Resistive Switching in Metal-Insulator-Metal Junctions

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Center of
Nanoelectronic Systems for
Information Technology

Seagate May 2006: email: HHKohlstedt@lbl.gov

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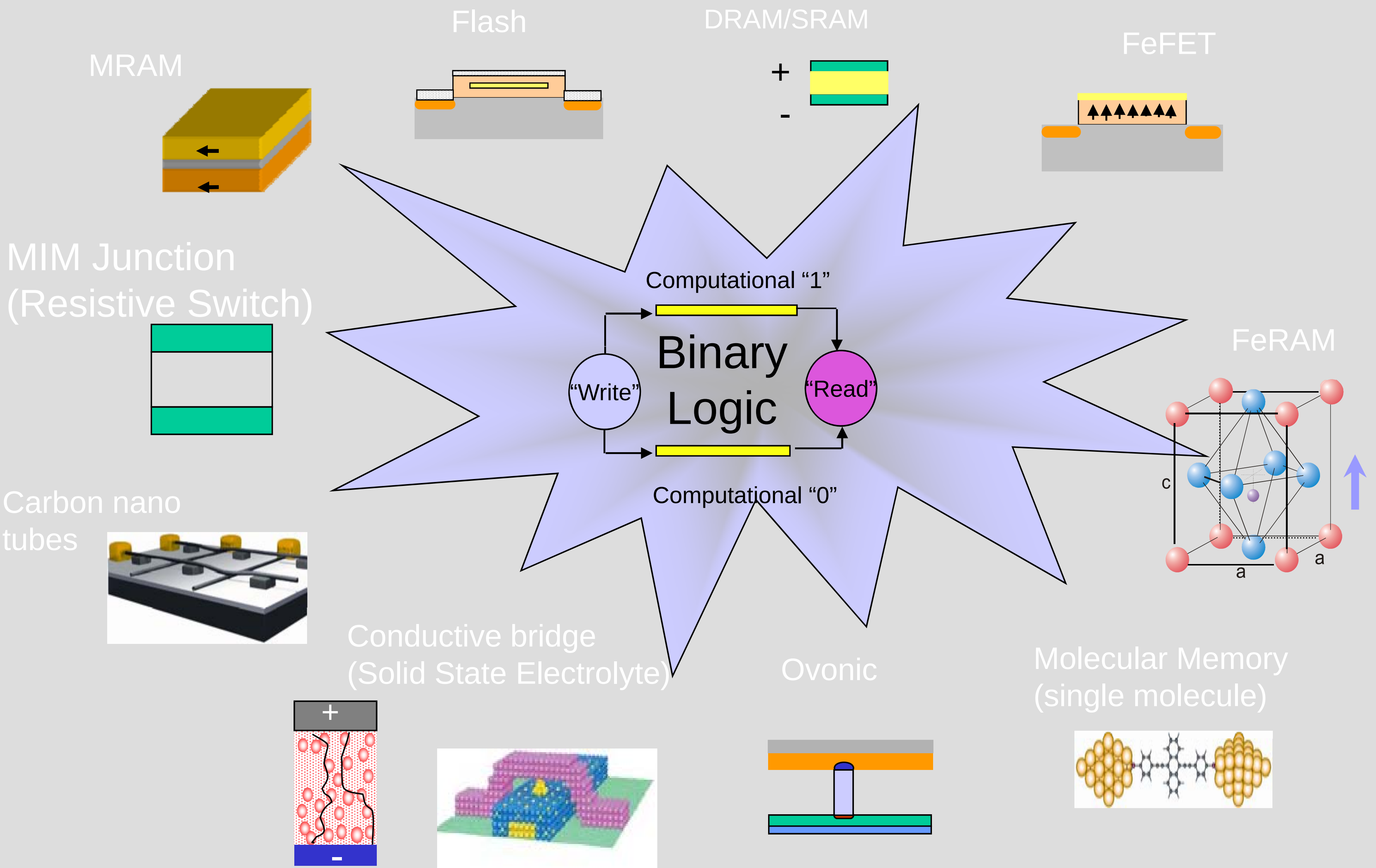
Charge and Resistance for RAMs



What is a resistive memory?

Read a Resistance = Resistive Memory

Examples

Charged Based:

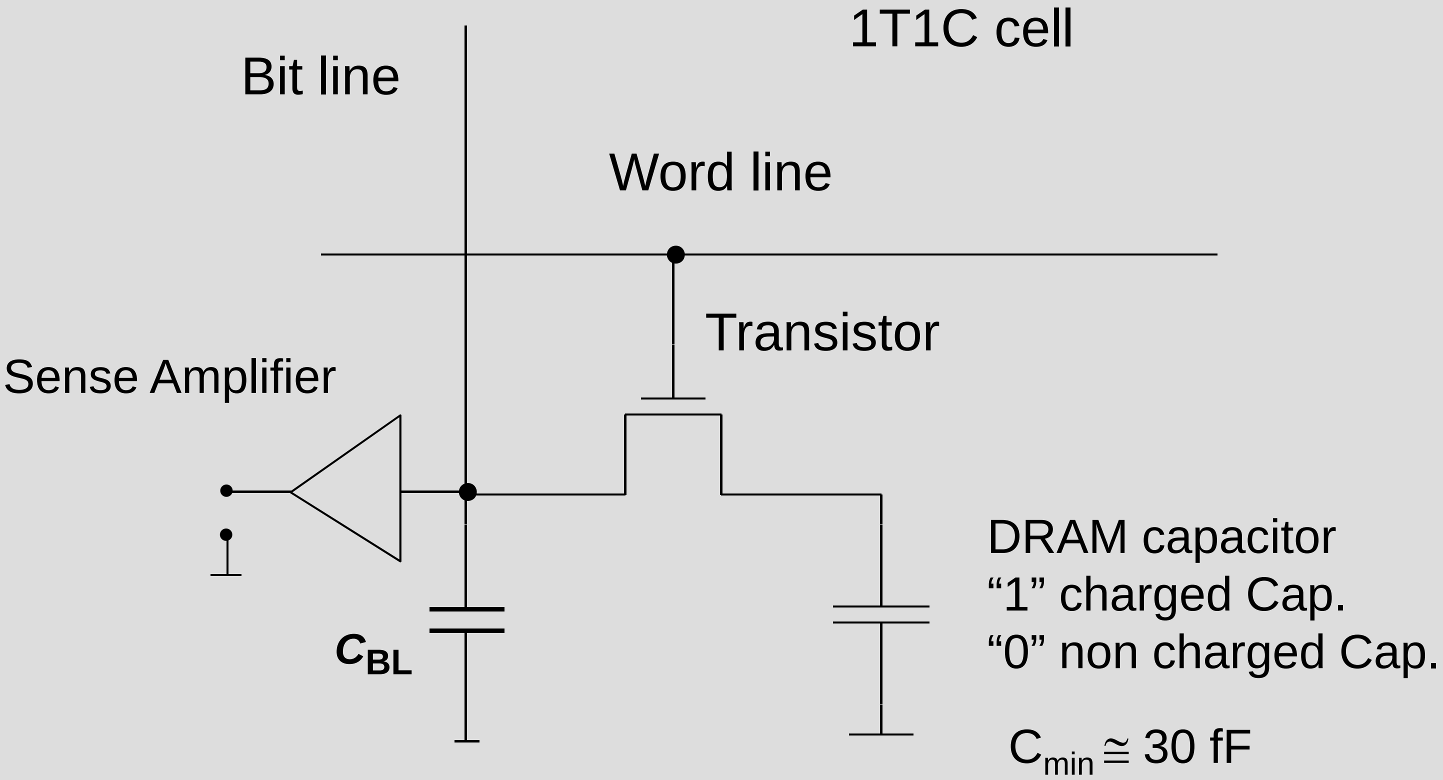
DRAM
FeRAM
SRAM
.....

Resistance Based:

MRAM
Flash
FeFET
Ovonic
....

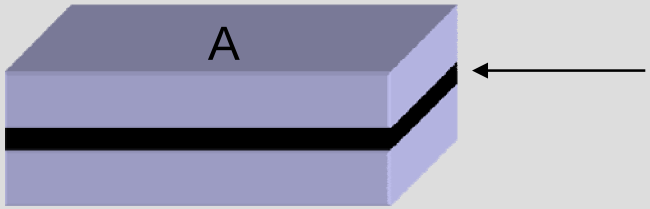
Why resistive storage Elements?

DRAM Cell


1T1C cell
Bit line
Word line
Transistor
Sense Amplifier
C_{BL}
DRAM capacitor
“1” charged Cap.
“0” non charged Cap.
$C_{min} \cong 30$ fF

Planar DRAM Capacitor

$C_{min} \cong 30$ fF



SiO_2 thickness d

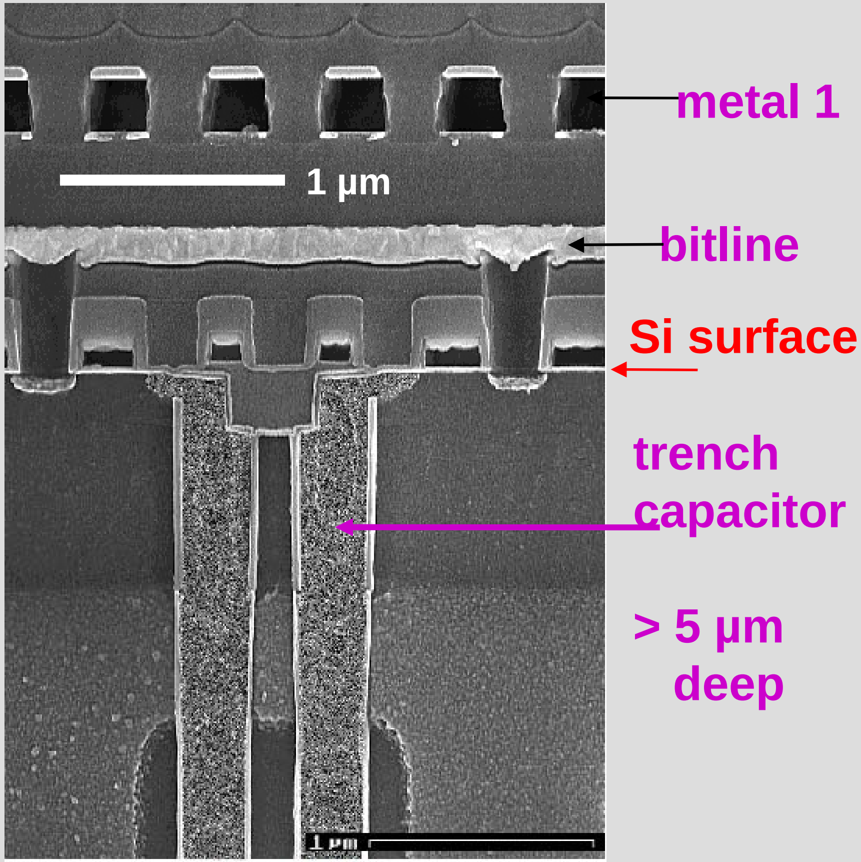
$Q = C\,U;\qquad C = \varepsilon_0 \varepsilon A / d$

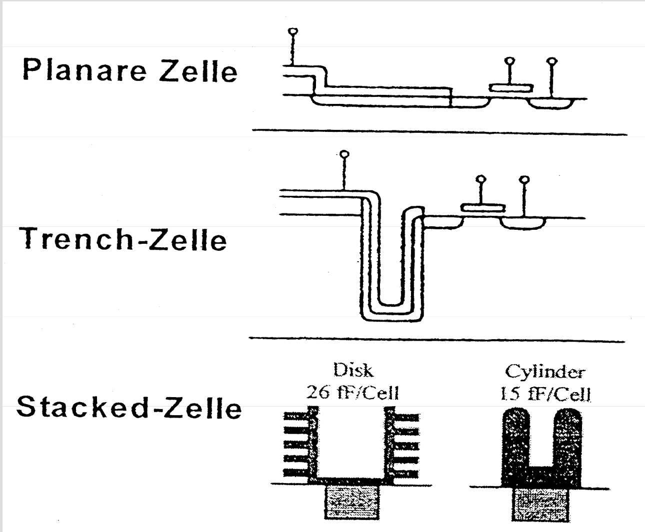
Decrease capacitor footprint (area A) $\Rightarrow$ reduces C (C_{min} limit)

- Reduce dielectric thickness d, tunneling limit (approx. 2nm)
- Increase area by using 3-D structures (keep footprint)
- Use high-k dielectrics (process compability with CMOS)

Developments: 3 D capacitors

Siemens / IBM : 1 Gbit, deep trench

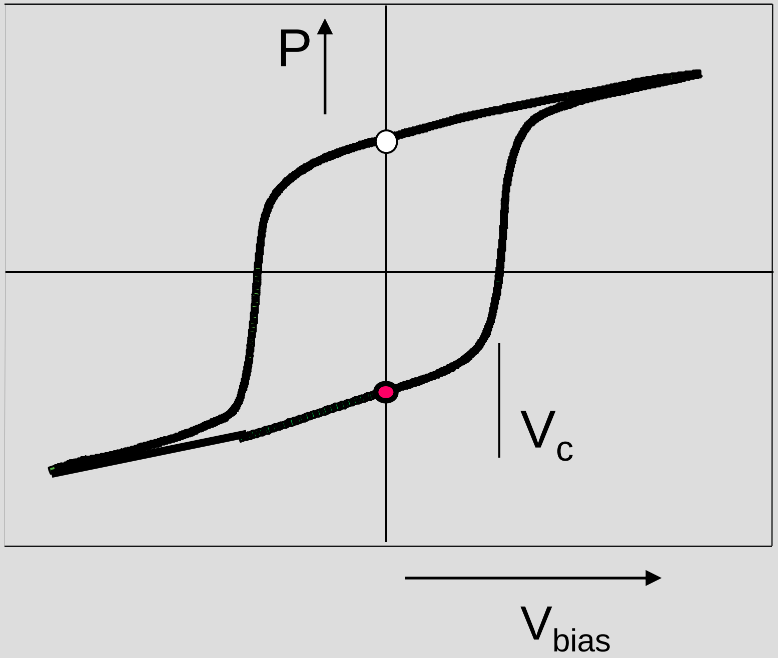


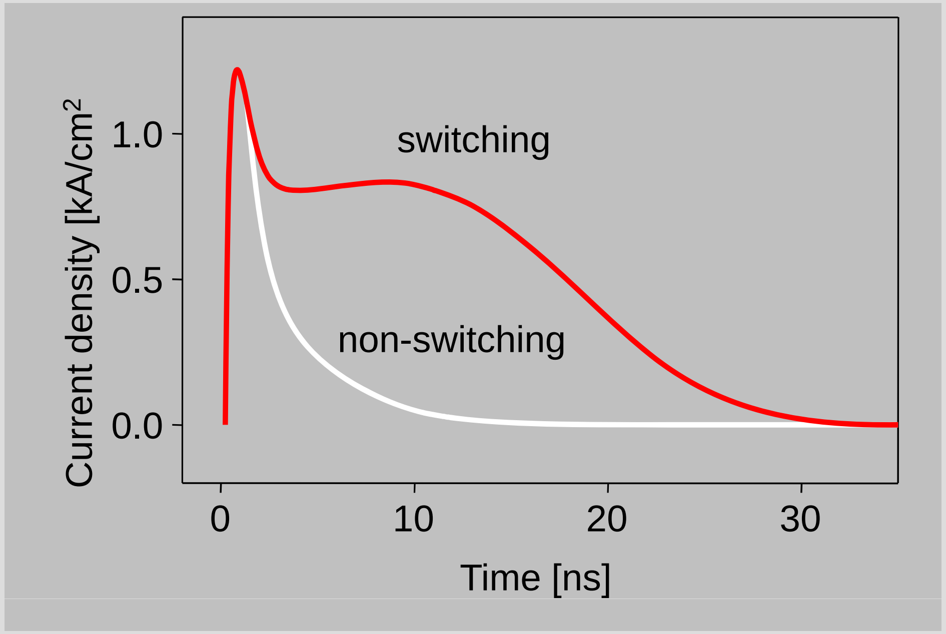


Tremendous efforts to stay on the road-map

Challenging technology – more and more expensive and complicated

FeRAM Capacitor: Pulse Polarization Switching





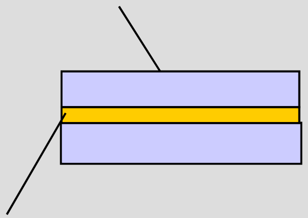
- Different remanent polarization states

  $\Rightarrow$ different **transient current behavior** to an applied voltage pulse

- Integrating the current $\Rightarrow$ switched charge Q_S and non-switched charge Q_{NS} (distinction between the two logic states)
- Destructive Readout

Scaling and 3D conformal Coverage

2D planar

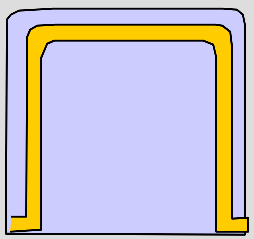


Transition from 2D to 3D technology

Minimum capacitance for sensing: 30 fF
Operation voltage 1 V
Q=CU n=Q/e
3×10^{-14}C needed for sensing: approx. 20.000 e^-

Planar capacitor:
A = 100 nm x 100 nm
$P_r = 10 \mu C/cm^2$
10^{-15} C
Q = P A
corresponds to 6000 e^- *not sufficient for data sensing!*

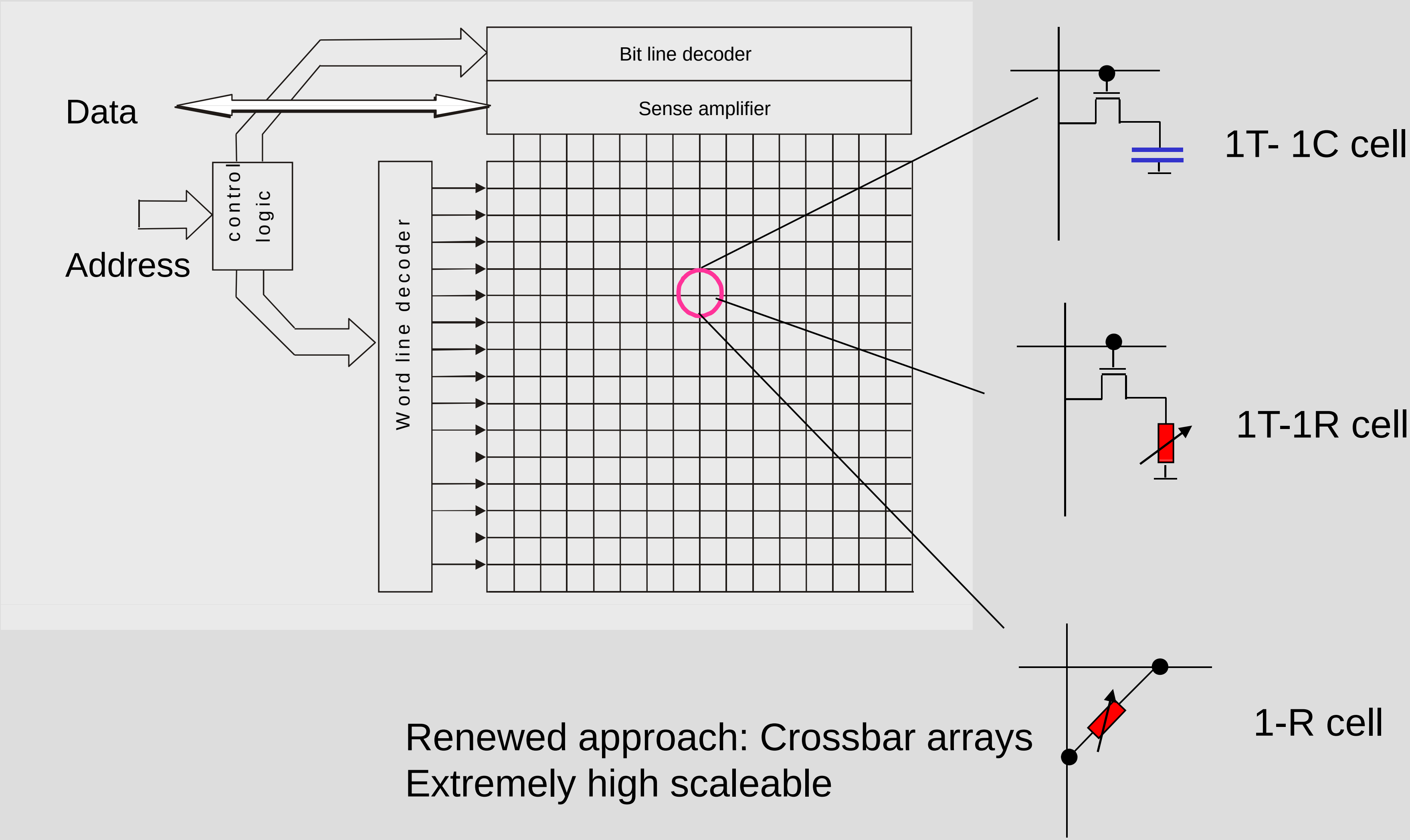
3D approach necessary!



Conformal coverage/MOCVD mandatory

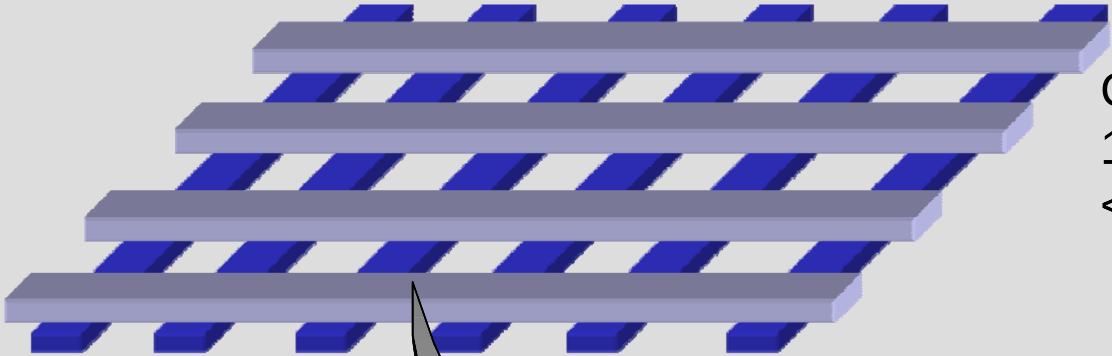
Supposed to be implemented in 2007-09 for 100 nm FeRAM node technology

Matrix Architecture: Random Access Memory



Renewed approach: Crossbar arrays
Extremely high scaleable

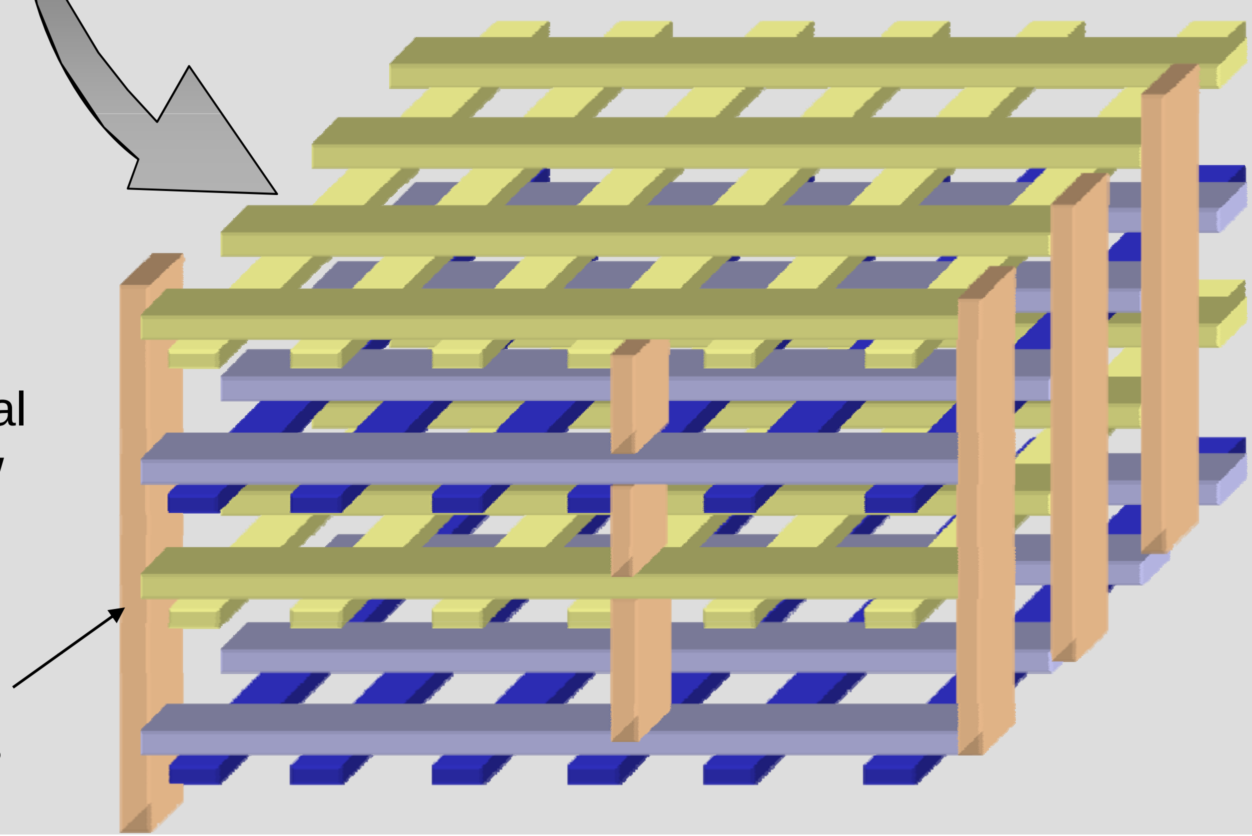
First step: Go 3-D



Crossbar resistor array
1R cells
< 10 nm feature size

3-dimensional array
by stacking:

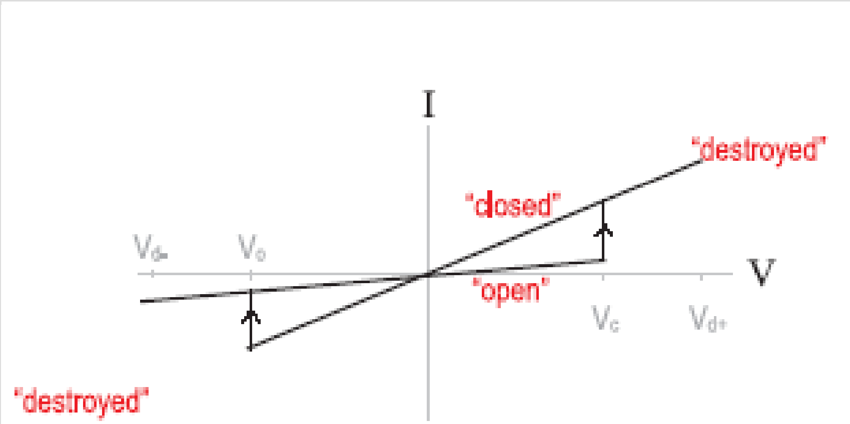
Although technological
difficult – nothing new

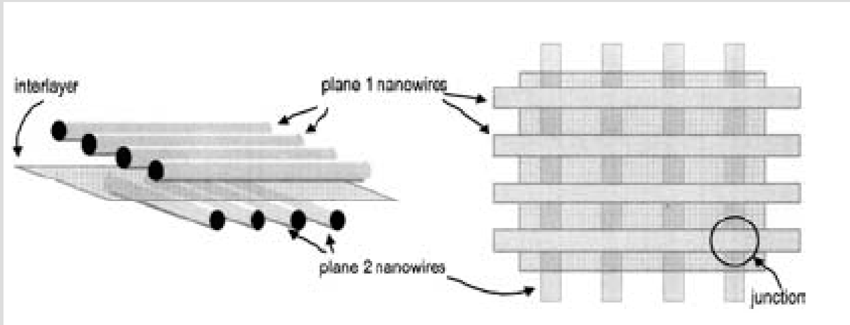


Interconnects

Second step: New Nanoelectronic Architectures

G. Snider et al., Appl. Phys. A 80, 1183 (2005) – Hewlett Packard

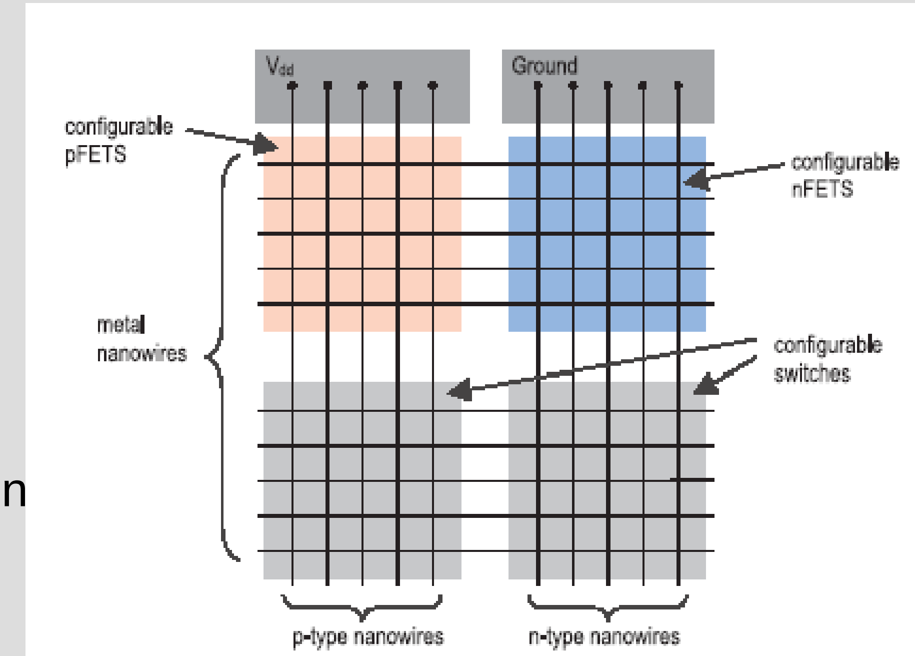




Approach:

Activate independently at the cross points different devices as:
(switchable) resistors, diodes or transistors

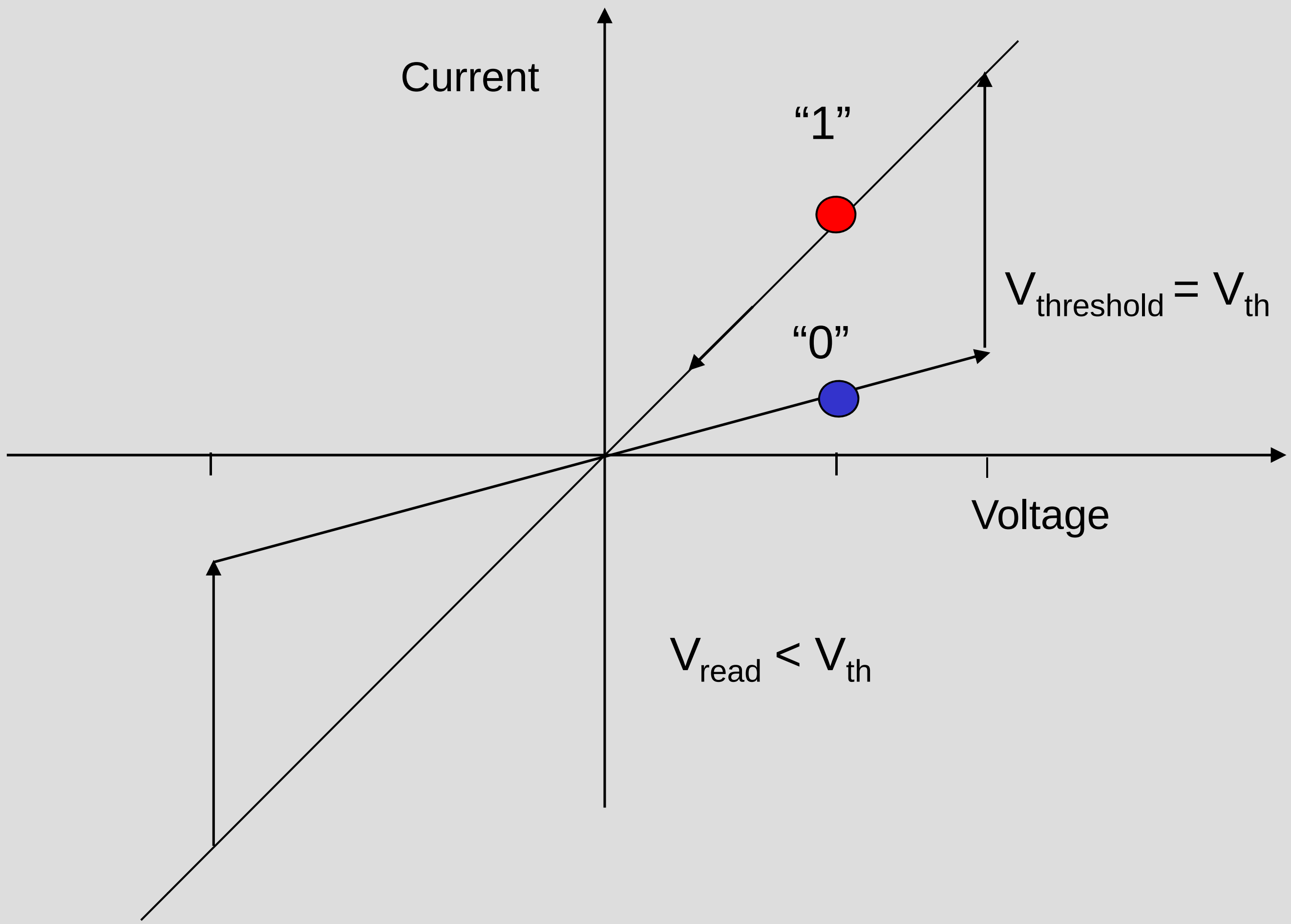
Create your own Computer **after** the fabrication process.



Beyond conventional memory architecture!
Field programmable arrays (FPGA)

The Resistive Memory Approach

Bi-stable (or multi-stable) resistors



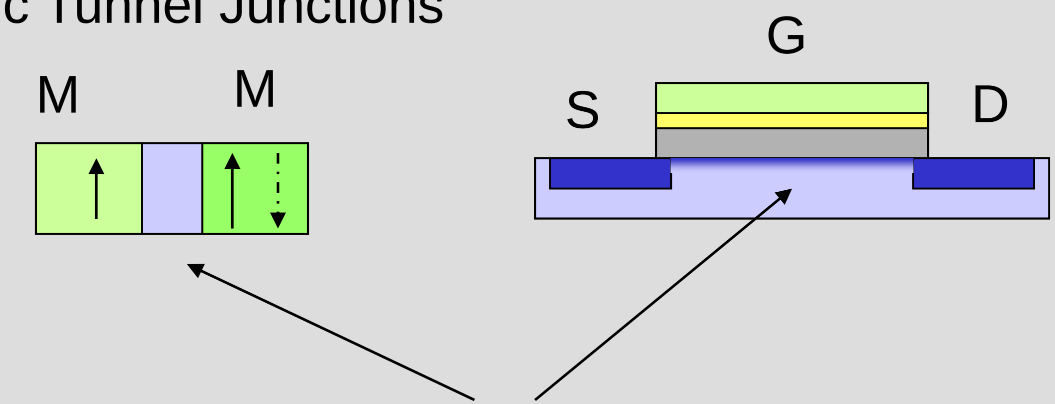
…more specific

Read a Resistance = Resistive Memory

Magnetic Tunnel Junctions

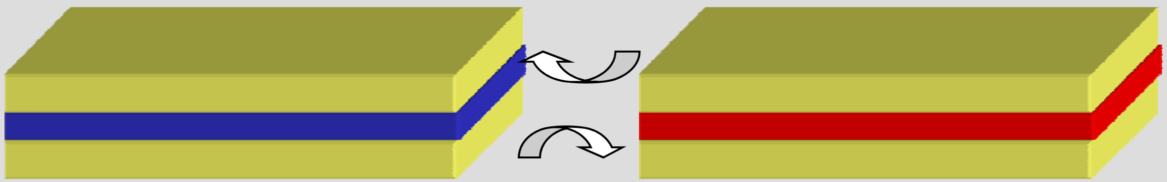
Flash

Indirect type:



No structural changes in the
transport region between on and off state

Direct type:



Structural changes

(e.g. Phase Change)

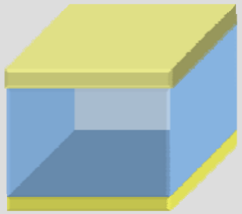
Two Parties:

Homogenous folks:
Those who believe the effect
is a volume or an interface effect across the entire
dielectric and/or interface

Filament (network) folks:
Those who believe the
effect is caused by filamanents which
are strongly localized in an inactive
surrounding

Overview Resistive Switches (Effects)

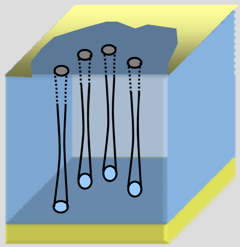
Homogeneous



? How homogeneous is the current transport - Filaments?

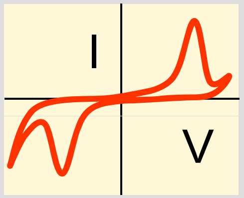
?Is a formation process important?

Local



?Which role play the interfaces?

Redox



- Red$^{\ominus}$ ⇄ Ox + e$^{\ominus}$
- Voltammogram

?Is the switching effect a pure electronic or ionic or a superposition?

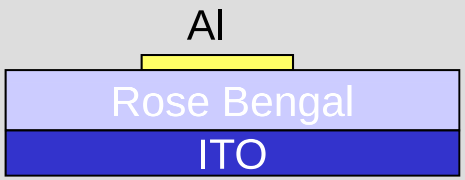
?Which kind of current transport is essential for R_H and R_L?

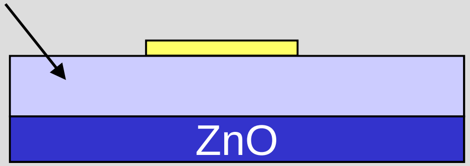
Not a surprise:

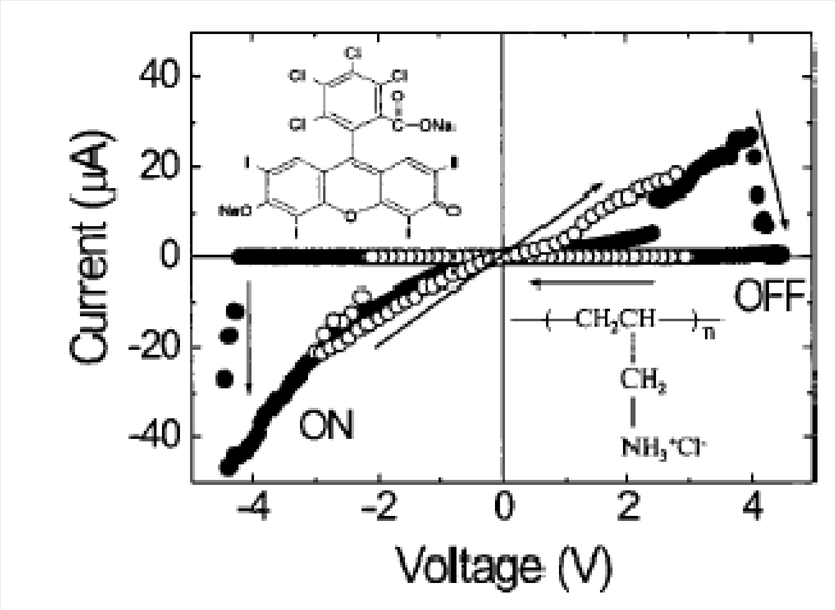
Number of models $\geq$ Number of groups in the field

Device Examples…

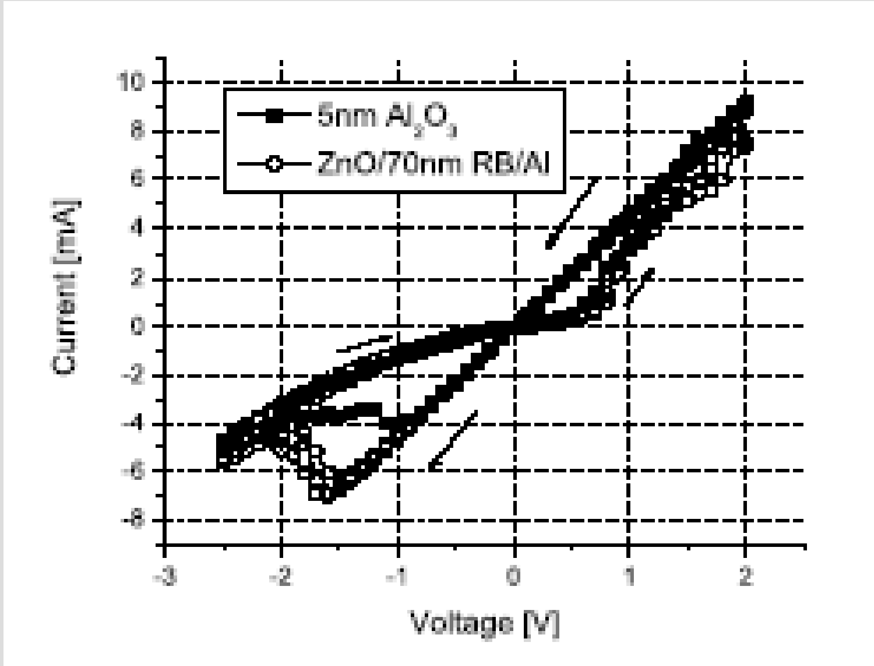
Examples: Organics







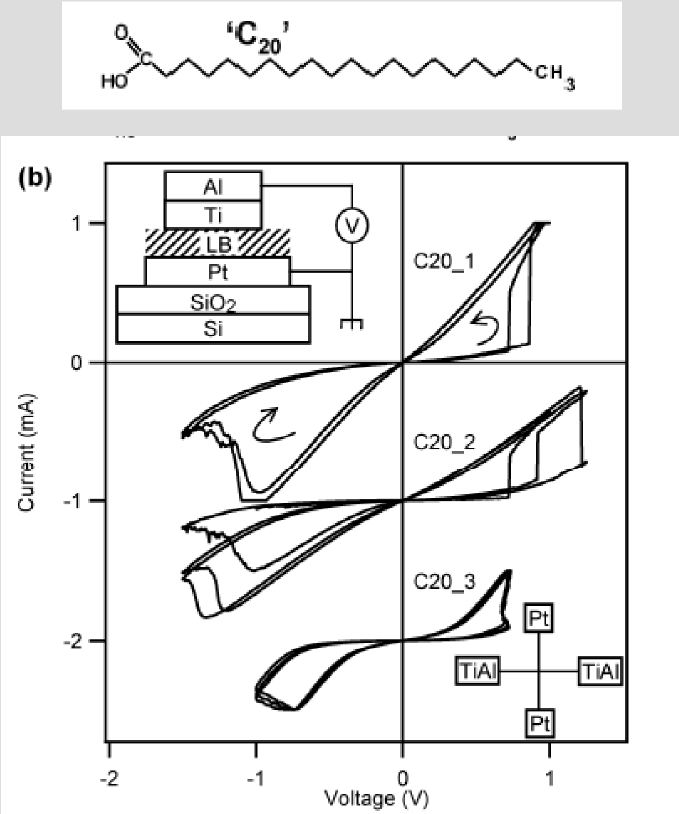
A. Bandyopadhyay and A. J. Pal,
APL **82**, 1215 (2003)

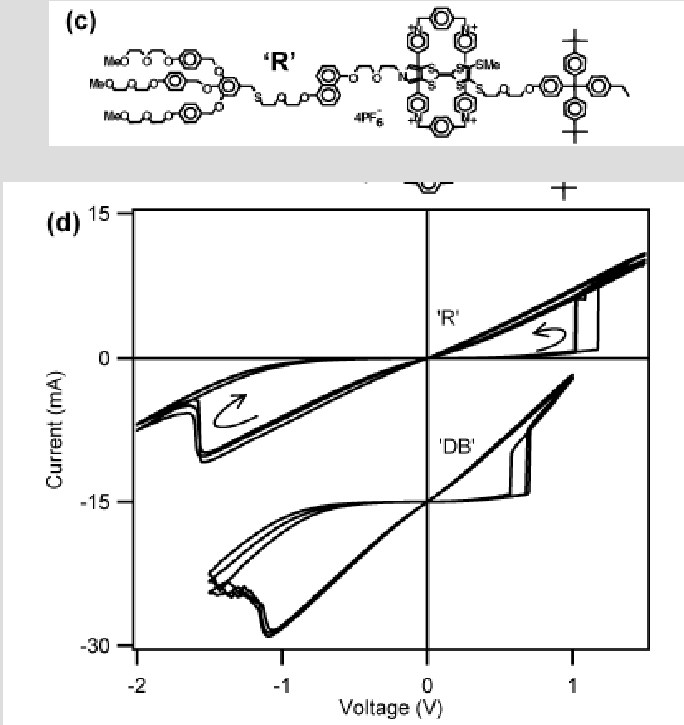


B. Lüssem et al.,
submitted to J. Appl. Phys.

Even without the Polymer, the I-V curves look very similar!

Organics

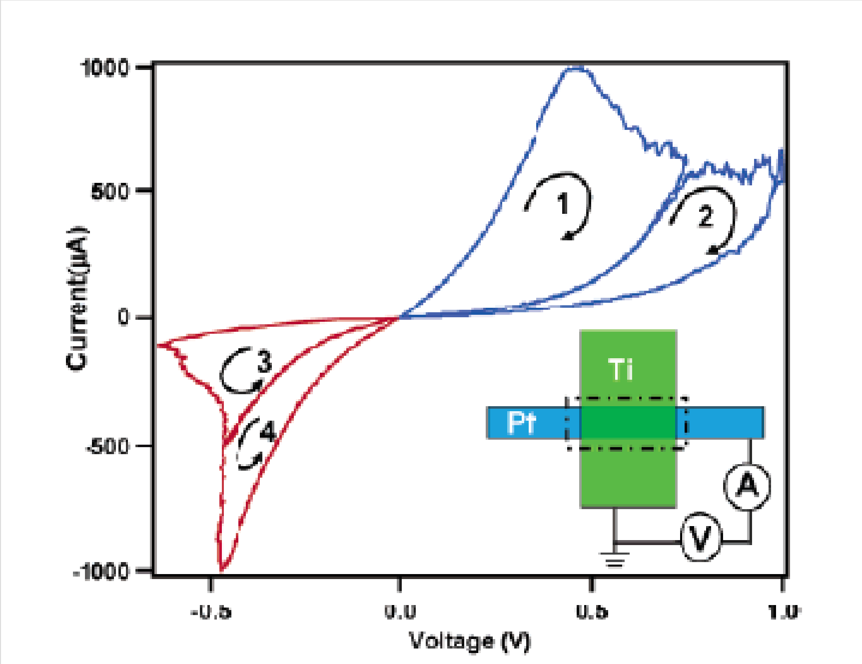


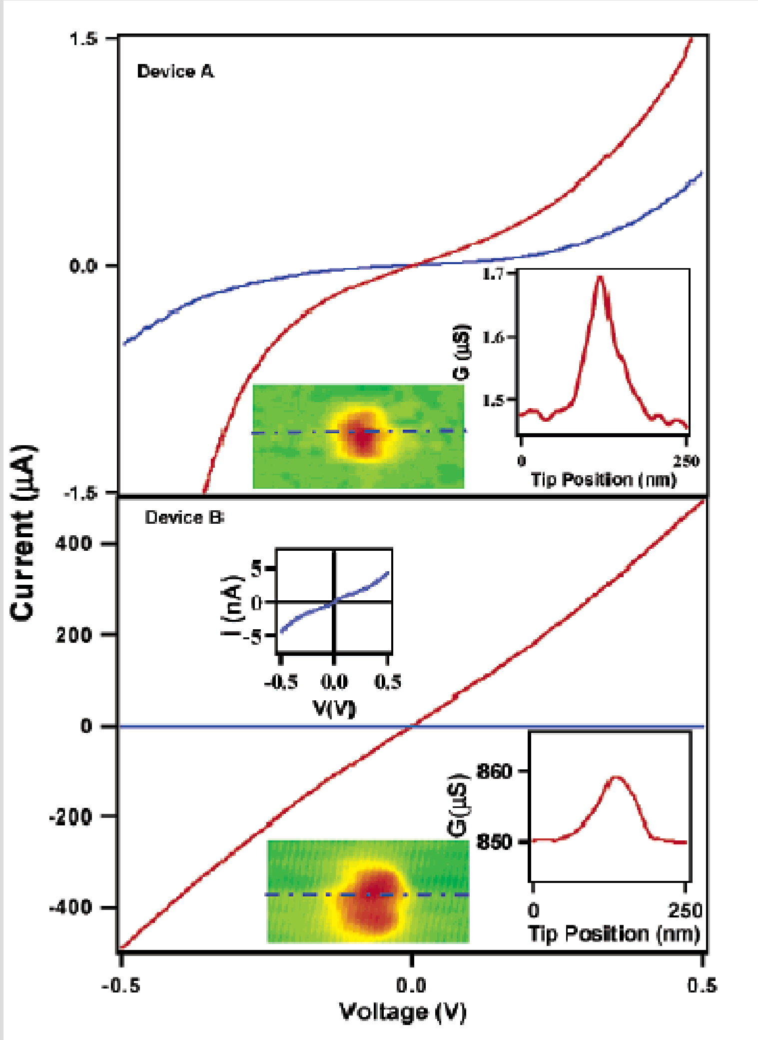


D. R. Stewart et al, Nano Letters 4, 133 (2004). HP

Very different organics show very similar I_V curves!

Organics



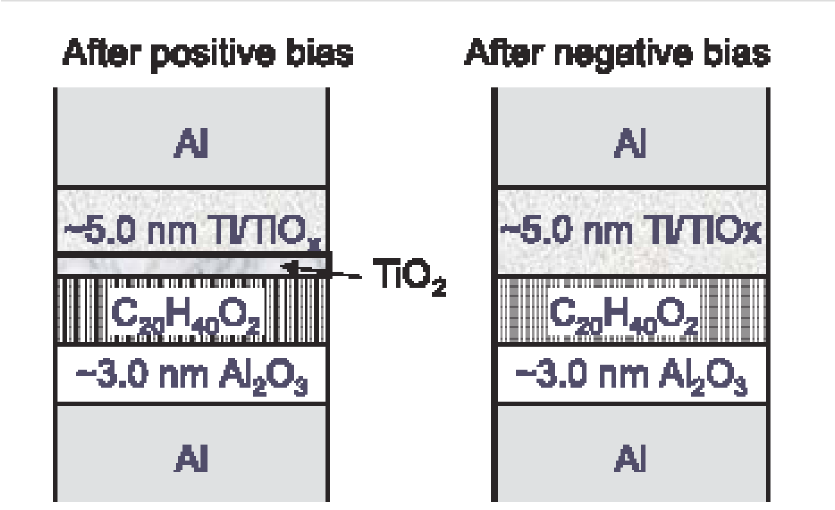


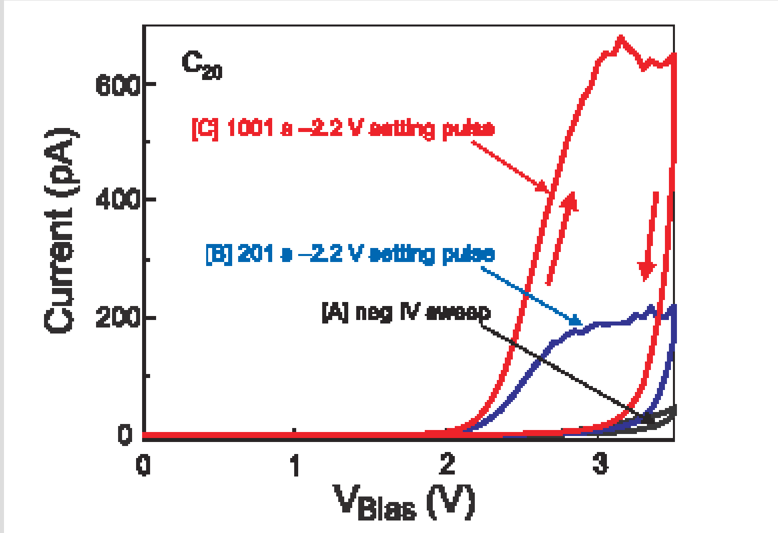
C. N. Lau et al., Nano Lett. 4, 569 (2004).
Hewlett-Packard

Conductive bridges (filaments) !

An Electrochemical Interface Model

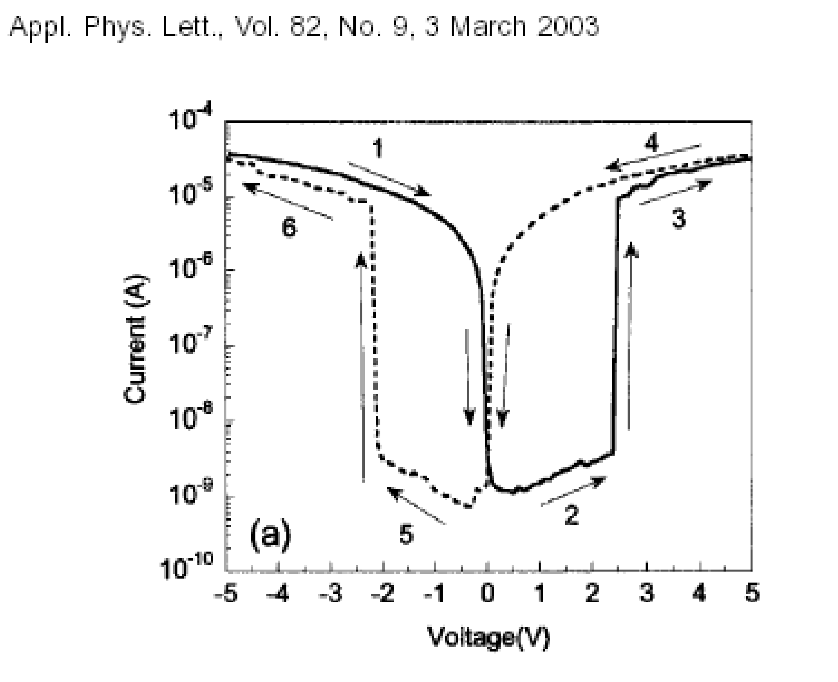
C. A. Richter et al., Appl. Phys. A **80**, 1355 (2005).

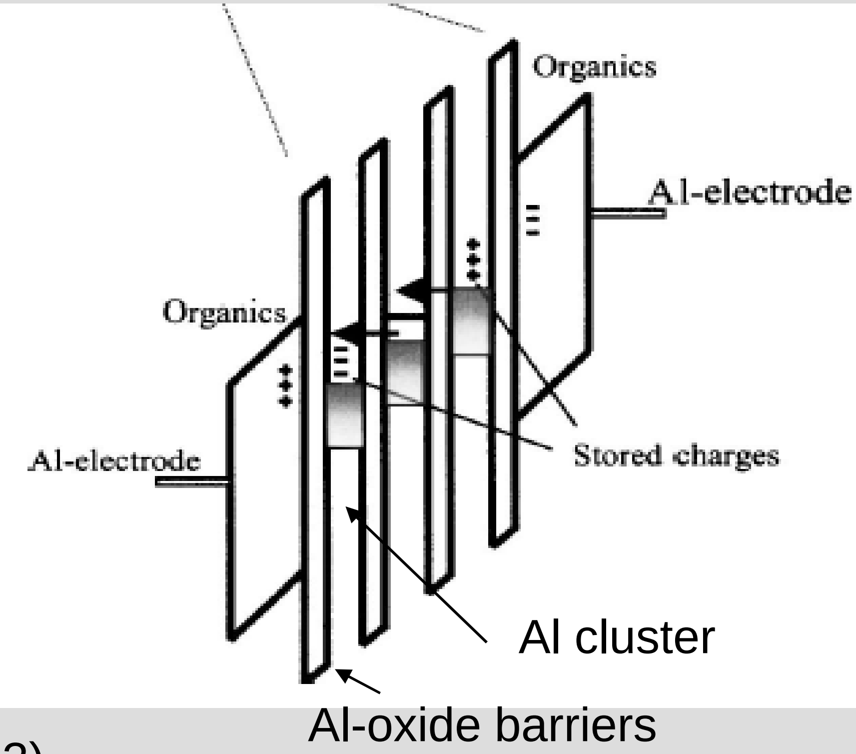




Oxidation and reduction of the Ti interface layer results in a bi-stable resistance.

Electron Trap Model: An Example





Ma et al., Appl. Phys. Lett. **82**, 1419 (2003).

Effect: Charging (decharging) by electrons in the (top) and (bottom) barriers
→ Change of the conductance of the adjacent organics.

See also: Nonvolatile Memory with Multilevel Switching: A Basic Model, M. J. Rozenberg, I. H. Inoue, and M. J. SánchezPhys. Rev. Lett. 2004

Examples: Inorganics

Material: *Transition metal oxide* Nb_2O_5 *(or sub-oxides)*

Based on: Nb-Nb_2O_5-Bi

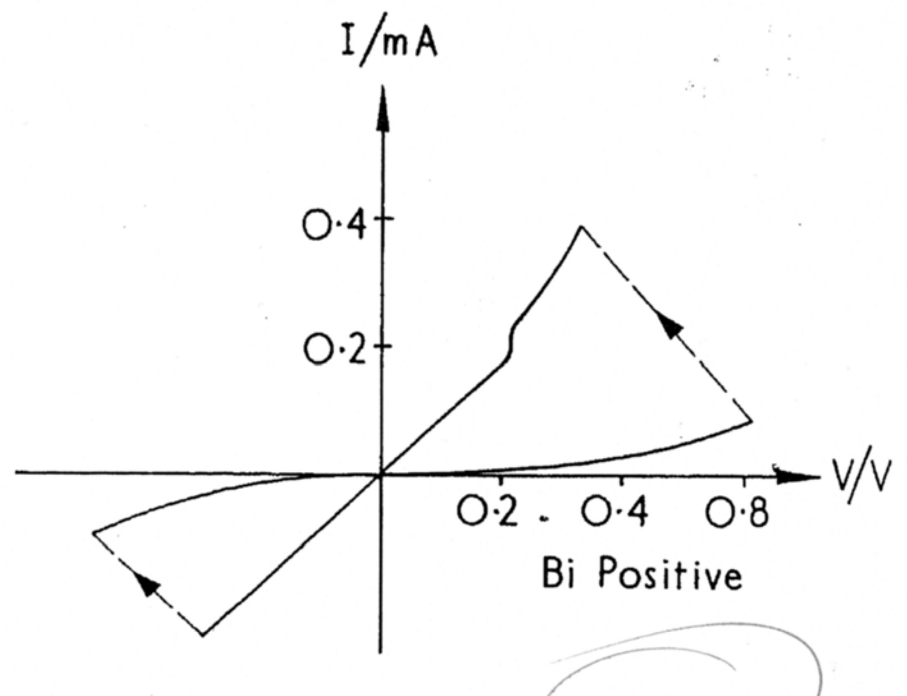


FIGURE 5 Showing memory states for Nb-Nb_2O_5-Bi structure. After Hickmott and Hiatt[18].

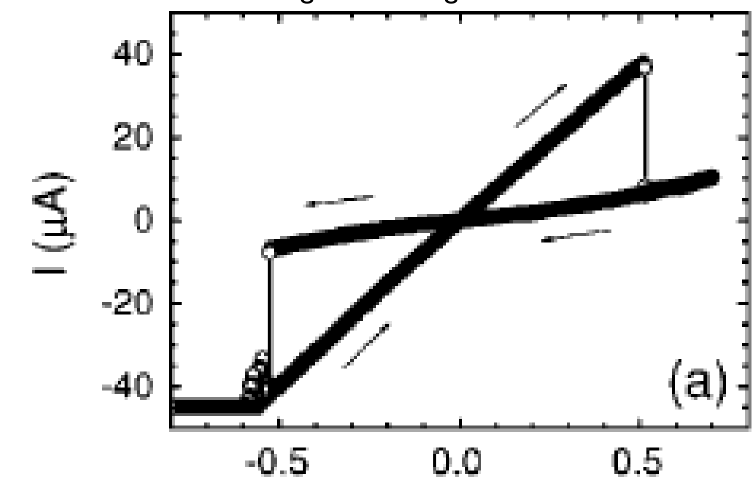
Year: 1977

D. P. Oxley, Electrocomp. Sci. and Techn. **3**, 217 (1977) and references therein

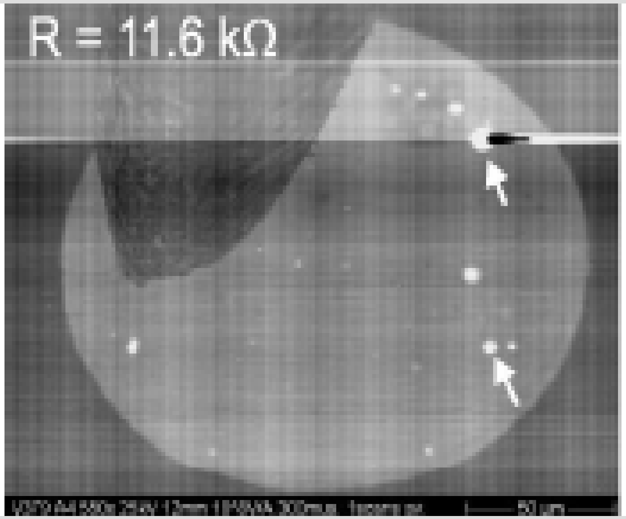
Inorganics

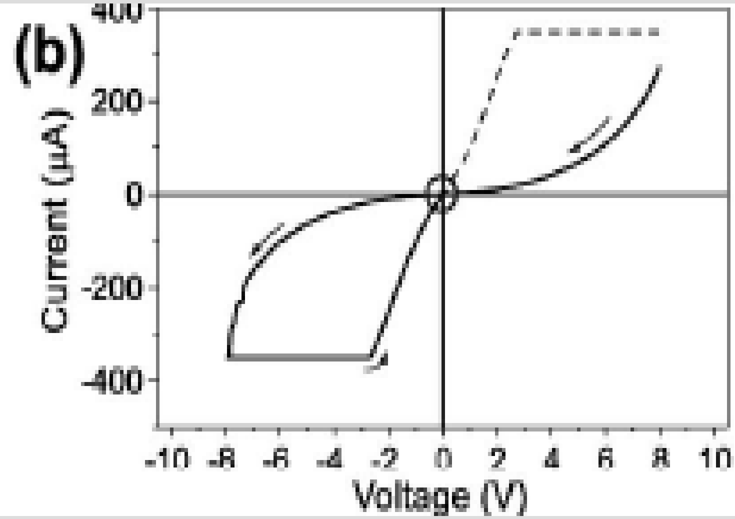
A. Beck et al., APL 77, 139 (2000)
IBM, IBM Zürich

$SrRuO_3/SrZrO_3$:Cr0.2%/Au



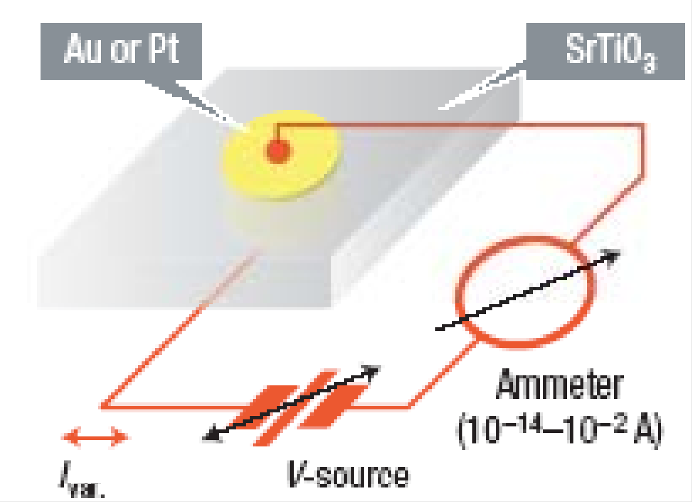
$SrRuO_3$ /SrZrO3:Cr0.2%/Pt

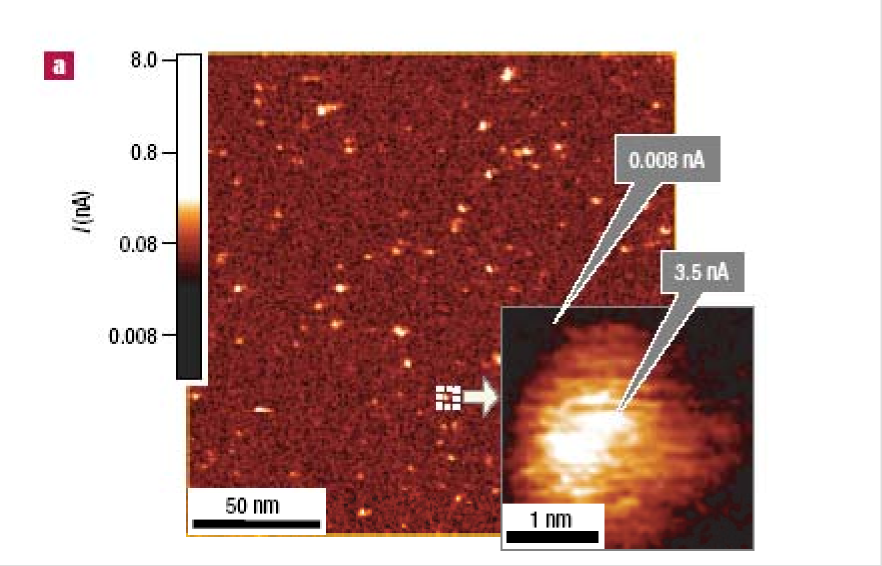




C. Rossel et al., J. Appl. Phys. 90, 2892 (2001). EBIC plus transport measurement
IBM Zürich

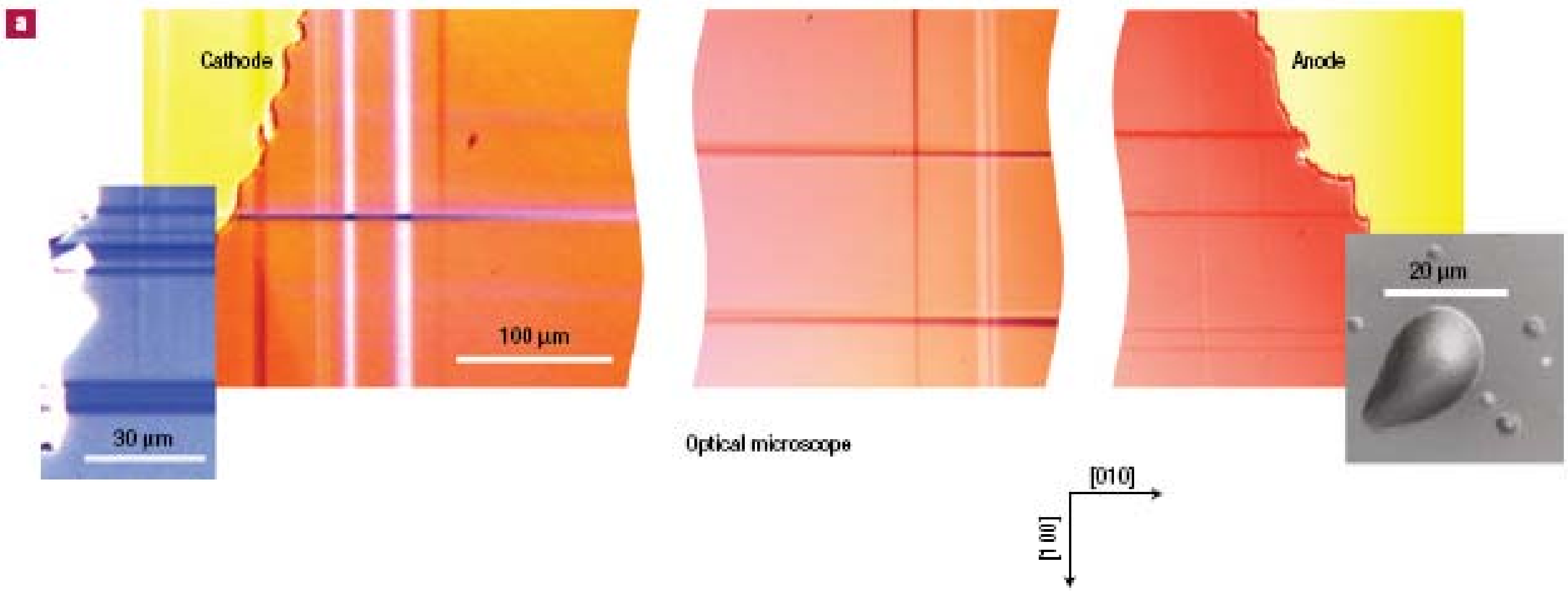
Resistive switching in $SrTiO_3$





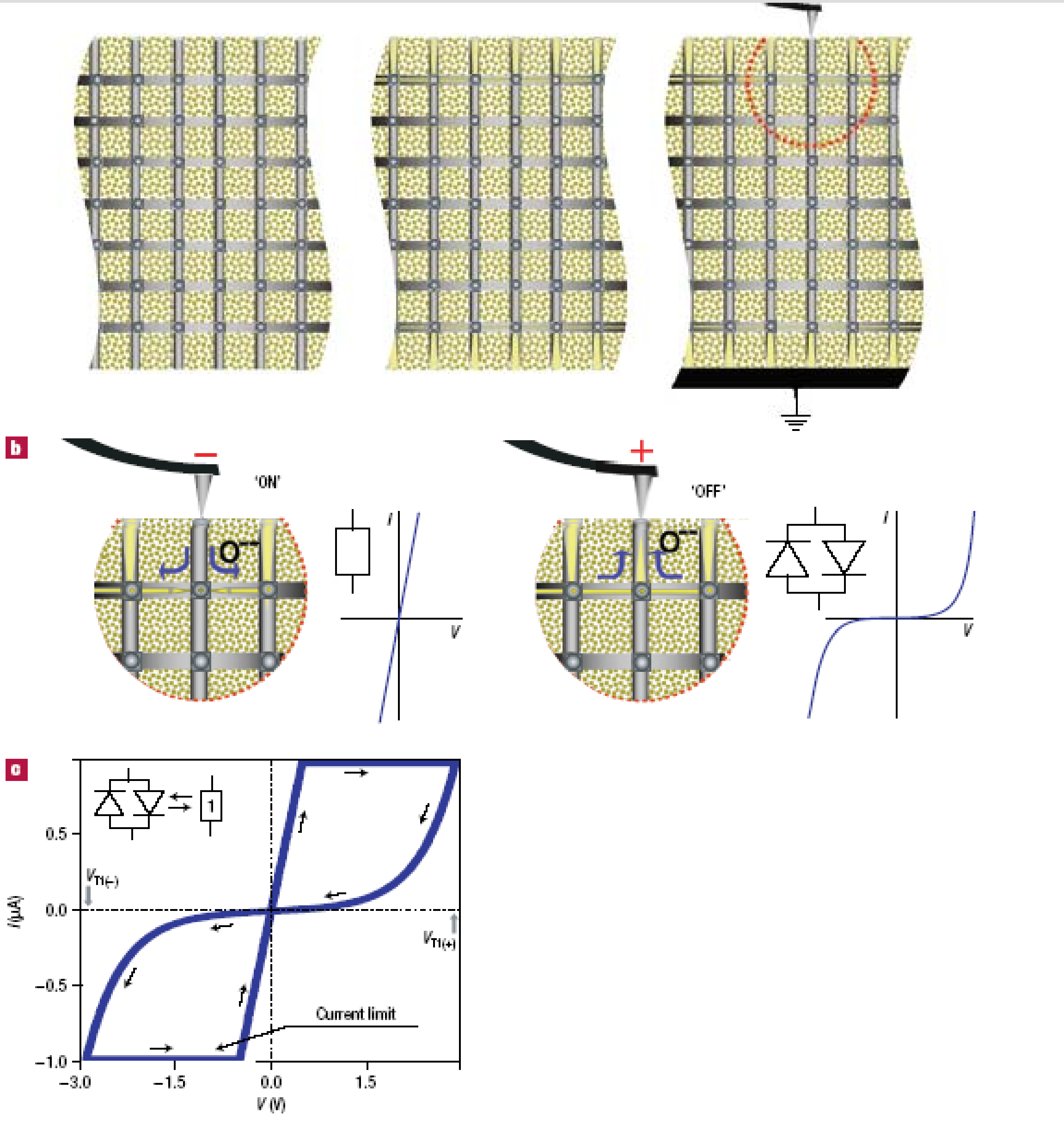
Switching the electrical resistance of individual dislocations in single-crystalline SrTiO3
K. Szot, W. Speier, G. Bihlmayer and R. Waser
Nature Materials 2006

Optical Inspection



K. Szot et al., Nature 2006

Filament formation

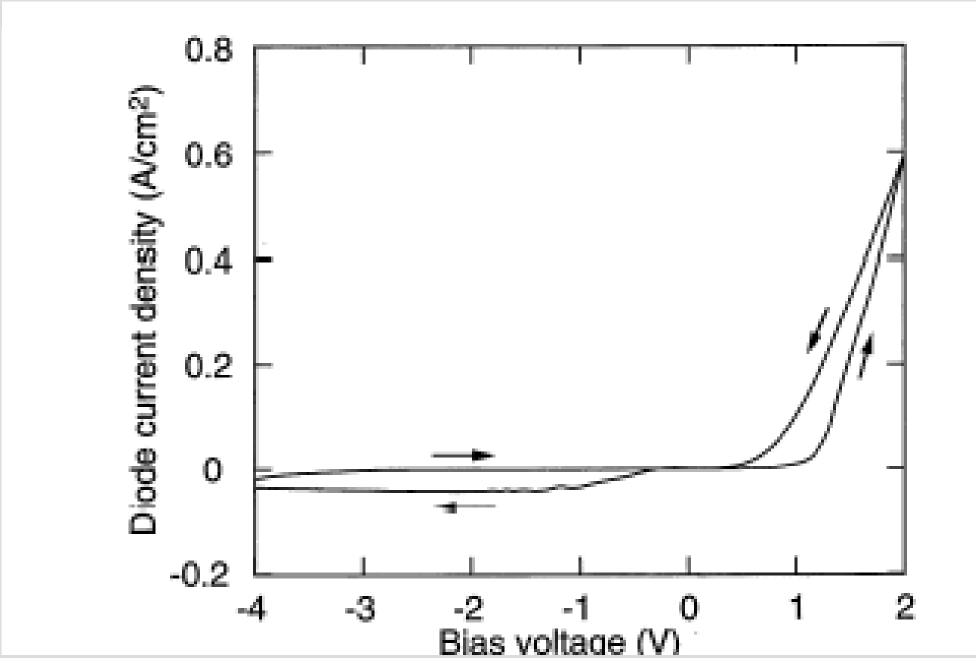


K. Szot et al., Nature 2006

Ferro-Resistive Switch

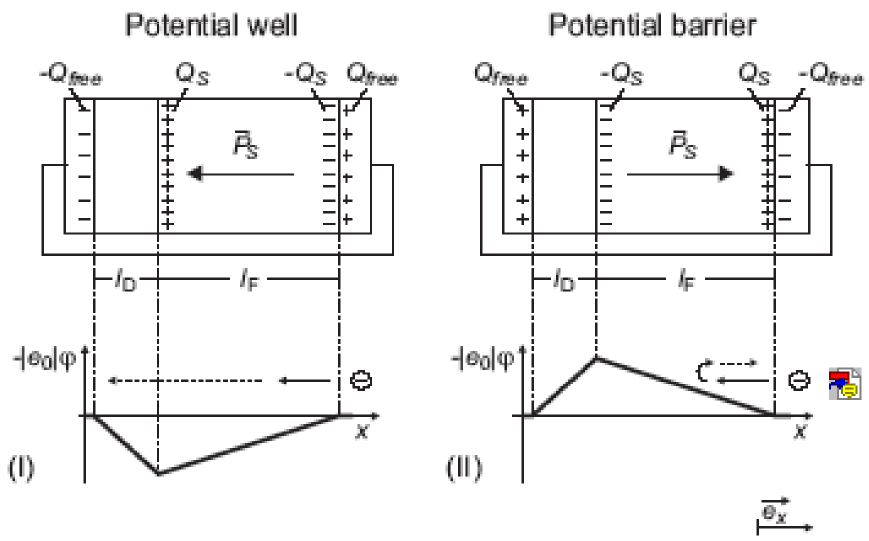
Material: $PbZr_xTi_{1-x}O_3$ *(ferroelectric-semiconductor)*

Based on: Pt-PZT-Nb:SrTiO3



K. Gotoh et al., Jpn. J. Appl. Phys. **35**, 39 (1996).

Ferroresistive Switching

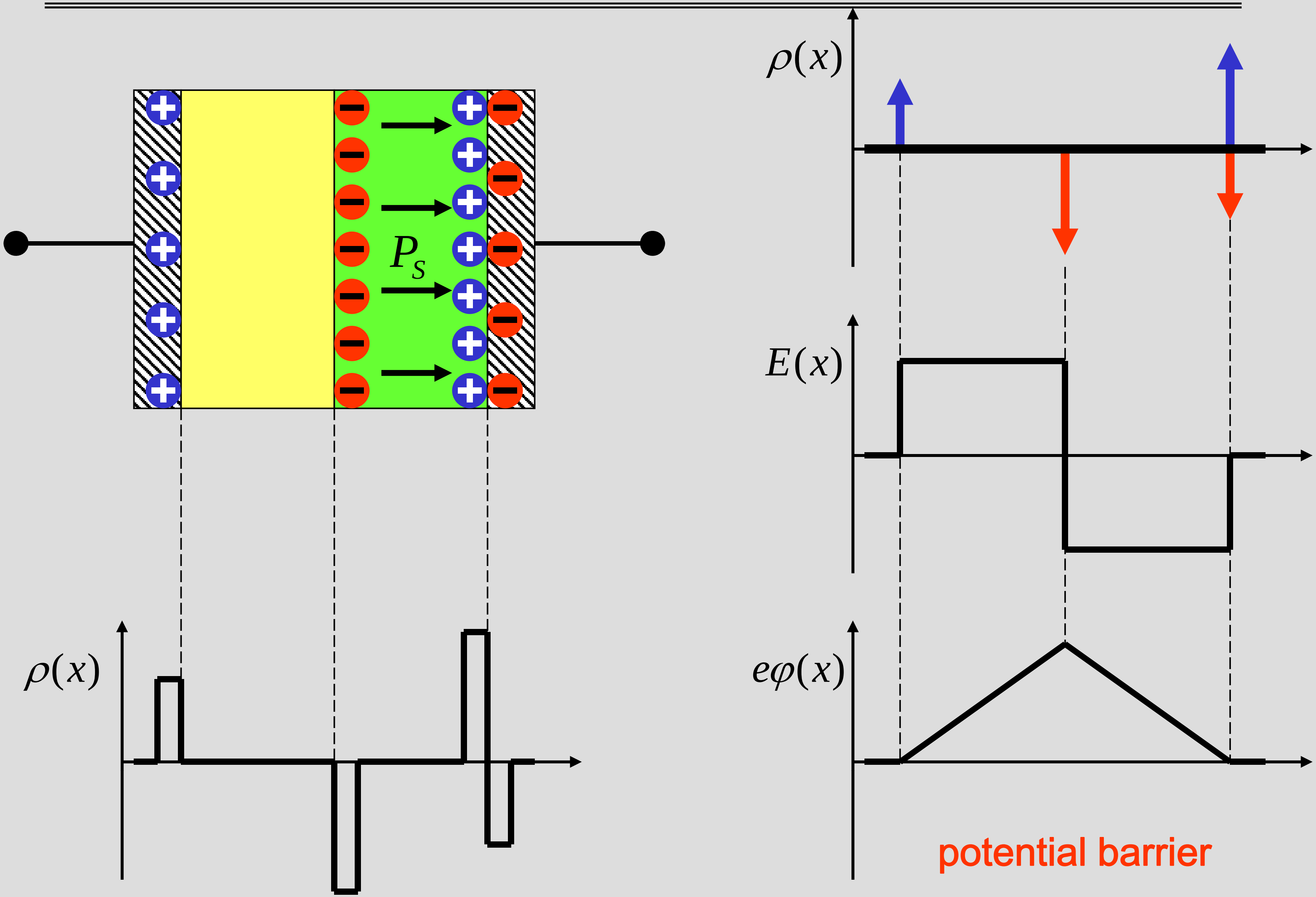


Self-consistent steady state solution:
Drift-Diffusion transport
and the Poisson equation.

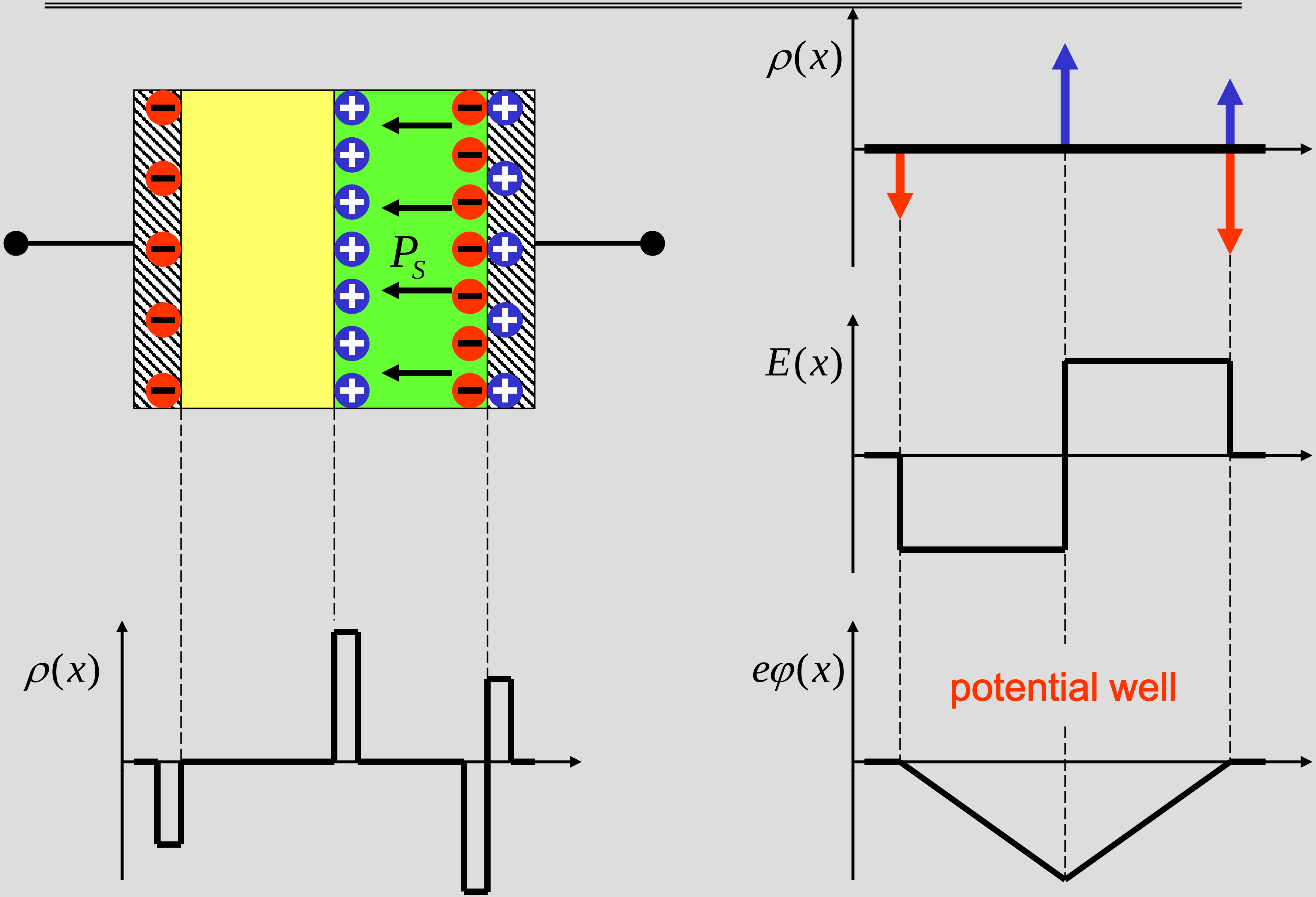
1-D Simulation of a Novel Nonvolatile Resistive Random Access Memory Device
R. Meyer and H. Kohlstedt
to be published in IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control

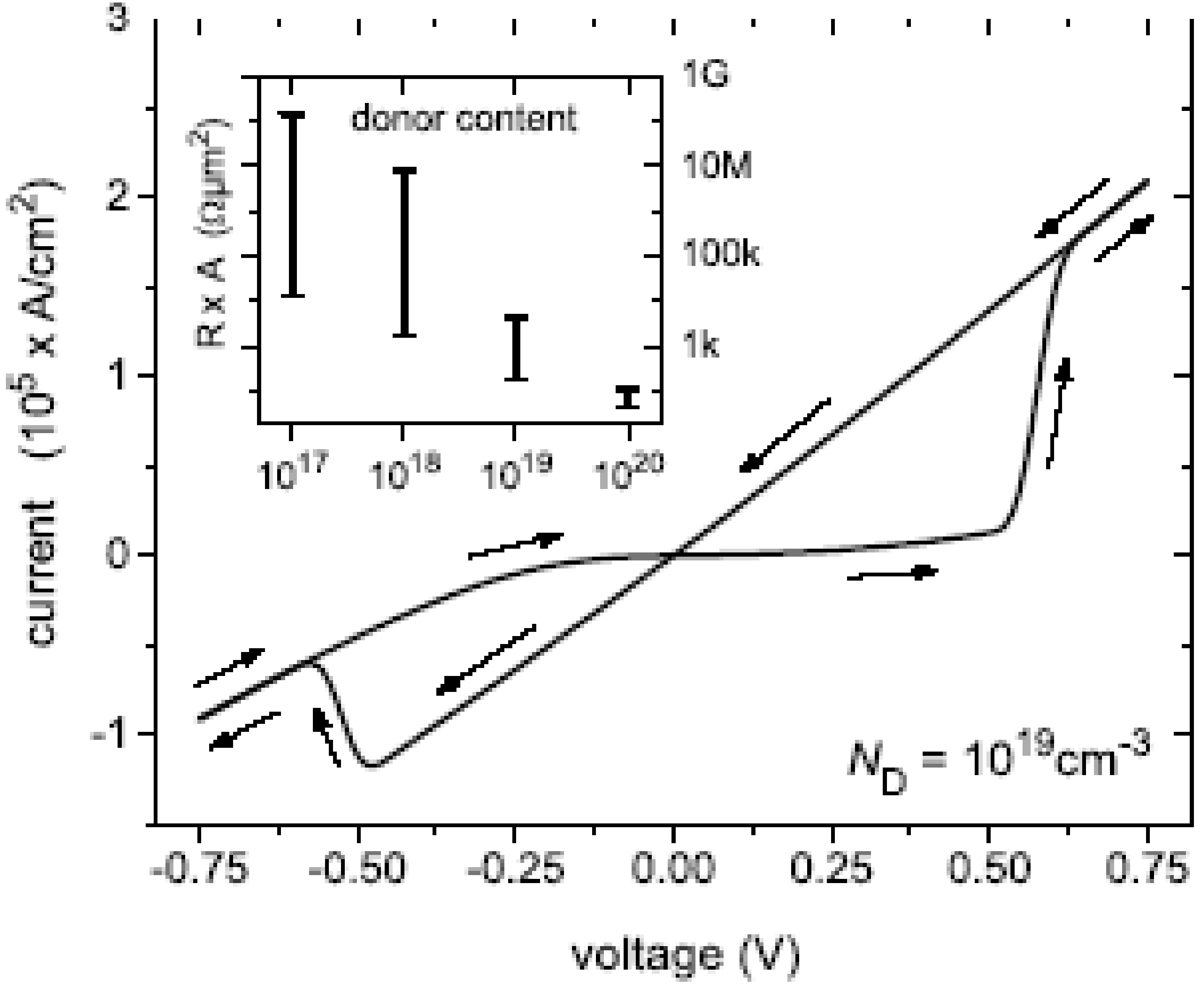
K. Gotoh et al.,
Jpn. J. Appl. Phys. **35**, 39 (1996).

FerroResistive-RAM



FRRAM

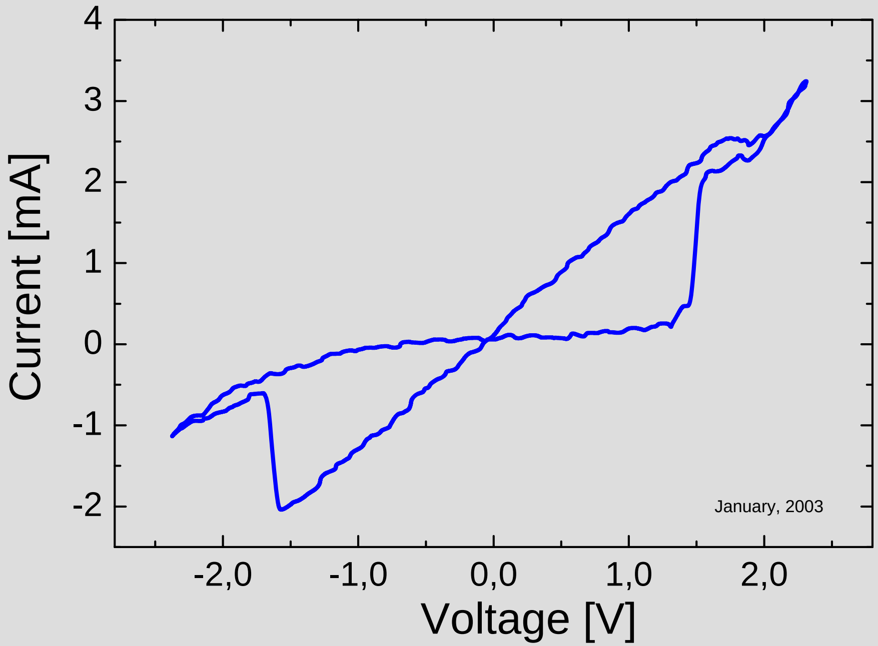




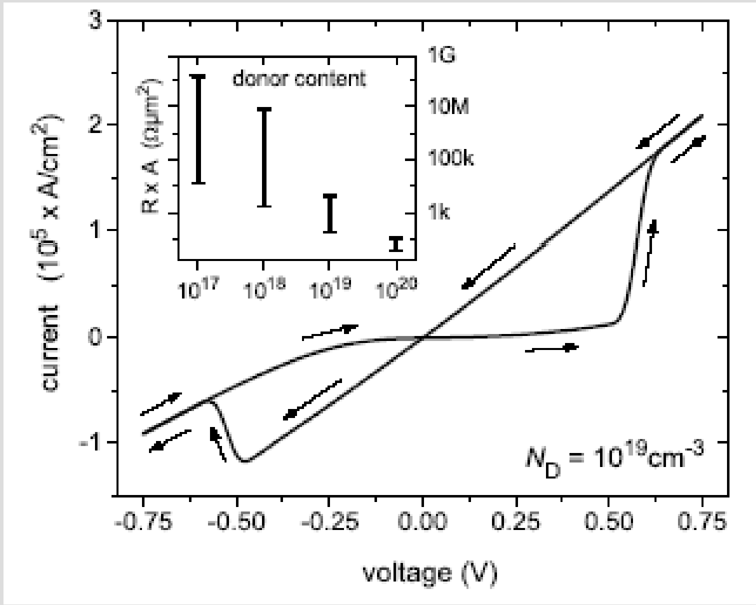
current (10^5 x A/cm^2)
voltage (V)
-0.75
-0.50
-0.25
0.00
0.25
0.50
0.75
3
2
1
0
-1
donor content
R x A (Ωμm^2)
1G
10M
100k
1k
10^17
10^18
10^19
10^20
N_D = 10^19 cm^-3

How to distinguish a ferroelectric origin from a non-ferroelectric one?

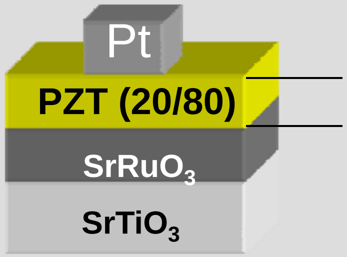
Experimental result



Numerical model



R. Meyer



Thickness: 6.4 nm

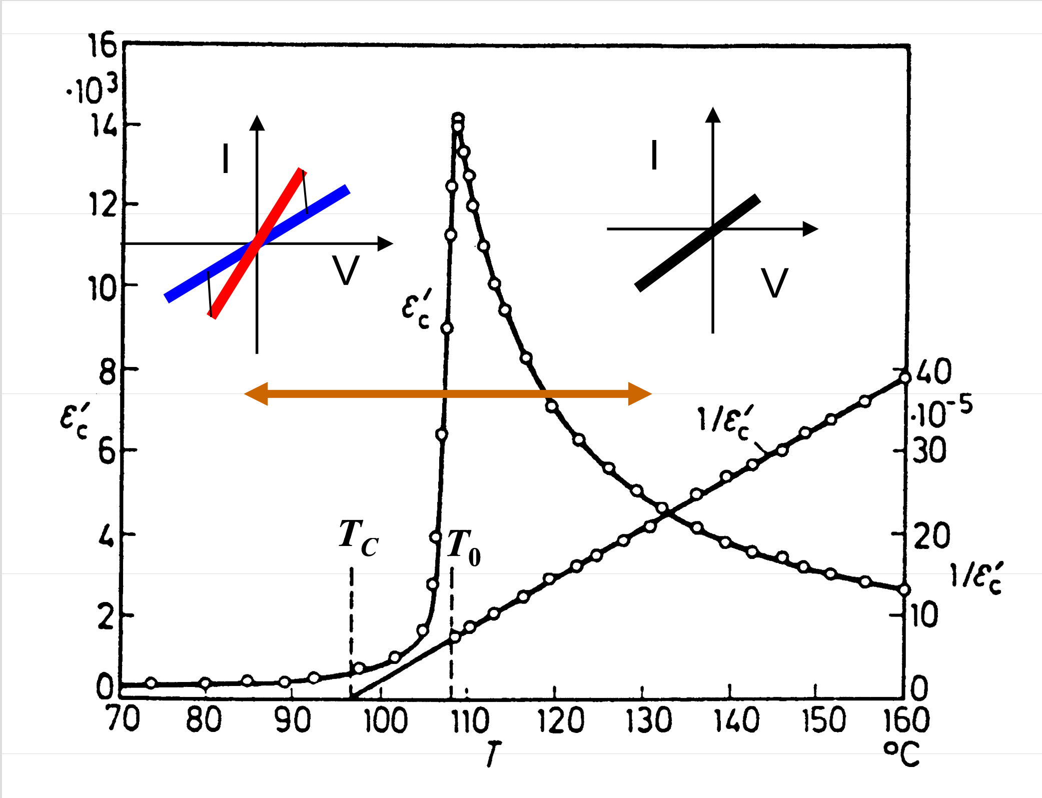
Area: 3 µm^2

Although the curves look similar – its not a proof!

Resistive Switching and Ferroelectric Origin
(across T_c)

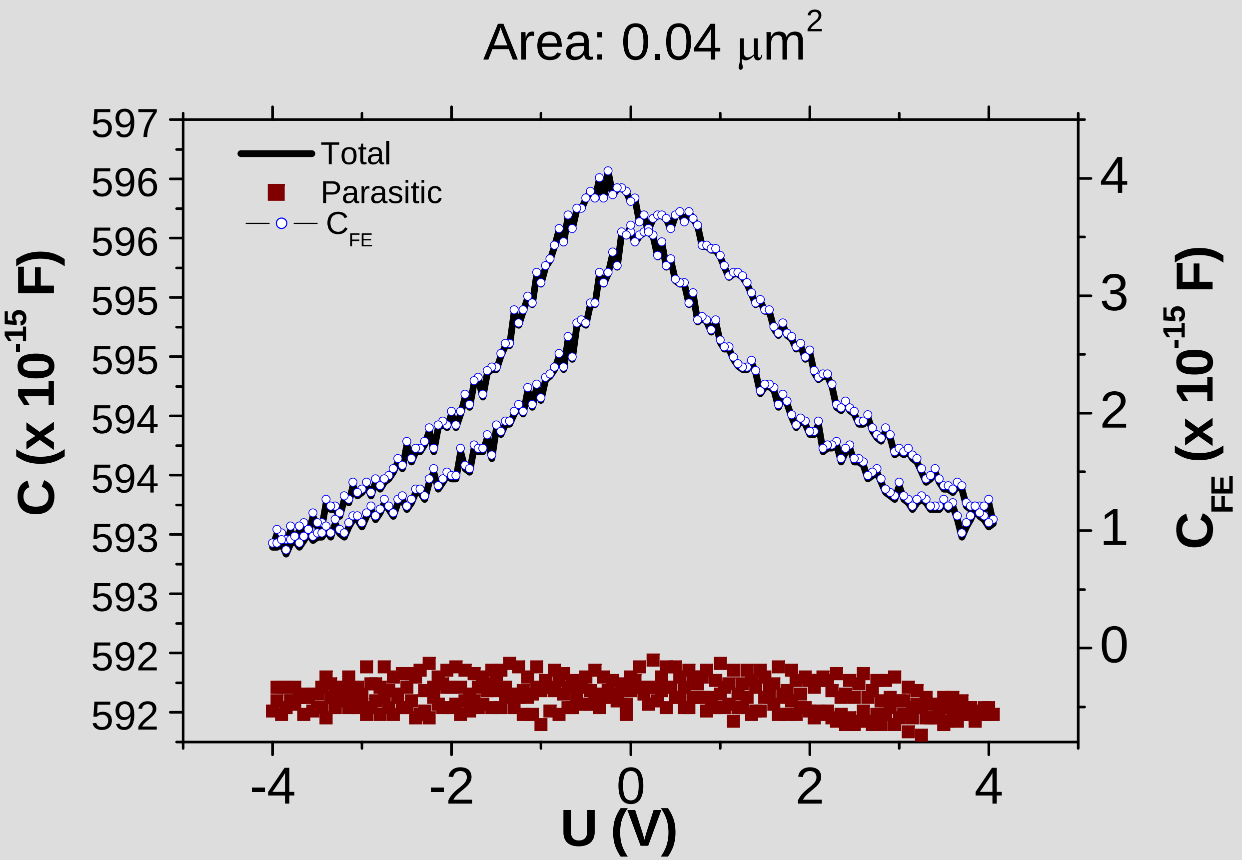
Switching ($T < T_c$) **no switching ($T > T_c$)**

$BaTiO_3$
Bulk



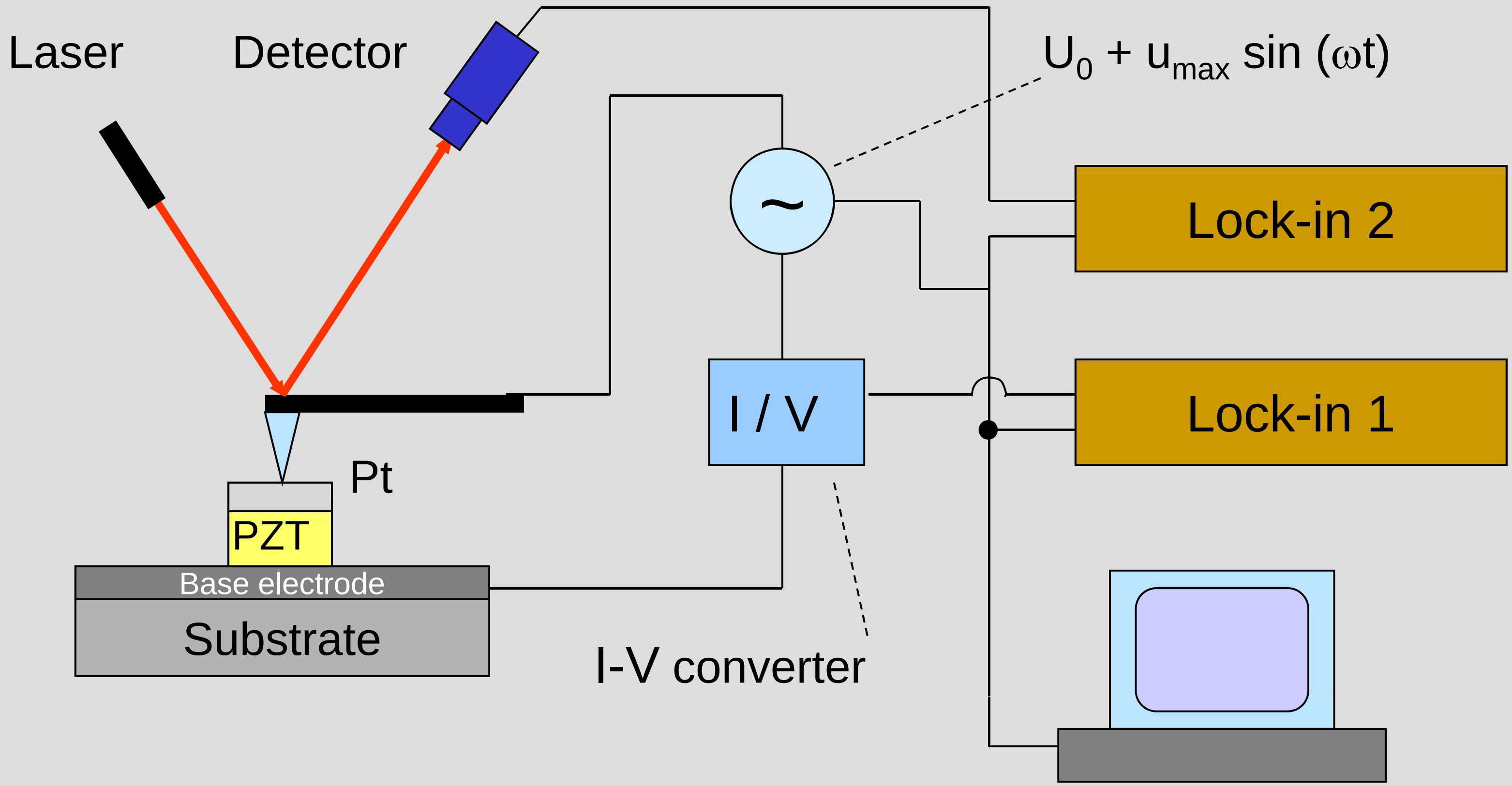
but in (ultra) thin films: T_c not known
broad phase transition
T_c modified by external field ➡ Interpretation difficult

Resistive Switching and Ferroelectric Origin



Simultaneous Measurement of different FE-Properties

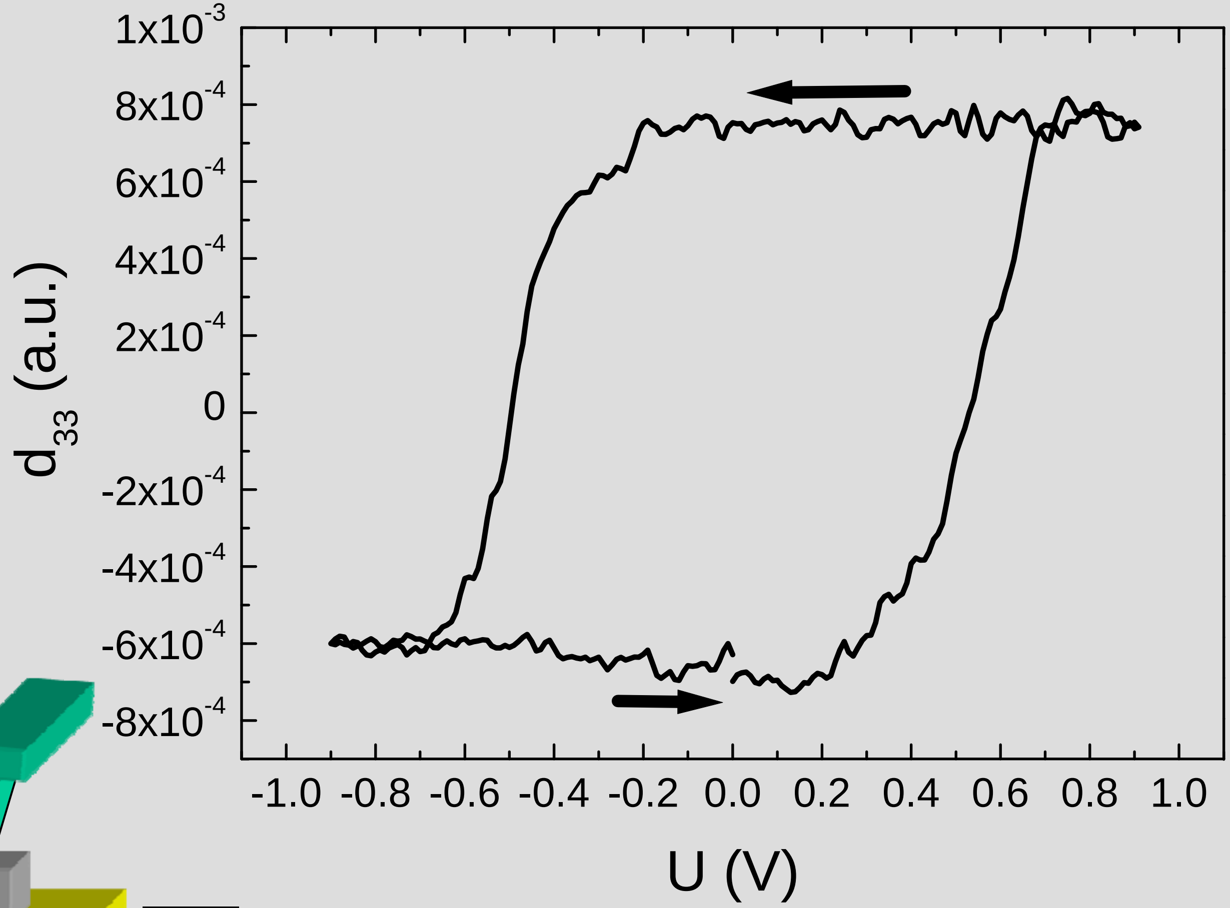
A. Petraru et al., to be published in Appl. Phys. A

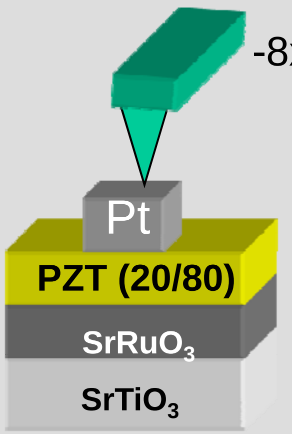


To measure d_{33}, C and I (resistive) vs. bias voltage simultaneously

Resistive Switching and Ferroelectricity

d_{33} vs. Bias

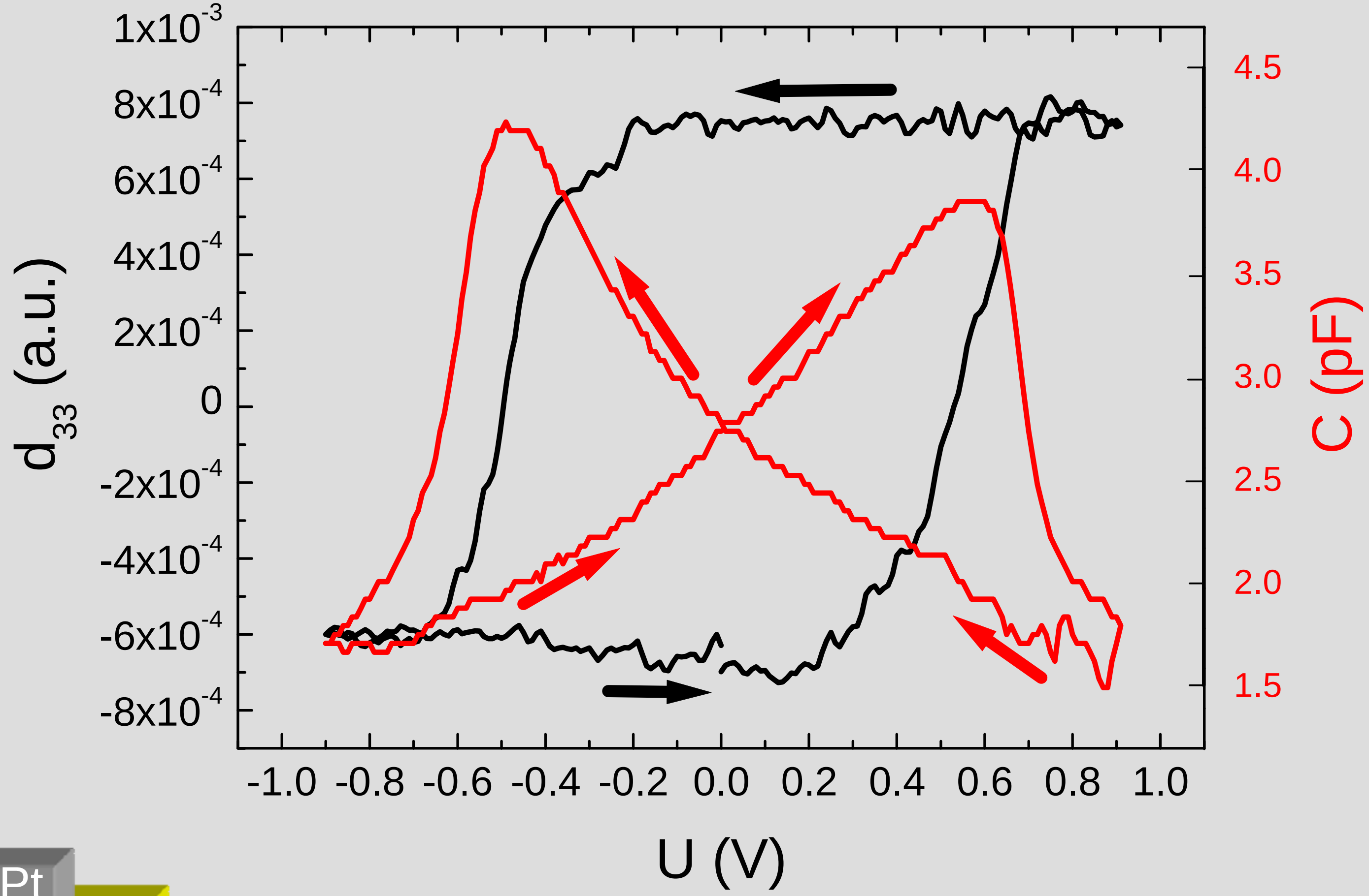


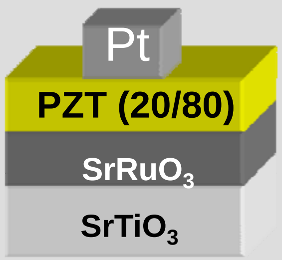


Thickness: 30 nm

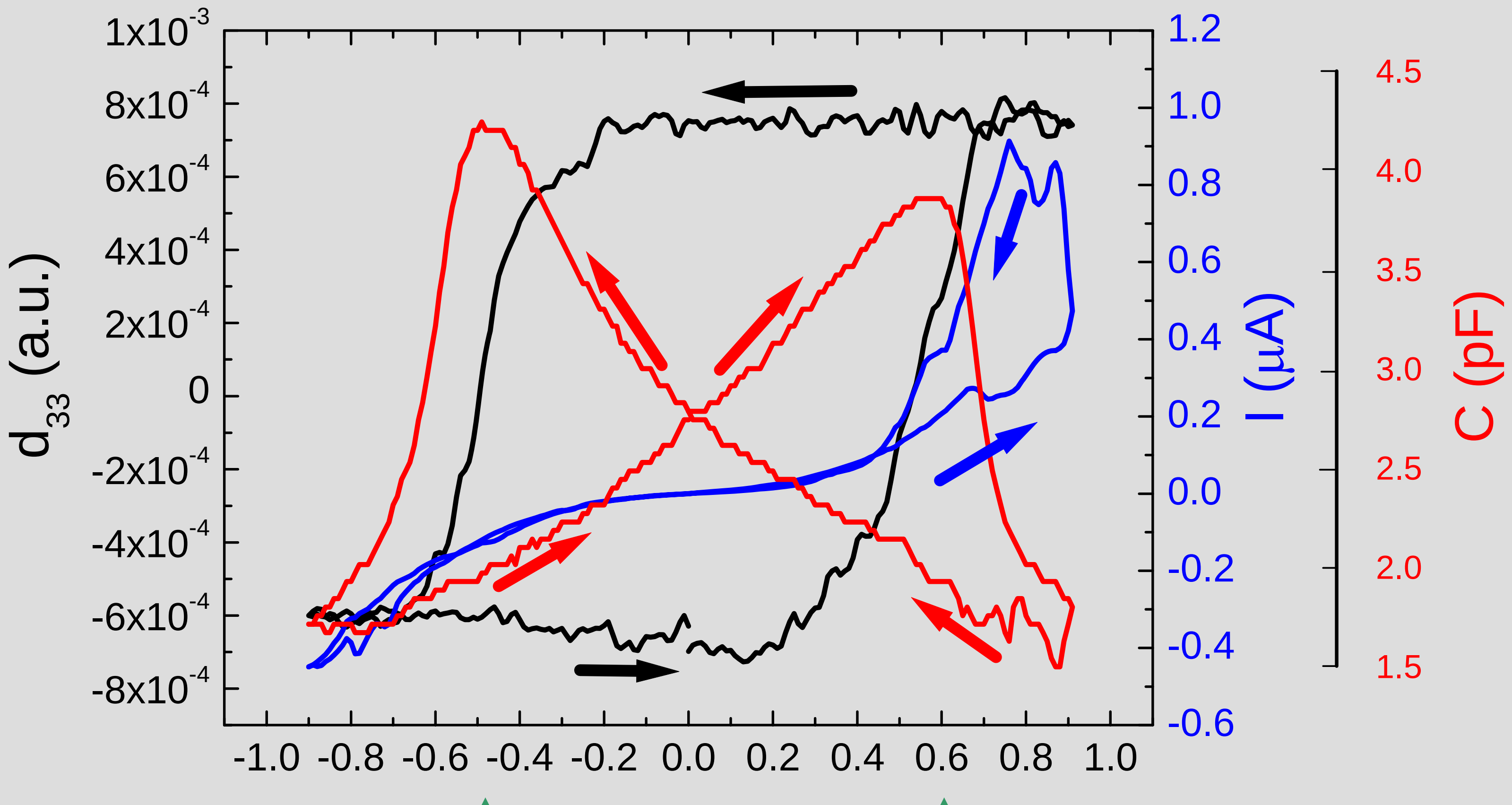
Area: 3 µm^2

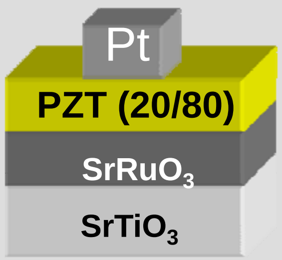
Resistive Switching and Ferroelectricity
d_{33}, C vs. Bias



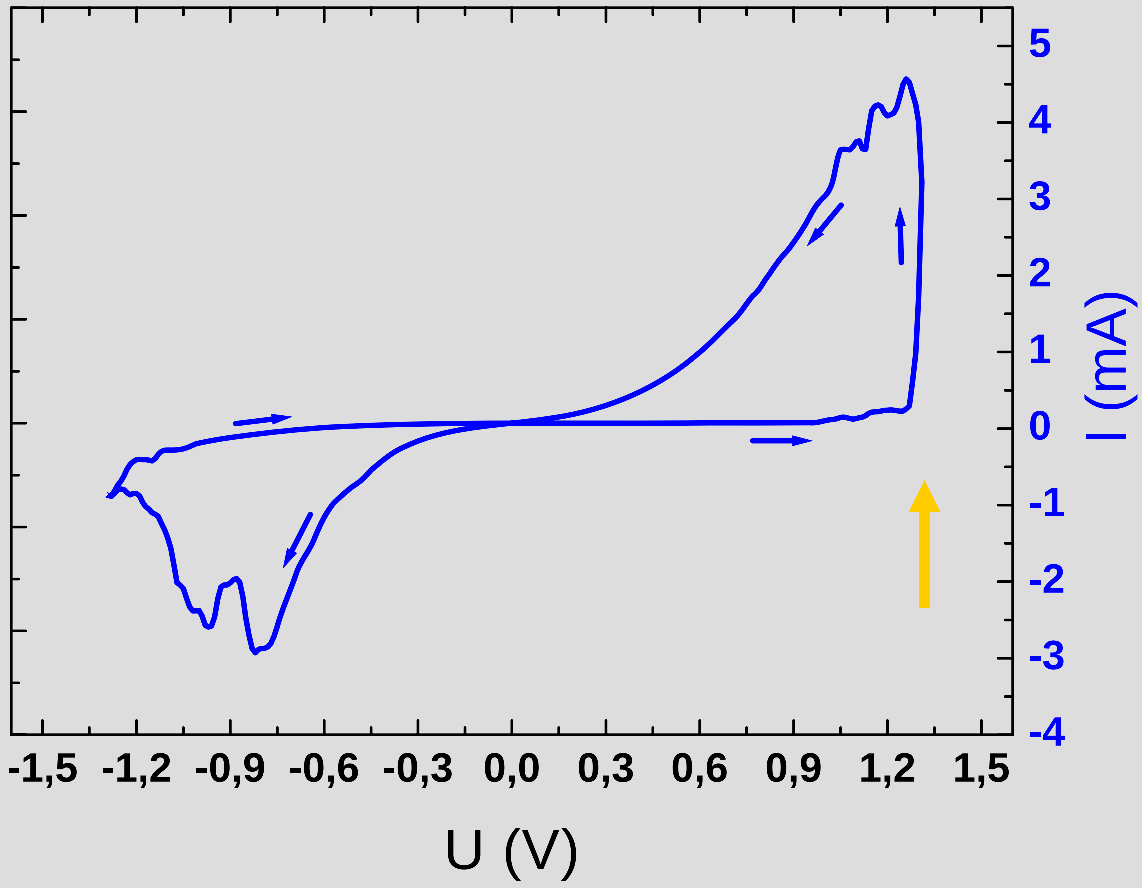


Resistive Switching and Ferroelectricity
d_{33}, C, $I_{res.}$ vs. Bias

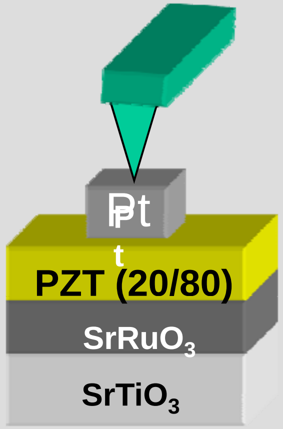




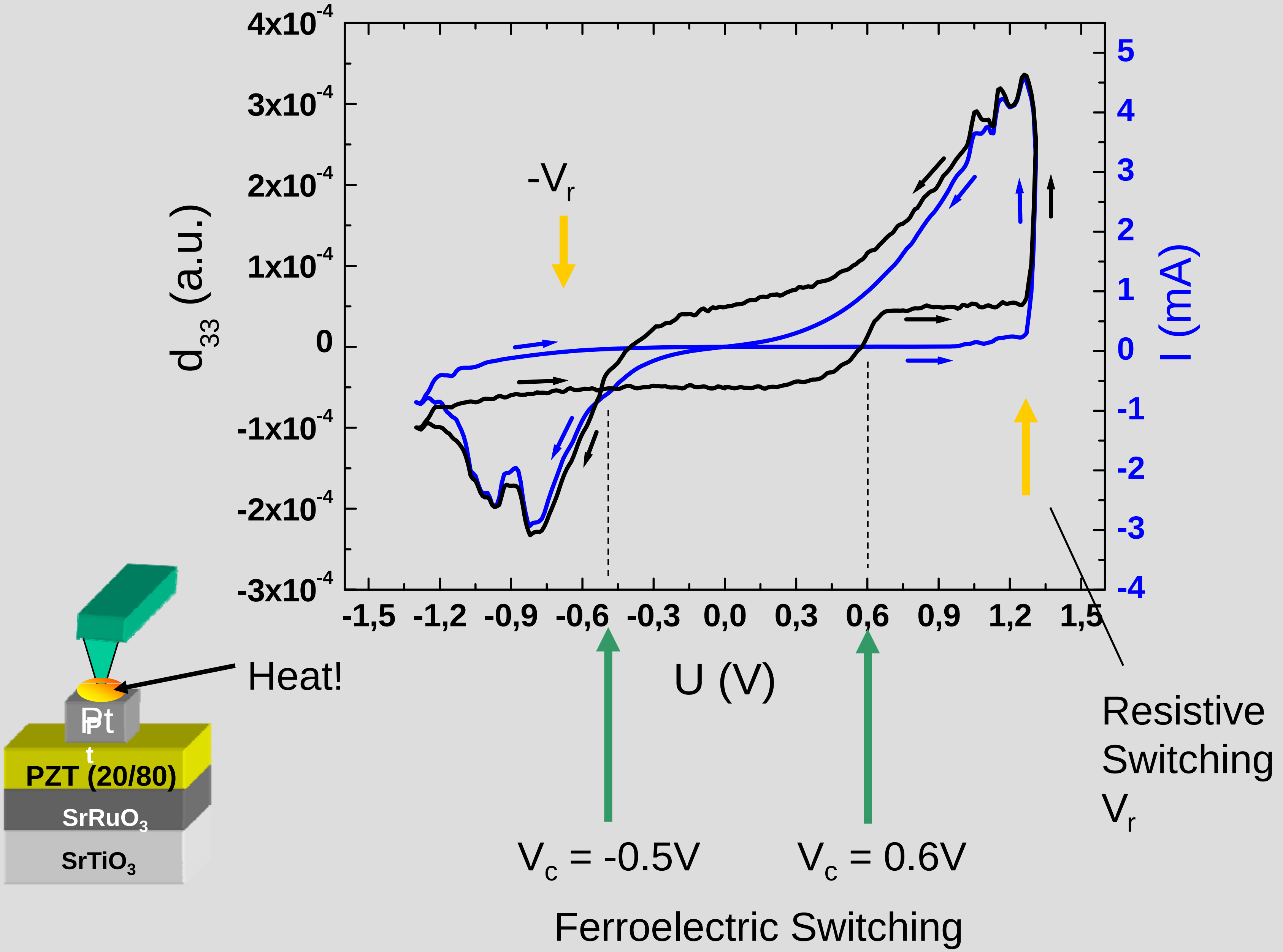
Increase Bias Voltage…



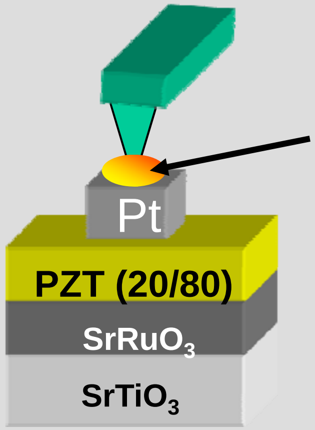
AFM



Resistive Switching and Ferroelectricity



Resistive Switching and Ferroelectricity



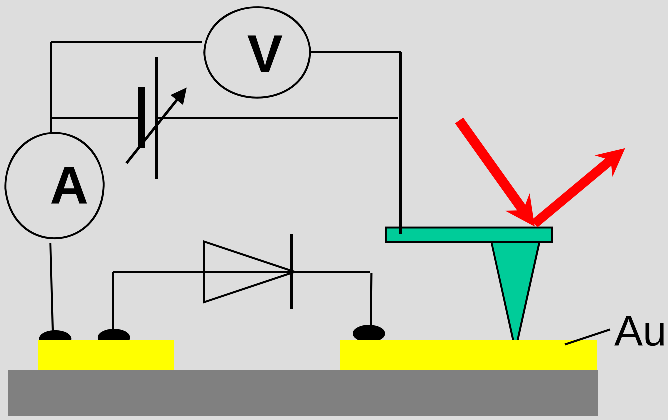
Current density high enough for heat generation?

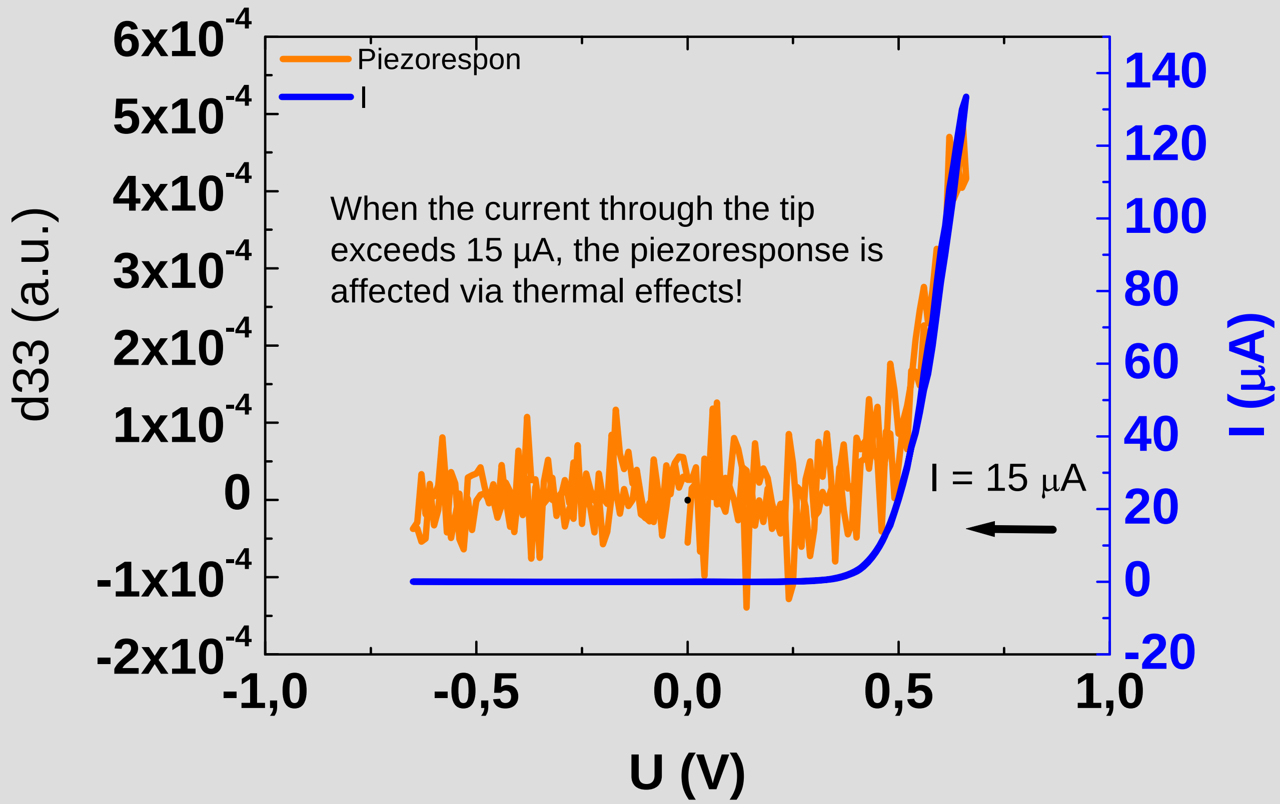
Estimation: $I = 10\ \mu A$, $r_{tip} = 5\ nm$

$J = I/A$

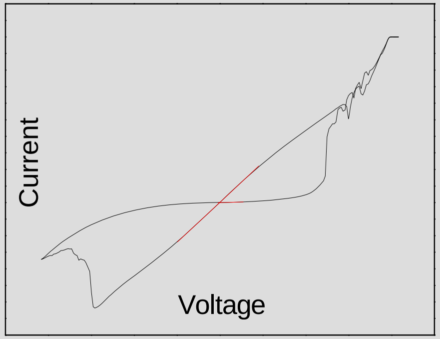
$J = 1.5 \times 10^7\ A/cm^2$

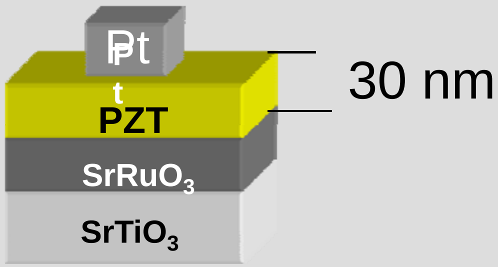
If current > 10 µA,
heating affects cantilever deflection

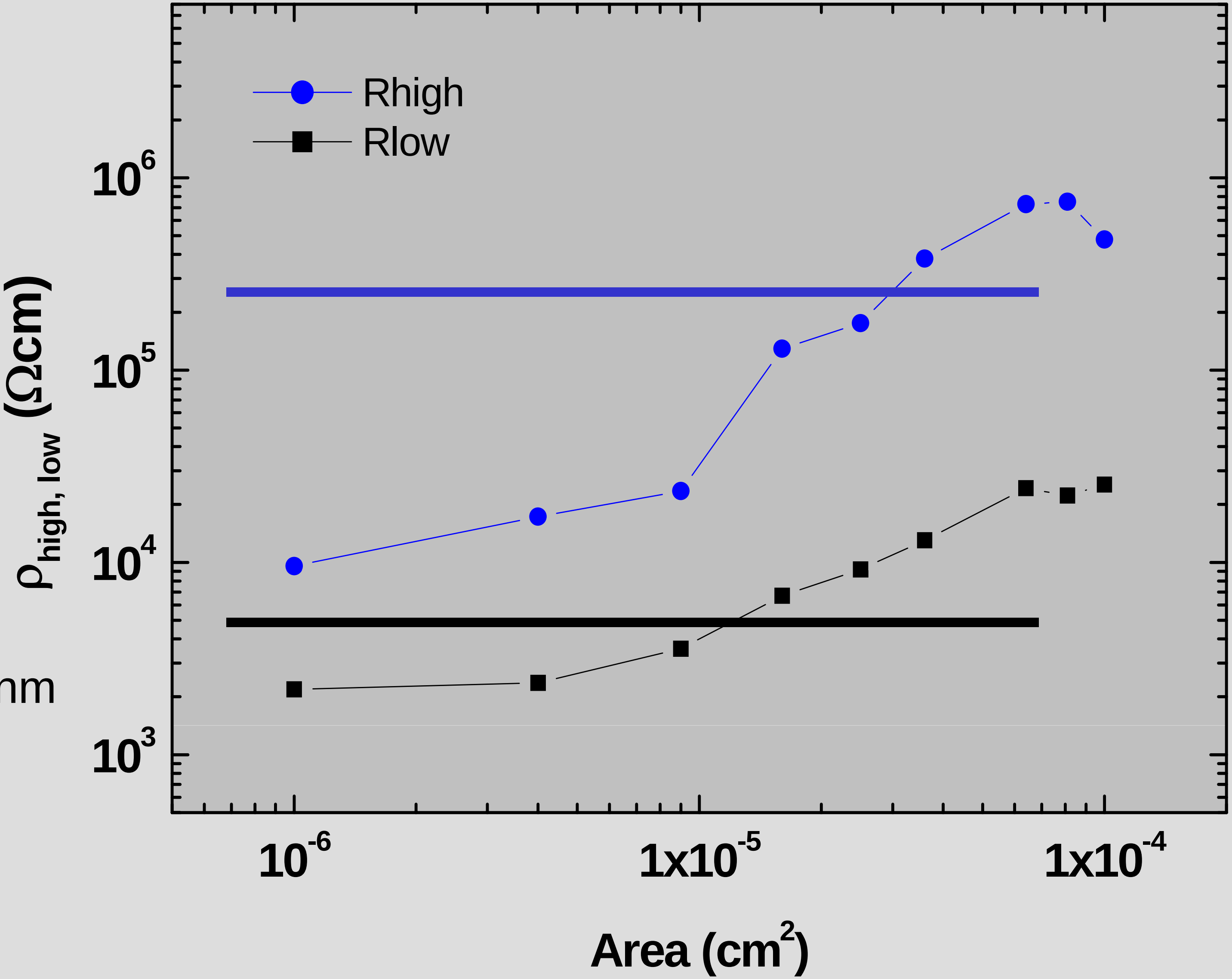

V
A
Au


6x10-4
5x10-4
4x10-4
3x10-4
2x10-4
1x10-4
0
-1x10-4
-2x10-4
d33 (a.u.)
Piezorespon
I
When the current through the tip
exceeds 15 µA, the piezoresponse is
affected via thermal effects!
I = 15 µA
140
120
100
80
60
40
20
0
-20
I (µA)
-1,0
-0,5
0,0
0,5
1,0
U (V)

Resistive Switching caused by Ferroelectricity?

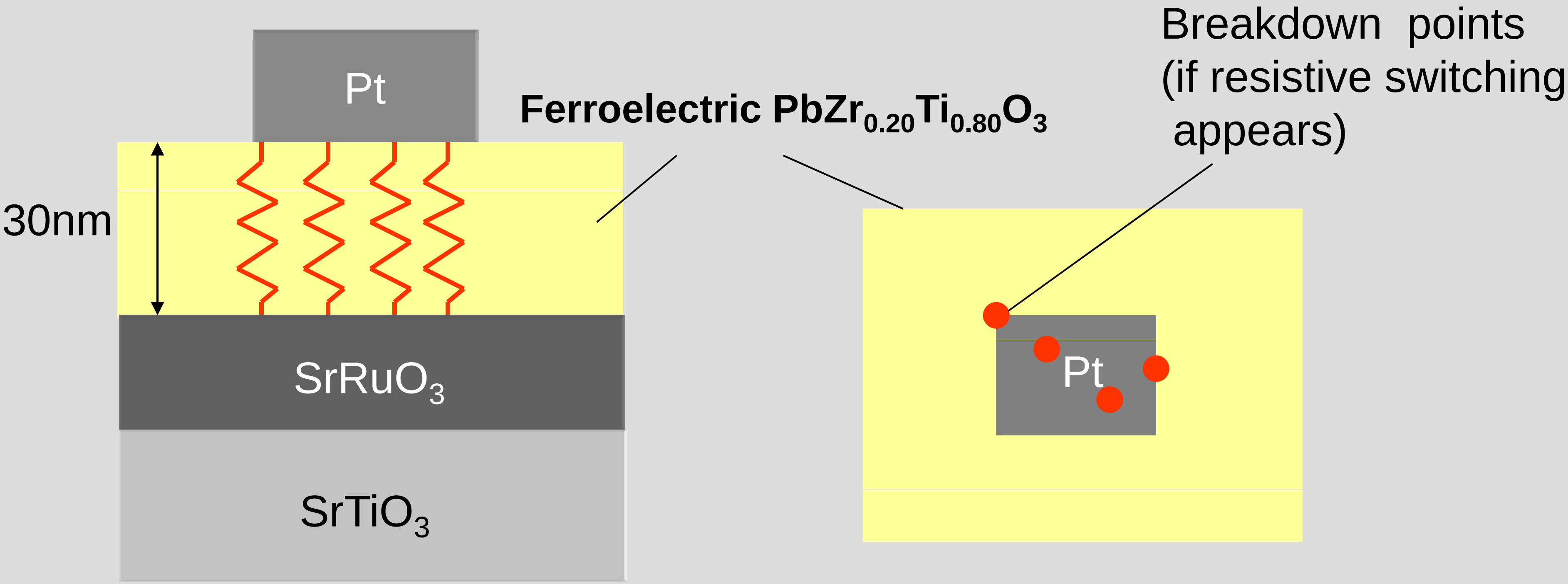






Resistive Switching: Filament Model

K. Szot, FZ Jülich



Schematic cross-section

Top view

D. M. Schaadt et *al.*, J. of Vacuum Science & Technology B **22**, 2030 (2004)

K. Szot et al. Switching the electrical resistance of individual dislocations in single-crystalline SrTiO3, to be published in Nature Materials

Resistive Switching: Filament Model

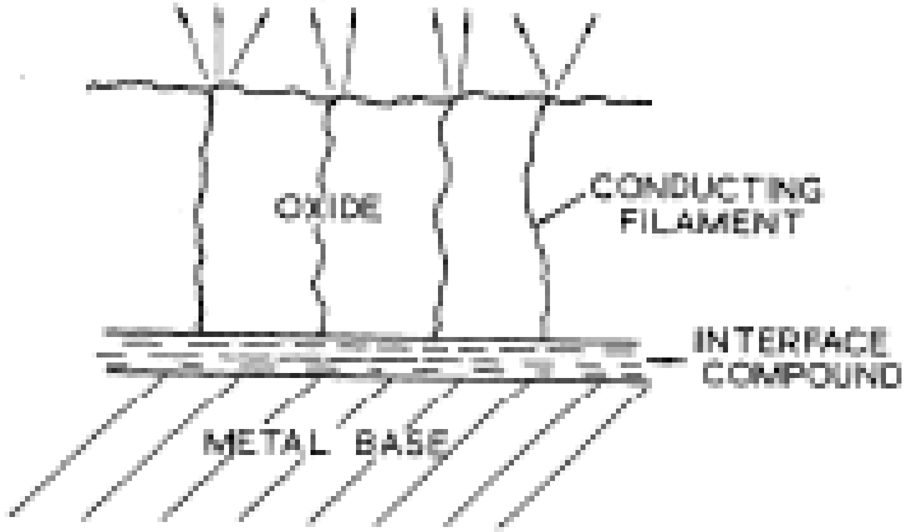


Fig. 3.

G. Dearnaley
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Rep. Prog. Phys.
33, 1129 (1970).

G. Dearnaley,
Thin Solid Films **3**, 1161 (1969).

Trends

Corssbar Arrays:
Resistive switches for crossbar arrays,
Many materials show resistive switching, no theoretical understanding, devices performance not yet sufficient for applications,
Aim: feature size < 10 nm, if possible single molecules
Fabrication: Nano-imprint/Self Assembly

3 Dimensional circuits

Field Programmable Arrays

Cognitive Memories

Overview Resistive Switches (Materials)

Insulator/Semiconductor/amorphous/crystalline/poly-crystalline

- Inorganic
  - Oxides:
    - Electronic
    - Mixed conductor(Ionic/Electronic)
  - Complex Oxides:
    - Ferroelectric
    - Mixed conductor(Ionic/Electronic)
  - Chalcogenides:
    - Ferroelectric
    - Mixed Conductor(Ionic/Electronic)
    - Phase Change
- Organic
  - Ferroelectric
  - Electronic
  - Mixed Conductor (Ionic/Electronic)
  - Single Molecule
  - Carbon Nanotubes

Summary

•Crossbar arrays are attractive for high-density memories
•Resistive switching is observed in many different materials
•Up to now no clear theoretical background
•The resistive switching is often a result of conductive bridges

•Ferroresistive material show resistive switching
The origin of the effect can be analyzed by simultanous measurement
Of different ferroelectric properties

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Research Center Jülich

„Displacive and Conductive Phenomena in Ferroelectric Thin Films: Scaling effects and switching properties“.

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J. F. Scott, Ferroelectric Memories, Springer Series in Adv. Microelectronics, (Springer-Verlag, Berlin Heidelberg, New York 2000).	*Good historical overview, Explains also principles of Ferroelectrics*
Nanoelectronics and Information Technology, R. Waser ed., Adv. Electr. Mat. And Novel Dev. Wiley-VCH Verlag Weinheim 2002.	*Broad Textbook with various topics in nanoelectronics, Some Chapters on Non-Volatile Memories: FRAM, FeFET, MRAM, Phase Change Materials*