

WHAT ARE MEMS? AND WHY DO WE CARE?

MATTHIAS PLEIL (UNIVERSITY OF NEW MEXICO)
SUPPORT CENTER FOR MICROSYSTEMS EDUCATION
IN COLLABORATION WITH THE
MICRO NANO TECHNOLOGY EDUCATION CENTER

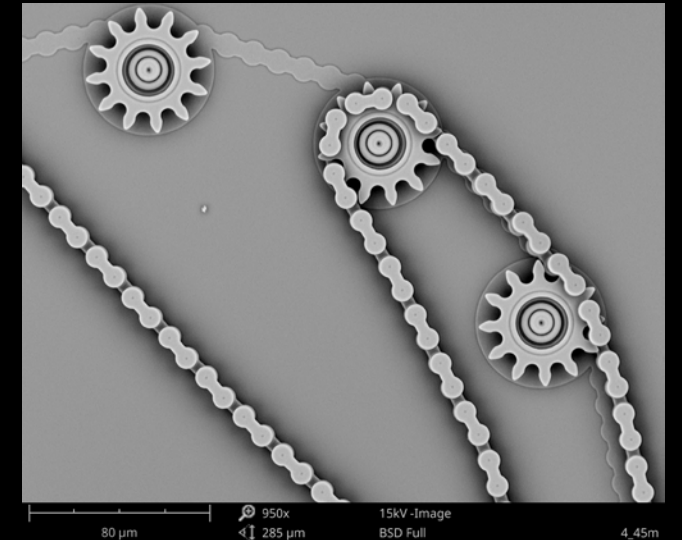
THIS MATERIAL IS BASED UPON WORK SUPPORTED BY THE NATIONAL SCIENCE FOUNDATION UNDER DUE GRANT No. 1700678

PRESENTATION AT A GLANCE

- APPLICATIONS
- DEVICES
- SYSTEMS
- TRENDS

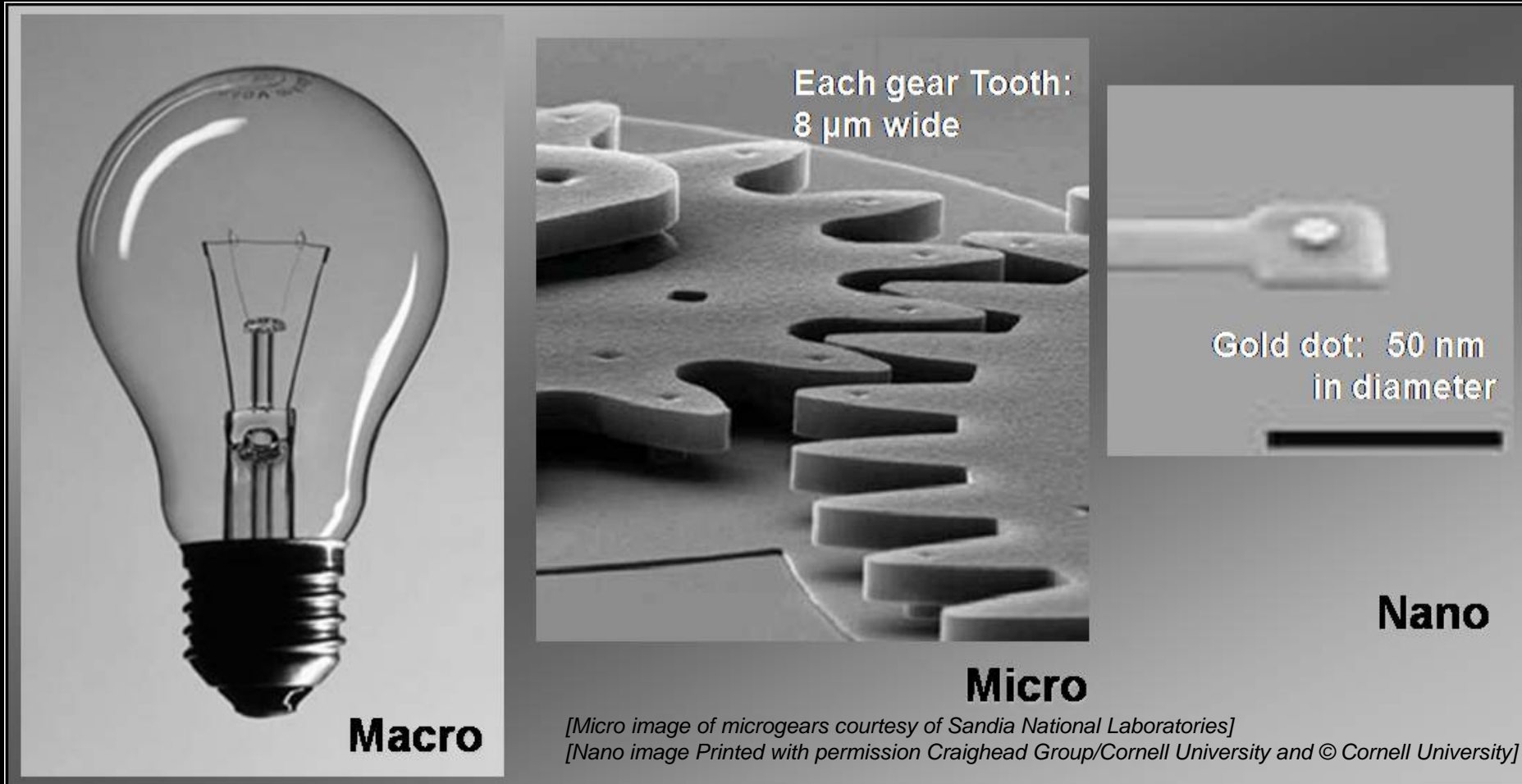
WHAT ARE MICROSYSTEMS (MEMS)?

- MICROSYSTEMS, = MICROELECTROMECHANICAL SYSTEMS
- MICRO SENSORS AND ACTUATORS
- MADE IN CLEANROOMS

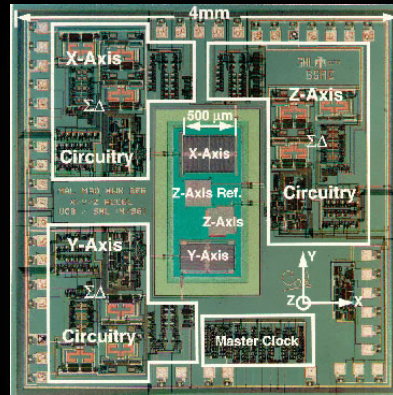


COMPARISON OF SCALE – MICRO VS NANO

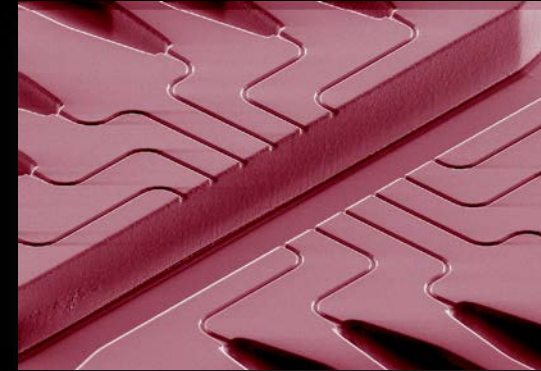
> 100 micro 100 micro – 100 nano 100 nano – 1 nano



TYPES OF MEMS DEVICES



Micro-Sensors & Actuators
3-axes accelerometer with electronic interface, used for airbag deployment
[Courtesy of Sandia National Laboratories]

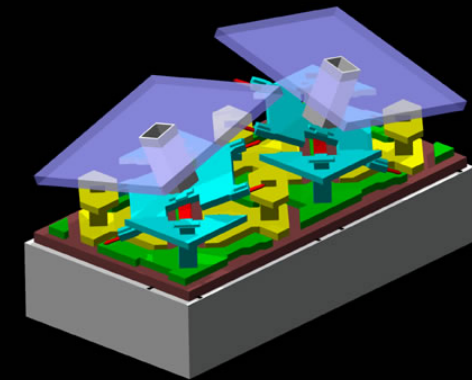


Microfluidics
Channels and chambers
[Courtesy of Luke Lee @ UC-Berkeley]



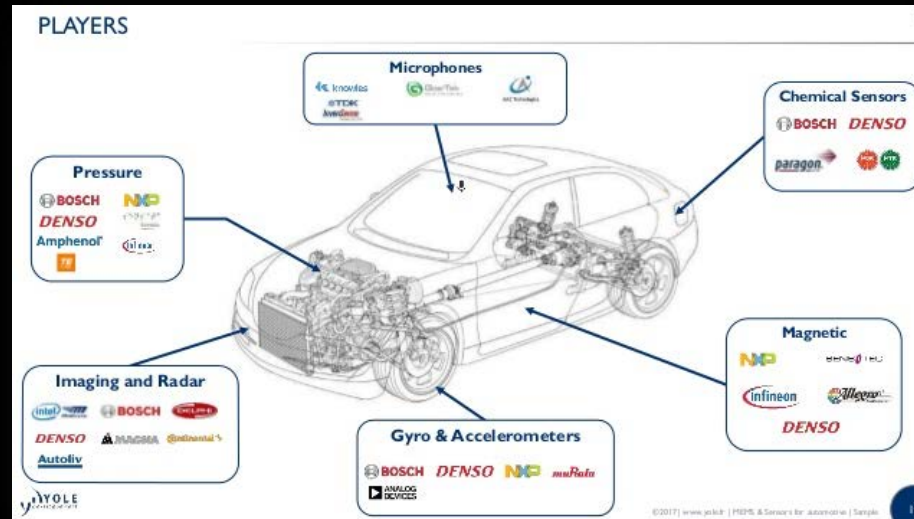
BioMEMS
Pacemaker
[Courtesy of Healthline]

Micro-optics
Digital Mirror Device



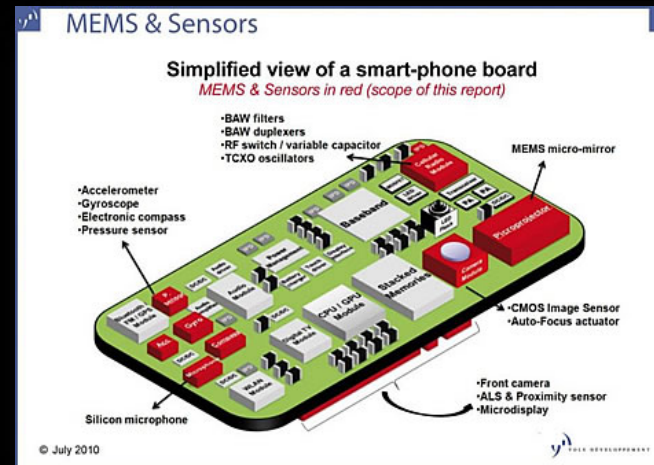
WHERE ARE MEMS FOUND?

- AUTOMOTIVE
 - SAFETY SYSTEMS
 - NAVIGATION
 - AUTONOMOUS SYSTEMS
- CONSUMER PRODUCTS
 - SMART PHONES
 - TABLETS
 - WEARABLES (FITBIT, GARMIN, IWATCH)
- IoT
 - REMOTE SENSOR SYSTEMS
 - MACHINE TO MACHINE COMMUNICATION
- BIOMEDICAL AND BIOCHEMICAL SENSING AND ACTUATION
 - MICRO SURGERY, CHEMICAL AND DRUG DELIVERY
 - POINT OF CARE LAB ON A CHIP



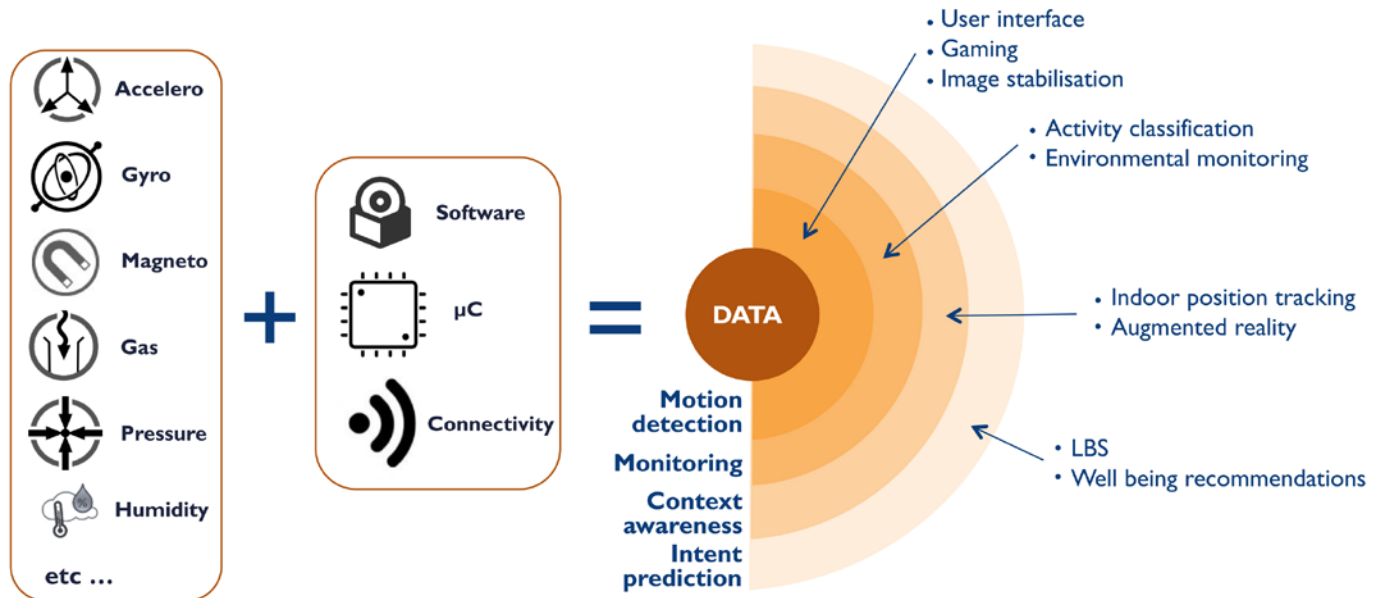
SMART PHONE FEATURES NEED MEMS

- ACCELEROMETERS
- 6-AXIS IMU
- MICROPHONES (4 IN THE IPHONE 6)
- GYROSCOPES
- 6-AXIS E-COMPASS
- PRESSURE SENSORS
- MAGNETOMETERS
- BAW FILTERS & DUPLEXERS
- SPEAKERS
- PROJECTION SYSTEMS
- FLIR CAMERA



Sensors in Smartphones... from sensing to predicting

(Source : Sensors for Cellphones and Tablets 2016 Market & Technology report, Yole Développement, June 2016)



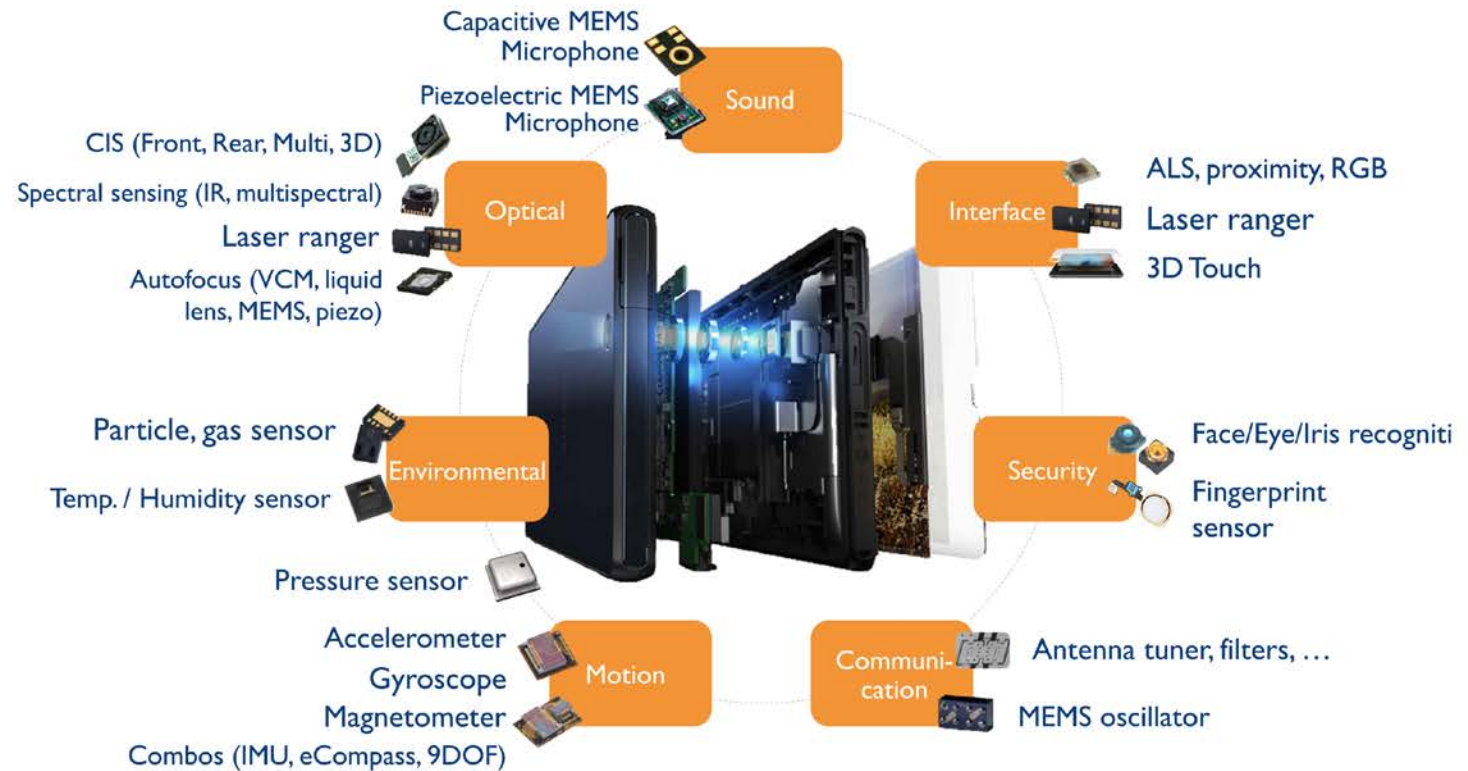
Inspired by Bosch

MEMS IN SMART PHONES



Mobile value proposition

(Source : Sensors for Cellphones and Tablets 2016 Market & Technology report, Yole Développement, June 2016)



MEMS COMBOS – MULTIPLE SENSORS IN ONE PACKAGE!

Bosch Sensortec BME680
Environmental Sensor



MEMS COMBOS – BOSCH EXAMPLE

MEMS

Example of reverse engineering/reverse costing analysis

(Source : Inertial MEMS Manufacturing Trends 2014, Yole Développement & System Plus Consulting, March 2014)

Package:

- Dimensions: 3mm x 3mm x 0.95mm)
- Type: LGA 16-pin
- Cost: \$0.165 (includes final test & yields losses)

ASIC accelerometer:

- Die area: 1.38mm²
- Process: CMOS 0.18µm 2P 4M.
- Cost: \$0.098

MEMS accelerometer:

- Die area: 1.96mm²
- Sensing axis: Three axes (X, Y and Z).
- Process:
 - Cap: Bulk micromachining (Isotropic etching).
 - Sensor: Epi-Poly Surface Micromachining.
 - Bonding: Glass-frit
- Cost: \$0.059

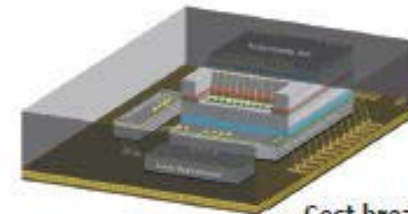
Z-Axis magnetometer + ASIC:

- Die area: 2.19mm²
- Sensing axis: One axis (Z)
- Process: CMOS 0.18µm 2P 4M.
- Cost: \$0.126

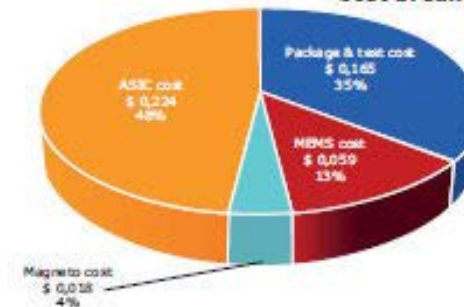
X/Y-Axis magnetometer:

- Die area: 0.61mm²
- Sensing axis: One axis (X or Y)
- Process: Thin film deposition
- Cost: \$0.009

Bosch Sensortec BMC050



Cost breakdown



© March 2014

SENSOR KINETICS – SEE ALL YOUR MEMS SENSORS

17:40 [Icons] +54 [Icons] 60%

Sensor Kinetics Pro | S | ? | ⋮

Magnetometer

Type: LGE Magnetometer Non-wakeup
Mfr: akm Ver: 146951
Power Consumption: 1.100mA
Resolution: 0.150 Range: 4911.994
Min Delay: 10000 μ s

Rate: 15Hz Units: μ T
Rate: UI X=23.063 Y=8.644 Z=-49.088

Derived 3-D Sensors

Gravity Sensor

Type: LGE Gravity Sensor
Mfr: qualcomm Ver: 1
Power Consumption: 0.515mA
Resolution: 0.010 Range: 156.990
Min Delay: 5000 μ s

Rate: 17Hz Units: m/s^2
Rate: UI X=0.4413 Y=0.4523 Z=9.7863

Linear Acceleration

Type: LGE Linear Acceleration Non-wakeup
Mfr: qualcomm Ver: 1
Power Consumption: 0.515mA
Resolution: 0.010 Range: 156.990
Min Delay: 5000 μ s

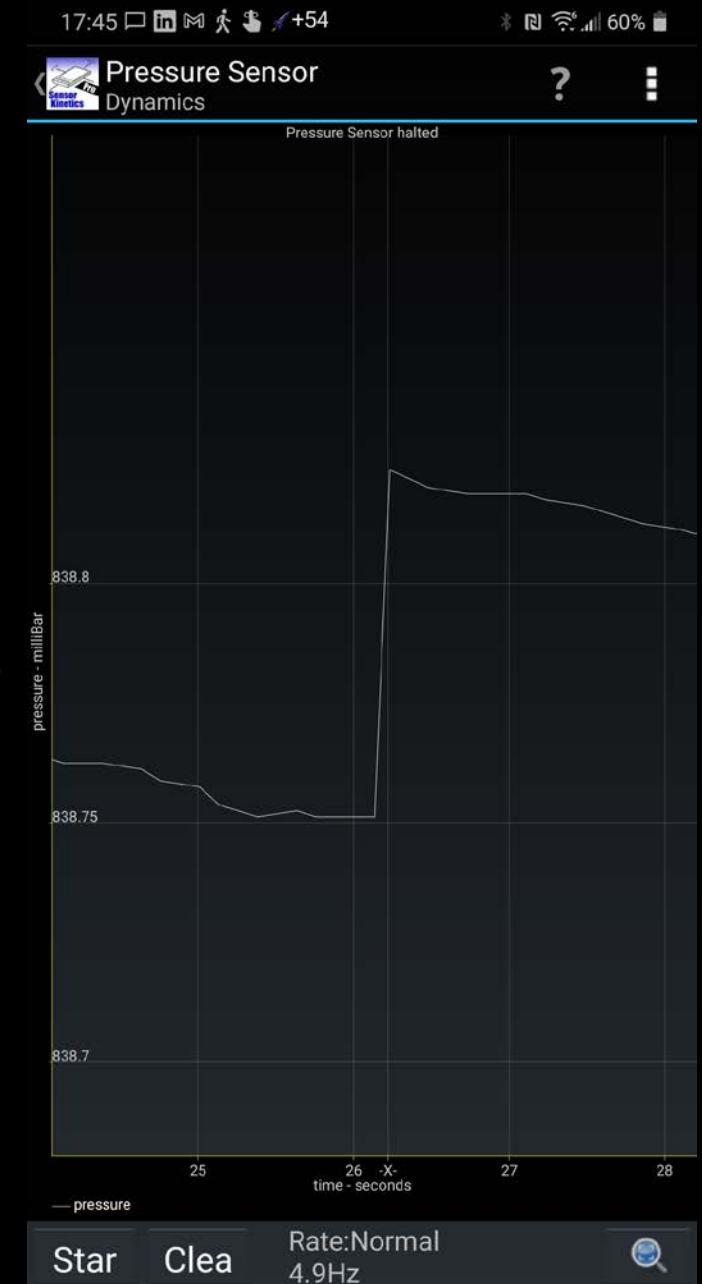
Rate: 17Hz Units: m/s^2

Sensor Kinetics
INNOVENTIONS, Inc. Tools
★★★★★ 7,058
Everyone
This app is available for your device
You can share this with your family. [Learn more about Family Library.](#) **Installed**

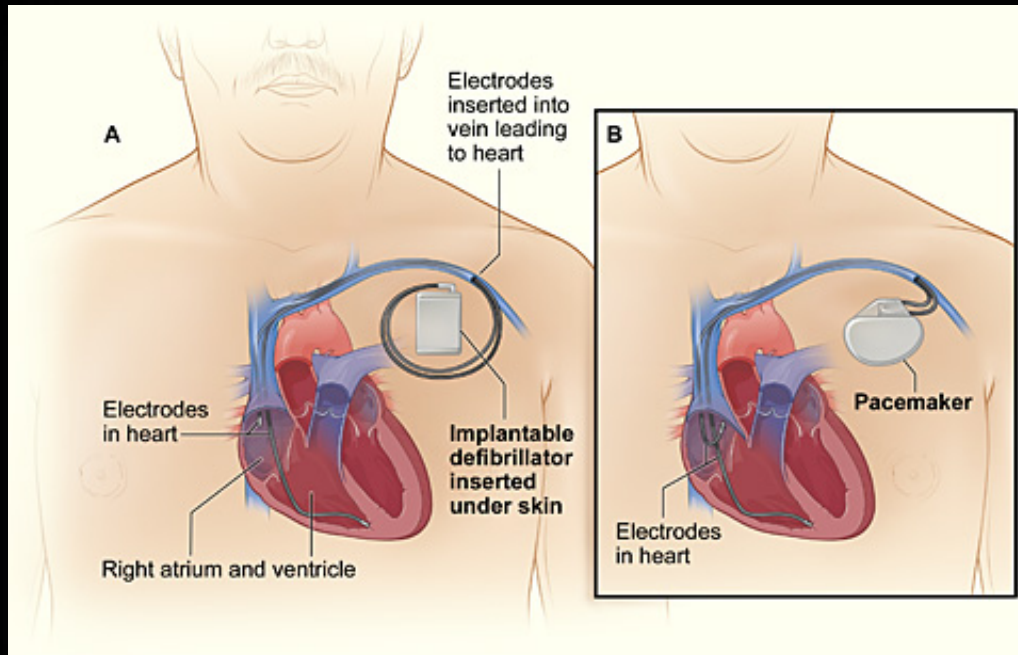
The screenshots show the app's interface with three main views: 1) A 3D visualization of sensor data with axes. 2) A detailed settings menu for various sensors including Magnetometer, Gravity Sensor, Linear Acceleration, Gyroscope, and Accelerometer. 3) A 'Gyroscope charting...' screen displaying a graph of rotation speed (roll, pitch, yaw) over time in seconds.

FOR HOMEWORK

- GET SENSOR KINETICS APP FOR YOU PHONE
- MEASURE THE PRESSURE AT THE FLOOR, AND AT YOUR DESK SURFACE, I GOT:
- 838.750mBAR AND 838.825mBAR WHAT'S THE HEIGHT?
 - 31mBAR ~ 1000FT, DELTA MEASURED 0.075mBAR = 2.4FT, I MEASURE 30IN, OR 2.5FT!!!

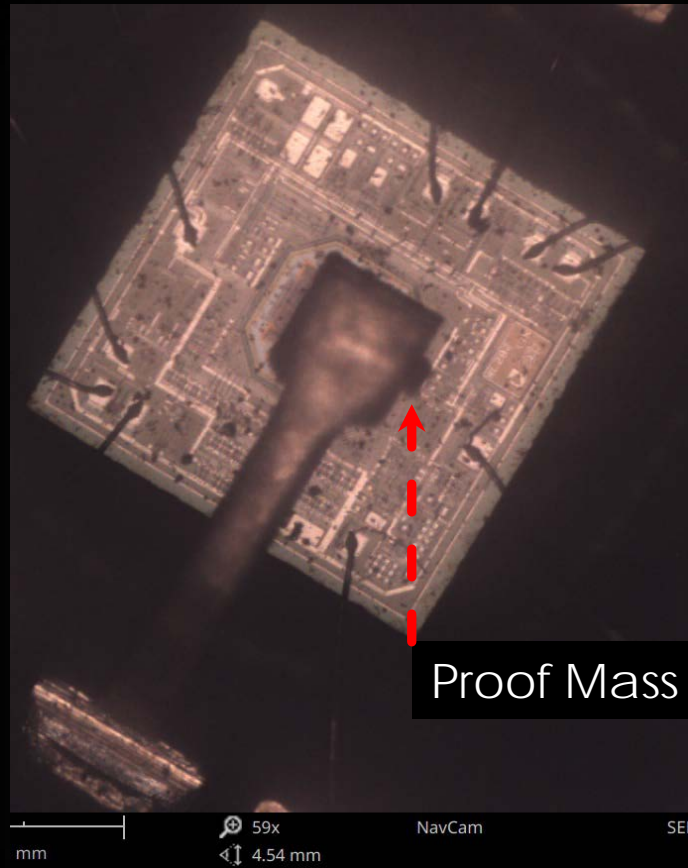


MEMS ACCELEROMETERS



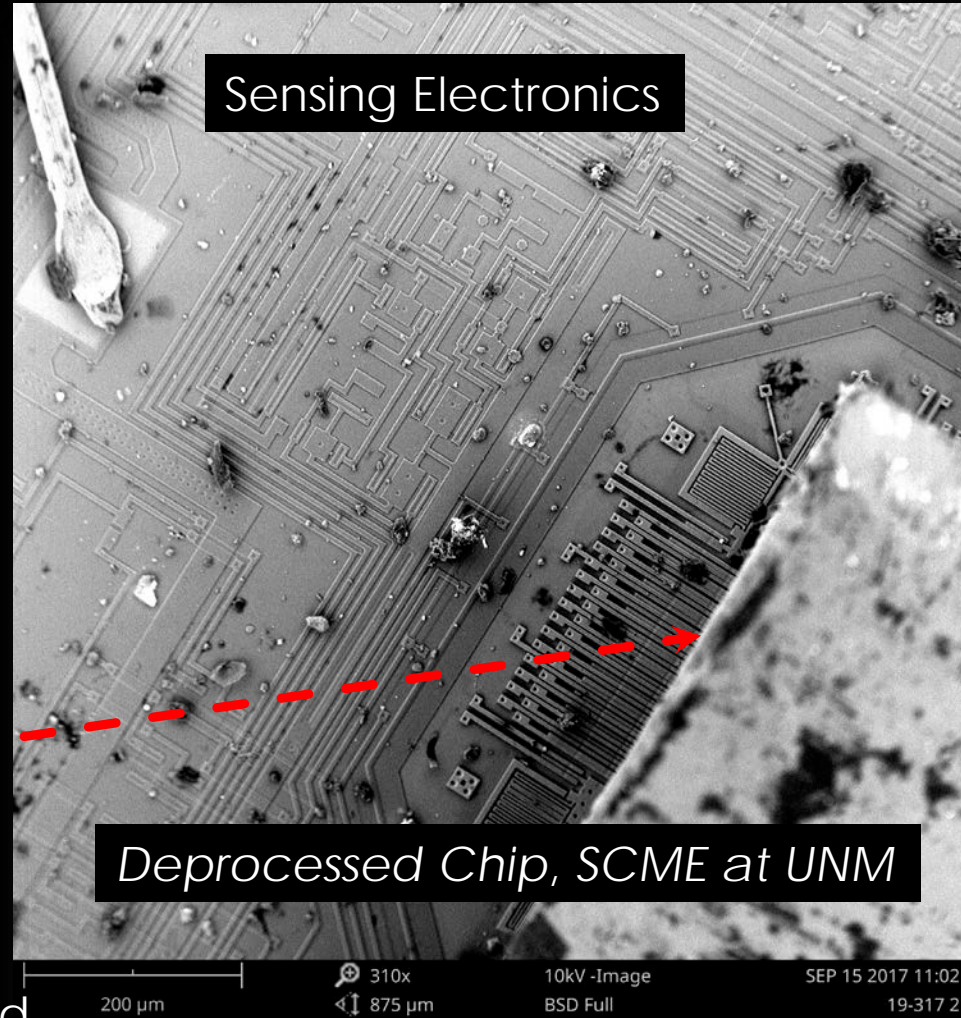
- PACEMAKERS AND DEFIBRILLATORS (INTERNAL AND EXTERNAL)
- IPHONES AND GAMING DEVICES
- AIRBAG DEPLOYMENT IN CARS
- ANTICRASH AND ANTI-ROLL SENSOR
- COMPUTER STABILIZATION
- CAMERA STABILIZATION
- GPS DEVICES
- POWER MANAGEMENT DEVICES
- VIBRATION SENSORS FOR MOTORS, FANS, AND COMPRESSORS

ANALOG DEVICES OUT OF PLANE ACCELEROMETER



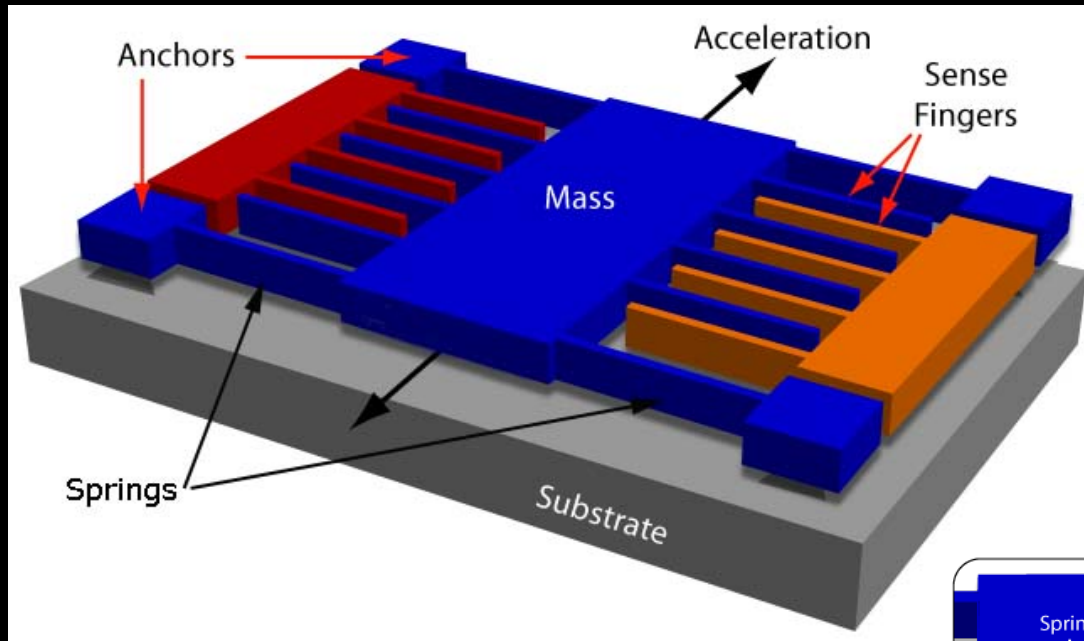
Proof Mass

Cantilever Based



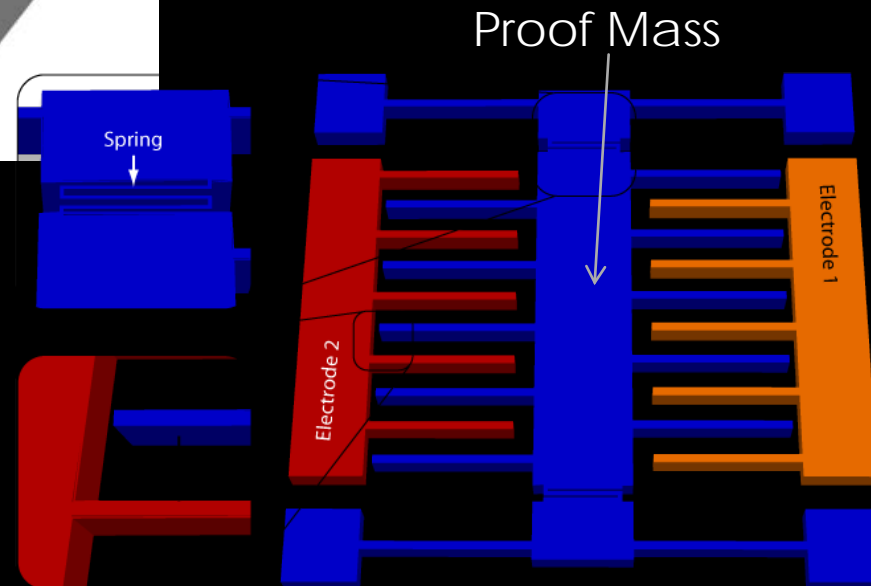
Deprocessed Chip, SCME at UNM

IN-PLANE MEMS ACCELEROMETERS

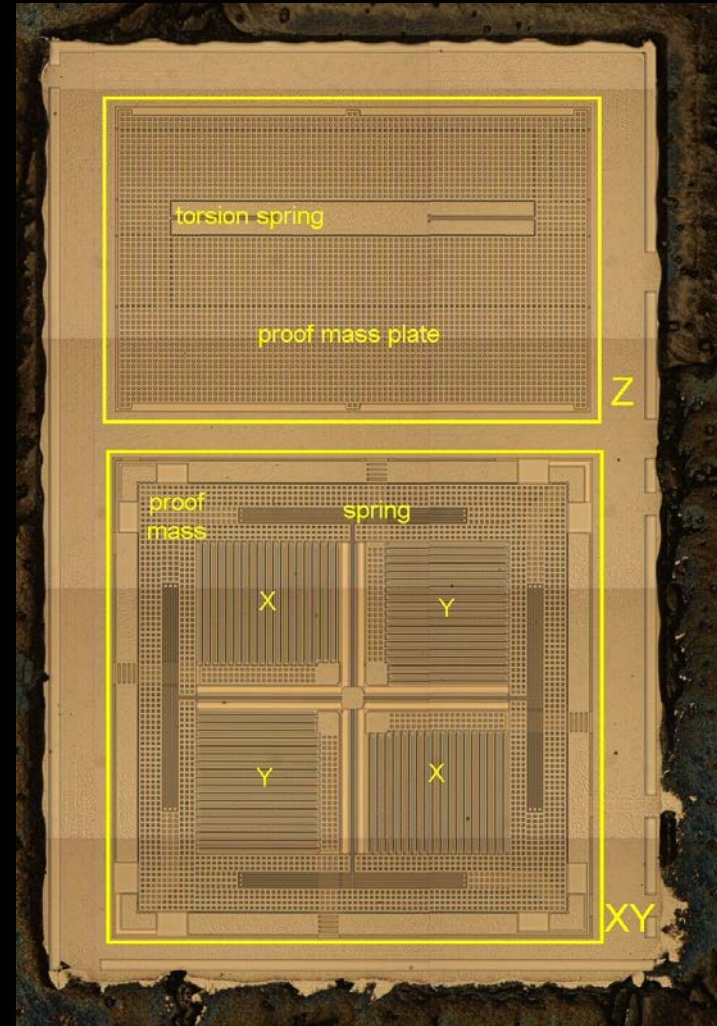
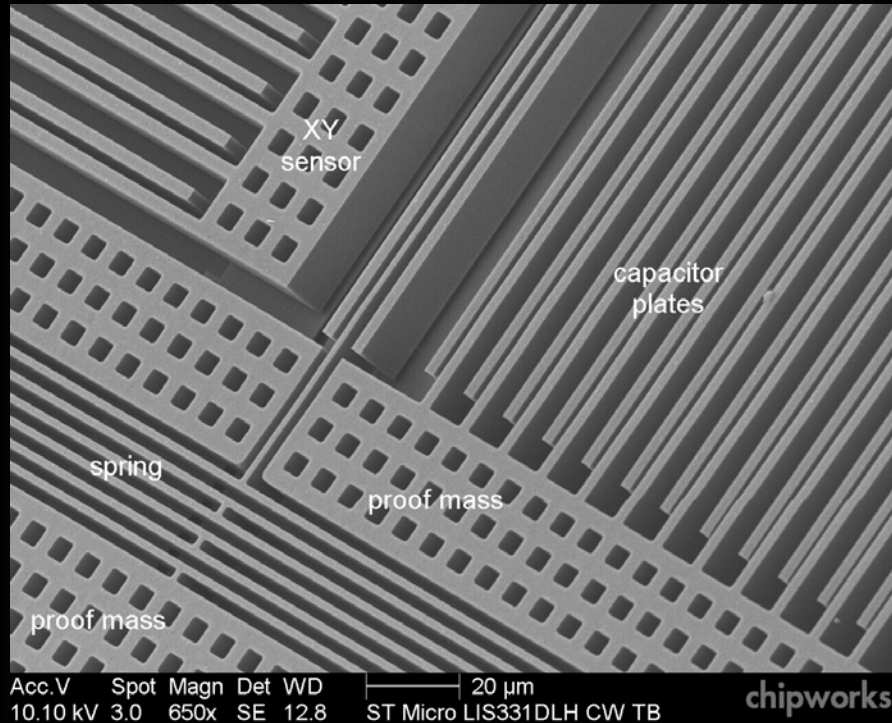


In-plane accelerometers use a set of fixed electrodes and moveable electrodes.

The moveable electrodes are part of a "proof mass" that moves linearly with acceleration or de-acceleration.

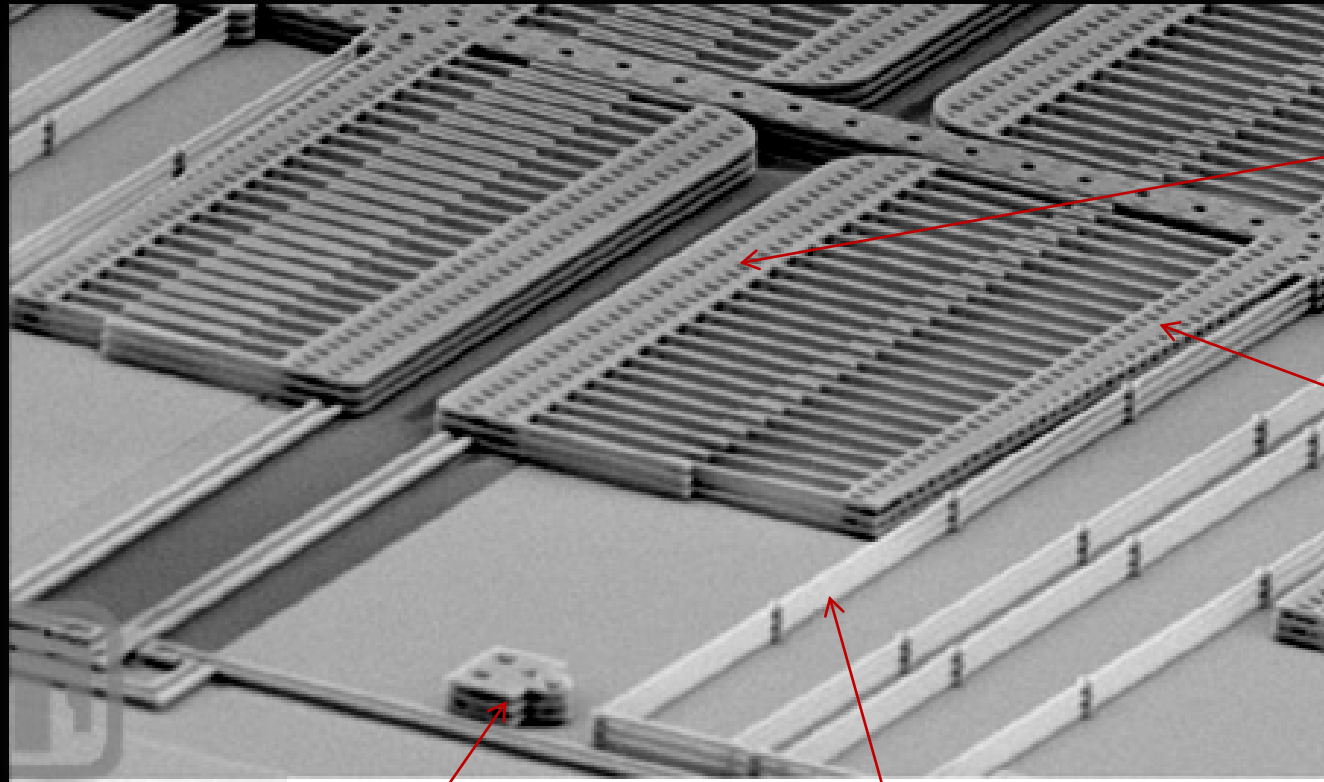


iPhone 4 MEMS Accelerometers



MOTION SENSING IN THE IPHONE 4:
MEMS ACCELEROMETER by St.J.
Dixon-Warren

ELECTROSTATIC COMB DRIVE ACTUATORS

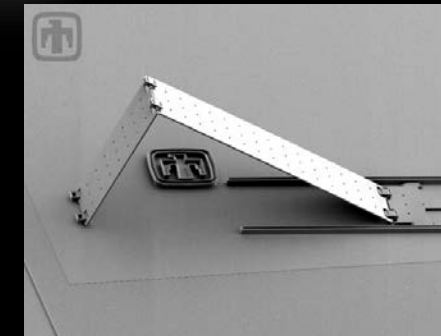


Fixed comb

Moveable comb

Travel stop

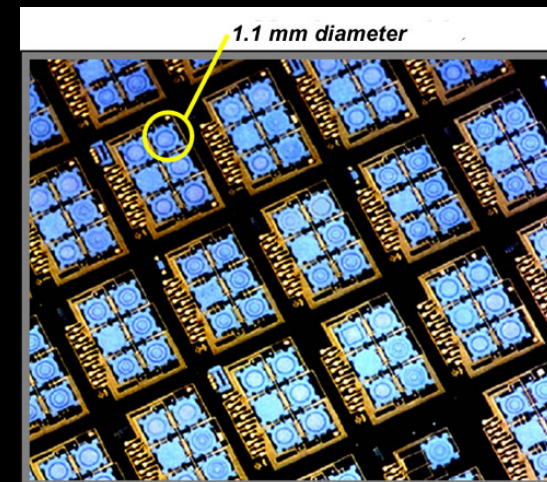
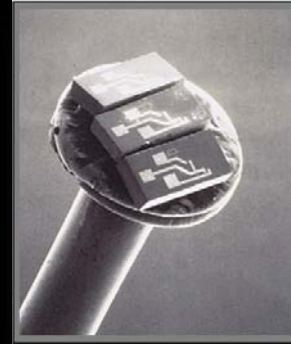
Spring



Comb drive showing Travel Stops and Springs of a Comb drive
[Images courtesy of Sandia National Laboratories, www.mems.sandia.gov]

PRESSURE SENSORS

- AUTOMOTIVE
 - ABSOLUTE AIR PRESSURE
 - TIRE PRESSURE
 - FUEL/OIL PRESSURE
 - AIR FLOW
 - AIRBAG DEPLOYMENT/WEIGHT & SENSING OF PASSENGERS
- BIOMEDICAL
 - BLOOD PRESSURE SENSORS
 - INTRACRANIAL PRESSURE
 - CEREBROSPINAL FLUID PRESSURE
 - INTRAOCULAR PRESSURE
 - ENDOSCOPES FOR ORGAN PRESSURE
- OTHER
 - BAROMETRIC PRESSURE
 - SMART DUST

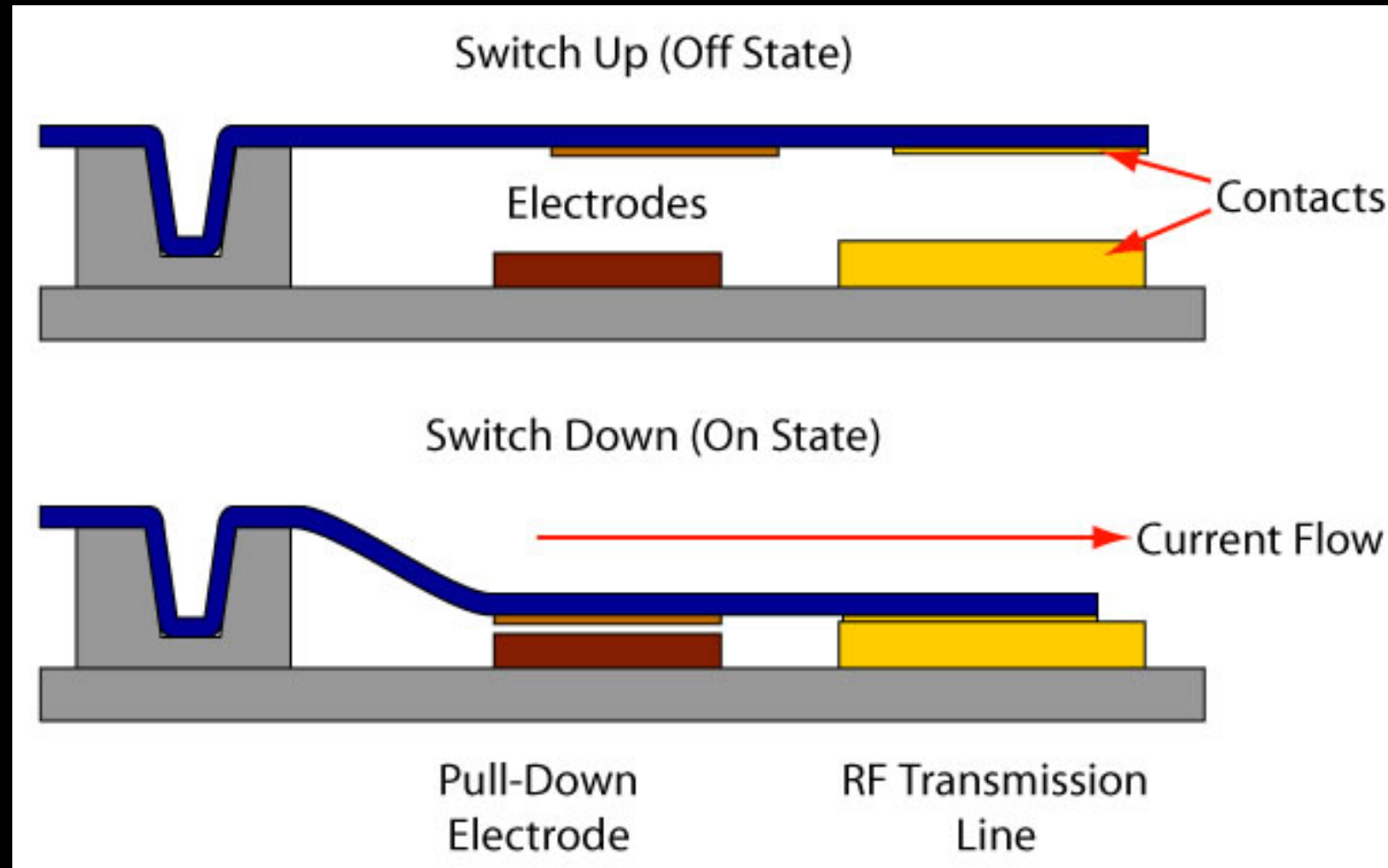


Barometric Pressure Sensors (Photo courtesy of Khalil Najafi, University of Michigan)

CANTILEVER-BASED MEMS

- ❖ BIOMEDICAL APPLICATIONS (BIOMEMS)
- ❖ PH SENSORS
- ❖ THERAPEUTICS
- ❖ ATOMIC FORCE MICROSCOPES (AFM)
- ❖ READ/WRITE STORAGE DEVICES
- ❖ ENVIRONMENTAL MONITORING
- ❖ FOOD PRODUCTION AND SAFETY
- ❖ RF SWITCHING
- ❖ PROBES

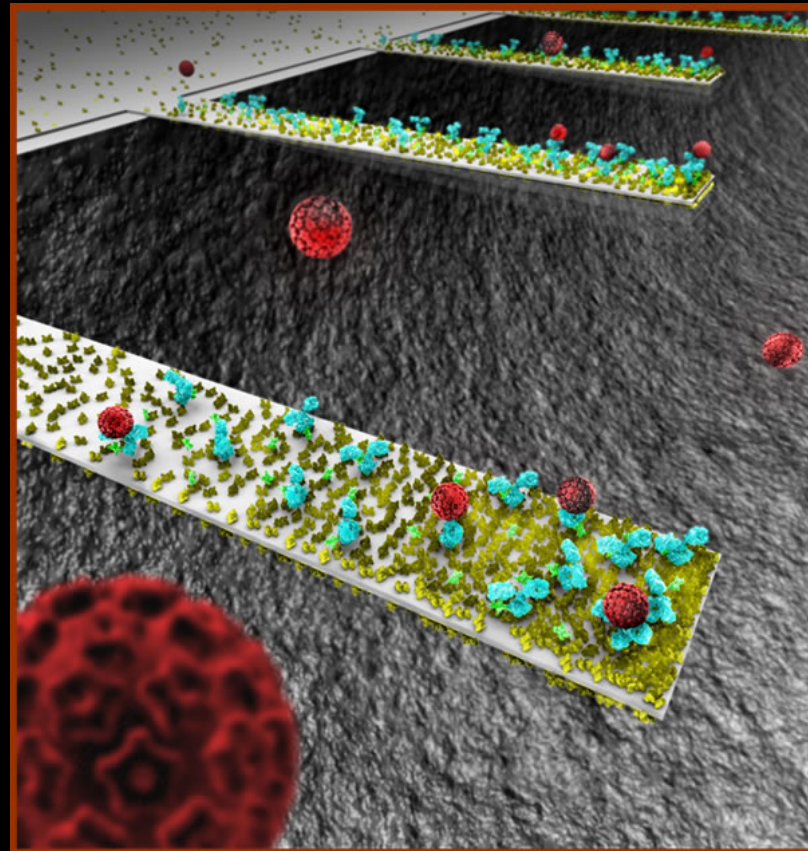
MICROACTUATORS - SWITCHES



MICRO-CANTILEVER CHEMICAL SENSOR

MEMS AND BIOMOLECULAR APPLICATIONS

MEMS CANTILEVERS ARE FABRICATED WITH SURFACE COATINGS ALLOWING FOR THE IDENTIFICATION AND REJECTION OF SPECIFIC BIOMOLECULES.



[Image generated and printed with permission by Seyet, LLC]

CANTILEVER BASED CHEMICAL SENSORS

- MICROCHEMICAL SENSORS ARE EITHER AN ARRAY OF CANTILEVERS OR A SINGLE CANTILEVER
- APPLICATIONS FOR CHEMICAL SENSOR ARRAYS
 - GAS LEAK DETECTORS
 - DETECTION OF CHEMICALS
 - BIOSENSORS
 - SENSORS FOR DNA HYBRIDIZATION AND PROTEIN BINDING
 - PH SENSORS
 - GLUCOSE SENSORS
 - BIOMOLECULAR ANALYSIS
 - CHARGED-PARTICLE FLUX DETECTOR
 - VARIOUS VOLATILE ORGANIC COMPOUNDS

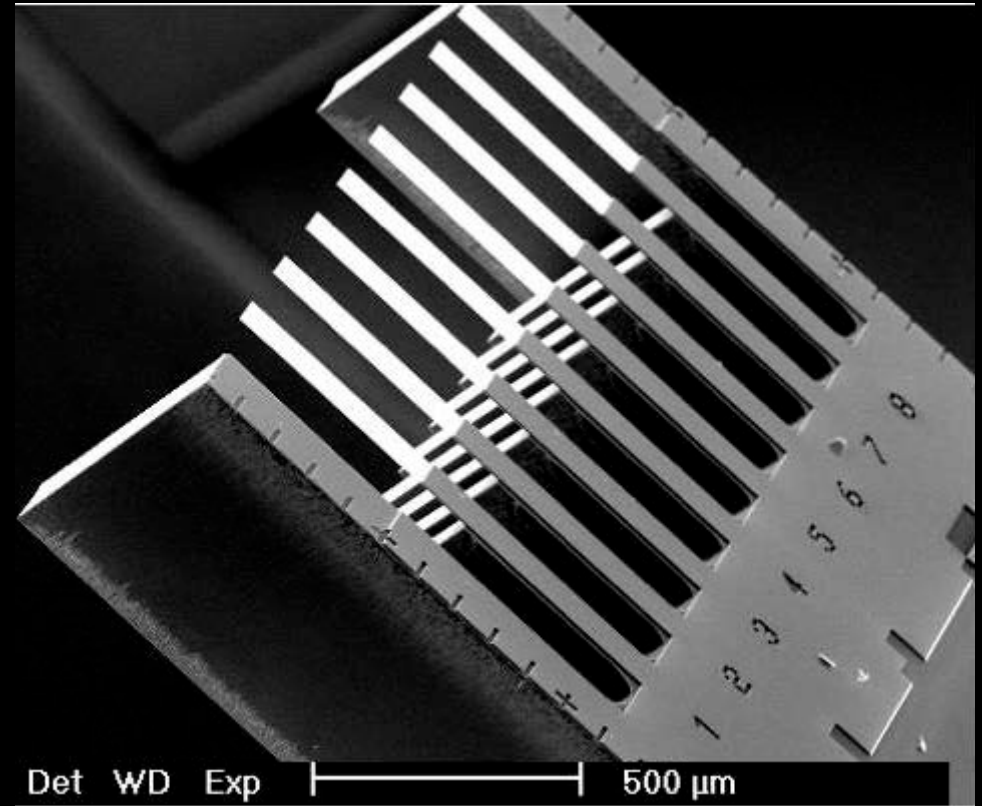
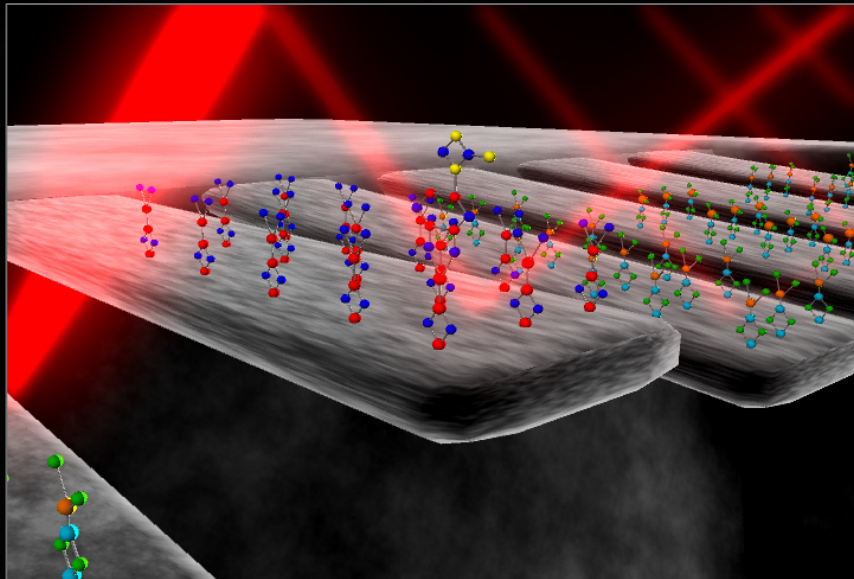


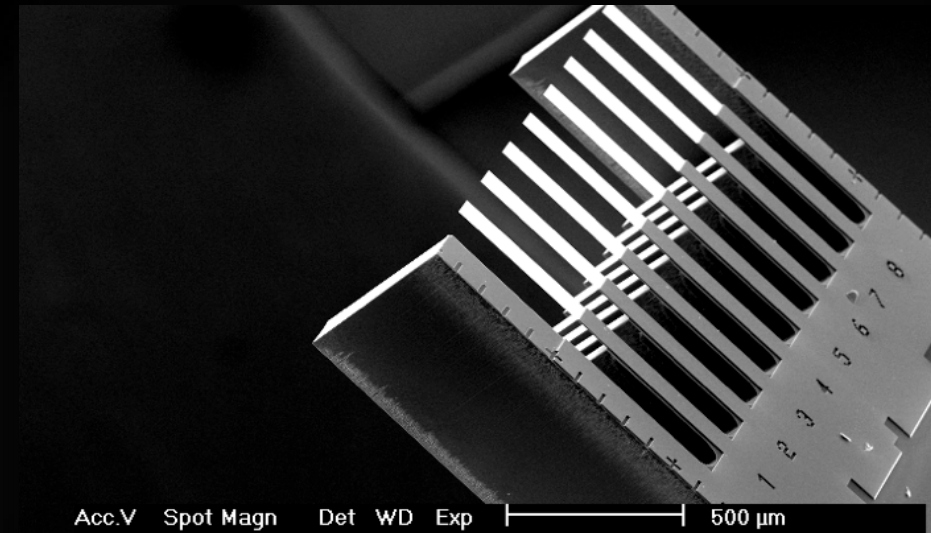
Image courtesy of Dr. Christoph Gerber, Institute of Physics, University of Basel

NANO ENABLES MEMS

A CANTILEVER SENSOR IS COATED WITH NANO-SCALE COATINGS THAT ENABLE THE SENSOR TO SENSE INDIVIDUAL CELLS, VIRUSES AND EVEN MOLECULES.



Functionalized cantilever array - SCME

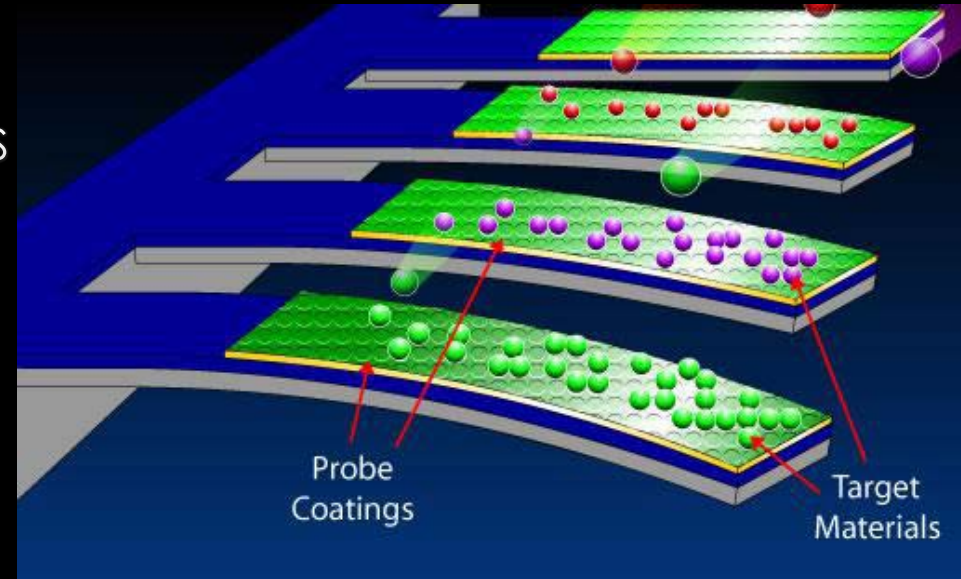


SEM image of a Cantilever Sensor Array

*These cantilevers were developed by the Swiss Nanoscience Institute for proteomic and genomic applications.
[Image courtesy of Dr. Christoph Gerber, Institute of Physics, University of Basel]*

CHEMICAL SENSOR ARRAYS (CSAS)

- DETECT & MEASURE THE AMOUNT OF A SPECIFIC SUBSTANCE IN A SAMPLE
- CAN DETECT SEVERAL SUBSTANCES SIMULTANEOUSLY
- CSAS ARE CHEMICALLY DISCRIMINATING

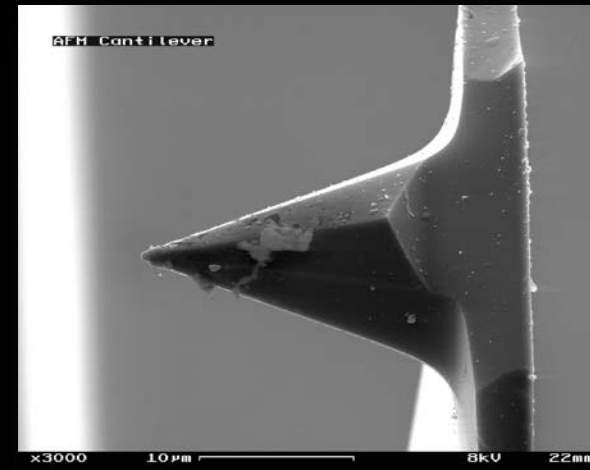
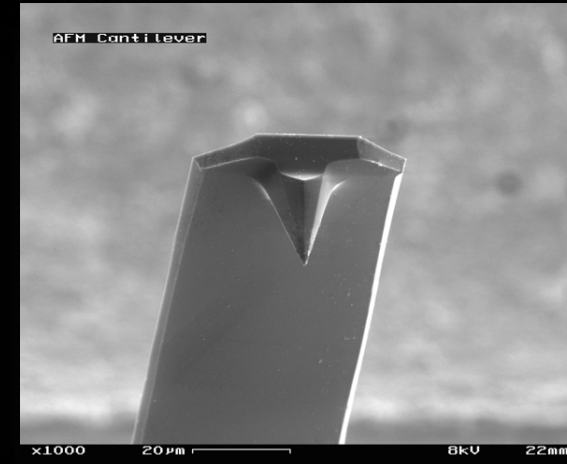
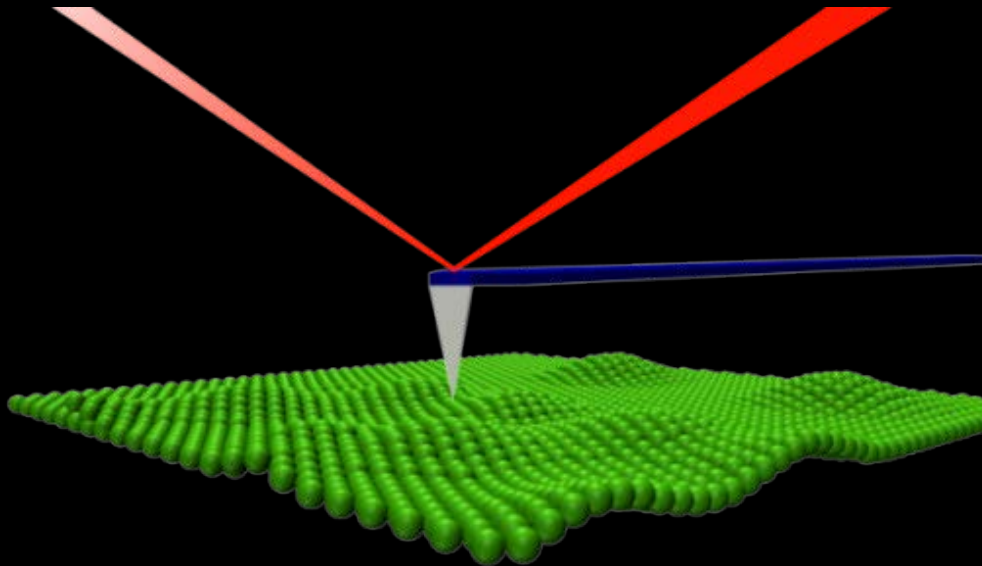


- Each cantilever is coated with a chemically sensitive probe coating
- By designing a CSA with a different probe coating on each cantilever, a CSA can be used to detect several different substances within the same sample.

MEMS ENABLES NANO - EXAMPLE

ATOMIC FORCE MICROSCOPE (AFM)

- CANTILEVER CAN BE 2 - 20 MM WIDE
- PROBE TIP CAN BE AS BIG AS 2 MM AT THE BASE, BUT AS SMALL AS 1NM AT THE TIP.

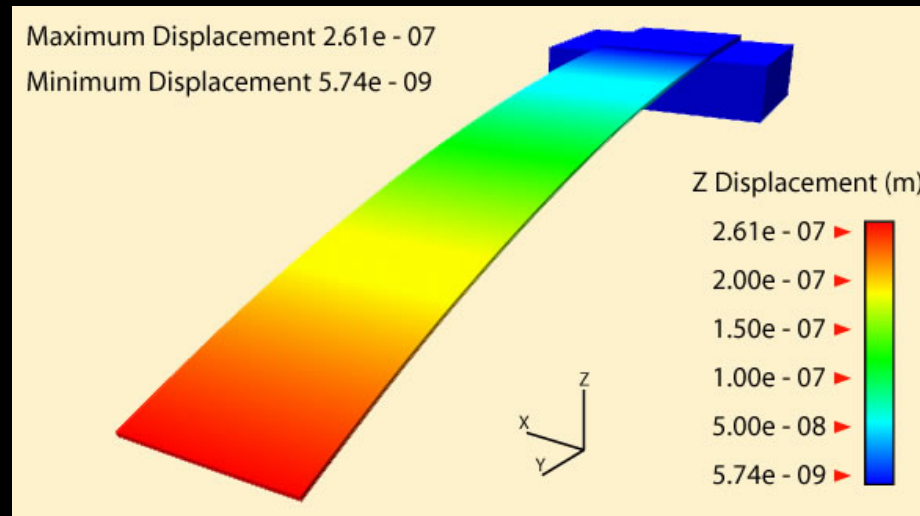


CANTILEVER CAPABLE OF DETECTING
CHANGES IN MASS OF 1 AG. CRAIGHEAD
GROUP/CORNELL UNIVERSITY, USA

WHAT'S AN ATTOGRAM?



MEMS CANTILEVERS AS TRANSDUCERS STATIC OR DYNAMIC MODES OF USE



A finite element analysis (FEA) model showing Microcantilever Displacement under Stress

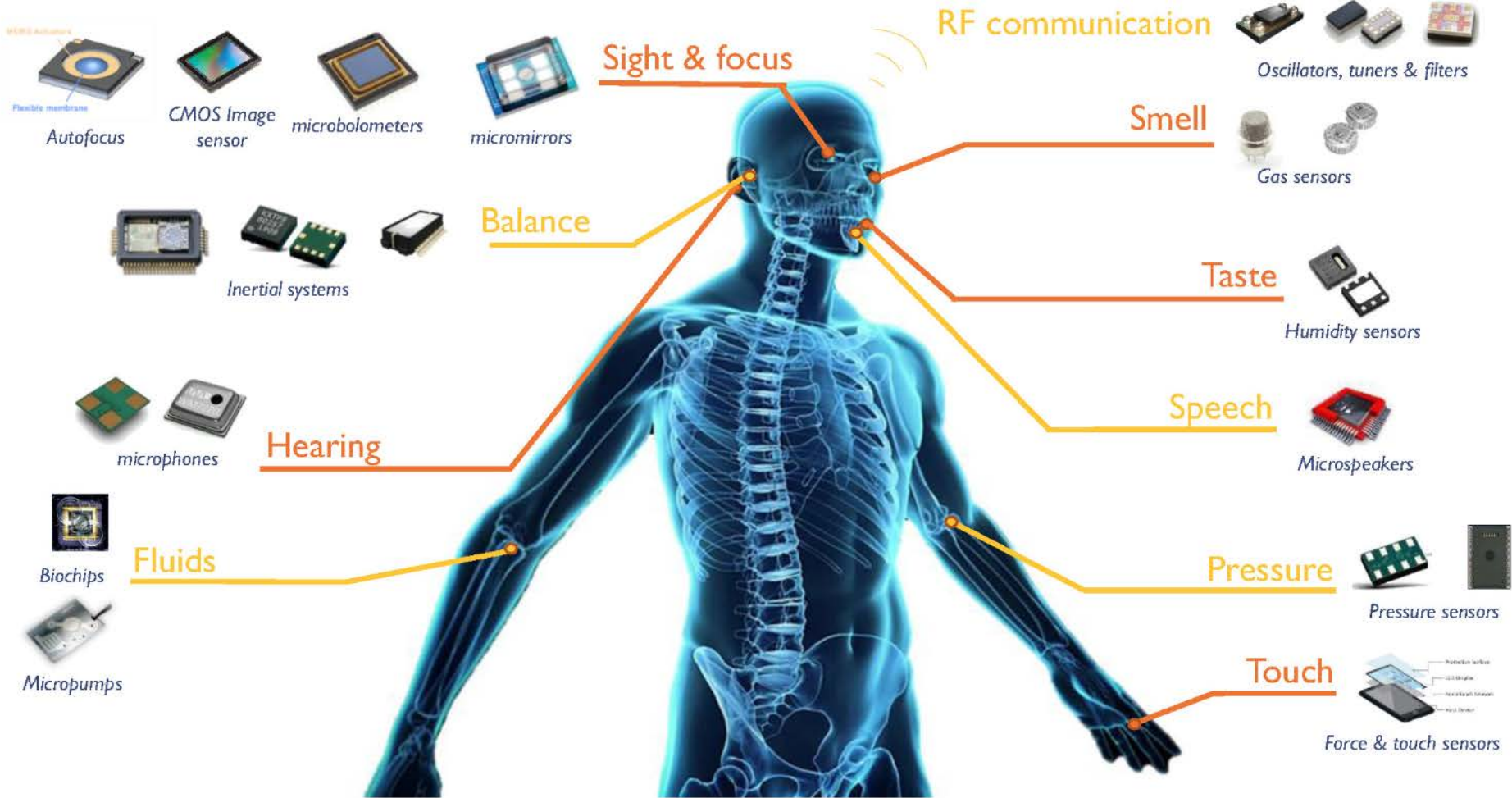
THE STATIC MODE MEASURES THE AMOUNT OF CANTILEVER DISPLACEMENT. THE DIAGRAM ILLUSTRATES THE DISPLACEMENT OF A MICROCANTILEVER DUE TO A THERMAL STRESS ON THE CANTILEVER'S SURFACE.

THE MAXIMUM DISPLACEMENT AT THE SUSPENDED END IS 255 nm . (THIS IS MORE THAN ENOUGH TO BE MEASURED IN THE MICROSCOPIC WORLD.)

WHAT YOU CAN LEARN WITH CANTILEVERS?

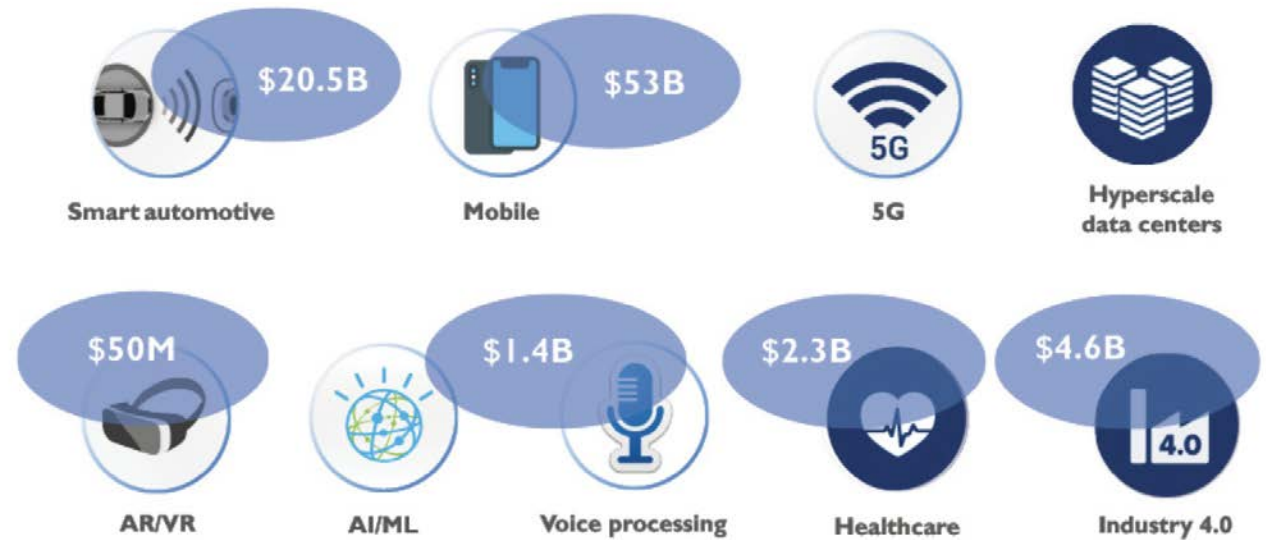
MEMS SENSORS – BIO MIMICRY

(Source: Sensors for Wearable Electronics & Mobile Healthcare, Yole Développement, June 2015)



Electronic megatrends: impact on the 2023 sensor & actuator markets per value

(Source: Status of the MEMS Industry, Yole Développement, May 2018)



• SENSOR TYPE:

- INERTIAL
 - ACCELEROMETER
 - GYROSCOPE
 - MAGNETOMETER
 - COMBO SENSOR
- PRESSURE
- MICROPHONE
- ENVIRONMENTAL
- OPTICAL
 - MICROBOLOMETER
 - PASSIVE INFRARED SENSOR (PIR) AND THERMOPILE

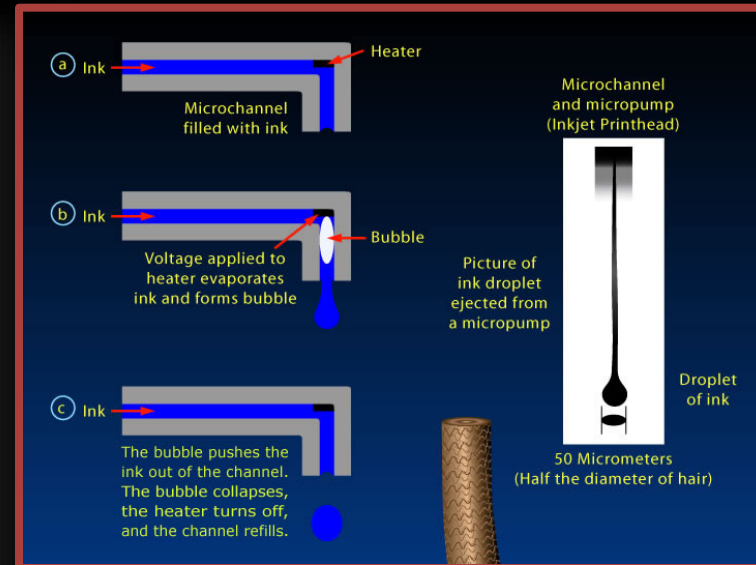
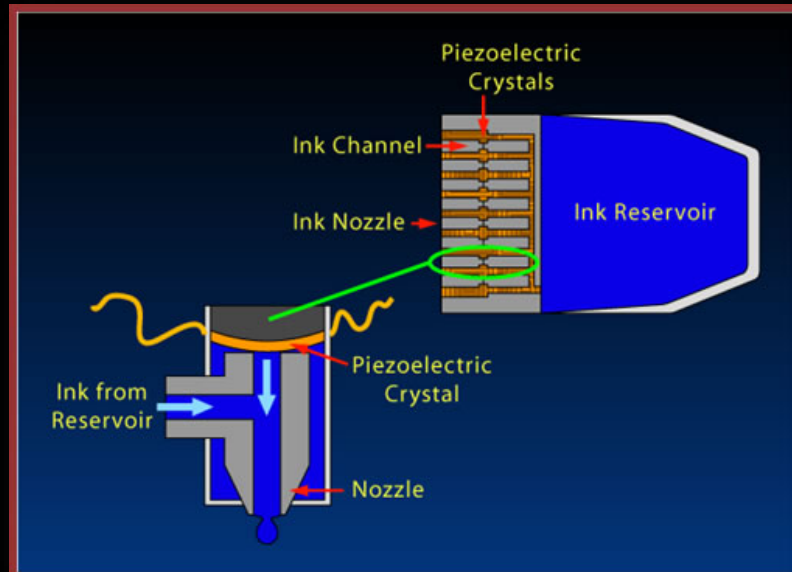
• ACTUATOR TYPE:

- OPTICAL
- INKJET HEAD
- MICROFLUIDICS
- Radio Frequency (RF)
 - Switch
 - Filter
 - Oscillator

MICROFLUIDICS

PRINTERS

- Piezoelectric and bubble printers provide high-resolution printing for graphic and photographic images
- Inkjet printheads can layer dots of different colors on top of each other, giving the image a richer appearance.

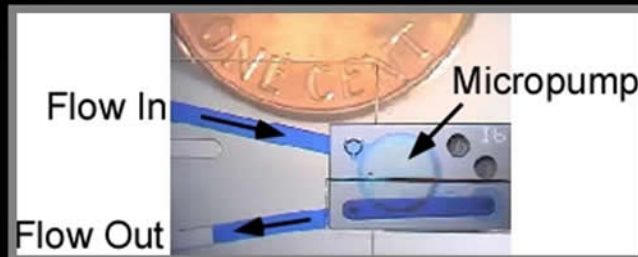
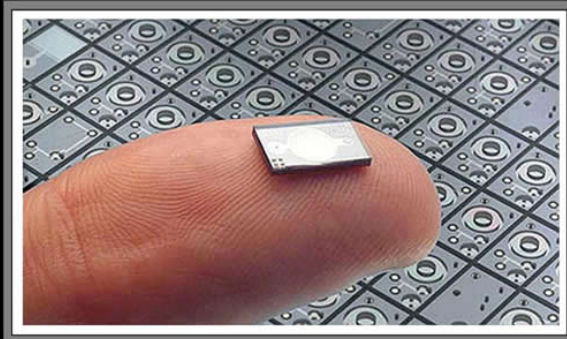


MICROPUMPS

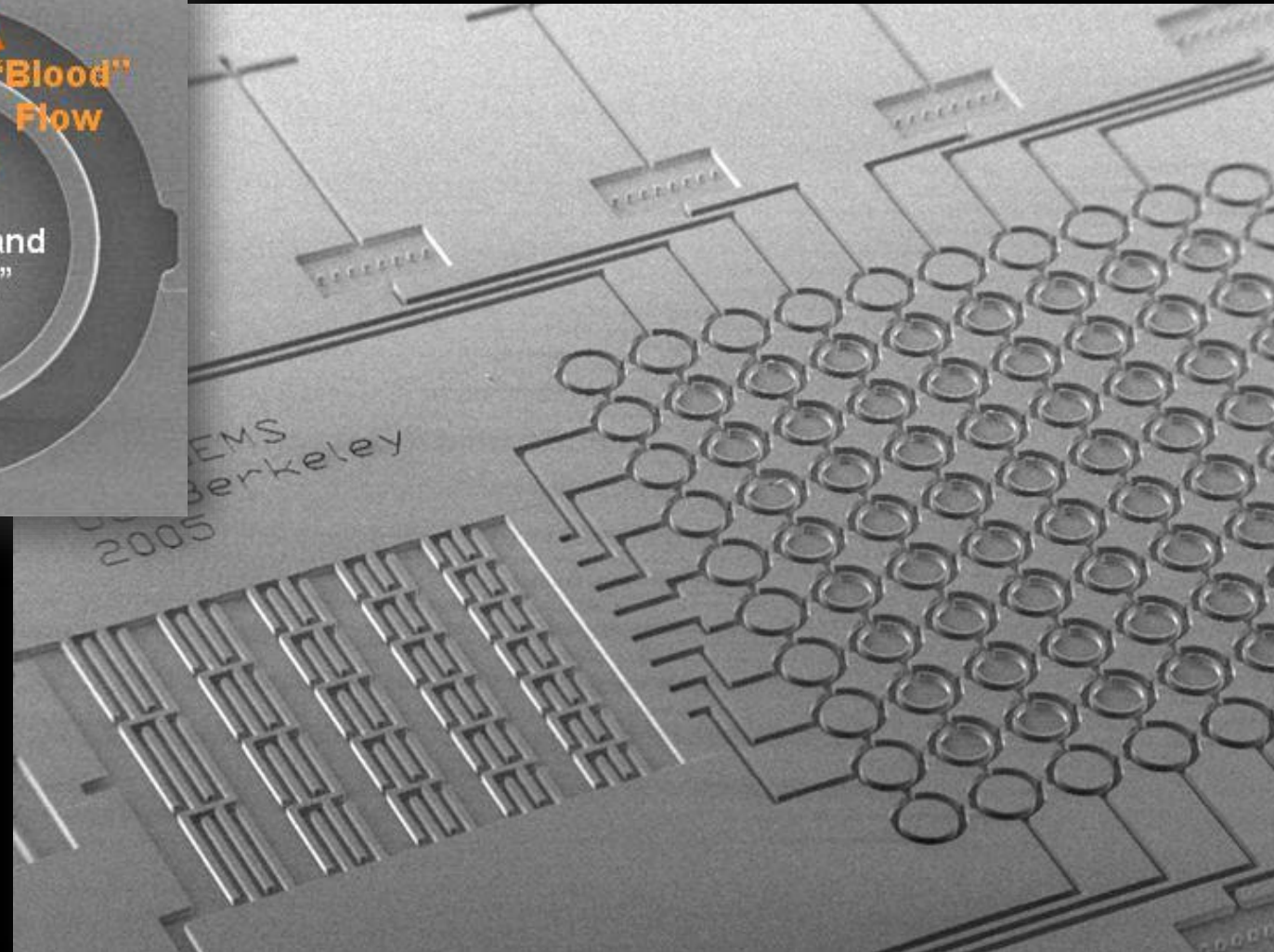
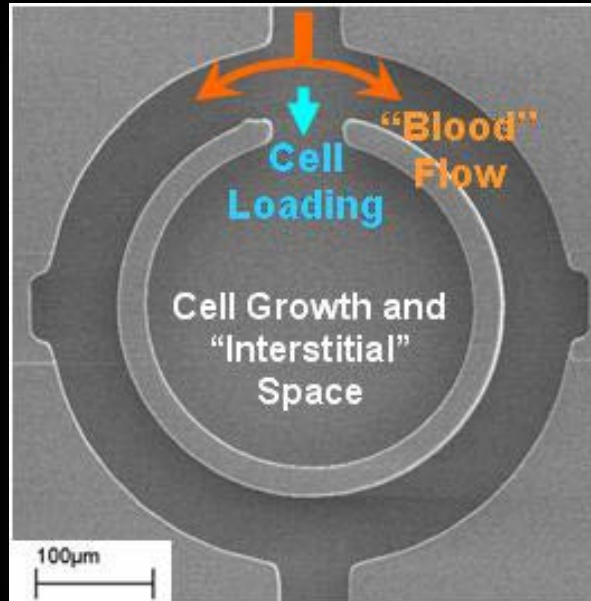
ALL OF THESE TECHNOLOGIES HAVE LEAD TO THE DEVELOPMENT OF A VARIETY OF DIFFERENT MICRO-SIZED COMPONENTS AND DEVICES.

Micropumps

Micropumps for insulin injections [Courtesy of Debiotech, Switzerland]



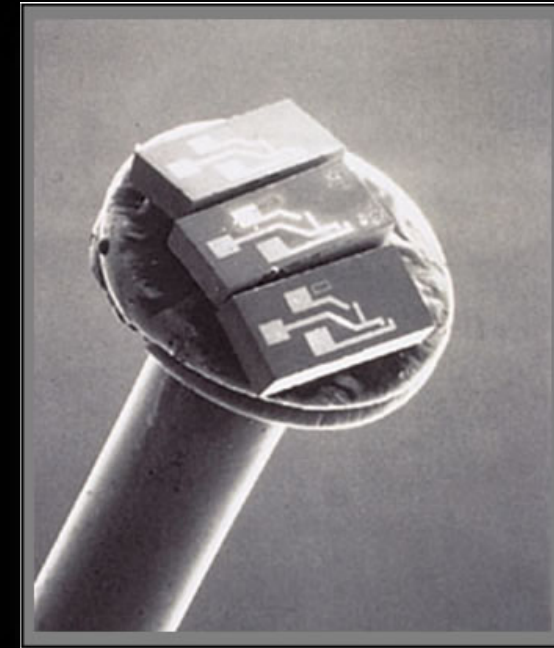
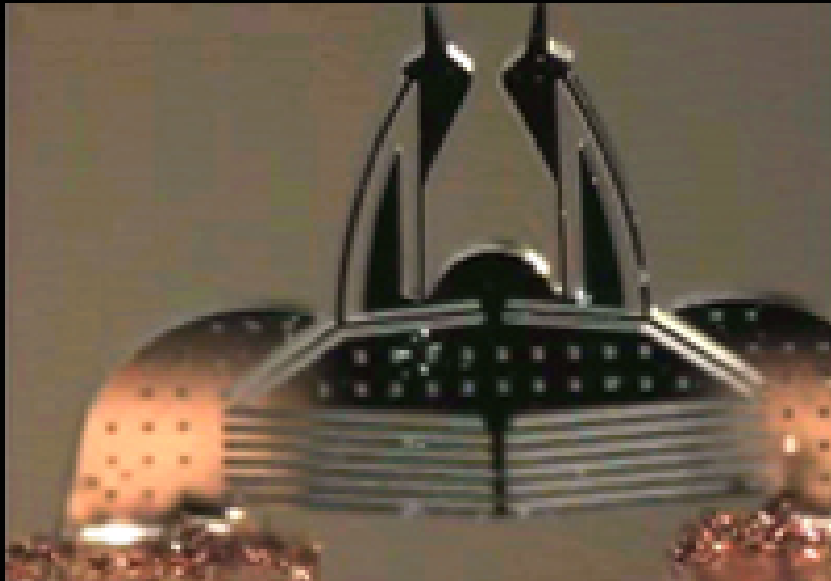
MICRO-FLUIDICS



BIOMEMS APPLICATIONS

BIOMEDICAL APPLICATIONS

- MICRO-PRESSURE SENSORS (PS) THAT MEASURE BLOOD PRESSURE, INTRACRANIAL PRESSURE
- MICROGRIPPERS AND TWEEZERS FOR NON-INVASIVE SURGERIES



MEMS Blood Pressure Sensors

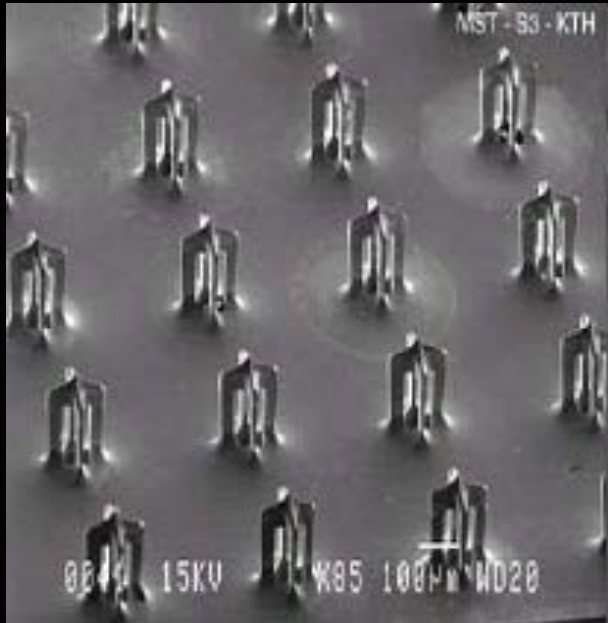
[Photo courtesy of Lucas NovaSensor, Fremont, CA]

Microgrippers

[Developed by and printed with permission © 2002 Zyvex]

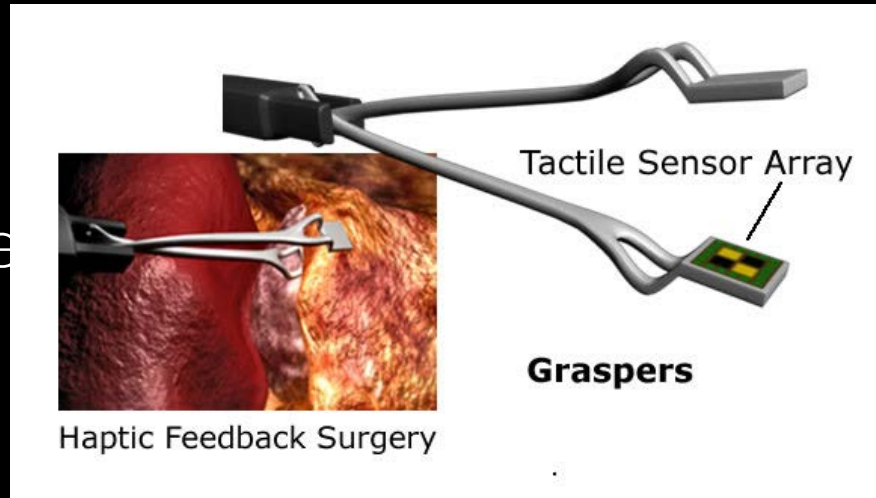
Therapeutics

- Drug Delivery Systems
- Devices for invasive surgeries
- Artificial prosthesis



Microneedles

[Images courtesy of Debiotech SA/Switzerland]



Micro-Needles



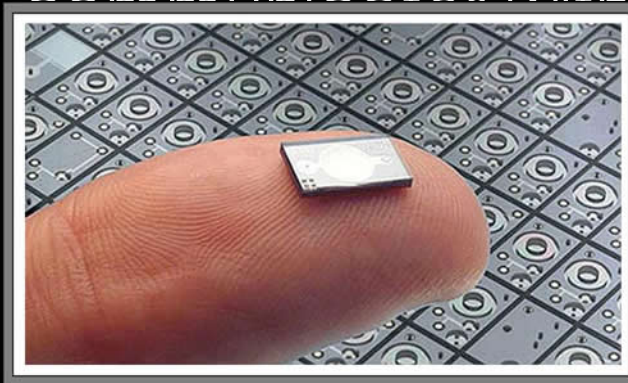
- Low permeability
- Short enough to not reach nerves
- Combined with microfluidic sensors to administer a preset



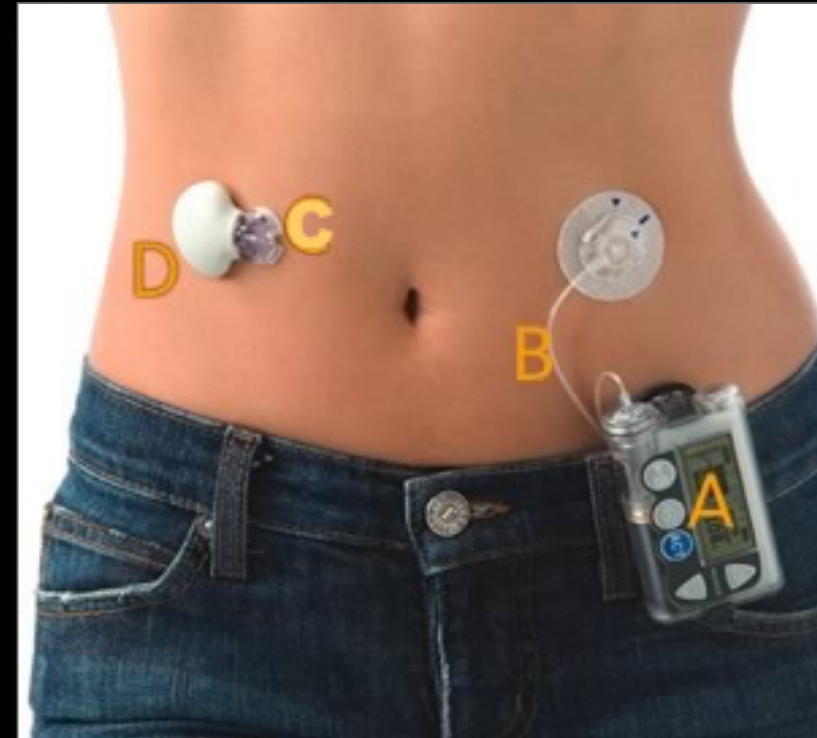
Drug Delivery – Insulin Delivery

Insulin pump, with MiniLink™ transmitter and infusion set

- External pump & computer
- Soft cannula that delivers insulin
- Interstitial glucose sensor
- Wireless radio device that communicates with the



*Micropump for insulin delivery
Image courtesy of Debiotech SA/Switzerland*

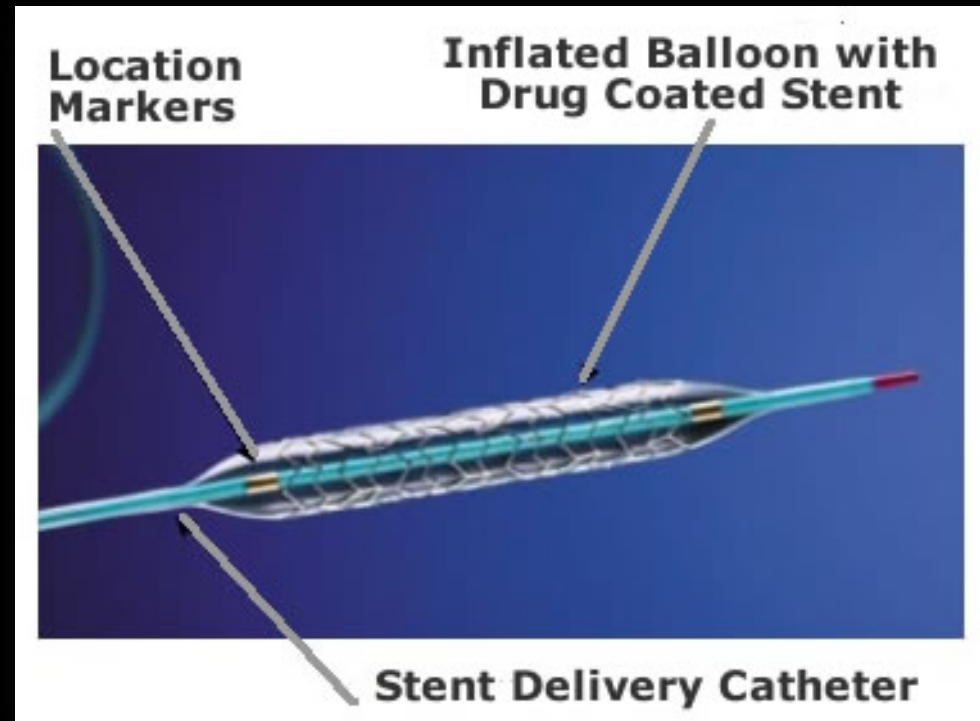


MiniMed Paradigm[R] 522 insulin pump, with MiniLink™ transmitter and infusion set.

[Printed with permission from Medtronic Diabetes]

Drug Delivery – Nanopore Coated Stents

- Used inside previously blocked arteries
- Stent coating is a medication slowly released to decrease restenosis
- Restenosis increases possibility of re-blockage.

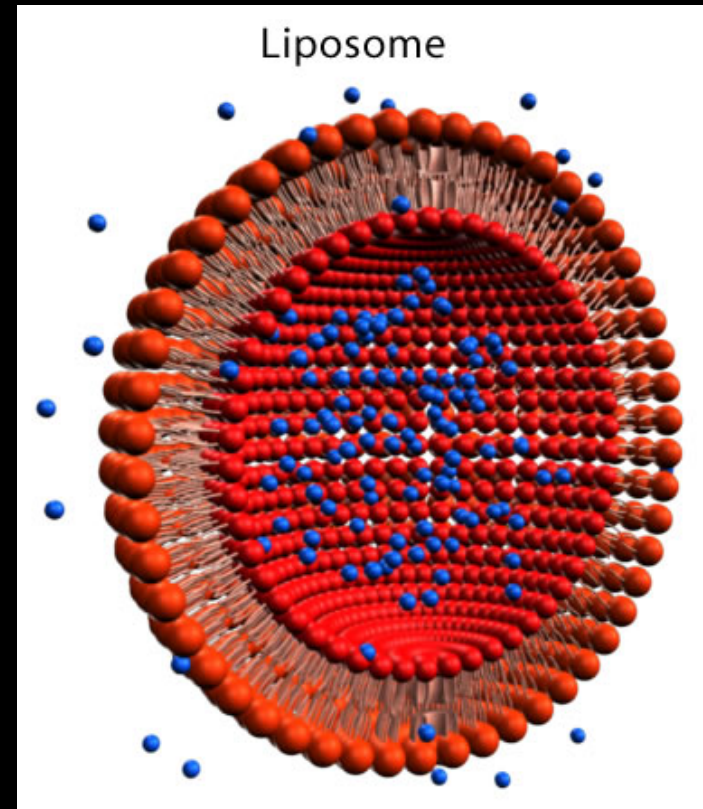


Drug-eluting Coronary Stent System

[Image source: FDA]

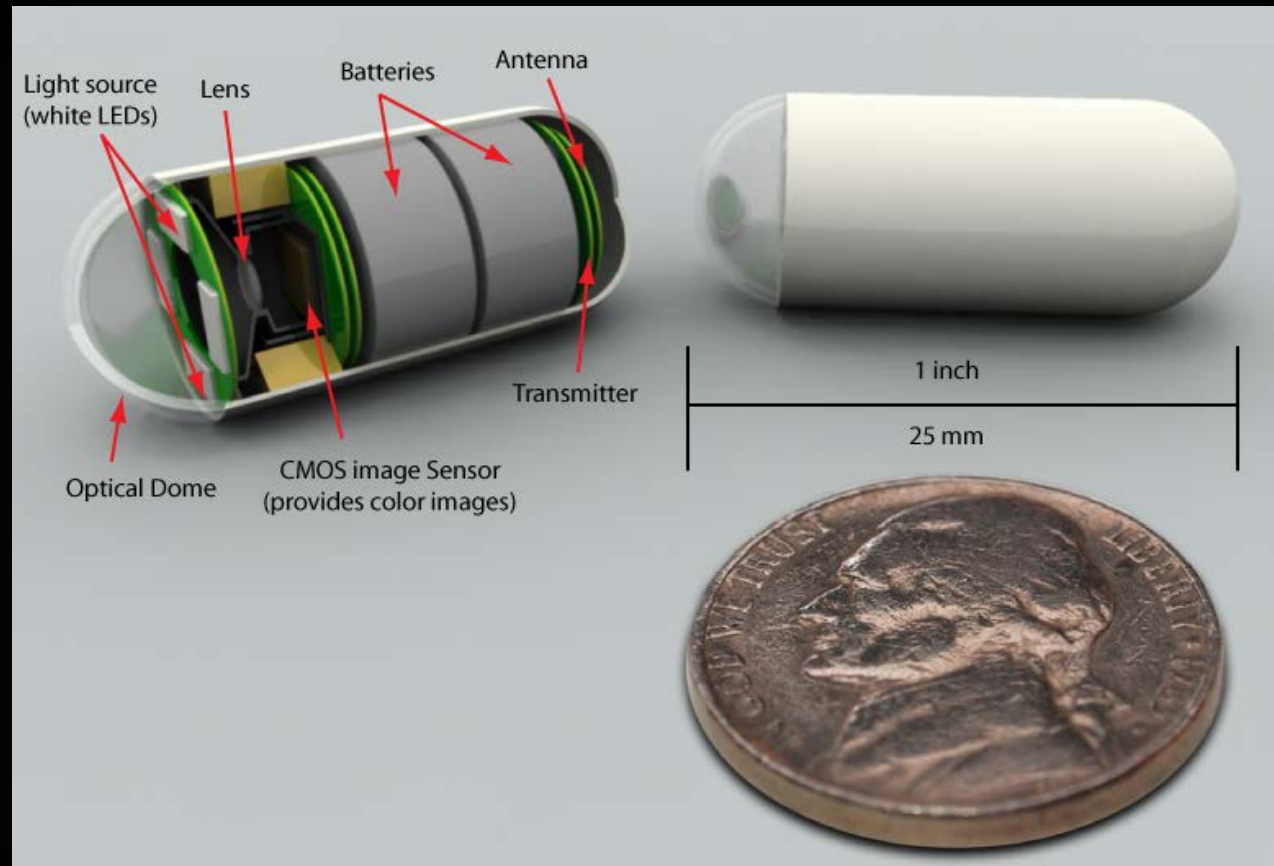
Drug Delivery – Liposome Vesicle

- Nano-sized cavity formed with cell membrane
- Filled with a drug (blue)
- Several can be injected into the bloodstream and guided to the target tissue
- The drug destroys or neutralizes the diseased tissue



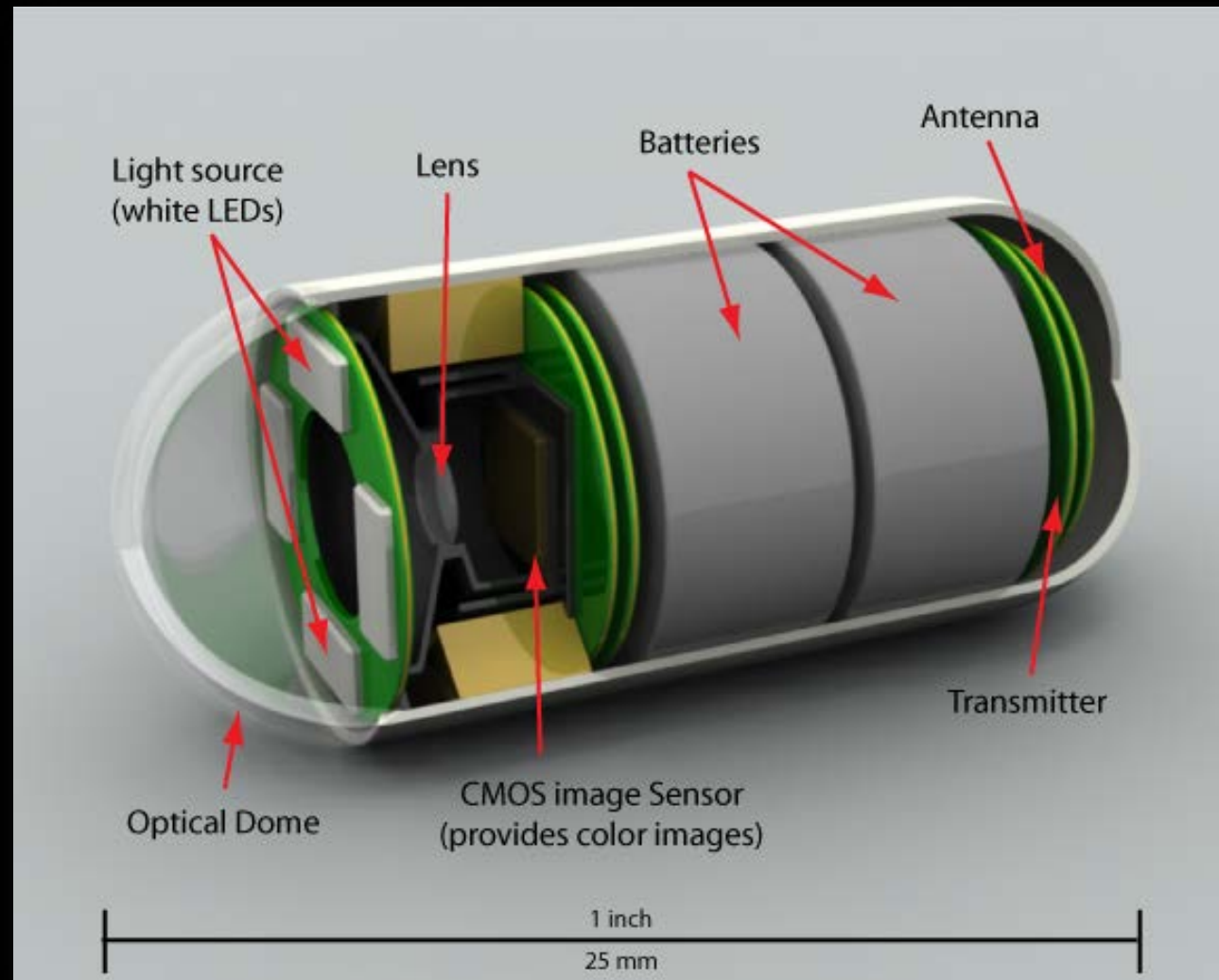
*Liposome vesicle filled with drugs
(blue)*

CAPSULE ENDOSCOPY



Graphics adapted from images by St. John Providence and Pine Hurst Medical

CAPSULE ENDOSCOPY

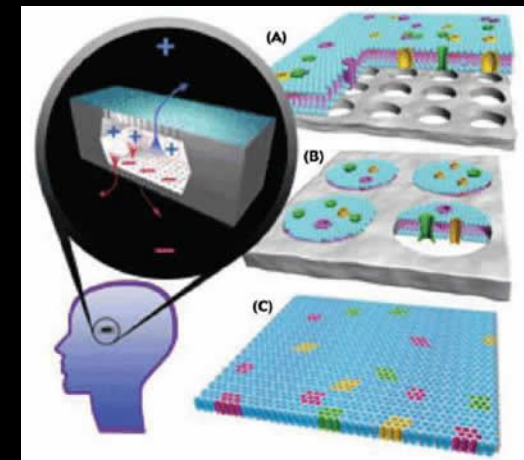
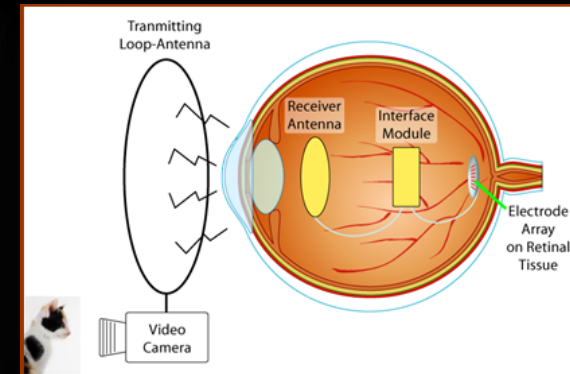


Artificial Retinal Prosthesis



Prototype of a Retina Implant

[Photo by Randy Montoya. Courtesy of Sandia National Laboratories]

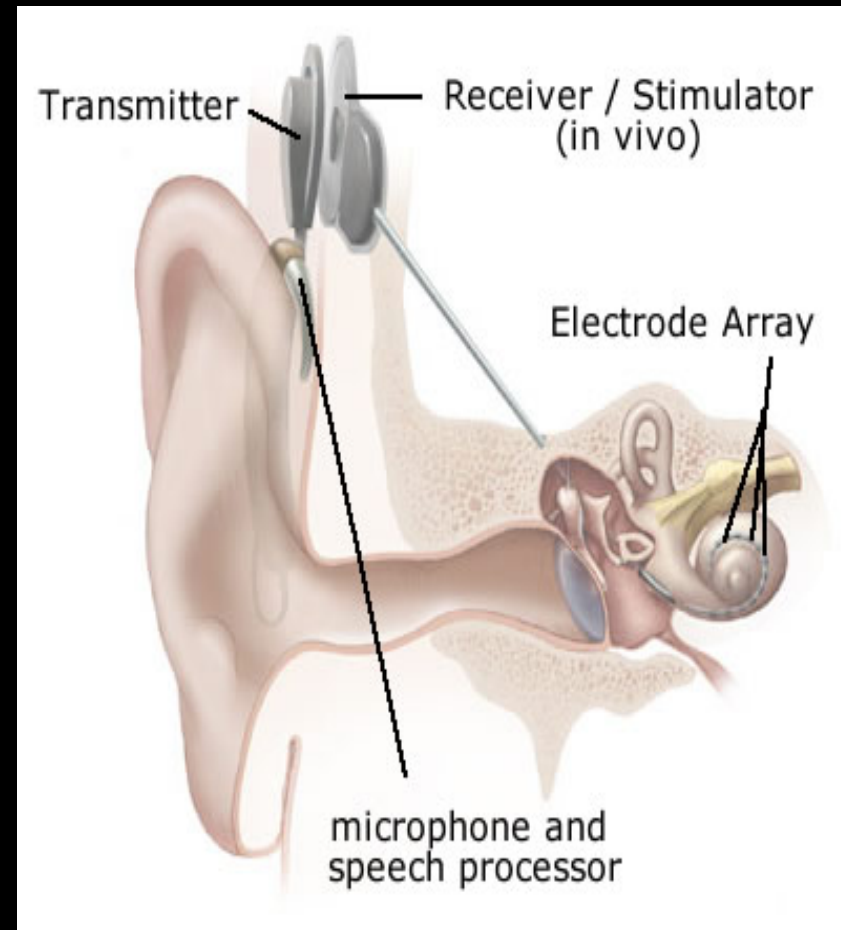


Battery Pack for Artificial Retina system

[Courtesy of Sandia National Laboratories]

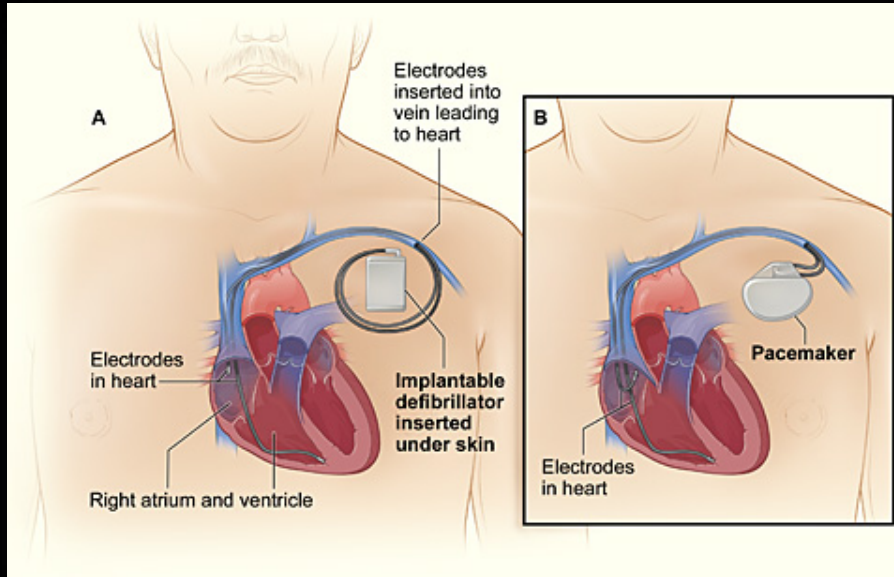
Cochlear Implants

- Contains a microphone, a speech processor, a transmitter and receiver/stimulator, and an electrode array
- The implant gives a deaf person a useful representation of his environment.
- Cochlear Implants are a type of "neuroprosthetic"



[Modified from image courtesy of National Institute of Health]

Pacemakers



MEMS accelerometers found in pacemakers and defibrillators



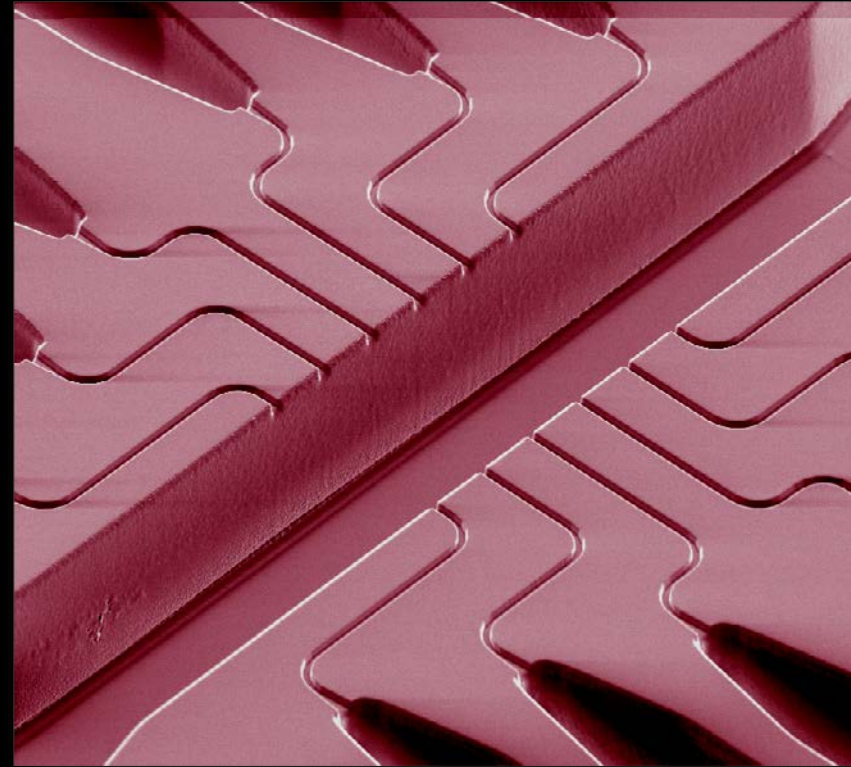
Pacemaker
[Courtesy of Healthline]

LAB-ON-A-CHIP (LOC) CONCEPT

THE BASIC CONCEPT OF LOC FABRICATION IS TO

- CREATE SEVERAL MICROCHANNELS FOR A LIQUID SAMPLE TO FLOW INTO, AS WELL AS
- SEVERAL MICROCHAMBERS WITH
- FUNCTIONALIZED SURFACES.

WHEN THE SAMPLE IS APPLIED TO THE INPUT CHAMBER, VARIOUS ANALYTES WITHIN THE SAMPLE ARE CAPTURED BY SPECIFIC PROBES WITHIN THE CHAMBERS.



A fabricated microfluidic surface showing microchannels and chambers..

[Image courtesy of BioPOETS, UC-Berkeley]

LAB-ON-A-CHIP (LOC)

- THIS LOC IS A MINI-LAB TESTED SUCCESSFULLY ON BOARD THE INTERNATIONAL SPACE STATION (ISS).
- THIS LOC DETECTS THE PRESENCE OF BACTERIA OR FUNGI ON THE SURFACES OF A SPACECRAFT FAR MORE RAPIDLY THAN STANDARD METHODS OF CULTURING WHICH CAN TAKE DAYS FOR A FINAL ANALYSIS.
- THIS LOC IDENTIFIED DIRTY SAMPLES IN 2 MINUTES!



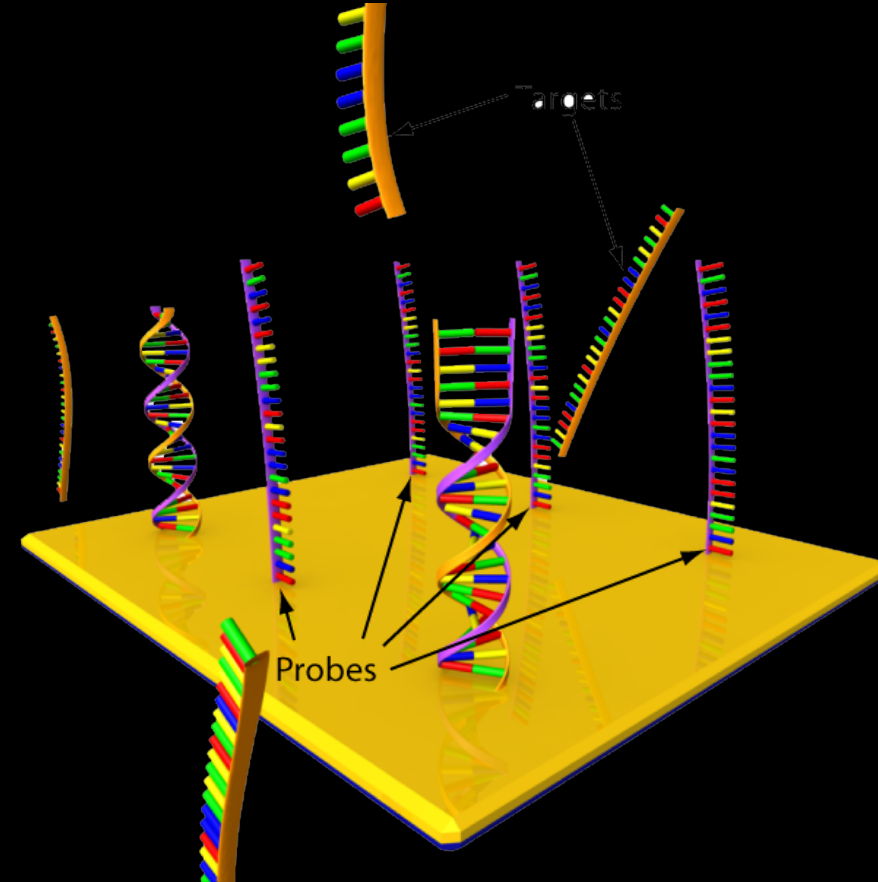
This LOC liquid samples to identify .

[Image courtesy of NASA]

BIOMARKERS FOR DIAGNOSTICS



*BioLOC's CD-Enzyme
Linked Immunosorbent
Assay - ELISA
(ELISA™ – Printed with permission from
BioLOC)*

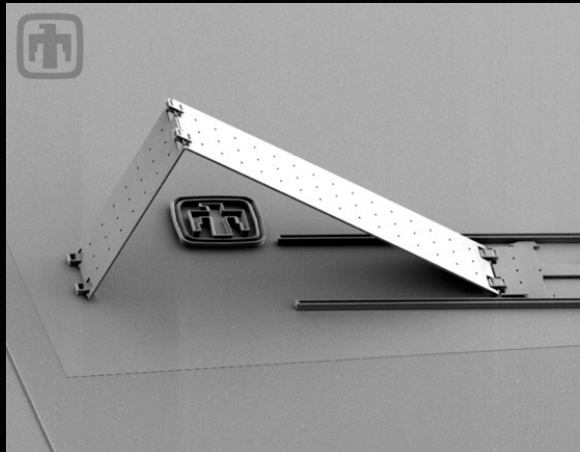


DNA Microarray used to identify
specific genes or one's gene
expression profile

MICRO-OPTICS

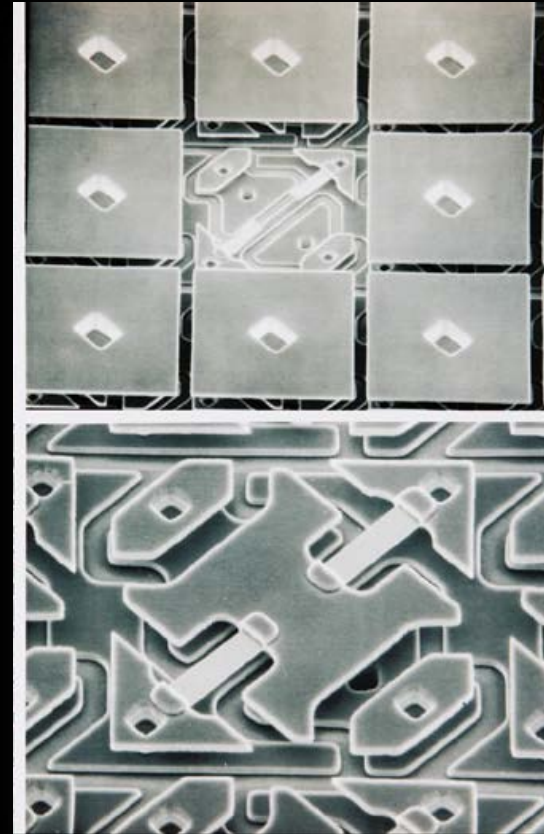
MICRO-OPTIC APPLICATIONS

- DIGITAL LIGHT PROCESSING (DLP) – DLP HAS REVOLUTIONIZED THE WAY WE SEE IMAGES PROJECTED ON A SCREEN.
- OPTICAL TRANSMISSION – MICRO-MIRRORS ALLOW FOR THE TRANSMISSION AND REDIRECTING OF DIGITAL INFORMATION WITHOUT THE NEED TO CONVERT TO ANALOG.



MEMS Pop-up mirror for optical applications.

[Image Courtesy of Sandia National Laboratories SUMMIT™ Technologies, www.mems.sandia.gov]

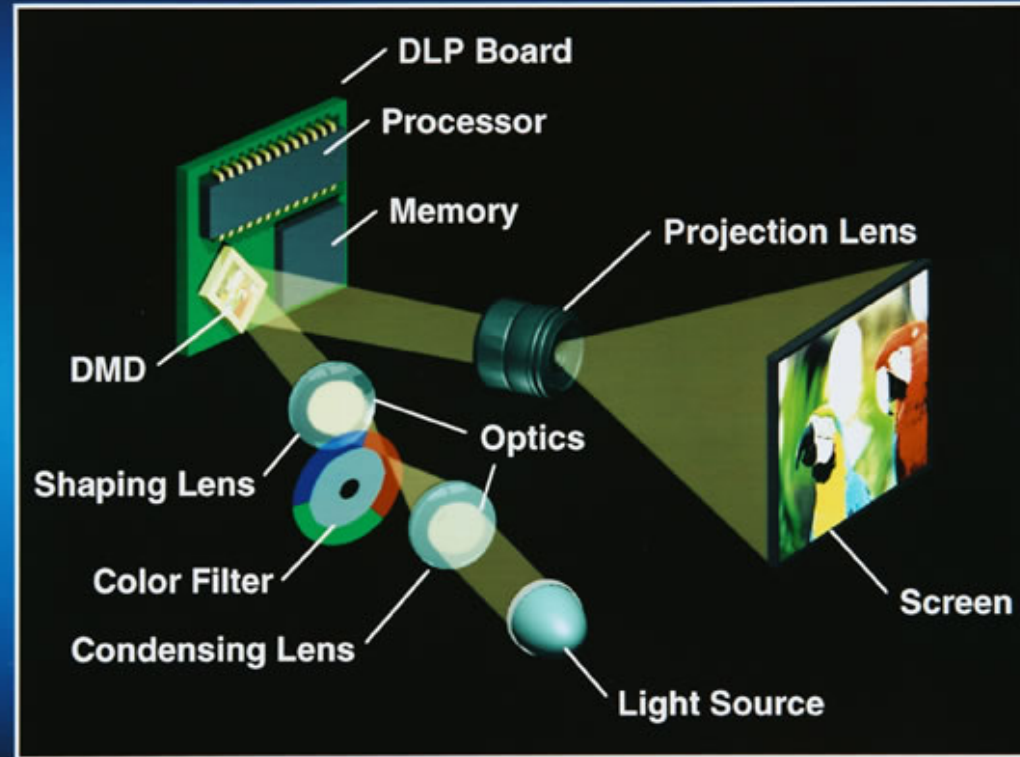


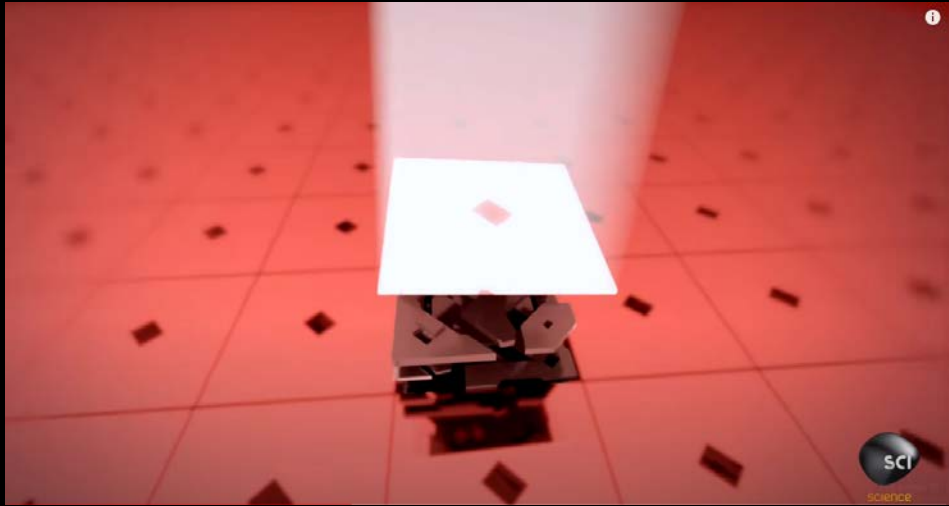
Digital Mirror Array (DMD) – each mirror is turned on/off as many as 30,000 times per second.

[Image Courtesy of Texas Instruments]

Digital Light Projection (DLP)

1 Chip DLP™ Projection





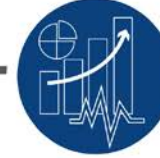


Larry Hornbeck, Texas Instruments, gets an Oscar, 2015
Academy Award of Merit



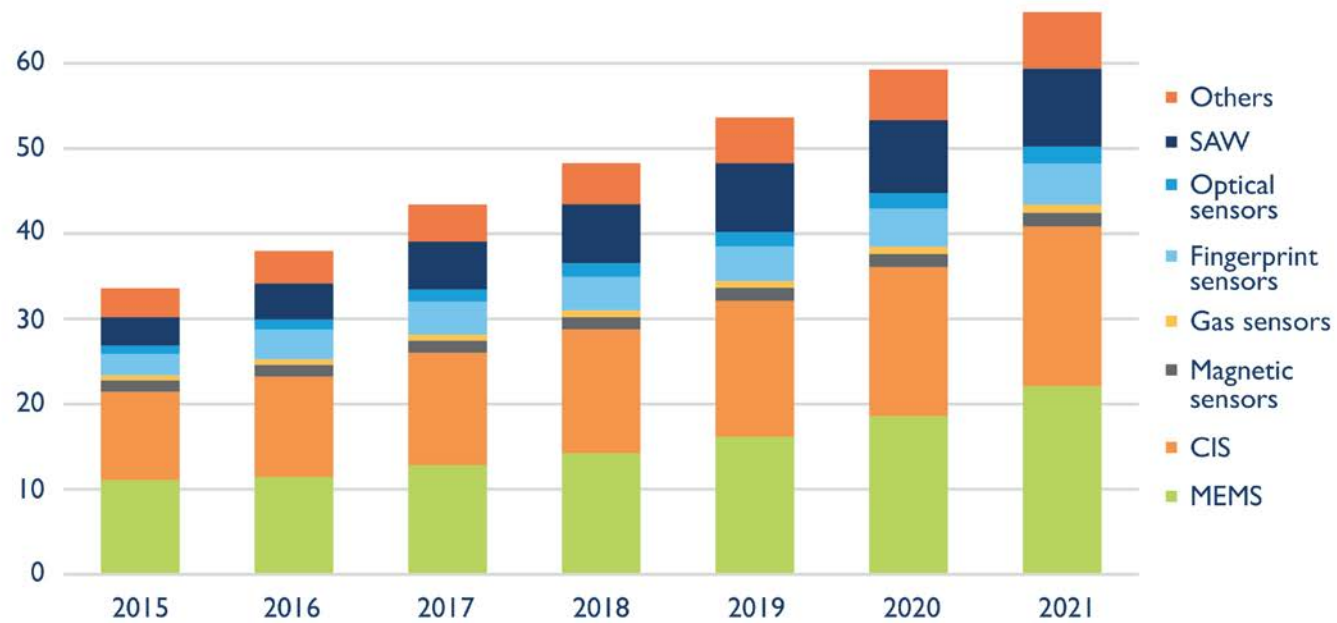
First Digital Movie 1999

SO... WHY DO WE CARE?



MEMS and sensors revenue market in B\$

(Source : Status of the MEMS Industry 2017, June 2017, Yole Développement)

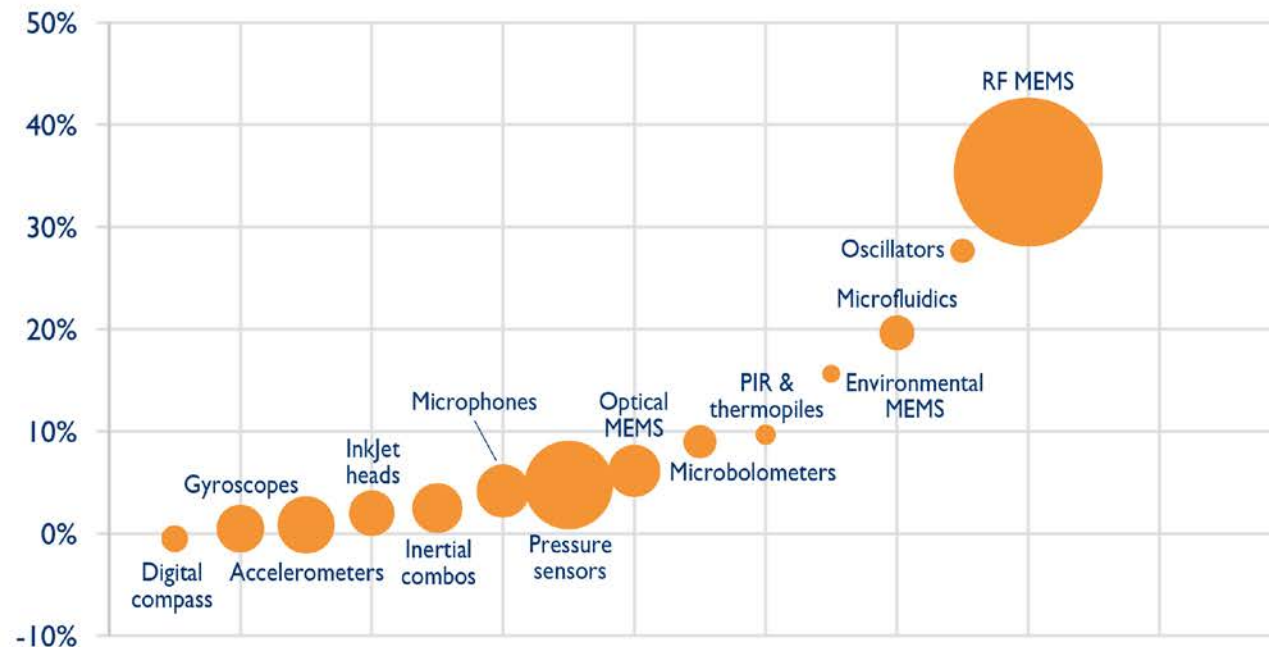


COMPOUNDED ANNUAL GROWTH RATE



2017-2022 MEMS CAGR for the different MEMS devices (bubble sizes are proportional to 2022 market size in M\$)

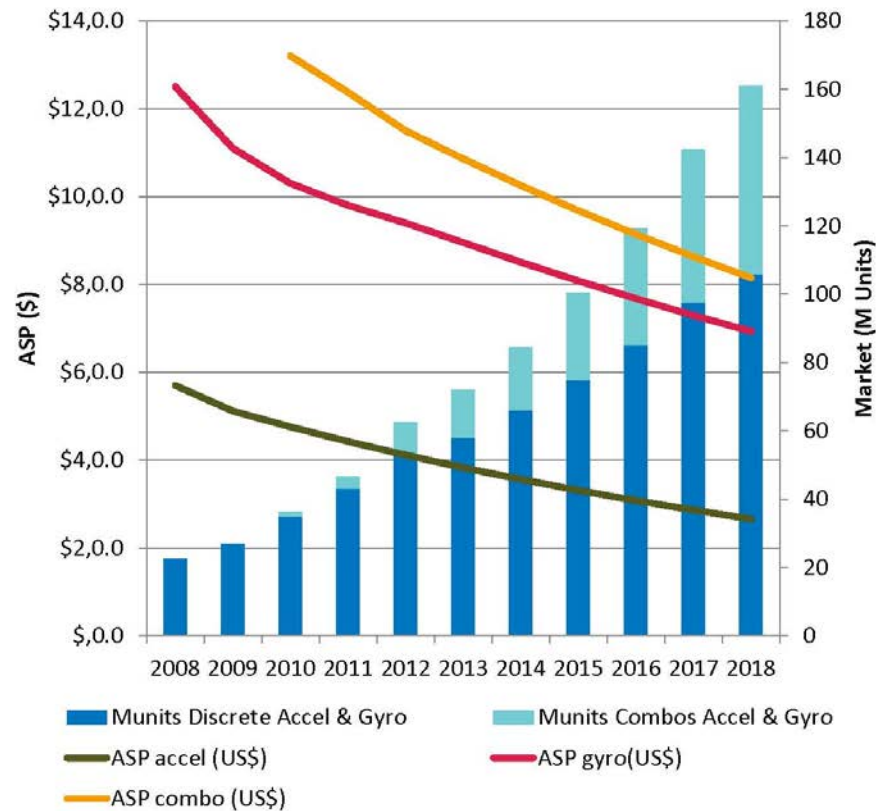
(Source : Status of the MEMS Industry 2017, June 2017, Yole Développement)



PRICE/UNIT DROPS

MEMS & SENSORS

2008 - 2018 ESC Accelerometers, gyroscopes and combos
Price is still dropping quarter after quarter... Strong pressure also in automotive
 (Source: Status of the MEMS Industry 2014, Yole Développement, August 2014)



- ESC market is growing, driven by regulations
- A big pressure on prices is seen on the market
- ESC combos are successful since their launch in 2010: they provide significant cost savings compared to discrete sensors

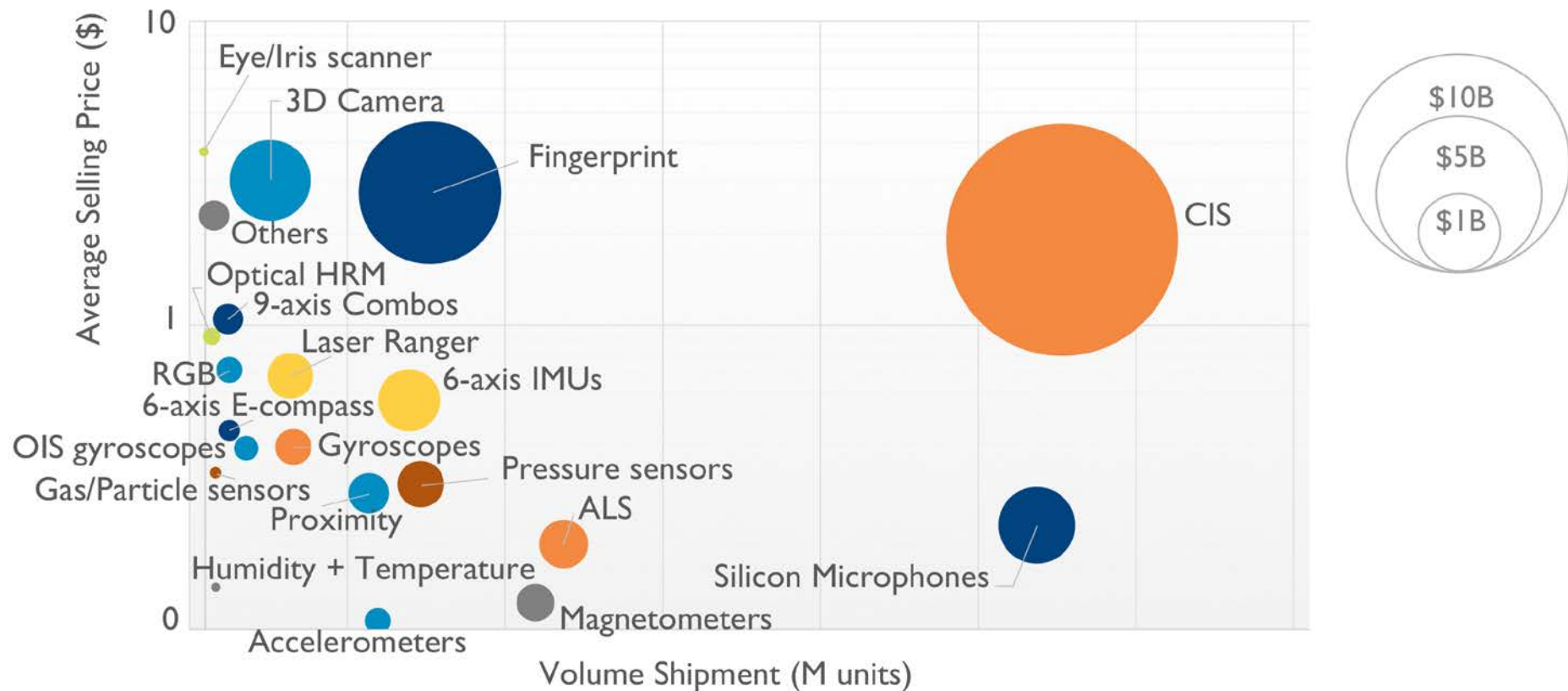
© August 2014

DIVING DEEPER: LET'S LOOK AT SENSORS

SENSORS FOR MOBILE PHONES AND TABLETS

Sensors landscape by 2021

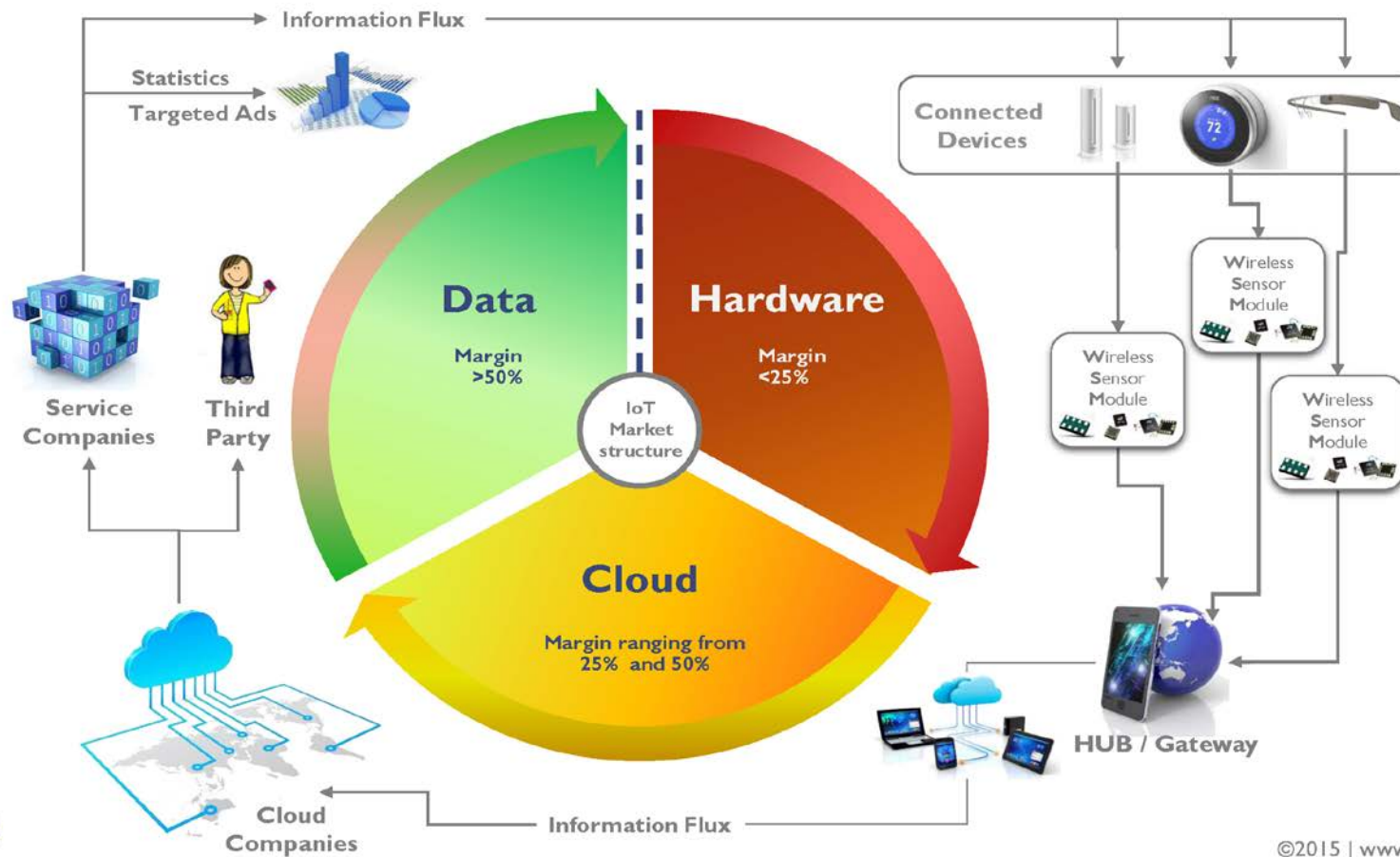
(Source : Sensors for Cellphones and Tablets 2016 Market & Technology report, Yole Développement, June 2016)



IOT OR IOE (INTERNET OF EVERYTHING) FROM 15B SENSORS IN 2015 TO 1T IN 2025

TECHNOLOGIES OF INTERNET OF THINGS (IOT) - IOT STRUCTURE

(Source: Sensors & Technologies for The Internet of Things: Businesses & Market Trends 2014 - 2024 Report, Yole Développement, May 2014)



2020-2030+ FUTURE SOLDIER TECHNOLOGIES

SENSOR MARKET FOR AUTOMOTIVE WILL BE DRIVEN BY AUTONOMOUS VEHICLES

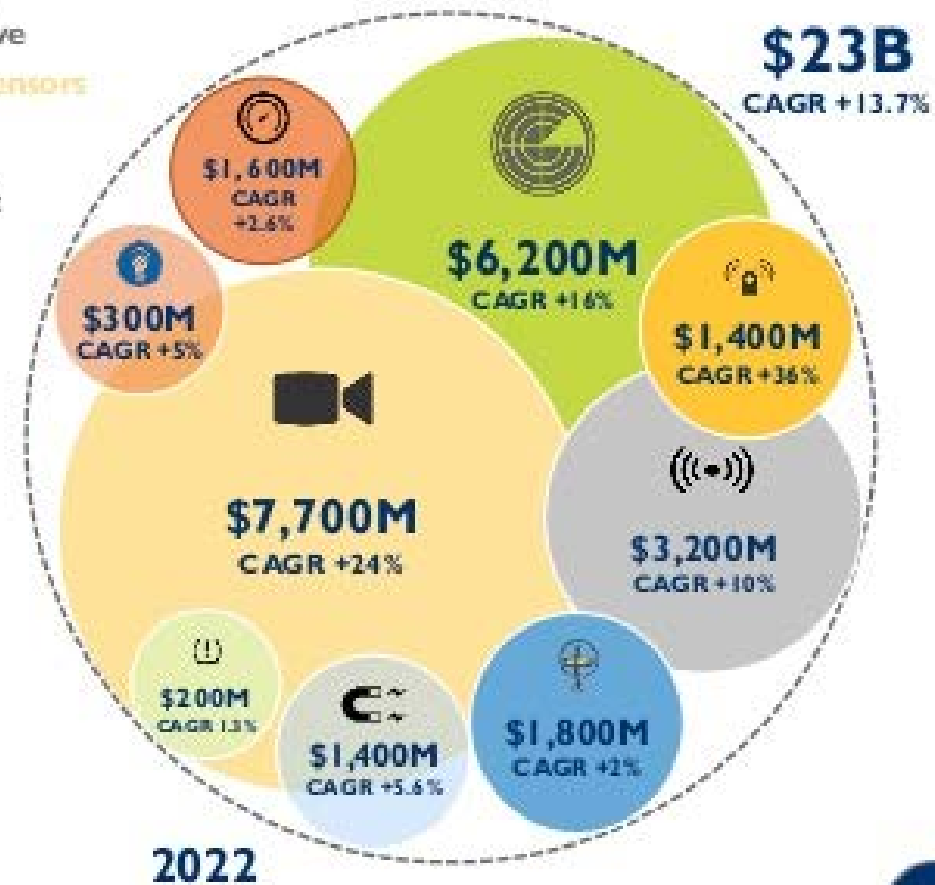
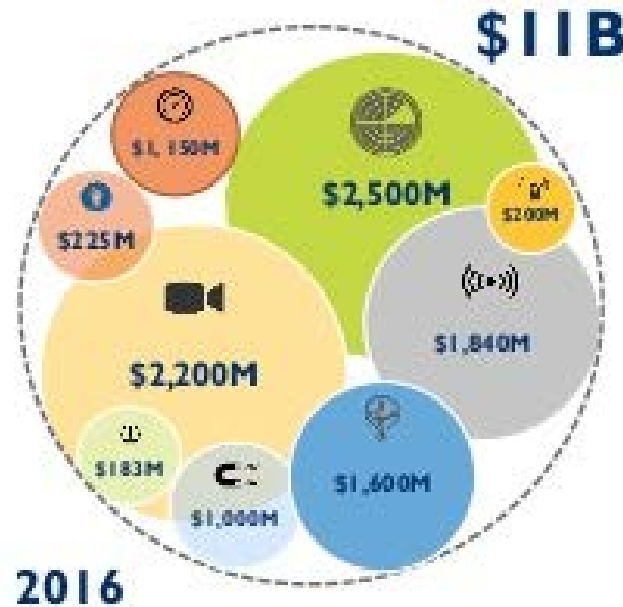
ECOSYSTEM OF THE SENSOR FOR AUTOMOTIVE INDUSTRY

2016–2022 Forecast

-- Total Sensor market value for automotive

-  **RADAR sensors**
-  **Imaging sensors**
-  **LiDAR sensors**
-  **TPMS**
-  **Chemical Sensors**
-  **Inertial**
-  **Magnetic**
-  **Ultrasonic**
-  **Pressure sensors**

The two main growth are for Imaging, RADARs and LiDAR sensors, driven by automation.



AUTONOMOUS CARS

EVERYWHERE/PARTIAL AD VS SOMEWHERE/FULL AD

(Source: Yole Développement, January 2016)

Somewhere/Full AD

Tech companies' approach

Where ?



Vehicle ?



Who ?



Full AD features



Everywhere/Partial AD

Traditional Automotive Industry

Where ?



Vehicle ?



Who ?



Partial AD features



VS

JOBS FOLLOW CAGR

SCME PROFESSIONAL DEVELOPMENT OPPORTUNITIES FOR YOU!

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- CLEANROOM PRESSURE SENSOR 4-DAY SHORT COURSE
- 40+ LEARNING MODULES
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WWW.SCME-SUPPORT.ORG



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1. MNT^eSIG – MICRO NANO TECH EDUCATION SPECIAL INTEREST GROUP

- MEETS EVERY 2-3 MONTHS ONLINE
- FACE TO FACE MEETING 1/YR AS PART OF HI TEC CONFERENCE (HIGH IMPACT TECHNOLOGY EDUCATION CONFERENCE) – NEXT YEAR IN ST. LOUIS
- MEMBER DRIVEN AGENDA
- www.MNTeSIG.NET
- MNT ATMAE FOCUS GROUP

CONTACT:

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