Nanosystems:

Devices, circuits, architectures and applications

Giovanni De Micheli

ISCAS 2010

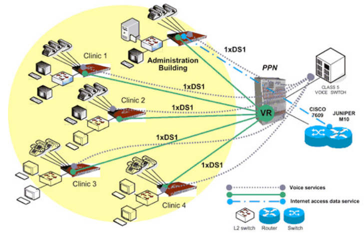
Emerging societal & economic problems

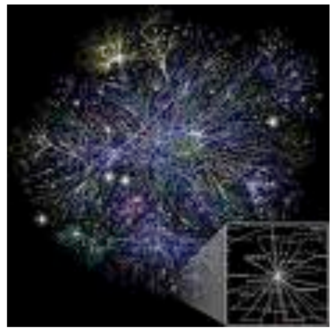
- World Economic Forum (Davos 10)
  - Improve the *State of the World*: Rethink, Redesign, Rebuild
- Summit on the *global agenda* (Dubai 09)
  - Most pressing technological/economic issues affecting the world growth
- Overlap of economic with broad engineering issues
  - Information technology boosts the value of specific advances in devices towards global solutions

Circuits and systems are key to solving major world problems

Main issues on the *global agenda*

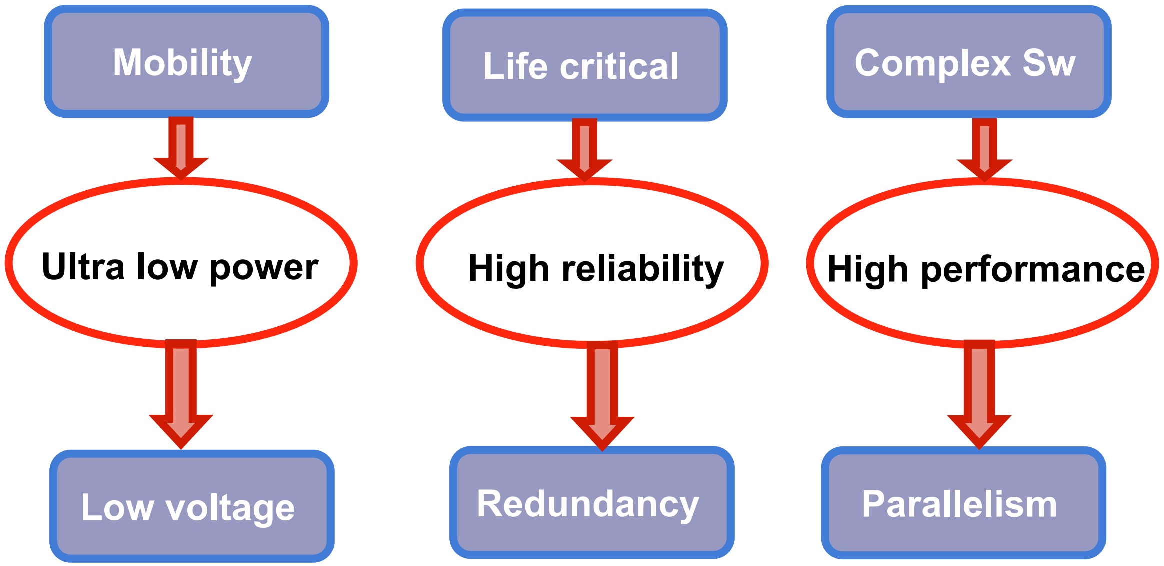
- Ensuring sustainability
  - Smart energy production and distribution
  - Intelligent water management
- Strengthening welfare
  - Better, affordable health care and wellness
  - Dealing with ageing and young population
- Mitigating risks
  - Preventing catastrophes and pandemics
  - Monitoring the environment
- Enhancing security
  - Future of the internet
  - Preventing cyber and physical attacks

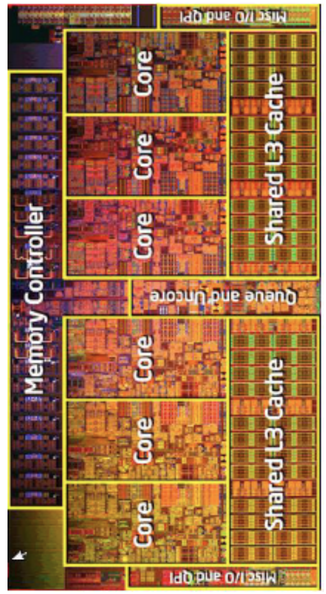




Requirements for integrated systems

- Unprecedented computing and storage capability
- Ubiquitous high-bandwidth communication
- Mobility, reliability, ease of use





- From processors to multi-processors
- How far can standard CMOS support the needs?

Nano-systems

Nano

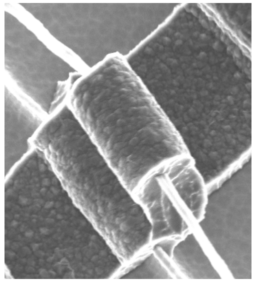
- Nanoelectronics:
  - CMOS < 32nm node
  - Silicon nanowires
  - Carbon nanotubes
- Nano-bio-sensing:
  - Size compatibility
  - Electro-chemistry

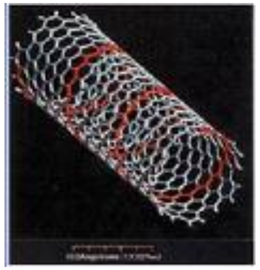
Systems

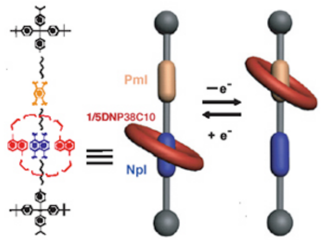
- Tera-scale systems:
  - Heterogeneity
  - Sensing, Processing, Communication, SW Transducers
- Complexity:
  - Design
  - Management

Beyond CMOS

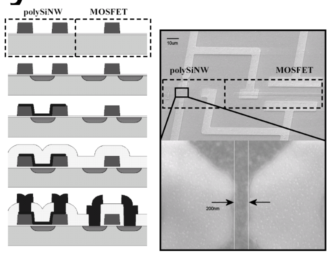
- Nano-technology provides us with new devices





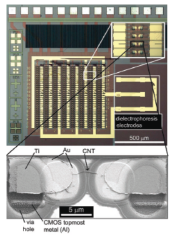


- Can they mix and match with standard CMOS technology ?



[Leblebici, EPFL]

[Infineon]

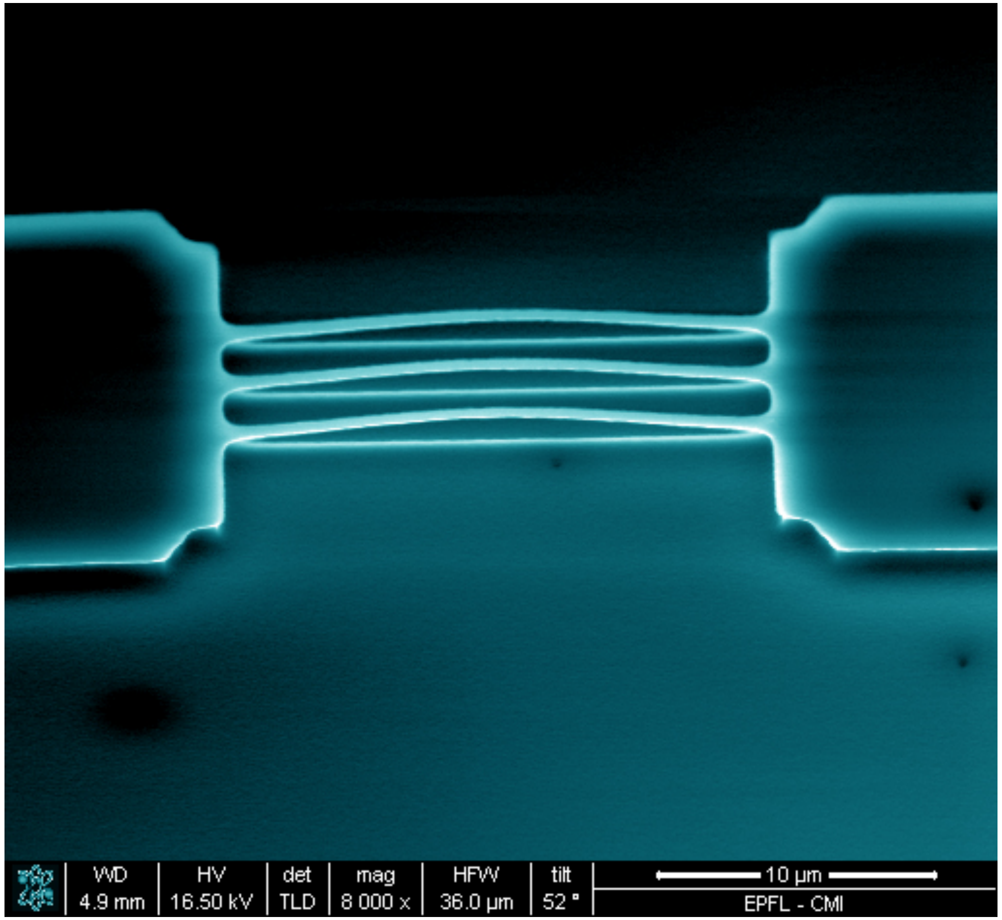


[Close, Stanford]

- What is the added value?

- What are the drawbacks of these technologies?

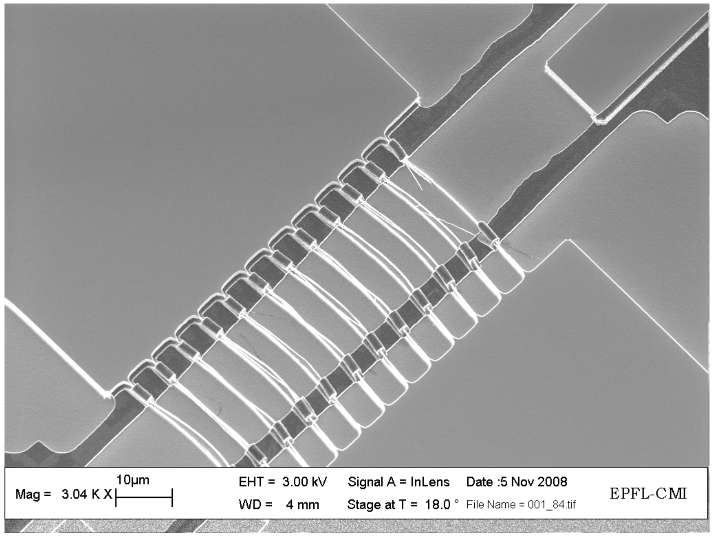
Nano-devices



Devices

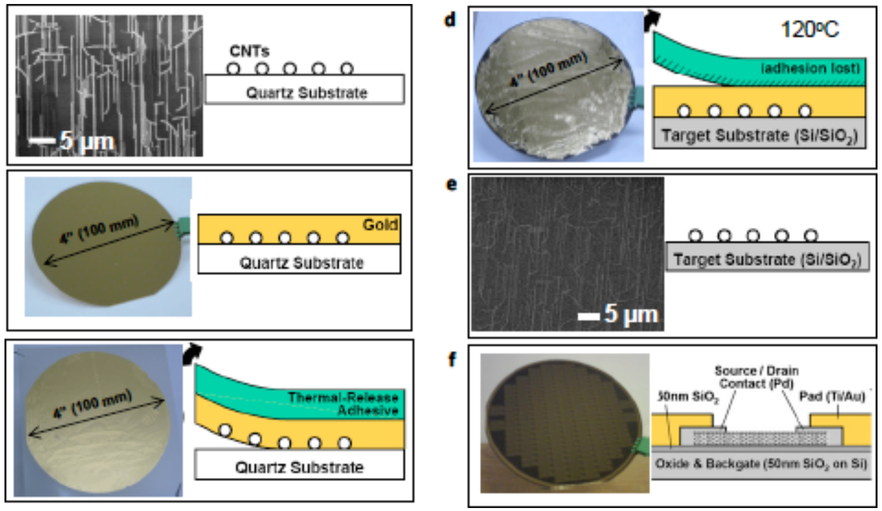
Silicon nanowires

- Silicon process
- CMOS compatible
- Top-down design

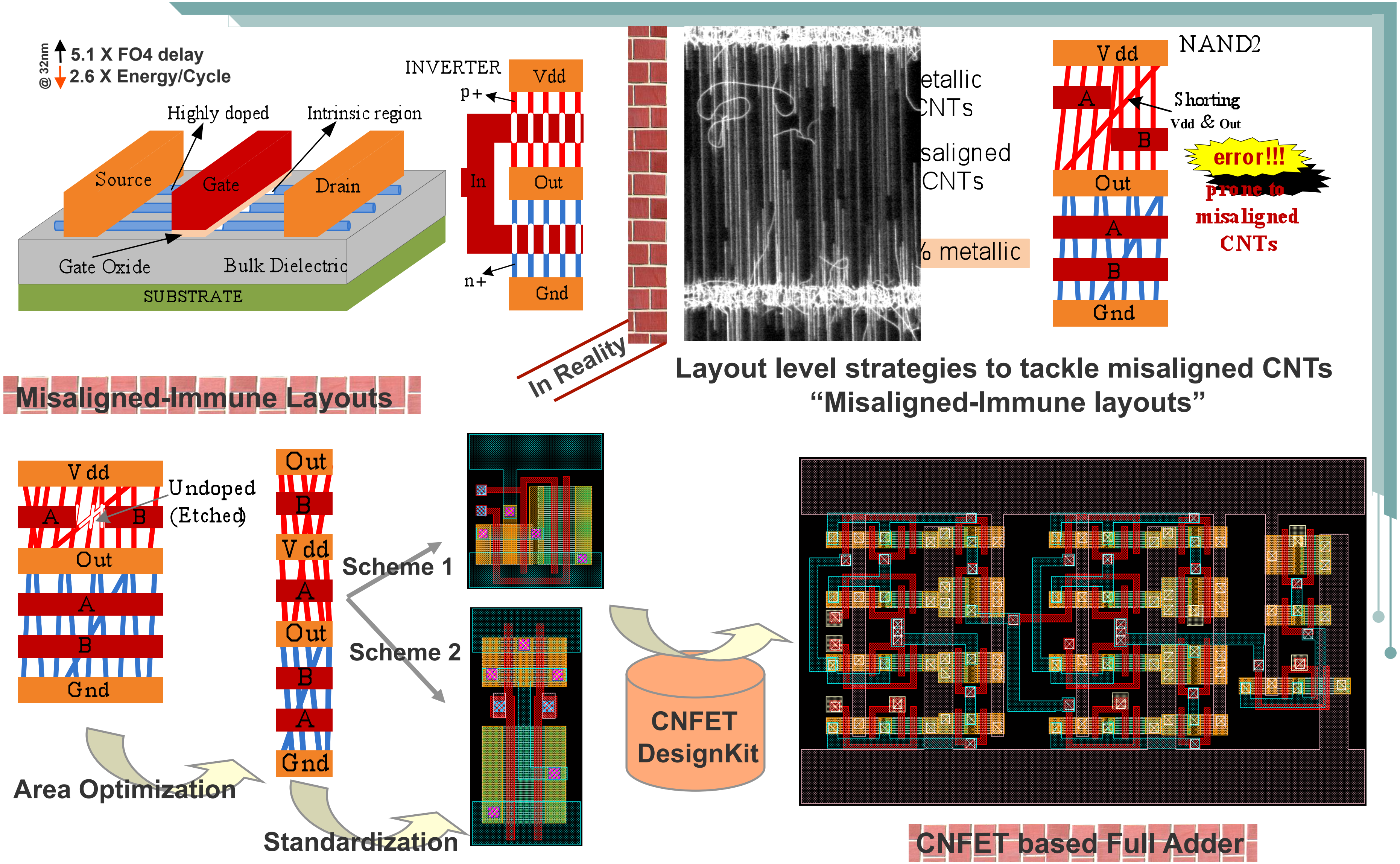


Carbon nanotubes

- Deposition or growth
- CMOS compatible
- Top-down patterning

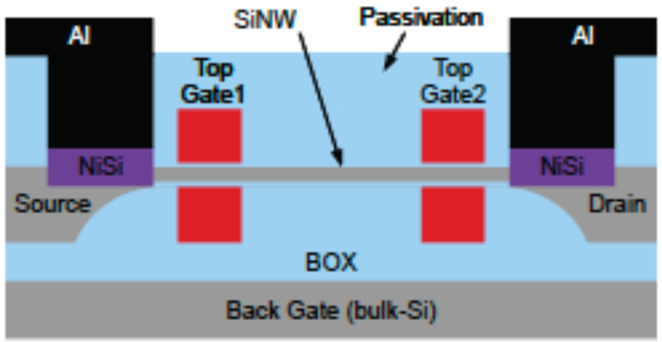


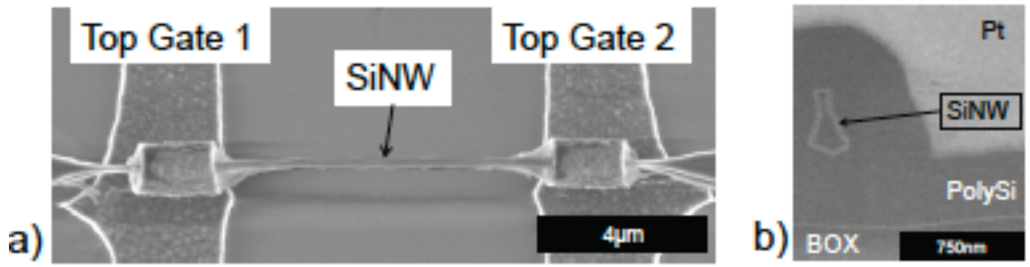
Imperfection-Immune Carbon Nanotube Circuits



Silicon Nanowires

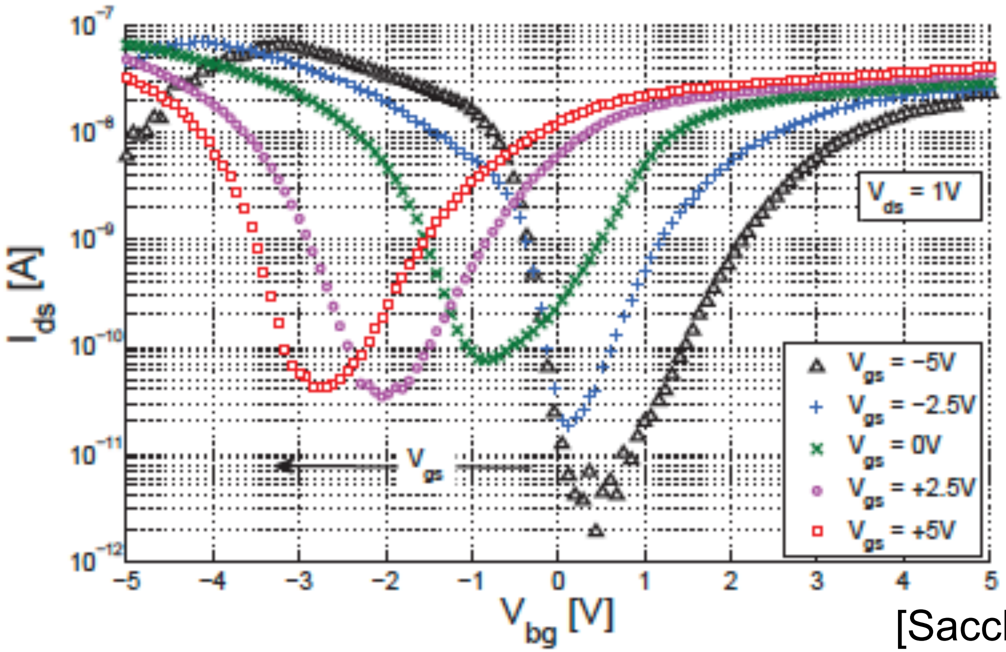
- *Silicon on Insulator* (SoI) wafer
- Deep reactive ion etching (DRIE)
- Gate all around transistors





Ambipolarity

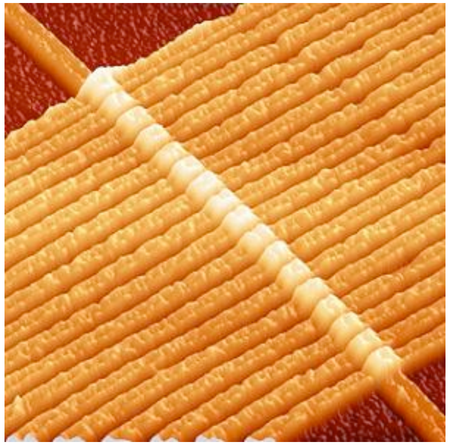
- Device characteristics controlled by backgate voltage
  - Four-terminal devices
  - Back gate determines type: *p* or *n*
  - Applicable to both CNT and SiNW FETs

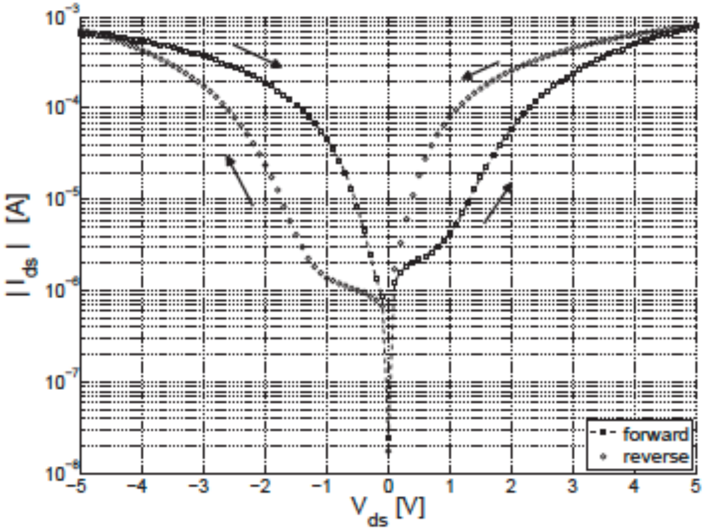


[Sacchetto – SiNW]

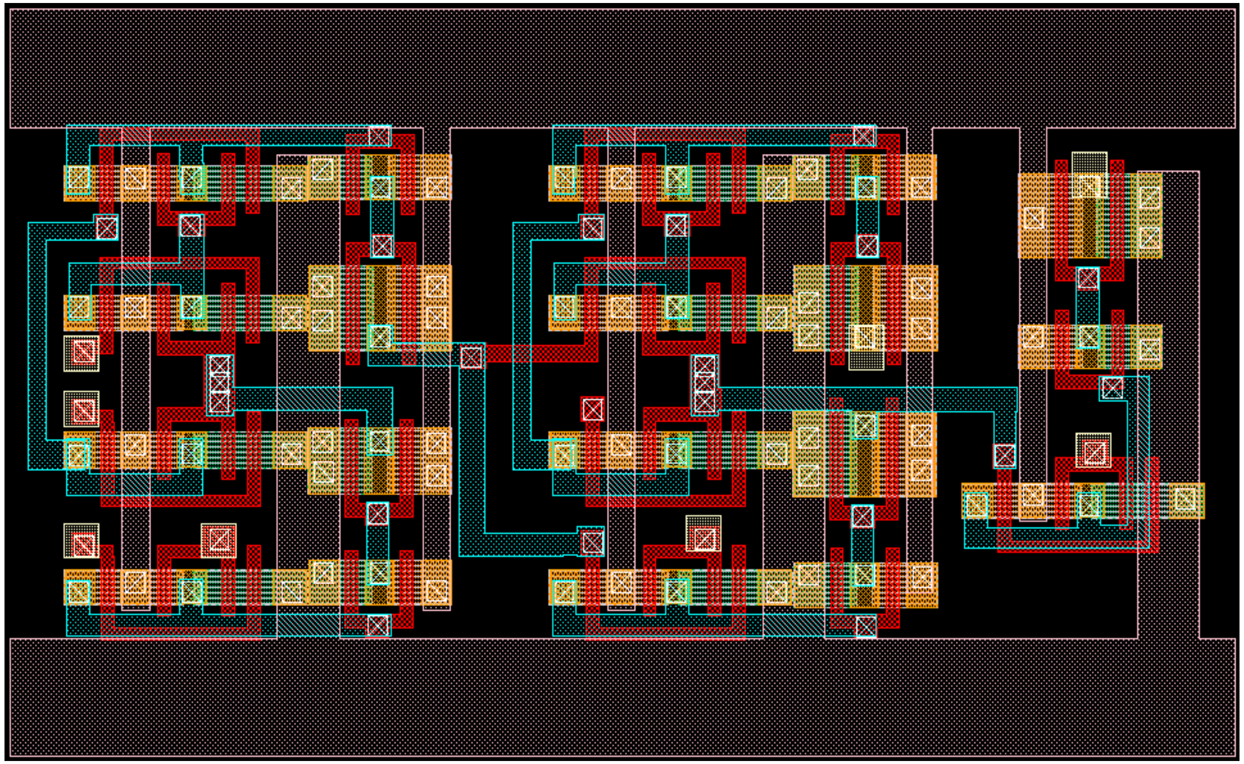
Memristive effects

- Memristor devices:
  - TiO_2 devices [Williams, HP]
  - SiNW Schottcky junctions [EPFL]
- Applications:
  - Resistive RAMs (RRAMs)
  - Digital components
  - Neural networks



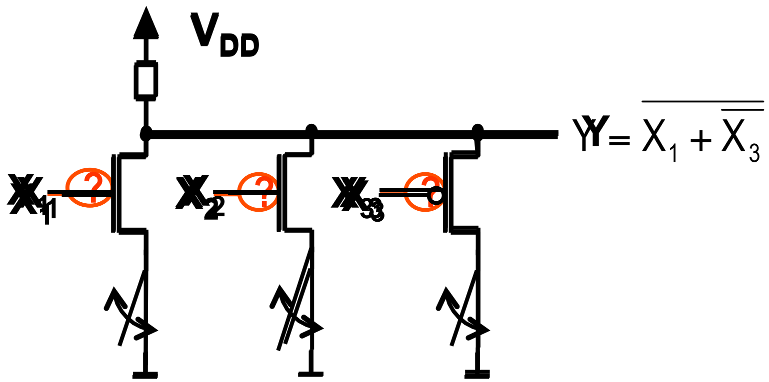


Nano-circuits

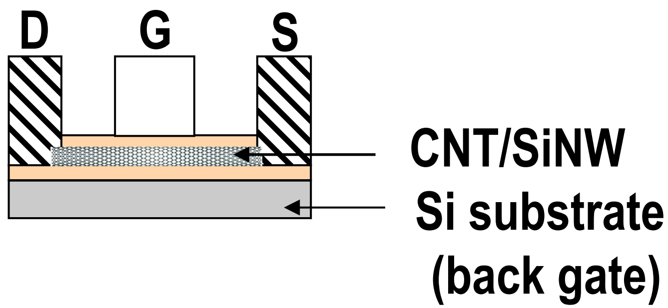


Logic abstraction of ambipolar devices

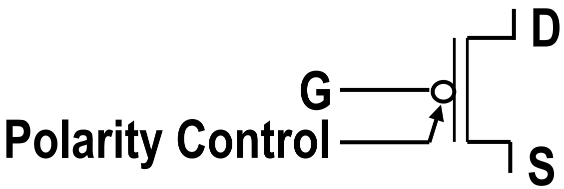
- Online polarity control:
  - On-line control: *p* or *n* device
  - Expressive power in realizing circuit function

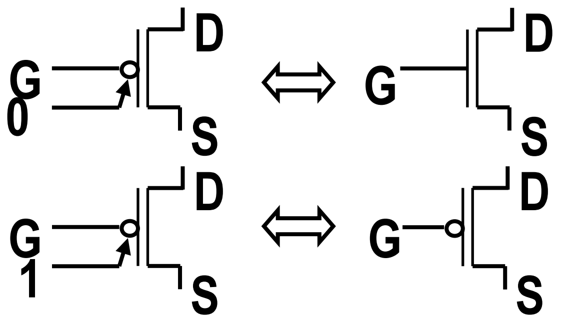


- Fabrication technology: double gate CNT/SiNW FET

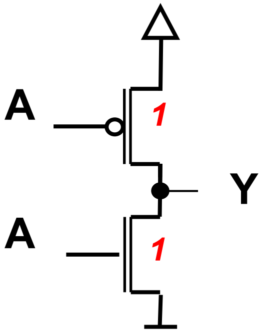


- Device symbol and operation:

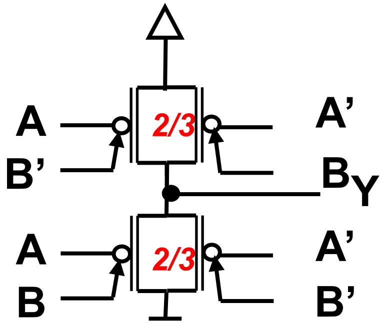




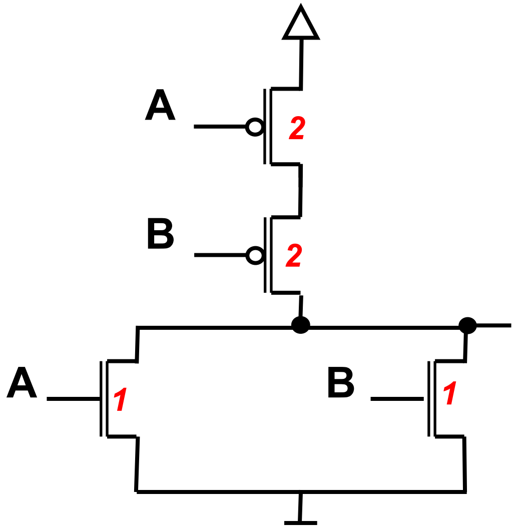
Static logic family



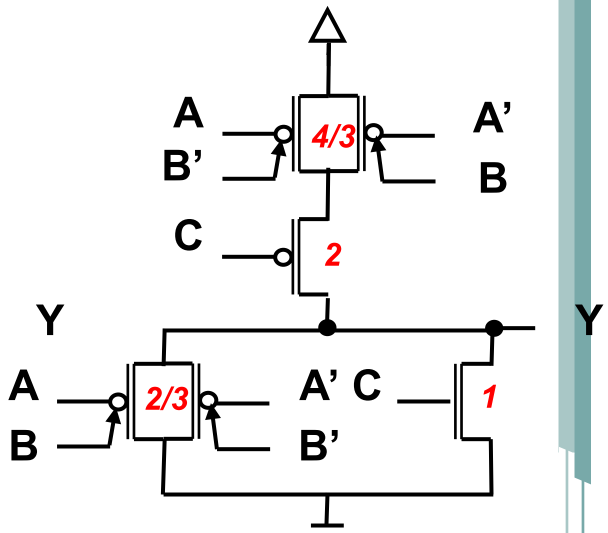
$Y=\overline{A}$



$Y=\overline{A \oplus B}$

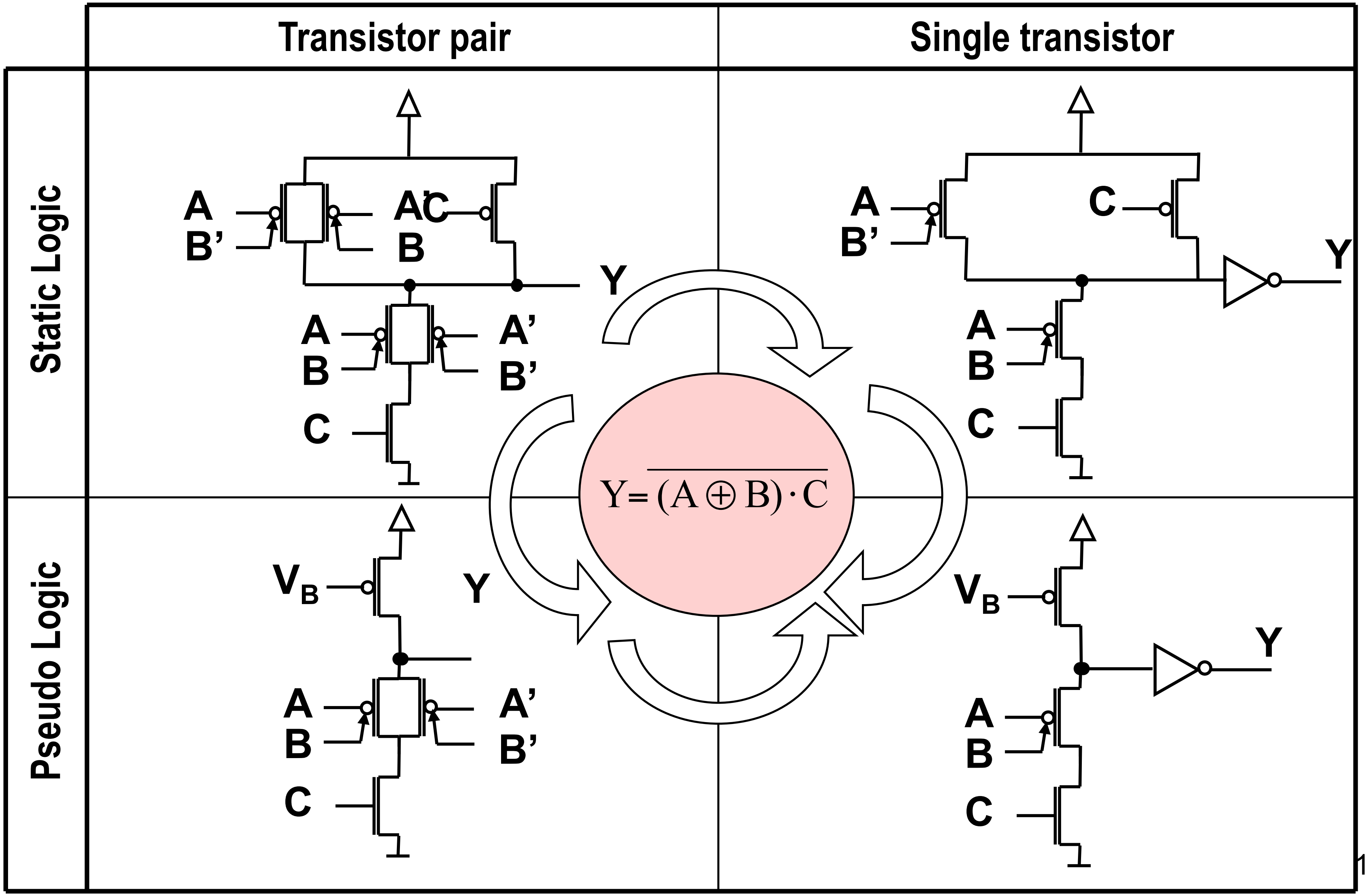


$Y=\overline{A+B}$



$Y=\overline{(A \oplus B)+C}$

Alternative logic families



Library characterization

- AMBI vs MOSFET:
  - Larger T count, but lower A
  - Static TP AMBI: equal normalized FO4 to MOS
- AMBI CNTFET families
  - TP pseudo vs TP static: 31% smaller, 33% slower
  - TP pseudo vs. ST pseudo: faster!

	CNT FET Technology									MOS FET Techno.		
	TP Static τ_1 ~0.6 ps			TP Pseudo τ_1 ~0.6 ps			ST Pseudo τ_1 ~0.6 ps			Static τ_2 ~3 ps		
	T	A	FO4/τ_1	T	A	FO4/τ_1	T	A	FO4/τ_1	T	A	FO4/τ_2
Avg.	9.1	12.3	9	5.6	8.5	12	3.7	11.5	24.1	4.9	12.7	9

T = Average transistor count

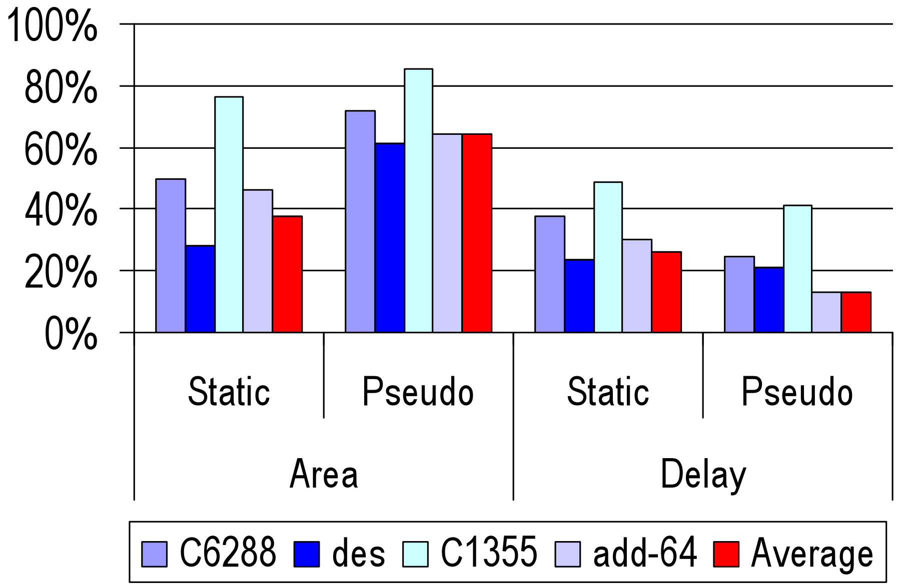
A = Average gate area

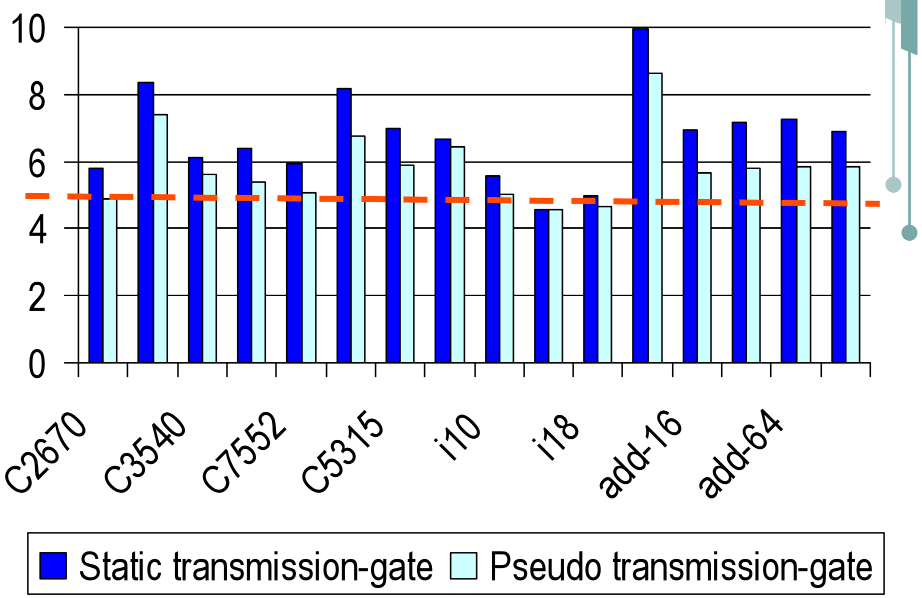
τ = Technology-dependent intrinsic delay

Multi-level logic synthesis results

- AMBI implementation needs fewer physical resources:
  - 38% fewer gates
  - 40% less logic levels
- Area saving: 38-65%
- Norm. delay reduction: 26-13%

- AMBI's τ is ~5× lower.
- Absolute speed-up:
  - 6.9x for TP static AMBI
  - 5.8x for ST static AMBI

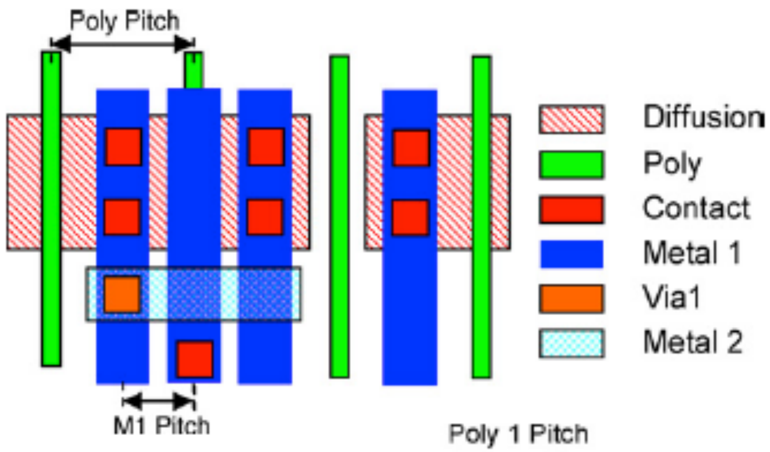


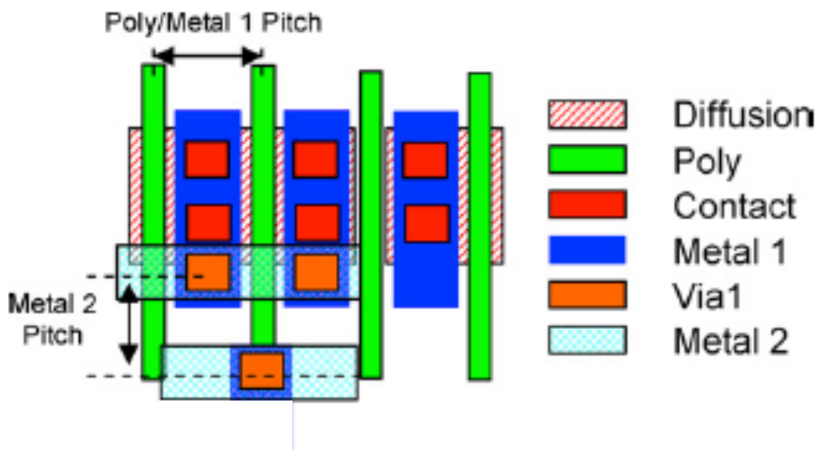


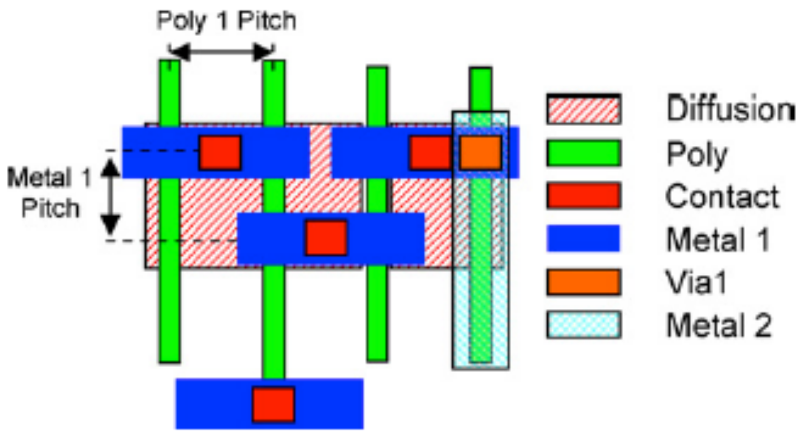
Nano-architectures

Regular fabrics

- Manhattan geometries
- Constraints on directions in each layer

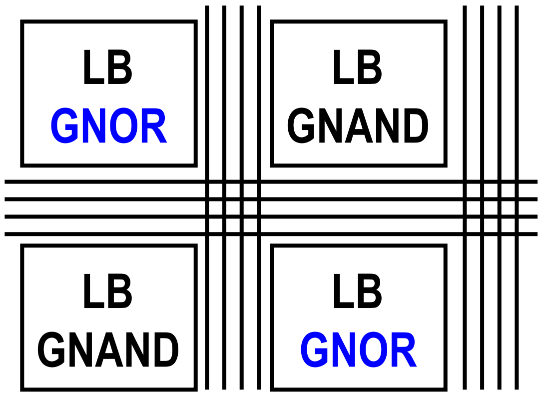


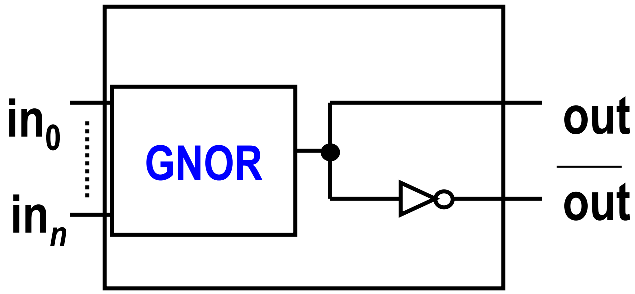


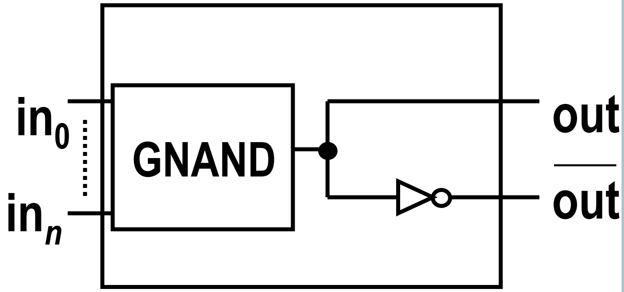


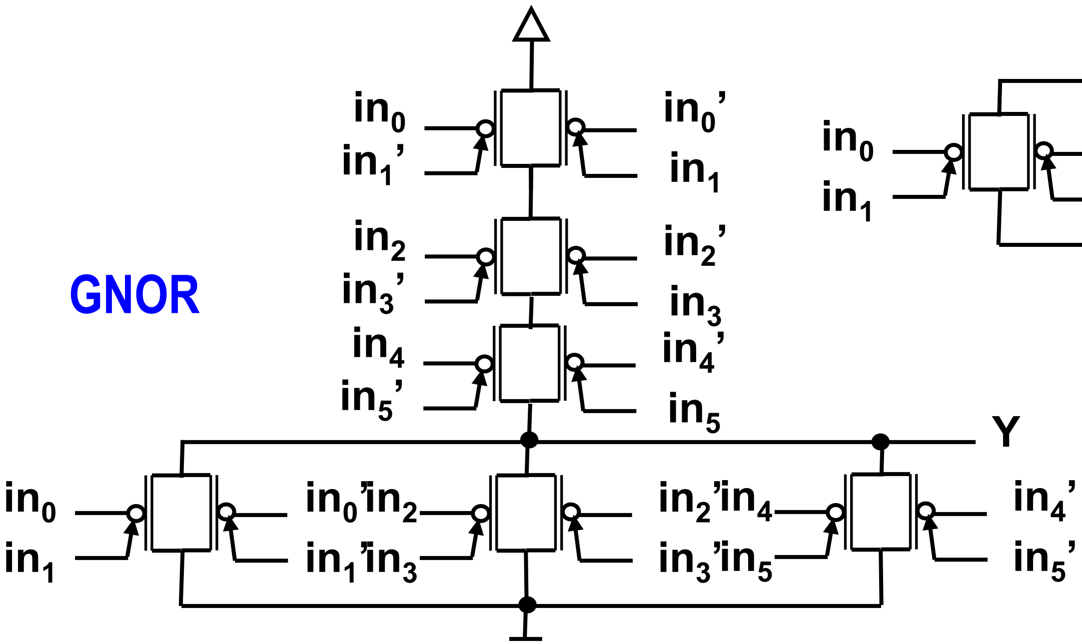
[Jhaveri et al. TCAD10]

Static regular fabrics

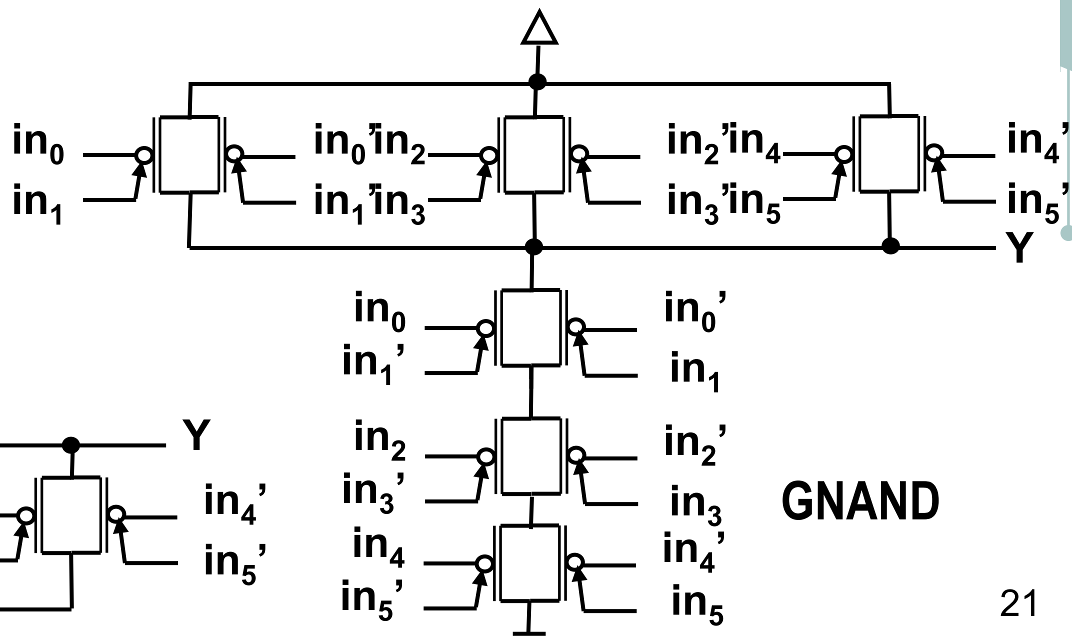






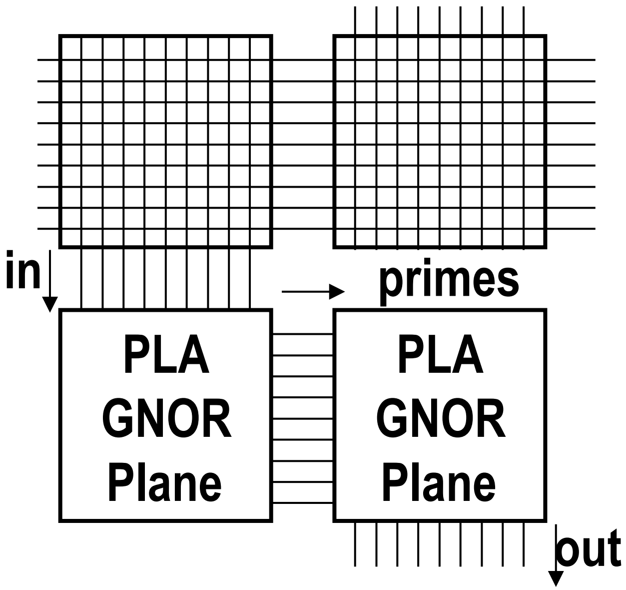


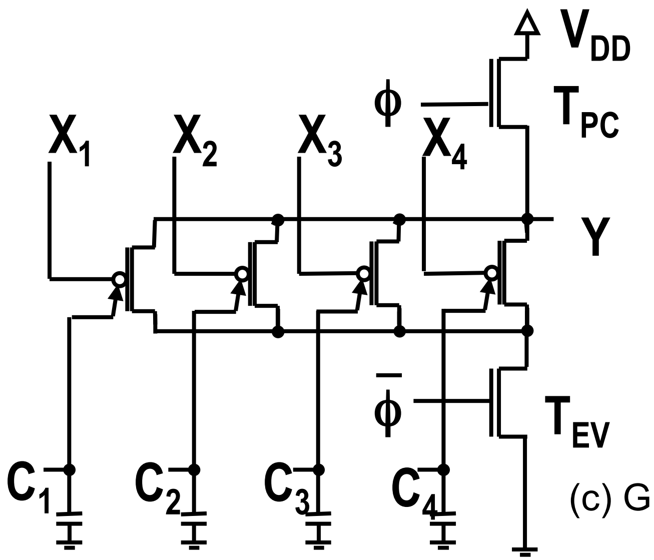
GNOR

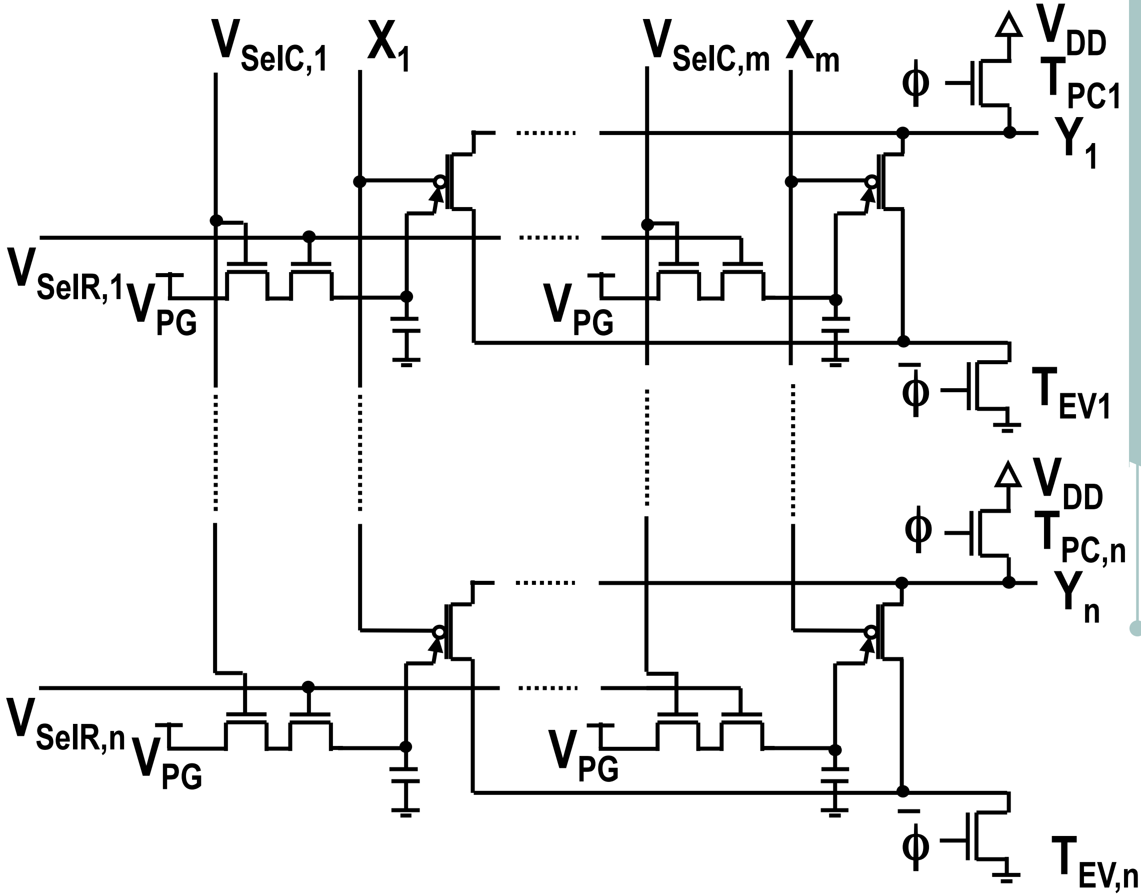


GNAND

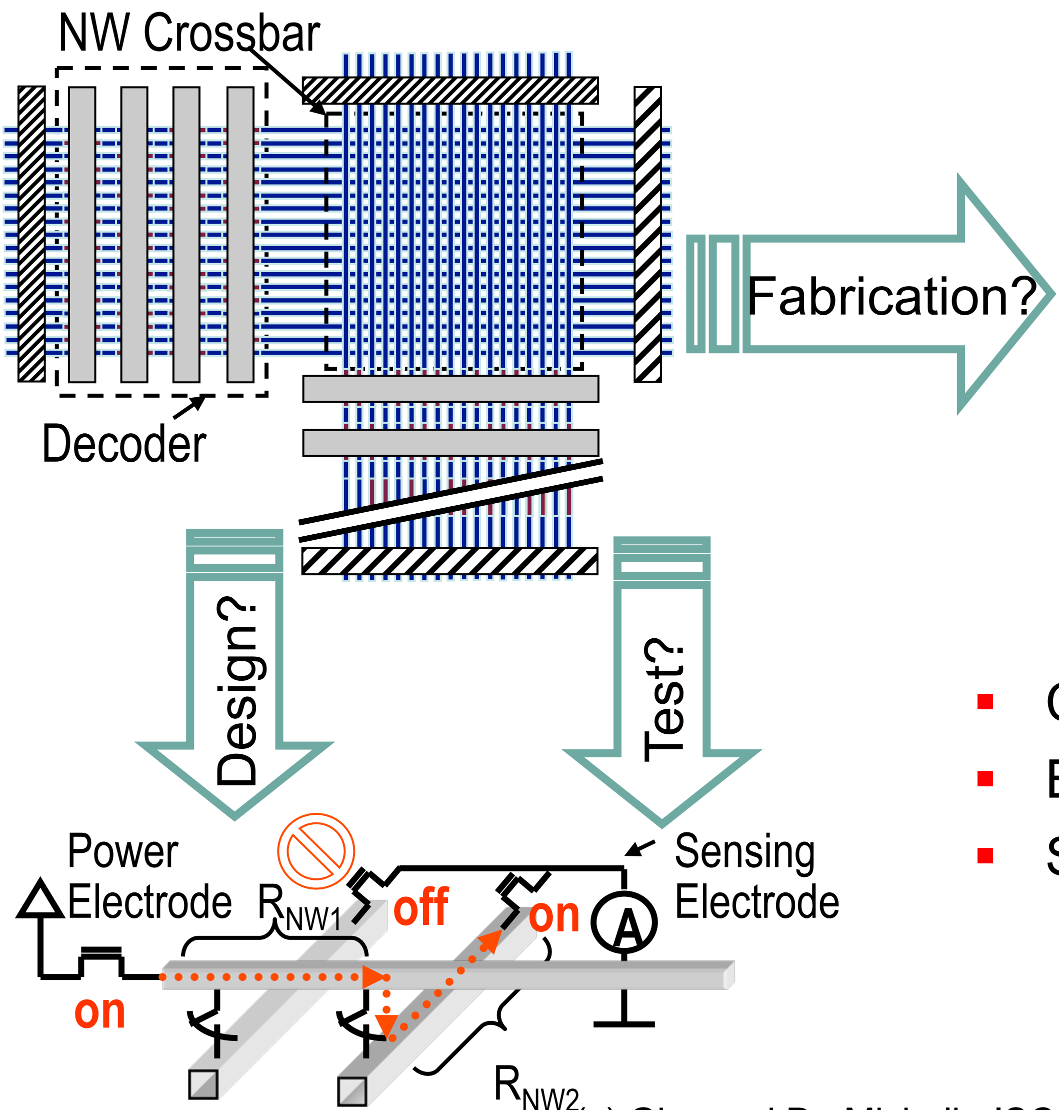
Dynamic regular fabrics

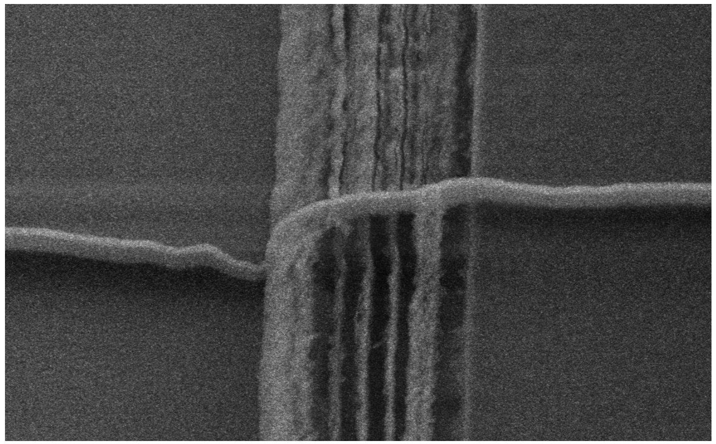






Nano-array design issues

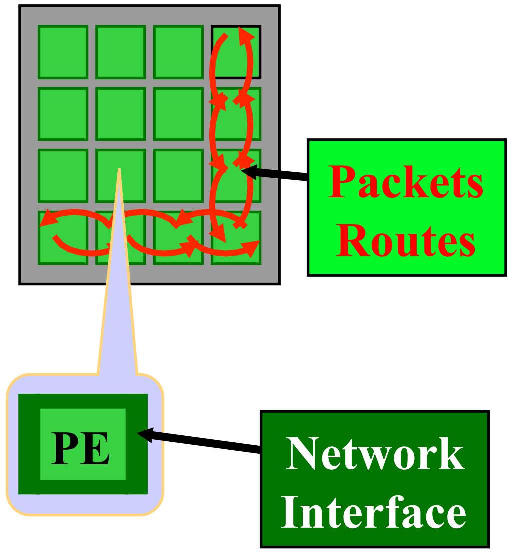




- Connecting array to meso-wires
- Easing test and self-test
- Support redundancy

Nanosystems: communication

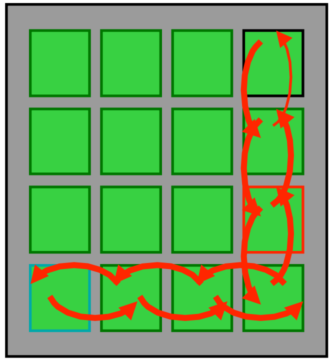
Networks on Chip



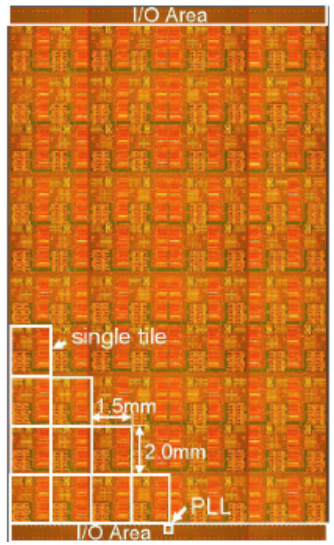
- Provide a structured methodology for realizing on-chip communication
  - Modularity
  - Flexibility
- Cope with inherent limitations of busses
  - Performance and power of busses do not scale up
- Support reliable operation
  - Layered approach to error detection and correction

Hierarchical nano-system view

- System:
  - Modules (PE) are processors



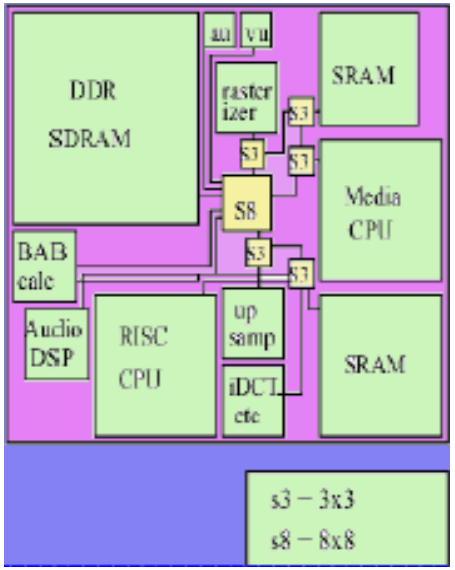
- Modules:
  - Submodules are nano-arrays
- The NoC provides the communication means
- What is the right functionality for a module in a nanosystem?
  - Look up table (FPGA)
  - Finite/program state machine (with stack)
  - Cellular neural networks (CNN)
  - Processor

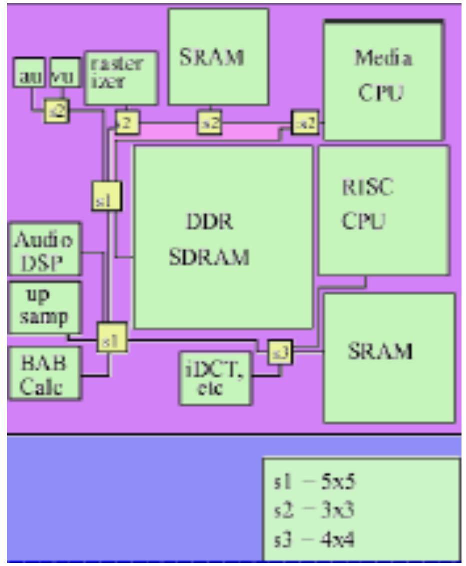


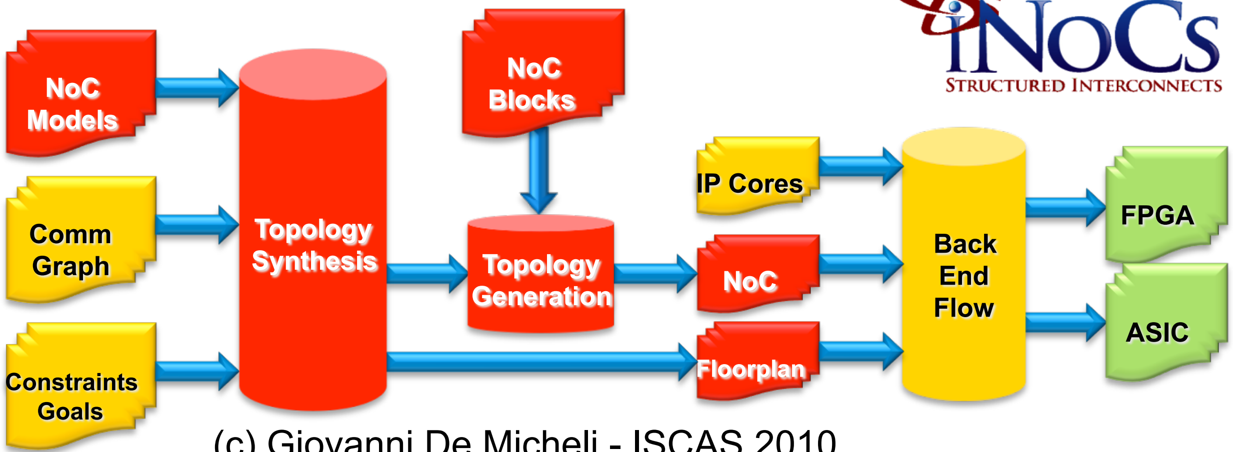
[Vangal, Intel07]

Design automation for NoCs

- Large design space
  - What topology
  - Which mapping
  - Which routes to use
- Optimize parameters
  - Link width, buffer sizes
- Simulate, verify, test



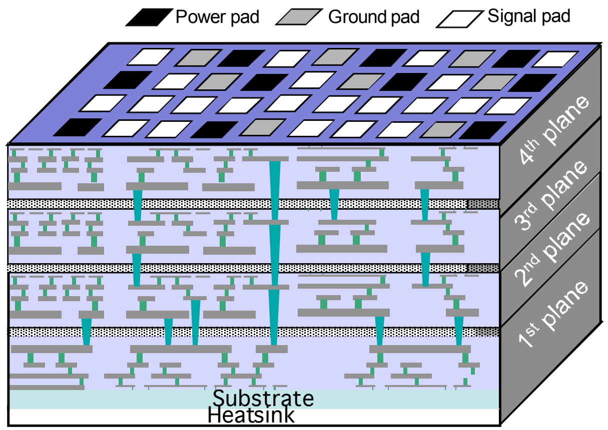


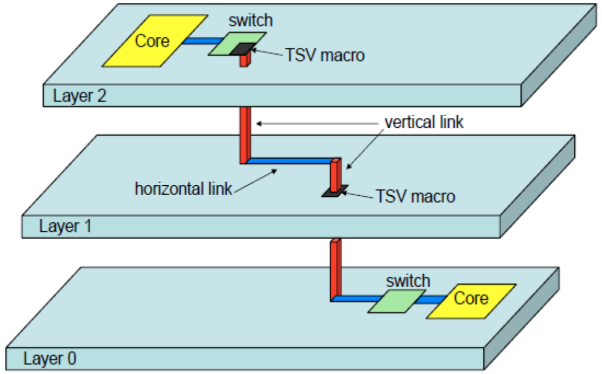


The vertical dimension

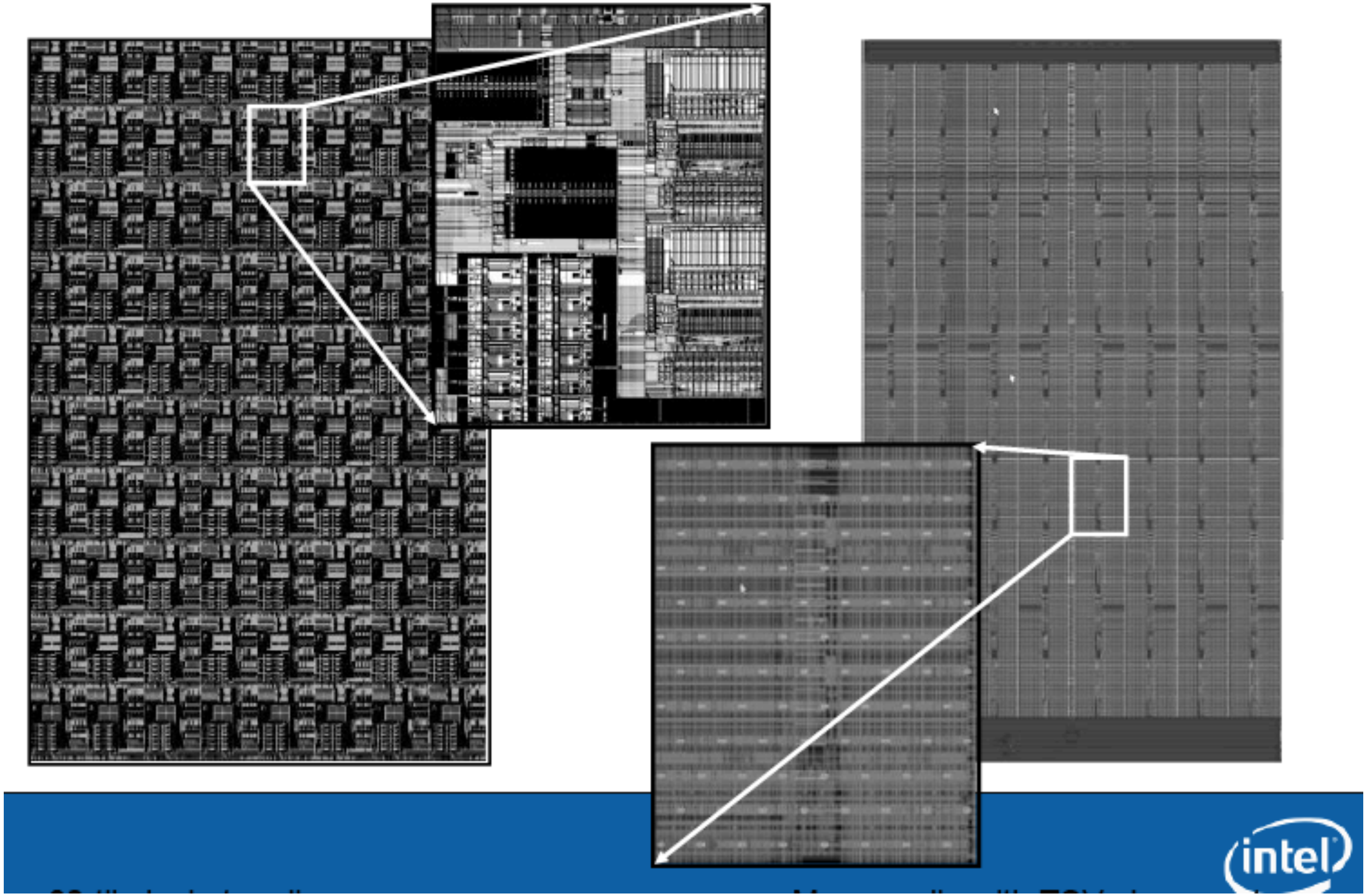
3-Dimensional integration

- Denser computational structures
  - Exploit *through silicon vias*
  - Shorter connections and access time
- Easier heterogeneous integration
  - Digital, analog, RF
- Strong thermal requirements
  - Heat generation, propagation and remova
- Novel design challenges
  - Routing, signal integrity, power distributio
- Reconfigurability
  - 3D networks on chip

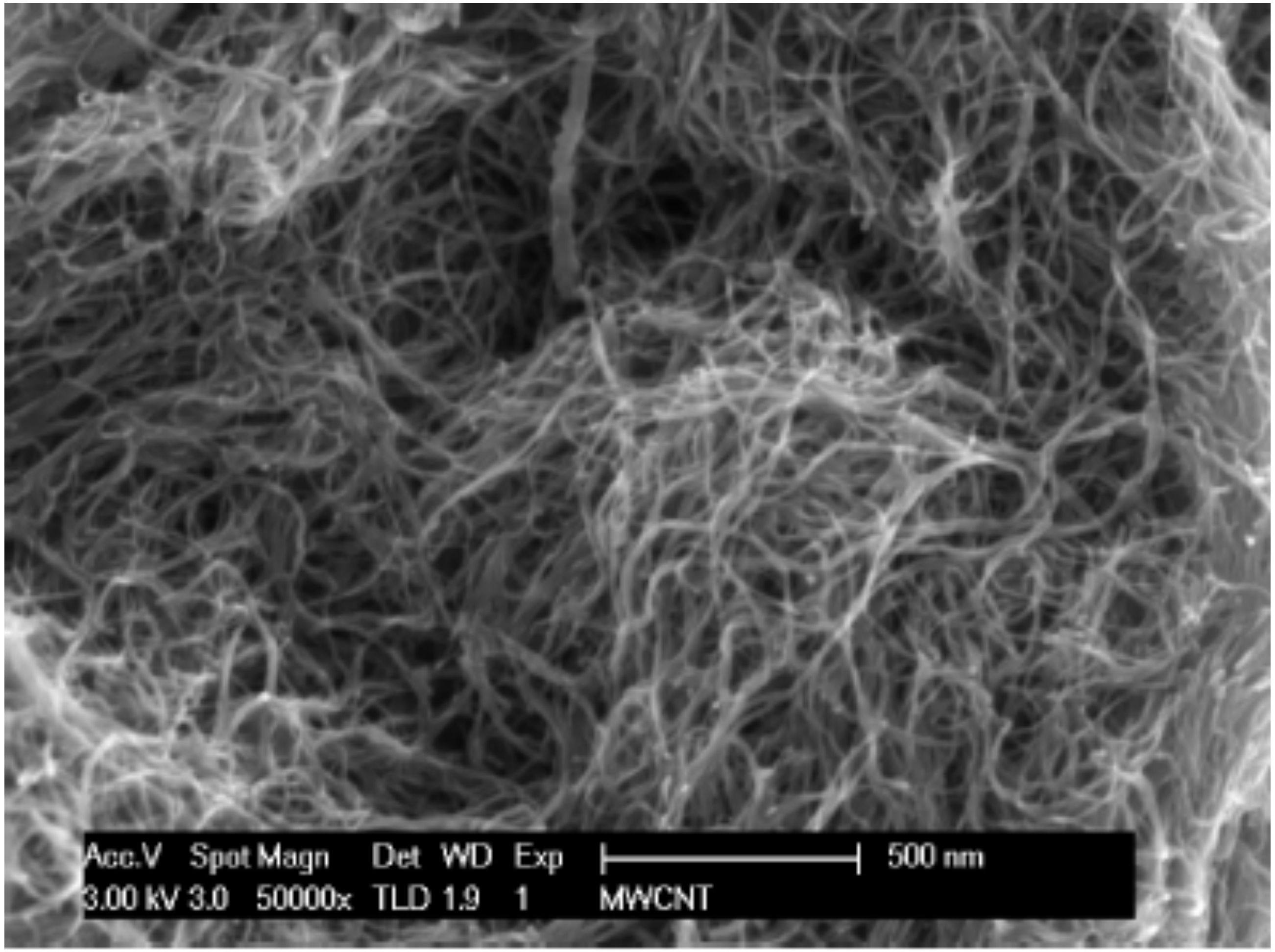




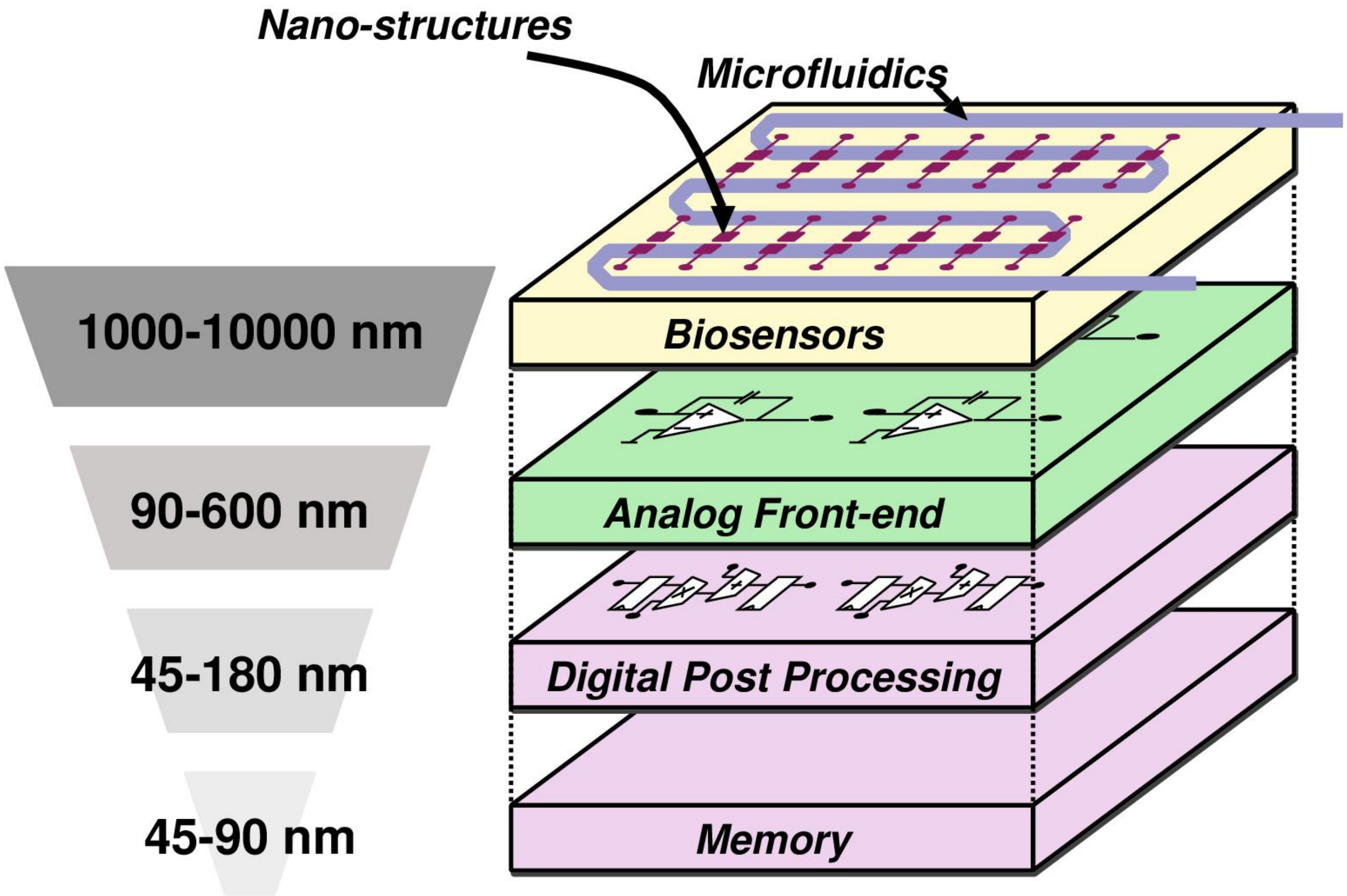
Processor and memory 3D integration



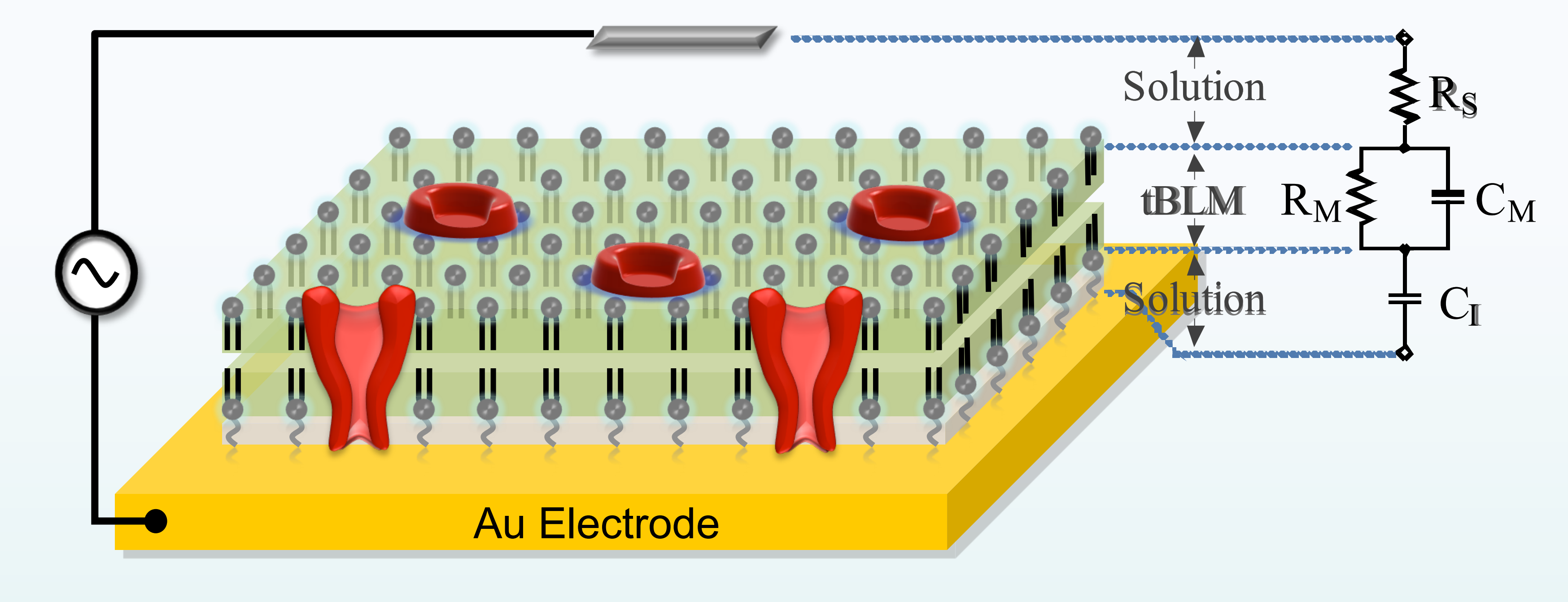
Nano-bio-systems



Nanosystems: the bio-layer

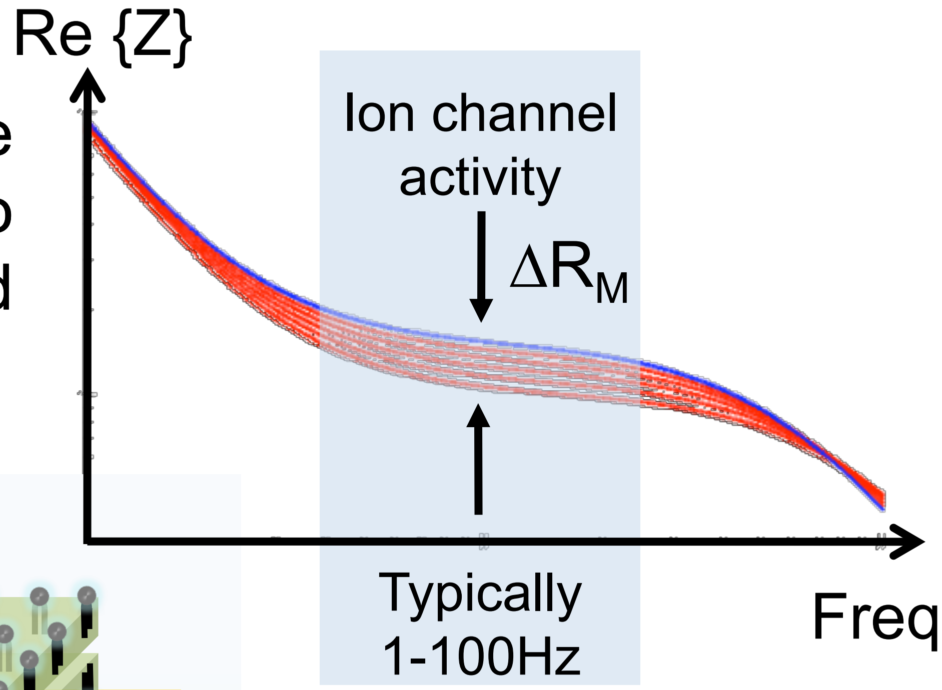


Integrated sensors

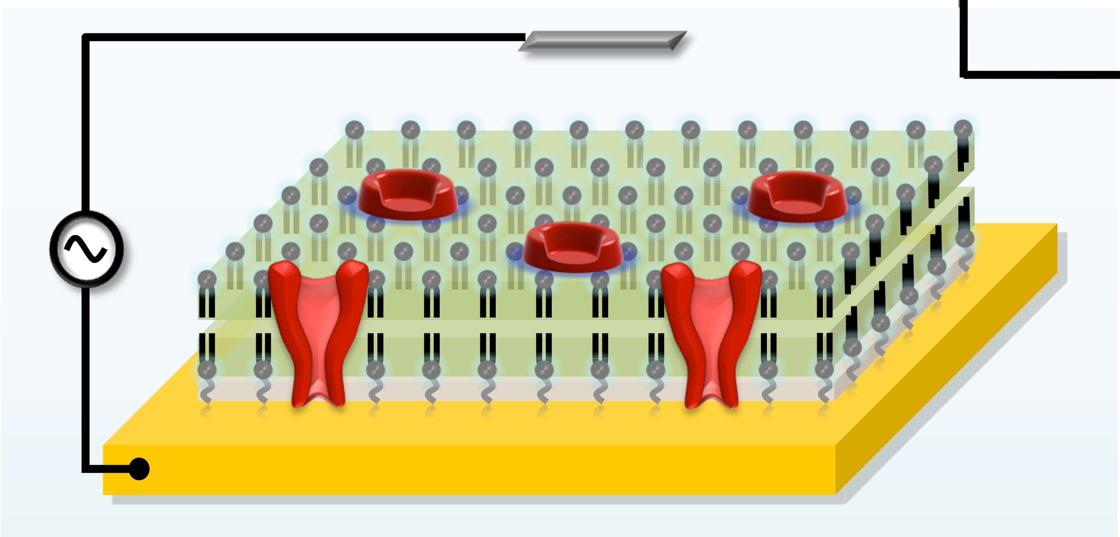


Modulation of membrane resistance

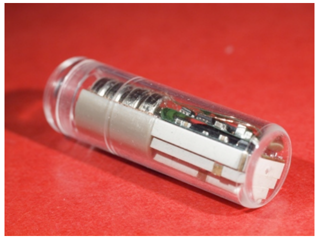
Modulation of the membrane resistance (R_M) is used to detect or quantify the ligand binding to an ion channel.



Increase of **Re(Z)** as a function of concentration is seen at mid-frequencies



Nano-systems: applications

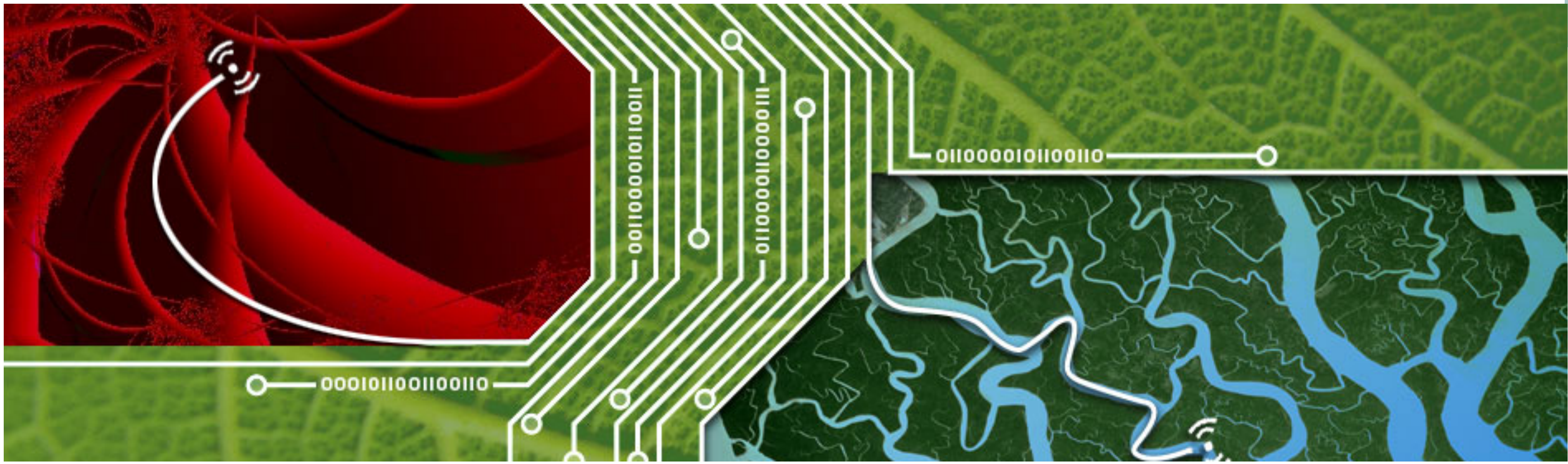


Nanosystems applications

- Health:
  - High-throughput biology, real-time medical monitoring
- Environmental monitoring:
  - Weather, pollution, seismic analysis
- Security:
  - Cryptography, secure communication
- Computing, communication, control
  - Scientific and consumer applications
- Defense:
  - Design of command and control systems

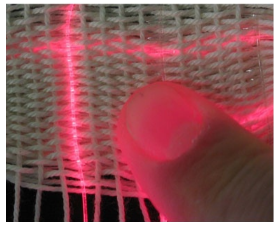
Nano-Tera.ch

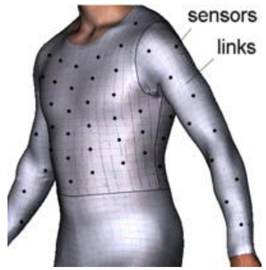
- Health:
  - High-throughput biology, real-time medical monitoring
- Environmental monitoring:
  - Weather, pollution, seismic analysis
- Security:
  - Cryptography, secure communication

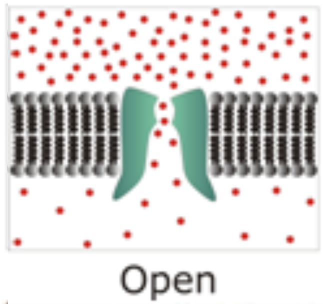


Electronic health

- Body monitoring
  - Biosensors
  - Body area networks
  - Smart textiles
- Clinical support
  - Remote diagnosis
  - Drug delivery
- Prevention
  - Monitoring nutrition
- *Challenges:*
  - *Non-invasiveness*
  - *Safety and security*

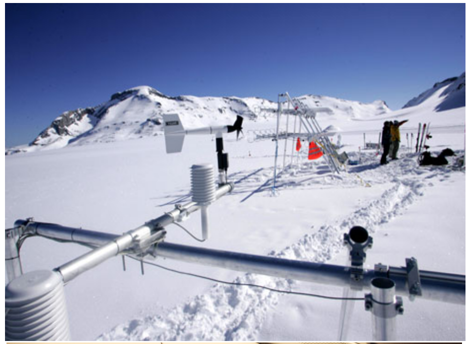






Environment

- Monitoring heat, wind, vibration
  - Earthquake, flood prediction
  - Movement of glaciers
- Controlling pollution
  - Water, air purity
  - Bio-contamination
- Emergency relief control
  - Real time support for reaction
- *Challenges:*
  - *Seamless presence and biodegradability*
  - *Autonomous and adaptive operation*



Human enhancement

- Deep interaction of nanosystems with humans
  - Deep brain stimulation
  - Prosthetics, artificial organs
- Correcting deficiencies, extending capabilities
  - Vision, audition, memory
  - Ethical and legal limitations

Conclusions

- Nano-systems exploit new technologies and devices:
  - *Silicon nanowire* and *carbon nanotube* devices
  - *Ambipolarity* can be efficiently used in logic design
  - *Memristive* effects can be effectively used for memory design
- New nano-architectures and design styles:
  - *Regularity* of the fabric is key to robustness
  - 3-Dimensional integration gives an extra degree of freedom
- Hybridization of new technologies opens new frontiers
  - Nano-bio-systems to probe and interact with living matter
  - Profound impact on health, environment and human evolution

Thank you