Bridging Technology and Design in More than Moore

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NANO-TEC

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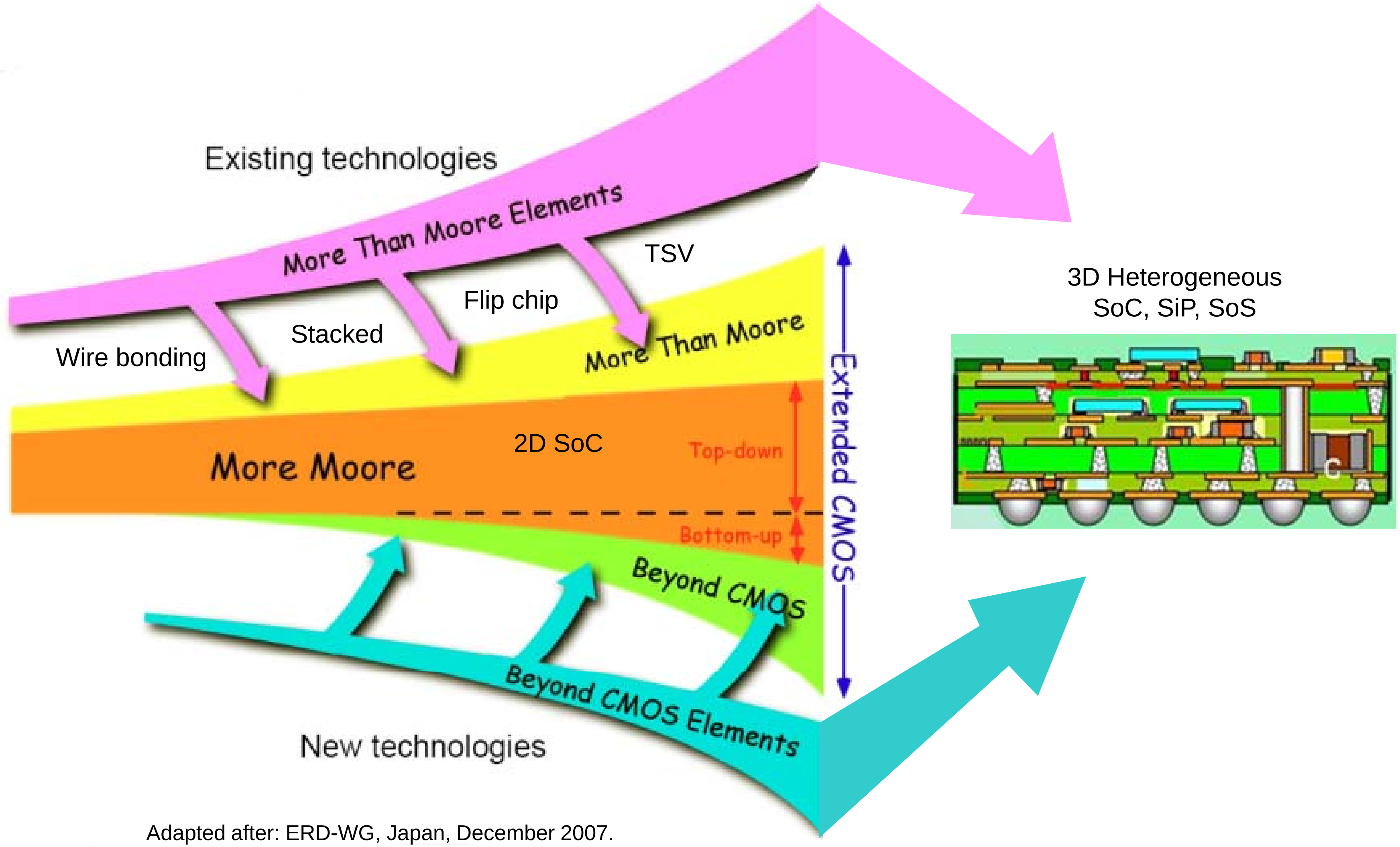
Outline

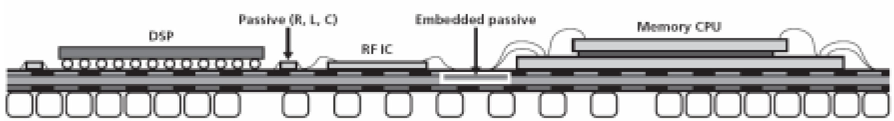
- **Evading Moore's Law**
- **From 2D IC to 3D Extended CMOS**
- **Novel functionality enabled by 3D integration:**
  - **RF MEMS**
  - **TSV for RF applications**
  - **3D integrated devices**
  - **Sensing**
  - **CNT**
  - **Silicon nanowires**
  - **Optics**
  - **Energy harvesting**

3D Extended CMOS



Adapted after: ERD-WG, Japan, December 2007.

SoC vs. SiP



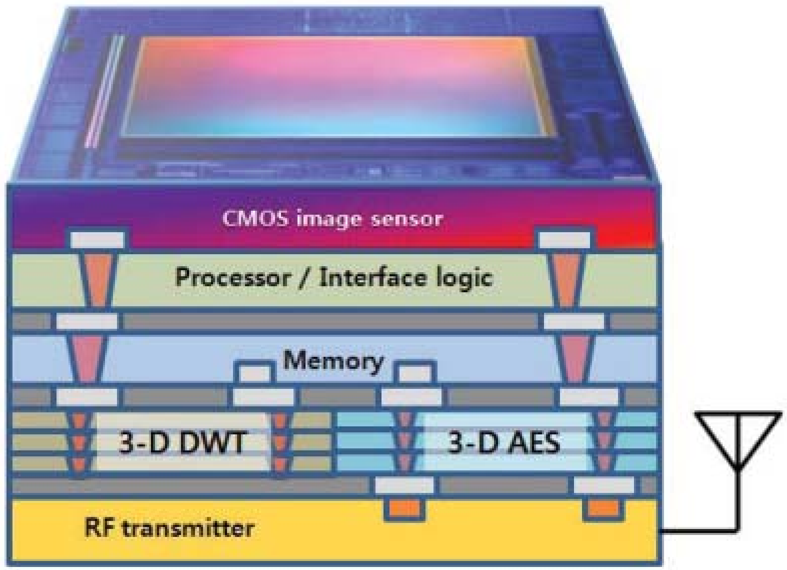
System on Chip (SoC)	System in Package (SiP)
Conventional CMOS integration “More Moore”	**Heterogeneous integration “More than Moore”**
✓ **Advanced integration based on the size reduction** ✓ **Cost reduction**	✓ **Flexiblility** ✓ **More functionalities** ✓ **High density**
× **Technological compatibility**	× **Complex design of system, circuit, package and board designers**
Digital, analog, mixed signal into a single chip → **Planar or stacked**	CMOS, RFICs, MEMS, Optics, Energy in a single package → **Wire bonding and flip chip**

3D IC stacked with TSVs

System on System (SoS)

Each die can be designed and fabricated with dedicated and optimized technology to efficiently:

- Enhance the performance of SoS
- Optimize individual functions within SoS
- Reduce SoS power consumption



S.-J. Lee, IEEE SOC Conf 2009

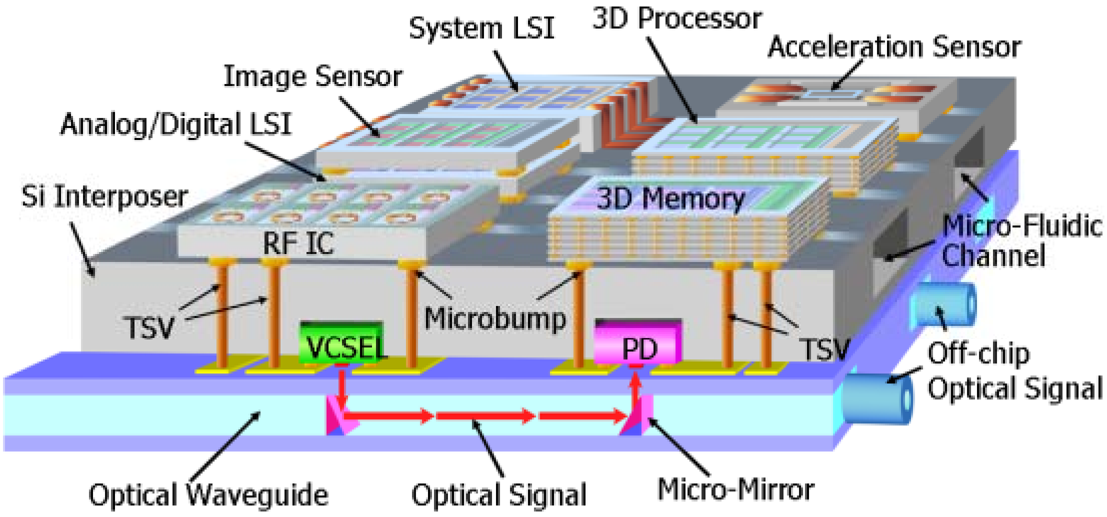
Heterogeneous Functionality

1) RF MEMS
   - ❑ Beam steering concept for complex WSN
   - ❑ 3D integrated inductors for RF tunable filters
   - ❑ Planar filters and UWB tunable LNA
2) Sensing
   - ❑ CNT sensing
   - ❑ Si nanowires sensing
3) Optics
   - ❑ Opto-electronic and Photonics
4) Energy scavenging

Heterogeneous Blocks for 3D

Heterogeneous integration components:

- MEMS & RF transmitter
- Sensors (image, acceleration, pressure, bio, etc)
- Optics (photonics)
- Energy Scavenging
- Memories
- Logic circuits
- Processor
- Power ICs



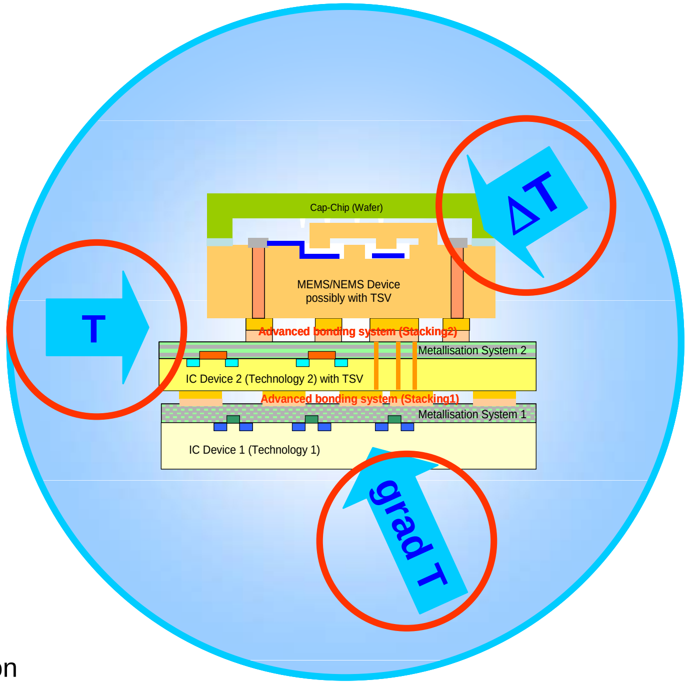
K.-W. Lee, IEDM 2009

3D Heterogeneous Integration

New application specific technologies for heterogeneous integration of complex advanced microsystems

- 3D integrated antenna and RF MEMS
- Sophisticated new nanosensor systems

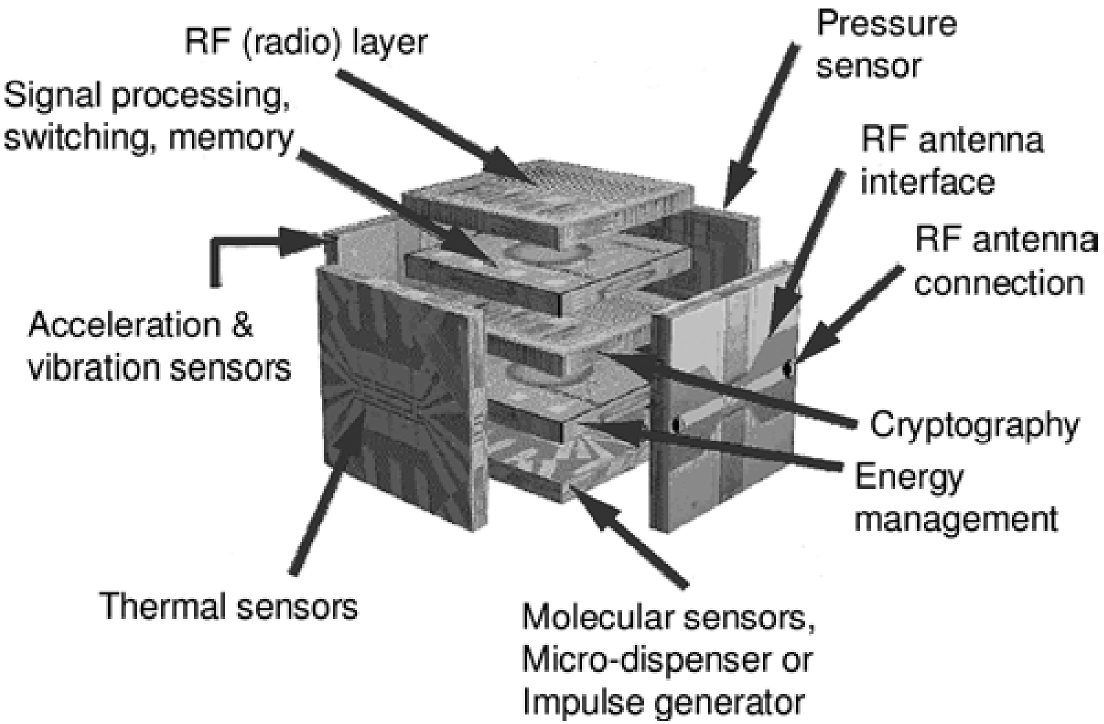
  Highly reliable and robust 3D processes
  Fragile mechanical structures in MEMS/NEMS
  Stress induced by TSV and bonding system
- Efficient system design support
  Architectural design of heterogeneous systems
  Tool set to predict functionality (incl. test devices)

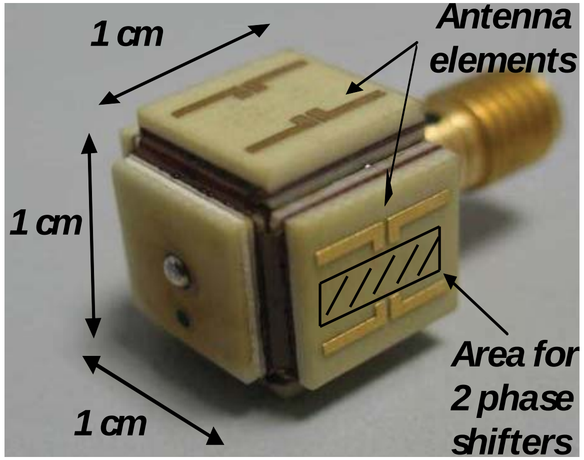


e-BRAINS is supported by the European Commission
under support-no. ICT-257488z

Wireless Sensor Networks

Specific optimized 3D-technologies for the integration of the different sub-modules (MEMS, ICs, memories, antennas and power modules)





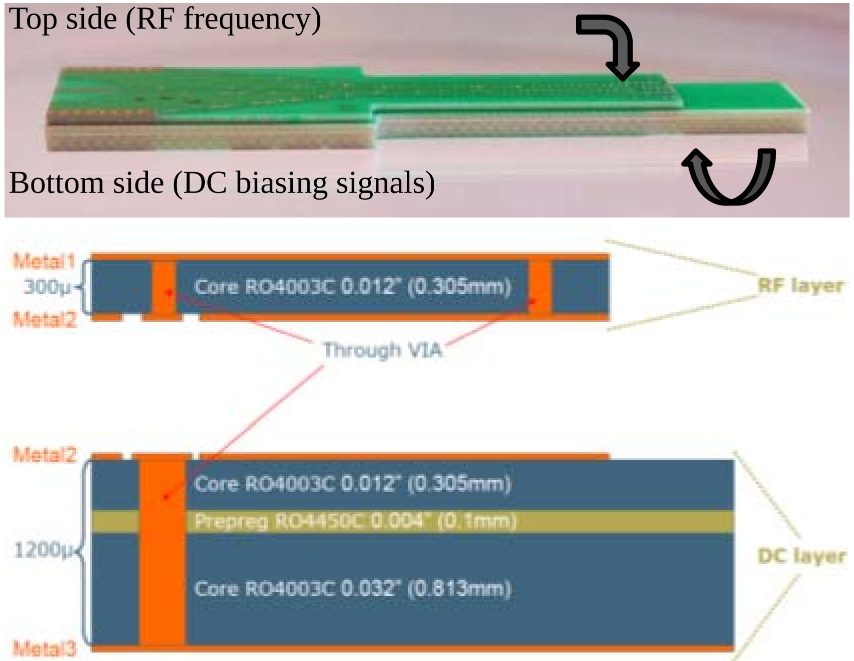
Radio System at 17 GHz

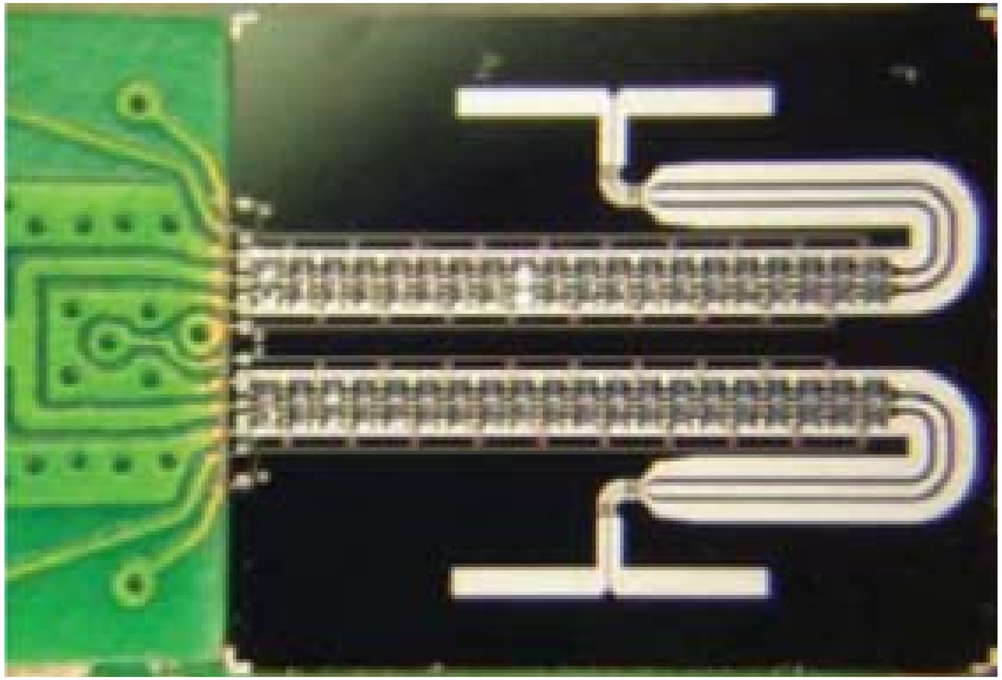
e-CUBES concept for space applications (sensor node or satellite) with multifunctional layers

3D Integrated Antenna & RF MEMS

Antenna array prototype test chip

- 2 PCB laminated of different thicknesses to accommodate the Si core (300 mm).
- PCB board designed to measured the chip connecting by wire bonding the RF signal and the DC biasing signals

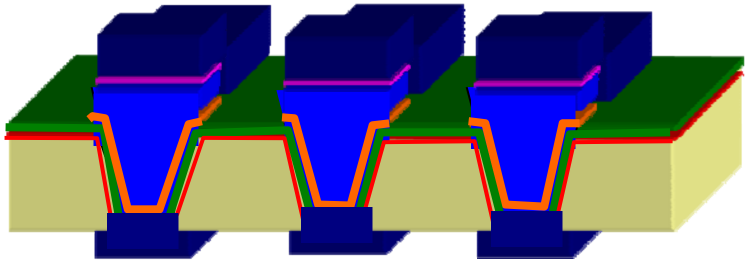




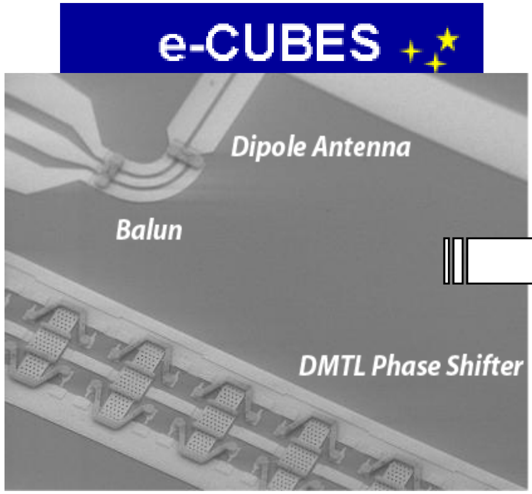
M. Fernández-Bolaños et al., Microelectron. Eng., 2010.

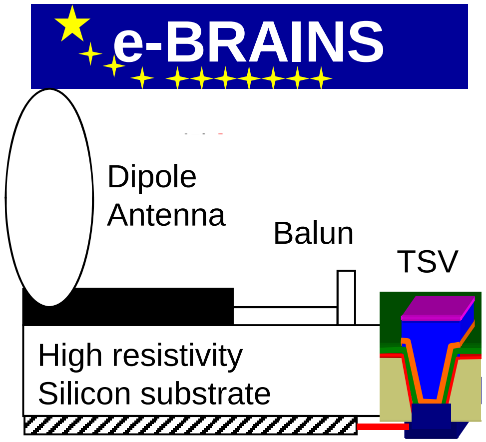
3D Integrated Antenna & RF MEMS

Future RF MEMS on TSV with 3D vertical interconnections



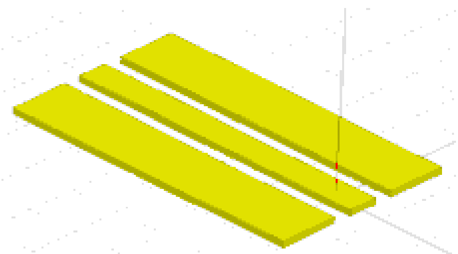
Antenna-Phase Shifter 3D Integration for beam steering applications



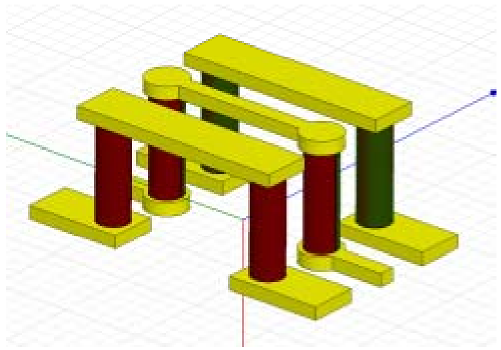


RF MEMS Phase Shifter

Optimize and compare insertion losses in a simple CPW and TSV CPW



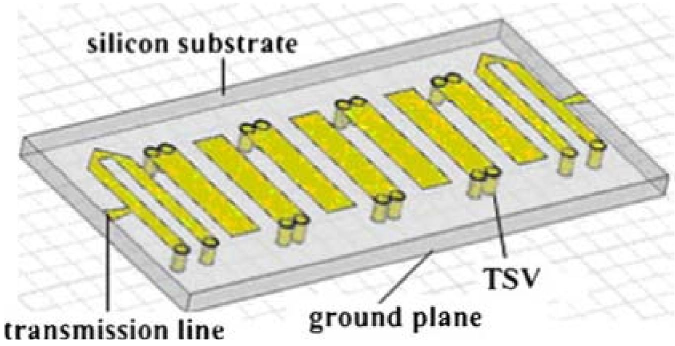
Simple CPW – 3D view

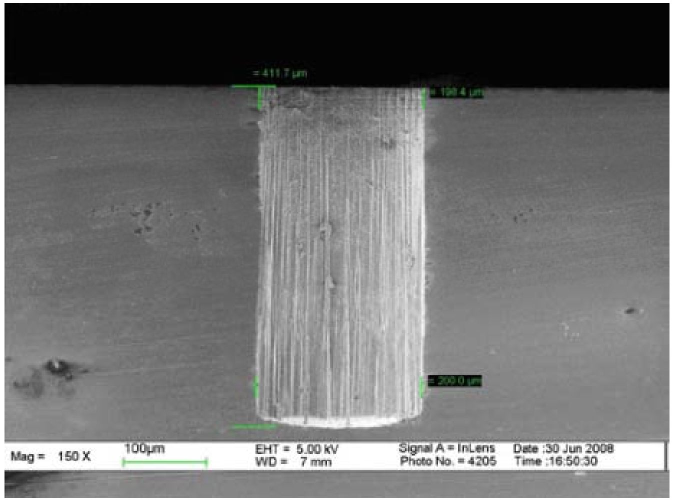


TSVs CPW – 3D view

Other 3D Integrated RF MEMS Examples

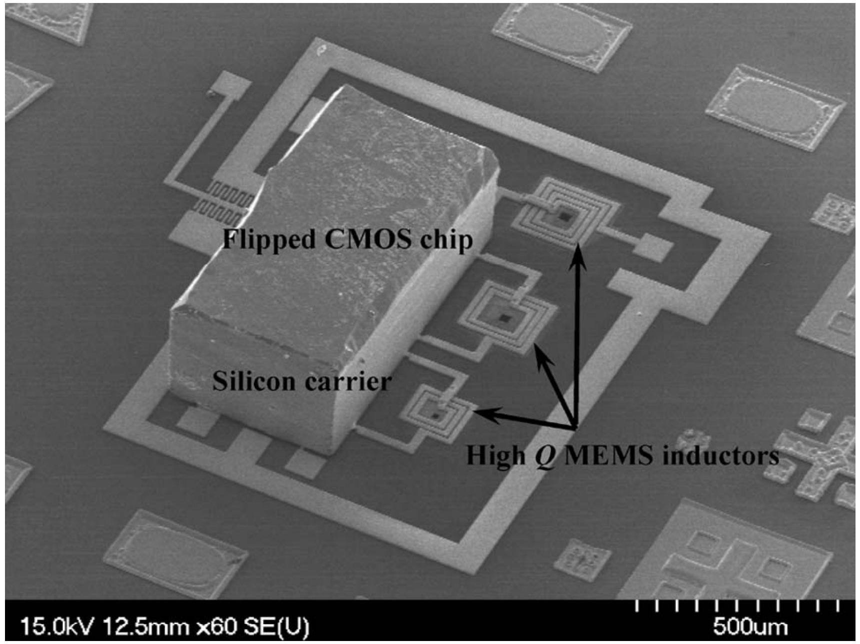
Ku band miniaturized bandpass filter using TSVs





J. Zhu et al., Microsyst. Technol. (2010) 16:1045-1049

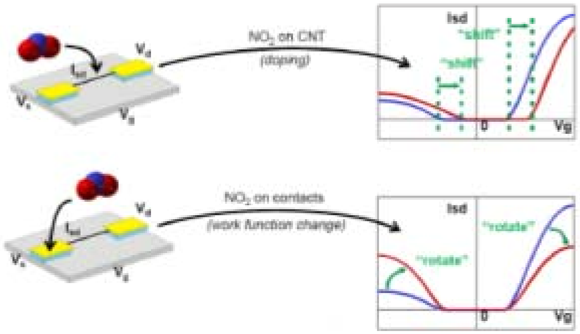
RF MEMS heterogeneous chip integration with Au-Au thermocompressive bumpless interconnections



T.-Y. Chao et al., IEEE Trans. on Electron Devices, v. 57 (2010)

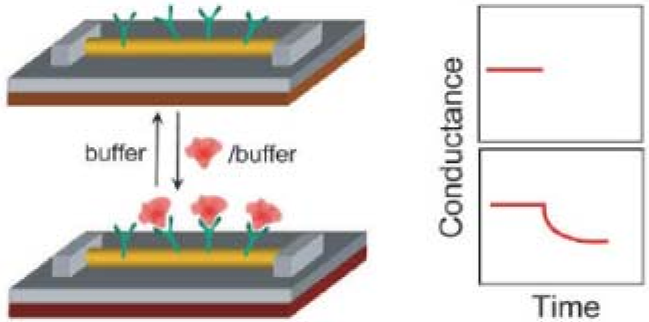
Nanotube Gas Sensors

o **Molecular detection:**
- Current and Vt modulation (SWCNT FET)



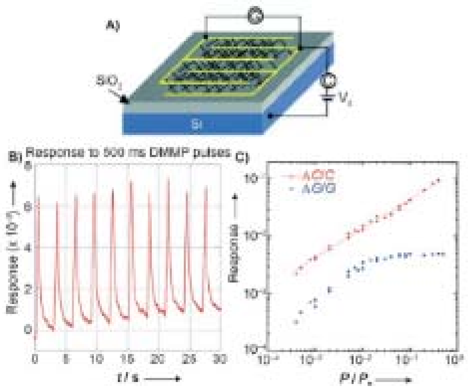
C. Hierold, ETH Zurich

o **Conductance sensing (Si nanowire)**



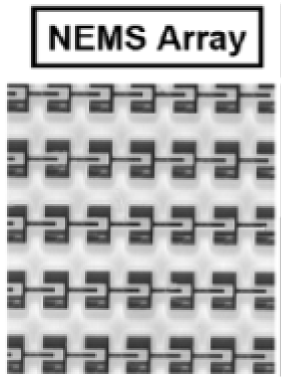
F. Patolsky, Materials Today 2005

o **Gas detection:**
- Capacitive & conductance sensing (capacitive CNT arrays)



I. Heller, Nano Lett 2008

o **Mass sensing (NEM resonator)**



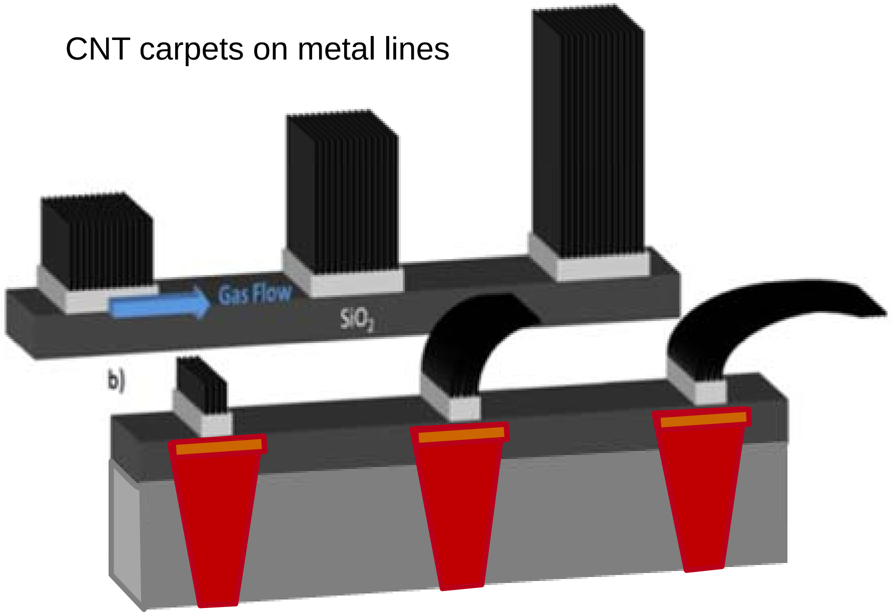
	Cal Tech (Zeptogram Microresonators)	Achievement 8/25/07
Chemisorbing Resonator	Mass Responsivity	5 Hz/ag
	Mass Resolution	~10^{-19} g (100 zg)
	Operating Pressure	1 atm (760 torr)
	Detector Response Time	< 20 ms
	No. of Sensor Elements	25,000
	Power Consumption	~100 mW
	Size	< 1 cm^3

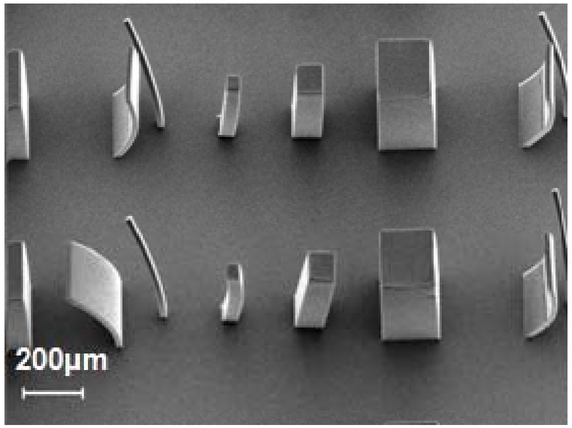
Y. T. Yang, Nano Lett 2006

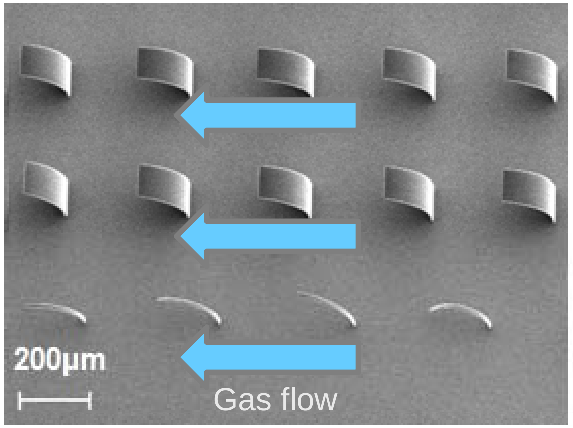
CNTS Arrays on TSV wafer

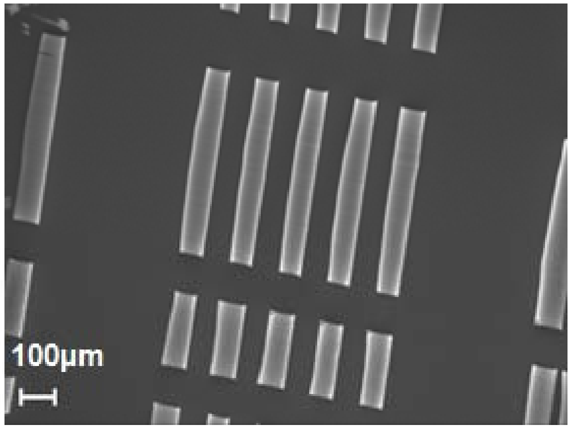
- Vertical and horizontal aligned CNTs during the same synthesis
- Horizontal alignment in the gas flow direction
- Similar density for vertical and horizontal CNT mats (1012 tubes/cm2)

CNT carpets on metal lines







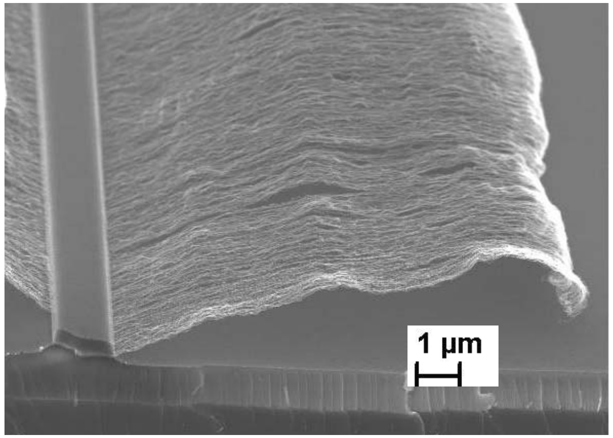


A. Arun EPFL PhD thesis, 2010

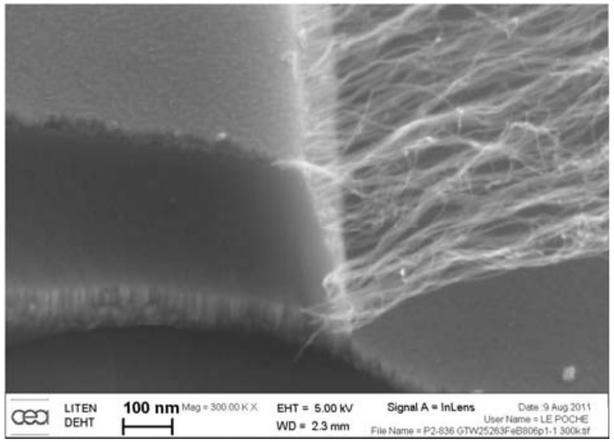
CNT Arrays for Gas Sensing

- **Horizontal and on-site growth of CNT arrays by CVD :**

- CNT growth initiated perpendicularly to catalyst surface

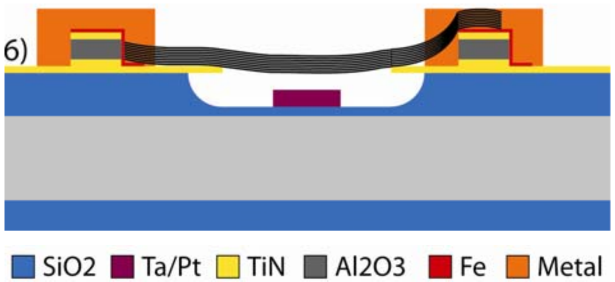


- Material selective CNT growth

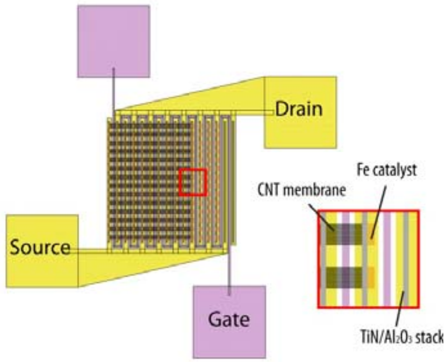


- **Selective gas detection through CNT functionalization and multiple readouts:**

- Resonance frequency, capacitance & conductance sensing (according to structures)



- Reliability and robustness

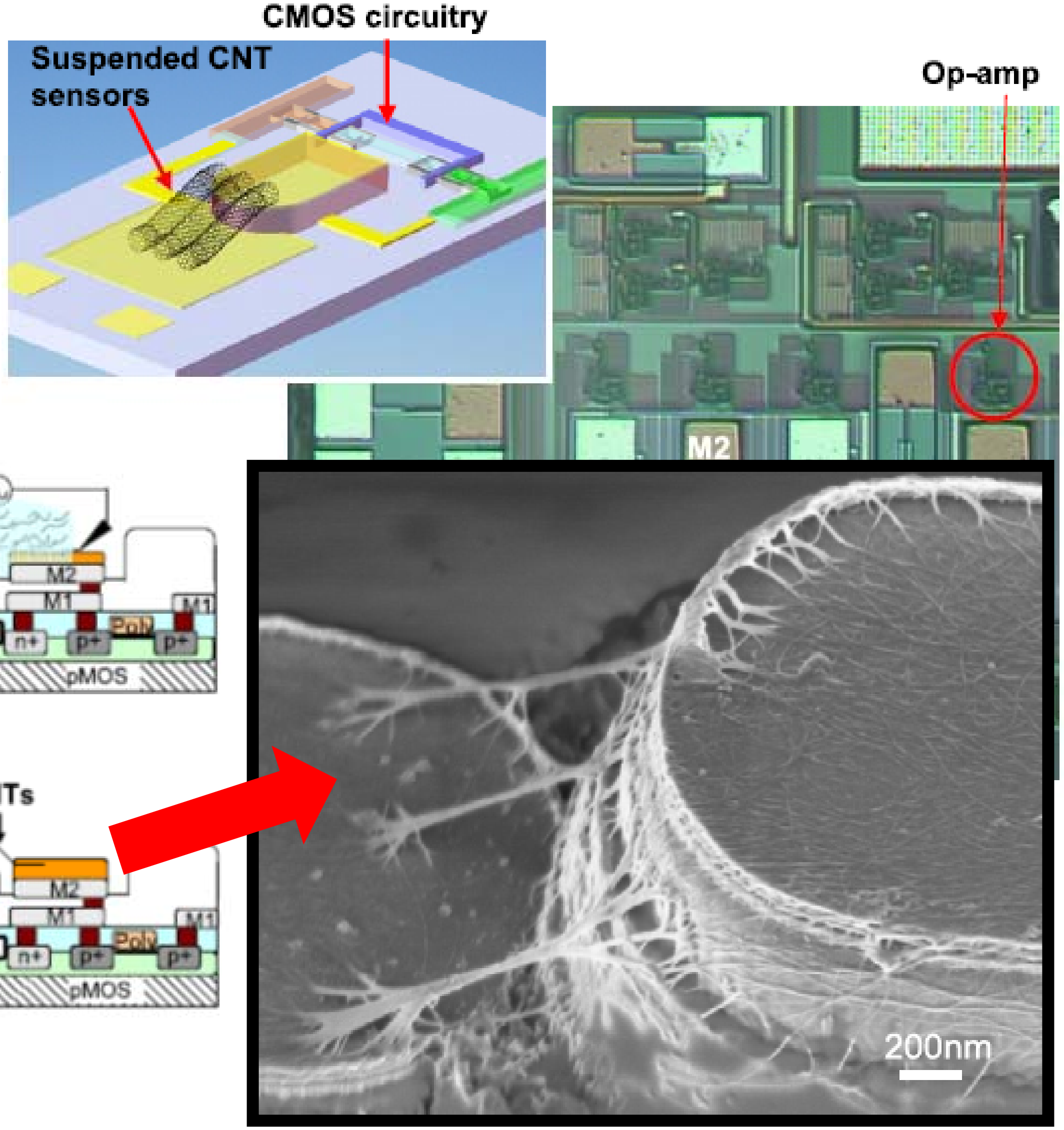


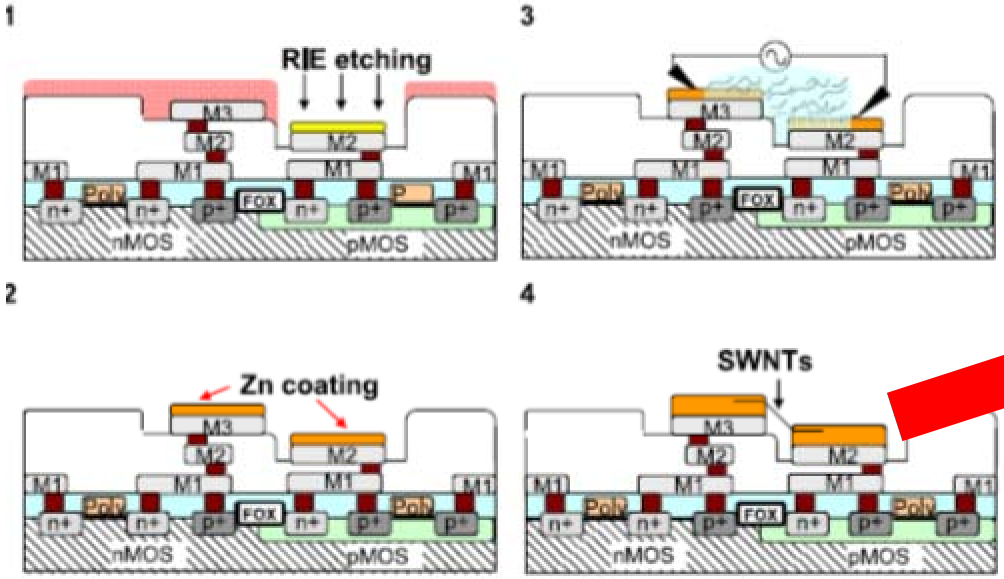
H.Guerin et al., 37th International Conference on Micro & Nano Engineering MNE 2011

SWNTs on CMOS

CNT integration for sensing applications

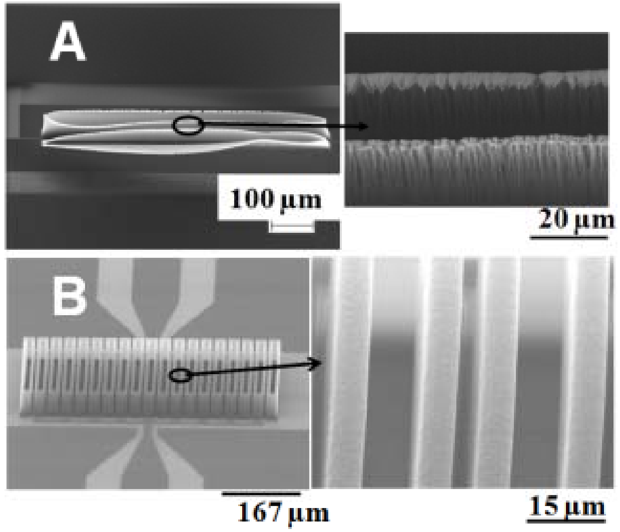
- Low voltage dielectrophoretic (DEP) assembly process

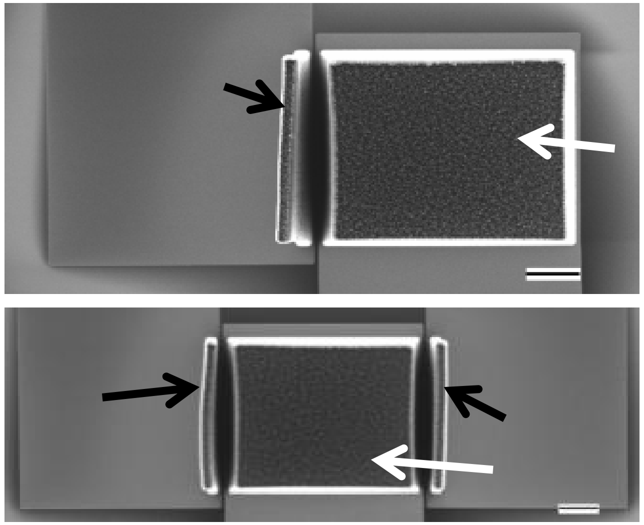


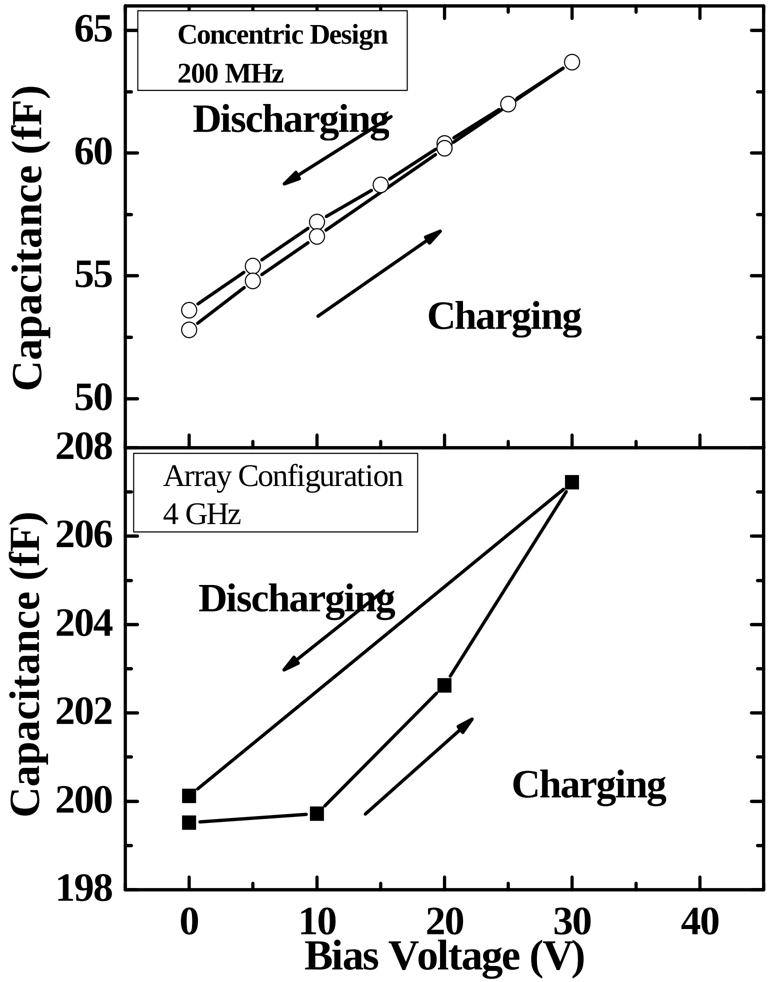


C.-L. Chen, Nanotechnology 2009

Capacitor: CNT on metal (TiN & Al)





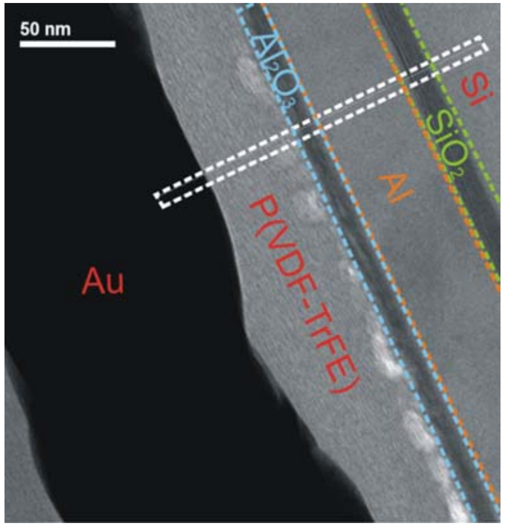


A. Arun EPFL PhD thesis, 2010

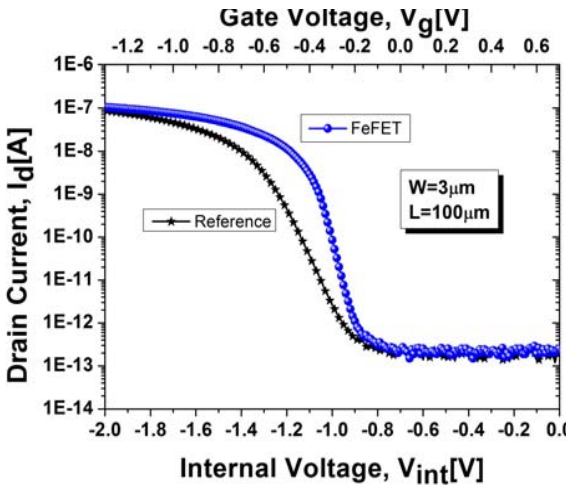
Negative Capacitance MOSFET

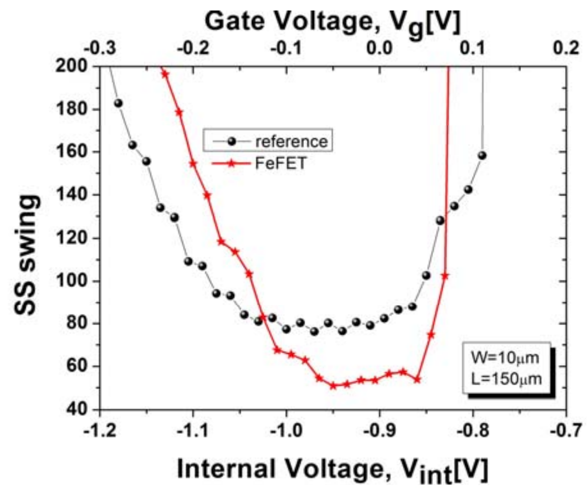
Novel Ferroelectric Transistor

- Internal voltage amplification due to negative capacitance in Fe-FETs
- Experimental demonstration of the subthreshold swing below 60mV/dec



TEM picture of the gate stack



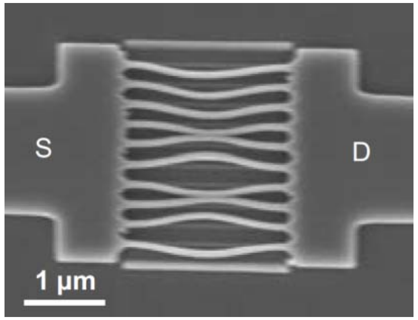


A. Rusu, G.A. Salvatore, D. Jiménez, A.M. Ionescu, Metal-Ferroelectric-Metal-Oxide-Semiconductor Field Effect Transistor with Sub-60mV/decade Subthreshold Swing and Internal Voltage Amplification, IEDM 2010, San Francisco, December 2010

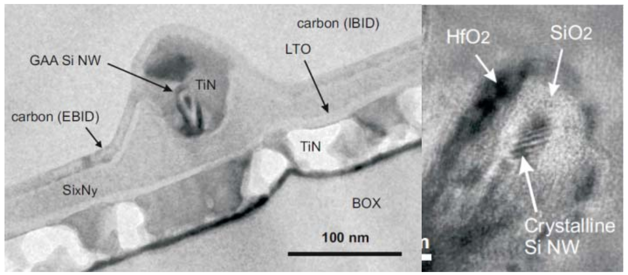
Strained NWs as CMOS boosters

Suspended Si nanowires for innovative stress-based nanoelectronic applications

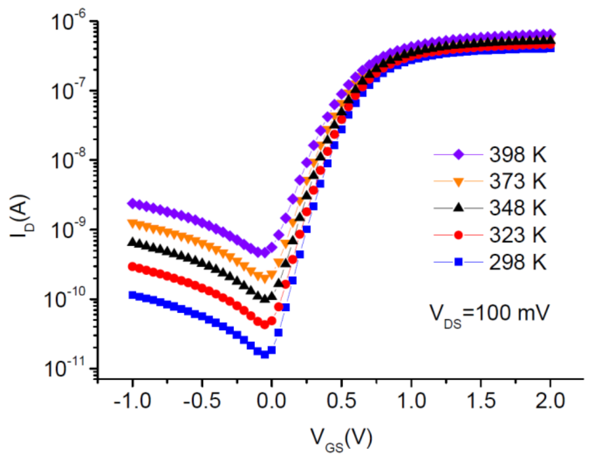
- Elastic local buckling as CMOS booster: **1.2-5.6 GPa** on a single wafer
- Deeply scaled Si nanowire MOSFETs by stress-limited oxidation (**~4 nm cross-section**)
- ALD high-k/metal-gate stack: strain engineering and EOT scaling



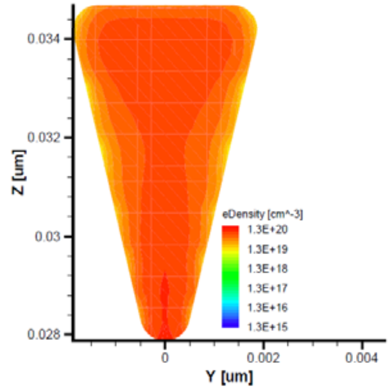
Ultra-strained array of GAA Si NWs (~5.6 GPa),
M. Najmzadeh, IEEE ISDRS 2011, Maryland, USA.

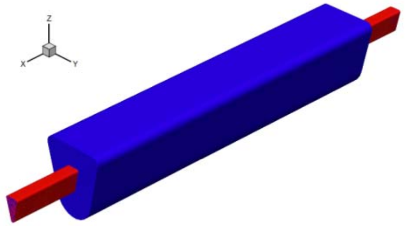


GAA deeply scaled Si NW MOSFET with ALD
high-k/metal-gate stack (W~4 nm),
M. Najmzadeh, IEEE ESSDERC 2011, Helsinki, Fi.



GAA Si nanowires as high temperature
performance MOSFETs,
M. Najmzadeh, IEEE DRC 2011, CA, USA.

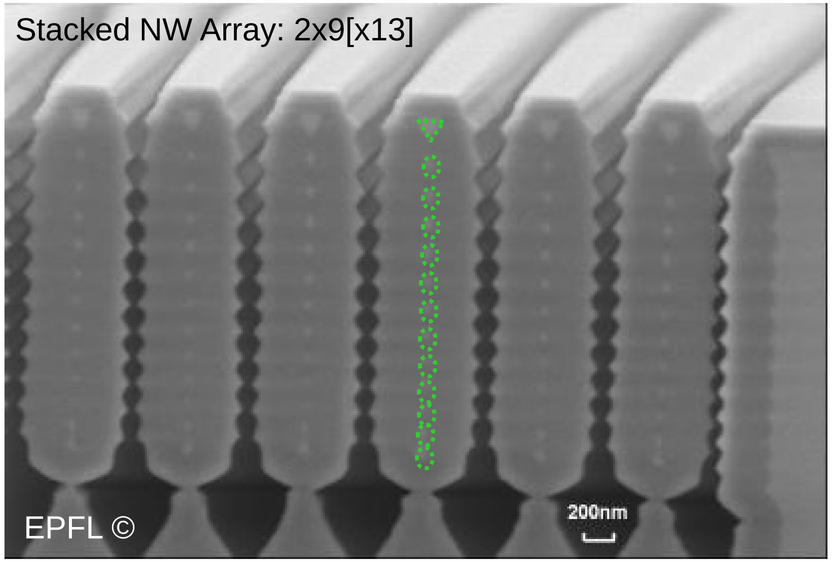


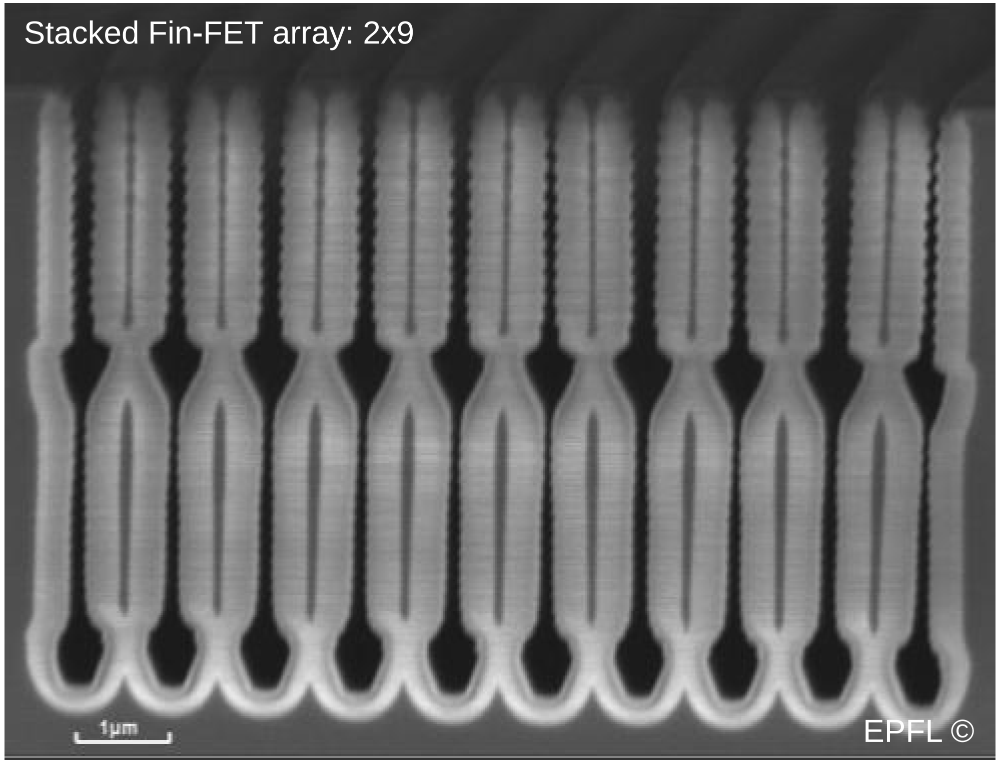


3D TCAD Sentaurus simulation of
GAA NWs for transport analysis,
M. Najmzadeh, SSE 2012.

3D Si nanowires sensors

- New concept in e-BRAINS: stacks-of-stacks
- 3D stacking of SiNWs in etched (microfluidic) cavity

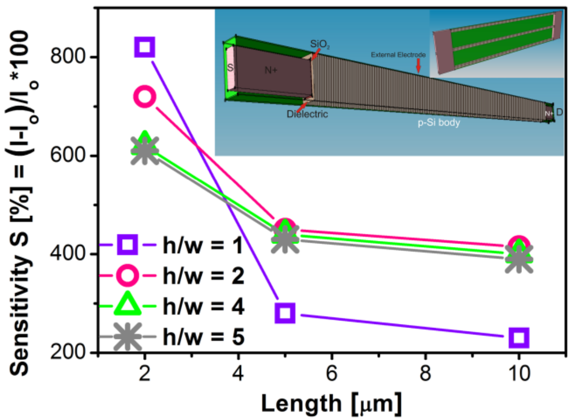


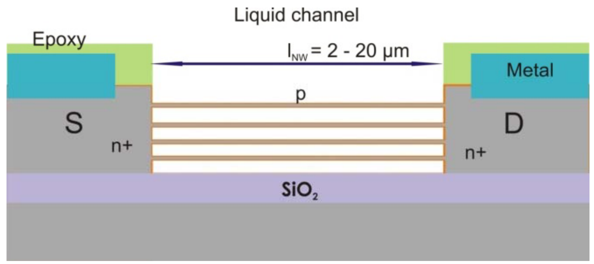


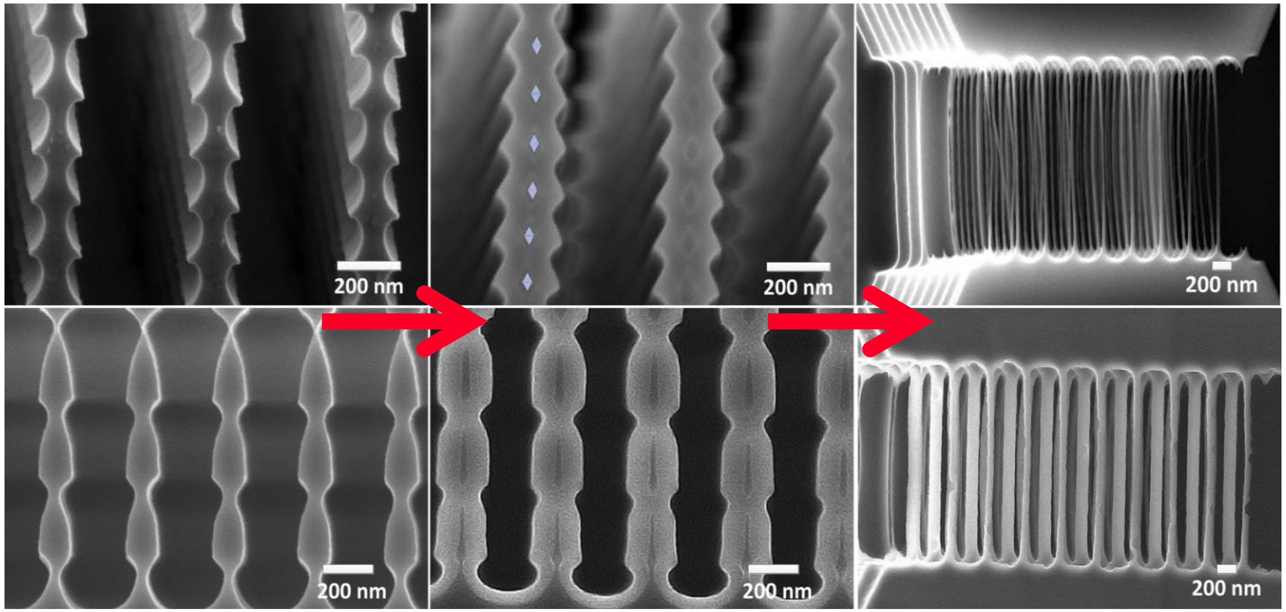
M. Bopp. EPFL PhD thesis, 2010.

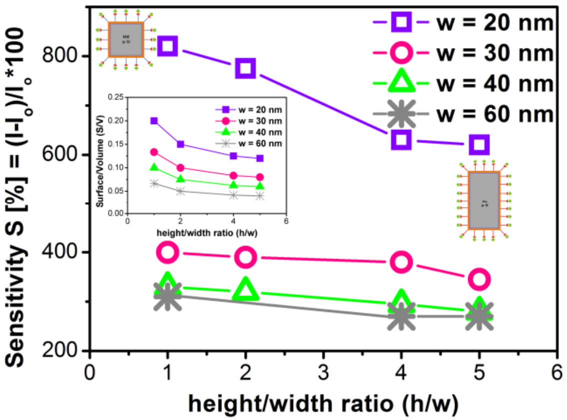
Si Nanostructures as Biosensor

- **Vertically Stacked Si Nanostructures**





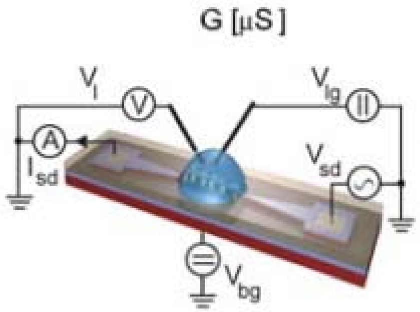


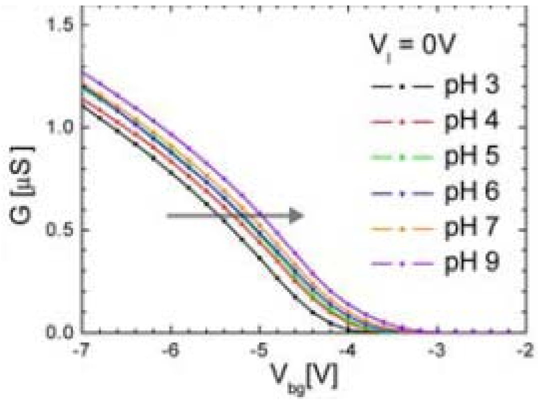


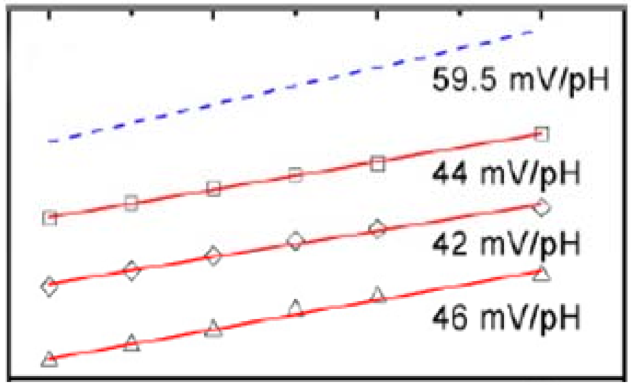
E.Buitrago et al., 37th International Conference on Micro & Nano Engineering, MNE 2011

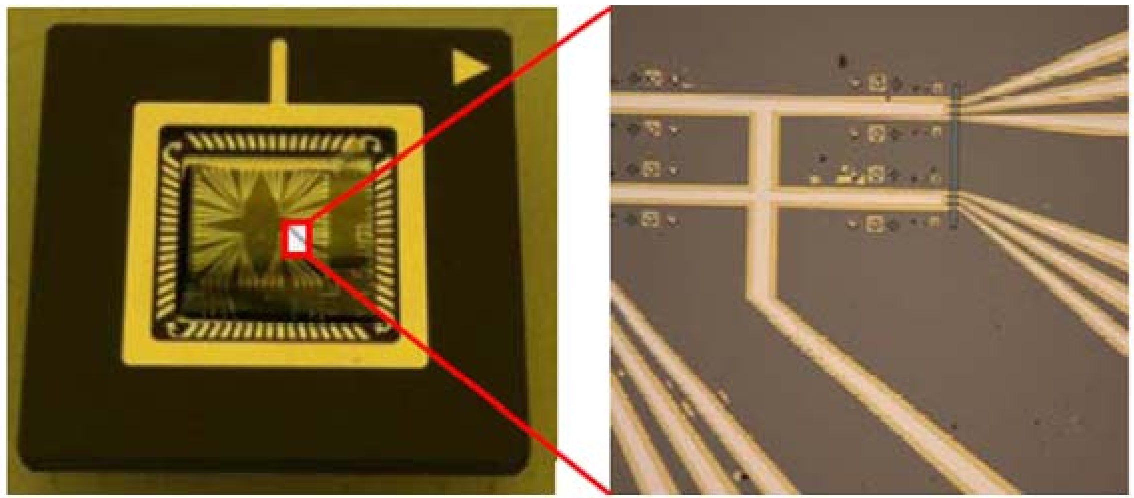
Si Nanowire Bio-Sensors

Nanotera Project on Silicon Nanowires Bio-sensors









O. Knopfmacher, Nano Letters 10, 2268 (2010)
S. Rigante, L. Lattanzio and A. M. Ionescu, FinFET for High Sensitivity Ion and Biological Sensing Applications, Microelectronics Eng (2011)

3D Opto-electronic Integration

Requirements:

High performance variable real-time signal processing

Functionalities:

Sensing moving speed:

integration of image sensor, MEMS accelerometer and RF IC

Computing:

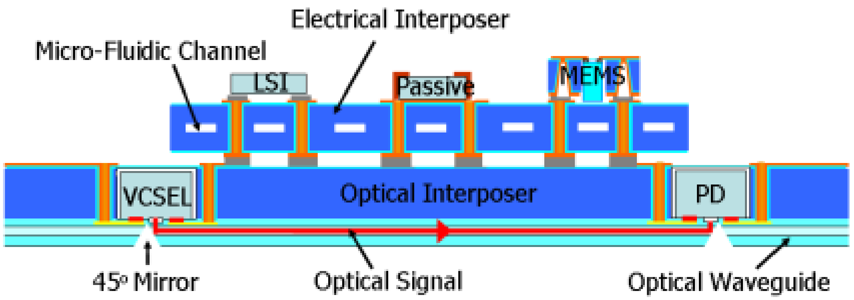
3D Memory and 3D processor

High speed information networking

Optical interconnects:

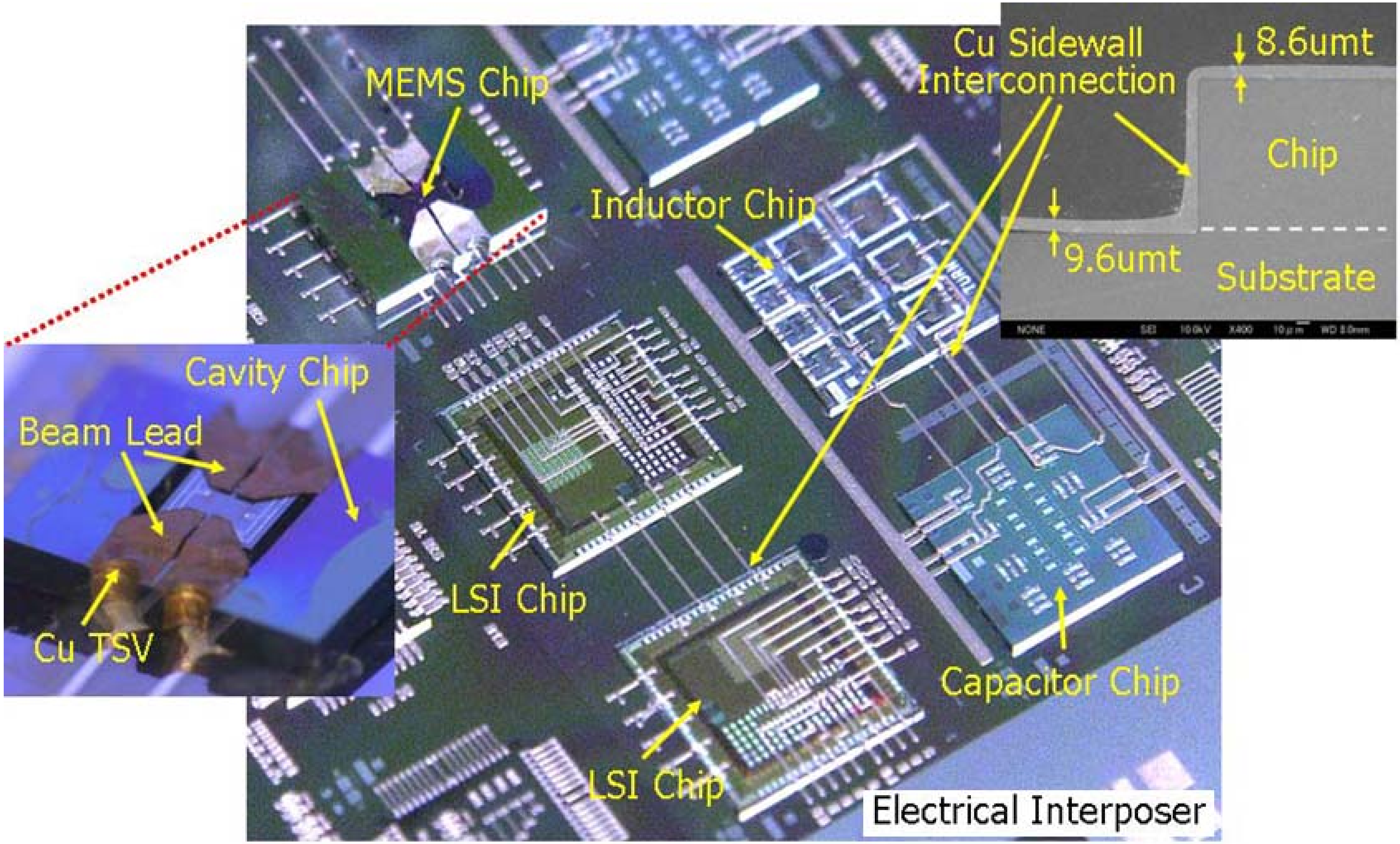
Photodiode and surface emitting laser (VCSEL)

Heat sinking from power consumption VLSI: Micro-fluidic channels



K.-W. Lee, IEDM 2009

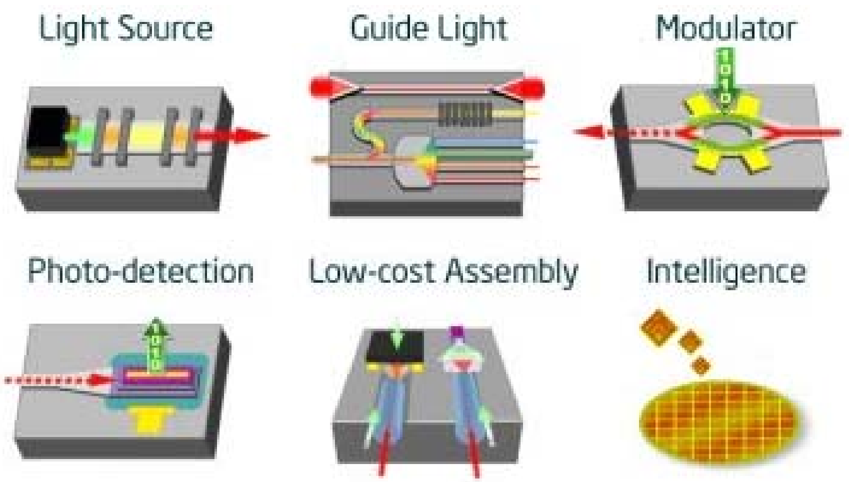
3D Opto-electronic Integration



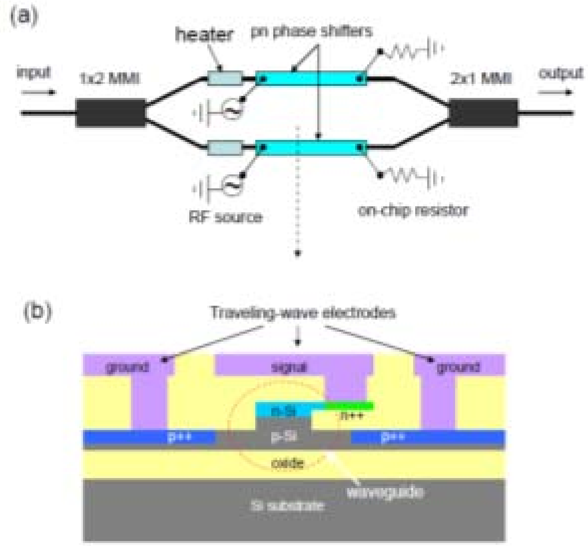
K.-W. Lee, IEDM 2009

Photonic Integration

«Siliconize» Photonics

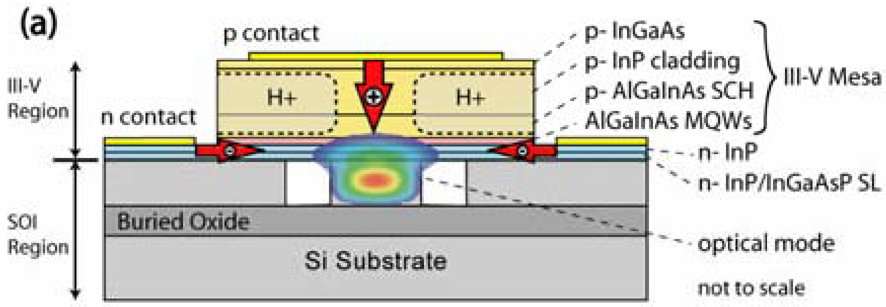


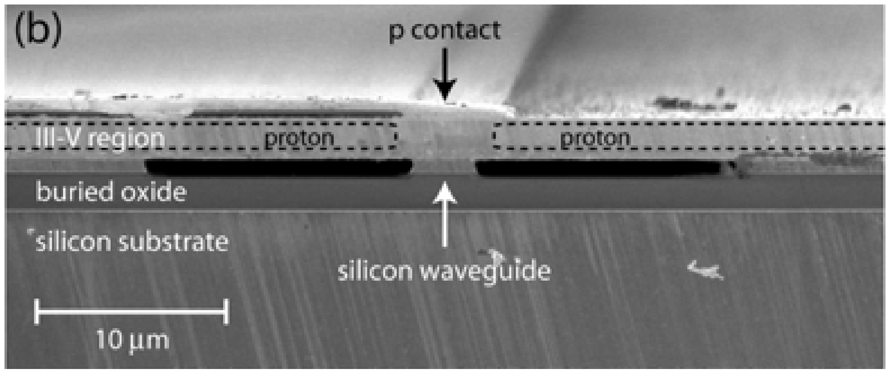
Optical Silicon Modulator



A. Liu, MPW/APMP 2008

Silicon Evanescent Laser



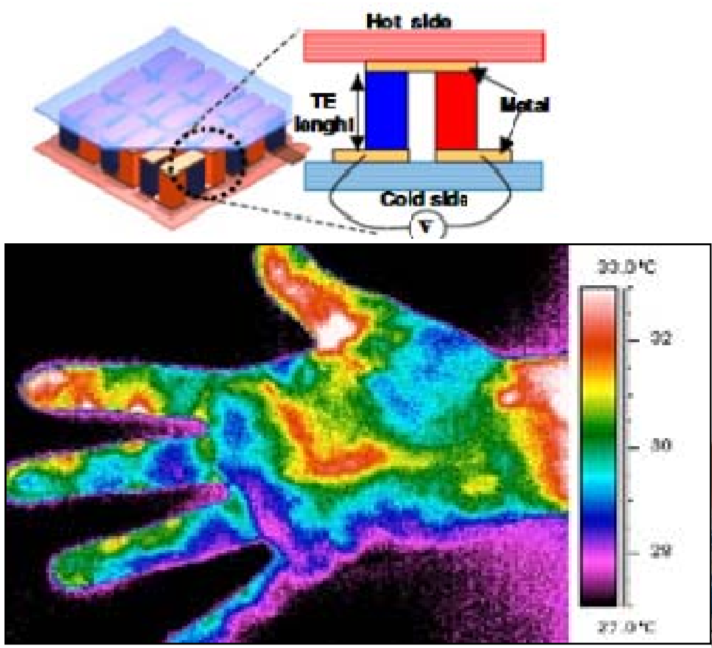


J. E. Bowers, CLEO 2007

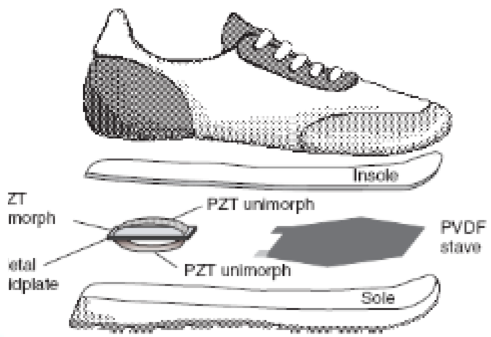
3D Scavengers

Autonomous micro-generators are in demand for a wide range of electronic system applications that harvest energy from the environment require to be located close to the source, examples:

- Walking (piezoelectric)
- Body Heat Miniaturized
- Thermoelectric Devices



J. P. Carmo, POWERENG 2009



N. S. Shenck, IEEE Micro 2001

Conclusions

The future of Nanoelectronics could be foreseen as a combination technology and design in More than Moore with the heterogeneous integration of a large variety of technologies, and their exploitation in System-On-Chip, System-In-Package or System on System, mearging various discrete subsystems using different optimized maufacturing process

Open questions:

- What are the requirements from Smart Systems to 3D?
- What advanced packaging technologies? Cost?
- What are the advantages of RF MEMS and what functionalities and performance by their heterogeneous integration with CMOS?
- Similar question for 3D optics and sensors.
- Is heterogeneous integration the enabler of life after CMOS?

Thank you for your attention!

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