Tecnologías para Microsistemas (MEMS)

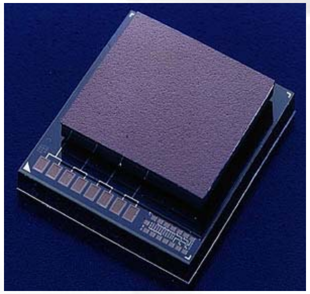
José A. Plaza Plaza

21-23 Mayo 2003

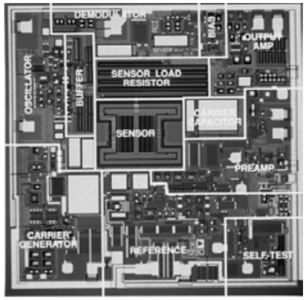
Sao Paolo, Brasil

Overview

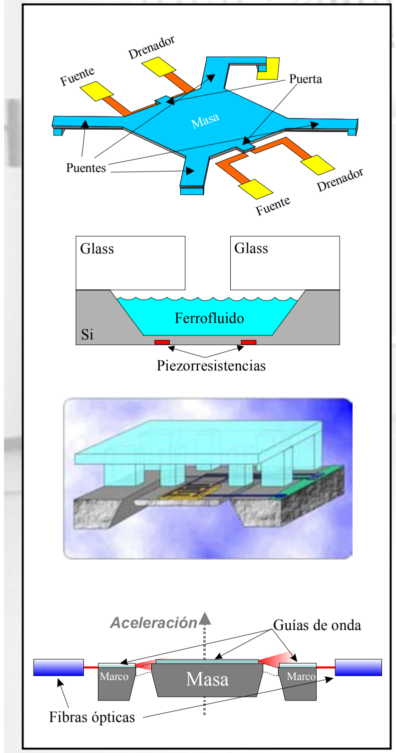
• Technologies for Microsystems



FLIP-CHIP ACCELEROMETER LETI



ADXL-50 ACCELEROMETER ANALOG DEVICES



Hybrid

Monolithic

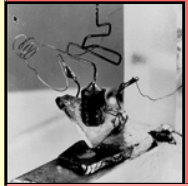
SYSTEM INTEGRATION

MICROELECTRONIC DEVICES

Bipolar **Bicmos**

CMOS 75%

III-V



Transistor

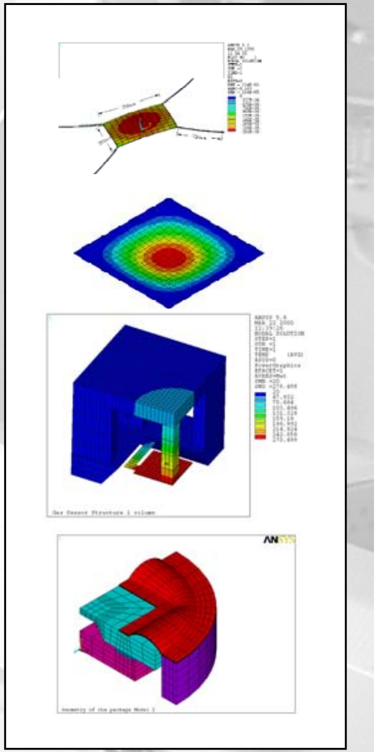
MICROSYSTEMS

Tec. Específicas

Design/Devices

Simulations

Microelectronic Technology



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- Introduction to Microsystems
  - Definition
  - Microsystems versus Microelectronics-Applications
  - Microsystems Advantages
  - Historic Evolution
  - Commercialisation and Market Considerations
- Microsystems Technologies
  - Introduction: Substrates and Materials
  - Processes of Microelectronics in Microsystems
  - Specific Processes for the Microsystems Fabrication
    - Example 1: Surface Micromachining
    - Example 2: Bulk and Surface Micromachining
- State of the Art and Future of Microsystems
- System Integration
  - Introduction to System Integration
    - Example 1: Monolithic Integration (Accelerometer+Optic Waveguides)
    - Example 2: Monolithic Integration (Gas sensor+Electronics)
    - Example 3: Hybrid Integration MCM-D (Accelerometer+Electronics)

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Definition

- **Microsystems**
  - **Europe**

    Microsystems: *Microstructure products have structures in the micron range and have their technical function provided by the shape of the microstructure. Microsystems combine several microcomponents, optimised as an entire system, to provide one or several specific functions, in many cases including microelectronics.* ***(Market Analysis for Microsystems, NEXUS Task Force, p 24) NEXUS: Network of Excellence in Multifunctional Microsystems)***

    MST, Microsystems Technology: *Microsystem Technology can broadly be defined as the development and integration of sensors, actuators and other three dimensional structures on the scale of, and using the* ***fabrication techniques*** *of integrated microelectronics.*

    TECHNOLOGY

  - **USA**

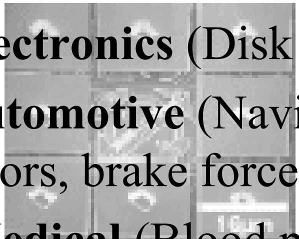
    MEMS: *MEMS stands for MicroElectroMechanical Systems, a class of small devices that integrates tiny mechanical and electrical components on a silicon chip.*
    MST: *commonly used in Europe, stands for Micro System Technology and is often used to describe MEMS*

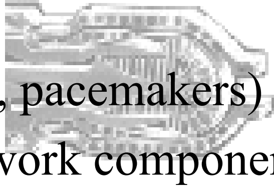
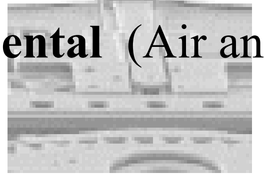
  - **Japan**

    Microengines: Evolution from Mechatronics.

Microsystems versus Microelectronics- Applications

- **Microelectronics**
  - **Base of the computational revolution and telecommunications.**
  - **1 Billon Dollars Market *(1 Trillion $)***
- **Microsystems**
  - **One of the most promising technologies for the 21th century**
  - **38.000 Millions Dollars Market in 2002 and an annual increase of 20%.**
- **Applications**
  - **Electronics** (Disk drive heads, inkjet printer)
  - **Automotive** (Navigation sensors, suspension control, intelligent tyres, airbags sensors, brake force sensors)
  - **Medical** (Blood pressure sensor, drug delivery systems, pacemakers)
  - **Communications** (RF filters and relays, fiber optic network components, projection displays)
  - **Defense** (Munitions guidance)
  - **Environmental** (Air and water quality, agriculture)



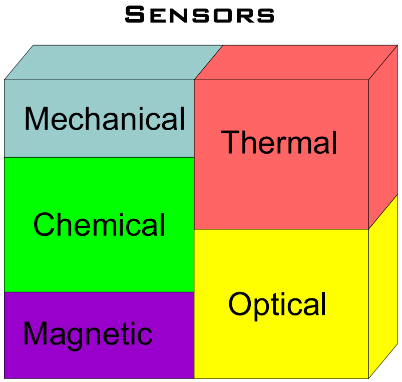

Microsystems Advantages

- **Advantages**
  - Batch mode of production: Low cost and Large volumes of production
  - Silicon based technology:

TECHNOLOGY

IC technology + Micromechanization

  - Possibility of electronics integration *(Smart MEMS)*
  - Small size, volume, weight and power consumption.
  - Robustness and viability.
  - Interdisciplinary: wide range of markets and applications
  - Bio-compatibility.**(BIO-CHIPS)**



Silicon (J.J. Berzelius 1824)

- Cheap and common
- Excellent mechanical, electrical and chemical properties
- Large electronic gap
- Charge density concentration can be easily controlled
- Stable silicon oxide with good properties

Historic Evolution

- **Historic evolution of the Microsystems due to technological achievements**

1950´s

1954 Piezoresistive effect in semiconductors is discovered (C.S. Smith)
1958 Silicon strain gauges commercially available

1960´s

1961 First silicon pressure sensor demonstrated
1967-68 Deep anisotropic etching, surface micromachining and anodic bonding

1970´s

1970 First silicon accelerometer demonstrated.
1979 First micromachined nozzle

1980´s

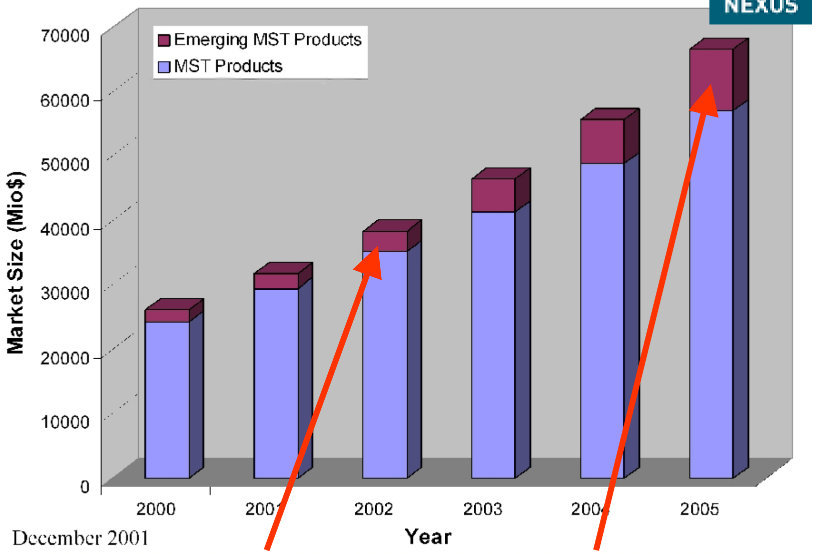
1983 First integrated pressure sensor (Honeywell)
1985 LIGA (W. Ehrfeld et al.)
1986 Silicon bonding
1988 First MEMS conference
1988 Batch pressure sensor using wafer bonding (Nova Sensor)

1990´s

1993 First surface micromachined accelerometer sold (Analog Devices, ADXL50)
1993 Digital mirror display (Texas Instruments)
1994 Deep Reactive Ion Etching is patented
1995 BioMems rapidly develops
2000 Mems optical-networking components become big business

Commercialisation and Market Considerations

- **2002-2005 Market**



38.000 millions $

68.000 millions $

Product Types	1996 Units (millions)	$ (millions)	2002 Units (millions)	(mil
HDD heads	530	4500	1500	12000
Inkjet print heads	100	4400	500	10000
Heart pacemakers	0.5	1000	0.8	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	0.006	3	0.15	40
TOTAL	**1595**	**$13,033**	**6807**	**$34,290**

- **Products commercialisation**

Product	Discovery	Evolution	Cost Reduction/ Application Expansion	Full Commercialisation
Pressure sensors	1954-1960	1960-1975	1975-1990	1990-present
Accelerometers	1974-1985	1985-1990	1990-1998	1998
Gas sensors	1986-1994	1994-1998	1998-2005	2005
Valves	1980-1988	1988-1996	1996-2002	2002
Nozzles	1972-1984	1984-1990	1990-1998	1998
Photonics/displays	1980-1986	1986-1998	1998-2004	2004
Bio/Chemical sensors	1980-1994	1994-1999	1999-2004	2004
RF switches	1994-1998	1998-2001	2001-2005	2005
Rate (rotation) sensors	1982-1990	1990-1996	1996-2002	2002
Micro relays	1977-1982	1993-1998	1998-2006	2006

(Walsh, S., Linton, J., Grace, R., Marshall, Knutti, S., MEMS and MOEMS Technology and Applications, edited by Rai Choudry, P., SPIE – The International Society for Optical Engineering, Bellingham, WA, Ch. 8, 2000.)

• Introduction to Microsystems

Commercialization and Market Considerations

• Commercialization

Technological problems

Scientifics problems
- Material Properties

Engineering problems
- Multi-field optimisation
- Packaging (specific, no *batch,* Cost dominance)

• Economic problems

$$Cost_{MEMS} = f(C_{development} + C_{production})$$

No Existence MEMS$_{\text{(TRANSISTOR)}}$

No generic device

The objective is the device not the technology (IC)

Fields:
- Electrical
- Mechanical
- Chemical
- Thermal
- Optical

→ ***Difficult for the Foundries***
(many different technologies)

Keys:
- Long development time (>10 years)
- Specific for every application

→ **Cost effective only for large volume production**

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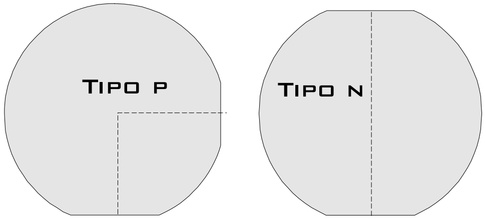
Introduction: Substrates and Materials

• Substrates

- Silicon wafers



Parámetro	Definición	IC	MEMS
Espesor	d [µm]	Estabilidad mecánica	Geometría
Orientación	Error [º]	±1	±0.1
Orientación *Flats*	Error [º]	±1	±0.2
Pulido		Una cara	Doble cara
Variación total espesor	dmax-dmin [µm]	4-10	<2
Concentración	%	±10	±100

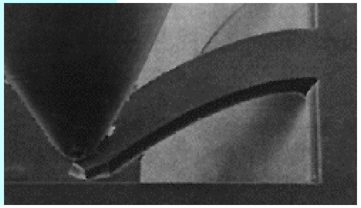
• Materials

Diversity

- Silicon: crystalline, polycrystalline, amorphous.
- Silicon compounds (Si_3N_4, SiO_2, SiC)
- Metals and metallic compounds (Au, Ti, Ni, Al, ZnO...)
- Ceramics
- Organics (polymers, enzymes, DNA, antibodies)

Properties

- Electrical
- Mechanical
- Thermal
- Biological
- ...



Introduction: Substrates and Materials

Silicon has a diamond crystalline system but it is considered as orthotropic cubic material for mechanical considerations.

Description	Symbol	Value	Units
Density [1]	ρ	$2.33*10^{3}$	kgr/m^{3}
Young Modulus [2]	Y	$1.69*10^{11}$	Pa
Young Modulus (110) [2]	Y_{110}	$1.6895*10^{11}$	Pa
Young Modulus (100) [2]	Y_{100}	$1.3002*10^{11}$	Pa
Poisson ratio (110) (100) [2]	$\nu_{110\ 100}$	0.2785	-
Poisson ratio (110) (110) [2]	$\nu_{110\ 110}$	0.0625	-
Shear Modulus (110) (100) [2]	$G_{110\ 100}$	$0.7951*10^{11}$	Pa
Shear Modulus (110) (110) [2]	$G_{110\ 110}$	$0.5085*10^{11}$	Pa
Thermal Conductivity [3]	K	150	W/(K*m)
Thermal expansion coefficient [1]	α	$2.33*10^{-6}$	K^{-1}
Residual Stress	S_{res}	0	Pa
Residual Stress Gradient	SG_{res}	0	Pa/µm

Materials constants

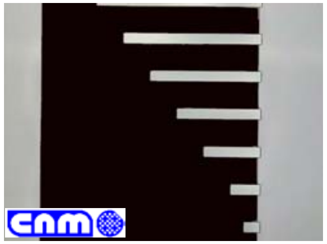
$C_{11} = 1.6564\ 10^{11}\ Pa$ $\quad S_{11} = 0.7691\ 10^{-11}\ Pa^{-1}$

$C_{12} = 0.6394\ 10^{11}\ Pa$ $\quad S_{12} = -\ 0.2142\ 10^{-11}\ Pa^{-1}$

$C_{44} = 0.7951\ 10^{11}\ Pa$ $\quad S_{44} = 1.2577\ 10^{-11}\ Pa^{-1}$

Test structures

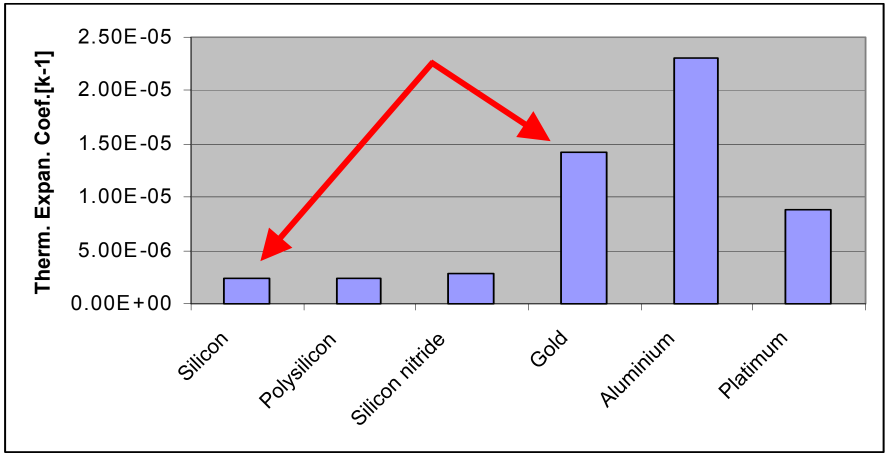
RING-BEAM



CANTILEVER BEAM

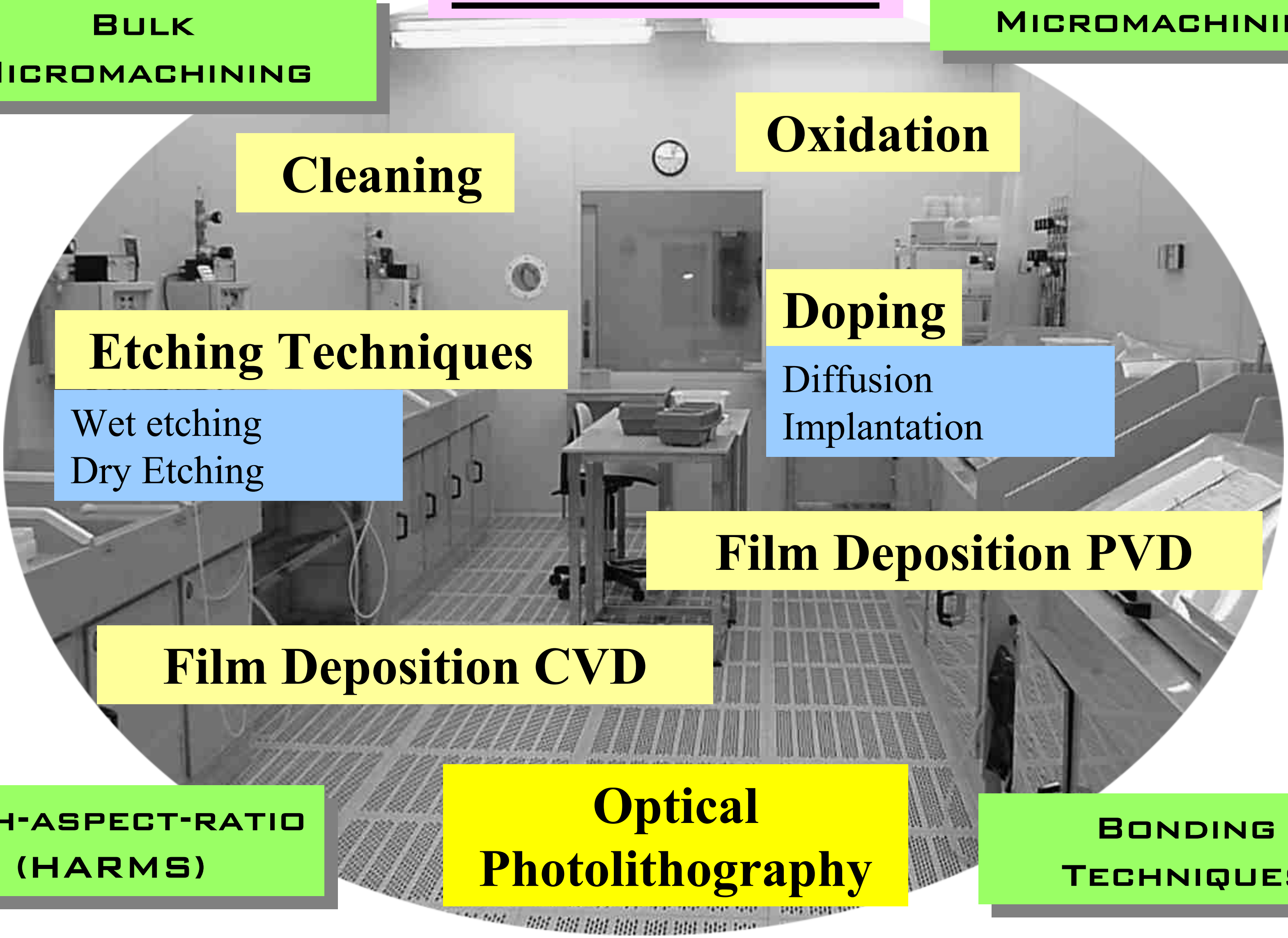
Young modulus, Stress, Stress Gradient

Combination of materials



- **Fabrication Process**

CLEAN ROOM



BULK MICROMACHINING

SURFACE MICROMACHINING

Oxidation

Cleaning

Etching Techniques

Wet etching
Dry Etching

Doping

Diffusion
Implantation

Film Deposition PVD

Film Deposition CVD

HIGH-ASPECT-RATIO (HARMS)

Optical Photolithography

BONDING TECHNIQUES

Processes of Microelectronics in Microsystems

- **Clean Rooms**
  - Humidity and temperature control, air quality control (Class) and desionized water..

- **Cleaning**
  - Related with the Yield (particles, organic residues, atoms and ions)

Etching Techniques

Elimination of films in determined areas.

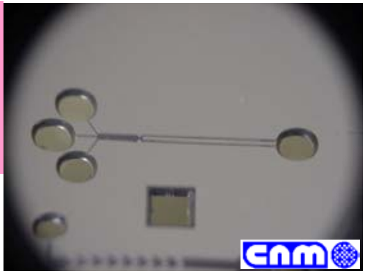
Selectivity **Anisotropy**

- **Wet Etching**
  - Elimination by dissolution in a etching medium

- **Dry Etching**
  - Elimination by RF plasma
  - High resolution
  - High control (anisotropy)
  - Small cost

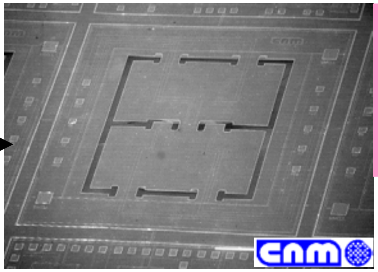
Elimination of mask layers

Small ethings for channels definition



MICROFLUIDICS

Release of moving structures



ACCELEROMETER

• Microsystems Technologies

Processes of Microelectronics in Microsystems

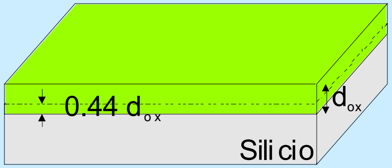
Oxidation

- High temperature (700-1250ºC)
- Simple and uniform process

- Dry oxidation
- Wet oxidation

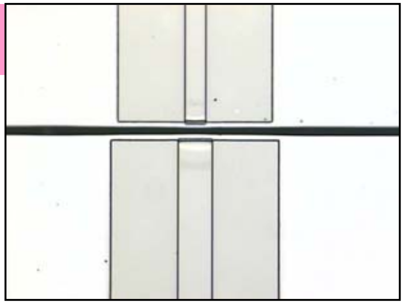
$Si + O_2 \rightarrow SiO_2$

$Si + 2H_2O \rightarrow SiO_2 + 2H_2$

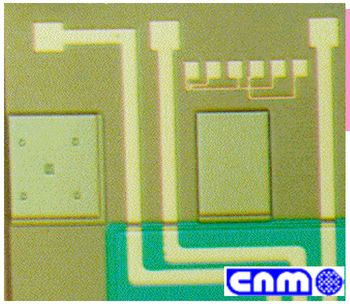


0.44% Silicon is consumed

MOEMS



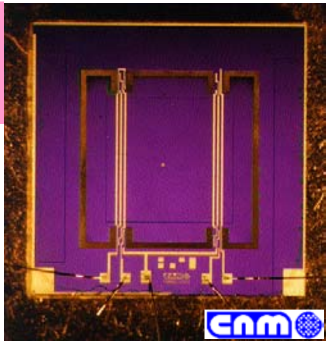
WAVEGUIDES



CONTACTS

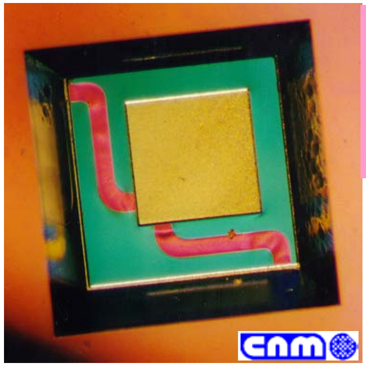
Dielectric between metal tracks and the silicon

Mask for silicon etching RIE-DRIE



ACCELEROMETER

Structural membranes
Thermal isolated membranes



GAS SENSOR
OXIDE MEMBRANE

Processes of Microelectronics in Microsystems

• Doping process

Diffusion

Movement of atoms from a high concentration to a low concentration regions.

Predeposition:

- Constant concentration in surface
- Solubility limit
- Species: B, P, Ar, Sb
- Gaseous, liquid and solid sources

Drive-in, impurities distributions:

- Constant total concentration
- High temperature process

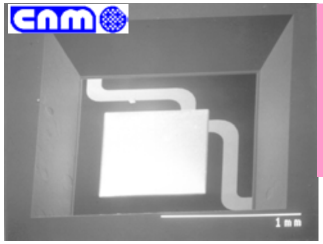
Implantation

Ionised atoms of a specie are accelerated to the wafer

- Species: B, P, Ar, Sb
- 1979-Most common

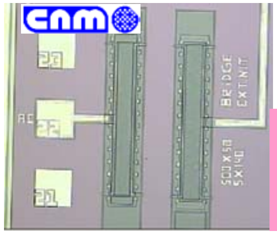
Advantages:

- Simple doping sources
- High precision of the dose
- High control of the doping profile
- Low temperature process
- Uniformity and good yield
- No solubility limit



GAS SENSOR

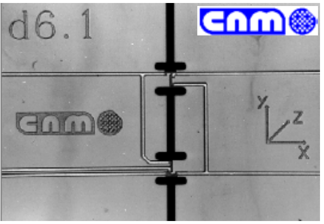
Etch-stop in high doped regions



ELECTRONIC NOSE

Electrostatic attraction electrodes

Piezoresistors



TRIAXIAL ACCELEROMETER

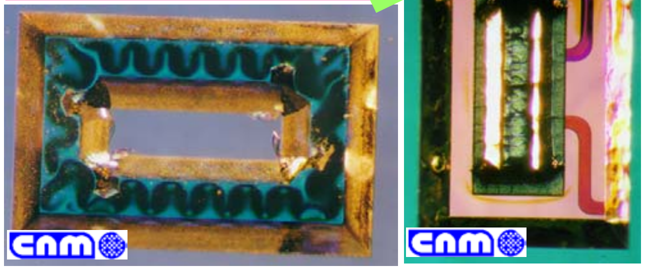
Processes of Microelectronics in Microsystems

CVD *(Chemical Vapour Deposition)*

- Deposition of a stable film by chemical decomposition and/or chemical reaction of gaseous species
  - Silicon, polysilicon
  - Silicon oxide
  - Silicon nitride
- **APCVD**
- **LPCVD**
- **PECVD**

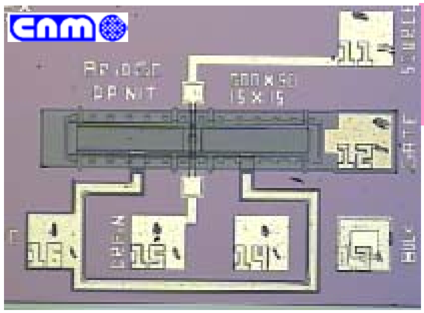
Stress/Stress gradient control

Low stress films



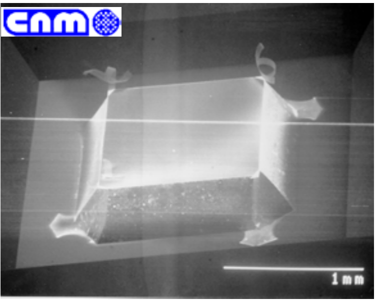
Dielectric membranes

Sacrificial and structural layers



Sacrificial layers
Silicon oxide
Structural layers
Polysilicon

Mask layers



Anisotropic compensation structures

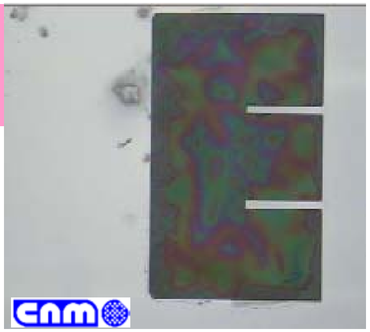
PVD *(Physical Vapour Deposition)*

- A gaseous material condense in the surface
  - Low temperature (100-500ºC)
  - Good homogeneity
  - Metallic masks, photoresist, *lift-off*
  - Variety of substrates and deposited films.

- **Evaporation**
- **Sputtering**

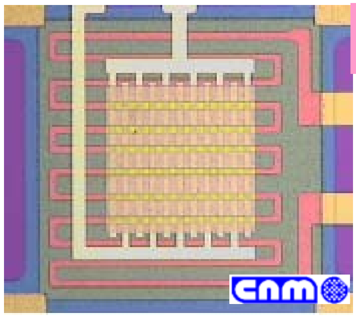
Aluminium metalisation

Surface functionalization



DNA Sensors

Electrodes



Heater resistors

Capacitive electrodes

Adherence films

Specific Processes for the Microsystems Fabrication

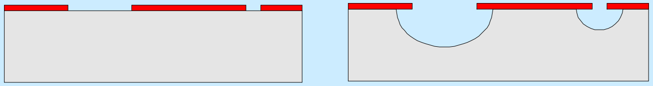
• Bulk Micromechanization

- Total or partial Micromachining of the whole wafer (3D)
- Cavities, channels and holes

CHEMICAL BATCH

Wet Etching

Isotropic etching:

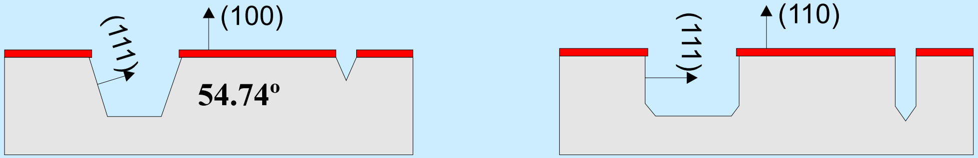


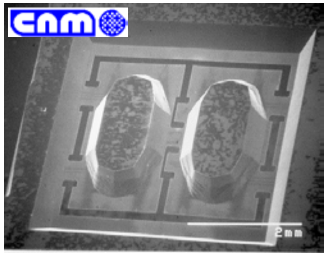
- HNA ($HF+HNO_3+CH_3COOH$)
- Slow, large lateral etching, diffusion problems(agitation)

Anisotropic Etching:

Selective
Reproducible
Low cost

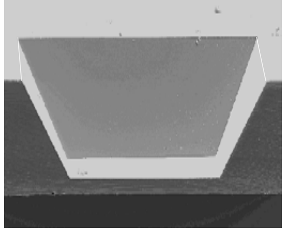
- Alkaline solutions: KOH, TMAH, EDP
- Fast, crystalline plane dependence $V_{(110)}>V_{(100)}>>V_{(111)}$





ACCELEROMETERS

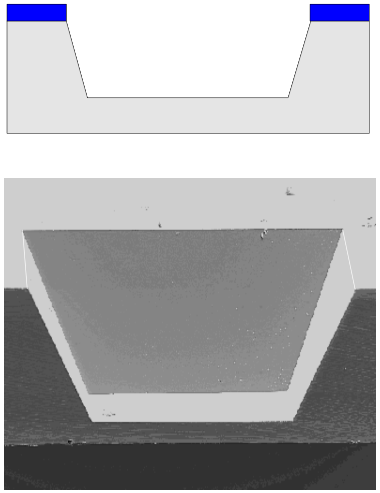
PIEZOELECTRIC GAUGES



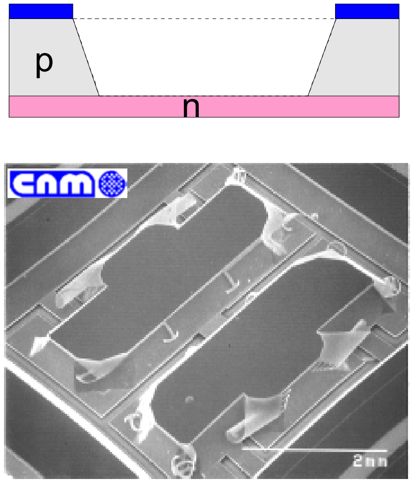
PRESSURE SENSOR

Specific Processes for the Microsystems Fabrication

• Etching stops techniques:

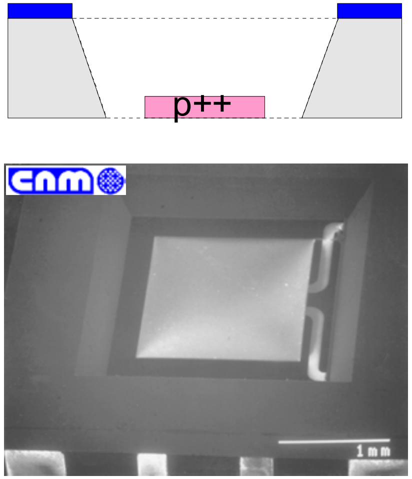


Time



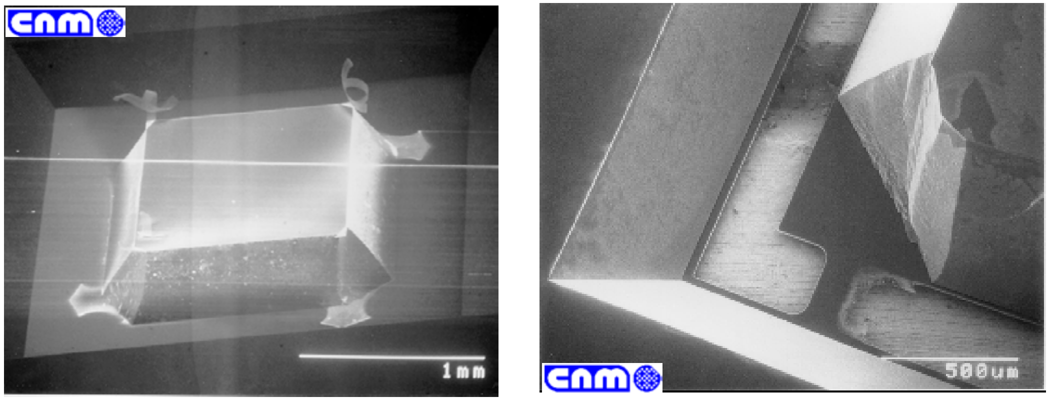
Electrochemical Etch- stop

Low etch rate layers



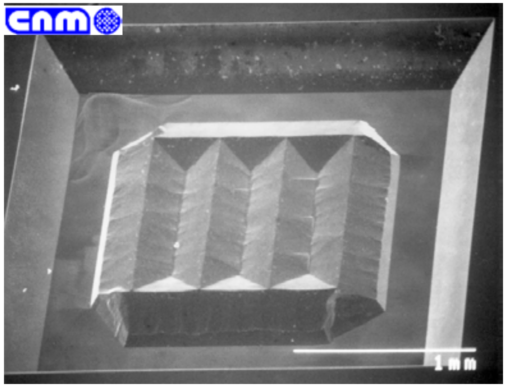
High doped zones

• Anisotropic etching considerations



Convex corners compensation

• Mask-Less



Mask-less

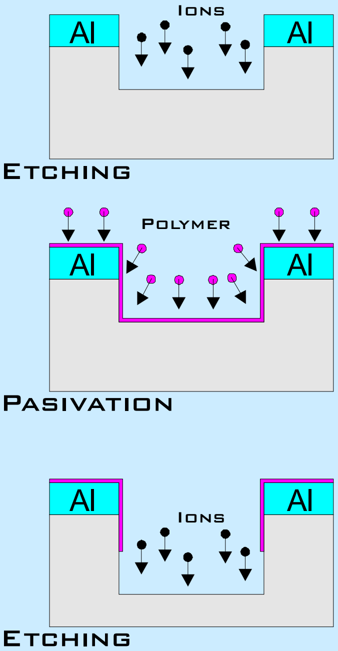
Specific Processes for the Microsystems Fabrication

•Bulk Micromachining

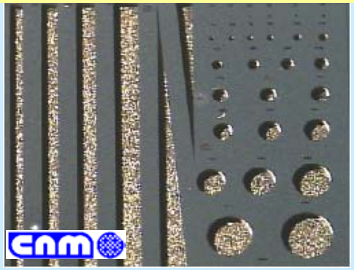
Dry Etching (DRIE)

Deep Reactive Etching (DRIE):

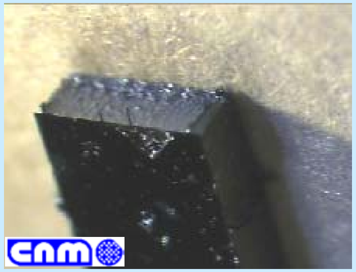
- Plasma etching + polymer deposition to increase the etching/lateral etching ratio
- Whatever geometry
- High selectivity to aluminium



Aspect ratio



Partial DRIE etching



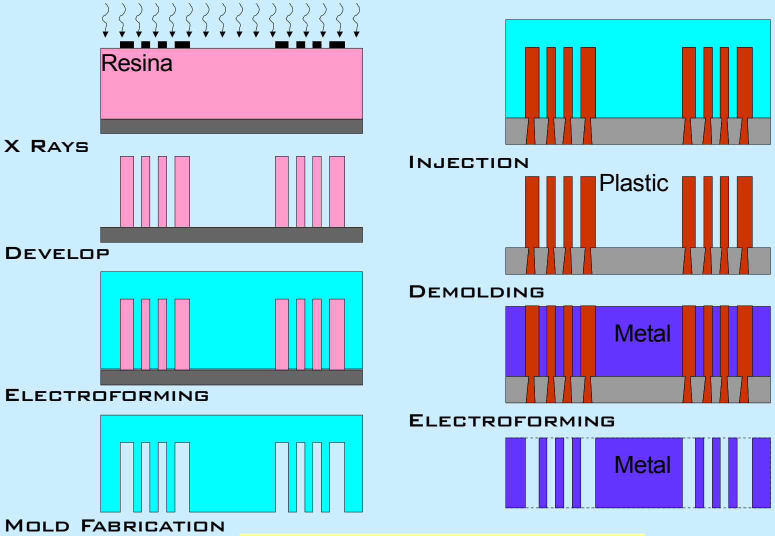
Total DRIE etching

• High-Aspect-Ratio Micromachining (HARM)

Replication

LIGA

- X ray lithography in a synchrotron, electroplating, moulding
- X-ray sensitive resist 0.2-0.6nm, PMMA
- High aspect ratio
- Gold mask (microns): Expensive
- Nickel-Cobalt, ceramics

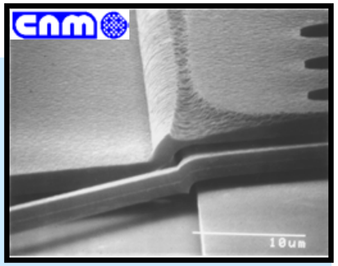


High price

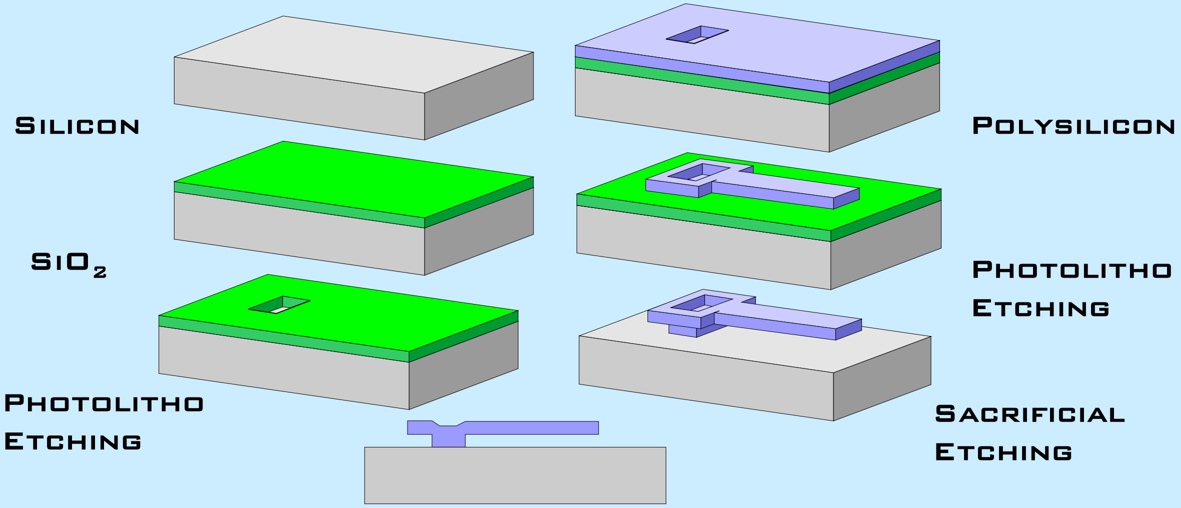
Specific Processes for the Microsystems Fabrication

•Surface Micromachining

- **Structural layers:** define the structure
- **Sacrificial layers** they are defined where the structure is to be released and they are removed where the structure is going to be anchored



DOUBLE CAPACITIVE ACCELEROMETER

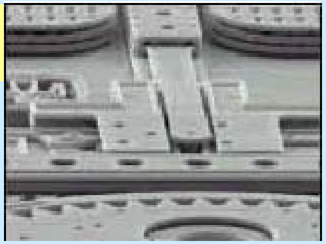


Structures on the surface of the wafer (2.5D)

- **Motor, gears, beams**

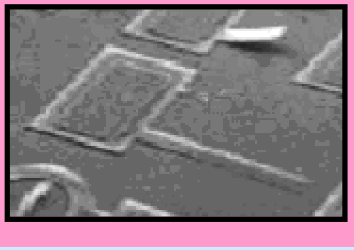
SANDIA

Complex designs

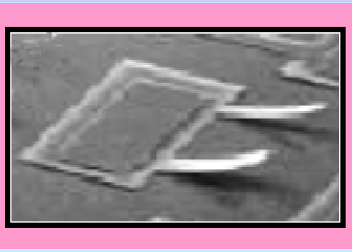


SANDIA (5 LEVELS)

Sticking



Stress and Stress Gradient

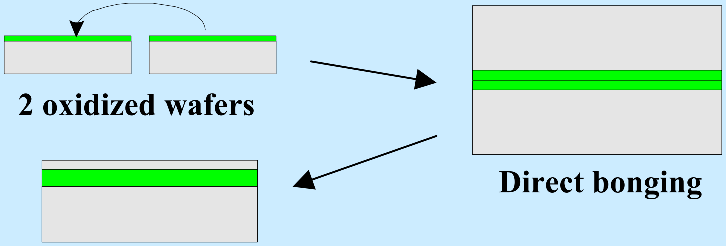


Specific Processes for the Microsystems Fabrication

• Bonding techniques

Wafer level packaging

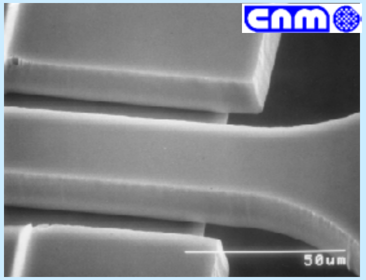
Direct bonding



- Silicon-silicon (with SiO_2)
- Very critical: cleaning, planarity.
- Hydrophobic and hydrophilic

Process:

- Cleaning (RCA1-RCA2)
- Contact (pre-bond) room temperature
- High temperature annealing (700-1000ºC)
- 3.3 J/m^2



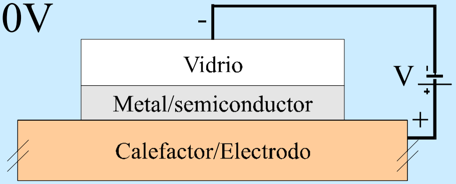
ACCELEROMETER (BESOI)

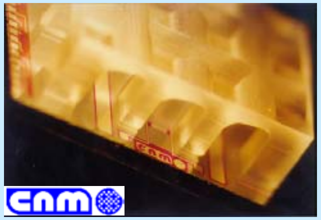
Anodic bonding

- Electric field assisted bonding
- Silicon to Pyrex #7740
- Less critical than DB
- SiO_2, Si_3N_4 and polysilicon
- Lot of devices: part of the device and/or stress reduction from the packaging.

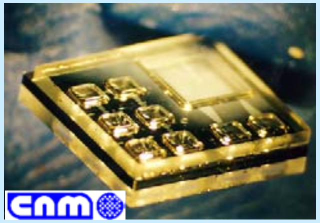
Process:

- Intimate contact
- Temperature 300-450ºC
- Voltage 50-1000V





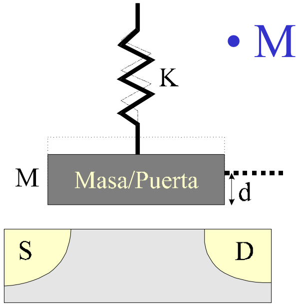
GAS SENSOR



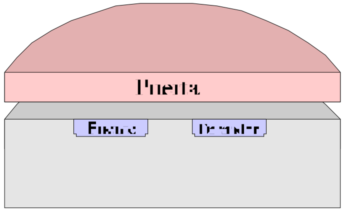
MICROFLUIDIC

Example 1: Surface Micromachining

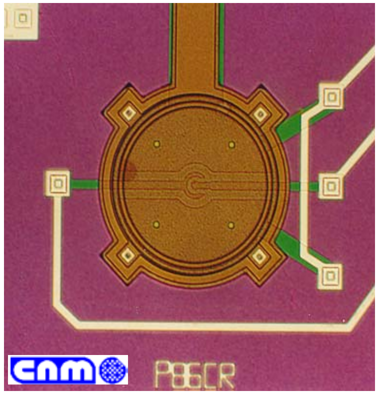
• FET sensors



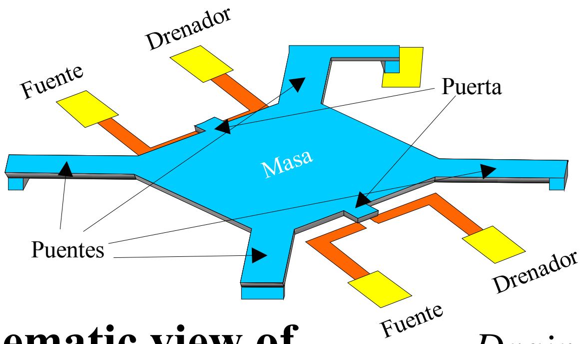
- Monolithic integration of sensors and transistors
  - Small size
  - High sensitivity



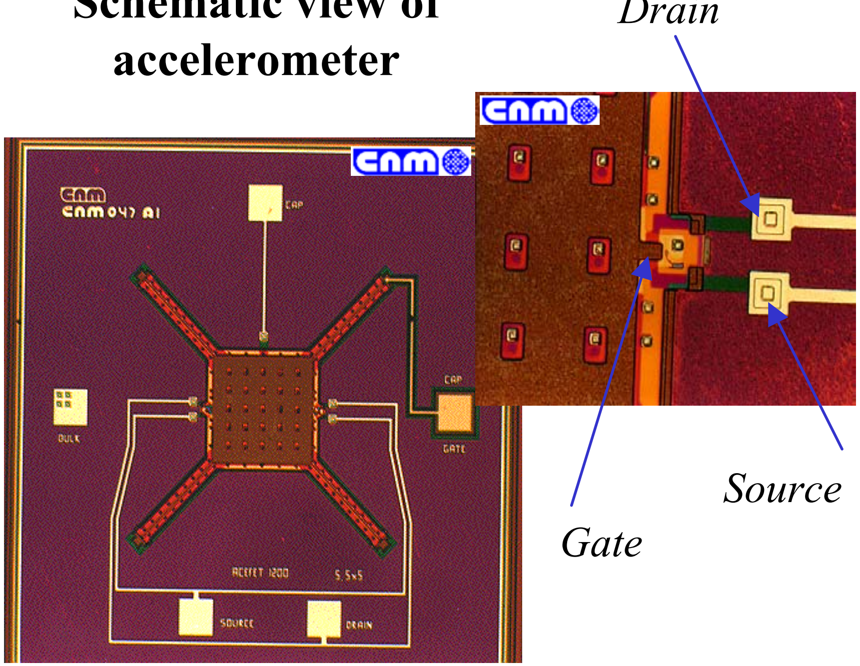
Schematic view of pressure sensor



Schematic view of accelerometer

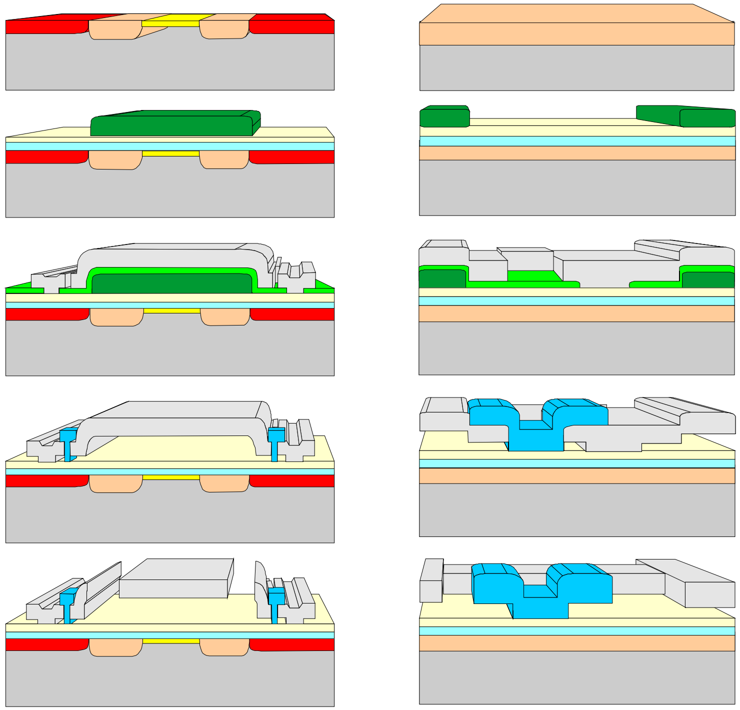


Schematic view of accelerometer

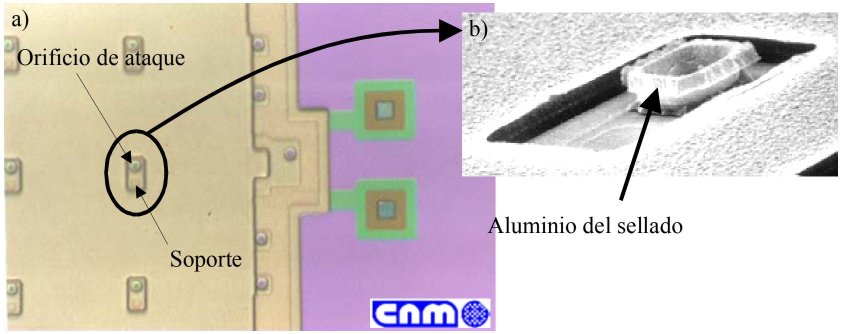


Example 1: Surface Micromachining

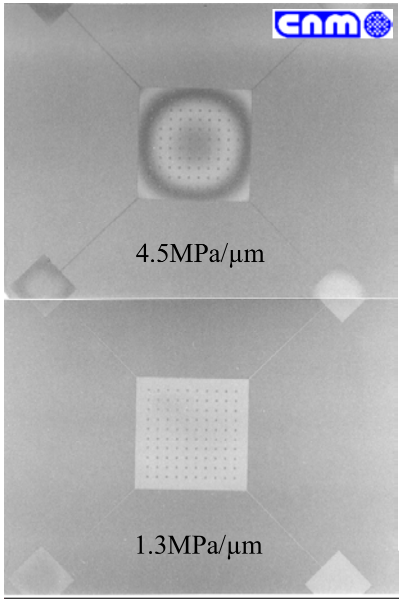
•Technology: Fabrication Process



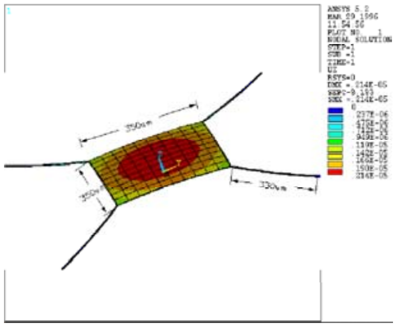
- Anchoring structures
- Dry etching (sticking avoided)
- Aluminum protection not necessary



• Technology: Stress and Stress Gradient



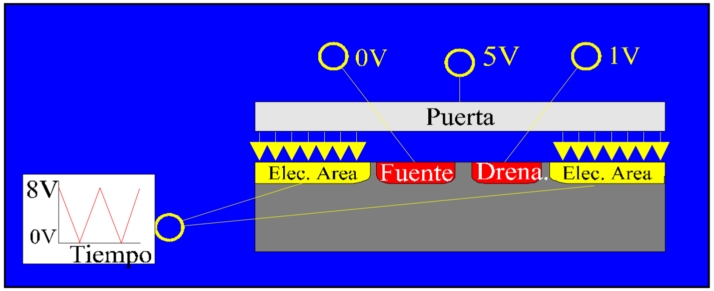
PICTURE FROM AN INTERFEROMETER MICROSCOPE

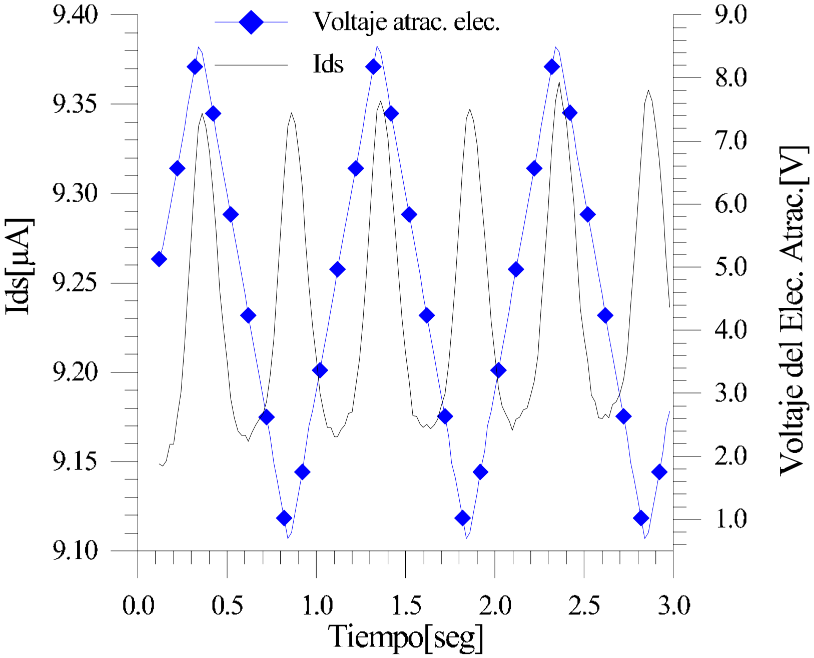


STRESS AND STRESS GRADIENT SIMULATIONS

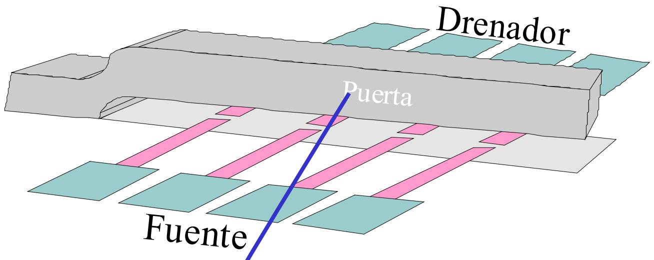
Example 1: Surface Micromachining

- **Characterisation**

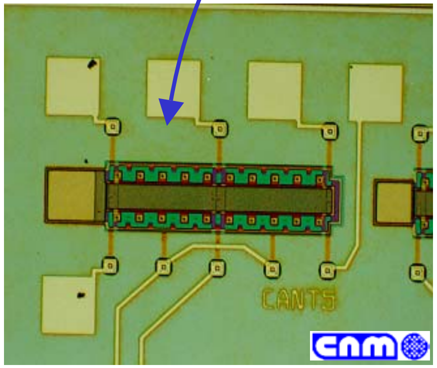




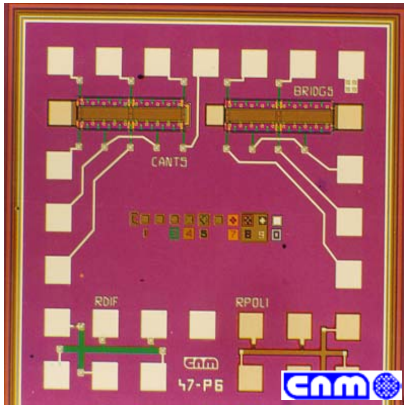
- **Test structure for stress and stress gradient characterisation**



SCHEMATIC DRAWING OF THE TEST STRUCTURE



PHOTOGRAPH OF A TEST STRUCTURES



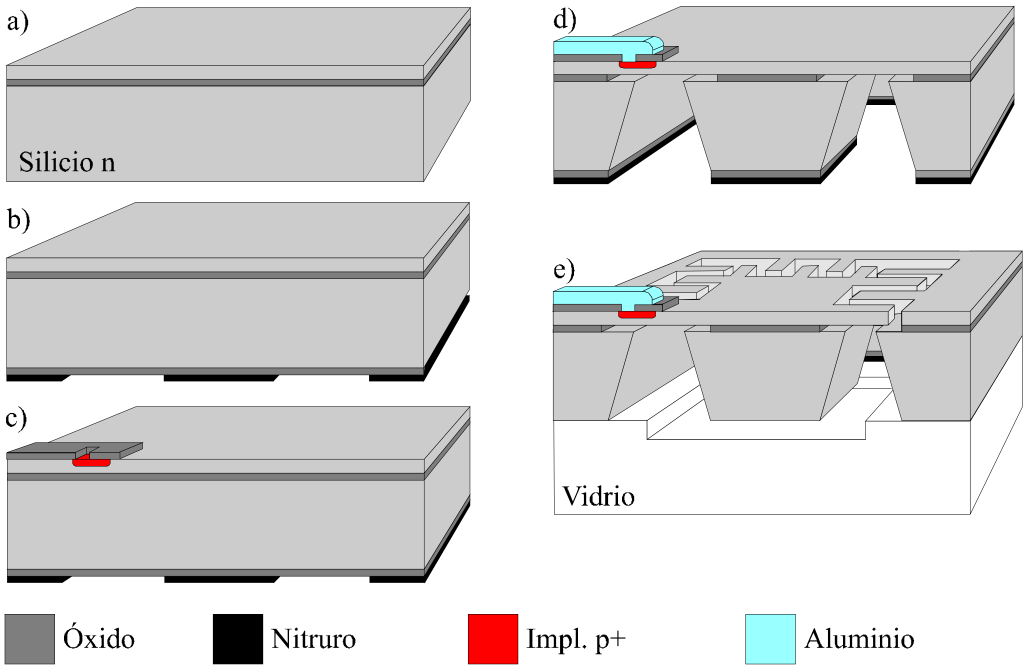
PHOTOGRAPH OF THE WHOLE DIE

Example 2: Bulk and Surface Micromachining

Piezoresistive accelerometers

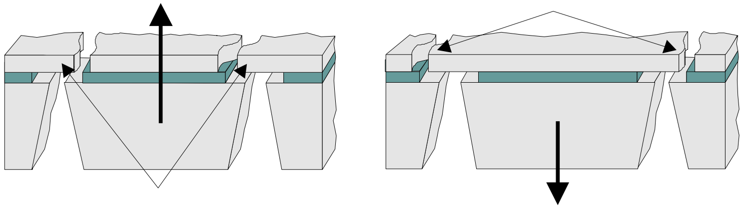
- **Technology**

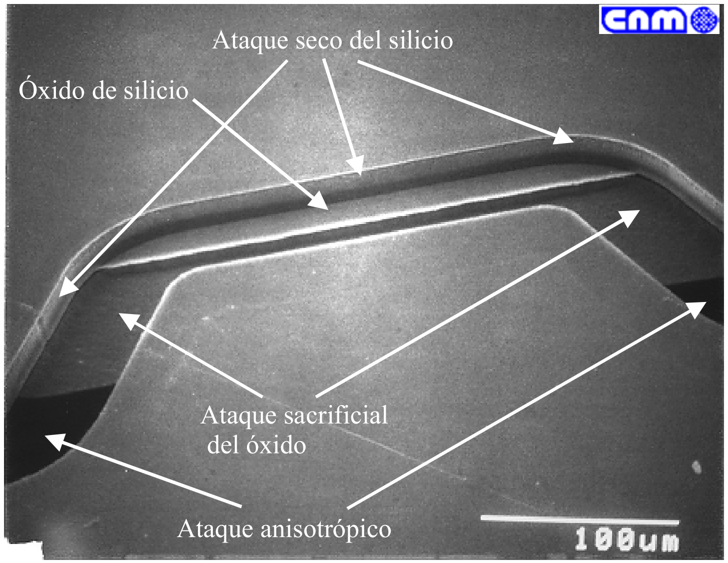
BESOI based technology (7 Masks)



- **Surface and Bulk Micromachining combination**
- **No Electrochemical Etch-Stop**

- **Overrange Protection System**

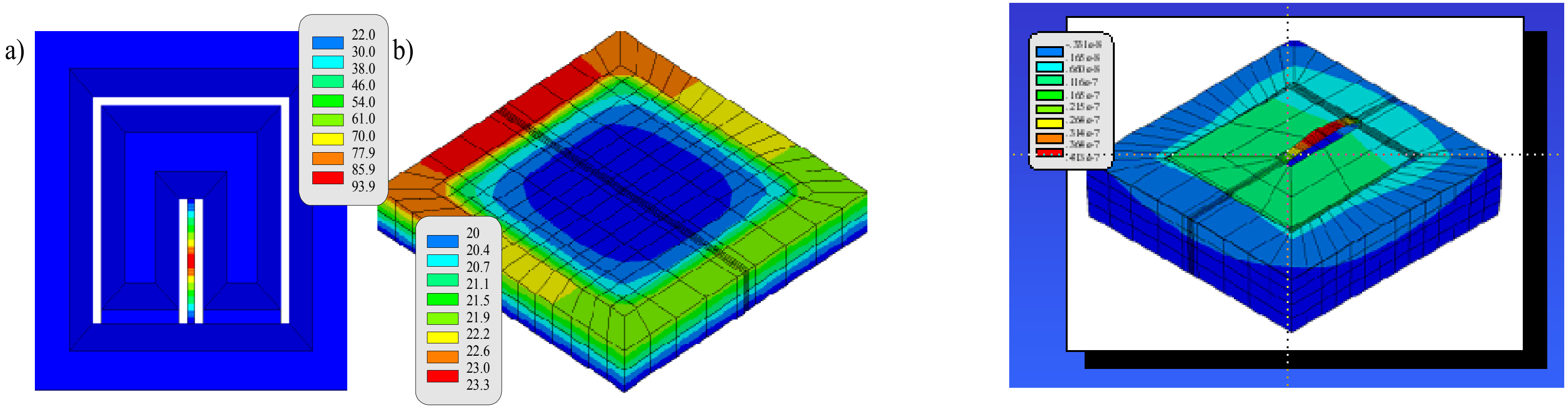




It does not require any photolithography or additional step.

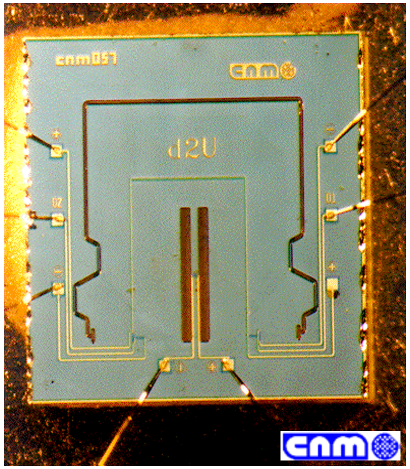
Example 2: Bulk and Surface Micromachining

- **Autotest Systems**

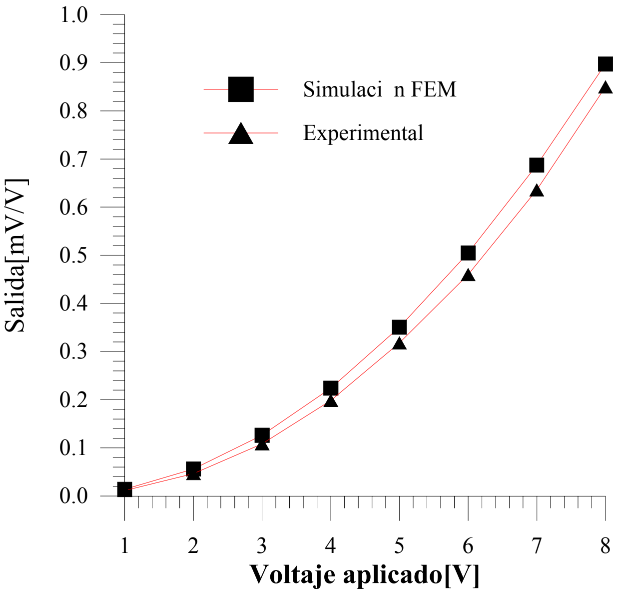


Couple FEM analysis

Additional mask Not required
Additional steps Not required



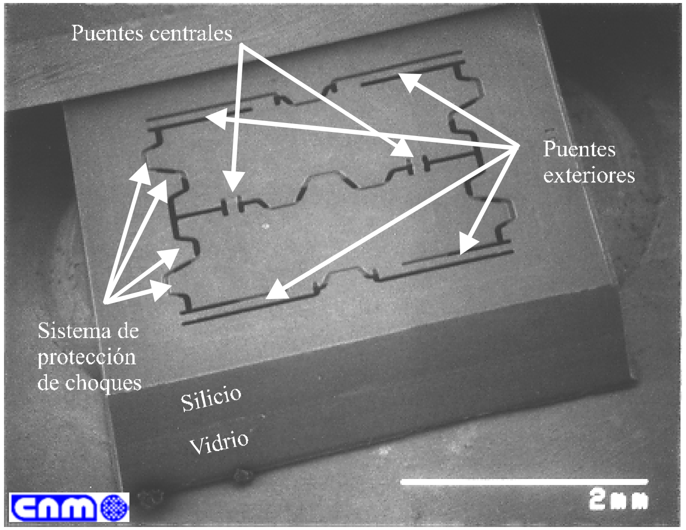
Cantilever beam accelerometer with autotest system



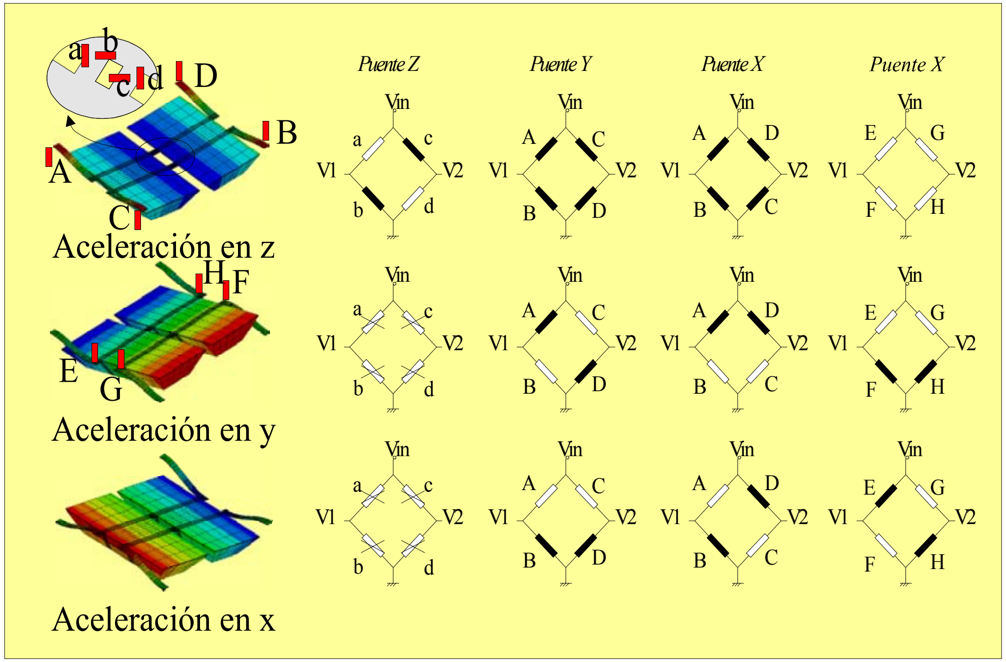
Output versus applied voltage
Self-test System

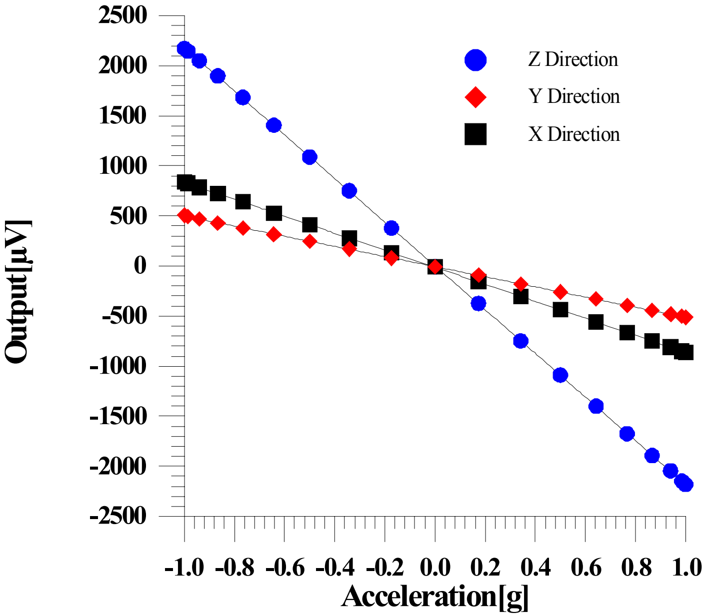
Example 2: Bulk and Surface Micromachining

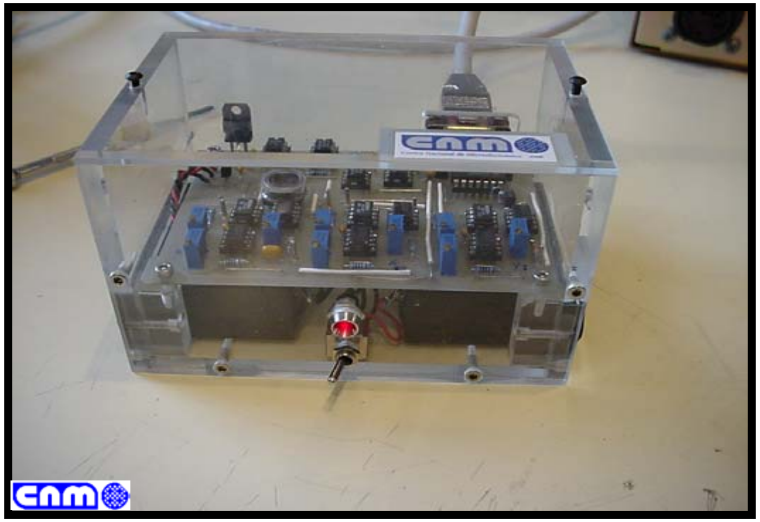
- **Triaxial Accelerometer**



FOTOGRAFÍA SEM DEL ACELERÓMETRO TRIAXIAL



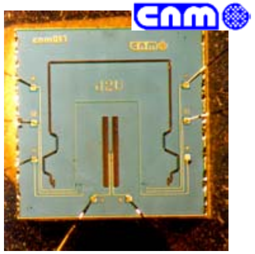


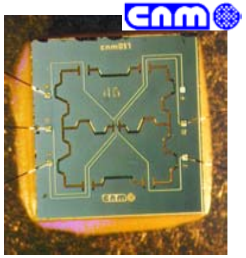


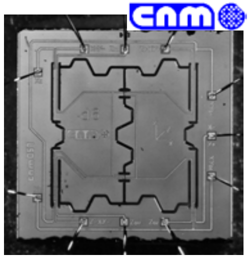
DEMONSTRATOR

Example 2: Bulk and Surface Micromachining


Cantilever Beam


Cantilever Beam Autotest System


Twin-Mass


Triaxial Accelerometer

- **Characterisation**

Electric

Carac. E	**AC2-d2**	**AC2-d2U**	**AC2-d5**	**AC2-posi(z)**	**AC2-posi(y)**	**AC2-posi(x)**
Ali on [V]	5	5	5	5	5	5
Impe. Entrada[kΩ]	2.493	2.468	2.619	1.511	1.592	1.592
Impe. S kΩ]	2.498	2.474	2.629	2.158	2.567	2.567

Static

C aticas	**AC2-d2**	**AC2-d2U**	**AC2-d5**	**AC2-posi(z)**	**AC2-posi(y)**	**AC2-posi(x)**
[mV/V]	19.31	1.9	13.54	9.55	1.05	1.7
ensi.[mV/V*g]	0.206	0.191	0.510	0.464	0.0926	0.160
No linealidad[%FS]	0.80	0.53	1.15	0.32	0.58	0.52
Histéresis[%FS]	0.72	0.73	3.95	0.09	0.32	0.50
Repetibilidad[%FS]	0.79	0.73	2.96	0.13	0.54	0.56
Der.cero [%FS/10’]	-	0.33	-	0.086	0.75	0.43
Creep[%F	-	0.28	-	0.043	0.22	0.74

Dynamic

Ca ámicas	**AC2-d2**	**AC2-d2U**	**AC2-d5**	**AC2-posi(z)**	**AC2-posi(y)**	**AC2-posi(x)**
má.[mV/Vg]	0.122	0.139	0.437	0.452	0.091	0.191
go medido[g]	10	10	10	2	10	4
No line. Din	0.71	3.0	0.6	0.82	1.65	0.29
Frec. Re	1420	1800	1876	715	949	1130

Cross-sensitivities

	AC2-d2	**AC2-d2U**	**AC2-d5**	**AC2-posi(z)**	**AC2-posi(y)**	**AC2-posi(x)**
sonan. Vg]	0.290	0.344	0.956	0.332	0.066	0.114

Index

- Introduction to Microsystems
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  - Microsystems versus Microelectronics-Applications
  - Microsystems Advantages
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  - Commercialisation and Market Considerations
- Microsystems Technologies
  - Introduction: Substrates and Materials
  - Processes of Microelectronics in Microsystems
  - Specific Processes for the Microsystems Fabrication
    - Example 1: Surface Micromachining
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    - Example 1: Monolithic Integration (Accelerometer+Optic Waveguides)
    - Example 2: Monolithic Integration (Gas sensor+Electronics)
    - Example 3: Hybrid Integration MCM-D (Accelerometer+Electronics)

State of the Art and Future of Microsystems

•Technological considerations

- **Technologies Integration**

- **Material Integration**
- **Technologies Development**
- **Technologies Integration**
  - Monolithic/Hybrid(MCM)
    - Electronic integration:
      More fast, high viability and less interconnections

- **Nanolithography**
  - NIL
  - EBL
  - AFM

MEMS → **NEMS**

- **Simulation**

- **Expensive and long time development**

$$Cost_{MEMS} = f(\boxed{C_{development}} + C_{production})$$

- **High complexity**
  - Design (CAD)
  - **Fabrication (Anisotropic etching)**
  - Devices (interdisciplinary)

- **Packaging and Interconnections**

- Protection from the environment
- Allow the access to the medium
- Allow interconnections
- No batch, expensive
- Integration (Packaging at Chip level)
- **Chemical and Biological applications**

State of the Art and Future of Microsystems

- **BioMEMS**
  - Microfluids Systems: (Microinjectors, microvalves, micropumps and Chemical sensors)
  - "Lab on Chip": ADN
  - "Pharmacy-on-a-chip" implanted

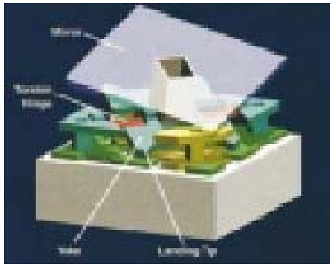
Cheap+small doses+fast → Biological applications; Home medical applications

MICROTITREPLATE

MICROPARTS

- **MOEMS**
  - Optic communications
  - Waveguides, Filter, Detectors

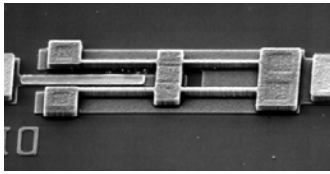
Cheap+small size+low power consumption+precision → Communications



DIGITAL MIRROR DEVICE, TEXAS INSTRUMENTS

- **RF Applications**
  - Mobiles, RF communications: Radars, GPS.
  - Capacitors, Inductors, Resonators, Filters, Microphones, Relays

High Q+Easy integration+stable +higher frequencies+low power consumption → Communications



FILTER