SAND2014-18822PE

Atomic Switch: Overview and Critical Discussion

2014 ITRS ERD Workshop
Albuquerque, NM
August 28, 2014

Matthew Marinella
Sandia National Laboratories
matthew.marinella@sandia.gov

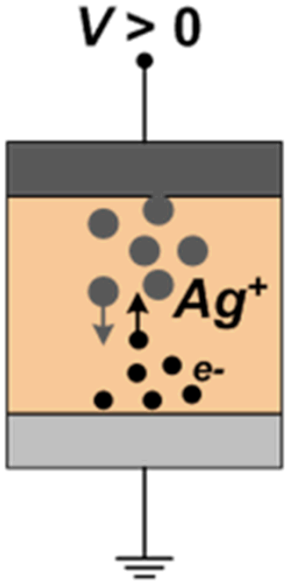
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Electrochemical Memories
- Atomic switch in Logic
  - FPGA and PLA-like implementation
  - Three terminal
  - Brain inspired computing
- Discussion

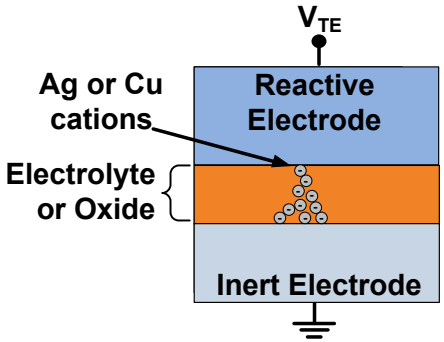
Electrochemical Metallization Memories

- Memory based on metal filament formation in chalcogenide
- Invented in late 1990's by Kozicki (Arizona State University)
- Several synonyms:
  - Programmable Metallization Cell (PMC)
  - Conducting Bridge RAM (CBRAM)
  - Nanoionic or Ionic Memory
  - Atomic switch
- Silver or copper filament forms in solid electrolyte
- Physics of this process studied since 1970's



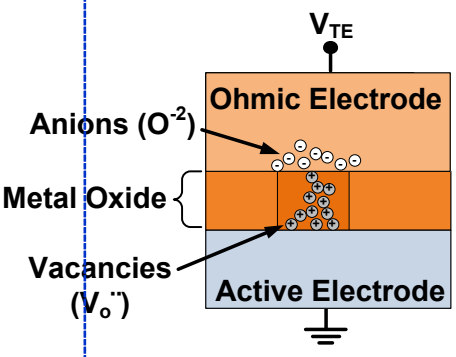
Courtesy DK Schroder

Electrochemical Metallization Bridge



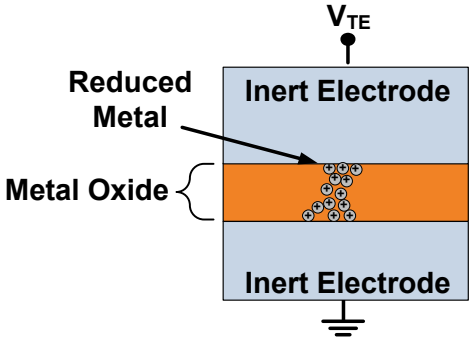
- Switching: Electrochemical formation and dissolution of Ag or Cu filament
- Cation motion (Ag or Cu)
- Chalcogenide or oxide insulating layer
- Switching depends on E-field direction
- R/W current independent of device area

Metal Oxide: Bipolar Filamentary



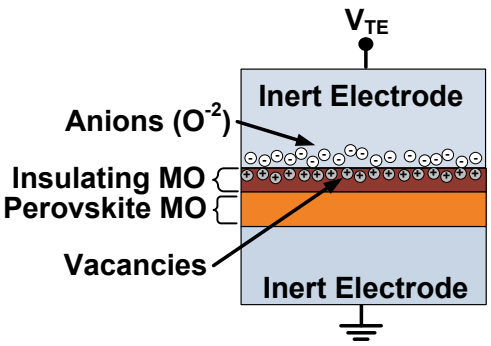
- Switching: Valence change and migration of oxygen vacancies
- Anion motion (O^{2-})
- HfO_x, TaO_x most common insulators
- Switching depends on E-field direction
- R/W current independent of device area

Metal Oxide: Unipolar Filamentary



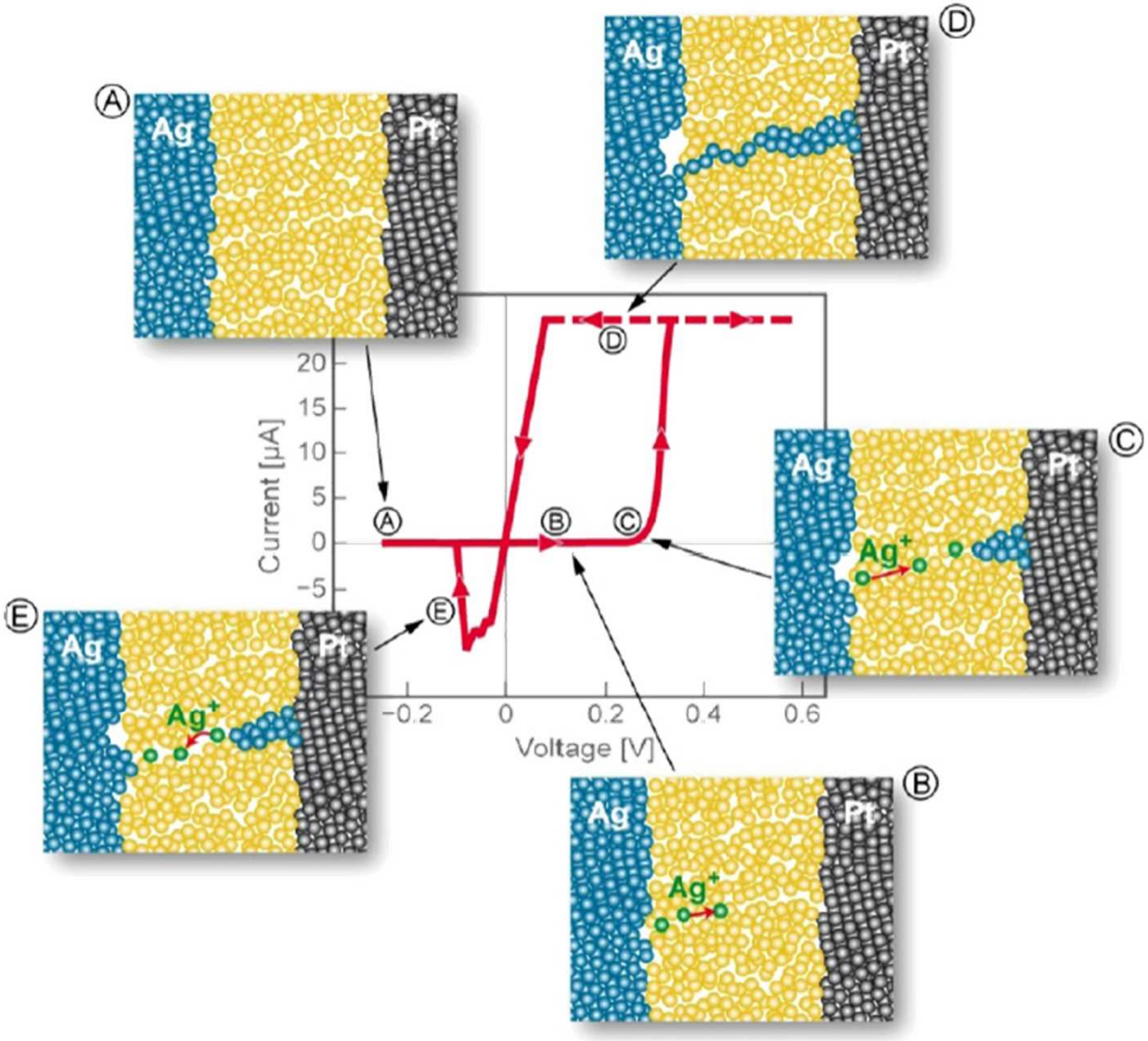
- Switching: Thermochemical change in oxide valence state
- Anion motion (O^{2-})
- Symmetric structure
- NiO_x most common material
- Switching independent of E-field direction
- R/W current independent of device area

Metal Oxide: Bipolar Non-Filamentary



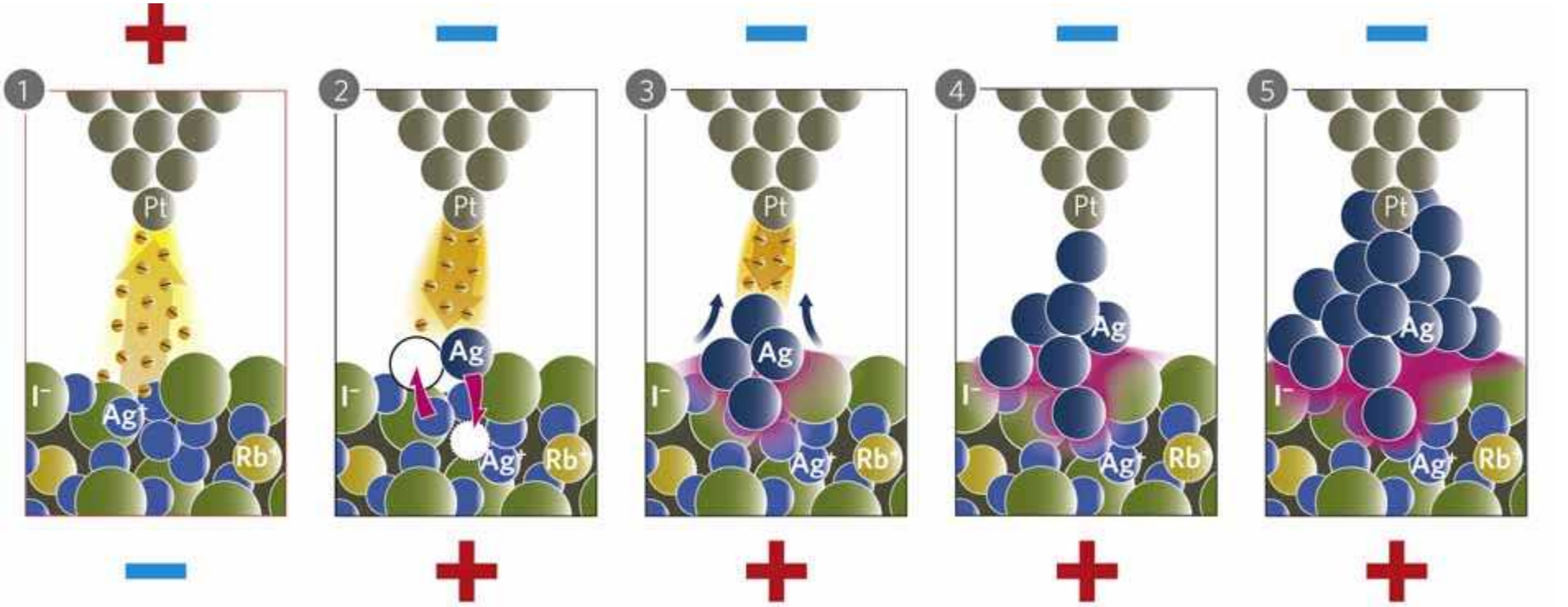
- Switching: Oxygen exchange causes Schottky barrier height change at interface
- Anion motion (O^{2-})
- Perovskite and insulating metal oxide
- Switching depends on E-field direction
- R/W currents depend on device area

Electrochemical Metallization Physics



Valov et al, *Nanotechnology* 22, 254003 (2011)

Original “Atomic Switch”



Valov et al, Nature Mat 2012

Some ECM Materials

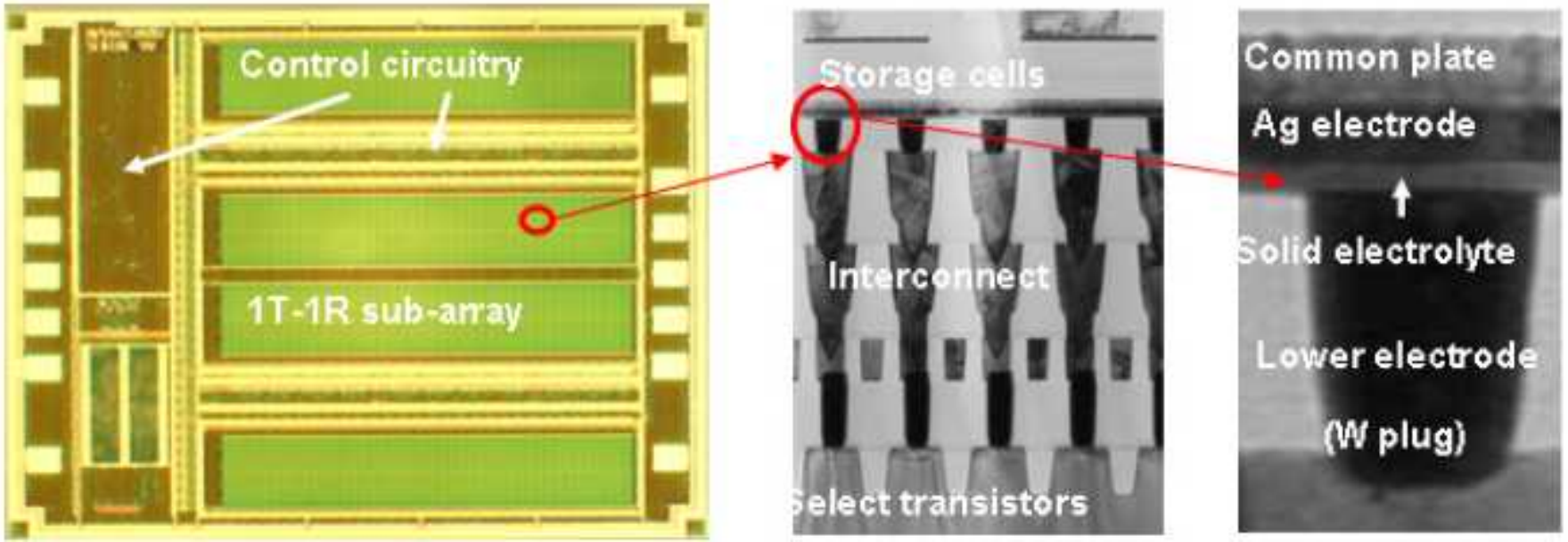
Electrolyte	Electrode metals	
	Ag anode	Cu anode
Ge_xS_y	*W*	*W*
Ge_xSe_y	*W, Ni, Pt*	*W*
Ge-Te	*TiW*	*TaN*
GST	*Mo*	
As-S	*Au*	
$Zn_xCd_{1-x}S$	*Pt*	
Cu_2S		*Pt, Ti*
Ta_2O_5		*Pt, Ru*
SiO_2	*Co*	*W, Pt, Ir*
WO_3	*W*	*W*
TiO_2	*Pt*	
ZrO_2	*Au*	
MSQ (SiO_2)	*Pt*	
CuTe/GdOx		*W*
Ge_xSe_y/SiO_x		*Pt*
Ge_xSe_y/Ta_2O_5		*W*
Cu_xS/Cu_xO		*Pt*
Cu_xS/SiO_2		*Pt*

Valov et al, *Nanotechnology* 22, 254003 (2011) & Kozicki, SFBA NVMW 2012

Commercial "Atomic Switch" Products

- 2012 Adesto Technologies, Sunnyvale, CA
- Ag/Solid electrolyte integrated with BEOL CMOS
- Low density serial EEPROM memory replacement

adesto™
TECHNOLOGIES



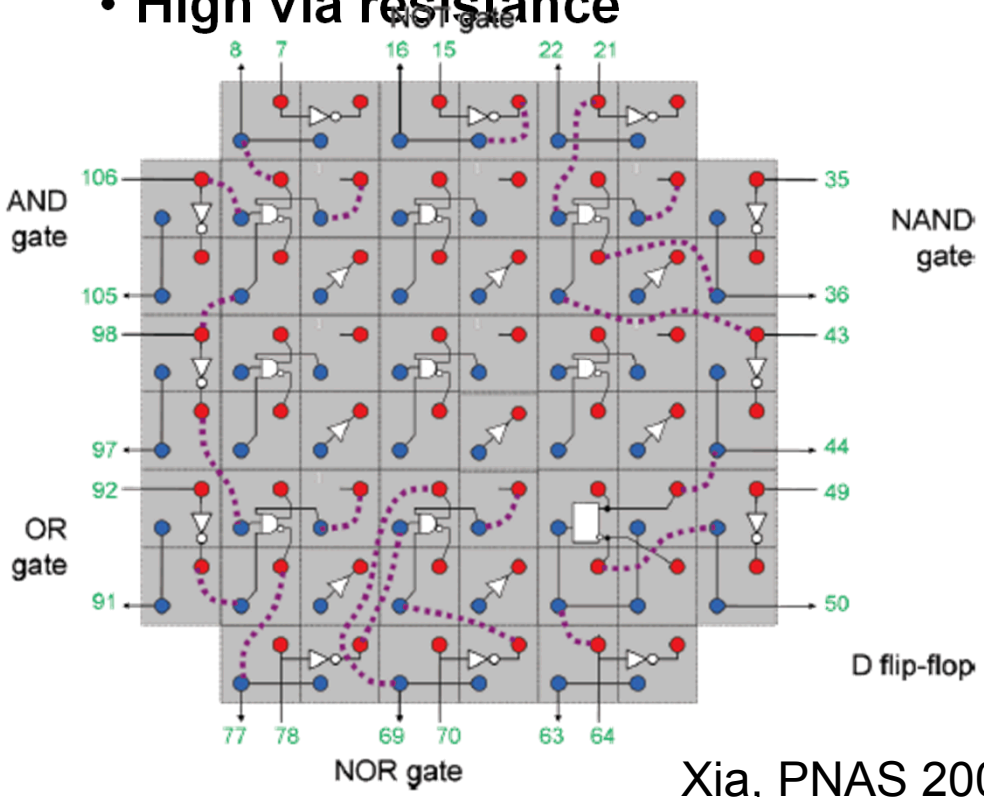
Valov et al, *Nanotechnology* 22, 254003 (2011), www.adestotech.com

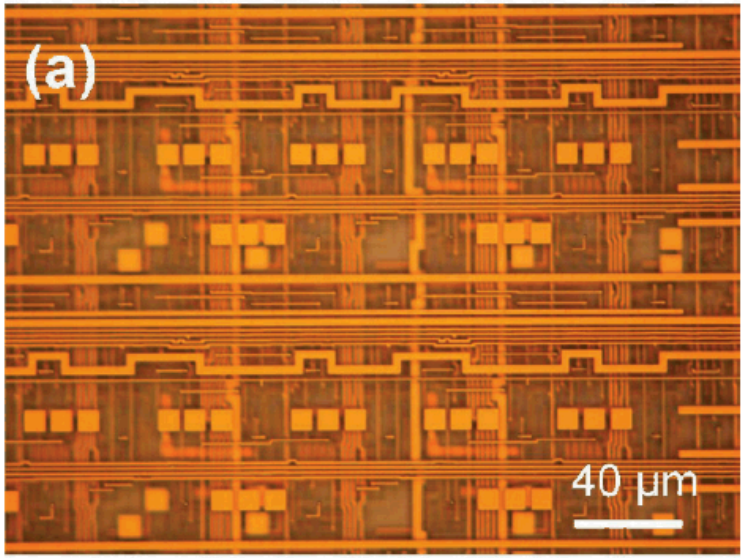
Atomic Switch: Logic Device?

- So, this sounds like a memory device
  - Why are we talking about it in a logic device workshop?

PLA and FPGA variants

- Rudimentary version of “field programmable gate array” demonstrated by HP in 2009, others have also shown
- Logic gates connected by memristors, aka gapless atomic switches
- High via resistance

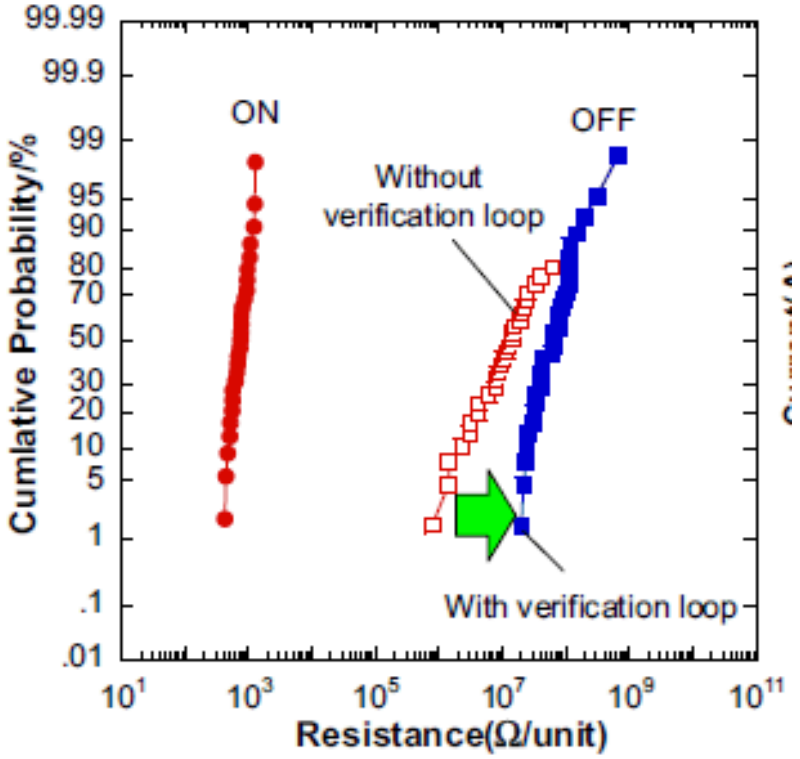


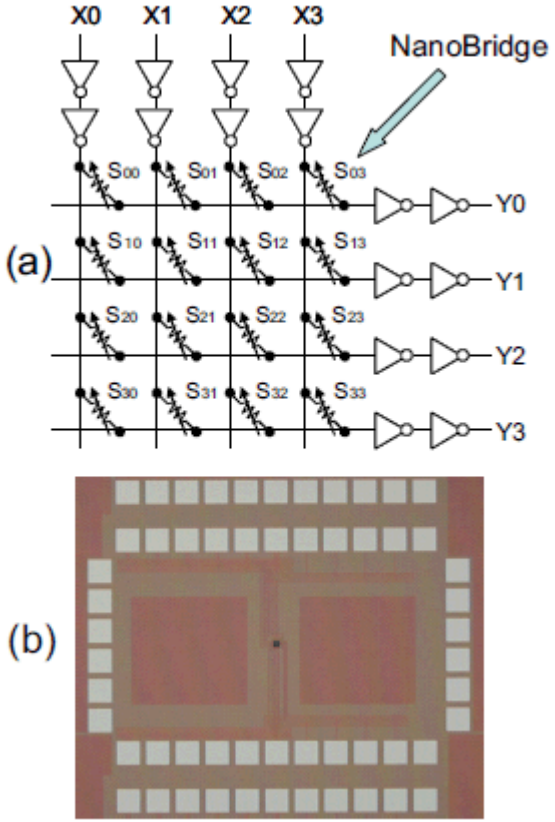


Xia, PNAS 2009

PLA variants

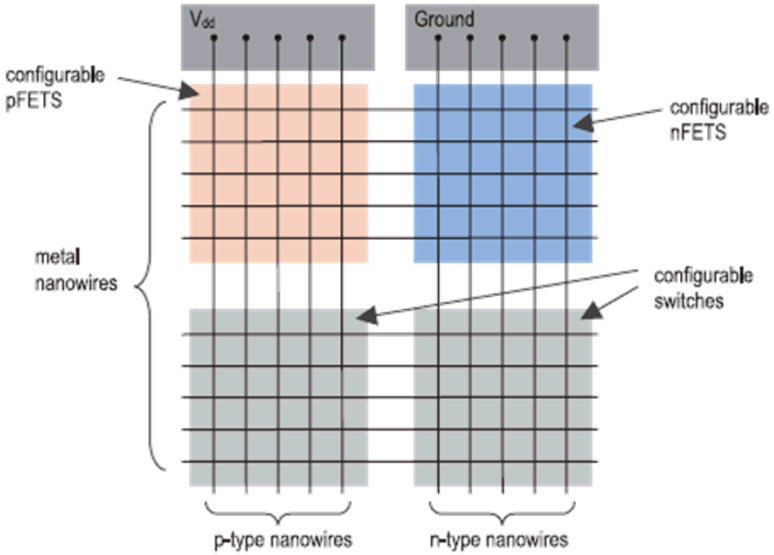
- NEC Nanobridge configuration
- Reasonably low interconnect resistance

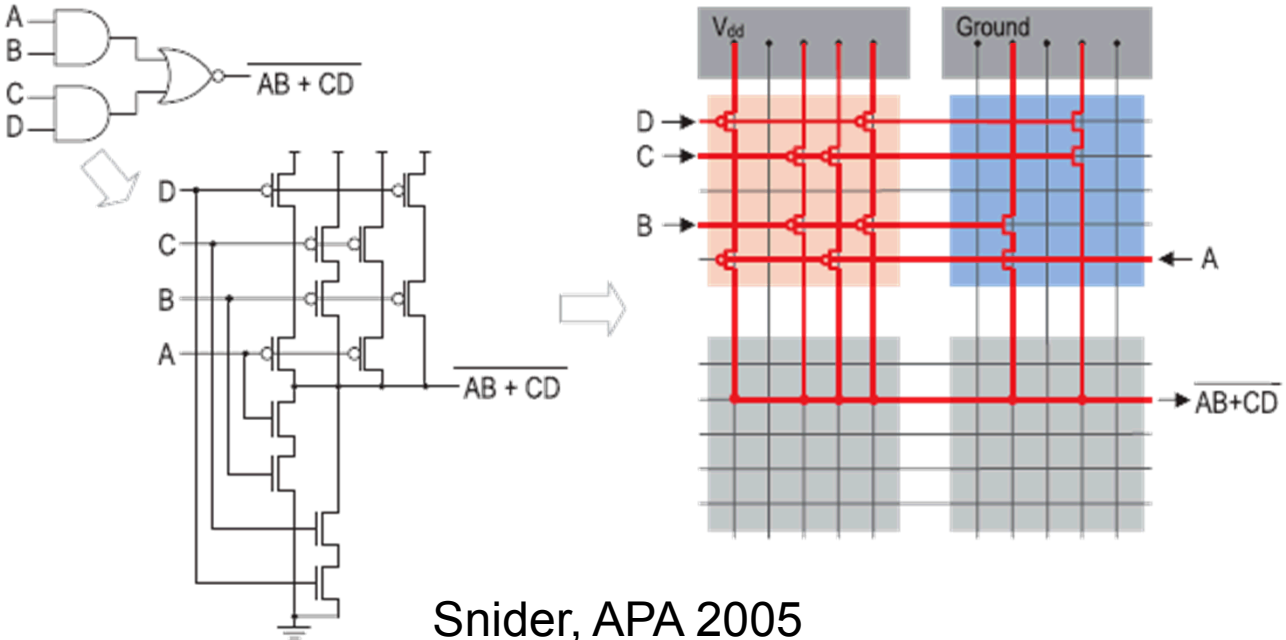




NEC: IEDM 2009

Variant of PLA

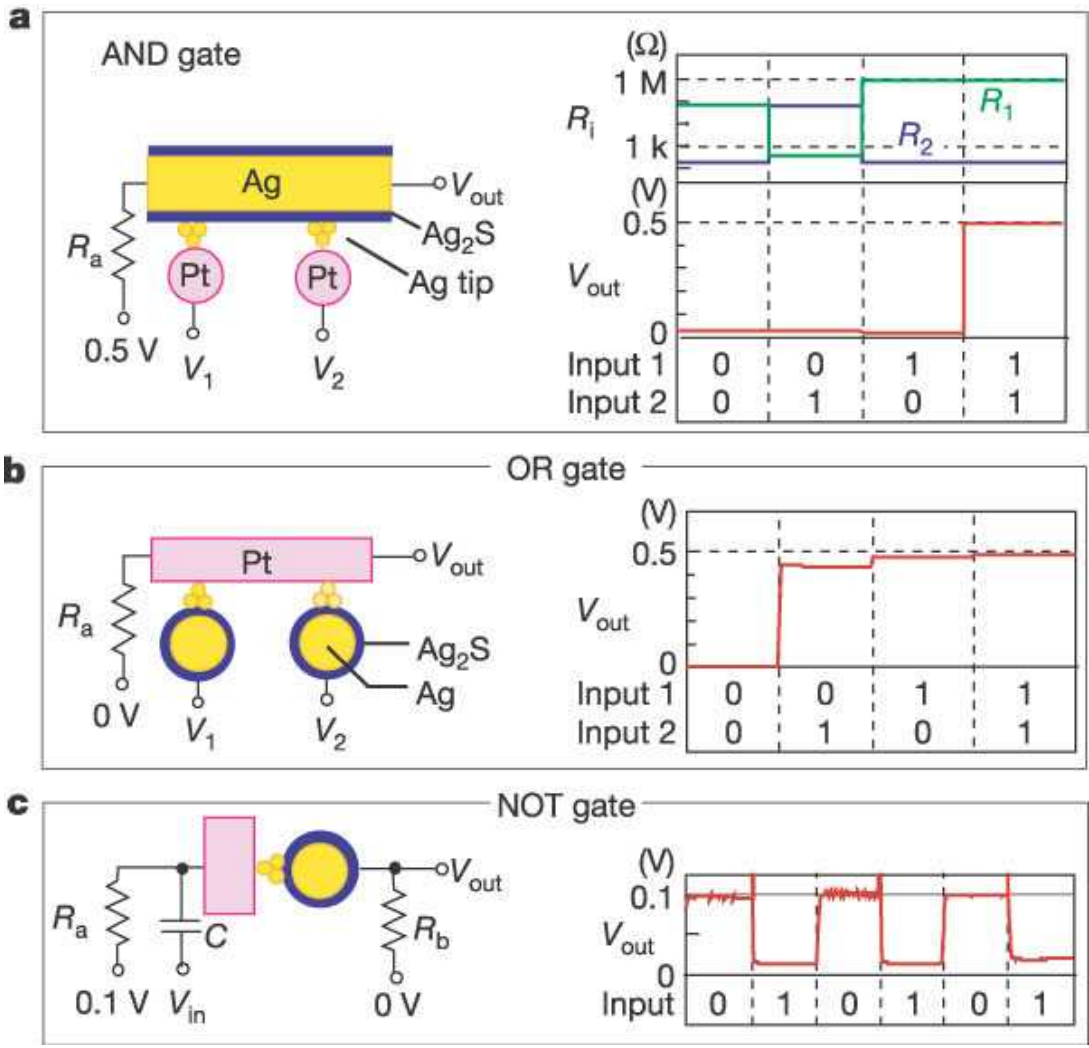




Snider, APA 2005

Atomic Switch Logic Circuit

- Voltage divider,
- High scalability, <5nm
- Poor power efficiency: consider AND case
  - R_a must be <= R1, R2
  - I = Va / R_a + R_1
  - Assume resistors are 1M LRS, 10 M HRS
  - V/2 = 0.25V, I=0.25uA
  - Static for 1M devices = 0.25 mA
- No method to reset devices

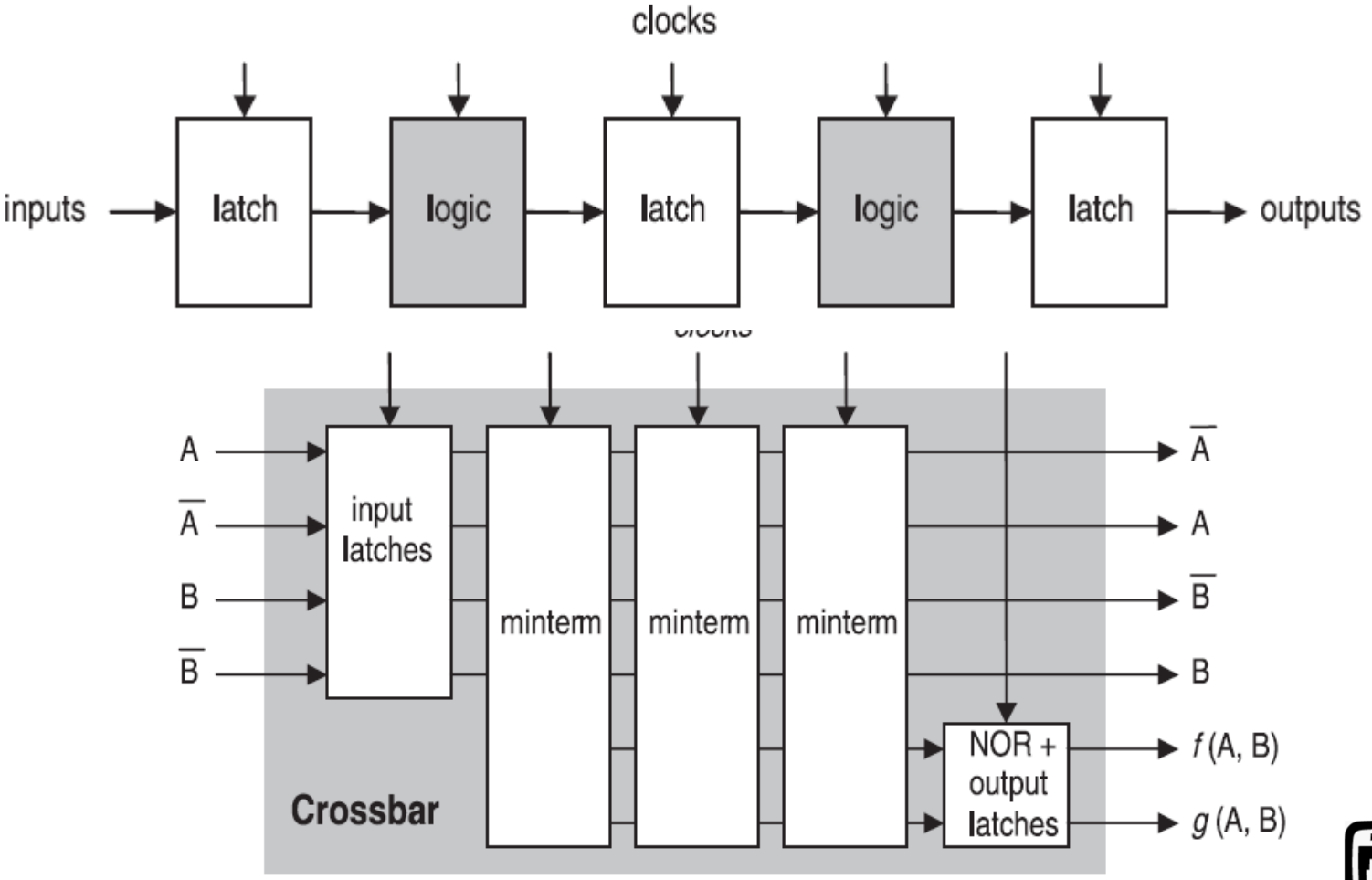


Terabe et al, Nature, 2005

Sandia National Laboratories

Atomic Switch (ReRAM) Logic Circuit

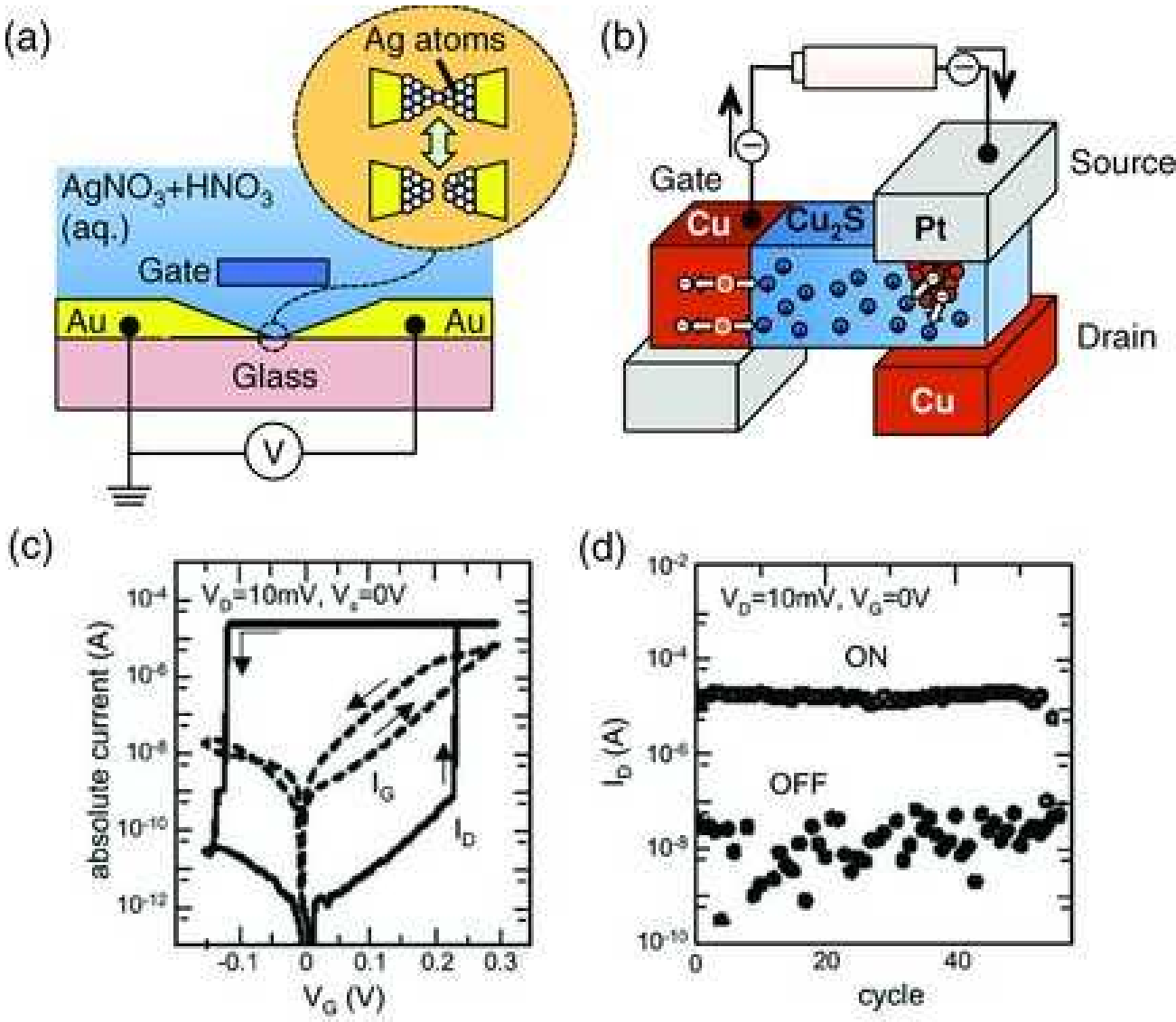
- **Full Architectures have been proposed**



Snider, APA 2005

Three Terminal Atomic Switch

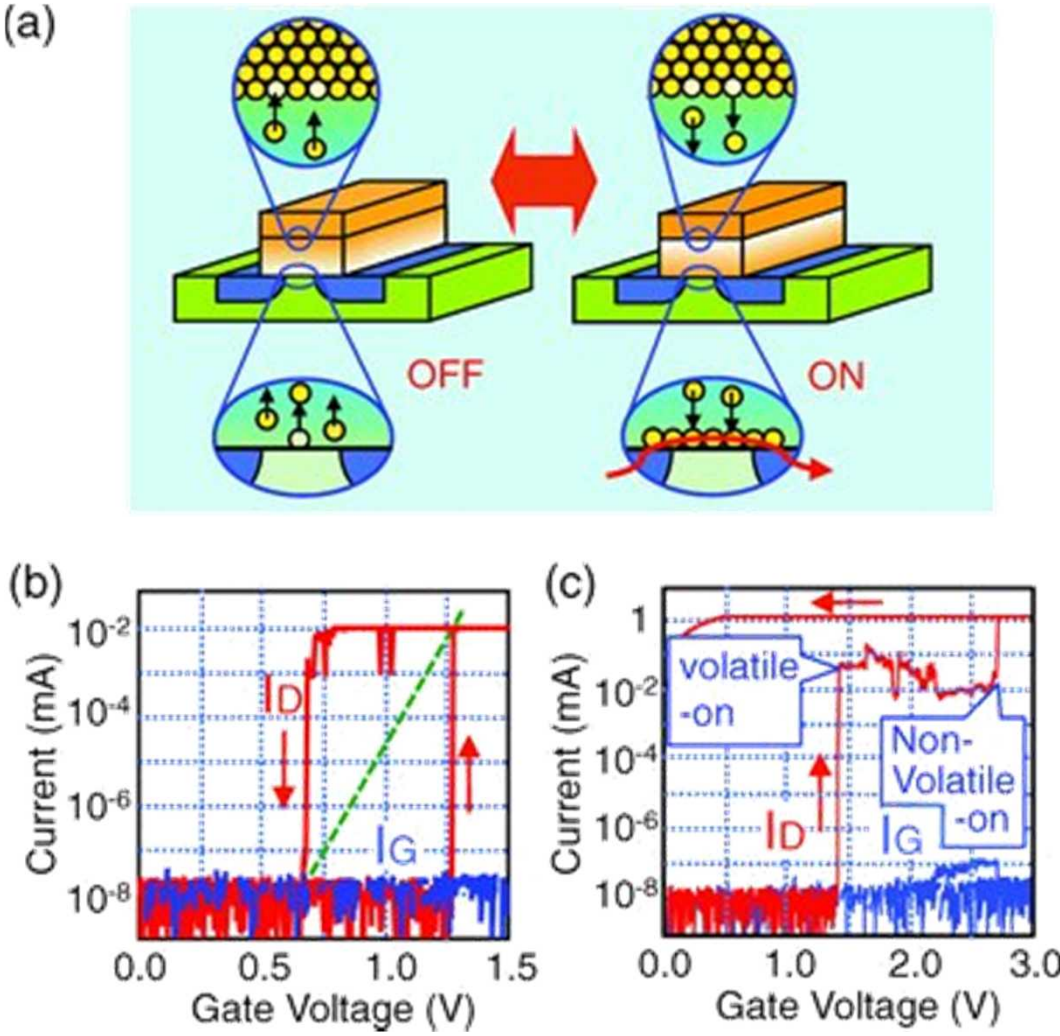
- Gate controls formation of Cu filament
- Gate current too high to function as transistor
- Also, V_{DS} could modulate
- Reliability: only 100 cycles



Banno et al, IEICE Transactions on Electronics, 2006

Improvement: "Atom Transistor"

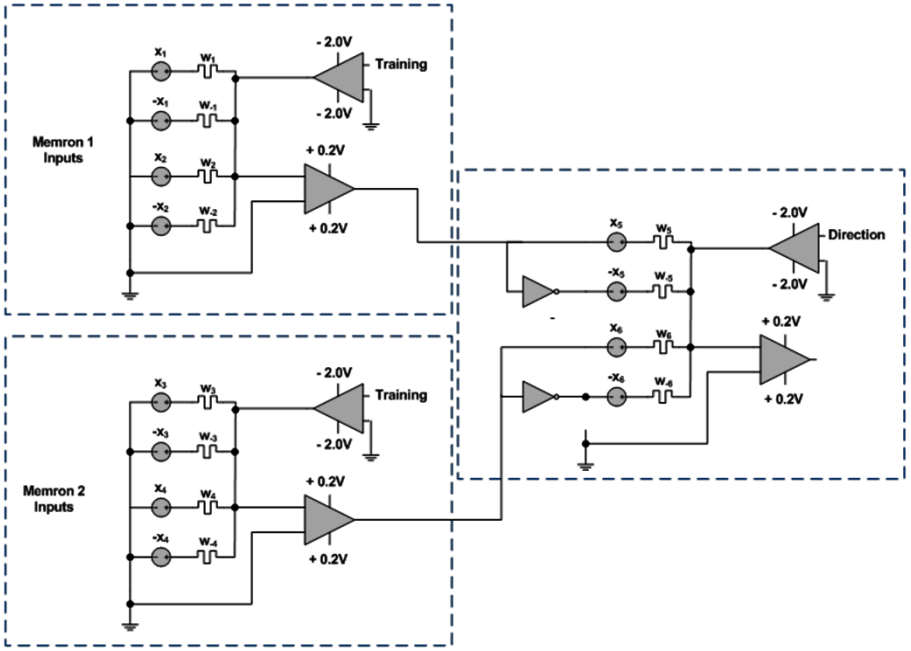
- Transistor-like structure with TaOx gate and copper contact
- Nucleation controlled: copper cations nucleate to form conducting channel
- Hysteretic ID-VG
- Volatile/non-volatile modes
- Subthreshold slope 100 mV/decade demonstrated
- Reliability: 10^6-10^8 cycles

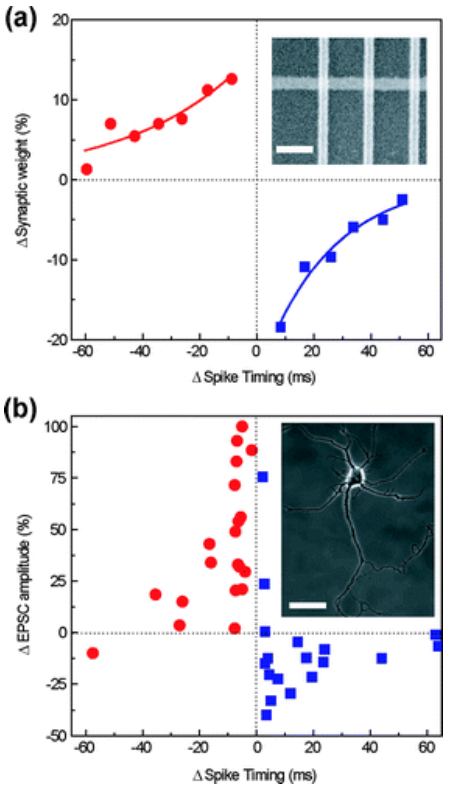


Hasegawa, Adv Mat. 2012

Brain Inspired Computing

- Atomic switch proposed as a synapse
- May enable highly efficient processing of neural algorithms
- Spike time dependent plasticity

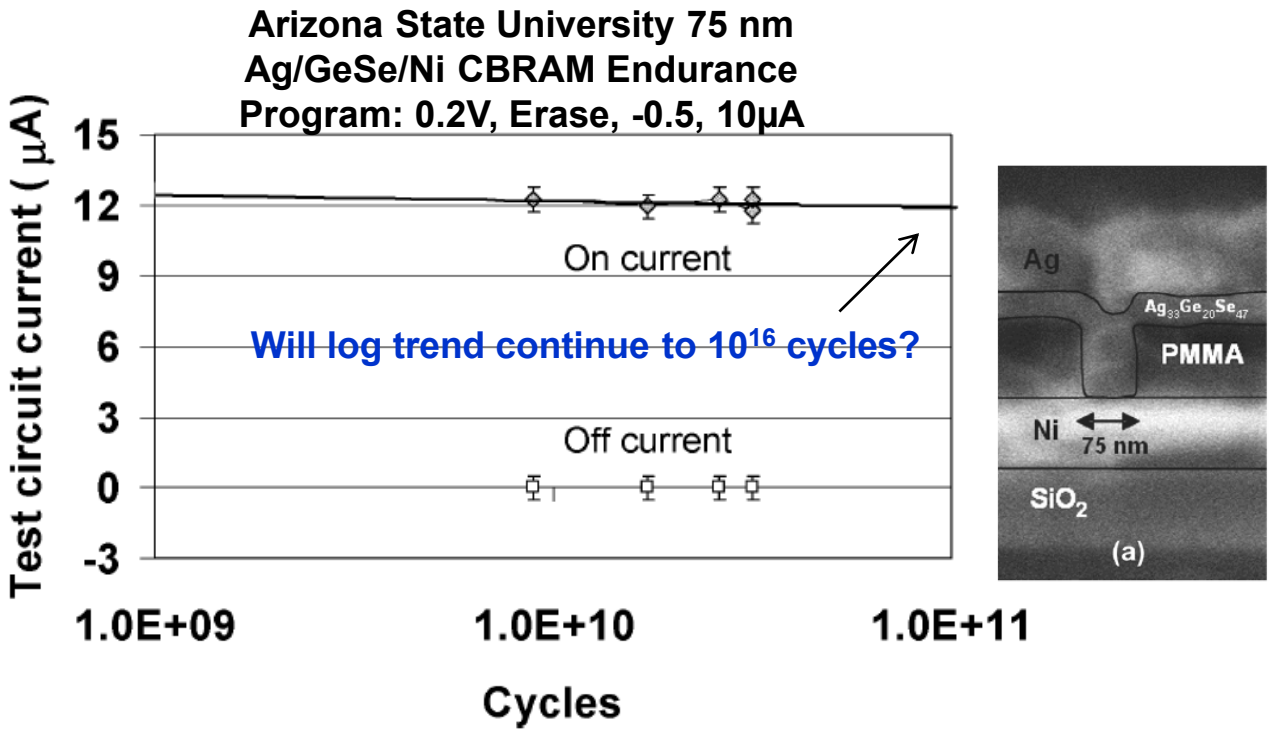




Jo et al, Nano Lett 2010

Endurance: Showstopper for Logic?

- 10^{11}-10^{12} cycles on single device; products much lower
- Typical HP Logic worst case:
  - 10^{9} switch/sec x $3x10^{8}$s (10 years) = 10^{17}cycles



Kozicki et al, TED, 4, 331 (2005)

Discussion Questions

1. What is the most likely point of entry for the atomic switch as a logic device?
2. How does the atomic switch compare to it's nearest competitors, with respect to logic processing?

Some opinions

- As a two terminal logic device, the atomic switch does not have a power efficient architecture
- As a three terminal logic device, only one simple demonstration of an Atom Transistor has been demonstrated
- There is promise for hybrid applications, such as FPGA and neural networks
- However, these are emerging architectures rather than devices

Discussion Questions

How to proceed:

- **Proposal 1:** Remove atomic switch from emerging logic devices. Cover in emerging architectures.
- **Proposal 2:** determine what we are referring to with an atomic switch in ERD logic. Cover this in the logic tables
- **Proposal 3**: remove from ERD/ITRS and cover in boneyard