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# Microsystem technology (MST)
## in our daily environment

Tutorial, '*Chip on the Island*': 20th SB Micro Conf. , Florianópolis, Sept. 4-7, 2005

# Microsystem technology (MST)
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- Introduction:
    - historical
    - What is MEMS, MST and SiP?
- Relevance of microsystems in daily life
- Scaling and miniaturization
- Examples: micro-machining and electrowetting
- More examples, developed at Philips
- Manufacturing, packaging and modeling
- Concluding remarks

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# Moore, 40 years ago (1965)….

## Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 eco… many as 65,000 compone…

By Gordon E. Moore

Passive integration

systems out of smaller functions, which are separately packaged and interconnected. The availability of large functions, combined with functional design and construction, should allow the manufacturer of large systems to design and construct a considerable variety of equipment both rapidly and economically.

### Linear circuitry

Integration will not change linear systems as radically as digital systems. Still, a considerable degree of integration will be achieved with linear circuits. The lack of large-value capacitors and inductors is the greatest fundamental limitations to integrated electronics in the linear area.

By their very nature, such elements require the storage of energy in a volume. For high Q it is necessary that the volume be large. The incompatibility of large volume and integrated electronics is obvious from the terms themselves. Certain resonance phenomena, such as those in piezoelectric crystals, can be expected to have some applications for tuning functions, but inductors and capacitors will be with us for some time.

The integrated r-f amplifier of the future might well consist of integrated stages of gain, giving high performance at minimum cost, interspersed with relatively large tuning elements.

Other linear functions will be changed considerably. The matching and tracking of similar components in integrated structures will allow the design of differential amplifiers of greatly improved performance. The use of thermal feedback effects to stabilize integrated structures to a small fraction of a degree will allow the construction of oscillators with crystal stability.

Even in the microwave area, structures included in the definition of integrated electronics will become increasingly important. The ability to make and assemble components small compared with the wavelengths involved will allow the use of lumped parameter design, at least at the lower frequencies. It is difficult to predict at the present time just how extensive the invasion of the microwave area by integrated electronics will be. The successful realization of such items as phased-array antennas, for example, using a multiplicity of integrated microwave power sources, could completely revolutionize radar.

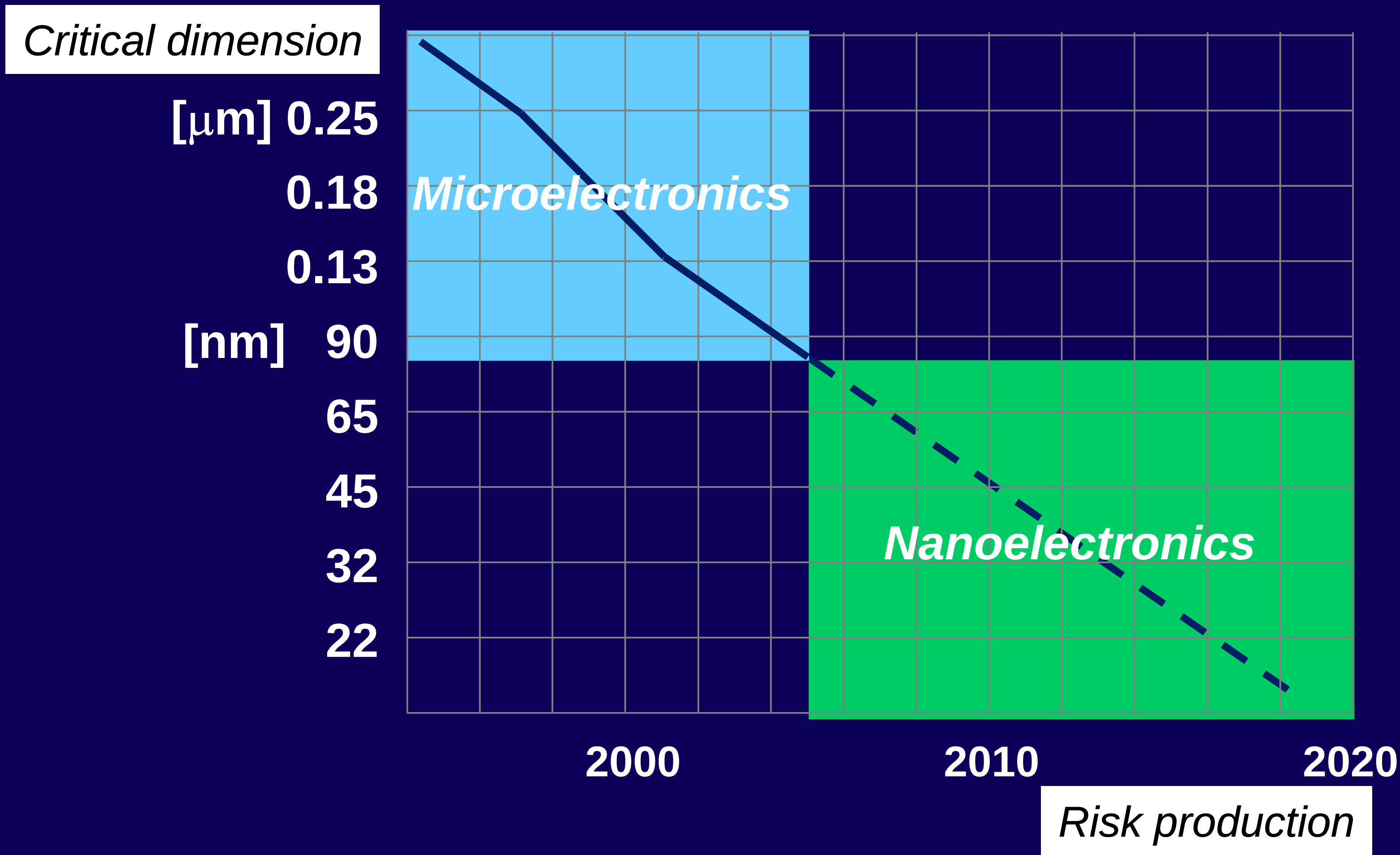
…ment of active semiconductor devices to the passive film arrays.

Both approaches have worked well and are being used in equipment today.

Electronics, Volume 38, Number 8, April 19, 1965

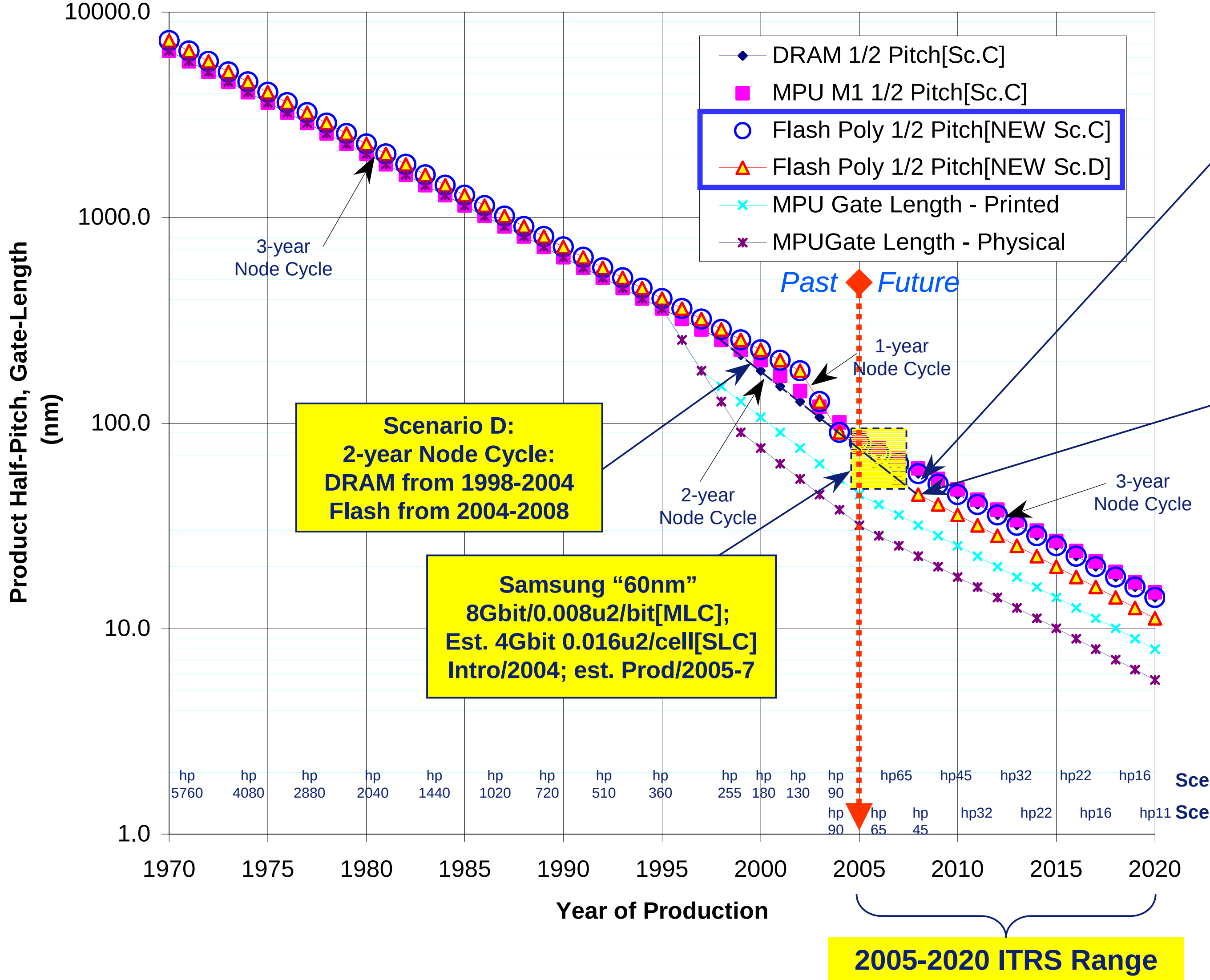
Smart system integration

# More Moore: the Brains



# More Moore: the Brains

**2005 ITRS Product Technology Trends - Half-Pitch, Gate-Length** [Proposal]



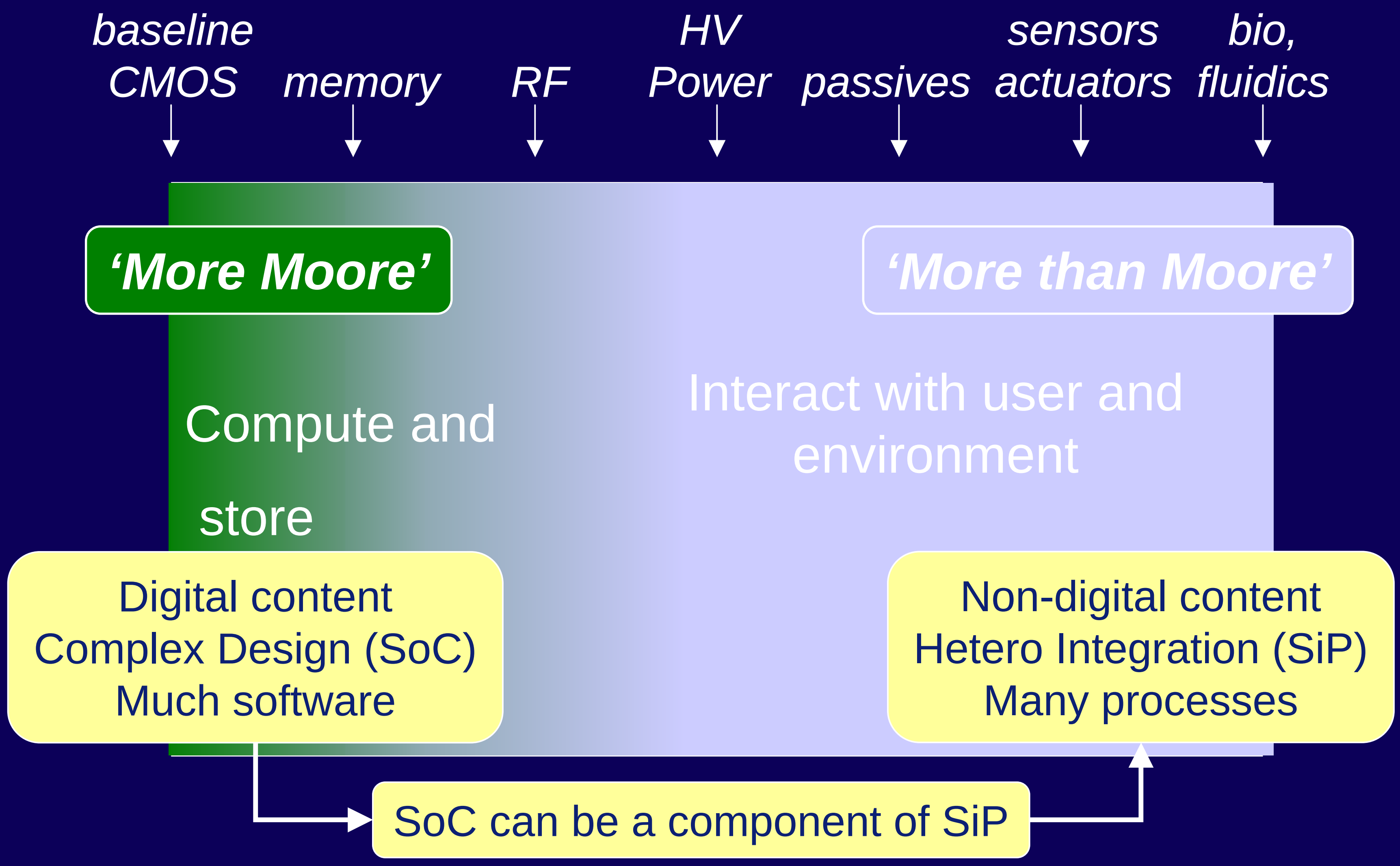

2005 ITRS Flash Proposal:

Scenario C = Catch DRAM @ 2004/90nm; then 3-yr cycle

Scenario D = Cross-over DRAM @ 2004/90nm; then 2-yr cycle to 2006/65nm and 2008/45nm; then 3-yr cycle

*Courtesy Alan Allan, IRC/ITRS*

# Intelligent systems compute & interact …



# … resulting in two system realization streams

- ‘More Moore’ → System-on-Chip (SoC)
  → Lowest cost per single function
  → Integrate all functions on one silicon wafer
  → Packaging is usually a commodity

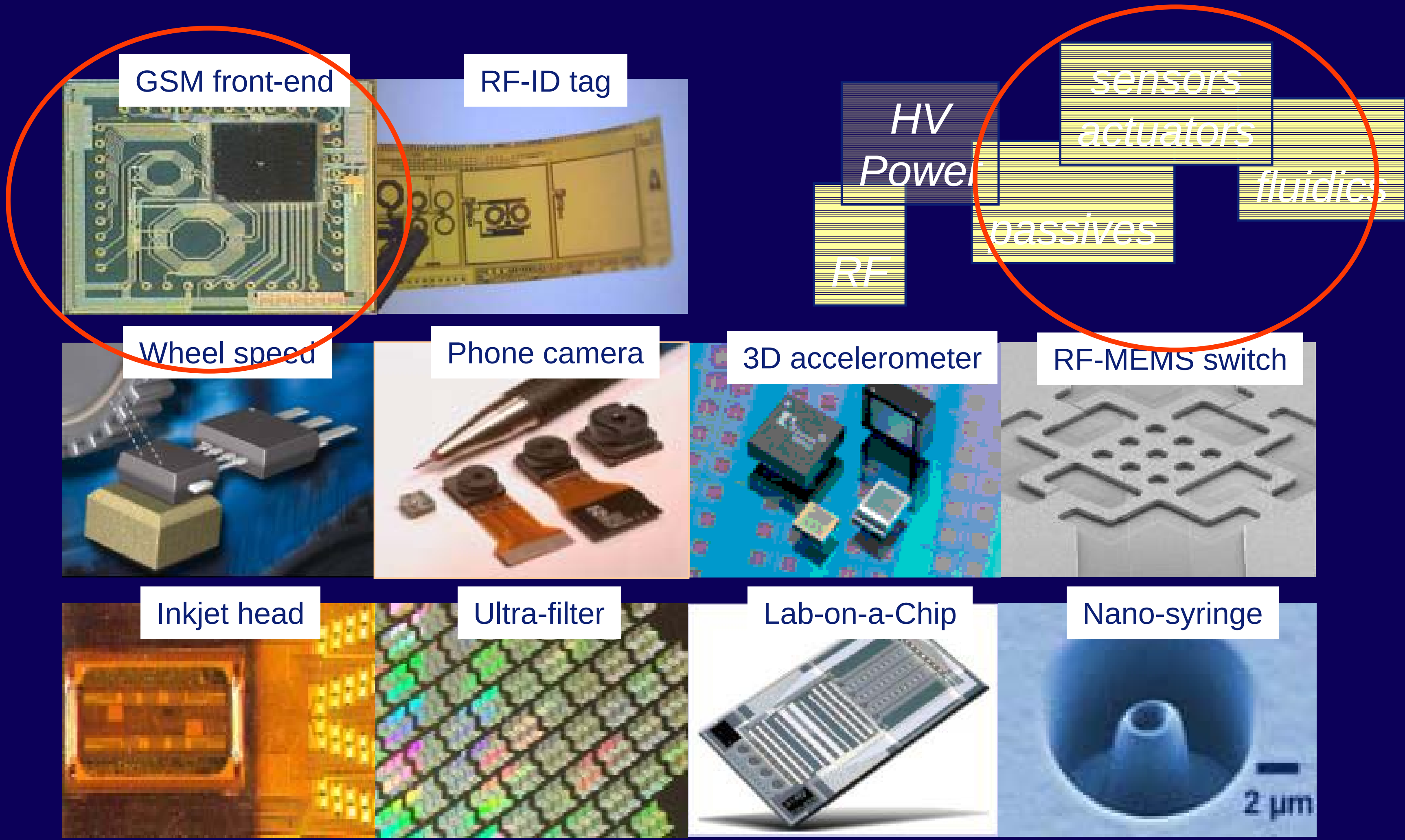
- ‘More than Moore’ → System-in-Package (SiP)
  → Highest value per total system
  → Integrate all functions in one module
  → Packaging is a functional element / key differentiator

- Both are complementing, not competing

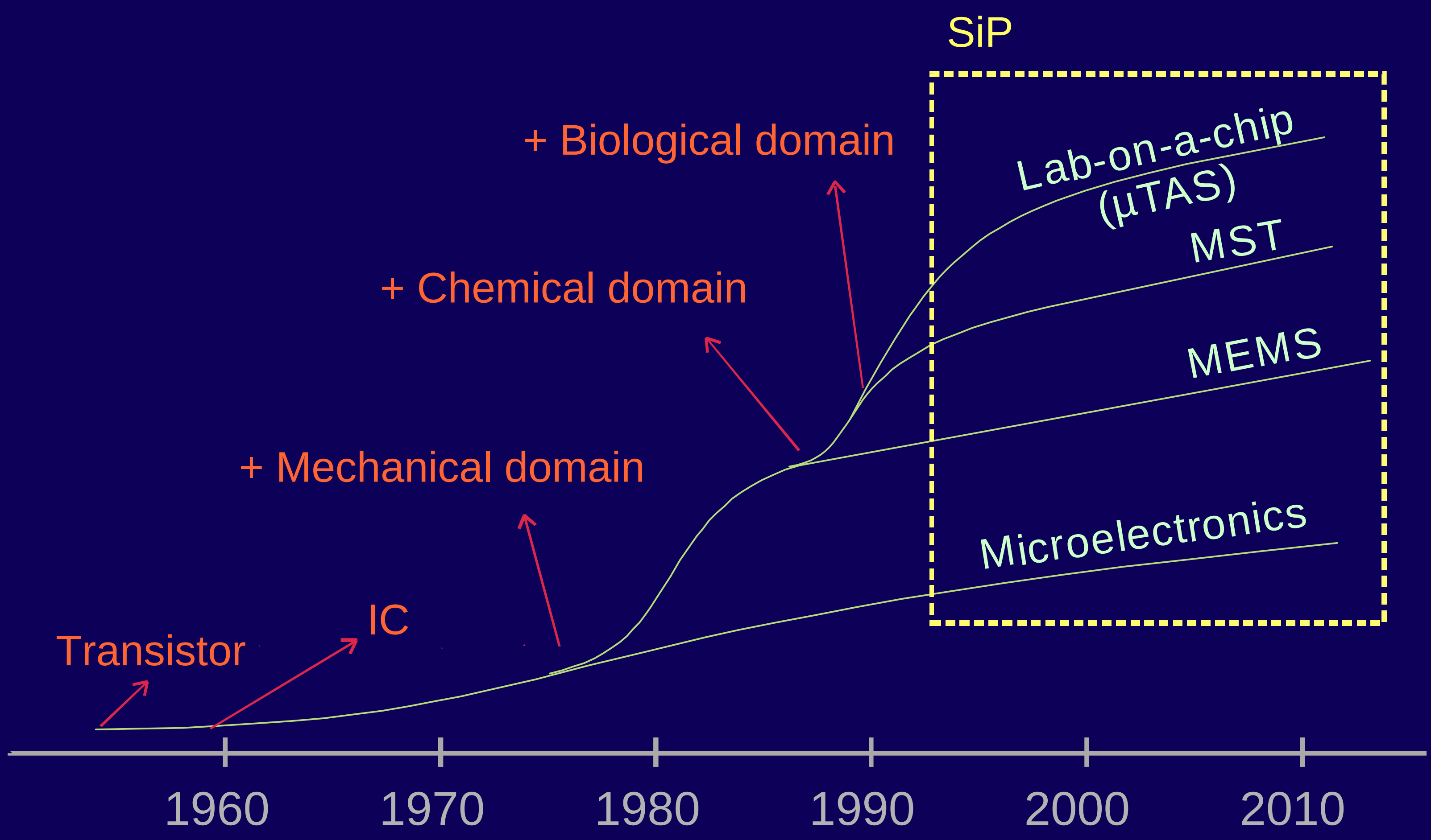
- Both will run in parallel for a long time to come

# … resulting in two system realization streams

- ‘More Moore’ → The Brains
- ‘More than Moore’ → The Arms, Legs, Eyes, Ears, …



# Definition of microsystems




System in Package (SiP):

A consumer-ready solution of a multi-domain node manufactured by inexpensive mass-volume production techniques

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# ‘Daily life’: Ambient Intelligence

Intelligence (Cambridge International Dictionary of English):

*“The ability to understand and learn and make judgements or have opinions that are based on reason“*

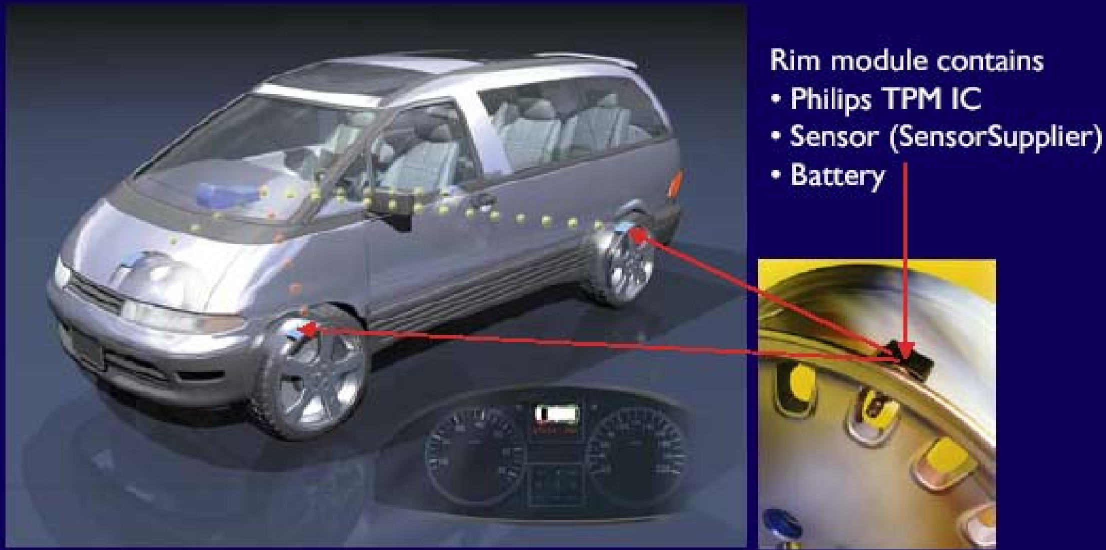
Ability to learn: sensors

retrieving signals from a noisy background

signal conditioning and combining sensor readings in order process and transmit useful information

SiPs, as interfacing nodes are the enablers of Ambient Intelligence

# Ambient Intelligence penetration in daily life




Autonomous tire pressure monitor (Philips)

Mecca phone (LG)


Autonomous camera pill
(Given Imaging)

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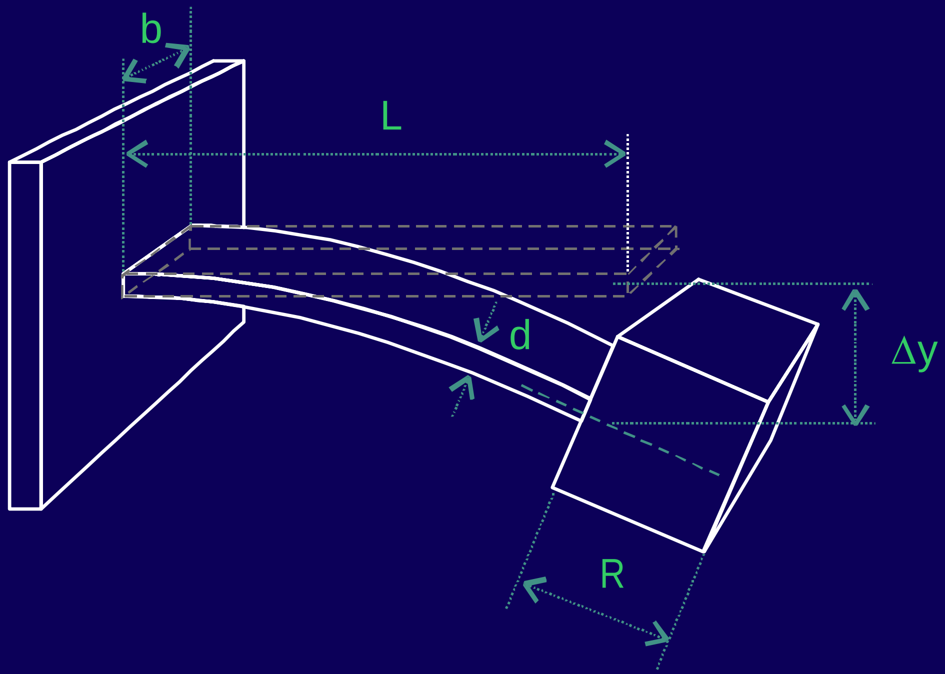
# Microcosmos

different proportions

*Microcosmos*, a Jacques Perrin film (Galatée Films, 1996)

# Scaling

an example




Spring: $$k = \frac{Ebd^3}{4L^3}$$

Mass: $$m = \rho R^3$$

$$\Delta y = \frac{mg}{k} = \frac{4g\rho}{E}\frac{R^3L^3}{bd^3}$$

$$\Delta y \propto S^2$$

# Scaling

| **Physical phenomenon** | **Scales with size S** |
|---|---|
| Time | $S^0$ |
| Van der Waal's forces | $S^{1/4}$ |
| Diffusion | $S^{1/2}$ |
| Size/velocity | $S^1$ |
| Bending stiffness | $S^1$ |
| Electrostatic force | $S^1$ |
| Surface | $S^2$ |
| Thermal loss | $S^2$ |
| (Muscle) strength | $S^2$ |
| Friction | $S^2$ |
| Volume/Mass | $S^3$ |
| Inertia | $S^3$ |
| Magnetism | $S^3$ |

Fluidics:

Small Reynolds Numbers

Laminar flow

- hydrodynamics mainly determined by *viscosity* and *diffusion*

- transport of heat and ions by *diffusion*

Large Reynolds numbers

Turbulent flow :

- hydrodynamics mainly determined by *convective* and *inertial forces*

-transport of heat and ions by *convection*

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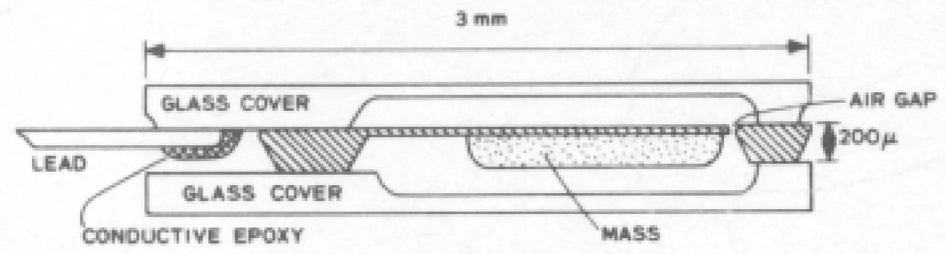
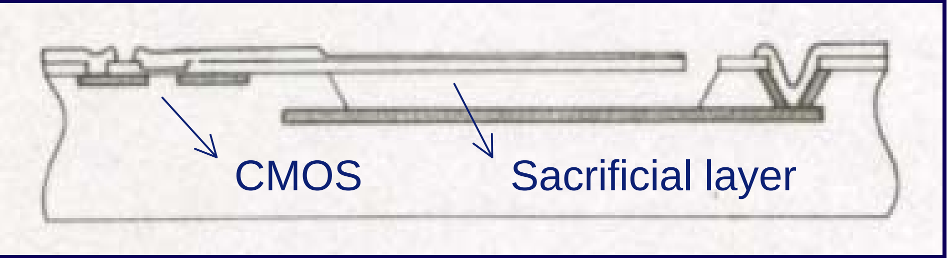
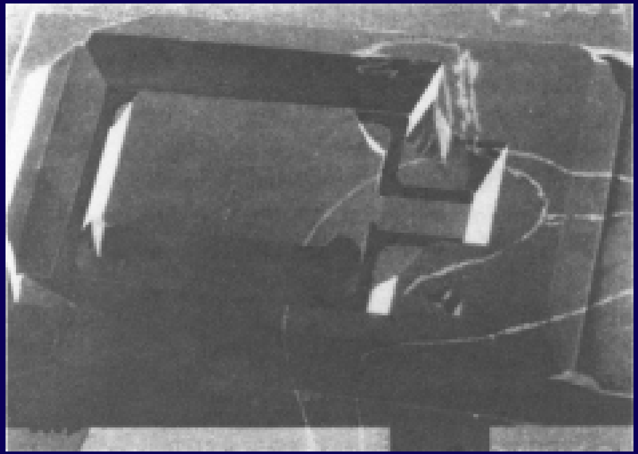
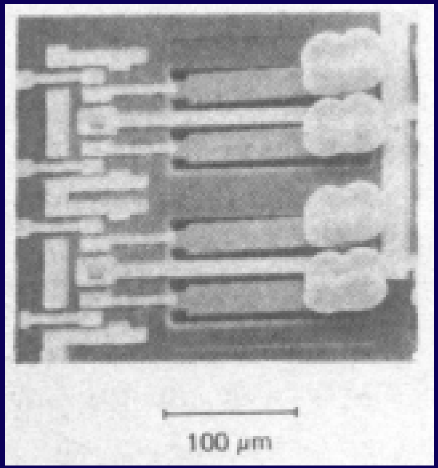
# Surface- and bulk-micromachining

*Accelerometers*






## 1979: Bulk micromachining

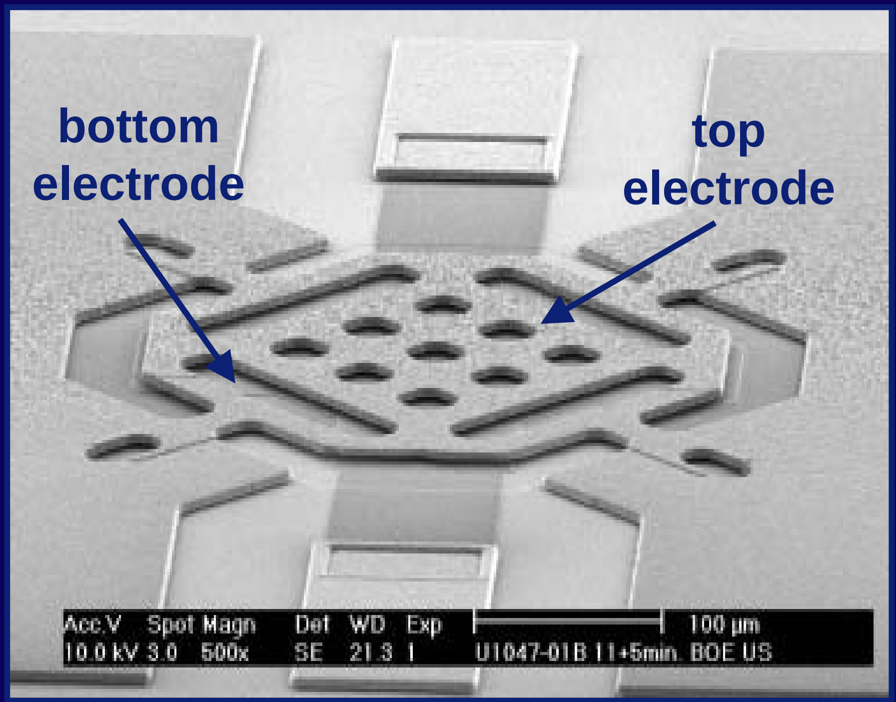
L.M. Roylance, J.B. Angell,
IEEE Trans. Electron Dev., ED-26 (1979) 1911

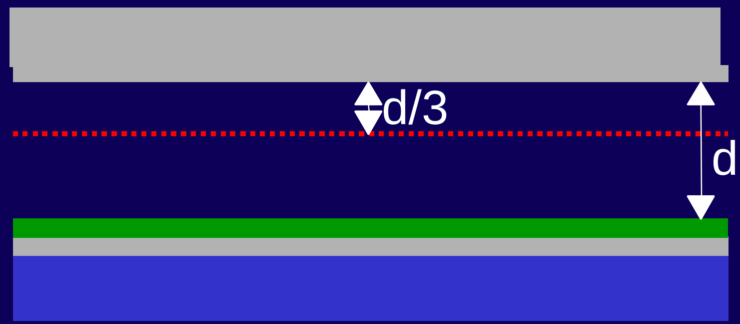
## 1982: Surface micromachining

K.E. Petersen, A. Shartel, N.F. Raley,
IEEE Trans. Electron Dev., ED-29 (1982)

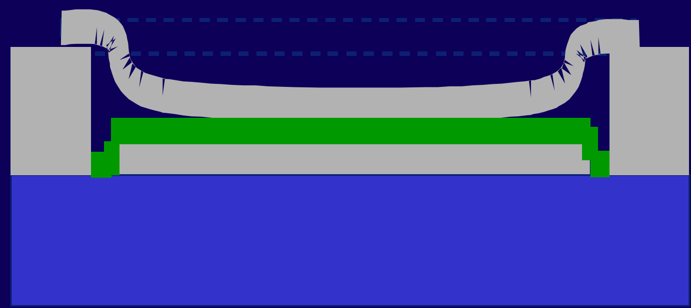
# RF-MEMS

*switchable/tuneable capacitors*



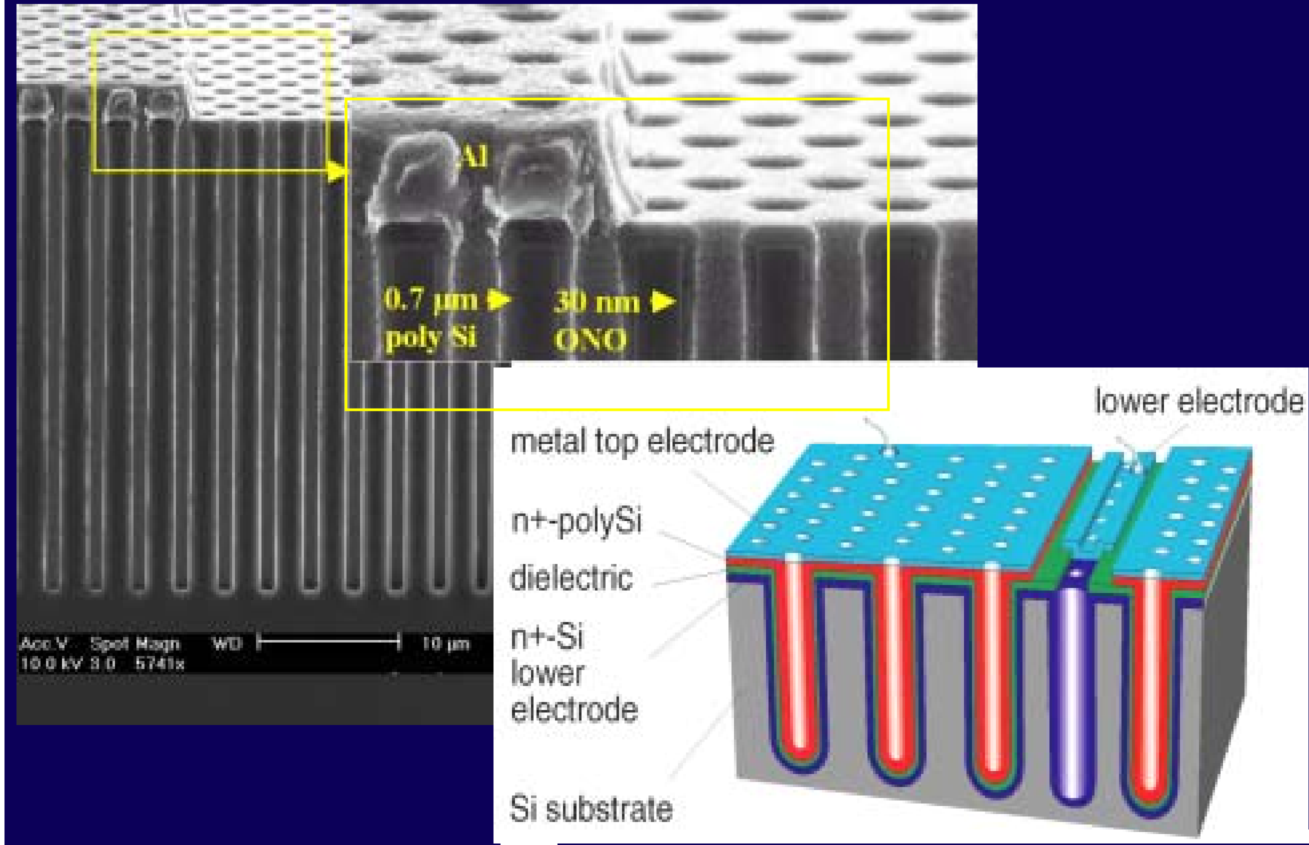

open (1 pF)

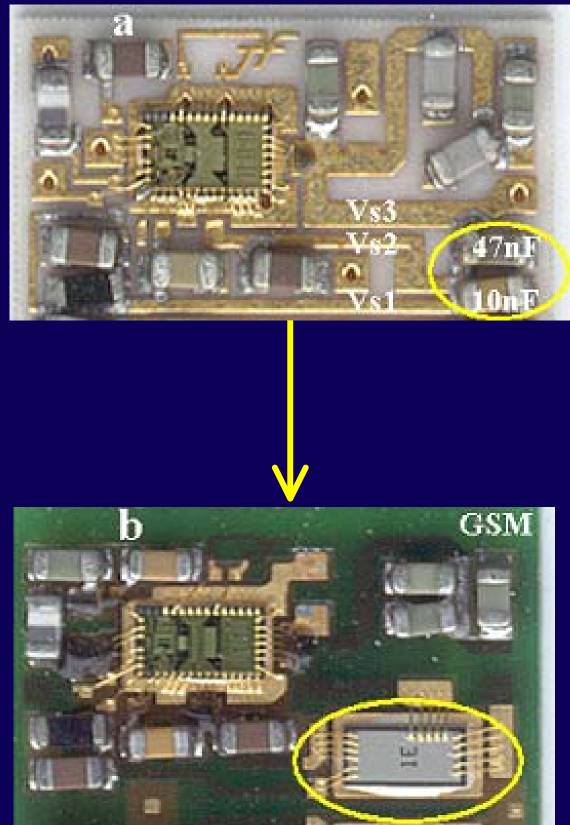


closed (20 pF)

Free-hanging metal membrane over air gap

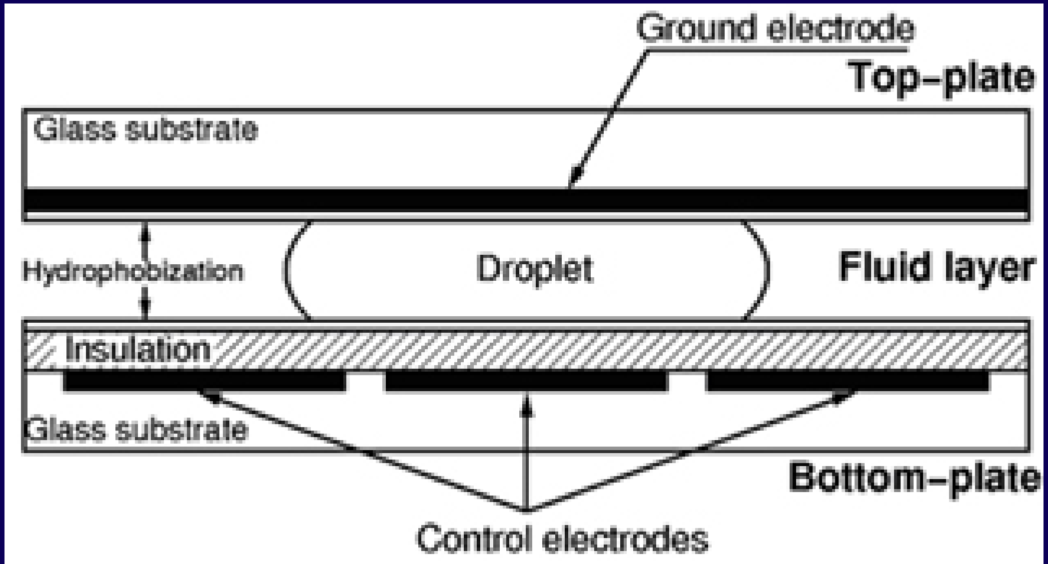
# Low-loss MOS integrated capacitors




GSM power amplifiers

# Fluidics: electrowetting






*Source: Digital Microfluidics,*
*Duke University, Durham, NC*
*http://www.ece.duke.edu/Research/microfluidics/*

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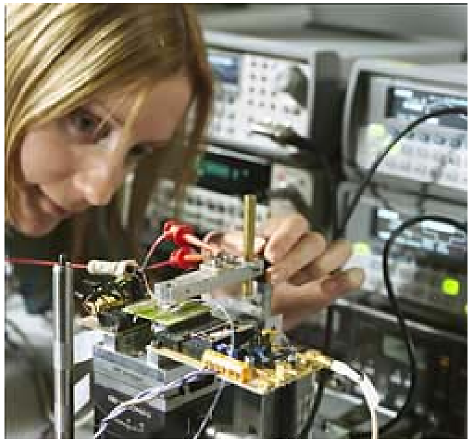
Philips Research Press Release

*June 24, 2004*

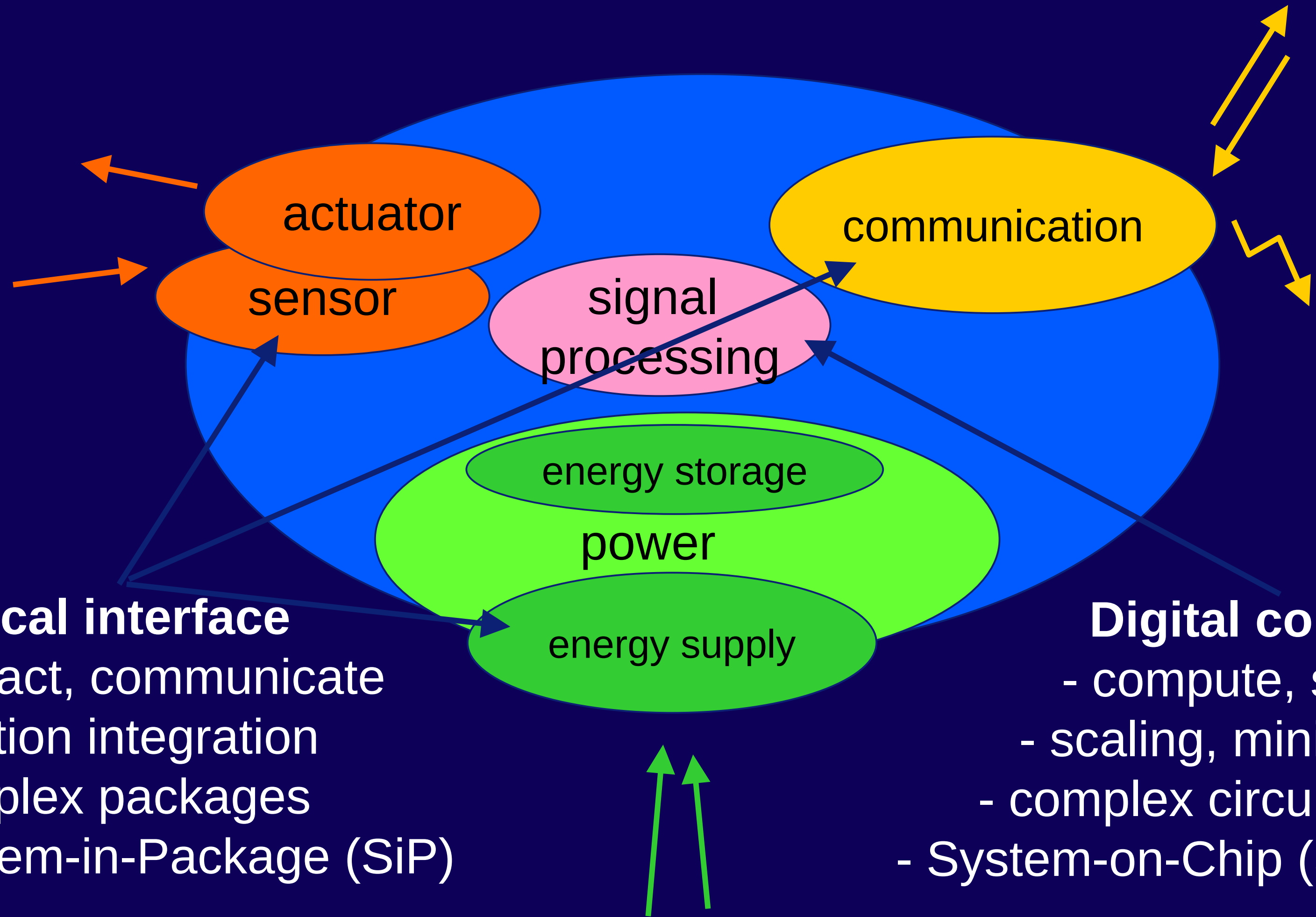
**Philips demonstrates magnetic biosensors for high-sensitivity molecular diagnostics**



# What’s in common?

- Devices integrated in a system-in-package (SiP)
- Integration across different technology domains
  *electronics, mechanics, optics, fluidics, magnetics, chemistry, biology*
- Physical building blocks for Ambient Intelligence (‘*daily life*’)

# Physical building blocks




**Physical interface**

- interact, communicate
- function integration
- complex packages
- System-in-Package (SiP)

**Digital core**

- compute, store
- scaling, miniaturization
- complex circuits
- System-on-Chip (SoC)

"More than Moore"

"Moore"

# Research strategy

- develop device concepts across technology domains
- integrate functions into one technology platform
- (re-)use available technologies

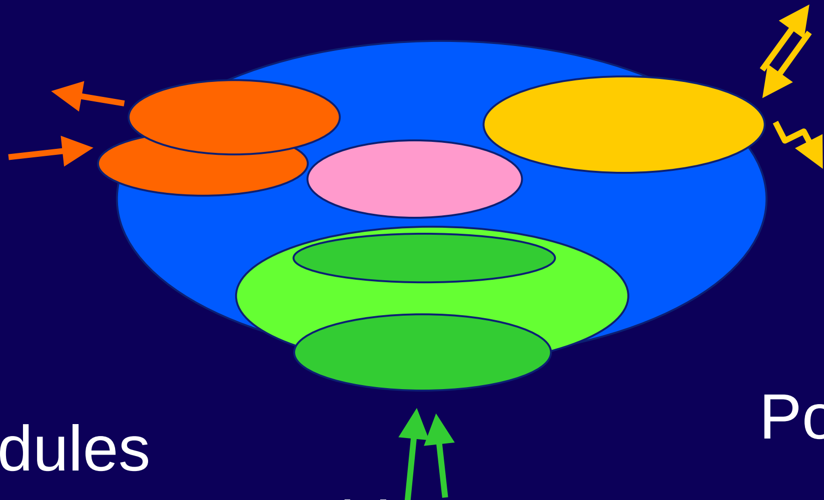
    *CMOS, passive integration, substrate transfer, magneto-resistive,..*

- optimize for an integrated system solution

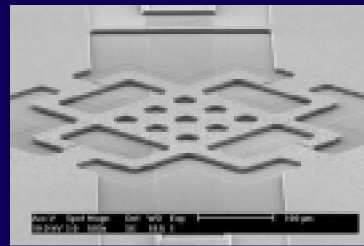
    *packaging, interface electronics, circuit design, algorithms*

# Research program

Sensors & actuators

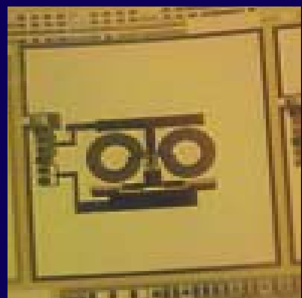


RF passive integration



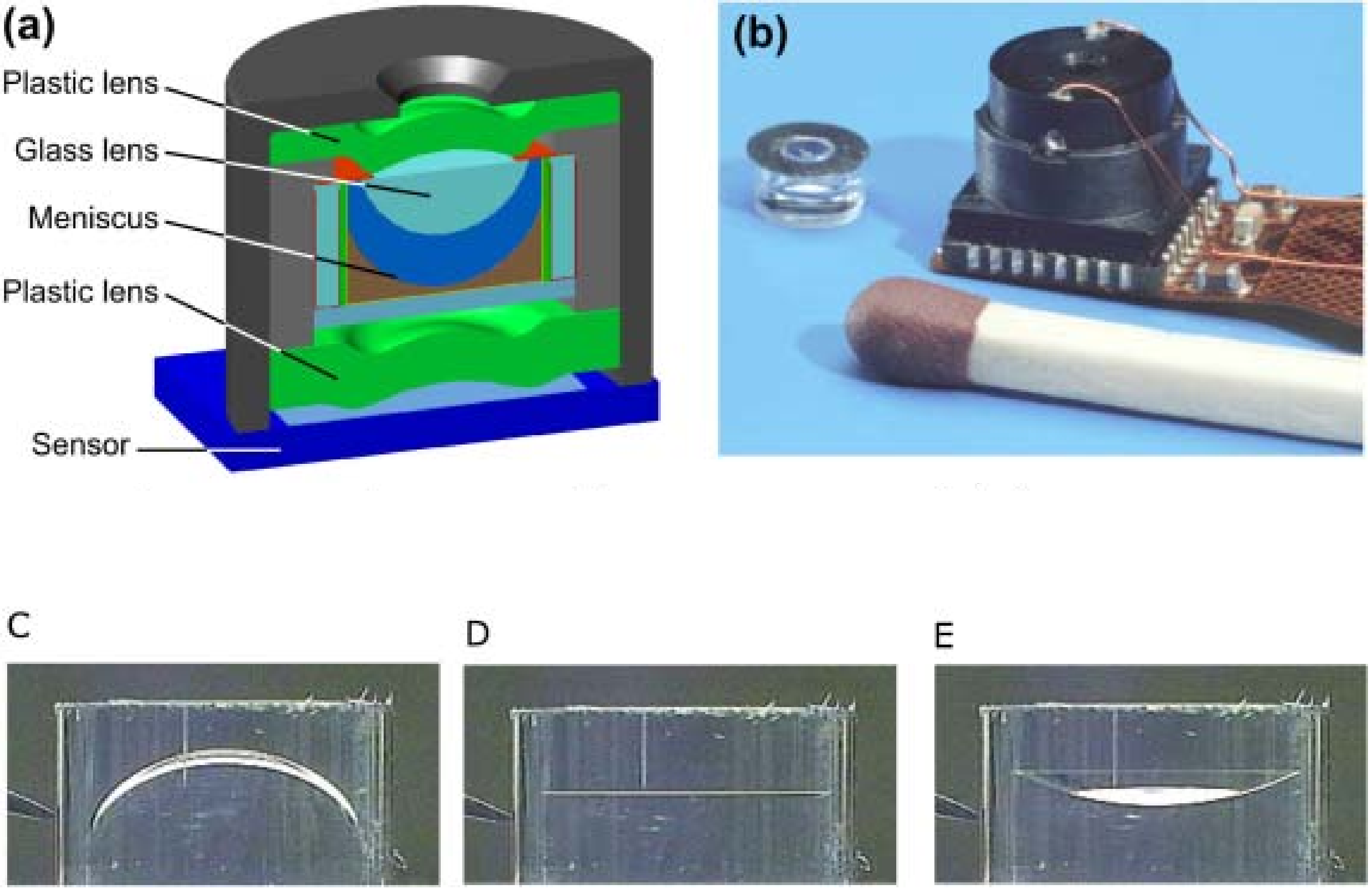
Smart LED modules

Portable energy &
autonomous devices



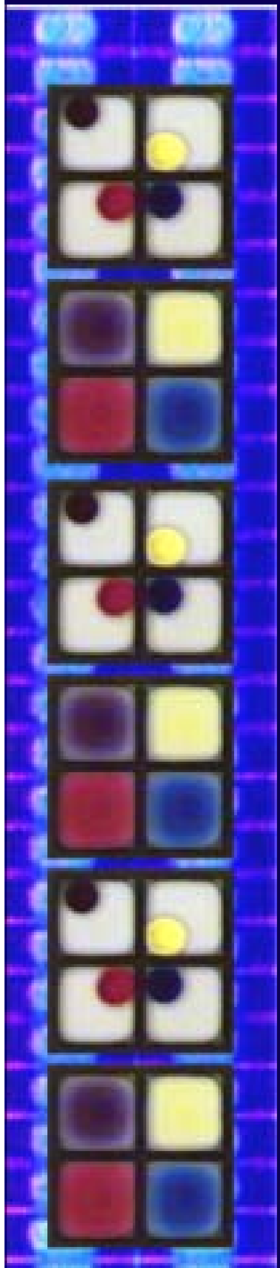
Polymer electronics

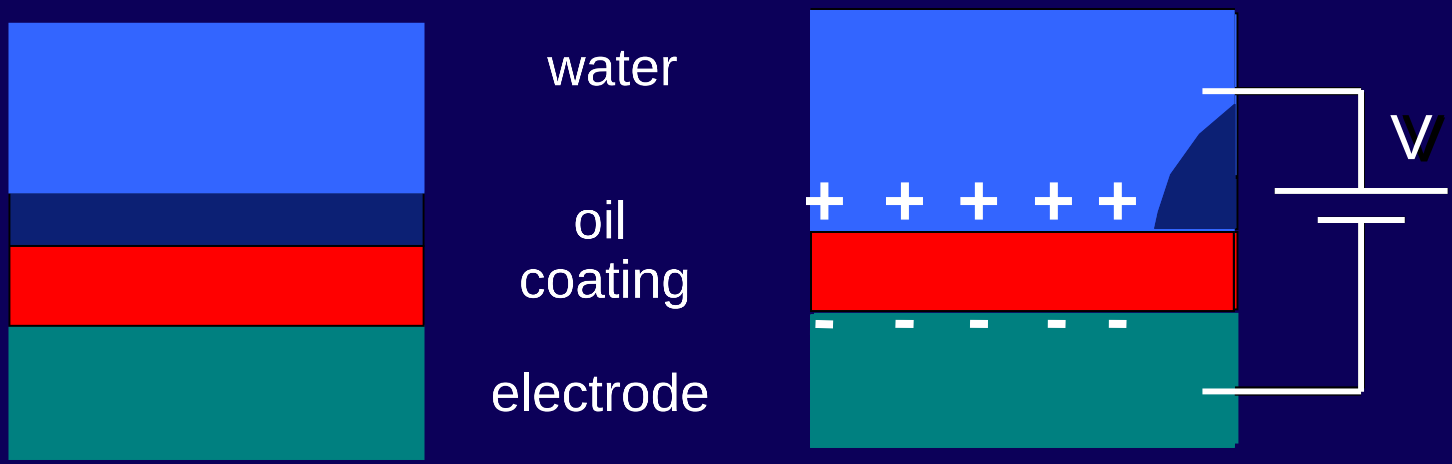
# Electrowetting: fluid focus lens



# Electrowetting display

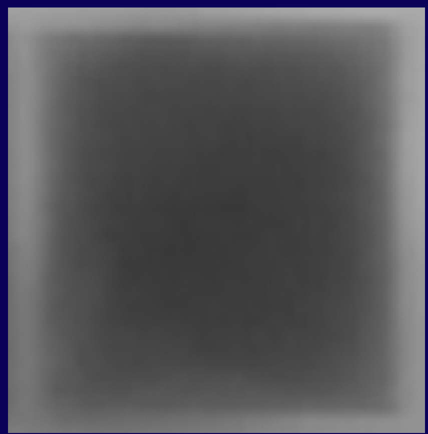
*Principle*

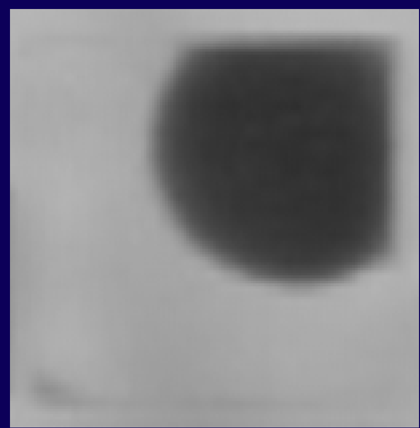





Homogeneous oil film

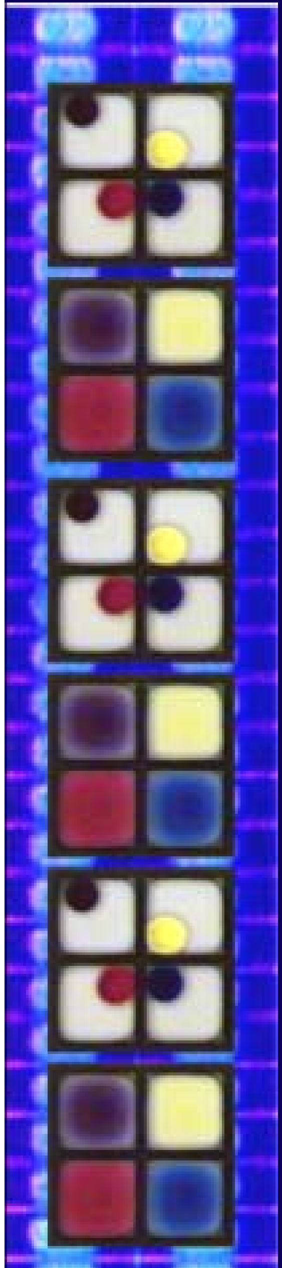
Oil pushed aside

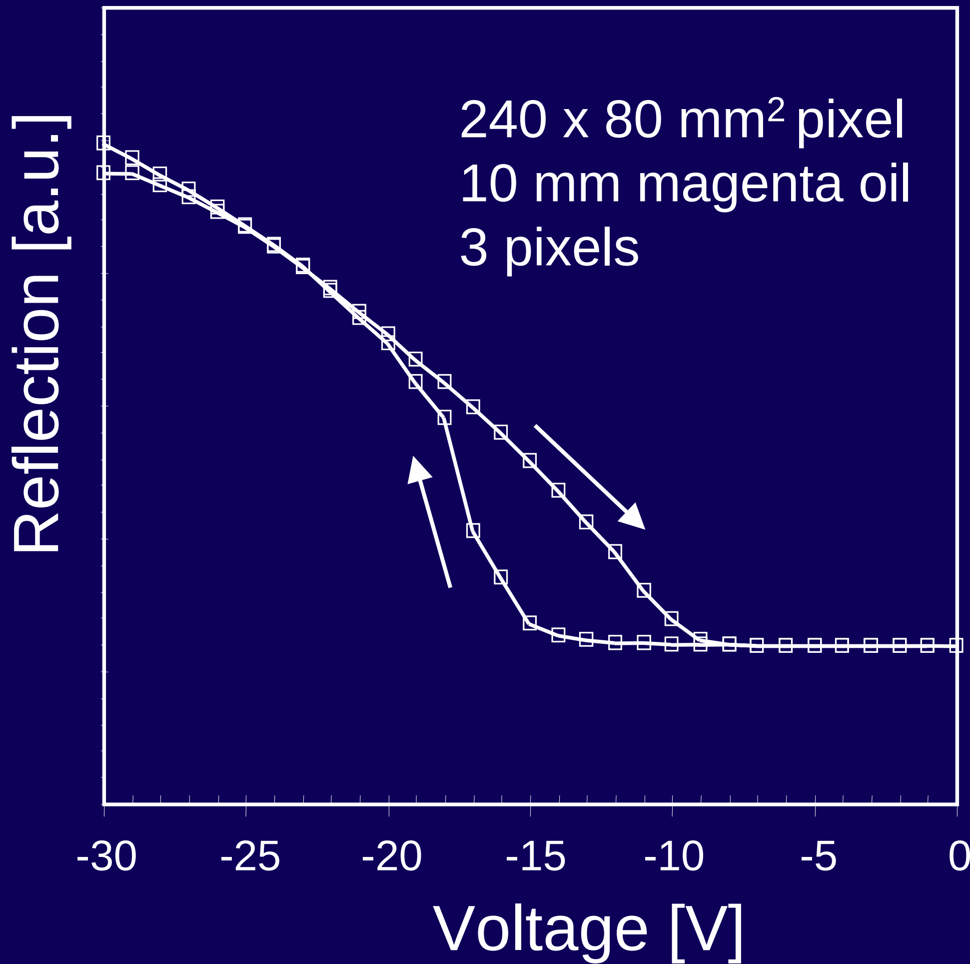




# Electrowetting display

*Electro-optic characteristics*






- Reflectivity 60 % (B/W)*
  40 % (color)
- Contrast > 15
- Analog grey scales
- Switching @ 100 Hz
- Power ~ AMLCD
- Cost & Manufacturing
  ~ AMLCD

* LCD 17 %

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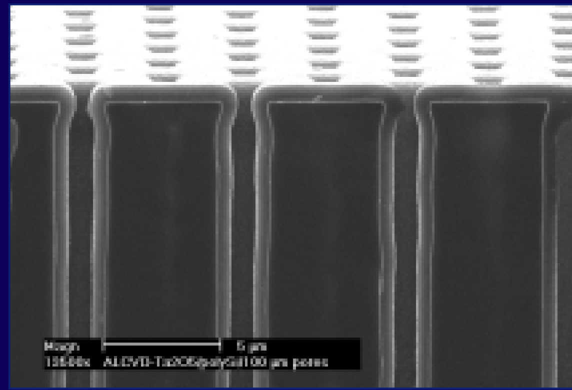
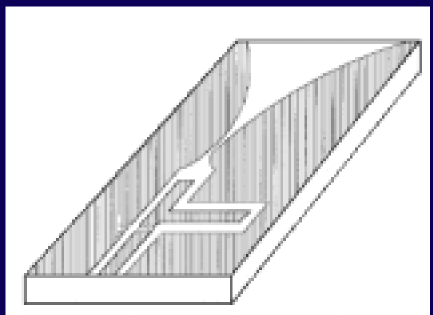
# RF Passive Integration

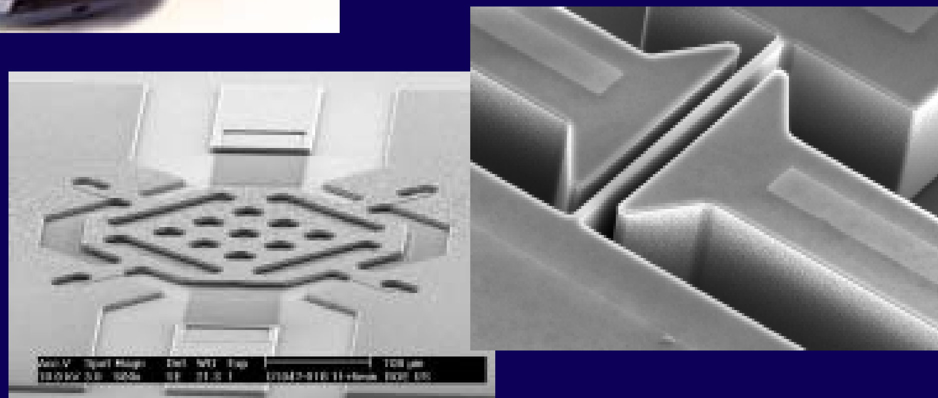
Bulk Acoustic Wave filters



High-density capacitors



mm-wave devices



Micro-mechanical switches & oscillators

# SiP solutions for mobile phones

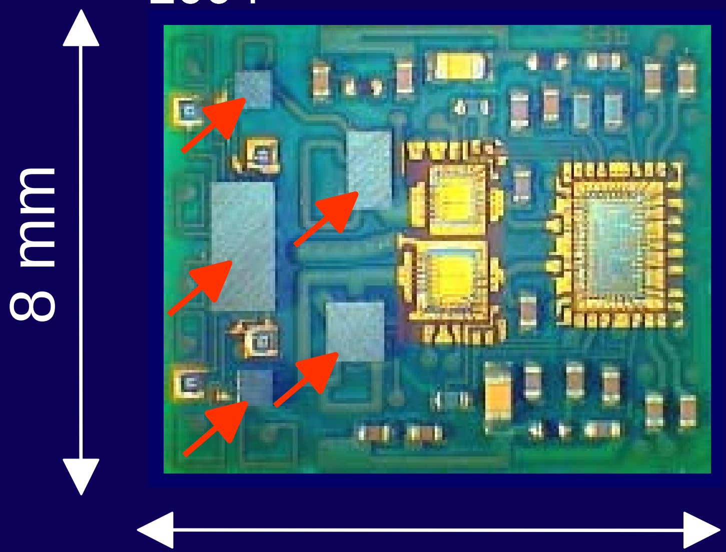
# RF Passive Integration on Si (PASSI$^{TM}$)

*thin-film inductors & capacitors*

1998


Single-band transmit module

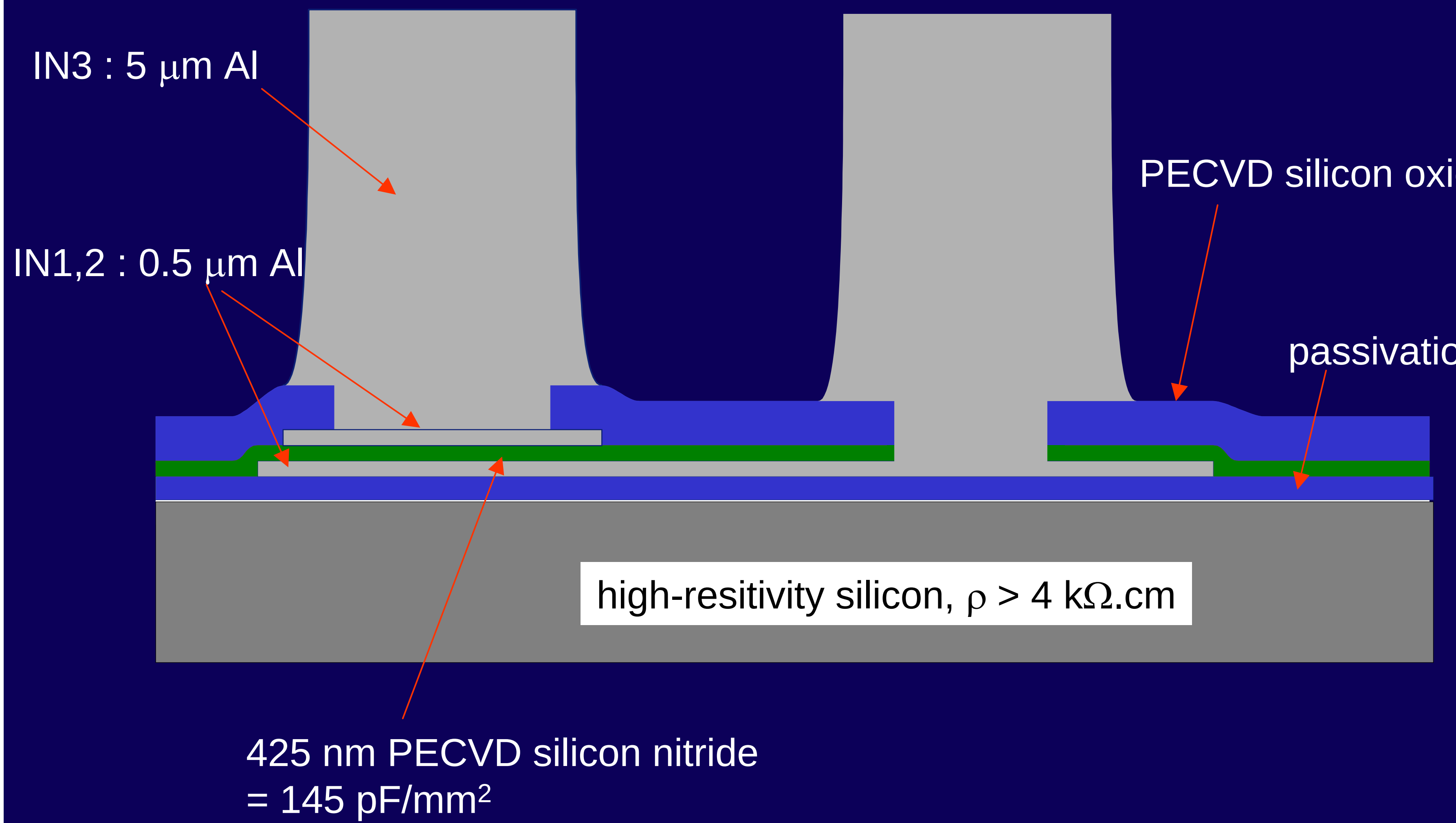
2004




Quad-band transmit module with 5 PASSI$^{TM}$ chips

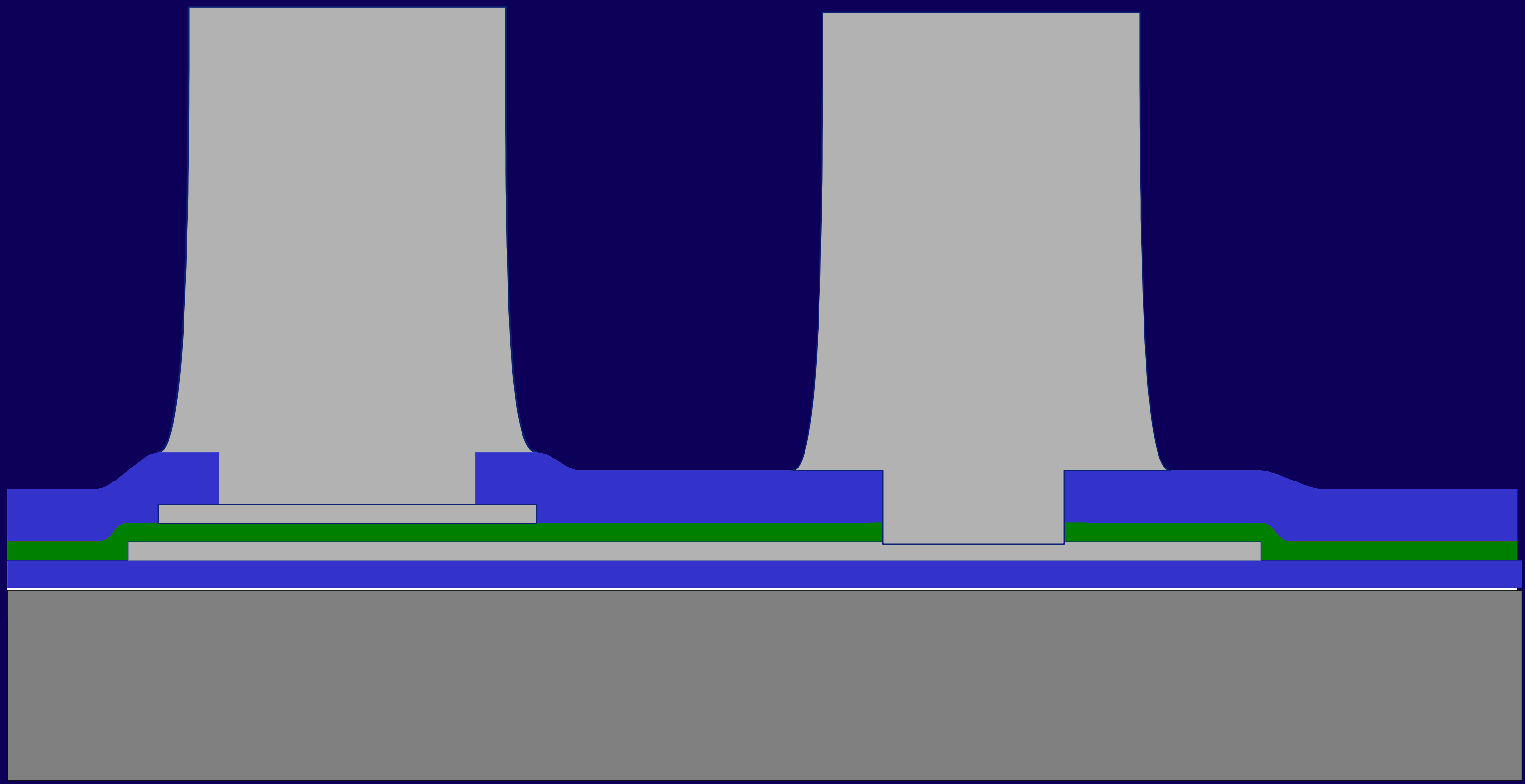
# RF Passive Integration on Si

*thin-film inductors & capacitors* (Philips PASSI™)



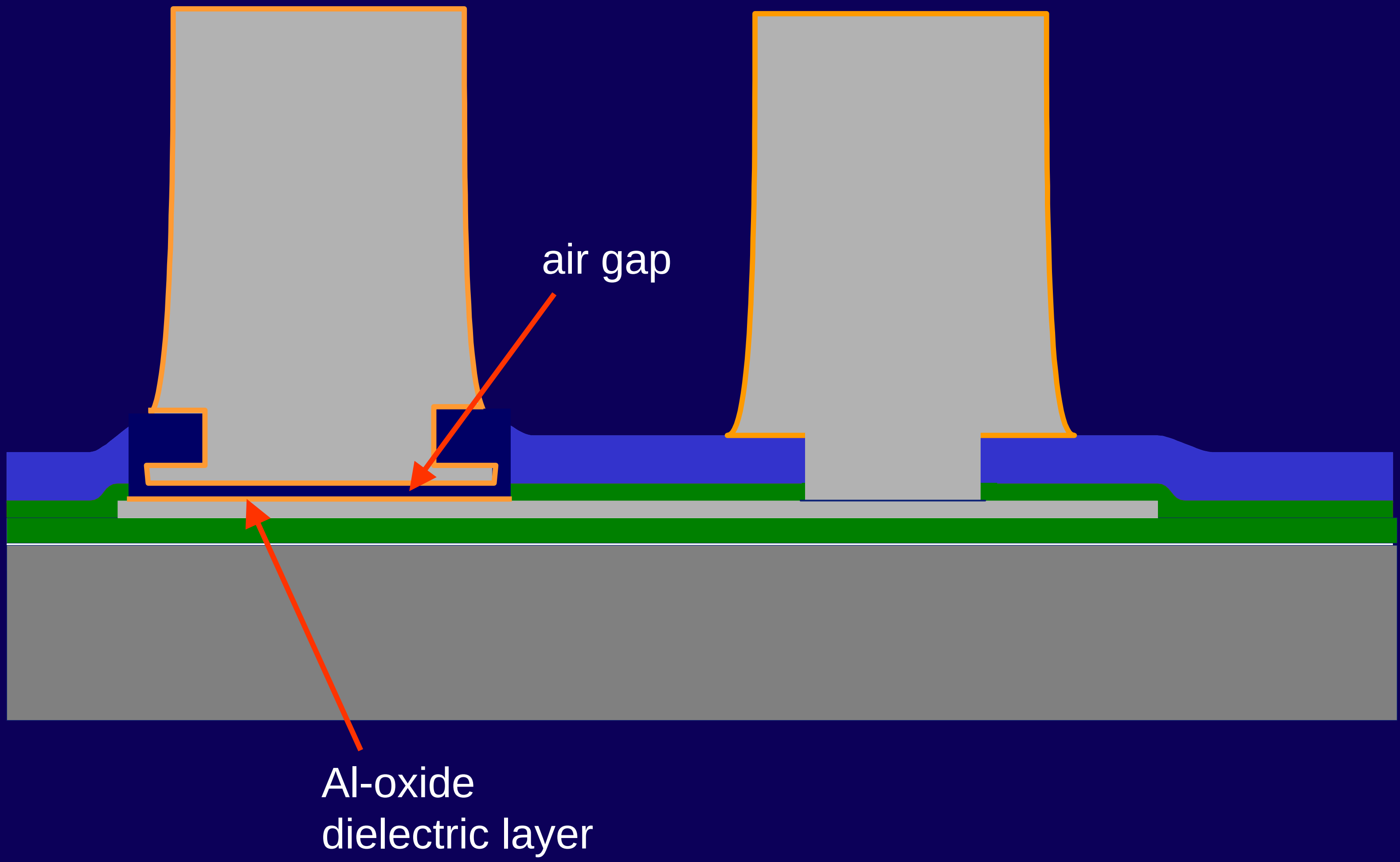
# RF Passive Integration on Si

*thin-film inductors & capacitors* (Philips PASSI$^{TM}$)



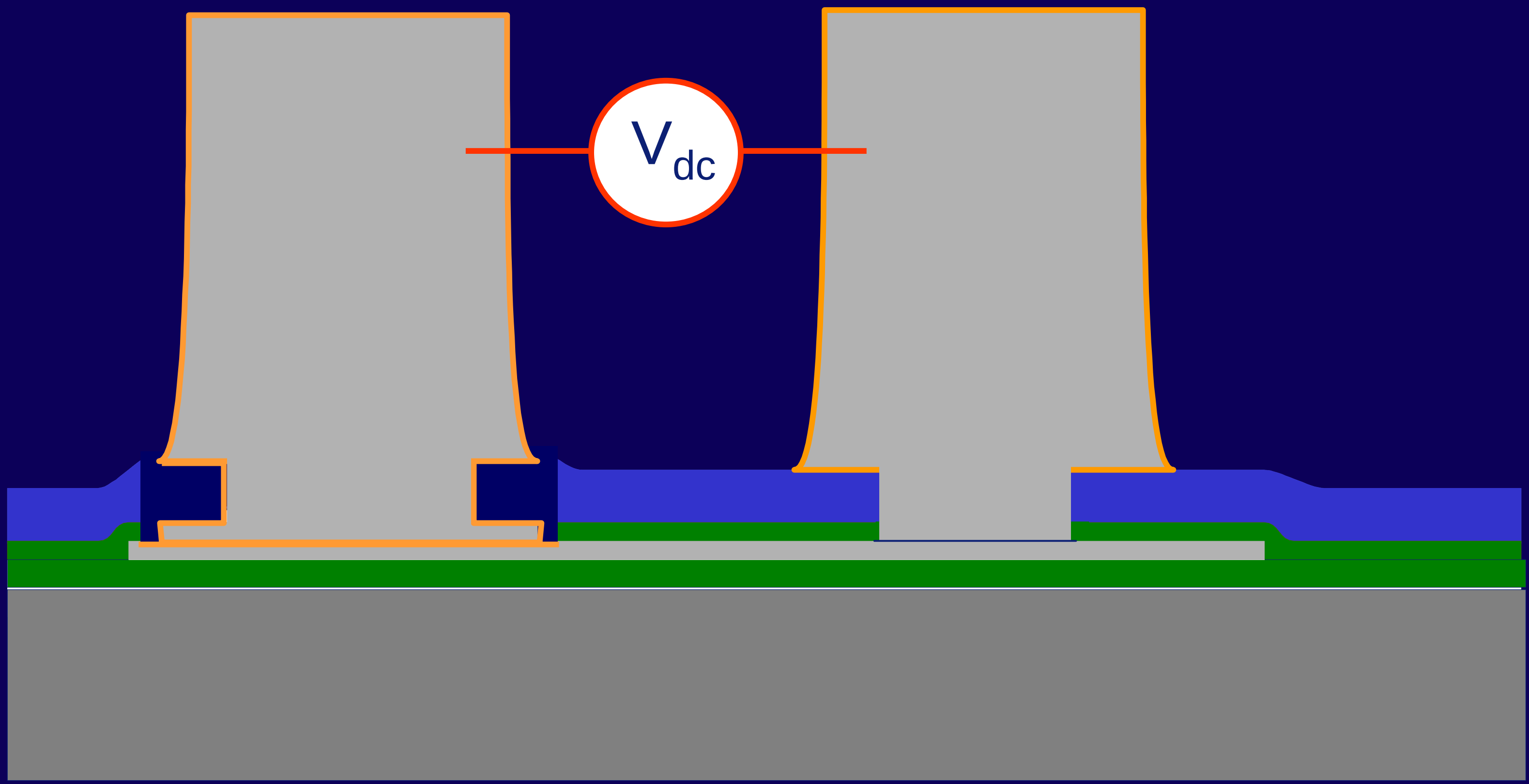
# RF Passive Integration + MEMS modules

*thin-film inductors & switchable capacitors*



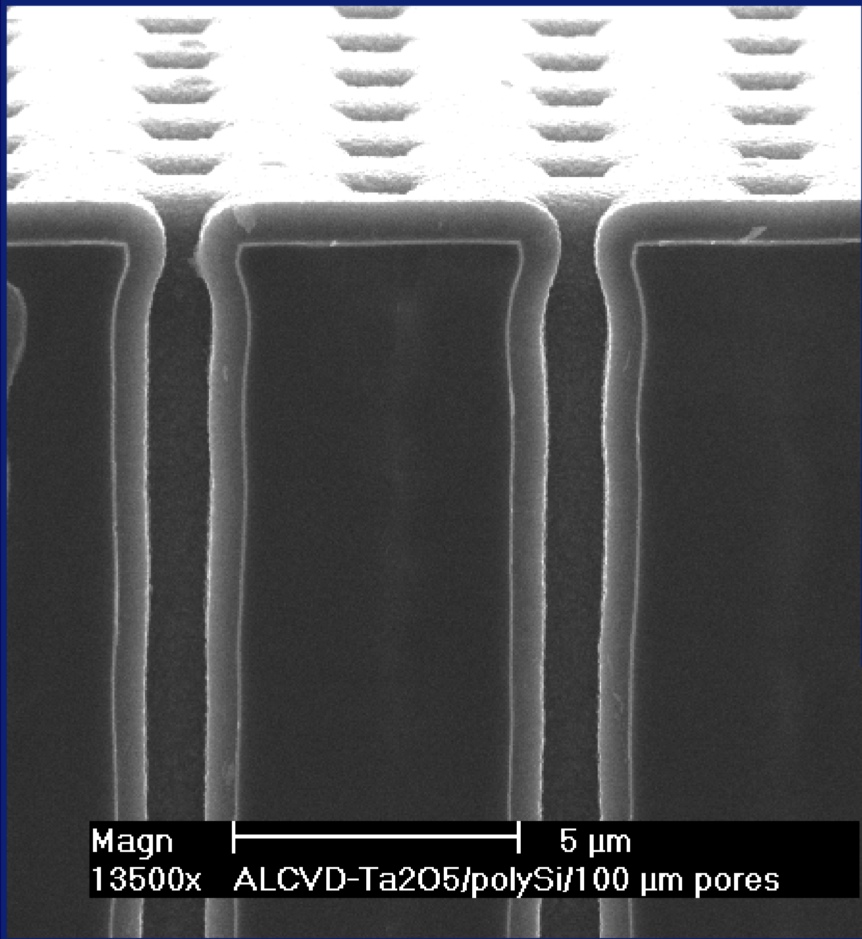
# RF Passive Integration + MEMS modules

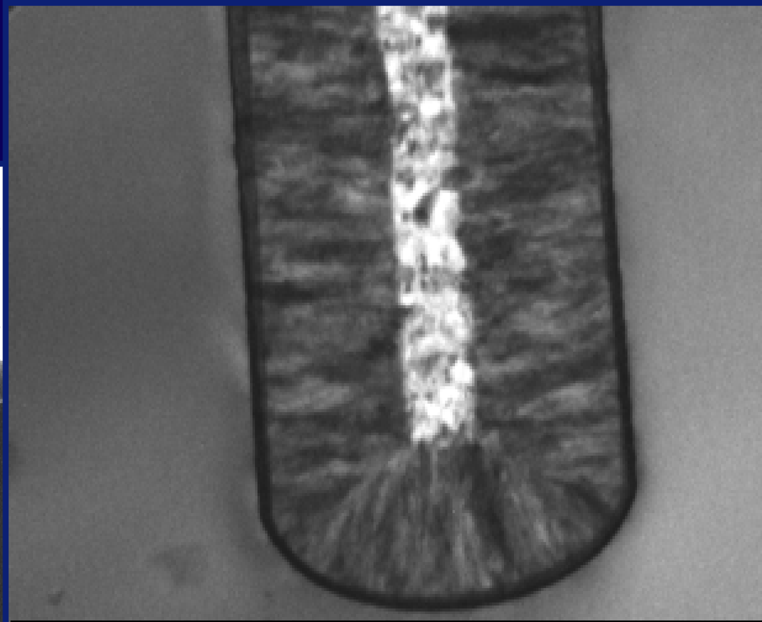
*thin-film inductors & switchable capacitors*



# High-value trench capacitors

1. Increase surface area
2. Increase dielectric constant

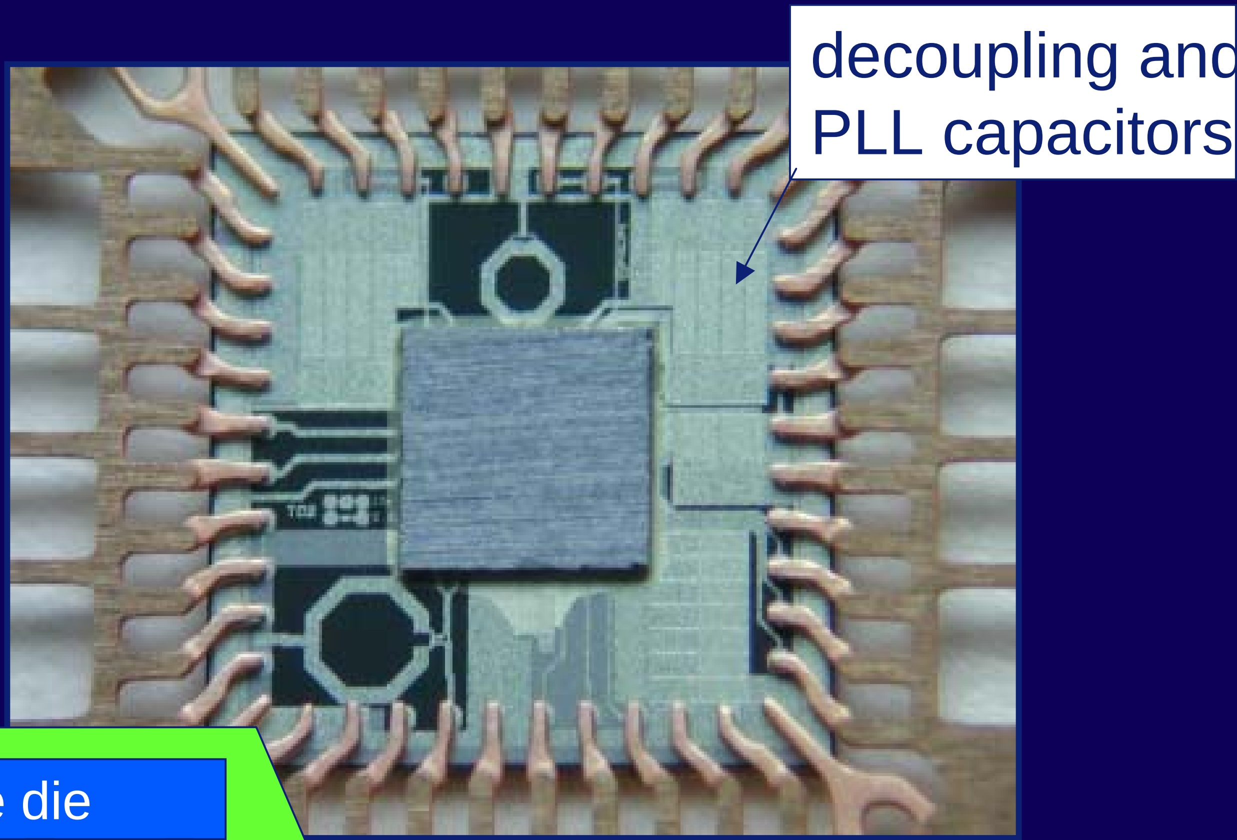


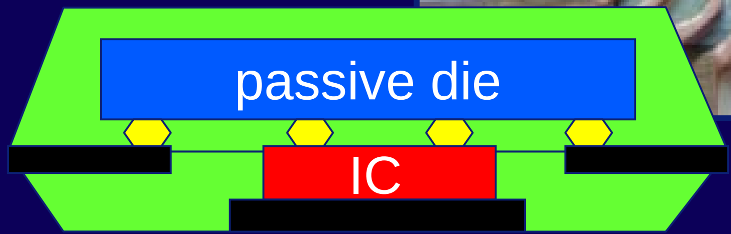



| | |
|---|---|
| $SiO_2$, SiN: | 30 - 90 nF/mm² |
| $HfO_2$, $Ta_2O_5$: | ≥ 250 nF/mm² |

Co-operation with *Jusung, ASM-I*

# Bluetooth *plug ‘n play* SiP module



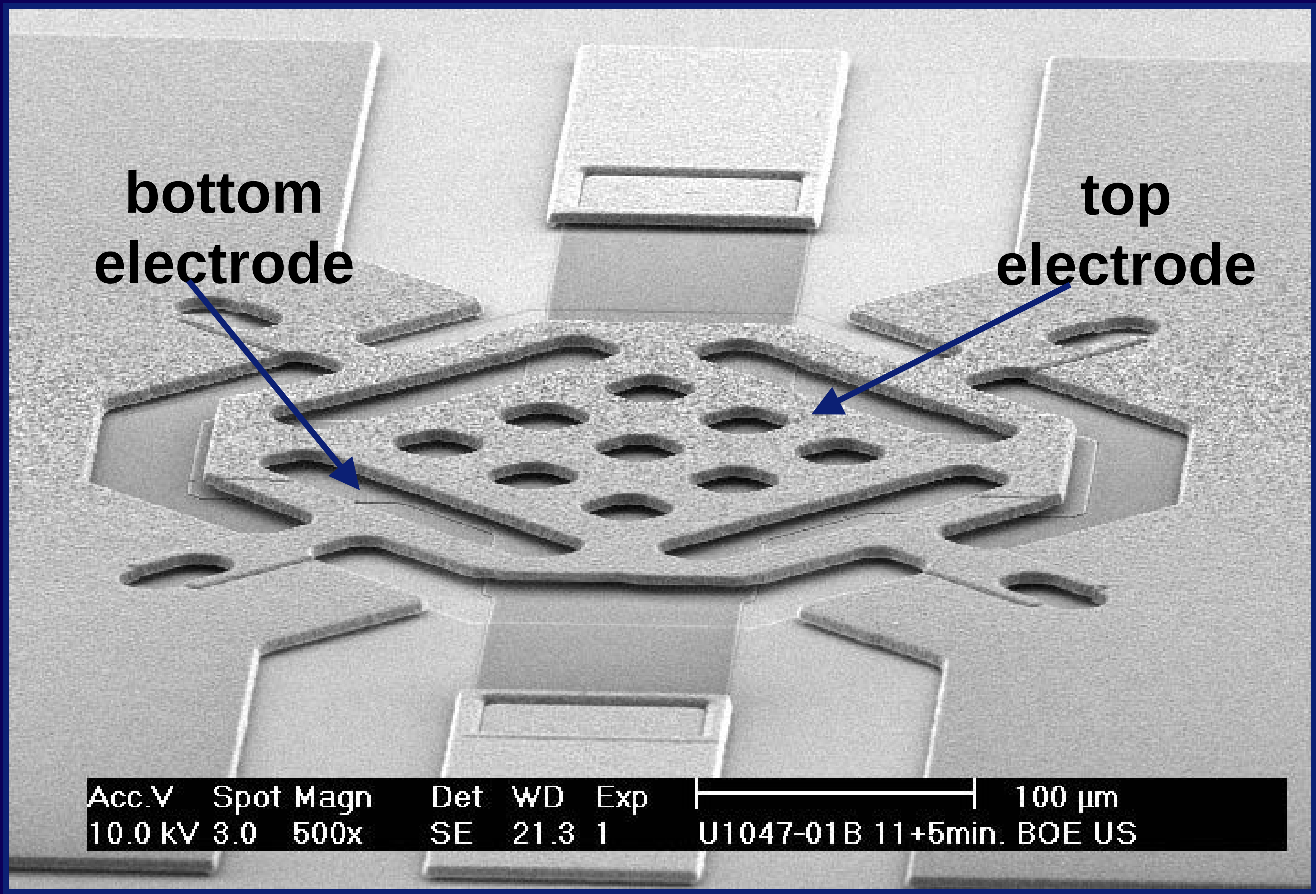



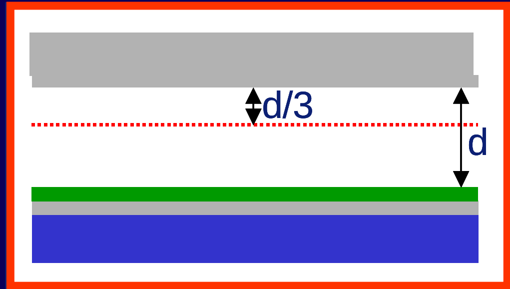

double flip-chip on lead frame
(HVQFN)

*Source: Philips, France*

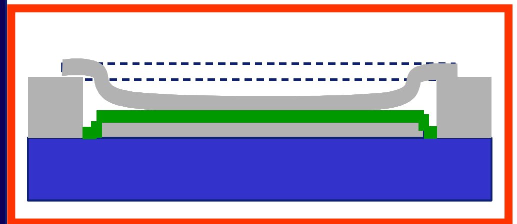
# RF-MEMS switchable capacitor

*Free-hanging metal membrane over air gap*



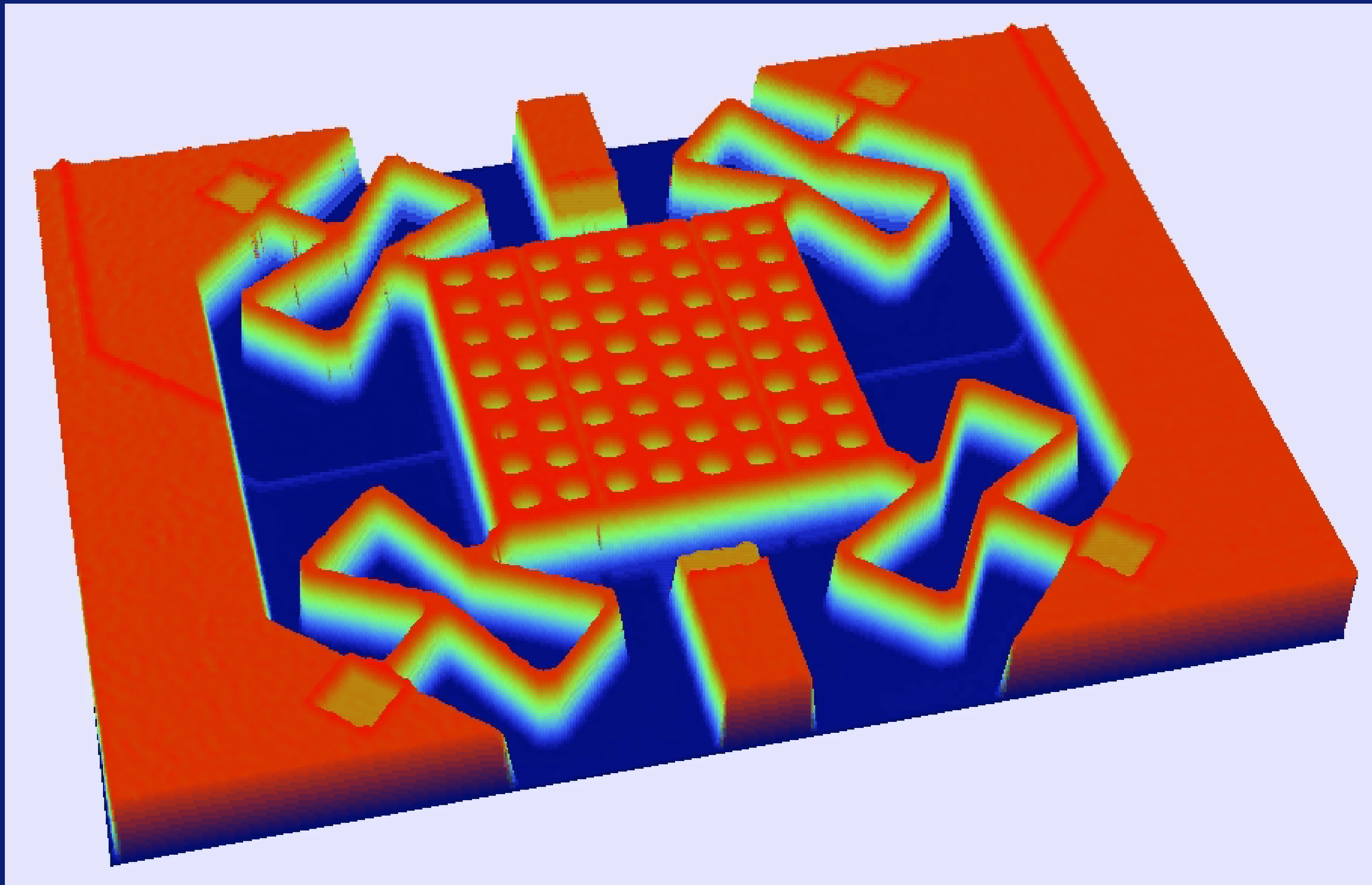

Open (1 pF)



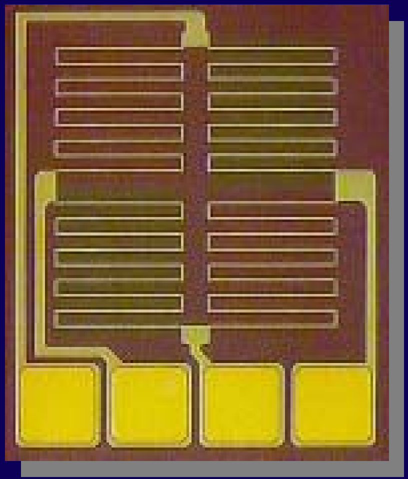
Closed (20 pF)

# RF-MEMS switchable capacitor

*Optical measurement*



# Sensors & actuators

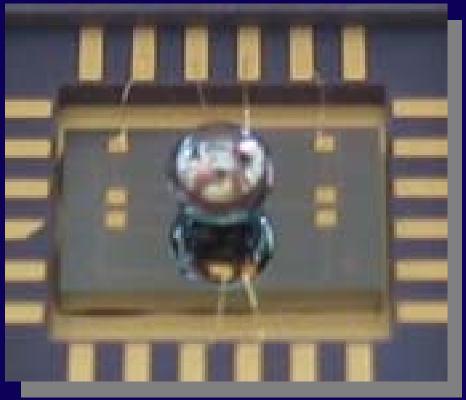


Magnetic sensor technology

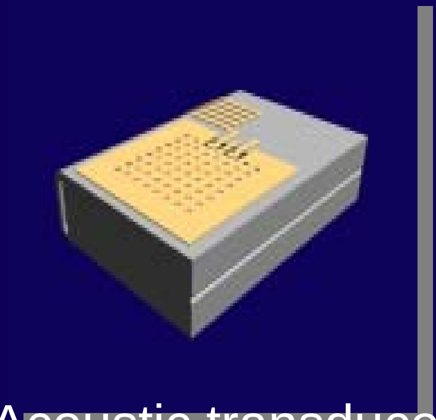
Magnetic mouse pointer

Electrowetting

Magnetic biosensor

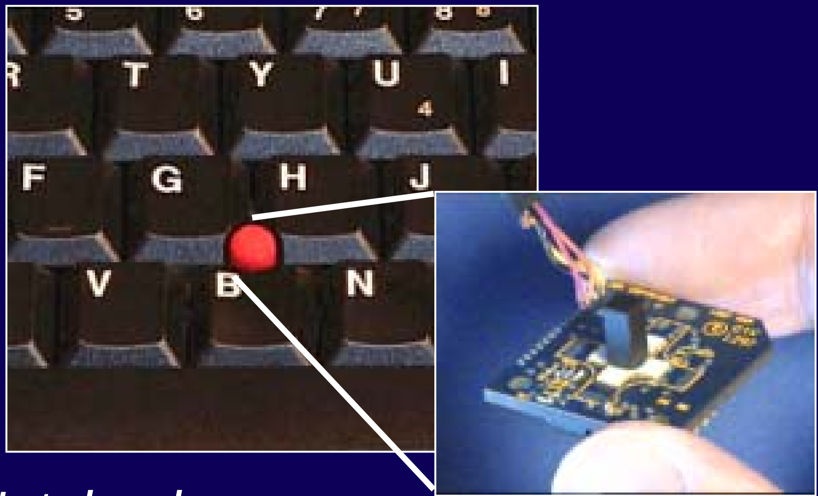


3D navigation



Acoustic transducers

# Integrated mouse pointer



*Notebooks*

*PDA's*

*Game consoles*

*Cell phones*

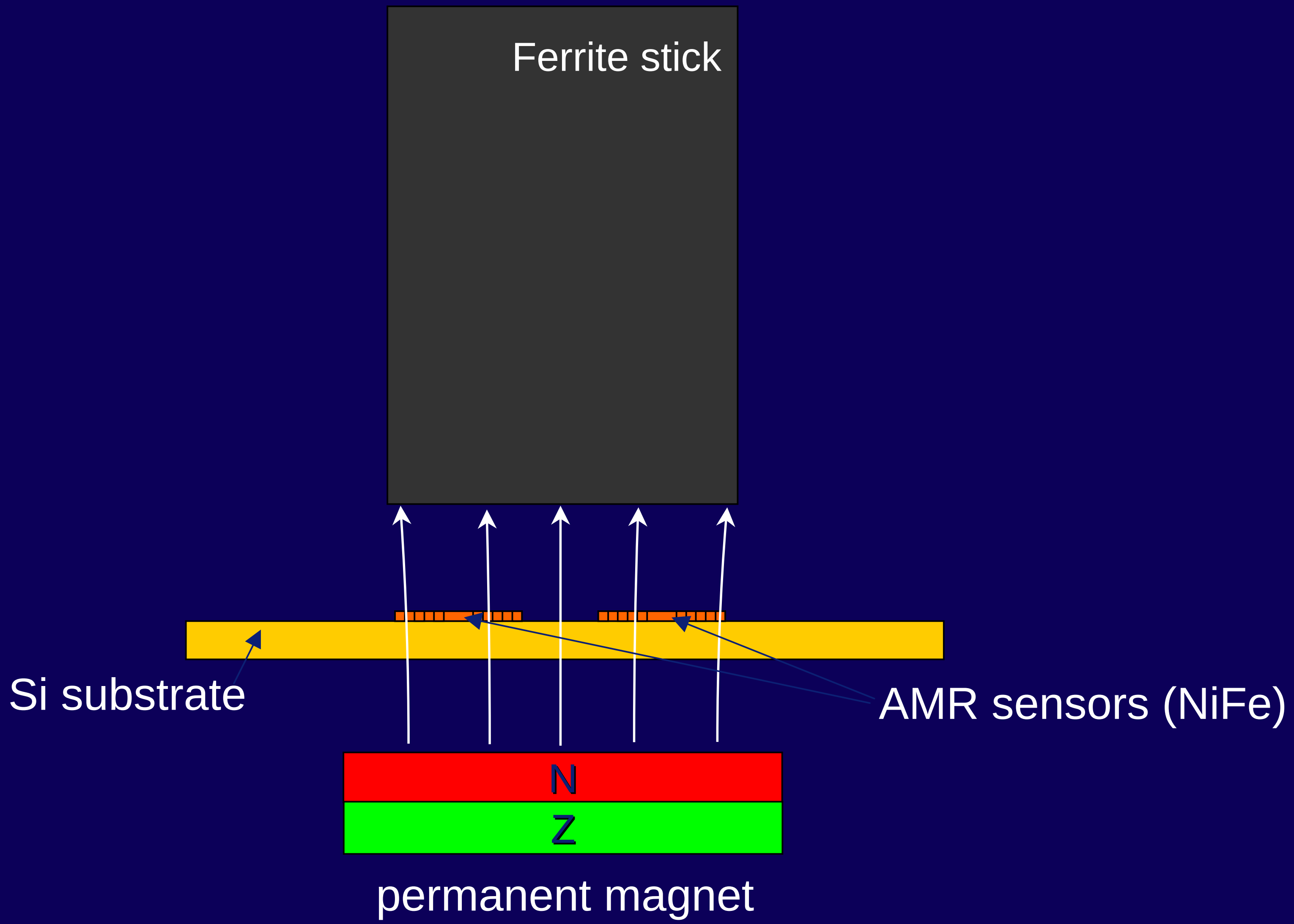

- Micro-controller is commodity
- Added value is in total solution (SiP)

↓

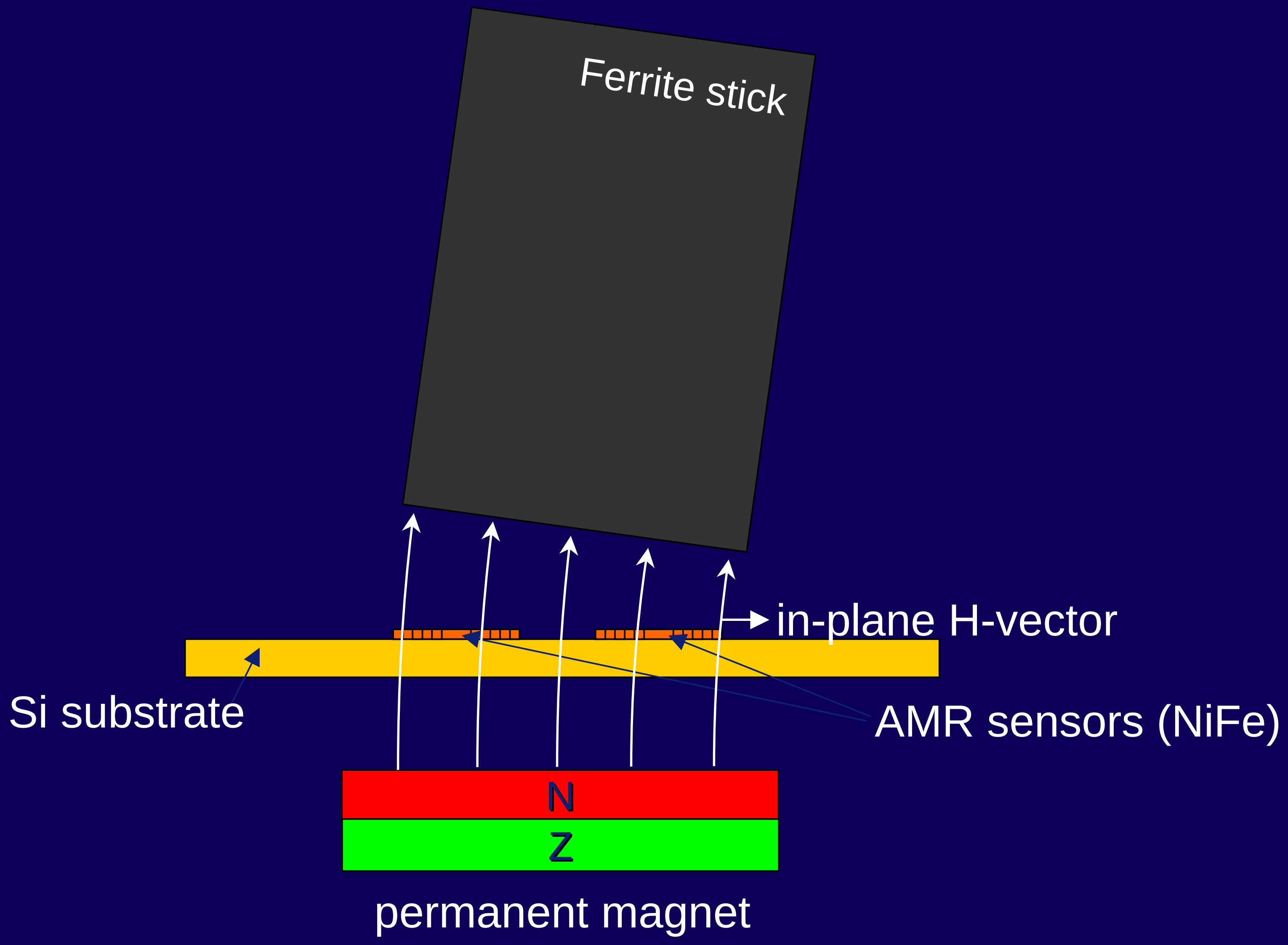
develop chip-size SiP solution

Electronics —— Sensor

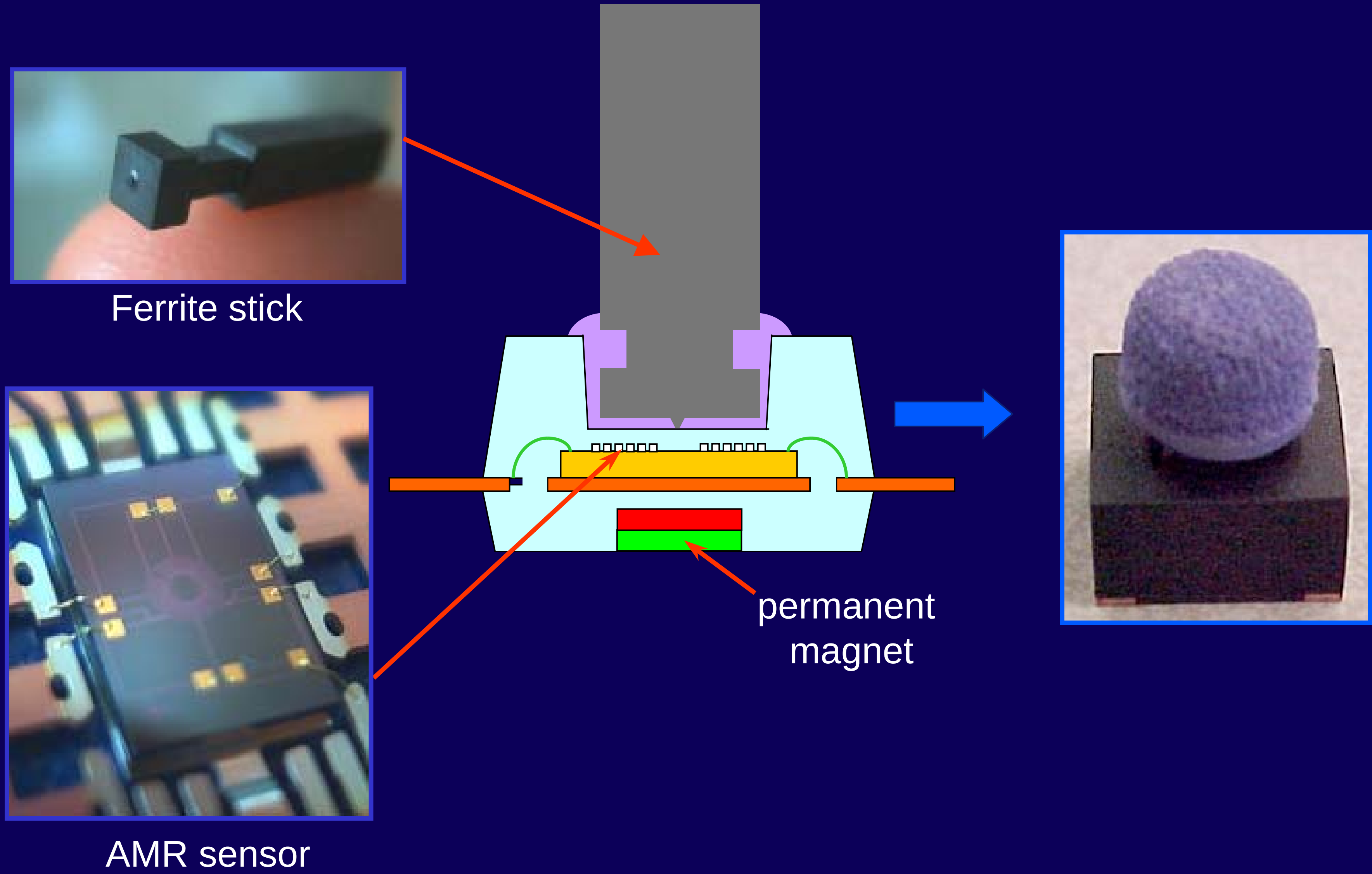
# Magneto-resistive sensing concept



# Magneto-resistive sensing concept



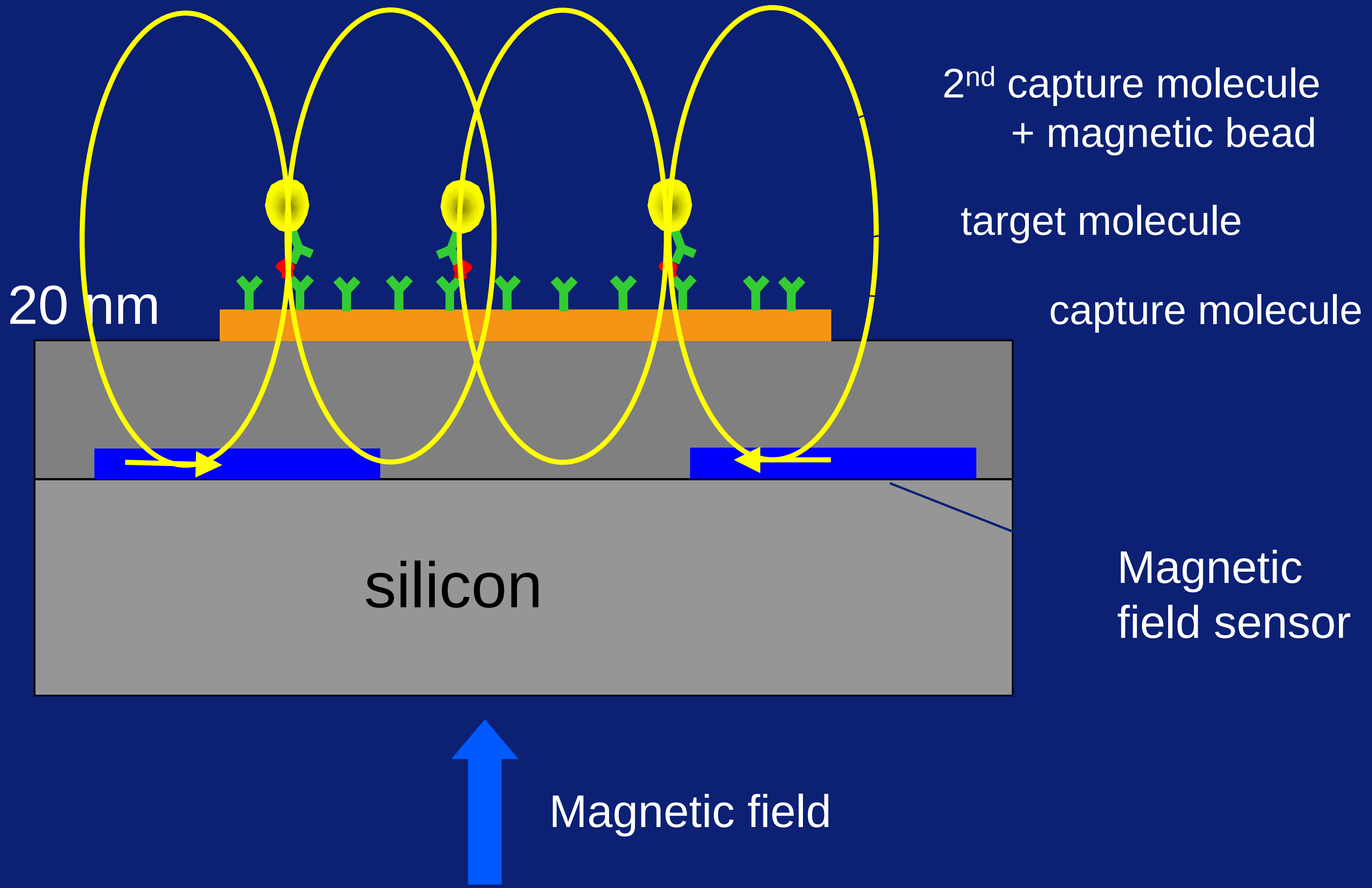
# Stick-in-chip module



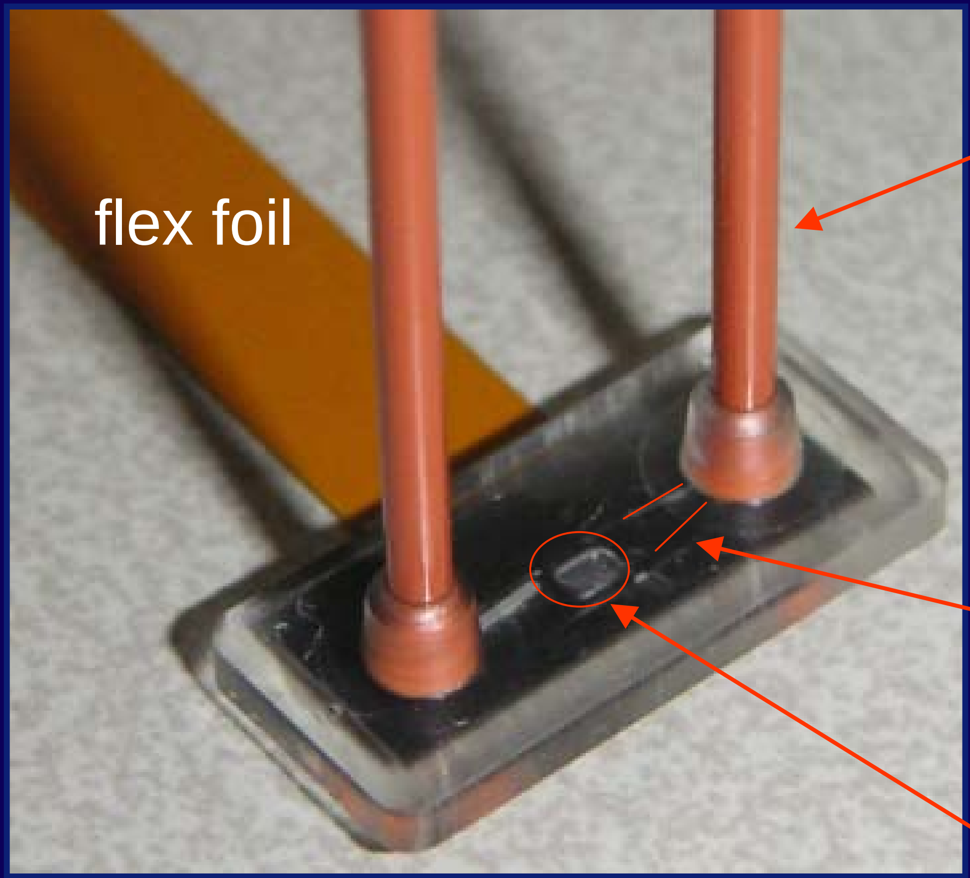

*In co-operation with IBM*

# Magnetic biosensor

*for point-of-care analysis in early stage*



# Biosensor cartridge



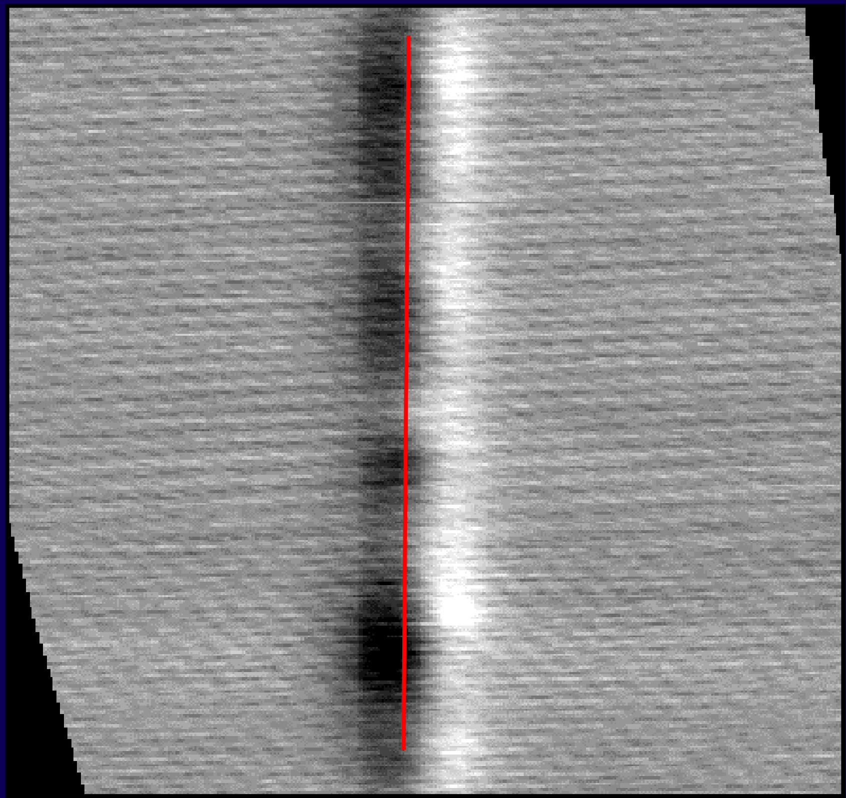

fluid injection

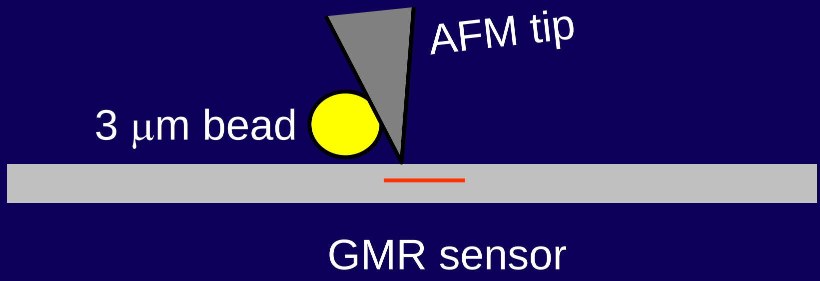
channel

sensor chip
(1 x 1 mm $^2$)

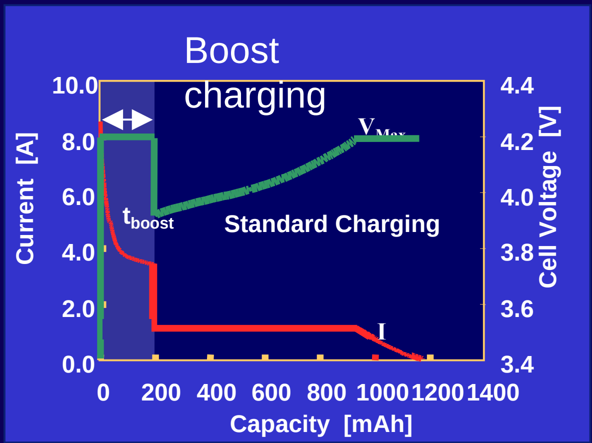
*In co-operation with Philips AppTech*

# Detecting single magnetic bead

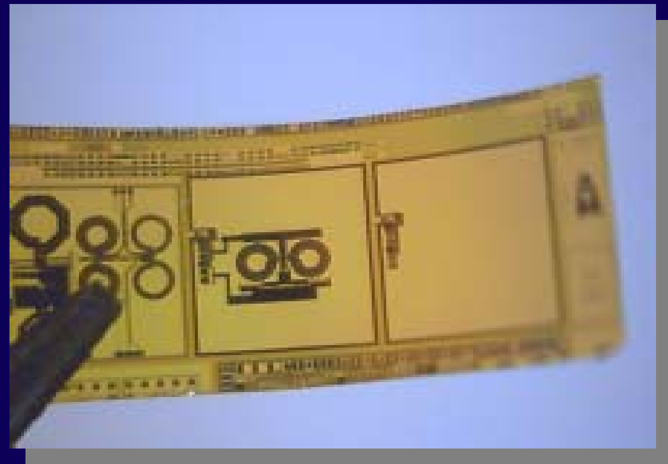




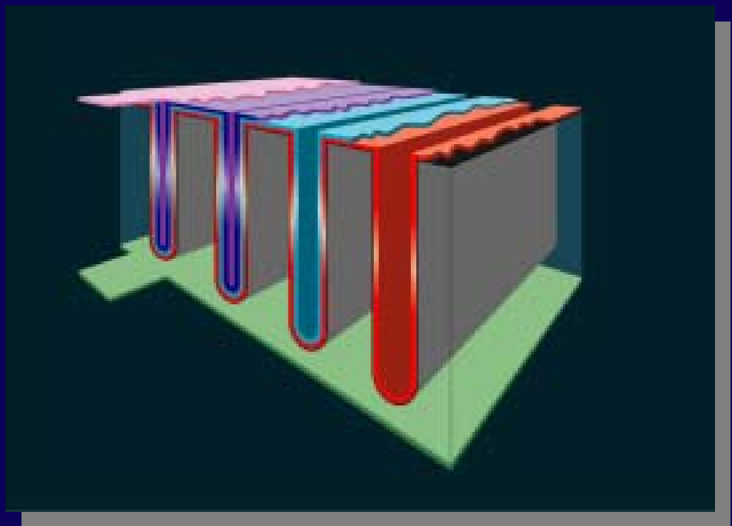
# Energy management & Autonomous devices




Battery management



Flexible RF-ID

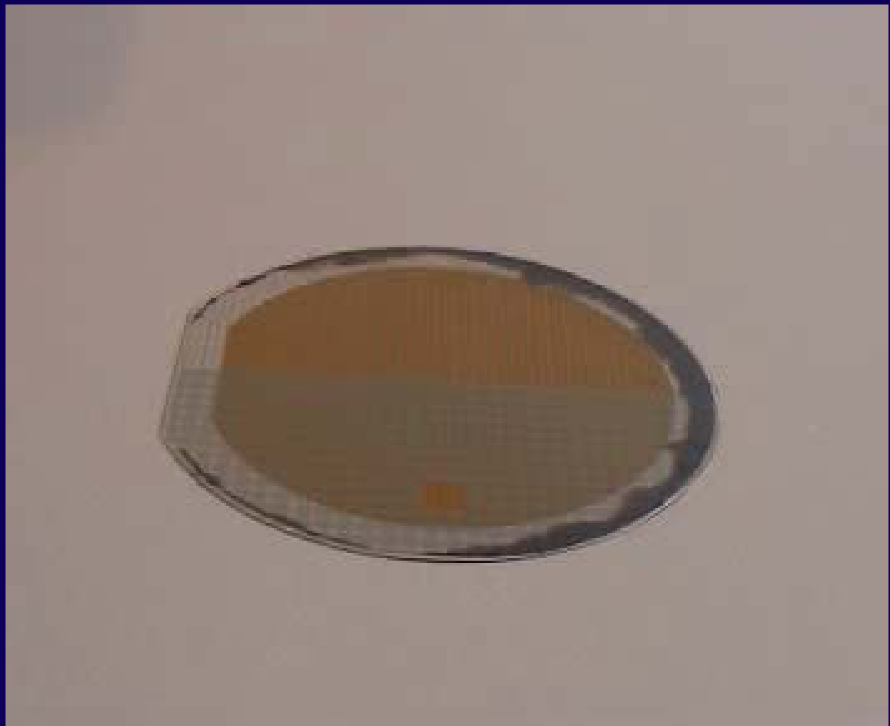


Battery-on-chip

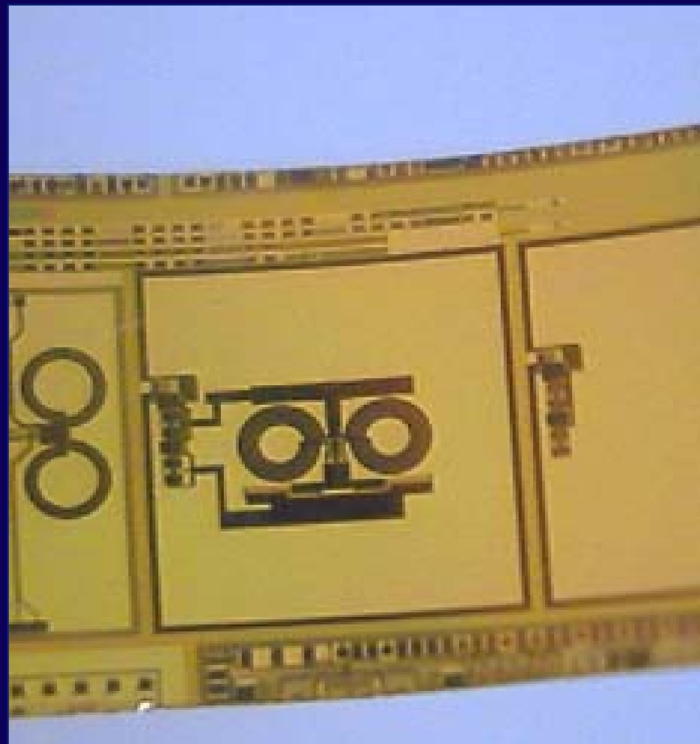
Autonomous sensor networks

# Integrated flexible RF-ID labels

*Flexible ultra-thin Si electronic circuits*



Substrate transfer technology



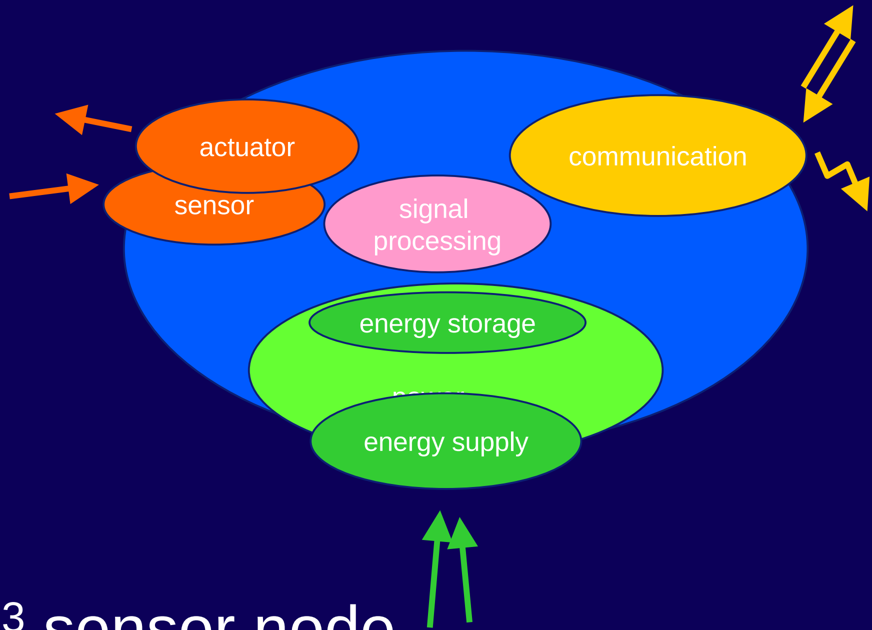
- Integrated antenna
- 5 µm thickness
- < 1 mm bend radius

# Applications

- value paper
- bank notes
- drug labeling
- electronic band-aid
- ……

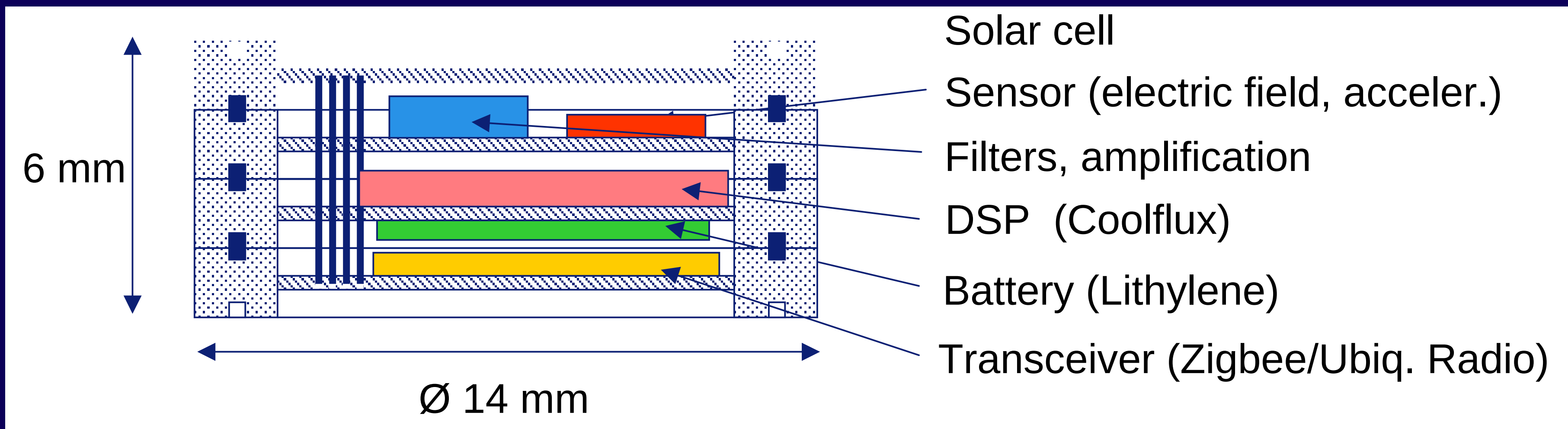

*In co-operation with a major paper manufacturer*

# Autonomous sensor networks




*towards "smart dust"*

1 $cm^3$ sensor node



# Towards home fetal monitoring


hospital

home

- skin contact required
- bulky & uncomfortable
- high power consumption

- incorporated in clothing
- long battery life
- simple status indicator

*In co-operation with Maxima Medical Center*

# Capacitive E-field sensor


Contactless ECG measured through clothing

# Microsystem technology (MST)
in our daily environment

- Introduction:
  - historical
  - What is MEMS, MST and SiP?
- Relevance of microsystems in daily life
- Scaling and miniaturization
- Examples: micro-machining and electrowetting
- More examples, developed at Philips
- Manufacturing, packaging and modeling
- Concluding remarks

# Manufacturing
## Basic substrates materials in microsystems

- Glass
- Semiconductors: silicon, GaAs, ...
- Silicon-on-Glass
- Polymers
- …..

# Glass Microfabrication

Glass is a versatile material:

insulating, hard, transparent, cheap, brittle, less resistant to high temperatures

Microstructuring techniques for glass:

Wet etching, dry etching, ultrasonic machining, Electrical Discharge Machining, laser structuring, powder blasting, photosensitive glass

Replication of glass microstructures:

Sol-gel process (spin-on-glass), photosensitive spin-on-glass

Bonding of glass:

Anodic bonding, fusion bonding, pressure-assisted bonding, chemical bonding, glass-metal bonding

Applications :

many

# Silicon Microfabrication

Silicon is a versatile material:

semi-conducting, hard, non-transparent, not so cheap, brittle, resistant to high temperatures

Microstructuring techniques for silicon:

Wet etching, dry etching, ultrasonic machining, Electrical Discharge Machining, laser structuring, powder blasting

glass

Replication of silicon microstructures:

*Hexil* process (LPCVD polySi), epitaxial growth

Bonding of silicon:

Anodic bonding, fusion bonding, pressure-assisted bonding, chemical bonding, silicon-metal bonding

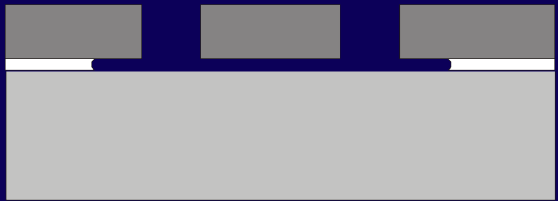
Applications :

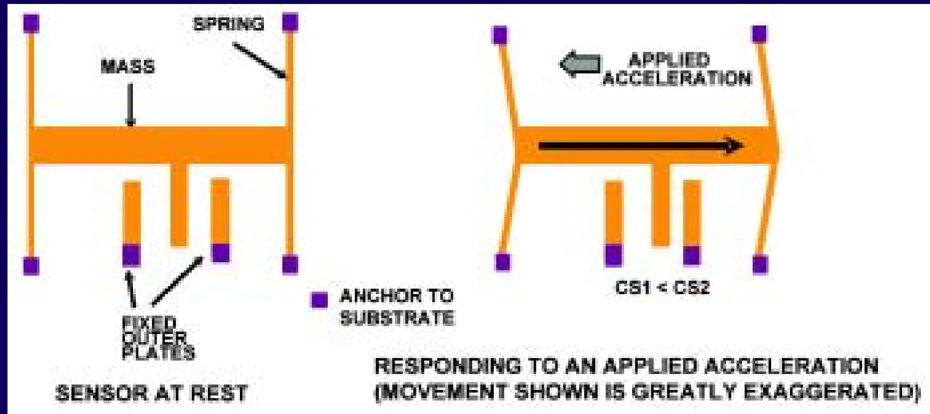
many, including integration with electronics

# Materials and production

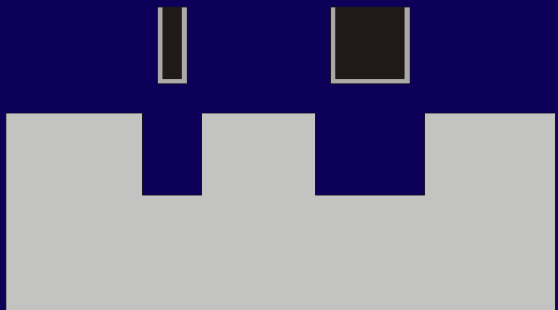
*What enables MST?*

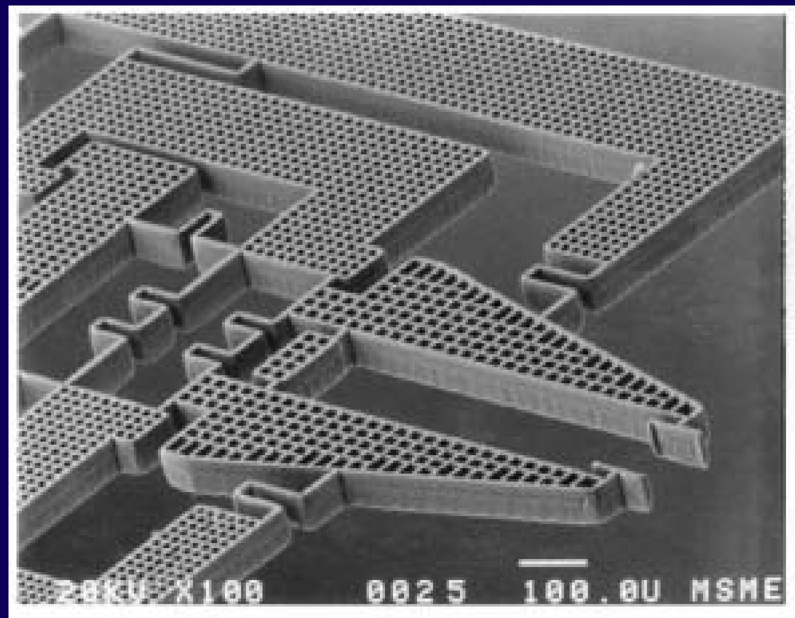
- Silicon on Insulator (SOI) wafers




- HEXSIL (MSME Precision Instruments)



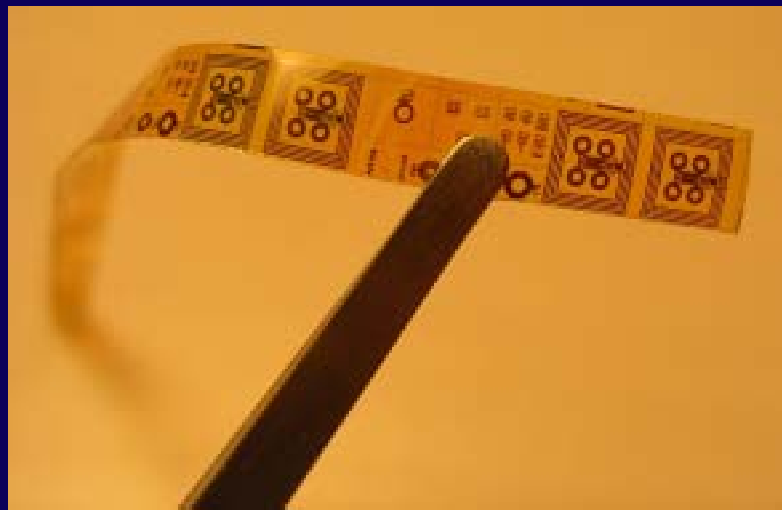
# Materials and production

*What enables MST?*

- Substrate transfer technology

*Flexible ultra-thin Si electronic circuits*

*Integrated flexible RF-ID labels*



- Integrated antenna
- 5 µm thickness
- < 1 mm bend radius

R. Dekker et al., IEDM 2003

# Manufacturing

## Bottlenecks for industrializing silicon MEMS manufacturing

- MEMS requiring structural changes in foundries
  RIE, KOH, problematic materials, …
- No universal set of microsystem processing technologies
  no multi-project wafers
- Diversity makes financial pre-calculations difficult
- MST requires multi-disciplinary skills, also at the foundry
  testing standards, production conditions, …
- Packaging
  diversity of products, thus packages

# Manufacturing

## Workhorse in MST: Deep RIE-etching

**Useful literature**

- on RIE etching (RIE lag, microloading, aperture effects, Aspect Ratio Dependent Etching, pattern factors)

  R. Gottscho et al. (AT&T Bell Labs), J. Vac. Sc. Technol. B **10** (5) (1992) 2133

- on Microsystems

  M. Madou, Fundamentals of Microfabrication, CRC Press, Boca Raton, 1997

- on Sensors & Actuators

  S. Middelhoek and S. Audet, Silicon Sensors, Academic Press, New York, 1989

# Manufacturing

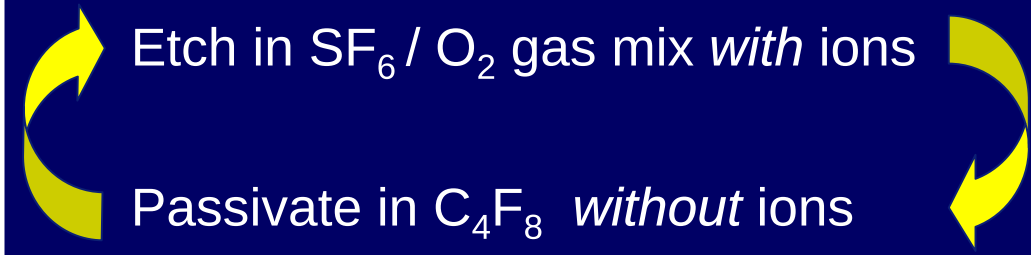
"*Sensors and Actuator cube*" * to maximize functionality

| in / out | rad | mech | therm | electr | magn | chem |
|---|---|---|---|---|---|---|
| **rad** | photolumin | rad pressure | radiative heating | photo conduction | photo magnetic | photo chem |
| **mech** | photo-elastic effect | conserv moment | friction heat | piezo-effect | magnetostriction | pressure-induced expl. |
| **therm** | incandescence | thermal expansion | heat conduction | Seebeck effect | Curie-Weiss law | endotherm reaction |
| **electr** | inject. lumin. | piezo-electr. | Peltier effect | p-n junction effect | Ampere's law | electrolysis |
| **magn** | Faraday effect | magnetostriction | Ettinghausen effect | Hall effect | magnetic induction | |
| **chem** | chemo luminescence | explos. reaction | exotherm reaction | Volta effect | | chem reaction |

** Source: S. Middelhoek and S. Audet, Silicon Sensors, Academic Press, New York, 1989, p. 20*

# Principle of ‘Bosch’ *dry* etch process

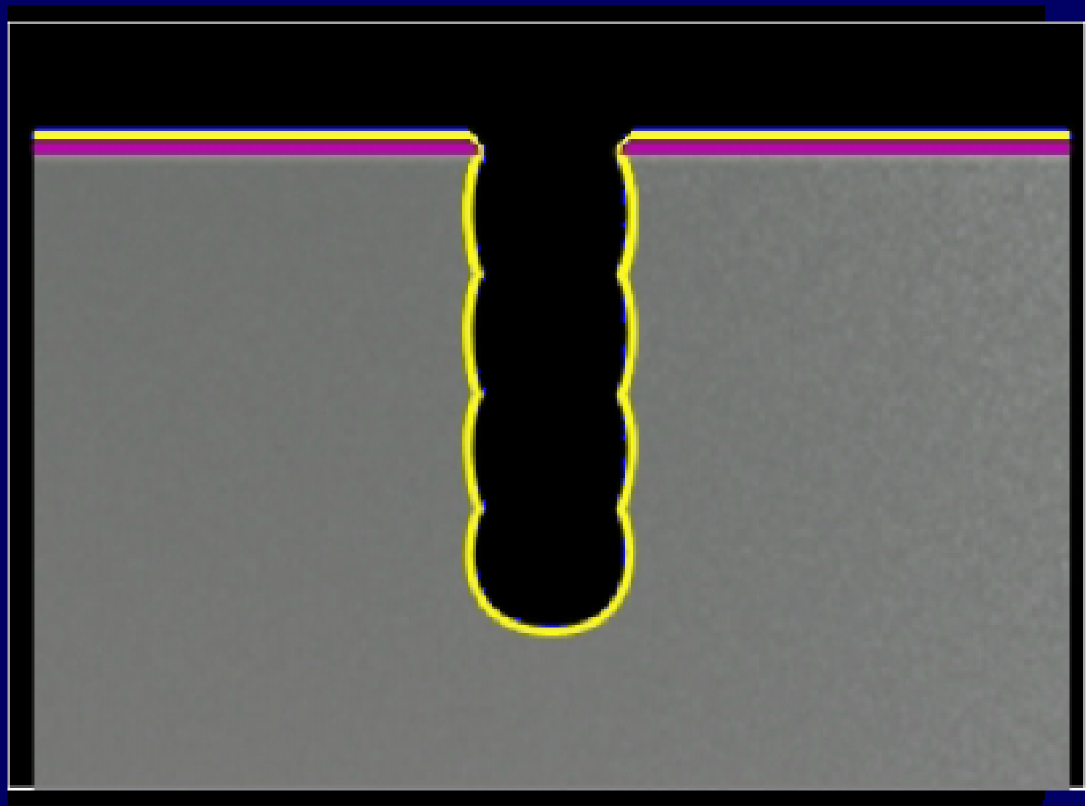
## ***Etch / passivate cycle:***



Etch in $SF_6$ / $O_2$ gas mix *with* ions

Passivate in $C_4F_8$ *without* ions

Hard mask : $SiO_2$ / resist ▶

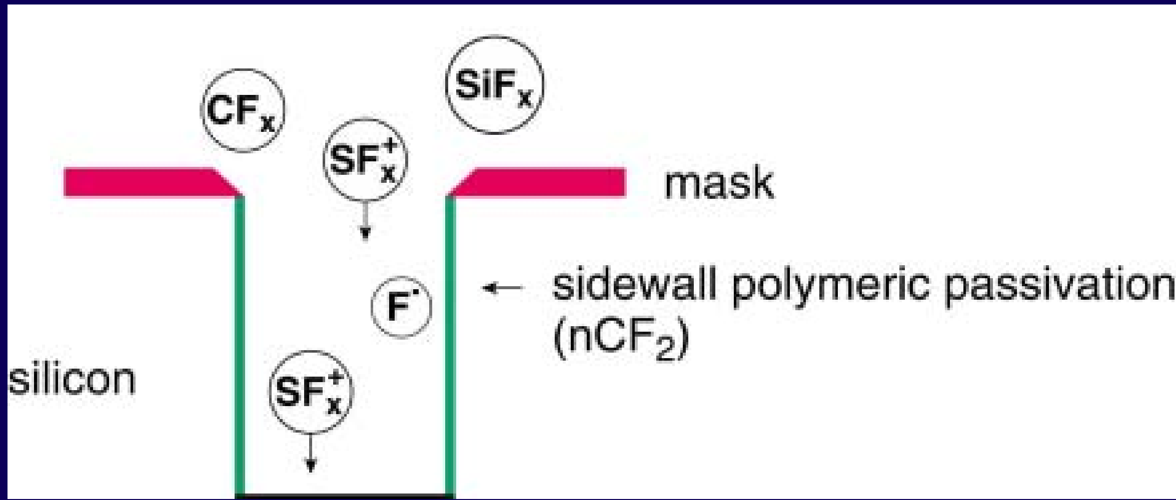


Etch rate: 5 - 0.5 μm/min

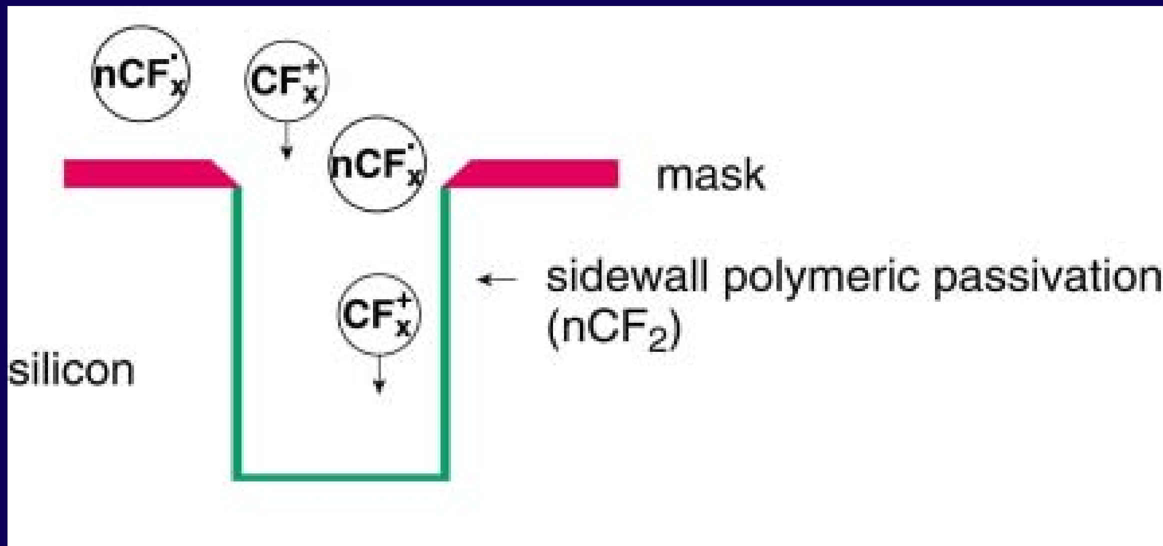
Aspect ratio: 20-25

# Dry etching at room temperature

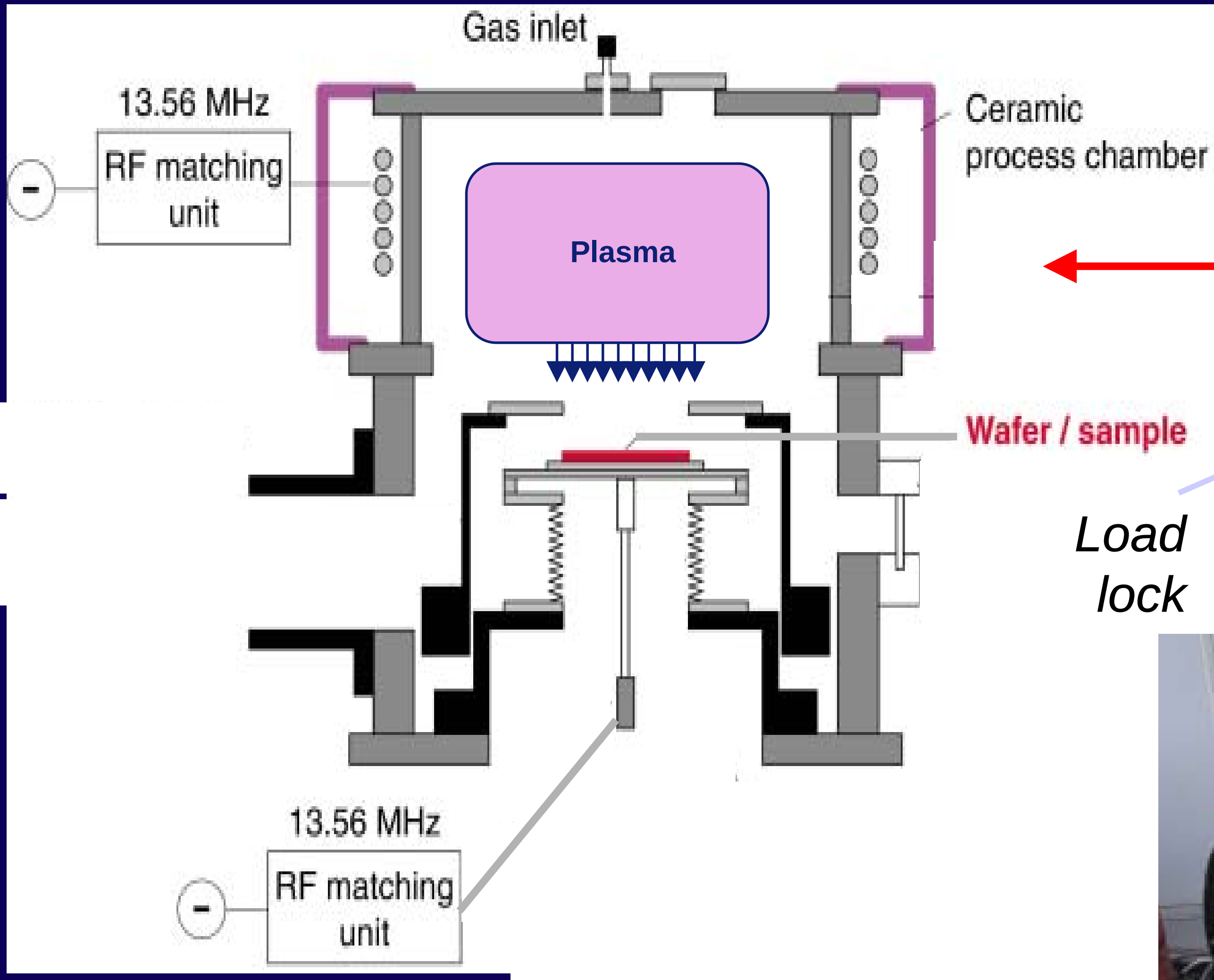
## 1. Etching with $SF_6$




## 2. Sidewall passivation with $C_4F_8$



# Inductively Coupled Plasma reactor



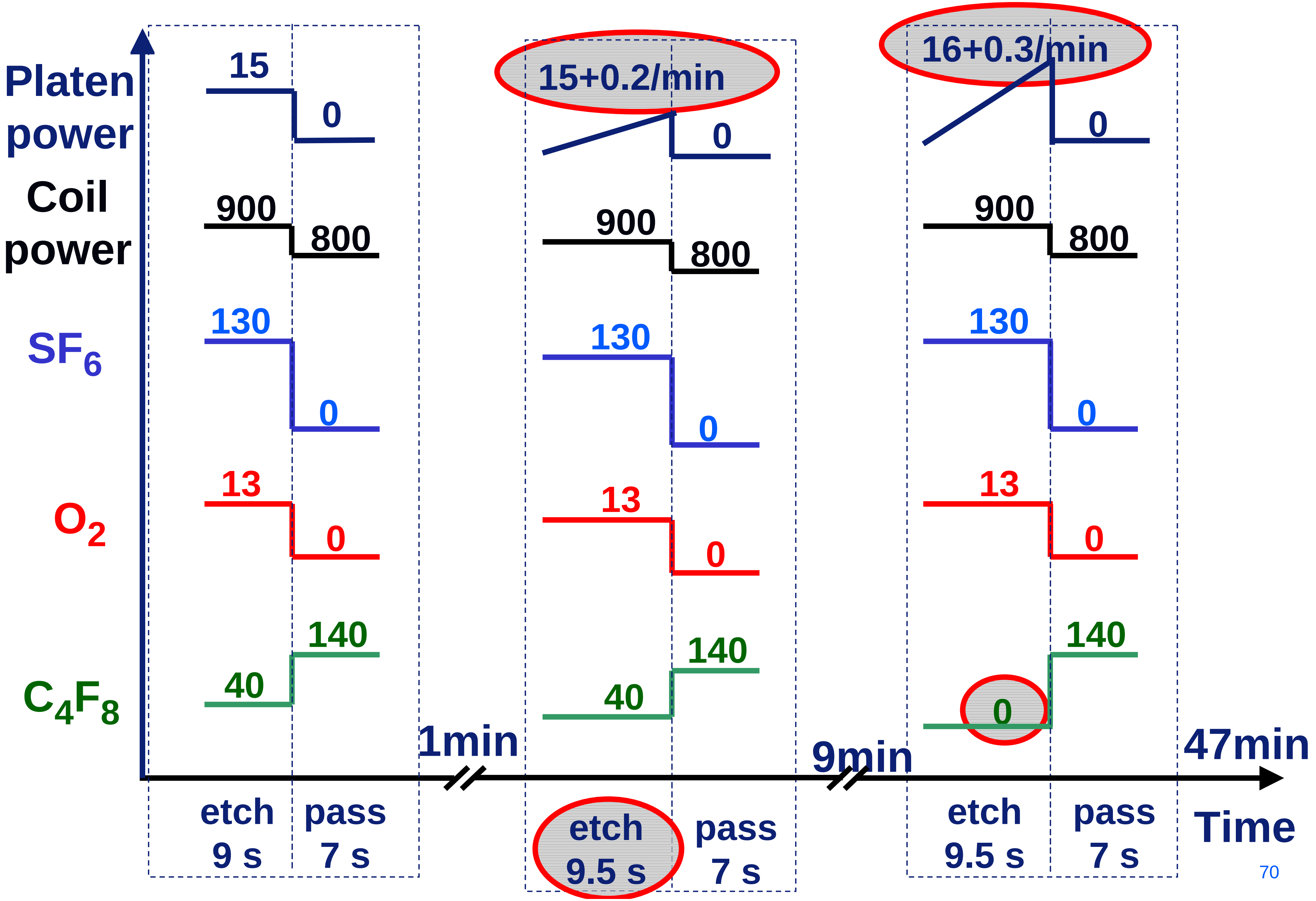


# Details of our macropore array mask

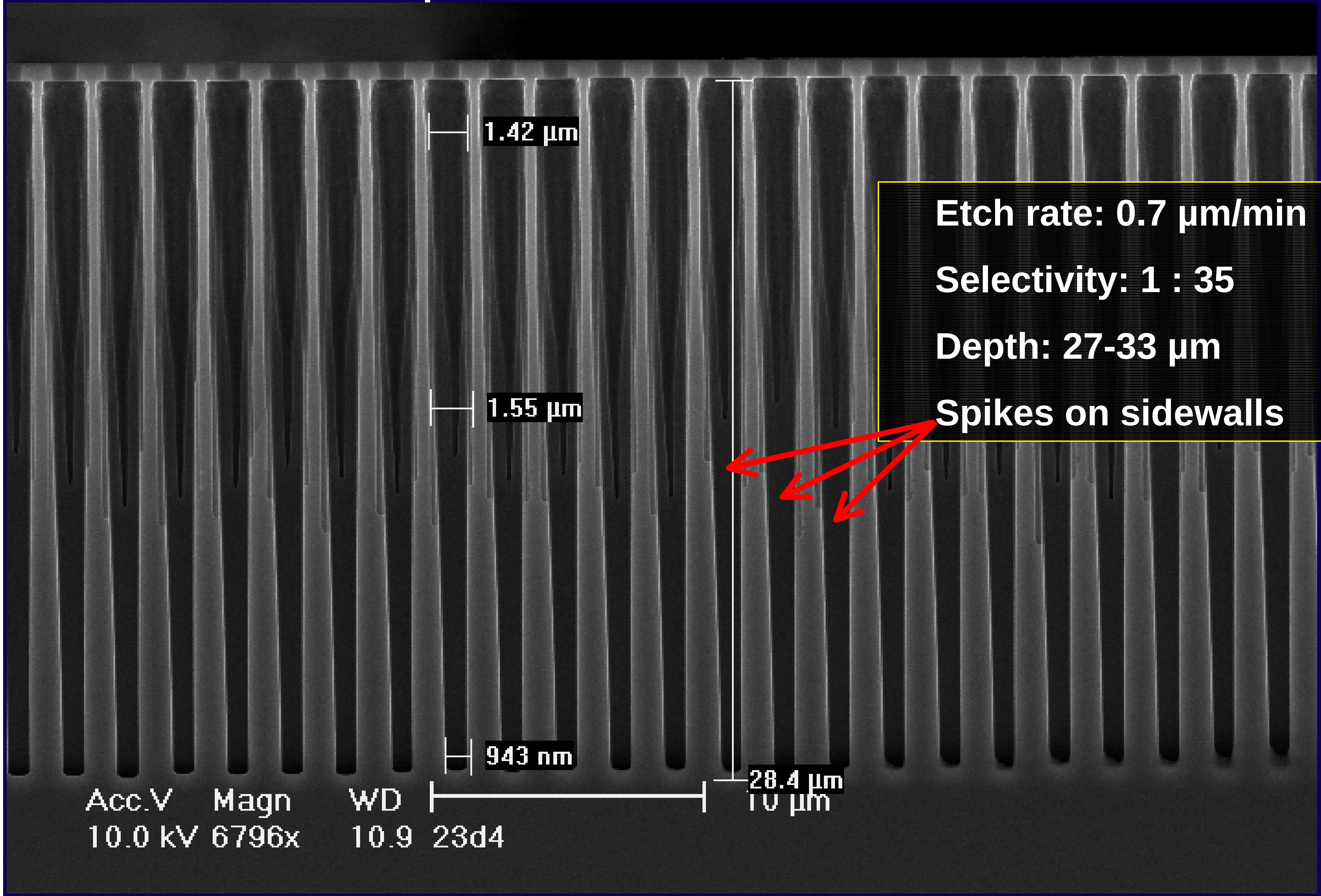
- Geometrical shape
  - Pores of 1.0, 1.5 and 2.0 µm diameter
  - Trenches of 10 x 1 $\mu m^2$ with different pitches
- Mask composition
  - 1.7 µm of TEOS-$SiO_2$
  - 6.5 % of silicon exposed on a 6-inch wafer

# Details of the original recipe

20 °C



# First results on pores STS-HRE




Etch rate: 0.7 µm/min

Selectivity: 1 : 35

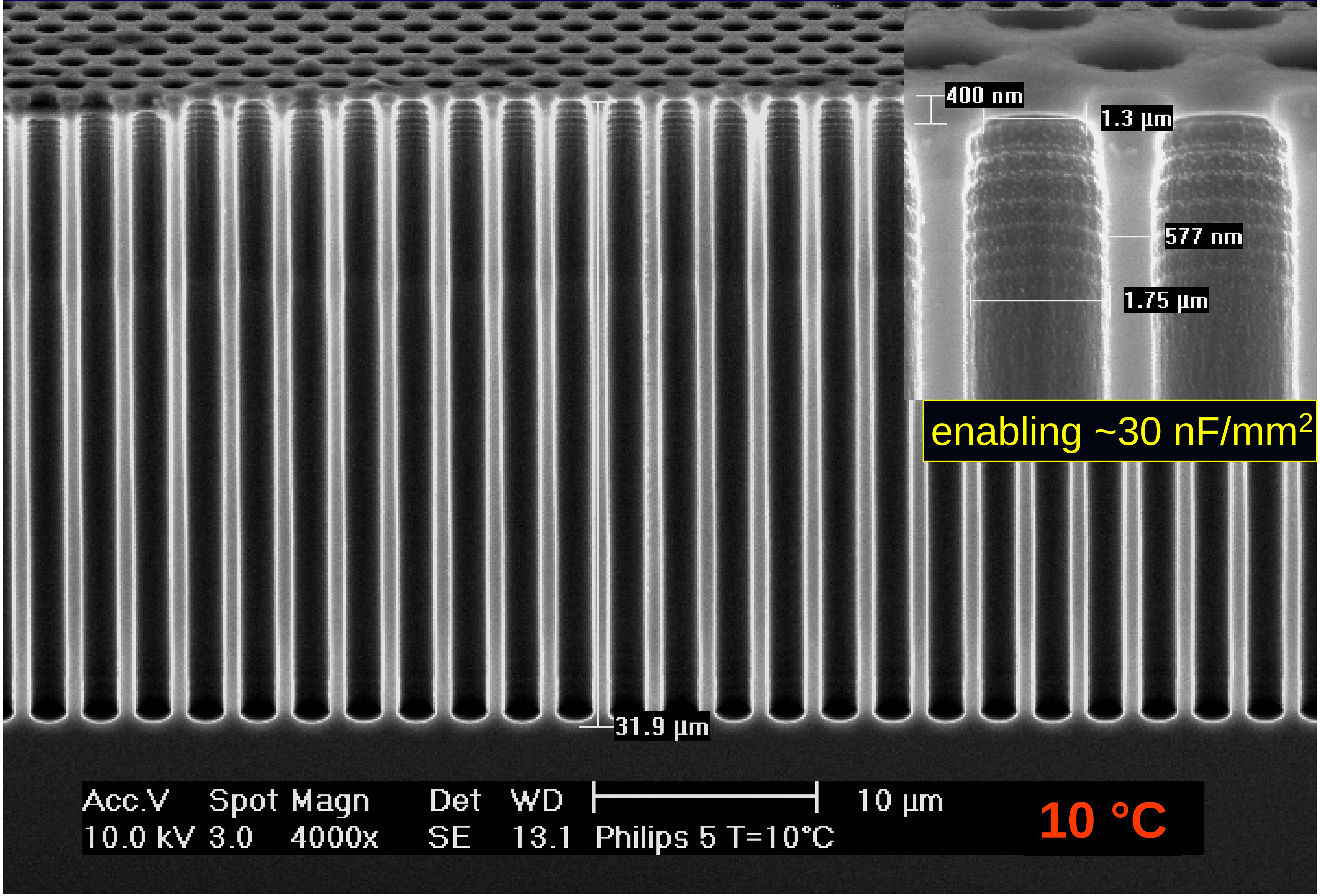
Depth: 27-33 µm

Spikes on sidewalls

# Etch parameters in RIE etching

| | Etch rate | Profile Anisotropy | Selectivity | Sidewall roughness |
|---|---|---|---|---|
| ↑Etch gas | ↑↑ | ↑↑ | ↑ | ↑ |
| ↑Dep gas | ↓↔ | ↔ | ↑ | ↓ |
| ↑Etch : Dep ratio | ↑ | ↑ | ↑↔ | ↑ |
| ↑Pressure | ↑↑ | ↑ | ↑ | ↑ |
| ↑Dep coil power | ↓↔ | ↓↔ | ↑↔ | ↓ |
| ↑Etch coil power | ↑ | ↑ | ↑ | ↑ |
| ↑Platen power | ↑↔ | ↑ | ↓ | ↔ |
| ↑Temperature | ↑↔ | ↓ | ↓ | ↔ |

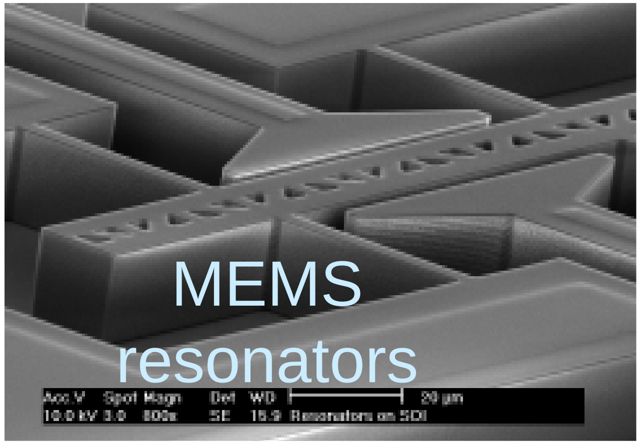
# RIE etching ('Bosch' process) for high-value capacitors

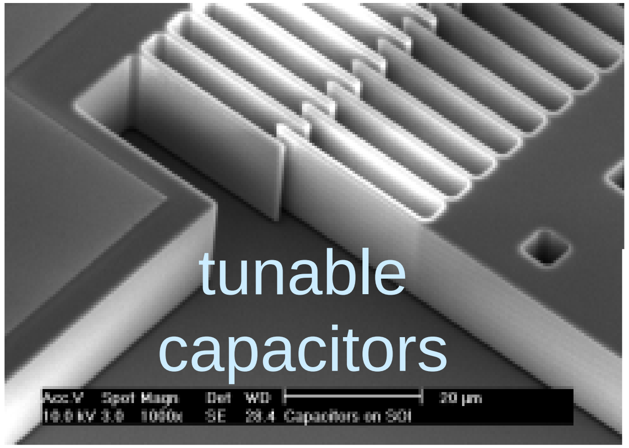


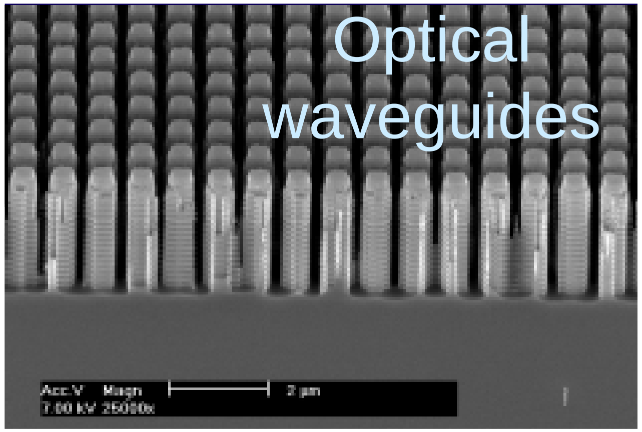

enabling ~30 nF/mm²

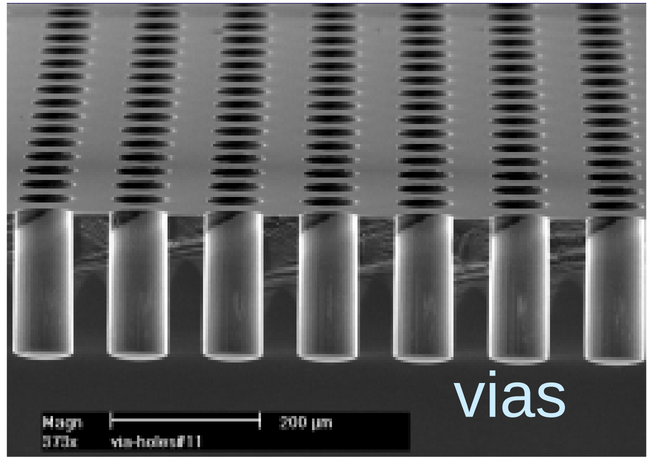
10 °C

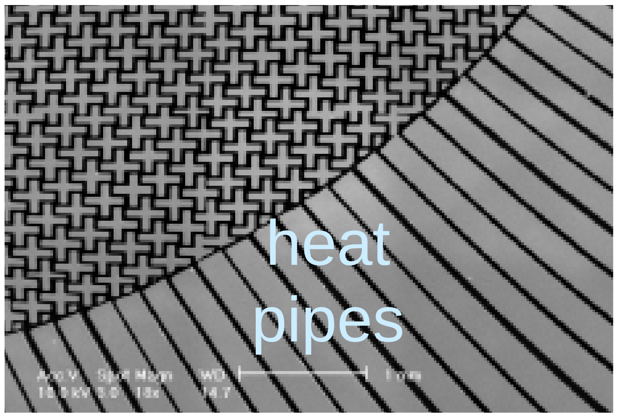
# RIE enabling a broad Si *micromachining* capability

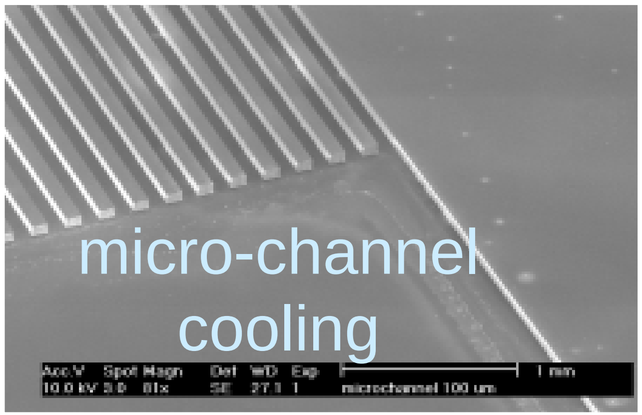


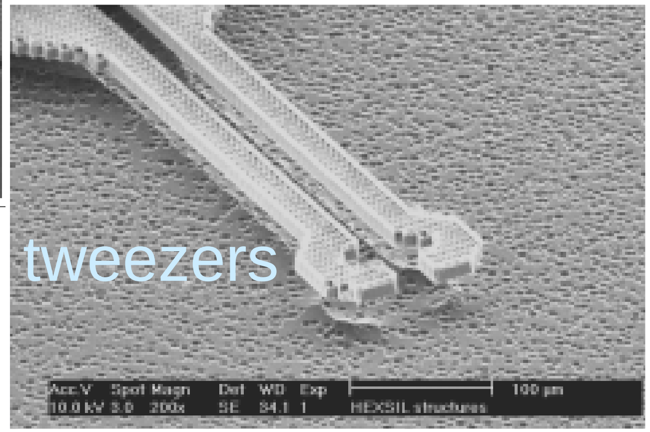



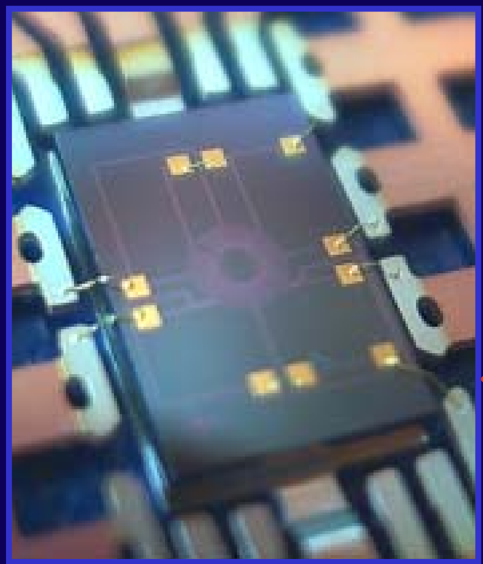
# Microsystem technology (MST)
in our daily environment

- Introduction:
  - historical
  - What is MEMS, MST and SiP?
- Relevance of microsystems in daily life
- Scaling and miniaturization
- Examples: micro-machining and electrowetting
- More examples, developed at Philips
- Manufacturing, packaging and modeling
- Concluding remarks

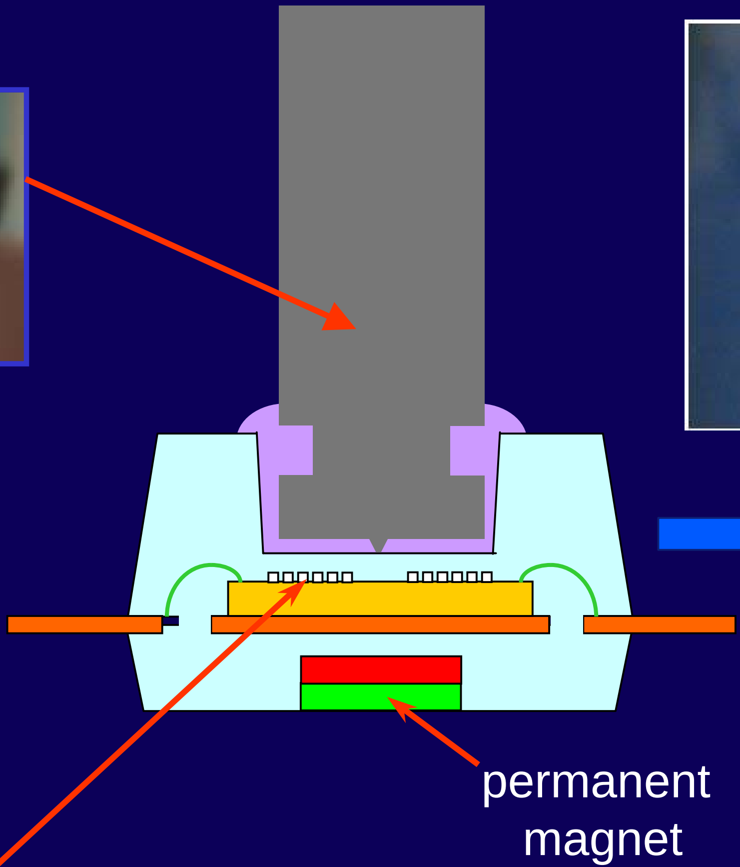
# Microsystem packaging

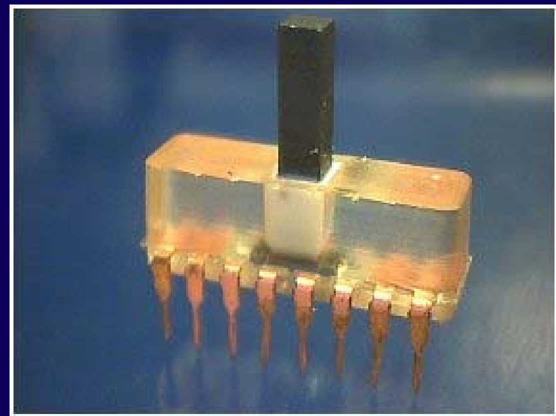
*Integrated track pointer ; stick-in-chip module*

Ferrite stick



AMR sensor

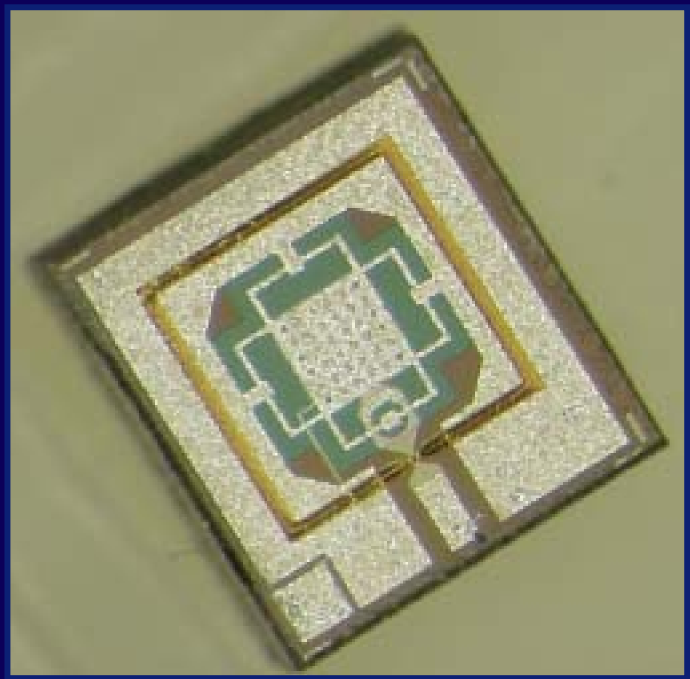


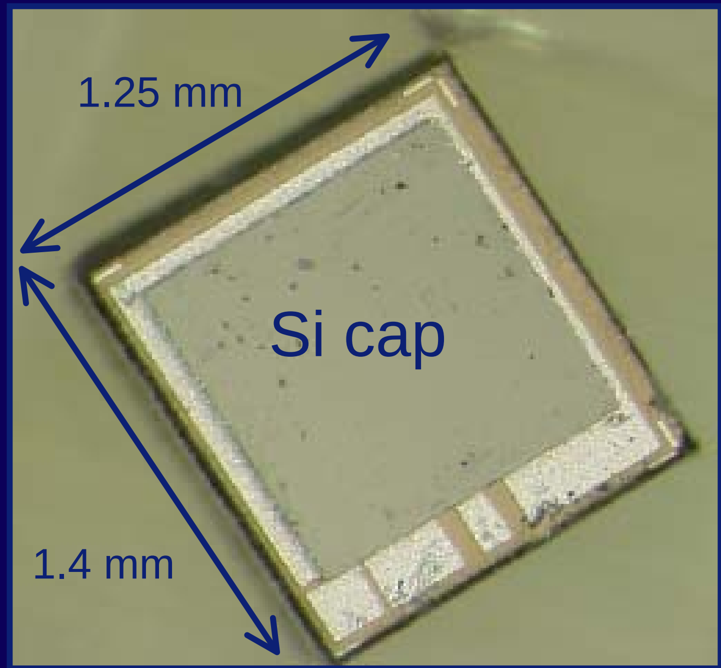
*In co-operation with IBM*

# Microsystem packaging
*RF-MEMS hermetic packaging*

'naked' die with solder ring



packaged product



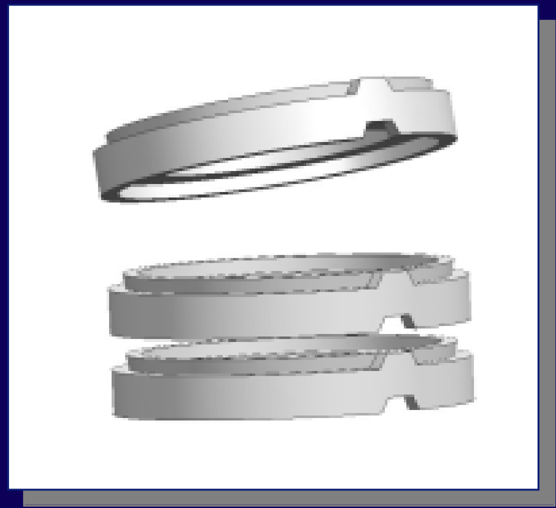

Trend in Packaging: from single-die to multiple dies, stacked in a SiP

*In co-operation with IMEC & Philips AppTech*

# Microsystem packaging

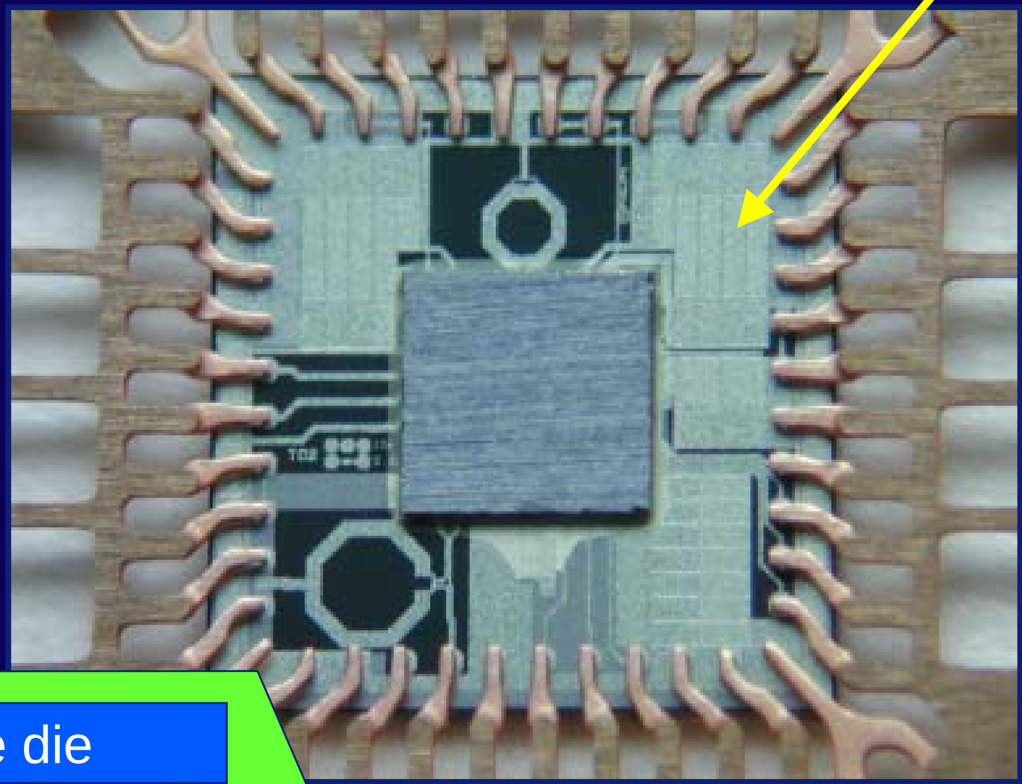
*Autonomous sensor network*

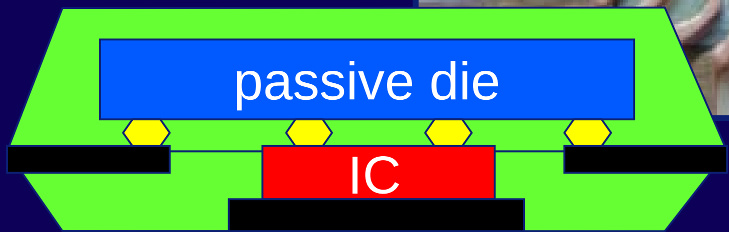
- Lego-like snap-on building blocks
- Outside of building blocks forms package
- Easily detachable/reconfigurable stack



# Microsystem packaging

*Plug-'n-play RF module*




double flip-chip on lead frame
(HVQFN)

*Source: Philips, France*

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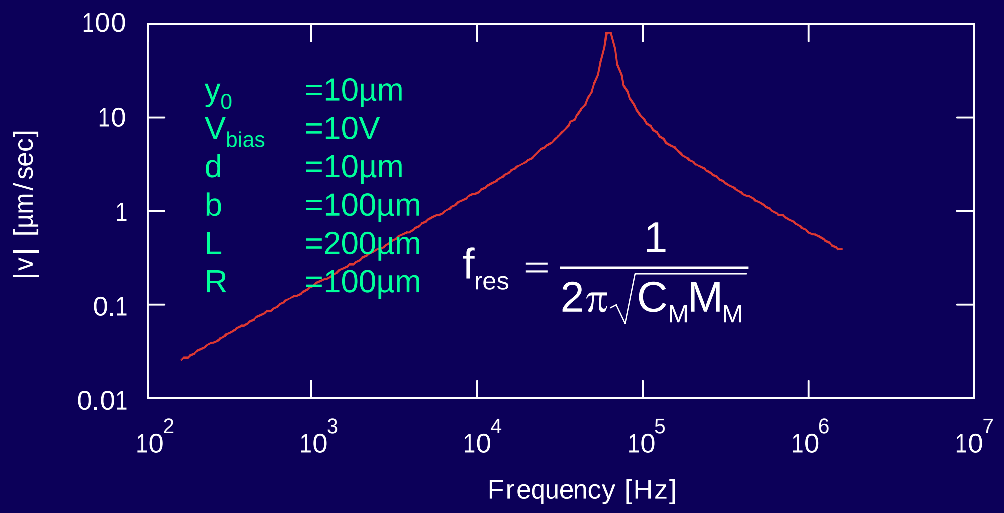
# MEMS Modeling

## Lumped elements with mechanical model (easier than FEM)



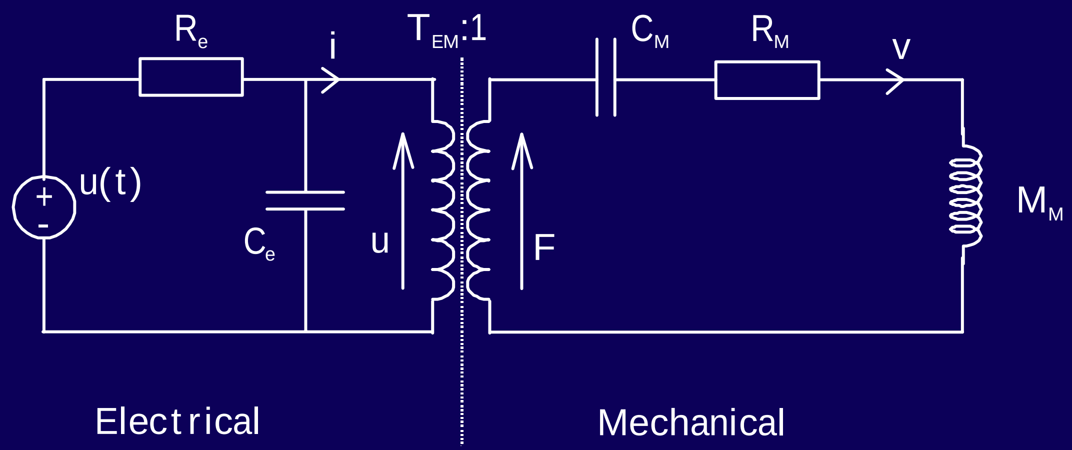

Mechanical:

- Spring $C_M$
- Mass $M_M$
- Friction $R_M$

Electrical:

- Resistance $R_e$
- Capacitance $C_e$

Transduction El.→ Mech. $T_{EM}$




$$T_{EM} = \frac{y_0^{\;2}}{\varepsilon_0 R^2 V_{Bias}}$$

# MEMS Modeling
## Lumped elements

| | | Electrical | | Mechanical | |
|---|---|---|---|---|---|
| State variable | $q$ | Charge | $q$ | Position | $x$ |
| f is “flow” of q | $f = \dot{q}$ | Current | $i = \dot{q}$ | Velocity | $v = \dot{x}$ |
| e is origin of flow | $e$ | Voltage | $u$ | Force | $F$ |
| Stored power | $e \cdot f$ [Watt] | | | | |
| Resistive element | $e = R \cdot f$ | Resistor | $u = i \cdot R$ | Friction | $F = R_f \cdot v$ |
| Compliance | $f = C \frac{de}{dt}$ | Capacitor | | Spring ($k^{-1}$) | |
| Inertial element | $e = L \frac{df}{dt}$ | Coil | | Mass | |

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# Concluding remarks

- Microsystems Technology as an inexpensive mass volume production technique is vastly penetrating our daily life: ***Ambient Intelligence is becoming reality***

- Scaling and cross-disciplinary device concepts into ***System-in-Package solutions*** create new multifunctional modules

- (Multi) ***technology re-use*** is key for low-cost

# Acknowledgment

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G. van de Walle
J. van Zon

PHILIPS

PHILIPS