Micro-Scale Engineering –I
Microelectromechanical Systems (MEMS)

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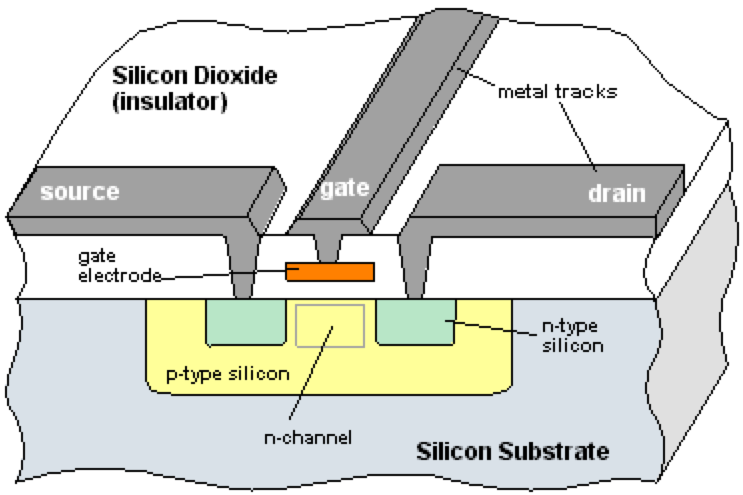
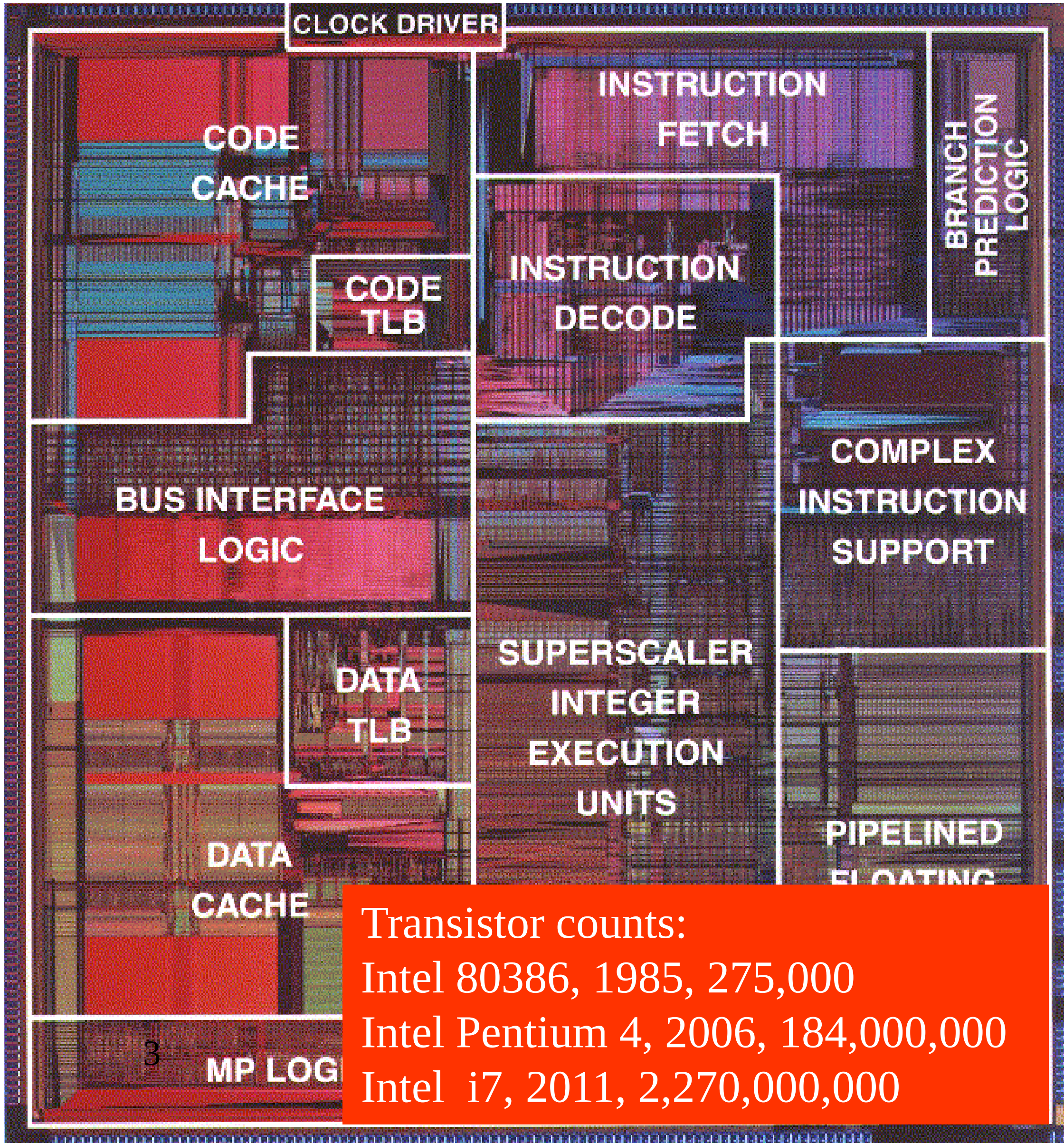
Contents

- Microelectromechanical systems (MEMS)
- Surface micromachining for a mirror
  - electrostatic actuation
  - pull-down voltage
  - stiction
  - thermal actuation
- Accelerometers and Gyroscopes
- Market and Trend

Integrated Circuits – Information Era

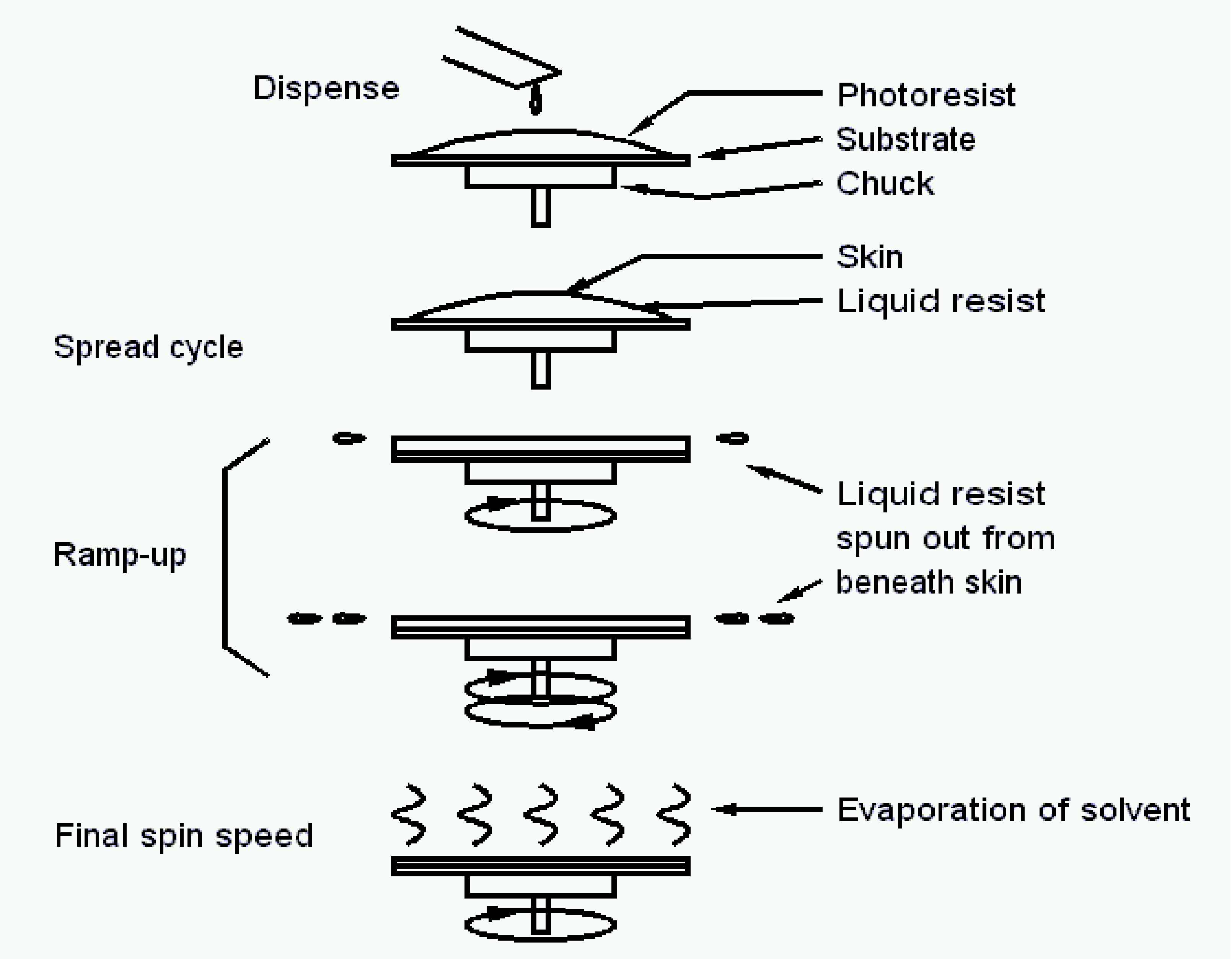
NMOS Transistor
(n-channel MOSFET)



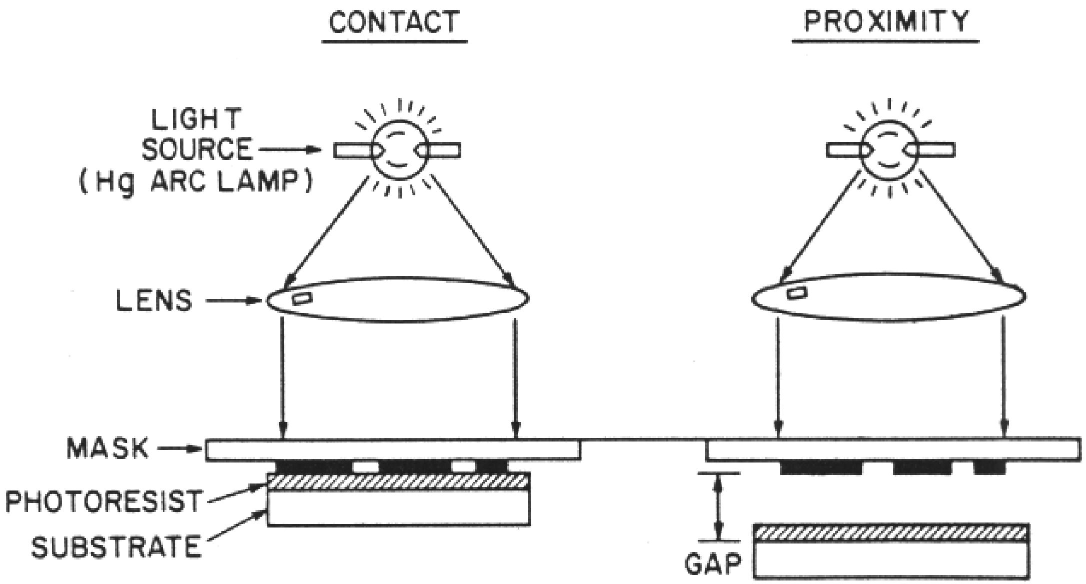


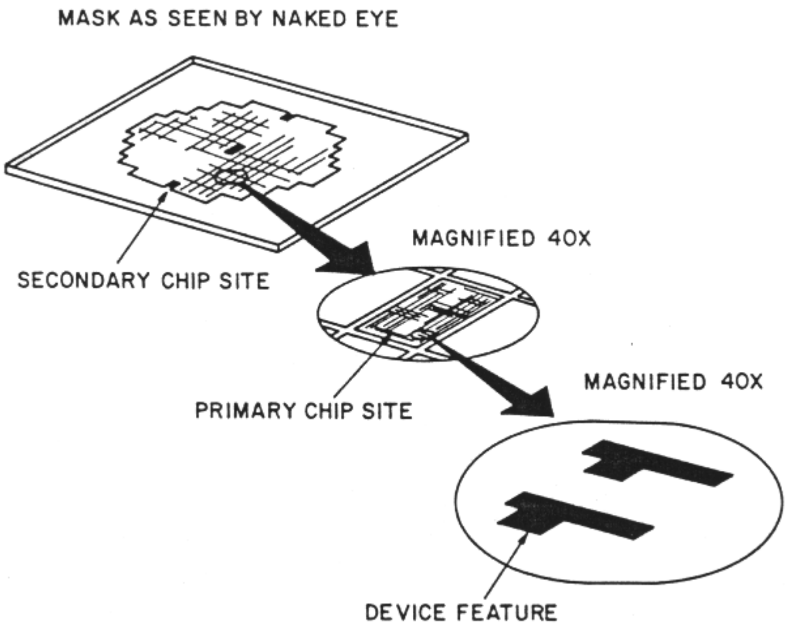
Transistor counts:
Intel 80386, 1985, 275,000
Intel Pentium 4, 2006, 184,000,000
Intel i7, 2011, 2,270,000,000

Spin Coating of Photoresist



Lithography

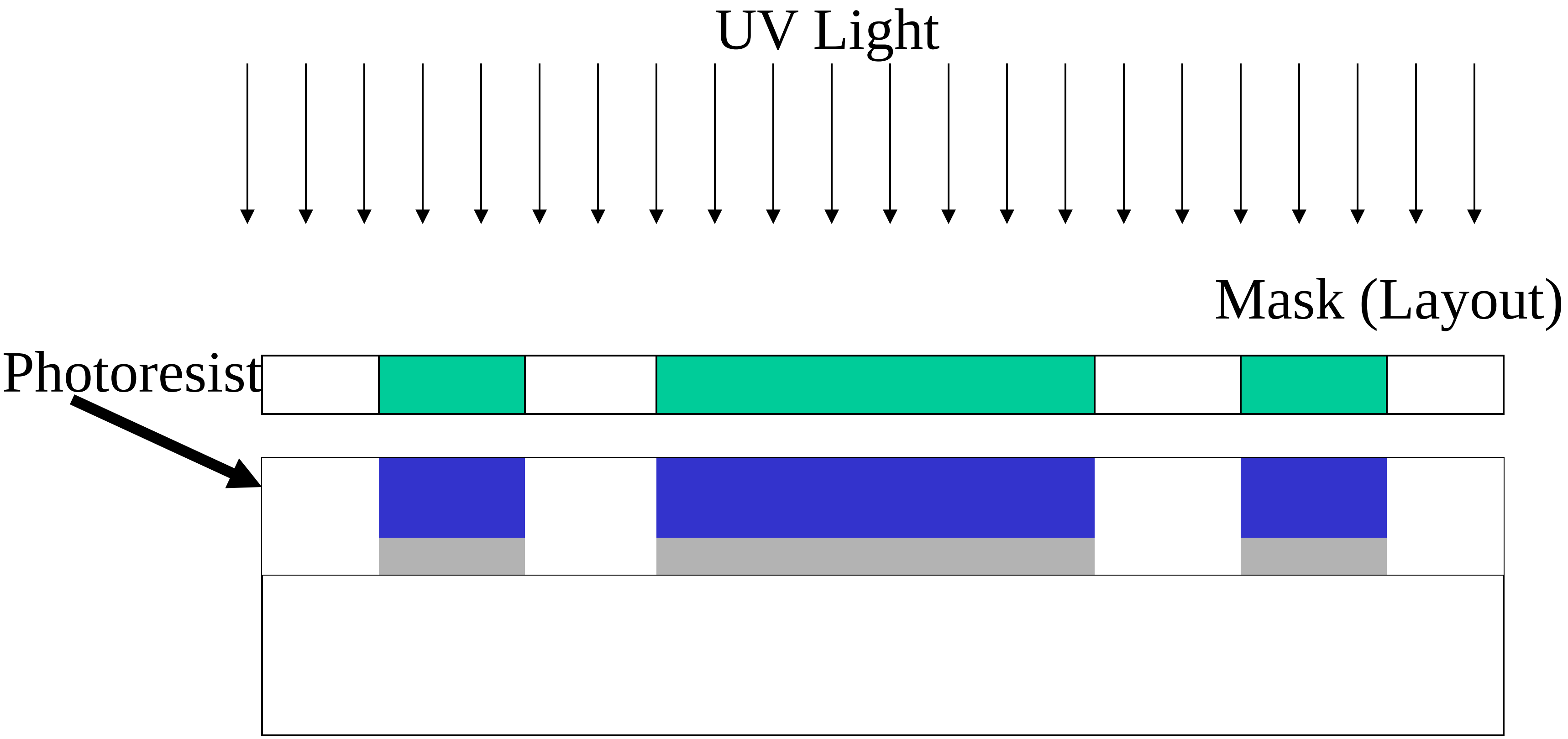




Exposure to ultraviolet light through a quartz mask.

S.M. Sze, *Semiconductor Devices*, Wiley, 1985.

Semiconductor Processing

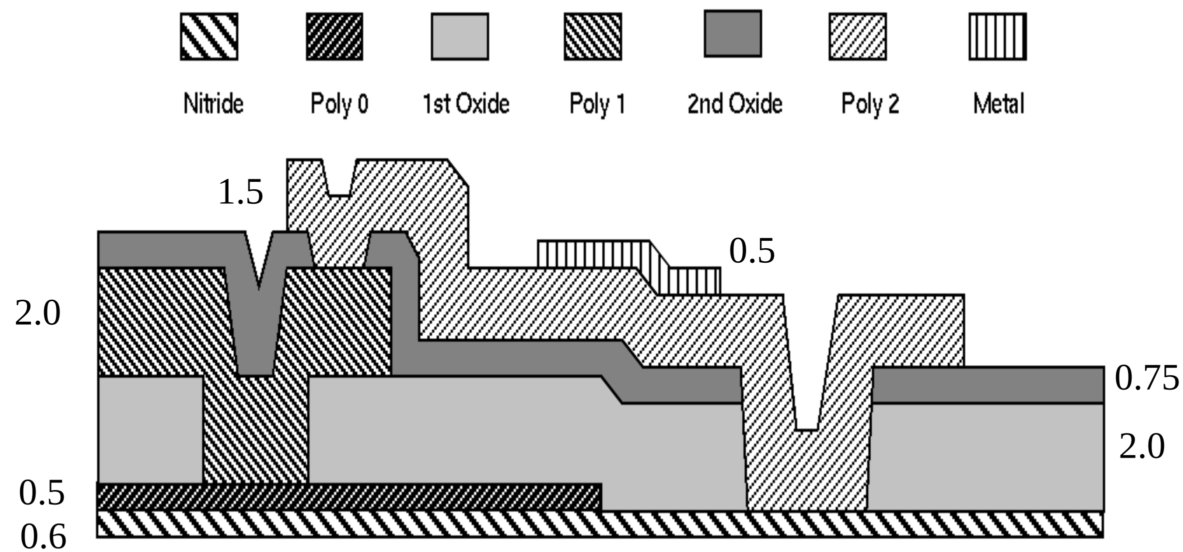


Batch Processing

Foundry Processes for Microelectromechanical Systems (MEMS)

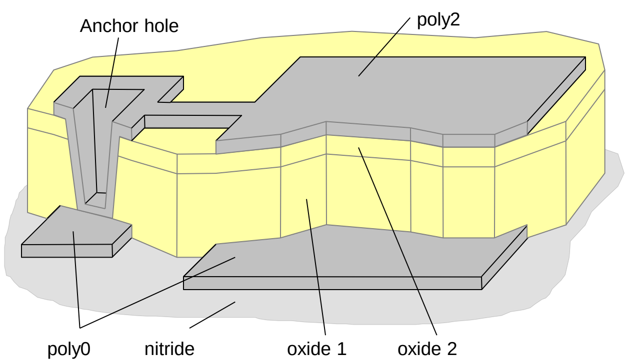
Multi-User MEMS Processes (MUMPS)

Layers and Nominal Thickness in Microns

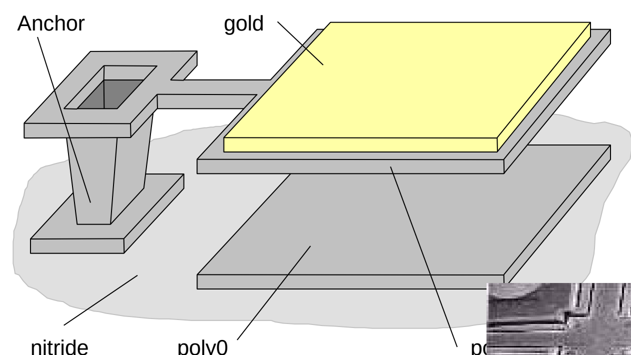


MCNC

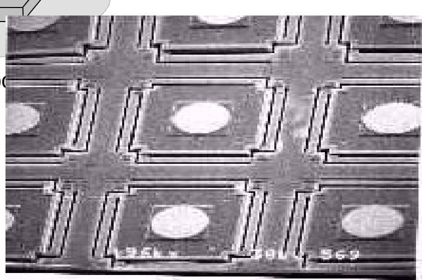
Example Design



(a) After Poly2 Deposition



(b) Released Device

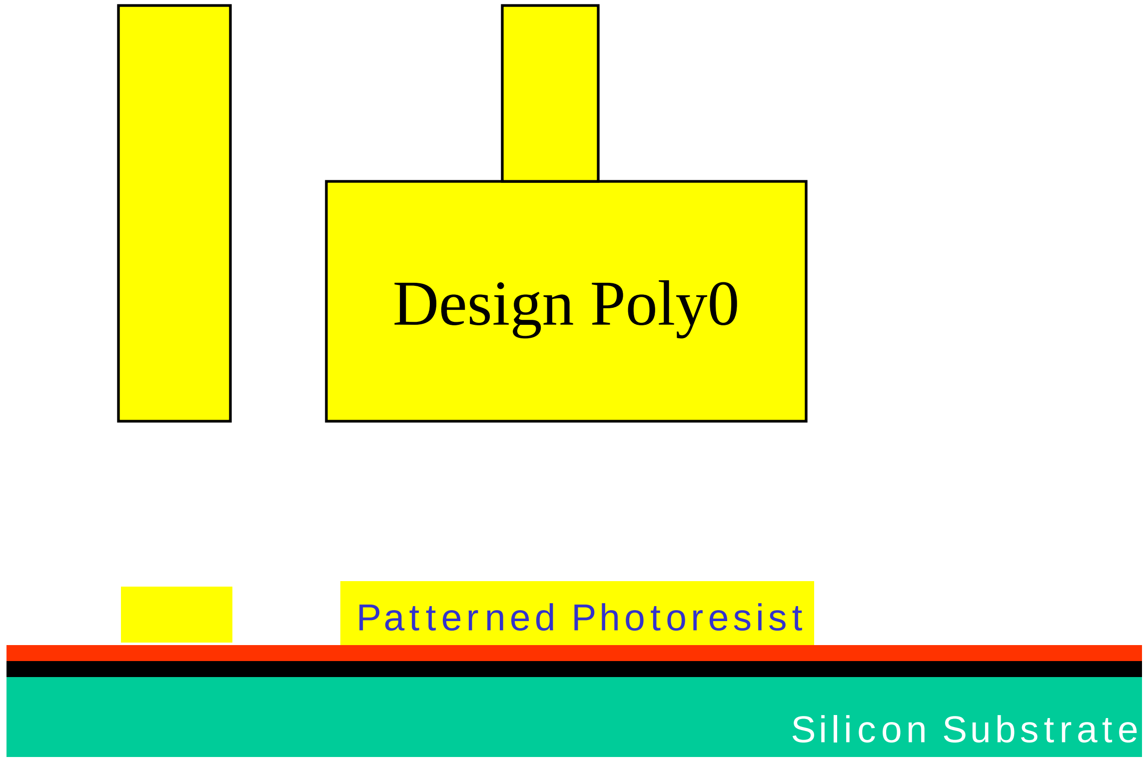


Add nitride
(600 nm, LPCVD
(low pressure chemical vapor deposition)

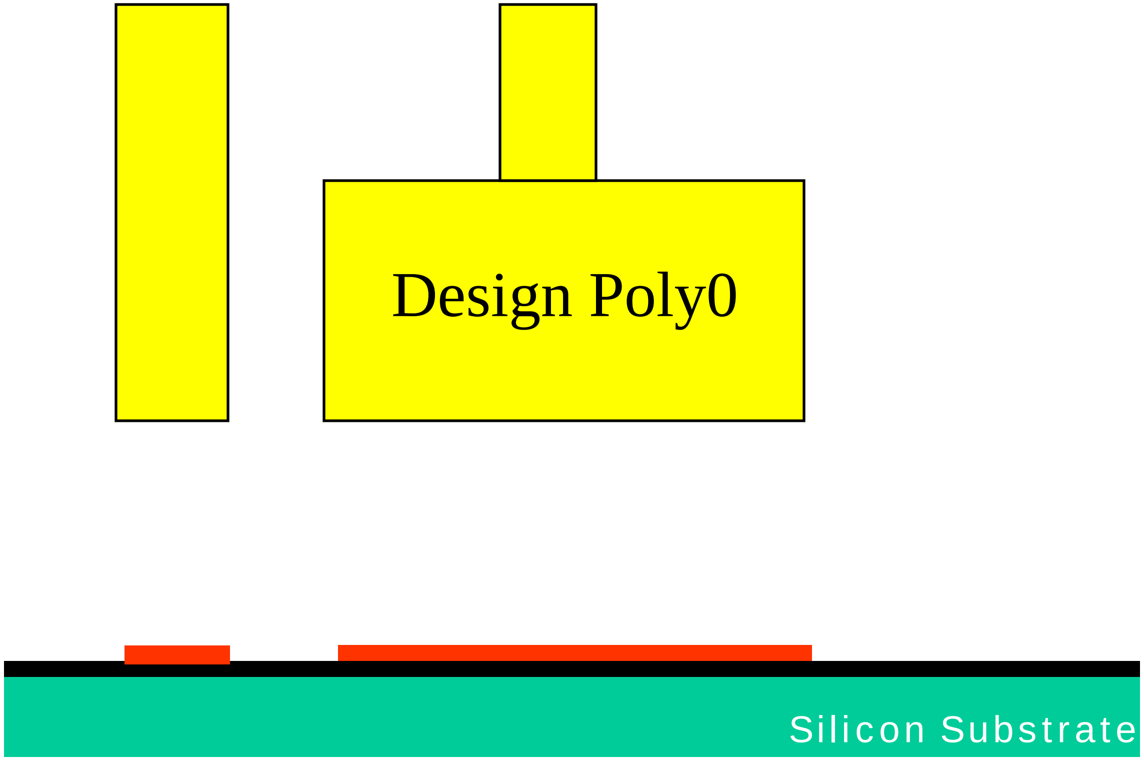
100 mm, n-type, 1-2 Ohm-cm, surface doped with phosphorus

Add Poly0
(500 nm, LPCVD)

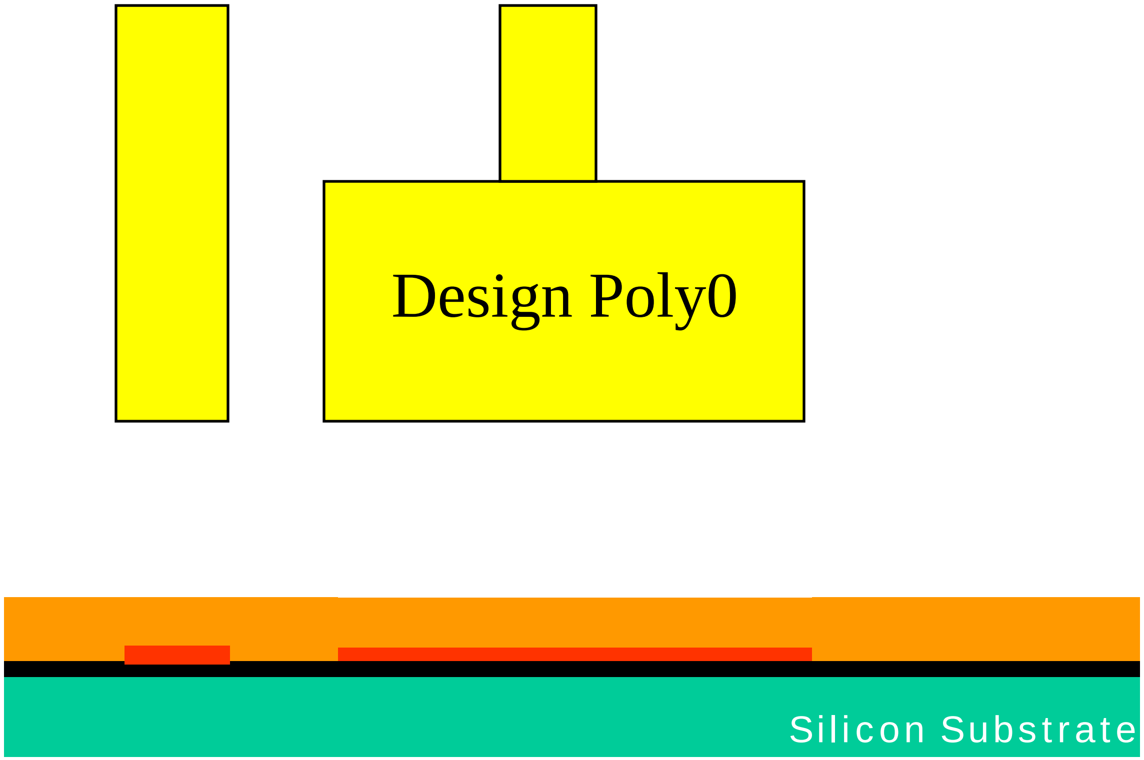
Patterning through 1st level mask (Poly0) using Photolithography



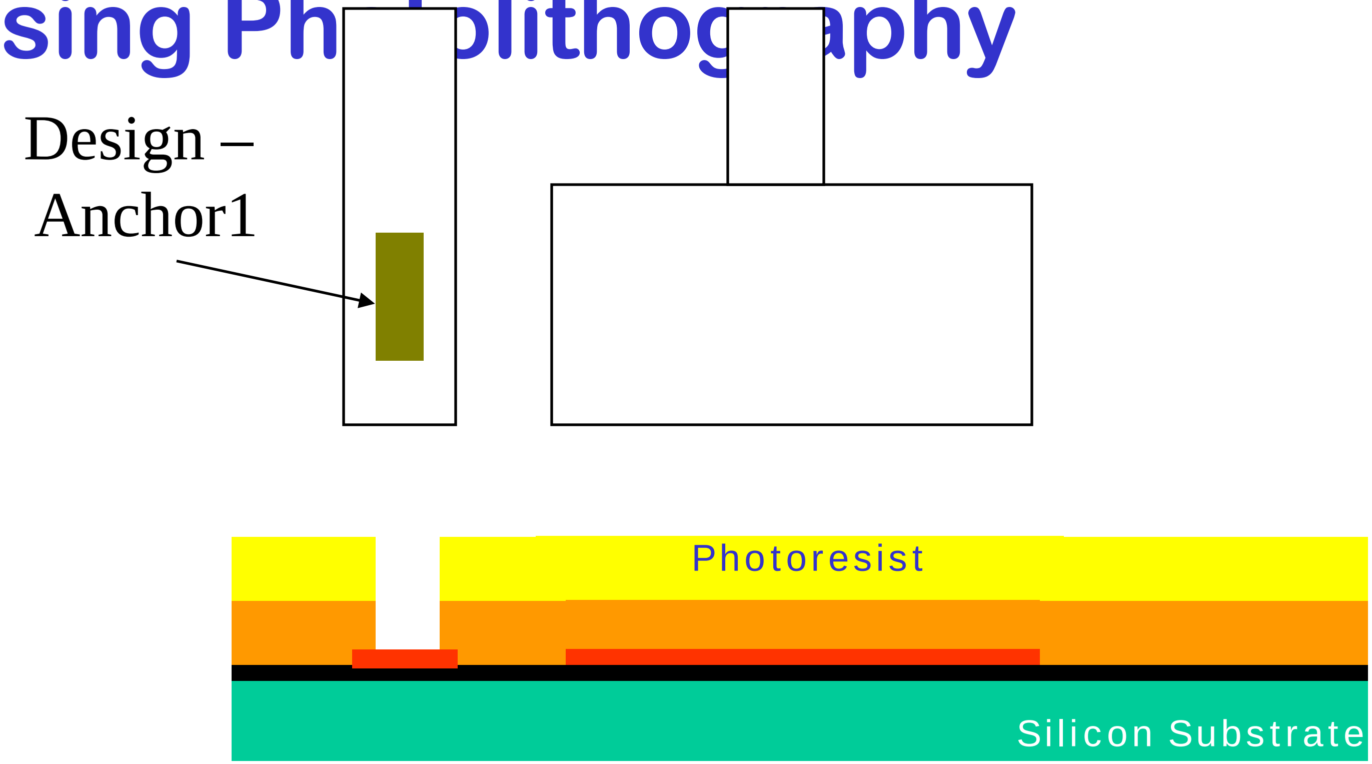
Removal of Unwanted Poly0 using Reactive Ion Etching



1st Oxide Deposition 2 um using LPCVD



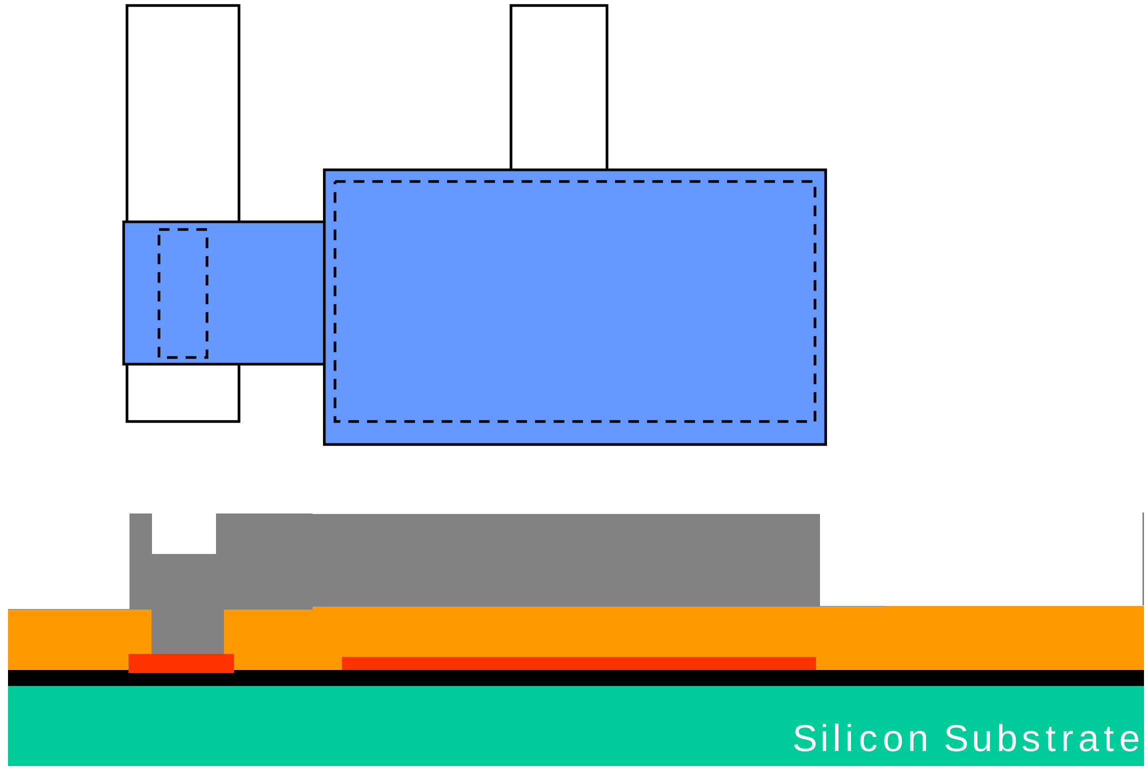
Patterning through 3rd level mask (Anchor1) using Photolithography and Deep RIE



Blanket un-doped polysilicon deposition(Poly1) 2 um using LPCVD…

followed by 200 nm PSG deposition and annealing at 1050 C for 1 hr

Patterning through 4th level mask (Poly1) using Photolithography... and Deep RIE



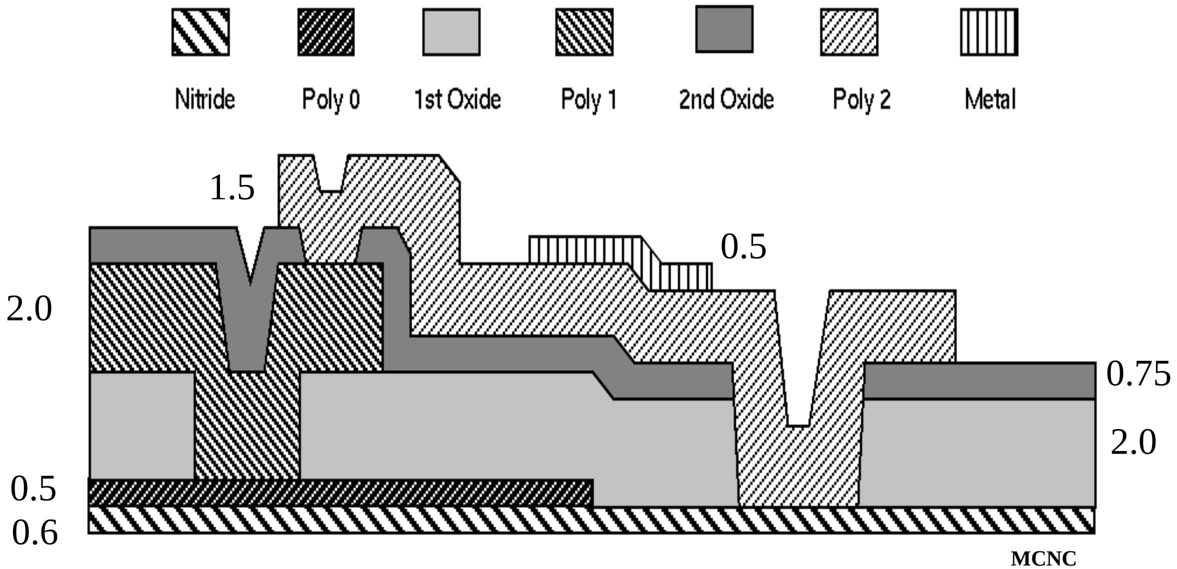
PSG layer etched first to form the RIE hard mask

Release of structures using HF
(46% HF, room temperature, 1.5-2 minutes; followed by several minutes in DI water and then alcohol by at least 10 minutes in an oven at 110 C

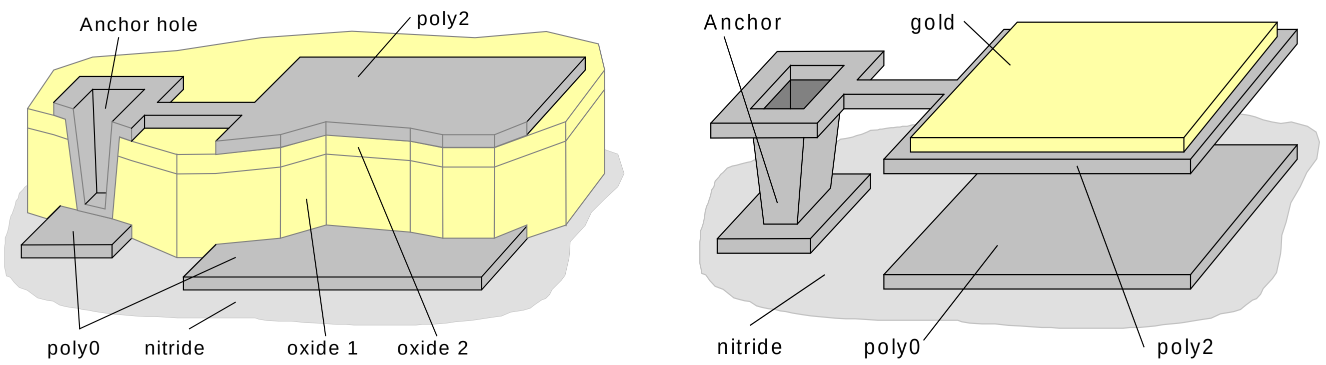
Microelectromechanical Systems (MEMS)

Multi-User MEMS Processes (MUMPS)

Layers and Nominal Thickness in Microns

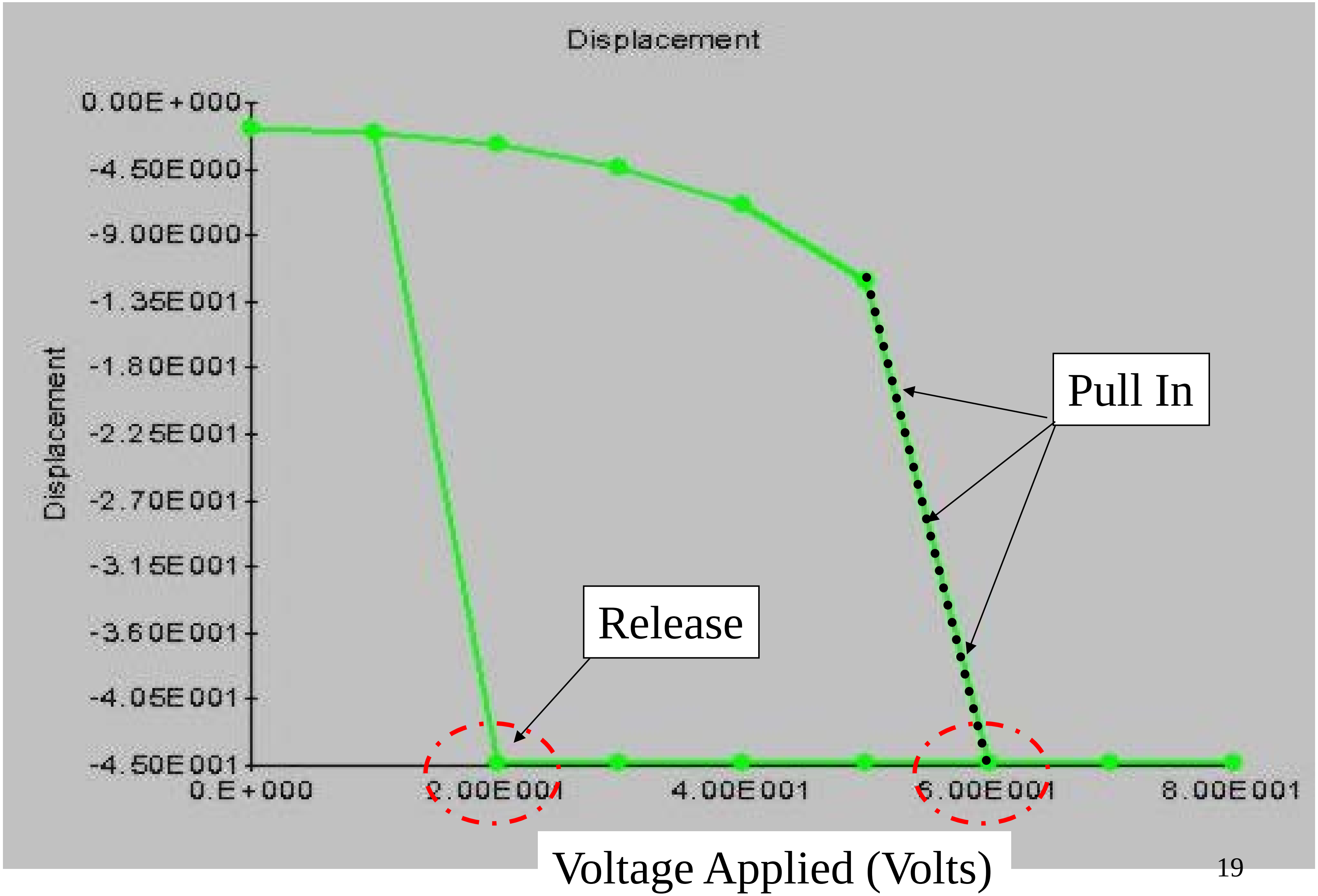


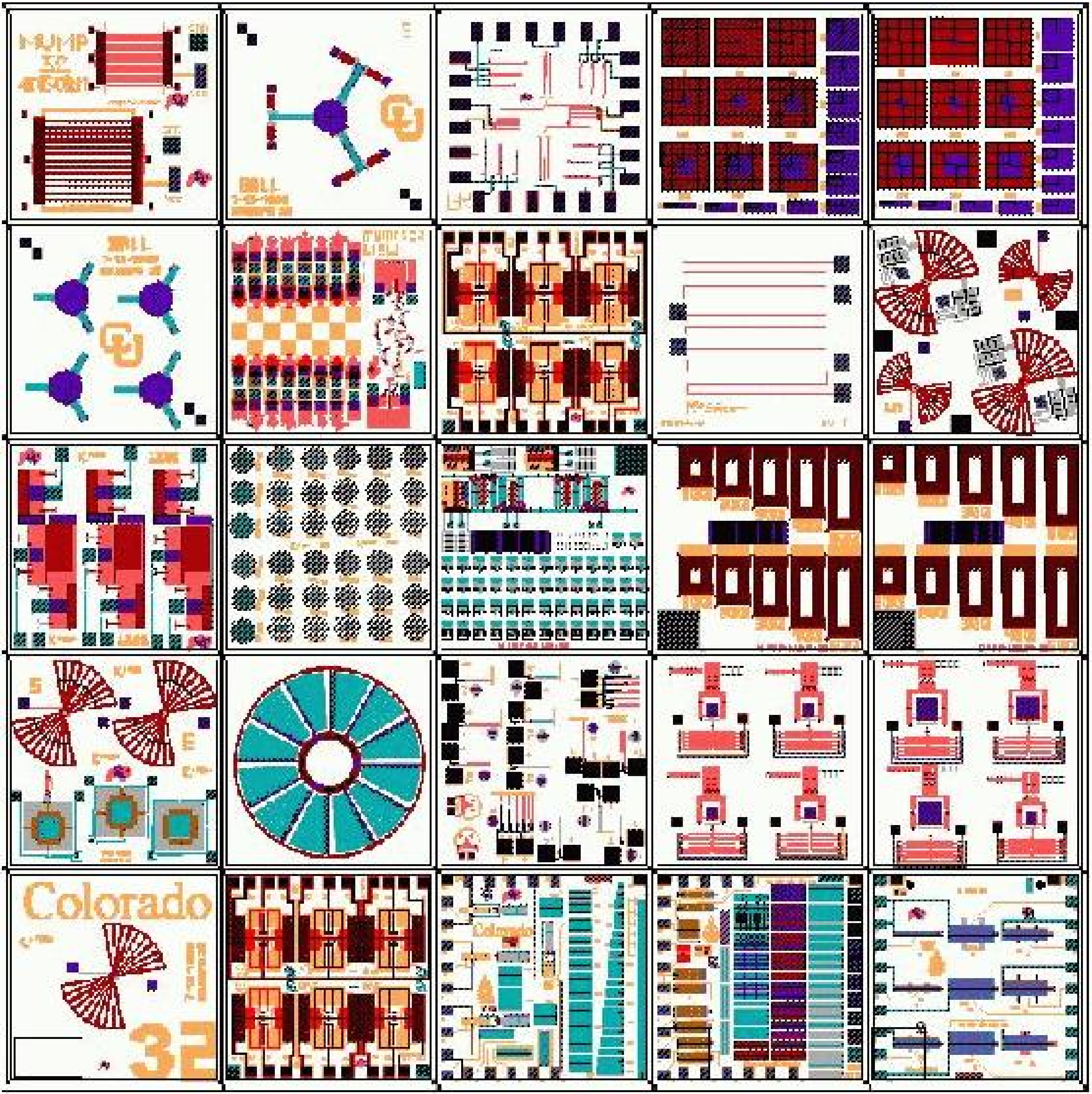
Example Design



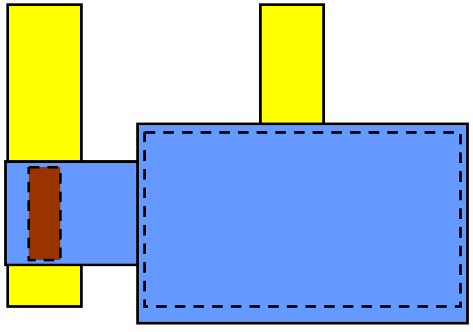
(a) After Poly2 Deposition (b) Released Device

Electrostatic Actuator



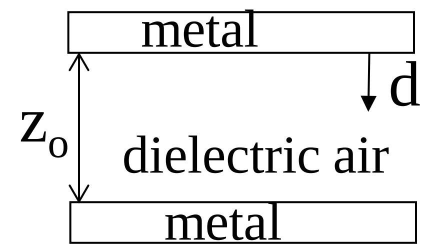


MUMPs Chip $1cm^2$



Electrostatic Force

- The energy stored at a given voltage is,



$$U(x,z) = -\frac{1}{2}CV^2 = -\frac{1}{2}\frac{\varepsilon_0 \varepsilon_r A}{z_0}V^2$$

- The force between the plates in the vertical direction is,

electrostatic vertical force between plates

$$F_e = F_z(z) = -\frac{\partial}{\partial z}U(x,z) = -\left(-\frac{1}{2}\right)V^2\frac{\varepsilon_0 \varepsilon_r A}{1}\frac{\partial}{\partial z}\left(\frac{1}{z}\right)$$

$$= -\frac{1}{2}\varepsilon_0 \varepsilon_r V^2 A\left(\frac{1}{z^2}\right)$$

(negative z direction)

force vs. distance is nonlinear

- The flexures can be modeled as cantilevers. For small deflections, a cantilever's restoring force is given by Hooke's law,

$$F_c = k\, d$$

force vs. distance is linear

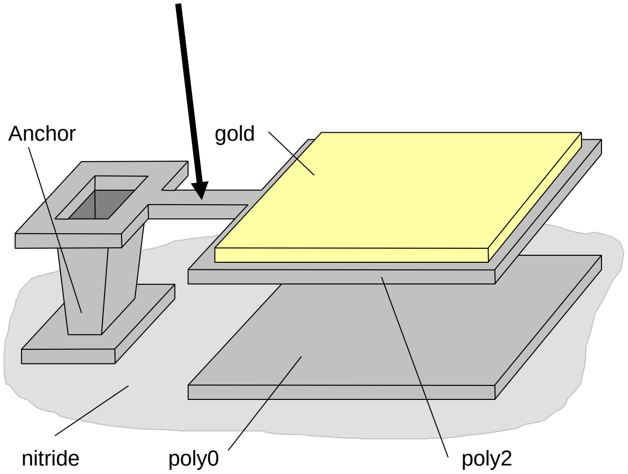
where, $k =$ flexure spring constant
$d =$ deflection distance

Restoring Force

- The flexure spring constant is given by,

$$k = \underbrace{\frac{Ewt^3}{4L^3}}_{\text{cross-sectional spring constant}} + \underbrace{\frac{\sigma(1-\mu)wt}{2L}}_{\text{stress term (due to residual stress)}}$$

Flexure



where, E = Young's Modulus
w = flexure width
t = flexure thickness
L = flexure length
σ = flexure material stress
μ = flexure material Poisson's ratio

- The flexure spring constant is determined during device design and construction, it is not a function of voltage or deflection. The equation for k is only an approximation !
- For stable deflection the electrostatic force is balanced by the restorative flexure force,

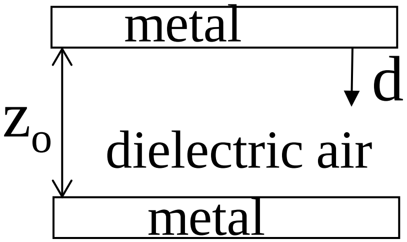
$$F_e = NF_c$$

where, N = number of flexures

Pull-Down Voltage

assuming free space between the plates we get,

$$\frac{1}{2}\frac{\varepsilon_0 A V^2}{z^2} = Nkd$$



solving for V as a function of d gives,

$$V = z\sqrt{\frac{2Nkd}{\varepsilon_0 A}}$$

replacing z by $z = (z_0 - d)$ gives,

$$V = (z_0 - d)\sqrt{\frac{2Nkd}{\varepsilon_0 A}}$$

This equation calculates the required voltage, V, to deflect the top plate of the piston actuator a distance, d, from the initial plate separation, z_0.

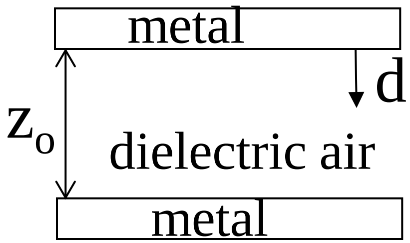
Maximum Deflection

- Note that we are trying to balance the nonlinear electrostatic force, F_e, with a linear force, F_c. An imbalance or "snap-through" occurs when the rate of change in voltage vs. deflection distance is zero:

$$\left.\frac{dV}{dd}\right|_{d=d_s} = 0 = (z_0 - d_s)\frac{1}{2}d_s^{-\frac{1}{2}}\sqrt{\frac{2Nk}{\varepsilon_0 A}} - \sqrt{\frac{2Nk}{\varepsilon_0 A}}d_s^{\frac{1}{2}}$$

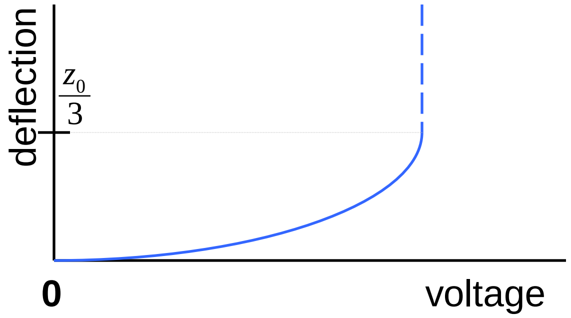
$$0 = \frac{1}{2}(z_0 - d_s)d_s^{-\frac{1}{2}} - d_s^{\frac{1}{2}}$$

$$0 = z_0 d_s^{-\frac{1}{2}} - d_s^{\frac{1}{2}} - 2d_s^{\frac{1}{2}} = z_0 d_s^{-\frac{1}{2}} - 3d_s^{\frac{1}{2}}$$



$$\Rightarrow \quad d_s = \frac{z_0}{3}$$

where, d_s = deflection distance from initial separation, z_0, to snap-through.

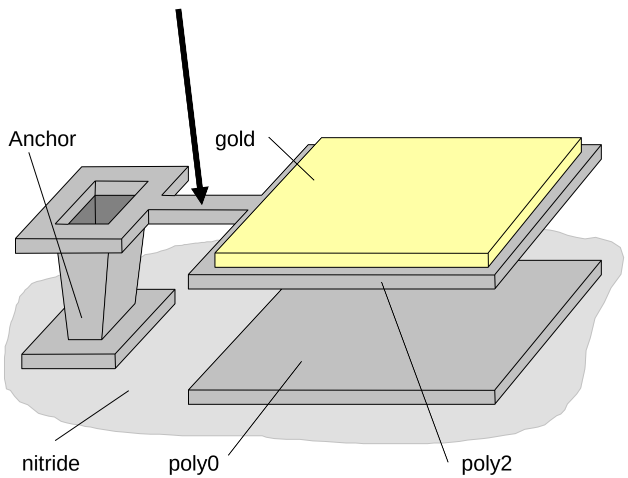


Note : The $\frac{1}{3}z_0$ rule also applies to cantilevers and microbridges.

An Example

- A plate: 250 μm square
- An air gap: 2 μm
- A flexure: 40 μm x 10 μm x 0.5 μm
- E = 169 GPa for the flexure
- k = 169,000 MPa x 10 x $0.5^3/(4 \times 40^3)$
  = 0.8 μN/μm
- d = 1/3 x 2 μm = 0.7 μm
- V = (2/3 x 2μm) x
  SQRT [(2x1x0.8x0.7)/(8.85E-6 x 250^2)]
  = 1.9 V

Flexure



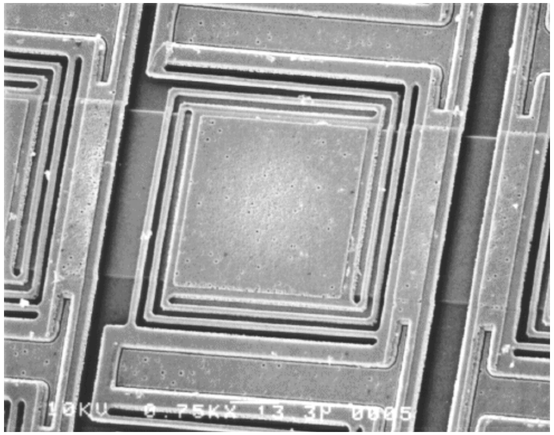
ε_o = 8.85E-6 pF/μm
1 Pa = 1 Newton/m^2 = 1 N/m^2
1 MPa = 1 μN/μm
1 V = SQRT (μN x μm/pF)

$$k = \frac{Ewt^3}{4L^3} + \frac{\sigma(1-\mu)wt}{2L}$$

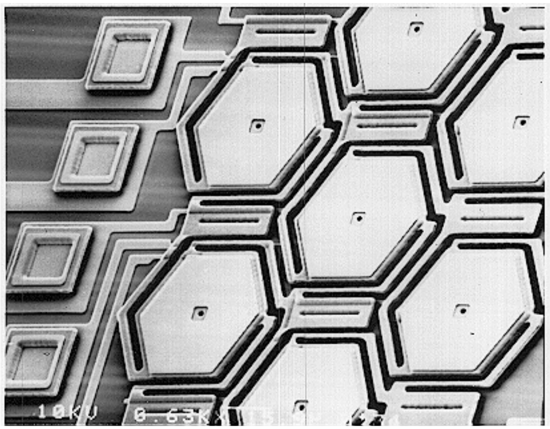
$$V = (z_0 - d)\sqrt{\frac{2Nkd}{\varepsilon_0 A}}$$

Piston Micromirrors

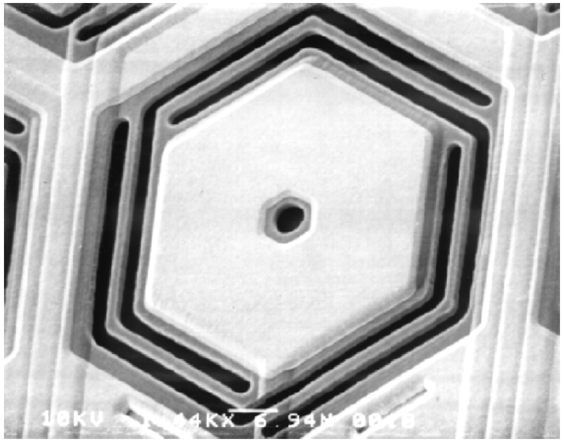
Evolution of a Piston Micromirror Over Four MUMPs Fabrication Runs



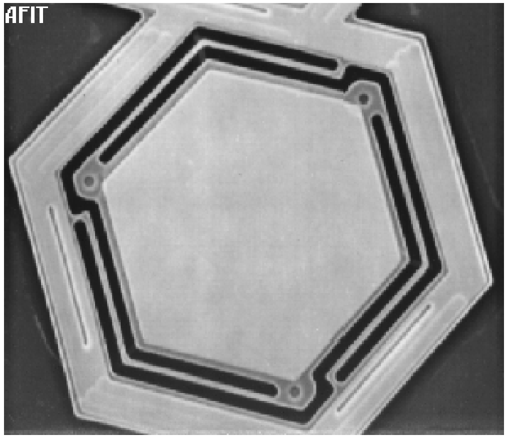
aluminum square mirror with four flexures



60 µm wide copper hexagonal mirror



50 µm wide gold hexagonal mirror



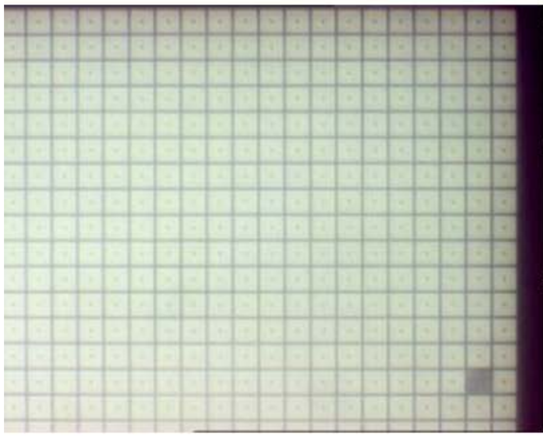
100 µm wide gold hexagonal mirror

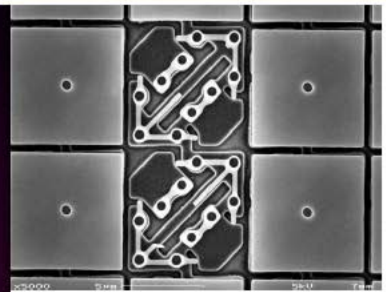
J.H. Comtois and V.M. Bright, AFIT

Digital Mirrors

DLP™

1996 TI brings DLP device to market

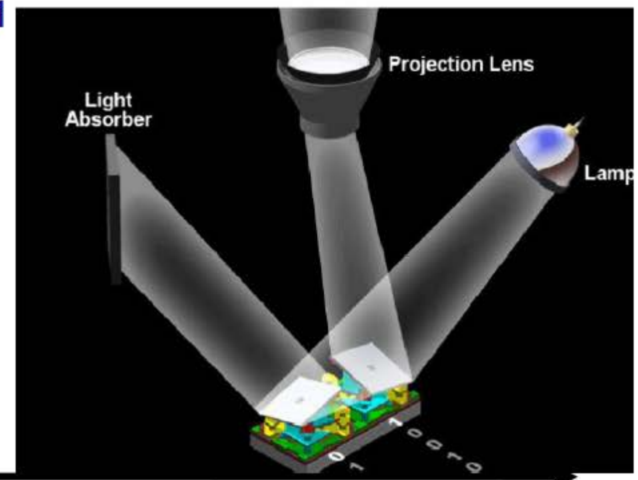




> 2300:1
DarkChip3
Current chip pitch: 11 µm

> 1800:1
DarkChip2

> 1500:1
DarkChip1



800:1
SRV + SMG

400:1
SRV

250:1
HH

50:1
B2

Contrast Ratio: Full On/Full Off

1992 | 1995 | 1997 | 2000 | 2003 | 2004

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cingular
12:34 PM

AT&T
9:42 AM

Nintendo


Mirror → Accelerometer?

Multi-User MEMS Processes (MUMPS)

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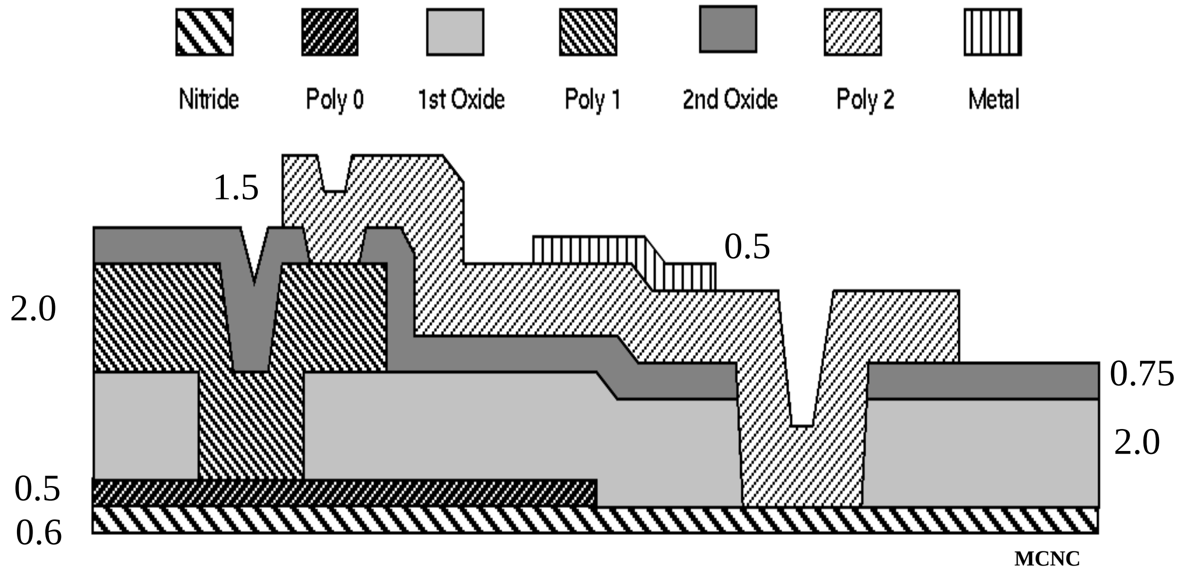
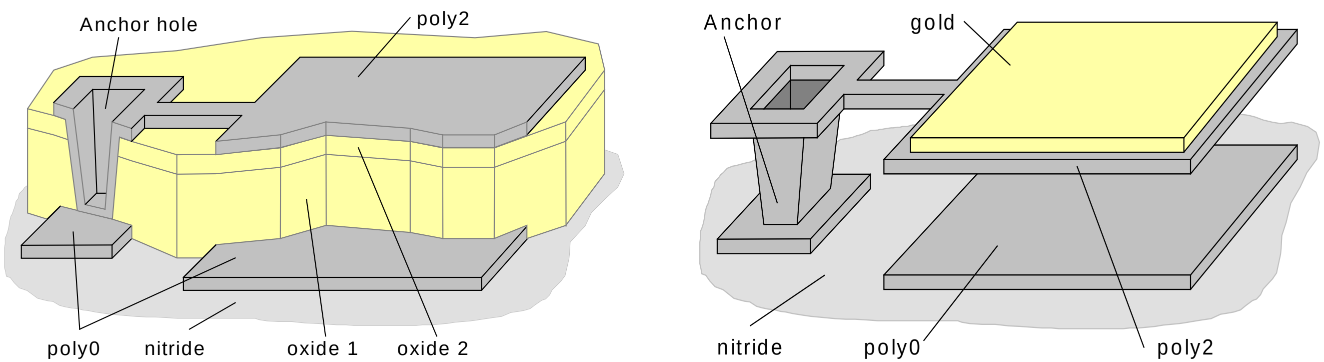
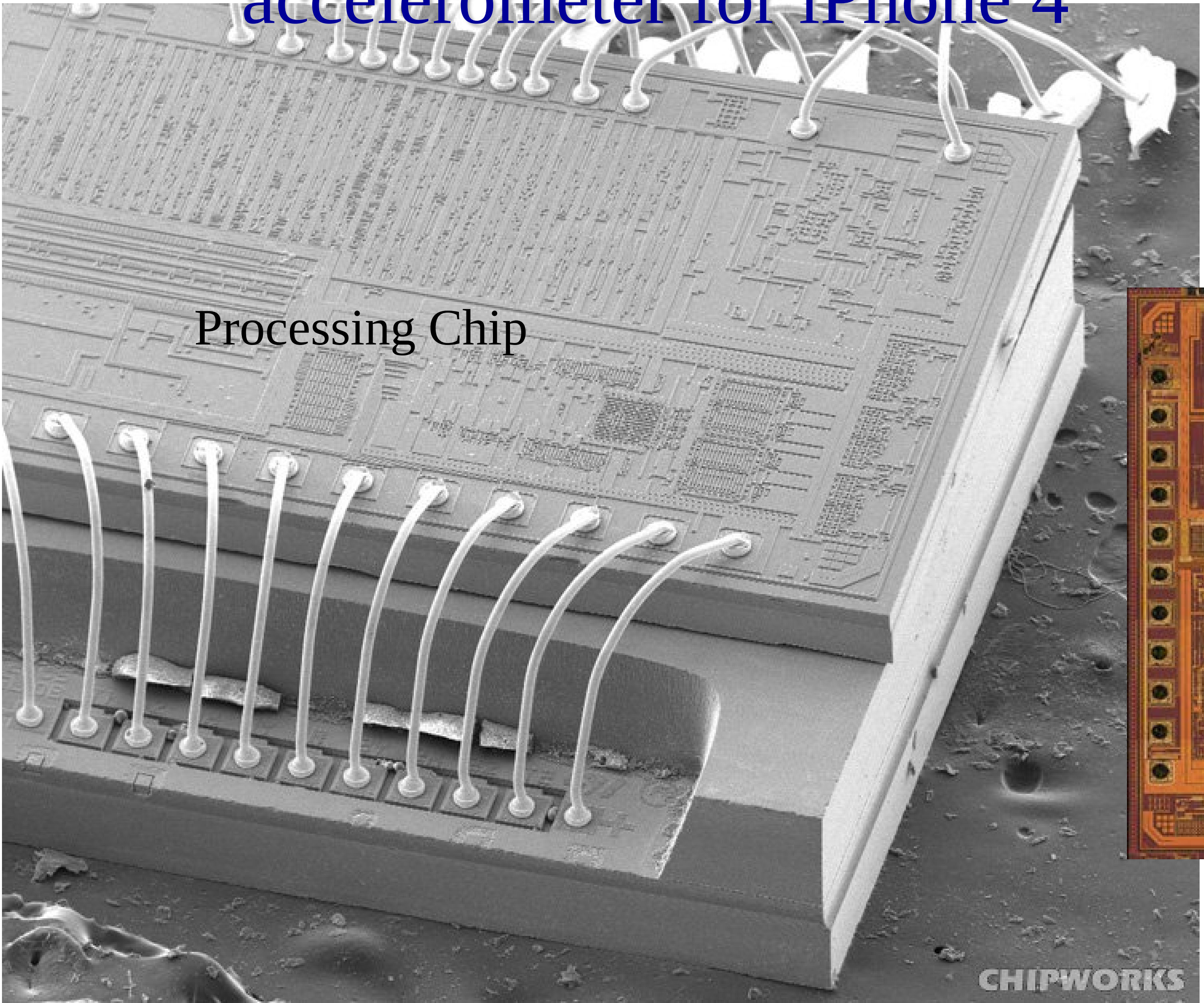


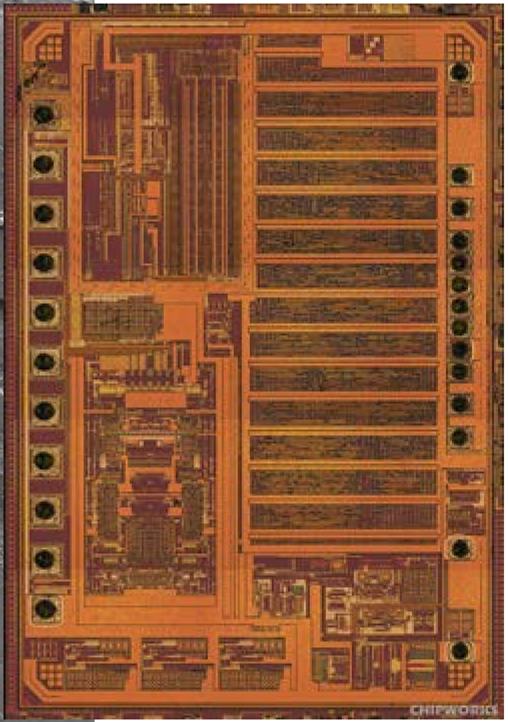
Example Design

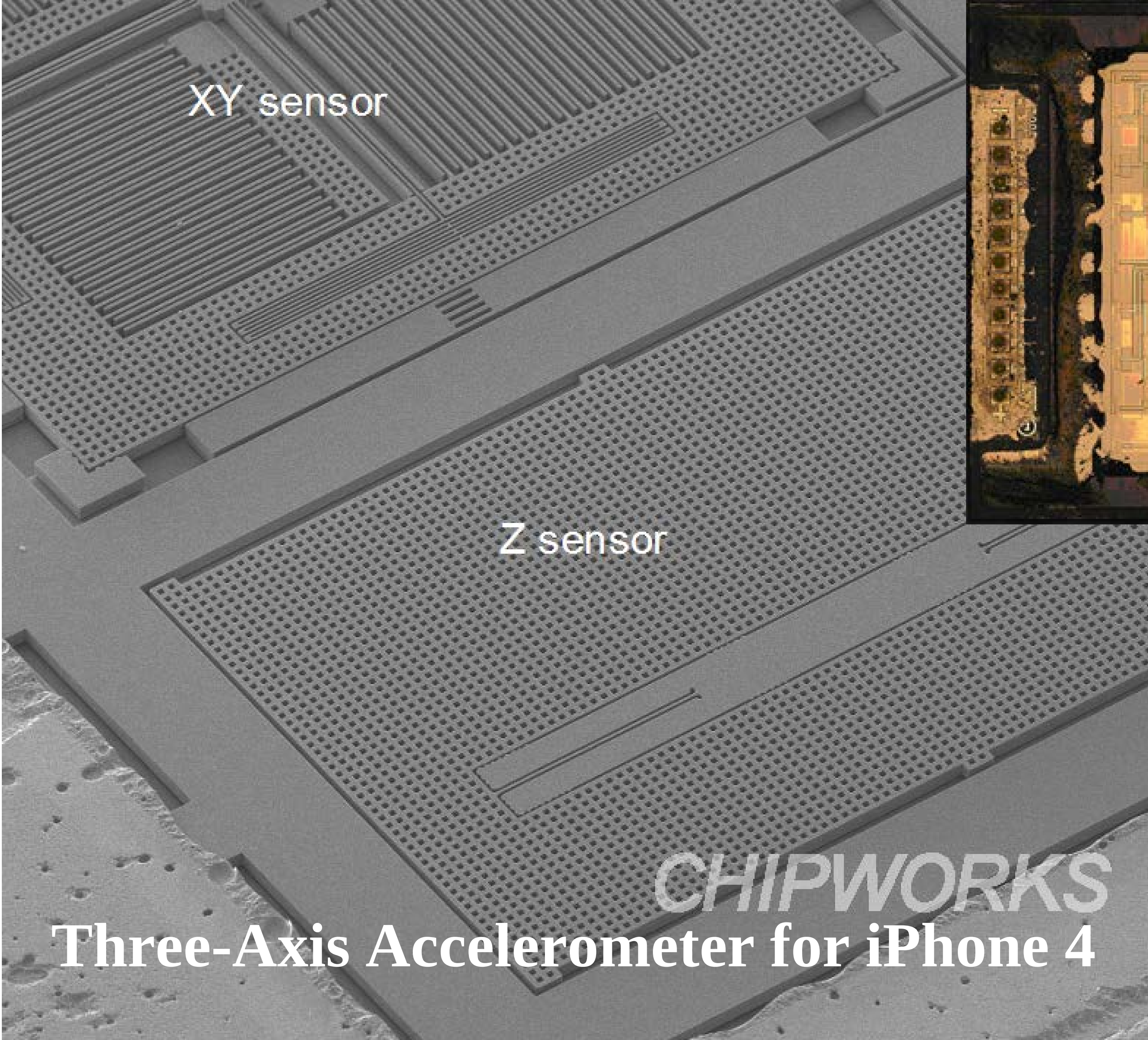


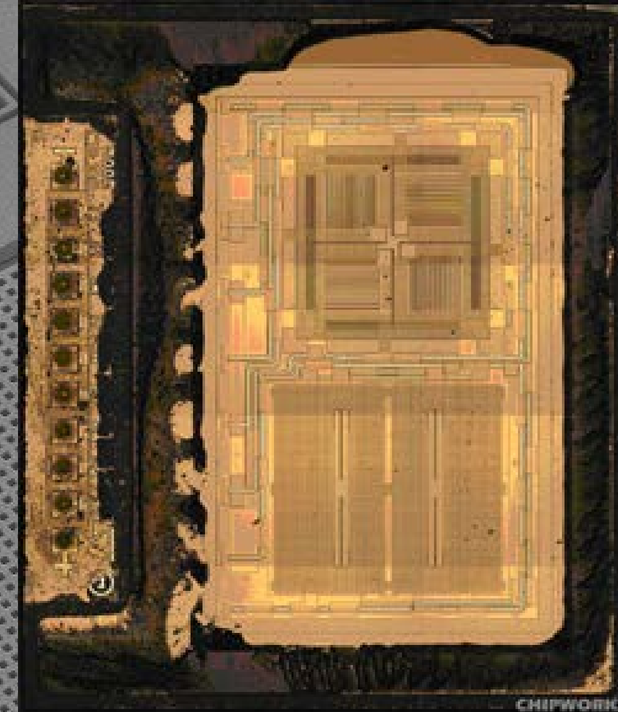
(a) After Poly2 Deposition (b) Released Device

STMicroelectronics LIS331DLH 3-axis accelerometer for iPhone 4





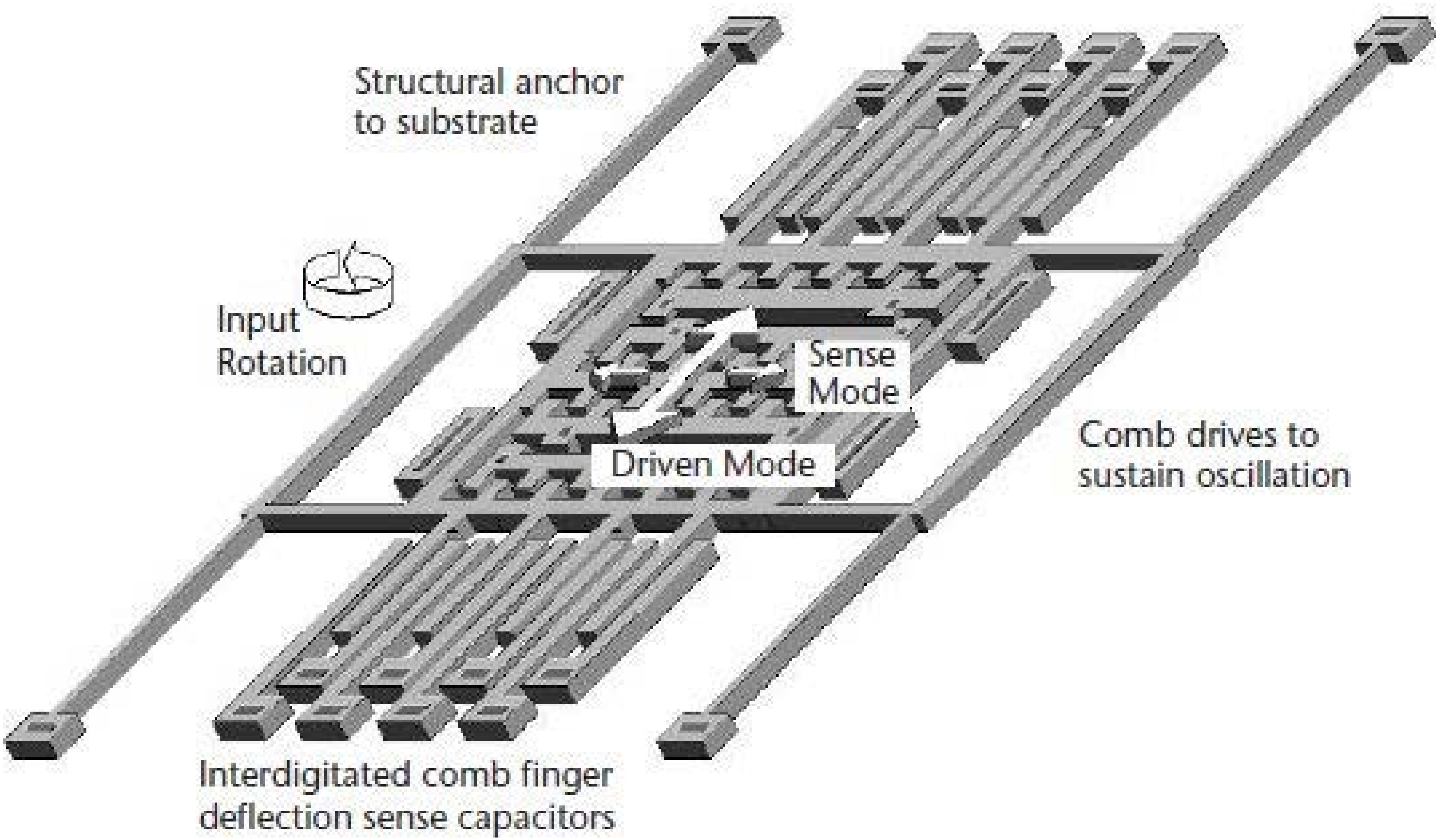




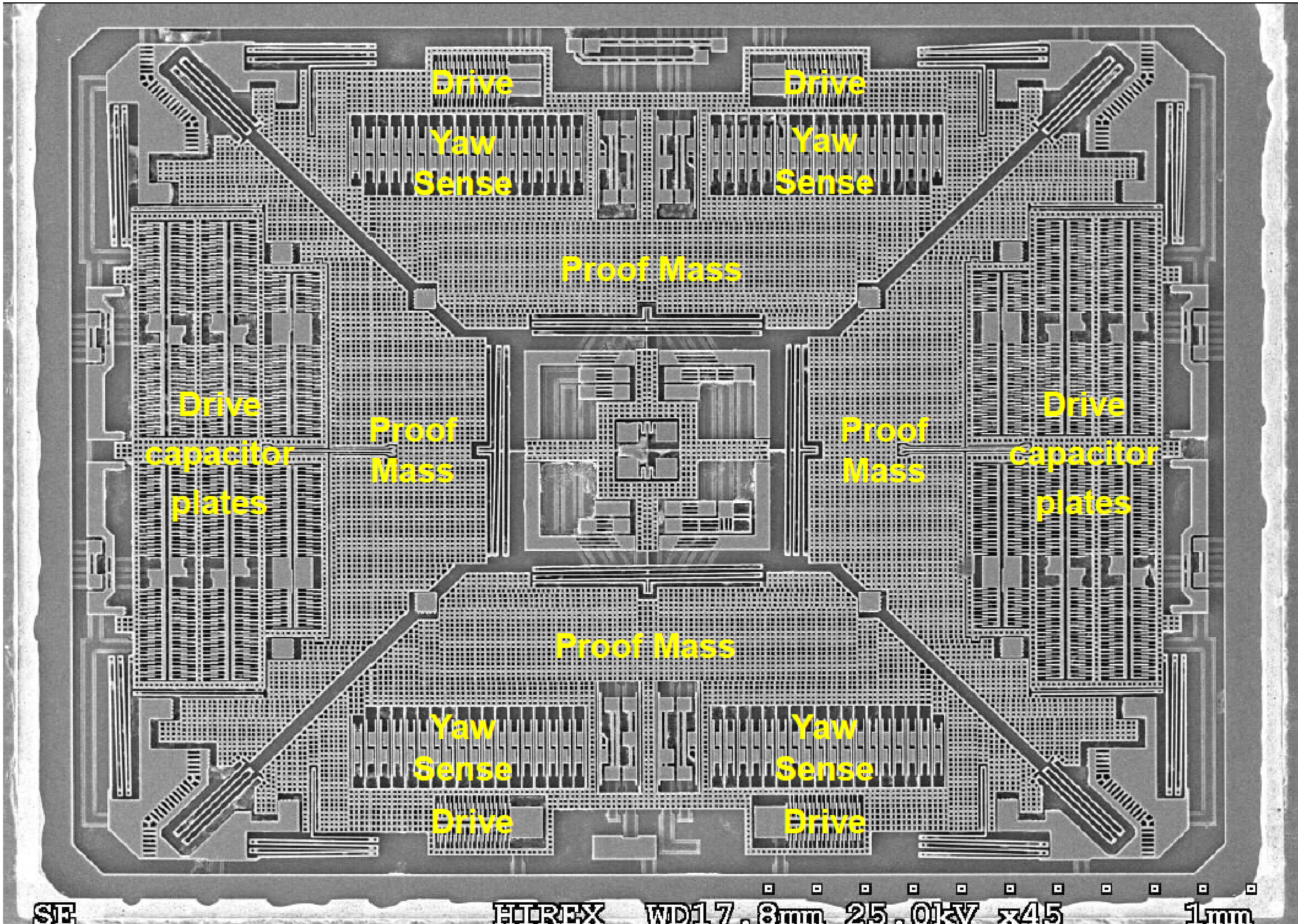
Three-Axis Accelerometer for iPhone 4

Applications of Accelerometers

MEMS Gyroscope



MEMS Gyroscope



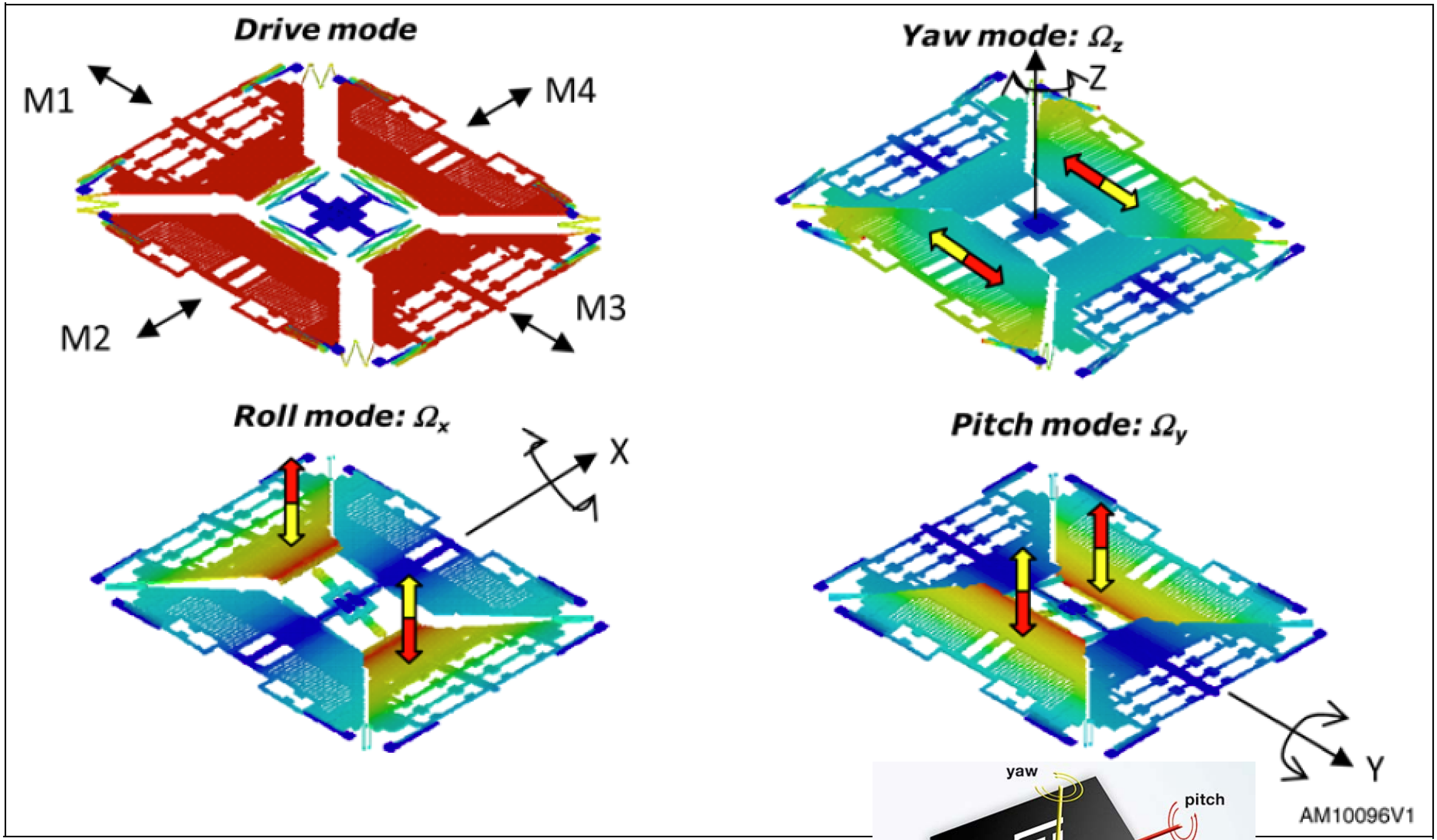
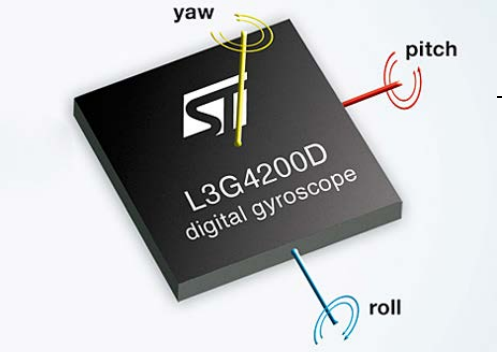
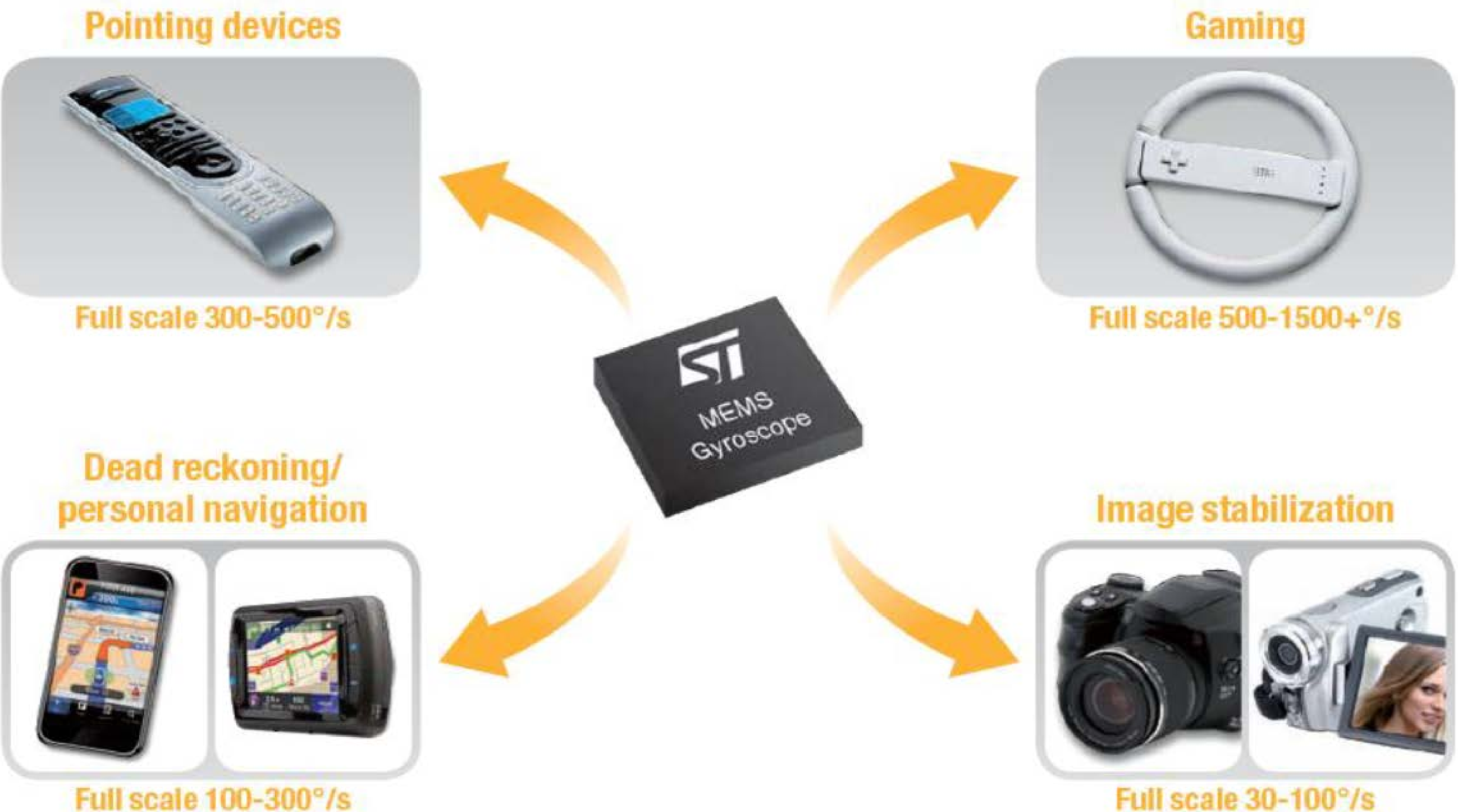


Figure 4 shows how the beating heart structure works.



Why was it a major breakthrough?

Applications of Gyroscope



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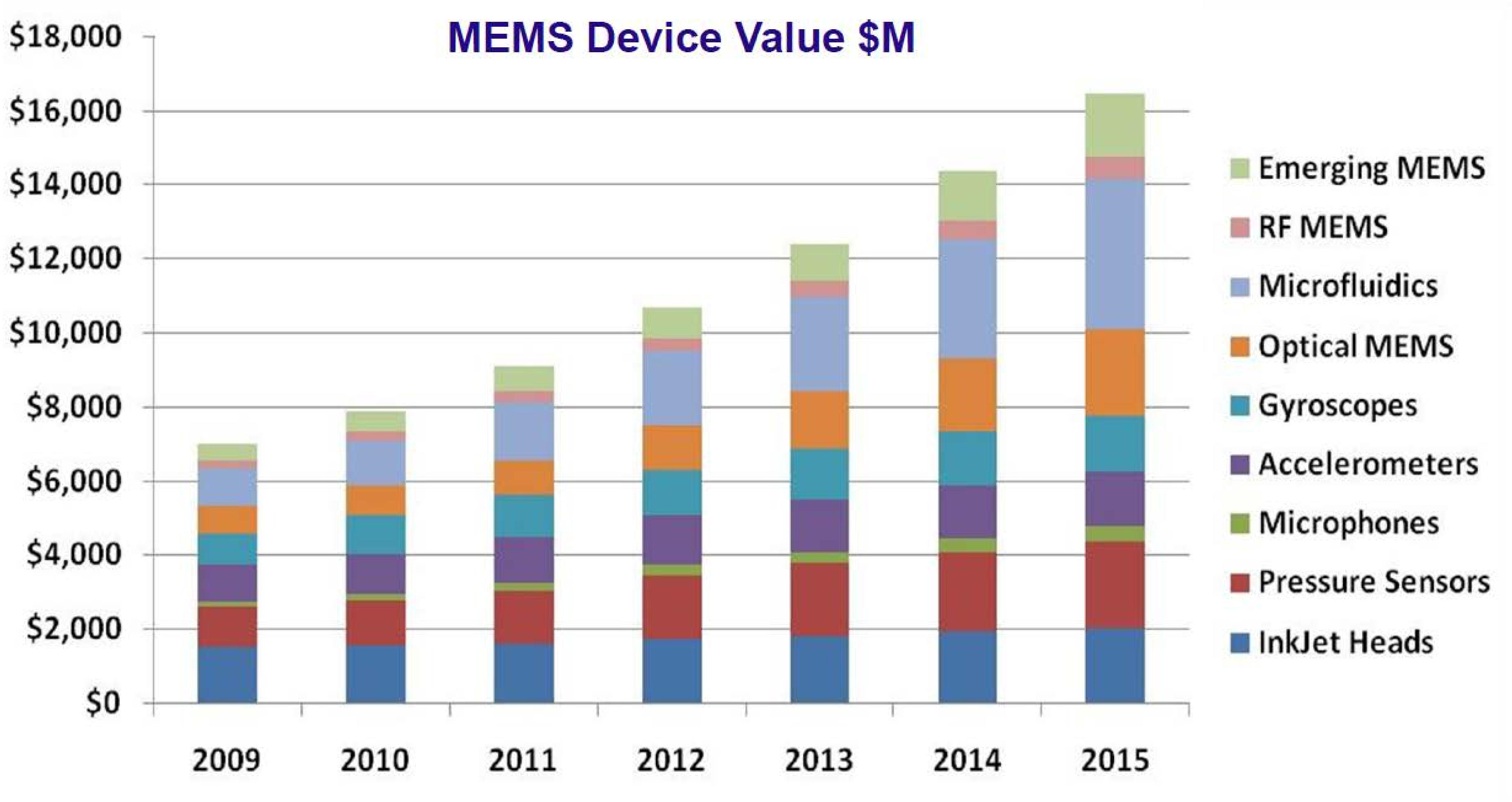
Why MicroNanoBio?

Most promising MEMS Markets

The highest growth segments:

- **Consumer applications:**
  - **Mobile phone and gaming represent real growth opportunities for a wide range of MEMS components.**
- **Life Sciences (diagnostic applications)**
  - **MEMS is very promising for diagnostic applications enabling rapid testing with or without biological reagents.**
  - **The technology penetration rate in this market is slow, but the opportunity is real given the level of investment and interest.**

MEMS Market



MEMS Device Value $M
$18,000
$16,000
$14,000
$12,000
$10,000
$8,000
$6,000
$4,000
$2,000
$0
2009
2010
2011
2012
2013
2014
2015
Emerging MEMS
RF MEMS
Microfluidics
Optical MEMS
Gyroscopes
Accelerometers
Microphones
Pressure Sensors
InkJet Heads

MEMS for Smartphones

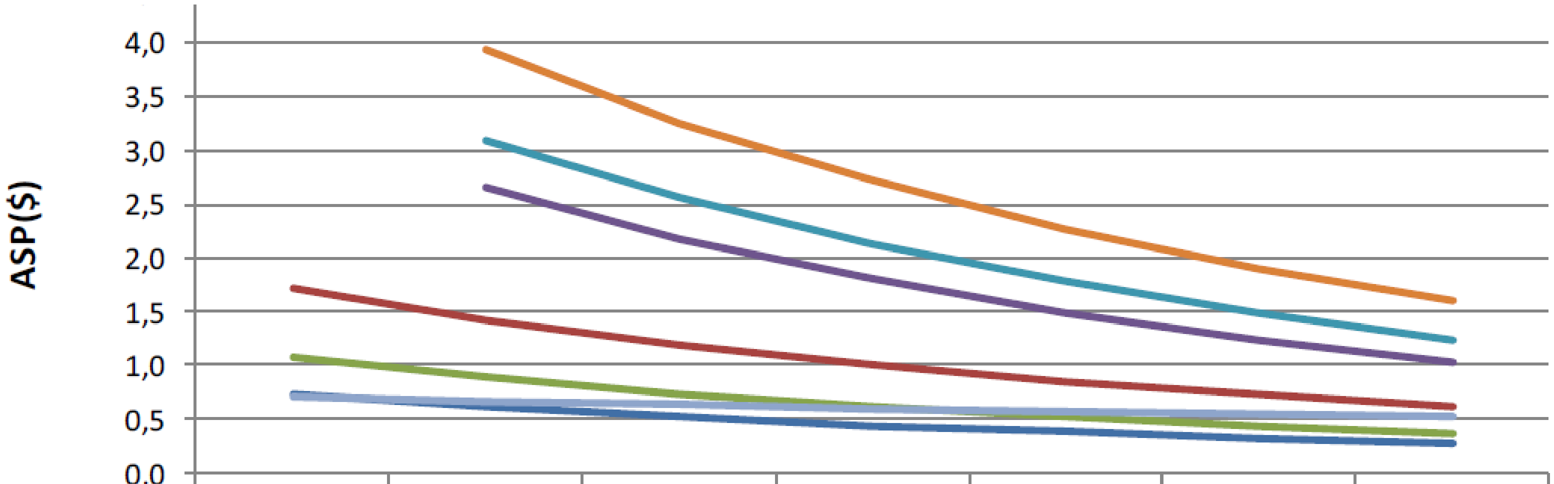
Product	New Features/Services	Reduce Cost	Improve Performance
Pressure sensor	LBS services		
Silicon Microphone		Reduce assembly cost	
Accelerometer	LBS services Games Multimedia applications		Power down mode
Gyroscope			Stabilized camera sensors
Micromirror	Image projection features		
Microdisplay			Ultralow power display Better sunlight viewability
RF switch and varicaps		One radio per mode front end modules (agile PA and agile filters)	Tunable Antenna Improve low quality PA operation
BAW/FBAR filters			WCDMA duplexers
Oscillators		Single chip timing reference system	
Micro fuel cells			Disposable fuel cartridge energy generator
Micro autofocus			Miniaturized autofocus camera phones
Micro zoom			Miniaturized zoom camera phones

MEMS for Smartphones

MEMS Product	Function	MEMS based applications
Pressure sensor	Altimeter	GPS/LBS services
Silicon Microphone	Voice sensing	Replacement of ECM
Accelerometer	Tilt sensing User motion sensing	User interface: menu scrolling & games Pedometer & wellness monitoring GPS/LBS services Power saving modes
Gyroscope	Hand jitter measurement User motion sensing	Stabilized camera sensors User interface: Games GPS/LBS services
Micromirror	Picoprojectors	TV/Image projections
Microdisplay	Low power display	Replacement of LCD display
RF switch and varicaps	Tunable matching networks	Tunable antenna, Tunable PA, Tunable filters
BAW/FBAR filters	WCDMA duplexers	Replacement of ceramic and SAW duplexers
Oscillators	Timing references	Replacement of quartz filters
Micro fuel cells	Disposable fuel cartridge	Power generation alternative or complimentary to batteries
Micro autofocus	Autofocus	Autofocus of >5M camera sensors
Micro zoom	Zoom	Optical zoom for >5M camera sensors
Fingerprint sensor	Fingerprint identification	User data protection

Low-Cost MEMS

ASP ($) evolution for MEMS inertial & orientation devices in mobile phones



	2009	2010	2011	2012	2013	2014	2015
3A ASP ($)	0,72	0,61	0,52	0,44	0,38	0,32	0,27
3M ASP ($)	1,08	0,89	0,73	0,61	0,52	0,44	0,37
3G ASP ($)		2,65	2,17	1,80	1,50	1,24	1,03
Combo A+M ASP ($)	1,71	1,42	1,18	1,00	0,85	0,72	0,61
Combo A+G ASP ($)		3,10	2,56	2,13	1,78	1,48	1,24
Combo A+G+M ASP ($)		3,94	3,25	2,71	2,27	1,90	1,59
Motion sensors ucontroller ASP ($)	0,70	0,67	0,63	0,60	0,57	0,54	0,51

Trend

It's simple: interaction between equipment, user and environment is essential and sensors are the building blocks of such interaction.

Automotive: cars need more sensors for safety and comfort of the occupants. The increase of electric and hybrid vehicles also means more sensors.

Medical and in vitro diagnostics: as world population ages, more assistance will be needed which means more sensors to understand activity of the patient, internally (implantables) and externally. More analysis, faster and with better efficiency means more microfluidics…

Environment analysis: growing need and increased difficulties to access quality water means more analysis & more sensors at all levels of water production.

Environmental control: governments are devising taxes based on amounts of particles released, access to information will enable taxes and MEMS sensor technology will provide the means, at the right cost, for such detection.

Consumer electronics: MEMS simplify HMI and provide "in situ" analysis. Mobility is a long term trend: mobility of portable electronics means smart and light weight systems with long lasting batteries, alternative power, wireless communications… MEMS sensors and actuators enable the continuing revolution of mobile electronics.