Molecular and Polymer Nanodevices

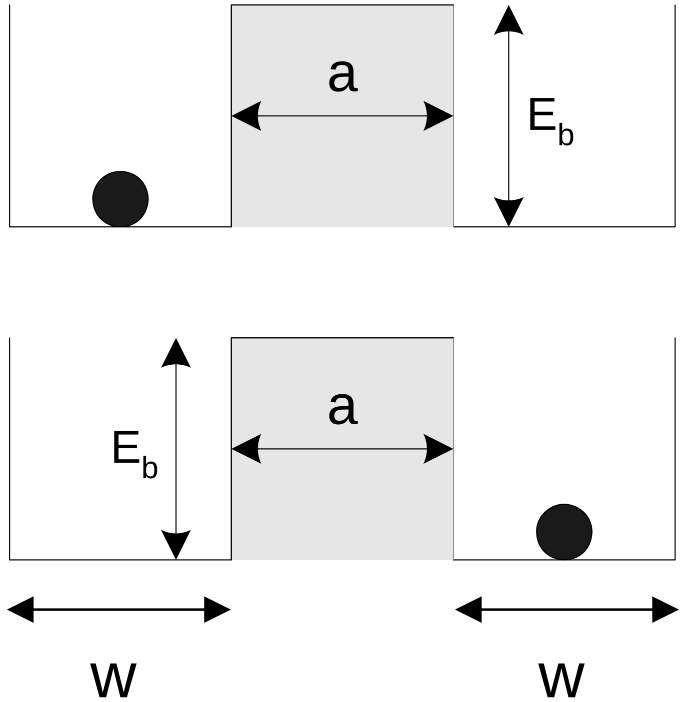
Nikolai Zhitenev

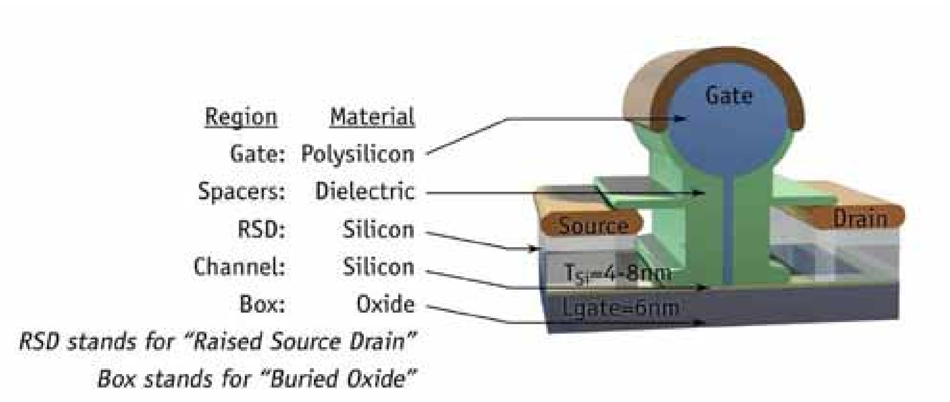
1. (Ultimate) Limitations of Silicon-based electronics
2. Molecular switches
3. Polymer and other switches
4. Summary and outlook

CNST
Lucent Technologies
Bell Labs Innovations

(Ultimate) Limitation:

Computational State decays because of Electron Tunneling



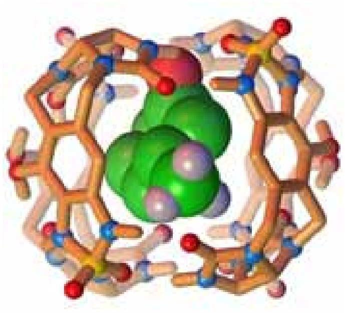


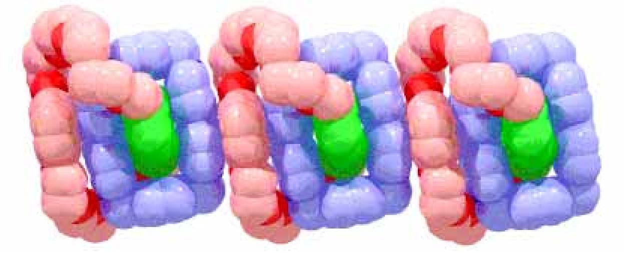
Semiconductor Research Corporation

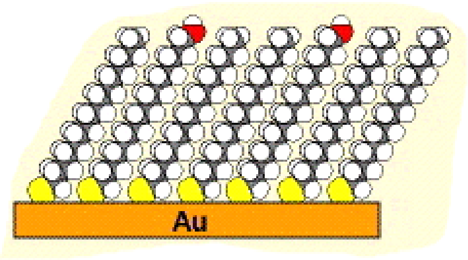
2006 hypothesis: Devices having feature sizes less than 5 nm should utilize particles whose mass is greater than the mass of an electron.

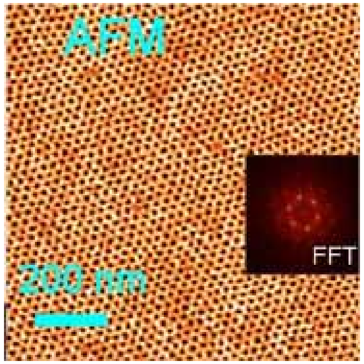
Why molecules?

1. Small
2. Exactly reproducible
3. Enormous variety, sophisticated electronic structure
4. Self-assembly (on different levels)
5. New types of devices



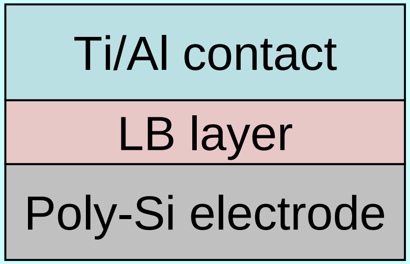


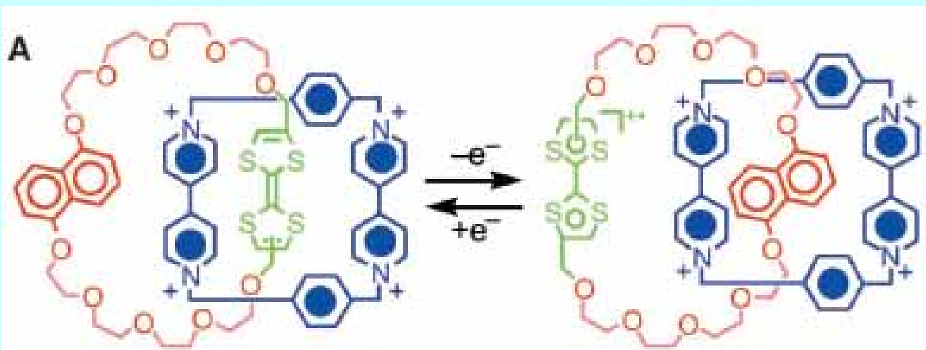


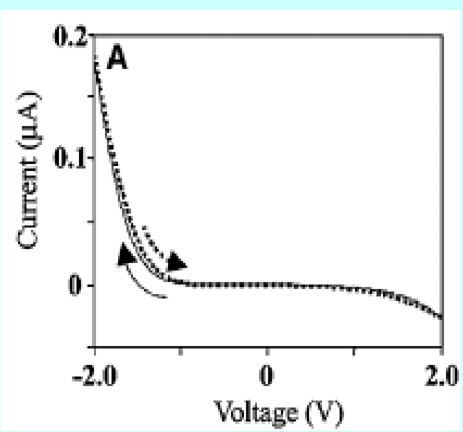


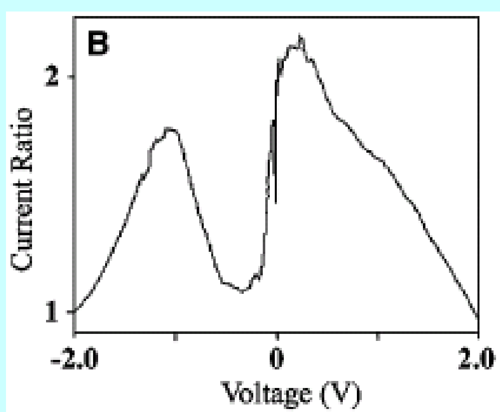
Electronically Reconfigurable Switch (LB monolayer)

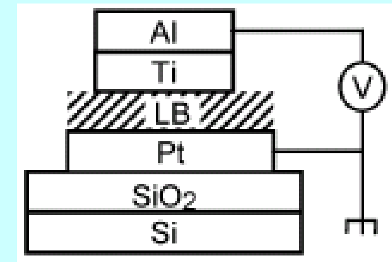
Collier et al., Science 2000

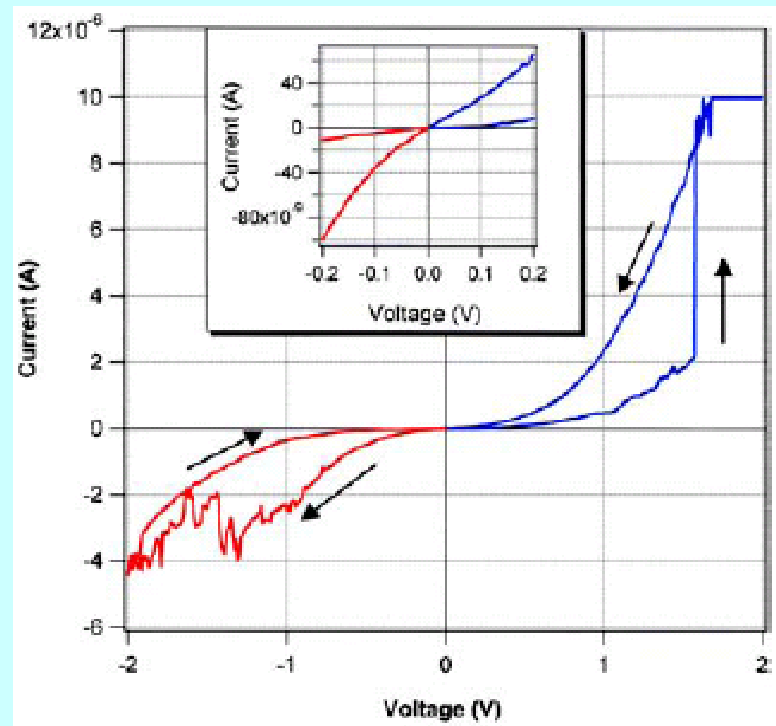










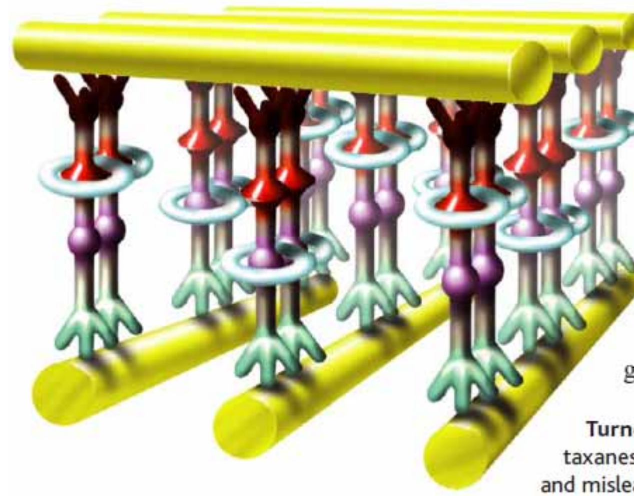


HP Labs

BREAKTHROUGH OF THE YEAR

In 2001, scientists assembled molecules into basic circuits, raising hopes for a new world of nanoelectronics

Molecules Get Wired



21 DECEMBER 2001 VOL 294 SCIENCE —ROBERT F. SERVICE

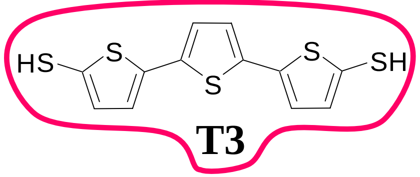
Molecular Electronics

Next-Generation Technology Hits an Early Midlife Crisis

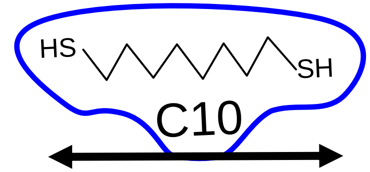
Researchers had hoped that a new revolution in ultraminiaturized electronic gadgetry lay almost within reach. But now some are saying the future must wait

24 OCTOBER 2003 VOL 302 SCIENCE —ROBERT F. SERVICE

Conjugated :

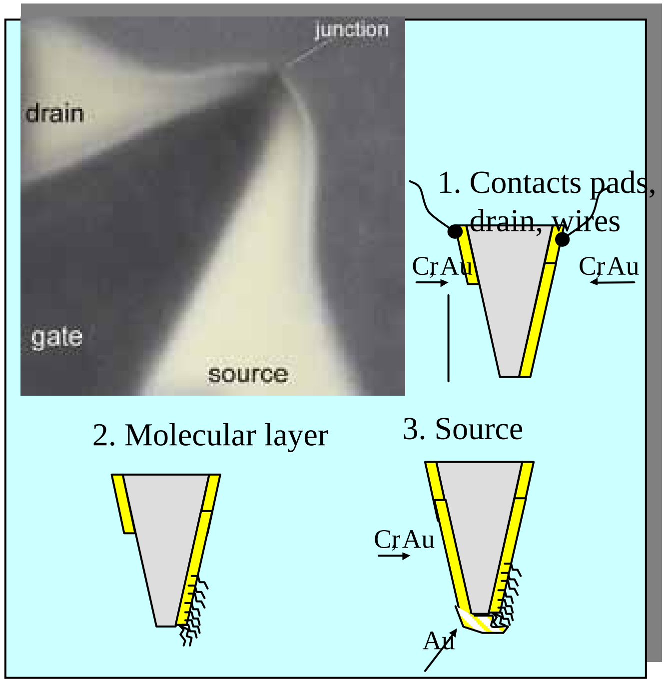


Saturated:

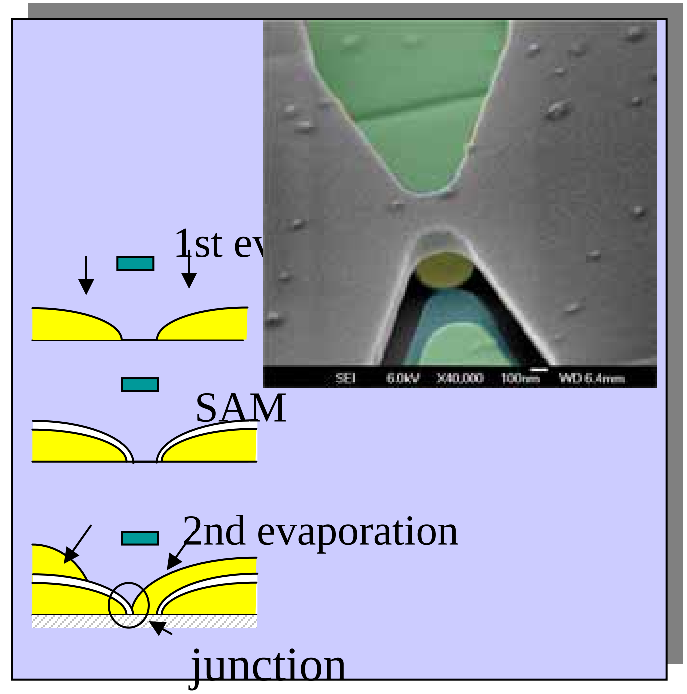


~1-1.5 nm

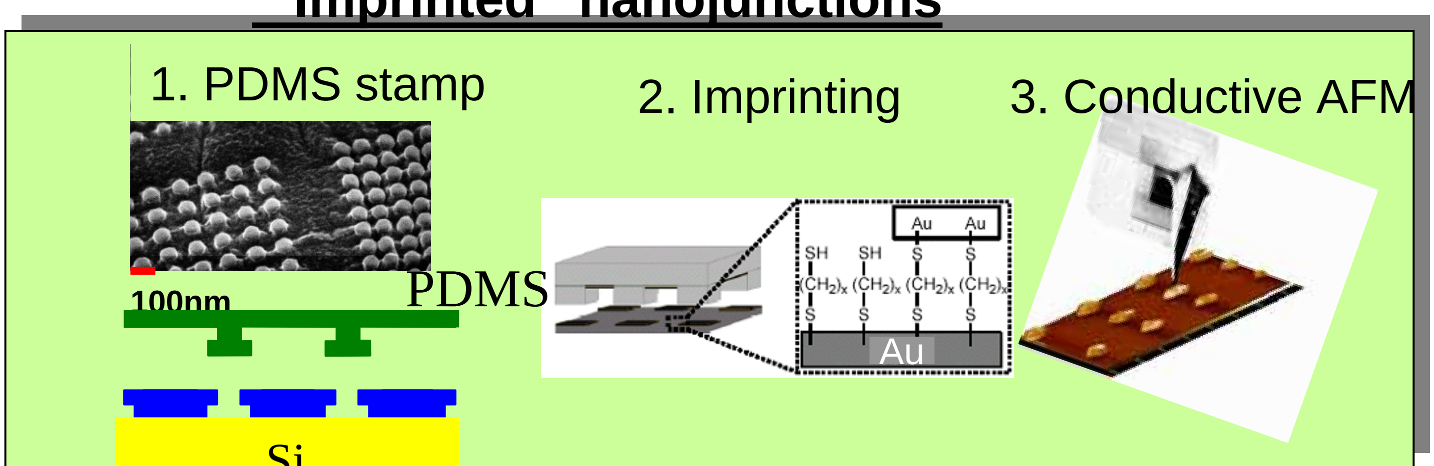
~"Single-molecule" junctions



"Fixed-area" nanojunctions

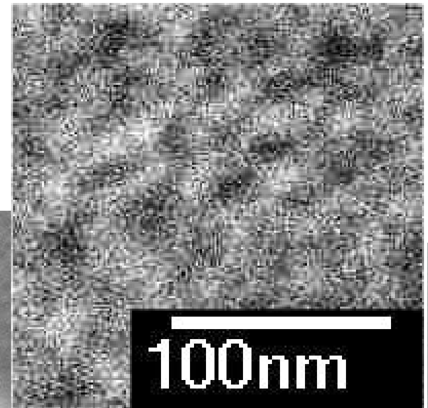


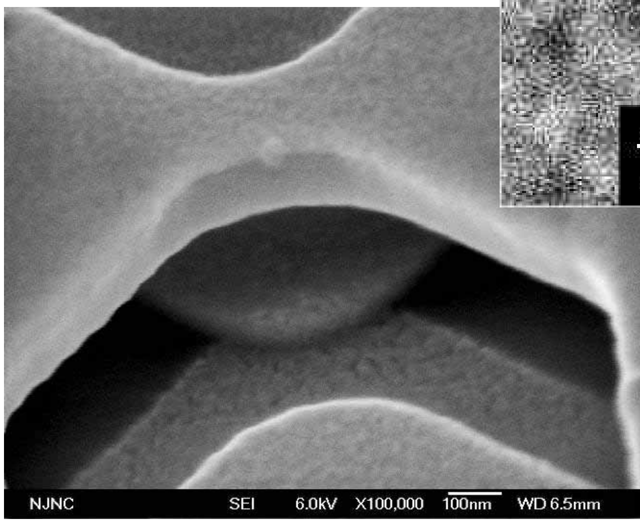
"Imprinted" nanojunctions



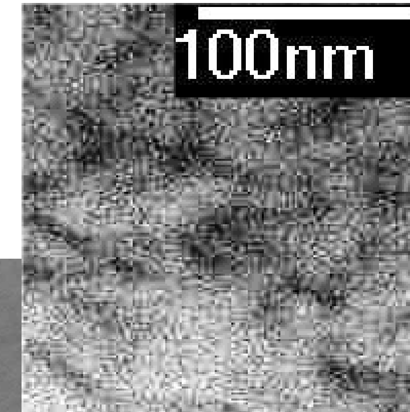
Topography of bottom electrode:

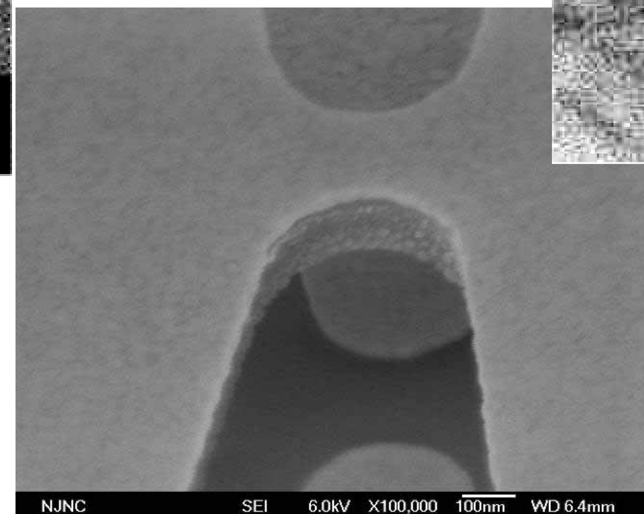
Au as deposited

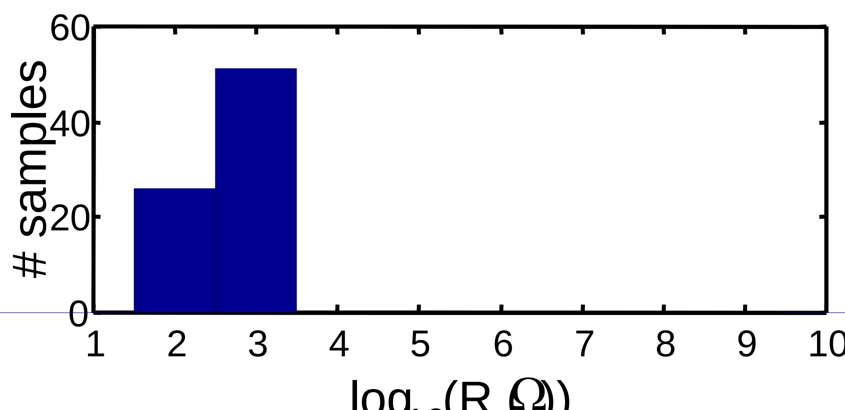


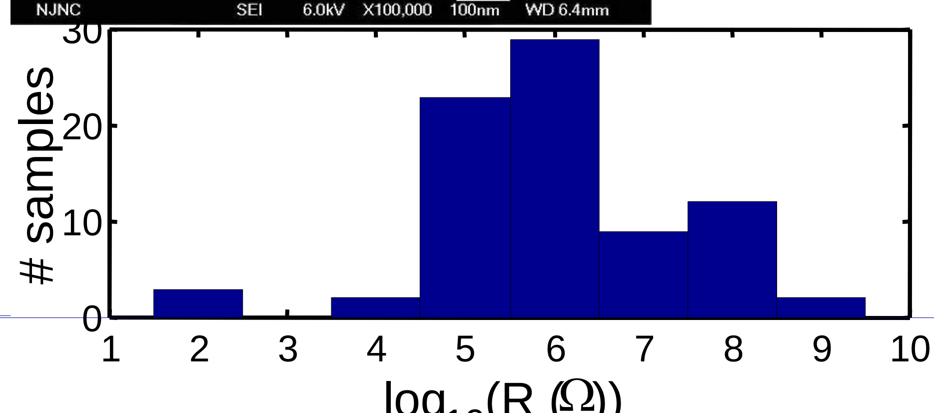


Au annealed at 300º C







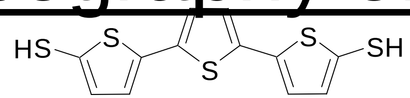


100 % junctions are "shorted"
((Au)- (T3)-(Au))

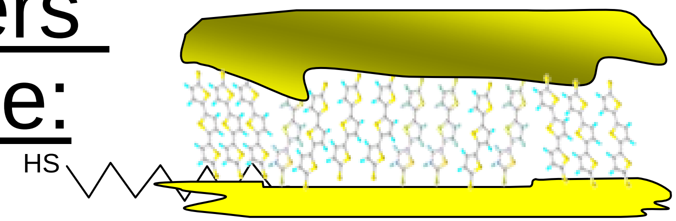
~100 % junctions are "good"
((annealed Au)- (T3)-(Au))

Molecular “wires” vs “barriers”

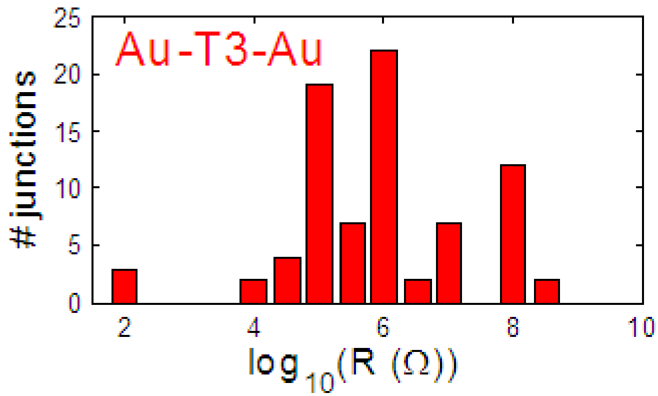
Topography of top electrode:

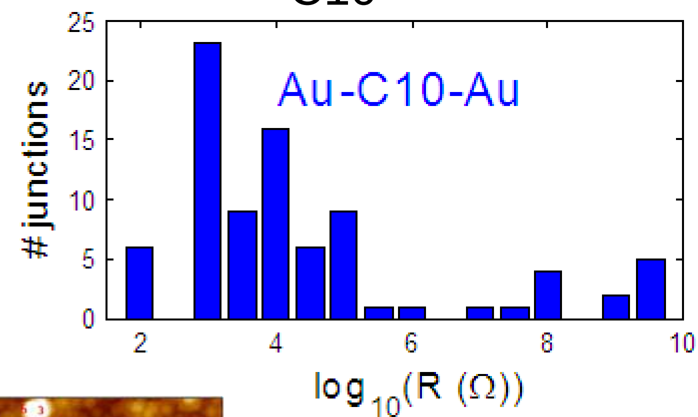


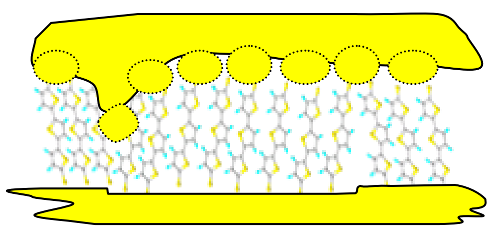
T3

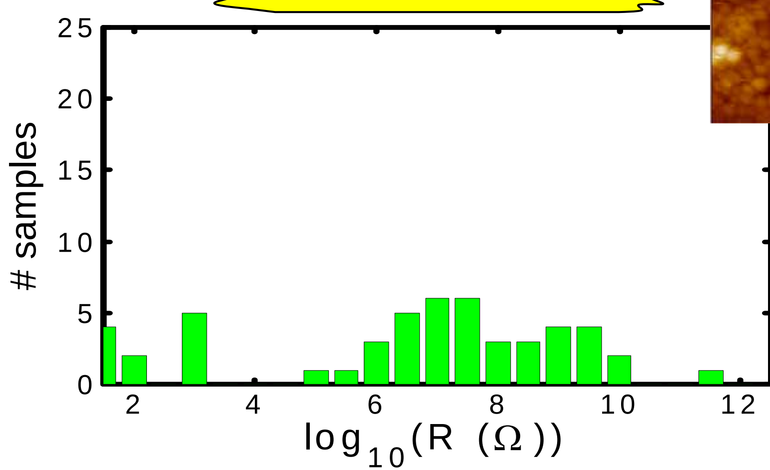


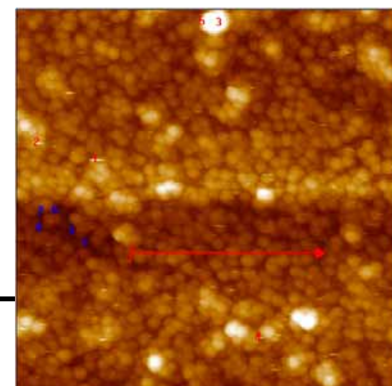
C10

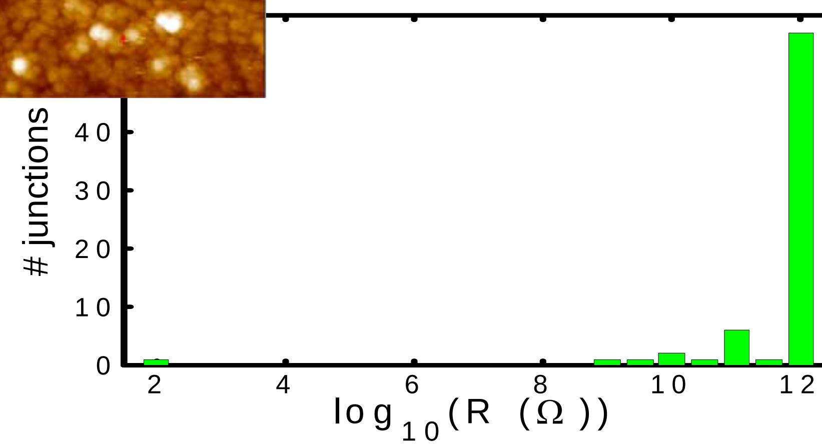




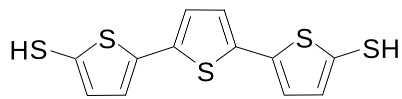








Chemical reactivity of electrodes:

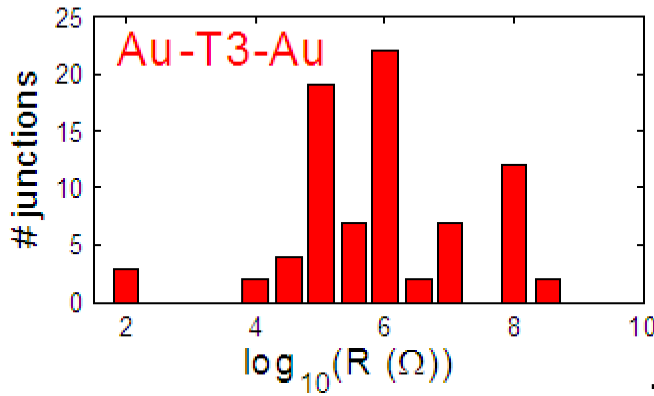


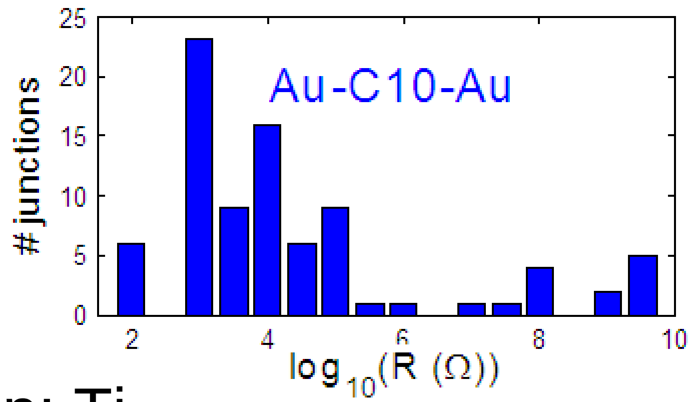
T3

Top: Au

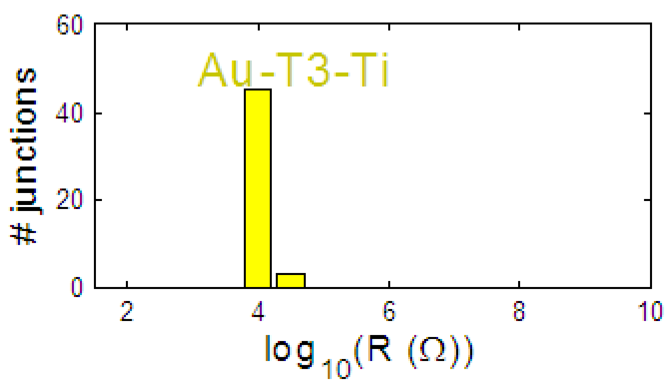
C10

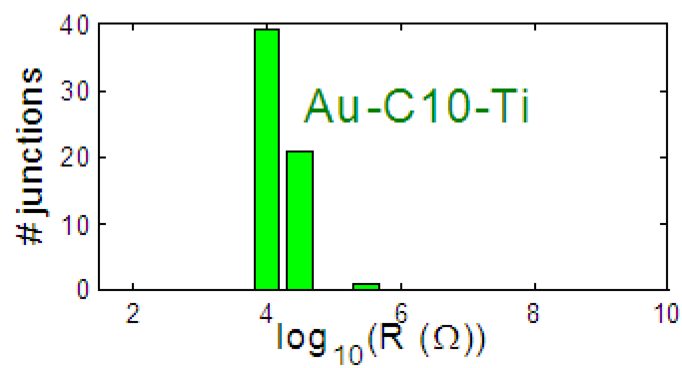
Weakly reactive metal





Top: Ti

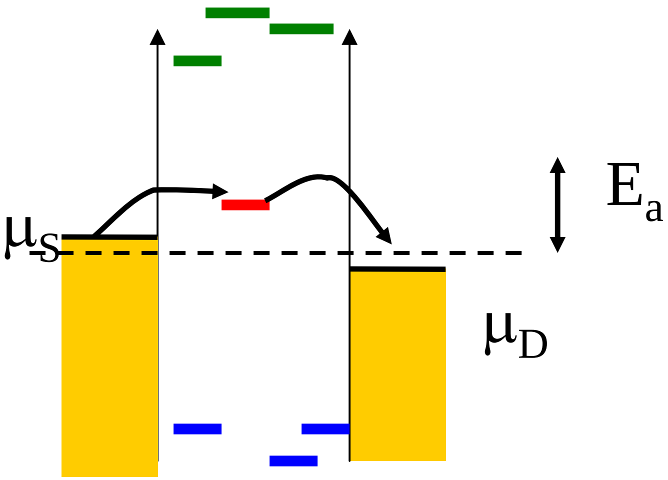




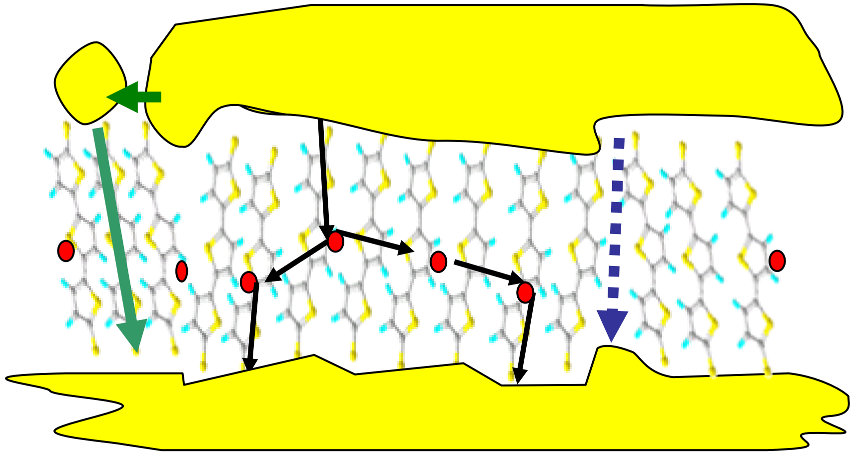
Strongly reactive metal

Problems with “short molecule” devices:

1. Typical metal-molecules devices are EXTREMELY LOW conductive – <u>energy level mismatch</u>



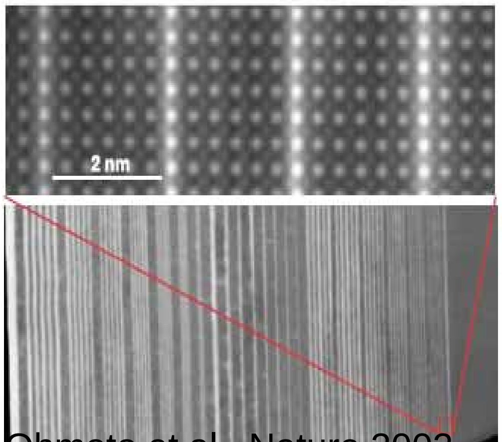
2. Conductance is dominated by *DEFECT* states (NOT molecular states)



“Ideal” or “Idealized” Systems vs. Reality

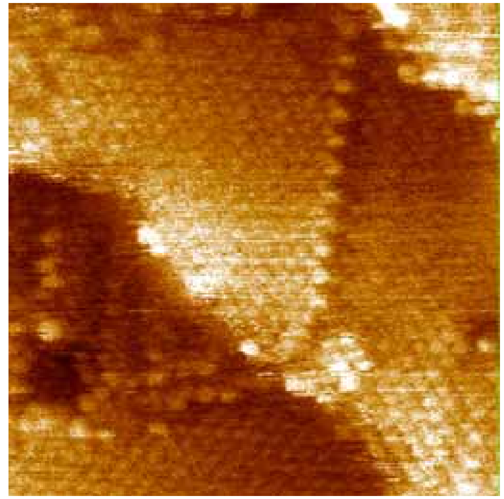
Epitaxial systems:

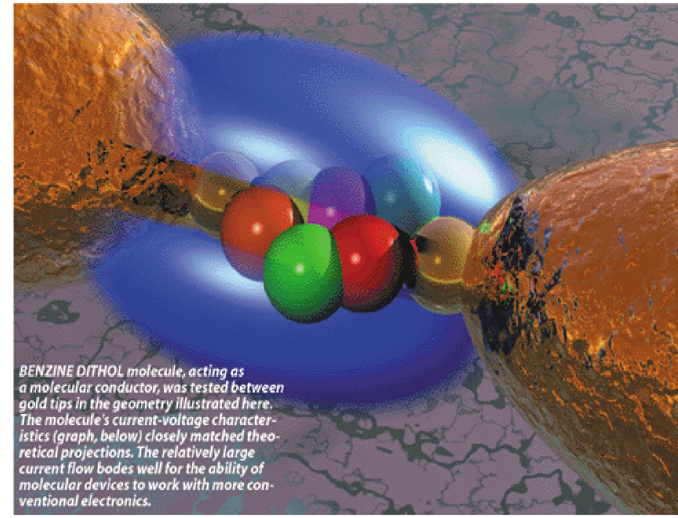
Oxide superlattices



Ohmoto et al., Nature 2002

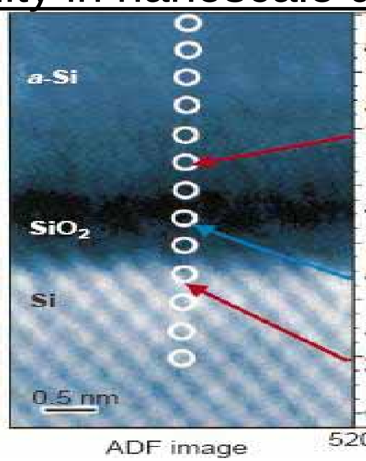
Molecular layers on metals:





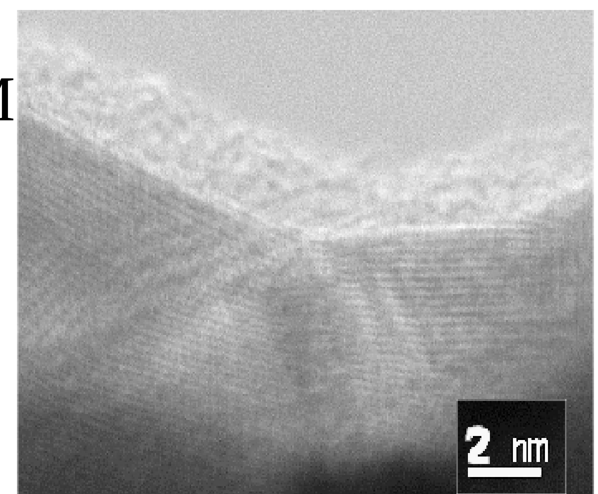
Reality in nanoscale devices = > disorder, dopants, material reactions

Muller et al., Nature 1999



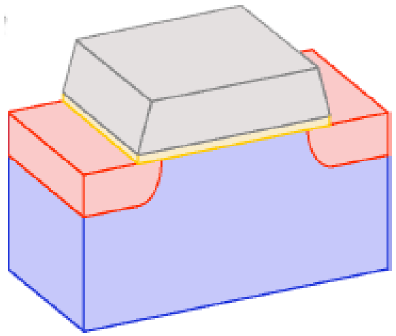
SAM

Au

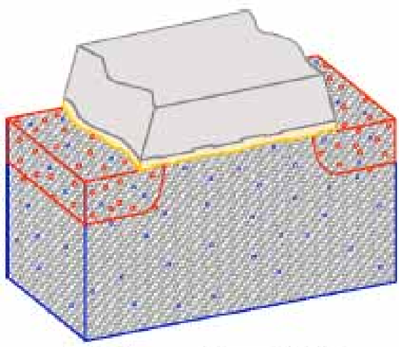


Problem: Defects

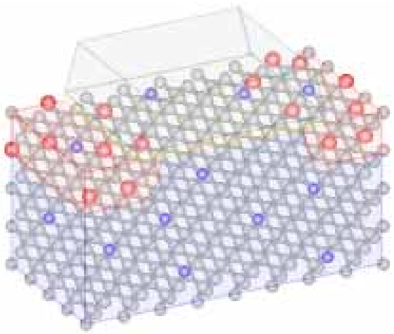
Sometimes: not enough DEFECTS



A 100 nm MOSFET

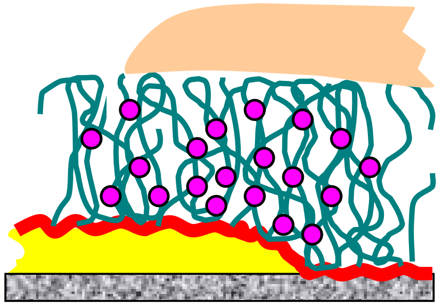


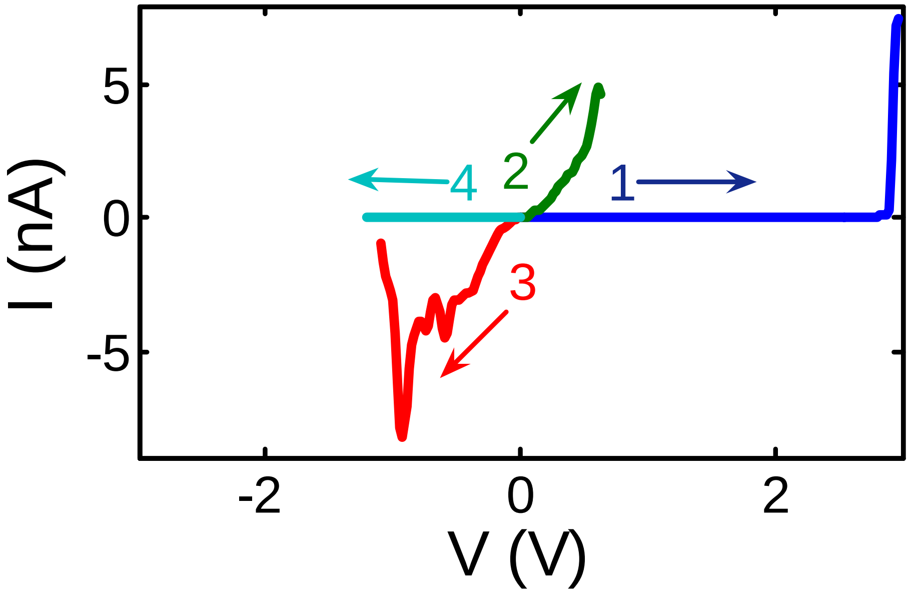
A 22 nm MOSFET



A 4.2 nm MOSFET

Possible Solution: plenty of “DEFECTS”

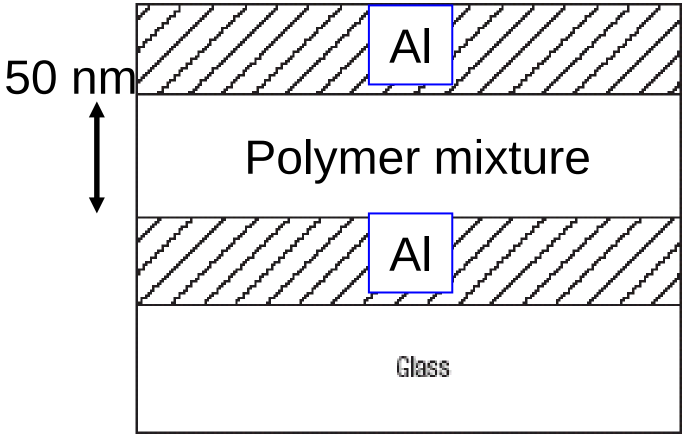


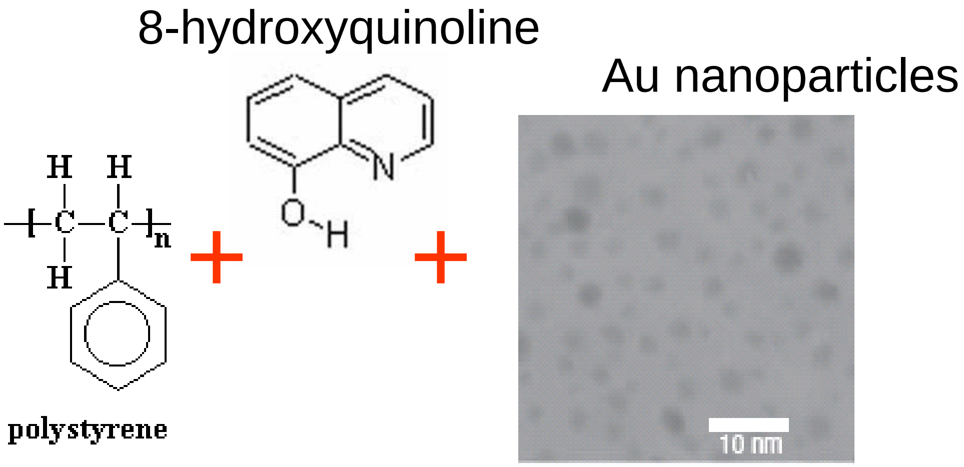


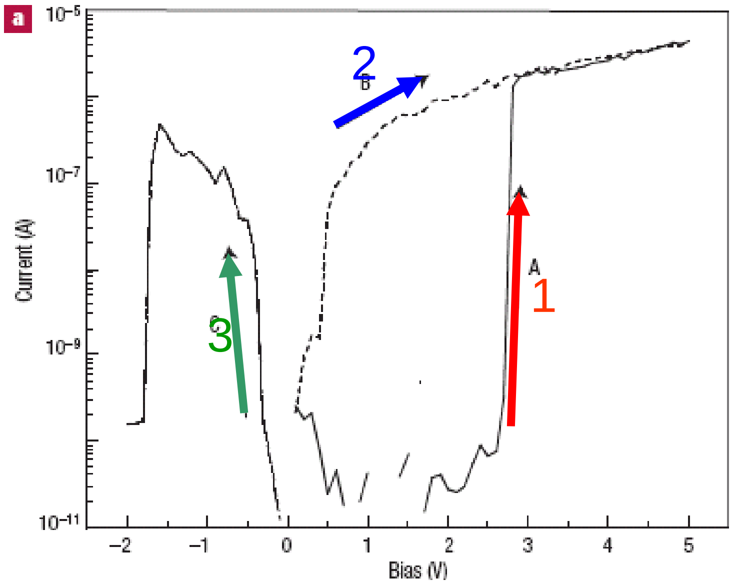
High density of ions enables Bistable Switching in tiny device!

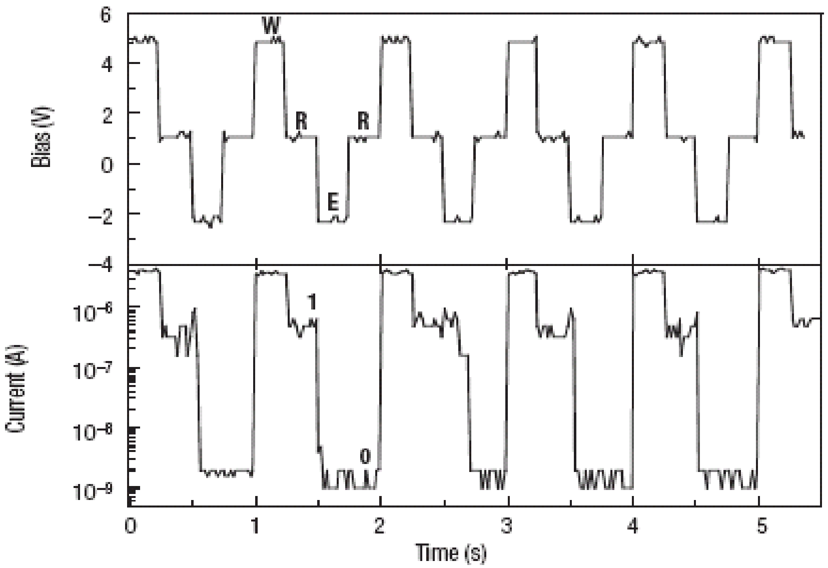
Programmable polymer thin film and non-volatile memory device

Ouyang et al, Nature Materials 2004







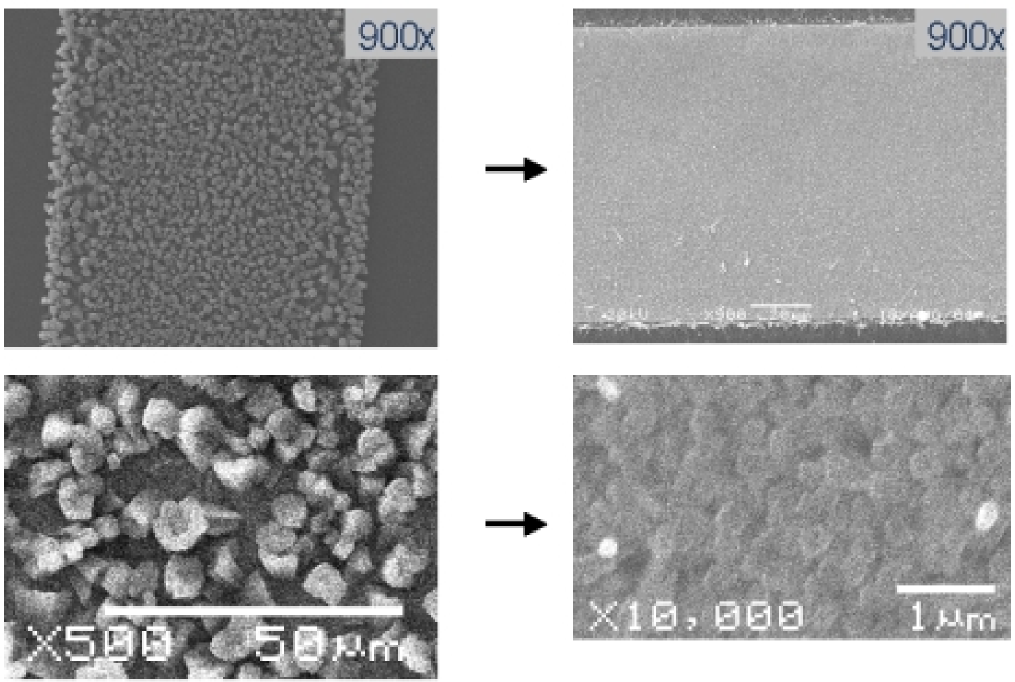


Charge-transfer organic for memory (IMEC)

CuTCNQ

$$[Cu^+(TCNQ^-)]_n \leftrightarrow Cu^0_x + [Cu^+(TCNQ^-)]_{n-x} + (TCNQ^0)_x$$

"OFF" state — "ON" state

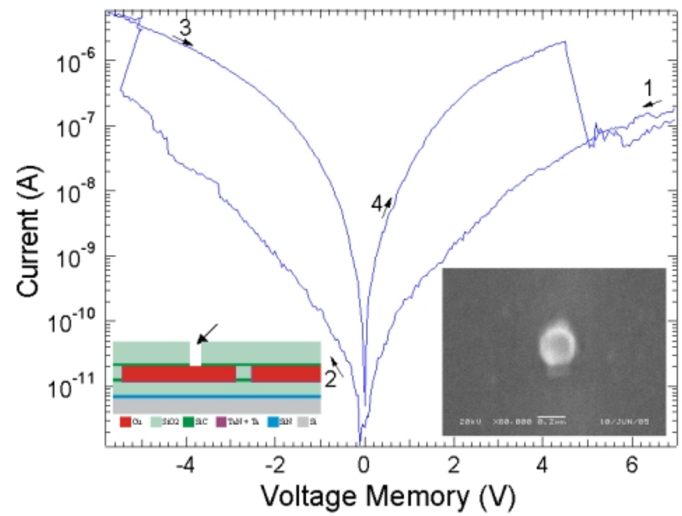


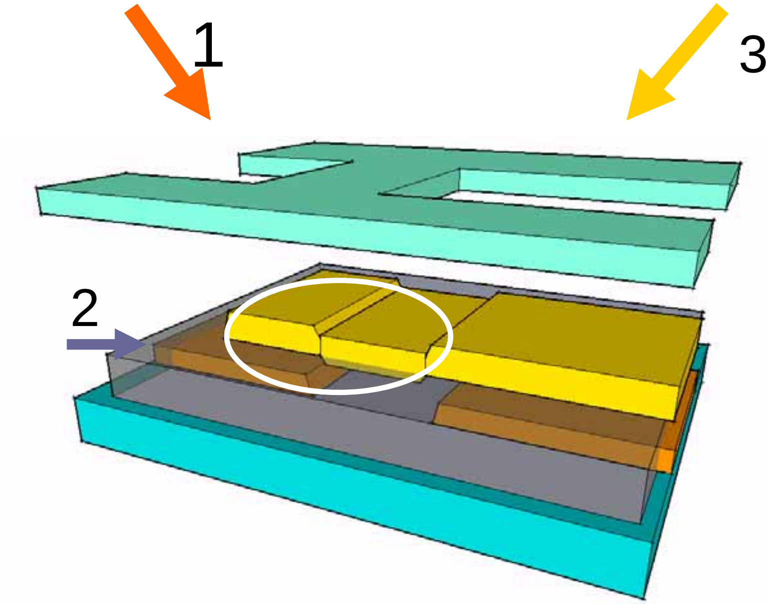
acetonitrile (RT)
(literature procedure)

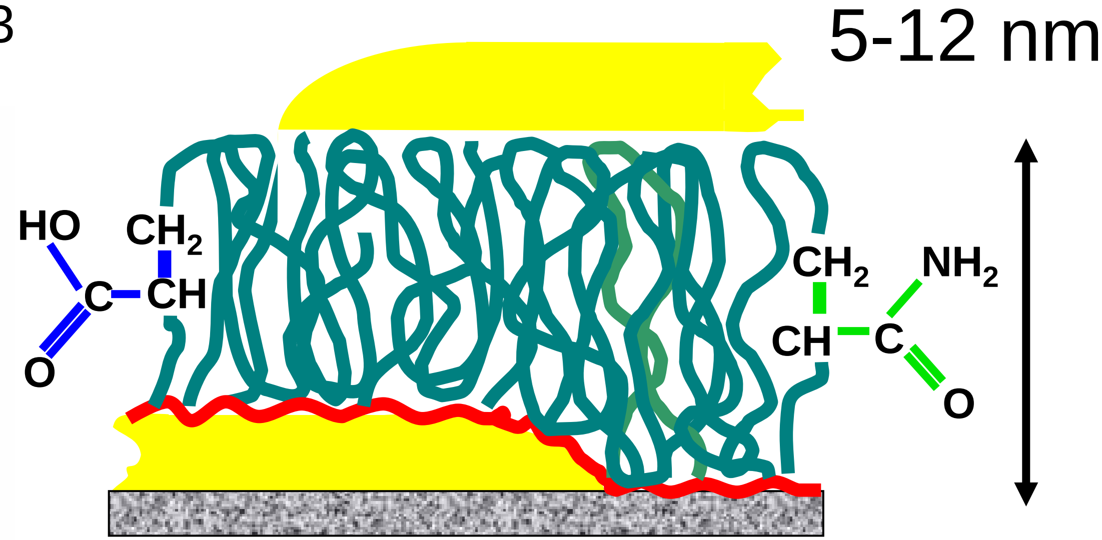
n-butyronitrile (110°C)
(IMEC work)

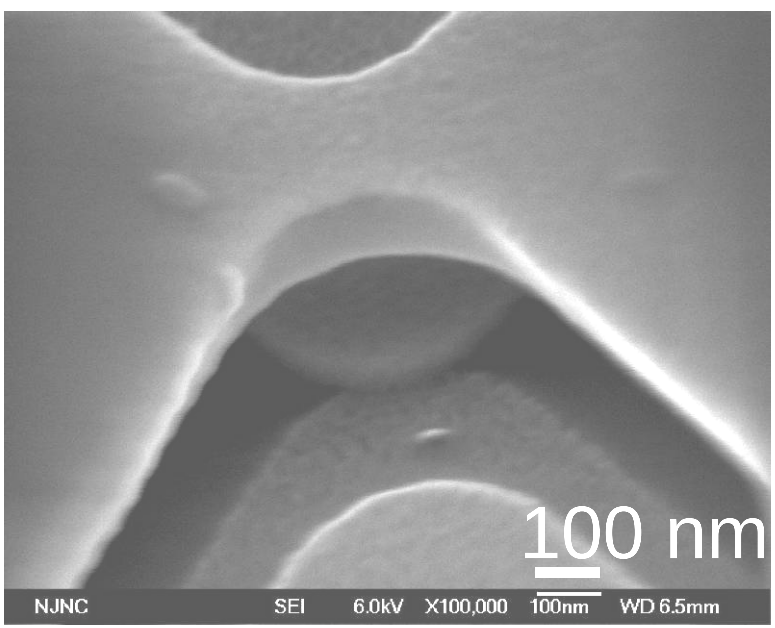
Template growth of CuTCNQ *inside* vias

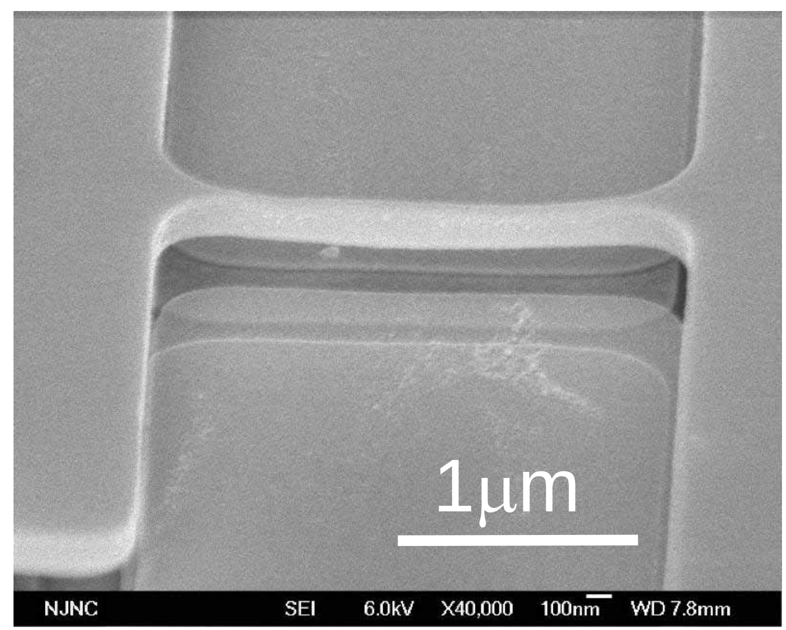
Improved reproducibility, 0.25µm diameter via, R = 220 kΩ



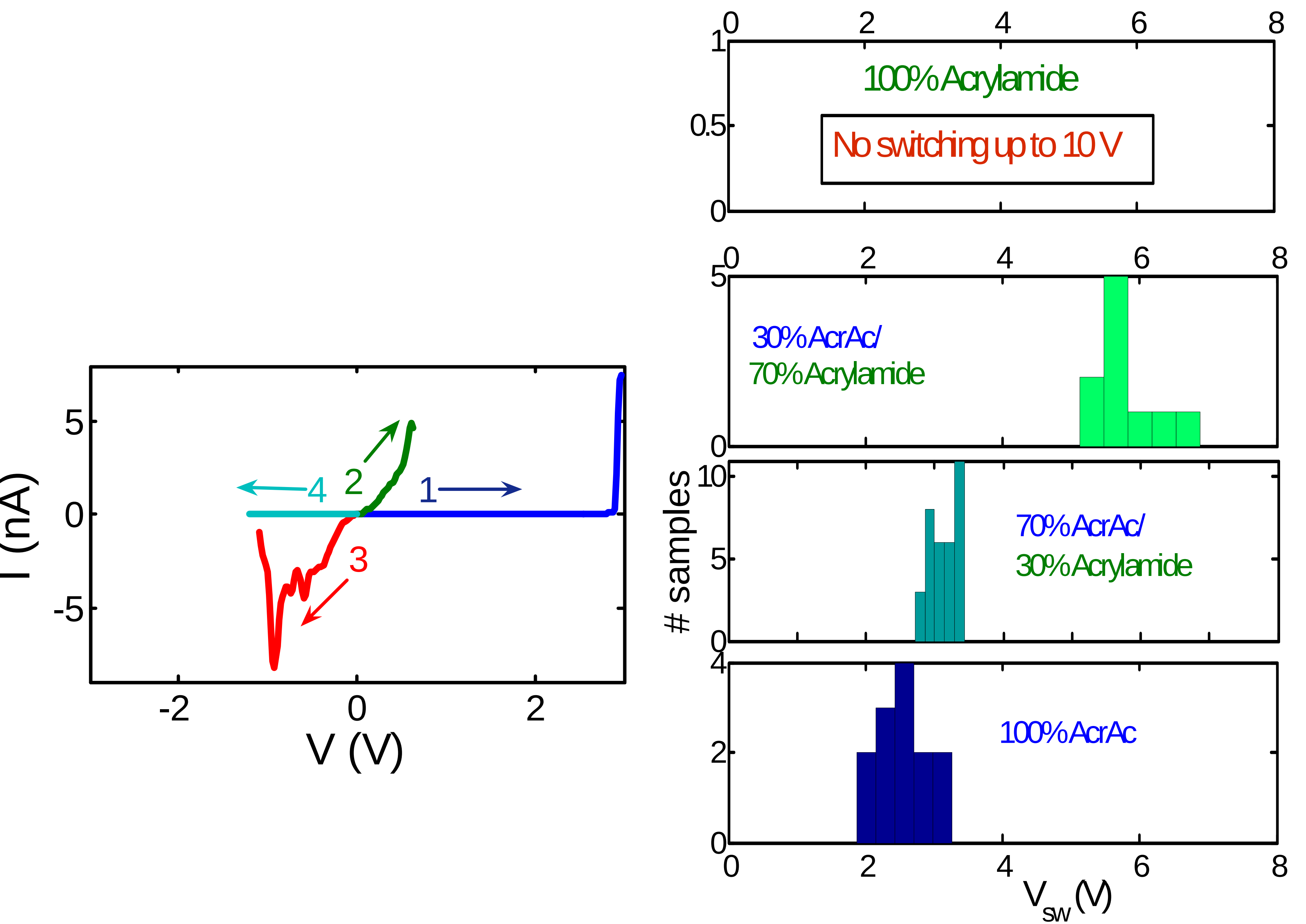

1
3
2


5-12 nm
HO
O
C
CH_2
CH
CH_2
NH_2
CH
C
O


100 nm
NJNC SEI 6.0kV X100,000 100nm WD 6.5mm

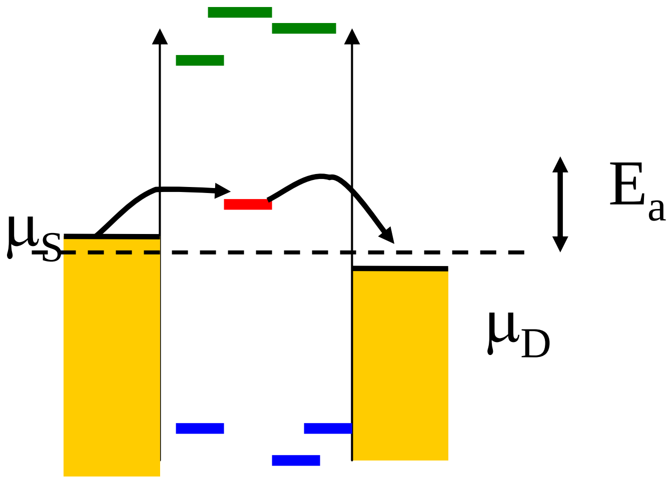

1μm
NJNC SEI 6.0kV X40,000 100nm WD 7.8mm

Electrical switching



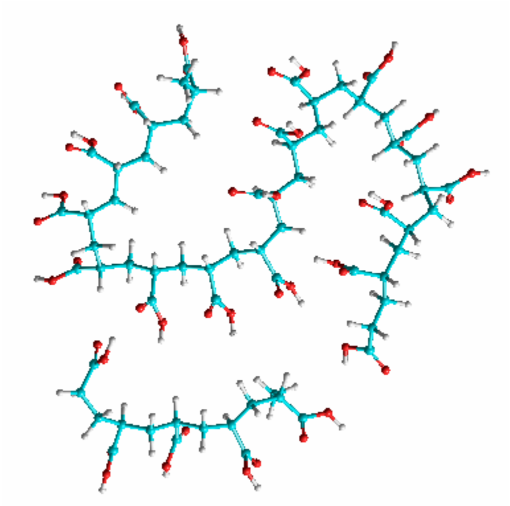
MODEL:

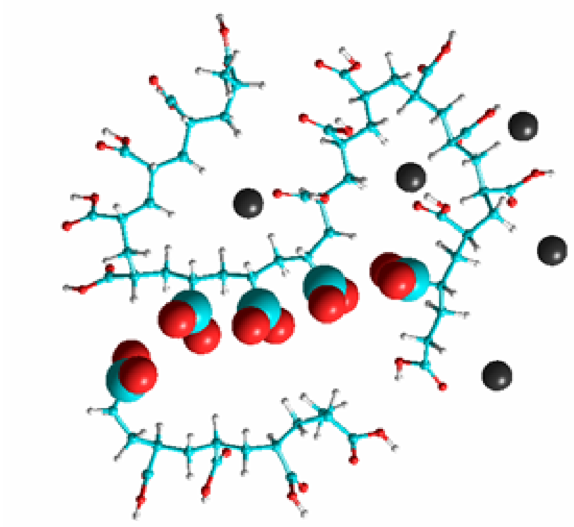
1) Electronic states are created by COO^- ions
2) Conducting chain formation



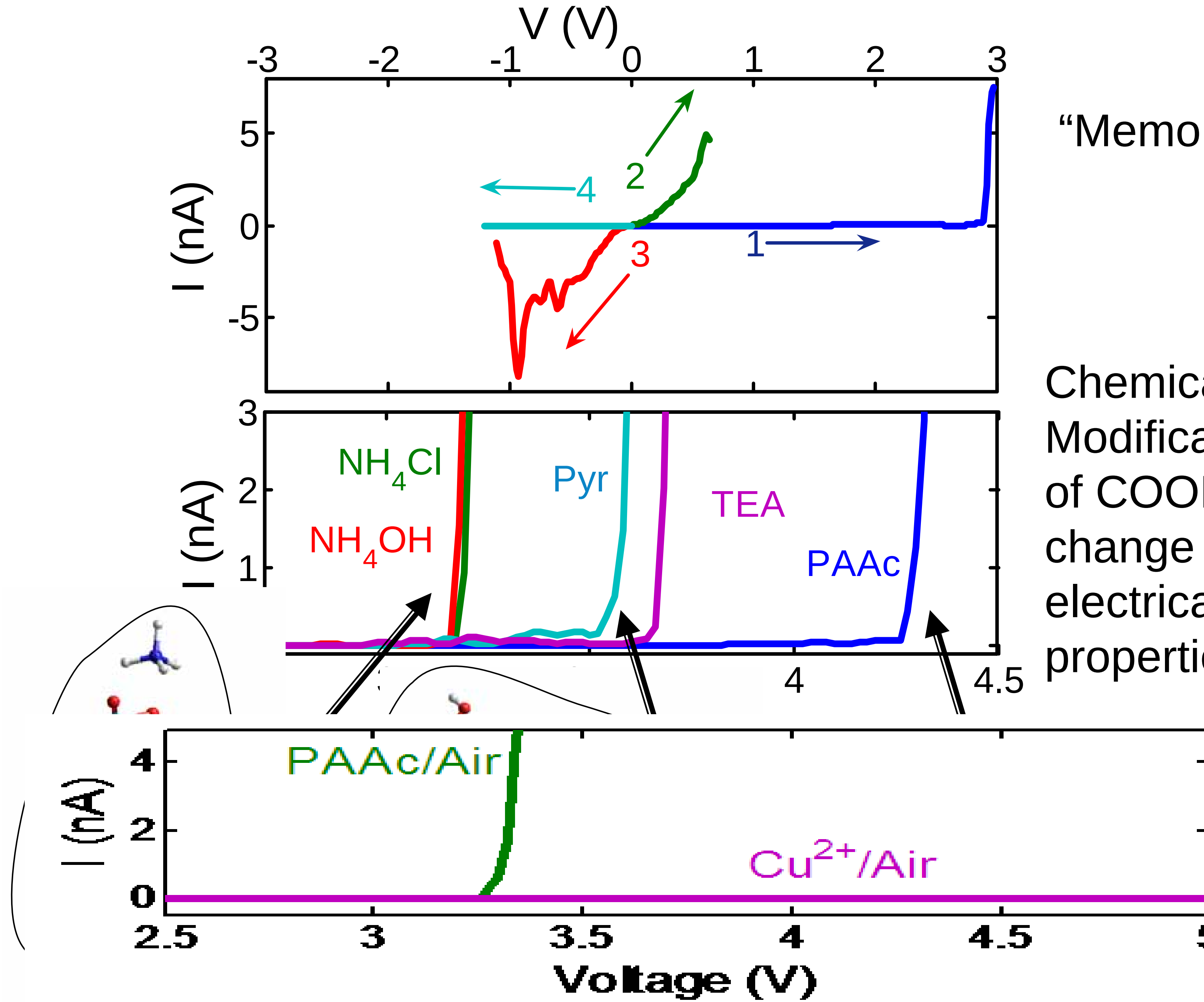
Conducting channel

Initial state



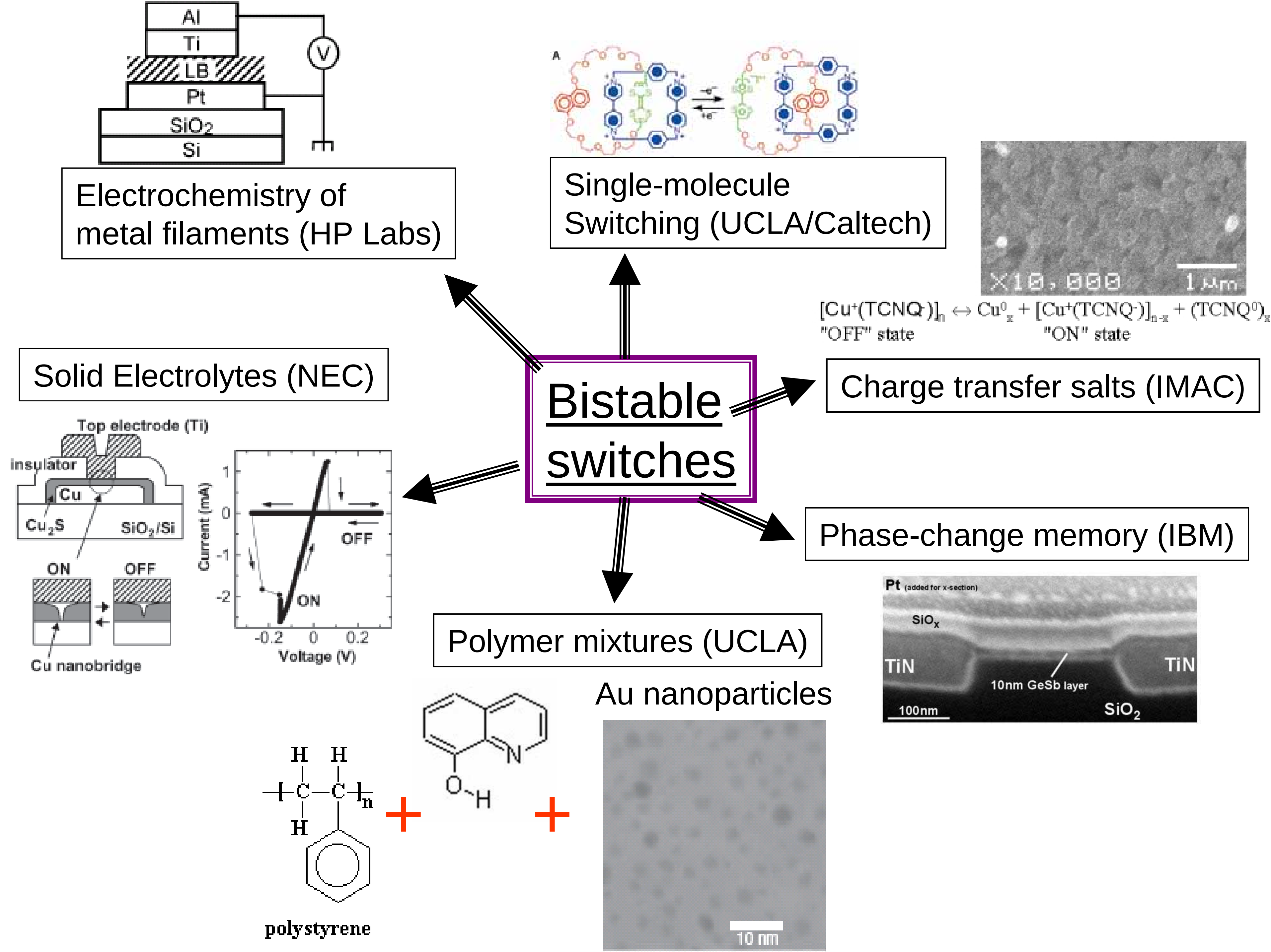


Metastable state stabilized by conformational change



"Memory"

Chemical Modifications of COOH change electrical properties


Bistable switches
Electrochemistry of metal filaments (HP Labs)
Al
Ti
LB
Pt
SiO2
Si
V
Single-molecule Switching (UCLA/Caltech)
Charge transfer salts (IMAC)
×10,000
1 µm
[Cu+(TCNQ-)]n ↔ Cu0x + [Cu+(TCNQ-)]n-x + (TCNQ0)x
"OFF" state
"ON" state
Solid Electrolytes (NEC)
Top electrode (Ti)
insulator
Cu
Cu2S
SiO2/Si
ON
OFF
Cu nanobridge
Current (mA)
Voltage (V)
Phase-change memory (IBM)
Pt (added for x-section)
SiOx
TiN
TiN
10nm GeSb layer
SiO2
100nm
Polymer mixtures (UCLA)
polystyrene
Au nanoparticles
10 nm

Summary

1. Opportunities beyond Silicon: **Ion / Atom** based **Switches**

2. Problems with atomically precise devices: **Defects**

3. Possible Solution: **Engineering** devices with high **"Defect"** de

4. Applications

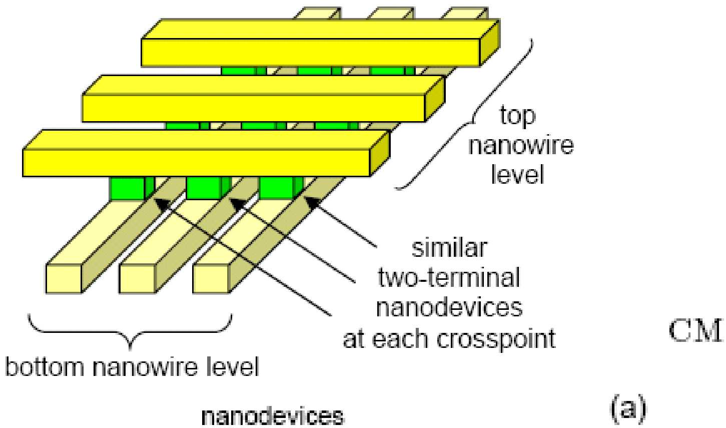
4. Applications

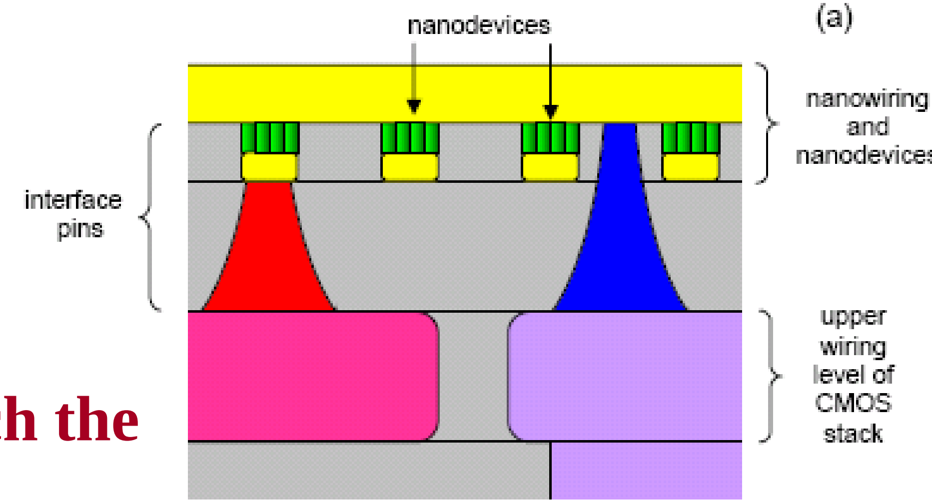
a) Memory

b) Memory + Logics

c) New architectures

d) New Functionality





When will computer hardware match the human brain?

Dell 8250 (Pentium®4)

10^3 MIPS

x 10^5