MAE 268 / MATS 254
MEMS Materials, Fabrication and Applications

Spring 2009

Time and Location: Tuesday & Thursday, 11-12:20 pm,
Room: SSB 106

Instructors:

Prof. Prab Bandaru
Prof. Sungho Jin
Prof. Frank Talke

An introduction to MAE 254/MATS 268

Tentative course outline (10 weeks):

5 weeks: Materials & Fabrication (Prab Bandaru)
3 weeks: Packaging (Sungho Jin)
2 weeks: Applications (Frank Talke)

1. Introduction & scaling issues

(a) Introduction to MEMS/NEMS, course objectives, survey of class,
(b) Why make systems small? Scaling issues in mechanical, electromagnetic, fluid, chemical and biological systems

2. MEMS micro-fabrication and materials

Microfabrication: Deposition and etching, Lithography, Etching (Dry vs. wet), Surface vs. bulk micromachining, electro-deposition

3. Principles of actuation; Electrostatic, magnetic; (Case studies)

- ADXL capacitive accelerometer,
- Texas Instruments’ Digital micro-mirror device (DMD)

4. MEMS Design and manufacture

- Optical MEMS: SLM: Grating light valve
- Radio-frequency MEMS,
- Biological: DNA amplification
- Designing MEMS: CAD and the MUMPS Process (Cronos)

5. Research & Future advances

- The future in MEMS, NEMS
- *Mid-term exam*

MEMS: Issues in Packaging

6. Principles of MEMS packaging

- IC packaging vs MEMS packaging
- Processes involved in packaging
- Effect of electrostatic charge and humidity

7. MEMS packaging materials and processes

- Solder bonding and wire bonding
- Hermetic sealing materials and processes
- Multilayer connections

8. Stability of MEMS components

- Cantilever geometry vs. metallization and surface treatment
- Stability of membrane geometry during packaging
- Stability during service

MEMS: Applications

9. Application of MEMS technology to ink jet printing

- continuous ink jet technology versus drop on demand ink jet technology,
- bubble jet print head design, color ink jet printing

10. Application of MEMS technology to magnetic and optical recording technology

- magnetic recording technology, head disk interface,

relationship between flying height and signal amplitude, optical recording

- thin film head design, MR head design,

HAMR (heat assisted magnetic recording) head design

Web site for the course

http://maemail.ucsd.edu/~mae268/

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MEMS Materials, Fabrication and Applications Spring 2009

Introduction	Course Outline	Homework & Solutions	Project info	Readings

Grading:

Homework (15%),
Final project and presentation (30%), ~ **June 4**
Mid-term (20%) ~ **April 30**
Final (35%) ~ **June 92 (11:30-2:30 pm)**

References:

(1) Fundamentals of Microfabrication, M. Madou, CRC Press, (2002)
(2) Microsystem design, S.D.Senturia, Kluwer (2001)
(3) Micromachined transducers Sourcebook, G. Kovacs, McGraw Hill, (1998)
(4) An Introduction to MEMS Engineering, Nadim Maluf, Artech, (2000)

Why Micro-/Nano-systems?

- **More efficient use of resources**
- **Small → Compact and Portable (Miniaturization)**
- **Greater sensitivity to forces: F = ma**
- **More vibration resistant**

(not much to vibrate !)

- A natural evolution from **Micro-electronics, Cheap**

(can make lots of them, **Multiplicity**, say millions on a chip like transistors)

New Science and Engineering, new laws of Physics/Chemistry?

Micro-electro-mechanical systems (MEMS) ----- "Micro machines"

MEMS sensors and actuators are everywhere

MEMS

Data storage
(magnetic head)

Fluid control
(micro-valves)

Micro-optics
(optical displays)

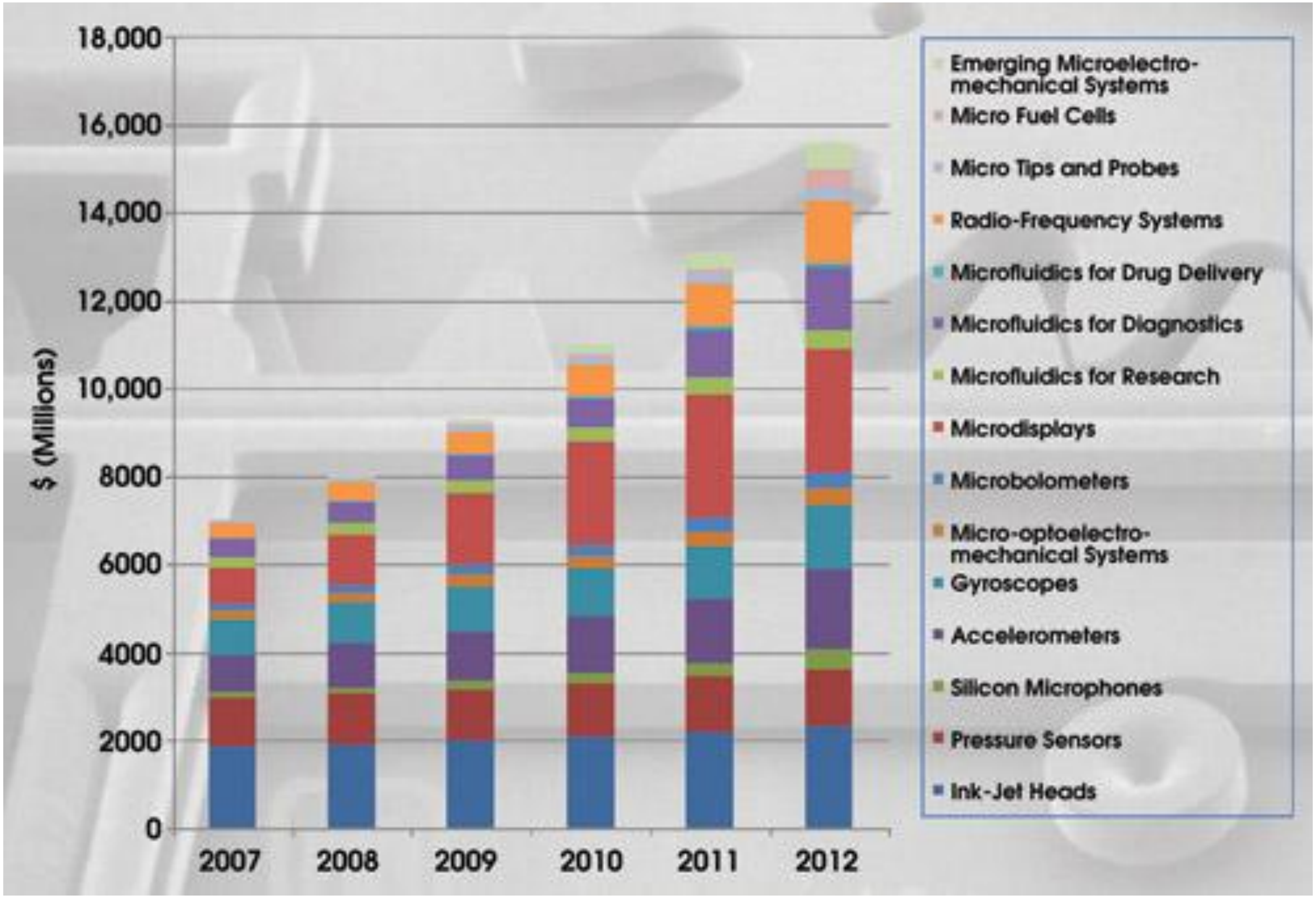
Micro-probing
(Atomic Force
Microscopy)

Biomedical
(DNA diagnostics)

VLSI processing
(micro-positioner)

Automotive
(suspension)

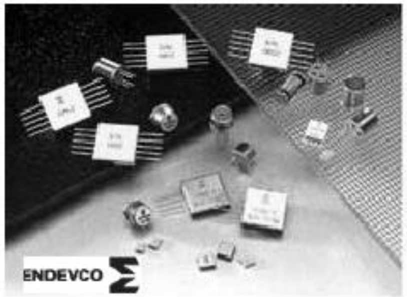
“Growth spurt seen for MEMS”



Photonics Spectra, November 2008 - Yole Développement Survey

Commercial Packaged MEMS

Microsensors



Print Cartridges

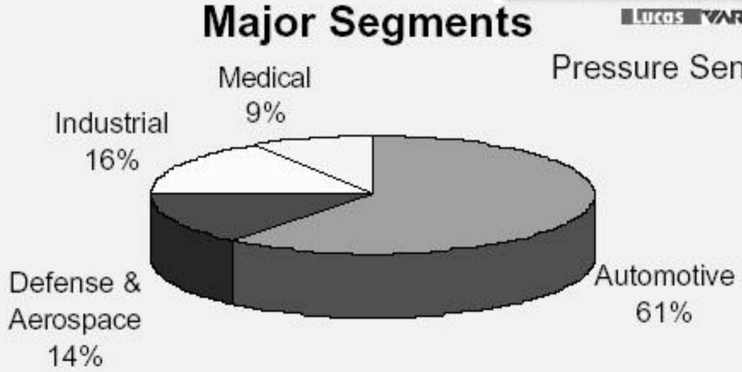
Microvalves

Accelerometers

Microfluidics

Lucas VARITY

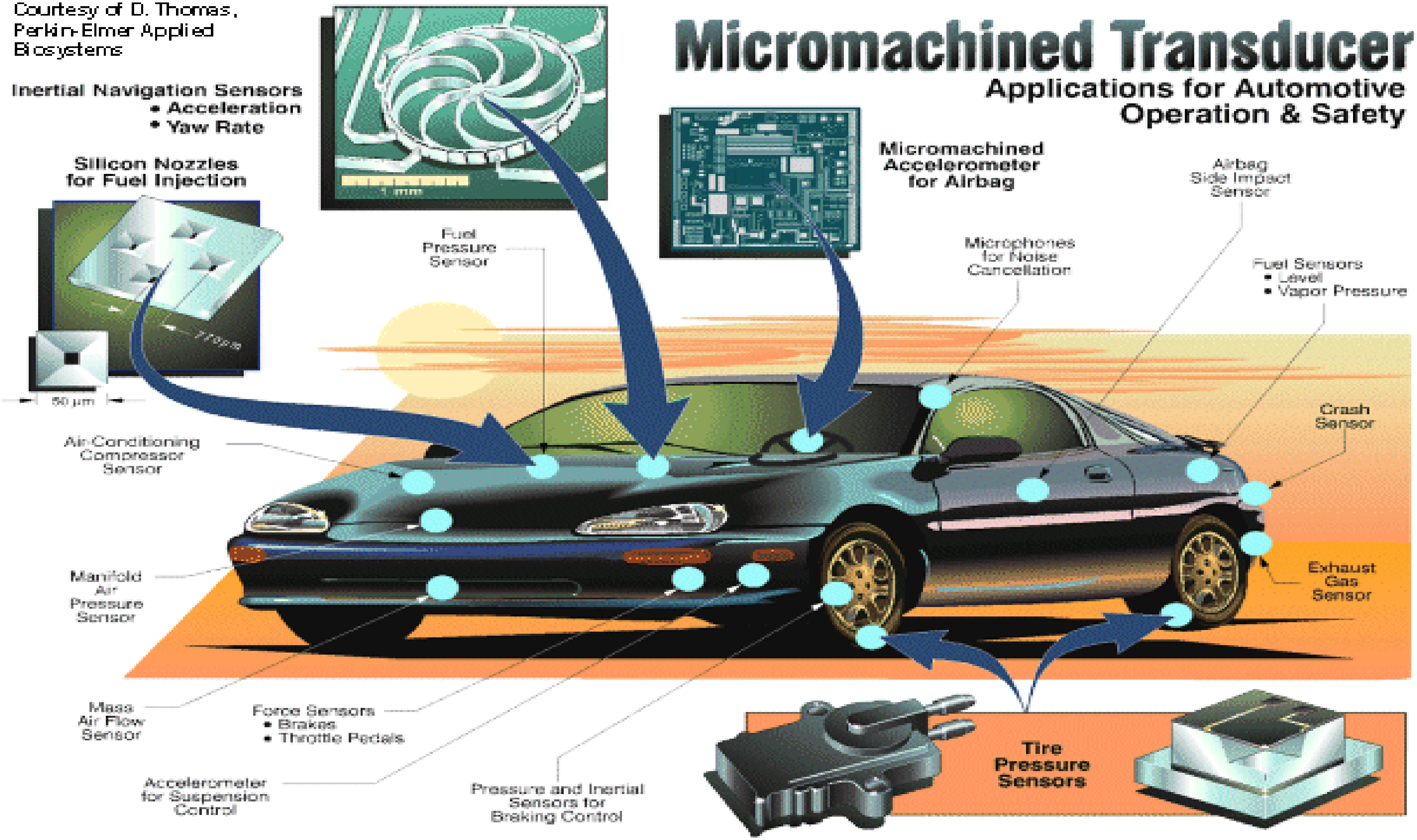
Pressure Sensors



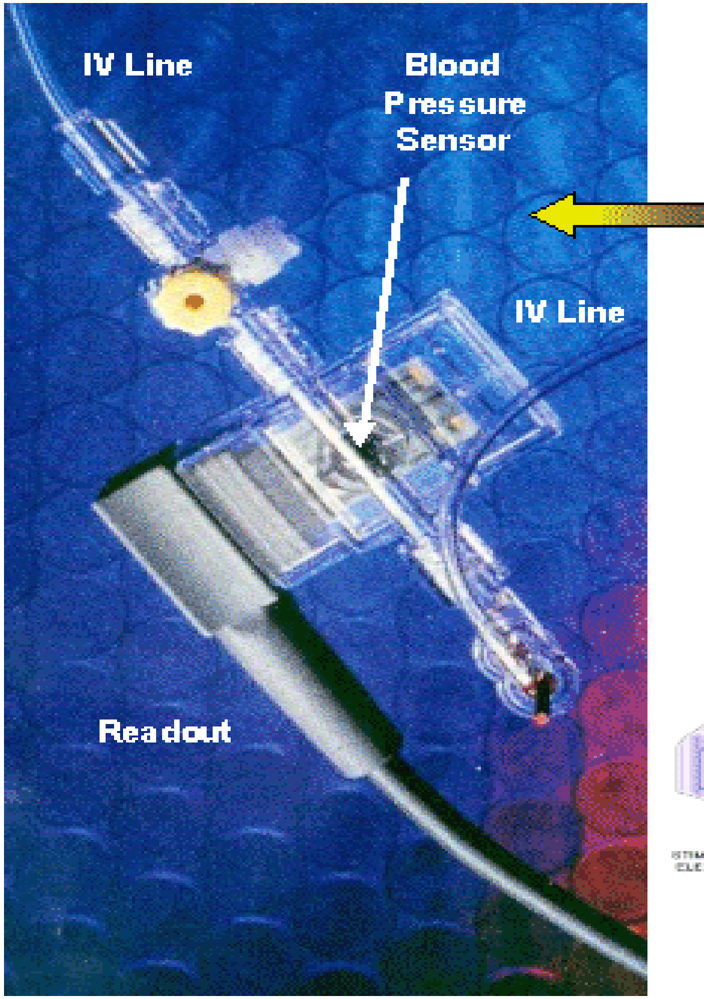
"U.S. MEMs-Based Sensor Markets"
Frost & Sullivan Report # 5999-32, 1999

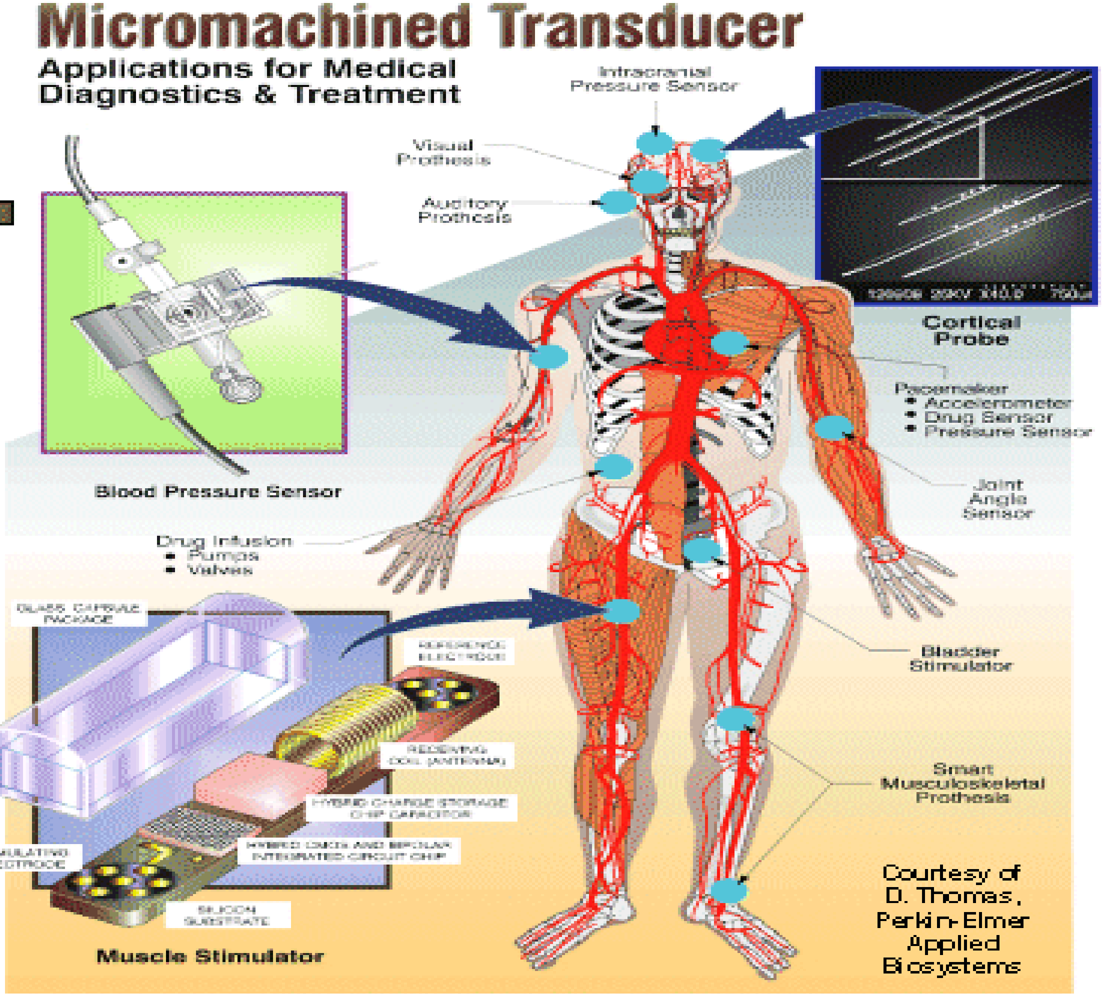
Projectors

Automobile MEMS



Biological MEMS

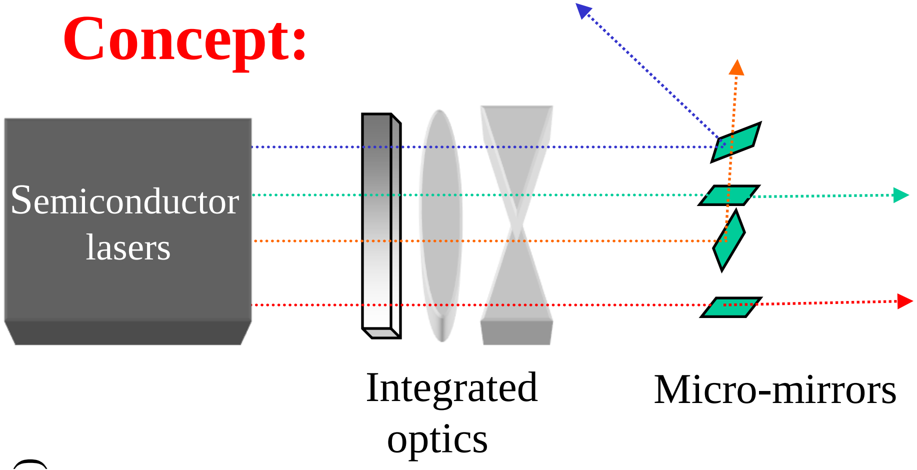




Courtesy of D. Thomas, Perkin-Elmer Applied Biosystems

Integrated optical MEMS

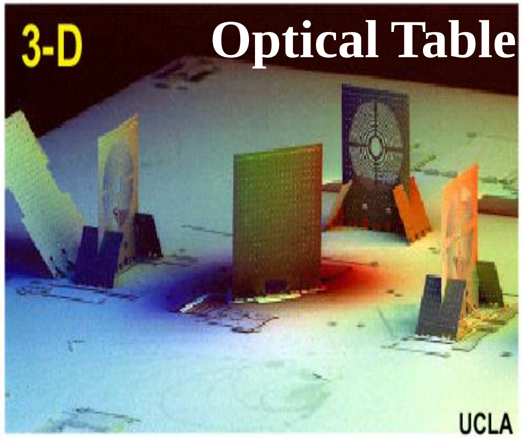
Concept:



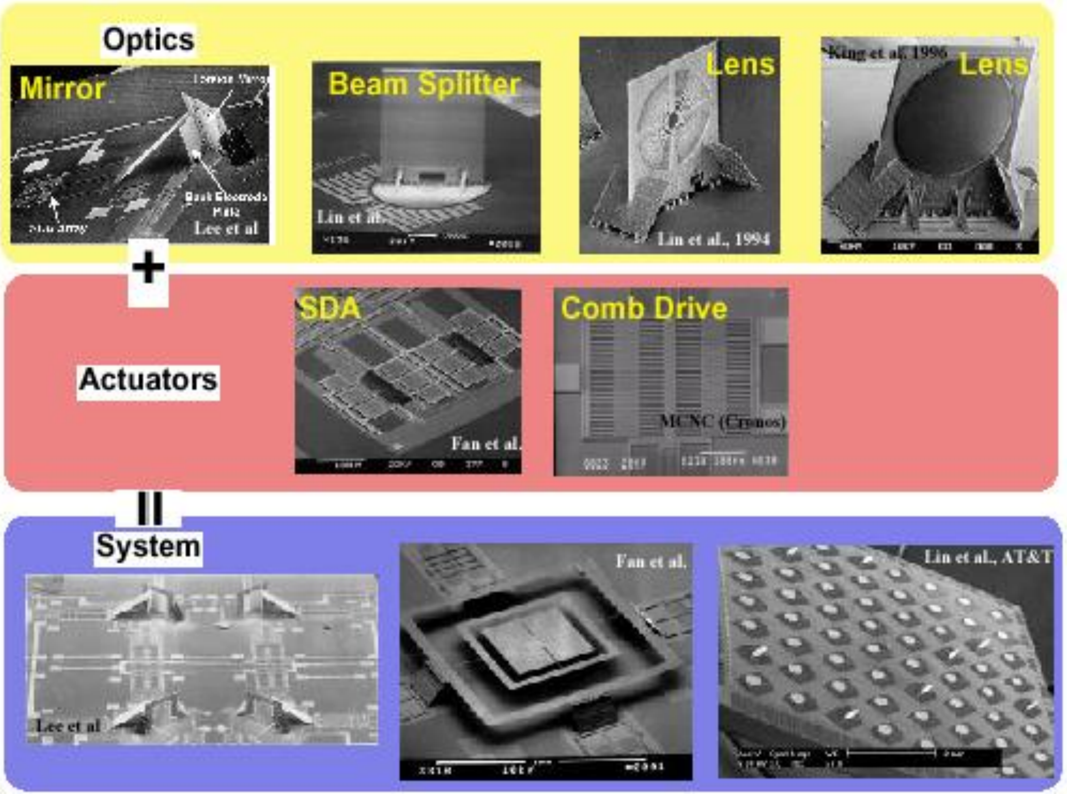
Semiconductor lasers

Integrated optics

Micro-mirrors

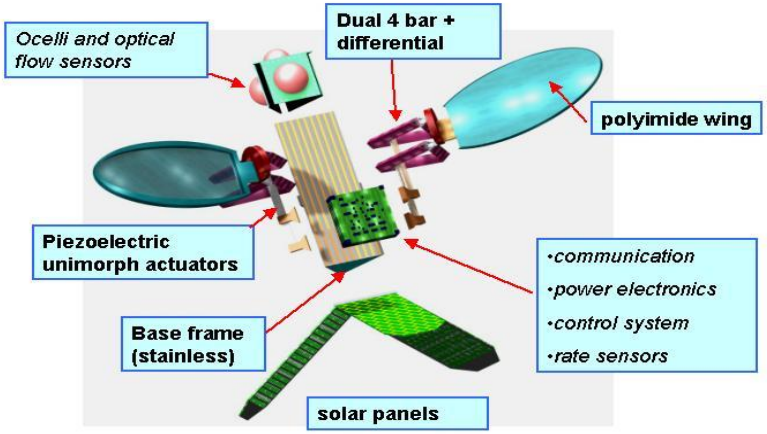


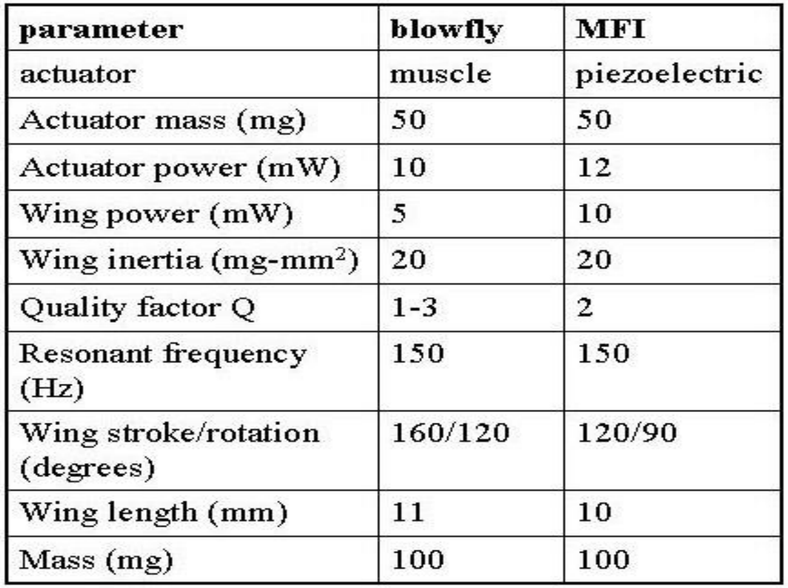
(M. Wu)



(slide courtesy: M.Wu & H. Toshiyoshi, UCLA)

Micro-mechanical flying insect





parameter	blowfly	MFI
actuator	muscle	piezoelectric
Actuator mass (mg)	50	50
Actuator power (mW)	10	12
Wing power (mW)	5	10
Wing inertia (mg-mm^2)	20	20
Quality factor Q	1-3	2
Resonant frequency (Hz)	150	150
Wing stroke/rotation (degrees)	160/120	120/90
Wing length (mm)	11	10
Mass (mg)	100	100

- **Polyimide wings**
- **(Pb,Zr)TiO$_3$:Piezo-electric actuators**
- **CdSe: solar panels**

Uses in defense (pico-satellites?), biomimetics

http://robotics.eecs.berkeley.edu/~ronf/mfi.html

NEMS
(Nano-Electro-Mechanical Systems)

$$\omega_o = \left(\frac{k_{eff}}{m_{eff}}\right)^{½}$$

ω_o : Vibration frequency of system
k_{eff}: effective force constant α l
m_{eff}: effective mass α l^3

→ ω_o increases as l (linear dimension) decreases
→ ***Faster device operation***

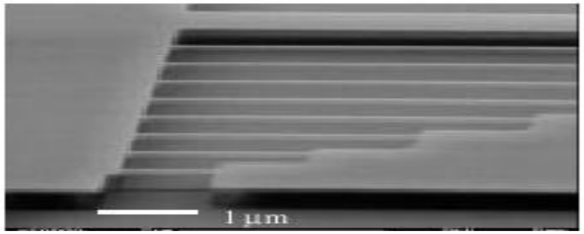
Si cantilever MEMS (100 X 3 X 0.1 μm): 19 KHz
NEMS (0.1 X 0.01 X 0.01 μm): 1.9 GHz

(Roukes, NEMS, Hilton Head 2000)

Promise true Nano-technology !

better force sensitivities (10^{-18} N)
larger mechanical factors (10^{-15} g)
higher mass sensitivity (molecular level)
than MEMS

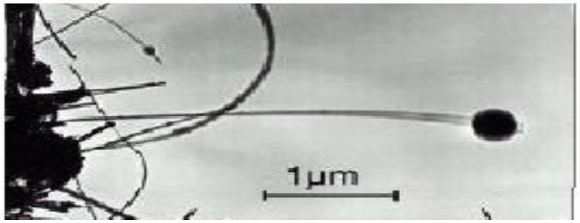
NEMS
(Nano-Electro-Mechanical Systems)



SiC/Si wires as electro-mechanical resonators

f: 380 MHz, 90 nm wires

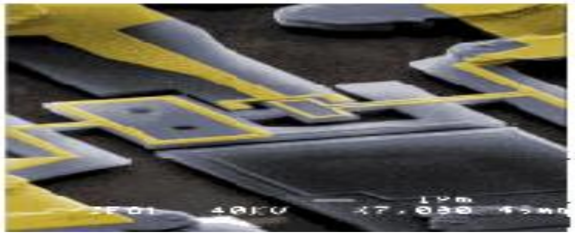
(Yang et al, J.Vac. Sci. and Tech B, 19, 551 2001)
(Carr et al, APL, 75, 920, 1999)



Carbon nanotube as a electromechanical resonator

f: 0.97 MHz, m: 22 6 fg, E: 92 GPa

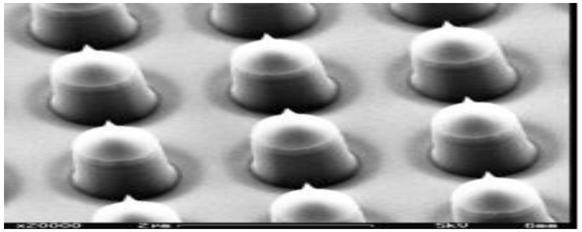
(Poncharal et al, Science, 283, 1513, 1999)



Nanometer scale mechanical electrometer

f: 2.61 MHz, Q: 6500

(Cleland et al, Nature, 392, 160, 1998)



Bio-motors

F1-ATPase generates ~ 100pN

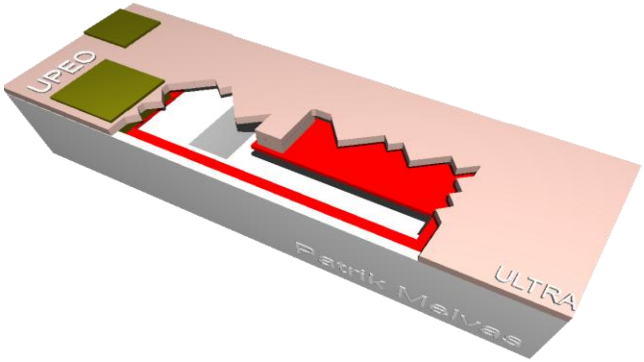
(Montemagno et al, Science, 290, 1555, 2000)

Bio-MEMS

Use bio-molecules as sensing material, c.f. a chemical sensor

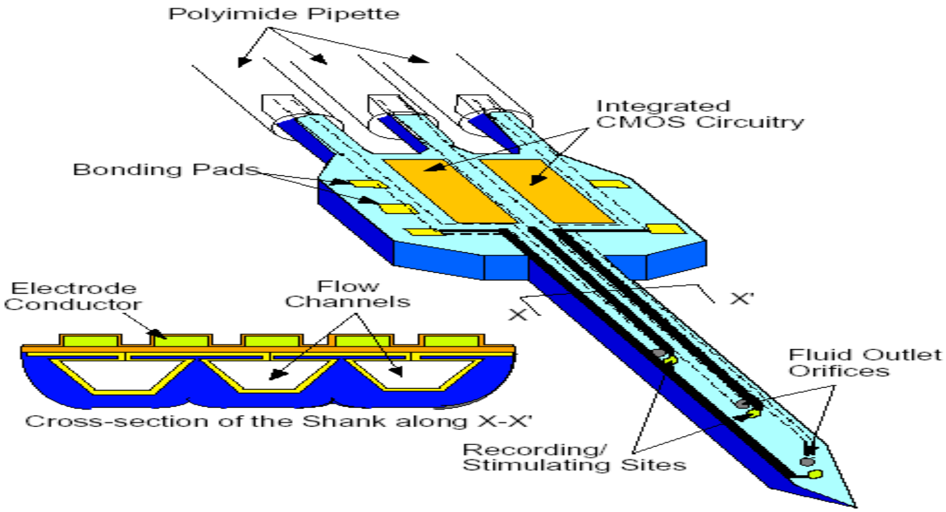
Two examples (potentially hundreds?):

1. **Cardiovascular pressure sensor**



KTH Microsystems

2. **Neural probes**



K.D. Wise, University of Michigan

Are mechanical laws different at small scales? YES!

If we scale quantities by a factor ‘S’

Area α S^2 Volume α S^3
Surface tension α S Electrostatic forces α S^2
Magnetic forces α S^3 Gravitational forces α S^4

- Surface Area/Volume effects
- Stiction: “Sticky friction”, due to molecular forces
  - surface tension pulls things together

SCALING OF: Mechanical systems
Fluidic systems
Thermal systems
Electrical and Magnetic systems
Chemical and Biological systems

Scaling Laws

At the micro-/nano-scale, engineering principles based on classical continuum models, are modified

- **atomic-scale structure**
(surface to volume ratio)
- **mean free path effects**
- **quantum mechanical effects**
- **noise**
    * **Johnson Noise**
    * **Shot Noise**
    * **1/f noise**

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SCALING OF: Mechanical systems
Fluidic systems
Thermal systems
Electrical and Magnetic systems
Chemical and Biological systems

Which dynamical variables are scaled?

- depends on our choice

e.g.

Mechanical systems

Constant stress → Scale independent elastic deformation, scale independent shape

Electromagnetic systems

Constant electrostatic stresses/field strengths

Thermal systems

Constant heat capacity & thermal conductivity

Scaling Issues in Fluids
Viscosity & Surface Tension

- Definition: A fluid cannot resist shear stresses

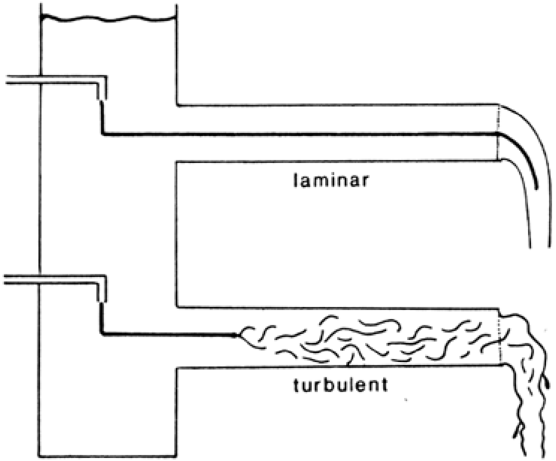
$$\text{Reynold's number (Re)} = \frac{v \rho l}{\eta}$$

Re is the ratio of inertial and viscous forces,
v: velocity, **ρ:** density. **l:** linear dimension

Viscosity dominates at: Re < 1

Re for whale swimming at 10 m/second ~ 300,000,000
Re for a mosquito larva , moving at 1mm/sec ~ 0.3

Re marks the transition between
Laminar/Smooth flow & Turbulent Flow (mixing)



In MEMS: always laminar flow!

Thermal Issues

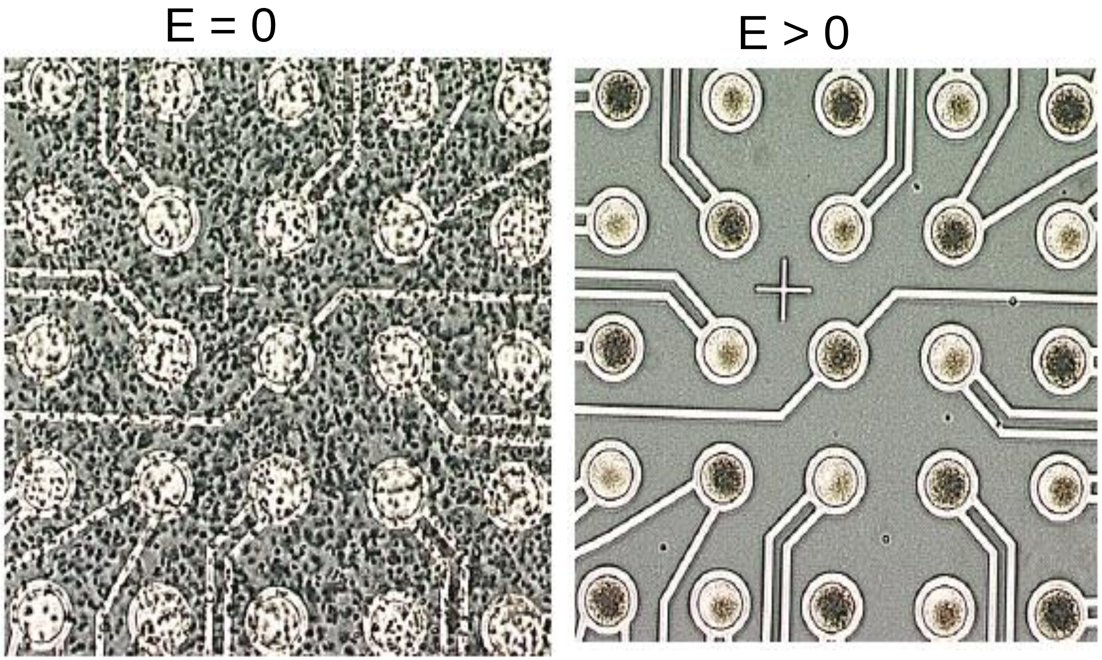
Easier to remove heat from a smaller sample

- Thermal Mass (specific heat X Volume) scales as l^3, but heat removal scales as l^2 (proportional to area)
- Evaporation or Heat loss increases as Surface Area/Volume increases

Electrophoresis

- Stirring vs. Diffusion, Diffusion is the dominant mixing process in MEMS

- Separation of bio-molecules, cells by the application of electric fields



E = 0

E > 0

Separation of different types of blood cells

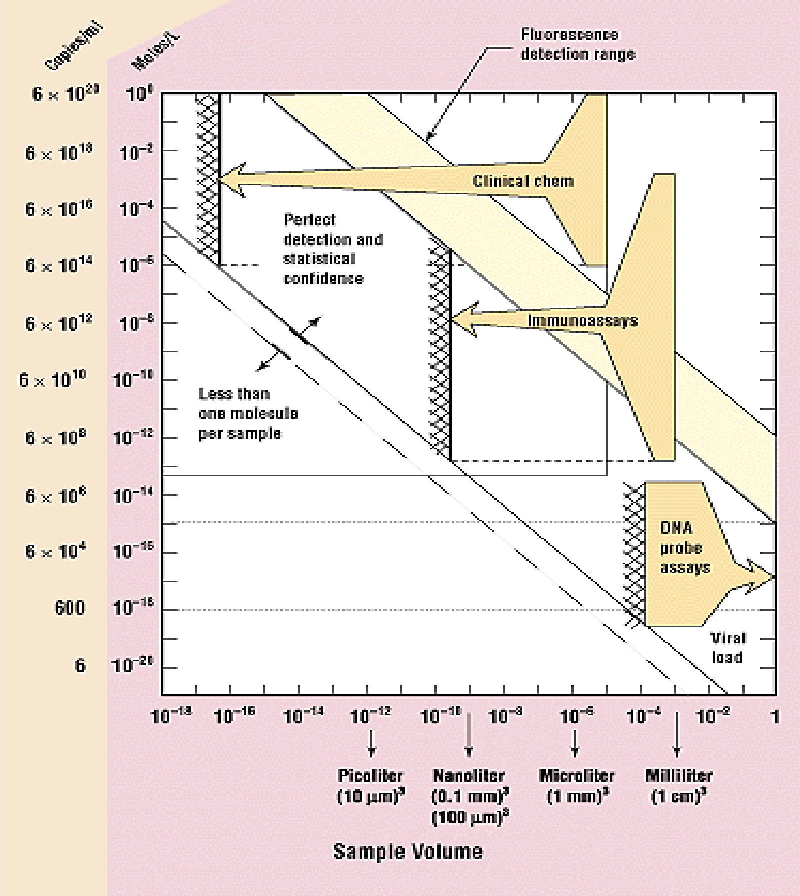
Miniature Clinical Diagnostic Systems

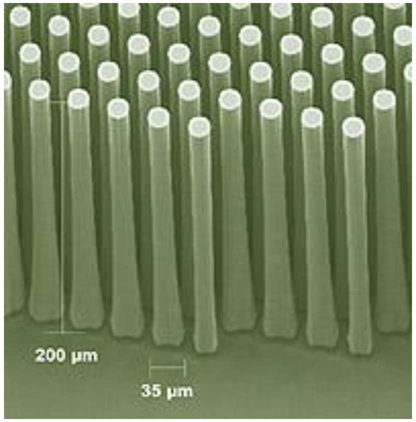
Fast, on-site, real time testing

Principle: High Isolation, Low Mass, Localized heating possible

- Polymerase Chain Reaction (PCR) for DNA amplification

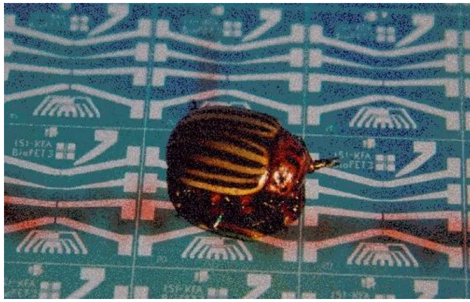
Scaling of Minimal Analytic Sample Size





Micro-fabricated DNA capture chip (Cepheid, CA)

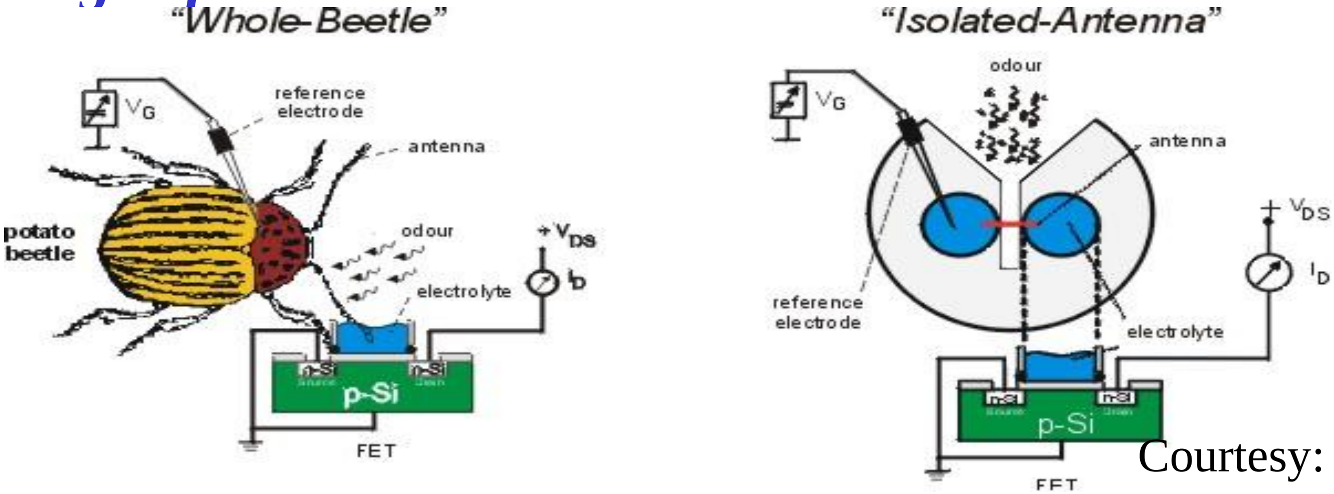
Scaling in Electricity and Magnetism



- Potentiometric devices (measure voltage) are *scale invariant*
- Amperometric devices (measure current) are *more sensitive* when miniaturized

e.g., μ-array electrochemical detectors (Kel-F) for trace amounts of ions

Electroplating is faster in MEMS



Courtesy: M. Schoning

Scaling in electromagnetic systems

Constant electrostatic stresses/field strengths

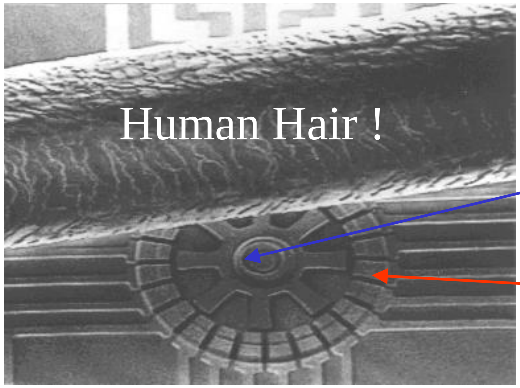
$$\text{Voltage} \propto \text{Electrostatic field} \cdot \text{length} \propto L$$

$$\text{Resistance} \propto \frac{\text{Length}}{\text{Area}} \propto L^{-1}$$

$$\text{Ohmic current} \propto \frac{\text{Voltage}}{\text{Resistance}} \propto L^{2}$$

Current density (I/A) is scale invariant

Scaling in Electricity and Magnetism



Sandia MEMS

Electric:

ε: dielectric permittivity (8.85 . 10^{-12} F/m)
E: electric field
(Breakdown for air: 30 kV/cm)

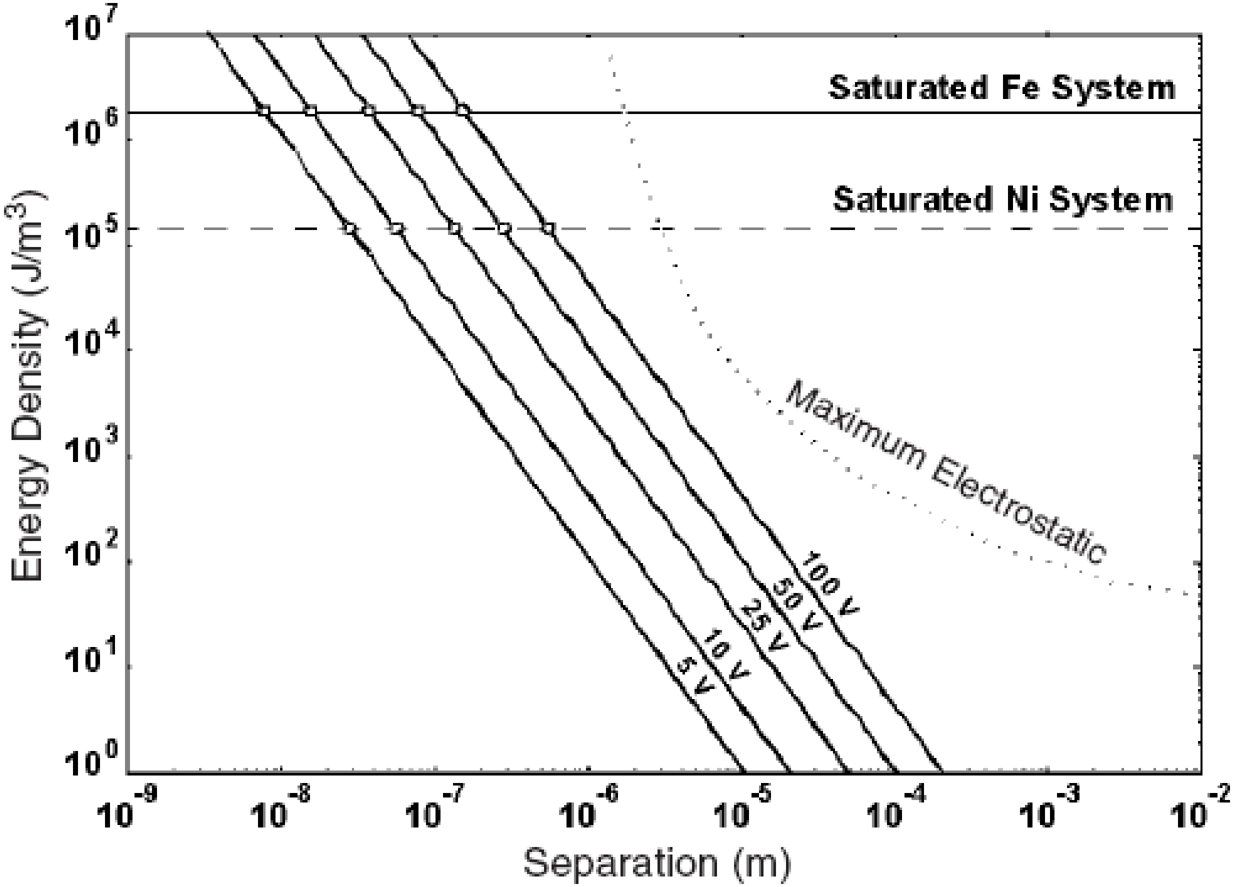
$$U_{\text{electric}} = \frac{1}{2}\varepsilon E^2$$

Magnetic:

μ: permeability (4π . 10^{-7} N/A^2)
B: Magnetic field

$$U_{\text{magnetic}} = \frac{1}{2}\left(\frac{B^2}{\mu}\right)$$

Electrostatics is more commonly used in MEMS



Macroscopic machines: Magnetic based

Microscopic machines: Electrostatics based

Judy, Smart Mater. Struc, 10, 1115, (2001)