RRAM: Mechanisms of Operation

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Classification of Two-Terminal Switching Devices

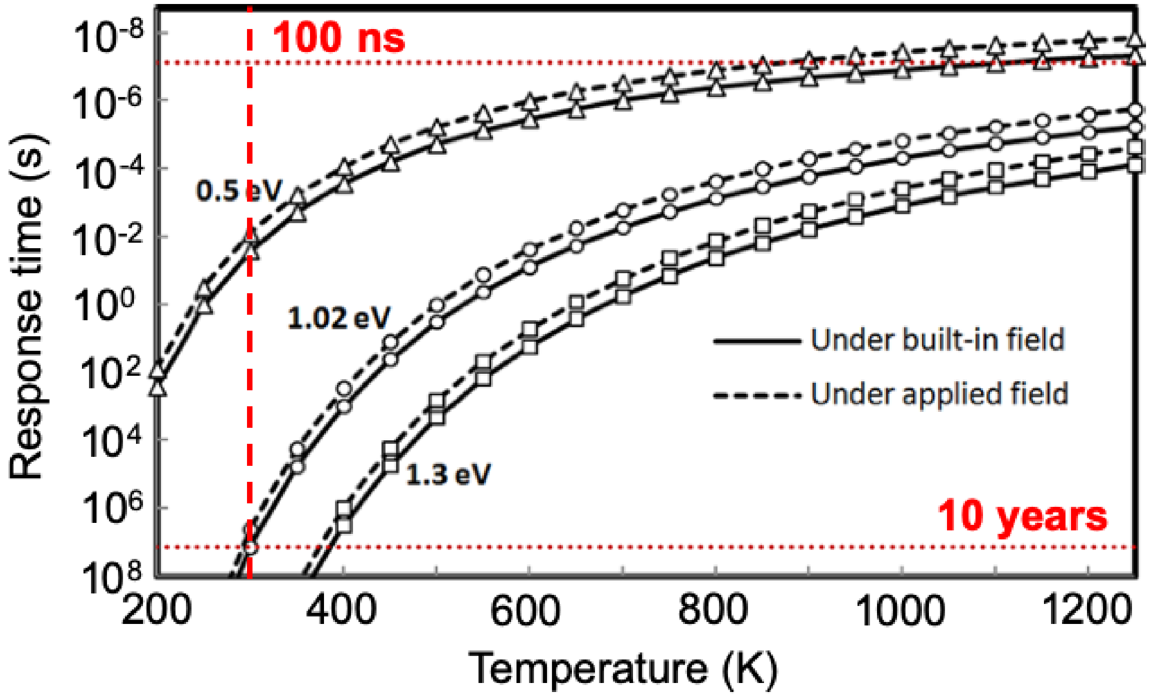
Valence Change Memory	***Thermo-Chemical Memory***	***Electro-Chemical Memory***
All are non-volatile. *Change of resistance is due to redistribution of ions.* *Conduction is filamentary in large devices*		
Mobile ions: *oxygen, exchange of oxygen with electrodes*	*either metal or oxygen of the functional oxide*	*mobile cations from the electrodes*
Type of switching: *bipolar*	*unipolar*	*bipolar*
Driving force: *electric field*	*temperature*	*electric field*
Temperature *high*	*high*	*low*

Application for Memory: Voltage-Time Dilemma

Ion mobility in electric field is proportional to diffusion rate.

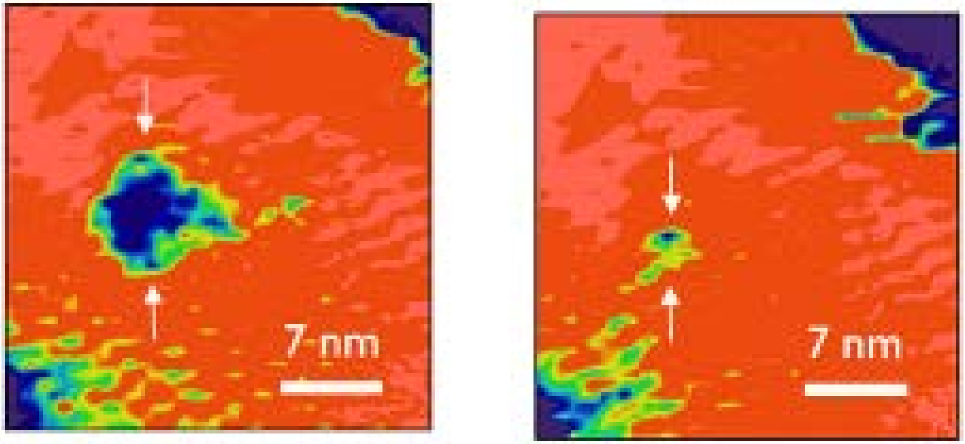
$$\mu_{ION} = \frac{D_{ION}}{kT}$$

Switching time (μ_{ION}) is bound to retention (D_{ION}).

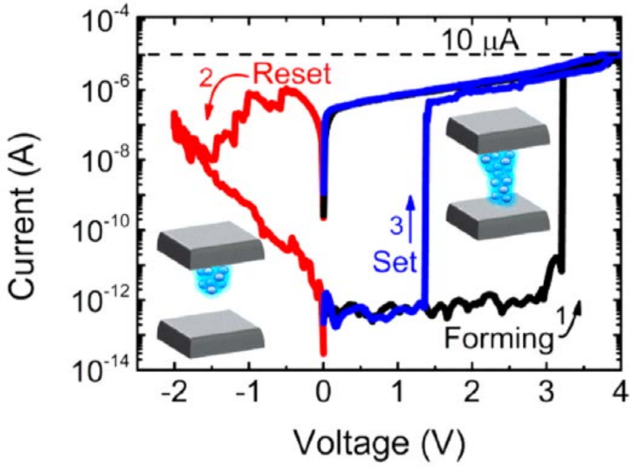


If desired retention / switching time ratio is 10^{15} the activation energy for diffusion must be high (>1.0 eV) and the temperature during writing very high (>1000K).

How Big Is the Filament?

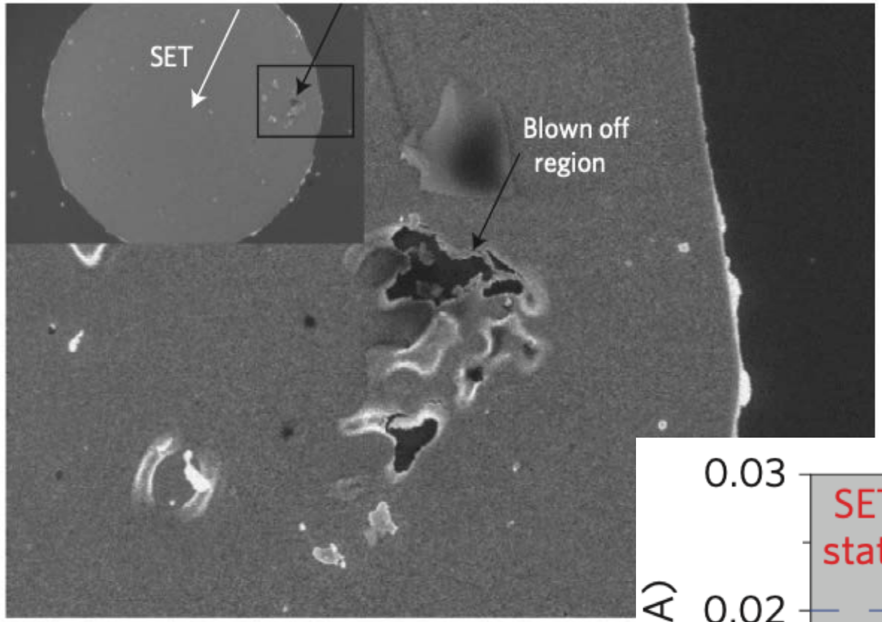


Filament diameter ~ 1 nm



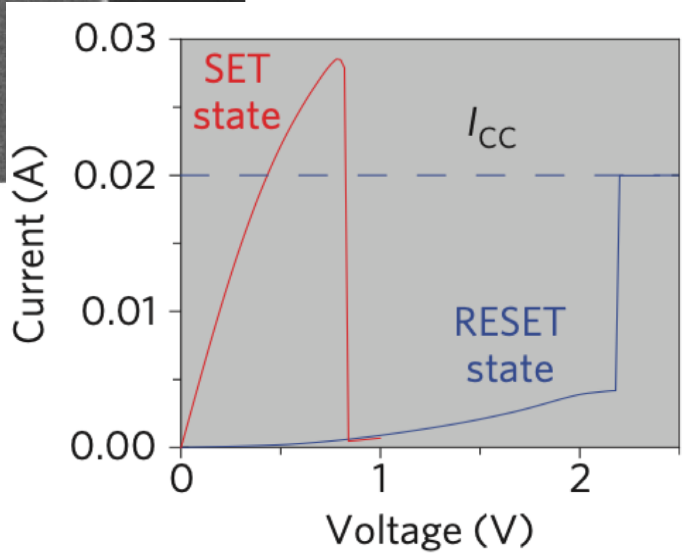
Power 40 μW

Celano et al., Nano Lett. 14, 2401 (2014)



Filament diameter 10 μm; 10^8 times bigger cross-section

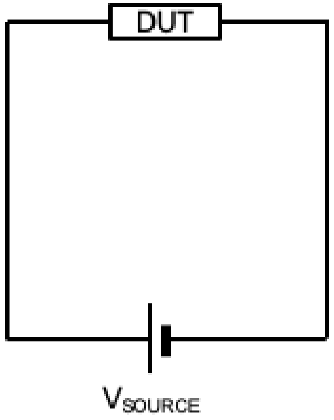
Power 40 mW

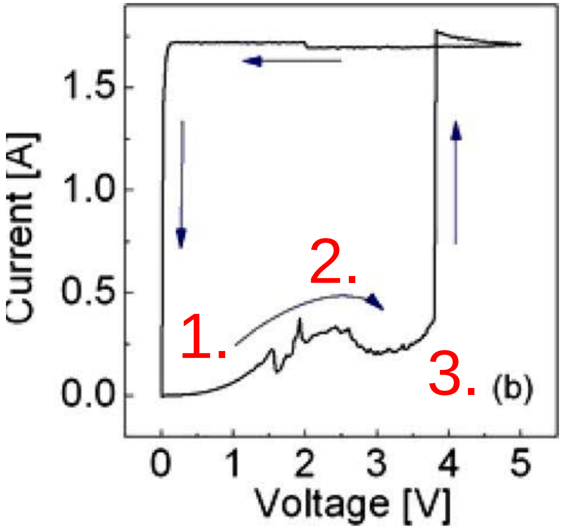


Kwon et al., Nature Nanotechnology 5, 148 (2010)

These two devices are highly unlikely to operate based on the same phenomena.

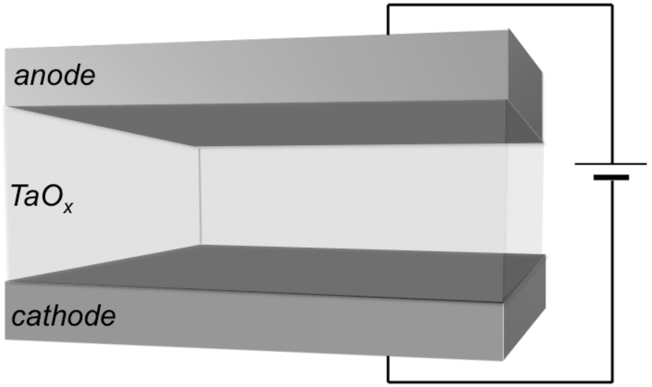
VCM: Electro-Formation - Standard Model



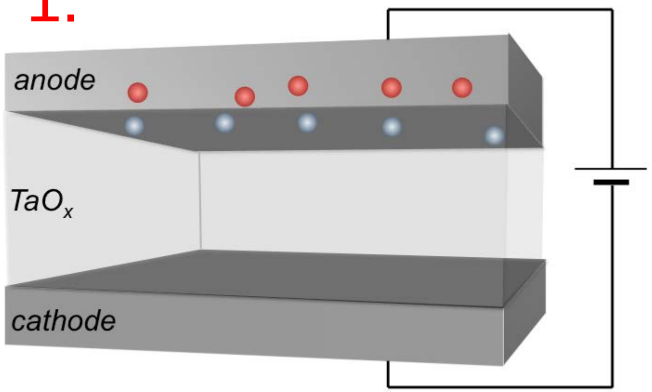


D. S. Jeong et al. J. Appl. Phys. 104, 123716 (2008)

$$O_O \leftrightarrow \frac{1}{2}O_2(gas) + V_O^{\cdot\cdot} + 2e'$$

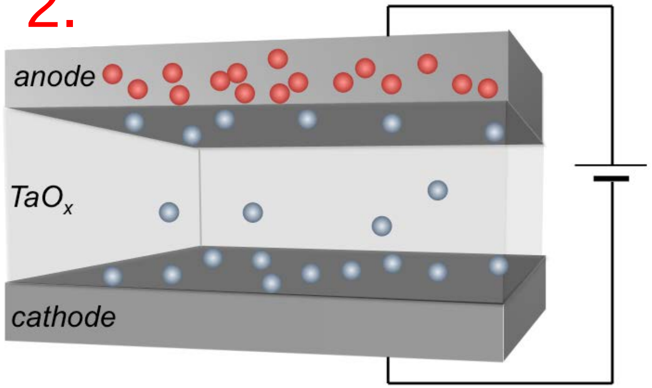


1.



Oxygen ions cross the interface with anode creating vacancies

2.



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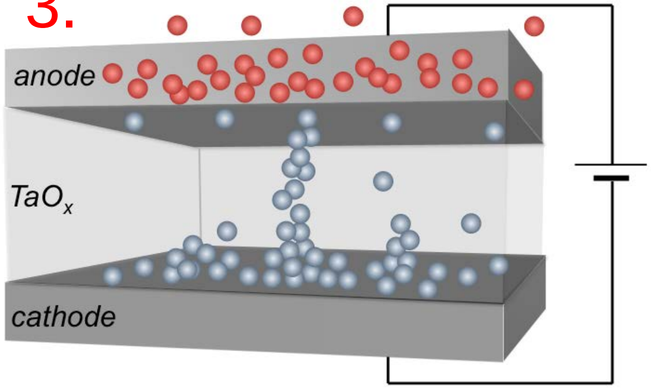
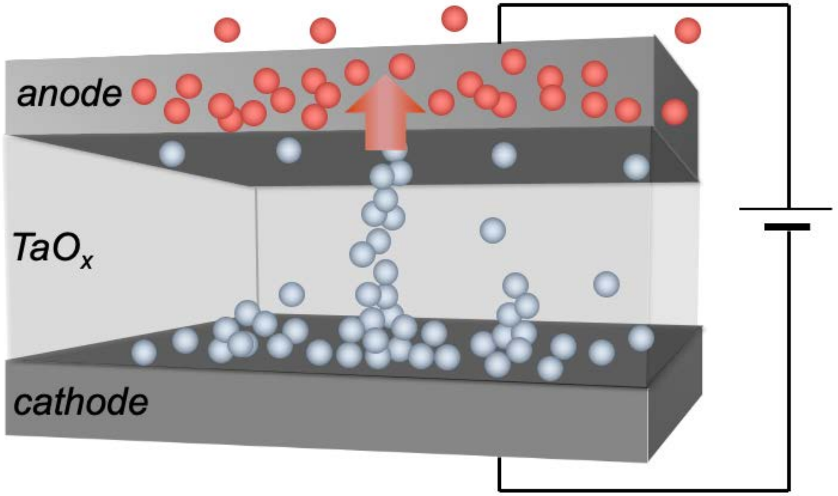


Vacancies drift toward cathode and accumulate there.

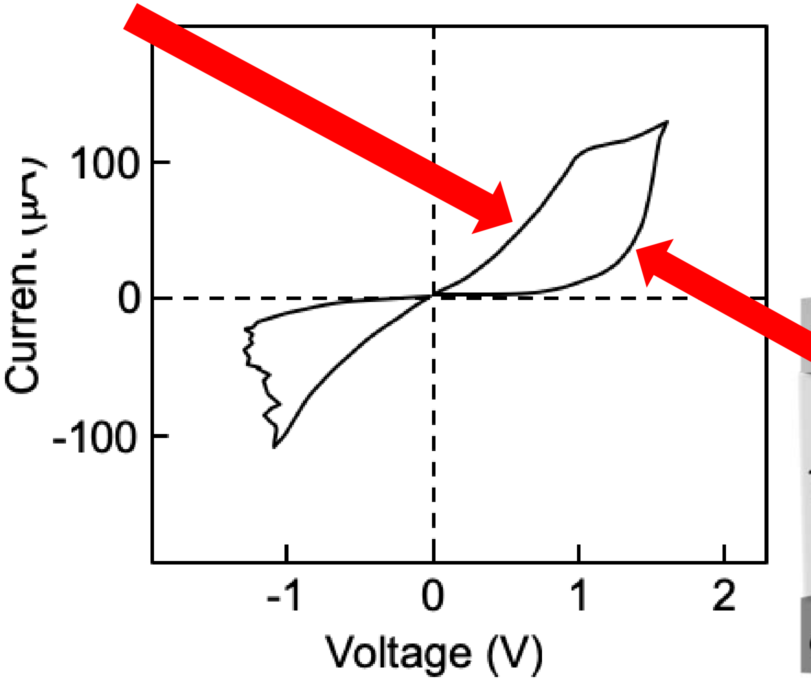
Eventually a filament is created and the current rapidly increases.

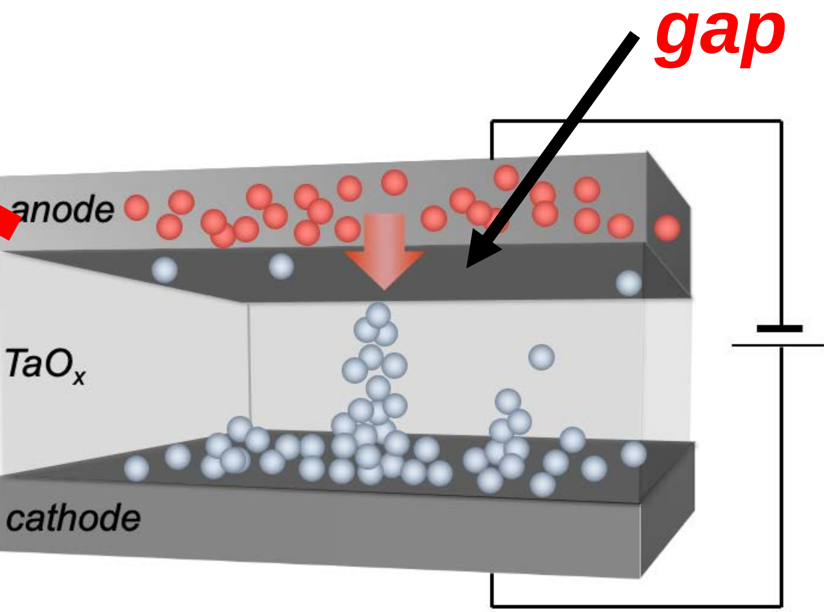
R. Waser et al. Adv. Mate. 21, 2632 (2009)

Bipolar Switching



Low Resistance State

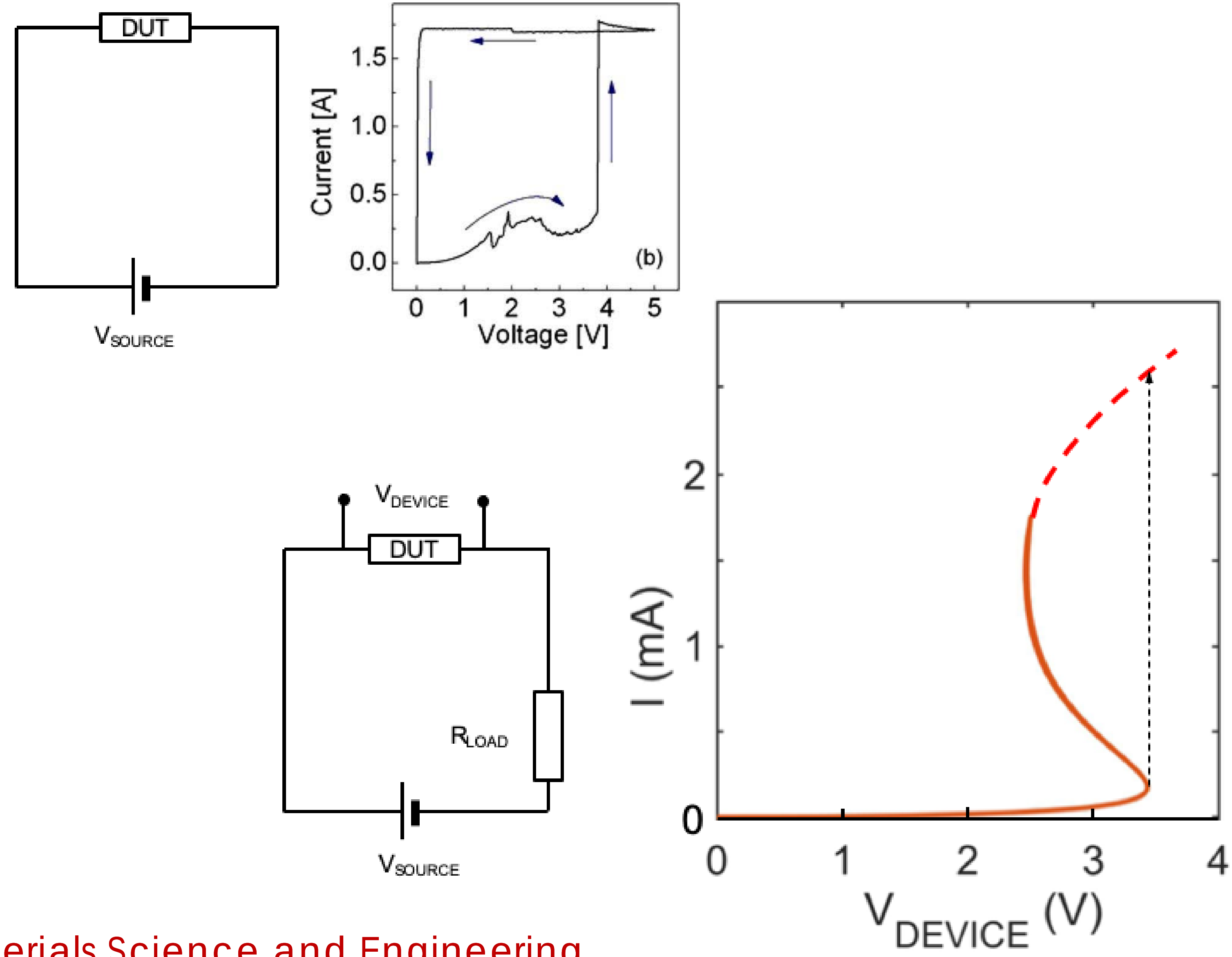




High Resistance State

Low Resistance State corresponds to conducting filament connecting both electrodes. High Resistance State is due to the appearance of a gap in the filament.

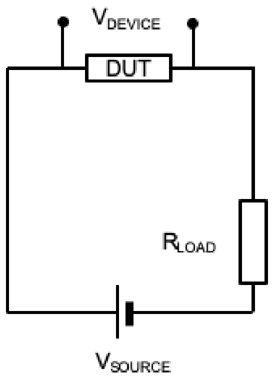
Alternative Model of Electro-Formation

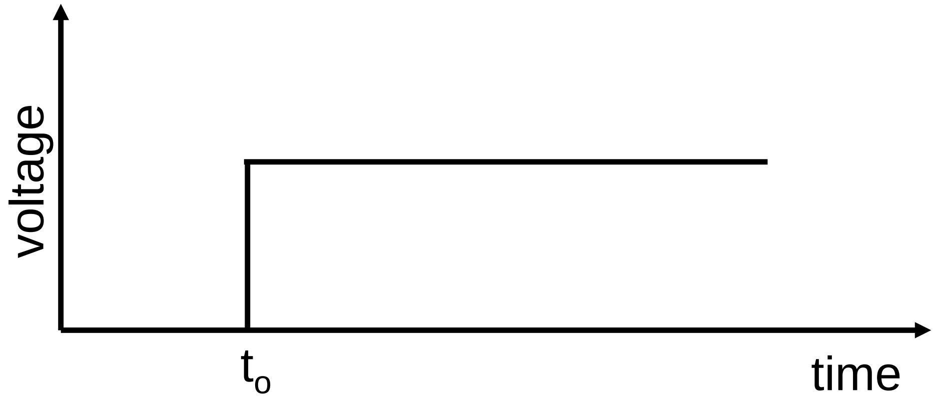


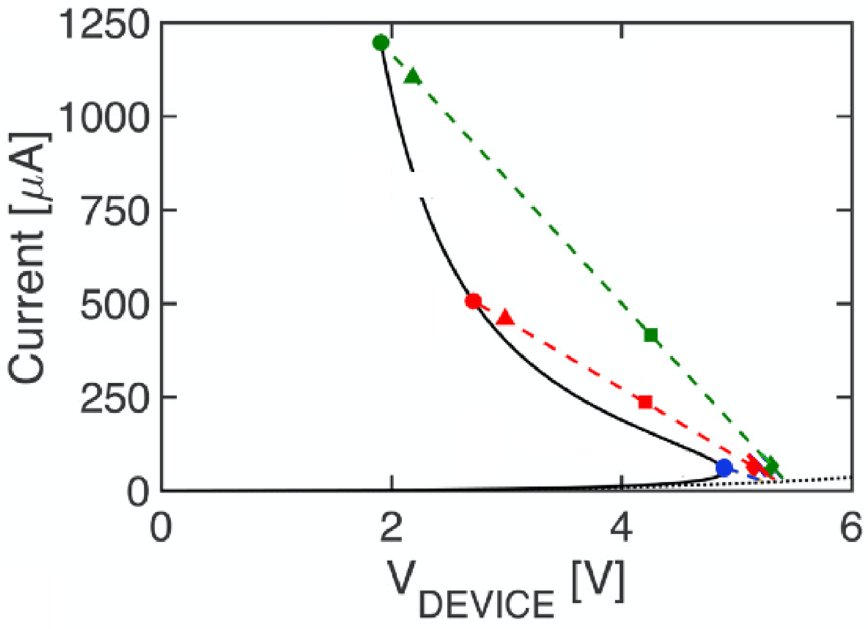
Most metal-oxide-metal structures show such S-type Negative Differential Resistance I-V. It is purely due to electro-thermal processes. No ion motion takes place.

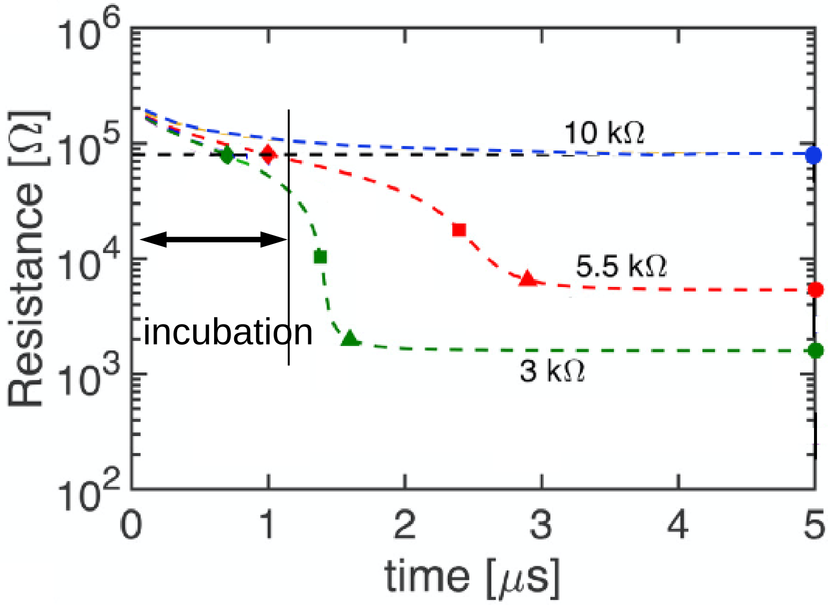
Most frequent origin of S-NDR and threshold switching is a positive feedback loop between current and temperature.

Characteristics of Threshold Switching



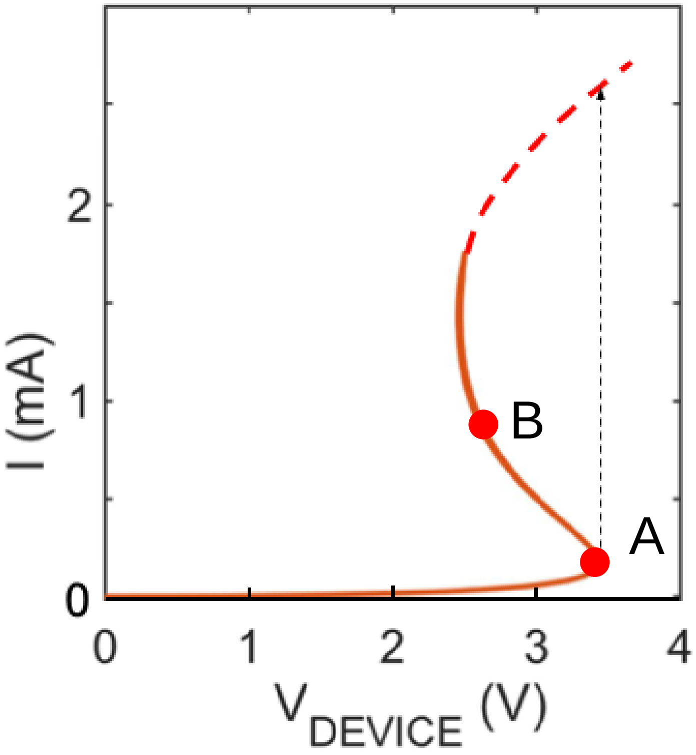


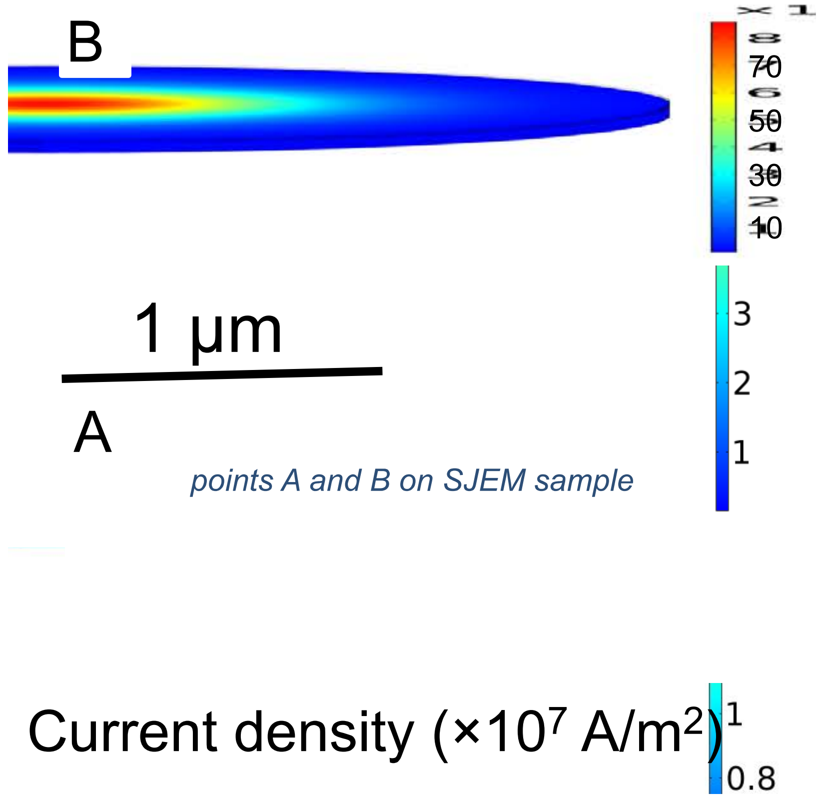




Slow-fast-slow dynamics characteristic of a runaway.

Spontaneous Current Constriction



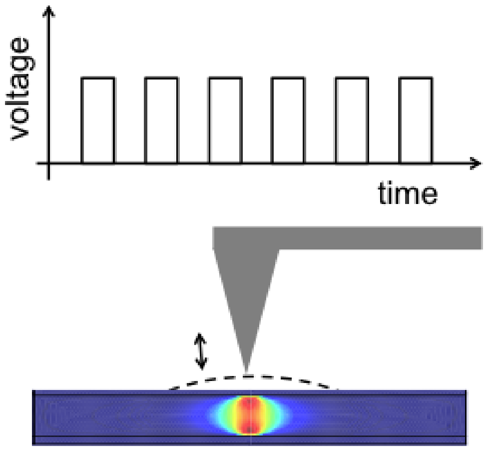


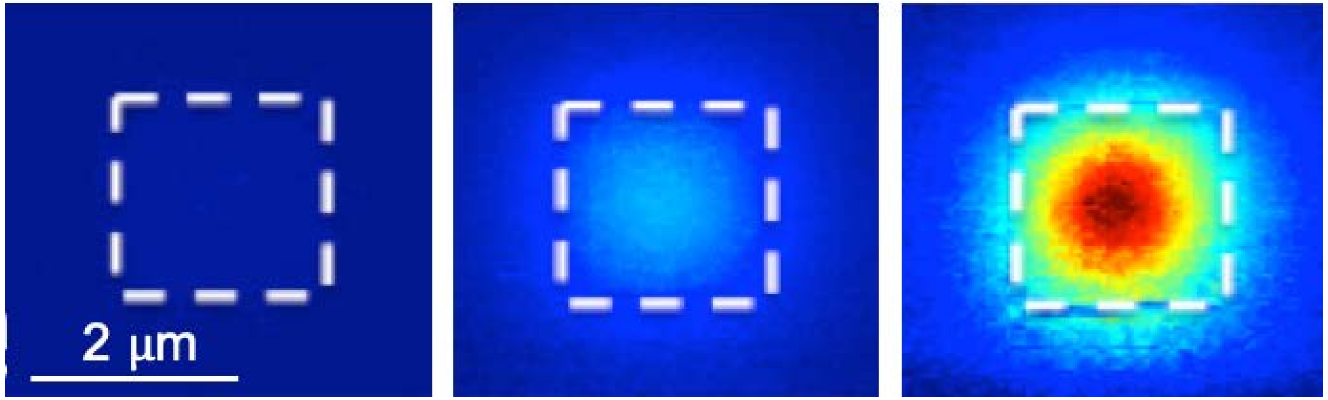
Finite element simulated current density distribution.

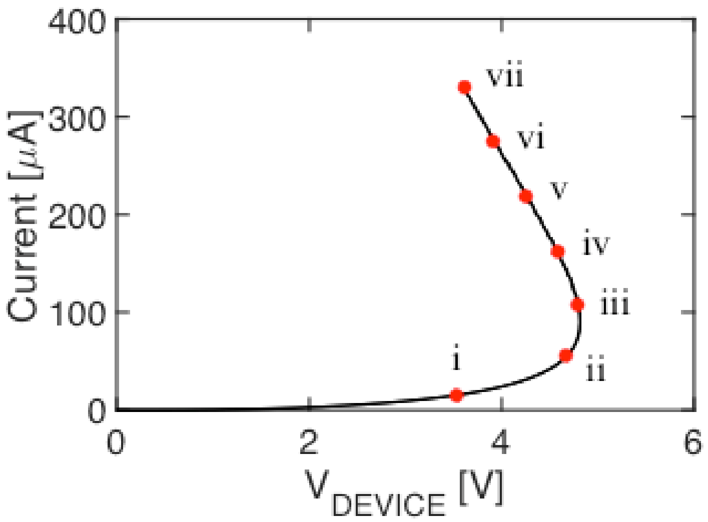
Current constriction does not require presence of any inhomogeneities or defects in the device. The size of constriction decreases with increase of $\frac{\partial\sigma}{\partial T}$.

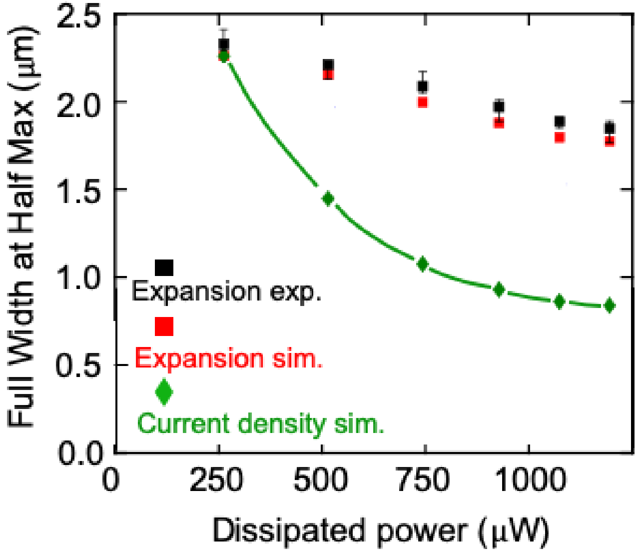
Experimental Observation of Current Constriction

Scanning Joule Expansion Microscopy



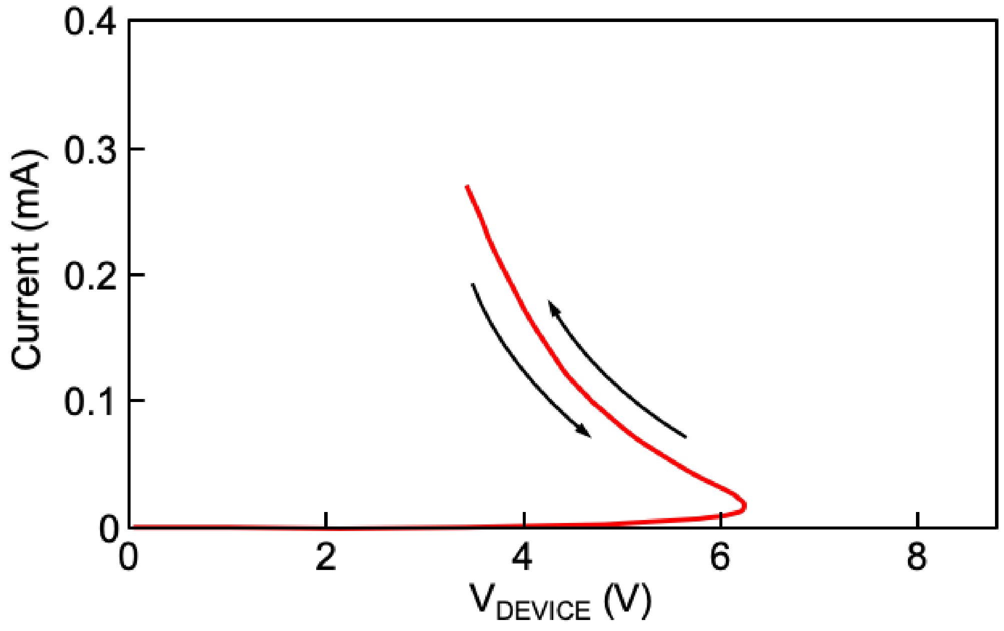


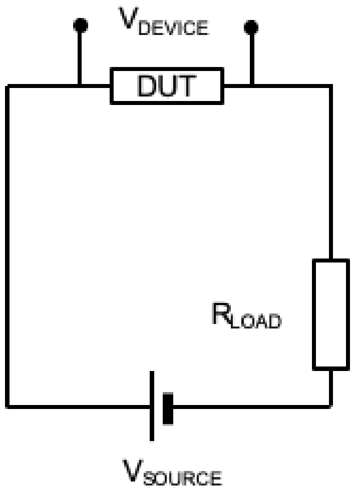




Goodwill et al. Nature Communications 10, 1628 (2019)

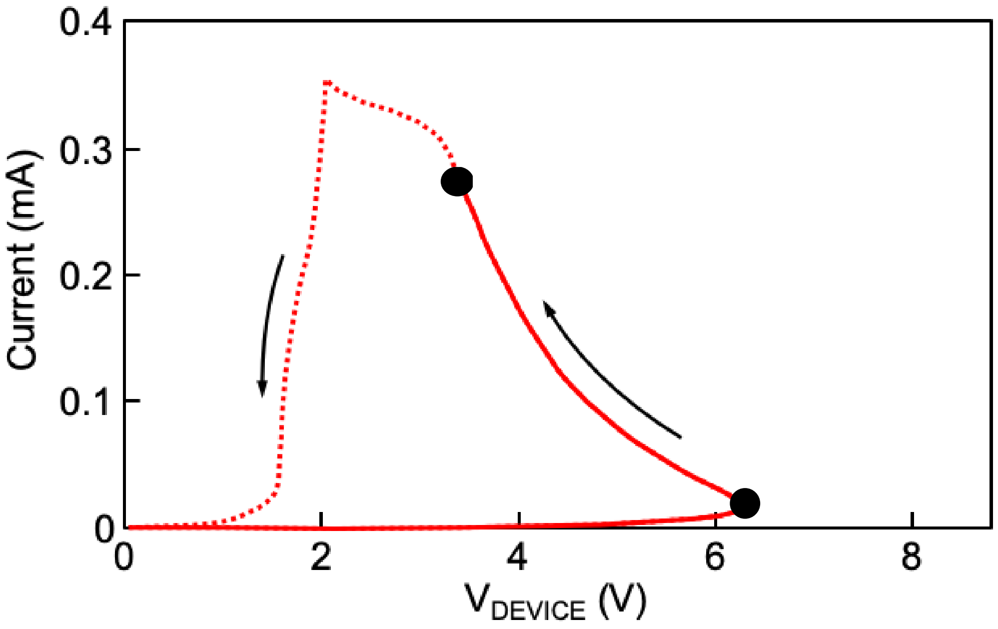
Formation of Permanent Filament

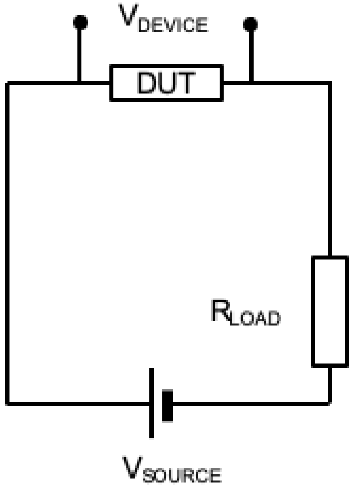




This I-V can be retraced millions of times without changes.

Formation of Permanent Filament

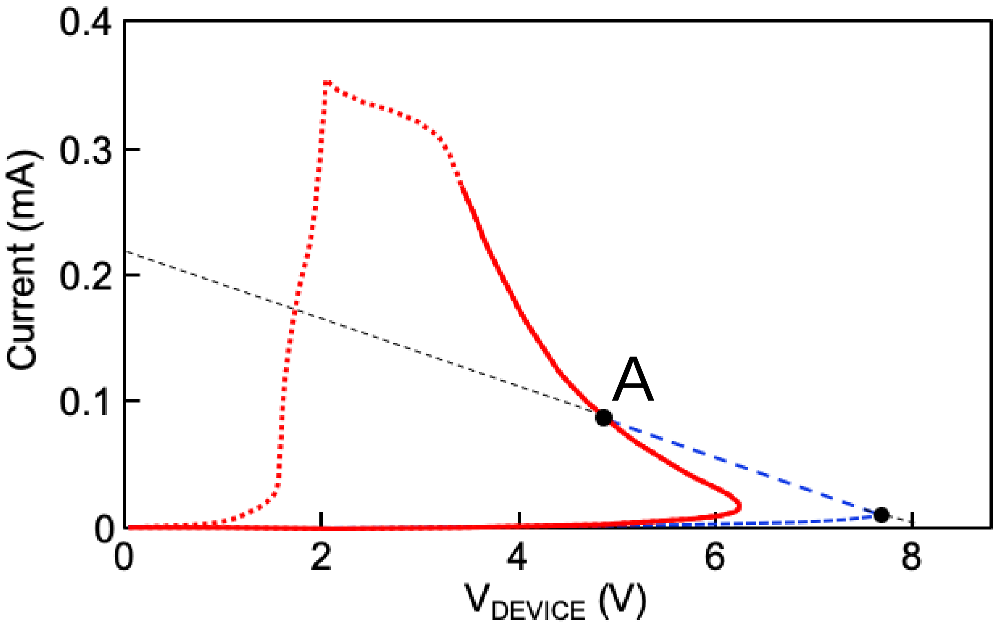


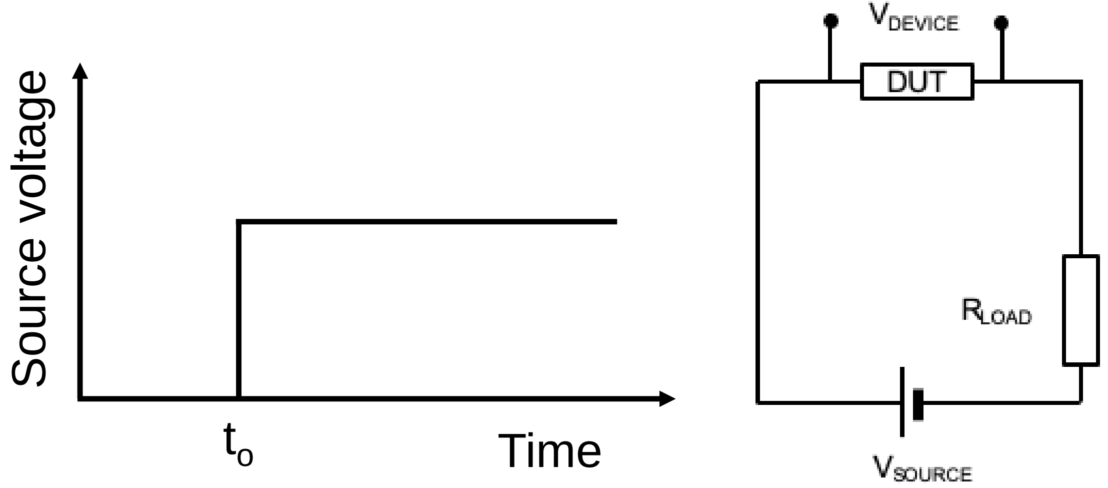


Increasing the device voltage (dissipated power and temperature) past certain point changes the I-V permanently.

Formation of Permanent Filament

Response to a long rectangular voltage pulse of 8V.

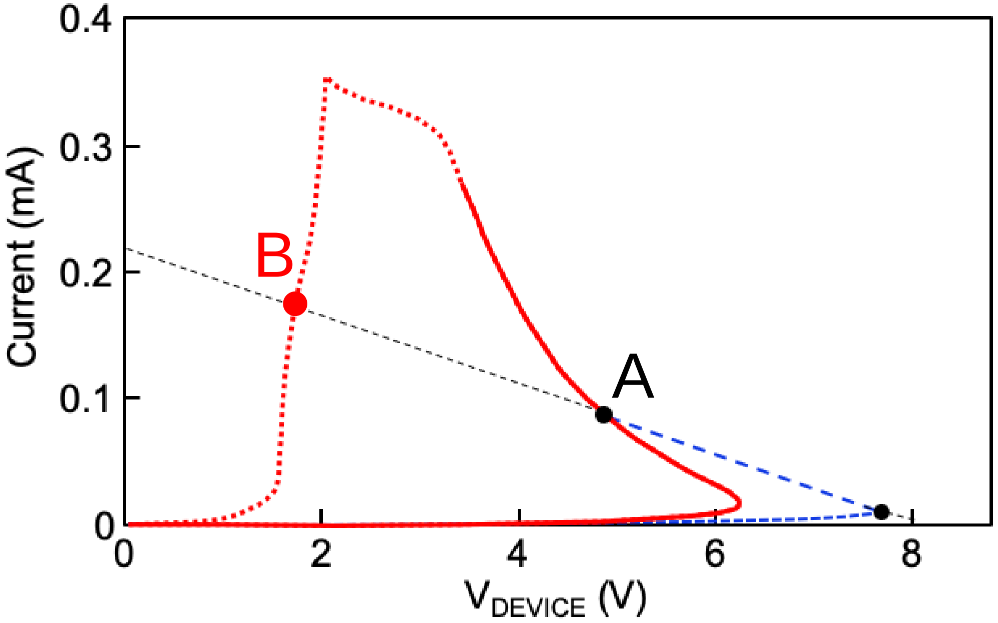


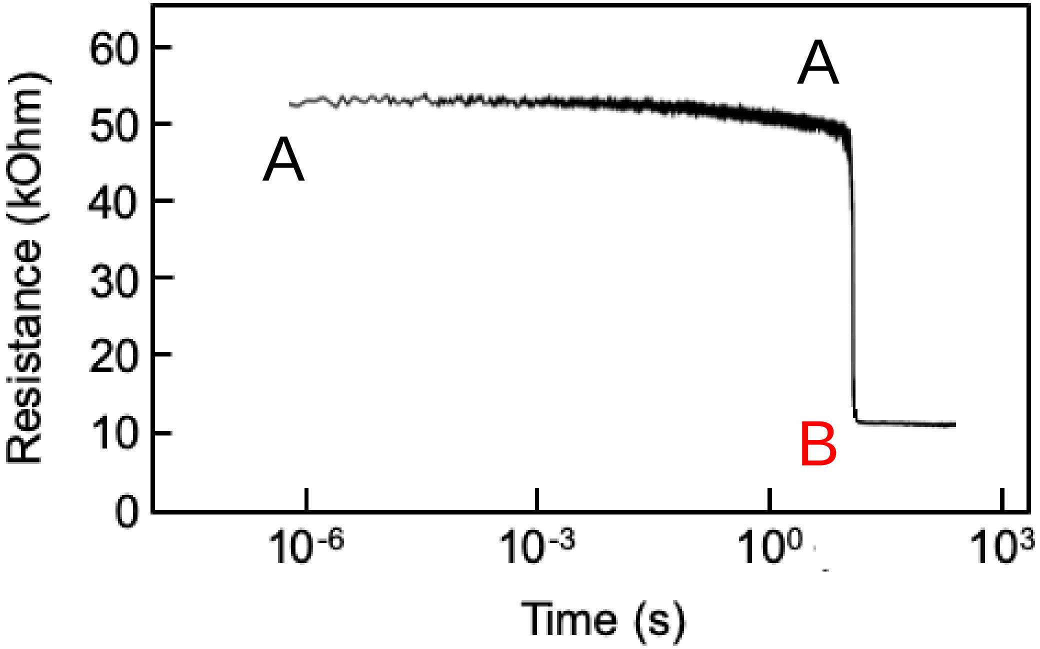


Device gets to point A in about 1 μs (time it takes to heat it up).

Formation of Permanent Filament

Response to a long rectangular voltage pulse of 8V.



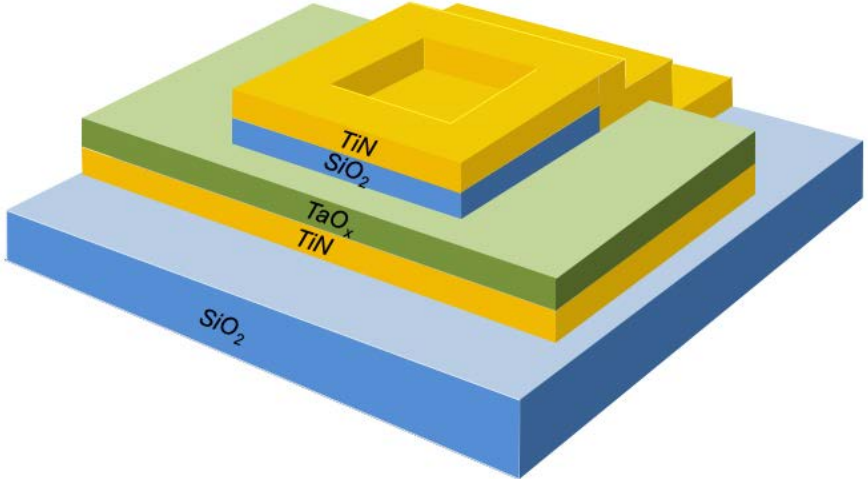


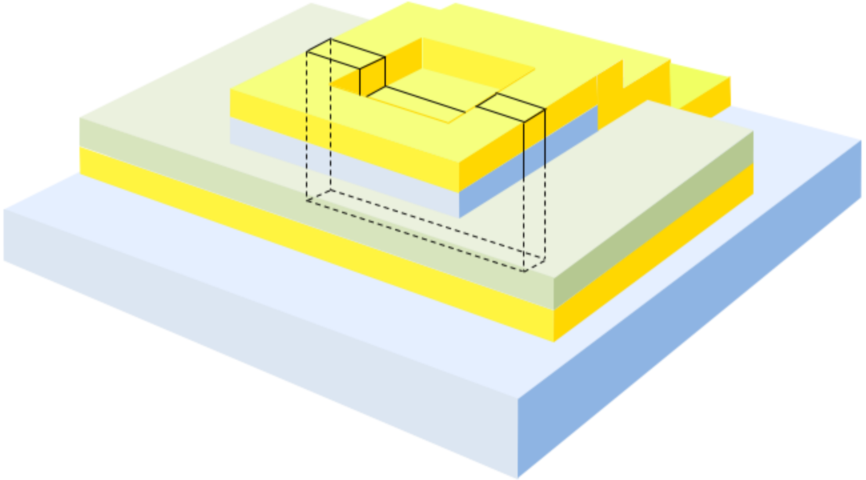
At point A, device incubates for a long time followed by a fast transition to B.

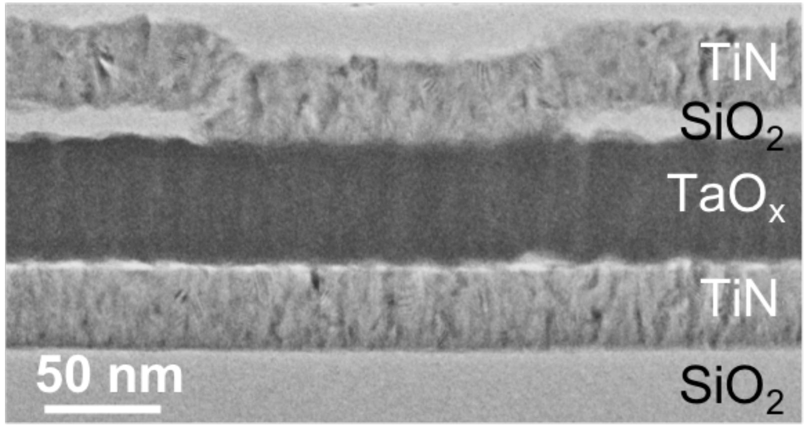
Formation exhibits slow-fast-slow dynamics indicative of a feedback loop and a second runaway process.

TEM Assessment of Physical Changes

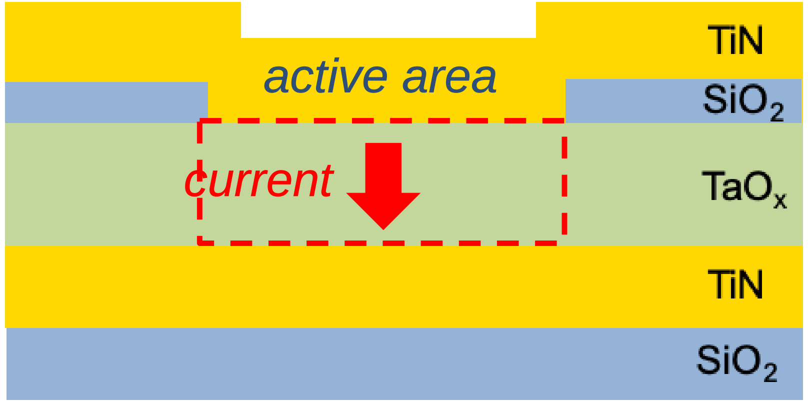
Device structure and geometry of TEM sample.



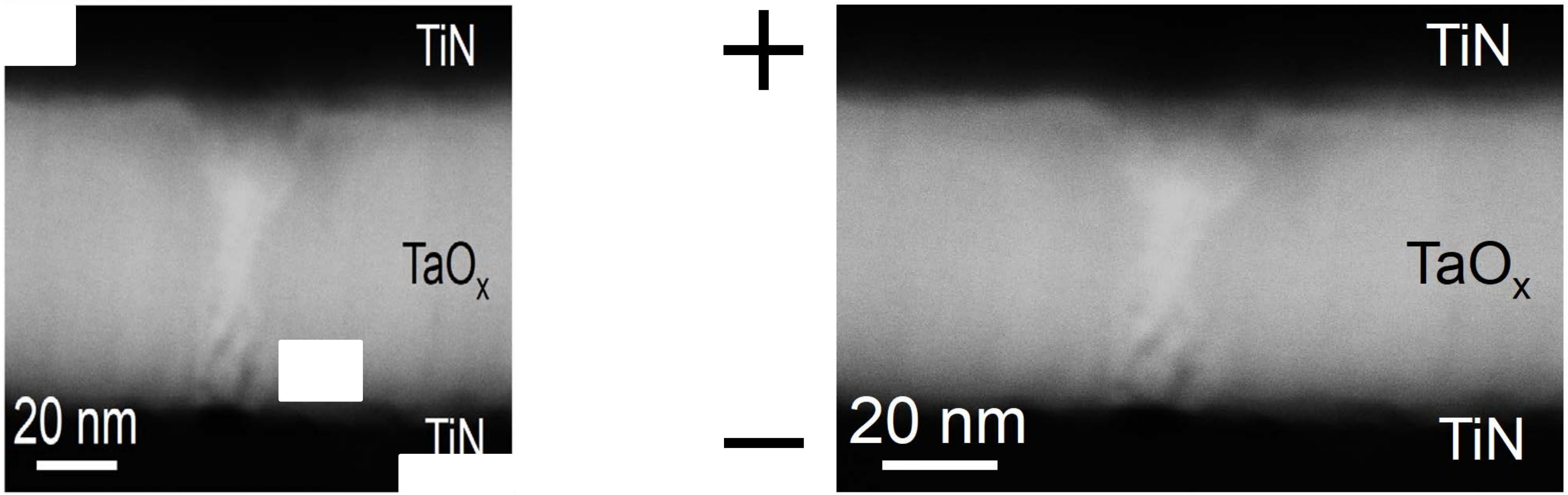




Bright field TEM cross-section of as-fabricated device

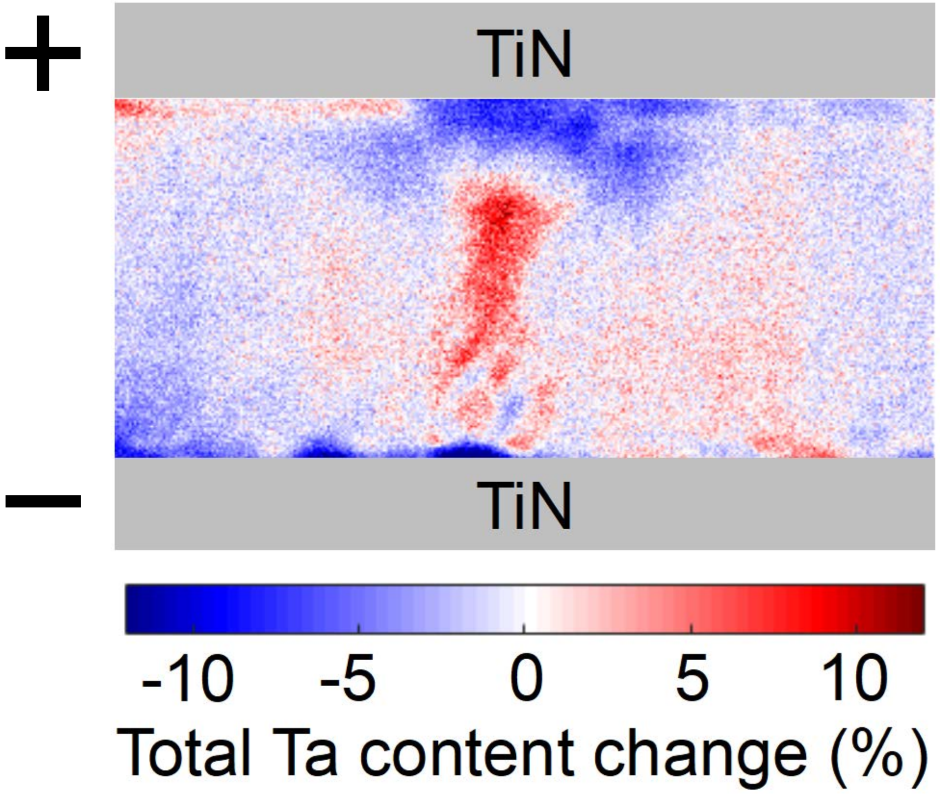


High Angle Annular Dark Field Imaging of Filament



Contrast in STEM HAADF corresponds only to total number of Ta ions in the beam path. Other ions in the device are too light to contribute.

How Does the Conducting Path Look Like?

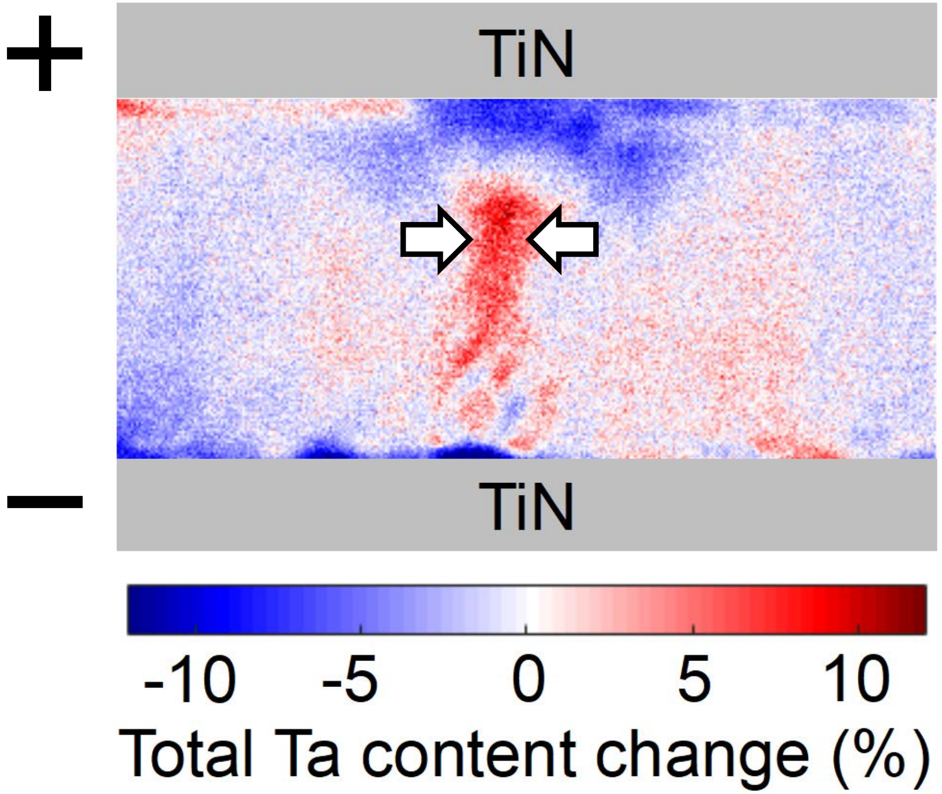


Ma et al. Adv. Electron. Mater. 1800954 (2019)

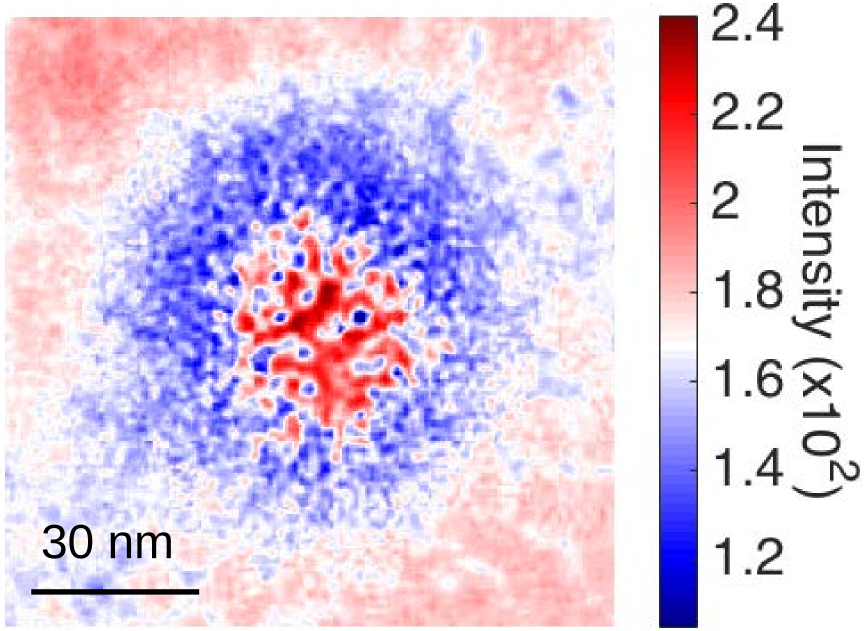
- *There is only one filament.*
- *It has the diameter of ~10 nm with local Ta density over twice the content in initial* TaO_2 *film.*
- *Filament has a gap of 10-15 nm wide located next to anode. Gap has composition of stoichiometric* Ta_2O_5*.*
- *Accumulation of Ta can be created only if Ta is moving.*

What is the Driving Force?

Cross-sectional view

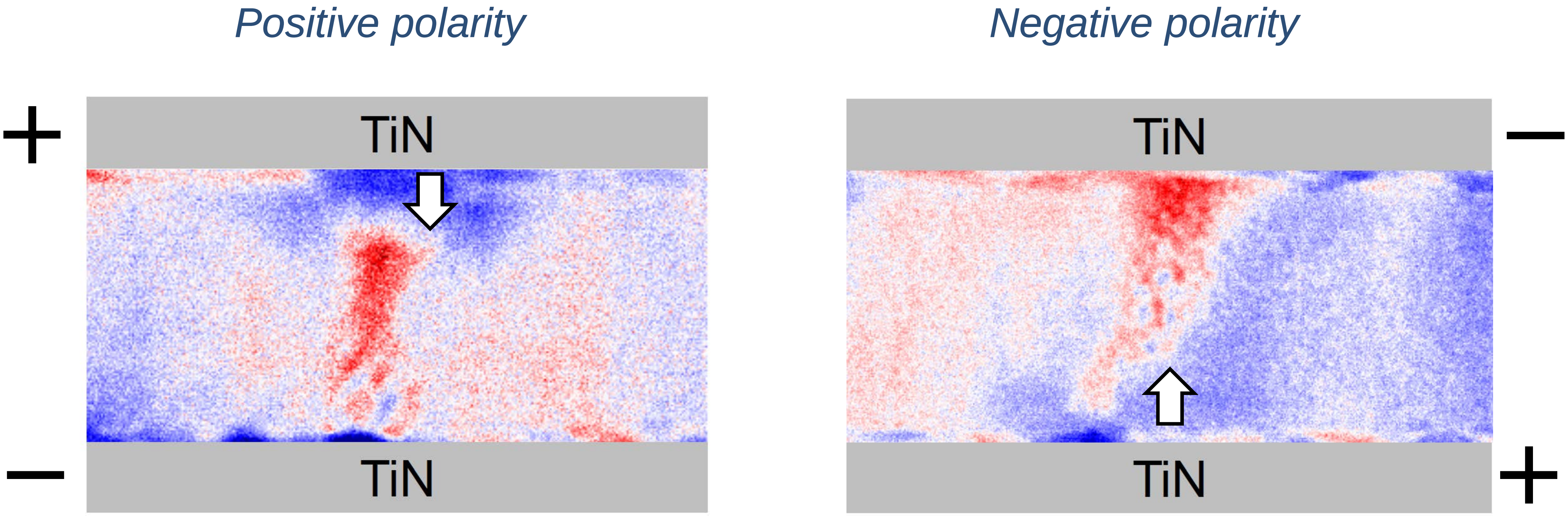


Plan view sample.



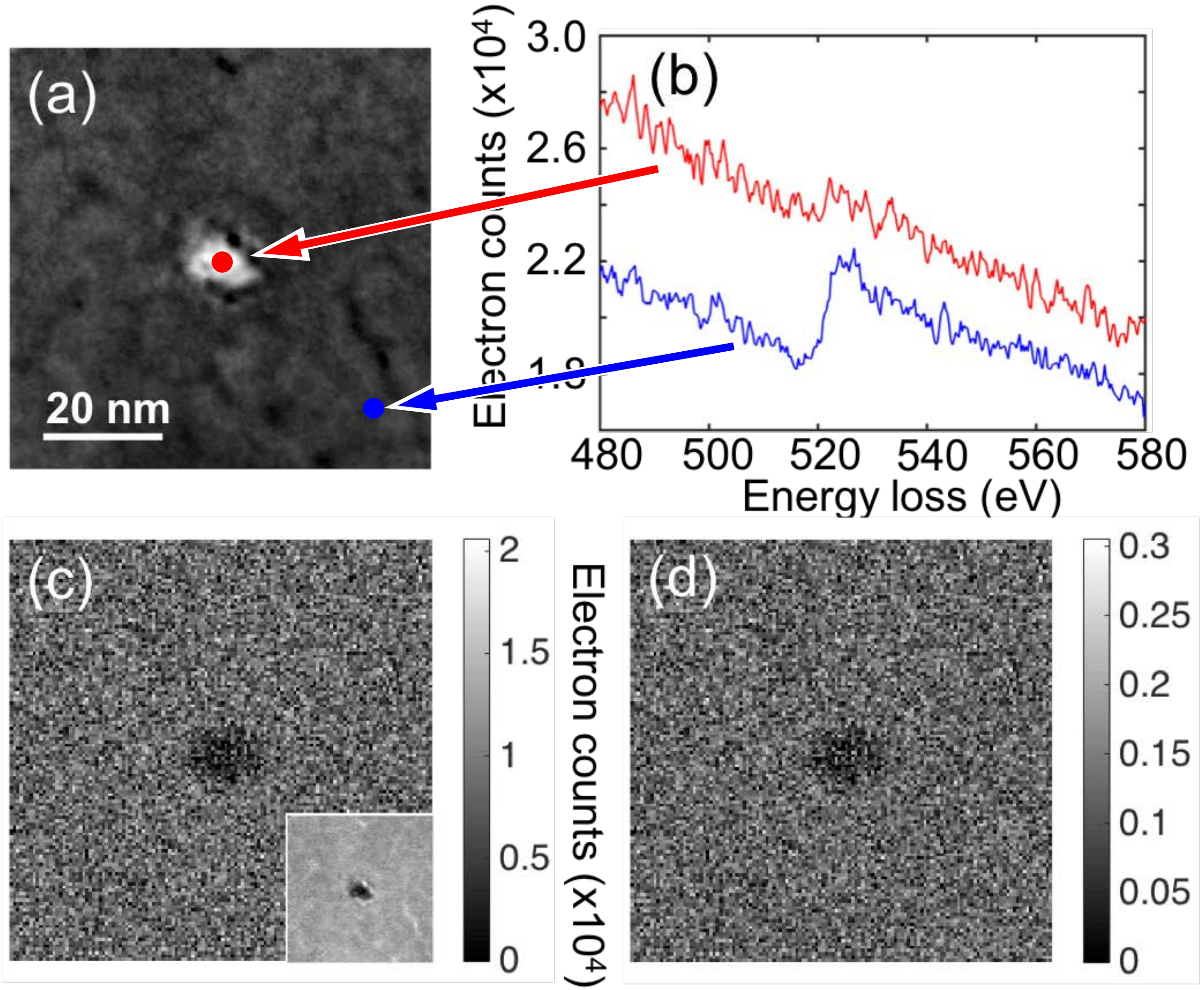
Depletion of Ta around the filament indicates lateral motion due to temperature gradient (thermodiffusion, thermophoresis, or Soret effect).

What is the Driving Force?



Ta ion also drift in the electric field as positively charged ions should.

Oxygen Distribution



HAADF

Electron Energy Loss Spectroscopy: O K-edge

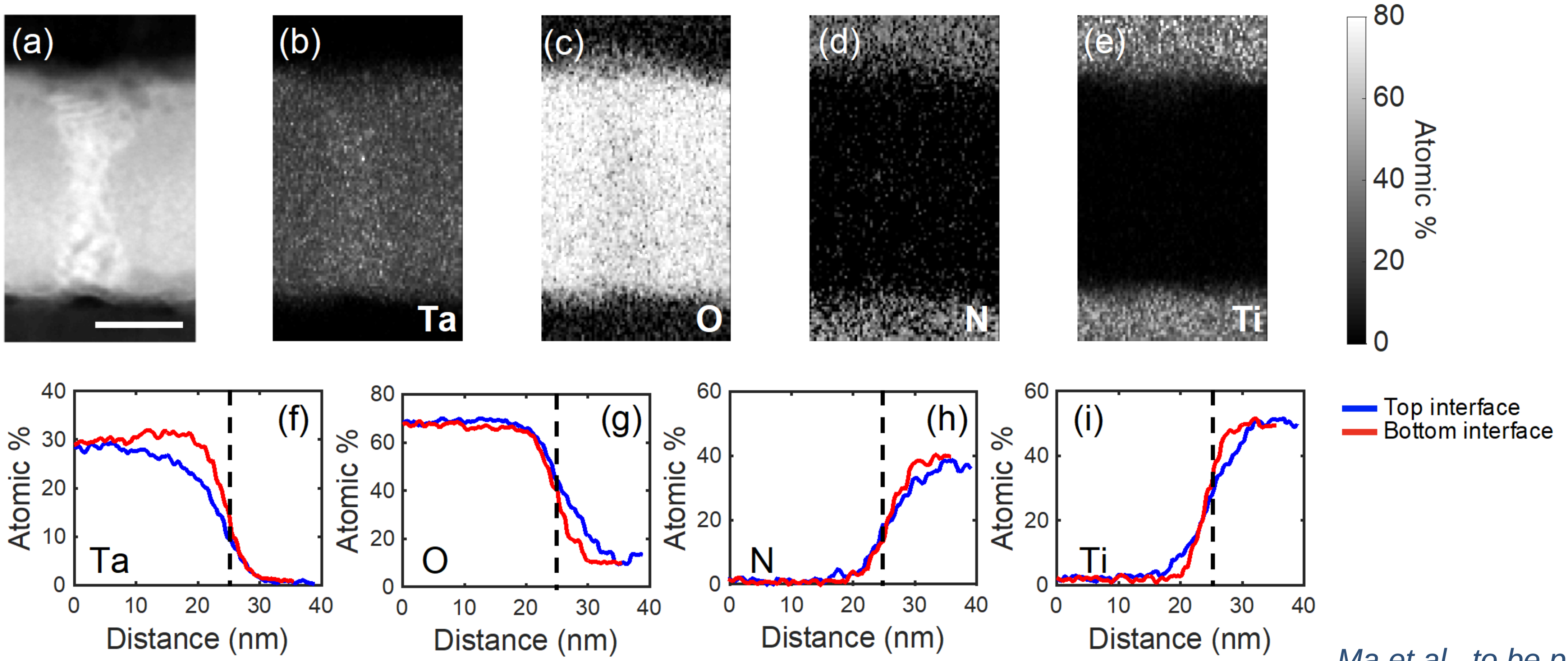
O K-edge intensity map

Corrected O K-edge intensity map

Ma et al. Adv. Electron. Mater. 1800954 (2019)

Filament (shown as bright area in HAADF) has lower O content than TaO_2 matrix. There is no sign of lateral motion.

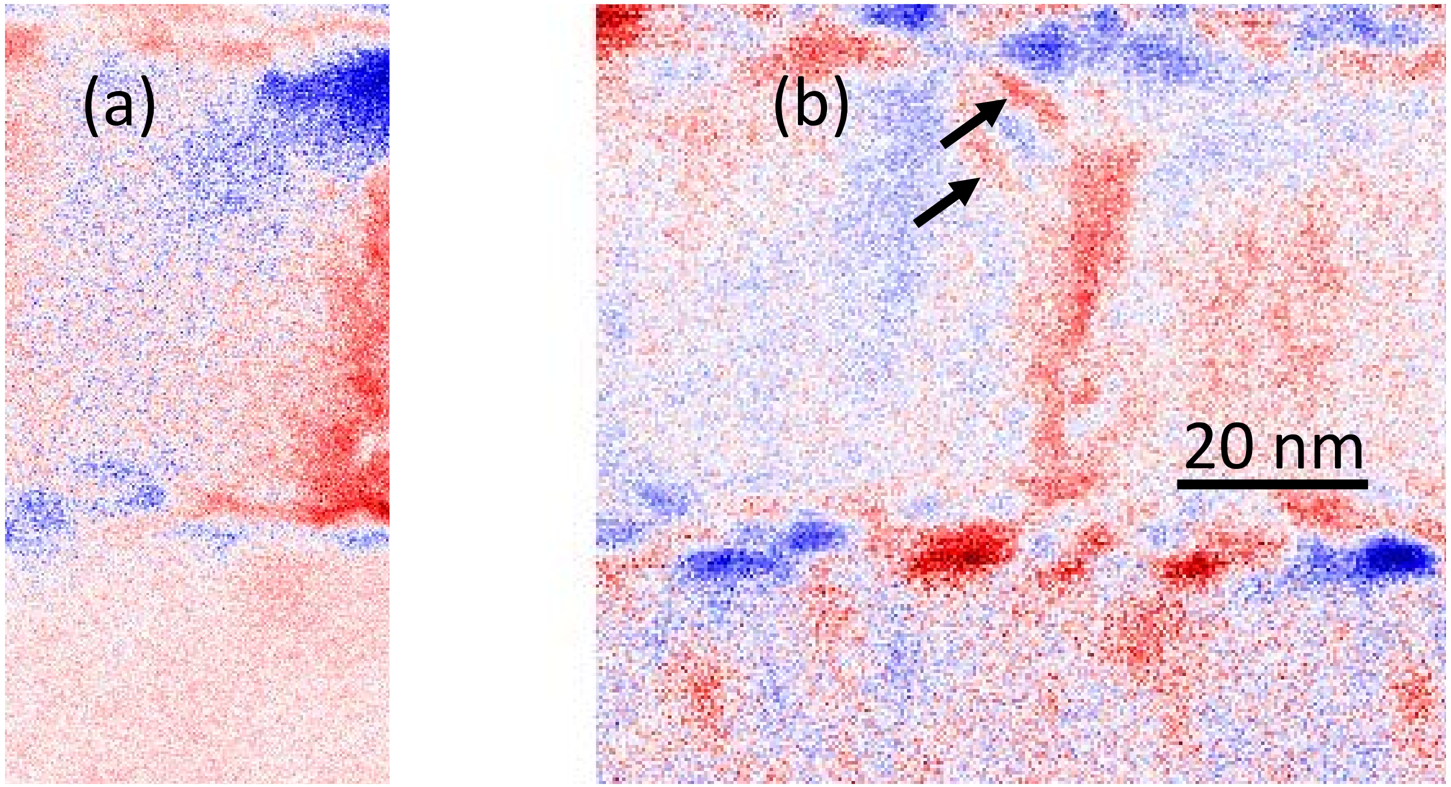
Inter-diffusion between TaO_x and TiN

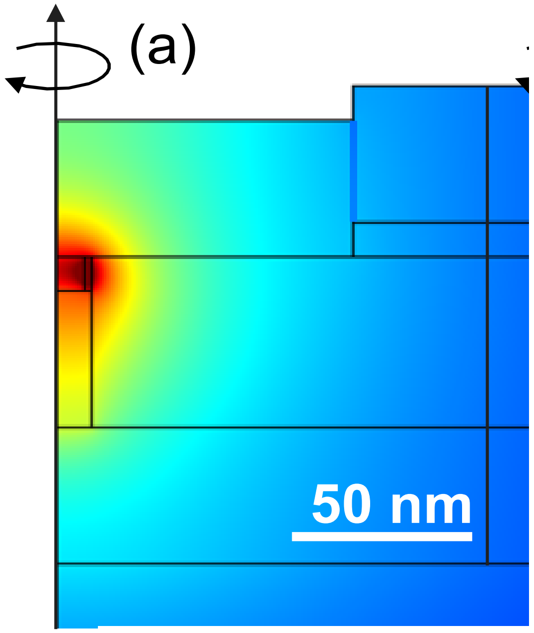


Ma et al., to be published

Elemental maps indicate oxygen presence in the TiN electrode above the filament. Ti and N content is lower at this location.

Switching in to LRS





Electro-formation creates a gap in the filament and the hot spot next to interface with anode.

Iontronics: Storing Information in Positions of Ions

Ions must be mobile
&
Temperature must be high
&
Devices must be small

⬇

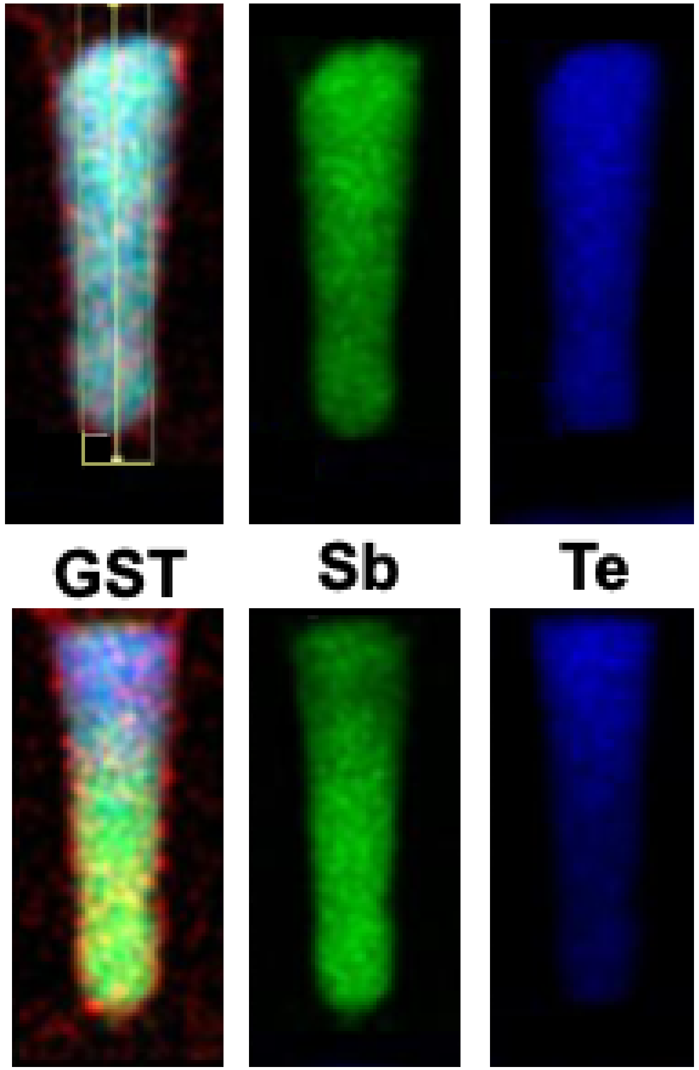
Current density is high

Temperature gradients are extremely high

⬇

Effects of electric field (field and carrier wind) are comparable to effects of temperature gradients.

We have only rudimentary understanding of these processes.



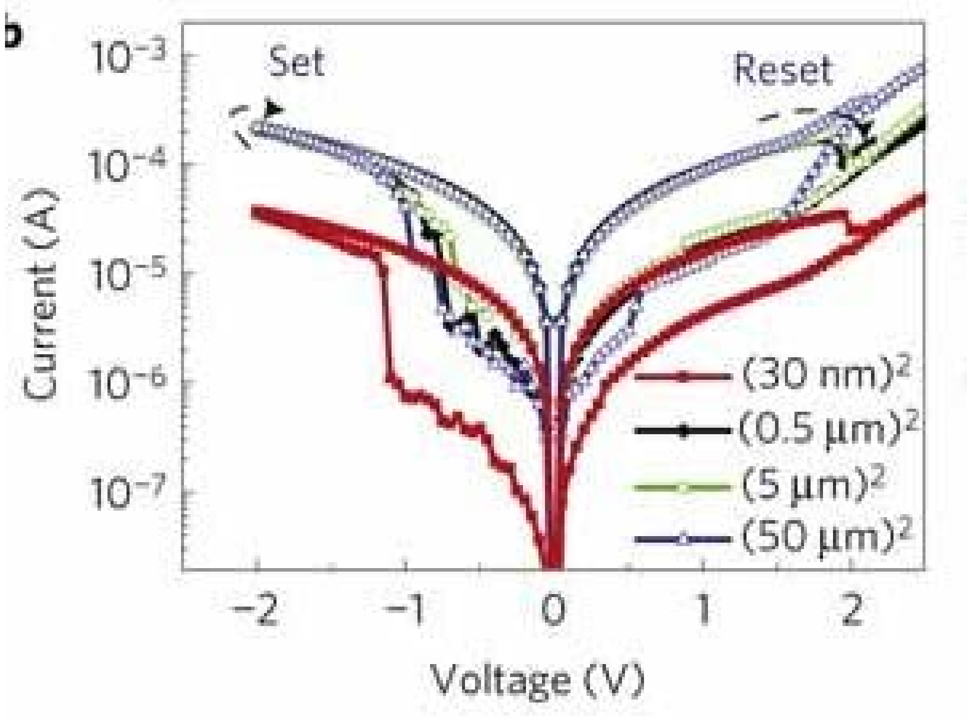
As-fabricated

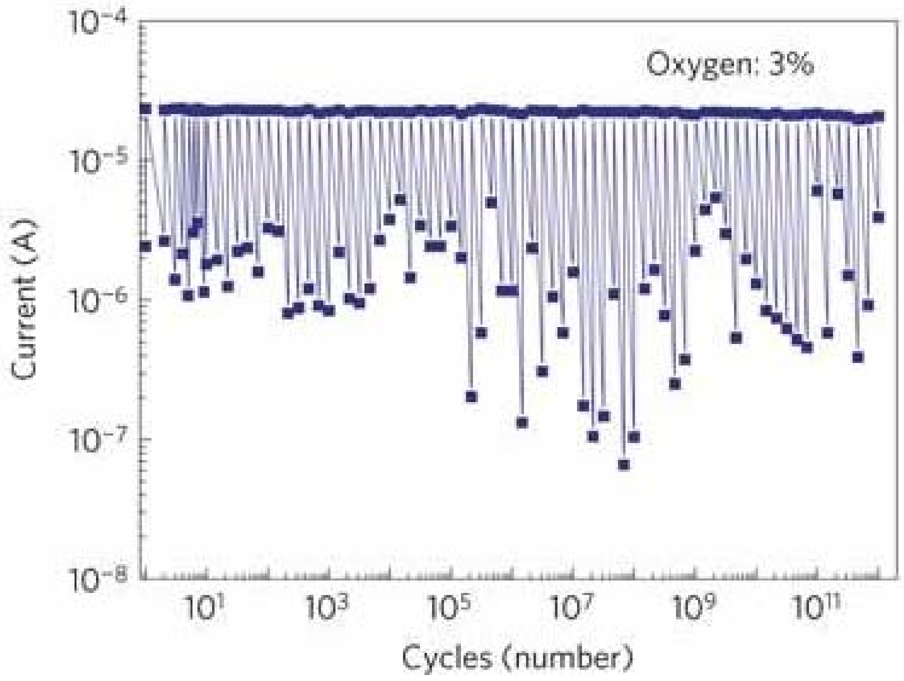
After 10 switching cycles

Kim et al. IEDM 2016

What Needs to Be Improved? Standard of Performance

Device: 30 nm Pt/Ta_2O_{5-x}/TaO_{2-x}/Pt/Ti/SiO_2/Si





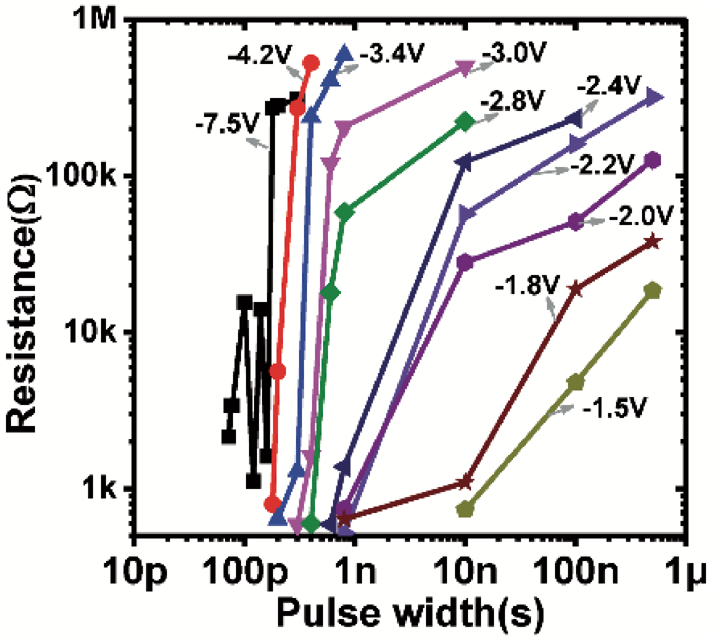
LRS resistance: $2x10^5$ Ohm, HRS resistance $1\text{-}5x10^6$ Ohm, switching voltage 1-2V, endurance 10^{11} for 500 nm device, switching speed 10 ns (at 6V), retention >10 years. No information on energy per switching cycle.

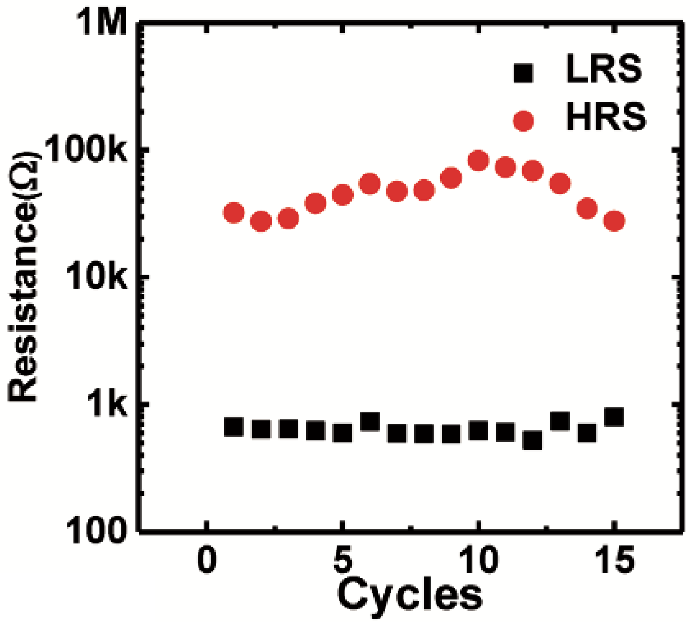
Lee et al., Nature Materials 10, 625 (2011)

Switching Speed

Shortest switching pulse reported: <100 ps

Choi et al. Adv. Funct. Mater. 16, 5290 (2016)





Wang et al. Adv. Electron. Mater. 3, 1700263 (2017)

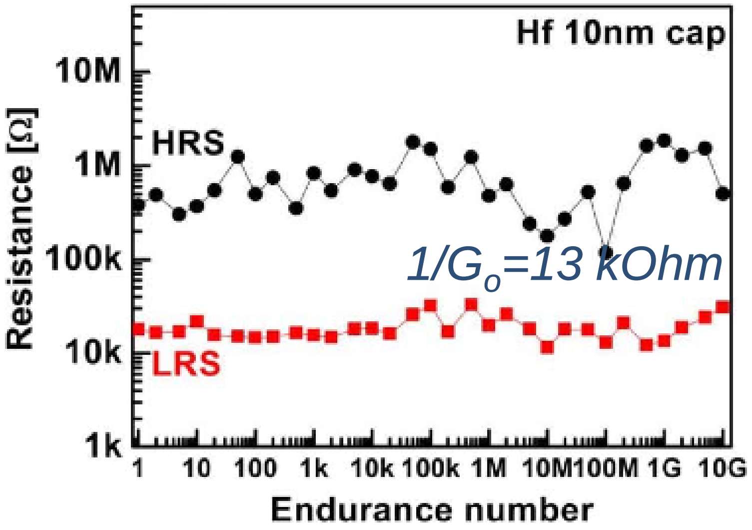
Leaves an open question whether one cans switch this fast devices with higher resistance and good endurance.

Increasing Resistance of LRS

Typical resistance values for LRS: 10^4, 5×10^3, 10^5, 2×10^4…

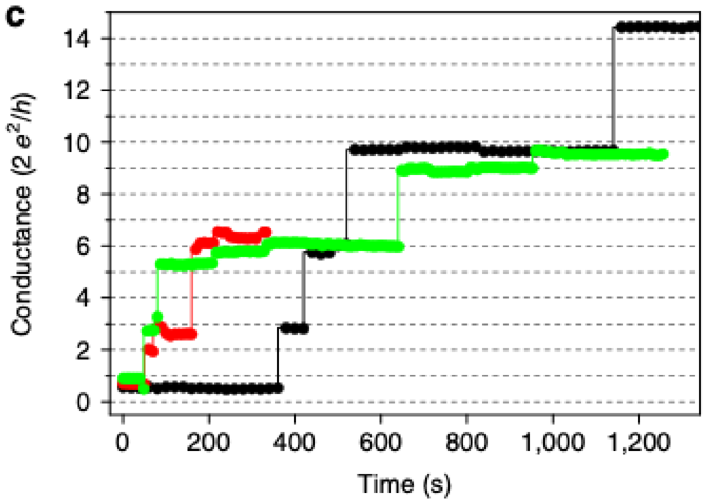
Needed: 10^7 Ohm (Gokmen and Vlasov, Front. Neurosci. 10, 333 (2016)),

10^5-10^6 Ohm (Islam et al., J. Phys. D: Appl. Phys. 52, 113001 (2019)

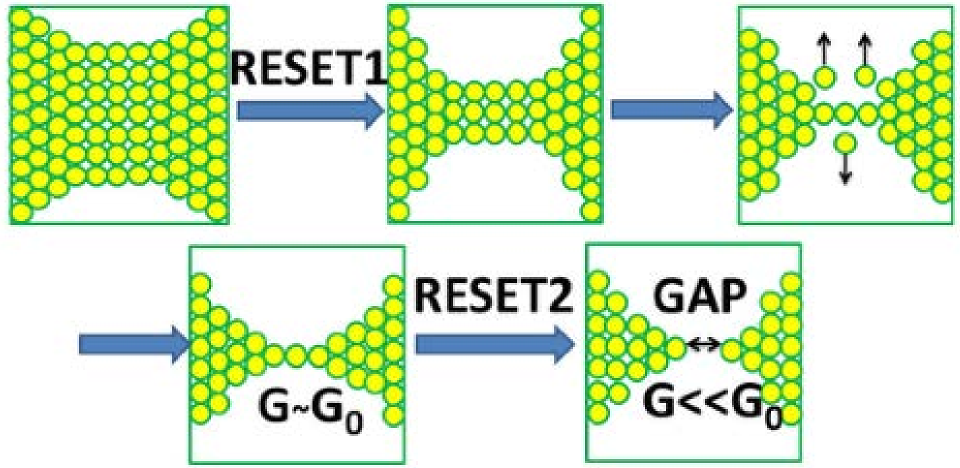


$1/G_o = 13$ kOhm

Chen et al. IEEE Trans. Electron Dev. 60, 1114 (2013)



Yi et al. Nature Communications 7, 11142 (2016)



Long et al. Appl. Phys. Lett. 102, 183505 (2013)

If the quantum point model is correct, it could be difficult to increase LRS resistance in a controlled way.

Endurance

Reported range od endurance: 10^6-10^{12}

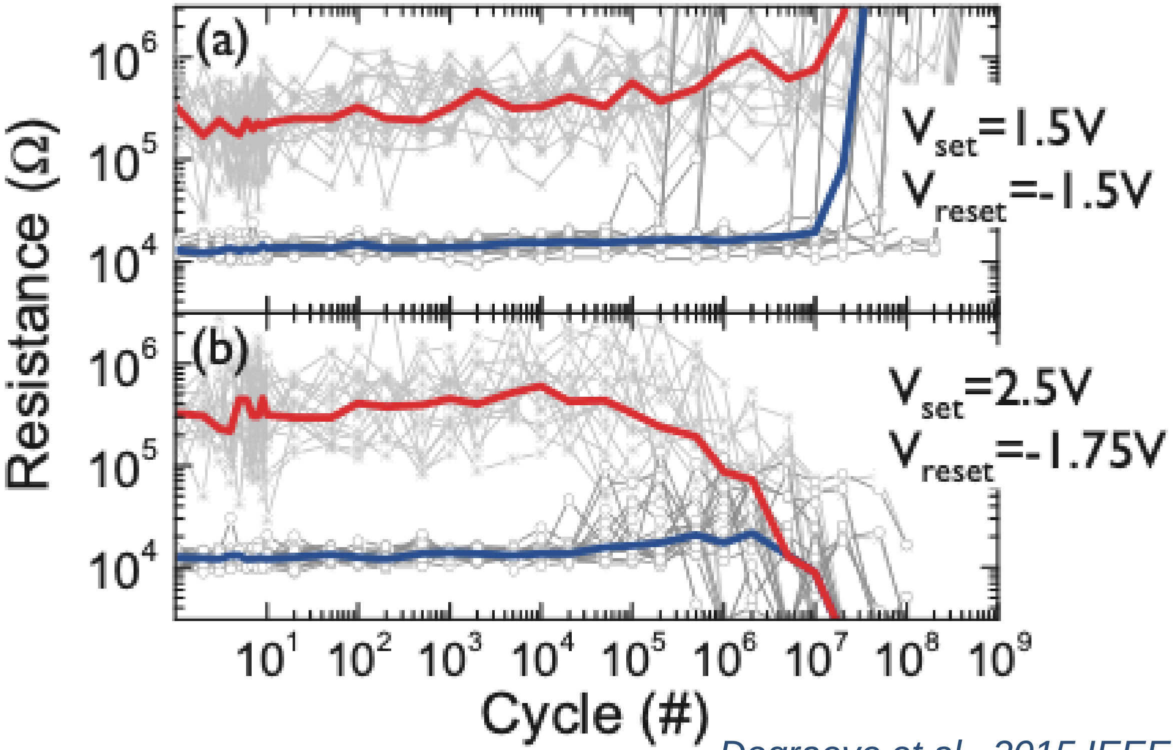
Lee et al., Nature Materials 10, 625 (2011)

Degraeve et al., 2015 IEEE VLSI

ITRS calls for 10^{12}-10^{14} for universal memory

Multiple mechanisms leading to failure:

(i) stuck-on-LRS
(ii) stuck-on-HRS
(iii) closing of LRS/HRS window

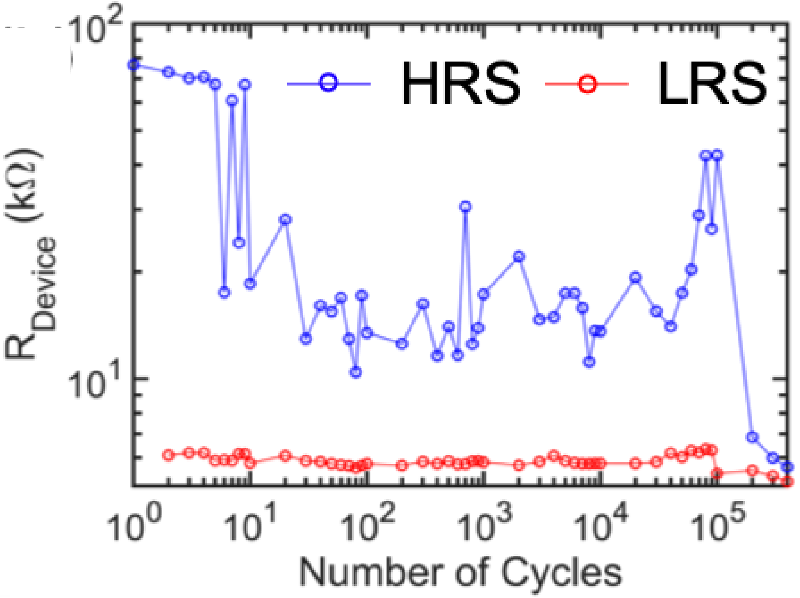


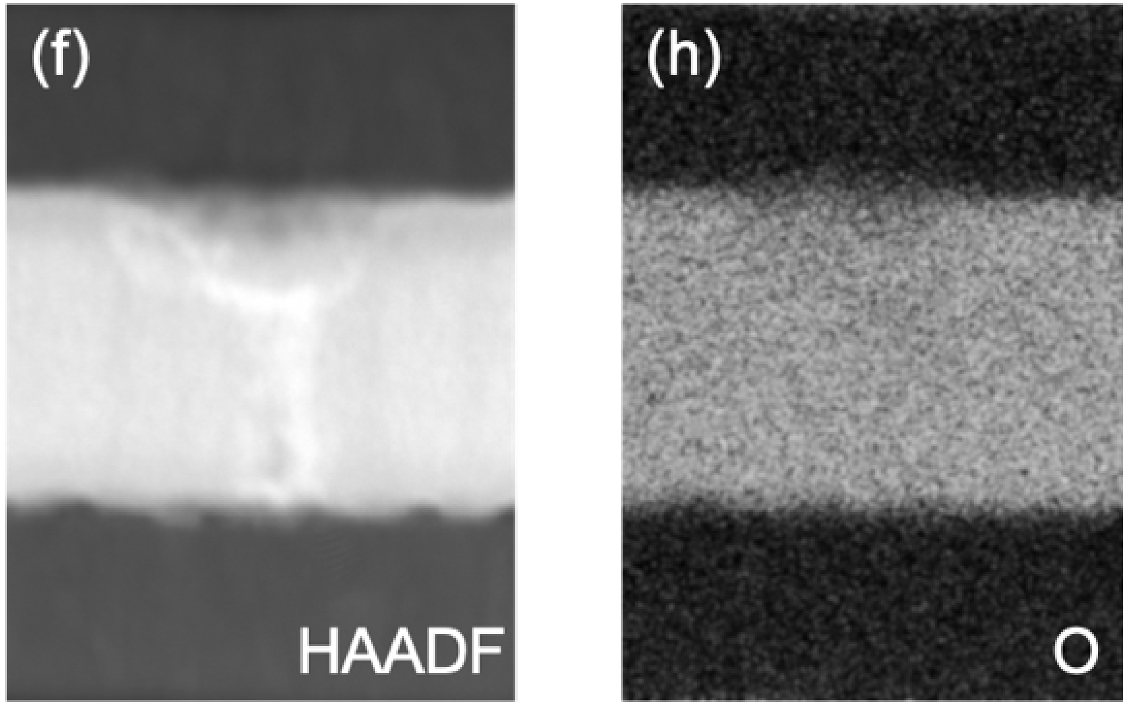
Degraeve et al., 2015 IEEE VLSI

Multiple failure mechanisms can operate in nominally identical devices.

Stuck-on-LRS Failure

Gradually increasing conductance of LRS is interpreted as increasingly “strong” and / or wide filament. Suggested as due to continued loss of oxygen to electrodes.

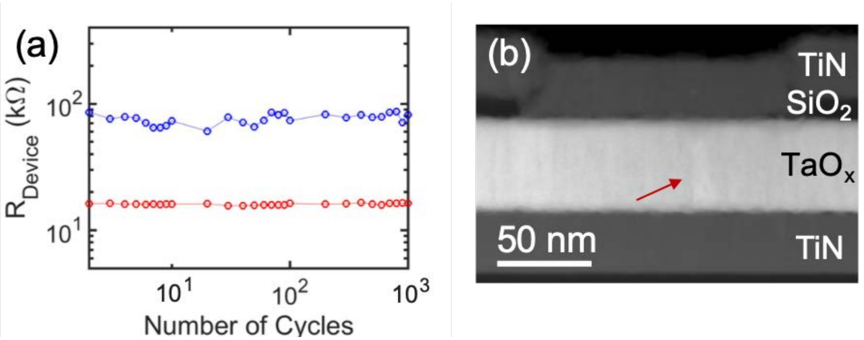


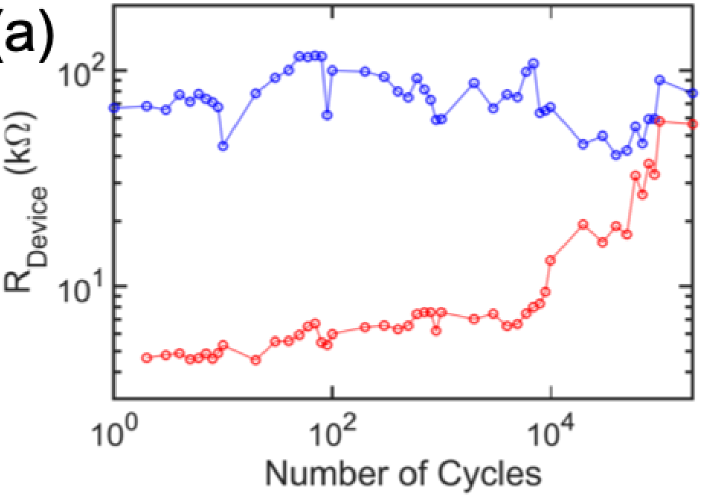


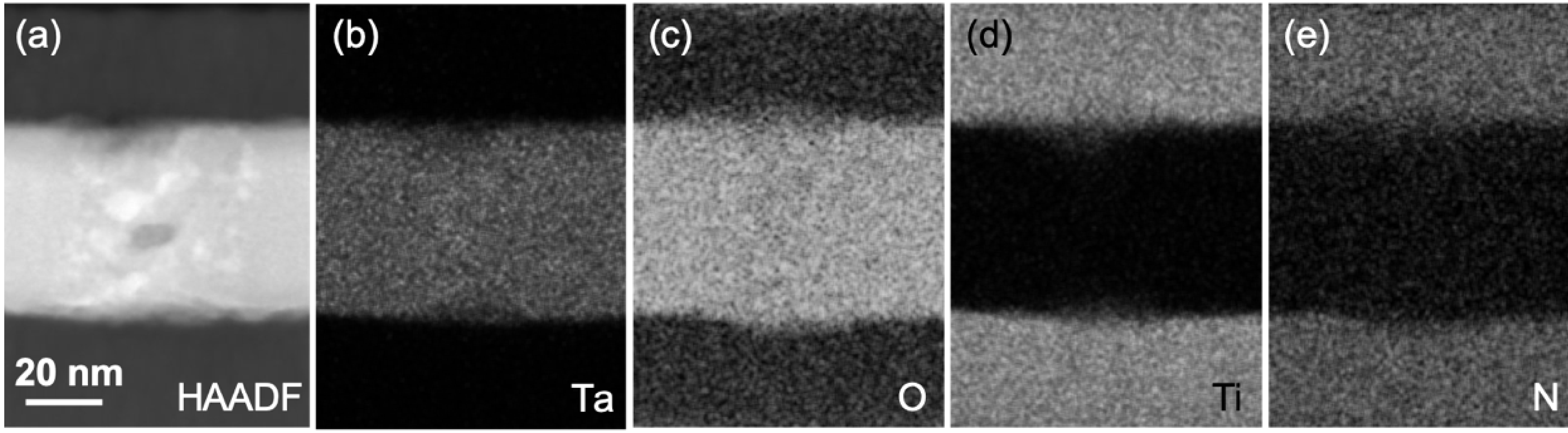
There is no apparent increase of oxygen content in the electrodes.

Ma et al. to be published

Stuck-on-HRS Failure







The filament in failed device has higher diameter but is not continuous. Could be the result of phase separation in Ta-O system. No obvious way forward.

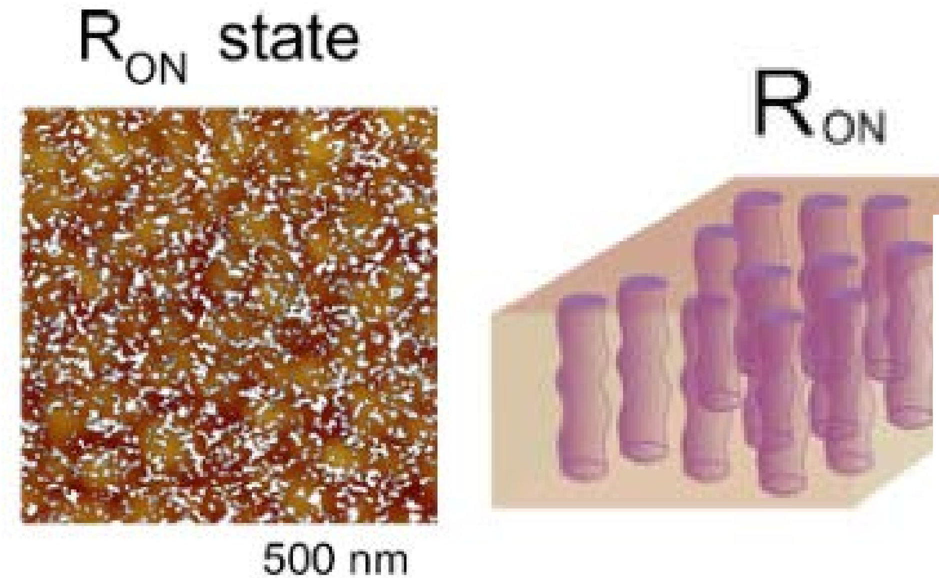
Conclusions

Resistive switching processes are more complex than initially assumed and are highly nonlinear. Understanding of many processes is still inadequate.

Most research projects focus on one property at the time.

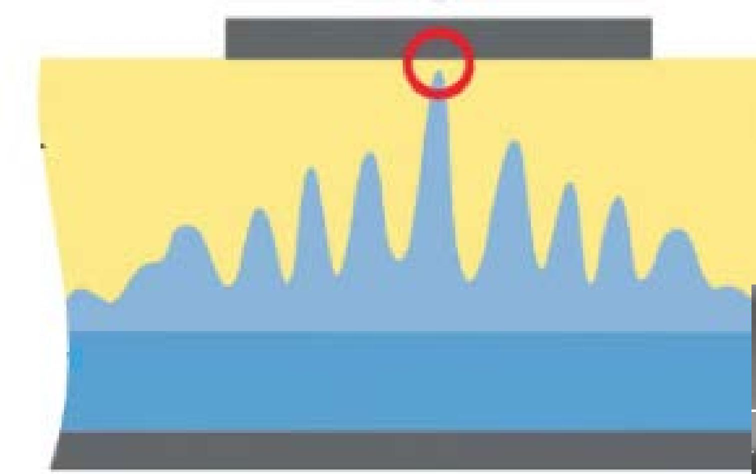
There are no clear benchmarks for materials and devices as the concepts for applications are rapidly evolving .

Is There One Filament or Many?



5x10^{11} cm^{-2} filaments

Wu et al. Appl. Phys. Lett. 104, 242906 (2014)



many partial filaments

Waser et al. Adv. Mater. 21, 2632 (2009)

one filament

Ma et al., Adv. Electron. Mater. 1800954 (2019)