

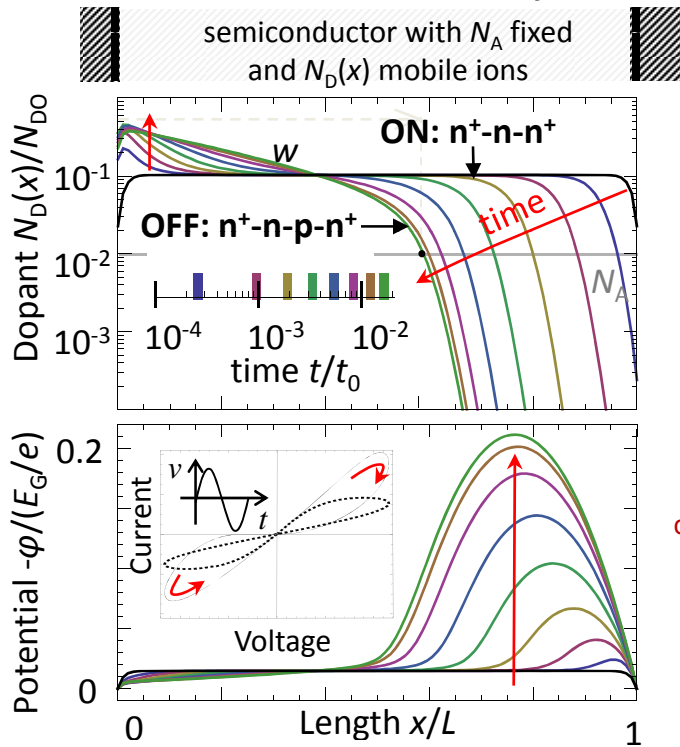
# OUTLINE

1. HP's memristor and applications
2. Models of resistance switching
3. Volatility speed tradeoffs
4. 3D circuit architectures
5. Proposal for evaluation framework





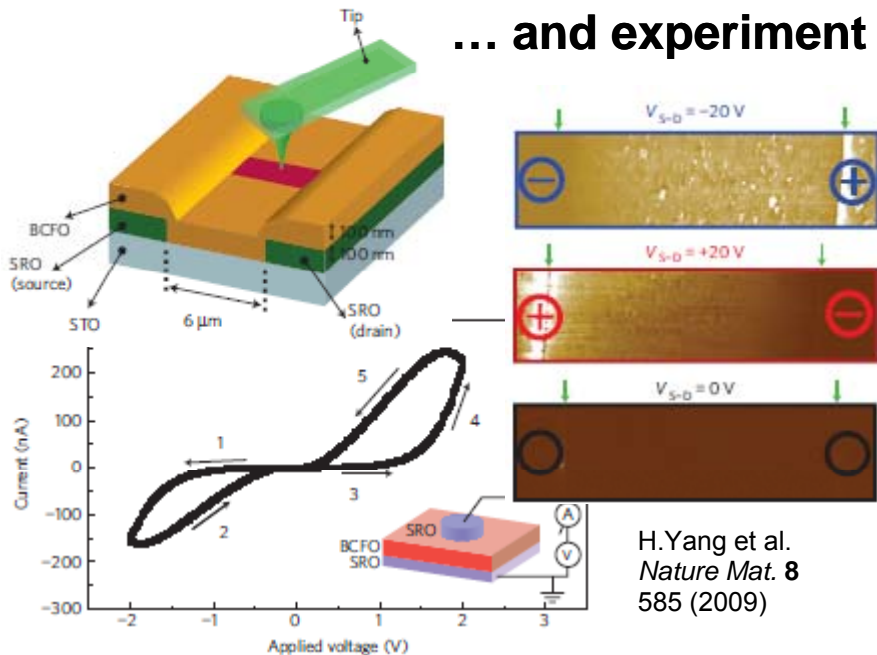
## bulk theory



D.Strukov et al. *Small* 5 1058 (2009)

1D model ... but initial conditions for 3D (i.e. after forming) are hard to simulate...

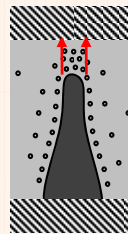
## ... and experiment



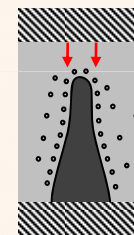
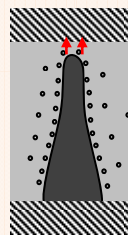
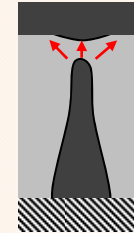
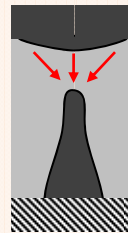
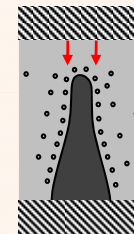
H.Yang et al. *Nature Mat.* 8 585 (2009)

## interface

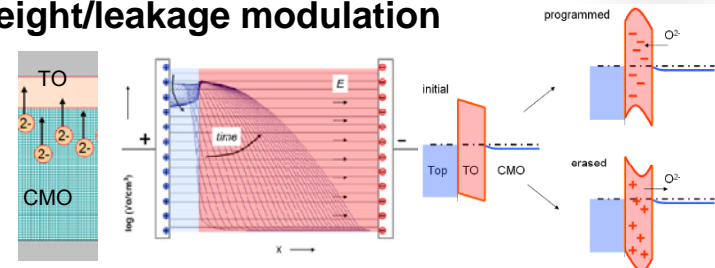
OFF  $\rightarrow$  ON



ON  $\rightarrow$  OFF

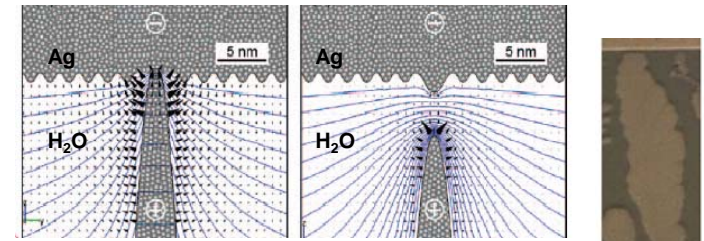


### I. barrier height/leakage modulation



e.g. two layer system: R.Meyer et al. *Proc. NVMTS* (2008)

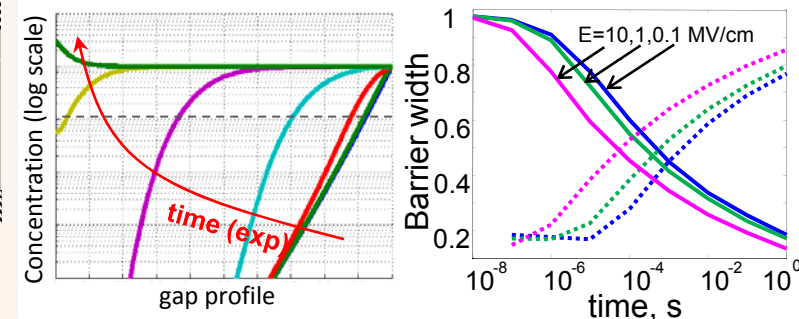
### Ia. barrier width/bridging due to radial ion motion



e.g. in CBRAM: X.Guo et al. *APL* 91 1 (2007)

chalcogenide electrolytes: M.N.Kozicki et al. *J Non-Crys. Solids* 352 567 (2006)

### Iib. barrier width/bridging due to vertical ion motion



D.Strukov et al. (preliminary data)

grossly simplified picture, mix of all mechanisms in reality...

# WRITE SPEED VS. RETENTION



## linear ionic transport

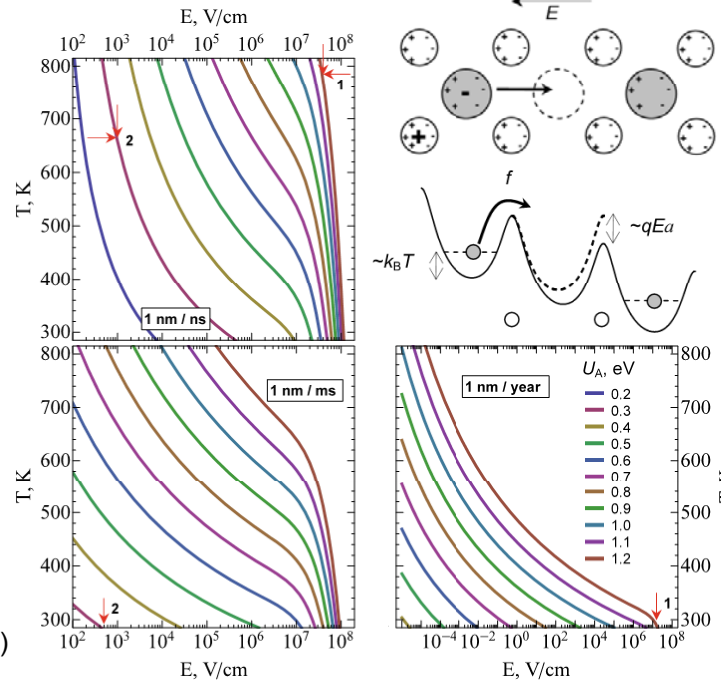
$$\frac{\tau_{\text{store}}(v=0)}{\tau_{\text{write}}(v=V)} \sim V \frac{\mu_I}{D_I} = \frac{V}{V_T}$$

## nonlinear effect due to temperature and/or electric field

e.g. temperature only:

$$\frac{\tau_{\text{store}}}{\tau_{\text{write}}} \sim \frac{V}{V_T} \left( e^{\frac{U_A}{k_B T_{\text{store}}}} - e^{\frac{U_A}{k_B T_{\text{write}}}} \right)$$

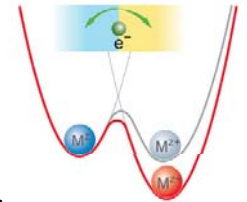
D.Strukov et al. *Appl.Phys.A* **94** 515 (2009)



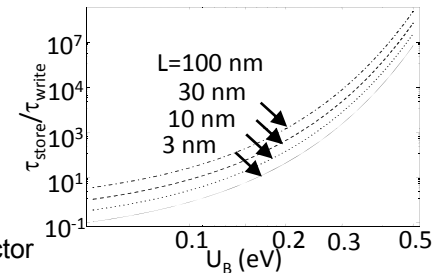
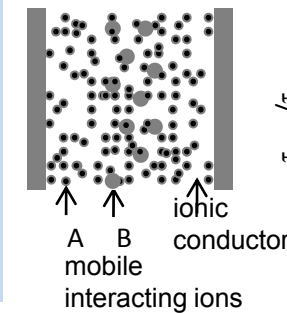
## other sources of nonlinearity?

→ Butler Volmer reactions

R.Waser et al. *Adv.Mat* **21** 2632 (2009)

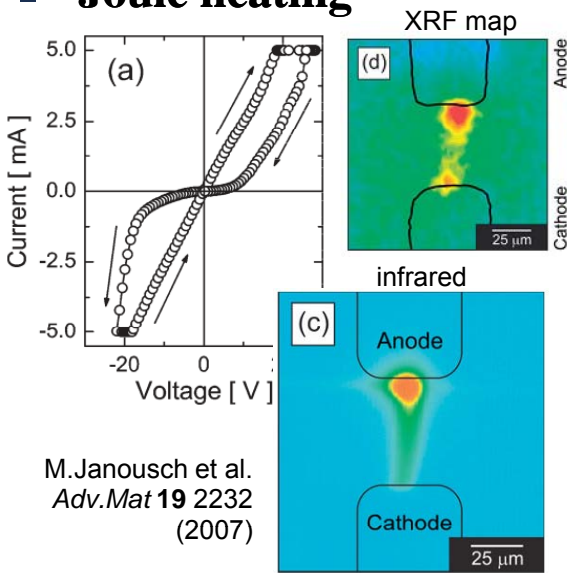


→ Electrochemical effects...

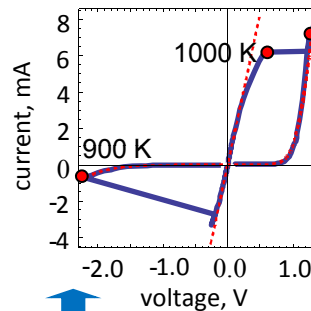


D.Strukov (unpublished)

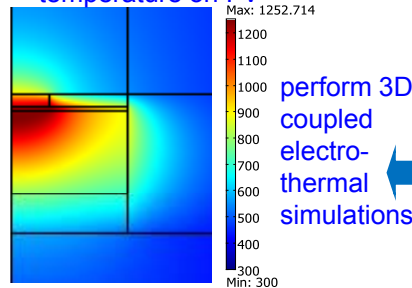
## Joule heating



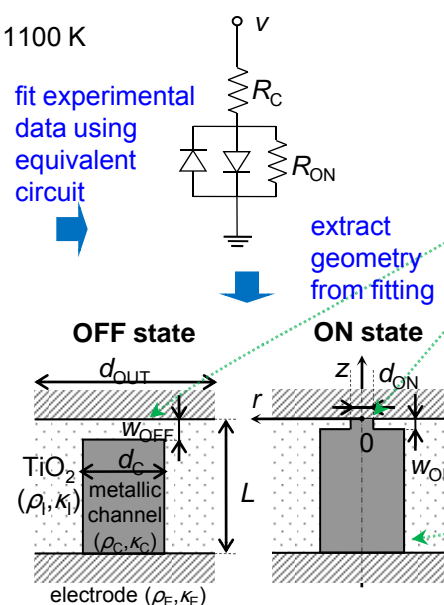
M.Janousch et al. *Adv.Mat* **19** 2232 (2007)



map temperature on I-V

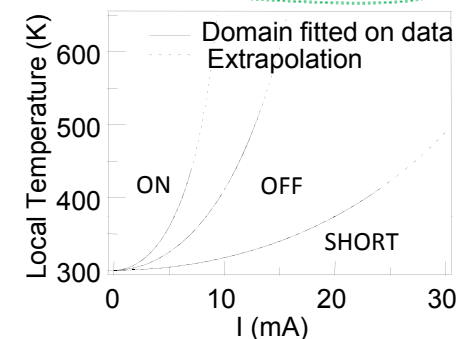
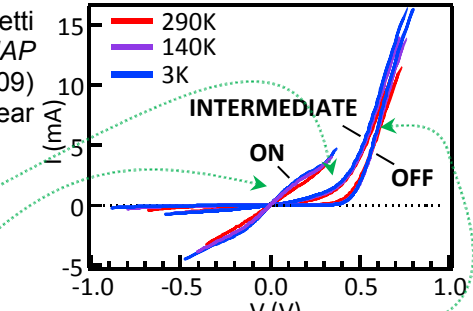


perform 3D coupled electro-thermal simulations



D.Strukov et al. *MRS* (2009)

J.Borghetti et al. *JAP* (2009) to appear



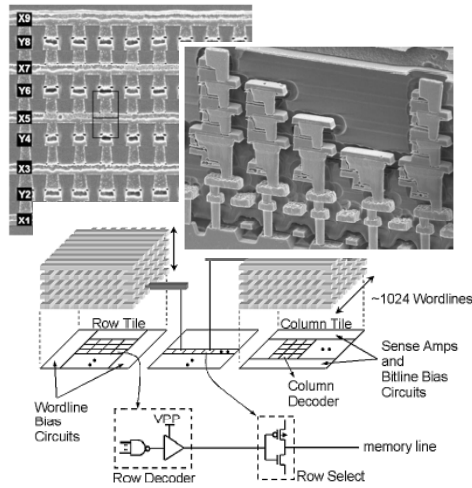
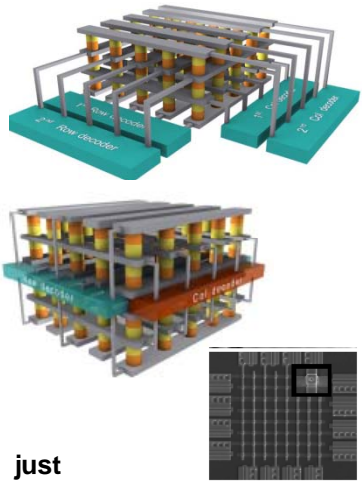
→ strong nonlinearity in ionic transport required for high retention, even more for half select



# 3D STACKING FOR CMOL CIRCUITS

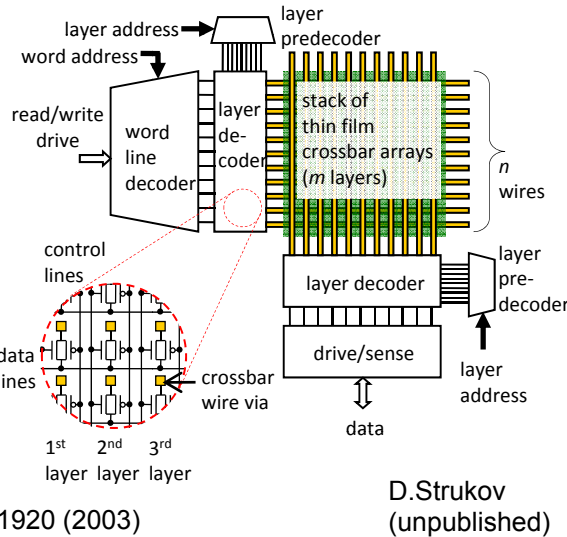


## peripheral



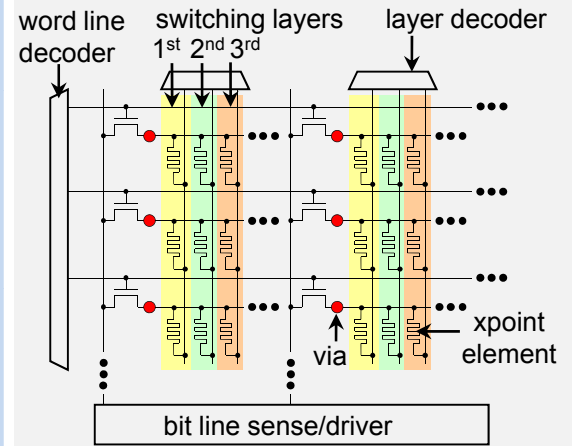
just few examples:  
M.-J.Lee *IEDM* 85 (2008)

M.Johnson *IEEE J Solid State Circuits* 38 1920 (2003)



## hybrid

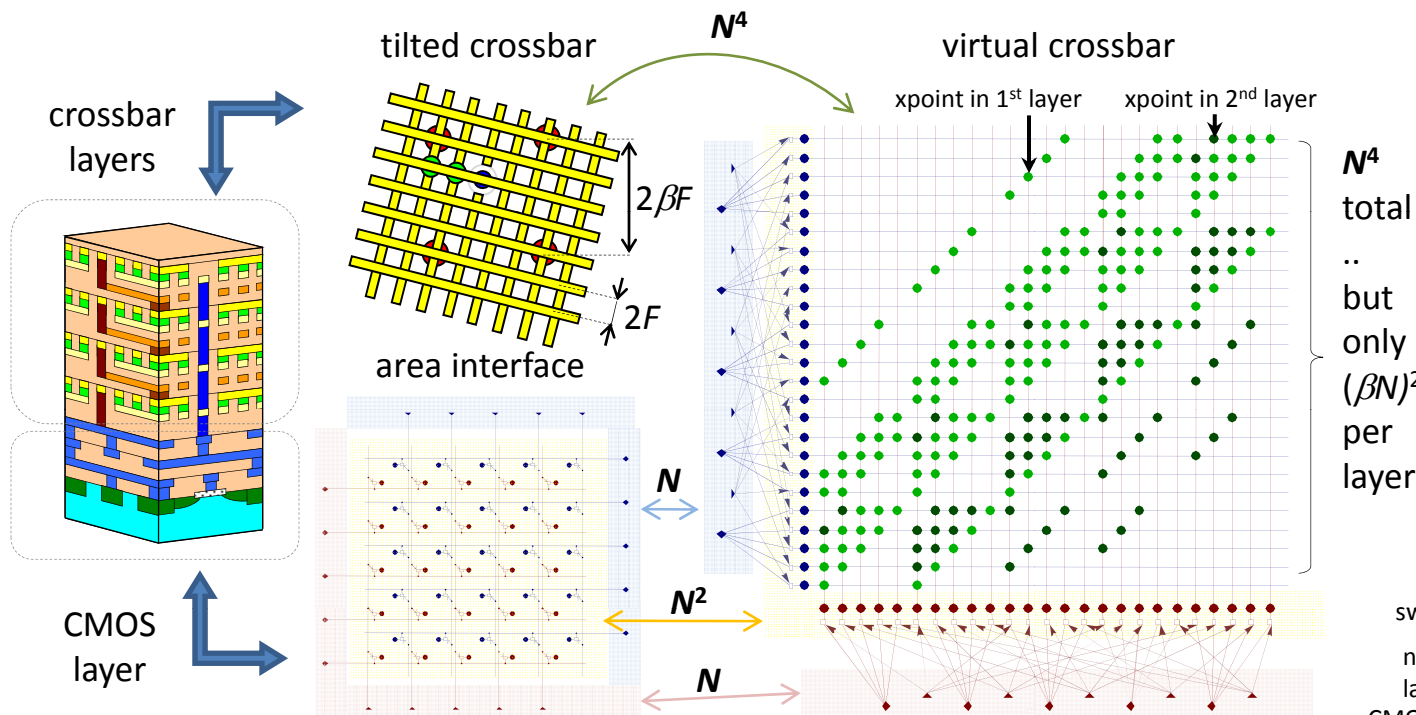
main idea: area + peripheral interface



→ less semi-selected devices for read op.  
→ parallel write for current controlled devices  
→ less maximum current density  
→ ... but less dense

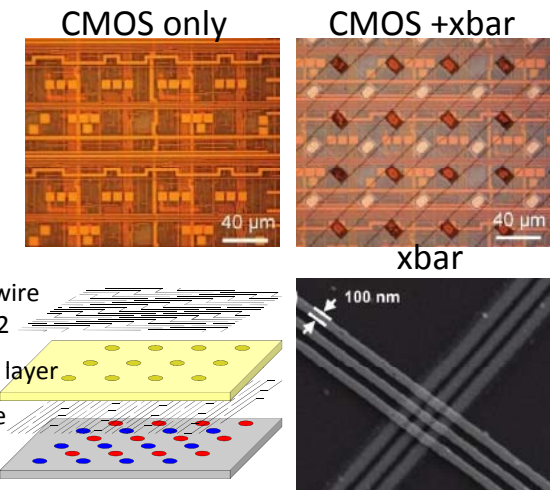
D.Strukov (unpublished)

## area distributed



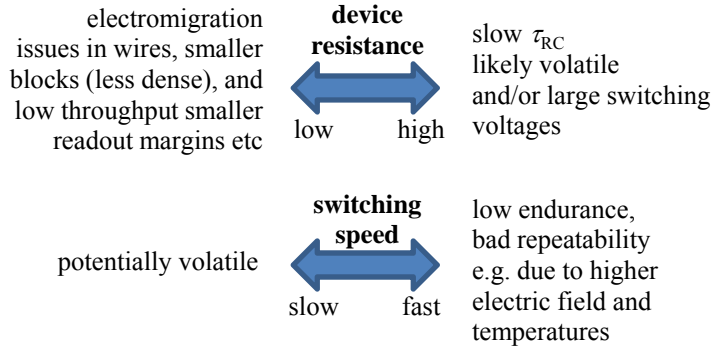
theory: K.Likharev *Interface* 14 43 (2005); D.Strukov et al. *PNAS* (2009)

...and exp with just one xbar layer: Q.Xia et al. *Nano Letters* (2009)

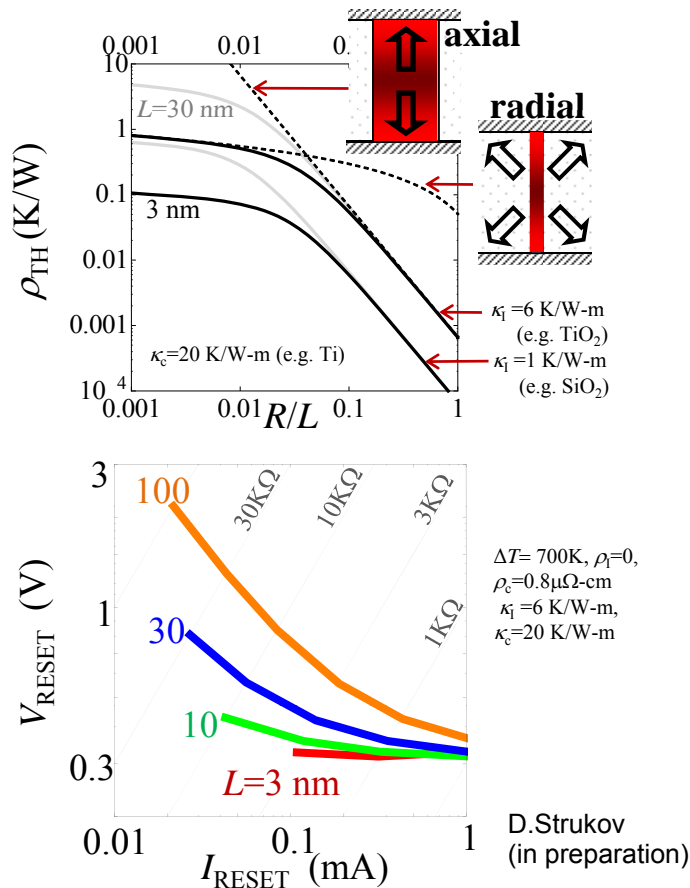




## intrinsic circuit and device tradeoffs



## e.g. reset current scaling



## proposal for software framework

### electronic device characterization:

- (1) nonlinearity in  $I-V$  shape;
- (2) nonlinearity in switching;
- (3) nature of the switching compliance for reset and set;
- (4) polarity of switching;
- (5) asymmetry of switching threshold voltages;
- (6) switching speed;
- (7) retention;
- (8) nominal set/reset voltage/current values;
- (9) variations in  $I-V$  shape upon cycling (repeatability);
- (10) endurance;
- (11) device yield;
- (12) forming step, etc.

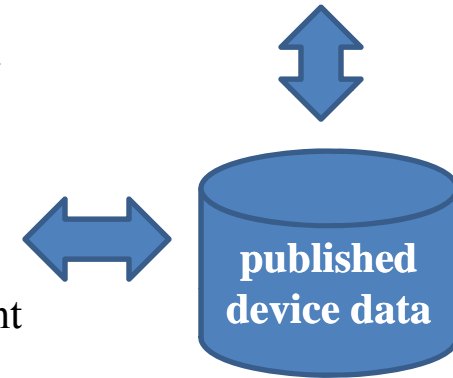
### design constrains:

density, cost, speed, power  
power density, throughput

### fabrication consideration:

design rules, electromigration specs,  
electrode thermal and electrical  
resistivity, manufacturing cost

## material device characterization



## OPTIMAL CIRCUIT ARCHITECTURE

via parametric search:  
circuit architecture,  
block size, sensing/  
biasing scheme, voltage  
scaling, def. tolerance  
scheme etc.

## main goals

- explore for more than drop-in replacement
- expose important missing device and circuit information
- help in focusing on the most important issues