Emerging Technologies for Computing

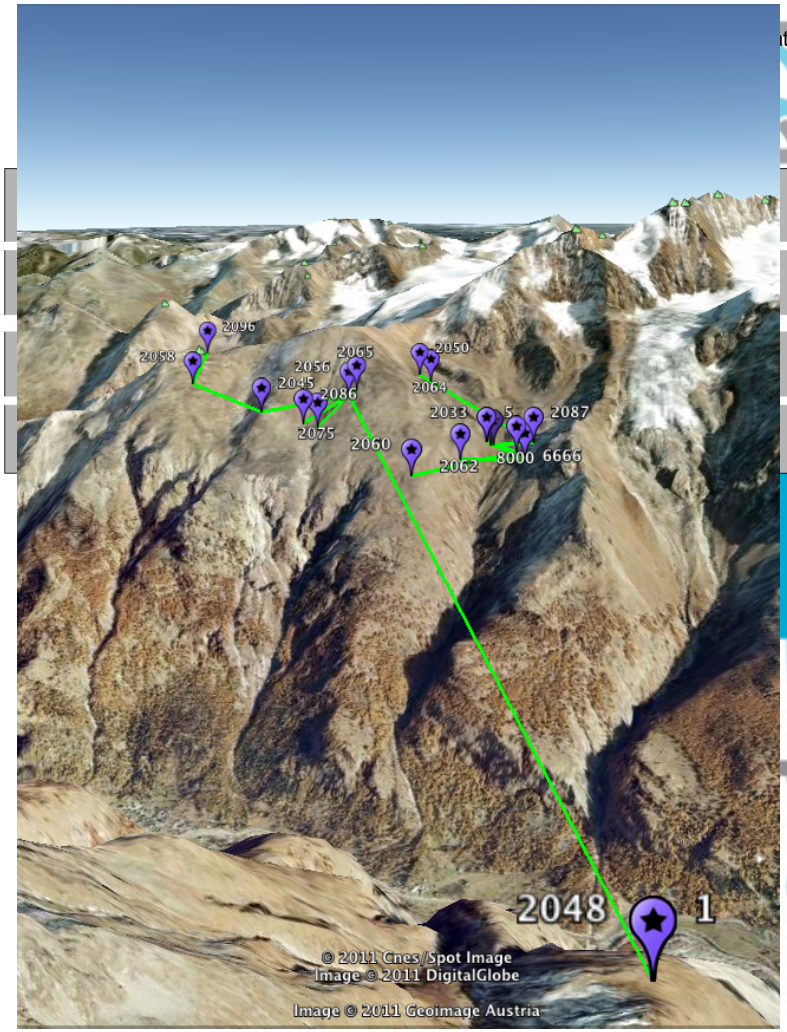
Giovanni De Micheli

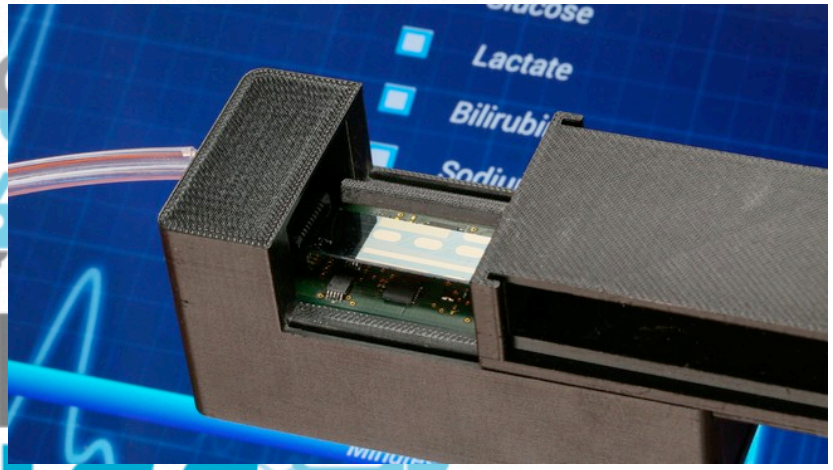
Outline

- **Introduction and motivation**
- Technological innovations
  - Emerging nanotechnologies and devices
- Design with emerging technologies
  - Physical and logic synthesis
- New technologies for broader computing systems
  - Device fusion
- Conclusions

Computing today

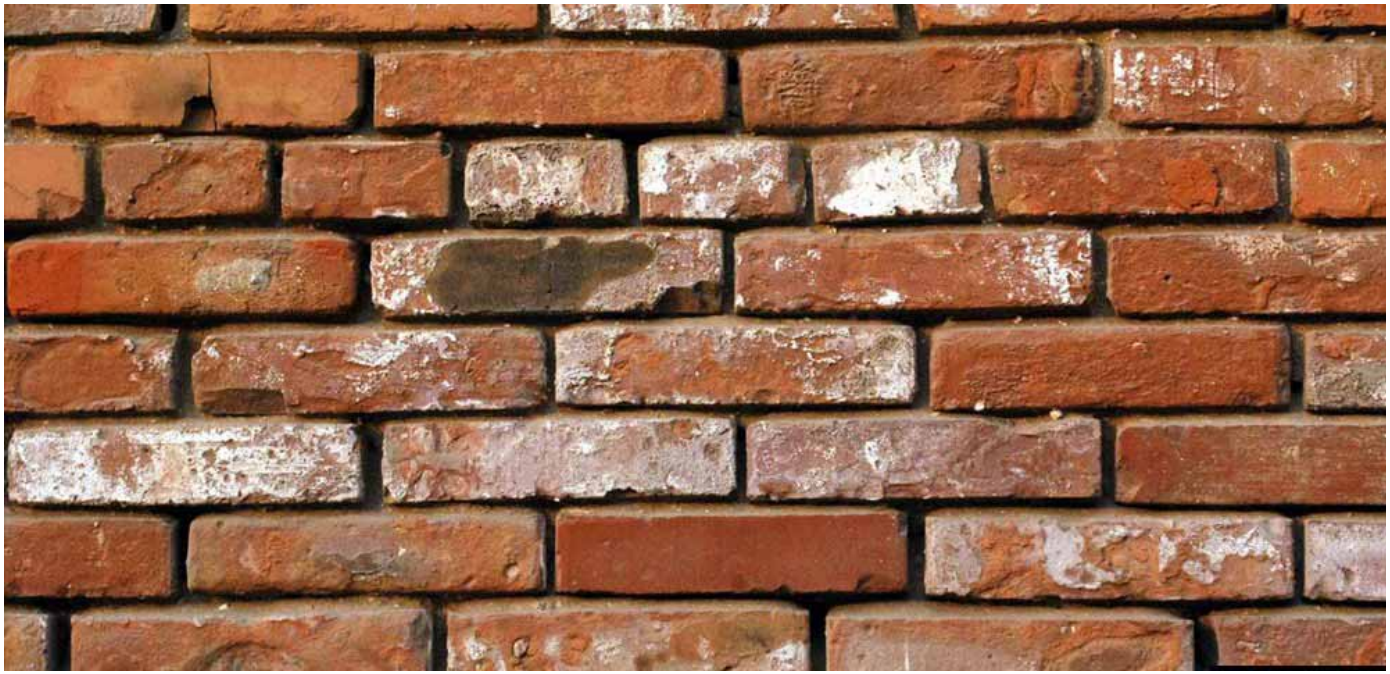
Computing today





Walls

- High-performance, energy-proportional servers
  - High speed computation and data retrieval
- Ultra-low power computing and communication
  - Connect myriad of devices for *Internet of Things*



Walls and game changers

- New computing paradigms
  - Quantum computing (superposition, entanglement)
  - Analog computing (memristors, dynamical systems)
  - Neuromoprhic computing
  - In-memory computing
- New materials and devices
  - Enhanced CMOS devices
  - Exploit heterogeneous integration
- Parallelism in algorithms and software
  - Exploit new computational methods
- Use new design methods and tools
  - Revisit hardware synthesis and design techniques

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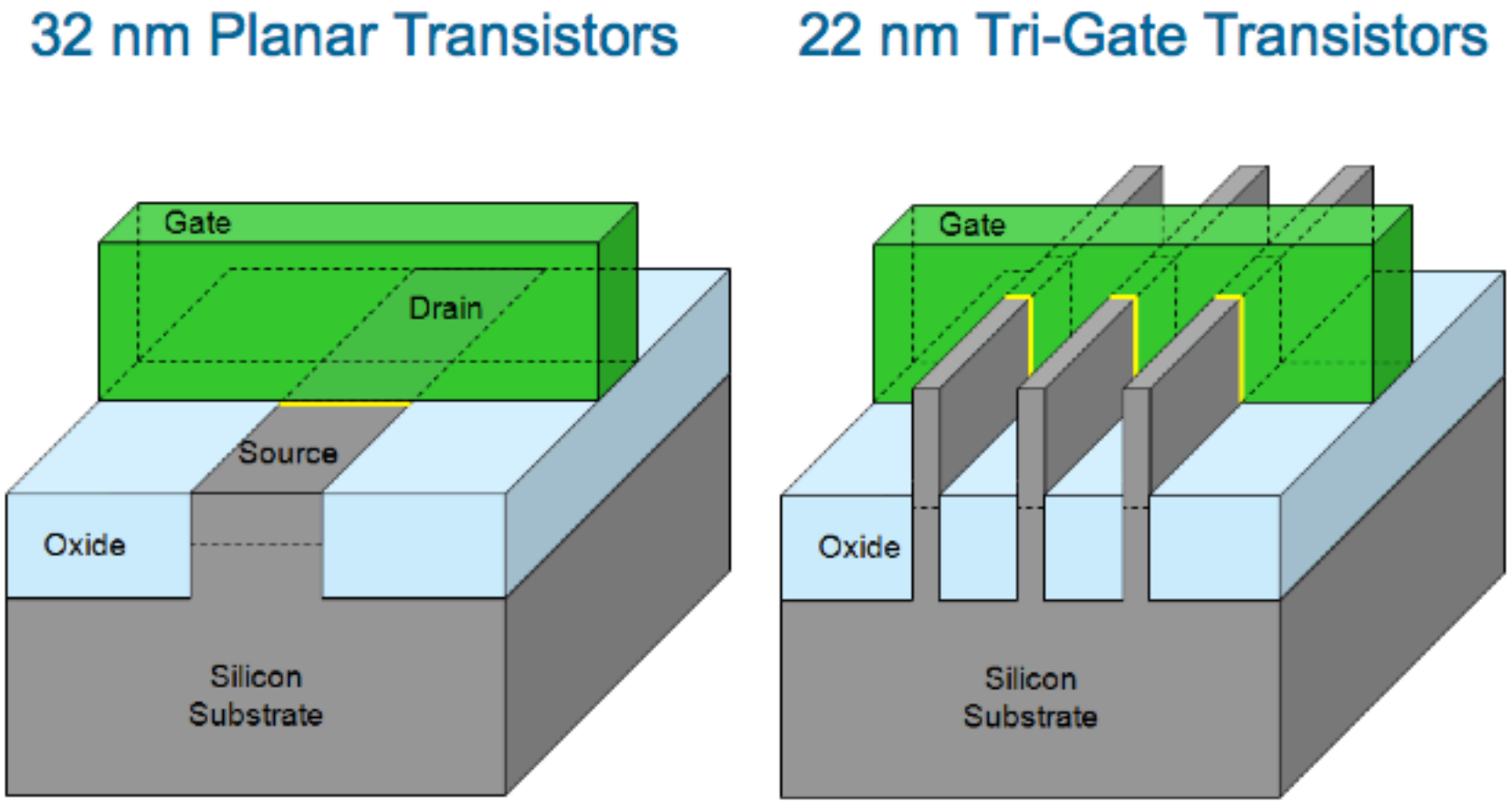
Semiconductor technologies

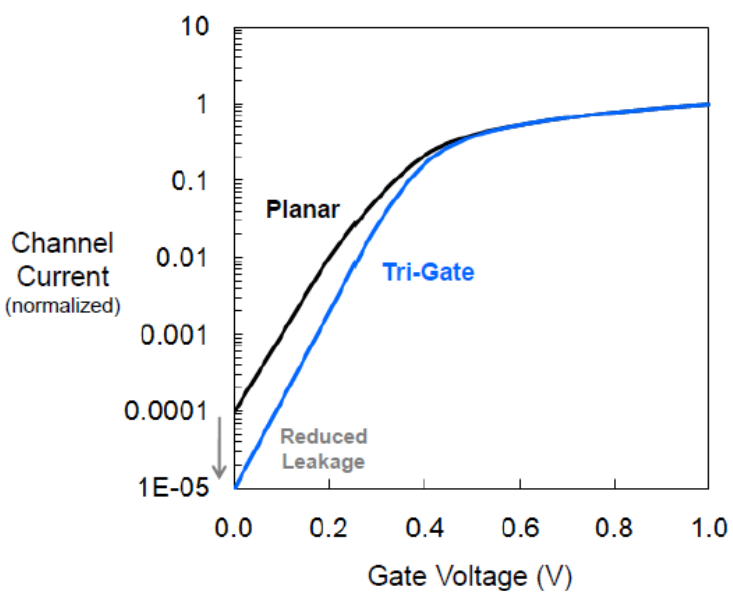
- Most manufacturing technologies have geometries in the nanometer range
- Recently-established nano-electronic technologies
  - Tri-Gate (FinFET) transistors
  - Fully-depleted Silicon on Insulator (FDSOI)
- Downscaling geometries is still effective
- Emerging nano-electronic technologies
  - New materials and devices for processing and memory

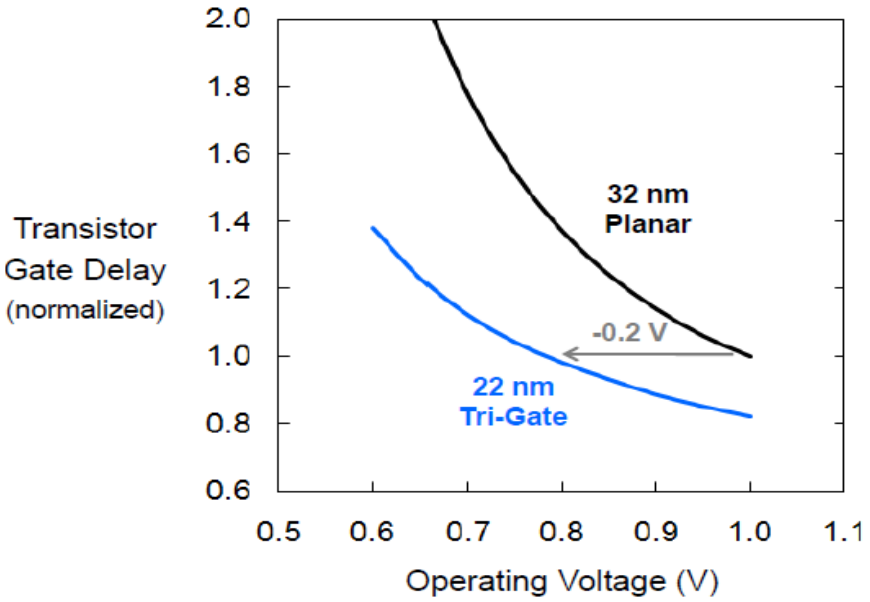
22 nm Tri-Gate Transistors



[Courtesy: M. Bohr]

Tri-Gate vs. planar transistors





- Smaller current for same gate voltage (when offf)
- Same gate delay for smaller operational voltage

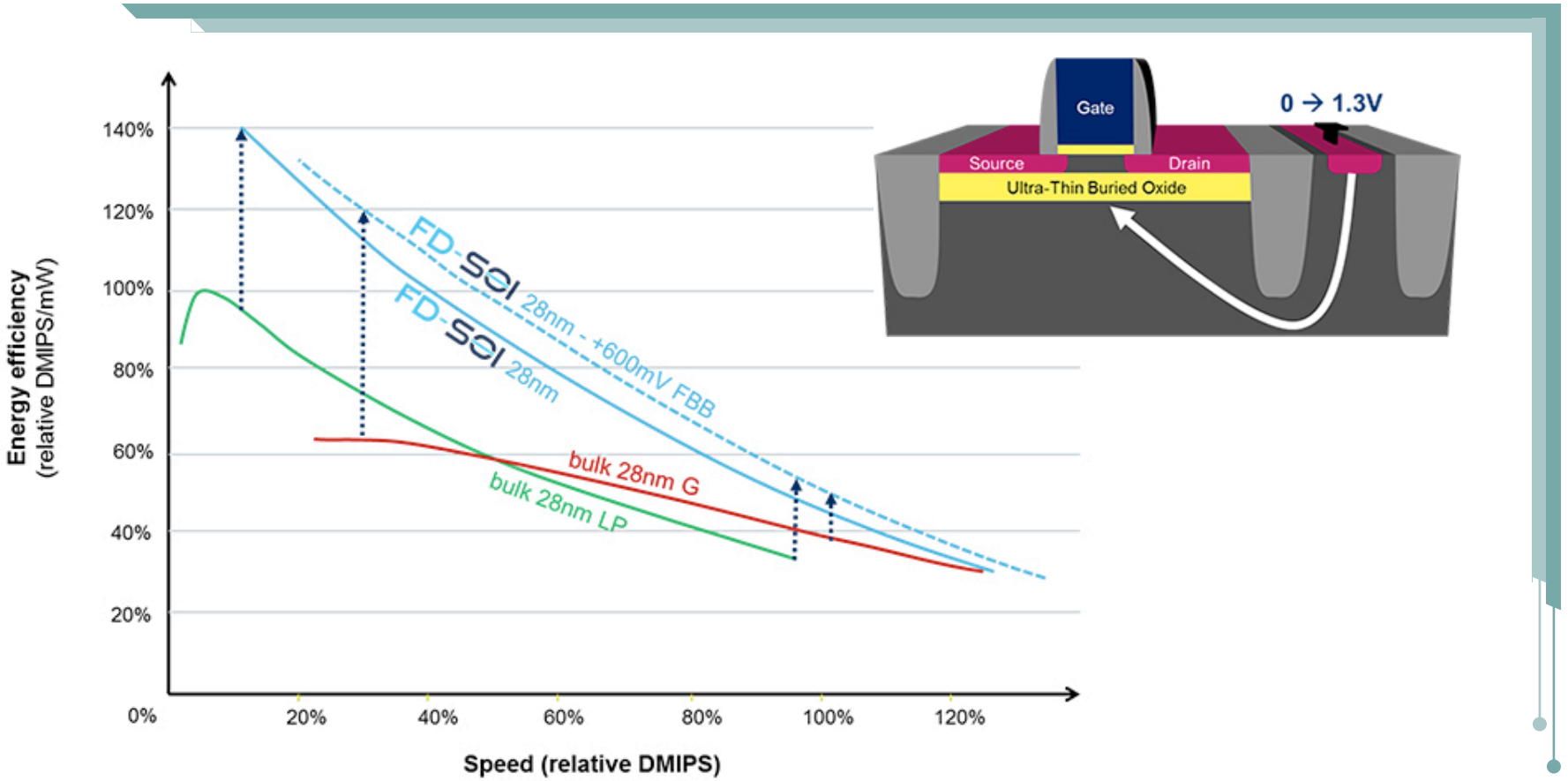
[Source: Intel]

Fully Depleted SoI Transistors

[Courtesy: STMicroelectronics]

- Transistor is built on top of buried oxide (BOX)
- Thin, undoped channel (fully depleted)
- Fine power-consumption control through body bias

Fully Depleted SoI Transistors



[Courtesy: STMicroelectronics]

- Energy efficiency
- Forward body biasing

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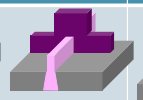
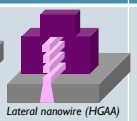
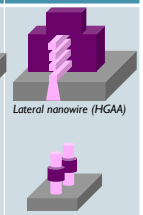
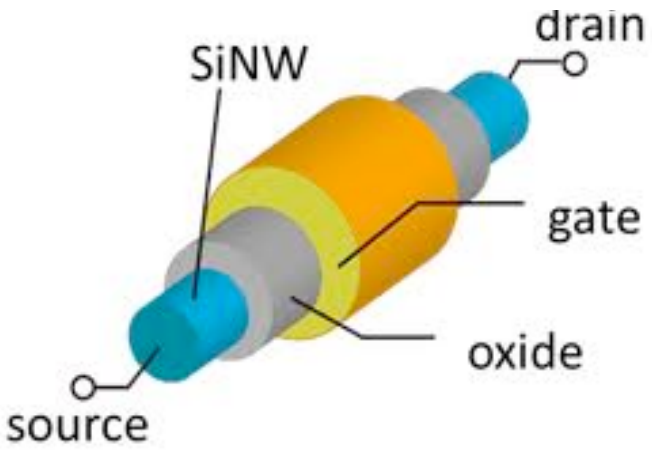
Emerging nano-technologies

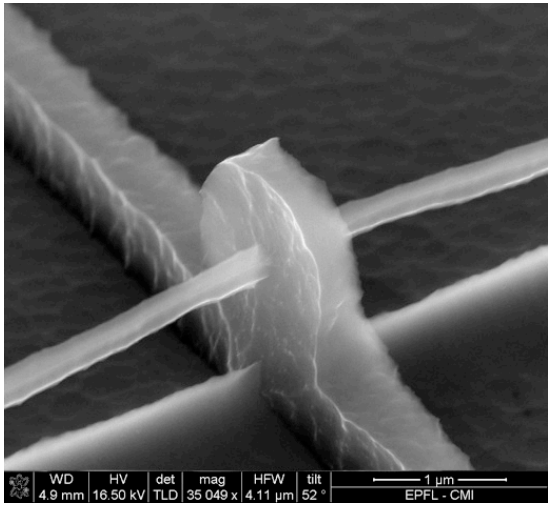
- *Enhanced* silicon CMOS is likely to remain the main manufacturing process in the medium term
  - The 7nm and 5nm technology nodes are on the way
- What are the candidate technologies beyond the 5nm node?
  - Silicon Nanowires (SiNW)
  - Carbon Nanotubes (CNT)
  - 2D devices (Flatronics)
  - … and many others

Early production	2014 iN14	2016 iN10	2017-2018 iN7	2018-2019 iN5	>2020 iN3
					
Vdd (V)	0.8	0.8-0.7	0.7-0.6	0.7-0.5	0.6-0.5
Gate Pitch (nm)	70-90, 193i	52-64, 193i	36-46, 193i	26-36, EUV, 193i	18-28, EUV, 193i
Device	FinFET	FinFET	FinFET {HGAA}	HGAA	HGAA {VGAA}
Channel nfet/pfet	Si / Si	Si / Si {SiGe}	Si / SiGe	Si/ SiGe	High mobility

- What are the differentiators and common denominators from a design standpoint?

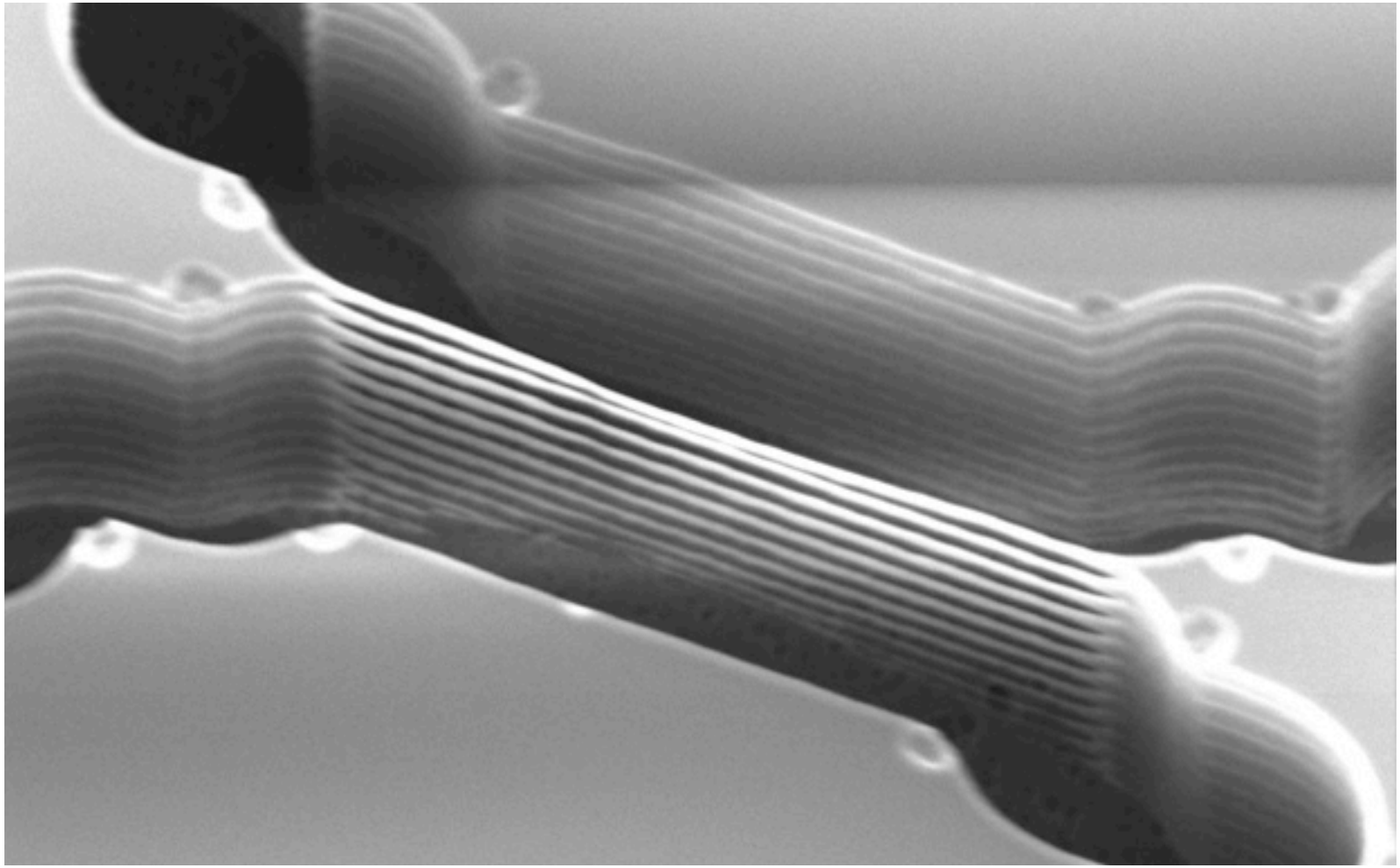
Silicon Nanowire Transistor



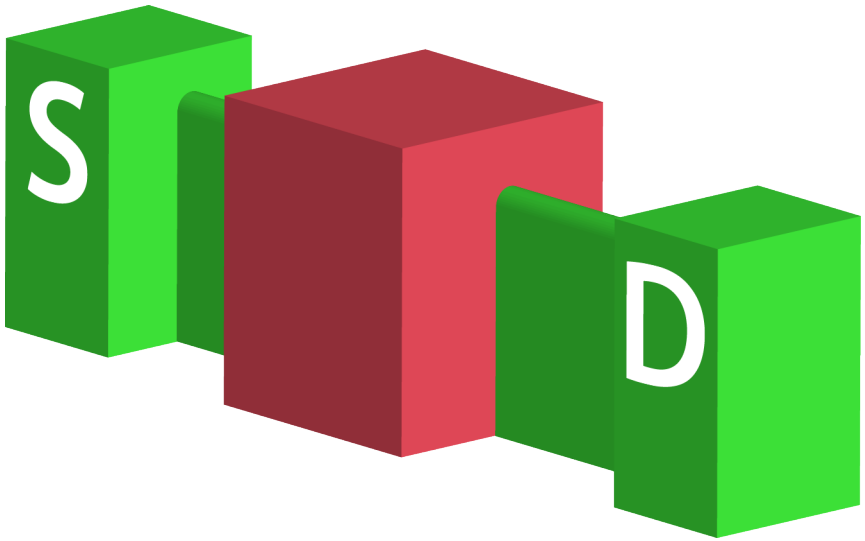


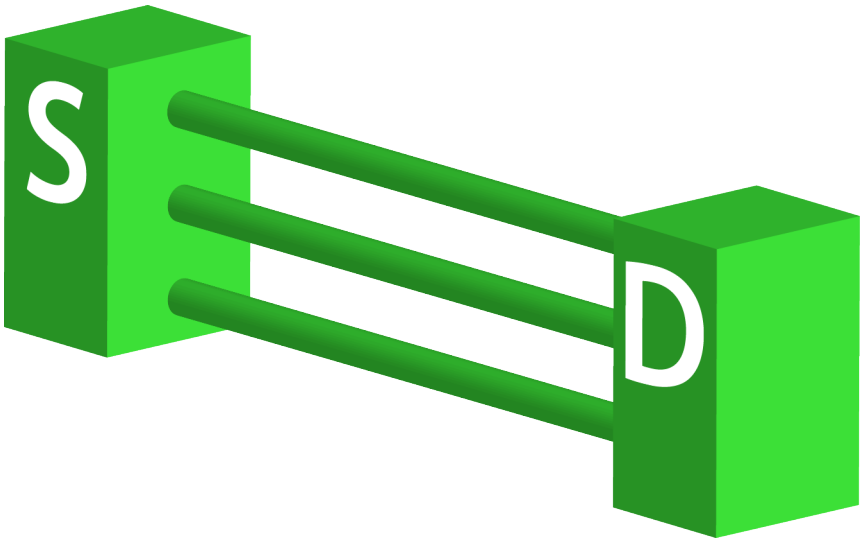
- Fully compatible with CMOS process
- Gate all around
- High I_{on} / I_{off} ratio

Vertically-aligned horizontal SiNW



FinFET to Nanowire FET

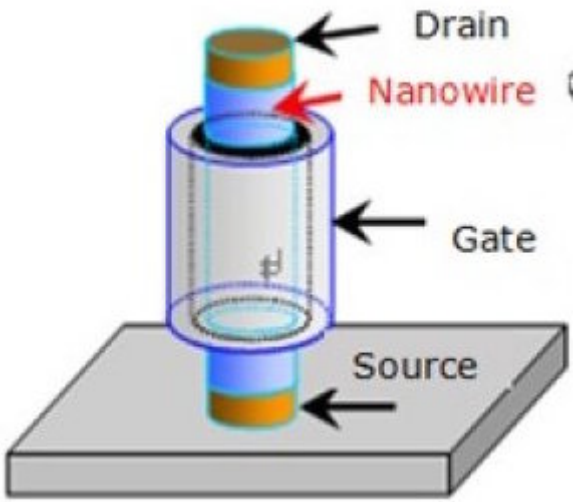


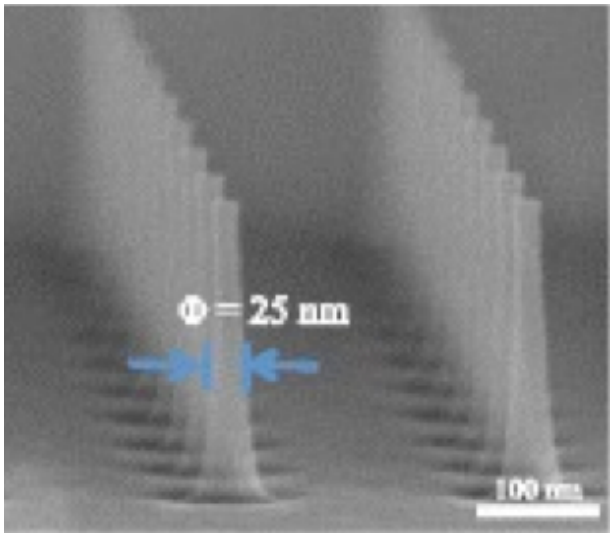


FinFET

NW FET

Vertical silicon nanowire transistors

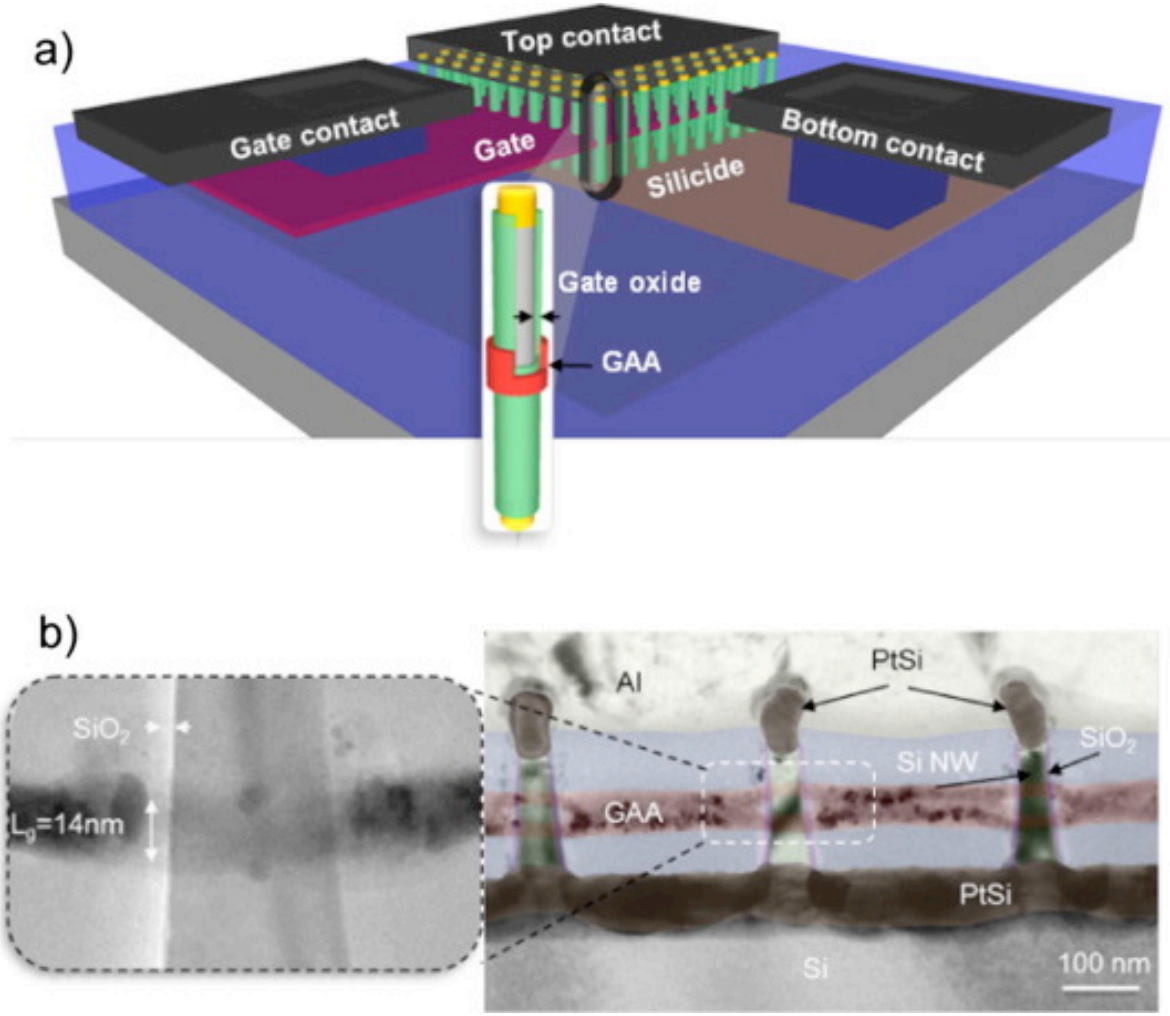




- Fully compatible with CMOS process
- Higher device density
- More complex fabrication process

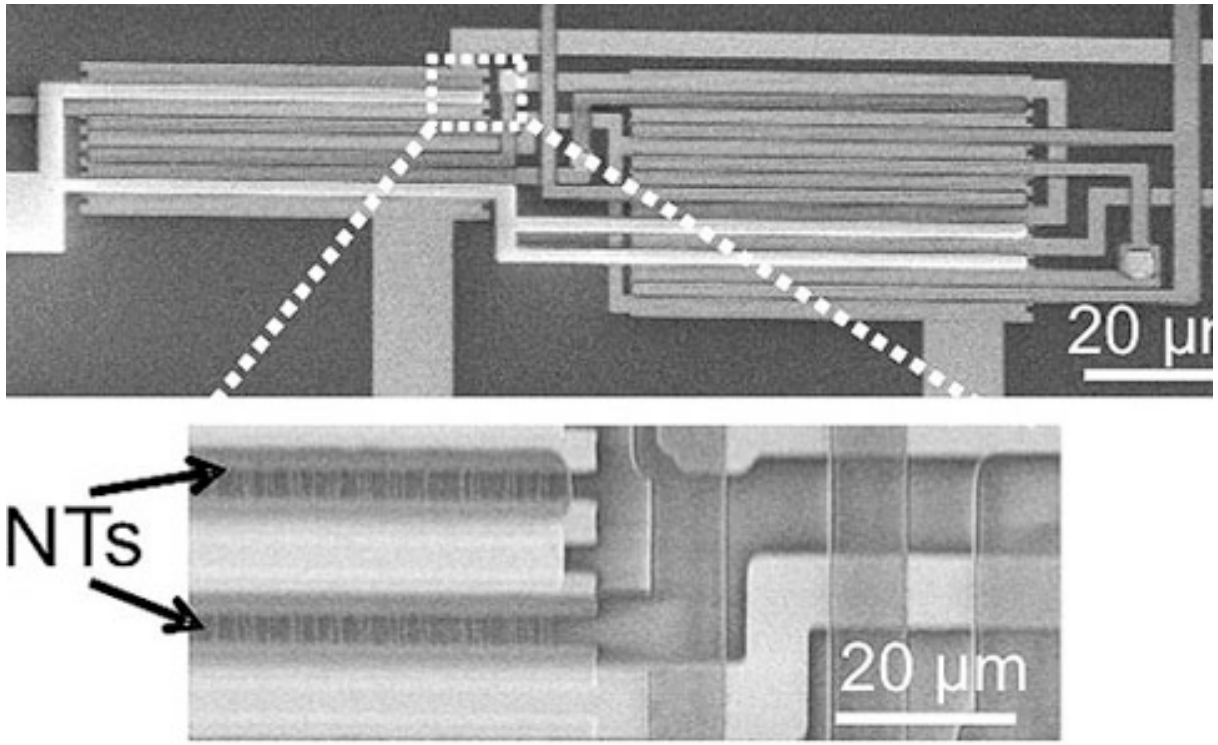
[Guerfi, Nanoscale 16]

Vertical silicon nanowire arrays



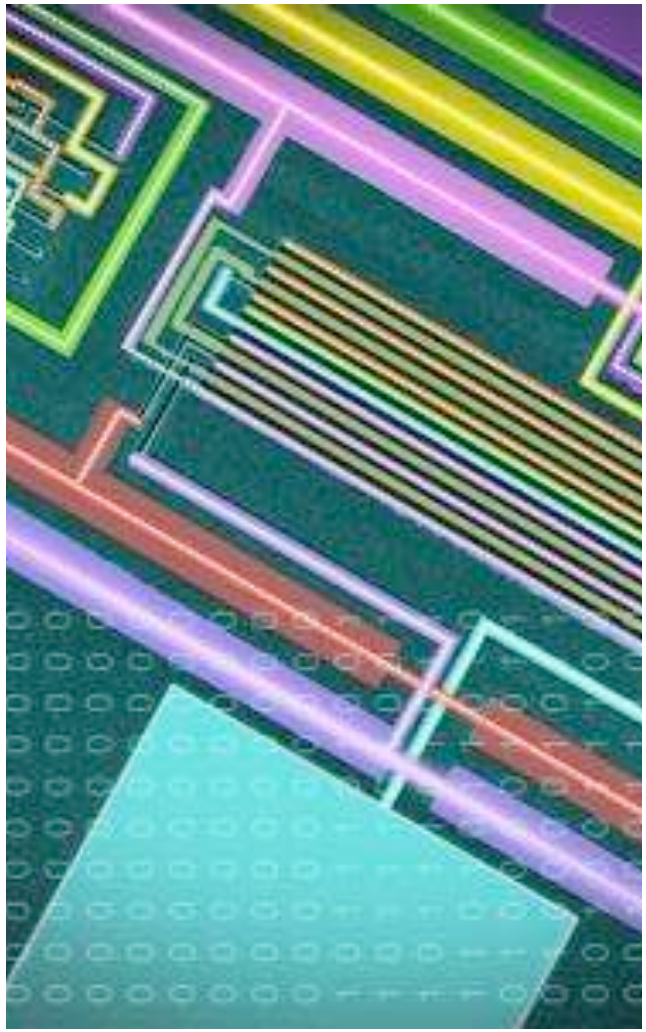
[Larrieu, SS Electronics17]

Carbon Nanotube Transistors

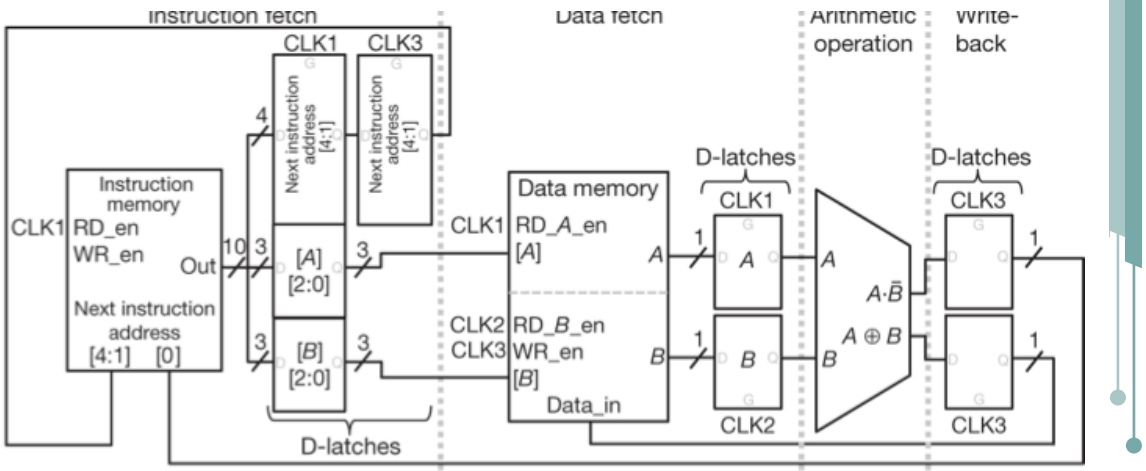


- CNTs benefit from higher mobility and thus higher currents
- CNTs grown separately but can be ported to Si wafers
- Handling CNT imperfection is major design and fabrication issue

CNT nanocomputer

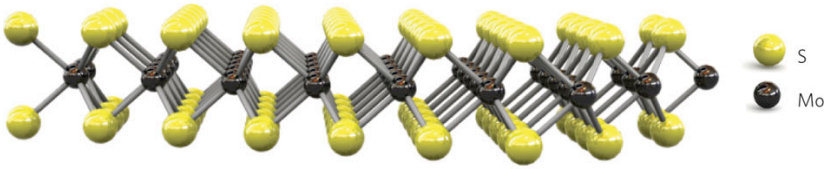


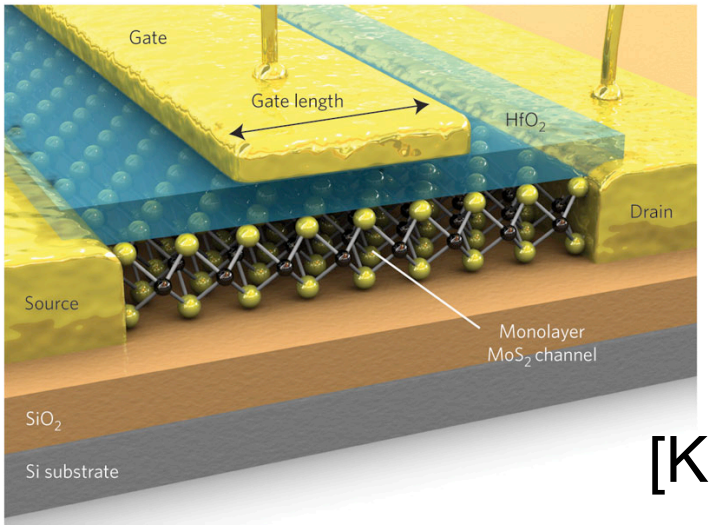
- First CNT computing engine
- Runs 20 MIPS instructions
- Multitasking



[Shulaker, Wong, Mitra et al, NatureNano 13]

2D electronic technologies

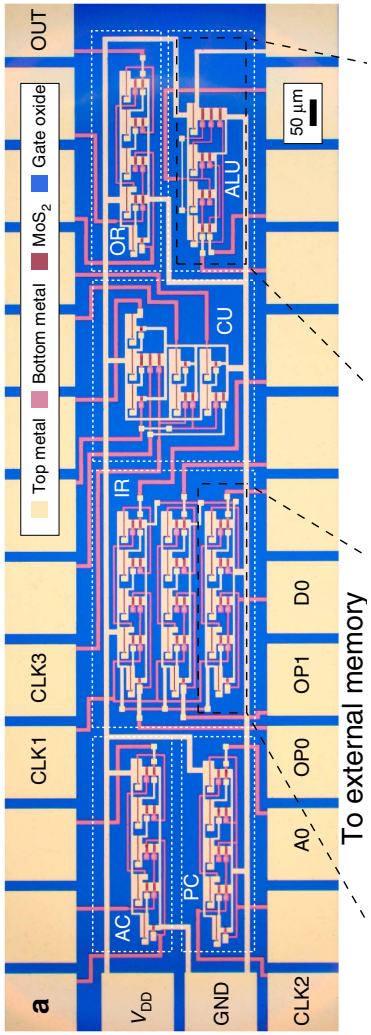




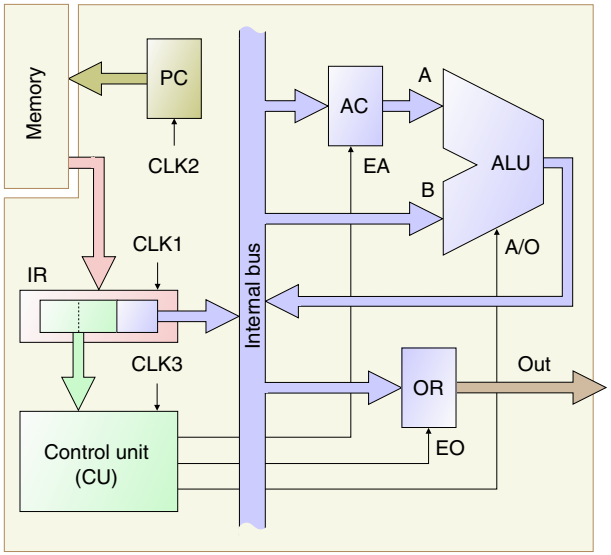
[Kis, Nature Nano 2011]

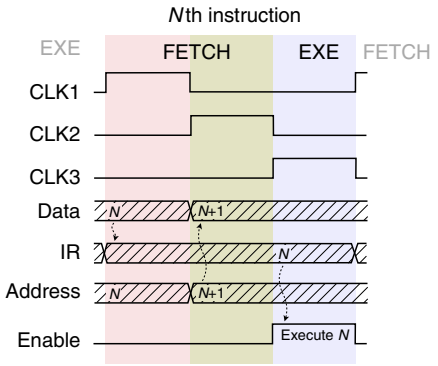
- Graphene, MoS_2 and other materials
- Single or few atomic layers
- High I_{on} / I_{off} ratio for MoS_2 (10^8) but n-type mainly

MoS_2 nanocomputer



- First MoS_2 computing engine
- Runs 4instructions
- 115 N-xtors (enhancement load)
- 2 micron feature size



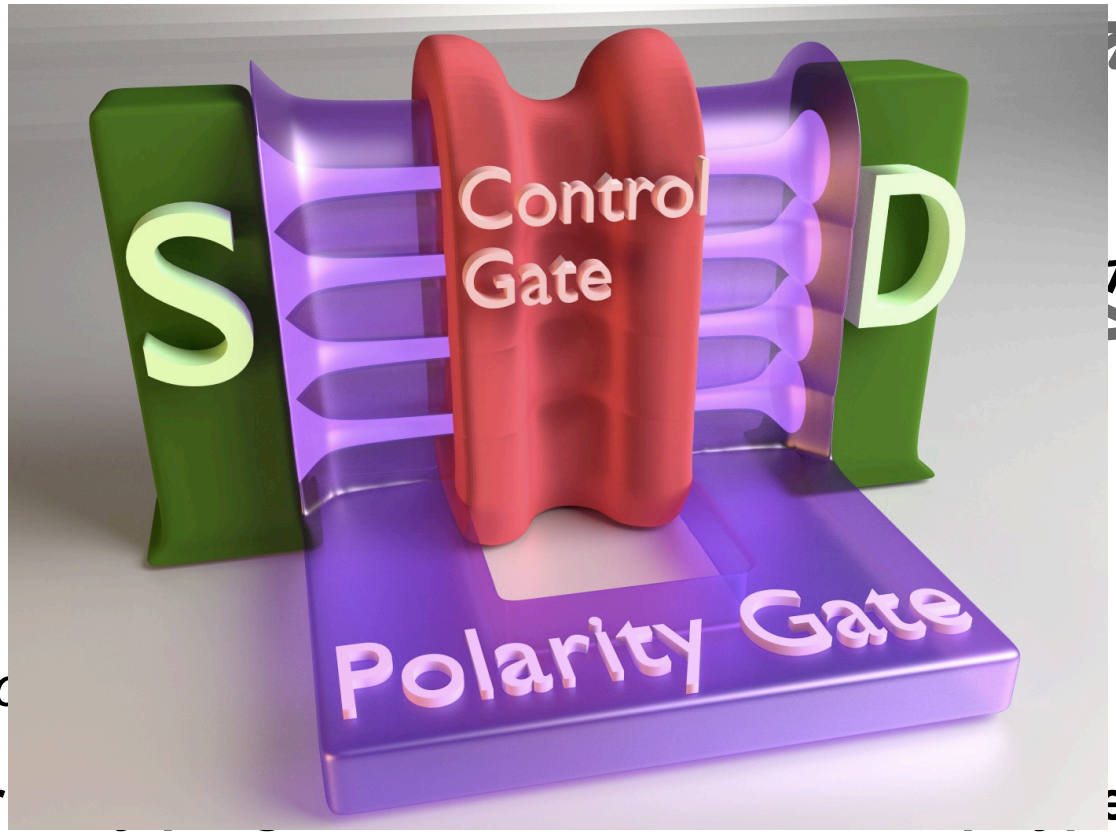


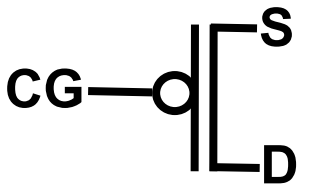
c

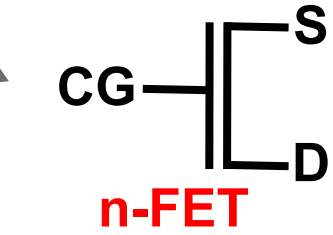
Command	Code	Example
NOP	00	NOP
LDA	01	LDA 0
AND	10	AND 1
OR	11	OR 0

[Wacter et al. Nature Comm, 2017]

Double gate SiNW FET

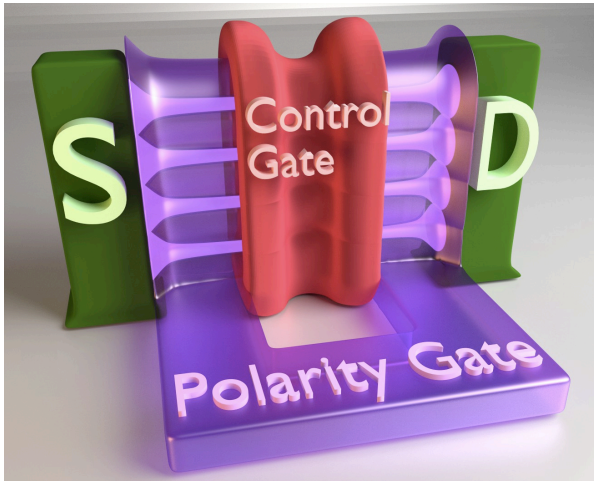


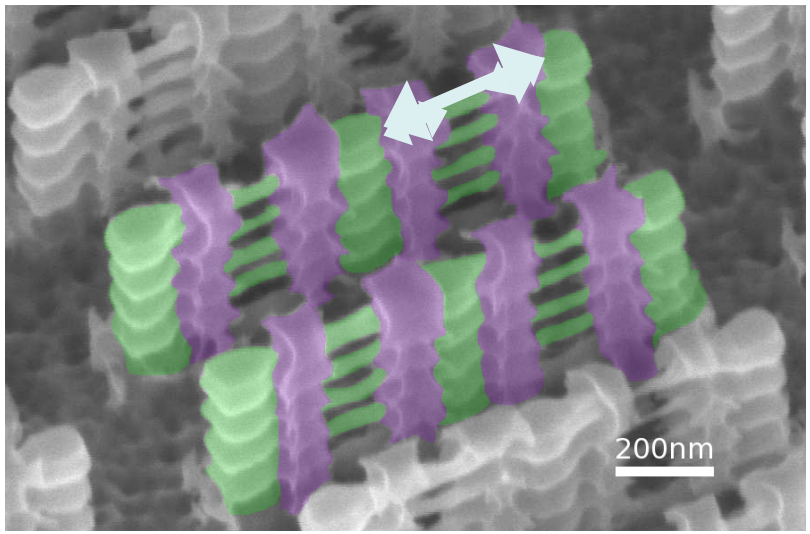


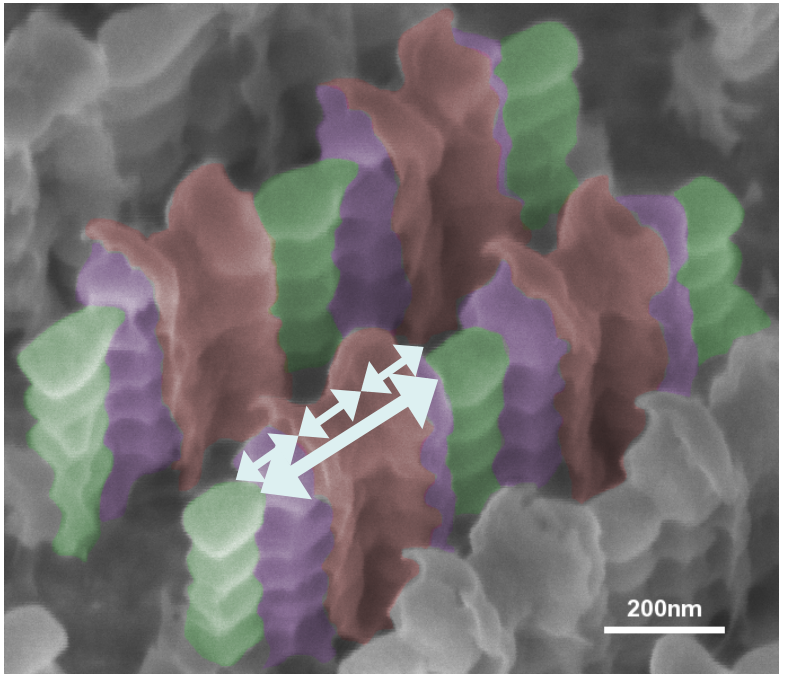


- *Electro*
- **Electr** **e** or **n-type**
- **Comparator**-activated switch

Fabricated device view

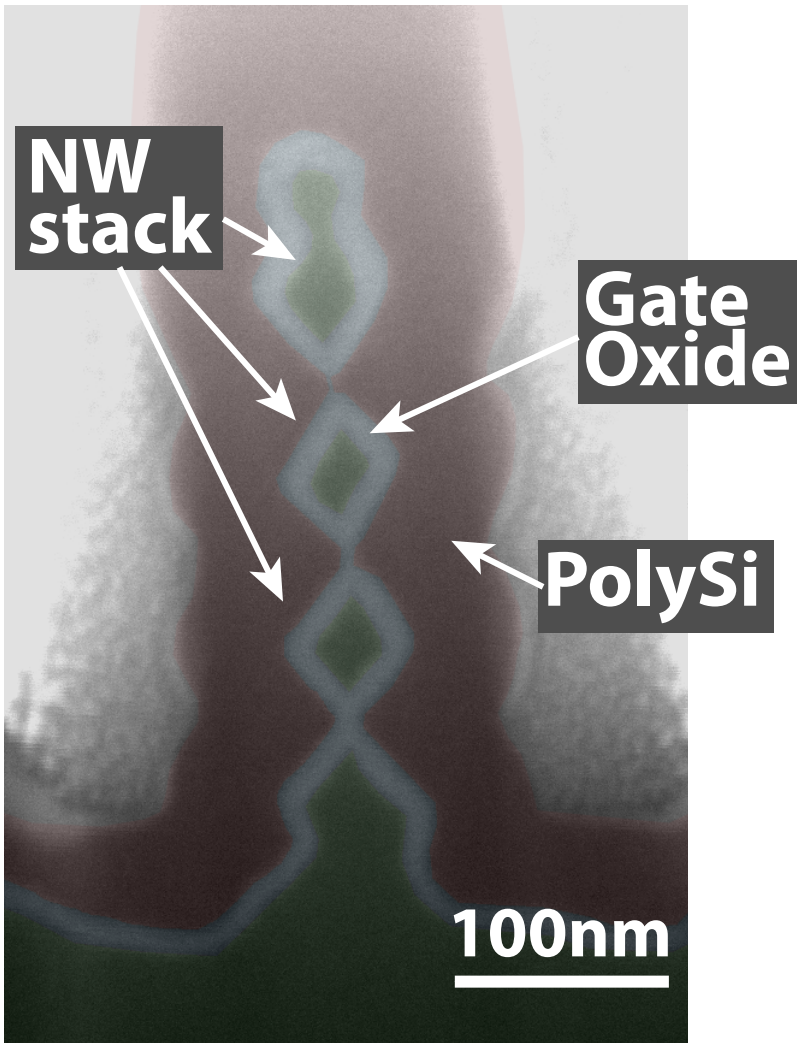


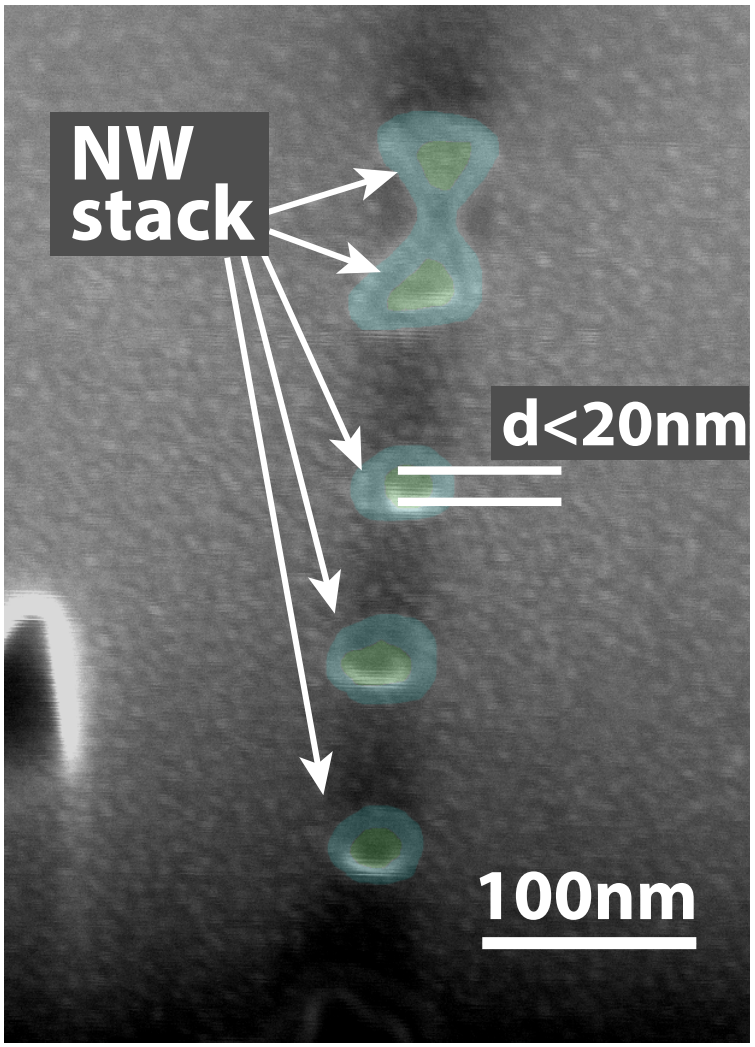




- **100 nm gate segments**
- **350-nm long nanowires**
- **20-40 nm wire diameter**

Device cross-sections





M. De Marchi et al., IEDM 2012, TNANO 2013.

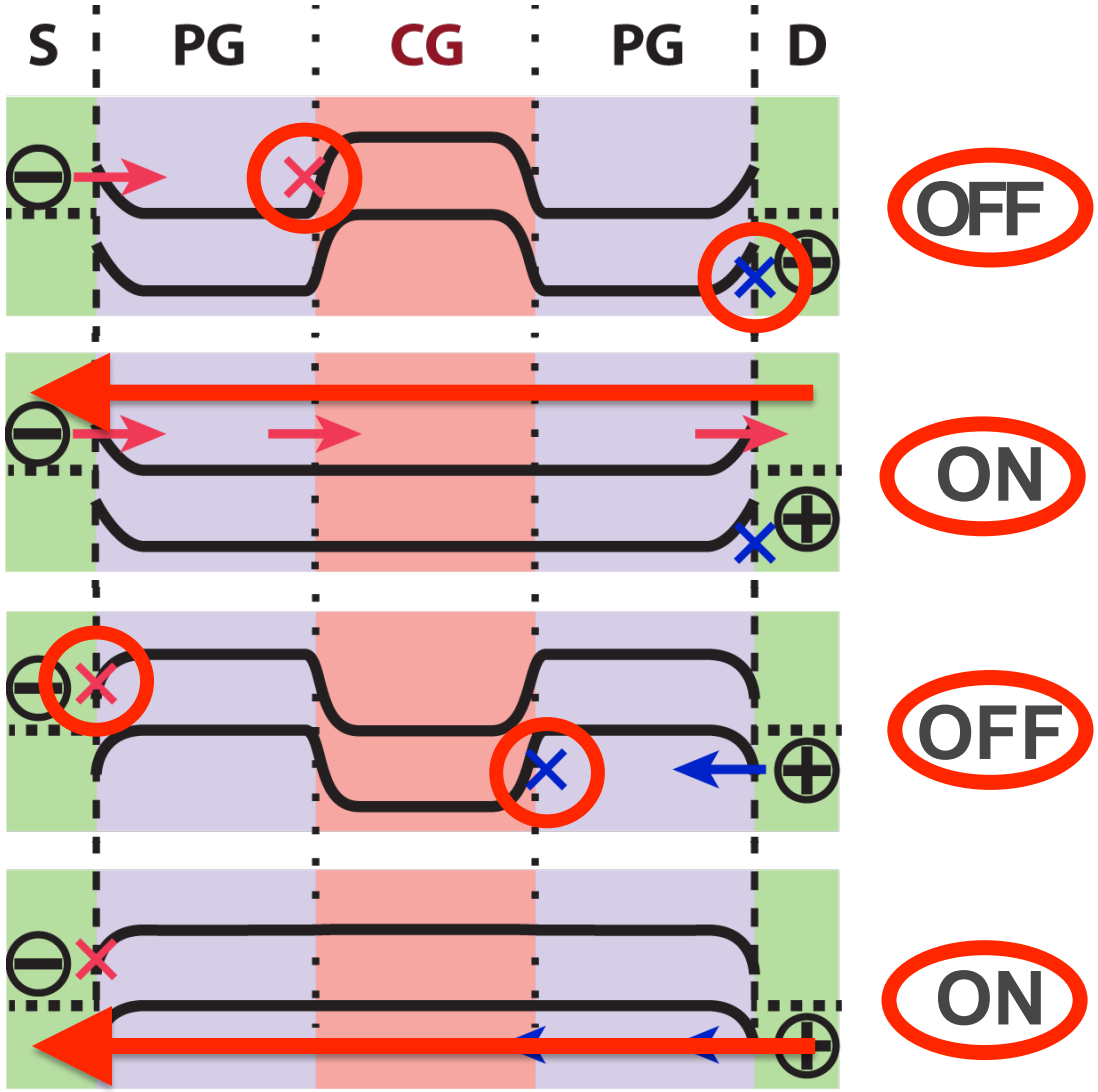
Device working principle

PG = 1→ n-type
CG = 0

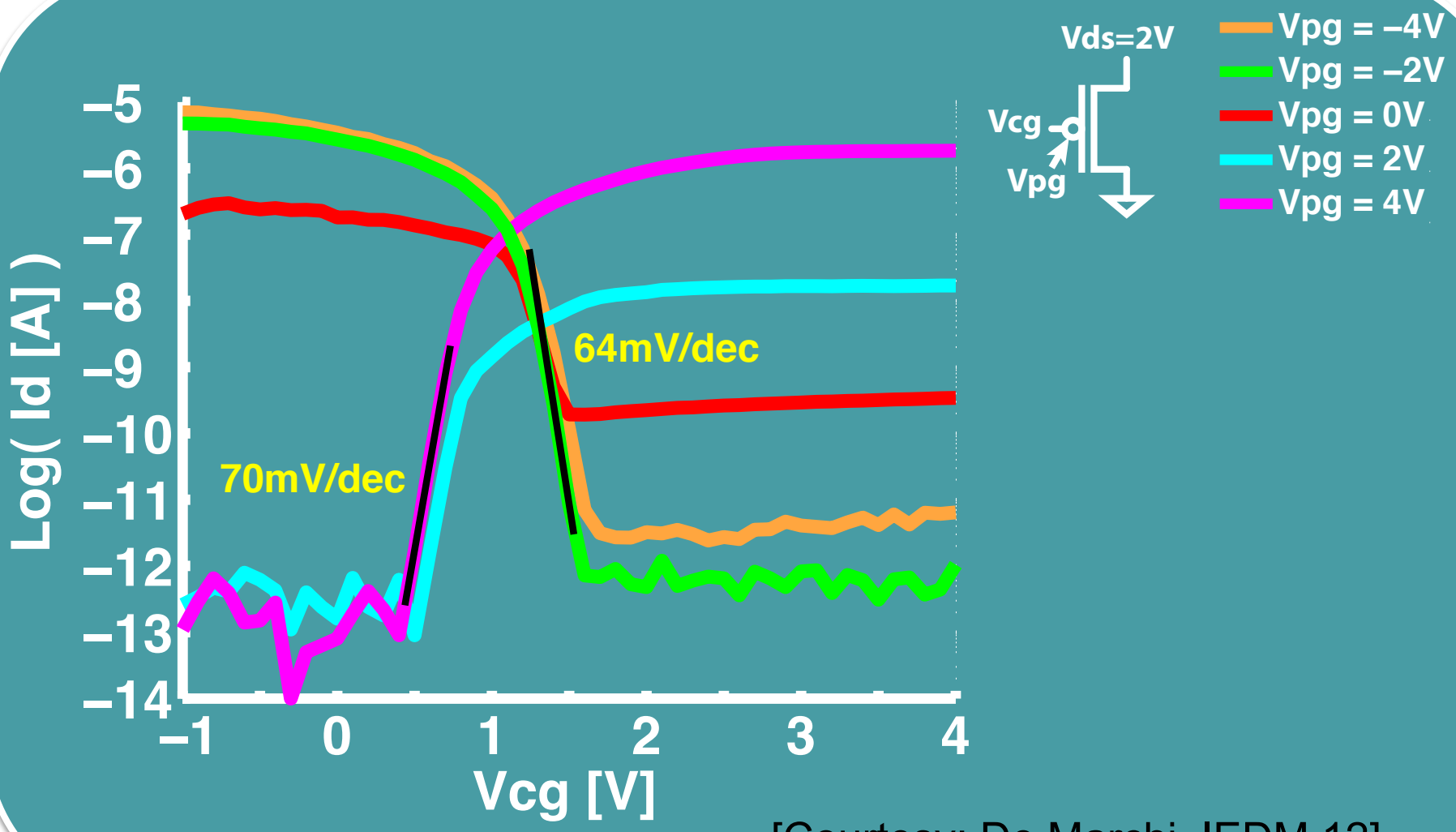
PG = 1→ n-type
CG = 1

PG = 0→ p-type
CG = 1

PG = 0→ p-type
CG = 0



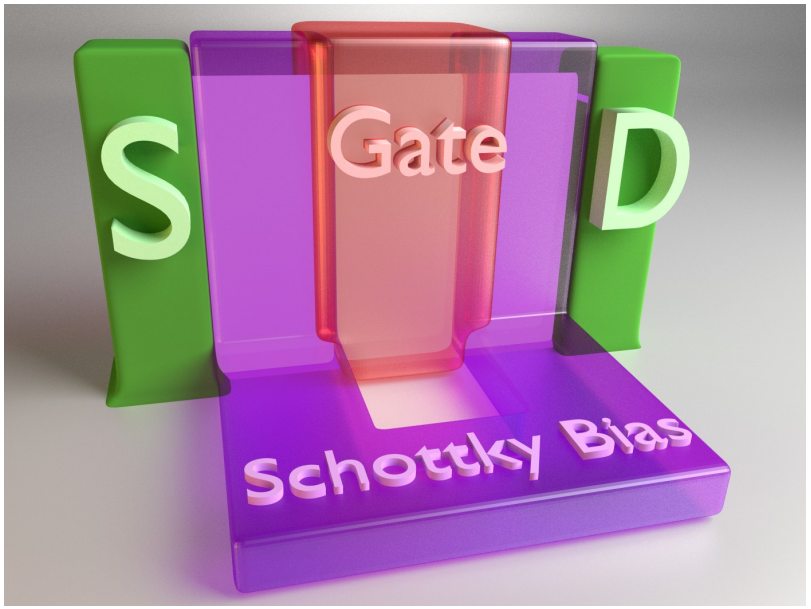
Device I_d/V_{cg}



[Courtesy: De Marchi, IEDM 12]

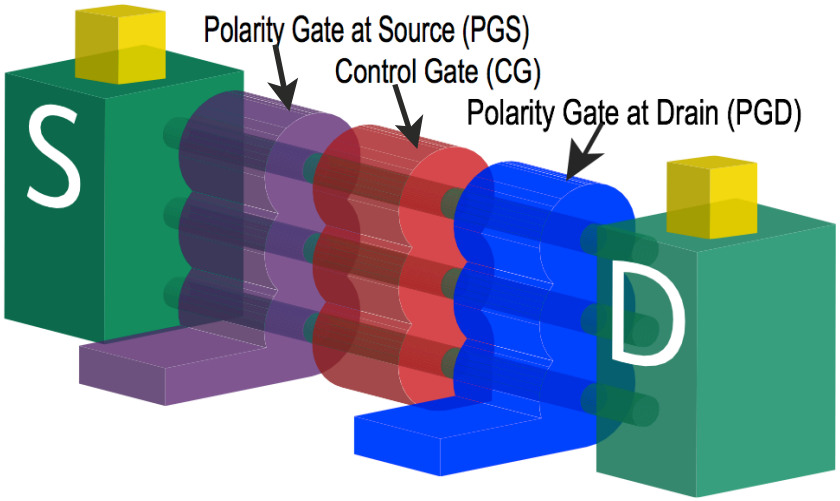
Similar devices

- Controlled devices can be realized with various materials and shapes (e.g., FINFET)
- SiNW controlled-polarity devices can be made with one polarity gate **on one side** [Heinzig]
- Polarity-gate bias can enable:
  - Steep Subthreshold
  - Multiple threshold voltages



Three-independent-gate SiNWFET

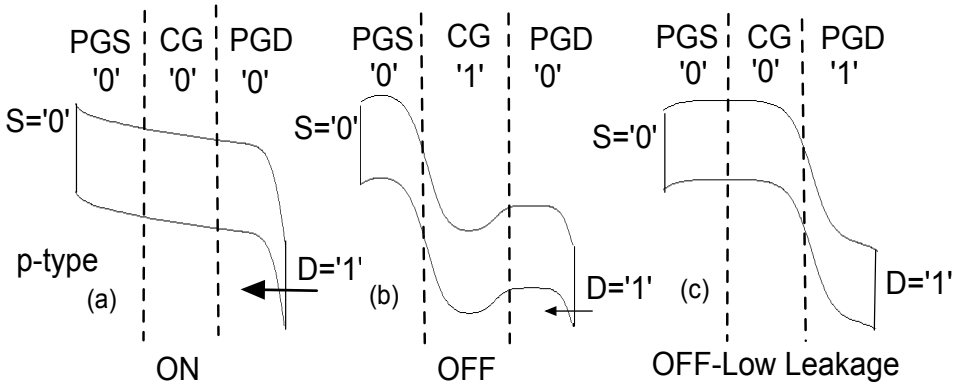
❖Structure



- **Vertically stacked nanowires**
- **3 independent gate regions**
- **Schottky barrier contacts at S/D**
- **Polarity and Vt controllability**

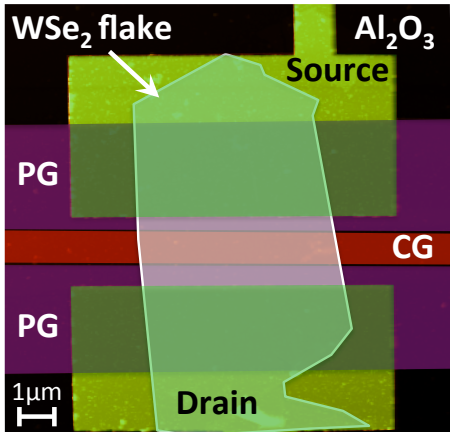
❖Electrostatic control

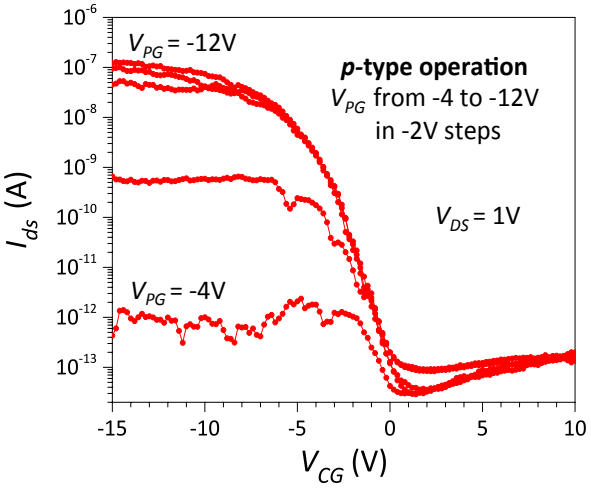
S	D	PGS	CG	PGD	State
0	1	0	0	0	ON (P-type)
		1	1	1	ON (N-type)
		0	1	0	OFF (LVT)
		1	0	1	OFF (LVT)
		0	0	1	OFF (HVT)
		0	1	1	OFF (HVT)

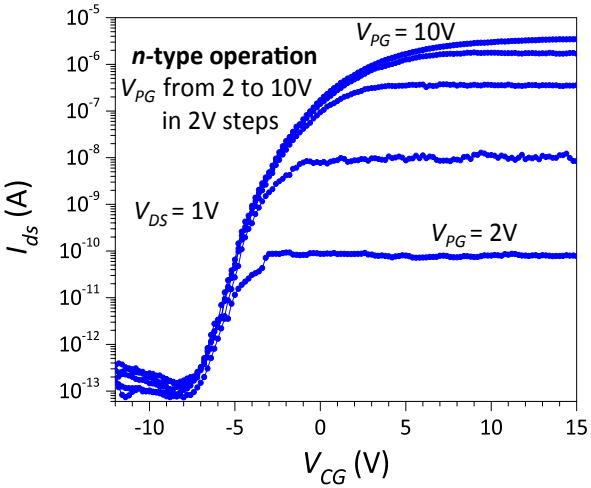


Controllable polarity in 2D

2D Controllable-polarity transistor (WSe_2)

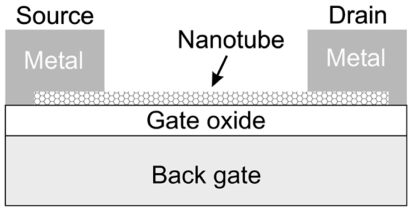




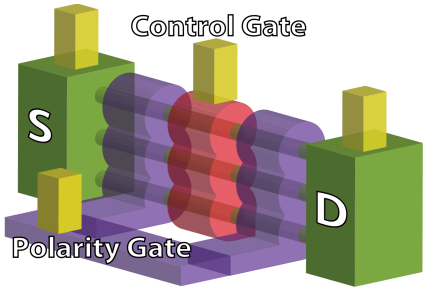


[Resta, Scientific Reports 2016]

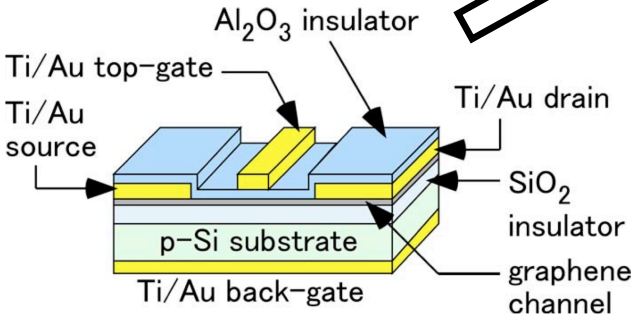
Modeling various emerging nanogates



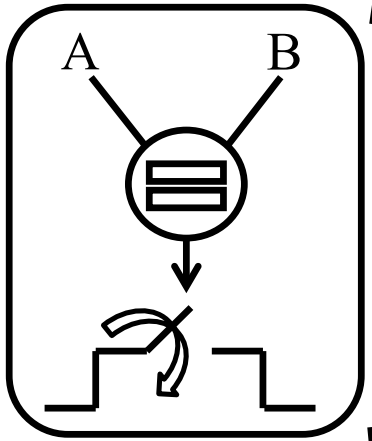
CNFETs

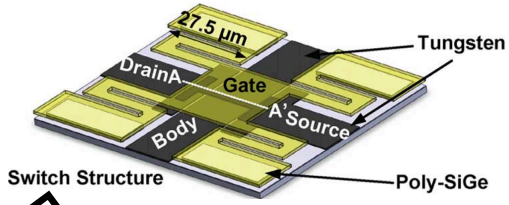


SiNWFETs

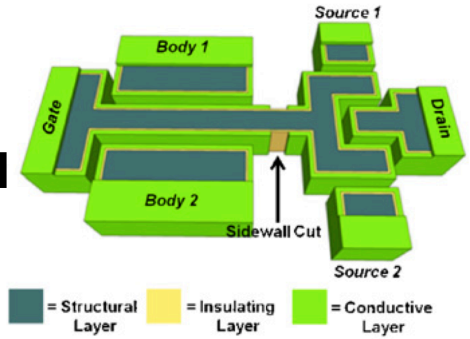


Graphene FETs

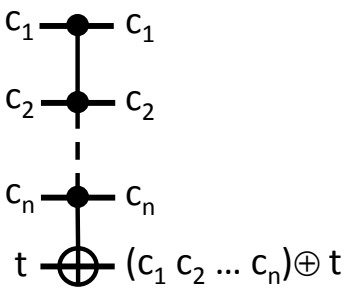




4T Nanorelays



6T Nanorelays



Reversible Logic

Outline

- Introduction and motivation
- Technological innovations
  - Emerging nanotechnologies and devices
- **Design with emerging technologies**
  - **Physical and logic synthesis**
- New technologies for broader computing systems
  - Device fusion
- Conclusions

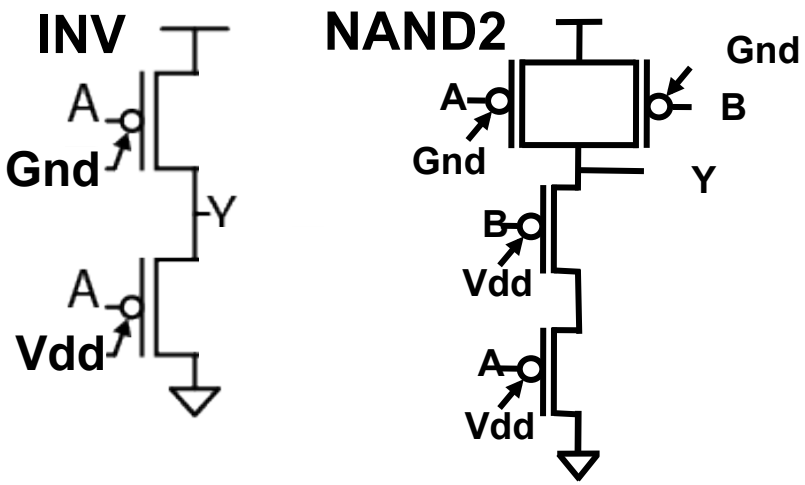
Logic level abstraction

- Three terminal transistors are switches
  - A loaded transistor is an *inverter*
- Controllable-polarity transistors compare two values
  - A loaded transistor is an *exclusive or* (EXOR)
- The intrinsic higher computational expressiveness leads to more efficient data-path design
- The larger number of terminals must be compensated by smart wiring
- Fine-grained programmability

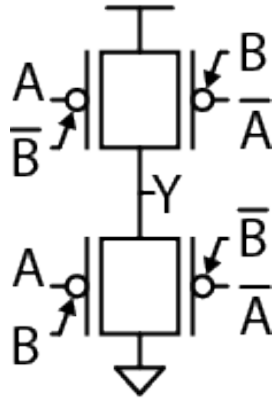
Logic cell design

- CMOS complementary logic is efficient only for negative-unate functions (INV, NAND, NOR…etc)
- Controllable-polarity logic is efficient for all functions
- Best for XOR-dominated circuits (binate functions)

Negative Unate functions	Binate functions

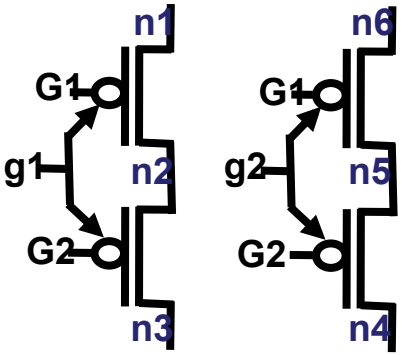


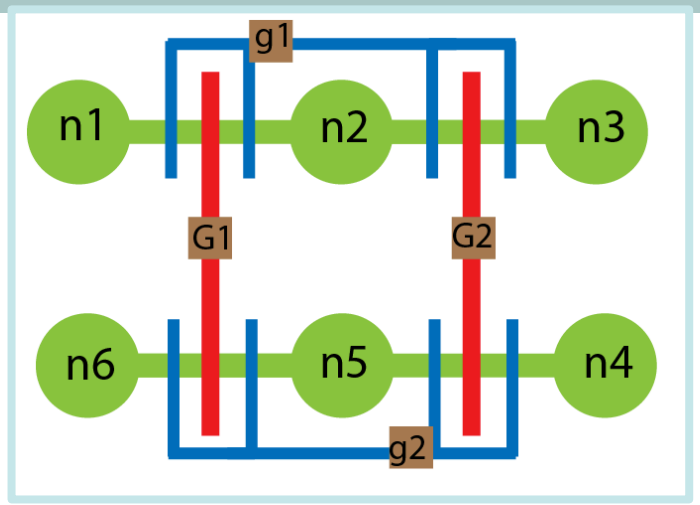
Similar to regular CMOS



Only 4 transistors when compared to 8 transistors with a regular CMOS

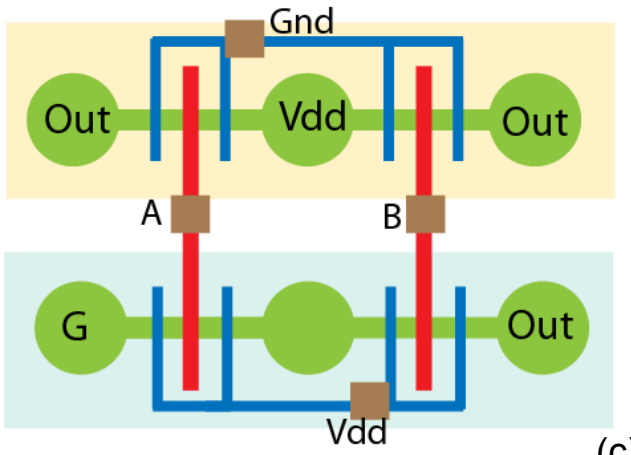
Layout abstraction and regularity



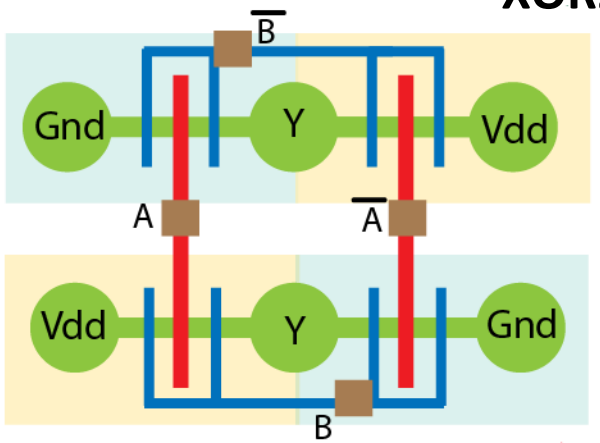


Two transistor pairs grouped together

NAND2



XOR2

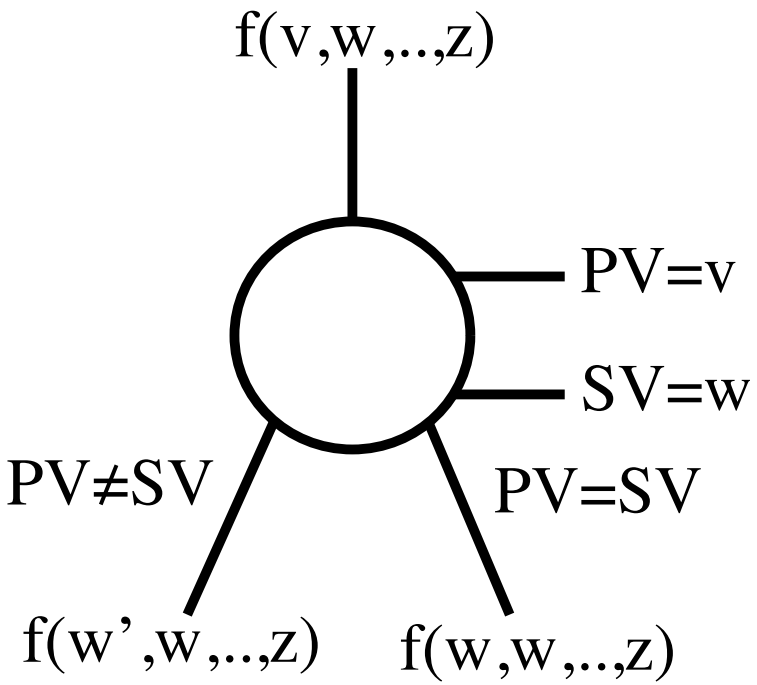


[Courtesy: Bobba, DAC 12]

Logic Design Abstraction:
Biconditional Binary Decision Diagrams

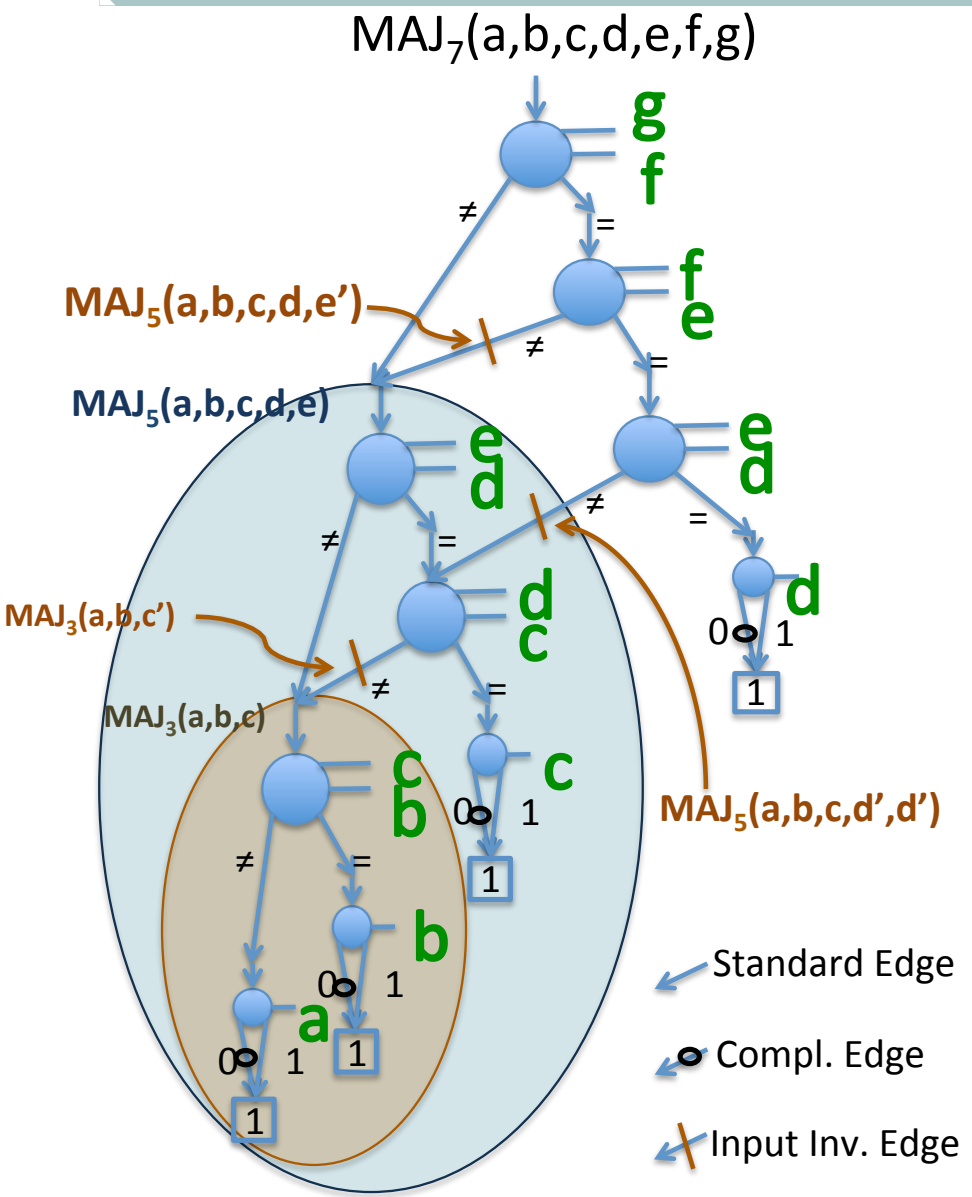
- Native **canonical** data structure for logic design
- *Biconditional* expansion:

$$f(v,w,..,z) = (v \oplus w) f(w',w,..,z) + (v \overline{\oplus} w) f(w,w,..,z)$$



- Each BBDD node:
  - Has two branching variables
  - Implements the *biconditional* expansion
  - Reduces to Shannon's expansion for single-input functions

BBDDs are Compact (Majority Function)



Number of nodes of MAJ(n):

$$\frac{1}{8}n^2+\frac{1}{2}n+\frac{11}{8}$$

MAJ(3): 4

MAJ(5): 7

MAJ(7): 11

....

New logic models and data structures

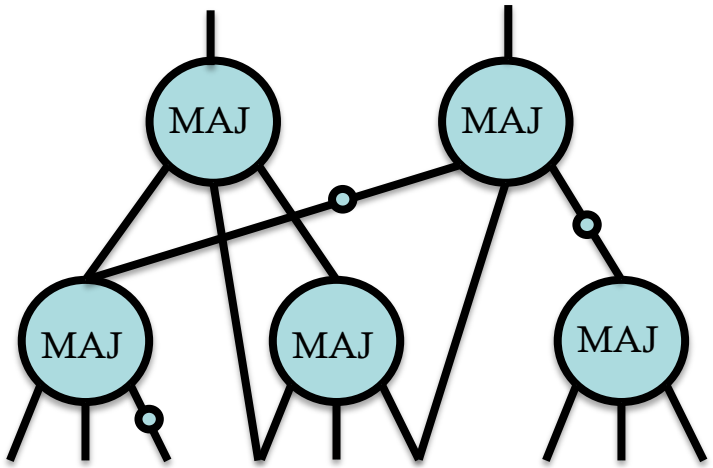
- Design with emerging devices requires exploring new logic models combining:
  - XOR primitives (programmable complementation)
  - MAJority functions (programmable AND/OR)
- The resulting models and algorithms have wide applicability to logic design (including CMOS)

Majority logic: a new/old paradigm?

In fact <x,y,z> is probably the most important ternary operation in the entire universe, because it has amazing properties that are continuously being discovered and rediscovered.

Donald Knuth, *The Art of Computer Programming, Vol. 4A*

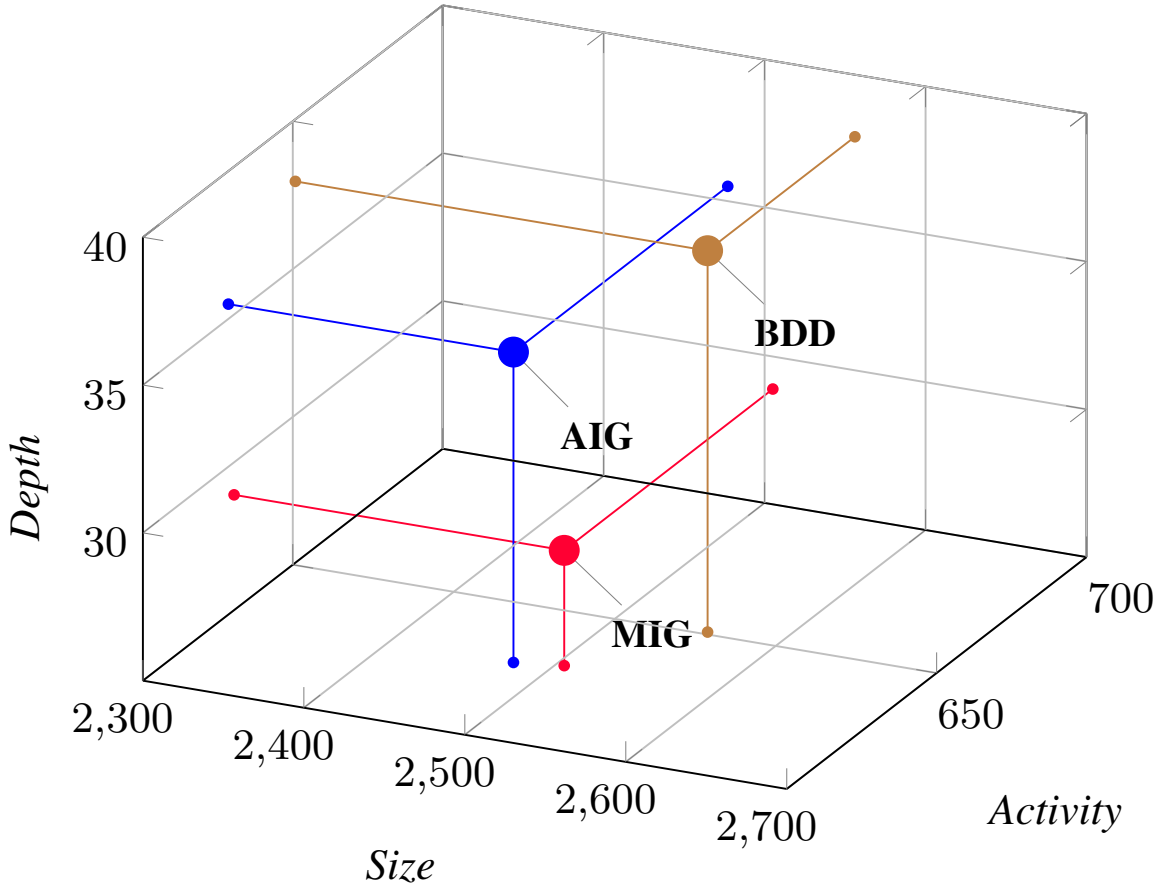
- Majority Inverter graphs as data structure for logic synthesis
- Reachable design space
- Surprising experimental results



[Courtesy: Amaru', DAC 14]

Experimental Results: MCNC circuits

Logic Synthesis: MIGthy



MIGs & AIGs better than BDDs

MIGs size & activity ~ AIGs

MIGs depth -20% w.r.t AIGs

CMOS Design Results

Advanced 22nm CMOS
MIG as front-end to LS & PD

Well-established 90nm CMOS
MIG as front-end to LS & PD

Behavioral

```
module div32 (a, b, quotient_uns, quotient_tc, remainder_uns,
 remainder_tc);
 parameter width = 32;
 input [width-1 : (
 output [width-1 :
 output signed [wi                                    r_tc;
 // operators for u                                   ainder
 assign quotient_ur
 assign quotient_tc = $signed(a) / $signed(b);
 assign remainder_uns = a % b;
 assign remainder_tc = $signed(a) % $signed(b);
endmodule
```

Area: 0.21 mm²

Delay: 11.22 ns

GC: 37k

MIG

```
assign w0 = (w39266 & w27196) | (w39266 & w42866) | (w27196 & w42866);
assign w1 = w44100 & w4464;
assign w2 = ~w19966 & w27946;
assign w3 = ~w22044 & ~w30809;
assign w4 = w42722 & ~b[26];
assign w5 = (~w30032 & w19016) | (~w30032 & w47192) | (w19016 & w47192);
assign w6 = ~w26074 & w5179;
assign w7 = (w42822 &                                  w16107);
assign w8 = ~w35174 &
assign w9 = ~w45553 &
assign w10 = ~w14416 &
assign w11 = (~w16181                                  & w16835);
assign w12 = (w27179 &                                 052);
assign w13 = (w2836 &                                  4);
assign w14 = ~w2529 &
assign w15 = (w43756 &                                 36731);
assign w16 = ~w44399 &
assign w17 = ~w22912 &
assign w18 = ~w30302 &
assign w19 = (~w23777                                  w50584);
assign w20 = w26809 &
assign w21 = (~w43756                                  w3953);
assign w22 = ~w36188 & w1158
assign w23 = ~w33838 & ~w16188;
assign w24 = ~w38787 & w19348;
assign w25 = w42096 & w20651;
assign w26 = (w45543 & w39924) | (w45543 & w25446) | (w39924 & w25446);
assign w27 = ~w34177 & w38267;
assign w28 = ~w10074 & ~w29118;
assign w29 = w25495 & w32055;
assign w30 = (w48190 & w13546) | (w48190 & w19290) | (w13546 & w19290);
```

Area: 0.18 mm²

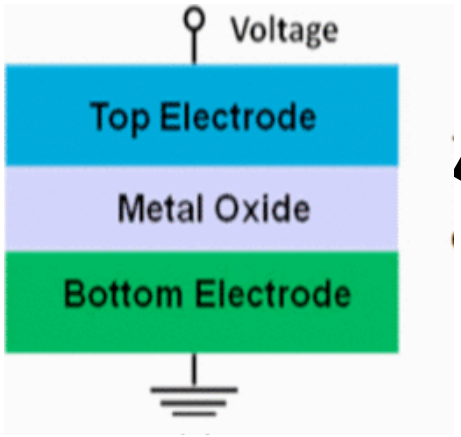
Delay: 10.10 ns

GC: 24k

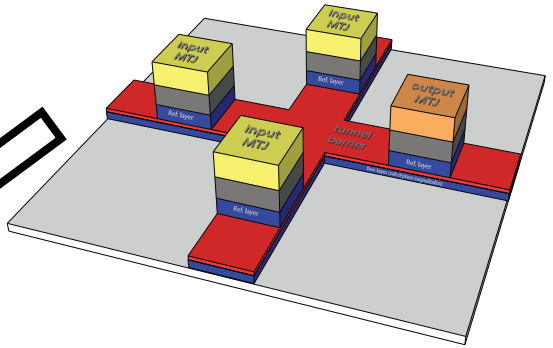
All circuits underwent formal verification with success

Both circuits underwent formal verification with success

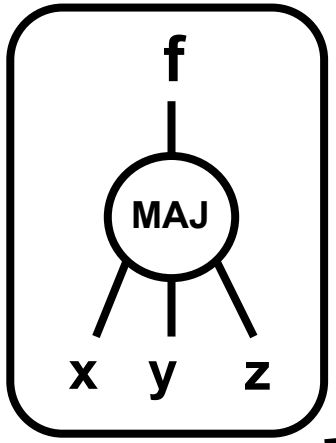
Modeling various emerging nanogates



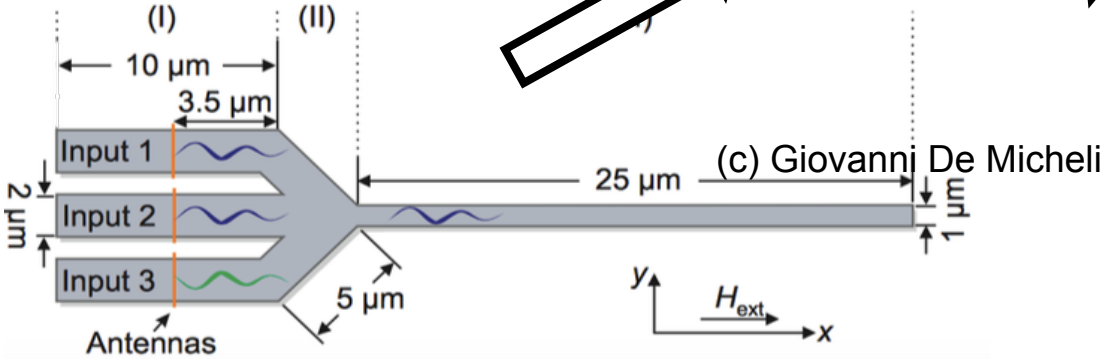
Resistive RAM



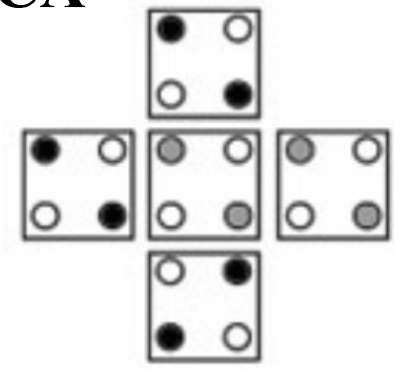
Spin Transfer Torque



Spin Wave Device

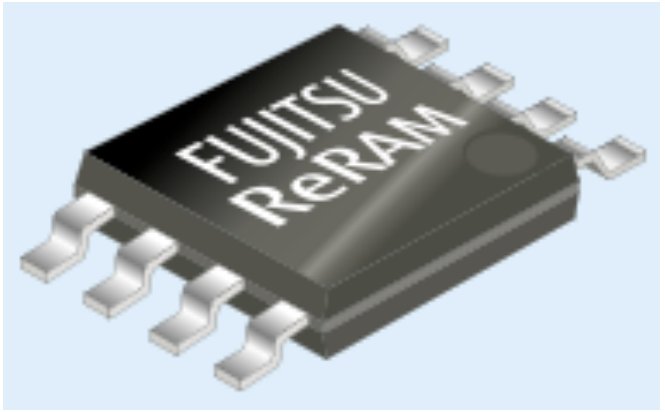


QCA



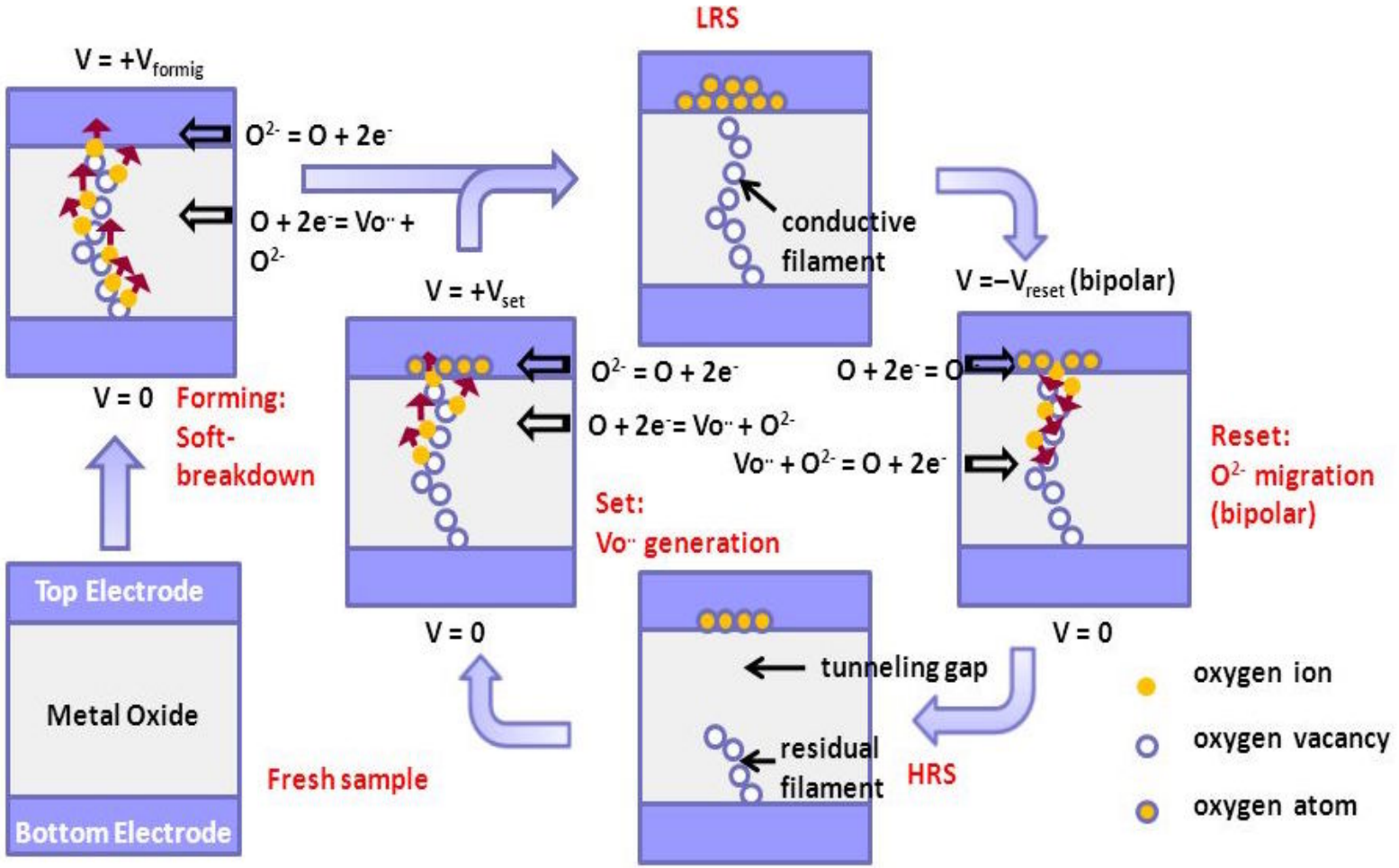
Resistive RAMs

- Non-volatile, low-power dense RAM arrays
- Based on resistive switching:
  - Various physical mechanisms
- Can be realized in the BEOL
  - 3D integration



[Fujitsu MB85AS4MT]
4M (512kx8)

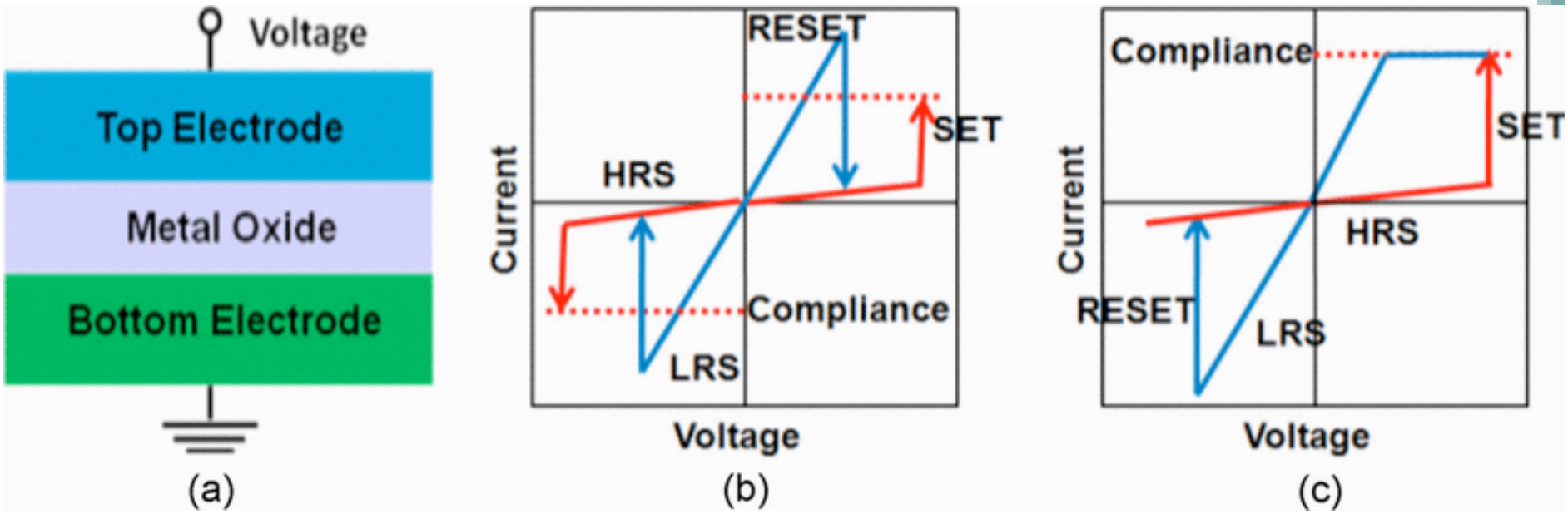
Oxide ReRAM switching



[Su et al.Functional Metal Oxide Nanostructures, 2011]

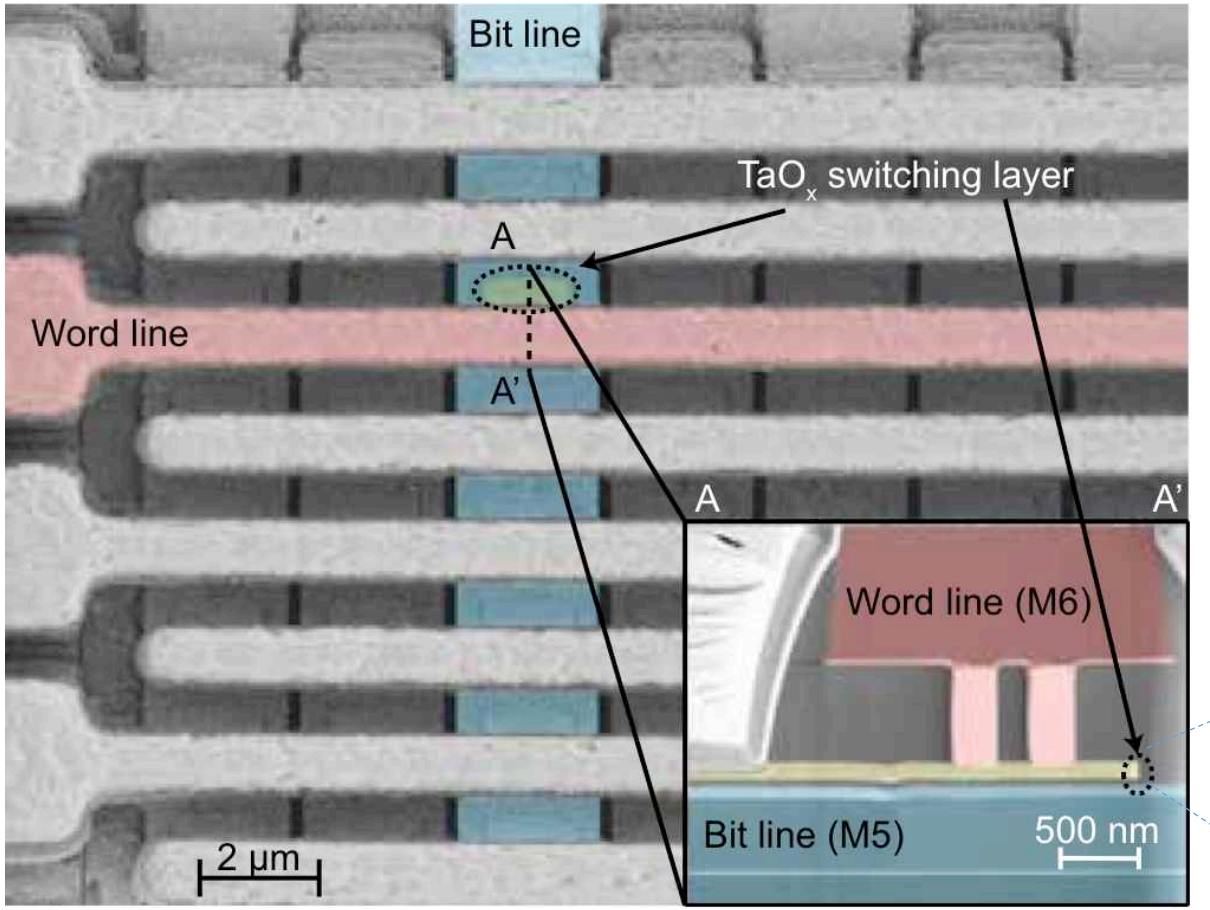
Oxide Resistive RAMs

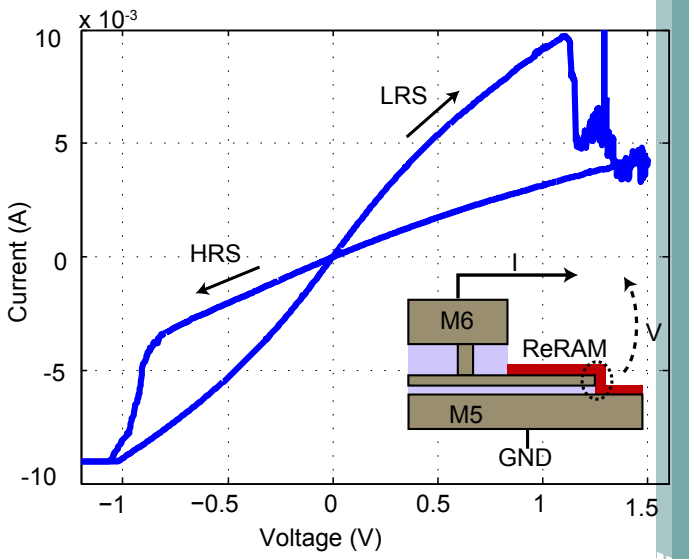
- Formation of an oxygen vacancy filament
  - Reversible write: set/reset
  - Low-current read
  - Unipolar and bipolar switching

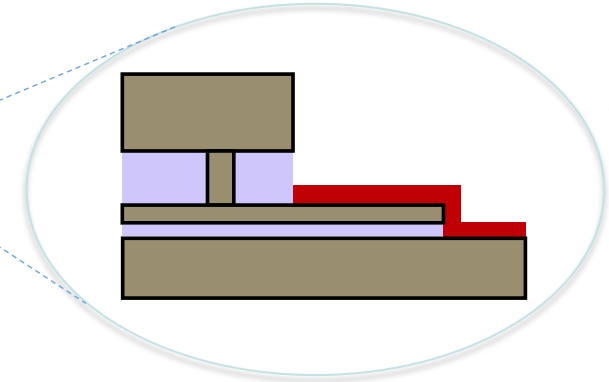


[P. Wong et al 2016]

ReRAM integrated devices





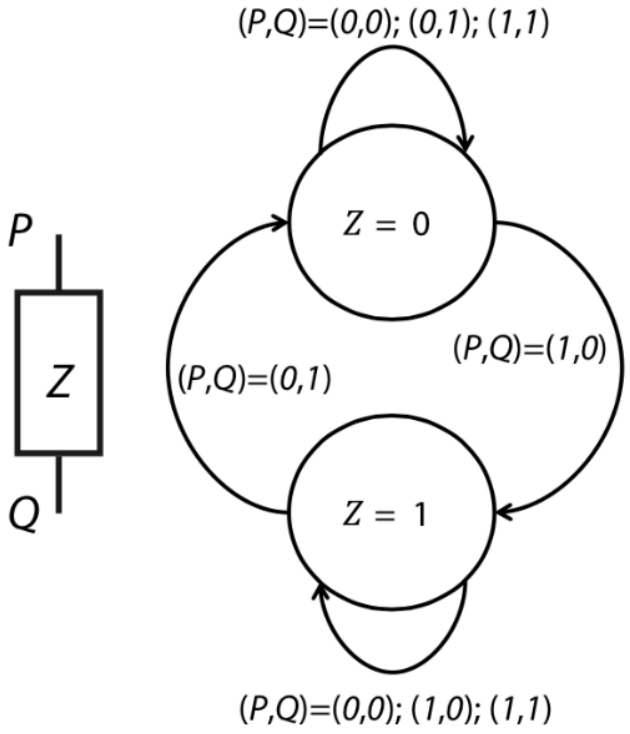


TiN/TaOx/TiN forming-free, V_{set} = -1V, V_{reset} = 1.3V

Sandrini, Microelectr. Eng. 2015

[Courtesy: Leblebici]

ReRAM as computational element



P	Q	Z	Z_n
0	0	0	0
0	1	0	0
1	0	0	1
1	1	0	0

$$Z_n = P \,.\, \overline{Q}$$

P	Q	Z	Z_n
0	0	1	1
0	1	1	0
1	0	1	1
1	1	1	1

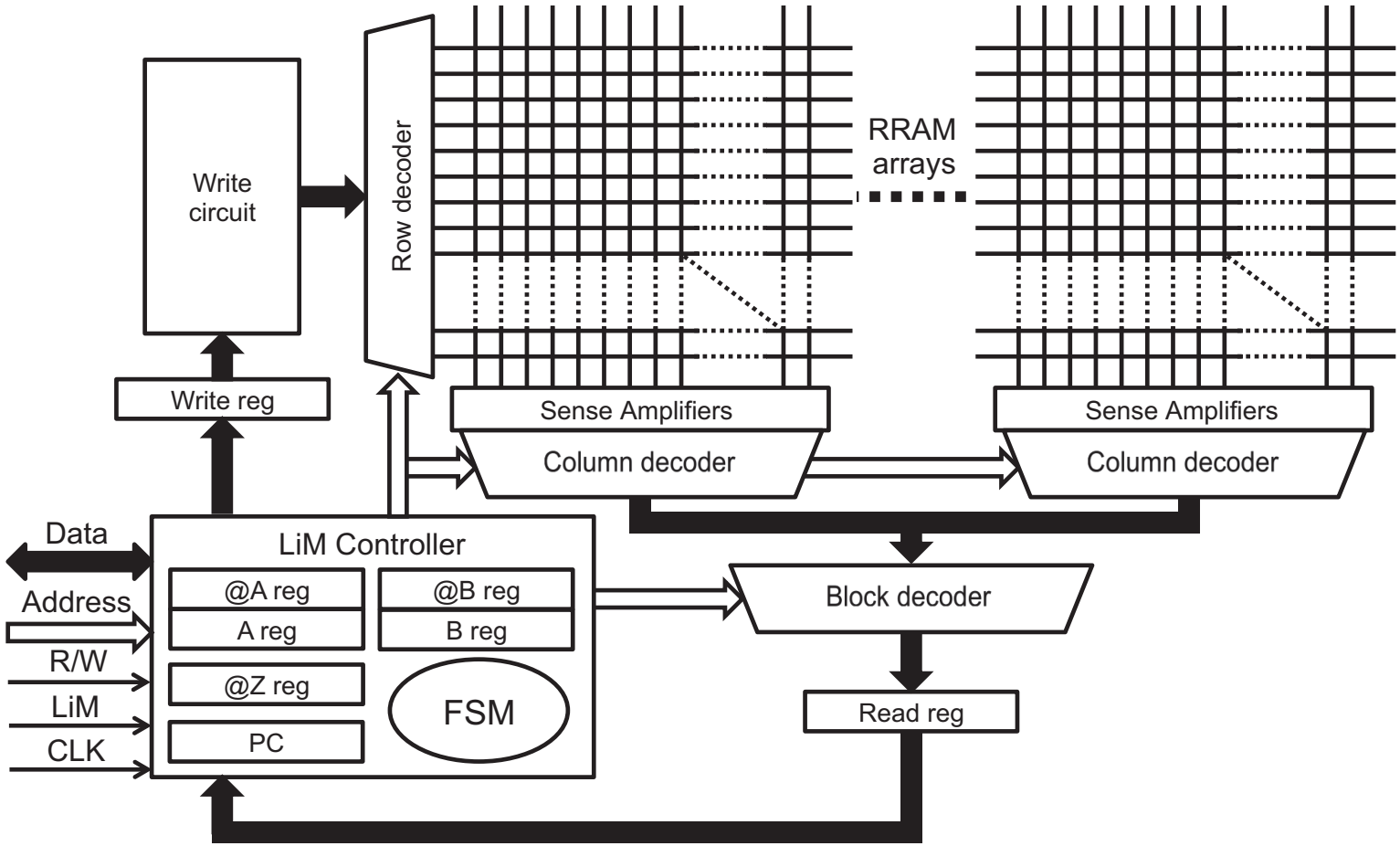
$$Z_n = P + \overline{Q}$$

Z_n = PZ+Q'Z+PQ'
Z_n = Maj(P,Q',Z)

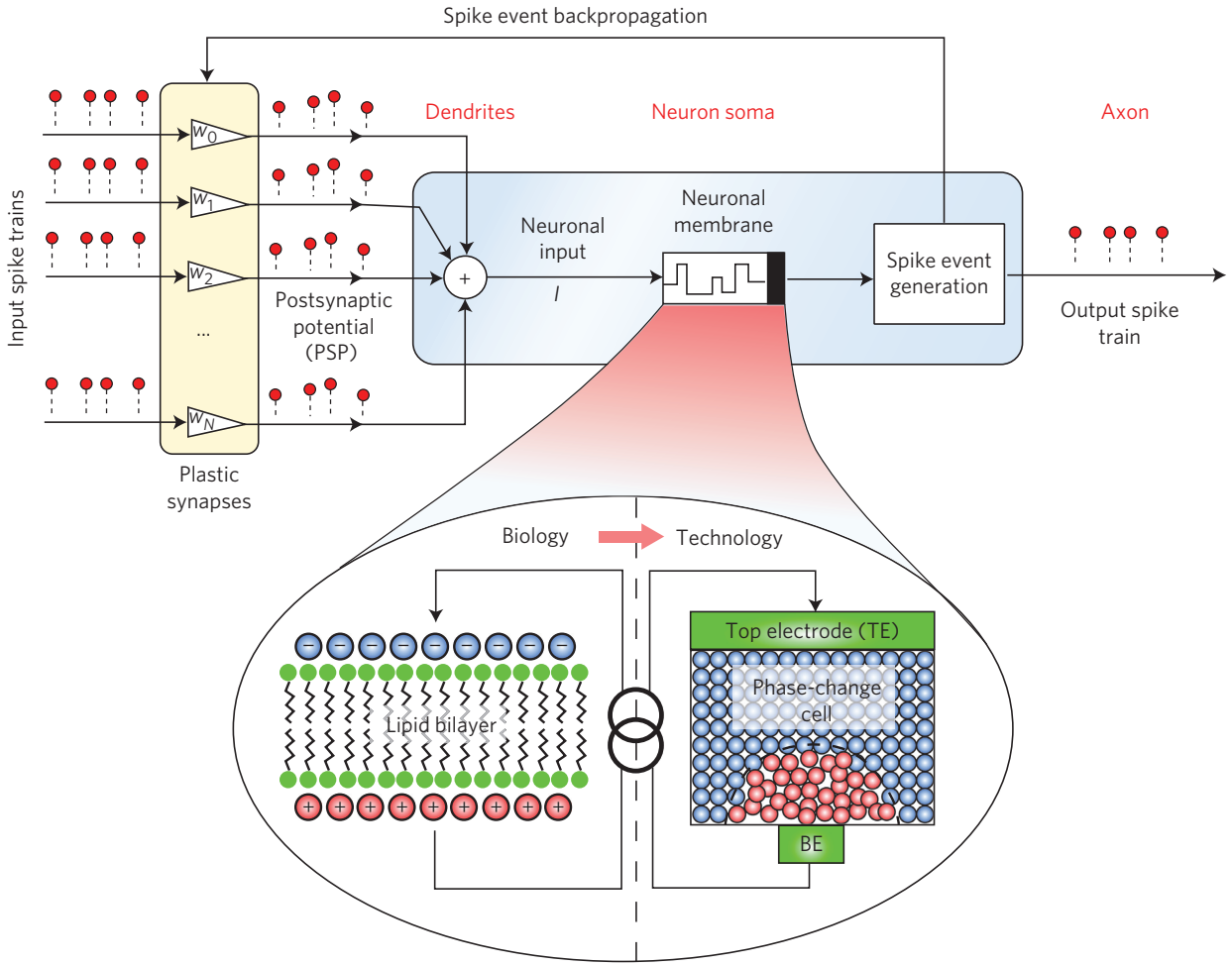
In memory processing/computing

- New paradigm for big data processing
- Data in main memory and operated upon locally
- Hardware:
  - Large memory arrays with embedded processors
  - Technology compatibility
  - What about ReRAM arrays?
- Convert small portion of memory array to perform computation
  - Map data flow computation to memory cell control
  - Create appropriate local controller
  - Use memory for storage

PLIM Architecture



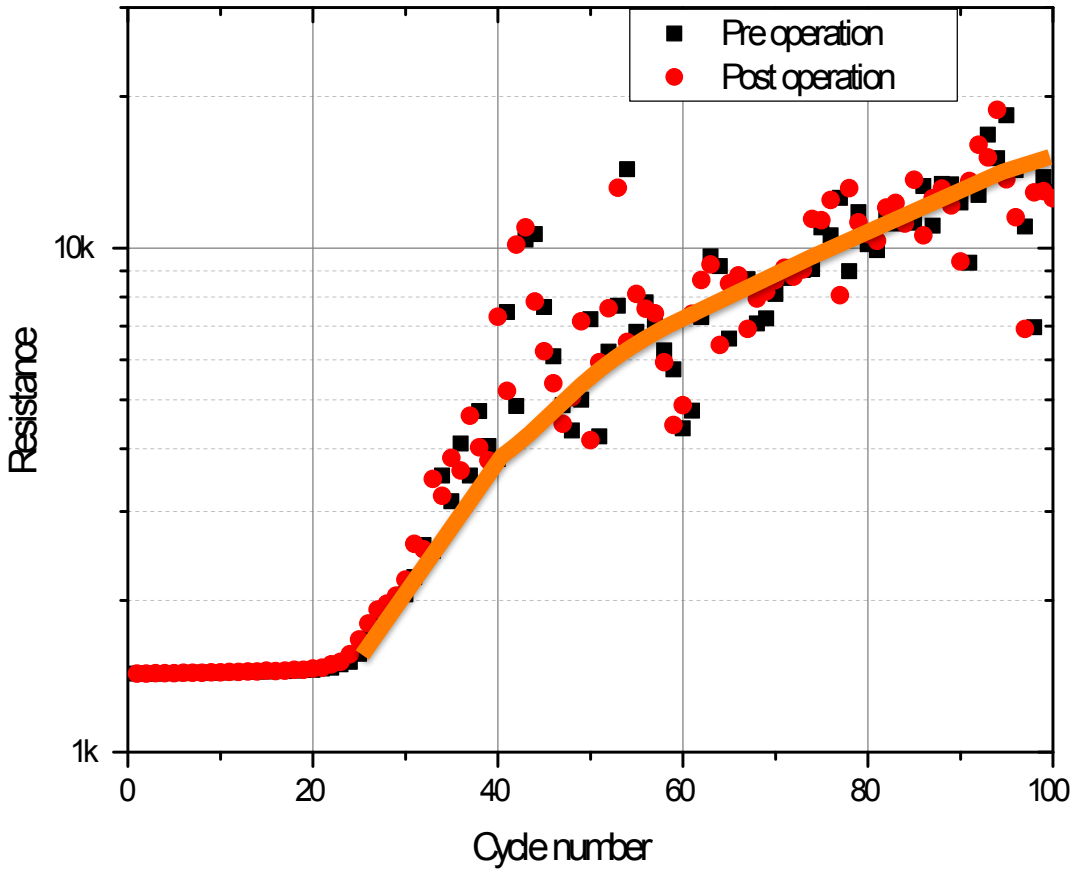
ReRAMs for artificial neurons



[Tuma et al, NatureNano 16]

Resistance modulation (# of pulses)

Pulses: -1V, 1us, 20%, 10ms between pulses



10x resistance modulation with less than 100 pulses

[Courtesy: Leblebici]

Outline

- Introduction and motivation
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  - Physical and logic synthesis
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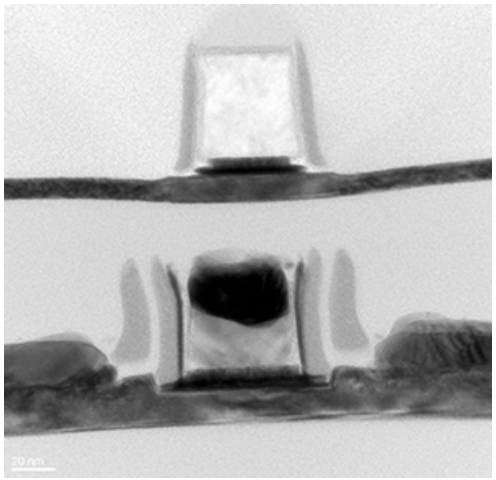
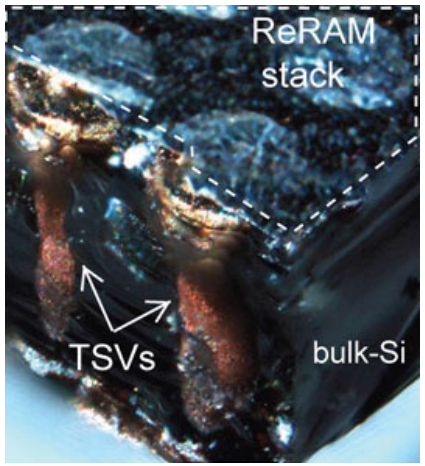
  - **Device fusion**
- Conclusions

What is next ?

- Technology hybridization
  - Fusion of sensing and computing
  - 3D integration with sensors
- Heterogeneous integration
  - Sequential integration



[Batude, IEDM 14]



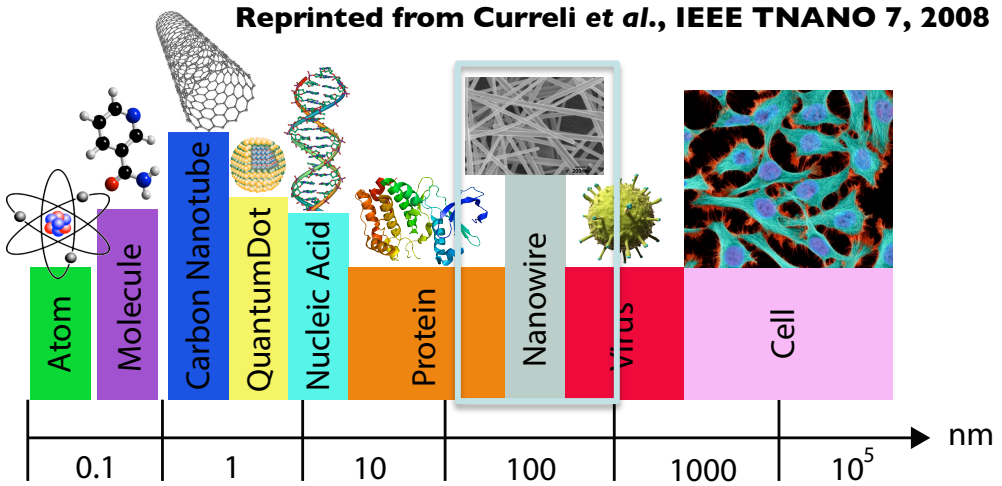
[Sacchetto, Nanoscale12]

SiNWs: ideal biosensing support

1. Nano size

- Best interface to proteins

SENSITIVITY

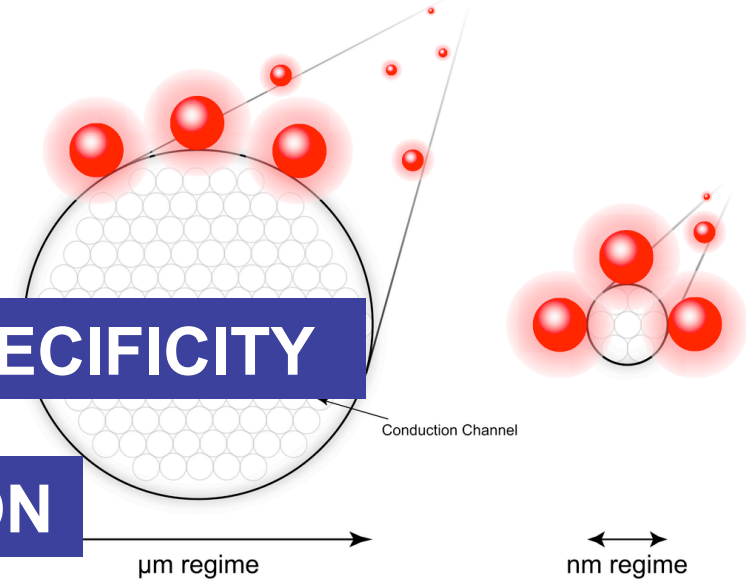


2. Surface-to-volume ratio

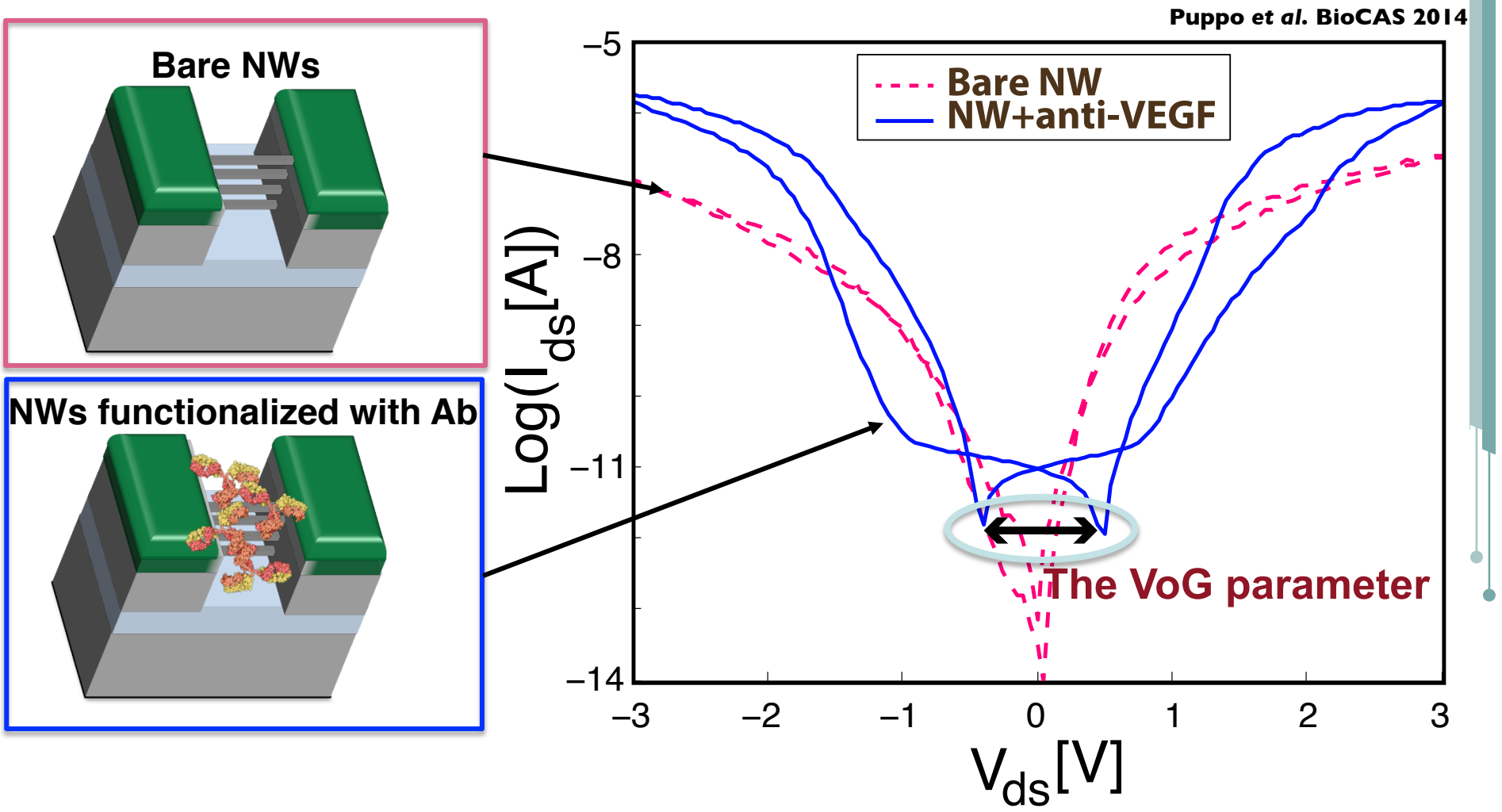
- Larger interaction area
- Charge confinement

3. Silicon biomodification → SPECIFICITY

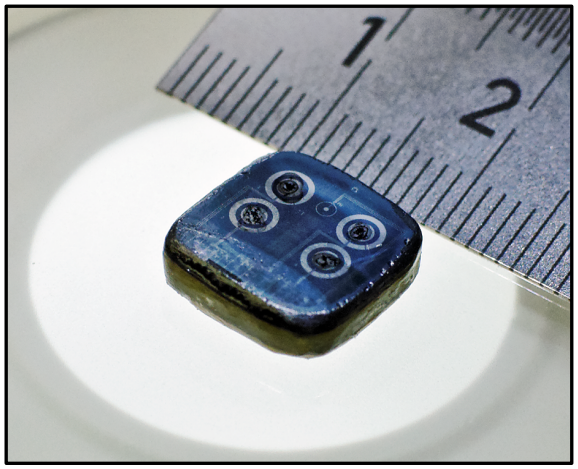
4. Compatibility → INTEGRATION



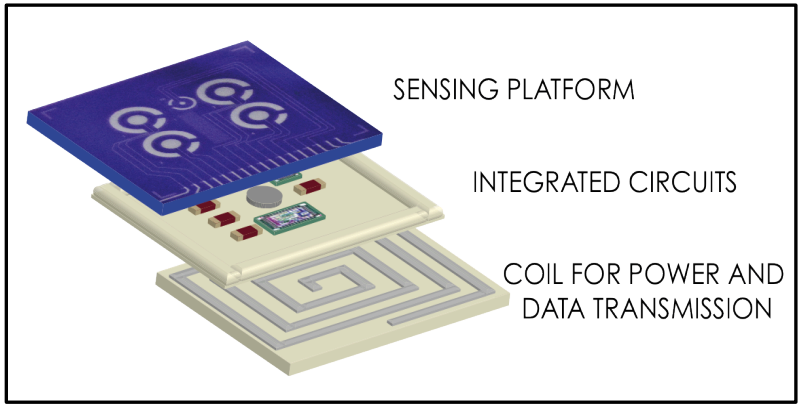
SiNW biosensors



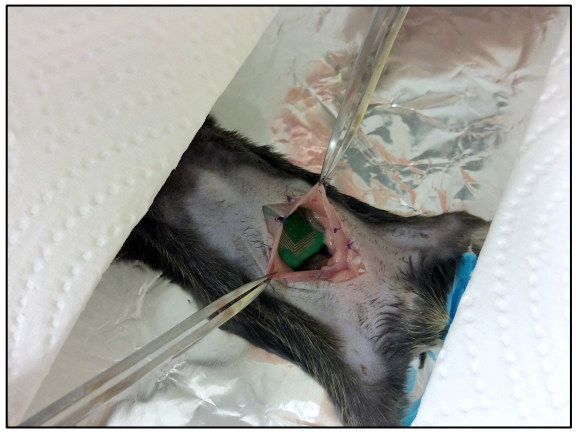
Example of sensor integration



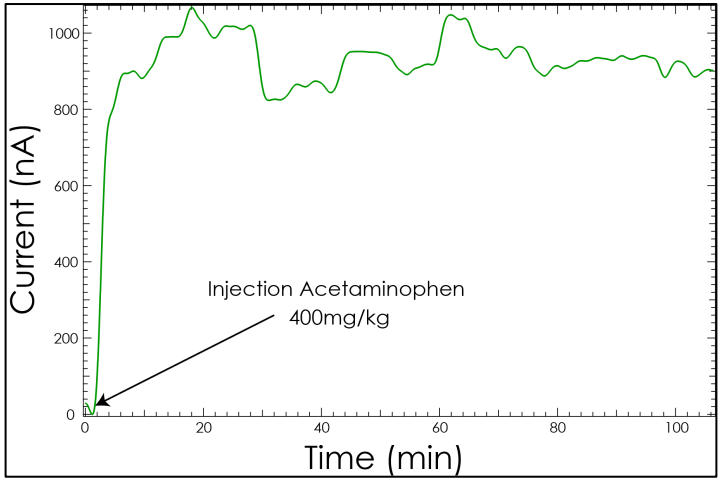
Muti-sensor for lab animals



Chip layers



Chip implant in mouse



Step injection response

[Baj-Rossi, 15]

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  - Device fusion
- **Conclusions**

Conclusions

- Computing is evolving in various directions and permeates everyday life and activities
- Computing is still mainly based on *von Neuman* architectures, switching theory and silicon devices
- New materials and devices can change the physical substrate of computation, making it more efficient and broader in scope
- Progress will require a strong coordination of technology, architecture and software as well as design methods and tools

Thank you

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