MEMS:
Architecture & Design

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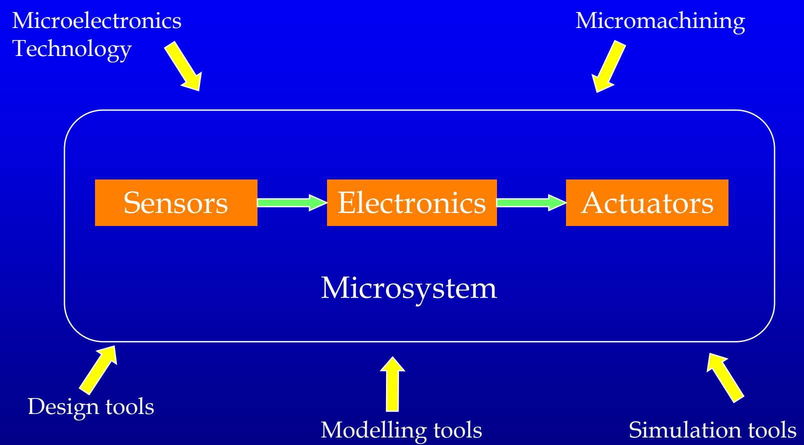
Outline

- Introduction.
- MEMS evolution.
- Sensors & actuators categorization.
- Interconnection architectures.
- Interconnection technologies.
- Design methodology.
- Test & qualification.
- Conclusions.

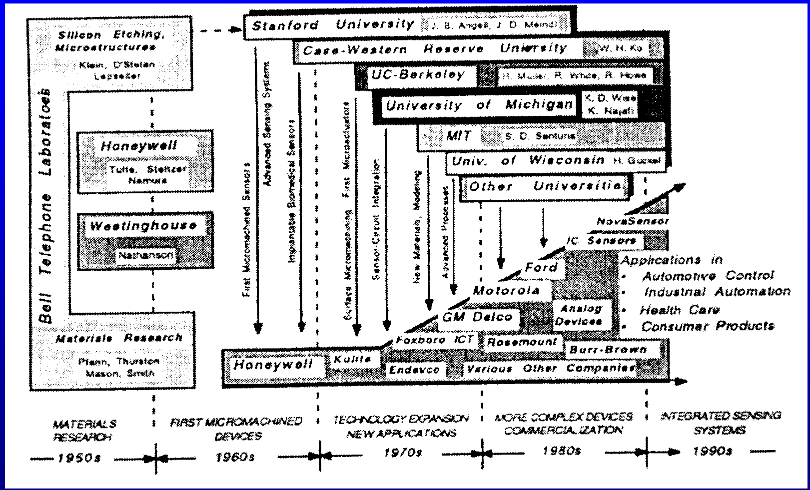
Introduction

- It is expected that microsystems will be used extensively in different applications.
- The main problem to increase the use of MEMS is:
  - To have a common design methodology.
  - To use a flexible interface architecture.
- The solutions proposed should be satisfied the special requirements of each sector.

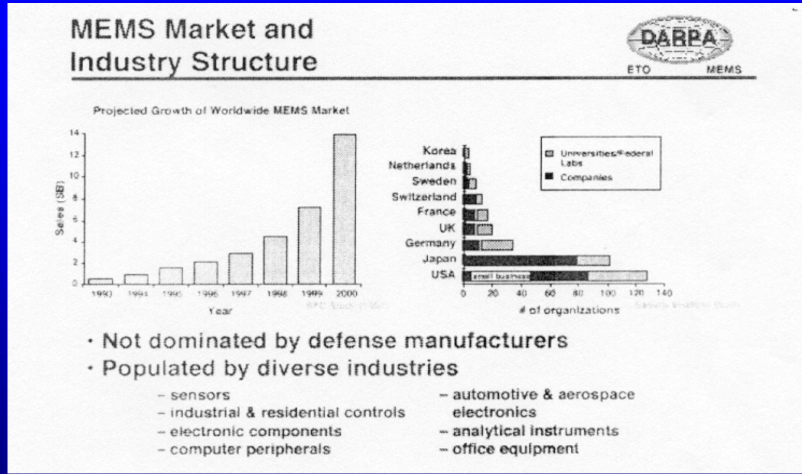
What is a Microsystem?



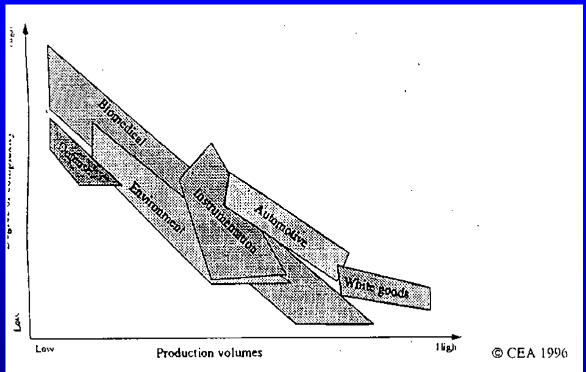
History of MEMS development



MEMS market (i)



MEMS market (ii)



ction volume and degree of complexity of microsystem products in each activity field

MEMS market (iii)

- Automotive (Airbags).
  - High volume/low cost.
- Computer and peripherals (Inkjet printers, hard-disc headers, ...).
  - High volume/low cost.
- Biomedical (big potential in the future)
  - One use devices. High volume/low cost.

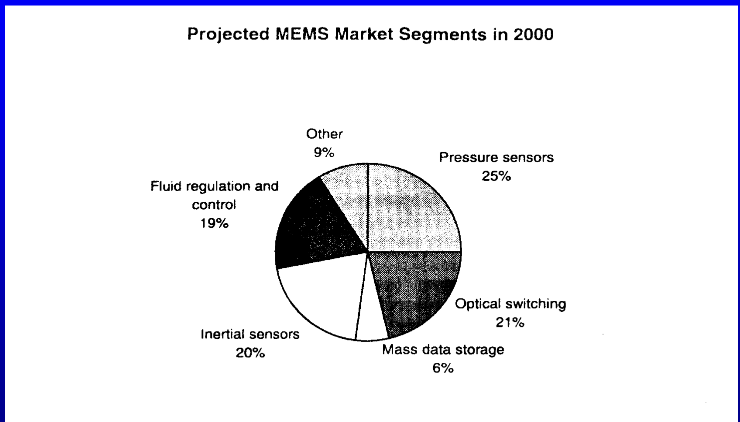
MEMS market (iv)

- Appliances and Domotica (pressure and gas sensors, ...)
  - High volume/low cost.
- Environmental sector (water and air analysis).
  - Depend on new laws and regulations.
- Instrumentation and aerospatial (advanced devices).
  - Low volume/high cost.

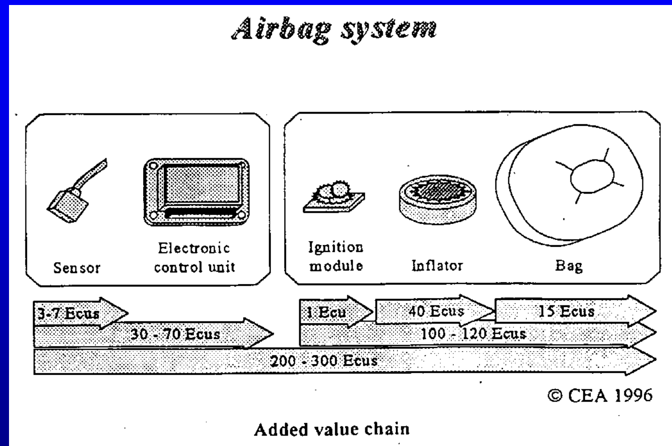
MEMS market (v)

EXISTING PRODUCTS	1996 Units (millions)	1996 US Dollars (millions)	2002 Units (millions)	2002 US Dollars (millions)
Hard disk drive heads	530	4500	1500	12000
Inkjet printer heads	100	4400	500	10000
Heart pacemakers	0.2	1000	0.6	3700
In-vitro diagnostics	700	450	4000	2800
Hearing aids	4	1150	7	2000
Pressure sensors	115	600	309	1300
Chemical sensors	100	300	400	800
Infrared imagers	0.01	220	0.4	800
Accelerometers	24	240	90	430
Gyroscopes	6	150	30	360
Magnetoresistive sensors	15	20	60	60
Microspectrometers	0.008	3	0.15	40
Total Existing Products		**14,330**		**34,440**
EMERGING PRODUCTS				
Drug delivery systems	1	10	100	1000
Optical switches	1	50	40	1000
Lab on a chip (DNA, HPLC)	0	0	100	1000
Magneto-optical heads	0.01	1	100	500
Projection valves	0.1	10	1	300
Coil on chip	20	10	600	100
Microrelays	-	0.1	50	100
Micromotors	0.1	5	2	80
Inclinometers	1	10	20	70
Injection nozzles	10	10	30	30
Anti-collision sensors	0.01	0.5	2	20
Electronic nose	0	0.1	0.05	5
Total Emerging Products		**107**		**4200**

MEMS market (vi)



MEMS market (vii)



Why MEMS? (i)

Why Microsystems ?

- Main properties:
  - Miniaturisation
  - Arrays
  - High resolution
- Main benefits:
  - Leading-edge performances
  - New applications
  - Cost-effective for high volume

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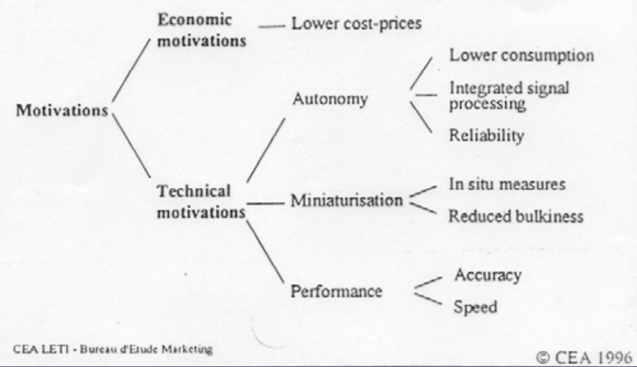
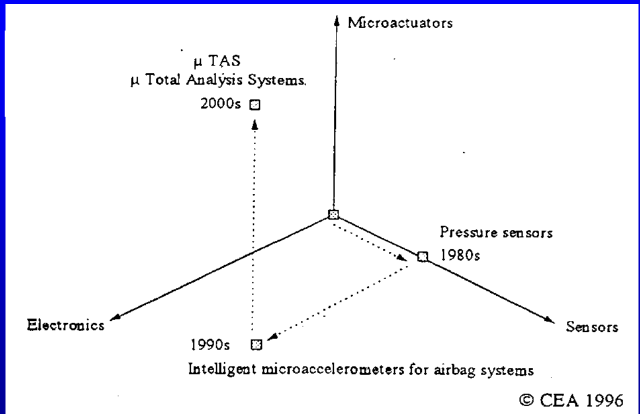
Why MEMS? (ii)

What are the motivations leading industrials into microsystem technologies ?



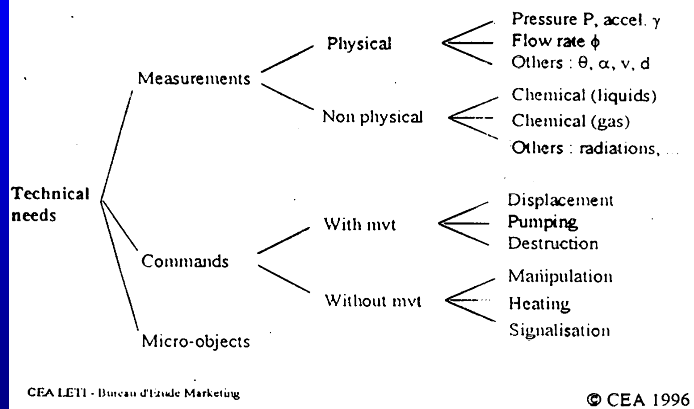
Why MEMS? (iii)



Evolution of microsystem developments

Why MEMS? (iv)

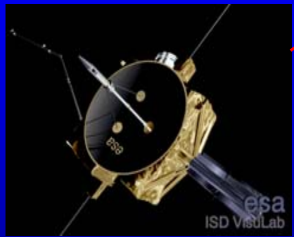
What are the technical needs of industrials?



Microsystems/MEMS for space applications

Navigation, ADC: Accelerometers
Giroscopes
Sun / earth / star sensors

Mechanical / thermal systems:
- embedded sensors (pressure, force, IR)
- embedded actuators (microswitches, microactuators, micromotors, …)

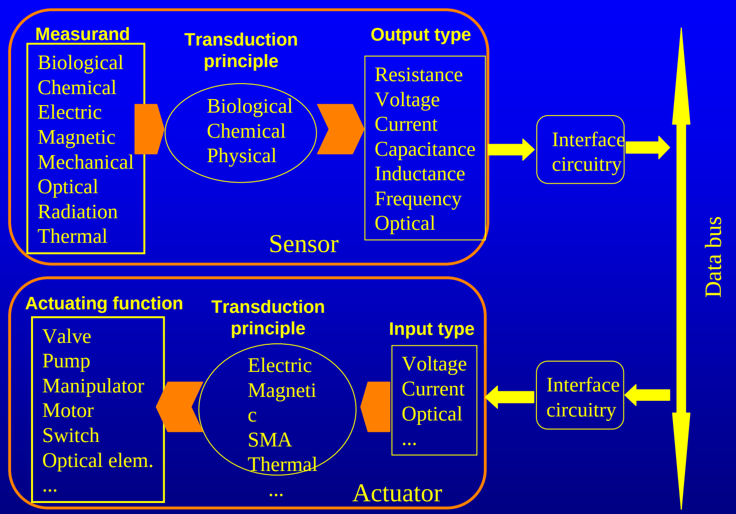


Instruments / payload:
- pressure, temperature, vibration, strain sensors
- chemical sensors
- magnetic field sensors
- microspectrometers
- optical / X-ray imagers
- bioreactors (including microfluidics)

Propulsion: micropropulsion engines (microvalves, micropumps, micronozzles, flow / pressure sensors, …)

Integrated **communications systems**

Sensor and actuator categorization (i)



Sensor and actuator categorization (ii)

- Sensors

Classification criteria	Categories
Measurand	Biological
	Chemical
	Electric
	Magnetic
	Mechanical
	Optical
	Radiation
	Thermal
Conversion phenomena (transduction principle)	Biological
	Chemical
	Physical
Output type	Single resistance
	Resistance bridge
	Voltage
	Differential voltage
	Current
	Capacitance
	Inductance
	Frequency
	Optical

- Actuators

Classification criteria	Categories
Input type	Electrical
	Optical
	Other
Transduction principle (actuating mechanism)	Electric: Electrostatic, Piezoelectric, Dielectric induction, Other
	Magnetic: Electromagnetic, Magnetostrictive, Magnetorheological, Other
	Shape memory
	Thermal: Thermal expansion, Phase transition, Other
	Other
Actuating function	Valves
	Pumps
	Manipulators(grippers,…)
	Motors
	Switches
	Optical elements
	Other

Sensor and actuator categorization (iii)

- Application in aerospatial sector
  - Launcher.
  - Satellite platform.
  - Satellite and payload.

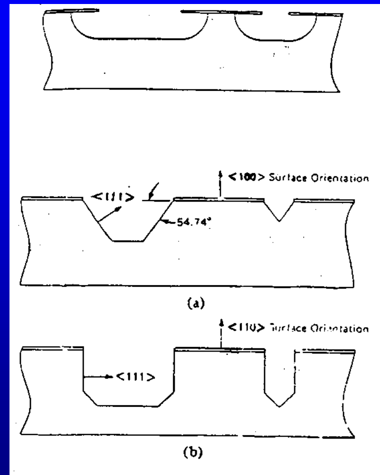
Subsystem	Microsystems
Propulsion	Microvalves
	Micropumps
	Micronozzles
	Flowmeter
	Pressure sensors
Attitude Determination and Control	Accelerometers
	Gyroscopes
	Sun sensors
	Star sensors
	Earth sensors
Thermal	IR sensor
	Thermal switch – Active refractive tiles
Power	Rechargeable micro-batteries
Sensors	Chemical sensors
	Pressure sensors
	Temperature sensors
	Magnetic field sensors
Structures and Mechanisms	Shape memory alloy actuators
	Pressure sensors
	Micro switches
	Micro-actuators and motors for miniaturized control systems
	Force sensors
Payload	Bioreactor
	Microspectrometers
	Microcamera
	Micromirrors

Micromachining & Assembling Technologies

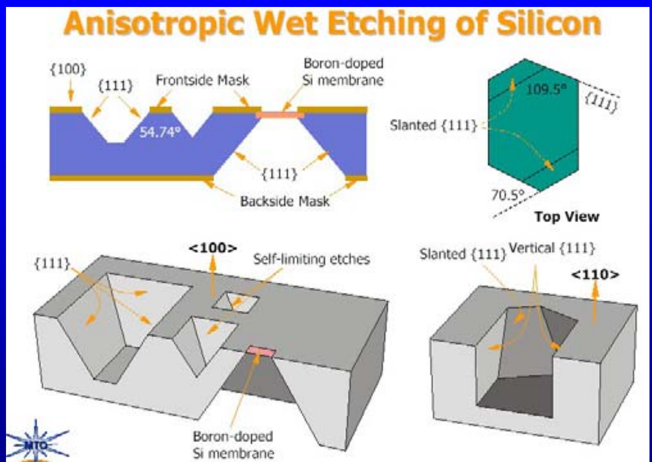
- Device micromachining:
  - Bulk micromachining
  - Surface micromachining
  - LIGA
- Assembling technologies:
  - Electroplating
  - Thin layers
  - Bonding

Bulk micromachining (i)

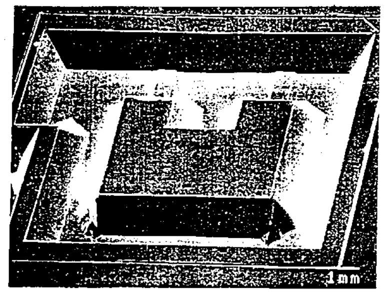
- Isotropic etching:
- Antistrophic etching:



Bulk micromachining (ii)



Bulk micromachining (iii)



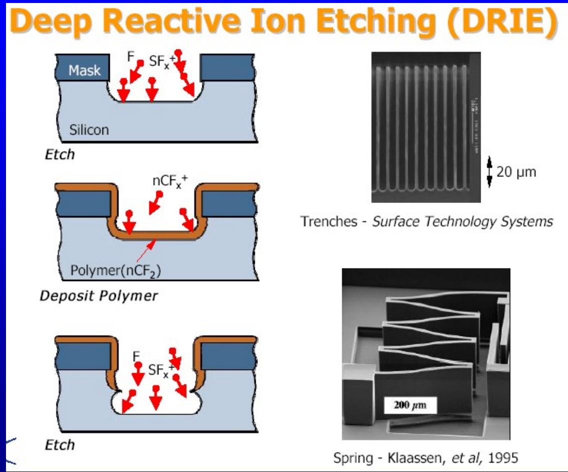
- Anisotropic wet etching
  KOH, EDP, TMAH

CMOS compatibility

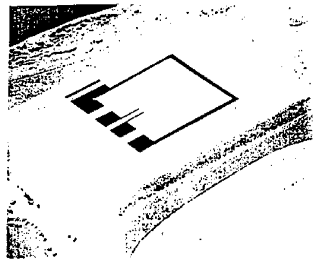
Post processing
- Front side
  - design rules + post-processing
- Back side
  - double side polished wafers
  - substrate thickness and doping
  - etch stop techniques (SOI, ECE)
  - extra masks
  - double side alignment

- **Applications:**
  - pressure sensor
  - membranes
  - Si threedimensional microstructures

Bulk micromachining (iv)



Bulk micromachining (v)



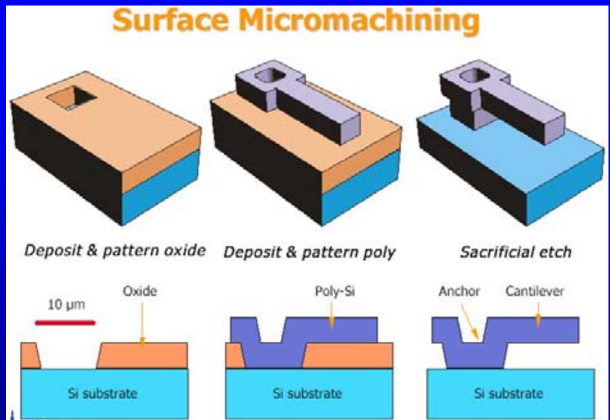
- Deep silicon dry etching
  RIE

CMOS compatibility

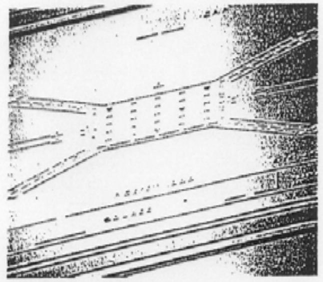
- masking layers
- design rules, extra masks
- difficult handling of fragile structures
- in combination with BESOI substrates: alternative to wet anisotropic etching for irregular geometries

- Applications:
  - normally used in combination with anisotropic wet etching for two sides micromachining
  - accelerometers, holes, ...
  - polysilicon structuring

Surface micromachining (i)



Surface micromachining (ii)



- Sacrificial layers technology
- Polysilicon microstructures

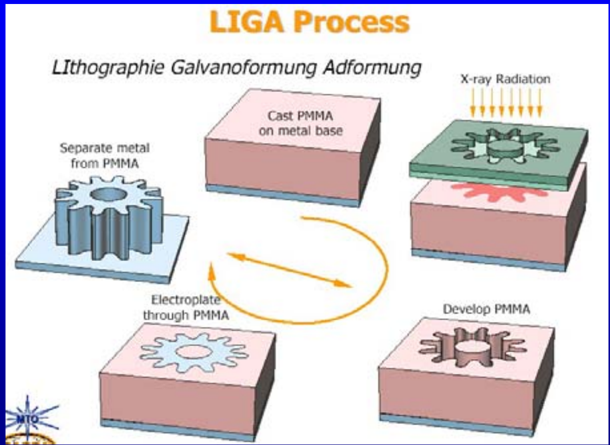
CMOS compatibility

- closed process module
  - extra annealing budget
  - extra masks (difficult process)
  - IC protection during sacrificial layer etching
  - sticking, dicing

- Applications:
  - microaccelerometers (capacitive)
  - microactuators: micromotors, microswitches
  - x-y tables, AFM tips
  - polysilicon microstructures

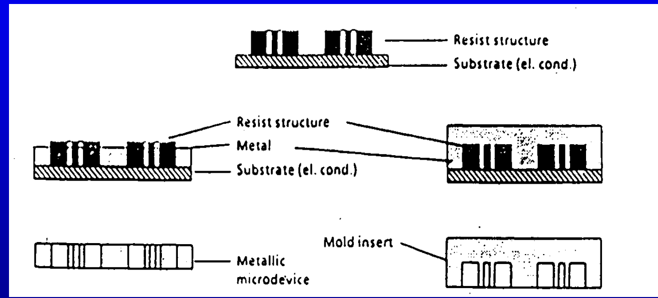
LIGA (i)

- Thick resist generation by X-rays lithography.



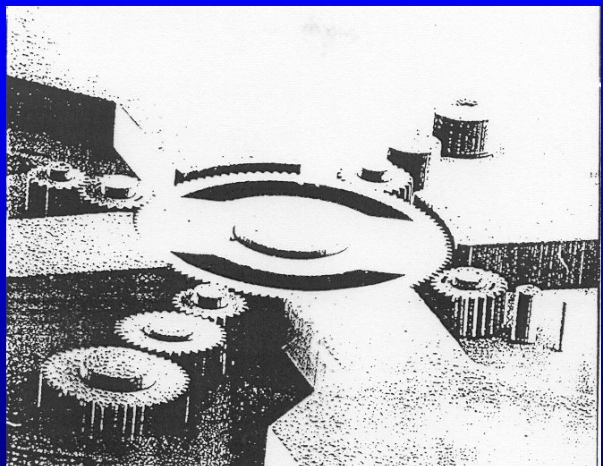
LIGA (ii)

- Metal or mold microstructure generation.



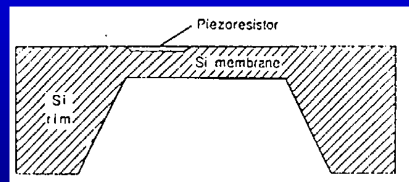
LIGA (iii)

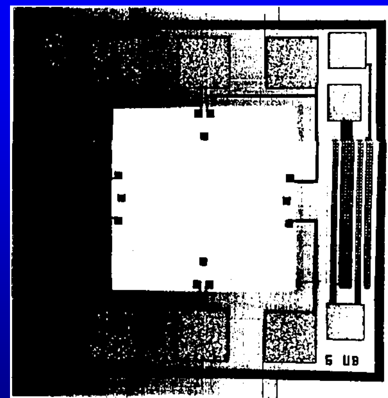
- Timing gear example



Pressure sensor

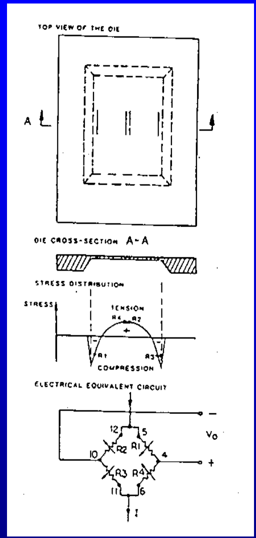
- Piezoresistive sensor by using bulk micromachining





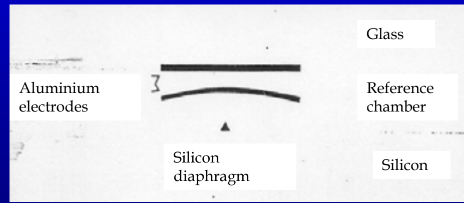
Pressure sensor

- Pressure measured as a resistance variation in a Wheatstone bridge structure



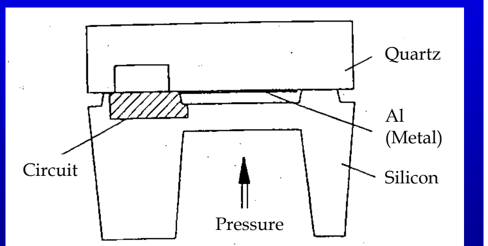
Pressure sensor

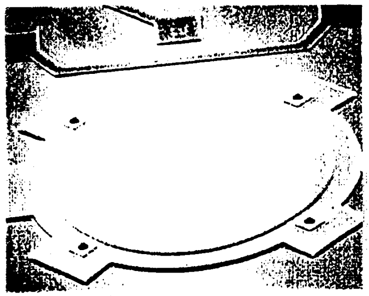
- Capacitive sensor by using bulk micromachining
  - Acts as a variable capacitor.
  - Needs of condition circuitry.
  - More sensibility (10-20 times).



Pressure sensor

- Capacitive sensor
  - Less dependent of temperature.
  - More critic package.

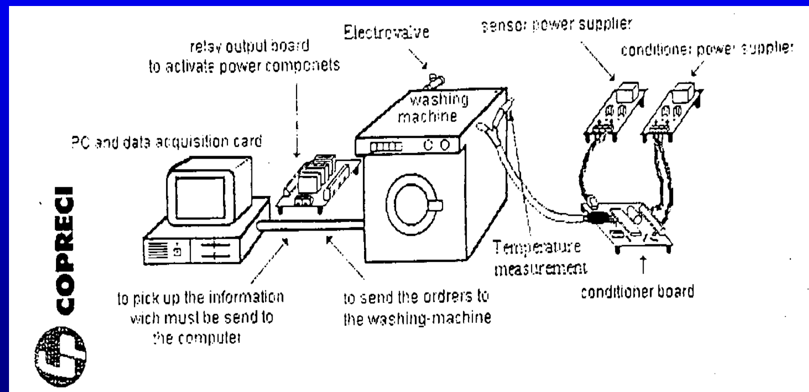




SEM micrograph showing poly 74μm-radius membrane sensor

Pressure sensor

- Washing machine application

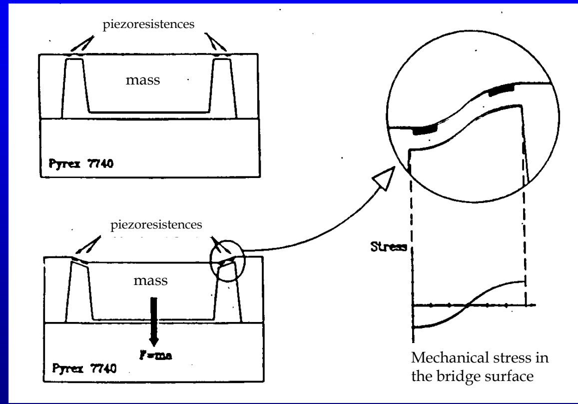


Pressure sensor

Pressure range	Aplication
<40mbar	Water level in water machines, dishwasher,...
100 mbar	Vacuum cleaner
200 mbar	Blood pressure measurement
1 bar	Barometer, fuel injection, ...
2 bar	Tyre pressure
10 bar	Motor oil & brakes pressure, Air conditioned.
50 bar	Pneumathic, Industrial robots
500 bar	Hidraulic, Building machinery

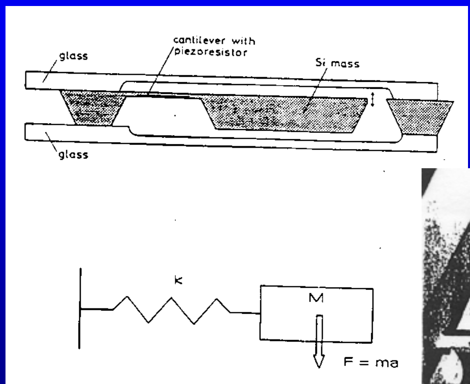
Accelerometers

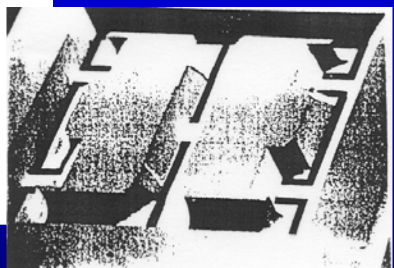
- Piezoresistive accelerometer



Accelerometers

- Cantilever and quad beams accelerometers



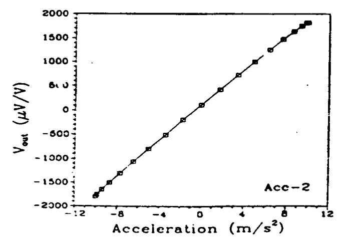


Accelerometers

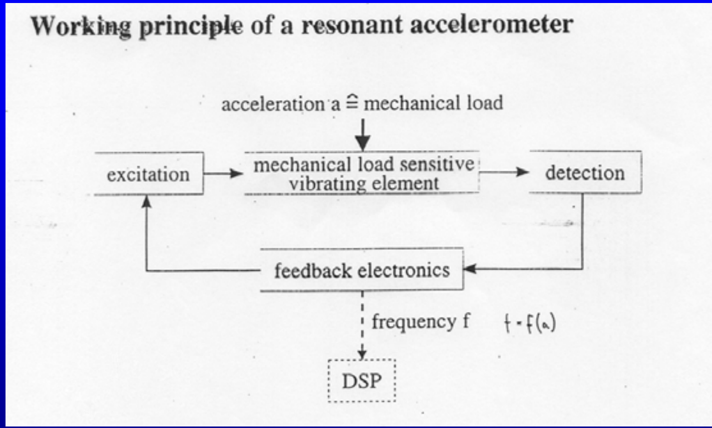
- **Experimental results**

⇒ **Sensitivity**

- Cantilever accelerometer: 2200 µV/V/g
- Quad beam accelerometer: 75 µV/V/g
- Twin - mass accelerometer: 220 µV/V/g

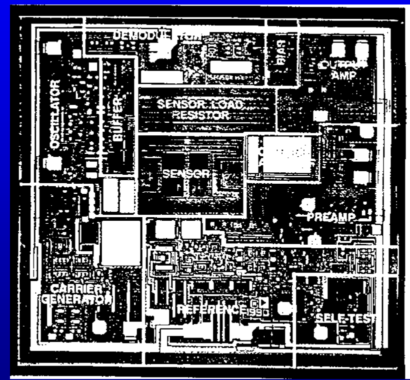


Accelerometers



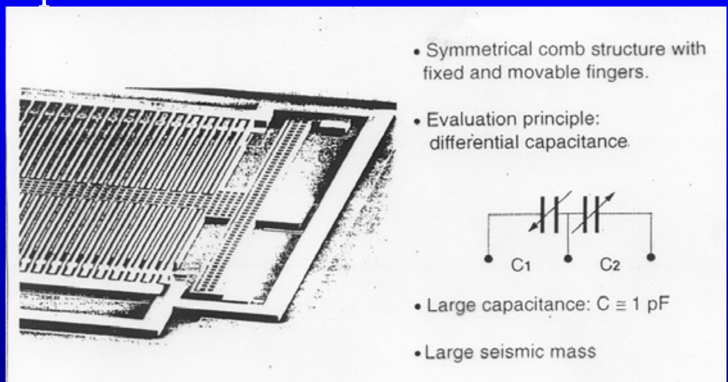
Accelerometers

- Integrated circuitry.



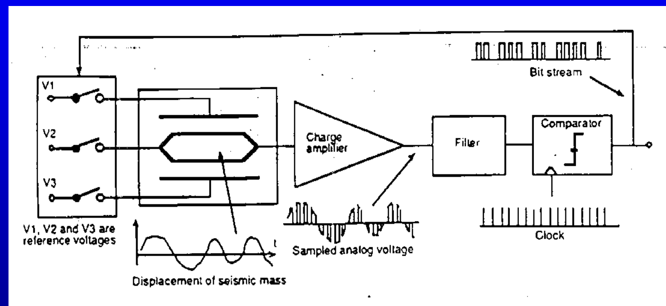
Accelerometers

- Capacitive accelerometers

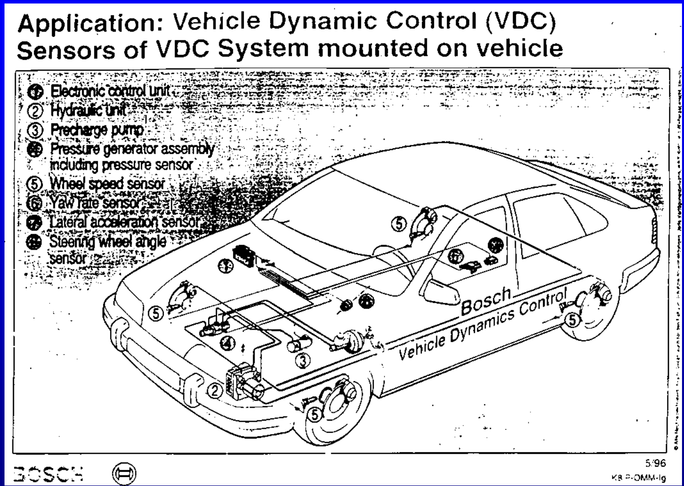


Accelerometers

- Measurement circuitry.



Car industry application



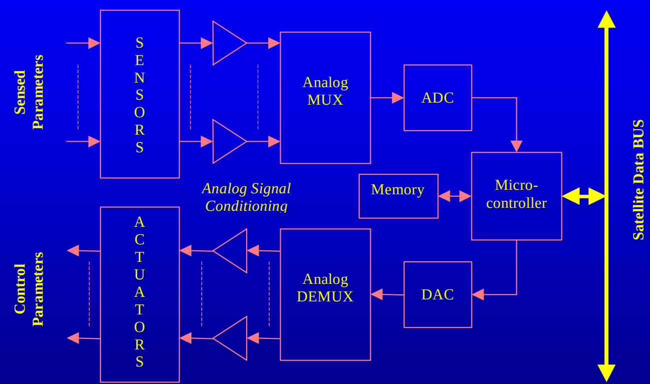
Read-out electronics

- Functions
  - Offset correction (output with no signal).
  - Compensation of temperature variation of sensivity.
  - Compensation of temperature variation of offset.
  - Amplification.
  - Analogue to digital conversion.
  - Digital bus interface.
  - Self-check (transducer and electronics).
  - Digital signal processing (processing unit),..
  - Calibration (adjustment of sensivity to a modelled curve):
    - » Analogue by resistor adjustment.
    - » Digital. RAM, EPROM
    - » Including compensation of non-linearities.

Read-out electronics

- Architectural approaches:
  - Classical:
    - » Analogue signal processing circuitry.
    - » Microprocessor with analogue interface capabilities.
  - Distributed:
    - » Intelligent sensors.
    - » Bus sensor.
    - » Dedicated processor.
  - Wireless:
    - » Same as the distributed solution with wireless system interface .

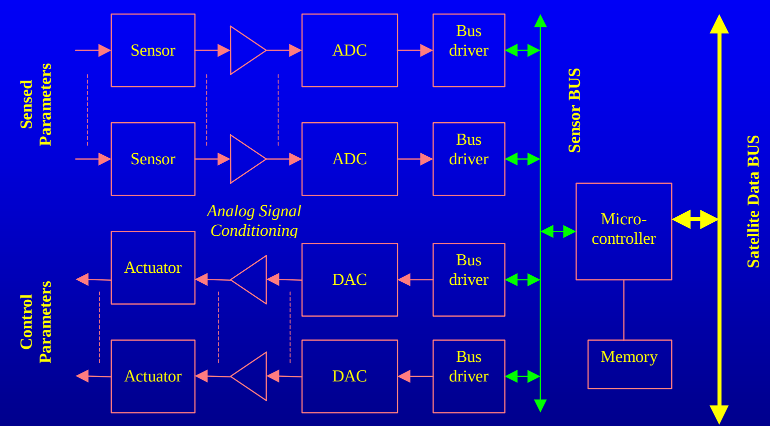
Classical interconnection (i)



Classical interconnection (ii)

- Advantages:
  - Easy to find microcontrollers and DSPs with internal memory, analogue and digital interface capabilities.
- Disadvantages:
  - Non modular solution.
  - Low signal-to-noise ratio.

Distributed interconnection (ii)



Distributed interconnection (ii)

- Advantages:
  - Modularity.
  - Interchangeability.
- Requirements:
  - Internal sensor bus.
  - Only for "short" distances.

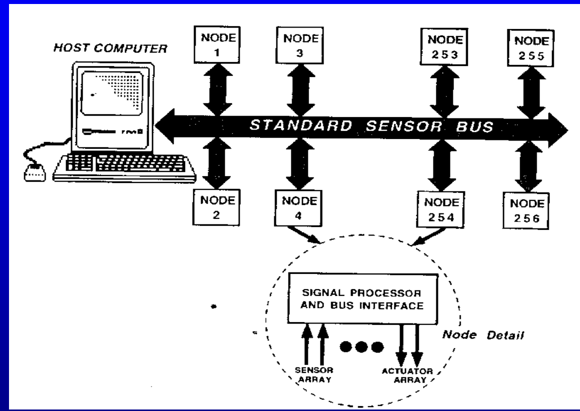
Sensor buses

Bus name	Number of lines	Type of data	Type of transmission	Data transmis-sion	Extra circuitry Cost	Standardization
MPS	13	Digital	Asynchronous	Parallel (half duplex)	Low	No
MSS	2	Digital	Synchronous-assynchronous	Serial (half duplex)	Low	No
IS^2	3	Digital or semidigital	Synchronous	Serial (half duplex)	Very low	No
IEEE-P1451	9 (power included)	Digital	Synchronous	Serial (full duplex)	Medium	Yes

Smart sensing systems (i)

- Host computer is the main controller.
- Usually is the only node allowed to initiate messages.
- When a node detects its address on the bus, it is the responsible for executing and responding incoming messages.

Smart sensing systems (ii)



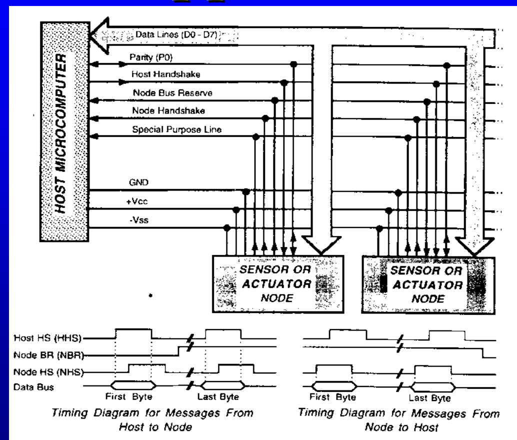
Smart sensing systems (iii)

- Command set for smart sensing nodes.

Command no.	Description
1	Reset
2	Emergency
3	Synchronize
4	Send data of all sensors
5	Send data of one sensor
6	Send identification information of all transducers
7	Send identification information of one transducer
8	Change an actuator output
9	Change the sensity node address
10	Change the sampling list

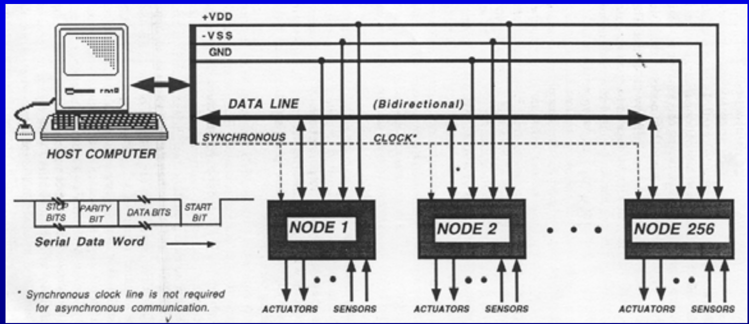
Parallel bus approach

- MPS from the University of Michigan, US.
  - Similar to the GPIB (IEEE-488) instrumentation bus.



Serial bus approach

- MPS from the University of Michigan, US.
  - Similar to RS-232 and RS-449 standards.



Smart sensing systems (iv)

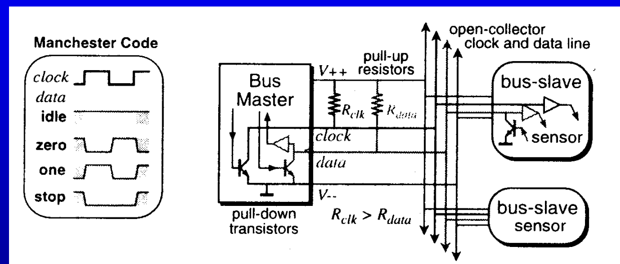
- Integrated Smart Sensor (IS^2) developed at the University of Delft, NL.
  - Requirements for a smart sensor bus.
    - » Minimum complexity at the bus-slave side.
    - » Minimum number of wire.
  - Characteristics.
    - » Two supply lines.
    - » Two serial communication lines.
    - » Open data transmission format.
    - » Manchester encoding + open collector lines.

Smart sensing systems (v)

- IS^2 communication protocol:
  - Not a single data active then the data line remains high.
  - Two idle states then the bus master can address a (sensor) bus slave by serially transmission.
  - During transmission the master keeps the clock line high to prevent cross-talk distortion.
  - The slave can put an asynchronous digital signal (pulse width or frequency modulated) or an analogue voltage on the data line.

Smart sensing systems (vi)

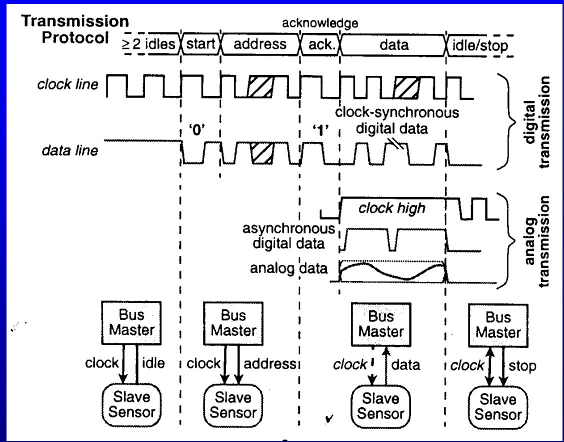
- IS^2 codification and interconnection:



Rclk = 500Ω

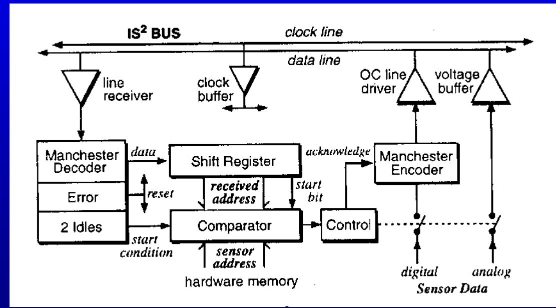
Smart sensing systems (vii)

- IS^2 communication protocol:
  - Address 8 bits => 256 sensors.



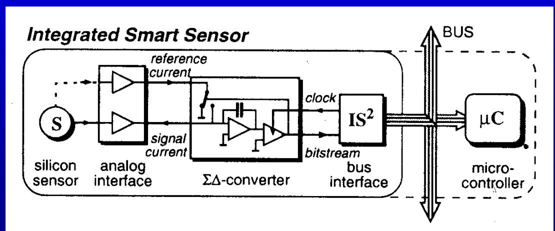
Smart sensing systems (viii)

- IS^2 hardware at the sensor (bus-slave):
  - It is very simple.
  - Approximately 20 gates and 12 flip-flops in CMOS technology.



Smart sensing systems (ix)

- IS^2 integration with an smart sensor:
  - Analogue interface with the ΣΔ converter.
  - The bit stream can easily be passed on by the IS^2 bus to the system's controller or another bus master.



Standard for A Smart Transducer Interface for Sensors and Actuators, IEEE-1451

- Simple transducer connectivity to existing networks.
- An interface between transducers and existing or emerging networks.
- Make easier the first network implementation, and significantly easier consecutive network implementations
- Reuse most of the first network software.
- Simplify the use of the existing control networking hardware and software, thus providing a rapid path to the market.

IEEE 1451parts

- The NCAP (Network Capable Application Processors).
- The software protocol (STIM-Smart Transducer Interface Model), that are necessary for the connection between the transducers and the NCAP.

STIM (i)

- In the STIM they are included:
  - Transducers (XDCR) Sensors &Actuators.
  - and the signal conditioning elements (Analogue to Digital and digital to analogue conversion, digital I/O ports, etc) that deliver a digital signal to the address logic which enables a selection of a specific transducer, and transmission of information to and from the NCAP.

STIM (ii)

- STIM may be used to sense or control multiple physical phenomena.
- Each phenomenon sensed or controlled is represented as a STIM transducer channel.
- A channel may be a virtual transducer in the sense that it behaves as a sensor or actuator, even though nothing outside of the STIM is sensed or changed.

STIM (iii)

- IEEE-P1451.2 proposes a novel system of digital encoding of transducer units in a form of a binary sequence of ten eight-bit bytes, to enable an automatic detection of used units.
- Each of the fields is represented as an unsigned integer.
- A unit is represented as a product of the SI base units, each raised to a rational power.
- This structure encodes only the exponents; the product is implicit.

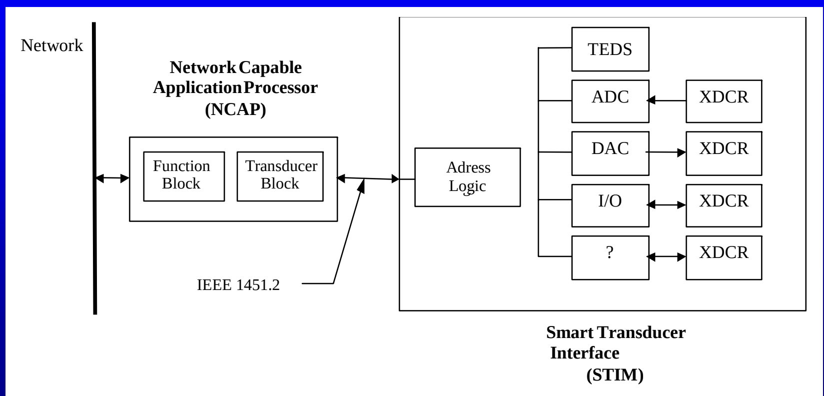
Transducer channels

- Sensor: A sensor measures some physical parameter on demand and returns digital data representing that parameter.
- Actuator: An actuator causes a physical or virtual action to occur that shall be related to data sent to the actuator.
- Event sequence sensor: An event sequence sensor produces a signal whenever a specific event occurs.
- Data sequence sensor: A data sequence sensor samples a stream of data with sampling time determined by the STIM.
- General transducer: For channels that have a different behaviour to the above channels.

NCAP

- NCAP enables treatment of all transducers as generic 1451 transducers.
- It learns about the specific transducer and its channel configuration by reading TEDS (Transducer Electronic Data Sheets) which are in the STIM and which store the technical information of the used transducers.
- NCAP then translates the generic 1451 transducer into a network-specific transducer using drivers to be provided by network manufacturers.

IEEE-P1451 transducer architecture



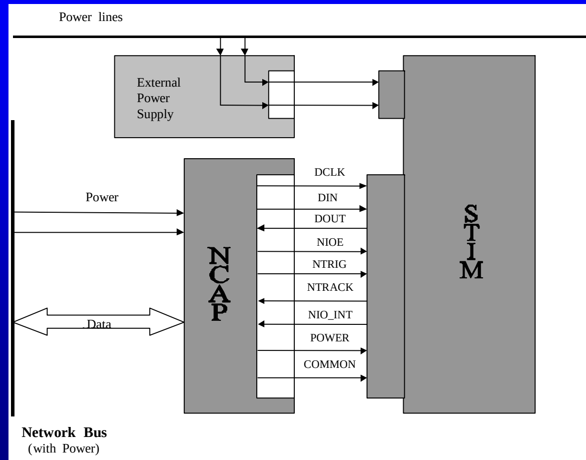
The primary STIM connector (i)

- Nine pins.
- Male (because the NCAP supplies power).
- Polarized.
- Appropriate female nine-pin mating connector shall be used on the NCAP.

The primary STIM connector (ii)

Pin	Signal name	FunctionalGroup	Abbreviation	Color	Direction NCAP	Direction STIM
1	Data_clock	Data	dclk	Black	Out	in
2	Data_in	Data	Din	Red	Out	in
3	Data_out	Data	dout	Orange	In	out
4	n_trigger_acknowledge	Triggering	ntrack	Yellow	In	out
5	Common	Support	Common	Gree	Power	Power
6	n_io_enable	Data	nioe	Blue	Out	in
7	n_io_interrupt	Interrupt	nio_int	Violet	In	out
8	n_trigger	Triggering	ntrig	Gray	Out	in
9	Power	Support	power	White	Power	Power

Connections between a NCAP, a STIM and the Network Bus



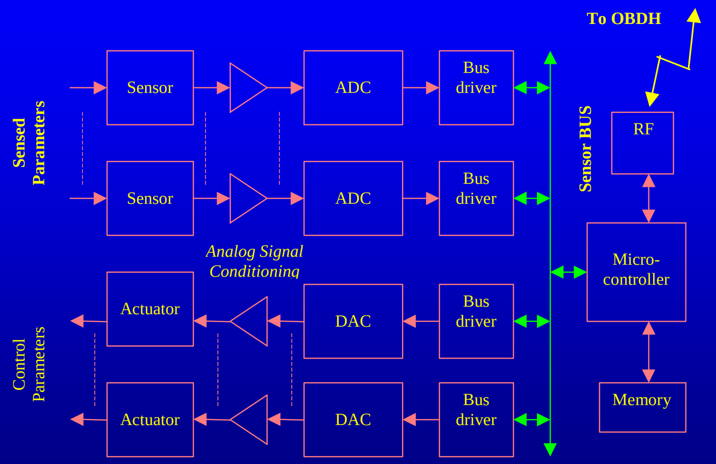
IEEE-1451 main features (i)

- Major transducers manufacturers, network providers and users are jointly developed the standard.
- Separation of the choice of network protocols from the choice of transducers.
- Allows digital or analogue inputs and outputs from sensors/actuators.
- Polling and interrupt modes.
- Calibration algorithm.
- Serial transmission full duplex, synchronous or asynchronous.

IEEE-1451 main features (ii)

- NCAP reads the data sheets of the sensors and their channel configuration from TEDS and then it translates this information to a sensor specific code (drivers).
- Facilities of plug-and-play.
- Total control over sensors and actuators, their communication channels and the data format that they send.
- Up to 255 channels per STIM.
- Robustness.

Wireless communication (i)



Wireless communication (ii)

- Problem to solve:
  - High number of cables and connectors.
- Solutions:
  - Common power supply lines.
  - RF communication or optical links for data transmission.

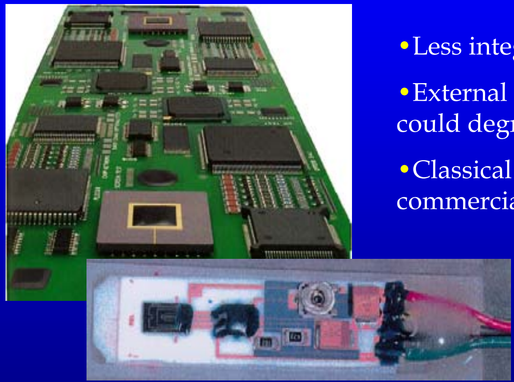
Interconnection technologies

- PCB and hybrid.
- MCM and 3D
- On-chip solutions

Interconnection technologies

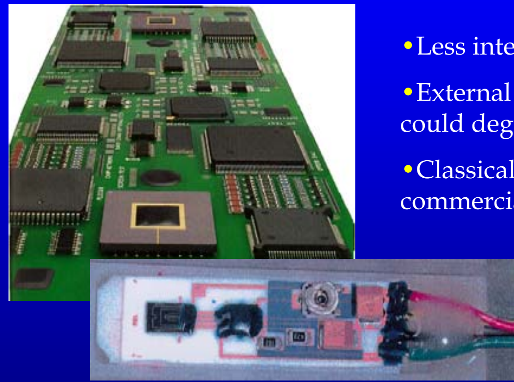
Technology Used	Line/space Size (μm)	Packaging Efficiency (%)	Technology available	Design costs	Power supply/ Dissipation
On-chip	0.3-3	100	S/A fabrication Process compatible	High	Lowest
MCM-D (active substrate)	10-50	30-60	KGD	Medium	Low
Chip on board (passive substrate)	100-200	15-30	KGD	Low	Medium
SMD on PCB	125-250	6-14	Standard components	Low	High
Through-hole ICs on PCB	200-300	1-3	Standard components	Low	High

PCB & hybrid interconnection



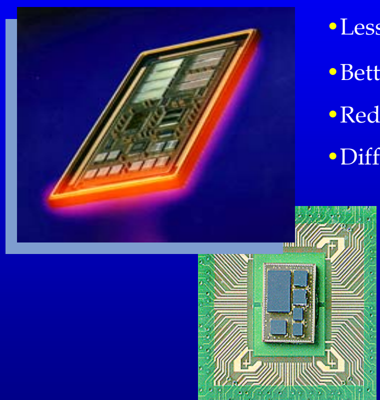
- Less integration capability.
- External package connections could degrade the system.
- Classical interconnection of commercial or military components.

PCB & hybrid interconnection



- Less integration capability.
- External package connections could degrade the system.
- Classical interconnection of commercial or military components.

MCM interconnection

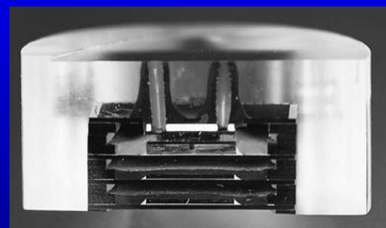


- Less space, mass & power consumption.
- Better immunity to noise.
- Reduction of energy dissipation capability.
- Difficulties to obtain KGD components.

3D interconnection

CSEM

- Similar to MCM, but more compact

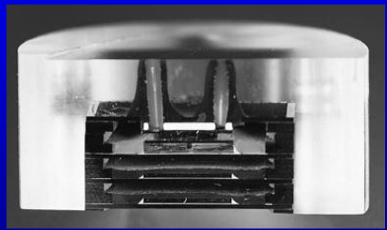


BARMINT-ESPRIT

3D interconnection

CSEM

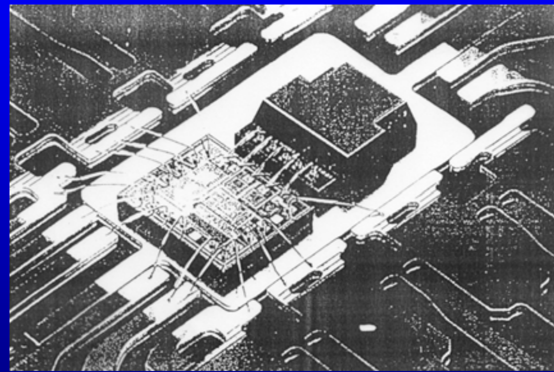
- Similar to MCM, but more compact



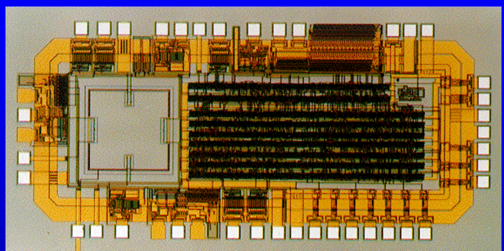
BARMINT-ESPRIT

Hybrid accelerometer

- Two dies connected into the same package.



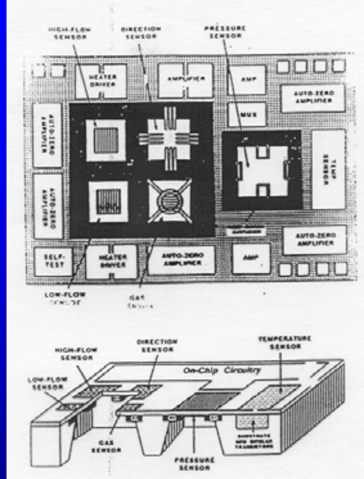
On-chip interconnection



- Best integration figures.
- A common technology for S&A process and CMOS circuitry it is needed.
- Difficult to apply to a non high volume markets.

On-chip MEMs

- Flowmeter example of on-chip solution.



Cross-sectional view and plan of a multi-element thermally-based mass flowmeter. (Reprinted courtesy of IEEE [20].)

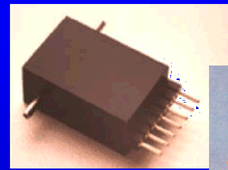
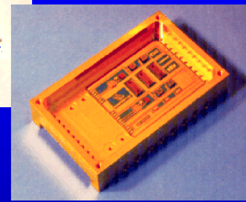
Sensor with electronics: Multi-chip or monolithic approach?

- Multi-chip
  - Media protection.
  - Low cost for low volumes
  - Easier and faster integration
  - Versatility
  - High cost in volume
  - More expensive packaging
- Monolithic
  - Size and weight
  - Reliability
  - Cost in volume
  - Temperature variation
  - Reduction of parasitics
  - Reduction of power consumption
  - Restrictions on sensors and circuits

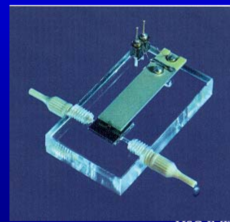
→ Choice depends on application

Non-electrical interconnects

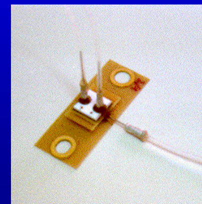
- Fluidics (liquid, gas)
  - No standard solutions
- Optics
  - Standards exist

Twente MicroProducts



HSG-IMIT



BARMINT-ESPRIT

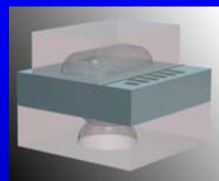
Polaroid

Microsystems packaging

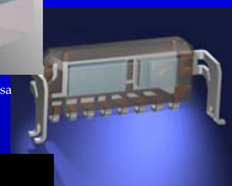
- Based on existing semiconductor / hybrid packaging technology.
- But there are significant differences:
  - Microsystems may need to interact with the environment.
  - Exposed to harsher operating conditions.
- The cost factor is important.
- Most requirements are related to the microsystem type and application → custom packaging.
- Packaging influences reliability and qualification testing
  → space applications have specific requirements.

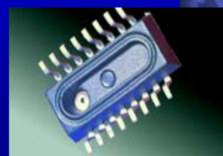
Microsystems packaging

Pressure sensor:

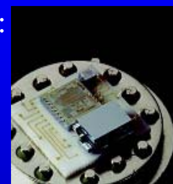


SensoNor asa





Accelerometer:



CSEM

Chemical sensor:

Sentron

Design methodology (i)

- A electronic systems can be described in three basic representations:
  - Behavioural: high-level constructs; language-based.
  - Structural: Schematics; precise constructs.
  - Physical/geometrical: layout.
- These representations allows the design process segmentation.

Design methodology (ii)

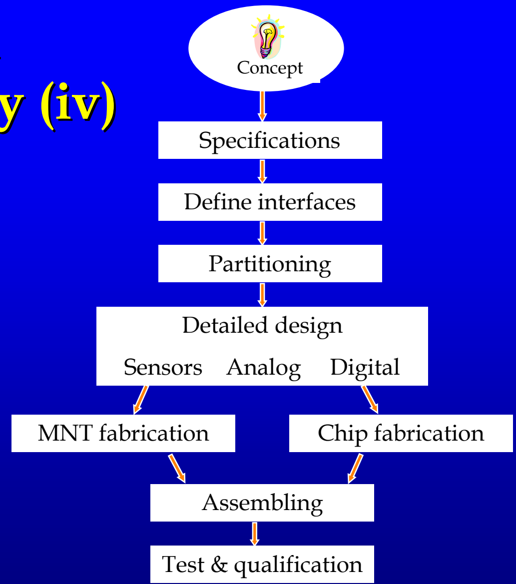
- Pressure sensor example:
  - Behavioural: $V_{out}=K(L^2/H^2)P$
  - Structural: Wheatstone bridge
  - Physical/geometrical: Membrane with piezoresistances on the top.

Design methodology (iii)

- Each representation has several levels of top-down functionality in the design process
  - Complete system.
  - Sensing + other circuitry subsystems.
  - Microsensors + electronic blocks.
  - Micromechanical elements + logic elements + analogue basic building blocks.
  - Membranes, cantilevers, ... + transistors, diodes,...+ R, C, L, ...

Design methodology (iv)

- Complete microsystem top-down design flow.



Design methodology (v)

- The design process must consider the complete system development including:
  - Transducer elements.
    - » Microsensors & microactuators.
  - Read-out electronics.
    - » Analogue signal processing.
    - » A/D converter.
    - » Digital signal processing and control systems.
    - » System interface.
  - Assembling.
    - » Physical interface.
  - Power management.

Design methodology (vi)

- Partioning:
  - How much of the system will be on chip.
    - » One-chip solution.
    - » Multi-chip solution.
    - » Standard component-based solution
  - Assembling requirements
    - » Level 0: assembling substrate.
    - » Level 1 & 2: packaging.

Design methodology (vii)

- Microsystem interface:
  - Electronic interface the measurement system including interconnect requirement.
  - Mechanical interface with the environment (with chemical, thermal and pressure/stress characteristics).
  - Materials requirements (for chemical, thermal, mechanical, ... Stability).

Design methodology (viii)

- Specifications concerning:
  - Functional, DC and AC requirements.
  - Fabrication technologies.
  - Package concept and materials.
  - Chips size.
  - Test procedures.
  - Acceptance and calibration procedures.
  - Estimated production.

Design methodology (ix)

- Detailed design by using integrated EDA environment.
  - Sensors and actuators:
    - » Mask design.
    - » Device modelization and simulation (Mechanical, thermal, electrical, ...).
    - » Behavioural modelization and simulation (VHDL-AMS).

Design methodology (x)

- Detailed design by using integrated EDA environment.
  - Analogue and mixed-signal:
    - » Full-custom design based on basic building blocks.
    - » Electrical modelization and simulation (SPICE, ELDO, ...).
    - » Thermal modelization and simulation (ANSYS,...).
    - » Behavioural modelization and simulation (VHDL-AMS).

Design methodology (xi)

- Detailed design by using integrated EDA environment.
  - Digital:
    - » Semi-custom design (Cell libraries, block generator & IP: Intellectual Properties).
    - » Behavioural & structural modelization and simulation (VHDL).
    - » Automatic Synthesis and P&R tools.
    - » Logical simulation with backannotation (temporal, thermal, electrical, ...).

Design methodology (xii)

- Detailed design by using integrated EDA environment.
  - Internal control and processing application:
    - » Embedded dedicated microprocessors.
    - » Embedded Software (operative system, system communication and application Sw).
    - » Hw/Sw co-design, co-simulation (C++, VHDL, VHDL_AMS, Spice, ELDO,...) and verification.

Test & qualification

- Environmental factors.
- Test &qualification requirements.
- Reliability: failure mechanisms.
- Test & qualification procedures.
- Design for testability.

Space environmental factors

- Radiation belts, plasma and cosmic rays.
- Atomic oxygen.
- Solar ultraviolet.
- Induced contamination.
- Upper atmosphere.
- Meteoroids and orbital debris.

Space radiation effects

- Induce two types of problems:
  - Single Event Upset (SEU)
  - Latch-up.
- Tolerance depends on the technology:
  - "Harden" SOS & SOI.
  - Commercial Off The Shelf (COTS).

Failure mechanisms

- Problems with definition of failure mechanisms due to the on-going development technologies.
- Common microelectronic technologies failures mechanisms:
  - Device interactions.
  - Integration structures.
  - Vibration and shock effects.
  - Hermiticity.
  - Requirements for outgassing.
  - Local sealing.
  - Vacuum environmental effects.
  - Radiation issues.
  - Actuators fractures.
  - Fabrication impurities.
  - Drift rates devices themselves.
  - Thermal variations.

Test procedures for qualification

- High temperature storage
- Thermal cycling
- Thermal shock
- Mechanical shock
- Humidity
- Endurance
- Vibration
- Bond strength
- Internal visual inspection
- Solderability
- Particle impact noise detection
- Seal test
- Radiographic inspection
- Die shear strength
- Thermographic test
- Electrical measurements
- Thermal vacuum
- Internal water vapor test
- Radiation tests

Design for testability

- To be taken in mind from early phases of microsystems conception.
- Testing requirements are very dependent on used manufacturing processes and application.
- Self-testing become of interest for space application.
- Boundary-scan can be integrated on active substrates.
- Only in some cases is possible the electrical generation of physical quantities.
- Some non electrical parts can only be verified indirectly.

Interfacing solutions in other sectors

- Automotive:
  - Non-unified connectors
  - Data bus protocols:
    - J1850 (USA), CAN (Germany, …), VAN (France, …)
- Defence & Aerospace:
  - Data bus protocols
    - MIL-STD-1553.

Standardization efforts (i)

- No technical committee working on MST until now on the international standardisation bodies (Europe: CEN, CENELEC, ETSI; World-wide: ISO, IEC)
- Existing standards:
  - Electrical interconnects: IEEE P1451 - Smart transducer interface standard for sensors and actuators.
  - Optical interconnects:
    - » DIN V 58001 - Integrated optics: Characteristics relevant for interfaces
    - » ISO/CD 14881 - Integrated optics: Interfaces - coupling parameters
    - » IEEE 1393 - Spaceborne fibber optic data bus.

Standardization efforts (ii)

- New standardisation activities:
  - European project (1998): Industrial standardisation in Microsystems Technology.
  - New IEEE Technical Committee on MEMS and sensor packaging (Components, Packaging and Manufacturing Technology Society, TC-17).
  - New NEXUS task force "standardisation".

Test & qualification

- To be taken in mind from early phases of microsystems conception.
- Problems with definition of failure mechanisms due to the on-going development technologies.
- The use of commercial technologies is changing the space qualification procedures.
- The introduction of DFT techniques increase the accessibility of internal nodes.

Conclusions

- To solve interface problems a distributed architecture microsystem has the advantage of modularity and interchangeability of intelligent sensors.
- The use of an internal sensor bus is basic and an standardization efforts would have to be continued.
- Several interconnection technologies are available, with specific requirements.
- The use of a integrated EDA environment allows to manage a complete microsystem design.

THANK YOU FOR YOUR ATTENTION

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