2011.10.5

MEMS-CMOS Integration and Beyond

Hiroyuki Fujita, Agnes-Tixier Mita, Hiroshi Toshiyoshi

Center for International Research on Micronano Mechatronics

IIS, The University of Tokyo

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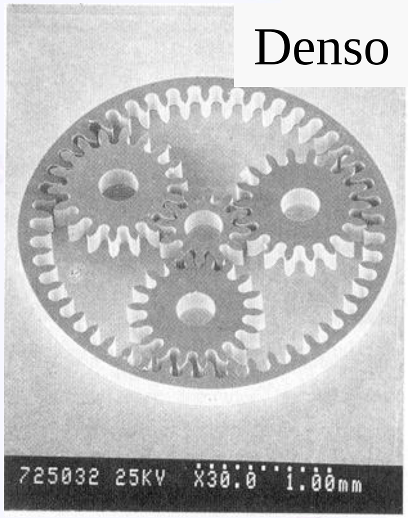
Content

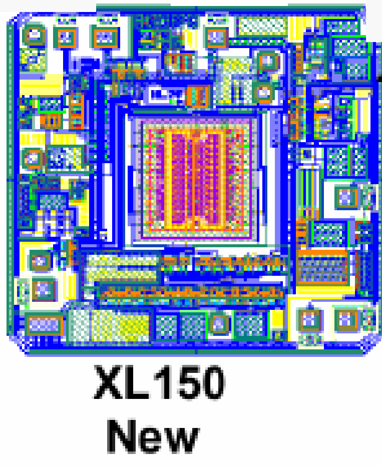
- MEMS trend toward MEMS-CMOS integration
- Examples of MEMS-CMOS integration
- Beyond MEMS-CMOS integration

Examples of MEMS devices

Denso

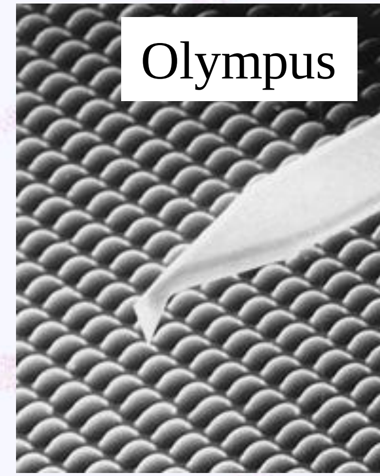


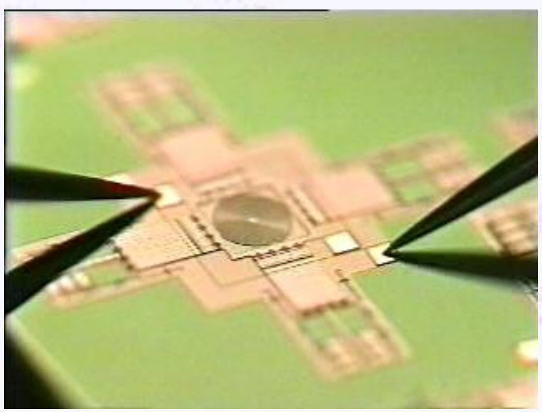
AD



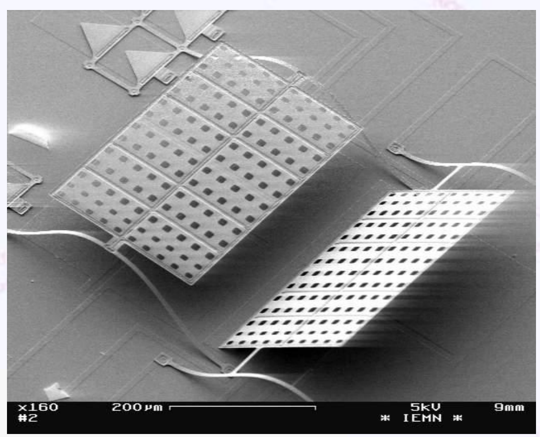
U-Tokyo

Olympus

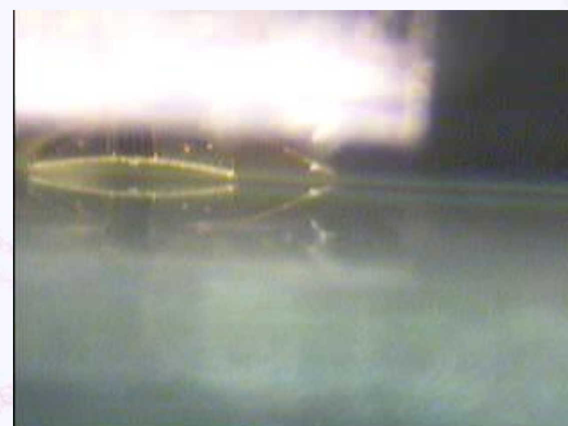




UC Berkeley



IEMN/CNRS



Northeastern Univ.

MEMS Development in Last Decade

- Almost all the important processes and devices in micro-scale already existed 10 years ago, e.g. DRIE, bonding, microactuators, etc.

↓

- **Technological sophistication**,
- **Application diversity** increase
- **Performance** improvement.
- **Commercial products** have flourished.

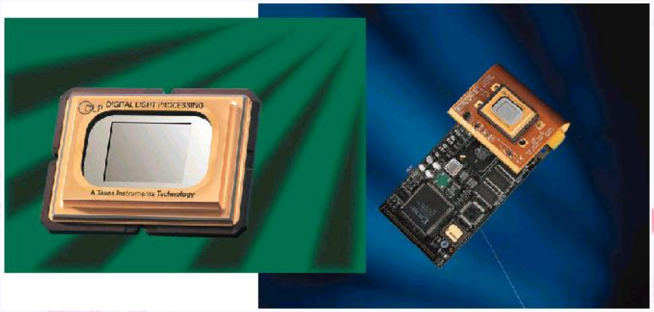
Now MEMS is everywhere around you, and even more in the future.

- In your car
- In your camera
- In your smart phone
- In your TV game controller
- In your video projector
- In your printer
- In your computer
- In your (?) robot

Nitendo Wii™ controller

Apple
i-Phone

Honda Asimo



Digital Light Processing™
Texas Instrument

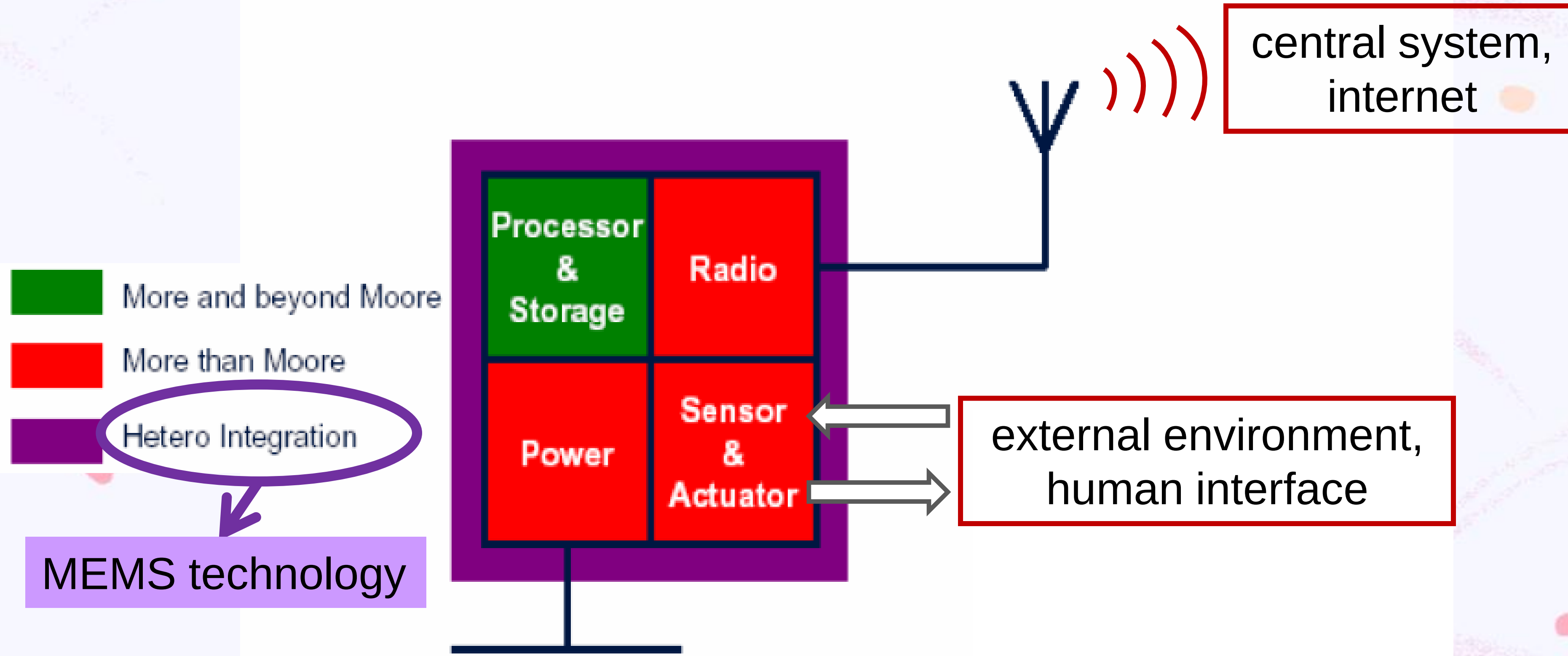
What comes next ?

- Almost all the important processes and devices in micro-scale already existed 10 years ago, e.g. DRIE, bonding, comb-drive, SDA, etc.

- **Technological sophistication**,
- **Application diversity** increase
- **Performance** improvement.
- **Commercial products** have flourished.

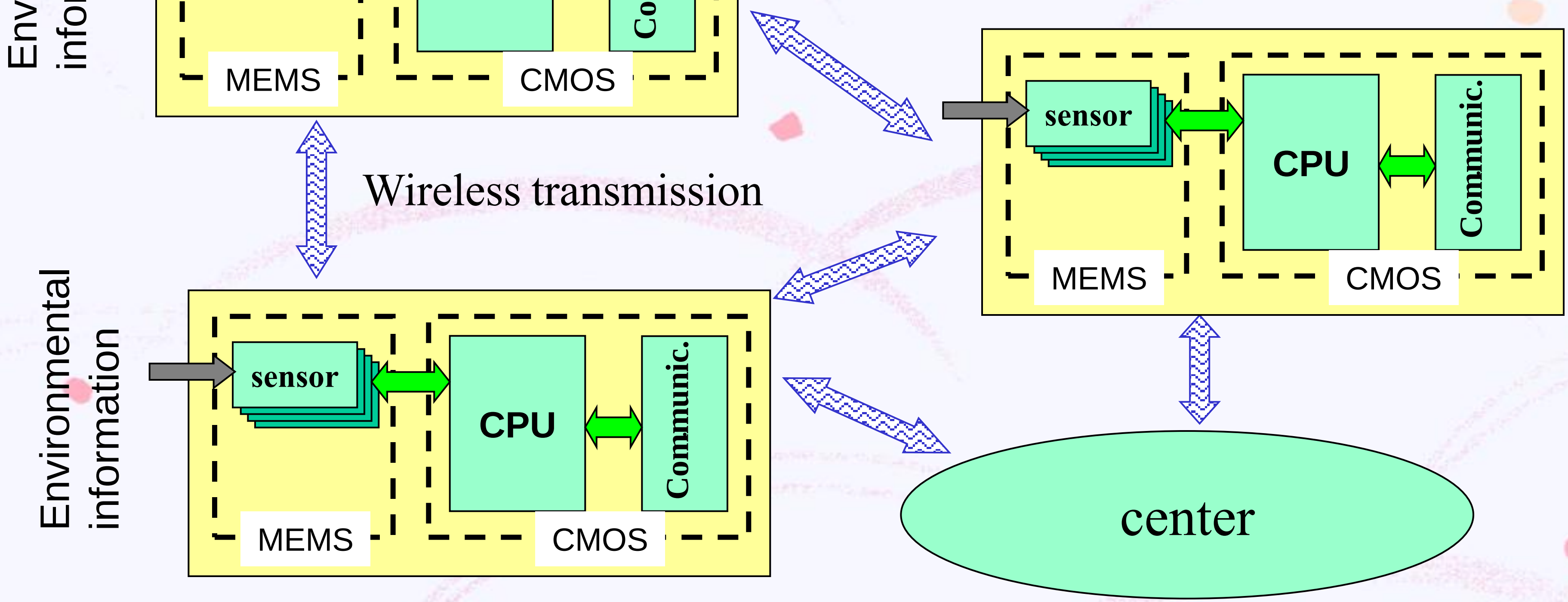
- In order to widen the application fields, heterogeneous integration of various functionalities becomes important. (More than Moore approach) niac

Intelligent systems incorporate 'More Moore' and 'More than Moore'

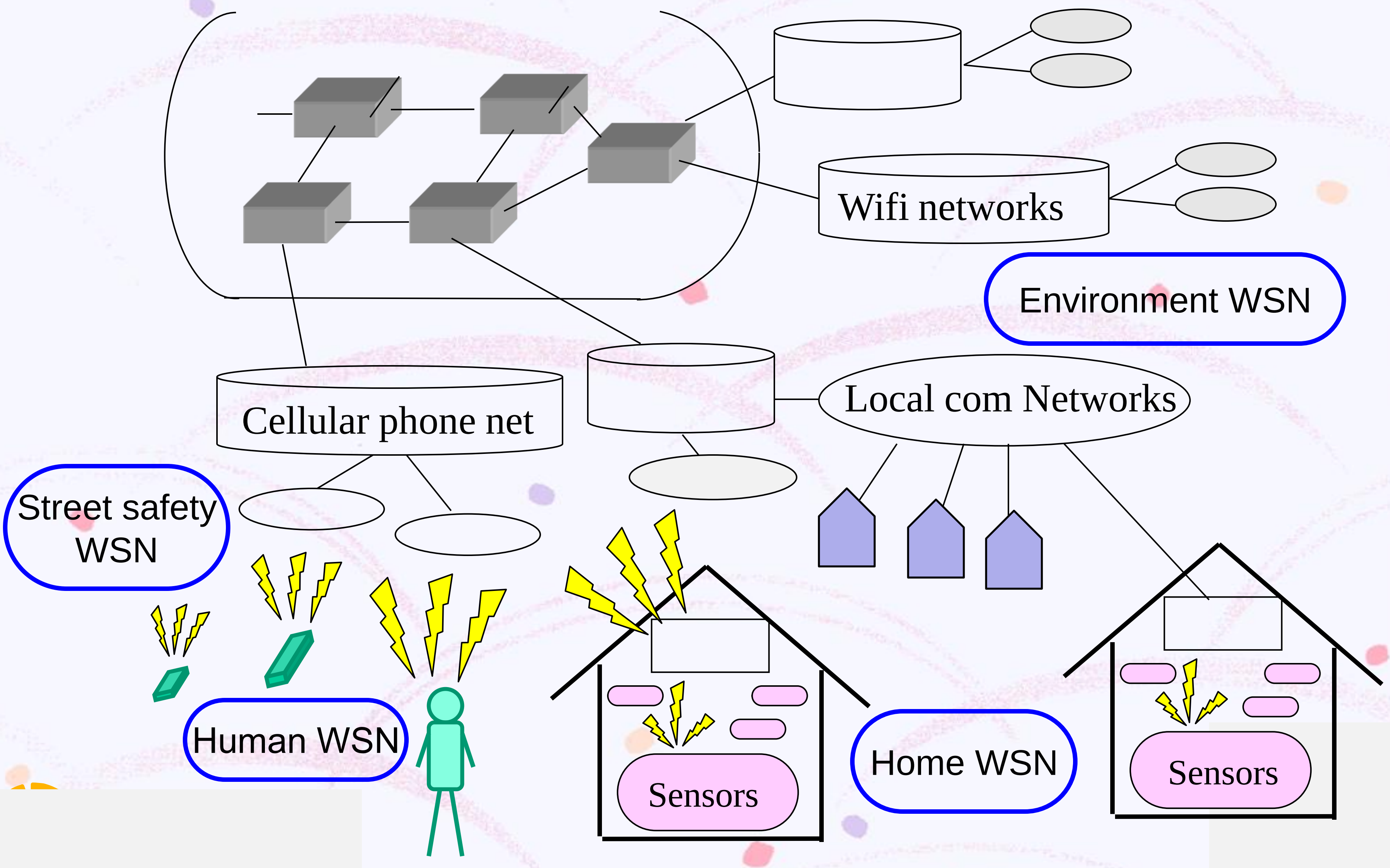


More than Moore, 2005/09/16

Micro wireless sensor network



MEMS wireless senor net(WSN) in communication hierarchy



Content

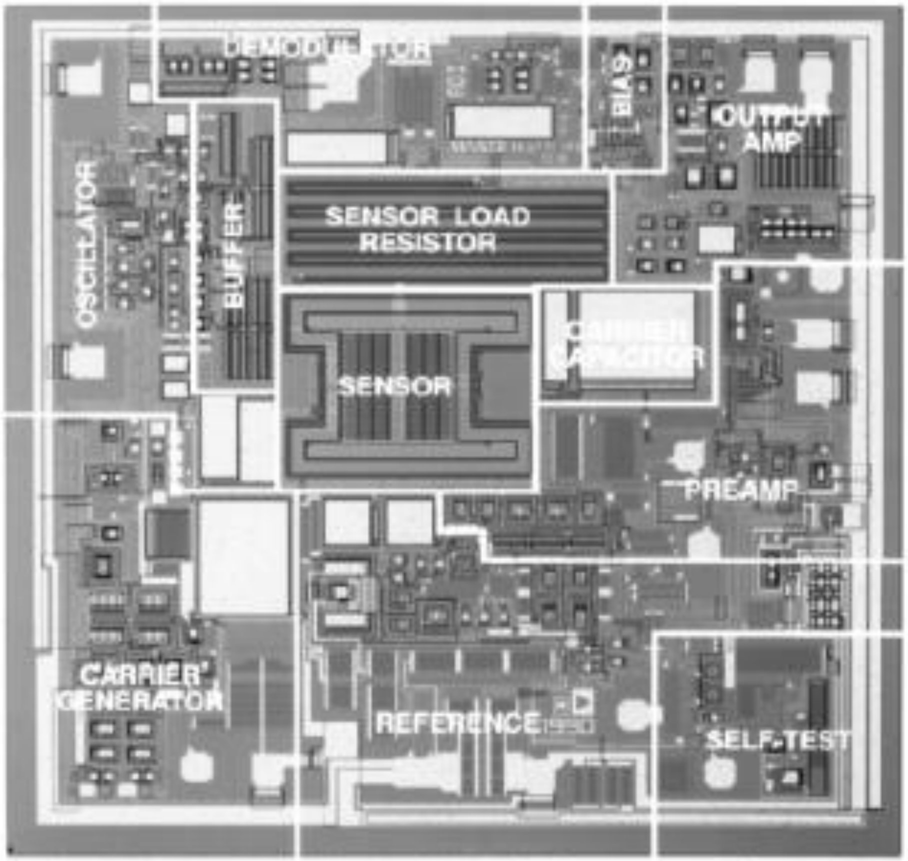
- MEMS trend toward MEMS-CMOS integration
- Examples of MEMS-CMOS integration
- Beyond MEMS-CMOS integration

MEMS-CMOS integration methods

- **Hybrid integration**, especially stack integration using TSV
- Monolithic integration by customized **fully mixed process**
- Monolithic integration by **MEMS processing first** followed by CMOS process
- Monolithic integration by **CMOS processing first** followed by MEMS process

CMOS-MEMS by surface micromachining

ADXL-50 Chip Diagram



Analog Devices' ADXL-50, the industry's first surface micromachined accelerometer, includes signal conditioning on chip.

- **Fully mixed fabrication** process.
- Poly-Si structure + SiO_2 sacrificial layer.
- Protection of circuits while releasing process is important.

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MEMS-CMOS integration methods

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- Monolithic integration by customized fully mixed process
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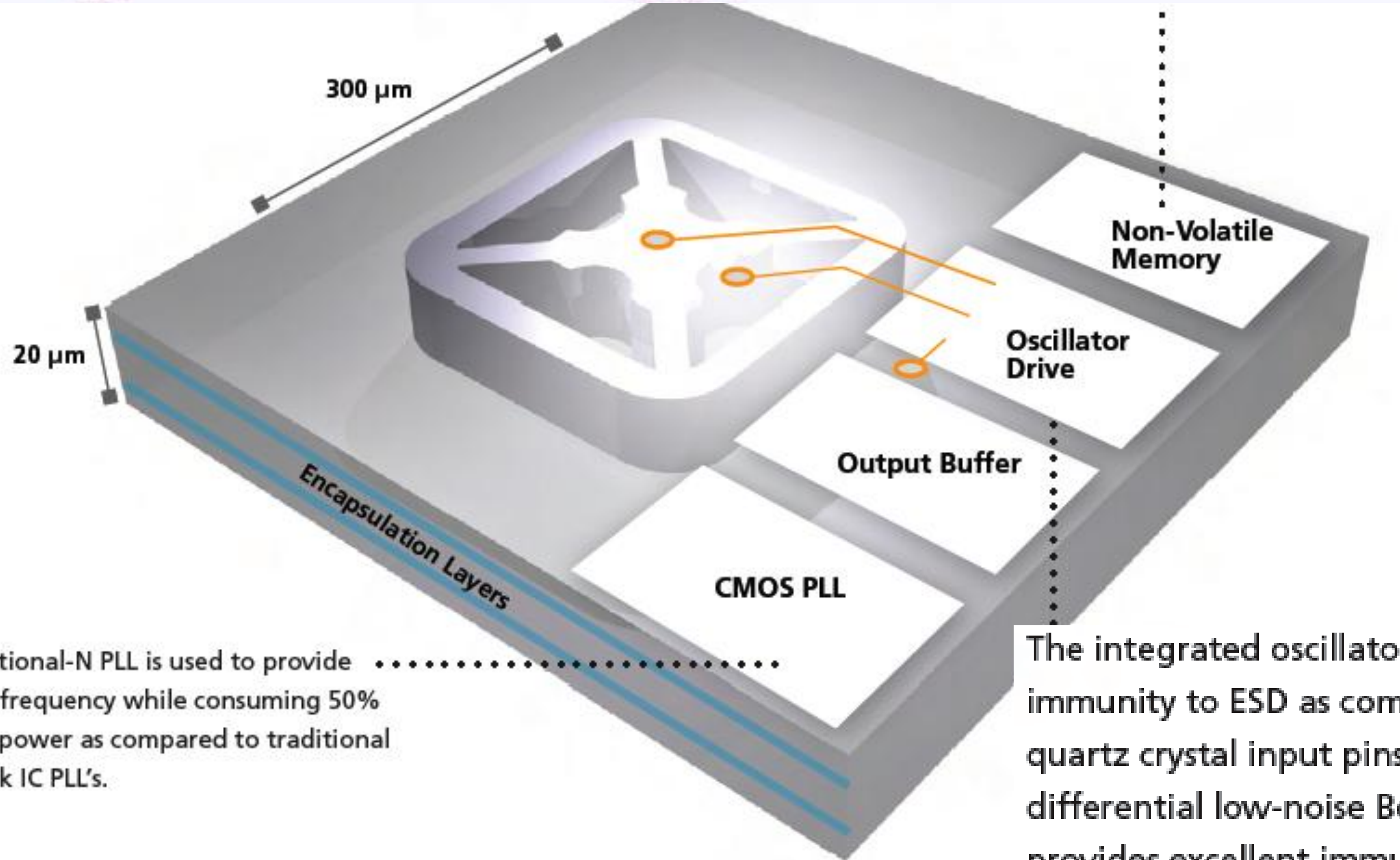
- Monolithic integration by CMOS processing first followed by MEMS process

SiTime MEMS resonator

M E M S -first approach for CMOS circuit integration

Non-Volatile memory enables rapid configuration of the SiT8002 family to instantly match the form, fit, and function of 100's of fixed frequency oscillators. In addition, the memory never wears out and requires no additional CMOS mask layers, keeping costs low.



Fractional-N PLL is used to provide any frequency while consuming 50% less power as compared to traditional Clock IC PLL's.

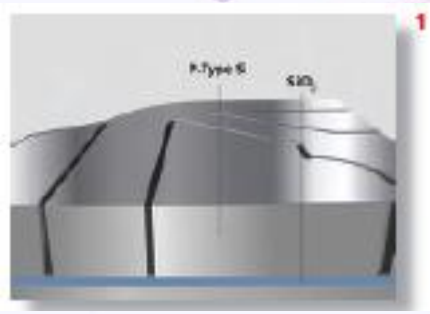
The integrated oscillator provides better immunity to ESD as compared to many quartz crystal input pins. In addition, the differential low-noise Boser Oscillator provides excellent immunity to electrical interference as compared to single-ended quartz devices.

http://www.sitime.jp/

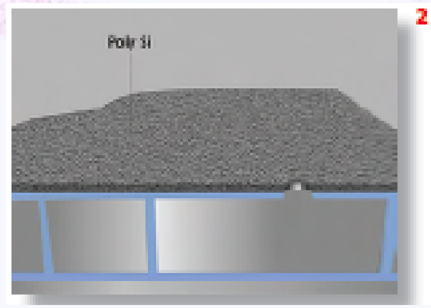
SiTime™

SiTime MEMS resonator

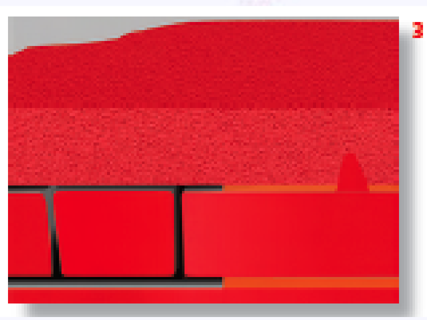
MEMS-first approach for CMOS circuit integration



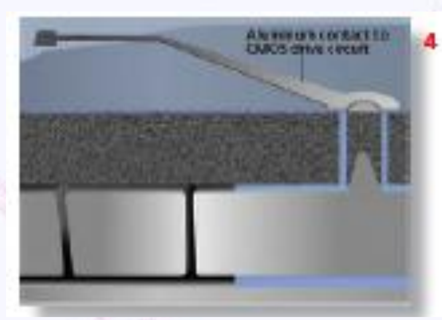
DRIE of SOI defining resonator (0.4um wide, 10um deep). Trenches filled by SiO2



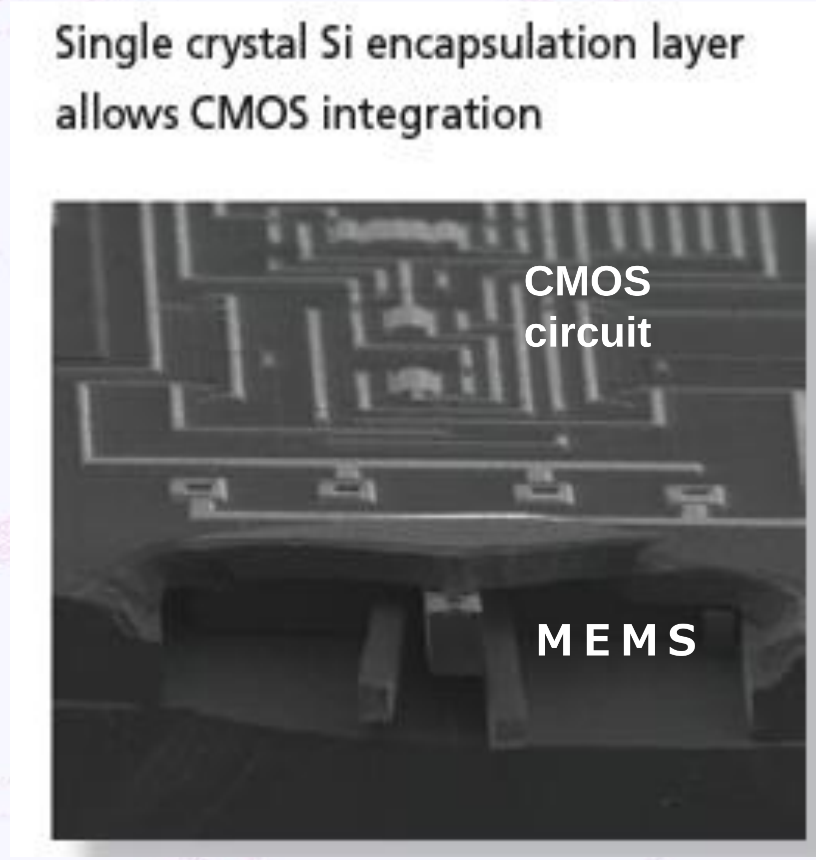
Thin epi-poly growth. Contacts and etch holes formation.



After sacrificial etching of SiO2, thick epi-poly growth.



Surface polishing and cleaning for next CMOS process. Contact isolation by DRIE



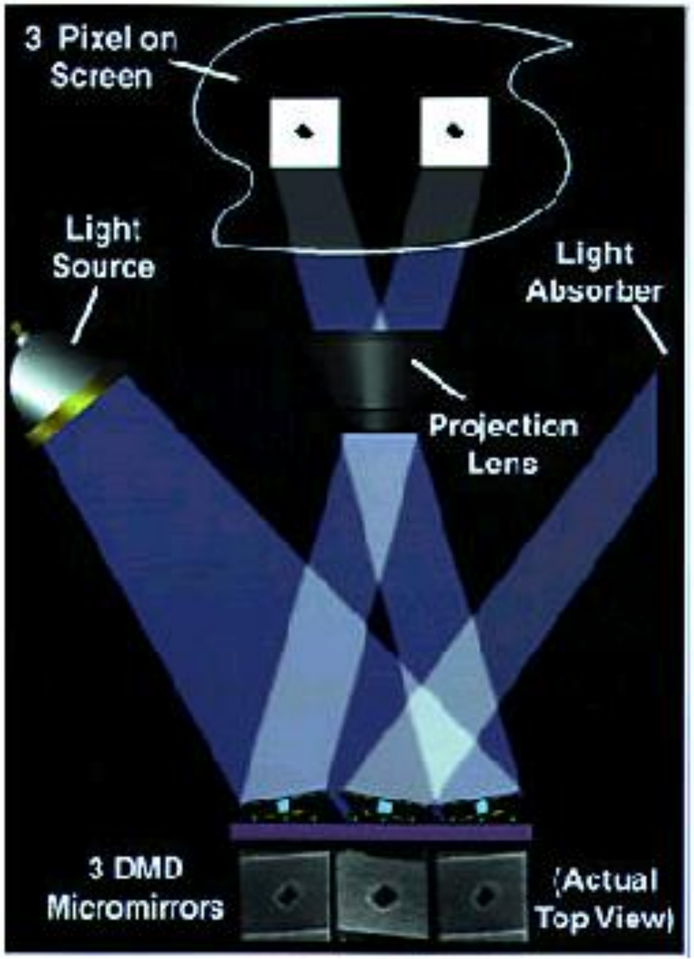
SiTime

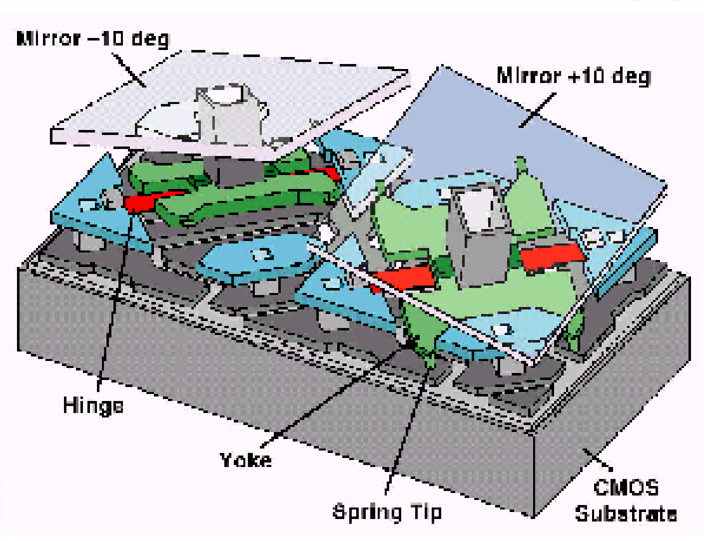
MEMS-CMOS integration methods

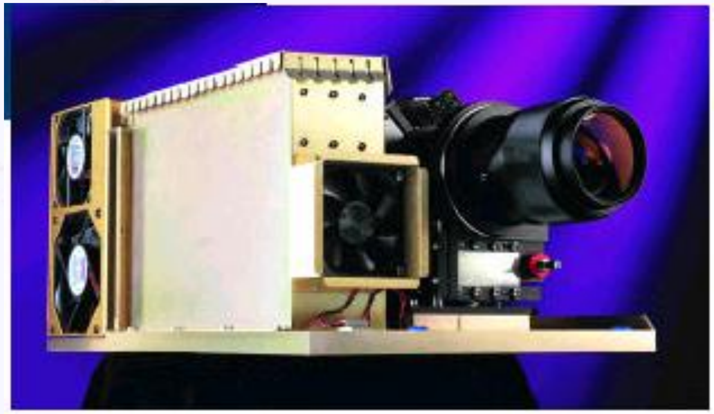
- Hybrid integration, especially stack integration using TSV
- Monolithic integration by customized fully mixed process
- Monolithic integration by MEMS processing first followed by CMOS process
- Monolithic integration by CMOS processing first followed by MEMS process

DIGITAL MIRROR DISPLAY (1)

P.F. Van Kessel et al., T.I., Proc. IEEE, Vol. 86, p 1687, 1998





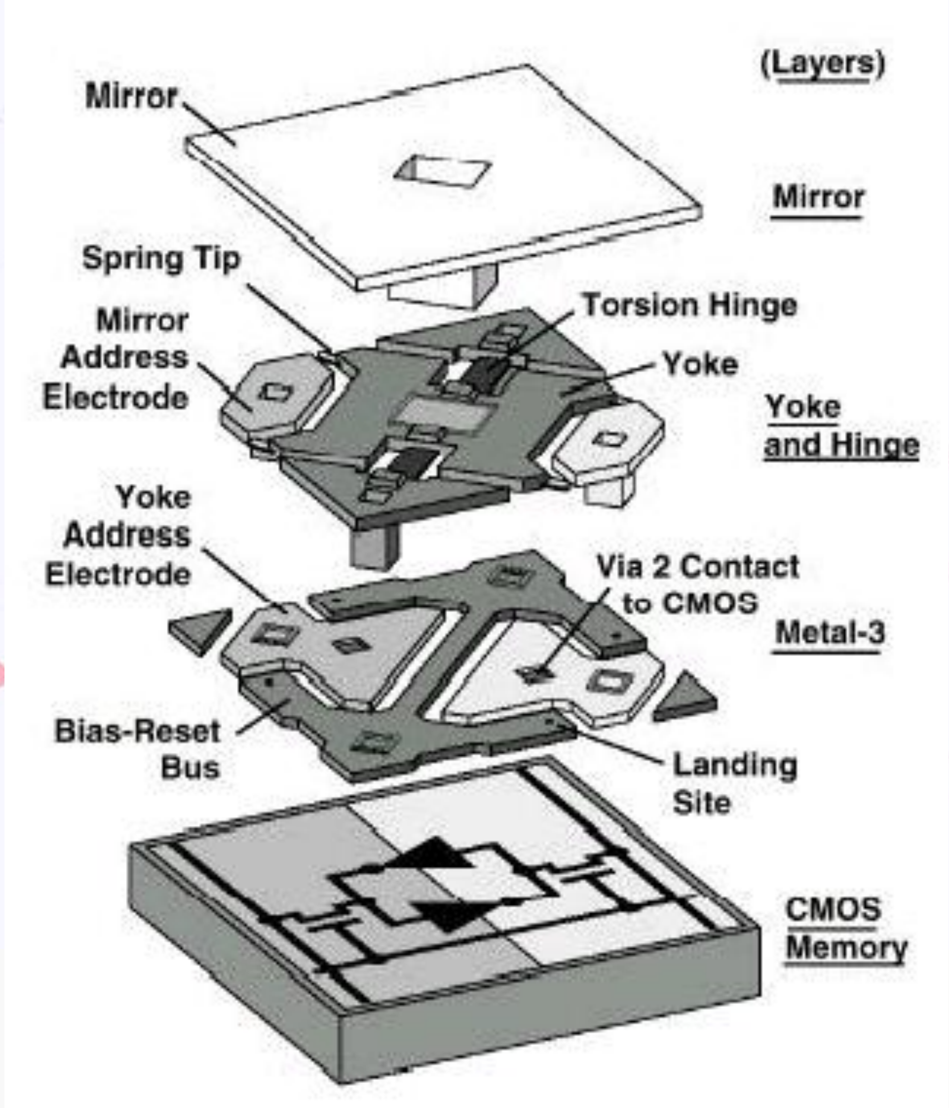


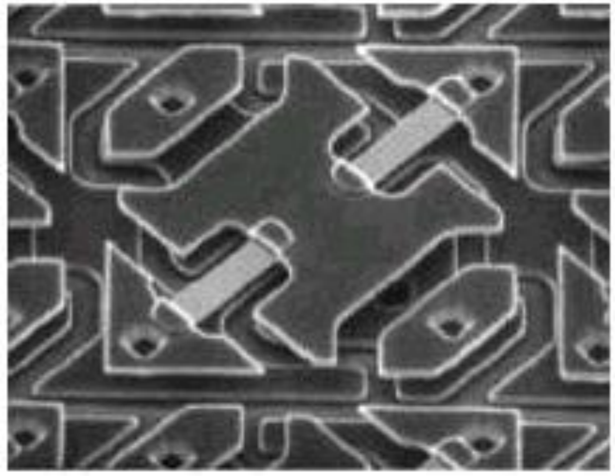
DIGITAL MIRROR DISPLAY (video)

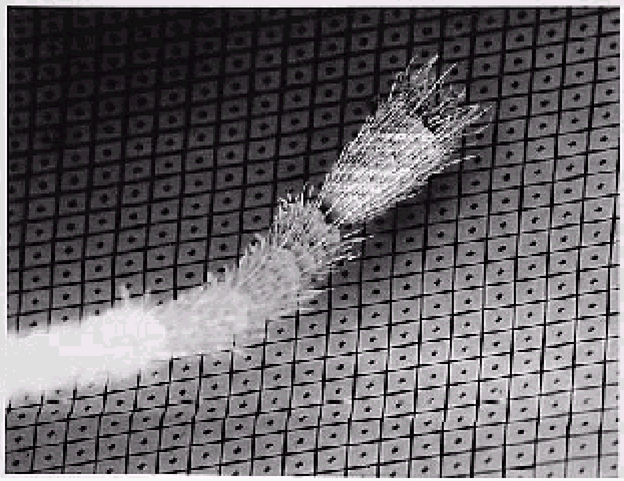
P.F. Van Kessel et al., T.I., Proc. IEEE, Vol. 86, p 1687, 1998

DIGITAL MIRROR DISPLAY (2)

P.F. Van Kessel et al., T.I., Proc. IEEE, Vol. 86, p 1687, 1998







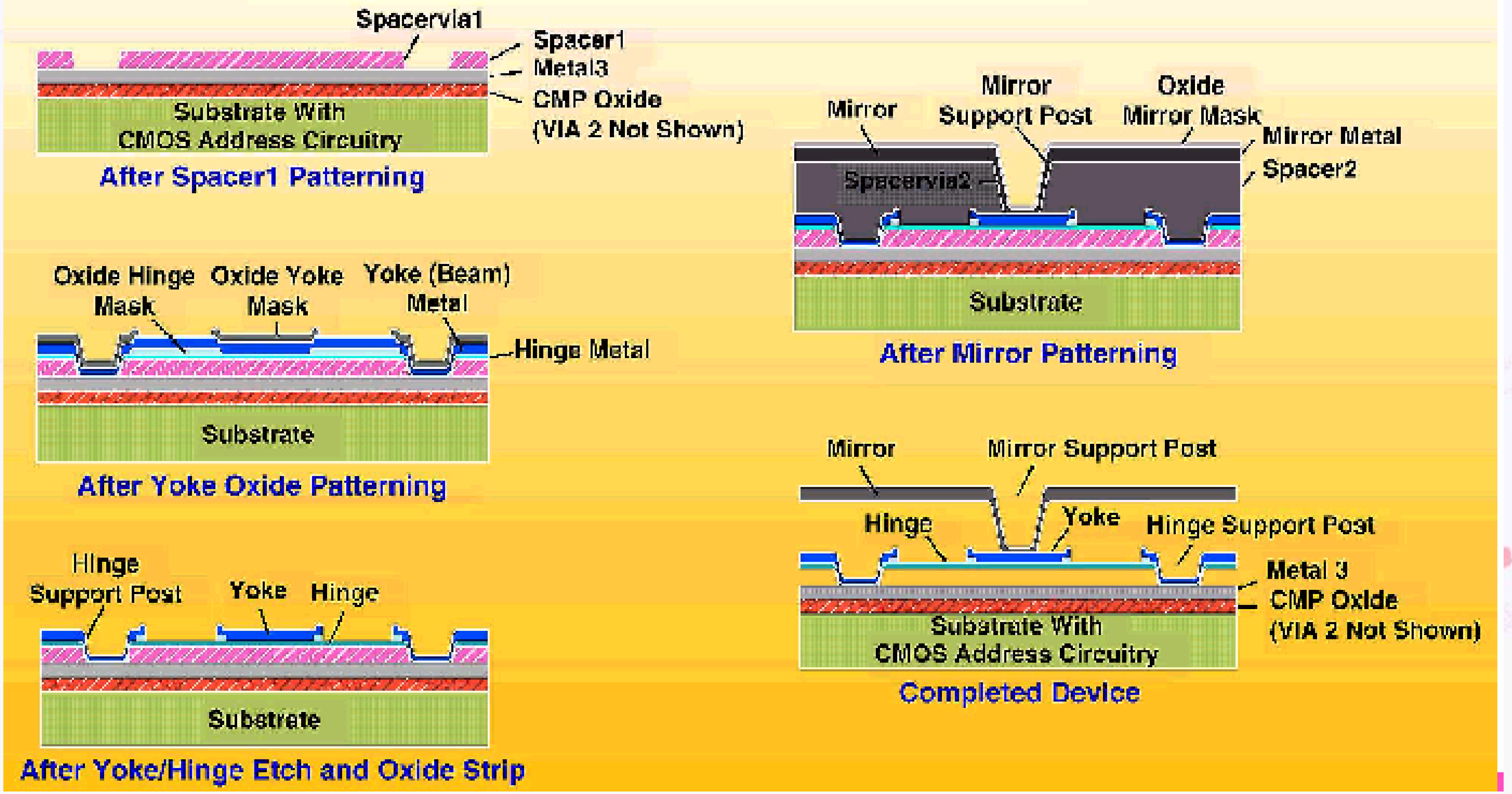
DIGITAL MIRROR DISPLAY (3)

P.F. Van Kessel et al., T.I., Proc. IEEE, Vol. 86, p 1687, 1998

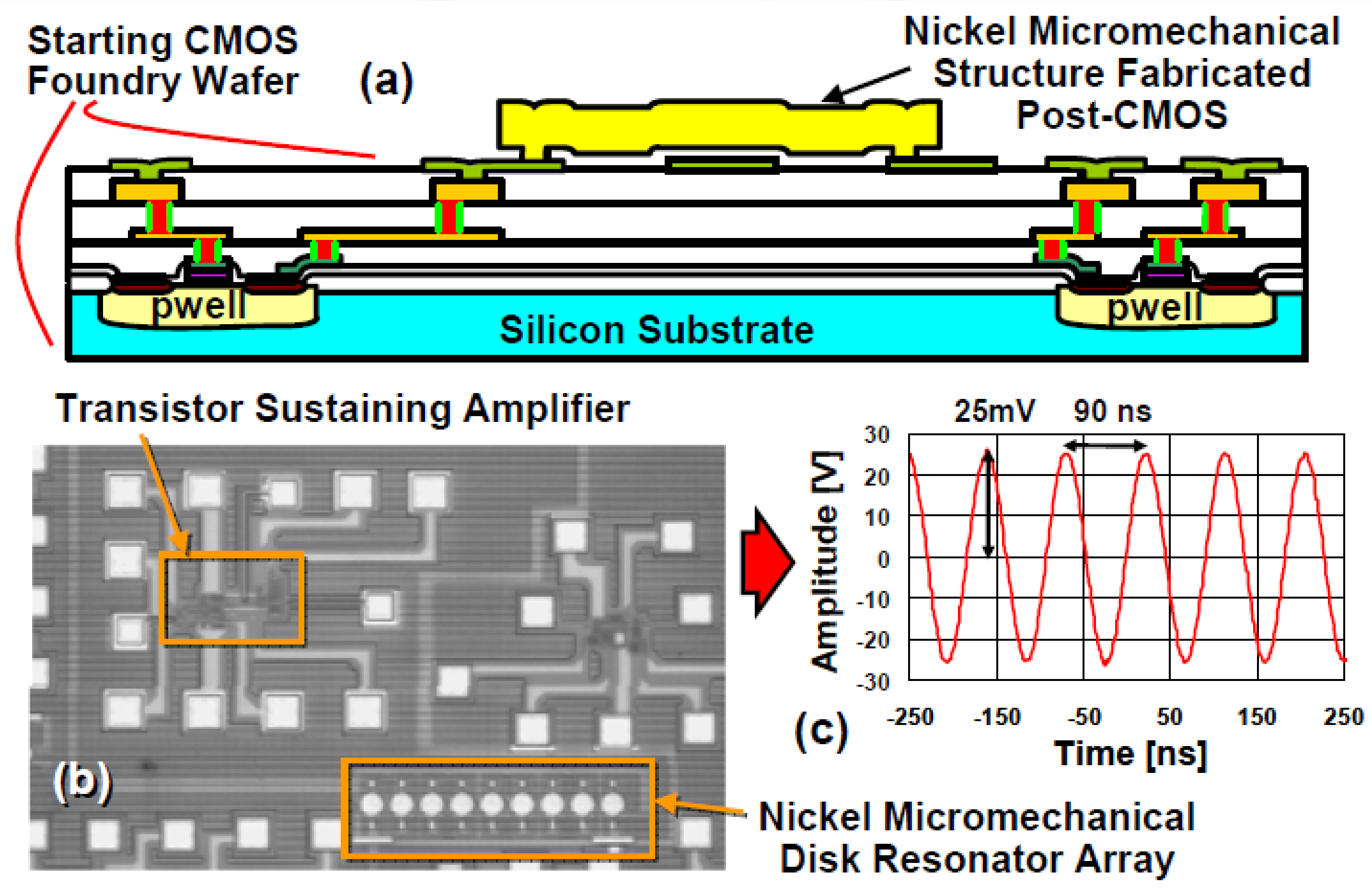
Al mirror ---- CMOS Process compatible

Photoresist sacrificial layer --- removed by plasma etching

DMD on CMOS SRAM by 6 mask process



Post-CMOS metal structure

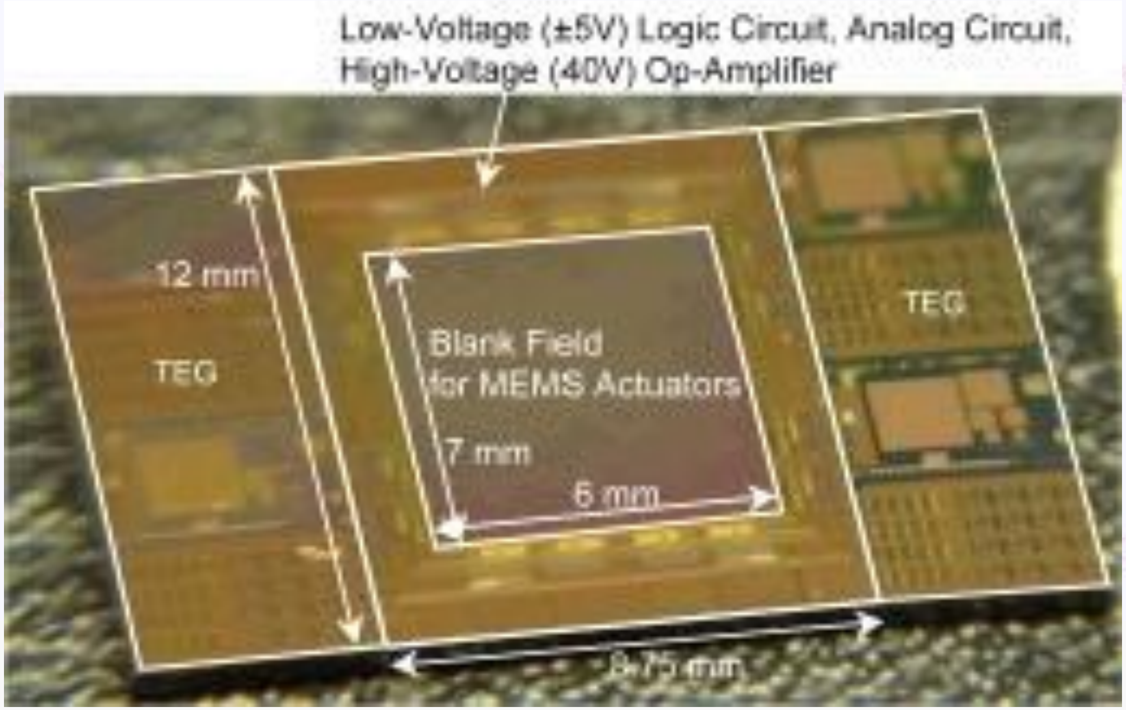


(a) Cross-section of the nickel MEMS-transistor integration process. (b) Die photo of a fully monolithic micromechanical resonator oscillator using this process. (c) Oscilloscope waveform.

Clark T.-C. Nguyen, UC Berkeley

Post-CMOS MEMS by Deep-RIE

Some space (7 mm x 6 mm) in 40V high-voltage chip is left for post processing of MEMS. MEMS devices are made in 8um-thick active layer of SOI substrate by deep RIE. Handling layer of 625um in thickness can also be structured by RIE. Each of four CMOS segments includes a 16-bit demultiplexer, a 12-bit DA converter, four operational amplifier with sample & holder.



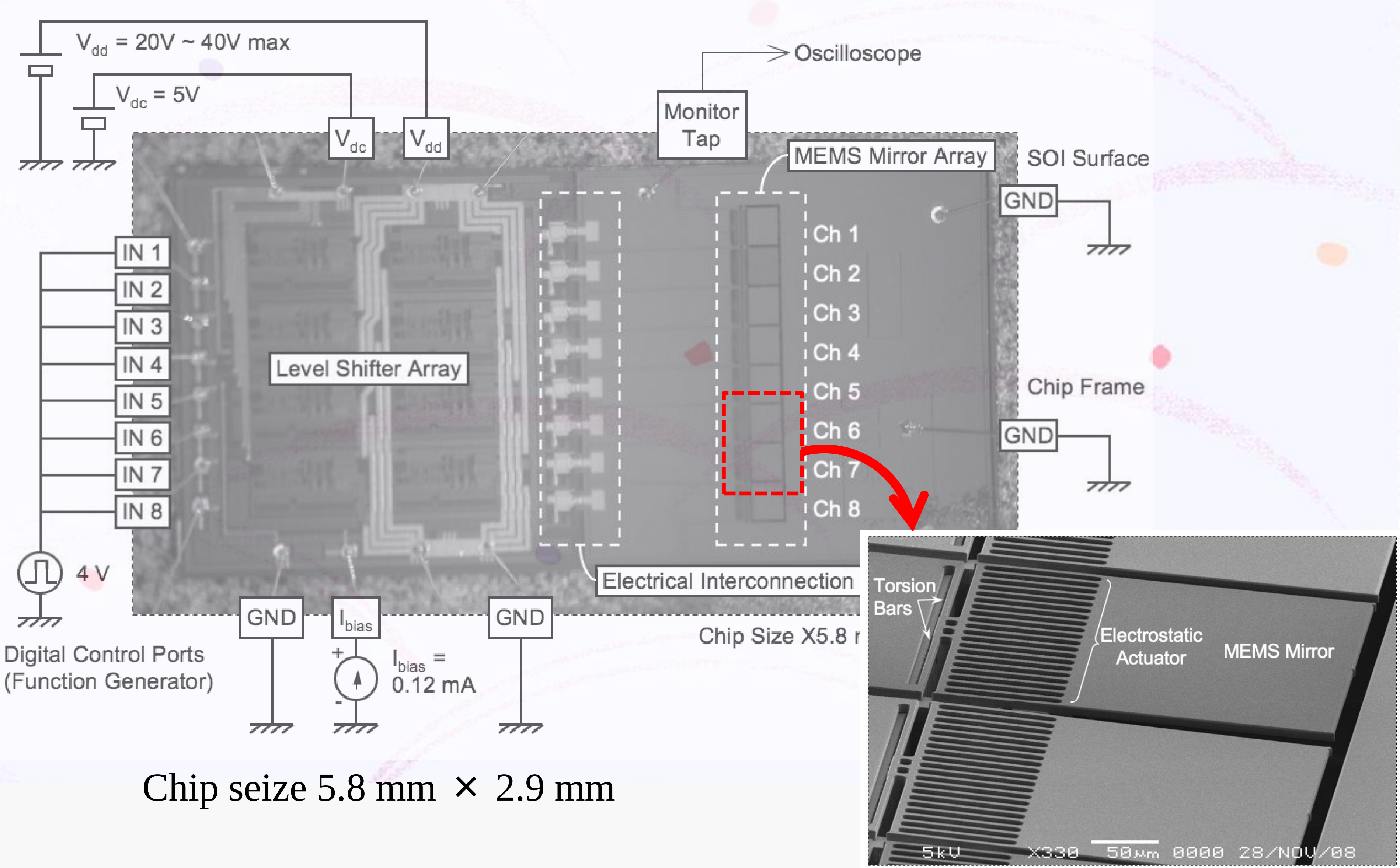
Source: Toshiyoshi Lab. IIS, University of Tokyo

A MEMS Digital Mirror Array Integrated with High-voltage Level-shifter

S. Maruyama, K. Takahashi, H. Fujita and H. Toshiyoshi
Institute of Industrial Science, The University of Tokyo, Tokyo, Japan

Transducers'09, Denver, CO, USA, June 21-25, p. 2314

CMOS-MEMS mirror array



Chip seize 5.8 mm × 2.9 mm

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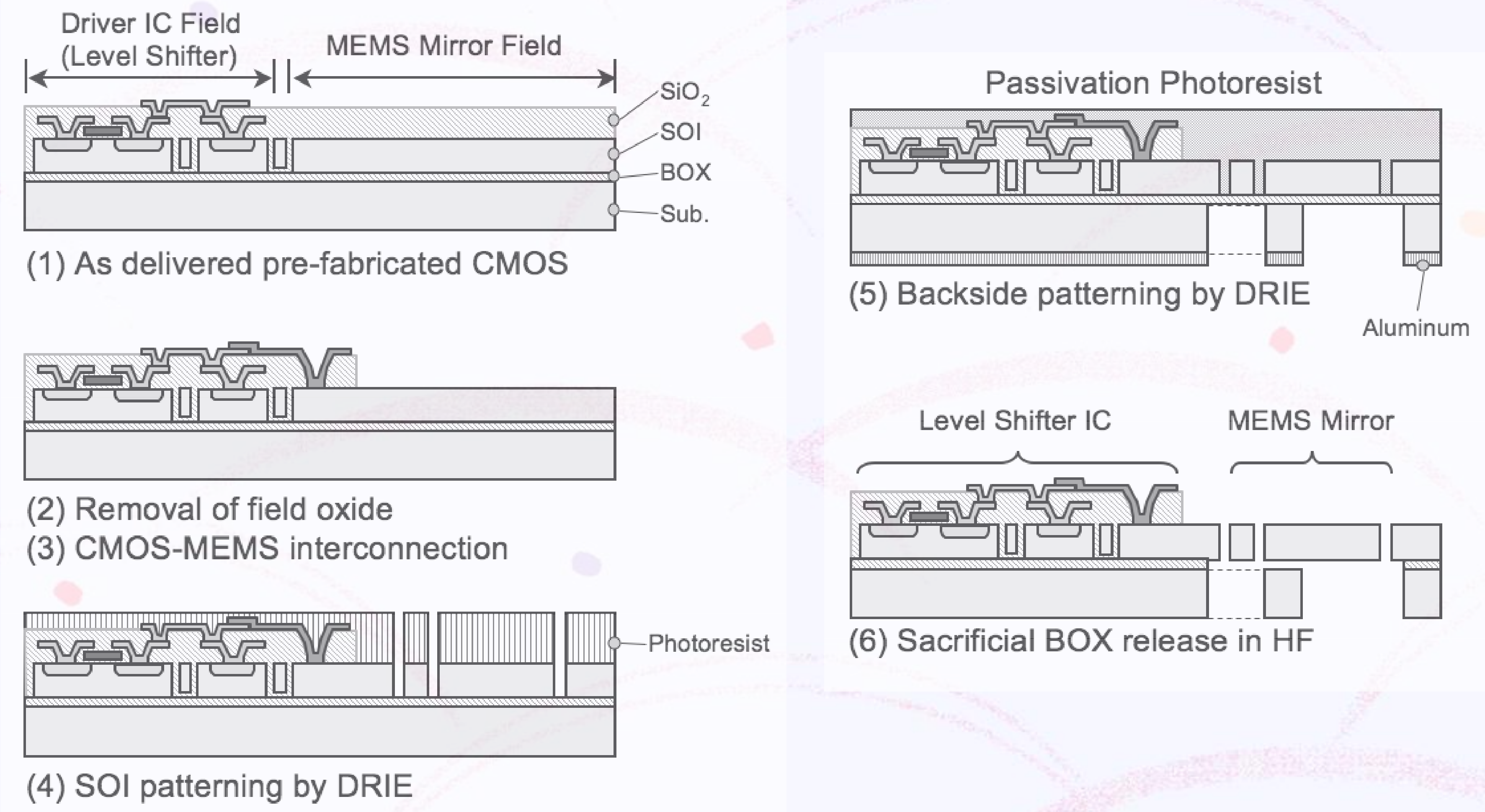
Post-CMOS MEMS fabrication



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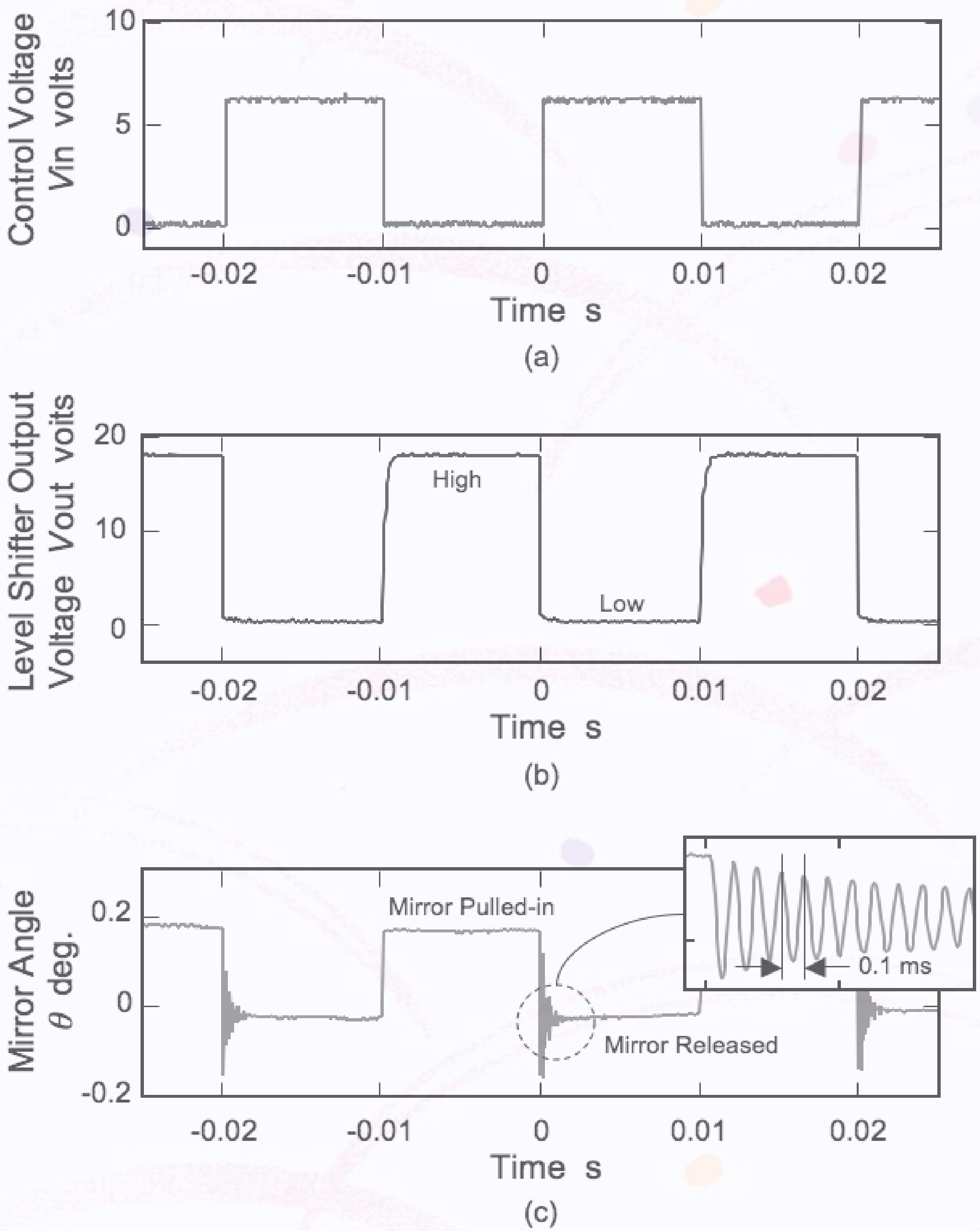
Operation result



(a) input voltage to the level shifter

(b) output voltage of the level shifter

(c) mirror angle.

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Keyword statistics at Transducers 2011

CMOS-MEMS integration
- CMOS foundry + post process
- Add functionality by CMOS integration (physical sensor, RF)

CMOS

CMOS MEMS

Accelero meter

Gyro

Pressure sensor

reliabil ity

Package

physical sensor

wireless

Wireless

RF MEMS

Resonator

Q-factor

Energy harvest (24)

Bio, micro fluid

Microfluidics (43)

Bio sensor

Humid sensor

Gas sensor

Micro valve

DEP

Droplet

PDMS

Parylene

CNT

Nano particle

Graphe ne

nano

Piezo electric (23)

AlN

PZT

ZnO

piezo material

SiC

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High-q, Large-Stopband-Rejection Integrated CMOS-MEMS Oxide Resonators with Embedded Metal Electrodes

Yu-Chia Liu[1], Ming-Han Tsai[1], Wen-Chien Chen[2], Sheng-Shian Li1,[2] and Weileun Fang[1,2]

[1] Inst. of NanoEngineering and MicroSystems and
[2] Dept. of Power Mechanical Engineering
National Tsing Hua University, Hsinchu, Taiwan

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Transducers'11, Beijing, China, June 5-9, 2011, p. 934

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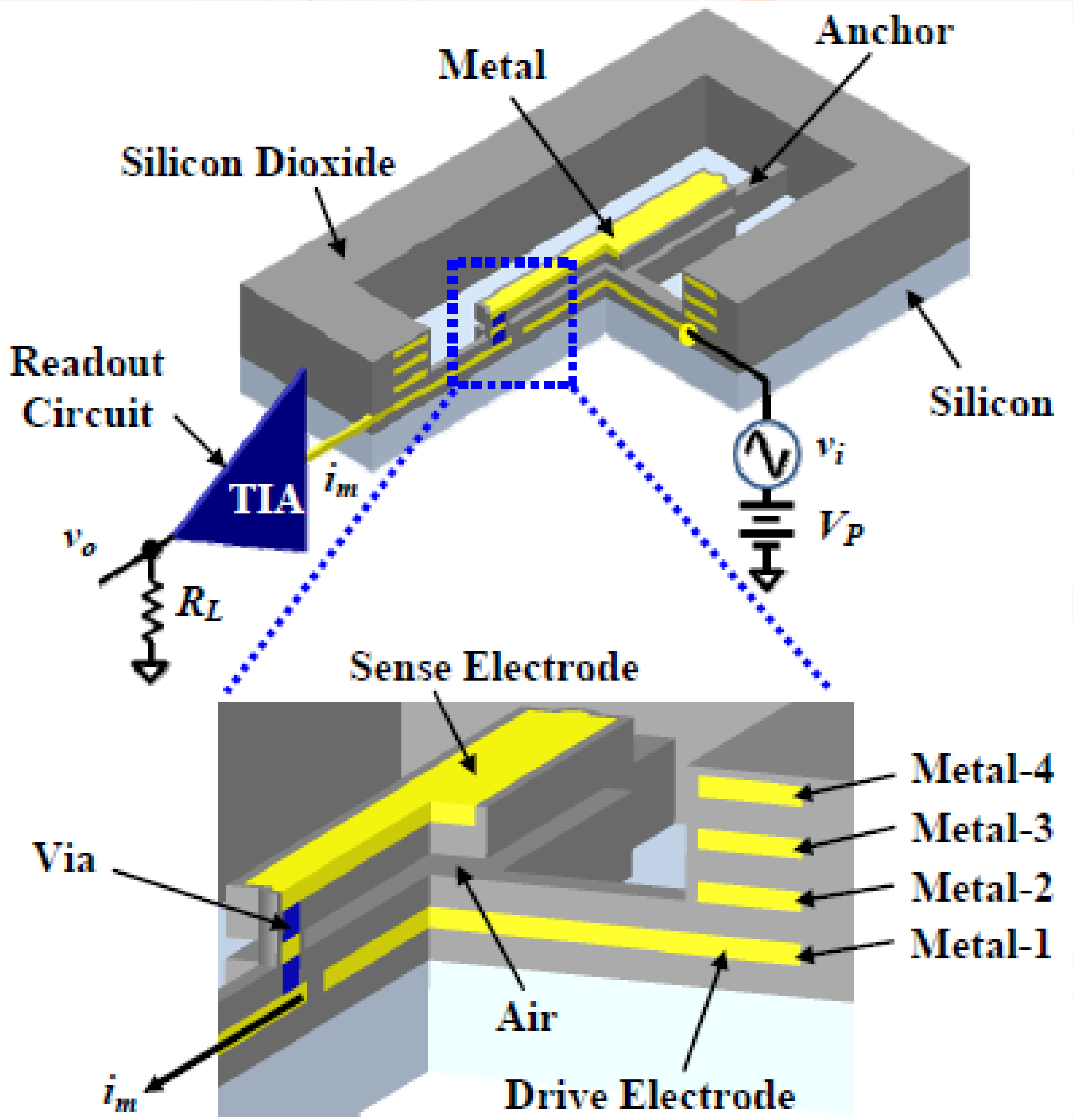
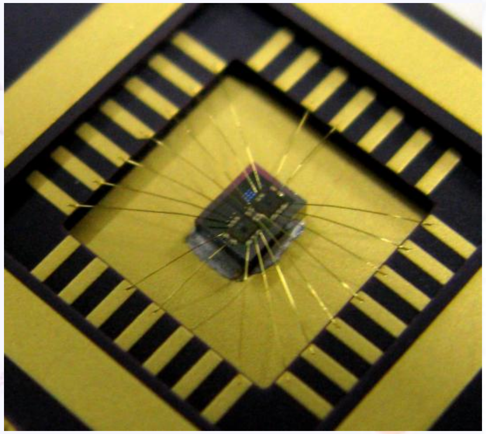


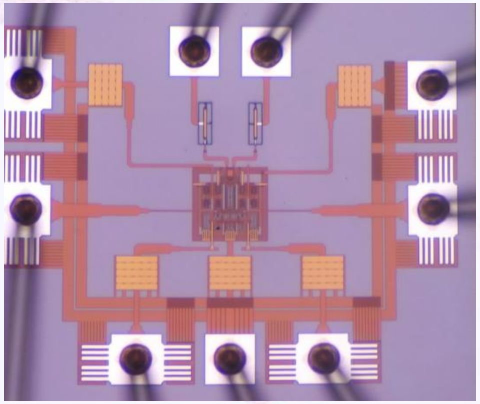
Perspective-view **schematic of an electrode-embedded CMOS-MEM oxide resonator**, including zoom-in of quarter cross-section view with signal transmission in a one-port test configuration.

Table 1: Design Parameters of the Capacitively-Transduced CMOS-MEMS Oxide Resonator.

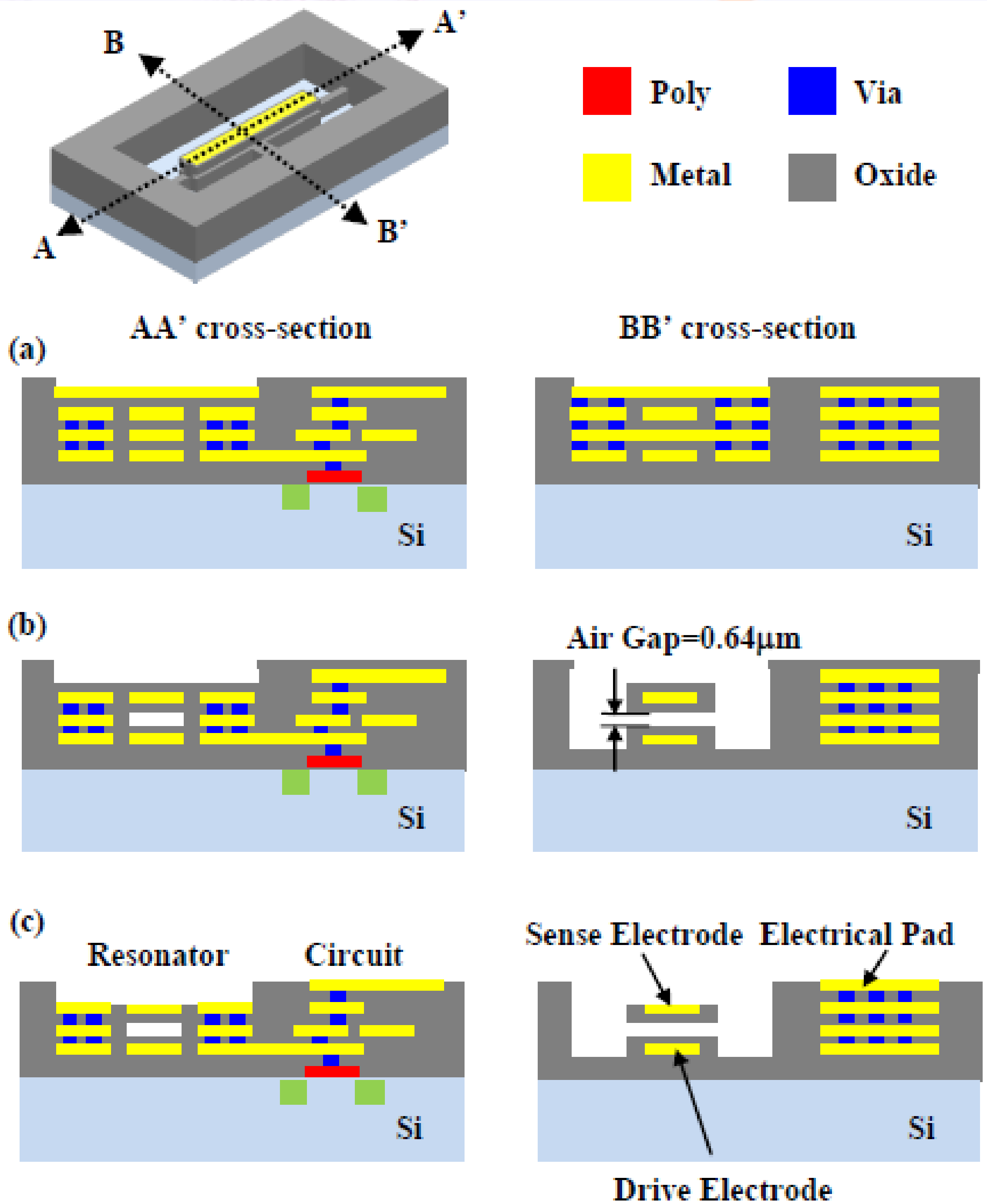
Design Parameter	Value	Unit
Beam Length, L_r	55	μm
Beam Width, W_r	4	μm
Air Gap, d_o	0.64	μm
Oxide Thickness, h_{ox}	1	μm
Structure Thickness, H_r	1.64	μm
Effective Mass, m_r	0.0388	nkg
Spring Constant, k_r	102	N/m
Resonance Frequency (Calculation)	2.58	MHz
Resonance Frequency (Simulation)	2.54	MHz



CMOS-MEMS chip in ceramic housing.



Die photo of monolithic CMOS-MEMS integration.



Fabrication sequence

(a) a chip manufactured by standard TSMC 0.35 μm 2P4M process,

(b) metal wet etching to form resonator structure and transducer's gap, and

(c) RIE dry etch to open the electrode pads.

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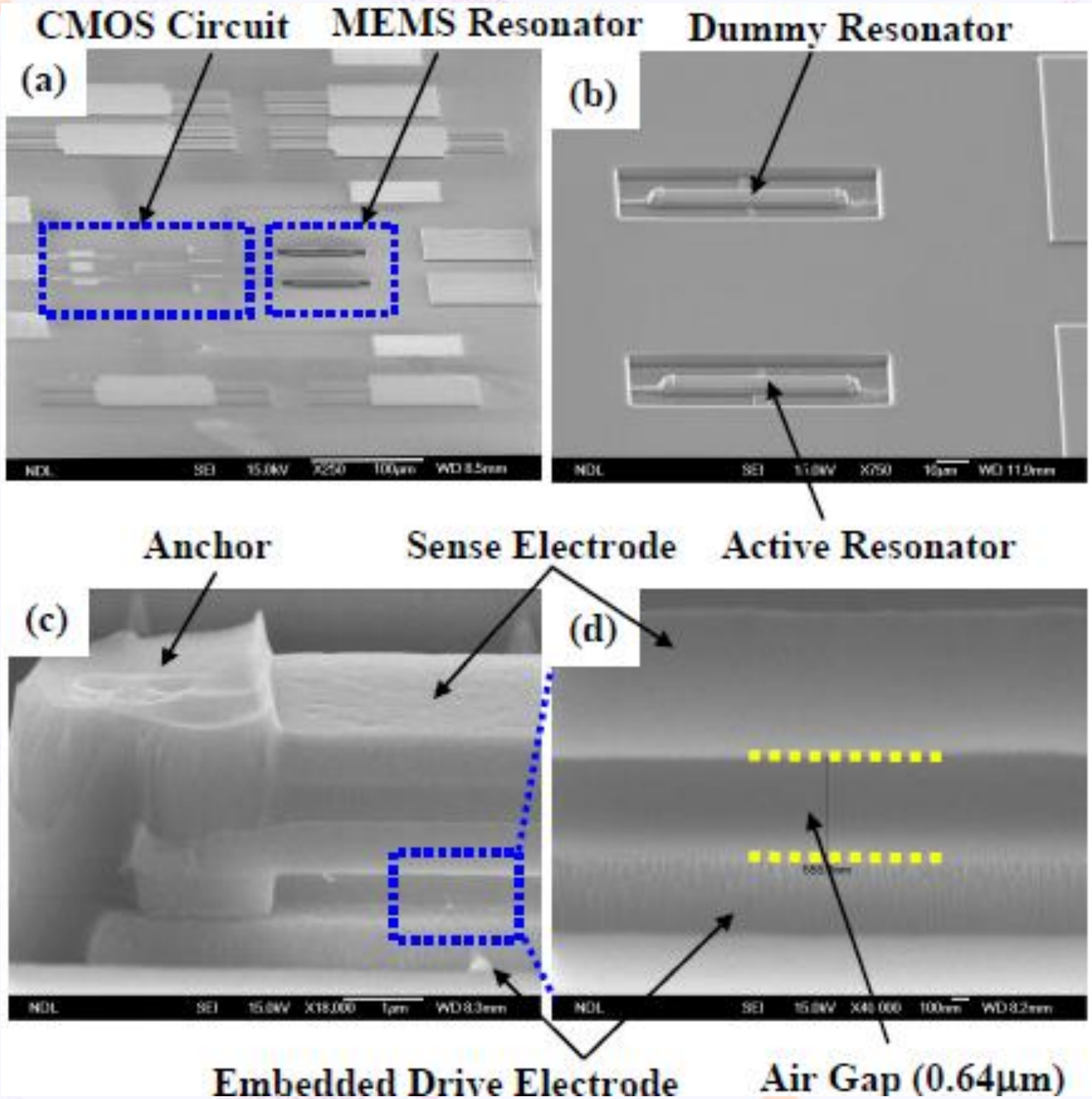


SEM views

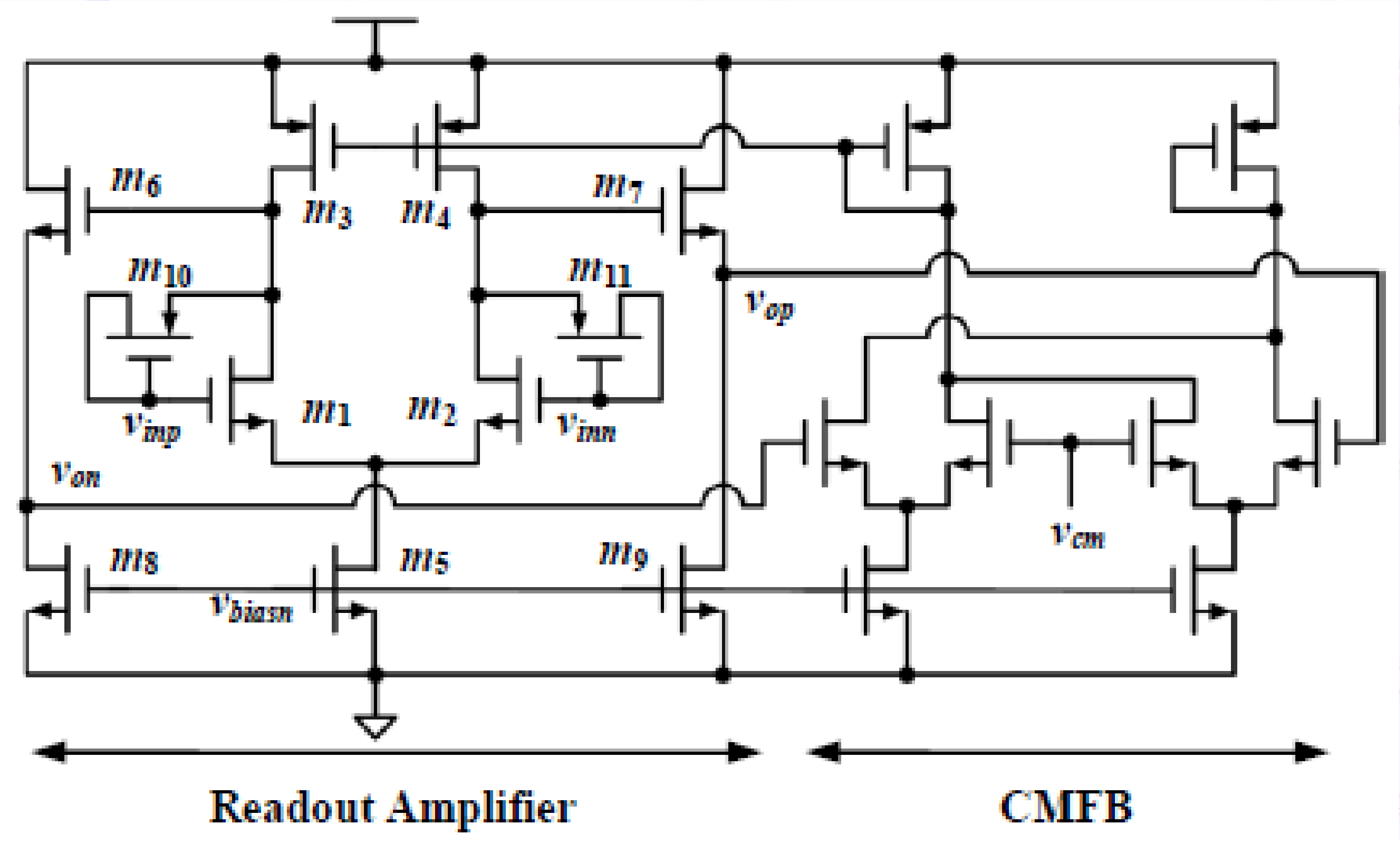
(a) CMOS-MEMS integration

(b) dummy device to suppress parasitic feed-through

(c) zoom-in of the out-of-plane resonator

(d) zoom-in of air gap

Schematic diagrams of a fully-differential readout amplifier.



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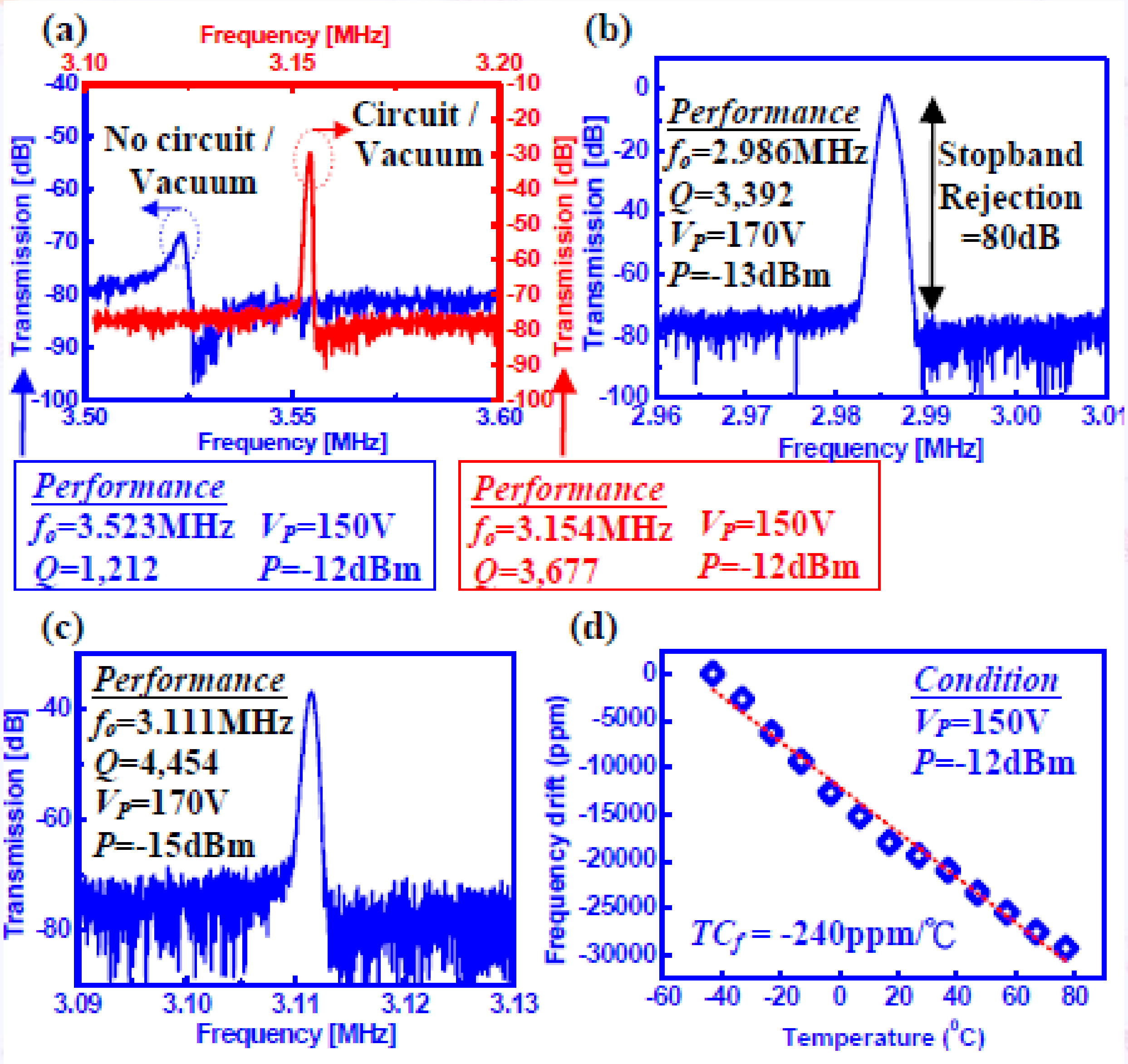

Measurement results

(a) with/without circuit tested in vacuum,

(b) frequency response with the highest stopband rejection,

(c) frequency response with the highest Q value,

(d) measured fractional frequency change versus temperature.

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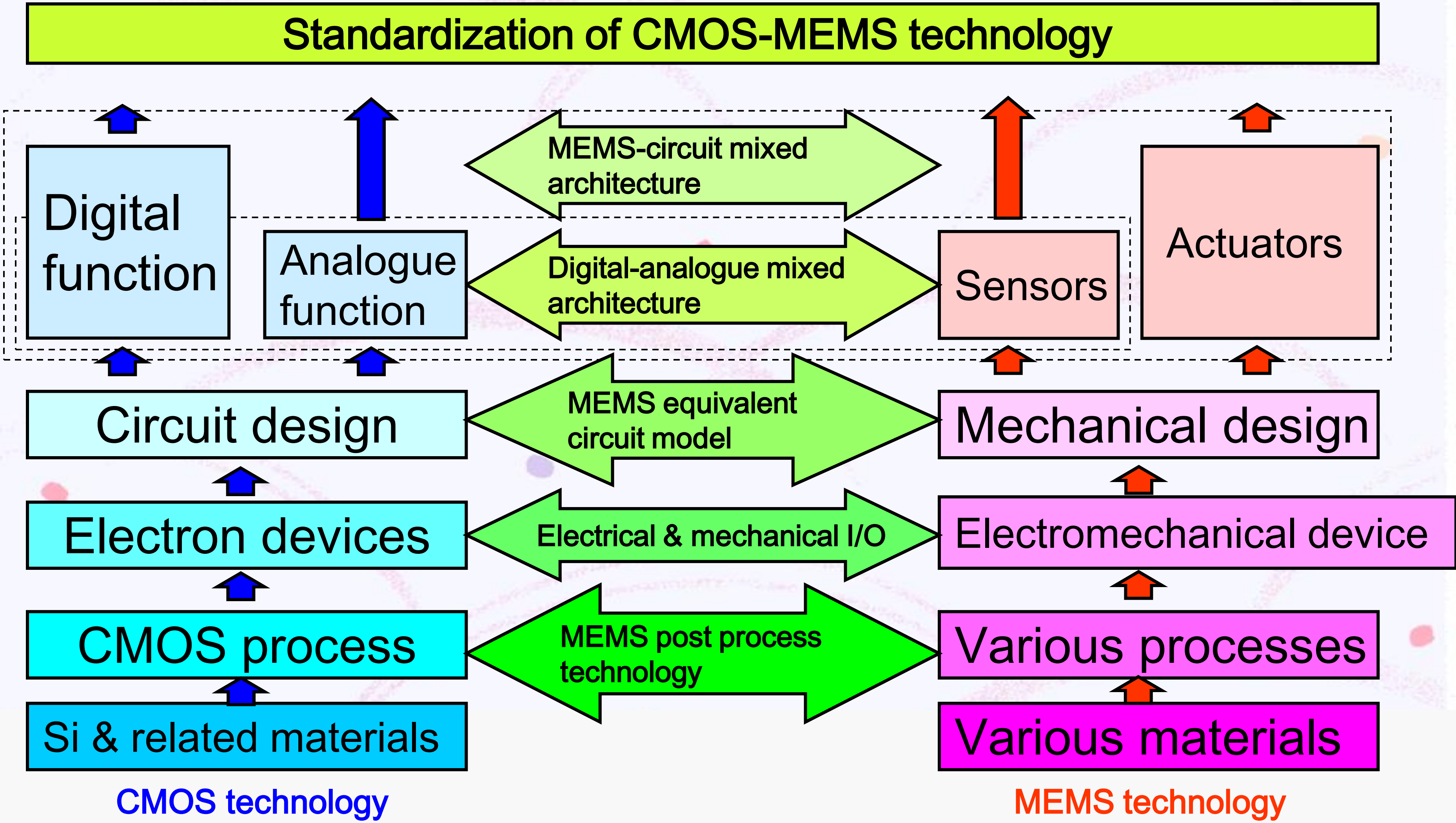
Table 2: CMOS-MEMS-Based Resonator Summary.

	This work	Ref [3]	Ref [5]	Ref [4]
Type	CC-Beam	Beam	SFR	FF-Beam
Materials	Metal + Oxide	Metal + Oxide	Metal + Oxide	Metal + Oxide
f_o (MHz)	3.11	6.33	6.18	14.5
Q	~3,300-4,400	~100*	~1,000	~1,500
SB rej. (dB)	~40-80	~4	~14	~10

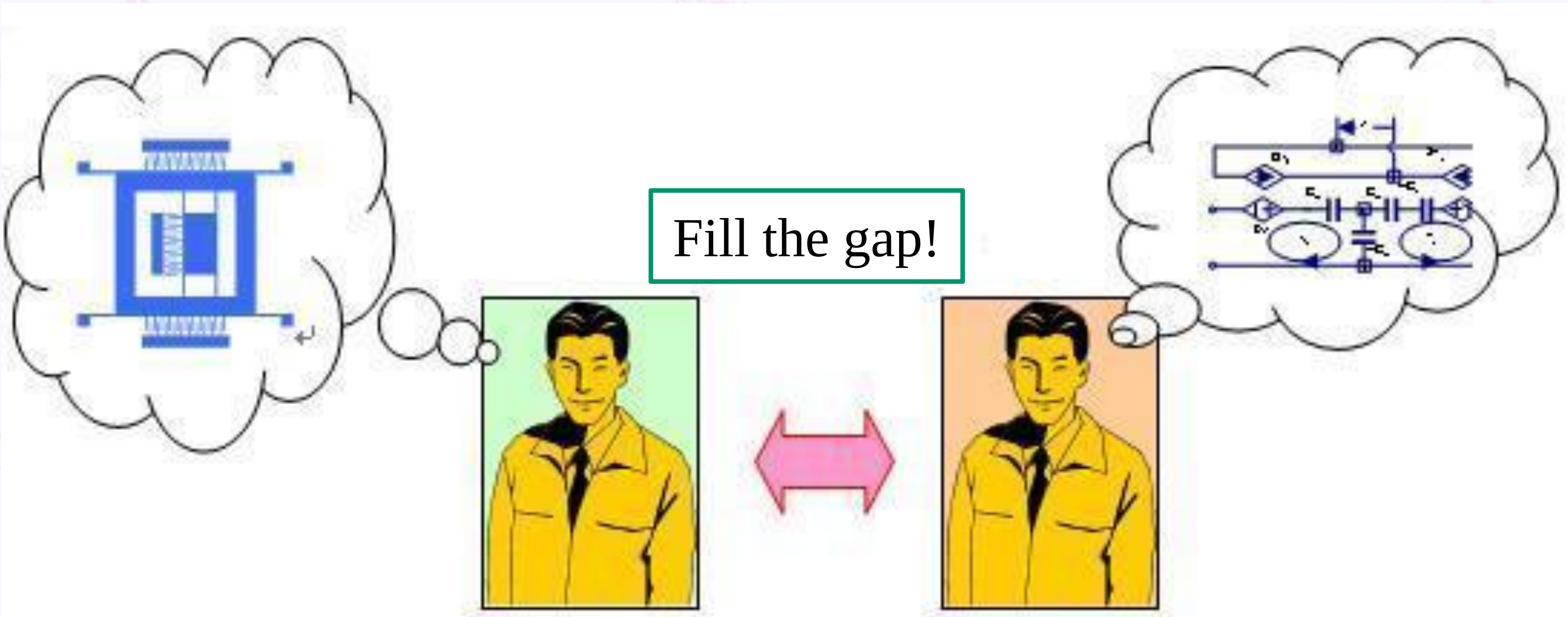
*Measured in atmospheric pressure.

Hierarchical integration of design & fabrication steps for CMOS-MEMS technology



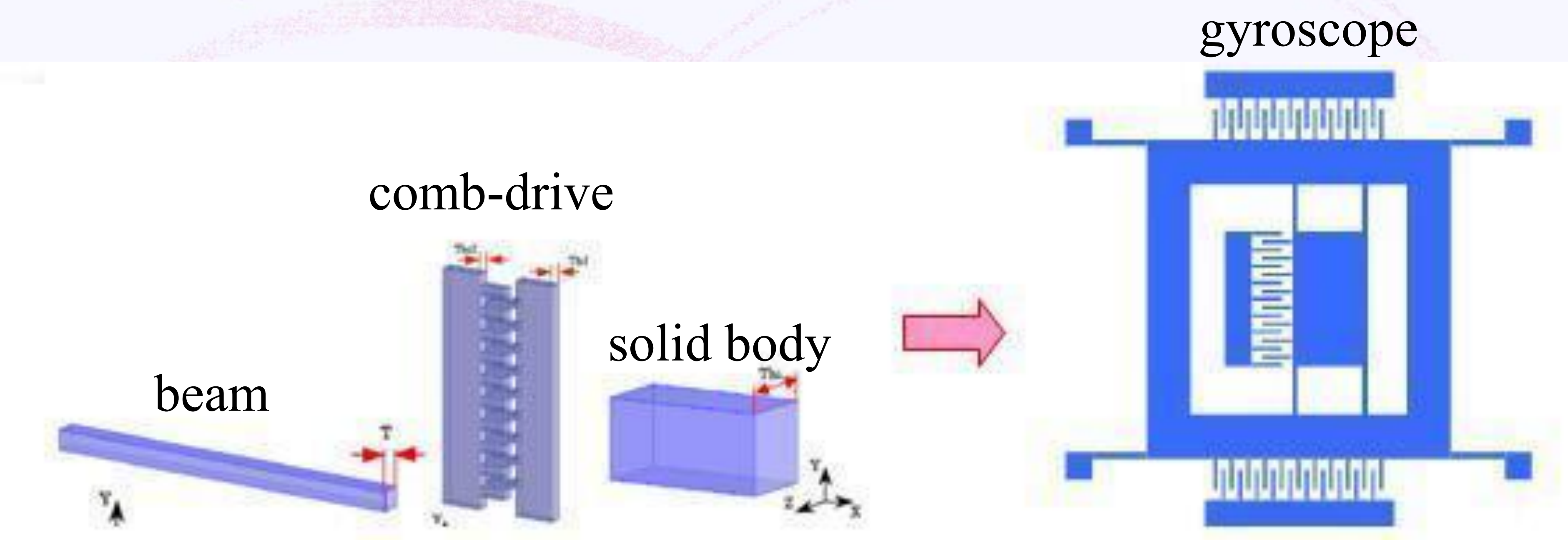
MEMS equivalent circuit model generator

http://memspedia.mmc.or.jp/WebLibrarySystem/



Useful to fill the gap between MEMS engineers and VLSI engineers

MEMS equivalent circuit model generator

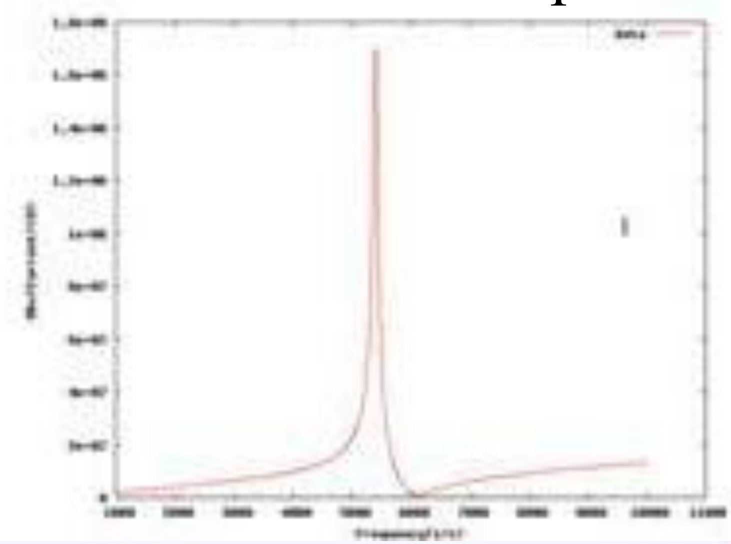


Connect basic components and construct a device
beam + comb-drive + solid body = gyroscope

MEMS equivalent circuit model generator

Define connections

Simulated output



Each element is represented by an equivalent circuit. Connect them with external electrical circuit and perform SPICE simulation.

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Process integration over the scale

0.1 | 1 nm | 10 | 100 | 1 μm | 10 | 100 | 1 mm | 10

nano technology region

- atom/molecule handling
- bio synthesis
- molecular synthesis
- self organization
- molecular recognition
- nano imprinting
- nano lithography
- self assembly
- ultra precision machining

Large-area electronics

- printing
- mechanical assembly
- weaving

bottom-up (building nano function elements)

top-down & bottom-up integrated process

top-down (miniaturization toward nano scale)

Large-area process

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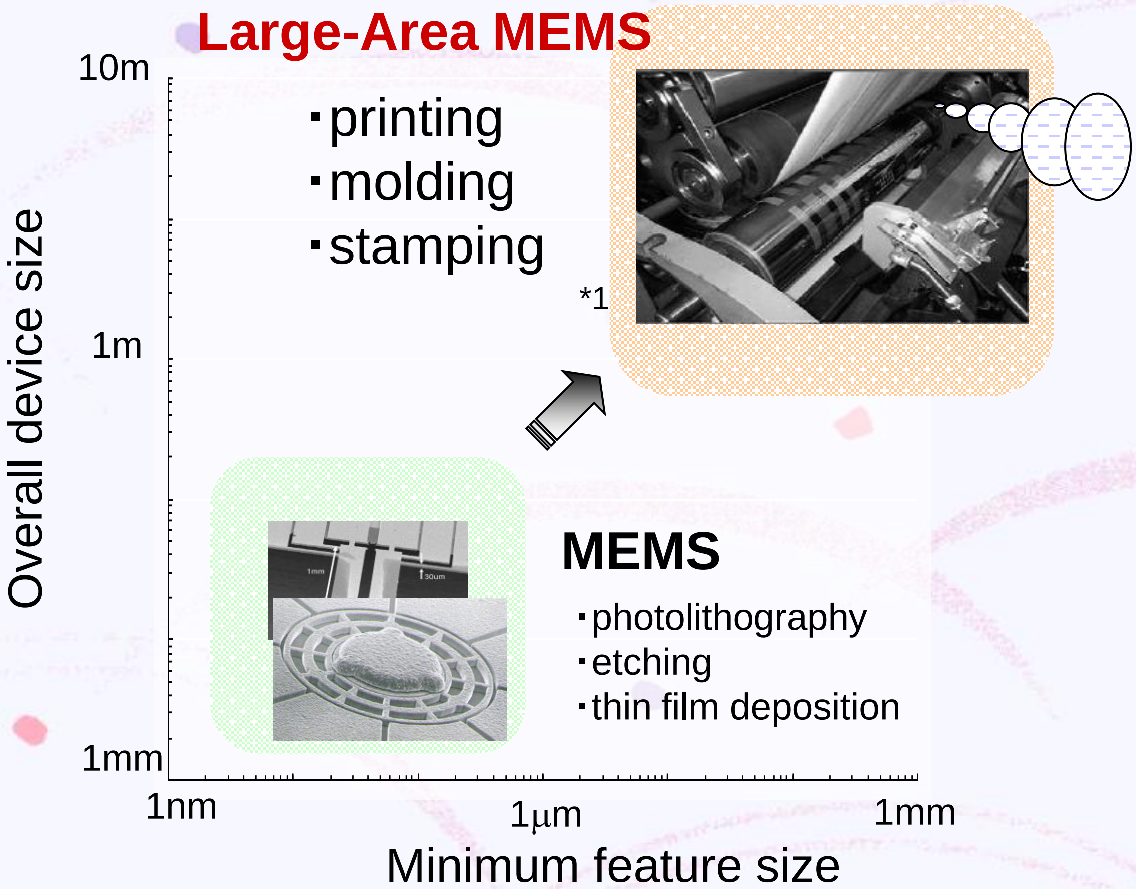
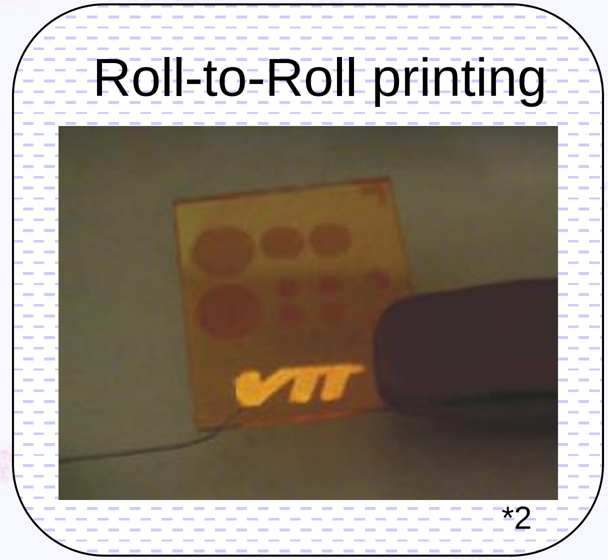
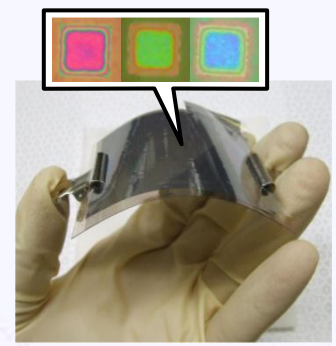
Large-Area MEMS







Flexible display

*1 : Mäkelä, Tapio; Jussila, Salme; Vilkman,M.; Kosonen, Harri; Korhonen, R. “Roll-to-roll method for producing polyaniline patterns on paper”, Synthetic Metals. Vol. 135-136 (2003), 41-42
*2 : http://www.vtt.fi/

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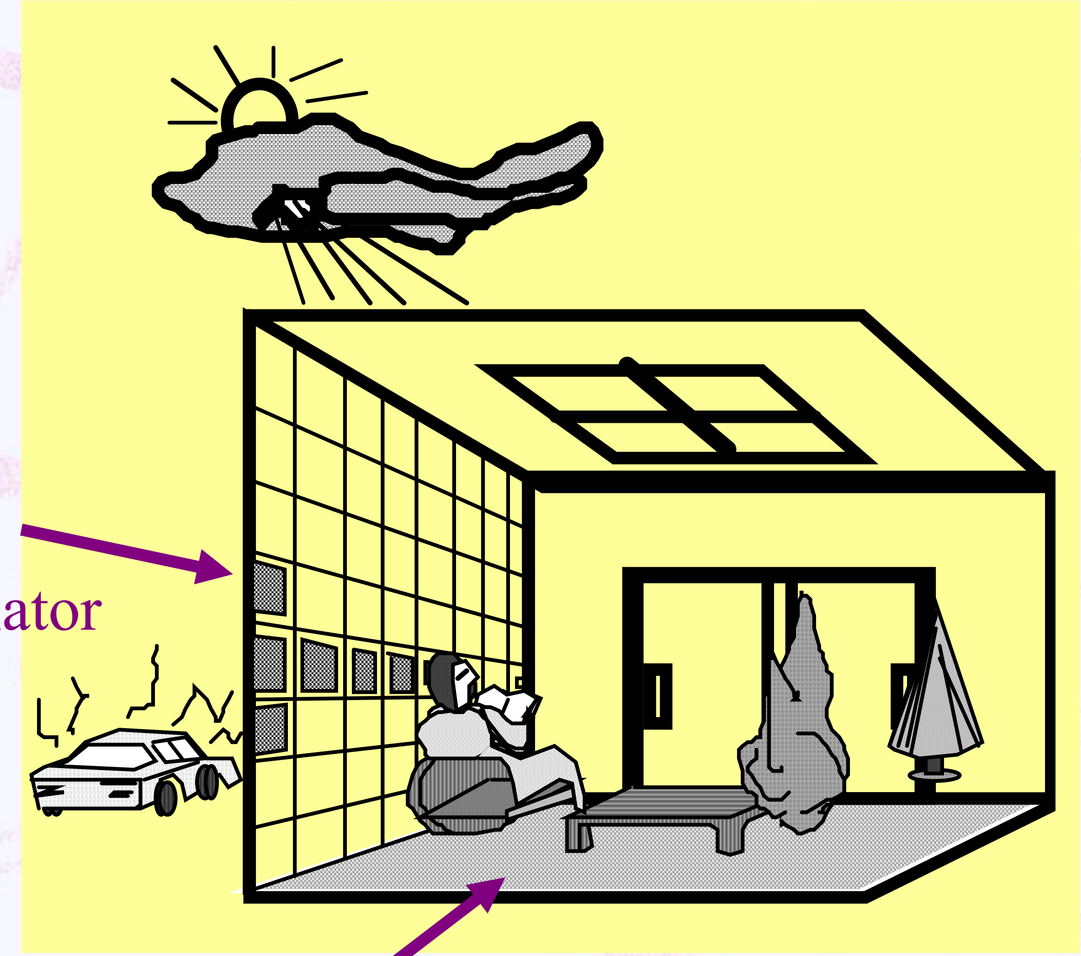
Smart-skin wall paper and carpets

Room environment is kept comfortably by arrayed MEMS sensors and actuators.



Optical sensor + LED
Microphone + speaker
Temp. sensor + heater
Humidity sensor + ventilator
Human sensor
on wall paper & carpet

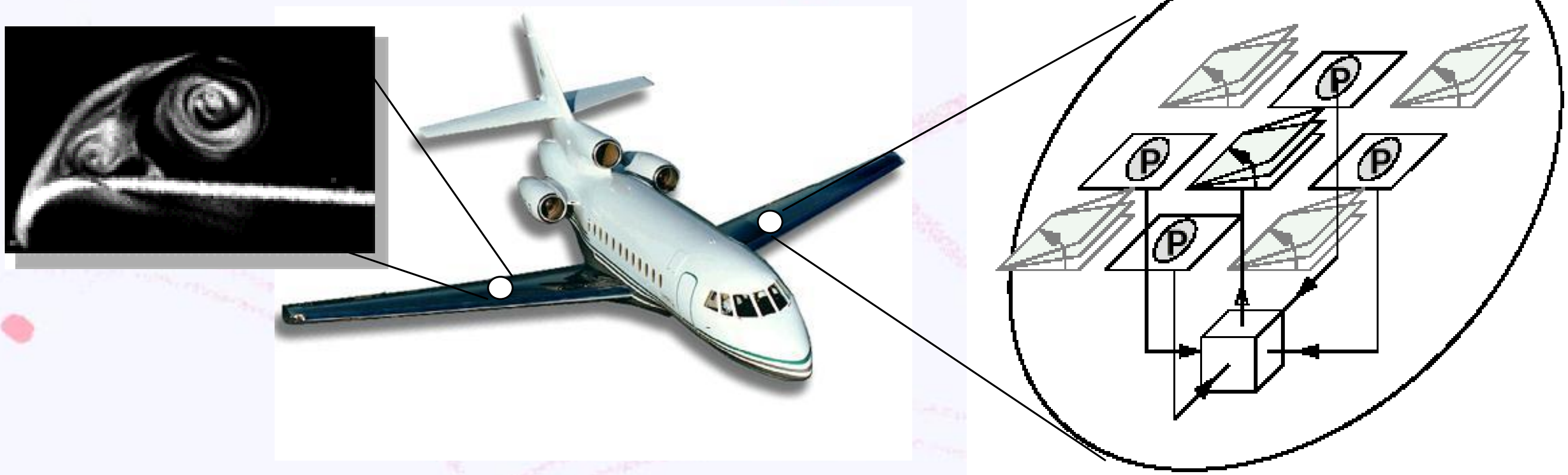
Active MEMS carpet for cleaning

Smart skin (intelligent surface)

Taking best advantages of MEMS features

3M : Miniaturization , Multiple , Microelectronics

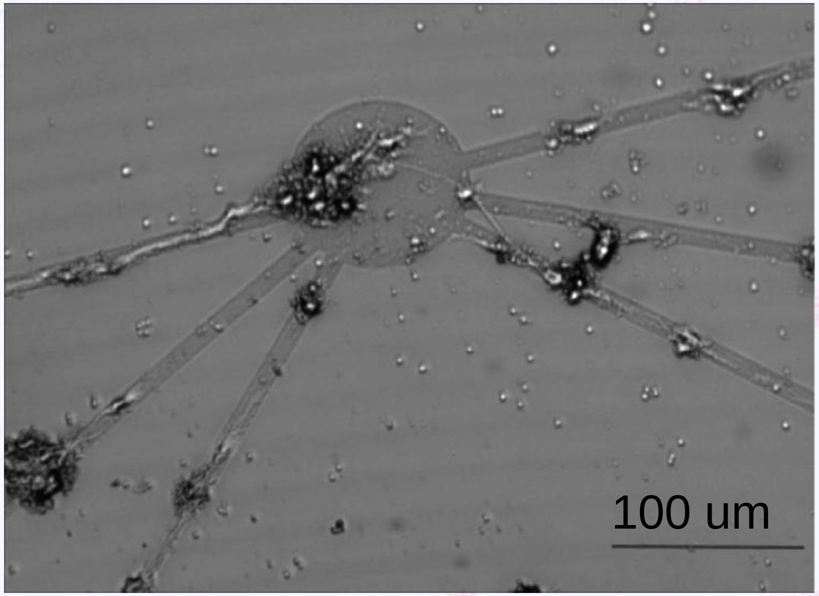
Adaptative Wing



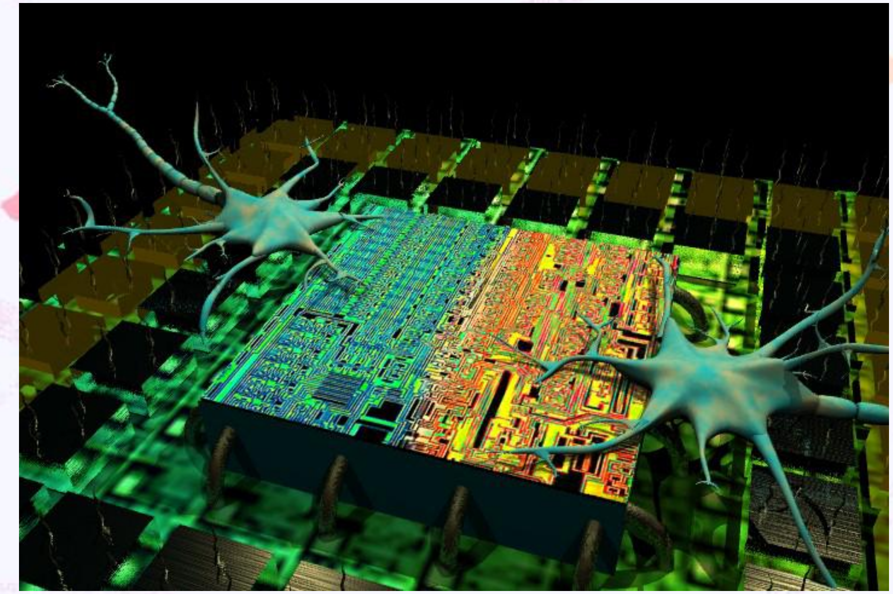
Sensors + Local data processing + Actuators

MEMS guided axon for BMI

4-dimensional micromachining including temporal development



Cultured neuron cells elongate axons along micro patterns on a chip



Prospected BMI

Future trends

- Micro/nano machining technology in the future must be the **integration of top-down methods** (such as MEMS or VLSI) and **bottom-up methods** (such as molecular synthesis and bio technology).
- **Autonomous MEMS instruments** to capture ambient information will be important for security, personal health care, and environmental protection. Wireless devices and the MEMS energy source will play key role.
- New fabrication technology for **large area integration** of various functional devices will be important. Such products as flexible/interactive display, MEMS wall paper for lighting/air-conditioning/noise-reduction, and smart clothes may be produced.

Conclusion

- MEMS Technology has matured and ready for CMOS-MEMS integration: *More-than-Moore*
- Four ways to integrate MEMS and CMOS. Hybrid integration is most practical. Fully mixed process and MEMS-first process are suitable to mass production of many devices. CMOS-first process is flexible and compatible with existing foundry system.
- Beyond CMOS-MEMS integration, bio/nano objects will be integrated on chip. Also process for smart skin will be required.

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