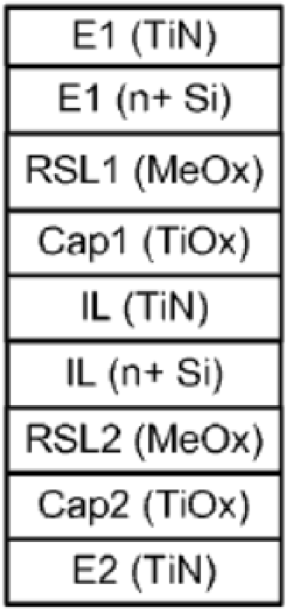
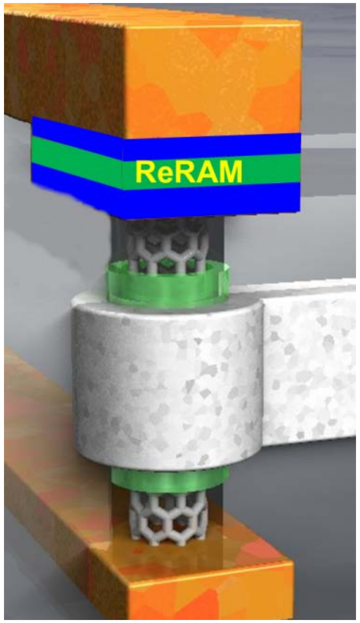
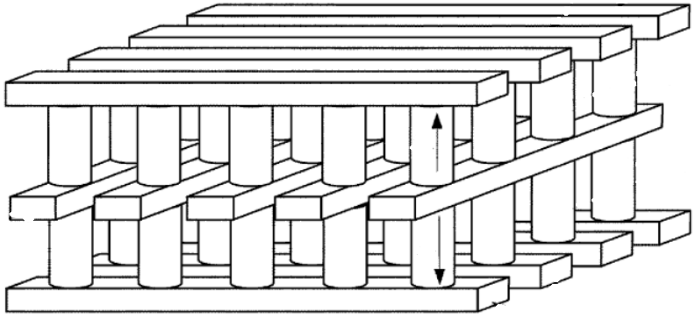
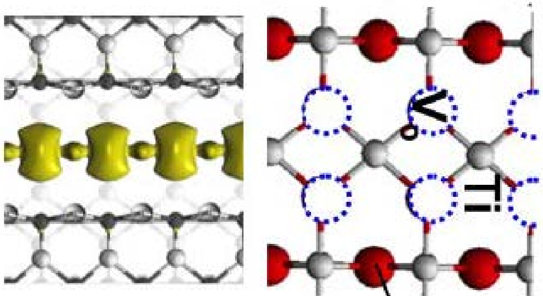
Material and design aspects of ReRAM technology



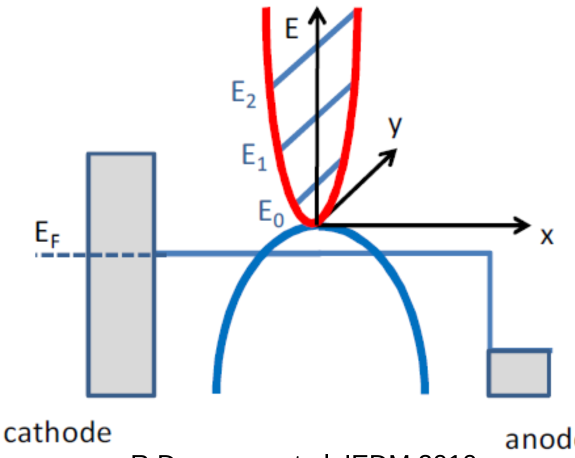
Kreupl et al., US 2011/0310654 A1



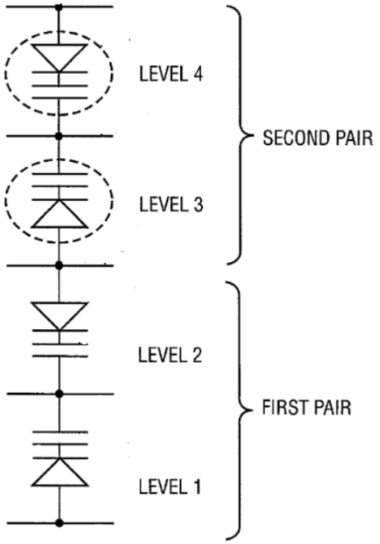




Kamyia et al. IEDM 2012



R Degraeve et al. IEDM 2010

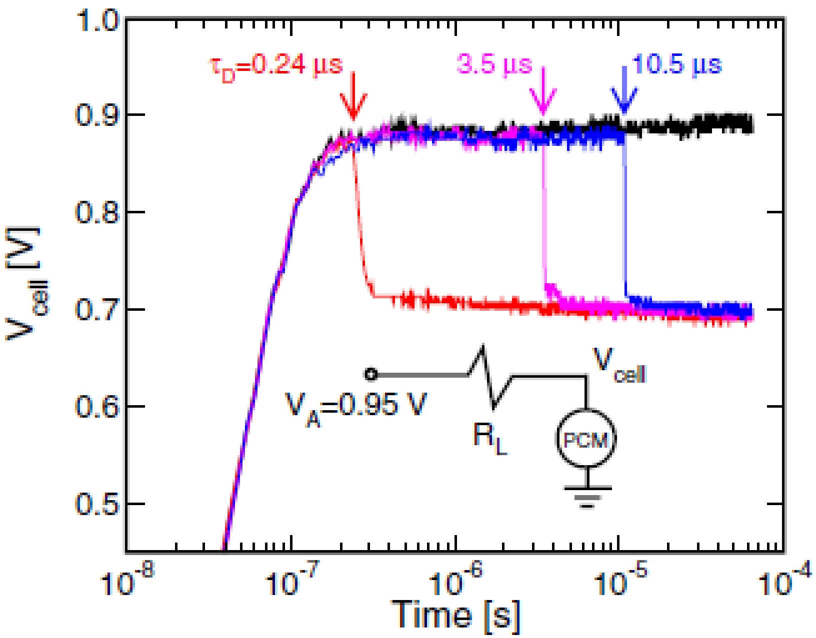


Outline

- ❑ ReRAM memory technologies (why there is no Memristor)
- ❑ The cell and its electromagnetic environment
- ❑ DC-I(V) sweeps don't tell you the truth (dynamic currents)
- ❑ Understanding current overshoot
- ❑ Where is the resistor in the cell?
- ❑ How to operate at low currents?
- ❑ In-cell resistor
- ❑ Contact resistor
- ❑ Active Feedback Cell (AFC)
- ❑ Summary

ReRAM Memory Technologies - why there is no Memristor -

❑ PCRAM, CBRAM, ReRAM (MeOx) are threshold switches

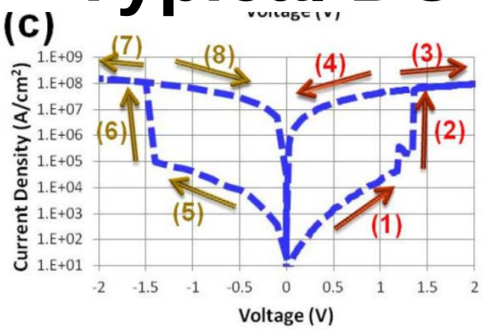


Lacaita et al, IEDM 08

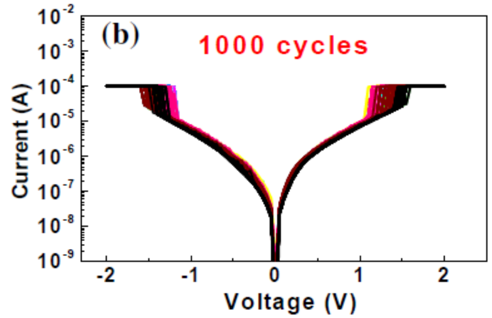
$$I_{Cell} = \frac{V_{appl} - V_{Cell}}{R_{Bitline}} - C\frac{dV_{Cell}}{dt}$$

- close to $V_{Threshold}$ it can take very long, so you need to operate at $V_{appl} > V_{Threshold}$
- This makes dV_{cell}/dt big, as time dt is ~ 100 ps

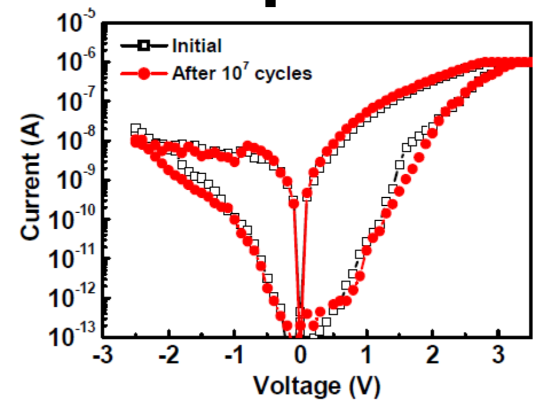
Typical DC I(V) showing low current operation



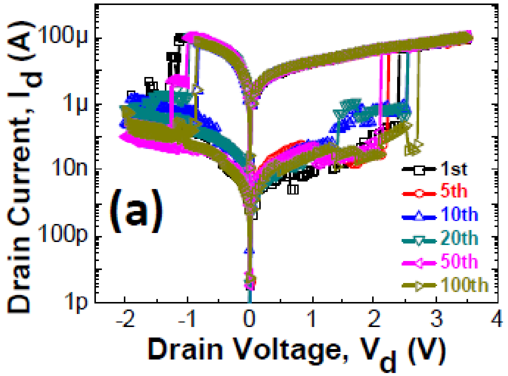
ChiaHua Hoet et al. IEDM 2012



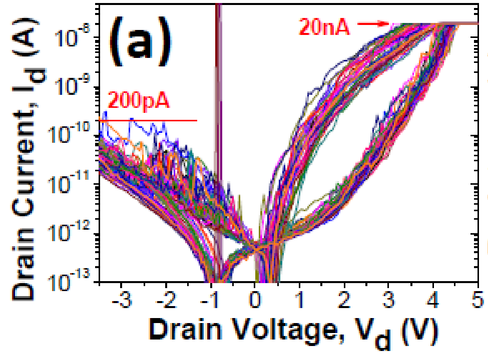
Myoung-Jae Lee et al. IEDM 2012



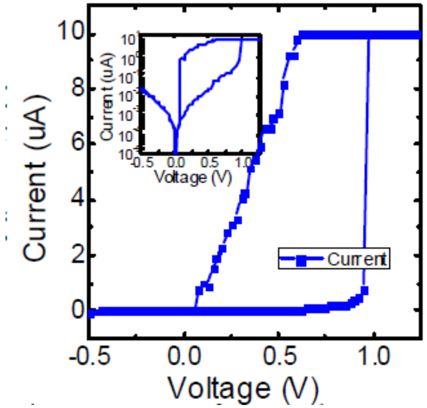
Seong-Geon Park et al. IEDM 2012



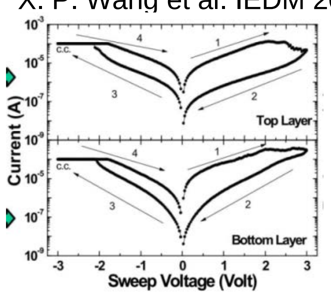
X. P. Wang et al. IEDM 2012



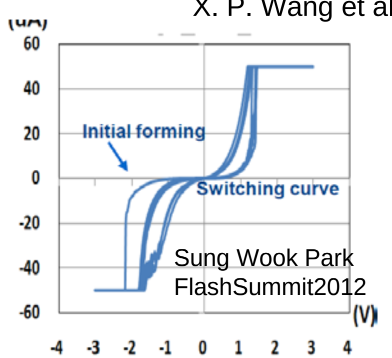
X. P. Wang et al. IEDM 2012



F.M. Lee et al. l VLSI 2012



W.C. Chien et al VLSI 2012

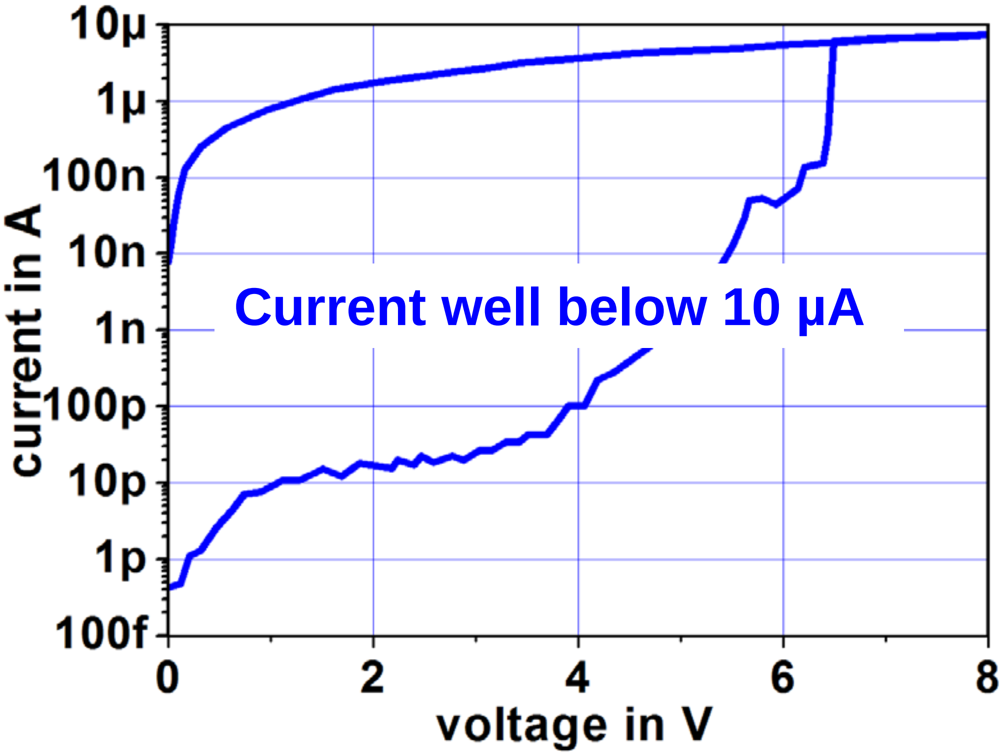


Sung Wook Park
FlashSummit2012

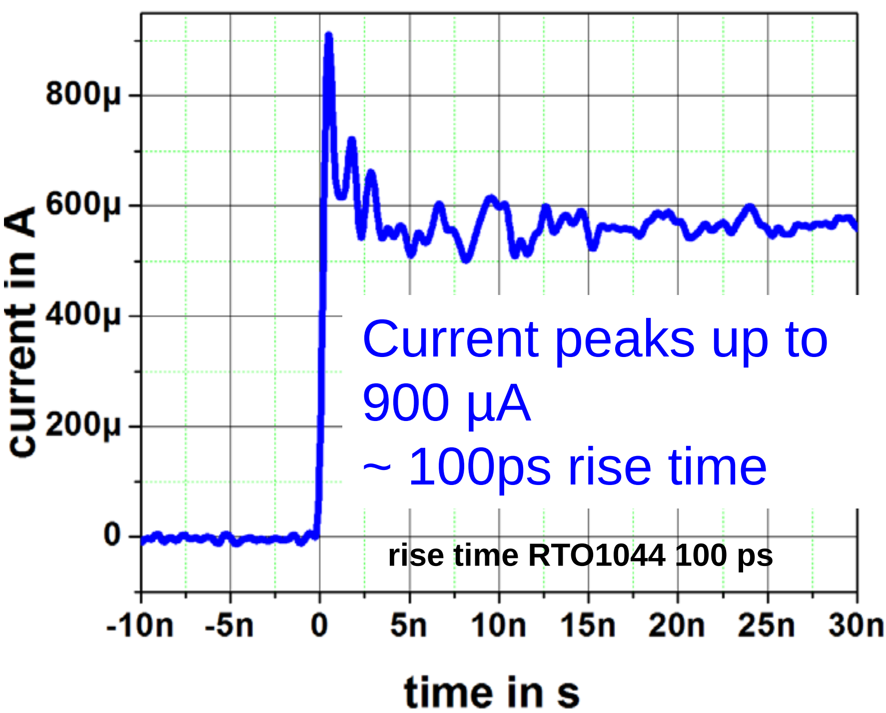
Is this low current true?
Depends on measurement setup!

Dynamic currents will be much higher

This is what SMU reads



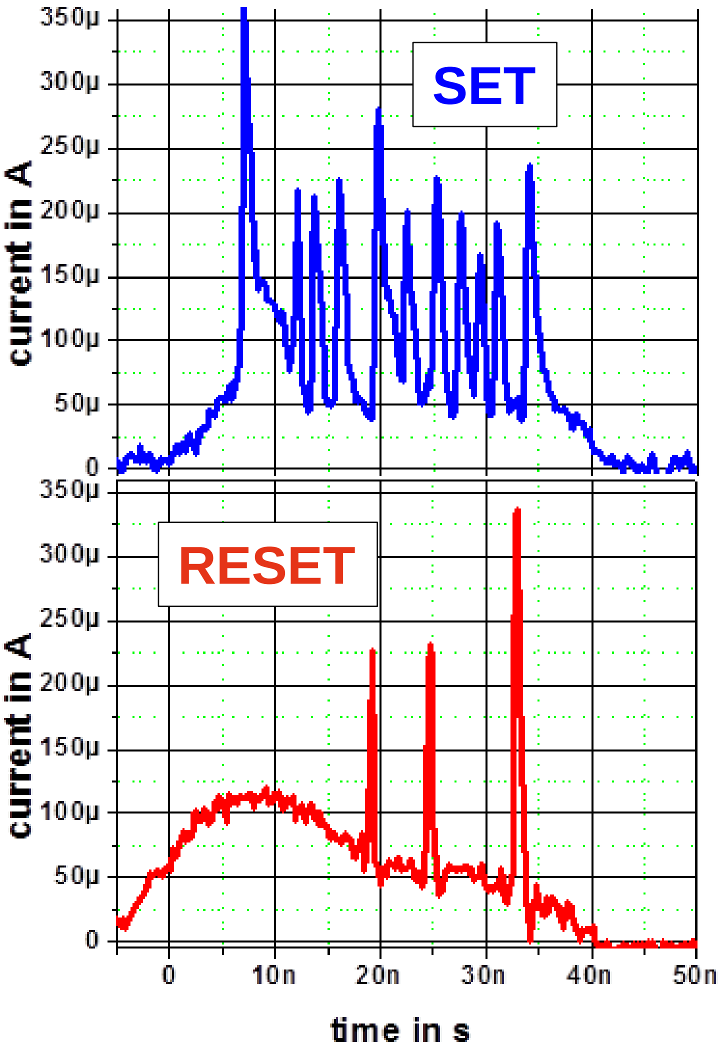
This is what goes thru the cell



Most published data give I(V) sweeps as evidence for low current.

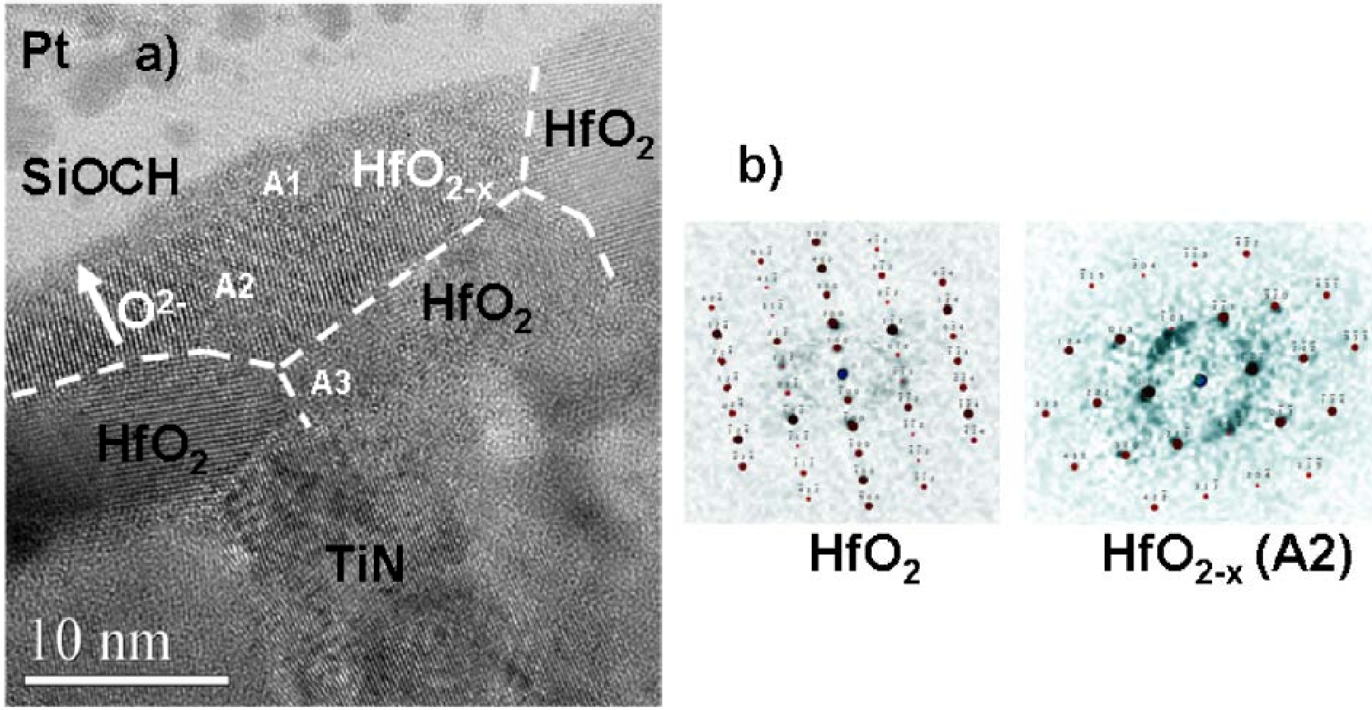
I(V) sweeps don't tell too much about the dynamic currents!

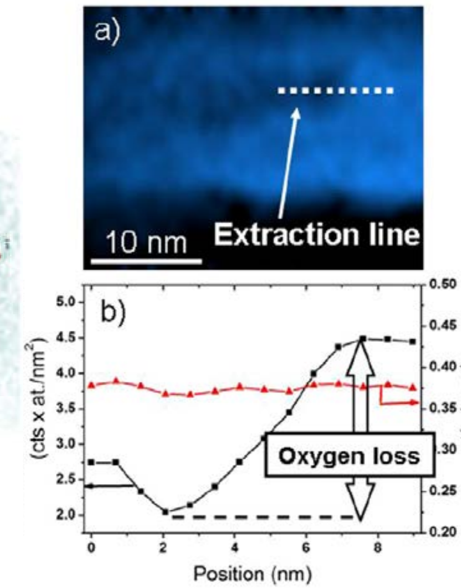
Dynamic currents in pulse mode



- High current peaks from capacitance
- The filamentary nature gives very high local temperature – current density!
- $T_{filament} = T_0 + j^2 \rho / C$ for t < 1 ns
- $T_{filament} = T_0 + j^2 \rho \frac{L^2}{8Ck_{th}}$ for t > 1 ns
- High T creates phase transformation, alloying, diffusion, electromigration etc.
- Key question:
  Will the material/cell switch at all if cap-discharge is neglectable
  – as in 1x nodes?
  Will it be stable?

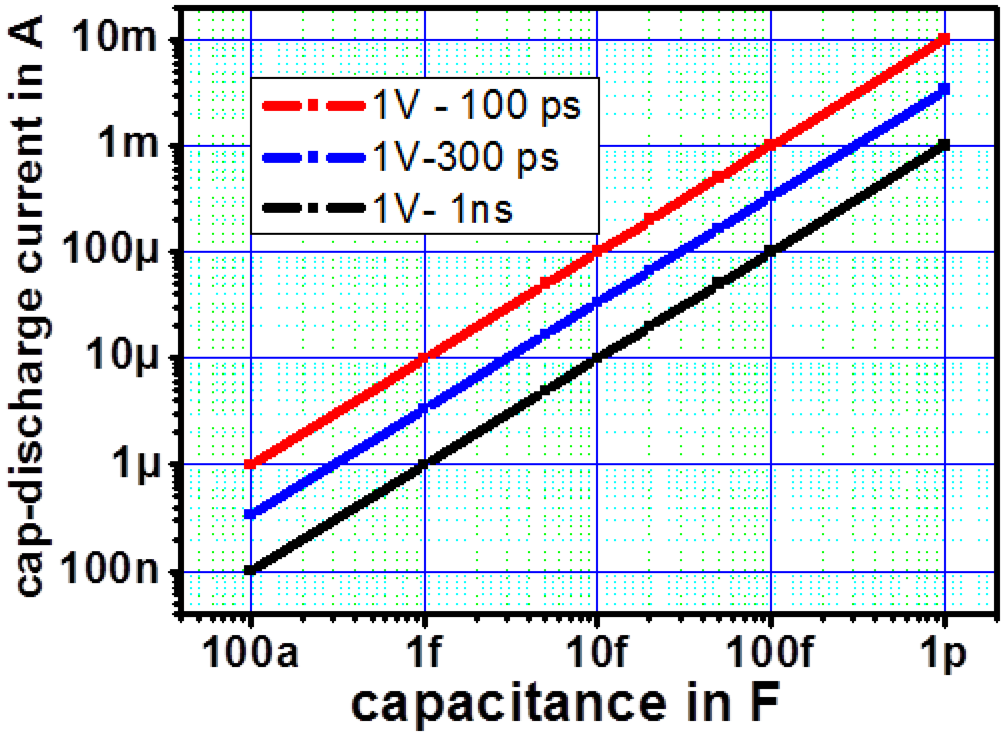
Amorphization and O-loss attributed to high current density





- ❑ Extensive analysis of nanofilaments in HfO2 by Calka et al. (2013) shows:
  - ❑ High T creates amorphization, diffusion and movement of oxygen
  - ❑ Accumulation of oxygen at the Pt anode
  - ❑ Crystallization of the TiN bottom electrode
- ❑ Will this mechanism work if current is reduced ?

Typical cap-discharge current

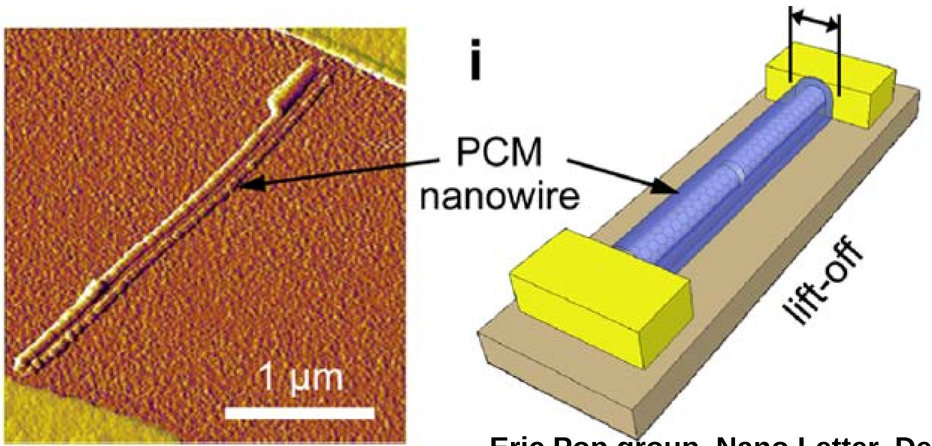


- Speed is within rise time of the scopes
- Relevant capacitance is within a sphere of $r = t^*v_{prop.}$ <100ps*$v_{prop.}$ (Wahlgren – horizon picture)

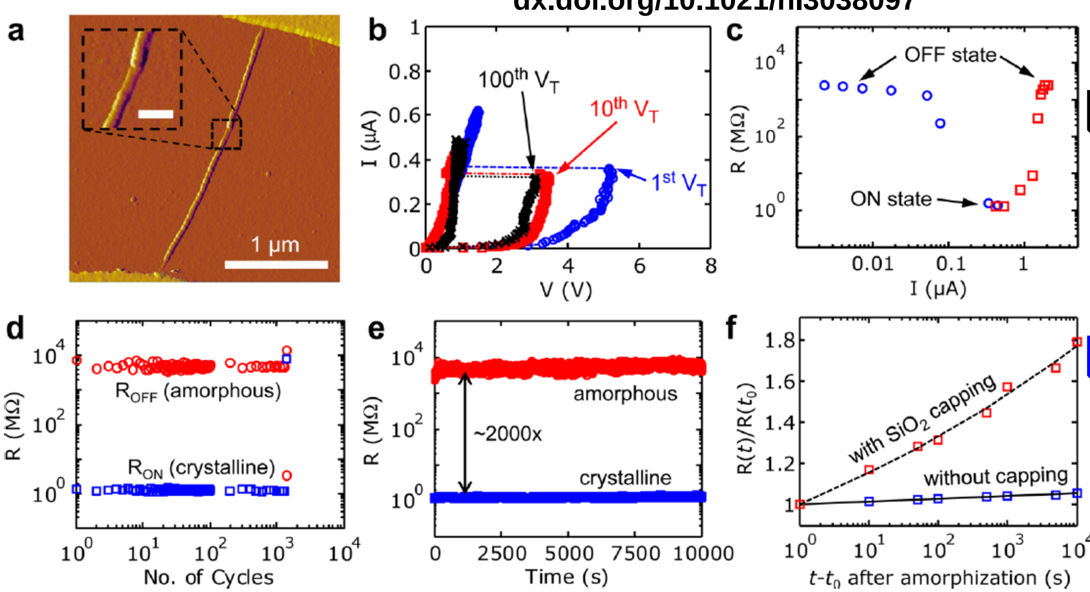
- My experience: cell R_{ON} is defined by first (forming) C*dV/dt
- That's the reason why most data have the same low R_{ON}, (<~ 20 kOhm) independent of the used material or stack

M. Terai et al., EDL 2010

0.1 µA set, ~1.6 µA reset by capacitance reduction

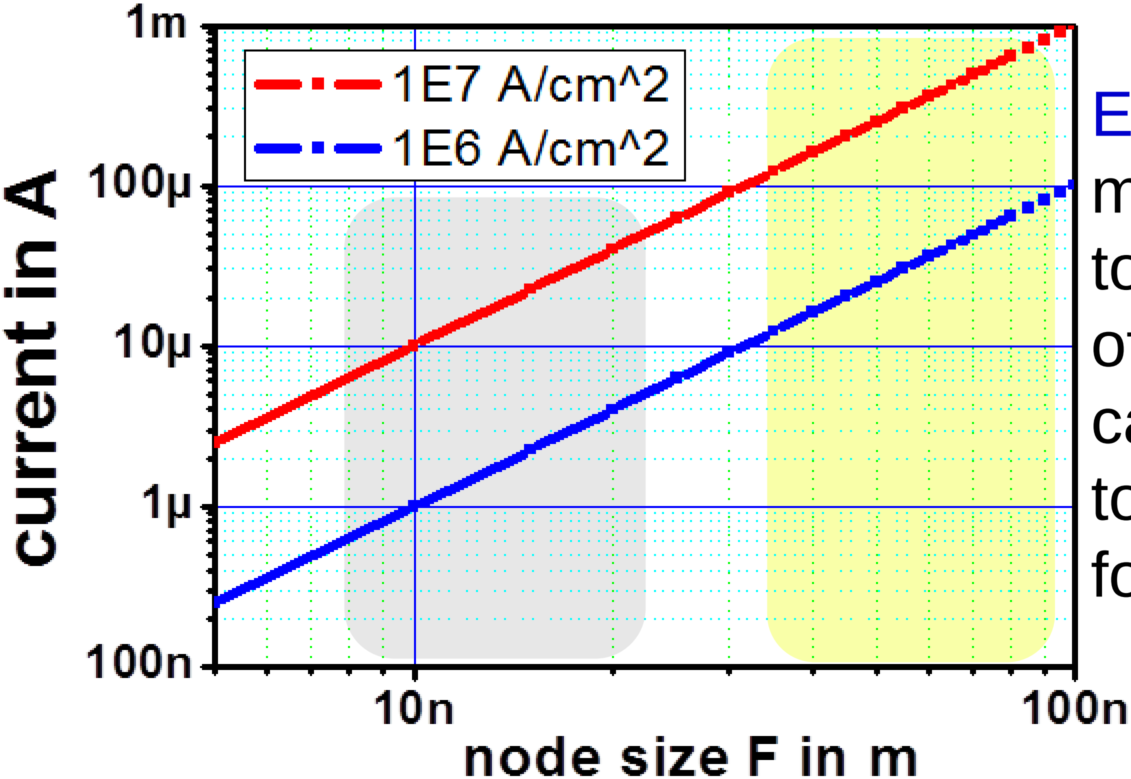


Eric Pop group, Nano Letter, Dec. 2012
dx.doi.org/10.1021/nl3038097



- ❑ Local capacitance reduction by using CNT contacts
- ❑ The resistance of the CNT (contact and quantum) shields the external capacitance
- ❑ The small contact area gives very small local capacitance
- ❑ Low current switching possible in a threshold-voltage controlled cell

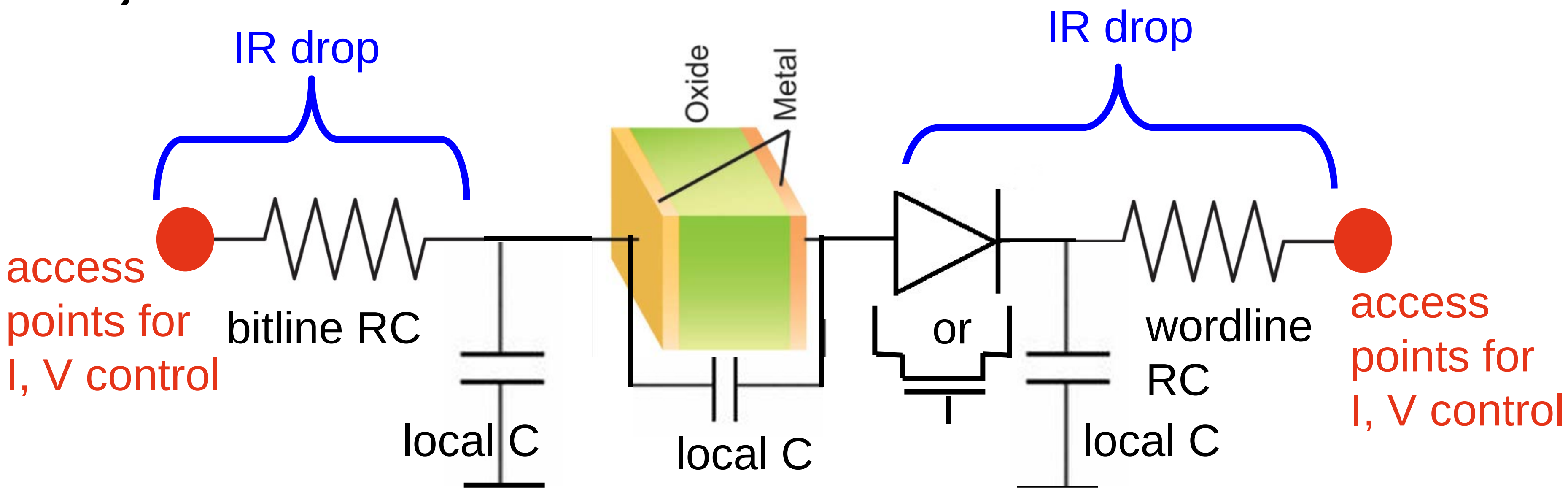
Typical currents and related current densities



E-field driven ion movement needs to flow the same amount of current like in the cap discharge event, to create the same field for bipolar reset.

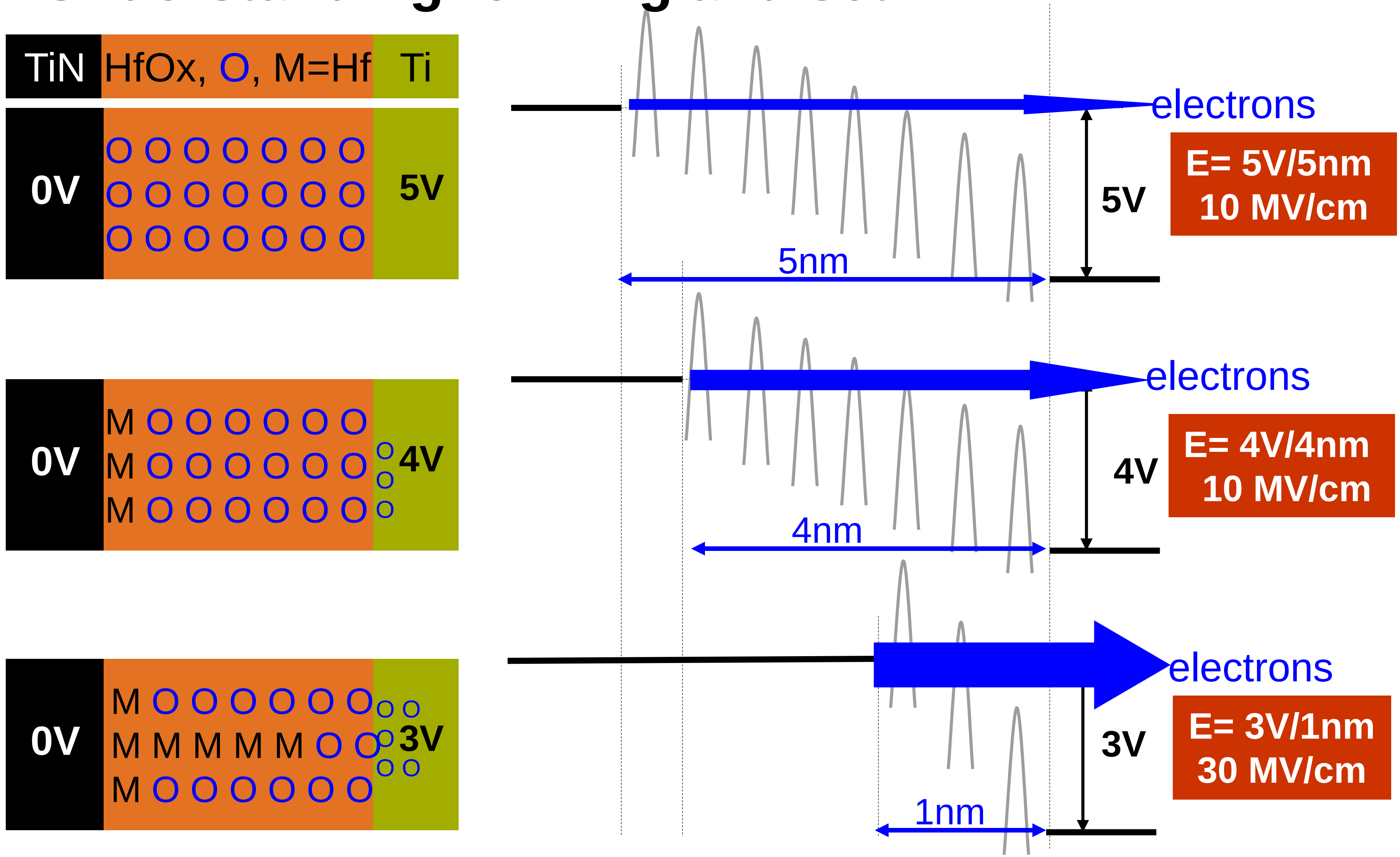
- At advanced nodes, current density is close to the reliability limit of most conductors and devices
- By $j^2\rho$, huge temperatures are induced, pulses should be as short as possible to limit this energy imprint

Bit-, word-line and device can't limit C-current



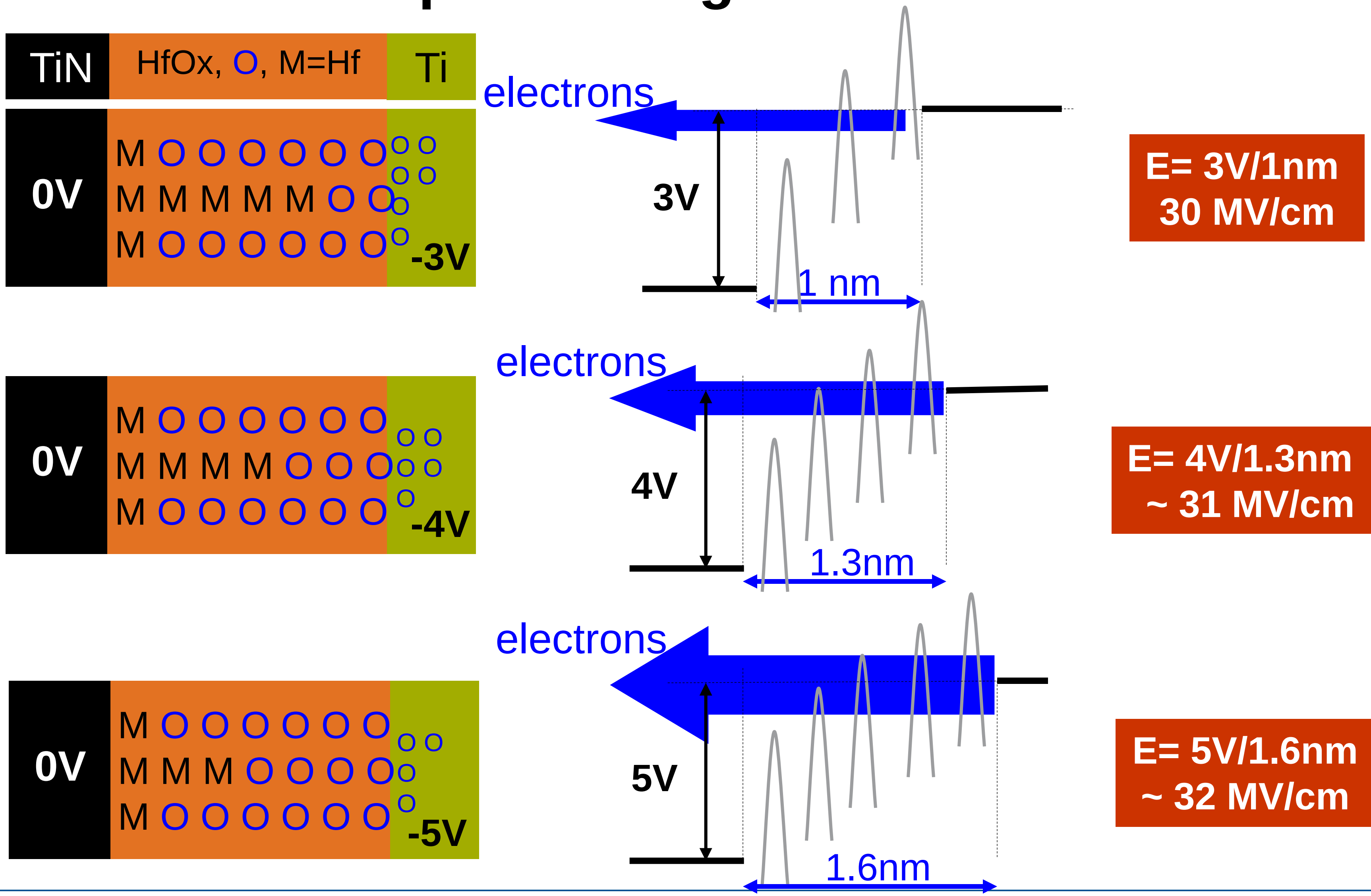
- Diode/FET or bit/word-line can only shield on long time scales
- Overall capacitive discharge is given by local capacitance which scales with (isolated) feature size
- Transistor has contact and diffusion capacitance, smoothes I_{peak}
- But for an high density array, bit/word-line cap is fixed and high!
- Local cap acts as "battery" providing high current density peaks

Understanding forming and set



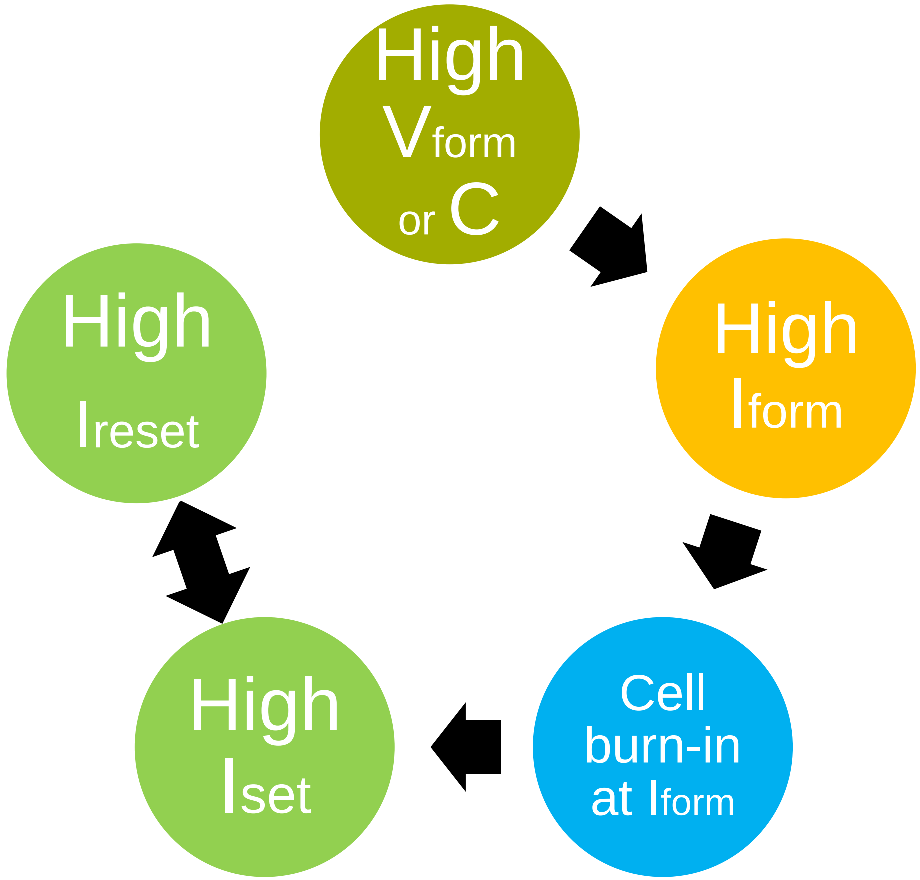
Kreupl et al., :US 2011/0310654 A1
US 2011/0310655 A1
US 2011/0310653 A1

Current transport during reset



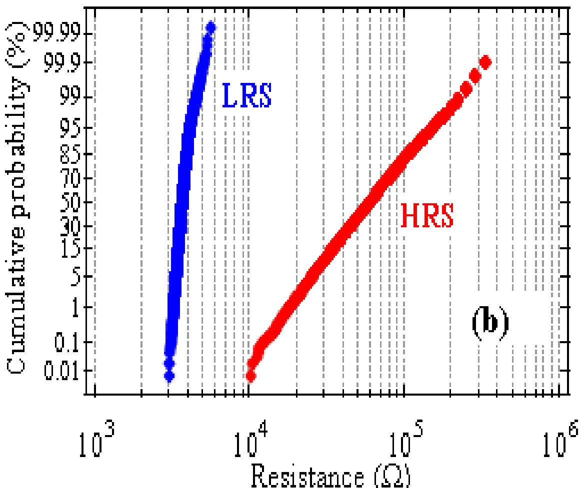
Kreupl et al., US 2011/0310654 A1
US 2011/0310655 A1
US 2011/0310653 A1

Vicious interdependence

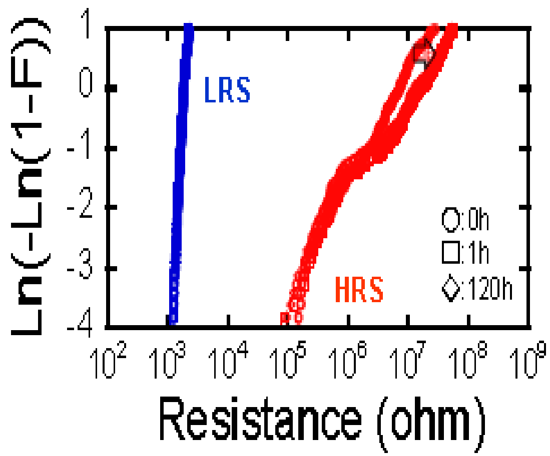


- High Vform and/or C:
  - cap-discharge
- High Iform :
  - transistor as current limiter?
  - diode as current limiter?
  - impact of pulse length?
- Low on-state resistance
  - fraction of one quantum channel
- best would be
  - low Vform and
  - smooth forming – no current peak
- Need built-in resistor!

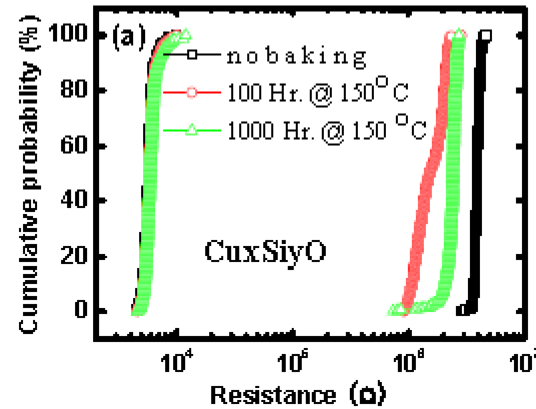
Low on-resistance state - a consequence of C-discharge



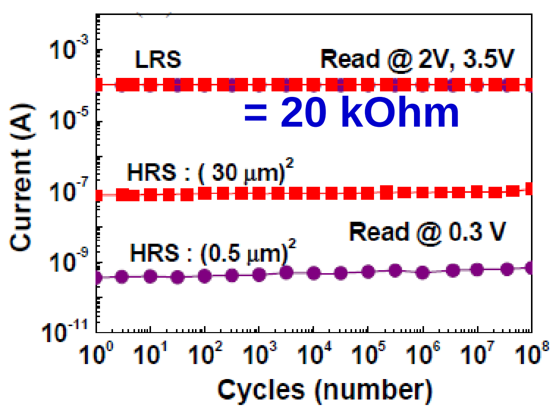
Panasonic, IEDM 2008



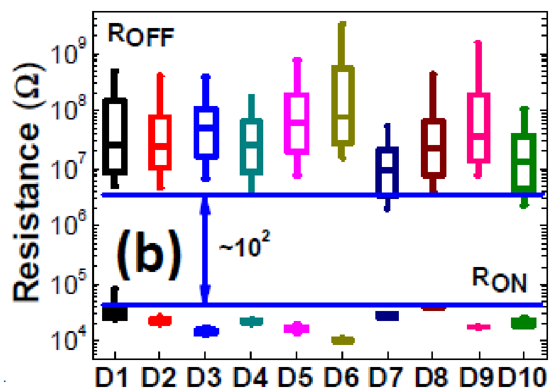
NEC, VLSI 2010



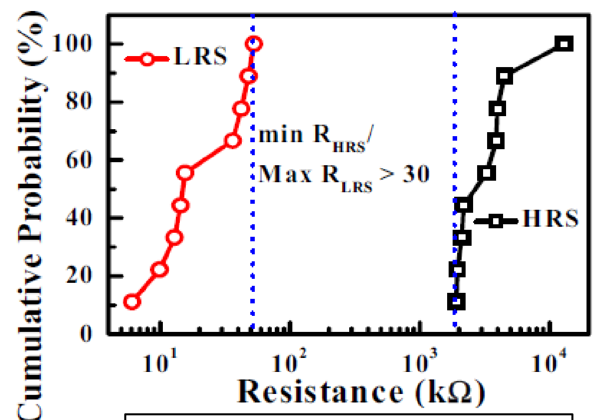
SMIC, VLSI 2010



Myoung-Jae Lee et al. IEDM 2012

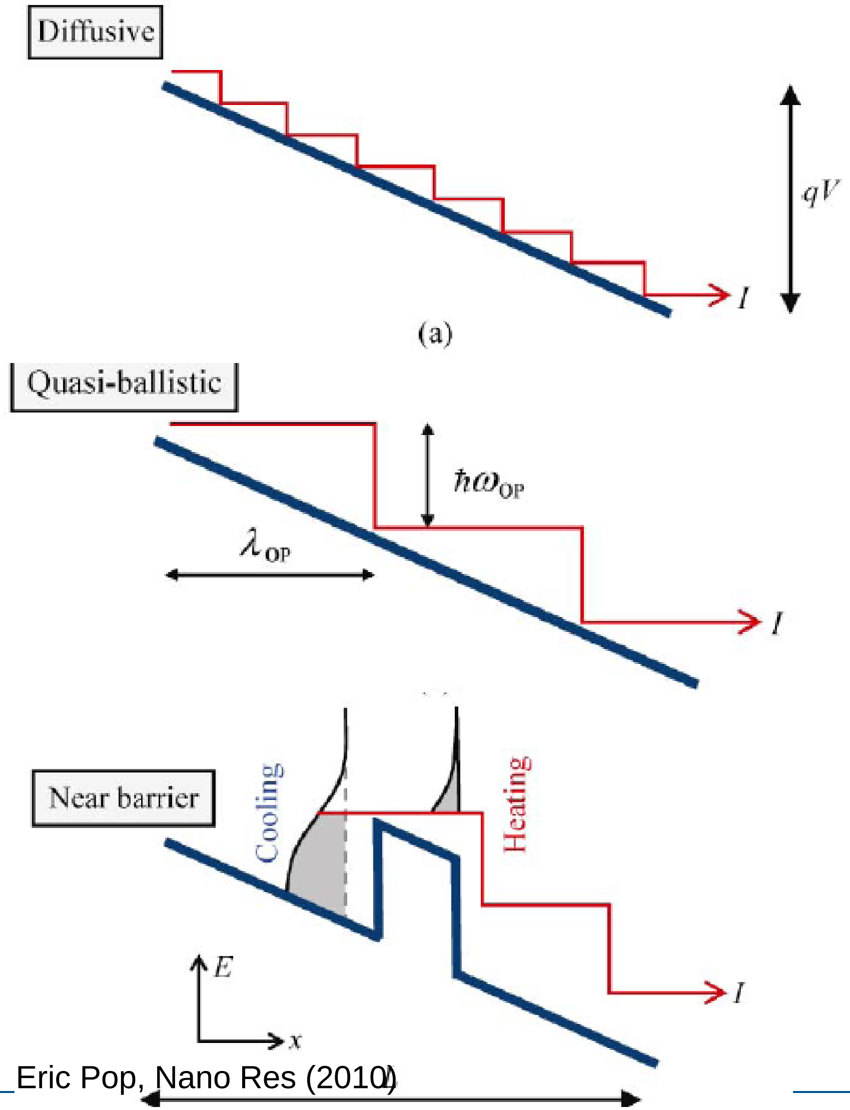


X. P. Wang et al. IEDM 2012



Yuan Heng Tseng et al., IEDM 2009

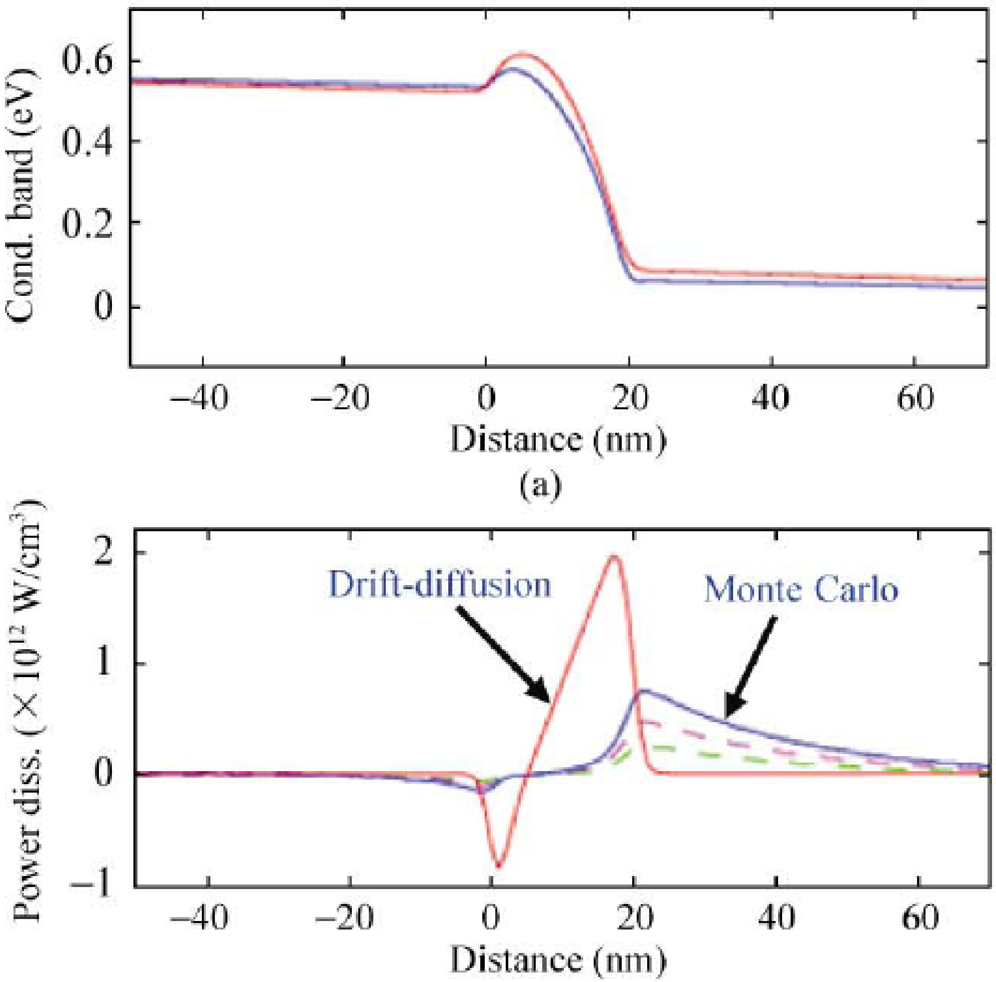
Pre- or in-cell-resistor needed to scatter charge



Eric Pop, Nano Res (2010)

- Resistance comes from charge scattering
- cell-oxides are thinner than the mean free path:
  - therefore we have no scattering
  - on-resistance is fraction of $R_{Klitzing}$
  - multiple quantum channels are formed
- best would be
  - High resistance path for the electrons
  - smooth forming – no cap discharge
- Need built-in resistor!

At nano-scale classical continuum is not valid



Eric Pop, Nano Res (2010)

$$P_V = jE$$

This classical equation is not valid on the scale of mean free path

electrons relax deep in the contact

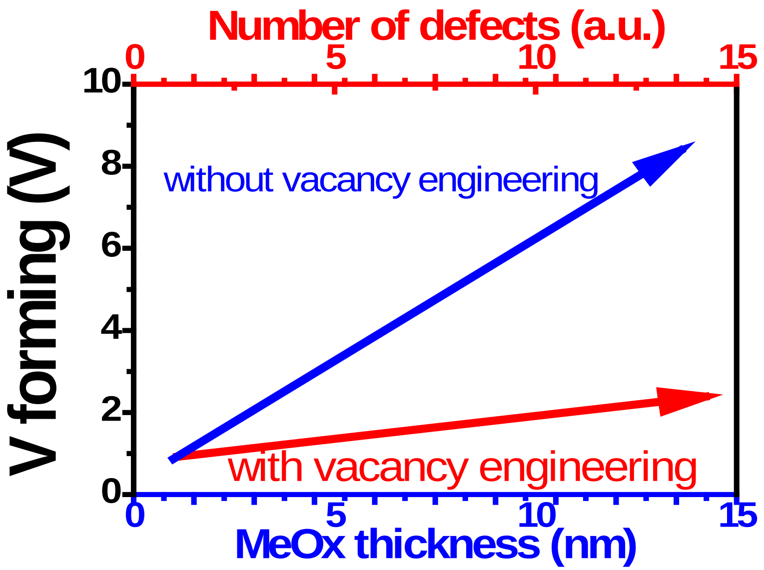
➔no direct heating in the MeOx channel

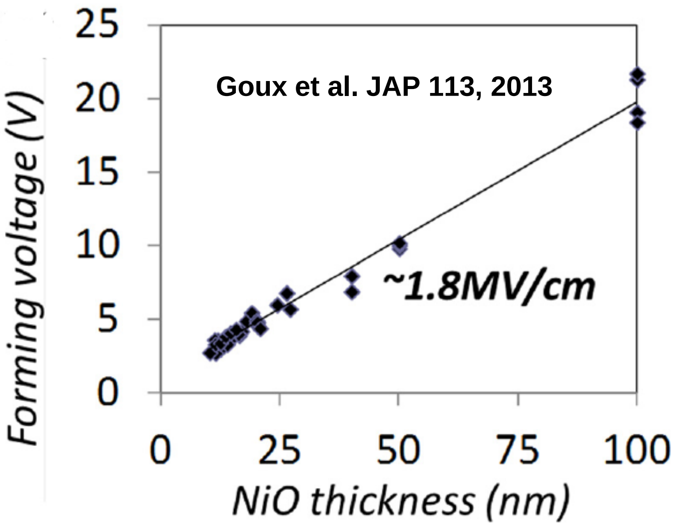
➔heat spreads from contact to filament

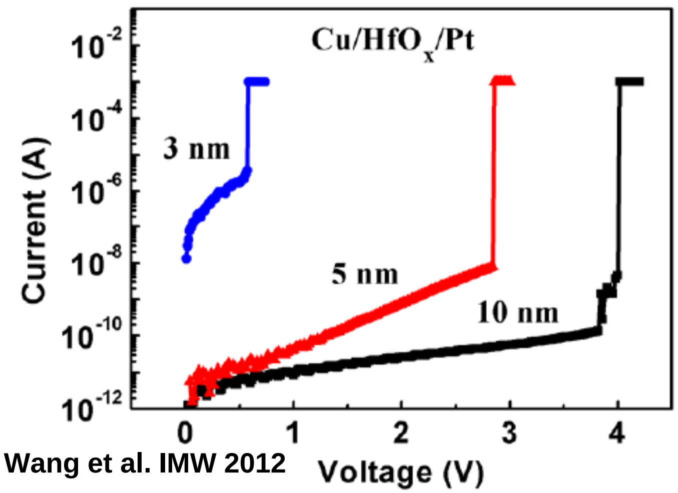
How to operate at low currents

- in-cell resistor $d > \lambda_e$
  - thicker oxide multiple layers
  - higher V_{form}
  - need cap-layer for V^O engineering
  - no retention strong T dependence
- out-of-cell resistor
  - no-C resistor
  - use contact resistance
  - bad area scaling
  - huge serial resistance
- capacitance reduction
  - only possible for academic samples
  - a densely packed array has high C
  - deal with a high C layout
- use Active Feedback Cell
  - with middle layer
  - with transistor
  - best: with vertical FET
  - diode does not work

In-cell resistor: MeOx thickness d > λ_e (mean free path)



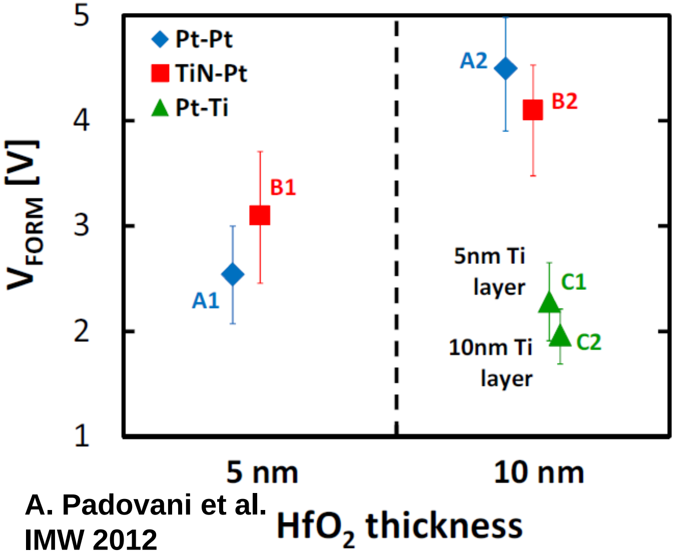




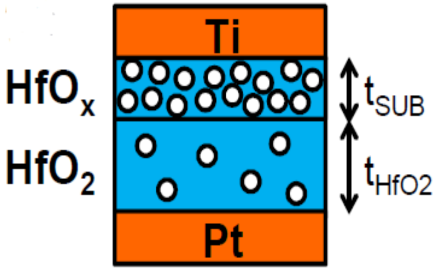
M. Wang et al. IMW 2012

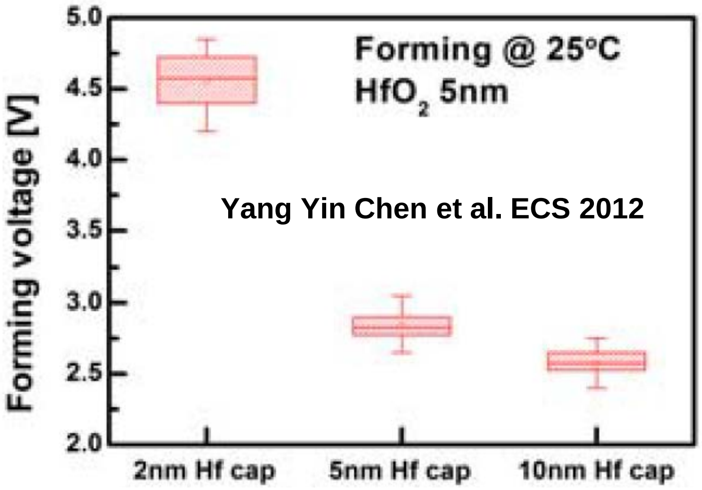
- ❑ Need to increase thickness of MeOx over mean free path to get scattering
- ❑ Forming voltage increases
- ❑ Needs to be compensated by vacancy engineering (Getter material like Ti, Hf, Ta …)

Vacancy engineering for reduction of $V_{forming}$

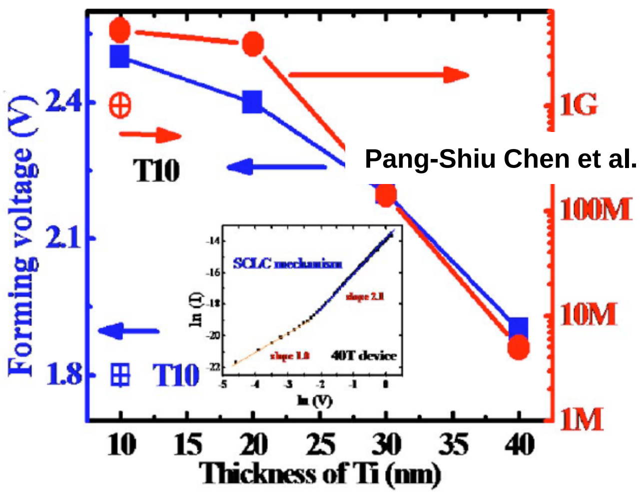


A. Padovani et al. IMW 2012





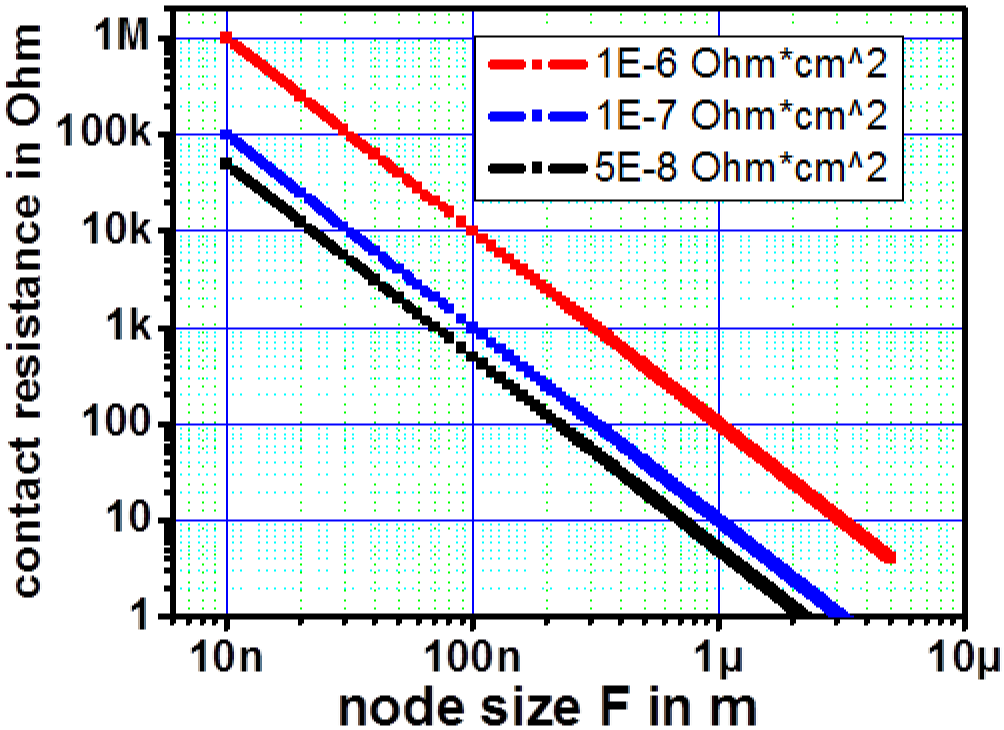
Yang Yin Chen et al. ECS 2012



Pang-Shiu Chen et al. ECS 2010

- Works by depleting MeOx!
- Not in all case homogeneously (Ellingham diagram)
- Strong dependence on temperature budget
- Still has the problem of cap-discharge

Current capping by contact resistance



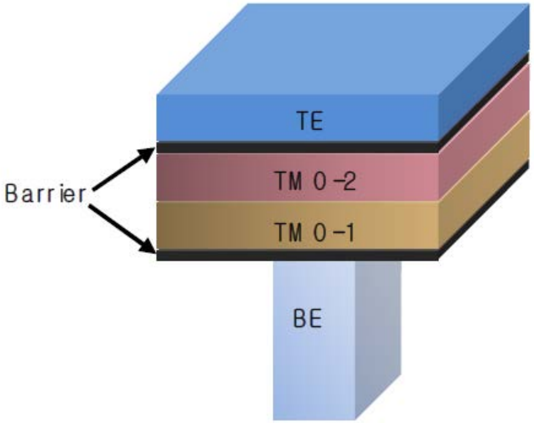
we have 2 contacts for a cell!

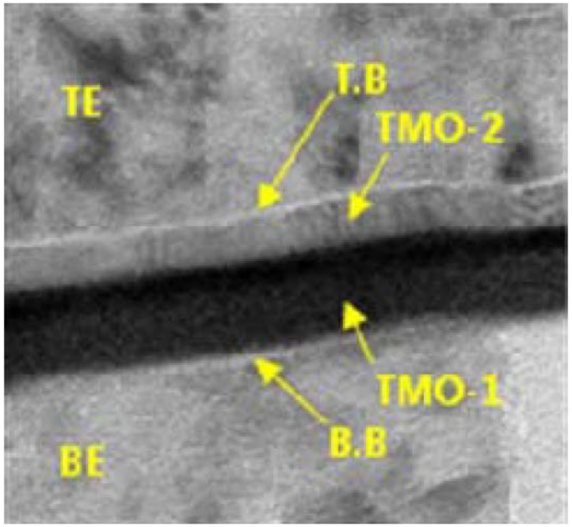
voltage drop at contact

J \ CR	1E-6	1E-7	5E-8
10 MA/cm²	10 V	1 V	0.5 V
1 MA/cm²	1 V	0.1 V	0.05 V

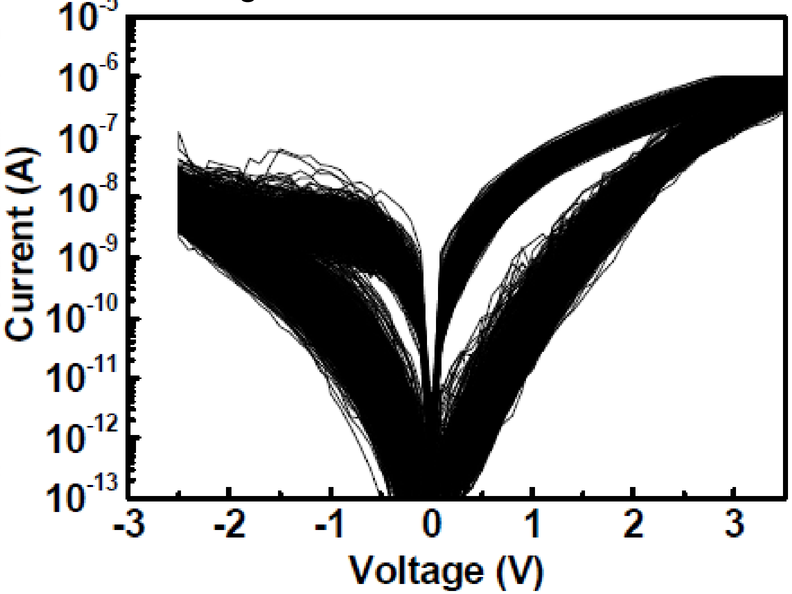
- Contact resistance (CR) contributes severely to overall resistance path
- Scales with area – what worked at ~100 nm, doesn't at ~10 nm!
- Associated voltage drop at high current densities is high

Current capping by contact resistance



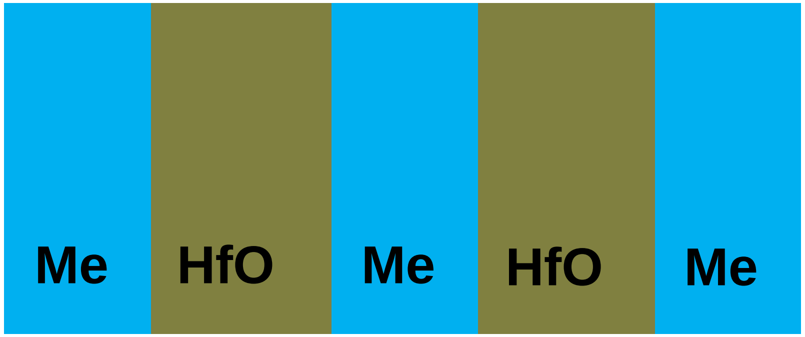


Seong-Geon Park et al., IEDM 12

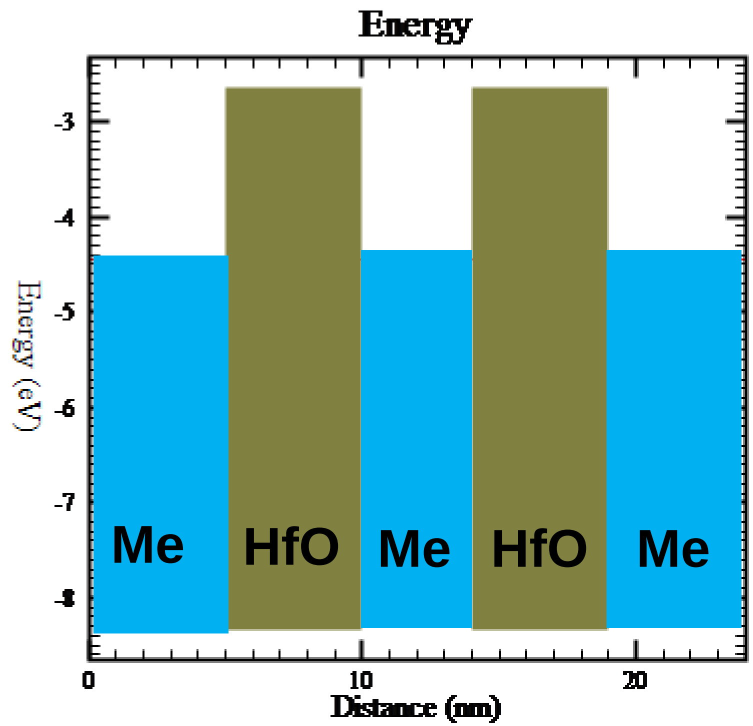


- From TEM one see thick MeOx (> 25 nm) and contact resistance by additional barriers
- High voltage already at very wide cell
  (cell width not given in paper, but from TEM d >100 nm)
- Associated voltage drop at reduced cell size will be huge!

Active Feedback Cell



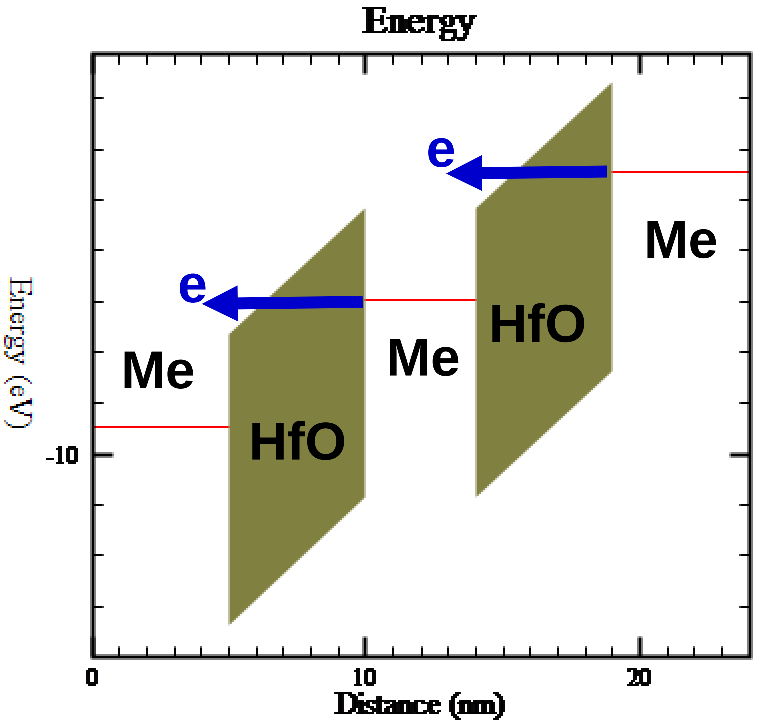
Me: metal or highly doped Si
HfO: any switchable MeOx
with capping layers for
vacancy engineering

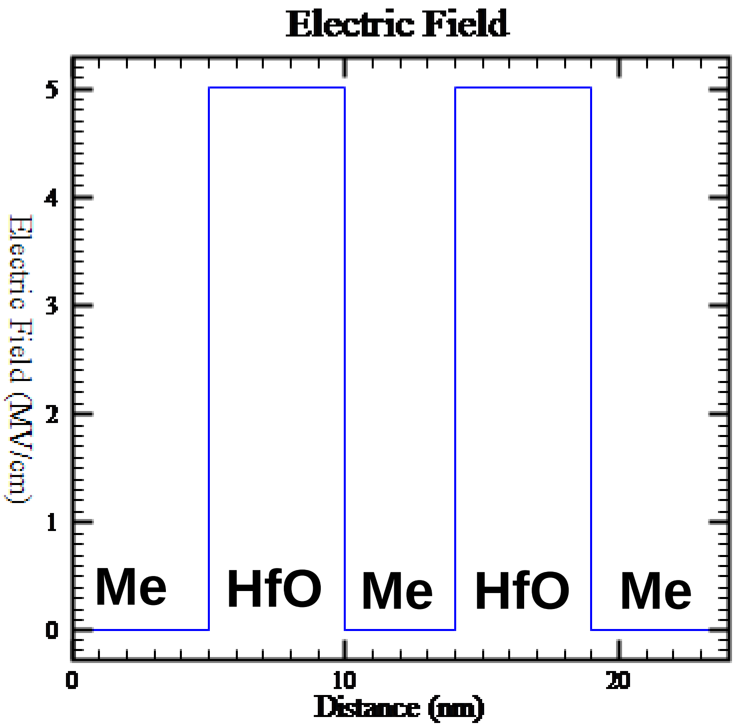


- Consider this double-barrier structure (this is not a CRS cell!!)
- This has no forming overshoot due to built-in active feedback

Kreupl et al., US 2011/0310654 A1
US 2011/0310655 A1
US 2011/0310653 A1

Active Feedback Cell

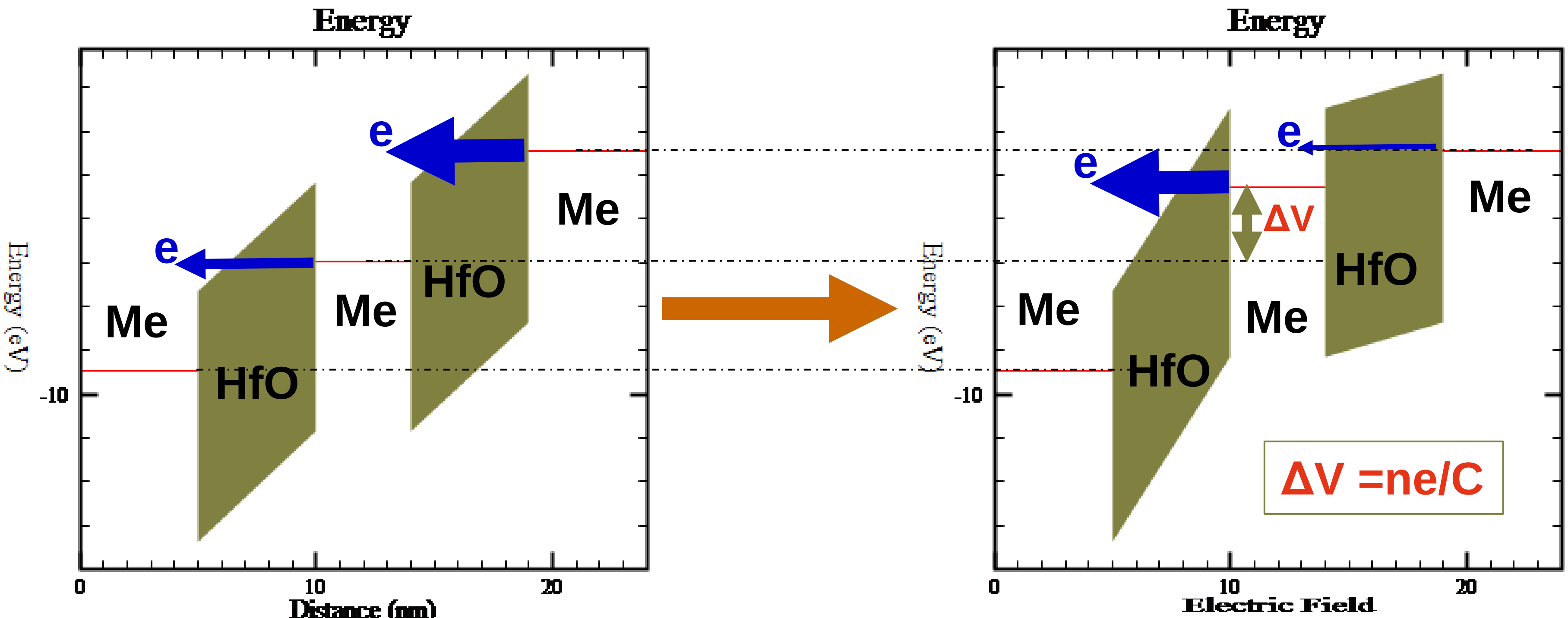




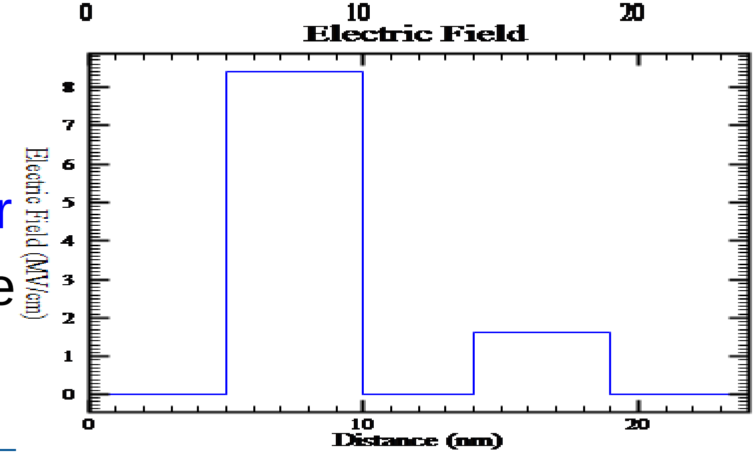
- For forming, a voltage is applied to the outer Me electrodes
- The field drops on the HfO layers and leads to O-movement
- The electron tunneling rate is almost equal for both layers, as I will show on the next slide and limits overshoot by active feedback

Kreupl et al., US 2011/0310654 A1
US 2011/0310655 A1
US 2011/0310653 A1

Active Feedback Cell

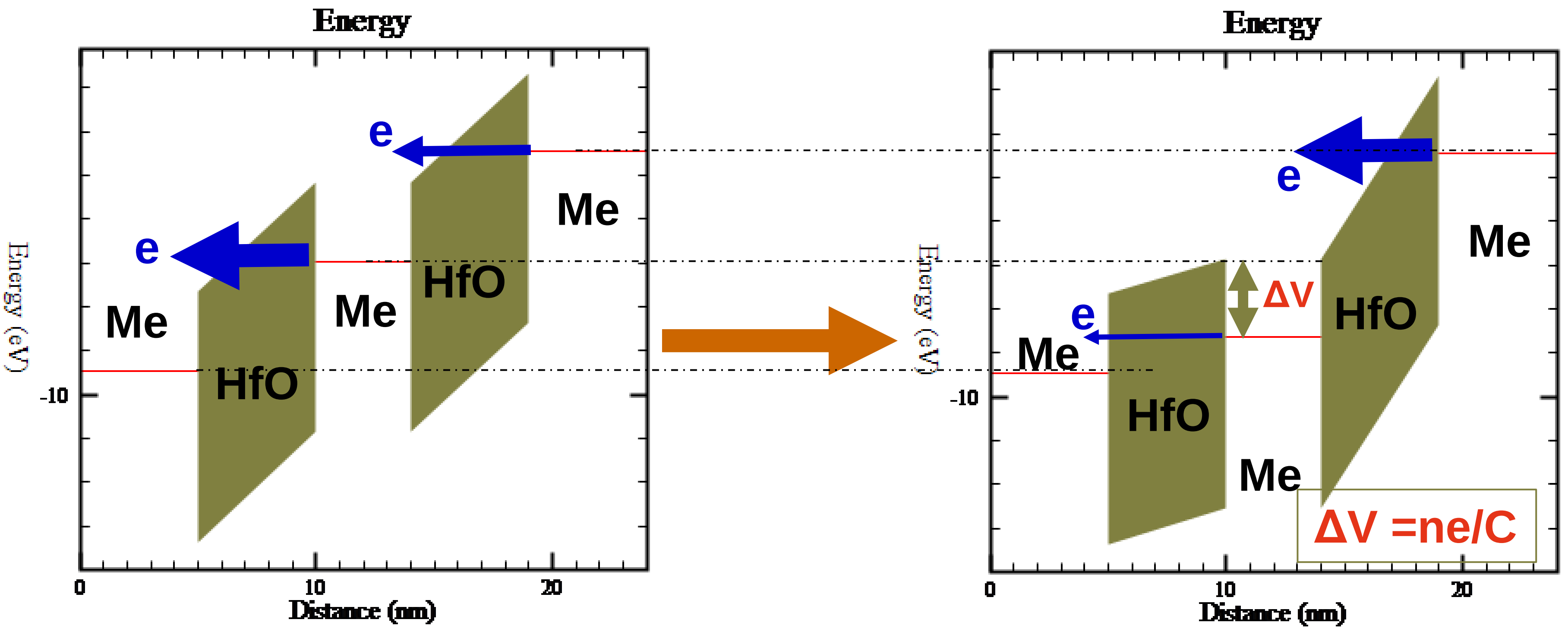


- Assume one junction will run away and has enhanced tunnel rates
- Injects more electrons in the middle Me layer
- As a consequence the potential in the middle electrode raises -> applied field drops
- The field on the other junction raises



Kreupl et al., US 2011/0310654 A1
US 2011/0310655 A1
US 2011/0310653 A1

Active Feedback Cell



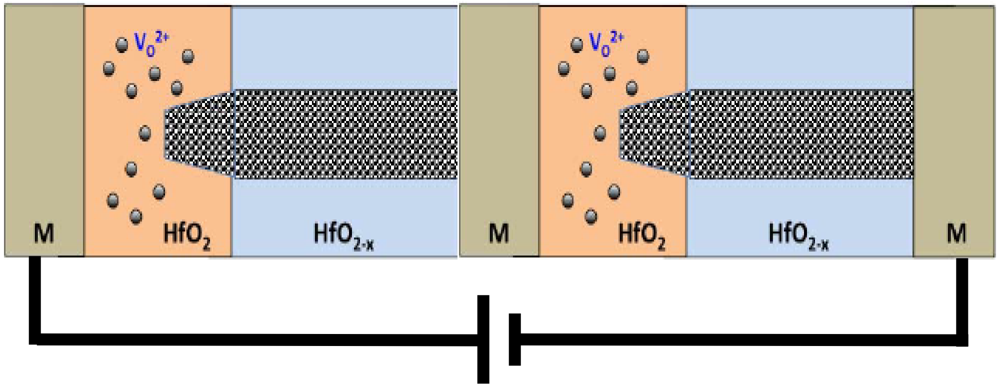
- Works the same if the other junctions breaks down
- The capacitance of the middle electrode determines the active feedback voltage

$$\Delta V = ne/C$$

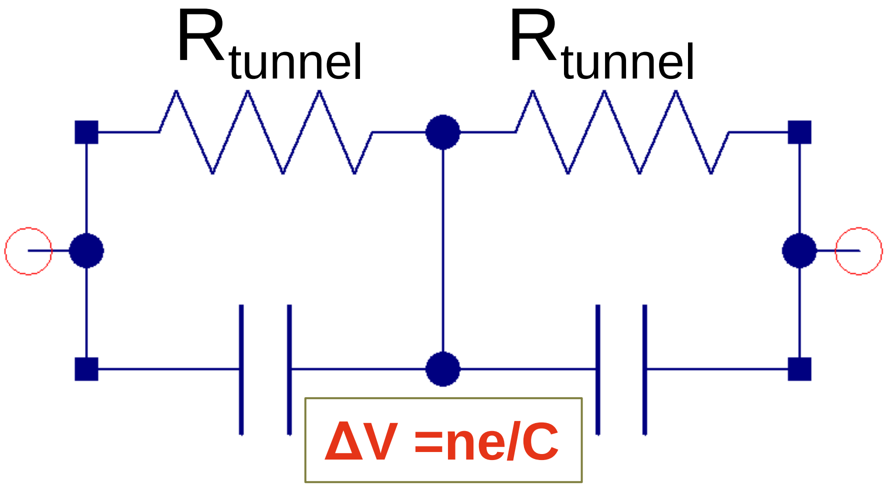
- Works instantly and well with diode as selector

Kreupl et al., US 2011/0310654 A1
US 2011/0310655 A1
US 2011/0310653 A1

Active Feedback Cell



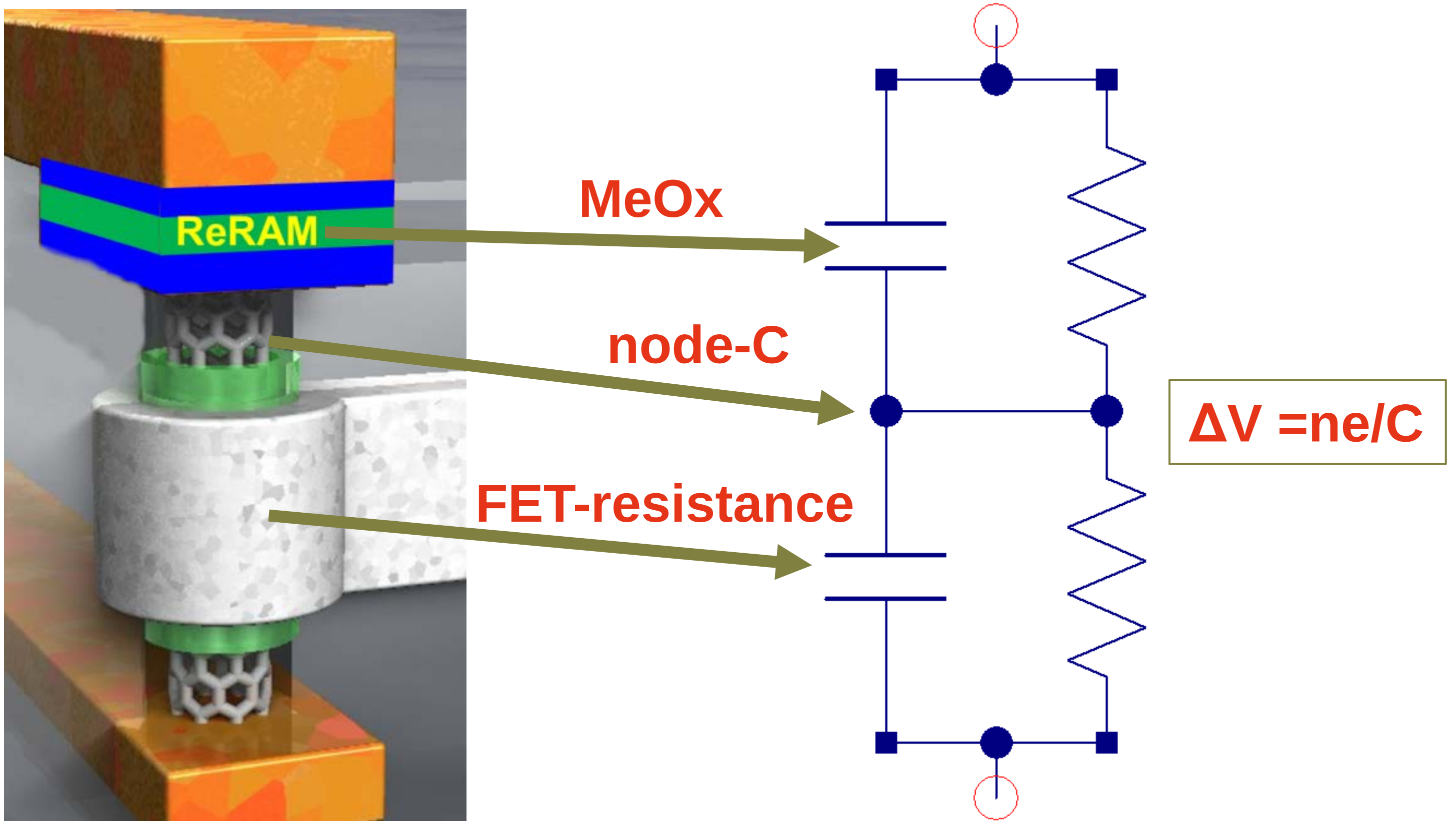
equivalent circuit



- Two filaments will form, but current overshoot is tamed by active feedback structure (like over-programming protection in floating gate NAND)
- The active feedback voltage depends on node capacitance of the middle electrode:
- for 1 fF: ΔV = 1.6 V for 10,000 electrons and current of dQ/dt= 1.6 µA
- for 10 fF: ΔV = 1.6 V for 100,000 electrons and current of dQ/dt= 16 µA

Kreupl et al., US 2011/0310654 A1
US 2011/0310655 A1
US 2011/0310653 A1

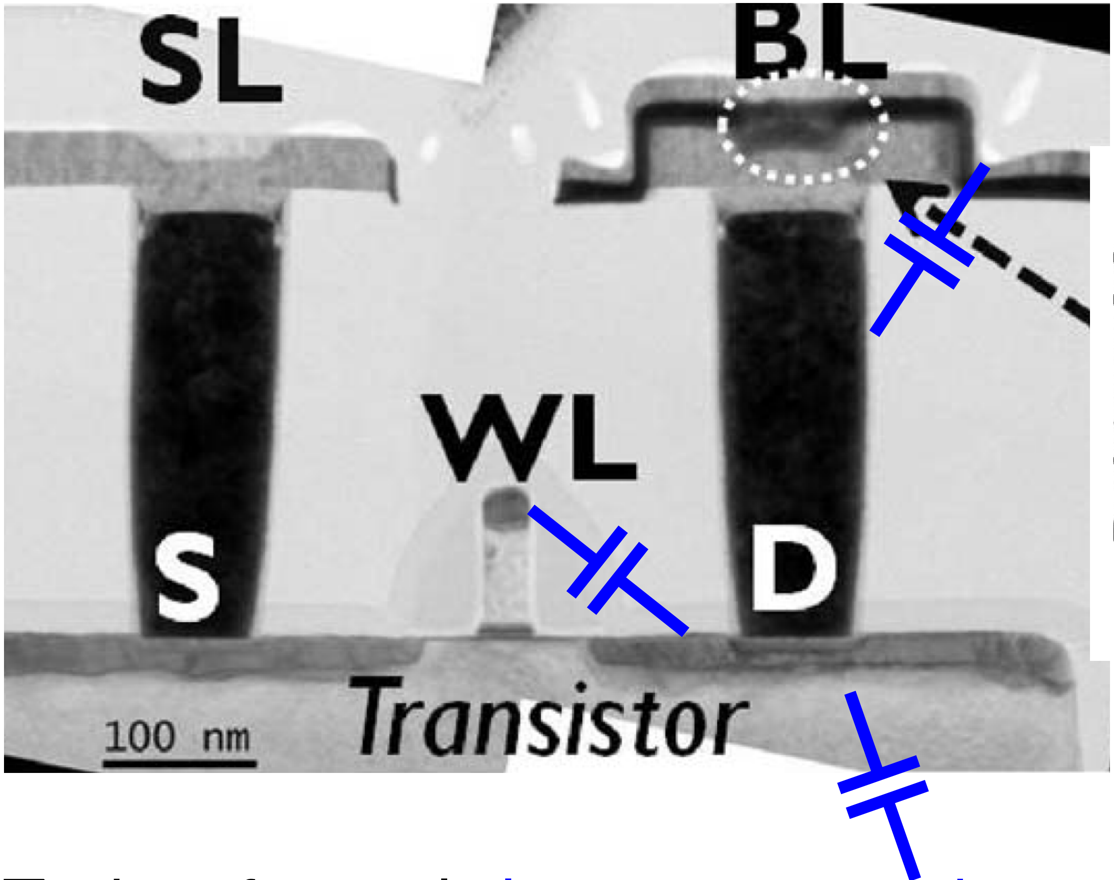
Active Feedback Cell (single junction) with FET



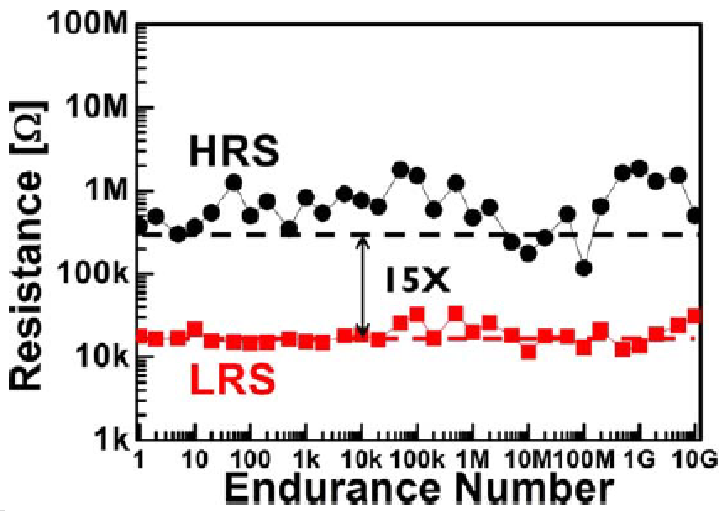
- ❑ Works also in single junction mode, if input capacitance of FET is low - small diffusion capacitance –best is vertical FET!!
- ❑ Does not work with diode – rf-model of diode is capacitor

Kreupl et al., US 2011/0310654 A1
US 2011/0310655 A1
US 2011/0310653 A1

Planar FET might have to high capacitance



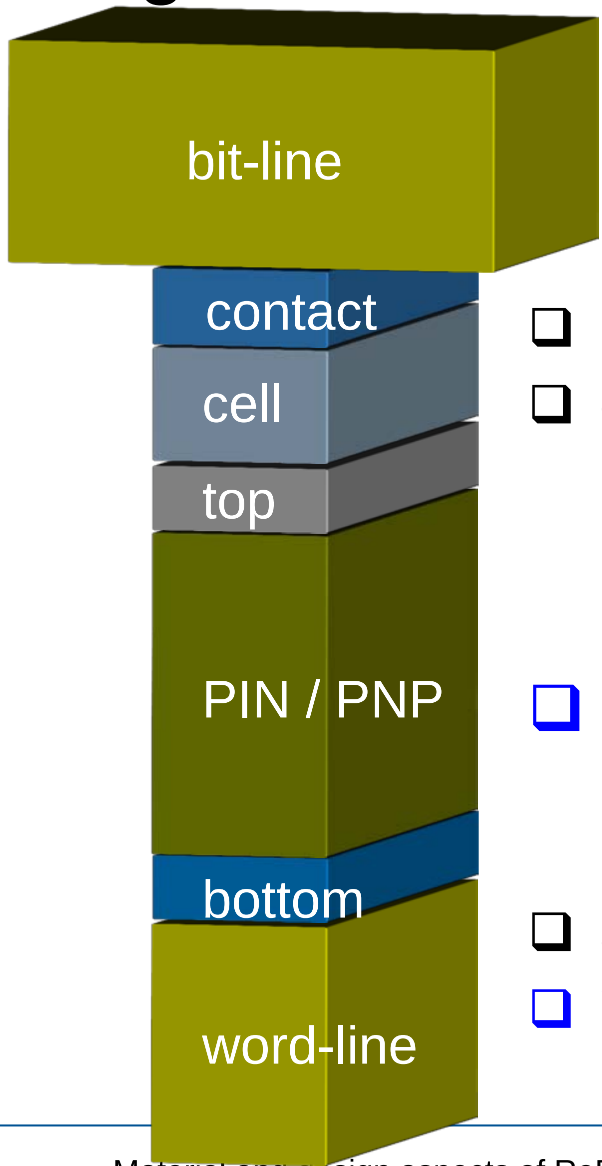
Yang Yin Chen et al., TED 2012

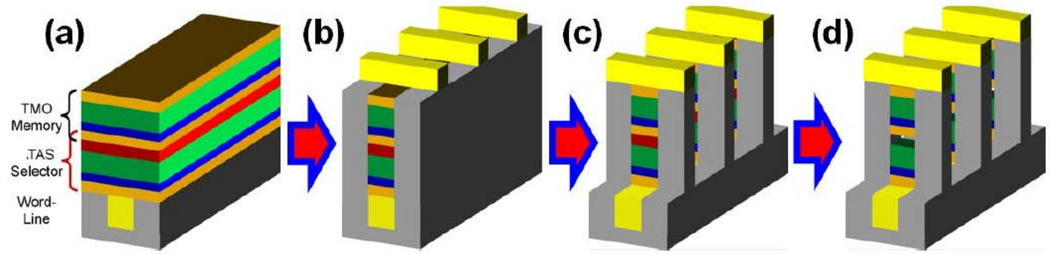


- Therefore only low on-state resistance cycling is possible
- But 10 G cycles have been obtained by short pulses

Integration challenges from SAPD

ChiaHua Ho et al., IEDM 12





- cost-effective integration requires SAPD
- etching of complicated high aspect structure:
  - sidewall implants in cell and diode from RIE
  - diffusion of etch species in carefully designed memory cell…
- etch-clean in complicated structures
  - How to clean etch damage in diode and memory cell?
- all "vacancy engineering" is gone after a plasma ash
- " all surface" effects dominate in sub 20 nm

Summary

- There is no memristor – cap-discharge is the culprit
- Oxygen vacancy ReRAM looks most promising
- Key is
  - reduction in operating currents and
  - achieving higher on-state resistance
- Current overshoot creates several quantum channels in the ReRAM cell, which have low resistance
- Four methods have been proposed to mitigate current overshoot
- Active Feedback Cell with vacancy engineering is most promising
- Key challenge: how stable are low current states?
  most MeOx studied at high j - what will be the right material?