INF5490 RF MEMS

L1: Introduction. MEMS in RF

Spring 2008, Oddvar Søråsen
Department of informatics, UiO

Today's lecture

- Background for course INF5490
- Course plan spring 2008

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

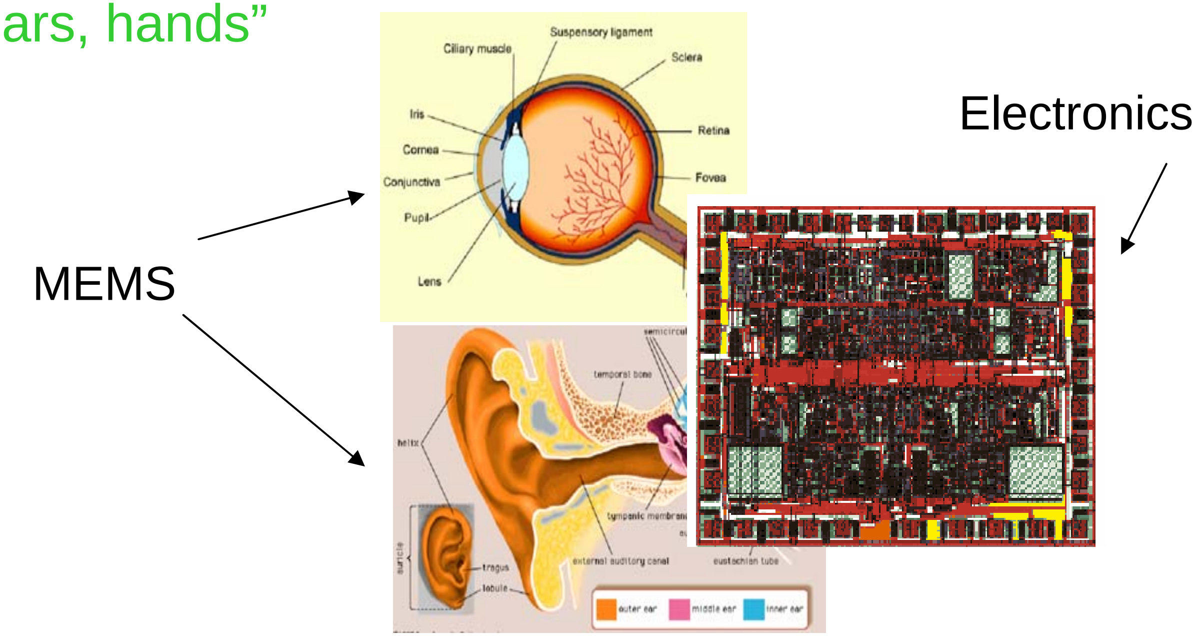
INF5490 RF MEMS

- New Master course at Ifi spring 05
  - ca 10-15 students/year
- **MEMS** (Micro Electro Mechanical Systems) is a relativ new research activity in the NANO group
  - (Ifi area of competence: MES, Micoelectronic Systems)

- Inspired by:
  - **National focus** on micro- and nano-technology (RCN)
  - **MiNaLab** (Micro Nano Technology-lab)
    - 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: ”eyes, ears, hands”



Why MEMS in the Nano-group?

- New possibilities to implement **integrated, miniaturized systems**
  - **B.** MEMS – components need **interfacing** electronics!

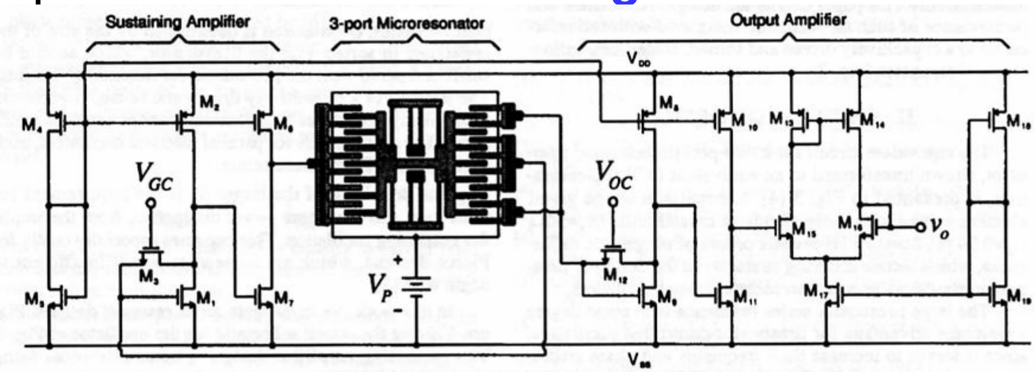


Fig. 4: Circuit schematic for the µresonator oscillator.

- Present **competence** at MES
  - Competence in modeling, analysis and implementing VLSI circuits and complex systems

Personal competence

- Physics → modeling and design of VLSI → system design → computer architecture/multiprocessors → **MEMS/microelectronics**

- Expanding my competence during a sabattical: MiNaLab 03/04
- Studying books and articles
- Seminars
  - RF MEMS-seminar by M.A. 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
- 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

Choice of focus → RF MEMS

- MEMS is a *broad* field of research
  - Need of focus → RF MEMS!

- ***”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 competance in circuit technology
- The course fits well into the MES education

- Actual theme
  - Increasing interest internationally for using MEMS in RF systems
    - Wireless Sensor Networks (WSNs)
- Large market: **wireless communication**
  - Tele communication, mobile business
  - Distributed intelligence (observation, actuation)
  - Environmental surveillance – sensor nodes
  - ”Ambient Intelligence”: units everywhere!
  - Patient surveillance - implants
- Growing commercial attention
- Basis for establishing new enterprises

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Information about course INF5490

- Course homepage:
  - http://www.uio.no/studier/emner/matnat/ifi/INF5490/v08/
  - Messages posted there!
- Weekly **lectures**
  - Thursday 10:15 – 12 in 3A
  - Detailed lectureplan on web
    - Lecture notes will be posted before lecture (pdf)

Group assignments

- **Class assignment** some weeks (consult web!)
  - Tuesday 14:15 – 16 in 3B
    - First time 29/1
  - Presenting plan and topics for ”obliger”
  - Presenting supporting literature
  - Assignments
    - Posted a week before
  - Practical aspects
  - Questions, discussion

Obliger

- **2 “obliger”** have to be **handed in**
  - Requred to take the exam
  - Hand in of 2 reports at specified deadlines
    - General guidelines available on web!
  - Each group consists of 2 students that collaborate
- Topic: micromechanical resonators and filters
  - Simulating using CoventorWare
    - 3-dim modeling, FEM-analysis (Finite-Element-Method)
    - High Level-modeling, ARCHITECT (new 2007)

CoventorWare

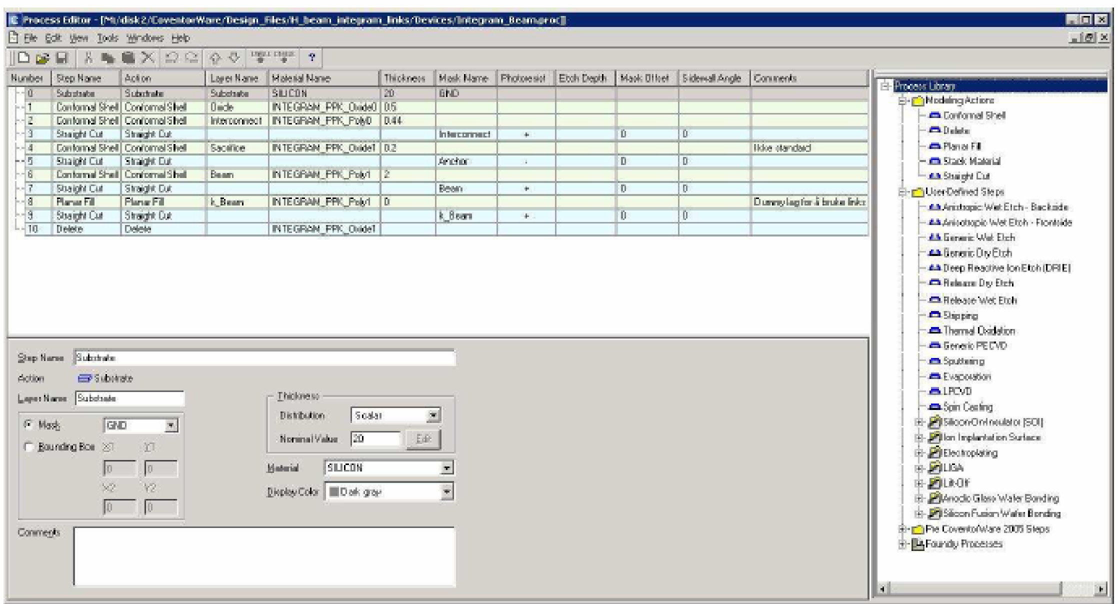
- “State-of-the-art” tool for FEM analysis
  - ”Finite-Element-Method”

- **“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!

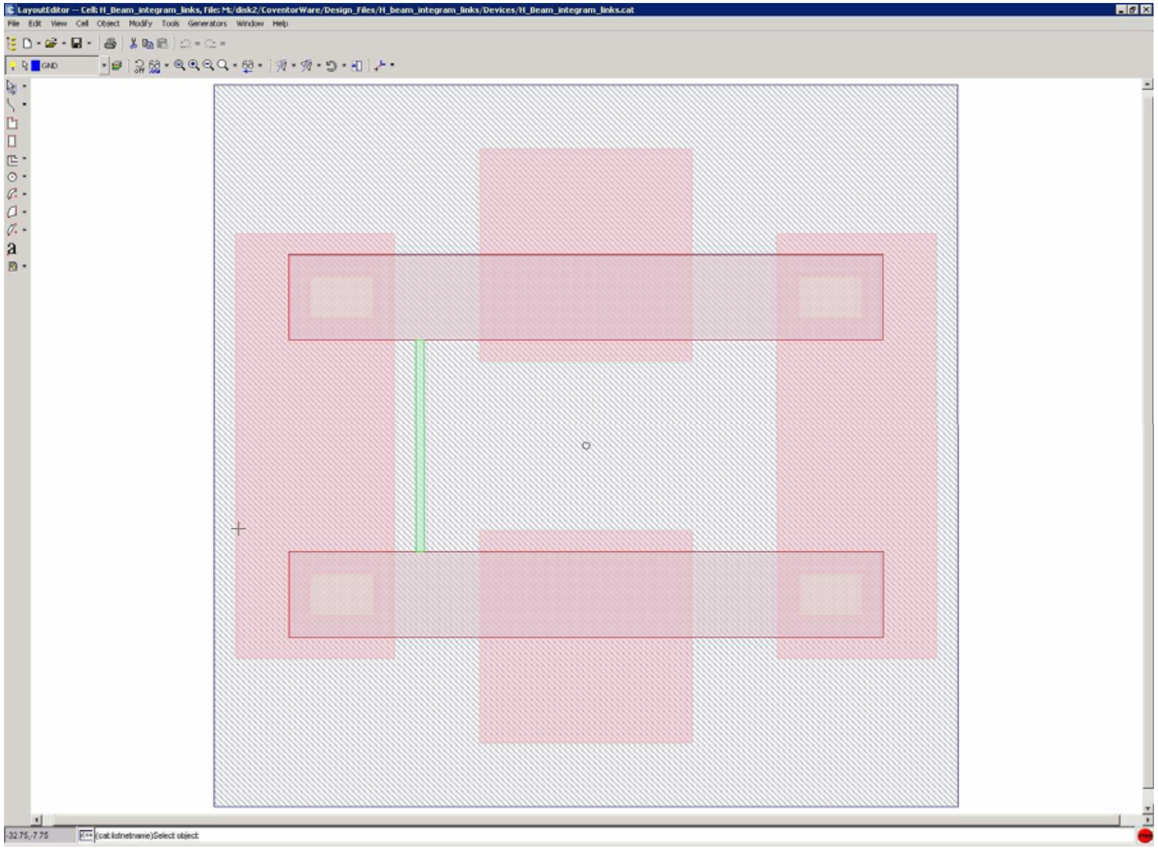
COVENTOR ACCELERATING MEMS Innovations™

Process-description

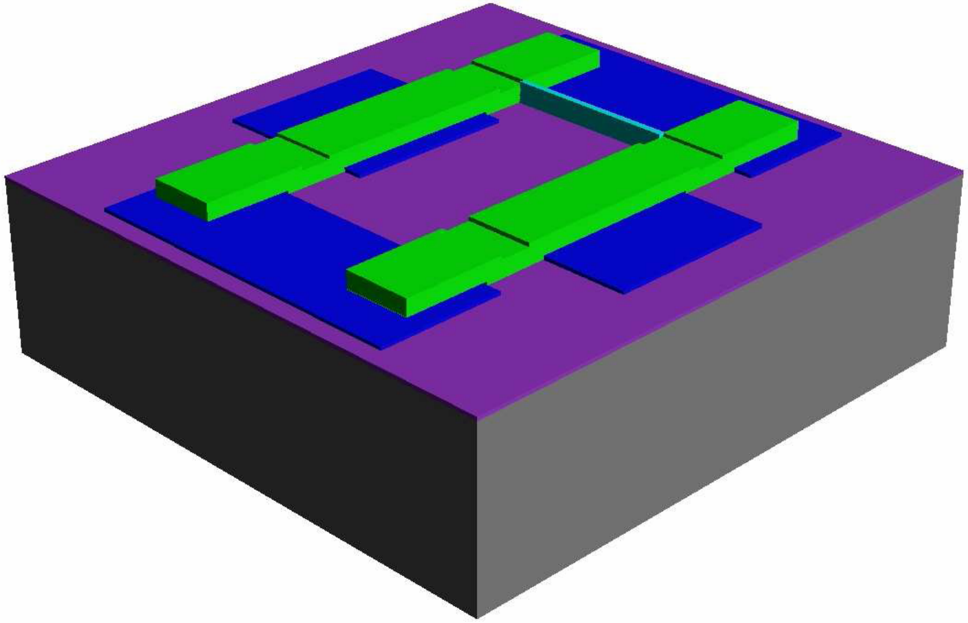
- Specify a **process file** compatible with the relevant “foundry” -process
  - Reduce complexity, idealization
  - Realistic: characteristic process features should be kept



Layout

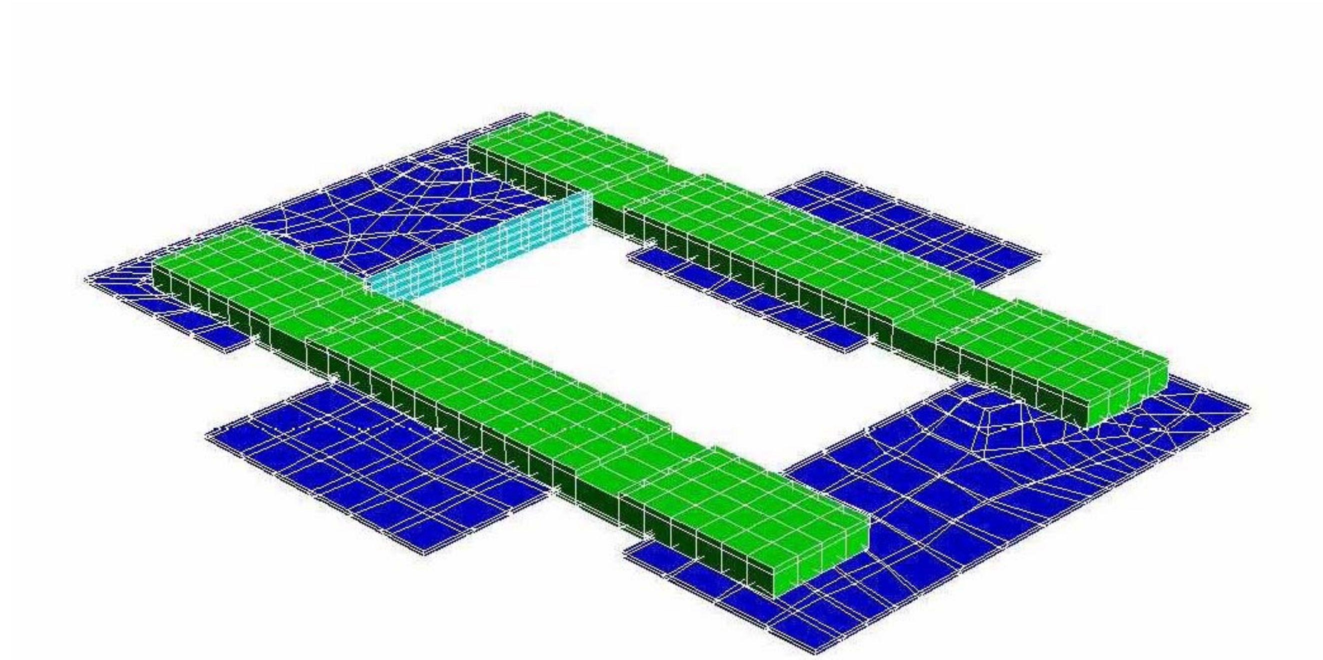


Building a 3-D model

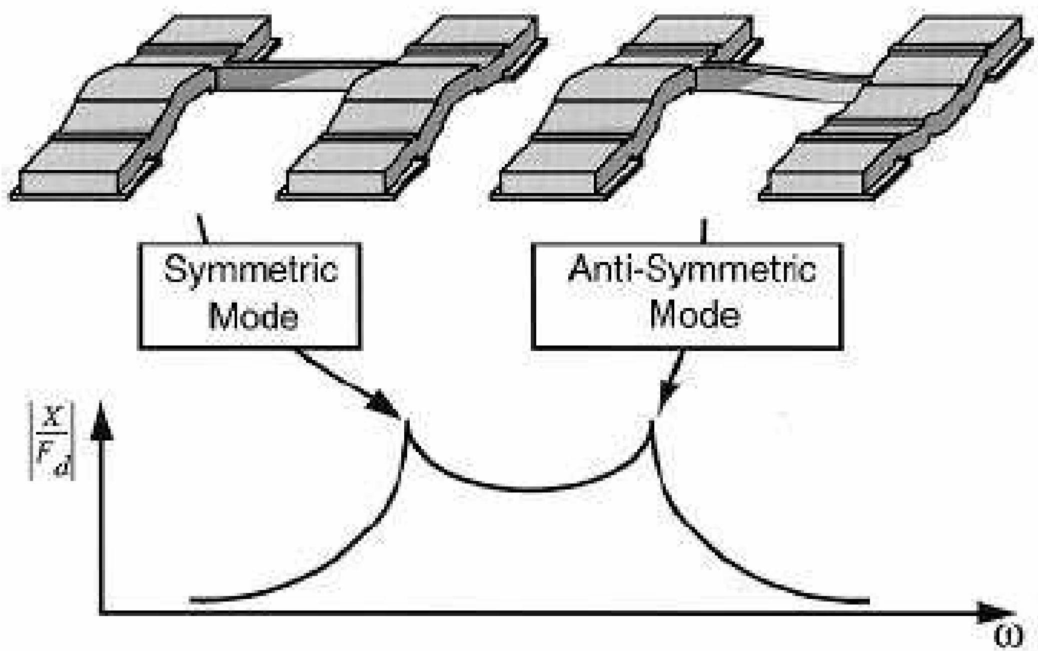


O-P Arhaug

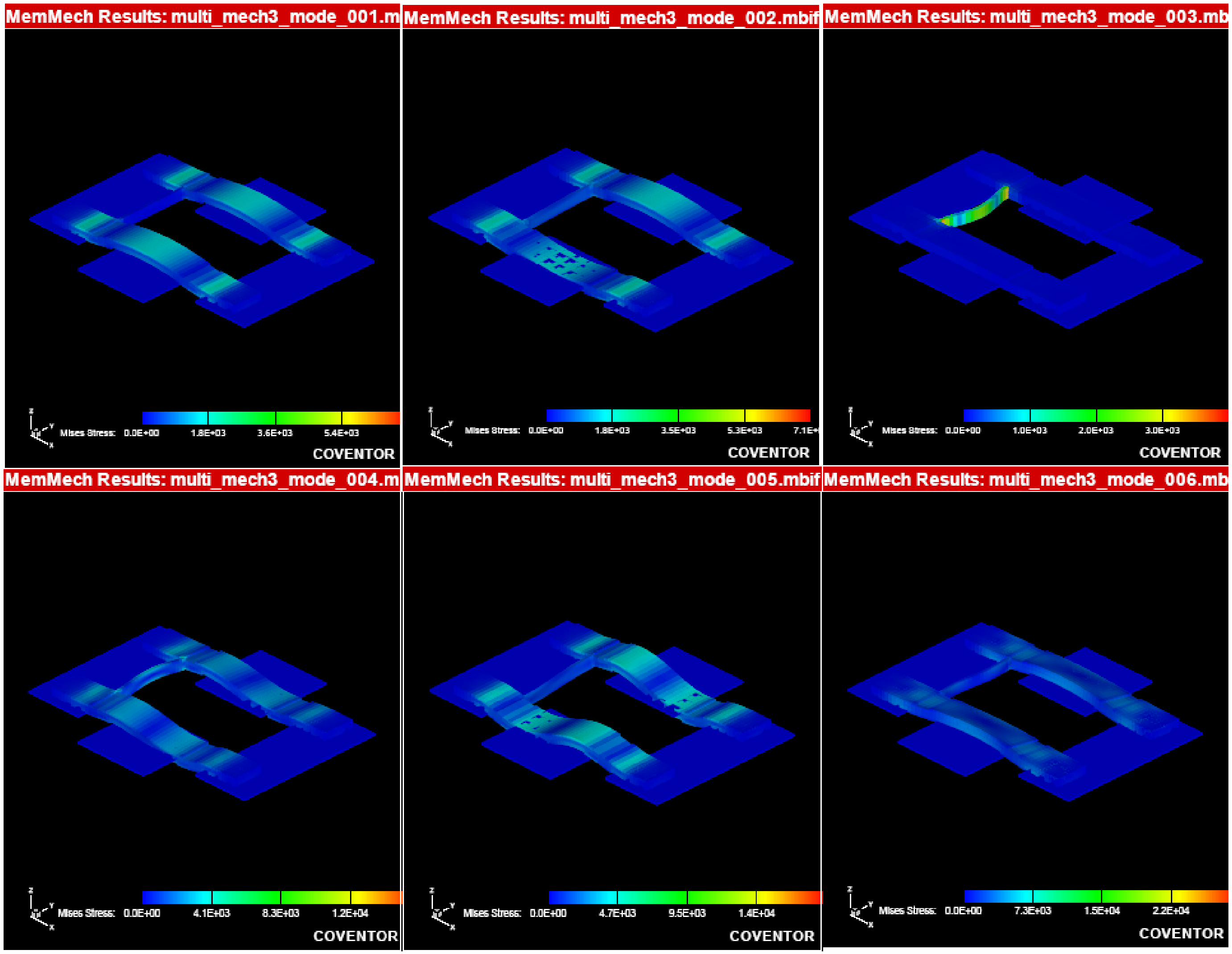
Meshed 3D -model for FEM analysis



Filter-function: 2 identical resonators

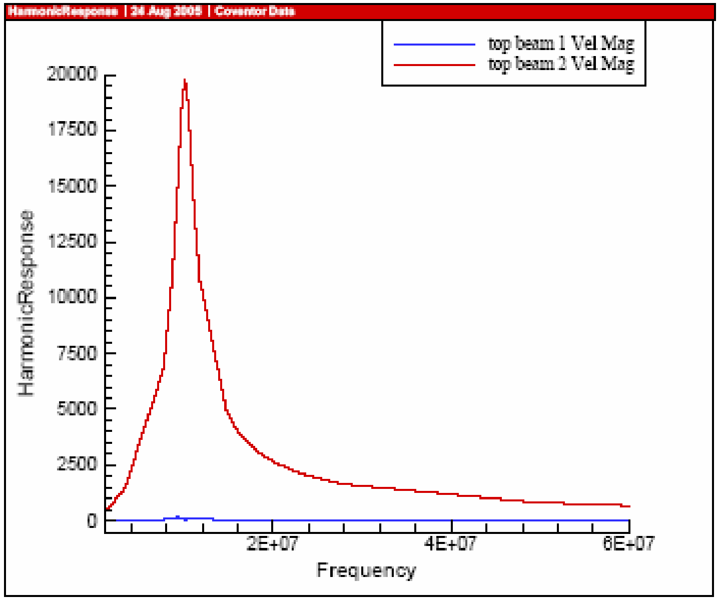


In phase Out of phase

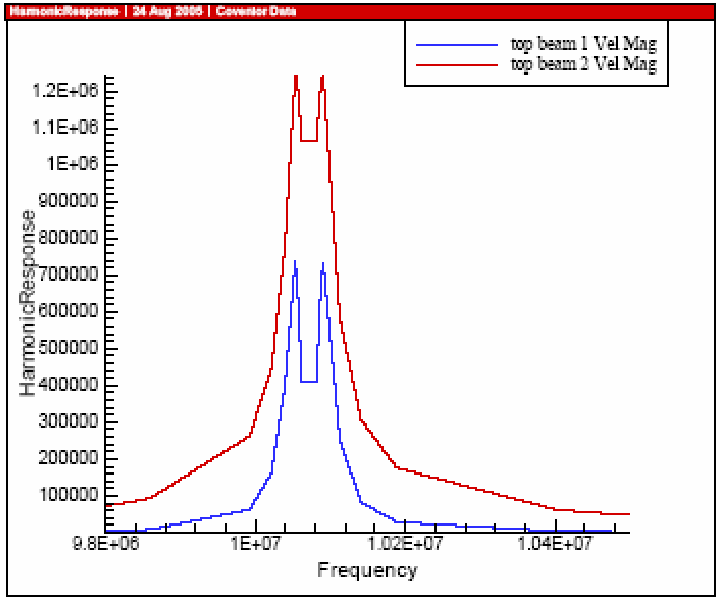


CoventorWare simulations for 6 resonating modes (O-P Arhaug)

Harmonic response for specific dampings



(a) 0,1



(b) 0,001

O-P Arhaug

Exam

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

- Relevant exam questions will be posted on web later
    - List for 2007 is available now!

Themes covered in the course

- RF MEMS is a **multi disciplinary** field
- **Main topics**
  - Micromachining (1 week)
  - Modeling (1 week)
  - RF circuit design (1 week)
  - Guest lectures on MOEMS (2 weeks)
    - ***M**icro-**O**pto-**E**lectro-**M**echanical **S**ystems*
    - Professor Olav Solgaard, Stanford University
  - Typical RF MEMS circuit elements (8 weeks)
    - Operation principles, models/analysis and examples
    - Switches, phase shifters, resonators, filters, capacitors and inductors
  - Packaging (1 week)
  - 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
  - No single book is particularly good

- Lecture notes **(IMPORTANT!)**
  - → Most of the syllabus as lecture notes (ca. 1000)
  - Posted on web before lecture

- Supporting literature?
  - Overview of literature given on the web

Contact information

- Responsible lecturer
  - Oddvar Søråsen, room 3411, phone: 22 85 24 56
  - oddvar@ifi.uio.no
- Responsible for groups/obliger/CoventorWare:
  - Jan Erik Ramstad
  - janera@student.matnat.uio.no
- Contact person CoventorWare: support
  - Yngve Hafting, room 3408, phone: 22 85 0447
  - yngveha@ifi.uio.no
- web pages
  - http://www.uio.no/studier/emner/matnat/ifi/INF5490/v08/

Quality assurance

- Course assessor
  - 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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- Introduction
  - MEMS in general
  - RF-systems
  - MEMS in RF-systems

Introduction to the topic

- 2 disciplines: RF and MEMS
- RF – ”Radio frequency”
  - High frequencies MHz, GHz
  - Used in wireless transmission
  - Many characteristic properties of **high frequency designs**
    - Course, Fall (Tor Fjeldly), recommended!
      - INF5480 RF-circuits, theory and design
    - Central/needed topics covered in INF5490

The Technology is: MEMS

- MEMS – Micro Electro Mechanical Systems
  (Microsystems, MST – Micro System Technology etc.)
- **Micromachining is central!**
  - Used in IC fabrication (Silicon)
  - Various processes available today
    - Often proprietary, specialized for a product
    - Different from CMOS (”second source”)
- MEMS is a promising technology for RF applications
  - Course on MEMS given by Liv Furuberg, recommended
    - FYS4230 Micro- and nanosystem modeling and design
  - Some central topics are covered in INF5490

MEMS in general

- 2 types: 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

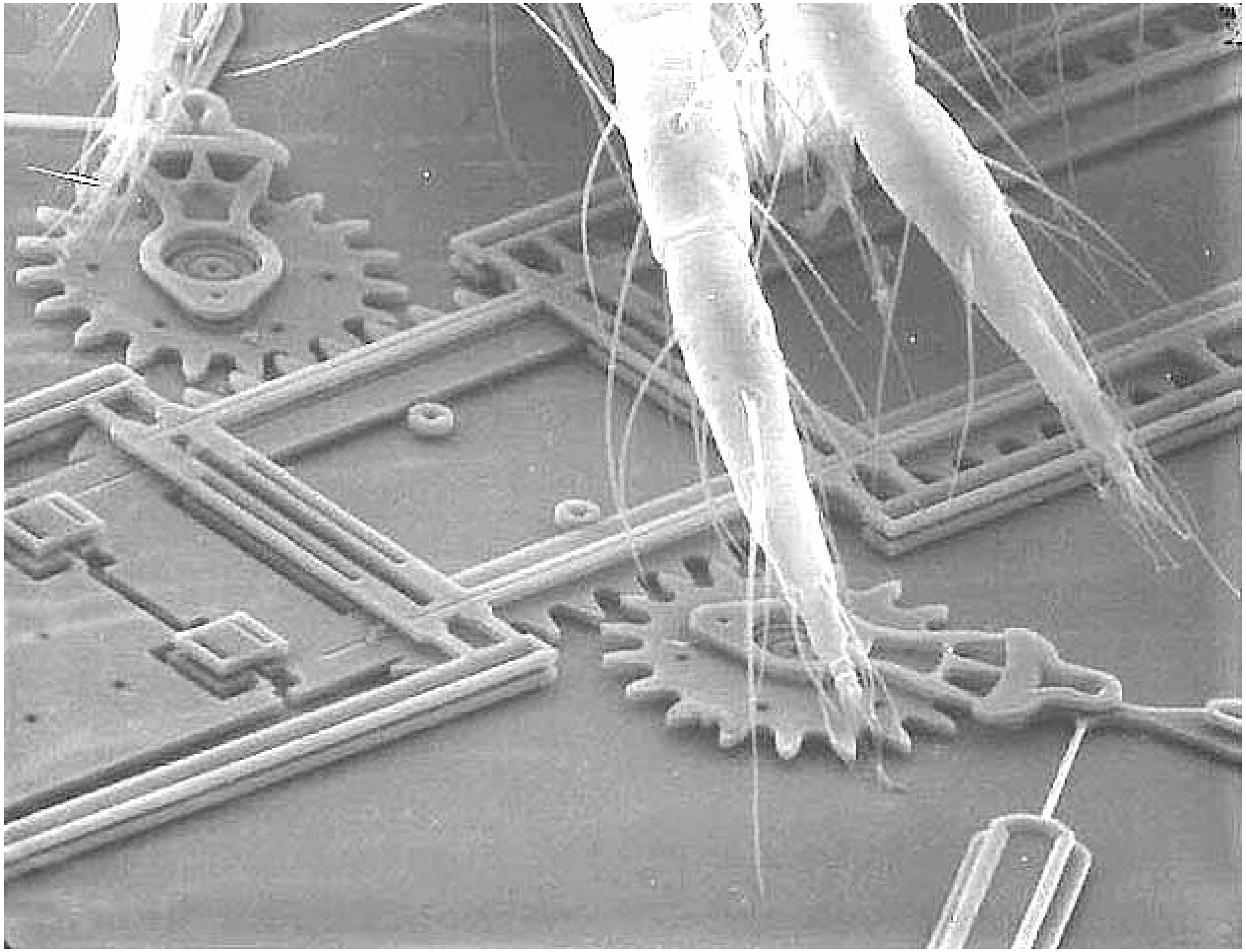
Actuation mechanisms

- MEMS structures can be actuated **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 produces an electric field, - and opposite!

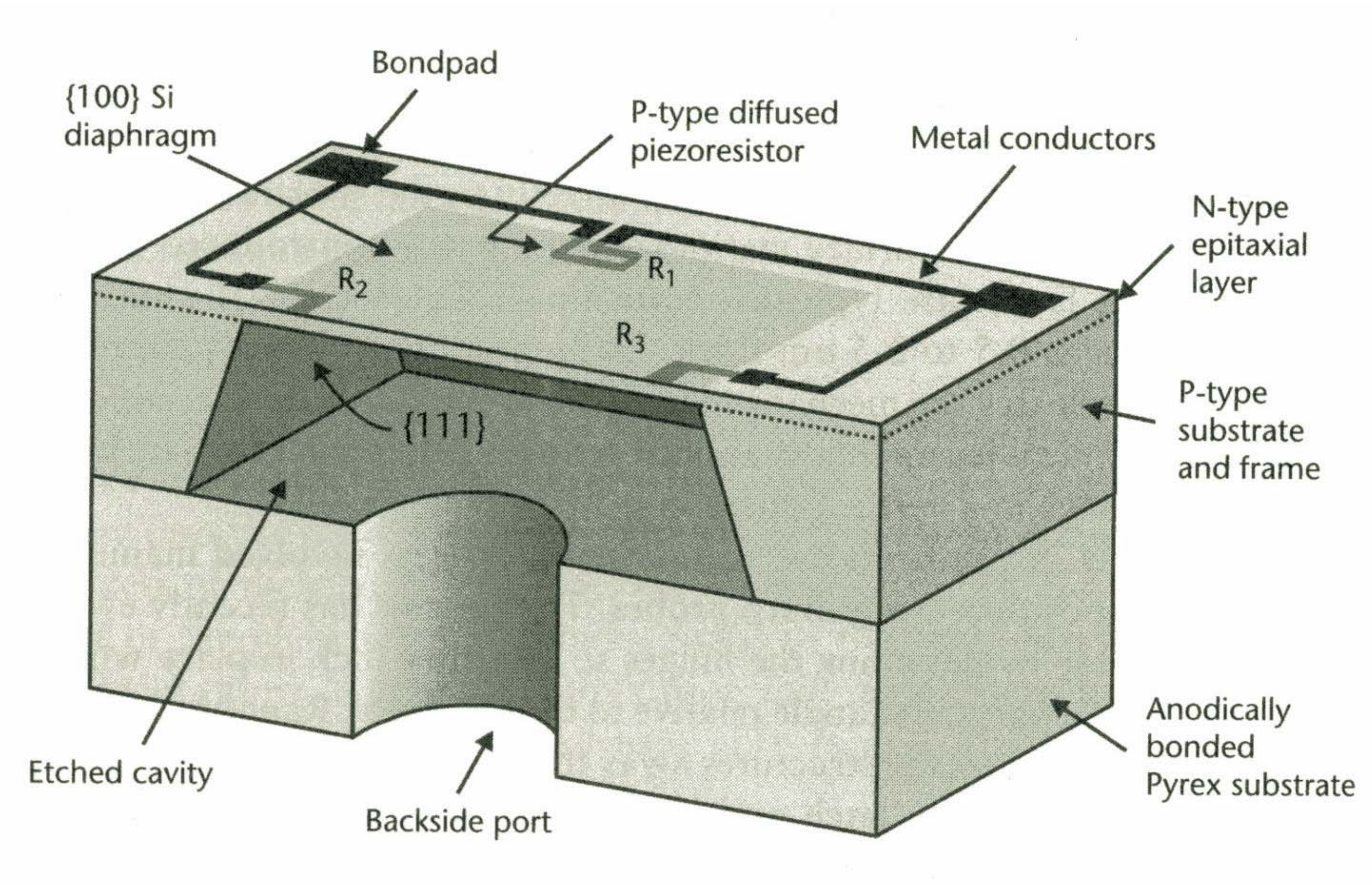
Some applications of MEMS

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

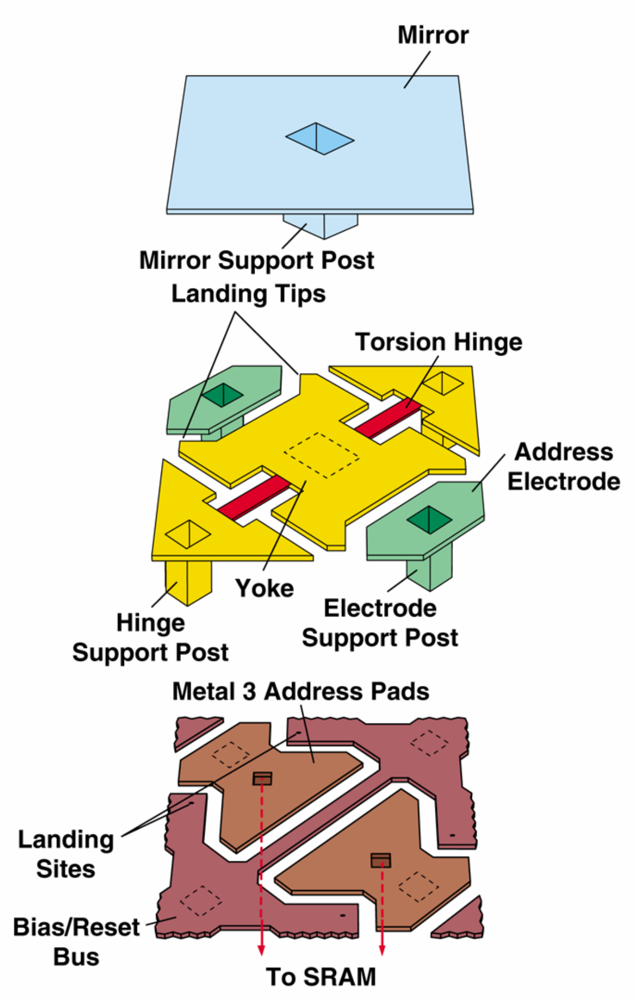
Micro motor fra Sandia



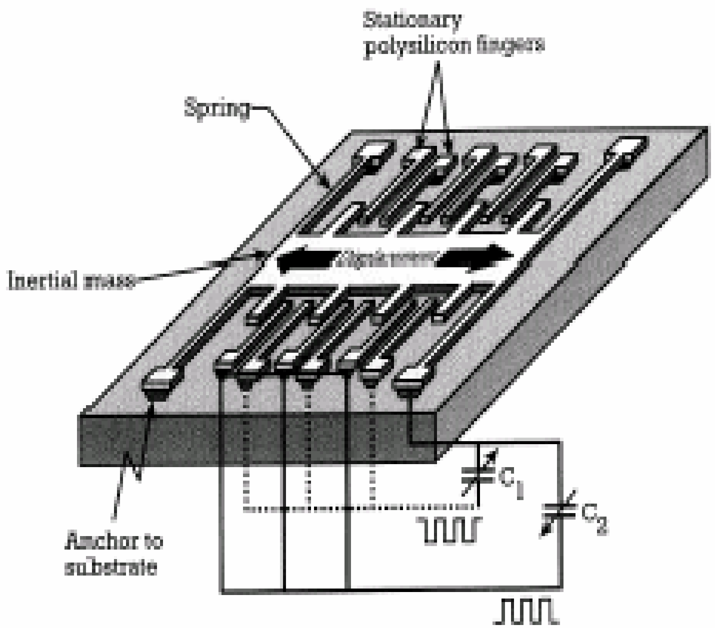
Pressure sensor



Micro mirror

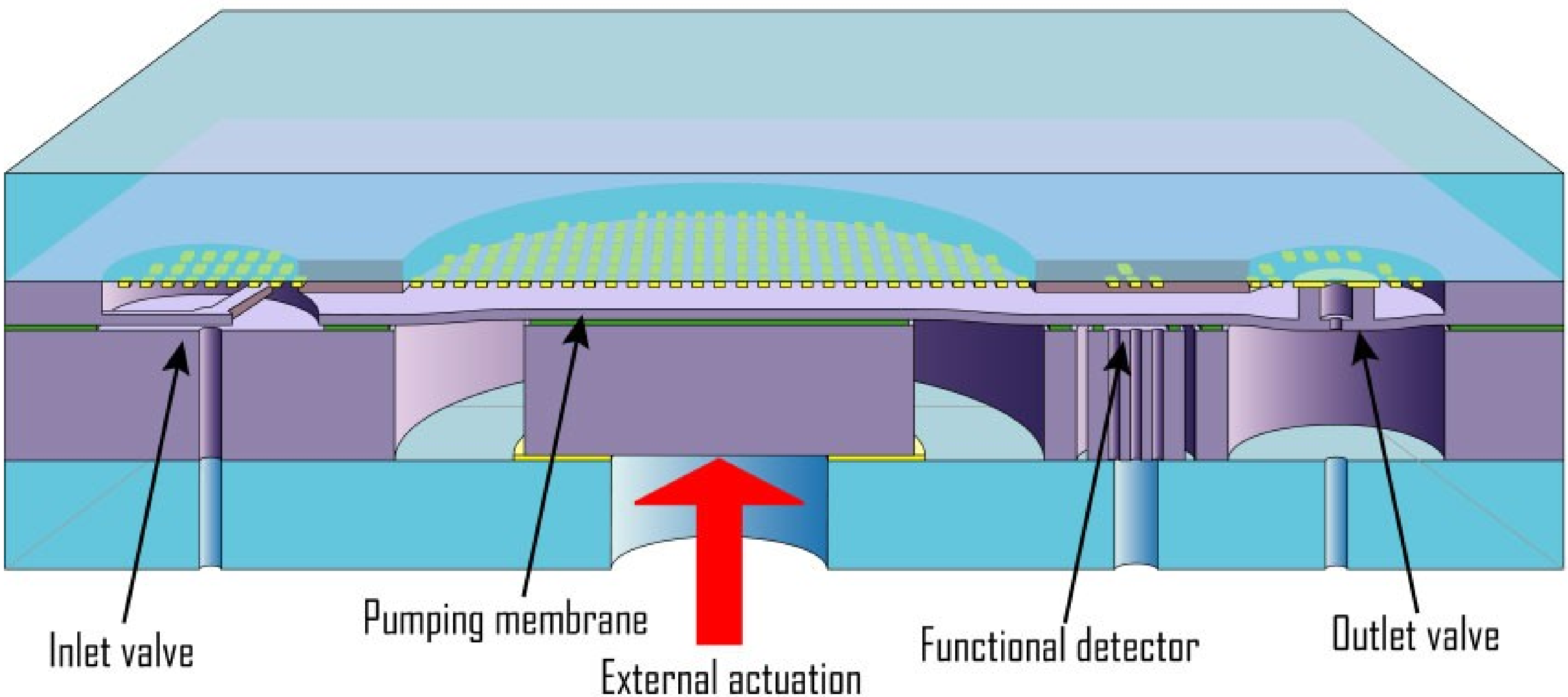


A Capacitive Accelerometer



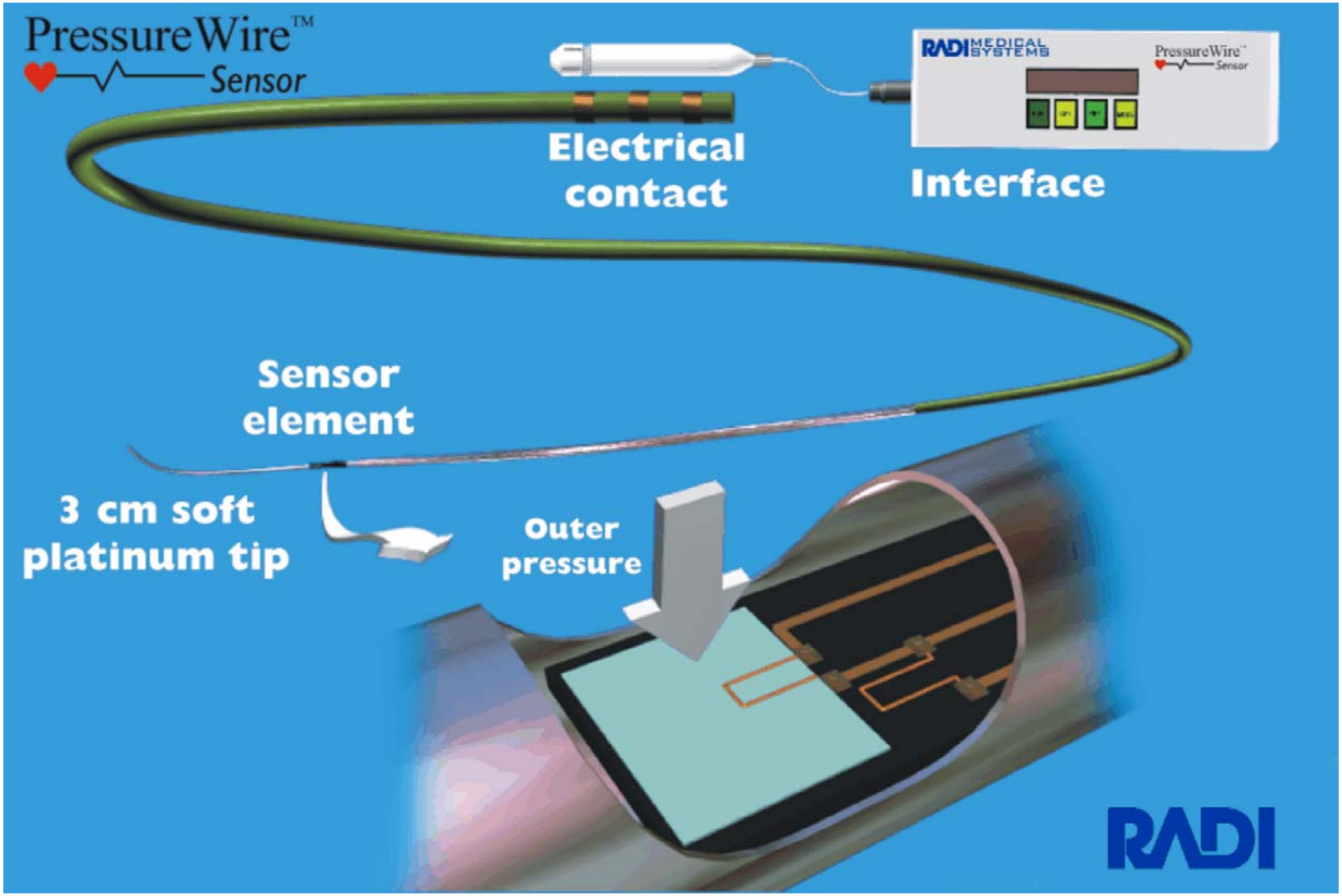
Technology Analysis: Drug Delivery

Debiotech Chip



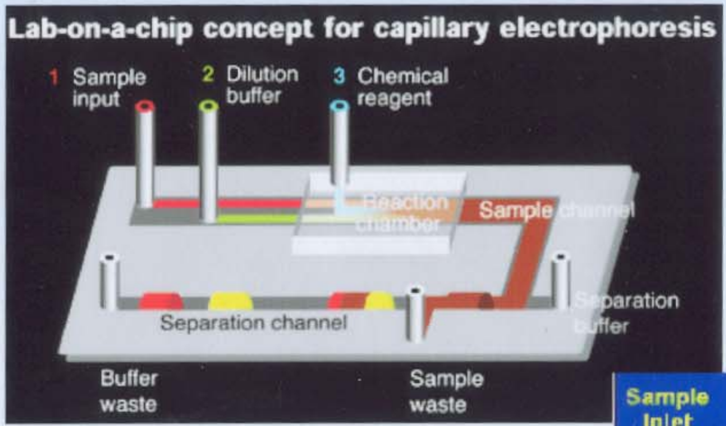
Source: Debiotech

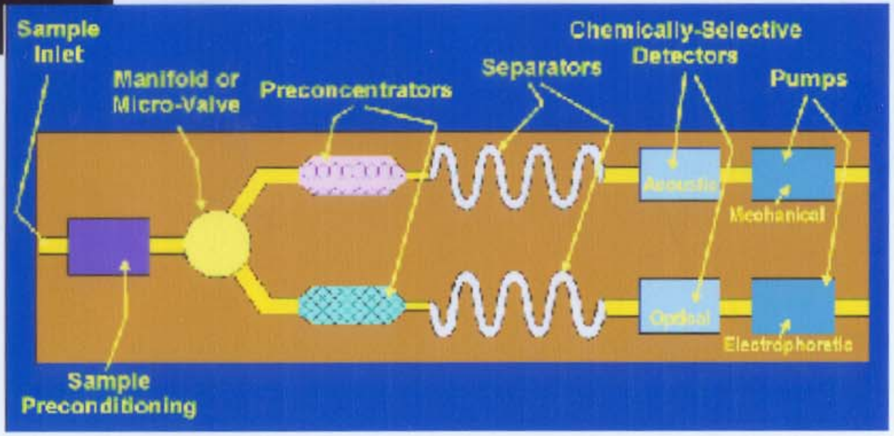
Radi Catheter



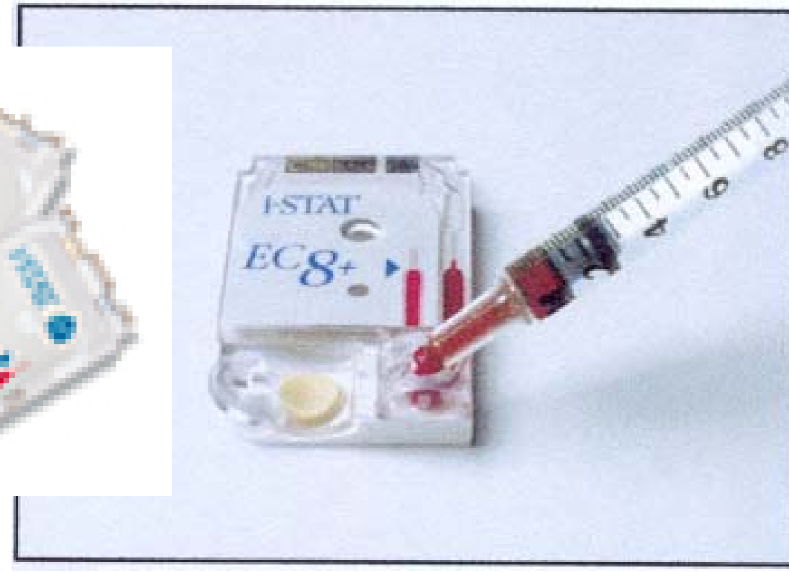
Biotechnology MEMS

"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

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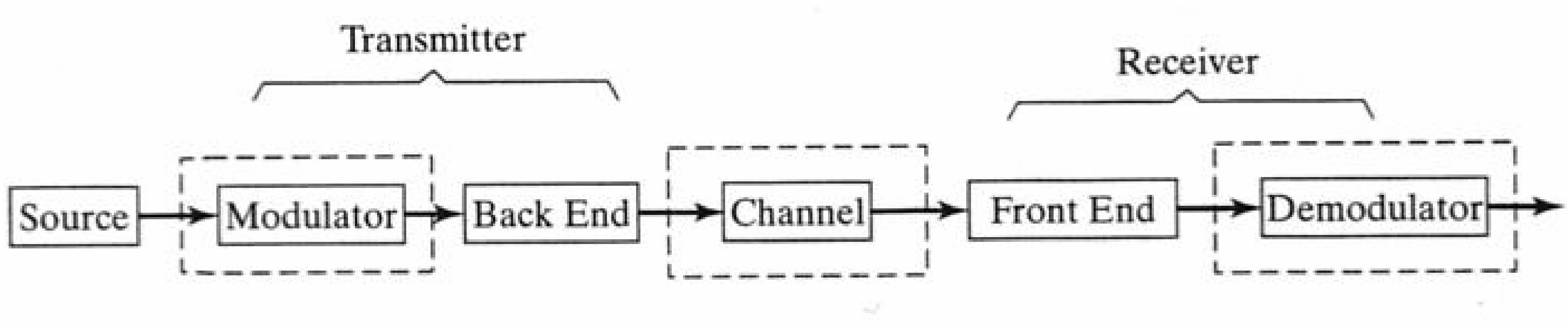
RF-systems in general

- Radio waves are used for transmittance/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 component performance requirements!**

RF-systems

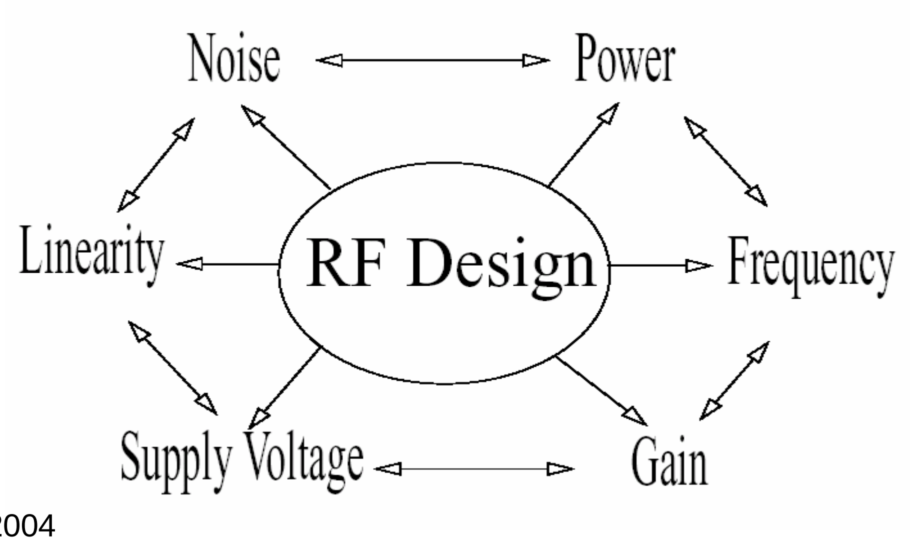
- RF-systems efficiency/performance
  – Ability to transfer **power**
  – Simultaneously use of limited **bandwidth**

- 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 design

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

RF Design Hexagon
Multi-objective approach

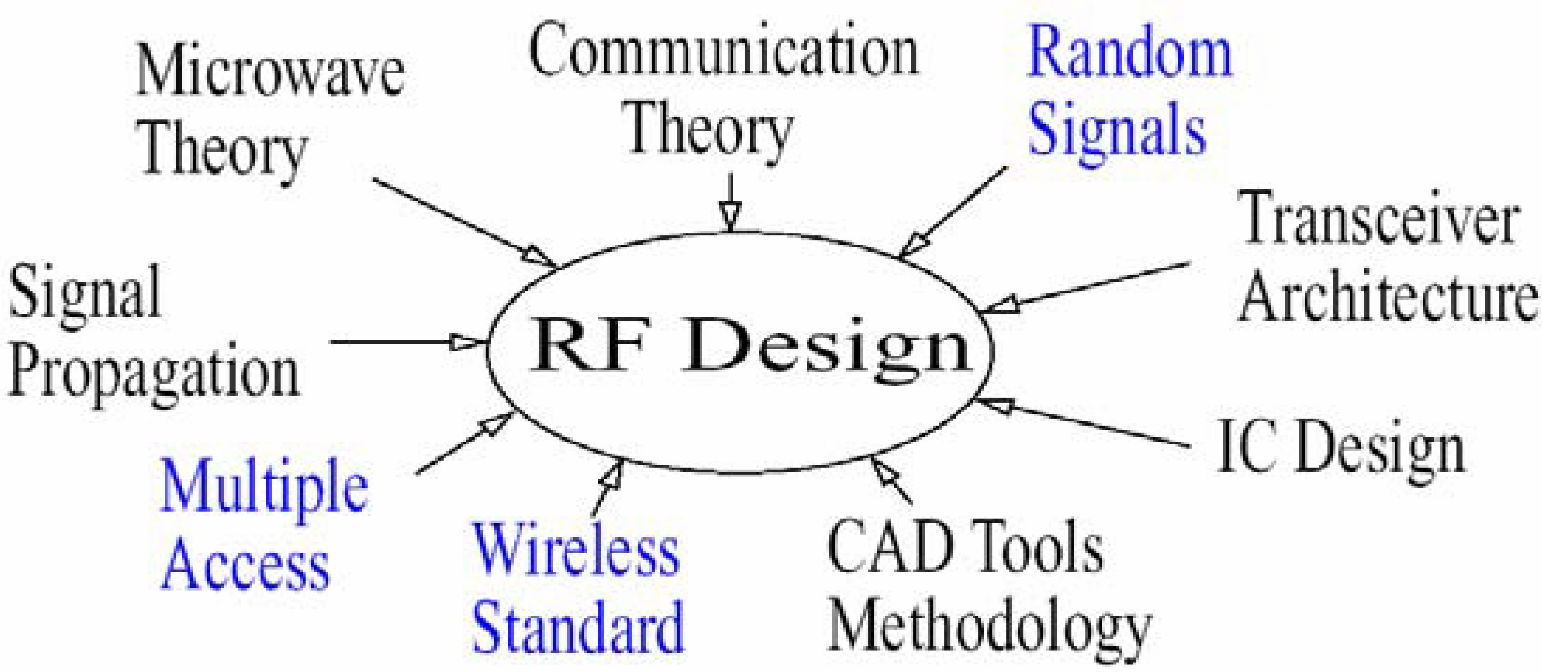


Jerzy Dabrowski, CMOS RF Transceiver Design, 2004

- CMOS-technology is a strong candidate for implementing critical parts of a transceiver!
  - **Impossible to fulfill all requirements of component performance**

Needed Disciplines in RF design

- Dabrowski 2004



Implications of RF

- 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

Communication standards

- Various standards exist

Overview of Standards

Standard	Access Scheme	Frequency band (MHz)	Channel Spacing	Frequency Accuracy	Modulation Technique	Data Rate (kb/s)	Peak Power
GSM	TDMA/ FDMA/ TDD	890-915 (Tx) 935-960 (Rx)	200 kHz	90 Hz	GMSK	270.8	0.8, 2, 5, 8 W
DCS-1800	TDMA/ FDMA/ TDD	1710-1785 (Tx) 1805-1850 (Rx)	200 kHz	90 Hz	GMSK	270.8	0.8, 2, 5, 8 W
DECT	TDMA/ FDMA/ TDD	1880-1900	1728 kHz	50 Hz	GMSK	1152	250 mW
IS-54	TDMA/ FDMA	824-849 (Tx) 869-894 (Rx)	30 kHz	200 Hz	$\pi/4$ QPSK	48	0.8, 1, 2, 3 W
IS-95	CDMA/ FDMA	824-849 (Tx) 869-894 (Rx)	1250 kHz	N/A	OQPSK	1228	N/A
Bluetooth	CDMA/ FDMA/FH	2400-2483	1000 kHz	20 ppm	GFSK	1000	1,4,100 mW
WCDMA (UMTS)	W-CDMA/ TD-CDMA	1920-1980 (Tx) 2110-2170 (Rx)	5000 kHz	N/A	QPSK	3840 (max)	125,250 500mW, 2W

Jerzy Dabrowski, CMOS RF Transceiver Design, 2004 6

- Will not discuss standards in INF5490!

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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 swithes 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, IMEC, LETI
  - Some relevant companies:
    - Analog Devices, Motorola, Samsung, ST Microelectronics
  - Institutes
    - Sandia, Fraunhofer

Typical RF MEMS components

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

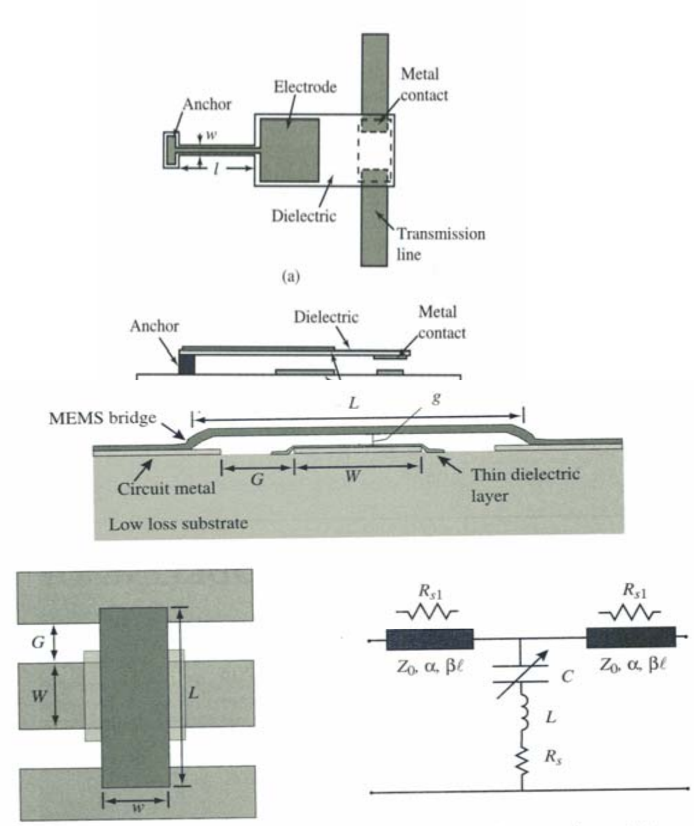
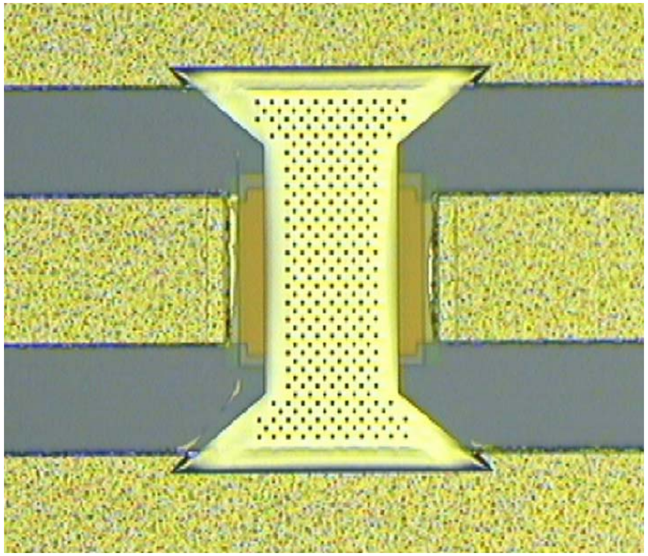


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).

Typical RF MEMS components

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

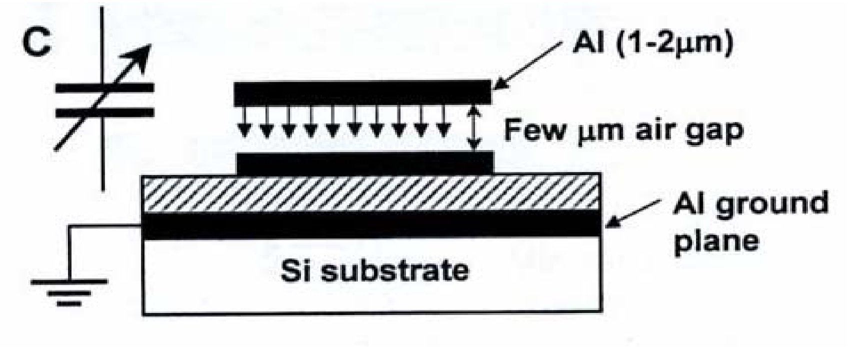


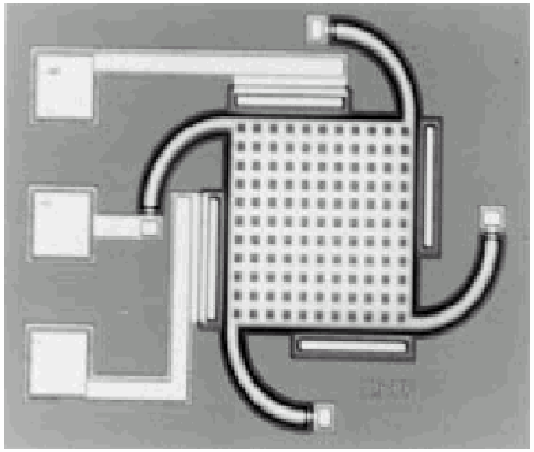
Ex.: microwave switch

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

Typical RF MEMS components

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





Typical RF MEMS components

- Switches
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- Inductors
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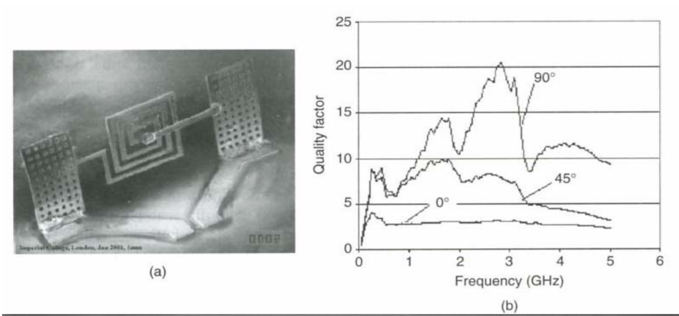
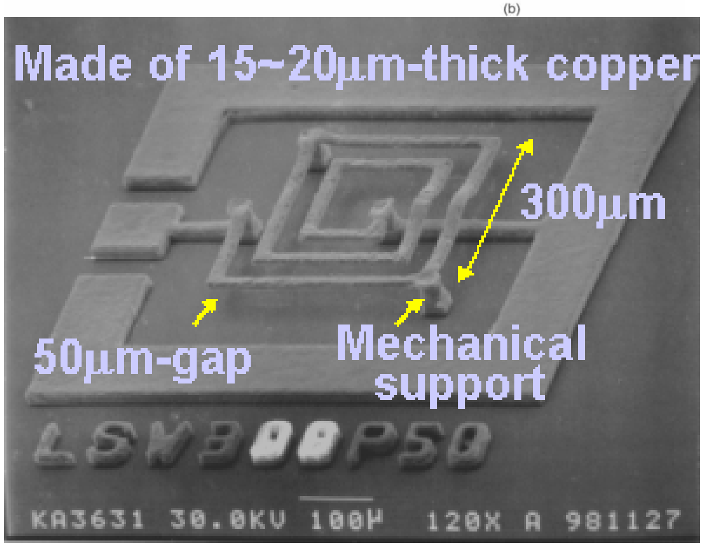
- Micromechanical filters
- Phase shifters



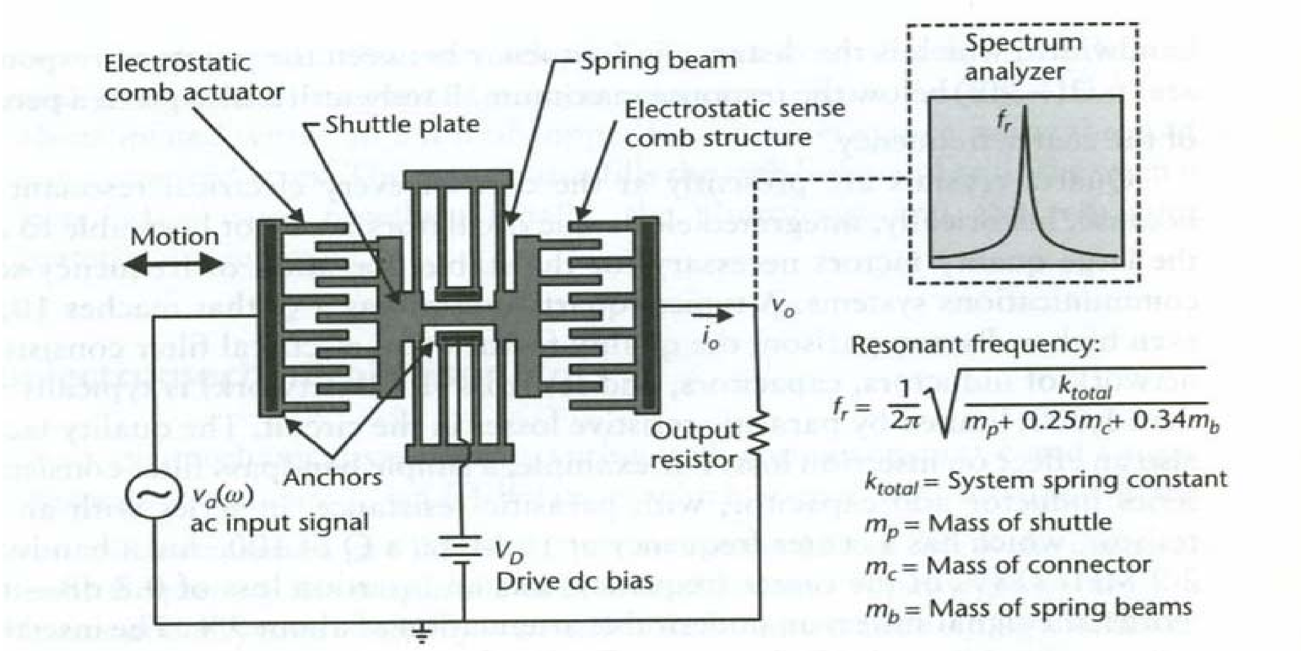


Typical RF MEMS components

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

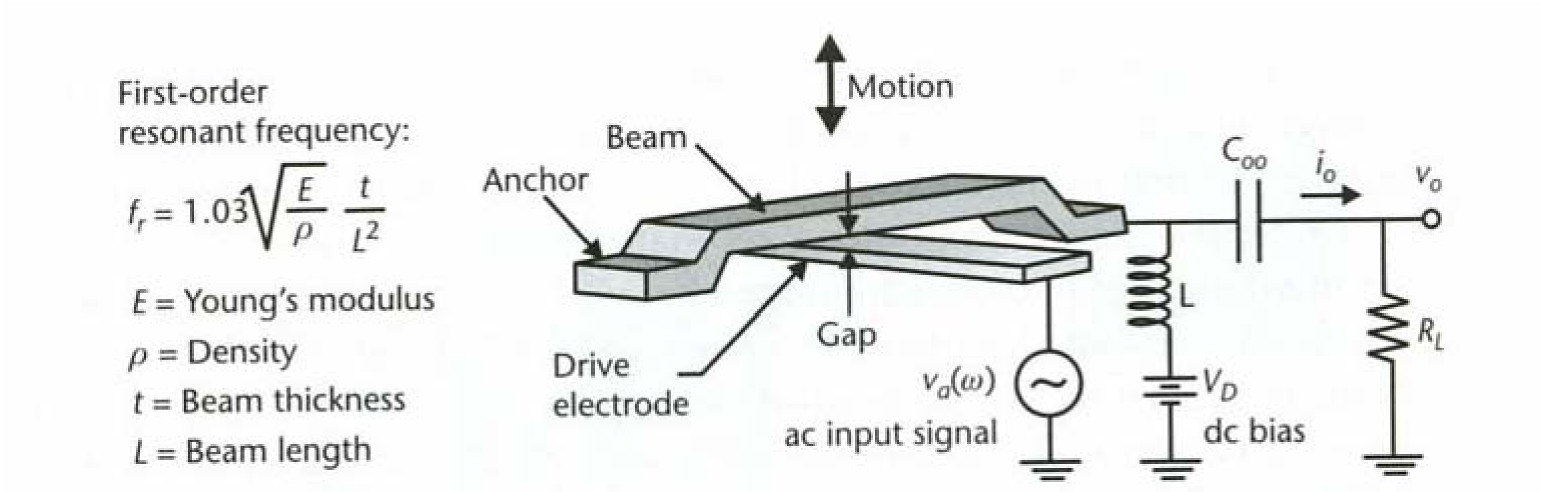
- **Focus on real vibrating structures →**
  - May be used to implement
    - oscillators
    - filters
    - ”mixer with filter”

Comb-resonator



lateral movement

Clamped-clamped beam resonator



Vertical movement

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

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

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

Challenges in RF transceiver implementation

- **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!

Bottlenecks in Current Microwave/MM-Wave Systems – Band Selection Filters

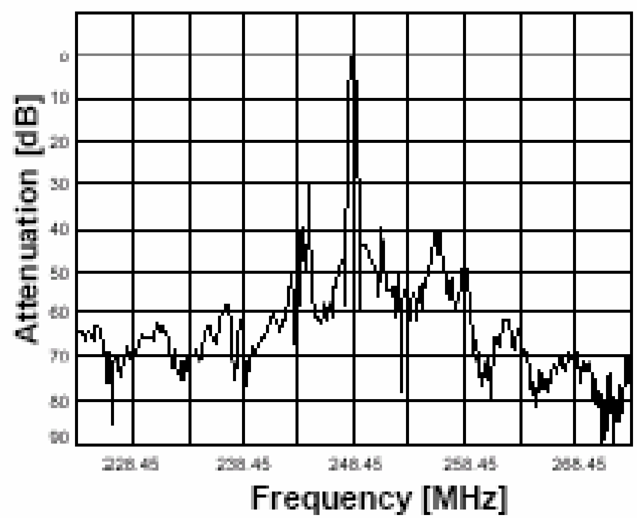
- **High-Q (Q ~ 1000's) filters are needed in heterodyne communication receivers for frequency selection in RF and IF bands**
- **Current solution: Off-chip surface-acoustic wave (SAW) filter**
  - **Bulky**

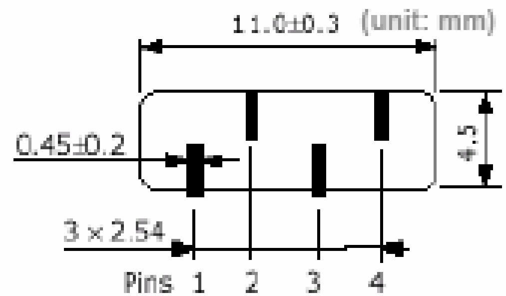
IF filter

f_0: 240MHz

Δf: 260kHz

Q: ~1000





RF filter

f_0: 868MHz

Δf: 600kHz

Q: ~1500

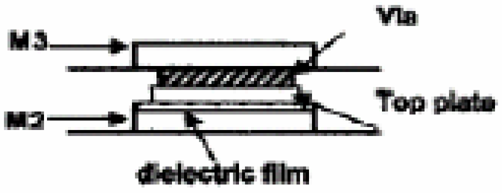
Bottlenecks in Current Microwave/MM-Wave Telecommunication Systems – Passive Elements

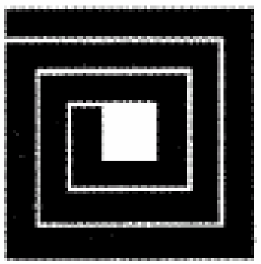
- Lack of high-Q (~ 1000) passive elements like inductors and capacitors in matching circuit or bias-Tee, etc.

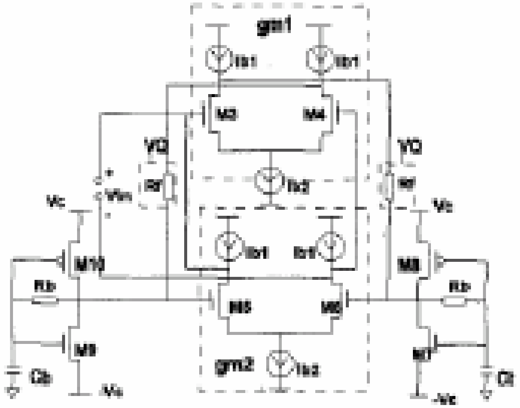
MIM Capacitor
- Low Q (< 100)

Spiral Inductor
- Low Q (~ 10)
- Low resonant frequency

Active Inductor
- Large Noise
- High Power consumption







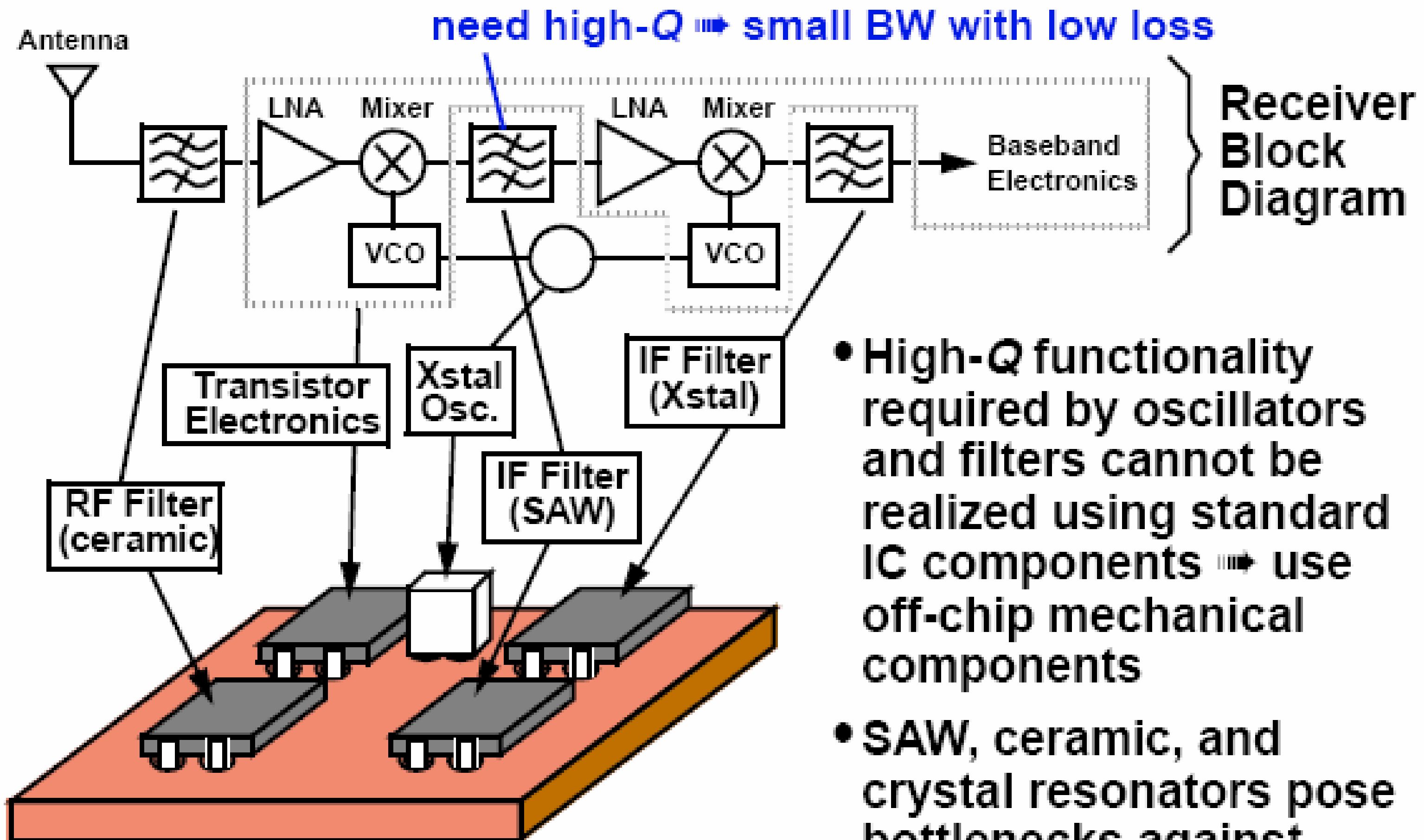
Use of RF MEMS

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

Minituarizing a transceiver

- A typical RF transceiver with discrete components →
  - Illustration by Prof. Clark T.-C. Nguyen, Univ of Michigan→ UC Berkeley
    - Nguyen has a large activity in RF MEMS: resonators
  - The figures show which parts that may be **replaced** by MEMS?

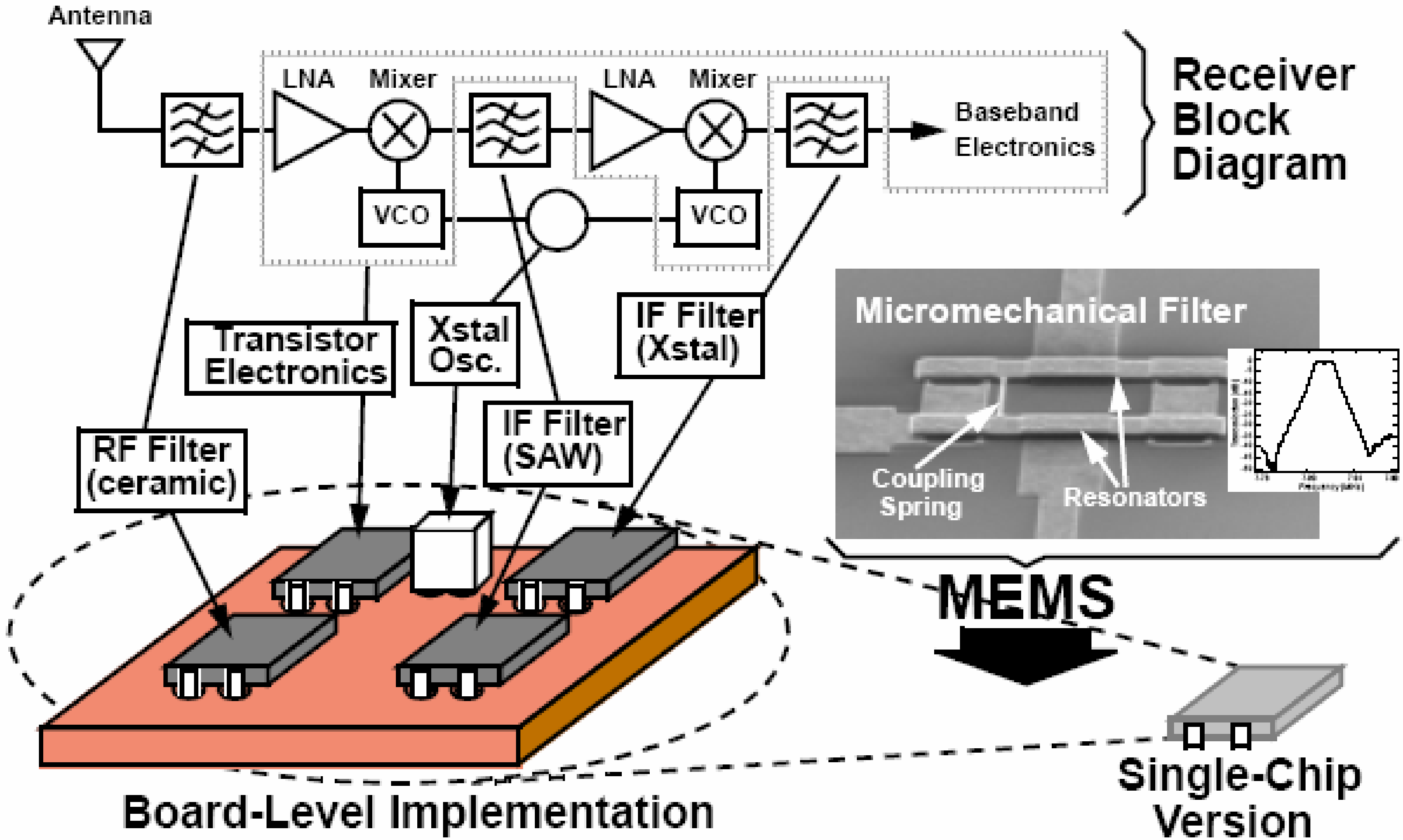
Miniaturization of Transceivers



Board-Level Implementation

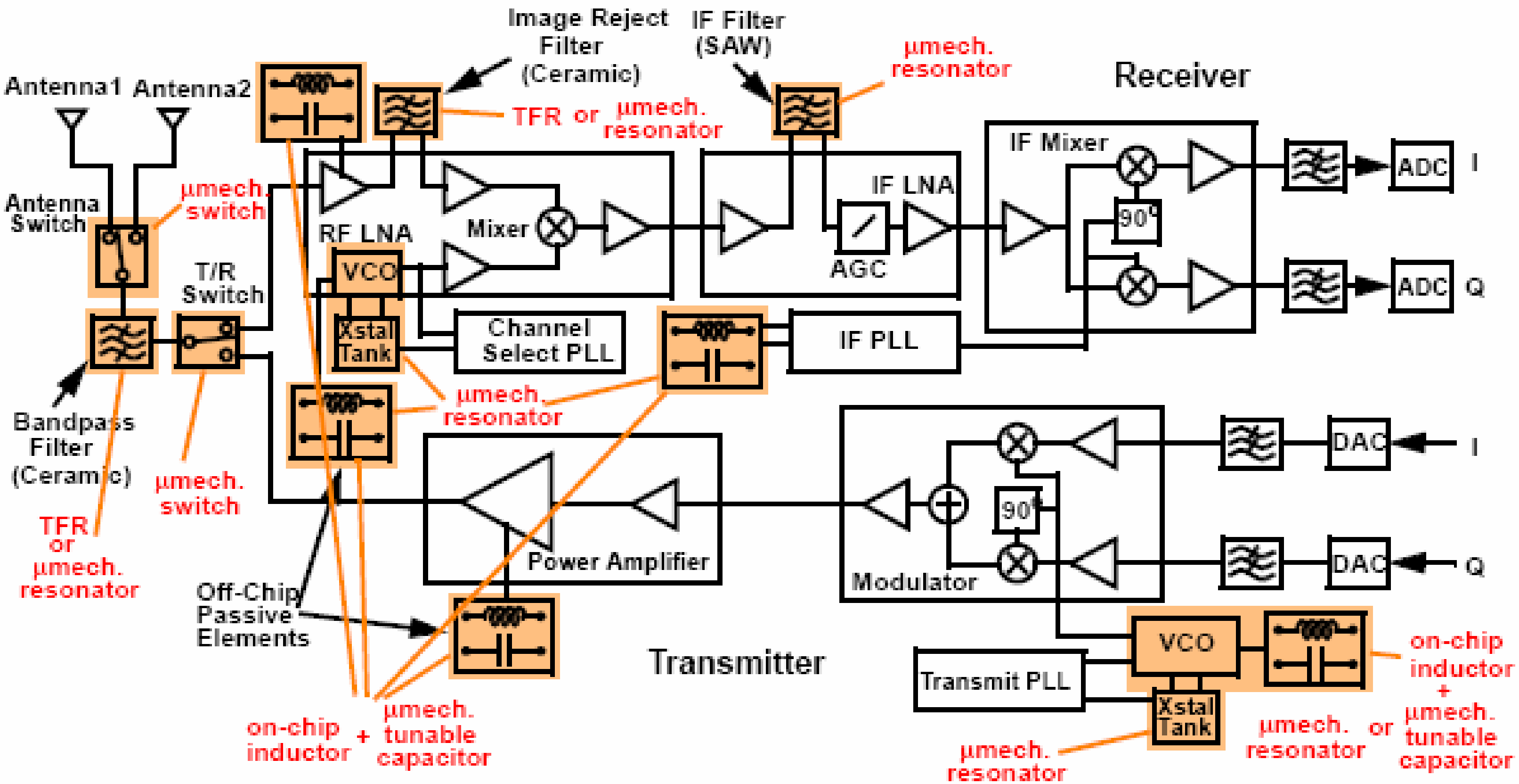
- High-*Q* functionality required by oscillators and filters cannot be realized using standard IC components ➠ use off-chip mechanical components
- SAW, ceramic, and crystal resonators pose bottlenecks against ultimate miniaturization

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

New RF architectures

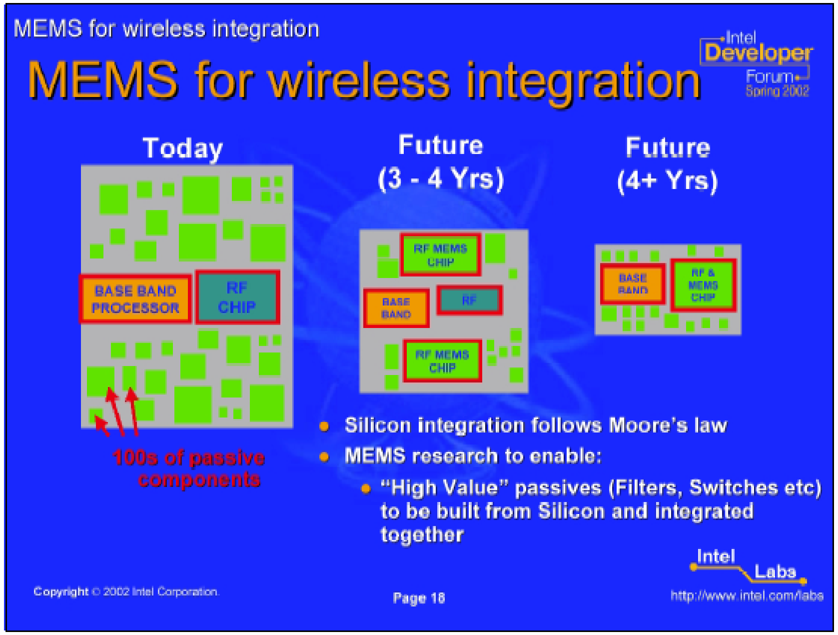
- New ways to design RF systems
  - MEMS technology may be used to implement a lot of small, low cost basic modules
    - Switches may then be used to switch between the modules
  - MEMS makes it easier to perform module based design
    - Micromachined lumped components may replace <u>distributed components</u>
    - Enhanced integration flexibility

Challanges 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”!



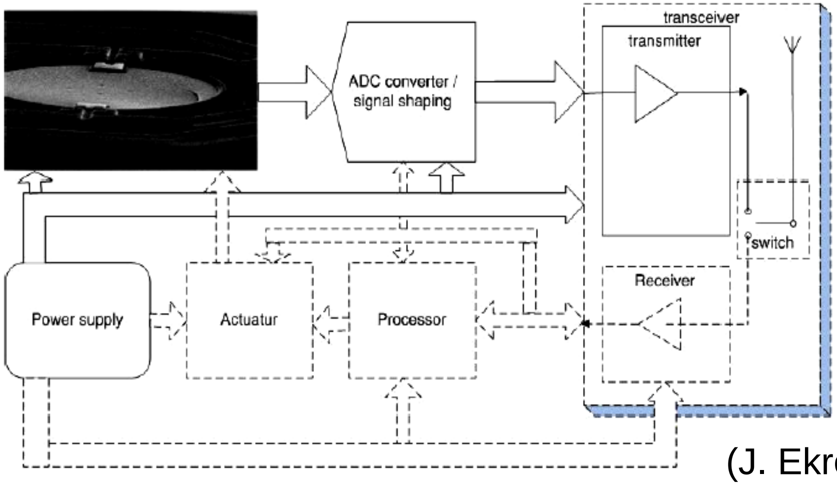
Perspectives

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

- Various technologies converge
    - Micromechanics and microelectronics
    - **Optics** and electronics
    - Passive components and active ICs

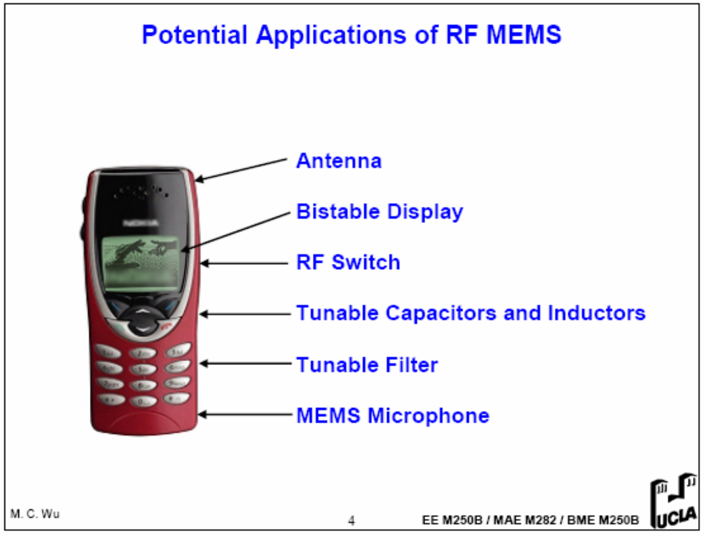
Use of RF MEMS

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



(J. Ekre)

- Mobile terminals



International activity

- RF MEMS is in focus on leading international conferences
    - ISSCC, IEDM (Int. Electron Devices Meeting)
    - MEMS-conferences and journals
        - See web-page!
- Europractice offers MPW (Multi Project Wafer)
- Increased industry attention and support of RF MEMS
    - Great potential
        - Miniaturization, increased performance, volume production
    - MEMS in general is not a big hit!
        - A few successes: airbag sensor, projector