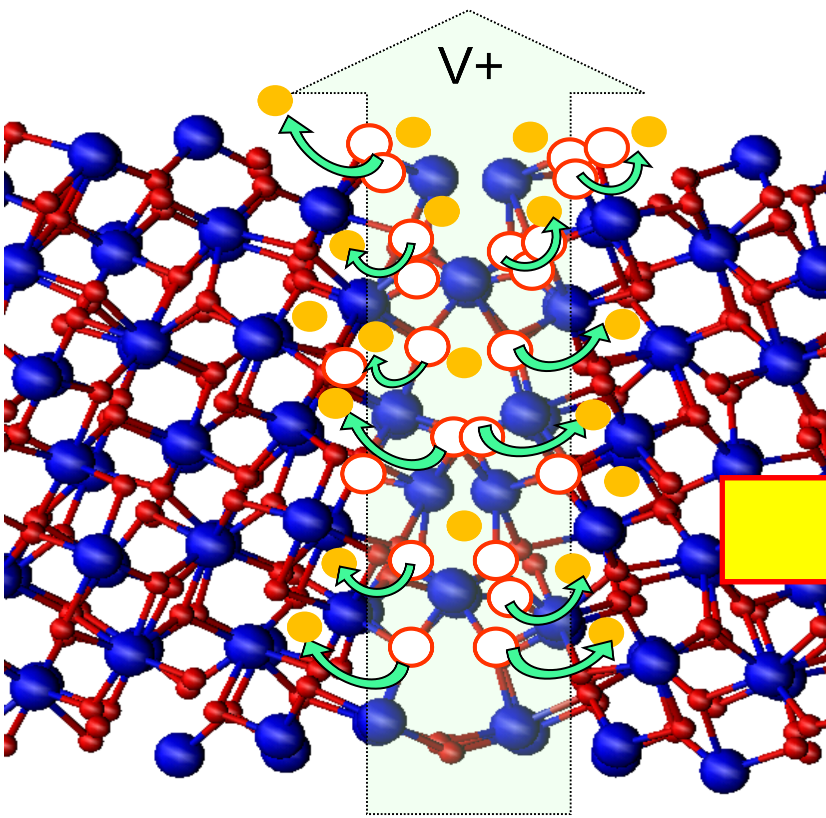
**G.Bersuker et al, JAP 2011*

Mechanism of Forming transient: Run-away Hf-O bond breakage process

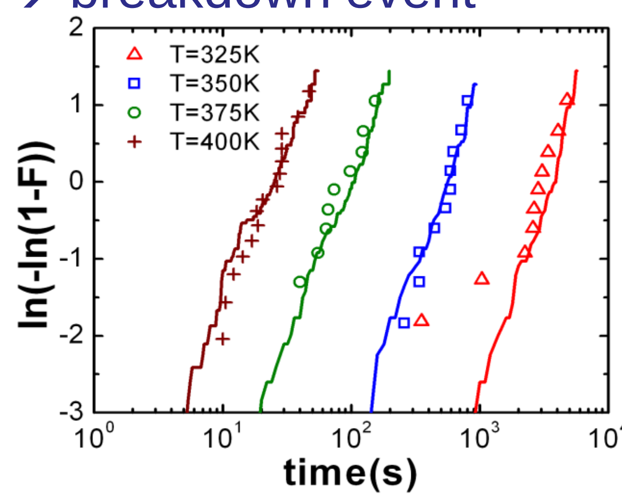
Bond breakage rate:

$$G_{xyz}(T,E_{ox}) = G_0 \exp\left(-\frac{E_{act}-\beta E_{ox,xyz}}{kT_{xyz}}\right)$$





Time-to-Forming: Weibull statistics
→ breakdown event



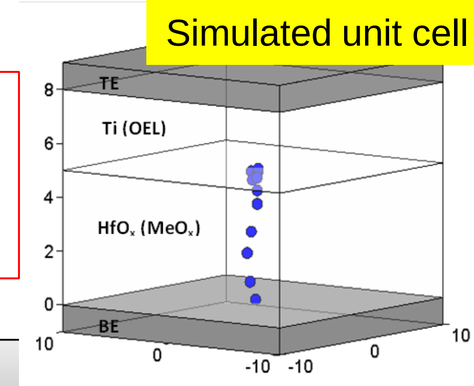
*L. Vandelli et al, IRPS'12

Bersuker & Gilmer, CH.9; Metal oxide "RRAM" technology in; "Advances in Non-Volatile Memory and Storage Technology" 2014, Pages 288–340

HfOx-Based RRAM fully Modeled

Program Description (3D Map creation)

Electron transport via vacancies → power dissipation → T+E field → new vacancies generation + oxygen diffusion →electron transport increases → power dissipation increases → … new vacancy generation + oxygen diffusion → ……filament formed



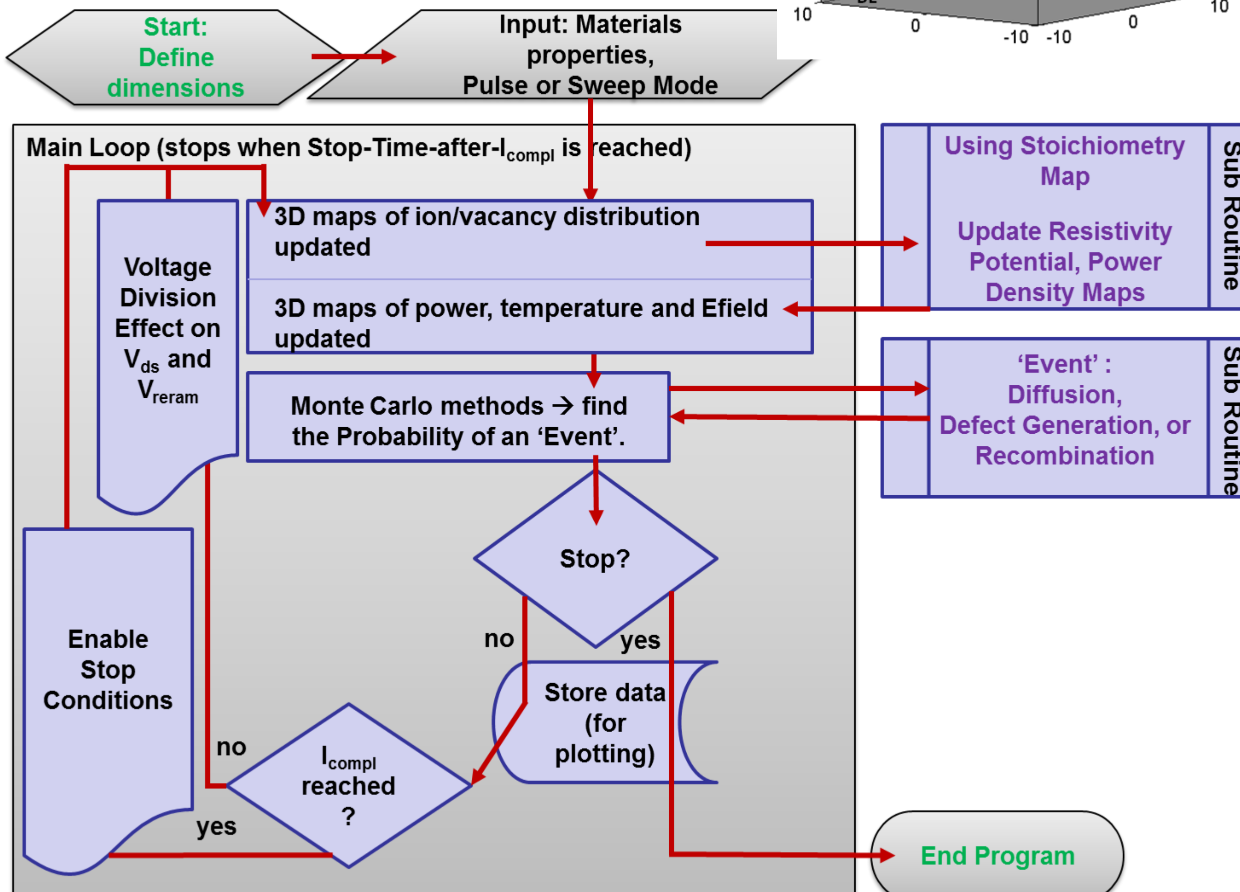
Main loop: numerically solving Fourier heat-transfer, charge continuity equations in each unit volume

$$\nabla \cdot \sigma \nabla V = 0$$

$$-\nabla \cdot k_{th} \nabla T = \sigma |\nabla V|^2$$

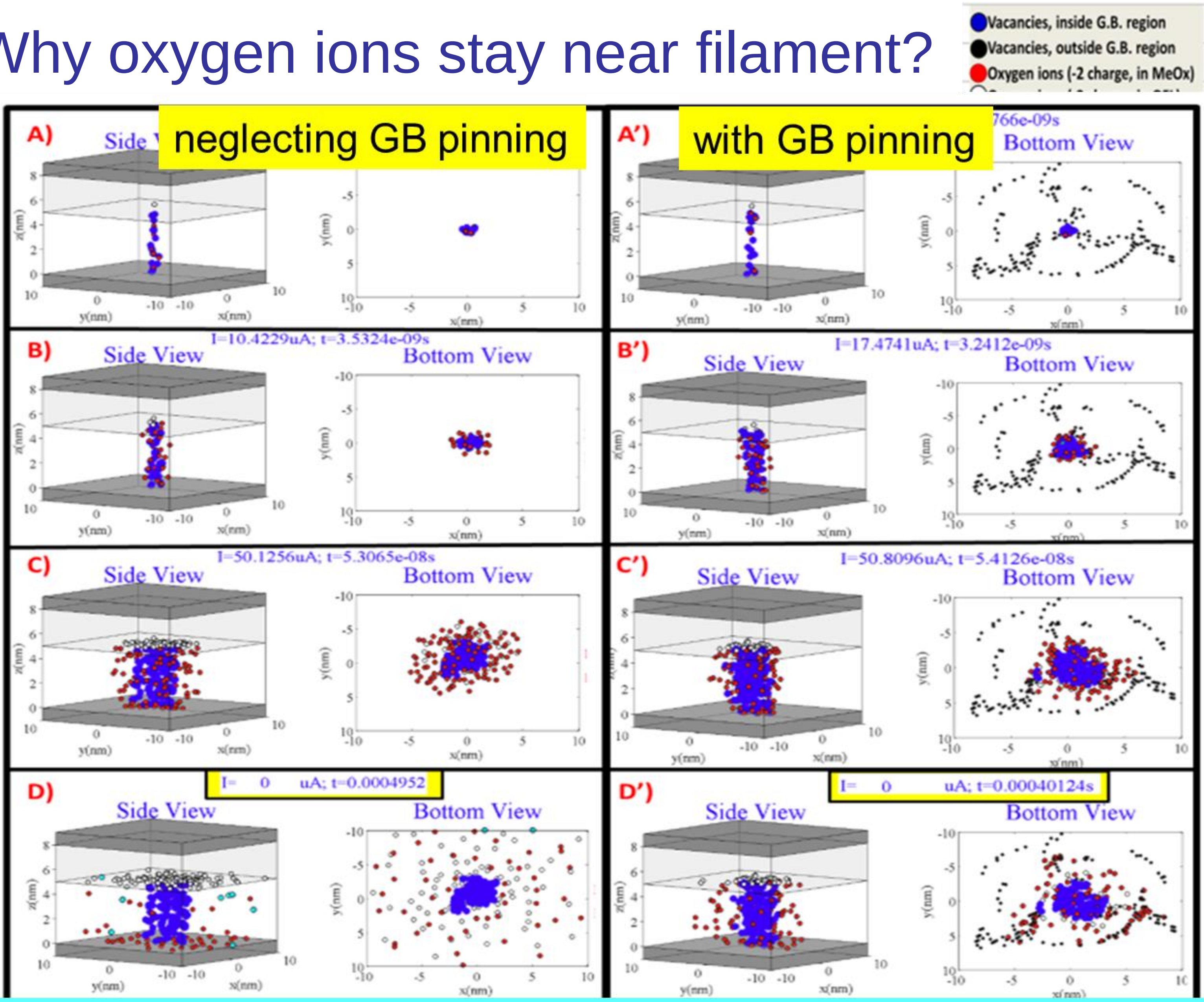
- **Resistivity**– local values depending on # of vacancies
- **Potential**
- **Power dissipation**
- **Temp. / E-Field**

→ 3D Map Update



Bersuker & Gilmer, CH.9; Metal oxide "RRAM" technology in; "Advances in Non-Volatile Memory and Storage Technology" 2014, Pages 288–340

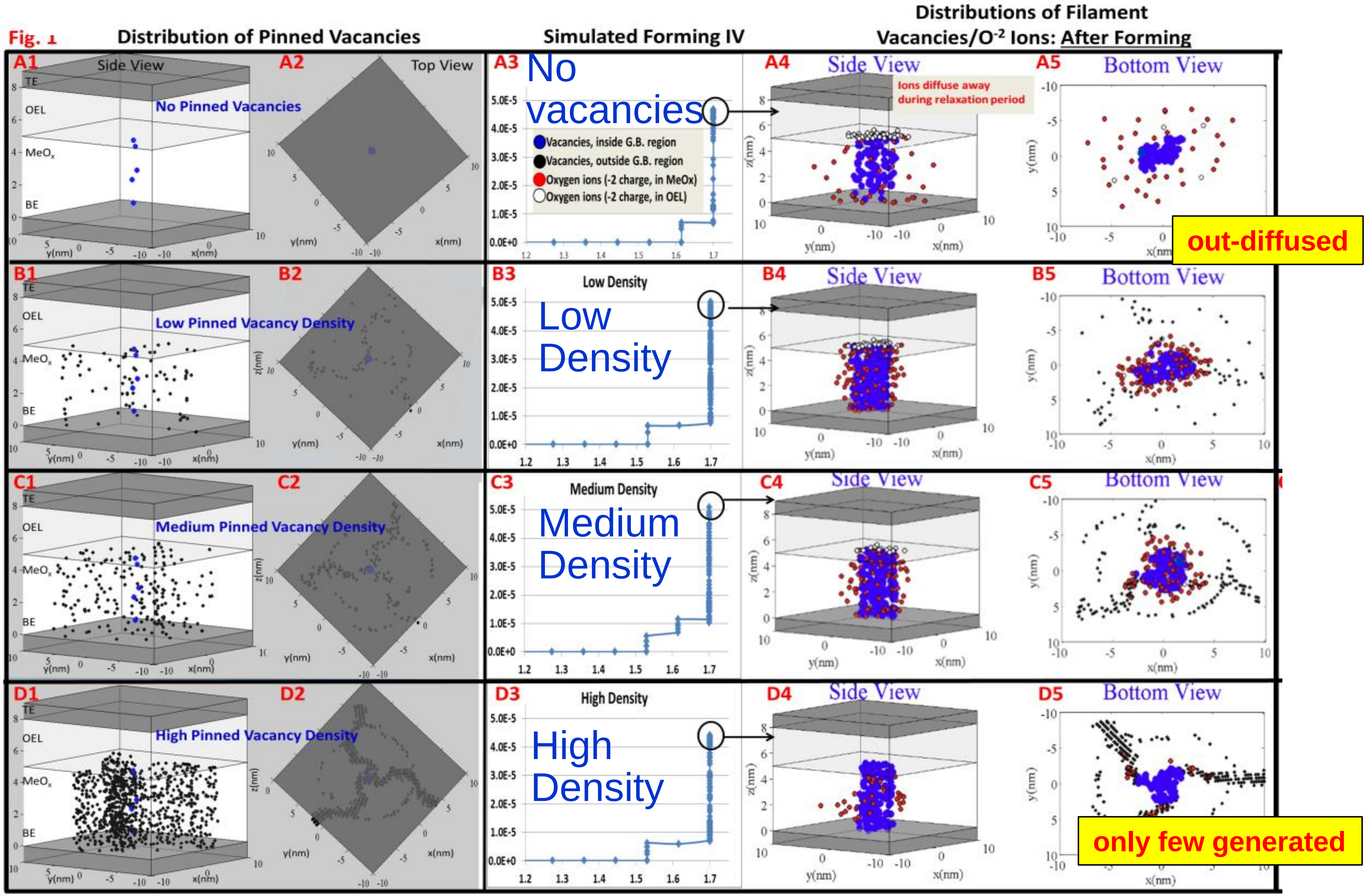
Why oxygen ions stay near filament?



O-ions 'caged' by positively charged 'pinned' vacancies at grain boundaries

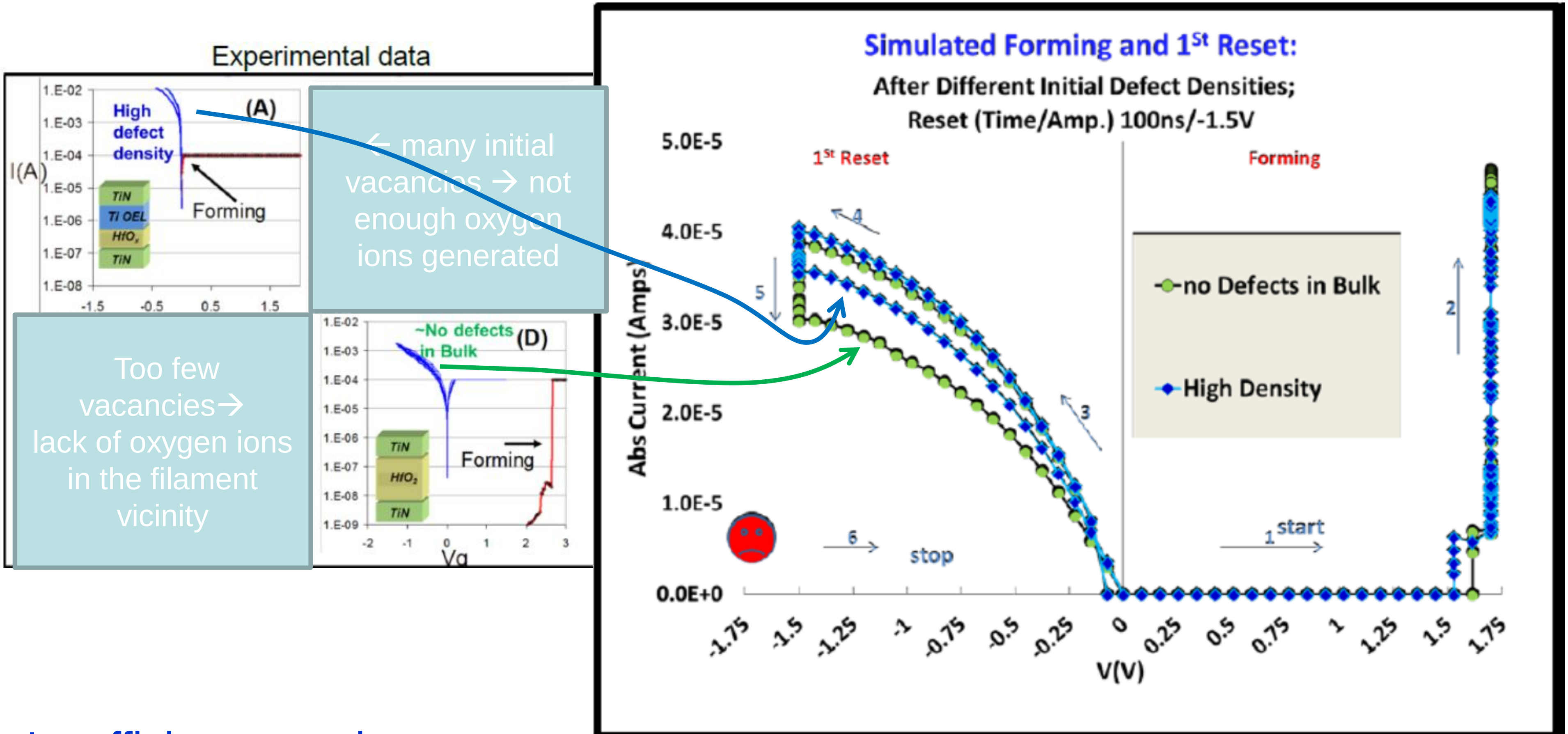
Bersuker & Gilmer, CH.9; Metal oxide "RRAM" technology in; "Advances in Non-Volatile Memory and Storage Technology" 2014, Pages 288–340

There is an optimum density of vacancies



Bersuker & Gilmer, CH.9; Metal oxide "RRAM" technology in; "Advances in Non-Volatile Memory and Storage Technology" 2014, Pages 288–340

Both Stoichiometric and High vacancy density films demonstrate poor reset



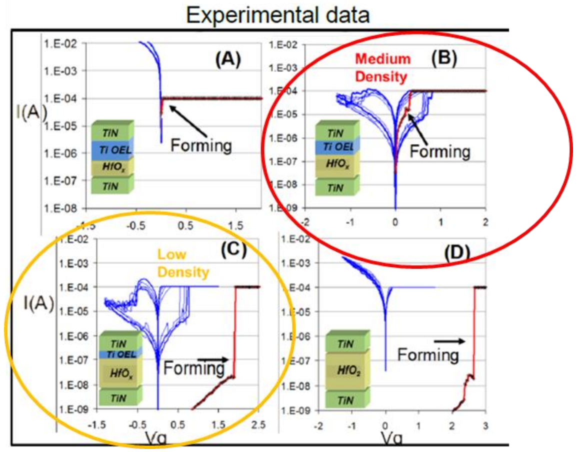
Insufficient reset in:

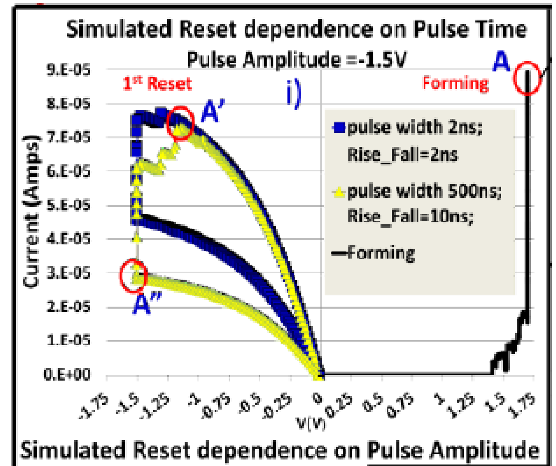
Stoichiometric hafnia: lack of oxygen ions due to recombination w/ vacancies

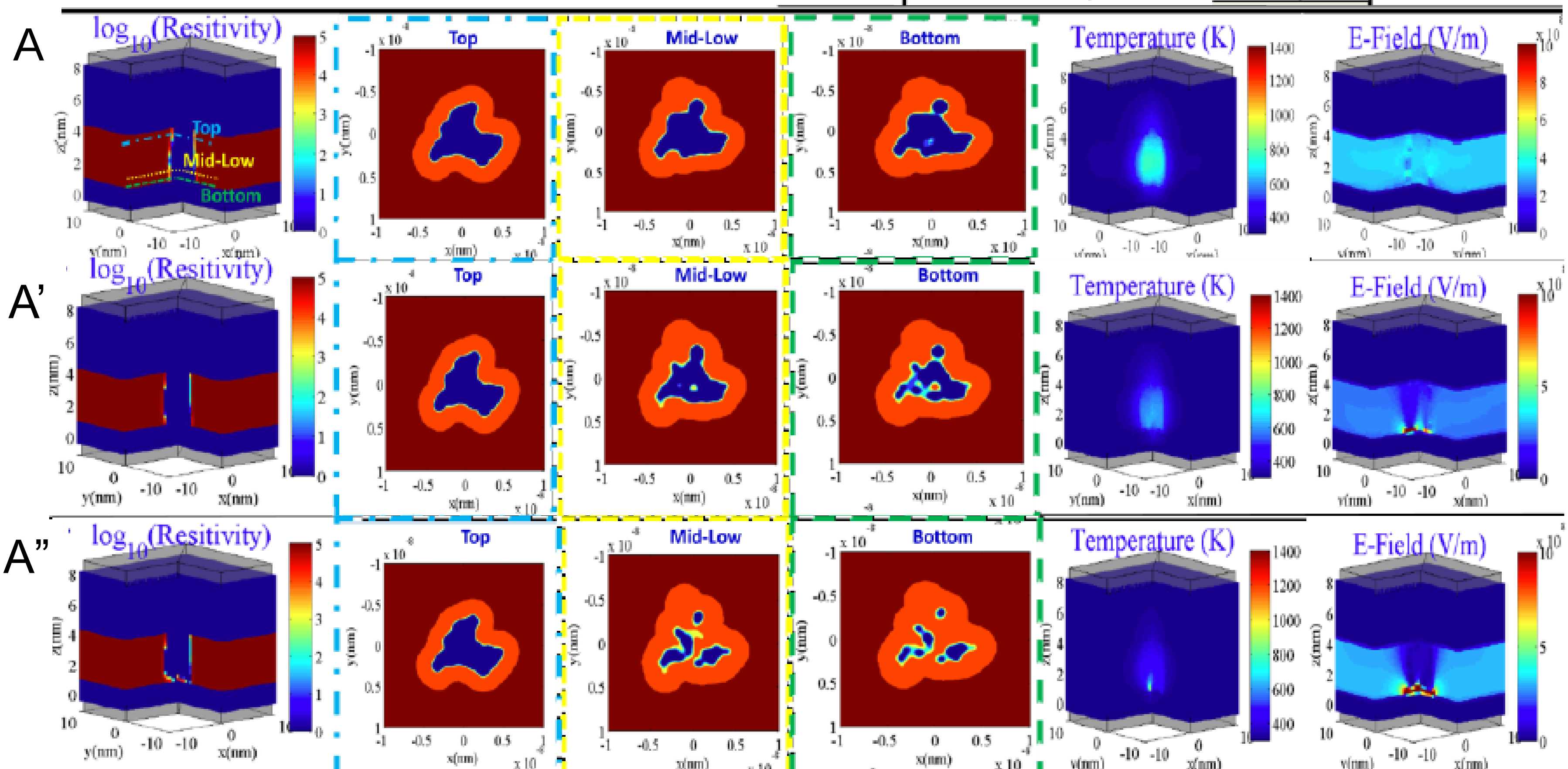
Highly substoichiometric hafnia: low number of generated oxygen ions

Bersuker & Gilmer, CH.9; Metal oxide "RRAM" technology in; "Advances in Non-Volatile Memory and Storage Technology" 2014, Pages 288–340

'Moderate' vacancy density results in best switching

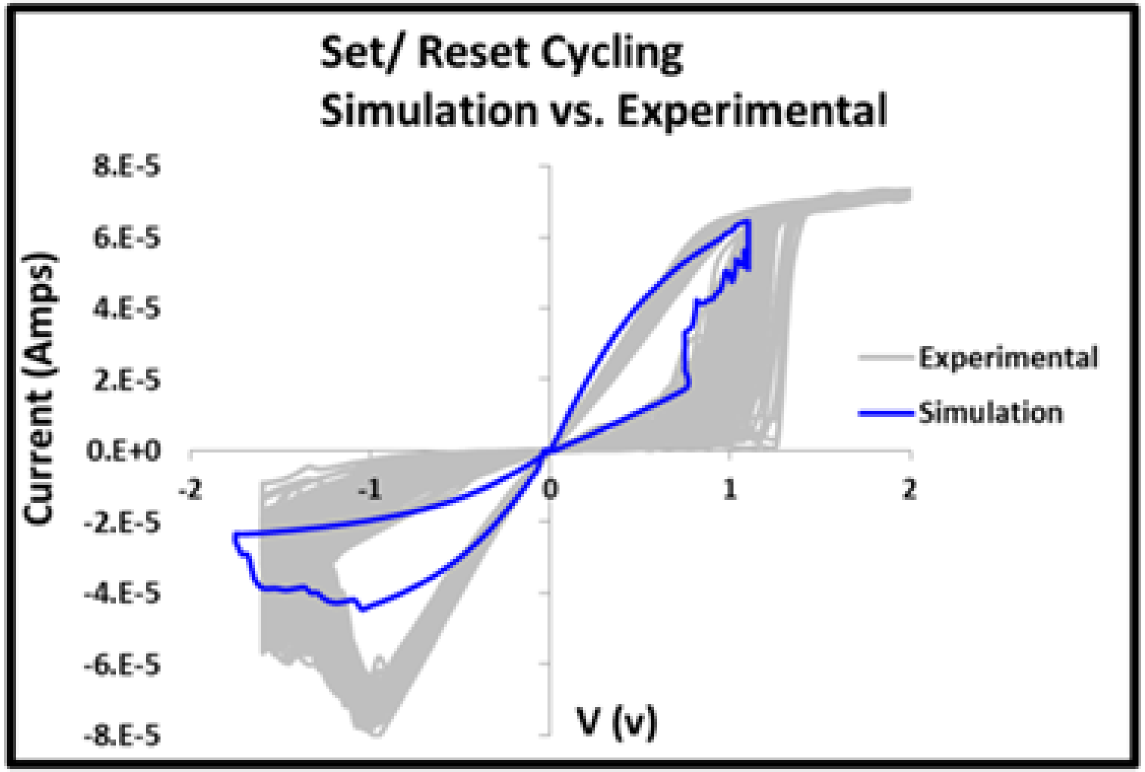






Bersuker & Gilmer, CH.9; Metal oxide "RRAM" technology in; "Advances in Non-Volatile Memory and Storage Technology" 2014, Pages 288–340

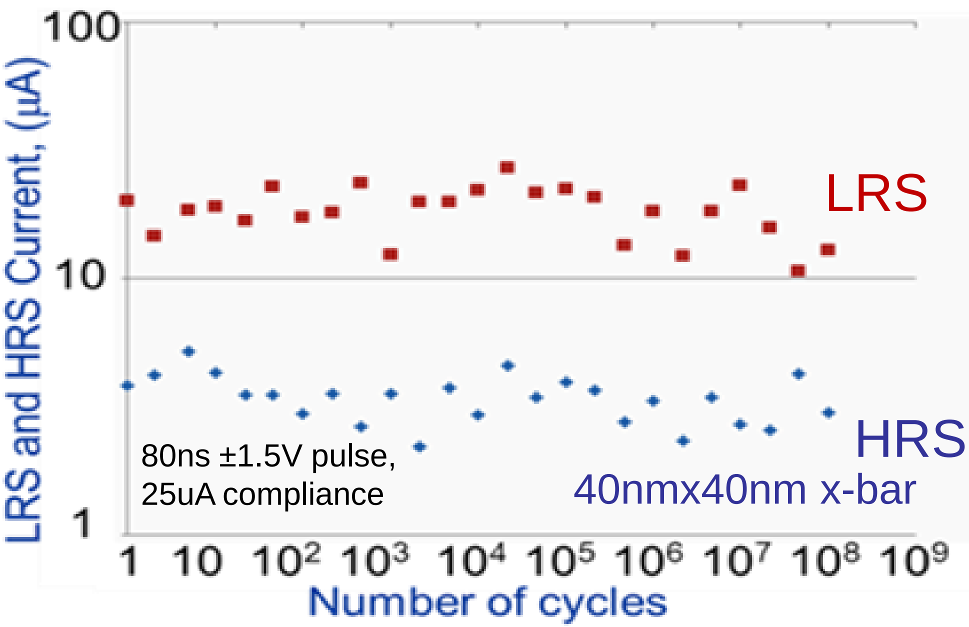
Simulated set/reset cycle

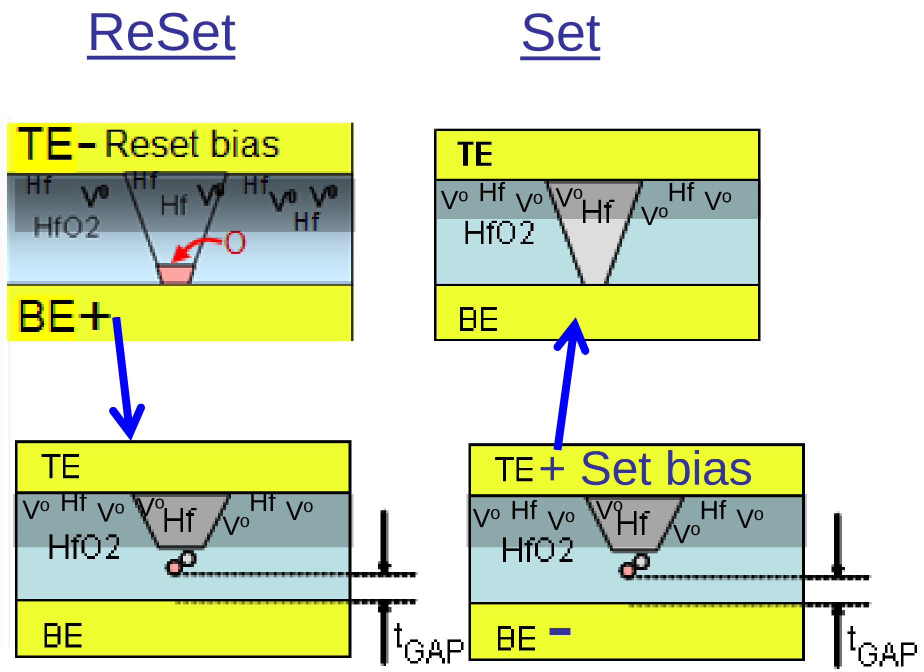


Bersuker & Gilmer, CH.9; Metal oxide "RRAM" technology in; "Advances in Non-Volatile Memory and Storage Technology" 2014, Pages 288–340

Summary

Asymmetric TiN\HfOx\Ti\TiN





- Model identifies **material properties** and **operation conditions** controlling RRAM performance (supported by O-vacancy Asymmetry Device data)
- Asymmetric stacks have preferred bipolar operation polarity
- O-vacancy Asymmetry Assists the Set-ReSet Mechanism
- Many techniques can introduce vacancies; **'OEL', Plasma, Reactive PVD, etc…**

The goal; creating vacancy profiles advantageous for the filament oxidation during reset and barrier break in set