INF5490 RF MEMS

LN01: Introduction. MEMS in RF

Spring 2010, Oddvar Søråsen
Department of informatics, UoO

Today's lecture

- Background for the course INF5490/9490
- Course plan spring 2010

- Introduction
  - MEMS in general
  - RF systems
  - MEMS in RF systems

INF5490 RF MEMS

- **MEMS** (Micro Electro Mechanical Systems)
  - A relatively new research activity in the NANO group
    - NANO competence: Design of mico/nano- electronic systems: modeling, analysis and implementation of analog and digital VLSI circuits and systems

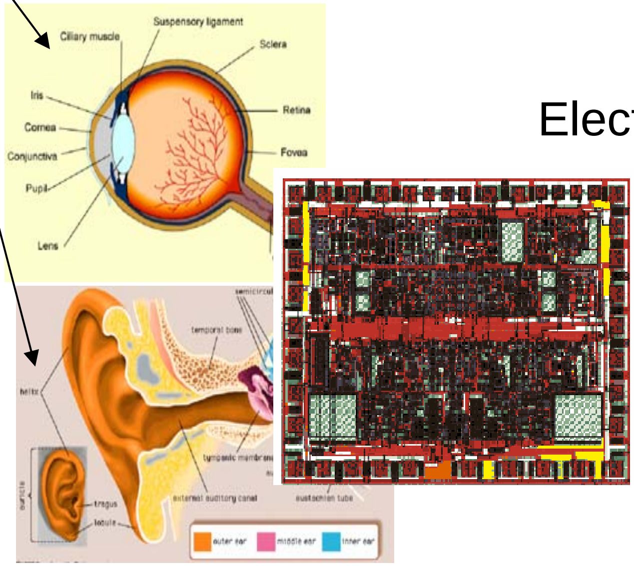
- Activity inspired by:
  - **National focus** on micro- and nano-technology
    - The Research Council of Norway
  - **MiNaLab** (Micro Nano Technology-lab), next-door
    - SINTEF lab
    - UiO lab

Why MEMS in the Nano-group?

- New possibilities to implement **integrated, miniaturized systems**
  - Electronic systems integrating MEMS give a new **degree of freedom** for designers
  - **A.** May integrate micro **mechanical** components in the systems: add: ”eyes, ears, hands”
  - **B.** MEMS – components need **interfacing** electronics!

MEMS

Electronics



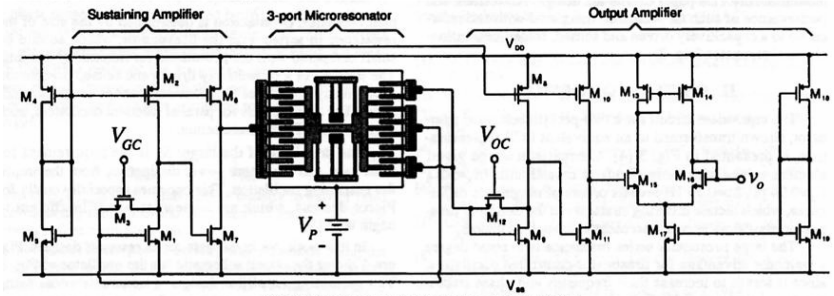
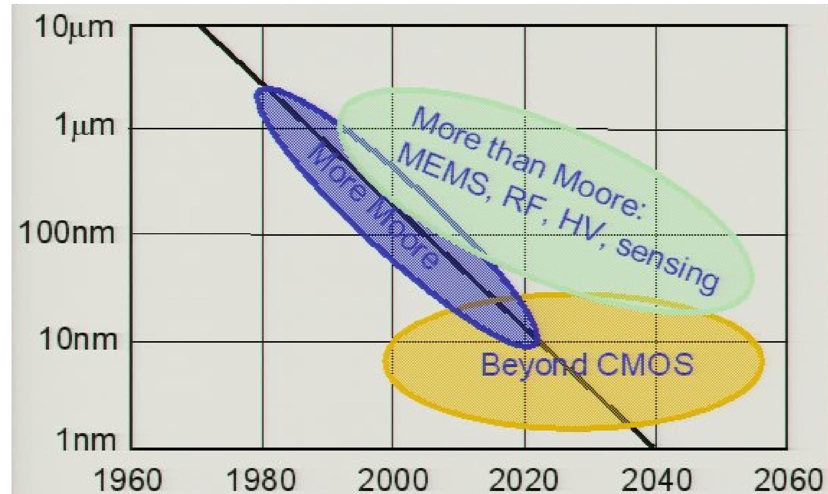
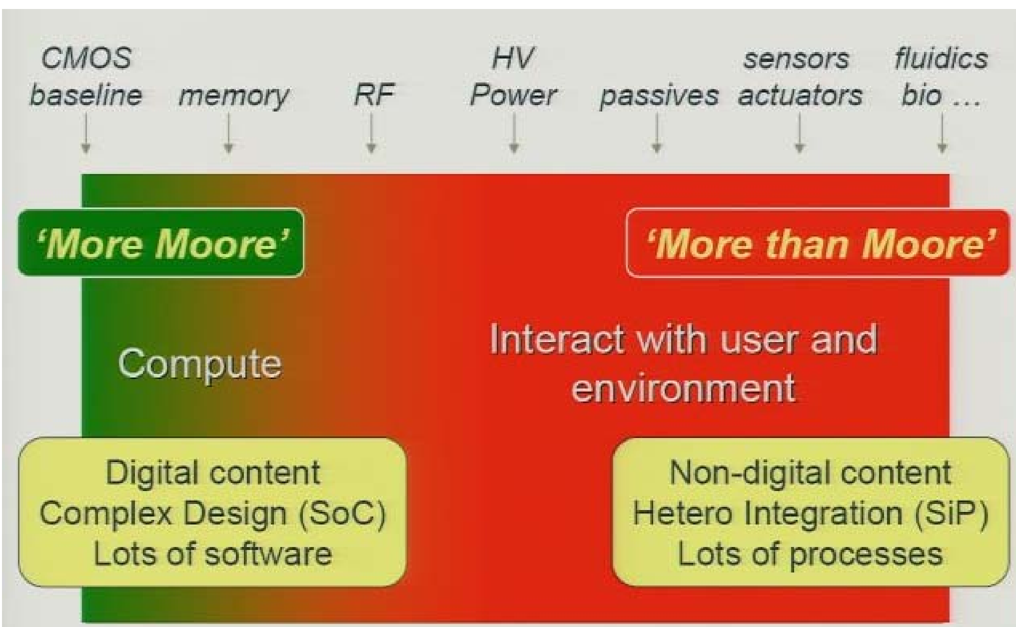


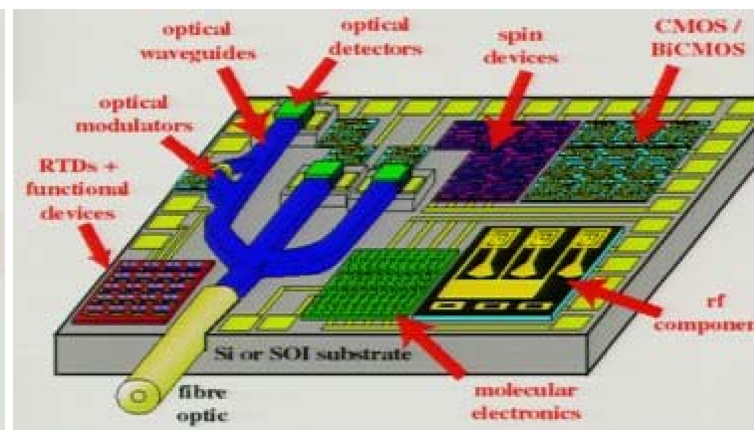
Fig. 4: Circuit schematic for the μresonator oscillator.

Interfacing to the ”real world”

- Enhancing ”More Moore” by ”non-classical” electronic components
- Achieve “Ambient Intelligence” by “More than Moore”







[Ref. A.M. Ionescu]

Personal competence

- Physics → modeling and design of VLSI → system design → computer architecture/multiprocessors → **RF MEMS, CMOS-MEMS cointegration**
- Sabattical at SINTEF MiNaLab 03/04
- Literature studies
- Seminars
  - RF MEMS-seminar by A.M. Ionescu, EPFL, at KTH H04
    - Arr: FSRM, Swiss Foundation for Research in Microtechnology
  - RF MEMS tutorial: G.M. Rebeiz, UCSD, in Tønsberg H05
    - Arr: IMAPS Nordic Cenference
  - Workshop on MEMS, IMEC, Leuven, H07
    - Arr: Europractice/STIMESI
  - Course on Cofabrication of MEMS and CMOS, IMEC, Leuven, H08
  - Tutorials and conference: Eurosensors XXIII, Lausanne, H09
- Visiting UC Berkeley and Carnegie Mellon University, H06
    - C.T.-C. Nguyen, G.K. Fedder ++
- Using the simulation package CoventorWare
- Supervising students i relevant fields (Master, Ph.D.)
- Research activity

Selecting a focus → RF MEMS

- MEMS is a *broad* field of research
  - A focus is needed → RF MEMS
  - Cofabrication of MEMS and CMOS

- ***”RF MEMS refers to the design and fabrication of dedicated MEMS for RF (integrated) circuits”***

  - 1a) Components **operate** micromechanical
    and/or
  - 1b) Components **fabricated** using micromachining

  - 2) Components are used in **RF systems**

Some arguments for an RF MEMS activity in the NANO group

- Challenging, promising and exciting field!
- Close connection to the basic competence in circuit technology
- The course fits well into the NANO Master/PhD education
- Actual theme
  - Increasing interest internationally for using MEMS in RF systems
- Large market: **wireless communication**
  - Tele communication, mobile business
  - Wireless Sensor Networks (WSNs)
  - Distributed intelligence (observation, actuation)
  - Environmental surveillance, – sensor nodes
  - Ambient Intelligence: - units everywhere!
  - Patient surveillance, - medical implants
  - ”Internet of things”
- Growing commercial attention
- Basis for establishing new enterprises

International activity

- RF MEMS is in focus on leading international conferences
  - ISSCC, IEDM (Int. Electron Devices Meeting), Eurosensors
  - MEMS-conferences and journals
    - See NANO web-page!

- *Europractice* and *CMP* offer MPW (Multi Project Wafer)

- Increased industry attention and support of RF MEMS
  - Great potential
    - Miniaturization, increased performance, volume production

  - **BUT MEMS in general is not yet a big hit!**
    - **A few successes: airbag sensor, projector**

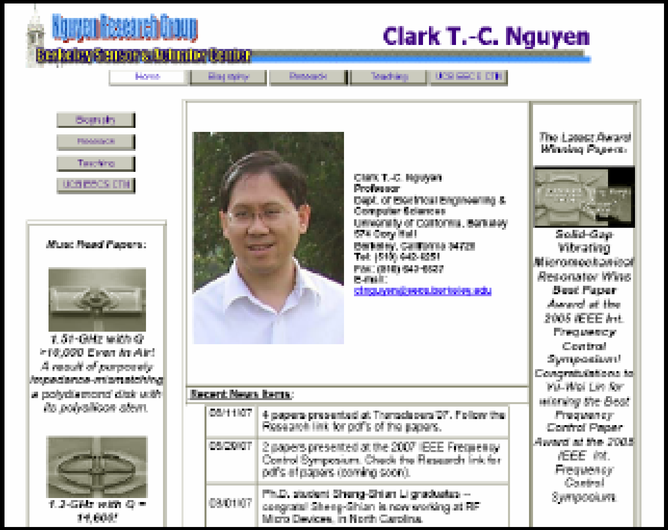
RF MEMS: where should I look for?

Top authors, books and web pages

RF MEMS

- Clark Nguyen

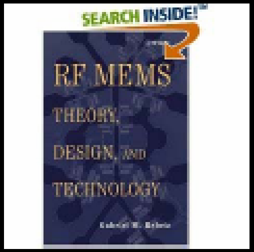
http://www.eecs.berkeley.edu/~ctnguyen/



RF MEMS

- Gabriel Rebeitz

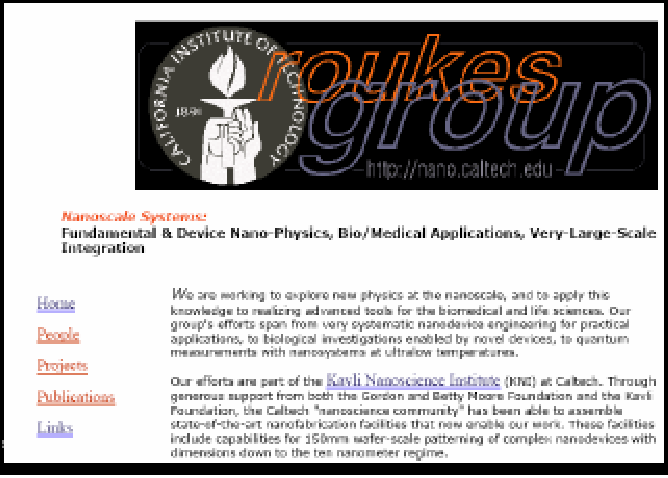
RF MEMS: Theory, Design, and Technology, Wiley, 2003.



NEMS

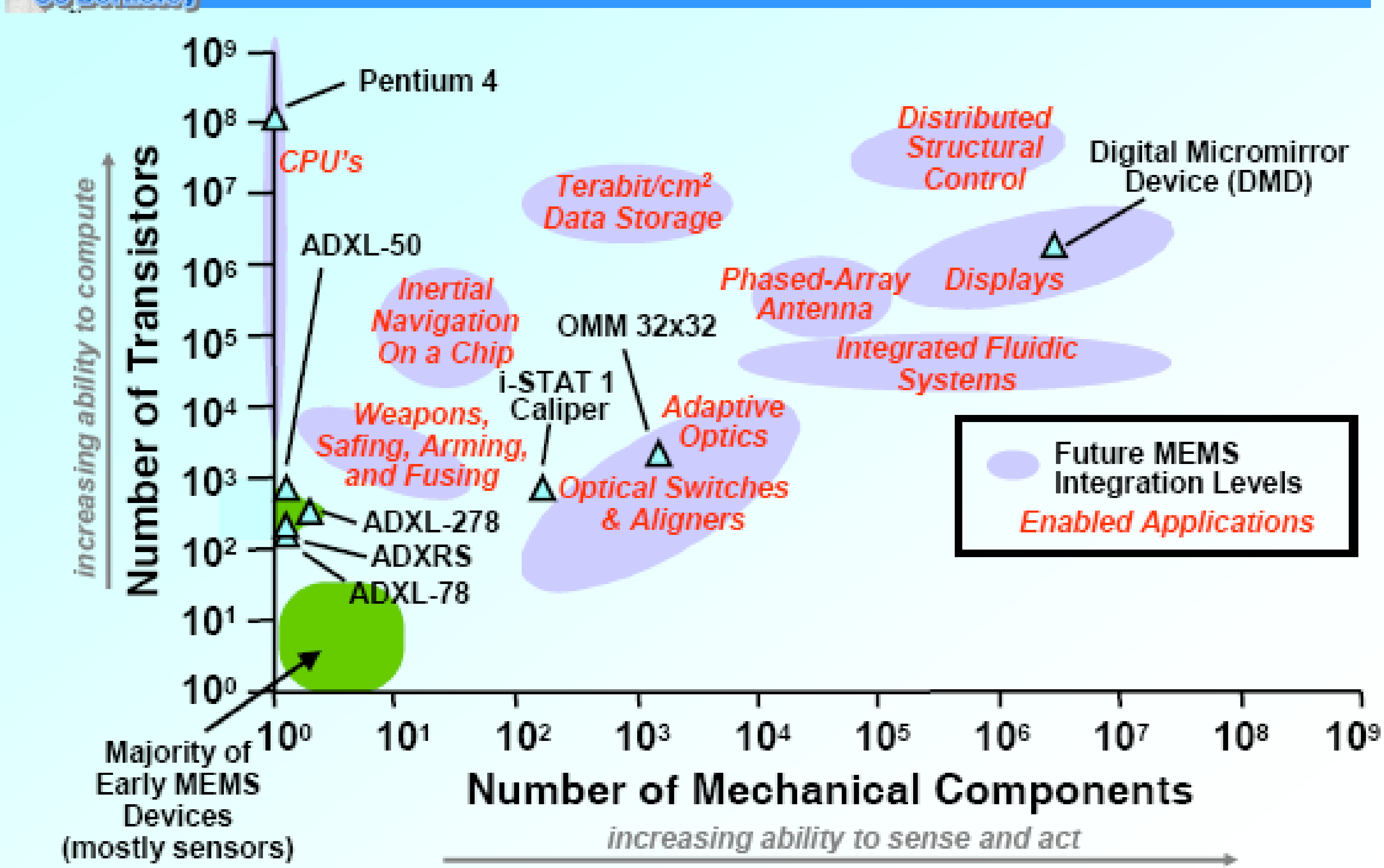
- Michael Roukes

http://nano.caltech.edu/



[A.M. Ionescu]

Technology Trend and Roadmap for MEMS



[C. Nguyen]

Today's lecture

- Background for course INF5490
- Course plan spring 2010

- Introduction
  - MEMS in general
  - RF-systems
  - MEMS in RF-systems

Information about course INF5490

- Course homepage:
  - http://www.uio.no/studier/emner/matnat/ifi/INF5490/v10/
  - Messages posted there! **CHECK regularly!**
- Weekly **lectures:** Oddvar Søråsen
  - Thursday 10:15 – 12 in 3B
  - Detailed lectureplan on web
    - Lecture notes will be posted on web before lecture (pdf)
- Language: English

Group assignments

- **Class assignment:** Dag Halfdan Bryn
  - ”Felles gruppe” – consult web for weekly plan!
  - Tuesday 14:15 – 16 in 3B
    - First time 26/1
  - Presenting plan and topics for ”obliger”
  - Presenting supporting literature
  - Work through assignments
    - Posted a week before
  - Practical aspects
  - Questions, discussion

Obliger

- **2 “obliger”** have to be done
  - Must hand in 2 reports at specified dates (see web)
    - **General guidelines available on web!**
  - **Approval** required for taking the exam
  - Each group consists of 2 students that collaborate
- Topics: micromechanical resonators and filters
  - Simulations using CoventorWare
    - 3-dim modeling, FEM-analysis (Finite-Element-Method)
    - High-level modeling, ARCHITECT

CoventorWare

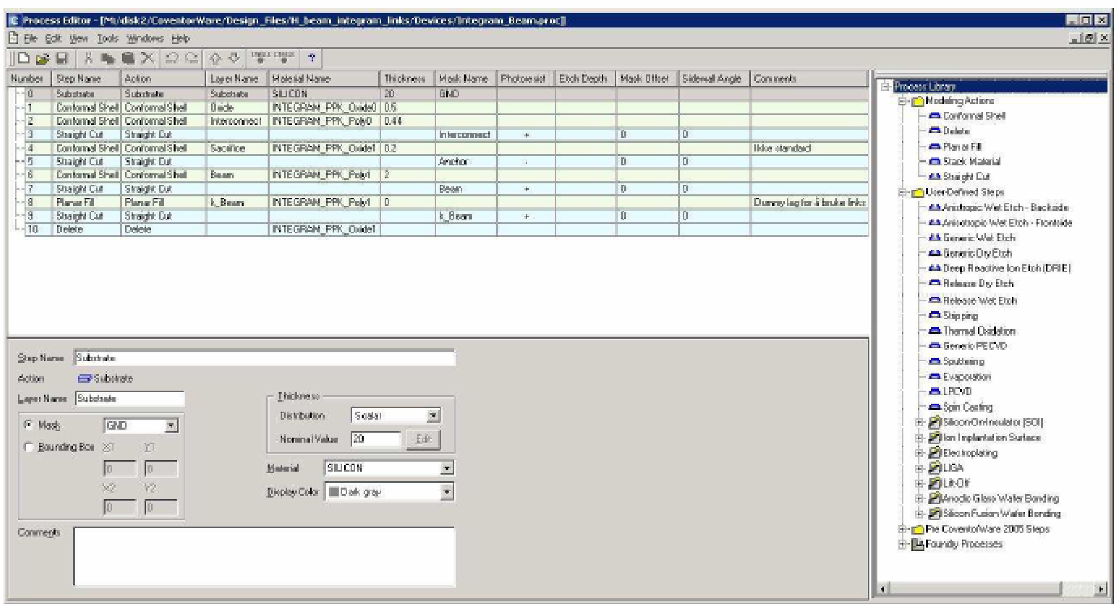
- “State-of-the-art” tool for FEM analysis
  - ”Finite-Element-Method”

- **“Bottom-up” prosedyre:**
  - 1) Build a 3D -model
    - Multiple layers: structural and sacrificial layers
    - Etching pattern, remove sacrificial layer
  - 2) Meshing
    - Tetrahedral, “Manhatten bricks”
  - 3) Solvers
    - Electrical/ mechanical/ coupled
    - Iterate!

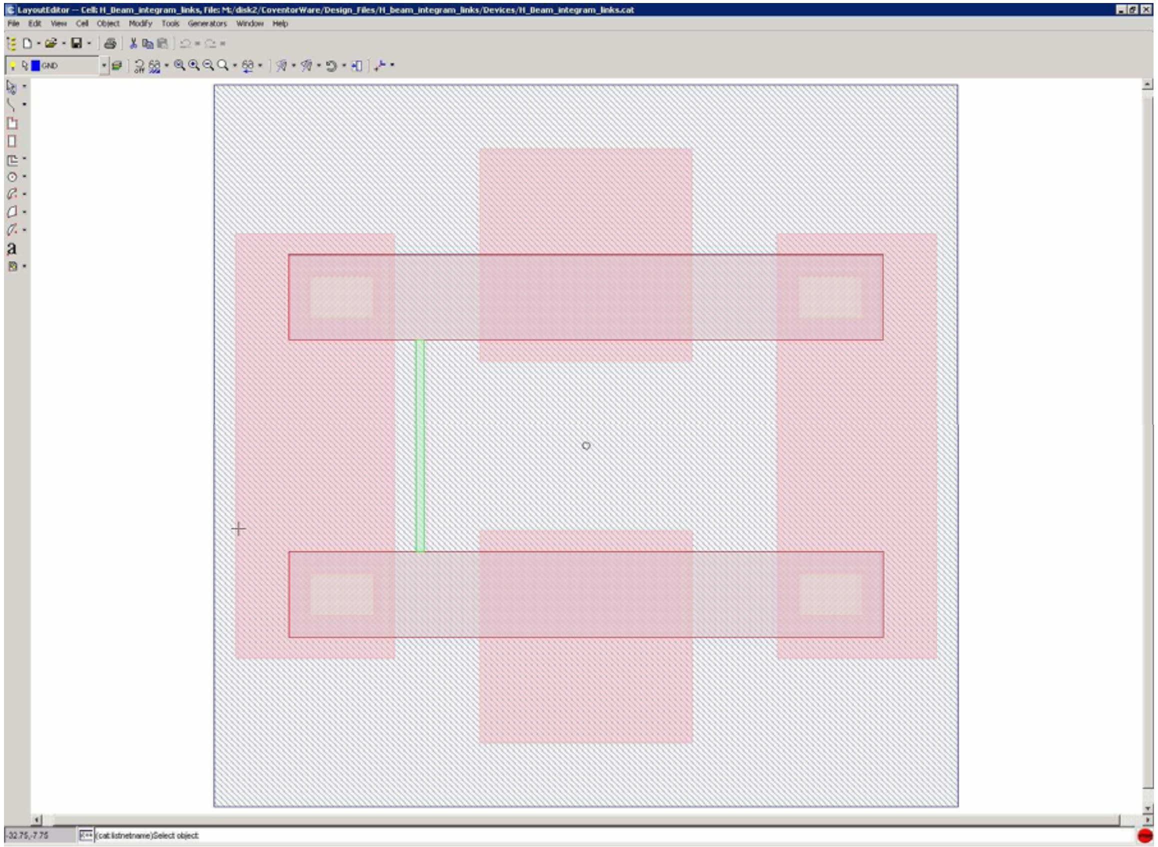
COVENTOR ACCELERATING MEMS Innovations™

Process-description

- Specify a **process file** compatible with the relevant “foundry” -process
  - Reduce complexity, idealization
  - Realistic: characteristic process features should be kept



Layout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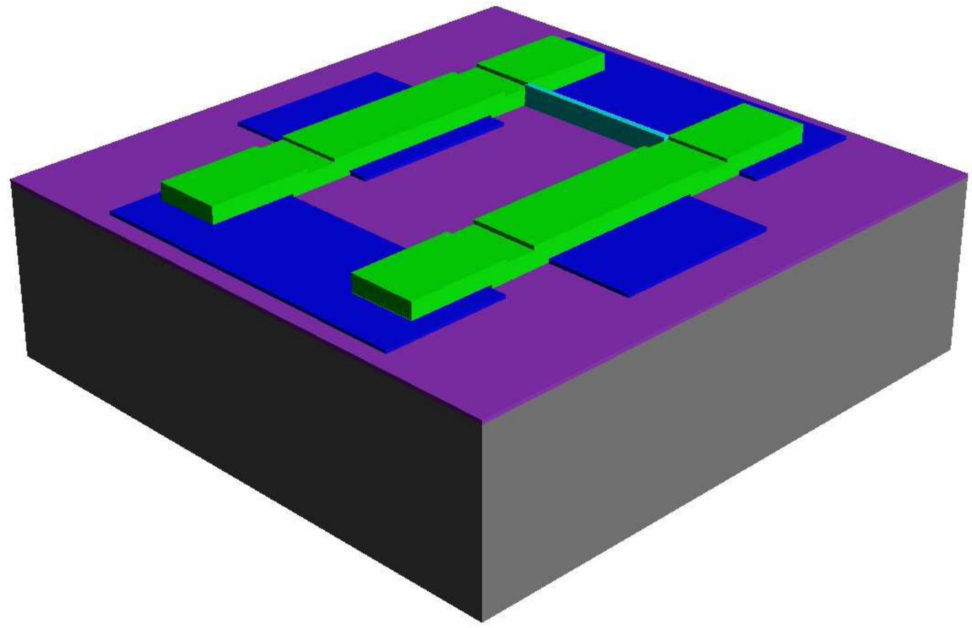
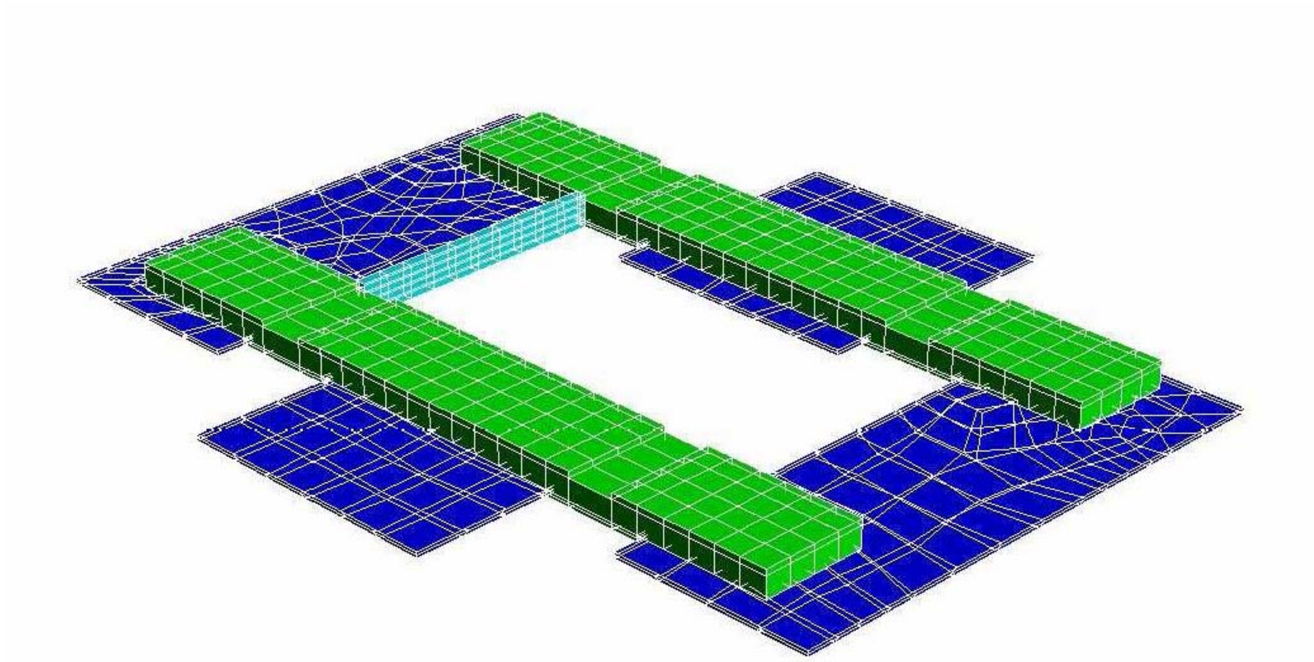
Building a 3-D model



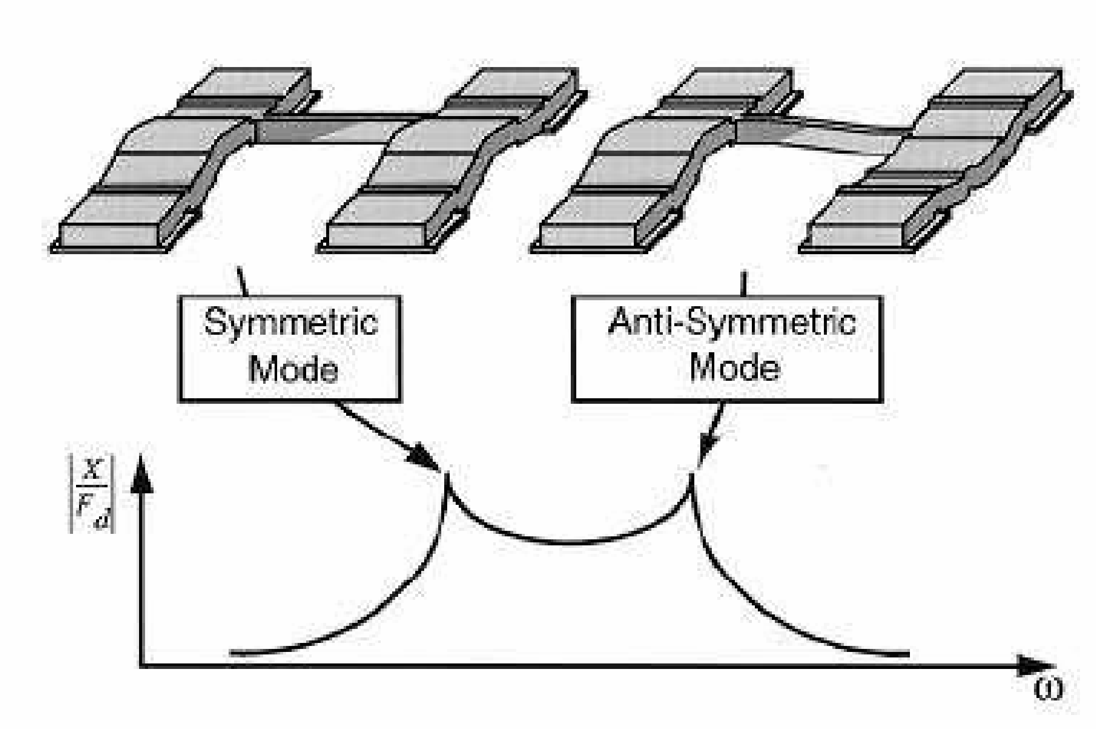
O-P Arhaug

Meshed 3D -model for FEM analysis

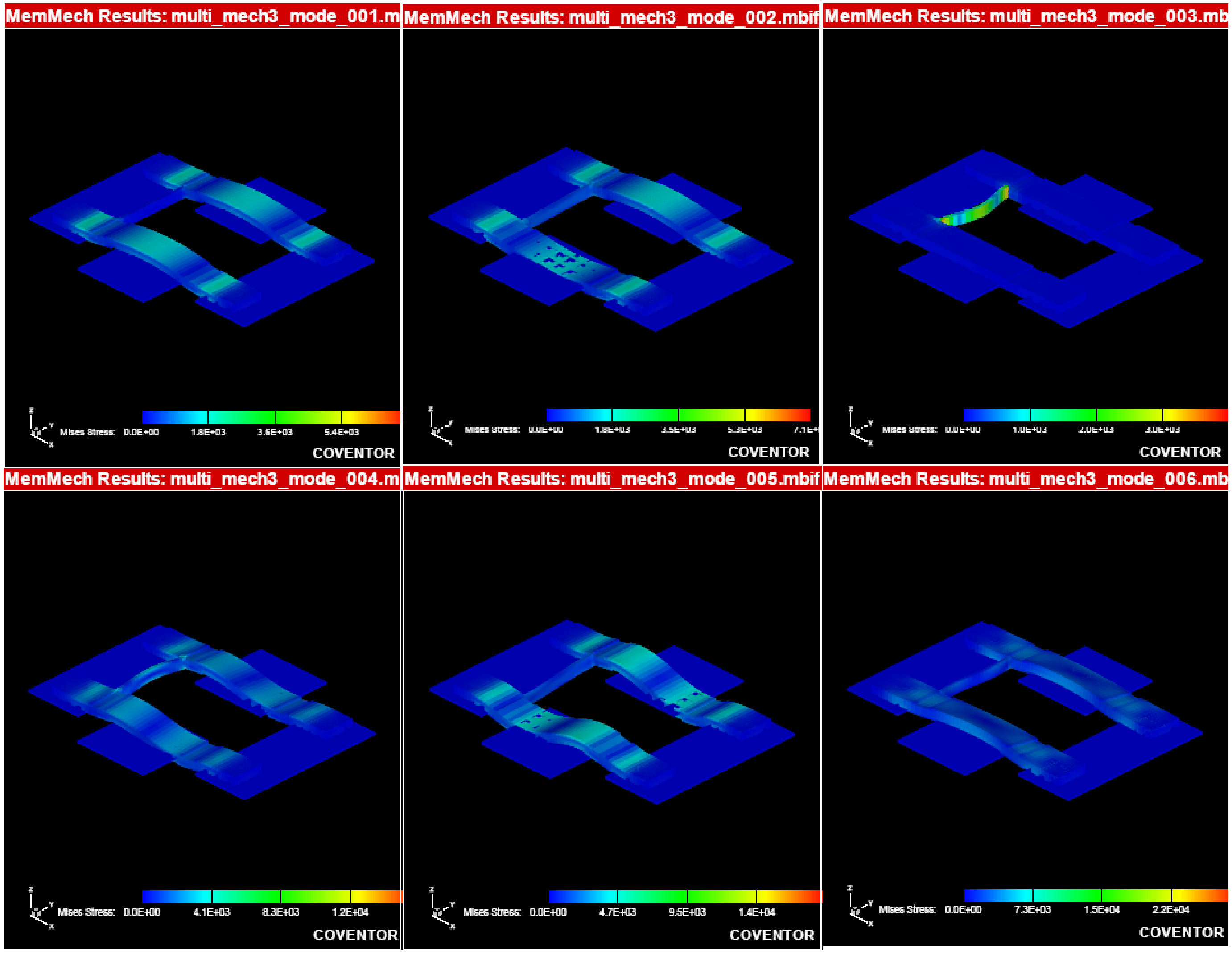


O-P Arhaug

Filter-function: 2 identical resonators

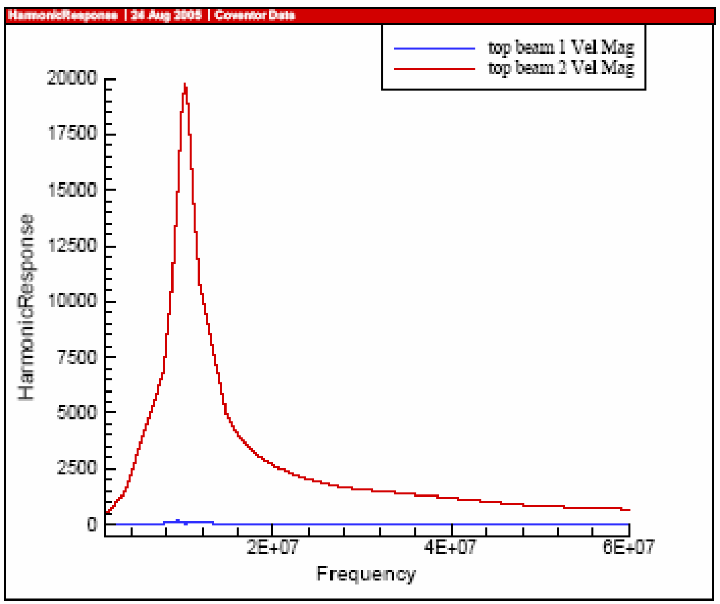


In phase Out of phase



CoventorWare simulations for 6 resonating modes (O-P Arhaug)

Harmonic response for specific dampings



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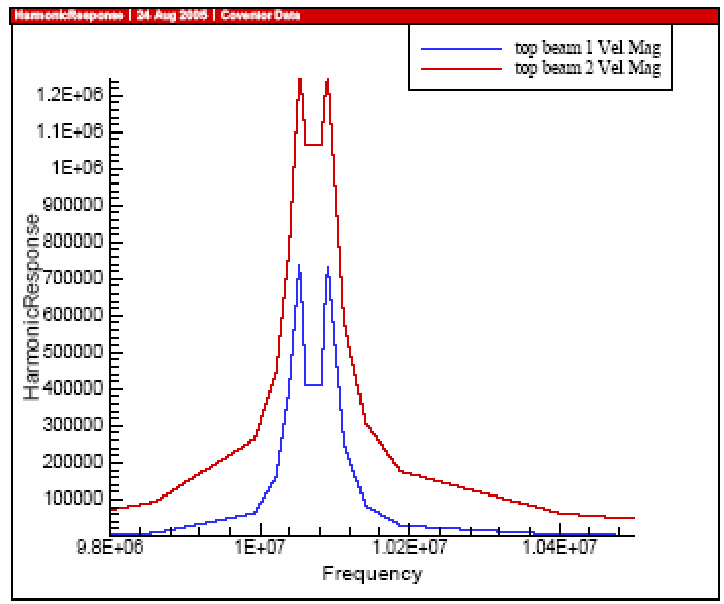

(b) 0,001

Exam

- Oral **exam** (45 min)
  - Option II: 3 hours written exam
    - Depending on the number of students

- Relevant exam questions will be posted on web later on
    - List for 2009 questions is available now!

Themes covered in the course

- RF MEMS is a **multi disciplinary** field
- **Main topics**
  - Introduction (1 week)
  - Micromachining (1 week)
  - Modeling (1 week)
  - RF circuit design (1 week)
  - Typical RF MEMS circuit elements (8 weeks)
    - Operation principles, models/analysis and examples
    - Switches, phase shifters, resonators, filters, capacitors and inductors
  - Packaging (1 week)
  - RF system design (1 week)
  - Repetition (1 week)

Literature

- Text book
  - Vijay K. Varadan, K.J. Vinoy, K.A. Jose, ***"RF MEMS and their applications".*** John Wiley, 2003. ISBN 0-470-84308-X
  - Supplementary: Ville Kaajakari: **"*Practical MEMS*",** Small Gear Publishing, 2009. ISBN: 978-0-9822991-0-4
  - No single book is particularly good
- Lecture notes **(IMPORTANT!)**
  - → Most of the syllabus is covered as lecture notes (ca. 1000)
  - Posted on web <u>before</u> lecture

- INF9490 version: Additional curriculum (to be defined)!
- Supporting literature?
  - Overview of literature given on the web course page, e.g.:
    - Gabriel M. Rebeiz, *"RF MEMS, Theory, Design, and Technology".* John Wiley, 2003. ISBN 0-471-20169-3
    - Stephen D. Senturia, *"Microsystem Design",* Kluwer Academic Publishers, 2001. ISBN 0-7923-7246-8

Contact information

- Responsible lecturer
  - Oddvar Søråsen, room 3411, phone: 22 85 24 56
  - oddvar@ifi.uio.no
- Responsible for groups/obliger/CoventorWare:
  - Dag Halfdan Bryn, room 3420
  - daghb@ifi.uio.no
- Contact person CoventorWare: support
  - Yngve Hafting, 5. floor Veilab, phone: 22 85 16 91
  - yngveha@ifi.uio.no
- web pages
  - http://www.uio.no/studier/emner/matnat/ifi/INF5490/v10/

Quality assurance

- Course assessor
  - Chief Scientist Geir Uri Jensen, SINTEF ICT, MiNaLab
- Quality assessment
  - The course coordinator is required to engage students in continuous **evaluation of the course**, offering the students an opportunity to provide continous **feedback** on the quality of the course. Thus, the course coordinator can make **improvements** based on this feedback

"Institutt for informatikk ønsker en kontinuerlig evaluering av både form og innhold i undervisningen.
Evalueringen skal gi studentene ved et emne mulighet til å komme med tilbakemeldinger underveis, slik at eventuelle forbedringer kan gjøres umiddelbart.
I tillegg skal underveisevalueringen hjelpe faglærer og instituttet til å fange opp god og mindre god undervisningspraksis og heve kvaliteten på emnet/undervisningen.
Emneansvarlig lærer utformer evalueringsopplegget i samråd med studentene som følger emnet og er ansvarlig for kunngjøring av tidspunkt og gjennomføring. Omfang og evalueringsmetode tilpasses hvert enkelt emne og avgjøres av faglærer.
Faglærer utfører eventuelle forbedringer og kommuniserer resultatet til studentene."

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  - MEMS in RF-systems

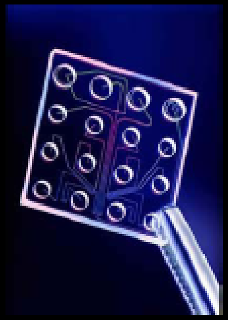
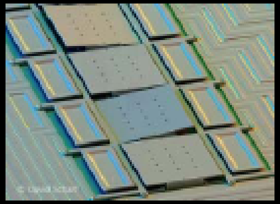
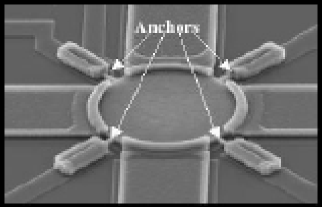
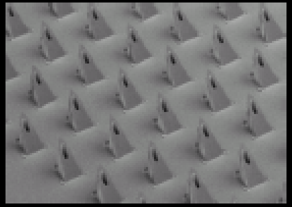
Introduction to the topic RF MEMS

- Observe: **2 disciplines** involved: **RF** and **MEMS**

- RF – ”Radio frequency”
  - High frequencies: MHz, GHz
  - Used in wireless transmission
  - Many characteristic, special properties related to **high frequency designs**
    - Course, Fall (Tor Fjeldly), **recommended!**
      - **INF5480 RF-circuits, theory and design**
    - Central/needed RF topics for INF5490 are covered in the current course

MEMS as enabling technology

MEMS = Micro-Electro-Mechanical Systems

Microfluidics	Optical	RF	Bio	Energy scavenging
				

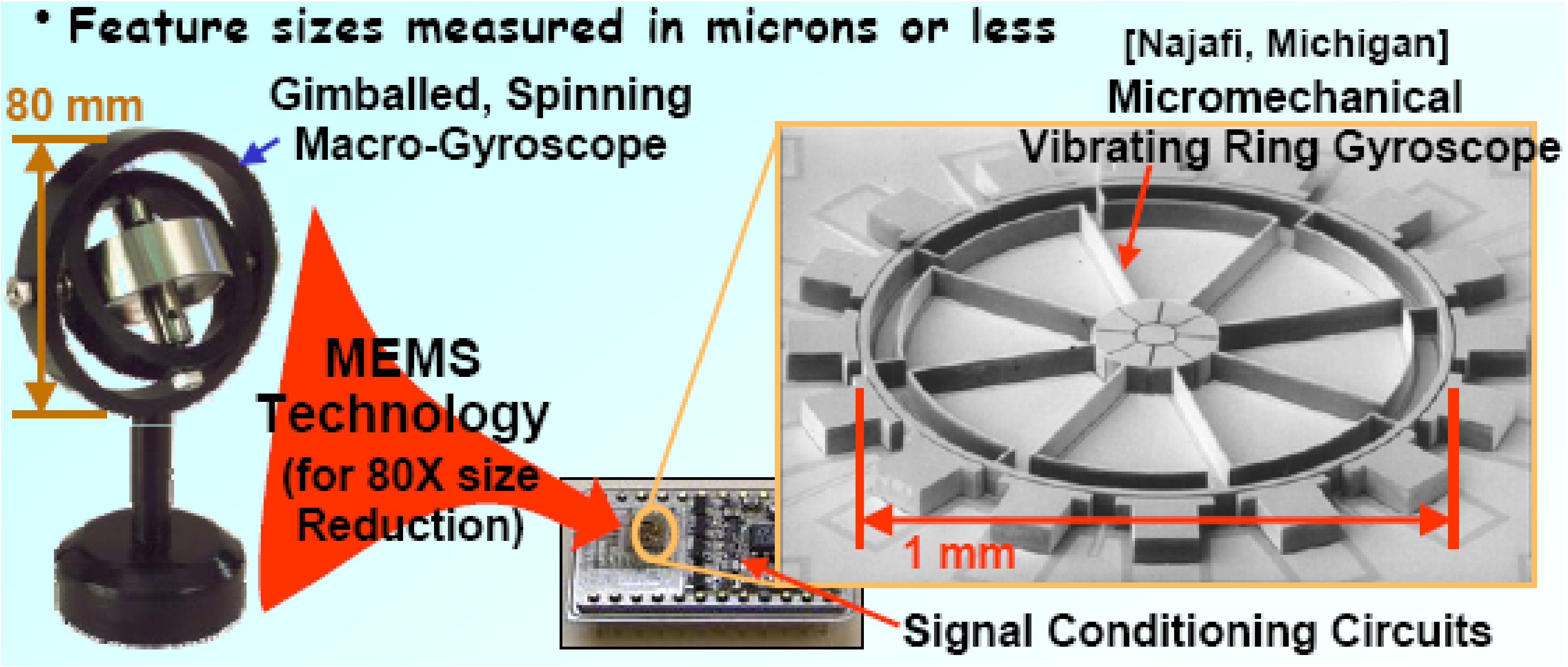
Functionalities you cannot perform with pure electronic functions

[A.M. Ionescu]

The Technology is MEMS

- MEMS – Micro Electro Mechanical Systems
  - Microsystems
  - MST, Micro System Technology
  - → NEMS (”nano”...), MEM/NEM
- **Micromachining is basic!**
  - Further developments of IC fabrication (Silicon)
  - Various MEMS processes available today
    - Often proprietary, specialized for a product
    - Different from CMOS (restricted ”second sourcing”)
    - + other materials: plastic and organic materials (polymeres)
- General course on MEMS given by Liv Furuberg, SINTEF, in the fall semester, **recommended!**
  - FYS4230 Micro- and nanosystem modeling and design
  - Some central topics are covered in INF5490
- MEMS is a promising technology for RF applications

”Scaling” is fundamental



[C. Nguyen]

MEMS in general

- 2 types of units: sensors and actuators
  - **Sensor:** (input)
    - ”Feels”/ are influenced by environment
    - Movement is transformed to electrical signals
    - Many examples (pressure, acceleration)
      - The earliest applications (1980s)
  - **Actuator:** (output)
    - Movable structure controlled by electric circuit
    - Ex. Micro motor
    - Ex. Capacitor with movable plates

Actuation mechanisms

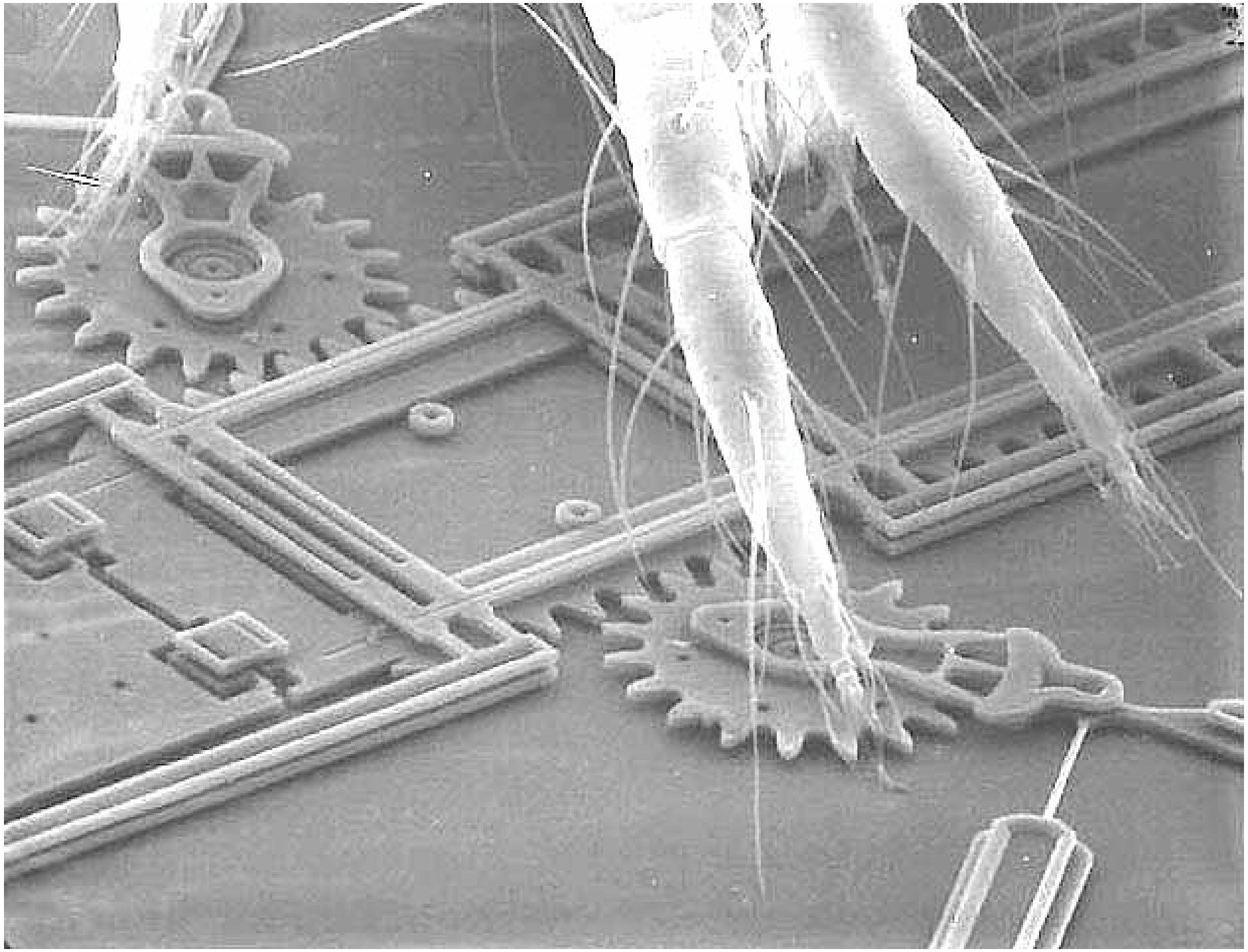
- MEMS <u>structures</u> can be actuated (= “moved”) **laterally** or **vertically**

- Actuation mechanisms (more in future lectures)
  - Electrostatic
    - Capacitor-structures: +/- charges attracted
    - Simple, low energy levels, enough for RF applications
  - Thermal
  - Magnetic
  - Piezoelectric
    - Strain (= “tøyning”) produces an electric field, - and opposite!

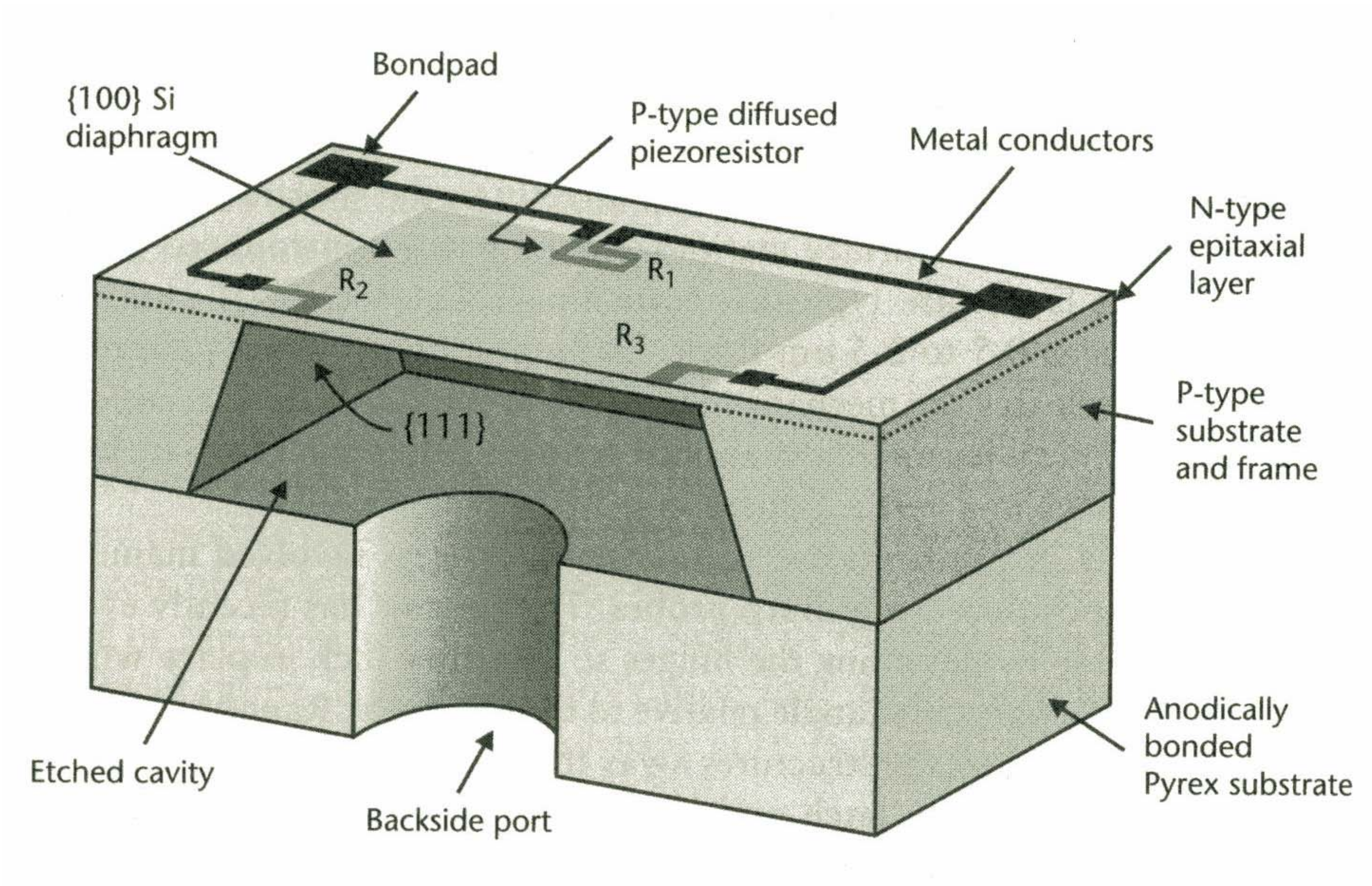
Some applications of MEMS

- **Automotive industry**
  - Micro accelerometers
    - Airbag-sensors (InfineonSensoNor)
  - Tire pressure sensors
- **Oil industry**
  - Pressure sensor in oil wells and oil tubes
- **Navigation**
  - Gyroscope
- **Biomedical**
  - Micro fluidic, chemical analysis
  - Implants
- **Optics**
  - Micro mirrors for projector, micro lenses for mobile phones
- **Computer industry**
  - Ink printer-head
- **Wireless communication**
  - RF MEMS switches

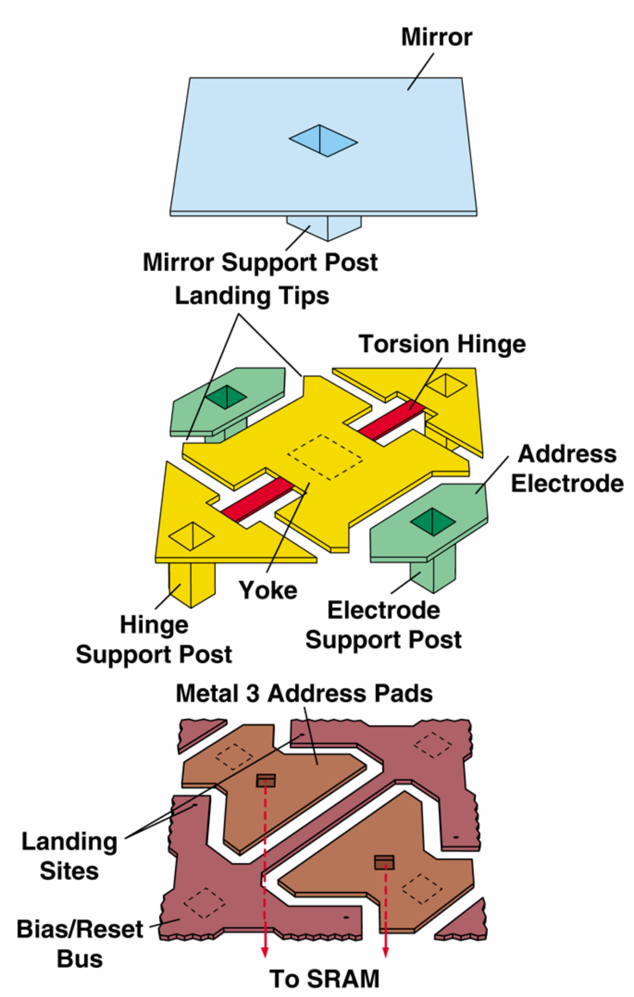
Micro motor fra Sandia



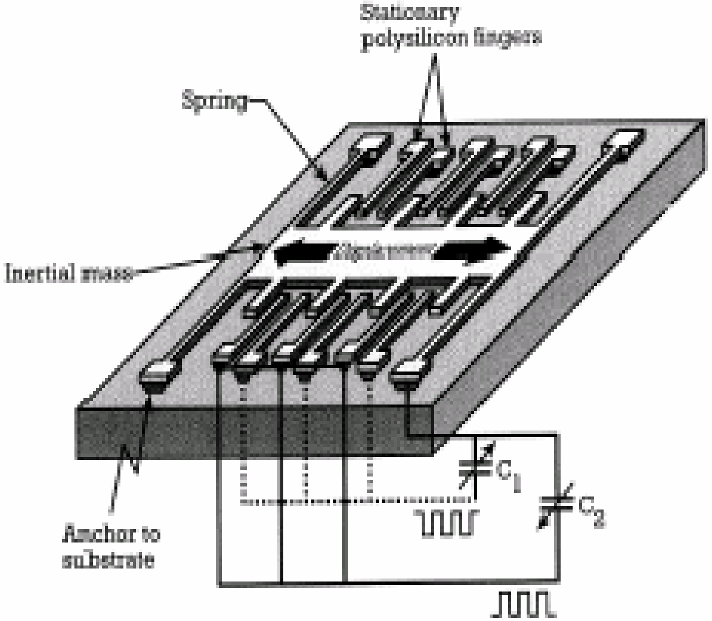
Pressure sensor



Micro mirror

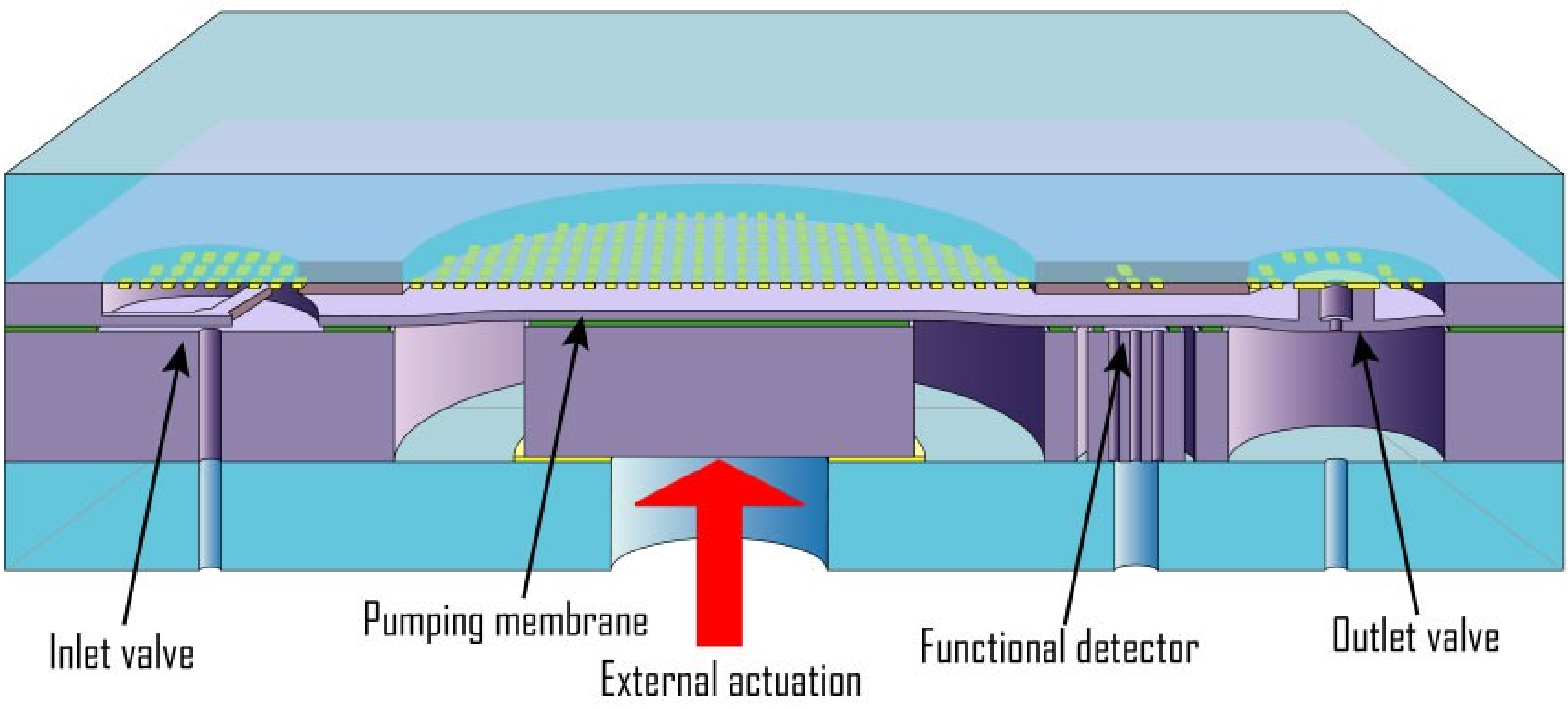


A Capacitive Accelerometer



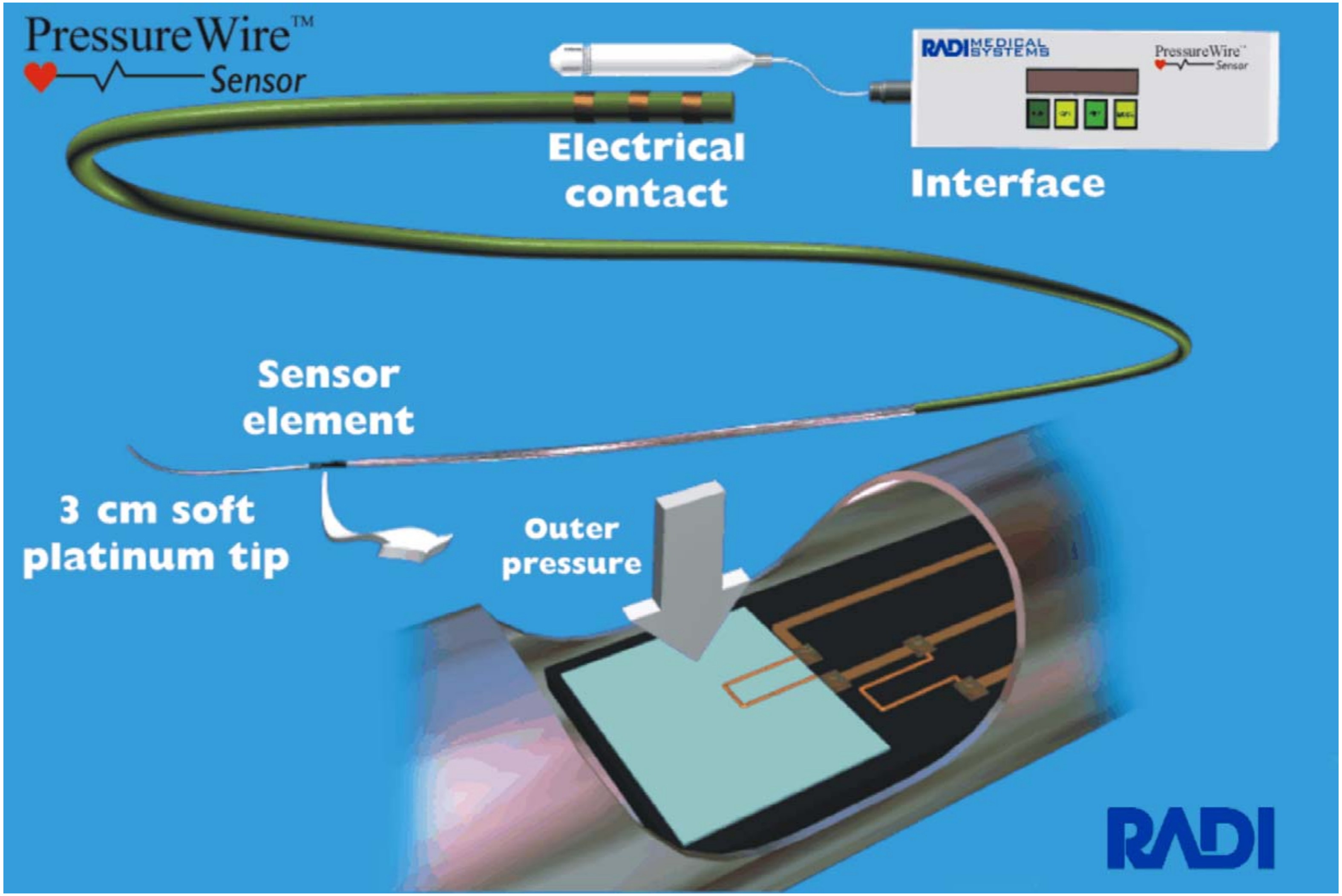
Technology Analysis: Drug Delivery

Debiotech Chip



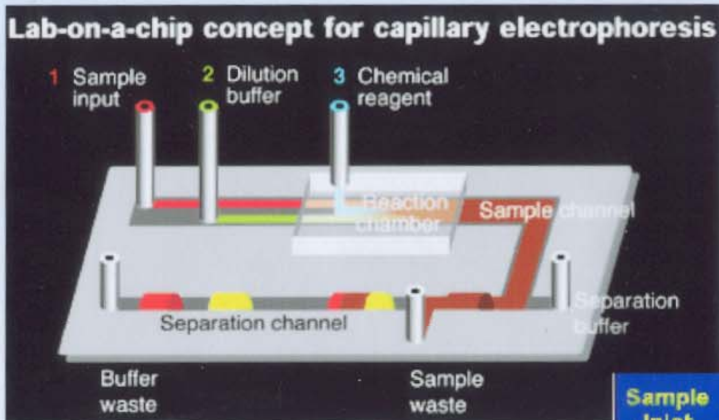
Source: Debiotech

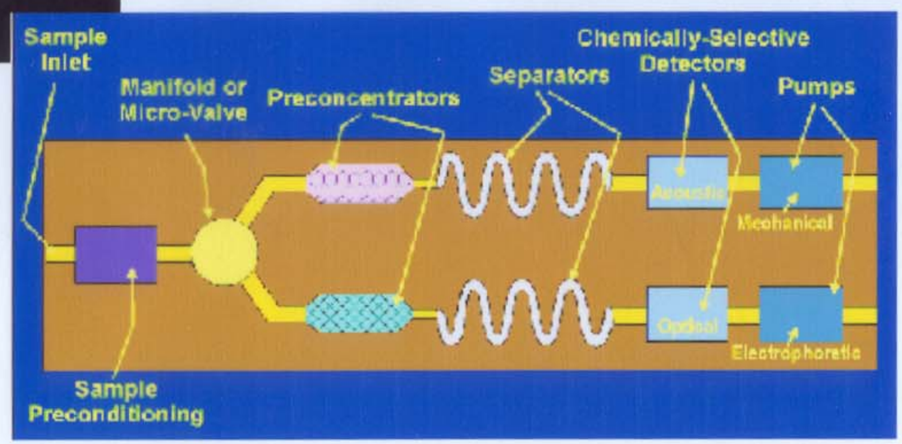
Radi Catheter



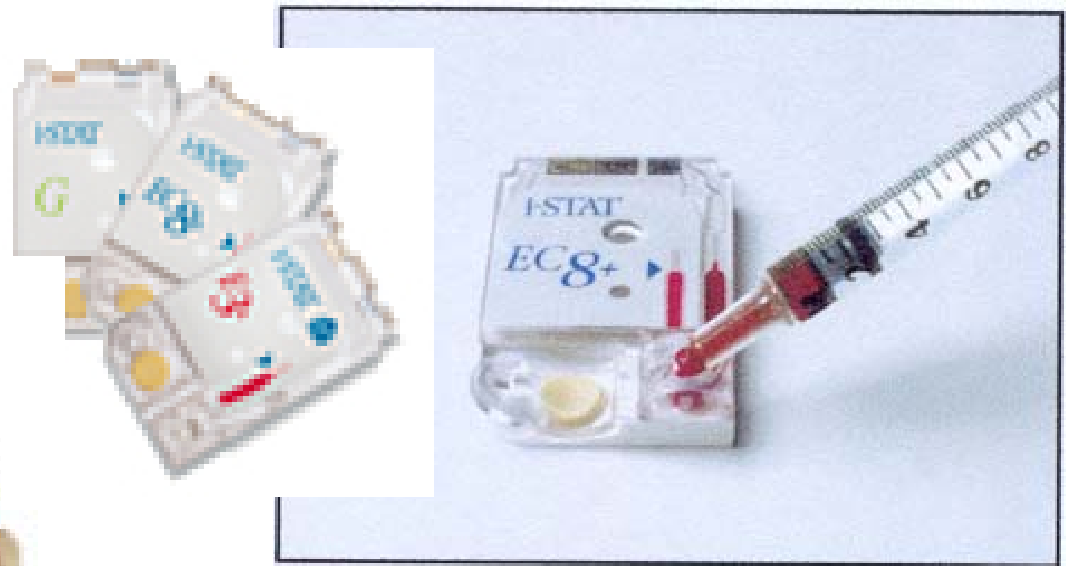
Biotechnology MEMS

"Lab-on-a-Chip"





iSTAT



- blood analysis
  glucose, urea, pH, blood gases,
- portable POC device
- analyser + disposable cartridges
- microfluidic channels
- micro-fabricated thin-film electrodes

Today's lecture

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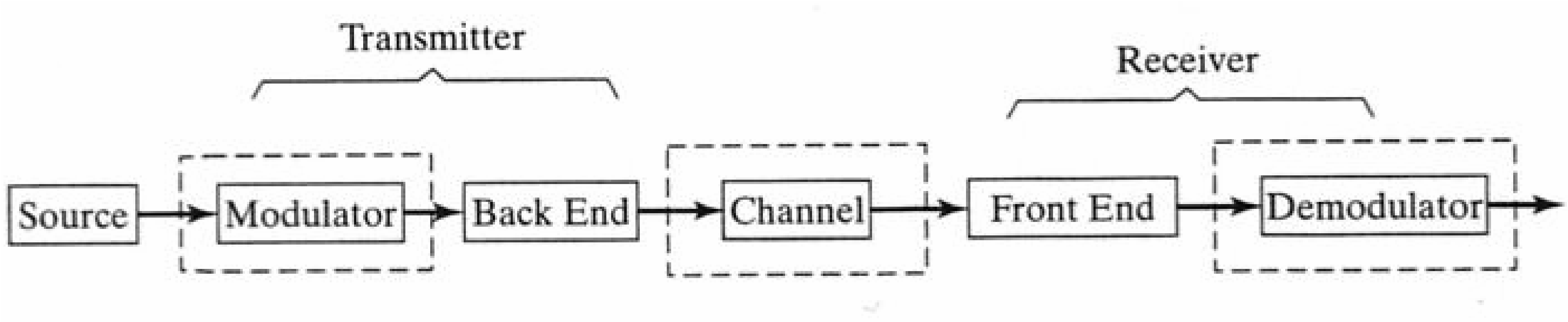
RF-systems in general

- Radio waves are used for transmitting/receiveing
    - Electromagnetic waves (Maxwells equations)
- Basic component: radio **”transceiver”**
    - Transmitter + Receiver
    - Methods for transmission
        - TDMA (Time Division Multiplexing Access)
        - FDMA (Frequency D M A)
- Signal quality depends on
    - Position
    - Environment, reflection
        - ”Multipath”
    - Noise (S/N-ratio, BER= bit error rate)

General communication system



Carrier modulation to represent Bit flow

Radio channel introduces noise and interference

Receiver converts the signal before demodulation

→ **High performance components are required!**

RF-systems

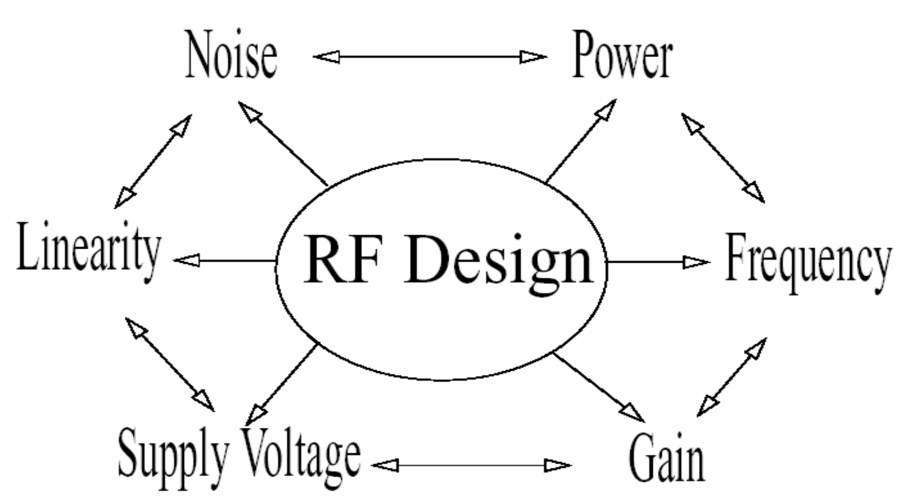
- Efficiency/performance of RF-systems
  - Ability to transfer **power**
  - Simultaneously use of limited **bandwidth**

- The frequency resource is limited
  - ”Sharp” RF-filtering needed to separate channels
  - The quality and performance of the RF components are critical to implement wireless communication systems
  - → **RF MEMS can meet critical requirements!**

RF design

- → **A major challenge for circuit designers!**
  - Many aspects have to be considered when doing RF design

RF Design Hexagon
Multi-objective approach



Jerzy Dabrowski, CMOS RF Transceiver Design, 2004

- CMOS-technology is a strong candidate for implementing critical parts of a transceiver!
  - **BUT not able to fulfill all requirements of component performance**

Implications of RF vs. circuit technology

- Increased frequency:
  - → shorter wavelength
    - in vacuum: $$\lambda \cdot f = c$$
  - → signal variations in short physical distances
    - voltage V, current I are not constant over the component dimension: → waves!
  - → smaller component dimensions are desired
    - small tolerance fabrication
    - micromachining

Table 1-1 IEEE Frequency Spectrum

Frequency Band	Frequency	Wavelength
ELF (Extreme Low Frequency)	30–300 Hz	10,000–1000 km
VF (Voice Frequency)	300–3000 Hz	1000–100 km
VLF (Very Low Frequency)	3–30 kHz	100–10 km
LF (Low Frequency)	30–300 kHz	10–1 km
MF (Medium Frequency)	300–3000 kHz	1–0.1 km
HF (High Frequency)	3–30 MHz	100–10 m
VHF (Very High Frequency)	30–300 MHz	10–1 m
UHF (Ultrahigh Frequency)	300–3000 MHz	100–10 cm
SHF (Superhigh Frequency)	3–30 GHz	10–1 cm
EHF (Extreme High Frequency)	30–300 GHz	1–0.1 cm
Decimillimeter	300–3000 GHz	1–0.1 mm
P Band	0.23–1 GHz	130–30 cm
L Band	1–2 GHz	30–15 cm
S Band	2–4 GHz	15–7.5 cm
C Band	4–8 GHz	7.5–3.75 cm
X Band	8–12.5 GHz	3.75–2.4 cm
Ku Band	12.5–18 GHz	2.4–1.67 cm
K Band	18–26.5 GHz	1.67–1.13 cm
Ka Band	26.5–40 GHz	1.13–0.75 cm
Millimeter wave	40–300 GHz	7.5–1 mm
Submillimeter wave	300–3000 GHz	1–0.1 mm

Today's lecture

- Background for course INF5490
- Course plan spring 2010

- Introduction
  - MEMS in general
  - RF-systems
  - MEMS in RF-systems

MEMS in RF-systems

- RF MEMS development started in the 90s
  - 1990: the first MEMS microwave switch better than GaAs (Hughes Res Lab)
  - 1995: RF MEMS switches from Rockwell Science & TI
  - From 1998: some universities do research in RF MEMS
    - Univ of Michigan, Univ of Calif Berkeley, Northeastern Univ, MIT, Columbia Univ, CMU (Carnegie Mellon), etc.
  - Some relevant companies:
    - Analog Devices, Motorola, Samsung, ST Microelectronics
  - Research institutes
    - Sandia, Fraunhofer, IMEC, LETI, SINTEF

Typical RF MEMS components

- Switches
- Variable capacitors
- Inductors
- Resonators
- Micromechanical filters
- Phase shifters

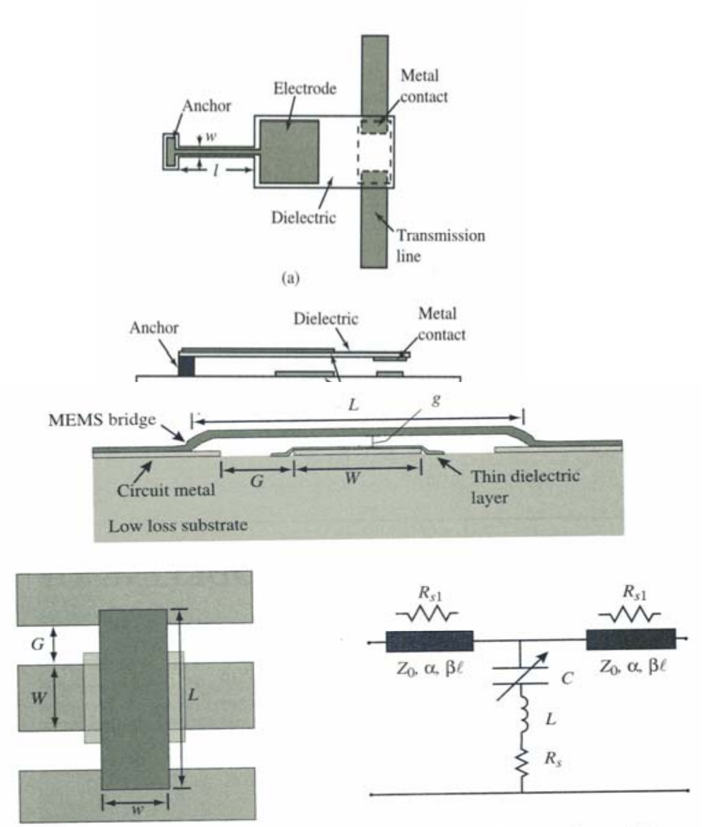


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).

Typical RF MEMS components

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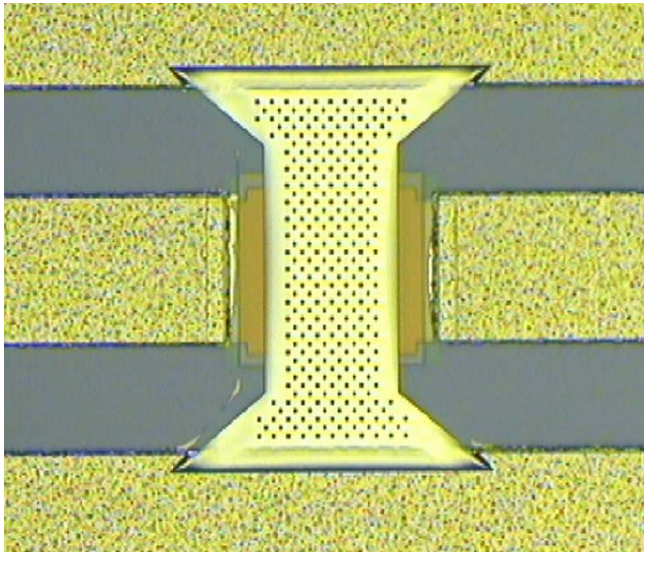

Ex.: microwave switch

- An early application of RF MEMS
  - Much activity, many examples exist
  - Benefits
    - **Electrostatic** actuation is typical: simple principle
      - El voltage → charge → attractive forces → mechanical movement
    - High signal linearity
    - Low DC ”standby power”
    - Low loss (”insertion loss”)
  - Challenges
    - Low switching speed (some µs)
    - Reliability of metal contacts (stiction, micro welding, wear-out)

Typical RF MEMS components

- Switches
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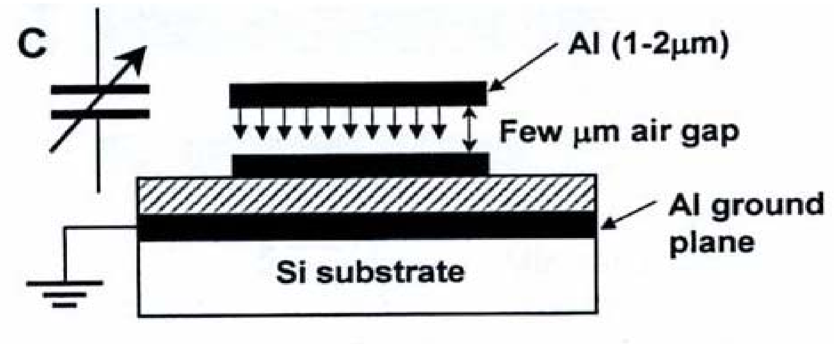

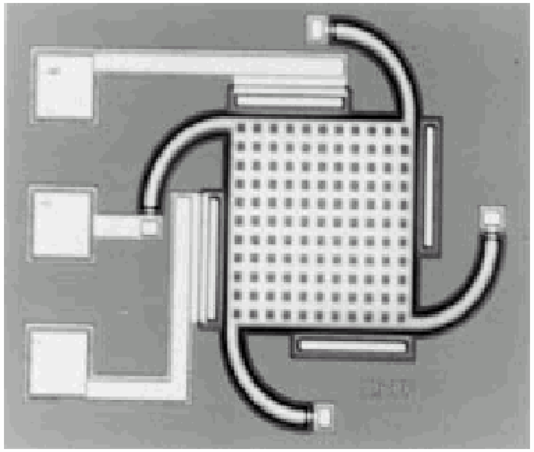

Typical RF MEMS components

- Switches
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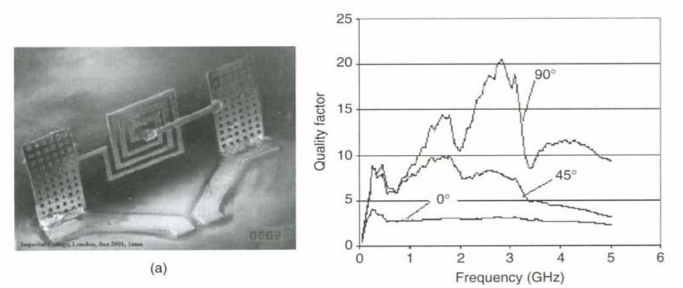
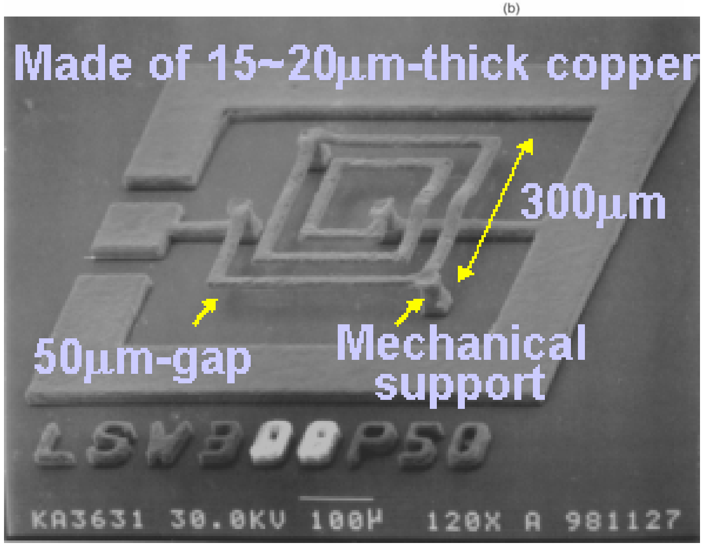


(a) (b)



Typical RF MEMS components

- Switches
- Variable capacitors
- Inductors
- Resonators
- Micromechanical filters
- Phase shifters

- MEMS also for: transmission lines and antennas

Typical RF MEMS components

- Switches
- Variable capacitors
- Inductors
- Resonators
- Micromechanical filters
- Phase shifters

- **In INF5490: focus on real vibrating structures →**
  - Can be used to implement
    - **oscillators**
    - **filters**
    - **mixers**

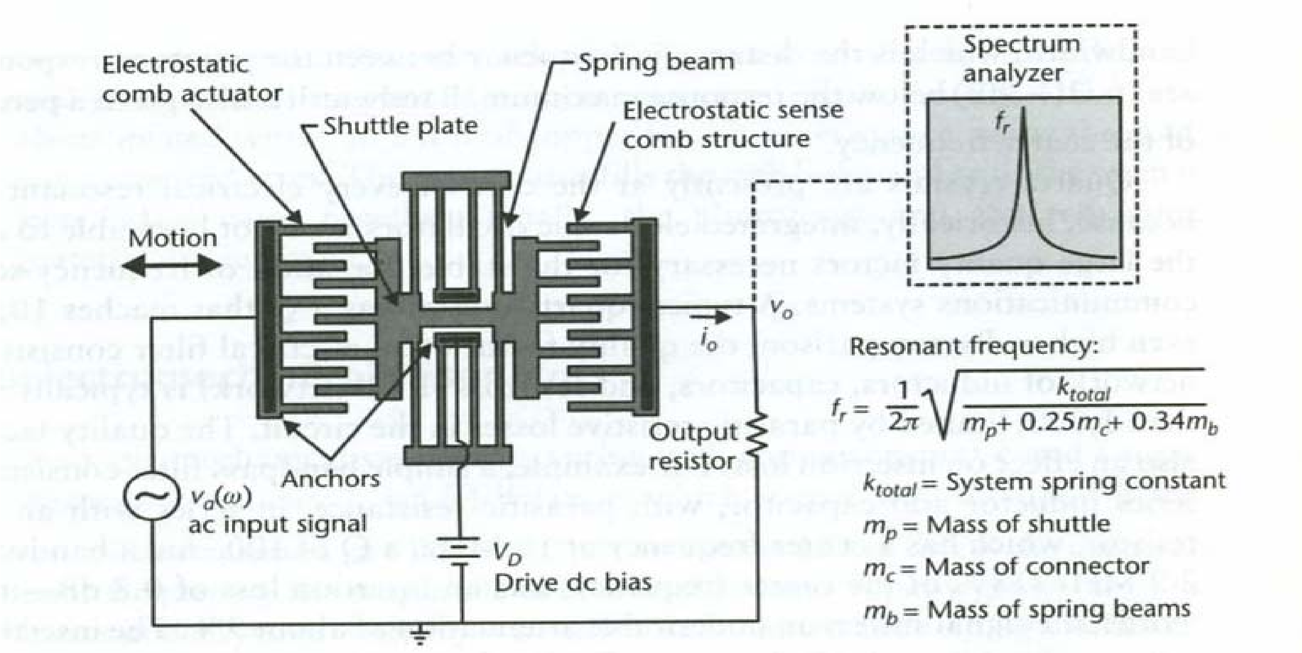
Micro-Electro-Mechanical resonators

High-Q with MEMS resonators: why?

- IC's cannot achieve Q's in the 1000's
  - transistors consume too much power to get Q
  - on-chip spiral inductors: Q ~ low 10's
  - off-chip inductors: Q's in the range of 100's
- *Vibrating mechanical resonances Q > 1000!*
- Competitor: quartz crystal resonators (in wristwatches) have extremely high Q's ~ 10^4 - 10^6

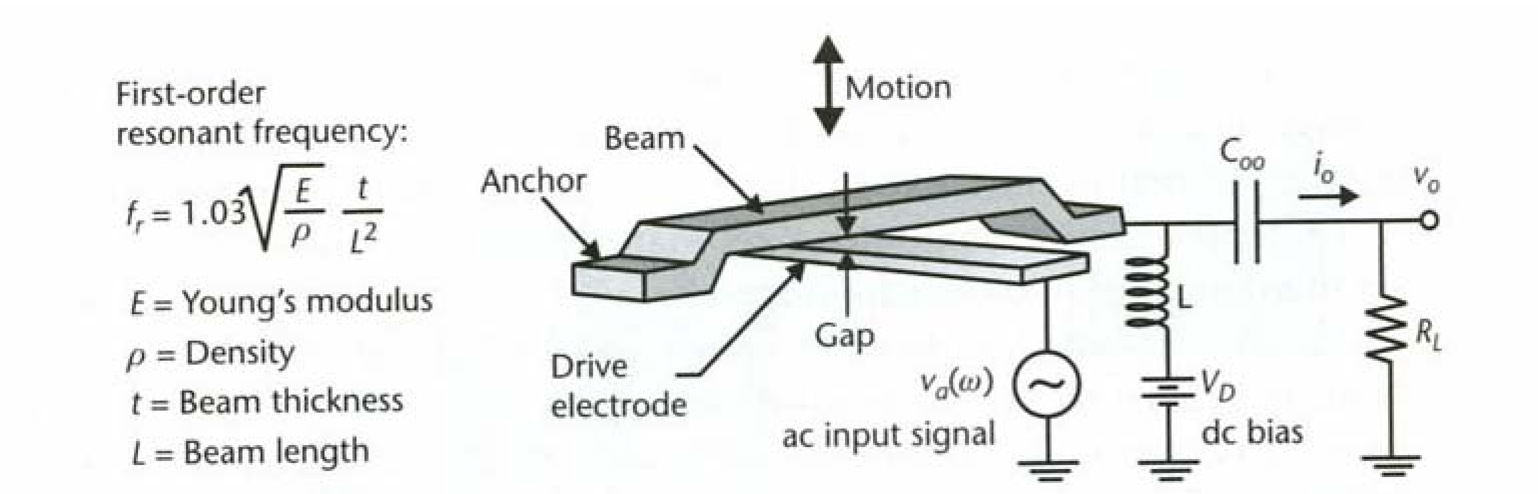
Source: Clark Nguyen, ESSDERC 2007.

Comb-resonator



lateral (horisontal) movement

Clamped-clamped beam resonator



Vertical movement

Benefits of RF MEMS

- Performance
- Power consumption
- Cost
- Miniaturization

Benefits of RF MEMS

- Higher **performance**
  - Increased selectivity: sharp filters
  - Increased Q-factor: stable ”tank” frequency
  - Reduced loss
  - Higher isolation, reduced cross talk
  - Reduced signal distortion
  - Larger bandwidth
- Lower **power consumption**
- **Reduced cost**
  - Batch processing
- Circuit and system **miniaturization**
  - System integration (μelectronics + MEMS)
    - Packaging: Multi-chip module
    - Monolithic integration: SoC (System-on-Chip)

Challenges in RF transceiver implementation of today

- Performance
- Miniaturization
- Reconfigurability

Challenges in RF transceiver implementation of today

- **Performance**
  - Integrated microelectronic components have **limited** RF performance
    - Technology: GaAs, bipolar Si, CMOS, PIN-diodes
    - ex. PIN-diode switch (inefficient), RF filter (difficult!)
  - **Off-chip components in RF systems** are needed!
    - matching networks, filters
    - crystal oscillators, inductors, variable capacitors

- **Miniaturization**
  - **Discrete, off-chip** components hinder miniaturization
  - PCB → uses up a large space

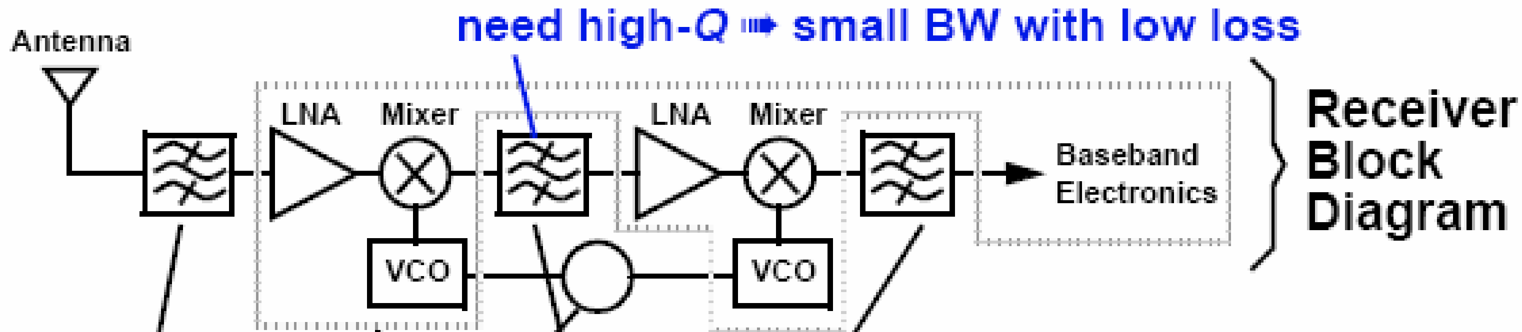
Challenges in RF transceiver implementation of today

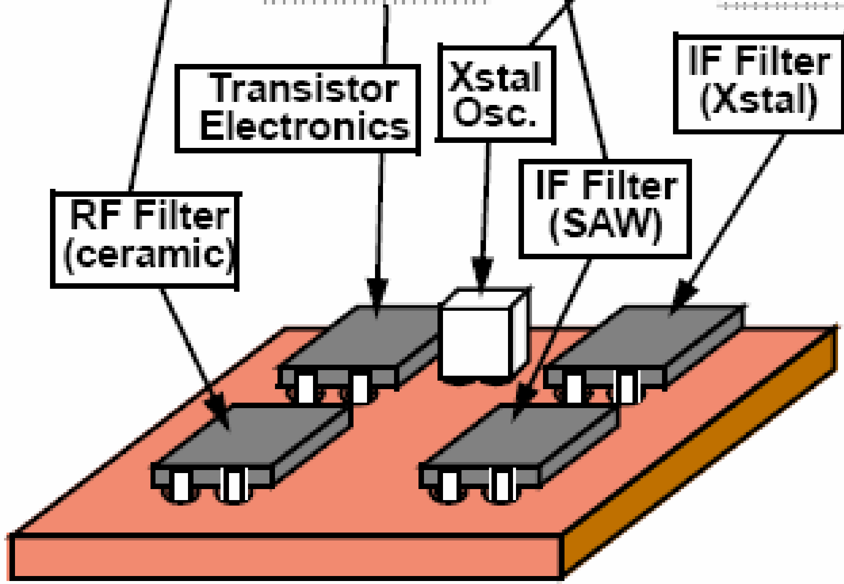
- **Reconfigurability**
  - Increasing demands exist that one single RF transceiver shall cover various standards and channels
    - Programmability is desired
  - Reconfigurable ”front-end” for ”sw defined radio”
    - RF MEMS may solve the problem!

Use of RF MEMS

- A) **Replacing** discrete components
- B) **New** integrated functionality
  - – New system architectures
    - Implement reconfigurable RF systems by using near ideal RF MEMS switches

Miniaturization of Transceivers

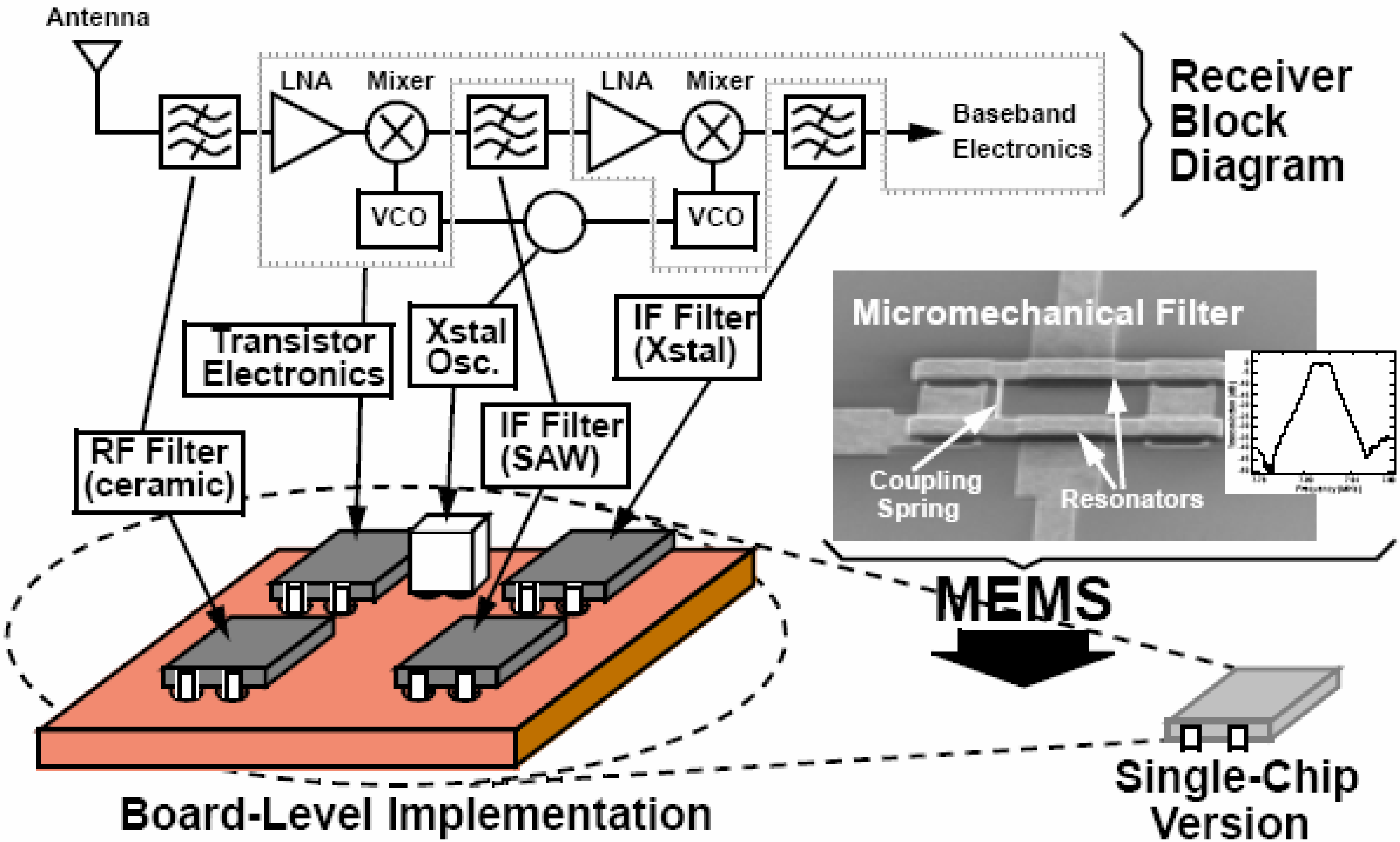




Board-Level Implementation

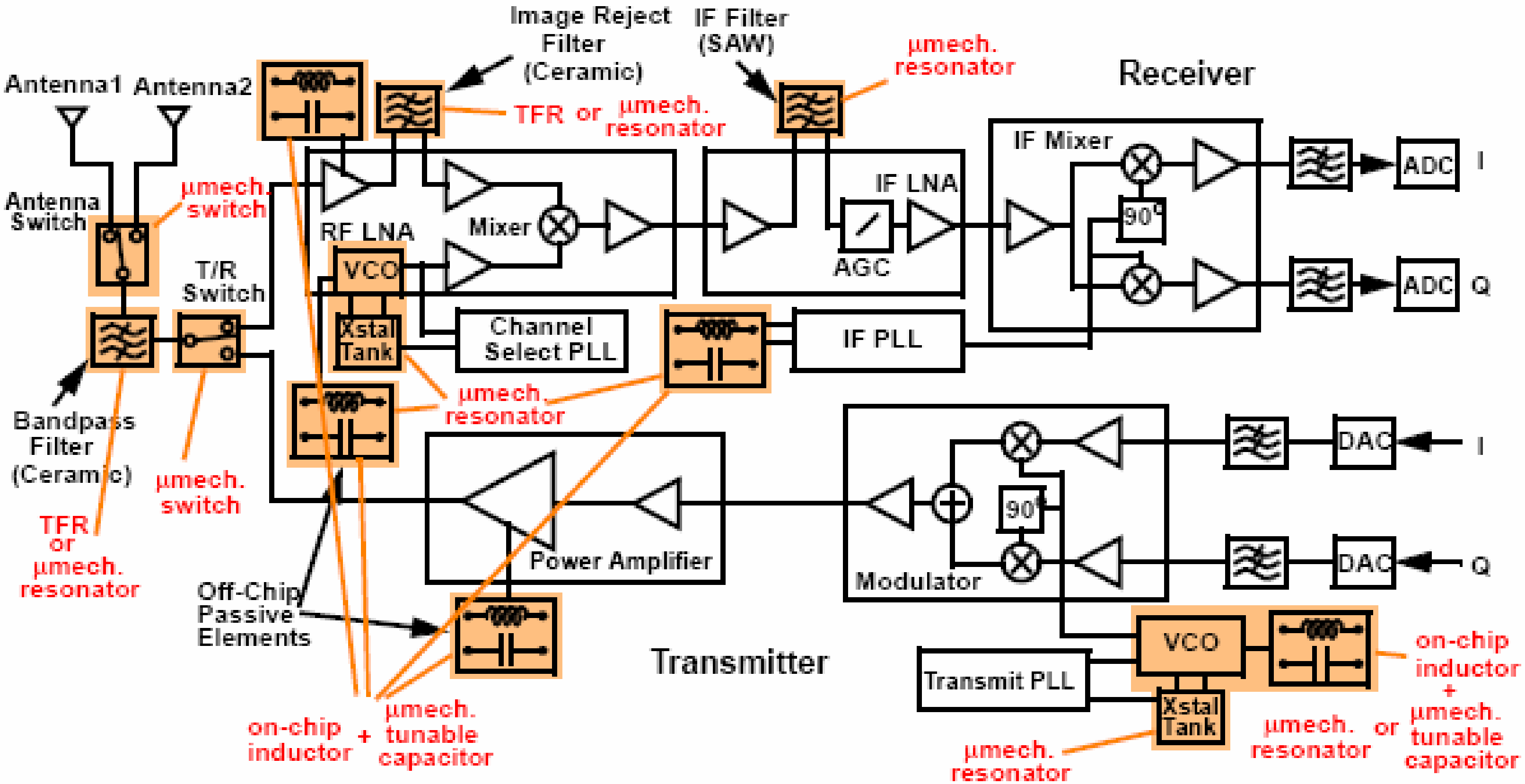
- High-*Q* functionality required by oscillators and filters cannot be realized using standard IC components ➠ use off-chip mechanical components
- SAW, ceramic, and crystal resonators pose bottlenecks against ultimate miniaturization

Target Application: Integrated Transceivers

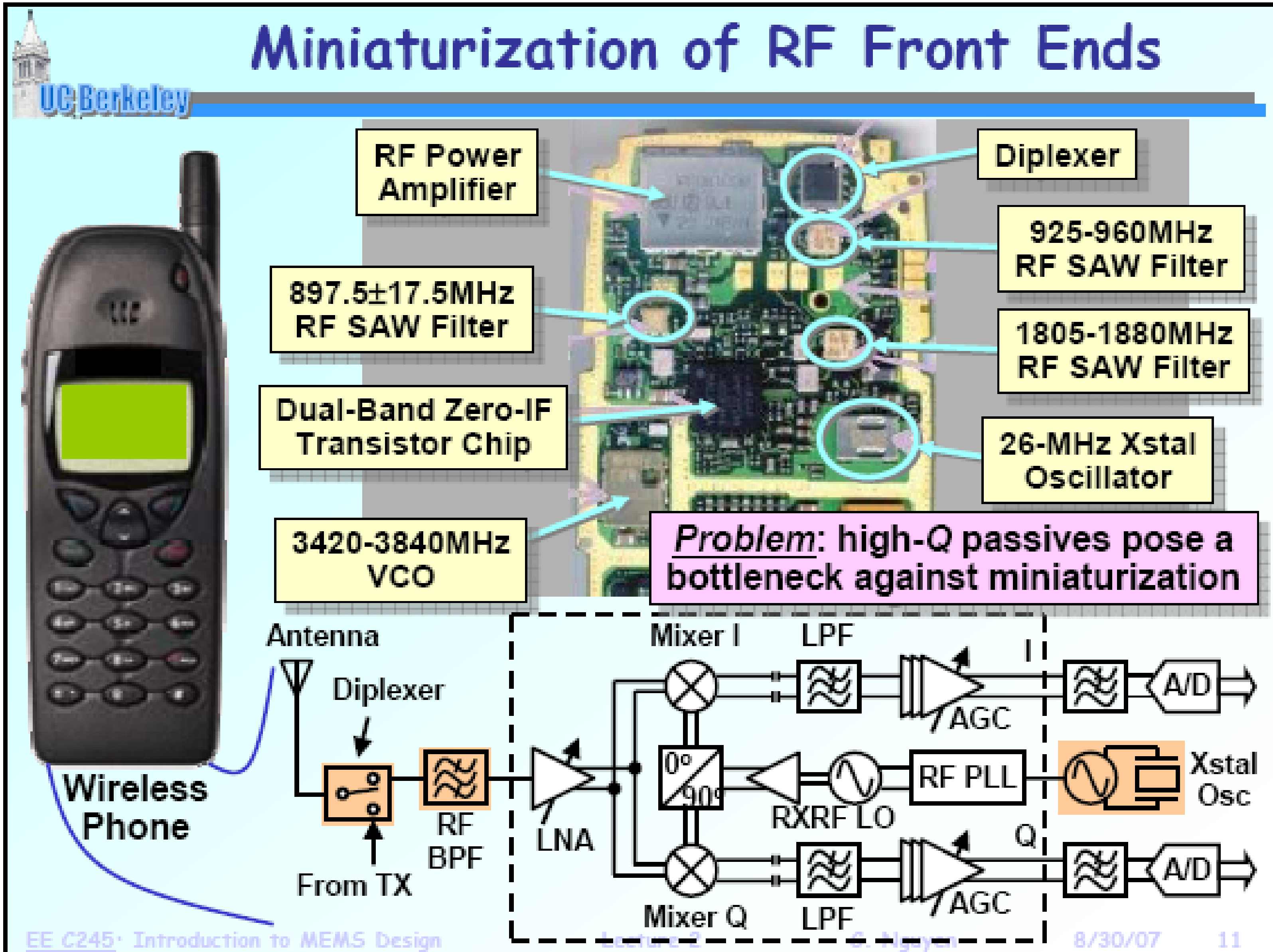


- Off-chip high-Q mechanical components present bottlenecks to miniaturization ➠ replace them with μmechanical versions

MEMS-Replaceable Transceiver Components



- A large number of off-chip high-Q components replaceable with μmachined versions; e.g., using μmachined resonators, switches, capacitors, and inductors


Miniaturization of RF Front Ends
UC Berkeley
RF Power Amplifier
Diplexer
925-960MHz RF SAW Filter
897.5±17.5MHz RF SAW Filter
1805-1880MHz RF SAW Filter
Dual-Band Zero-IF Transistor Chip
26-MHz Xstal Oscillator
3420-3840MHz VCO
Problem: high-Q passives pose a bottleneck against miniaturization
Wireless Phone
Antenna
Diplexer
From TX
RF BPF
LNA
Mixer I
LPF
I
AGC
A/D
0°
90°
RXRF LO
RF PLL
Xstal Osc
Q
Mixer Q
LPF
AGC
A/D
EE C245: Introduction to MEMS Design
Lecture 2
C. Nguyen
8/30/07
11

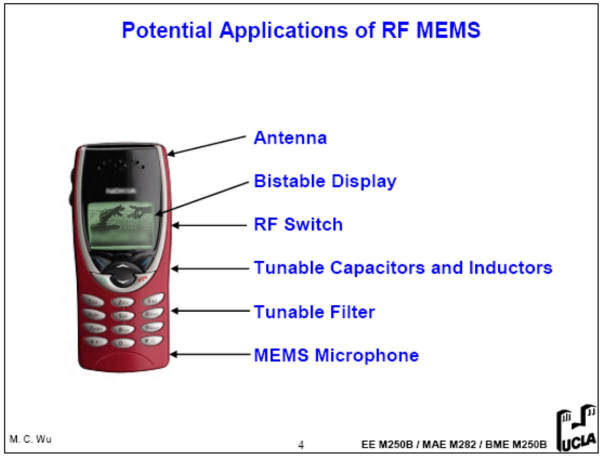
C. Nguyen]

New RF architectures

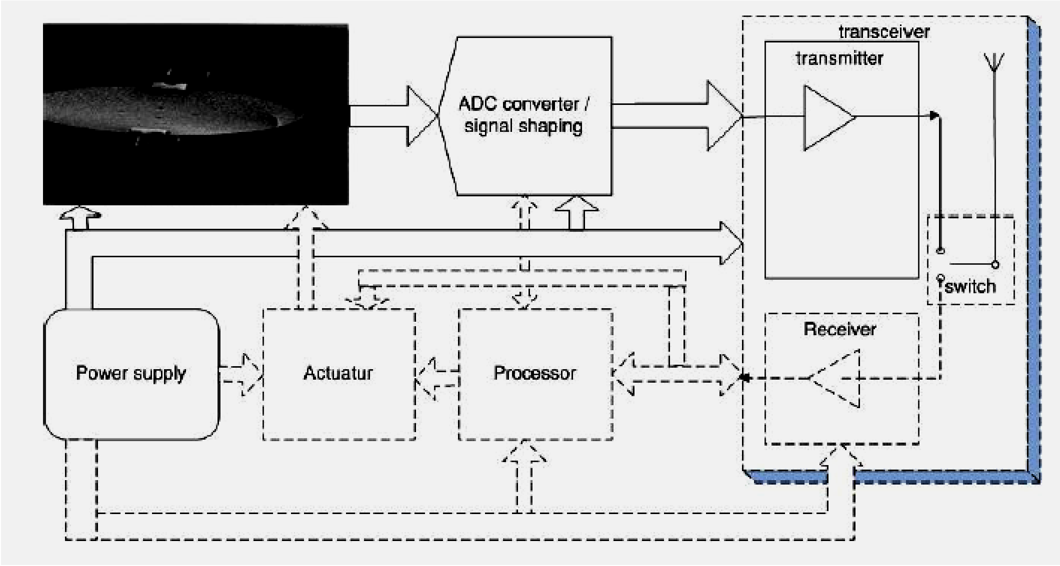
- New ways to design RF systems
  - MEMS technology may be used to implement a lot of small, low cost basic modules
    - Switches may then be used to switch between the modules
  - MEMS makes it easier to perform module based design
    - Micromachined “lumped” (= “discrete”) components may replace distributed components
    - Enhanced system integration flexibility

Perspectives

- Use of wireless (personal) communication increases
  - 3-4 G systems
  - Mobile terminals
  - Multi-standard units
    - ”15 radio systems in each unit?”



- Wireless sensor networks (WSNs)
  - Sensors everywhere
    - compact, intelligent
  - ”ambient intelligence”



[J. Ekre]

Current challenges for RF MEMS

- Actuation speed needs to be increased
  - Switches (typical 1-100 µs)
- Operating RF frequency needs to be increased for mechanical resonators and filters
  - Up to some GHz today (3 – 5 GHz)
- Good RF filter banks should be implemented
- Higher reliability
- Packaging
  - Vacuum
  - Modules of various materials and technologies
    - SiP – ”System-in-Package”
- **Monolithic integration** is desired
  - SoC – System-on-Chip

Integrated solutions?

- Fabrication of microelectonics and MEMS have much in common
- Combination of electronics and micromechanics
  - Integrated solutions on a Si chip
    - → **"Radio-on-a-chip"!**
  - One option: CMOS-MEMS