INF5490 RF MEMS

LN01: Introduction. MEMS in RF

Spring 2012, Oddvar Søråsen
Department of informatics, UoO

Today's lecture

- Background for the course INF5490/9490
- Course plan spring 2012

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

INF5490 RF MEMS

- **MEMS** (Micro Electro Mechanical Systems)
  - Extending the VLSI design research activities of the NANO group
    - Basic NANO competence: Design of mico/nano- electronic systems: modeling, analysis and implementation of analog and digital VLSI circuits and systems

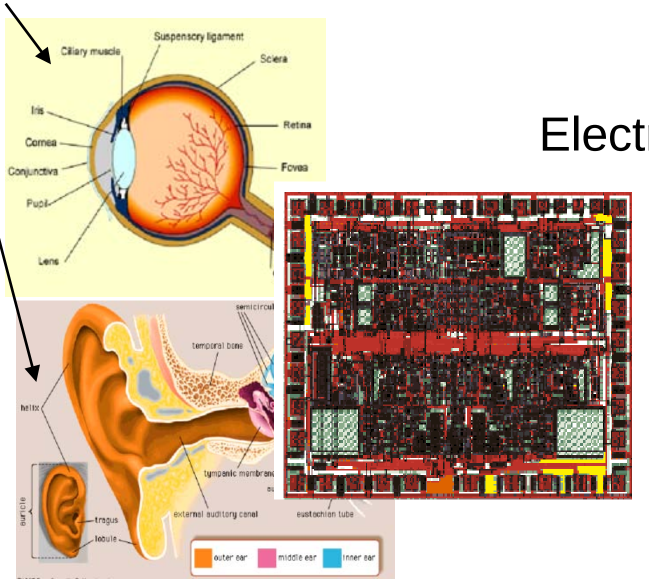
- Activity inspired by:
  - **National focus** on micro- and nano-technology
    - The Research Council of Norway
  - **MiNaLab** (Micro Nano Technology-lab), next-door
    - SINTEF lab
    - UiO lab

Why MEMS in the Nano-group?

- New possibilities to implement **composite, integrated, miniaturized systems**
  - Electronic systems with MEMS give a new **degree of freedom** for designers
    - **A.** Sensors and actuators **Mechanical** components integrated in the systems: ”eyes, ears, hands”
    - **B.** MEMS – components need **interfacing/driving** electronics!

MEMS

Electronics



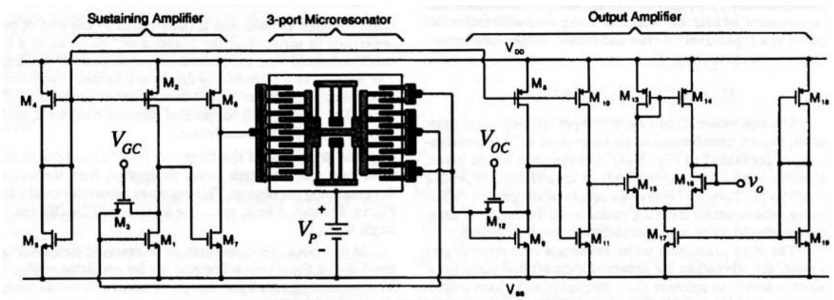
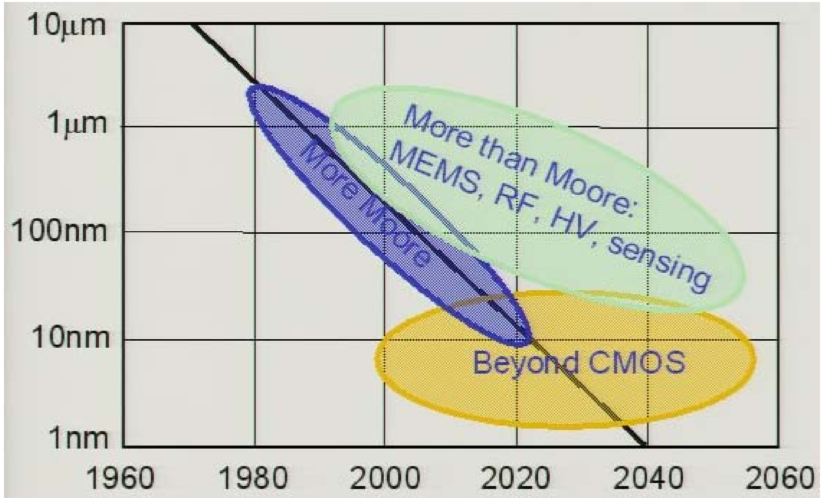
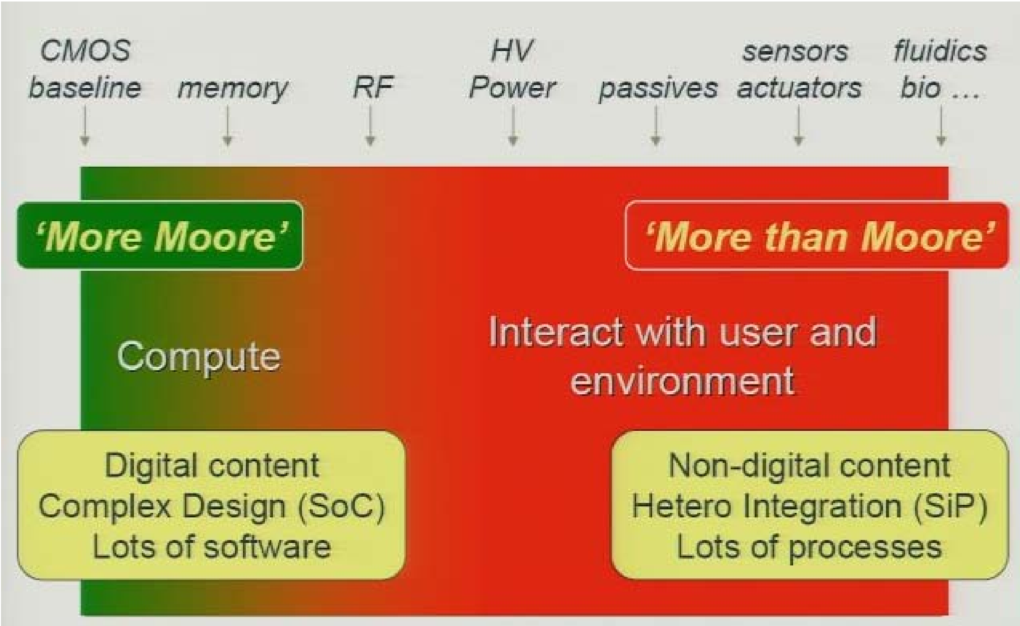


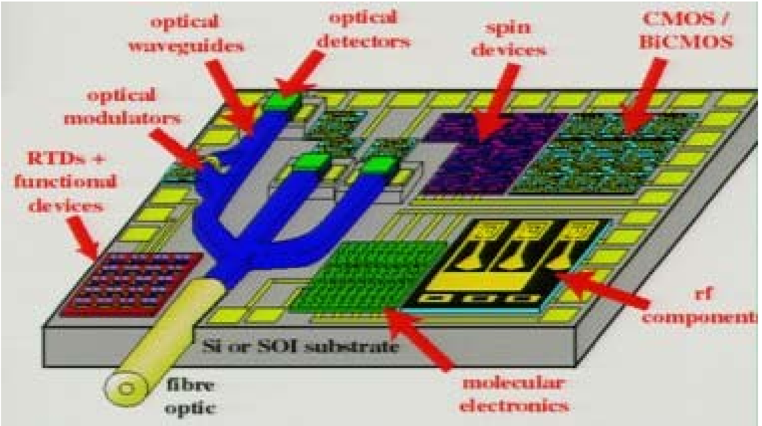
Fig. 4: Circuit schematic for the μresonator oscillator.

Interfacing to the ”real world”

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







[Ref. A.M. Ionescu]

Technology trends

Computational Infrastructure

- Stationary/backend
- Wired
- High end computing

Mobile access devices

- Human interaction
- Portable
- Mostly wireless
- Battery

Sensory swarm

- Miniature
- Wireless
- Autonomous/self-contained
- Controlling and sensing natural processes

[TSL]

Personal competence

Background

- Physics
- → modeling and design of VLSI (ASIC)
- → system design
- → computer architecture/multiprocessors
- → **RF MEMS, CMOS-MEMS co-integration**
- Sabattical at SINTEF MiNaLab 03/04
- Supervising students i relevant fields (Master, Ph.D.)
- Research activities

Input

- 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 ++
- Literature studies
- Using the simulation package CoventorWare

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**

Course 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 (Svein-Erik Hamran), **recommended!**
      - **INF5481 RF-circuits, theory and design**
    - However, basic/ “needed” RF topics for INF5490/9490 are covered in our course!

Why RF MEMS in the NANO group?

- Challenging, promising and exciting field!
- Close connection to the basic NANO 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
- Growing commercial attention
- Basis for establishing new enterprises

- 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”

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, video projector**

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

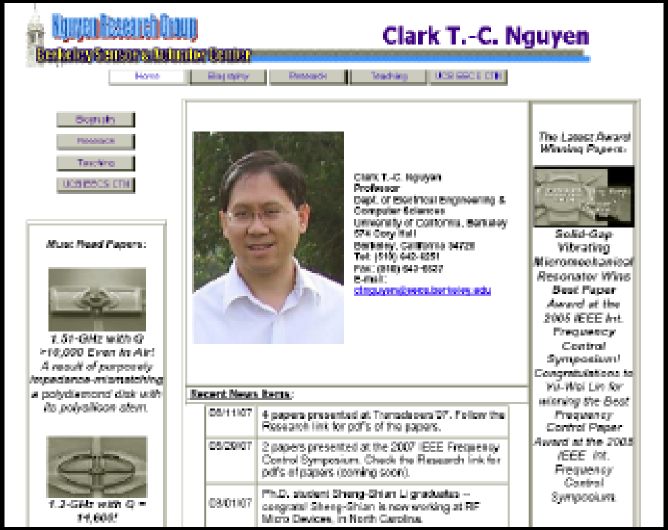
RF MEMS: where should I look for?

Top authors, books and web pages

RF MEMS

- Clark Nguyen

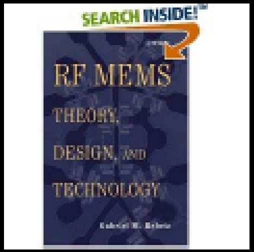
http://www.eecs.berkeley.edu/~ctnguyen/



RF MEMS

- Gabriel Rebeitz

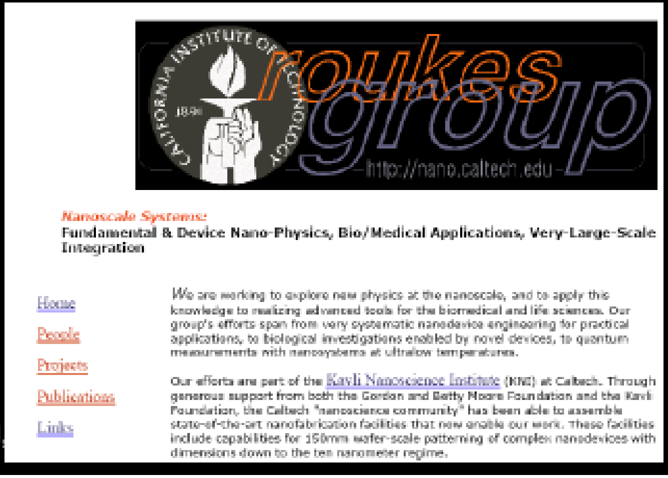
RF MEMS: Theory, Design, and Technology, Wiley, 2003.



NEMS

- Michael Roukes

http://nano.caltech.edu/



Today's lecture

- Background for course INF5490
- Course plan spring 2012

- 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/v12/
  - Messages posted there! **CHECK regularly!**
- Weekly **lectures:** Oddvar Søråsen
  - Thursday 10:15 – 12, in OJD 3437 (seminarrom C)
  - Detailed lectureplan on web
    - Lecture notes will be posted on web before lecture (pdf)
- Language: English (if requested by someone from the audience, - else Norwegian)

Group assignments

- **Class assignments:** Srinivasa Reddy Kuppi Reddi
  - ”Felles gruppe” – consult web for weekly plan!
  - Tuesday 14:15 – 16 in Java 2423
    - First time 24/1
  - Present plan and topics for ”obliger”
  - Present supporting literature
  - Work through week 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: features

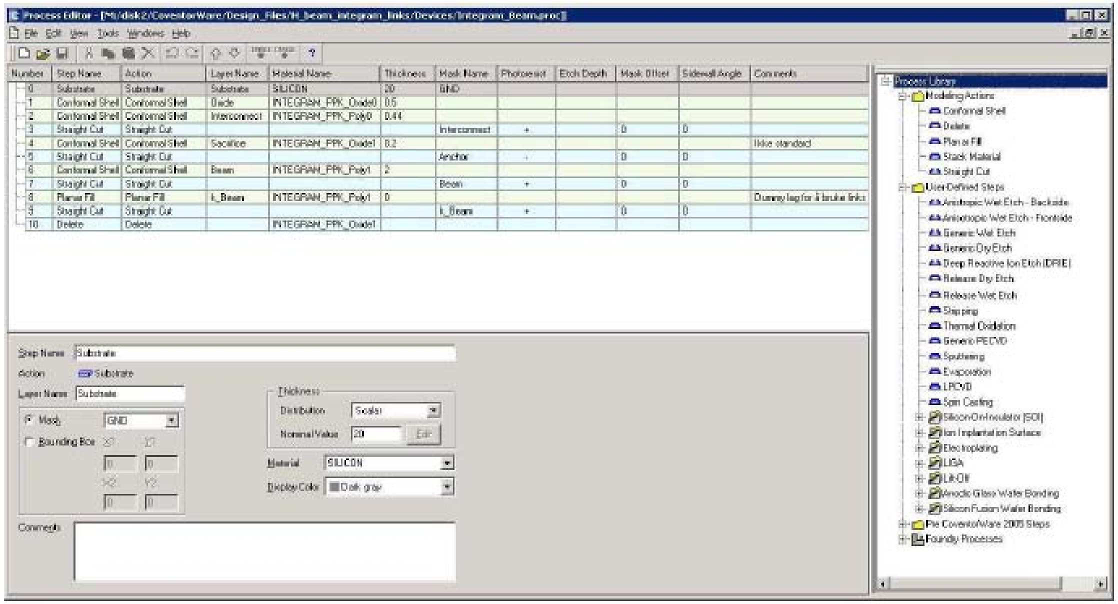
- "State-of-the-art" tool for FEM analysis
  - "Finite-Element-Method"

- **"Bottom-up" procedure:**
  - 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!

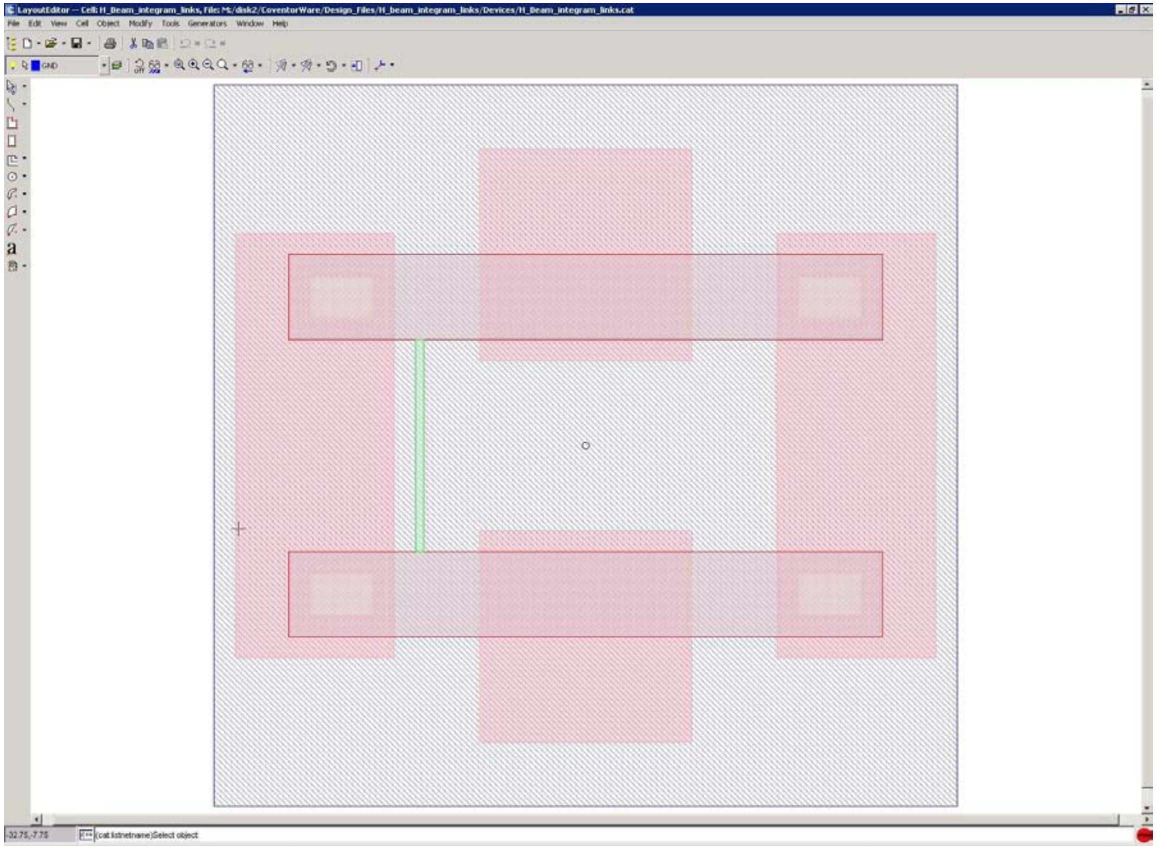
COVENTOR ACCELERATING MEMS Innovations™

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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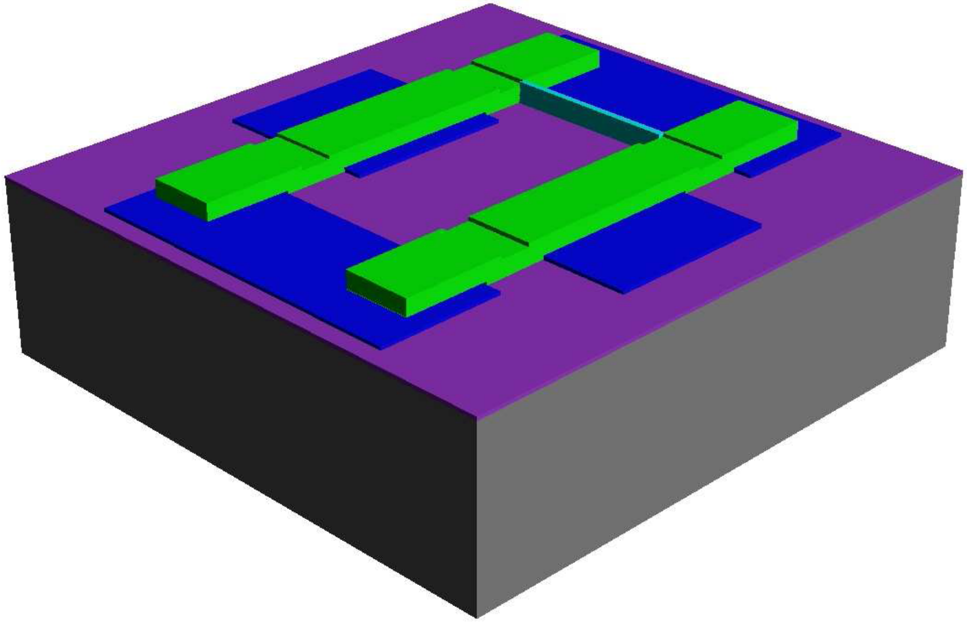
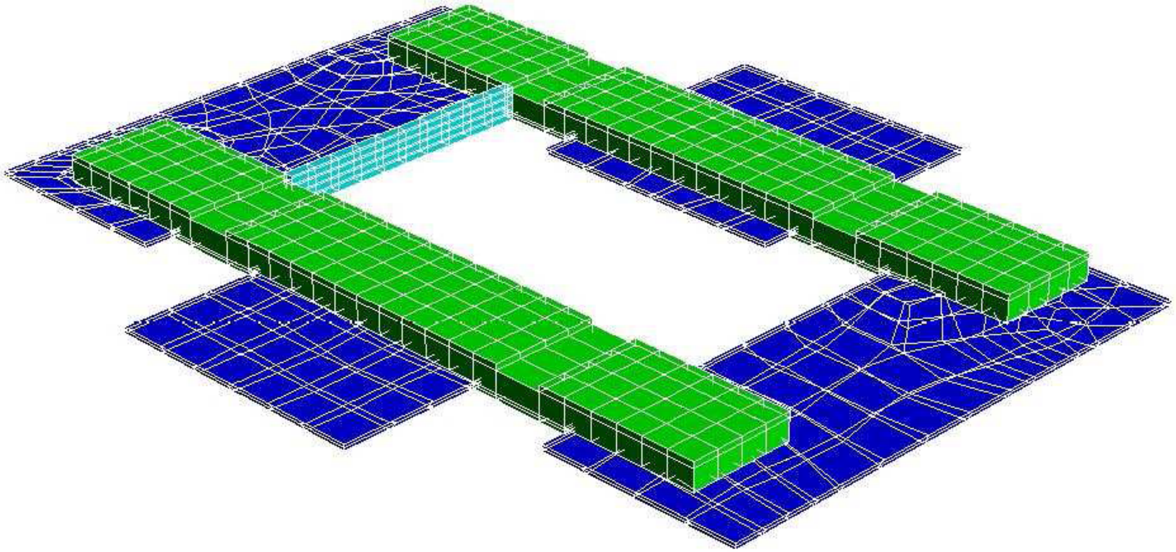
GND

Building a 3-D model

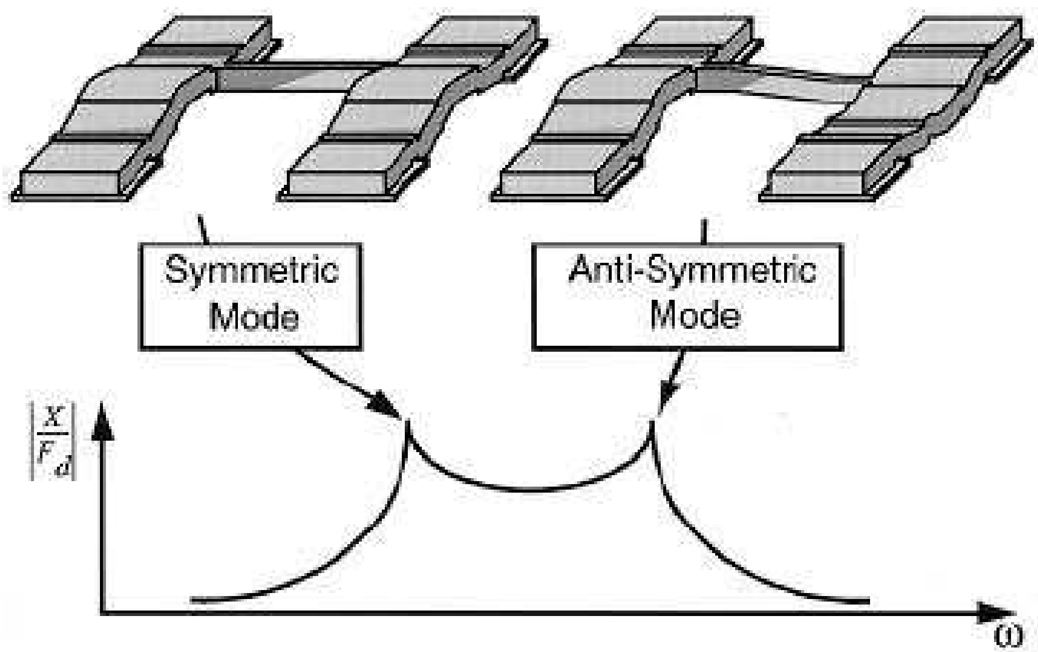


O-P Arhaug

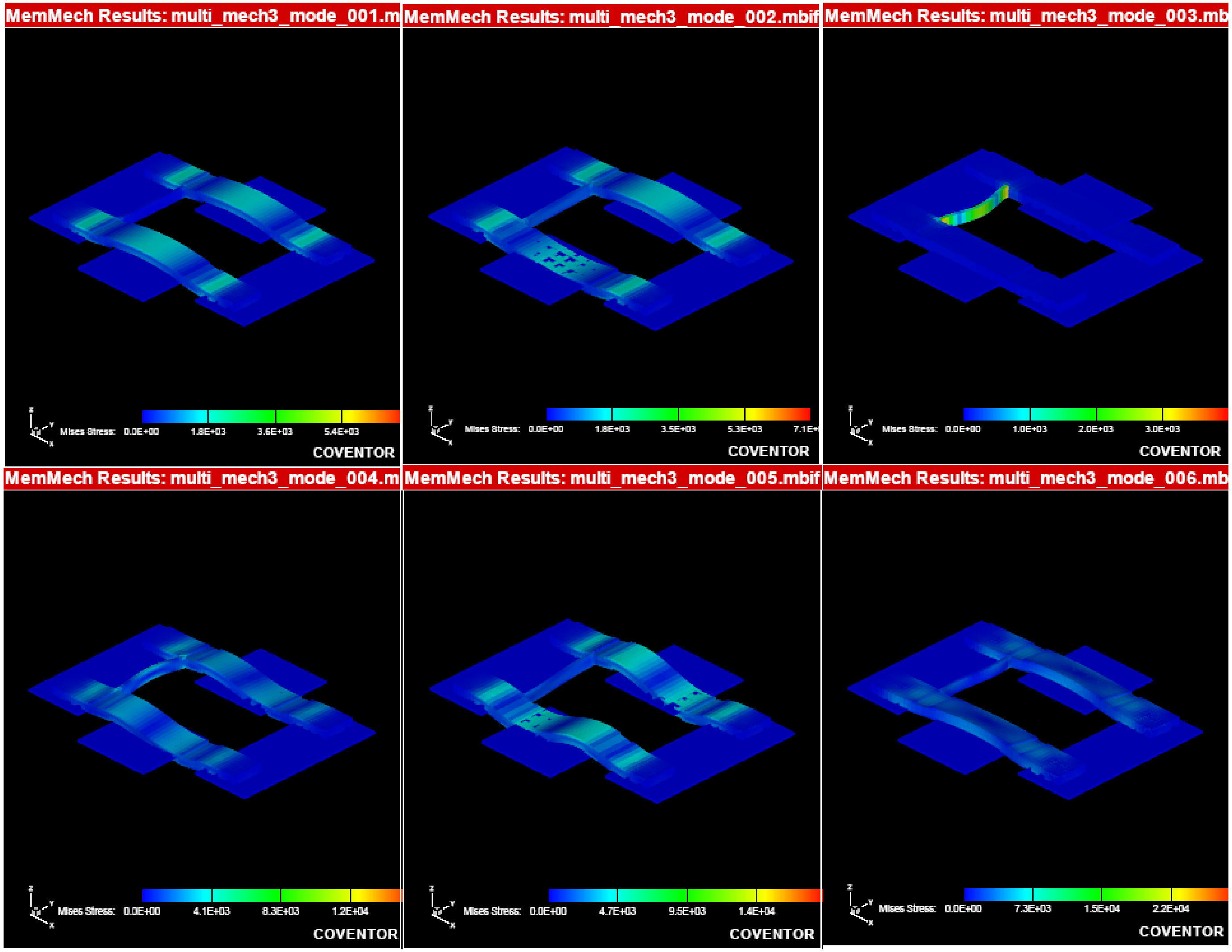
Meshed 3D -model for FEM analysis



Filter-function: 2 identical resonators

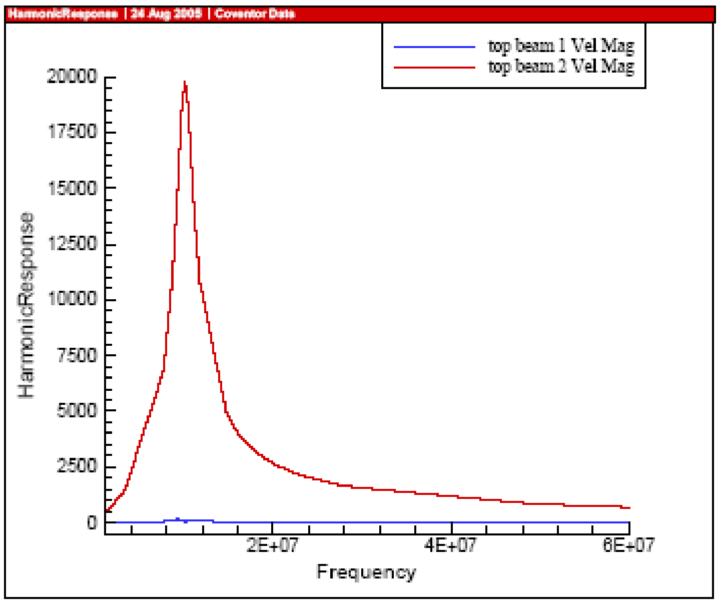


In phase Out of phase



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

Harmonic response for specific dampings



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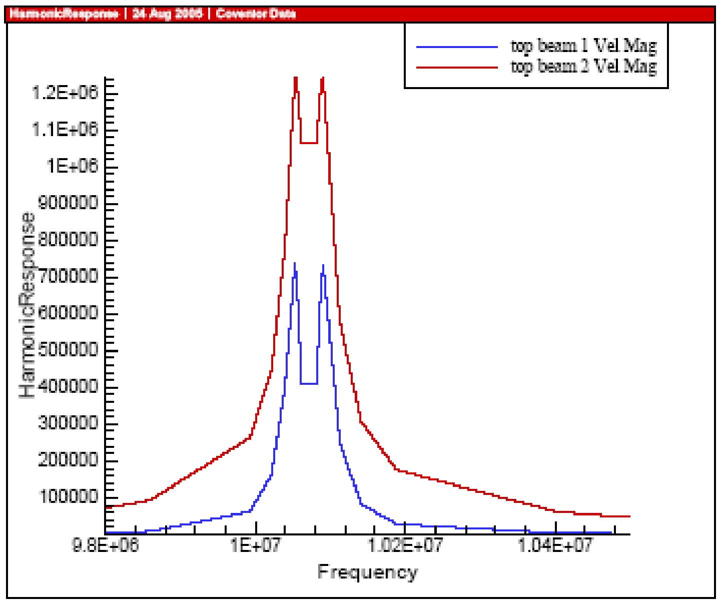


(b) 0,001

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
    - Lists for 2010/2011 questions are 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 does cover the course completely
- Lecture notes: **IMPORTANT!**
  - → Most of the syllabus is covered as lecture notes (ca. 1000)
  - Posted on web before lecture

- INF9490 version: Additional curriculum (articles specified on web)!
- 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 5412, phone: 22 85 24 56
  - oddvar@ifi.uio.no
- Responsible for groups/obliger/CoventorWare:
  - Srinivasa Reddy Kuppi Reddi, room 5401, phone 22 84 01 36
  - srinivar@ifi.uio.no
- Contact person CoventorWare: support
  - Yngve Hafting, room 4406, phone: 22 85 16 91
  - yngveha@ifi.uio.no
- web pages
  - http://www.uio.no/studier/emner/matnat/ifi/INF5490/v12/

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."

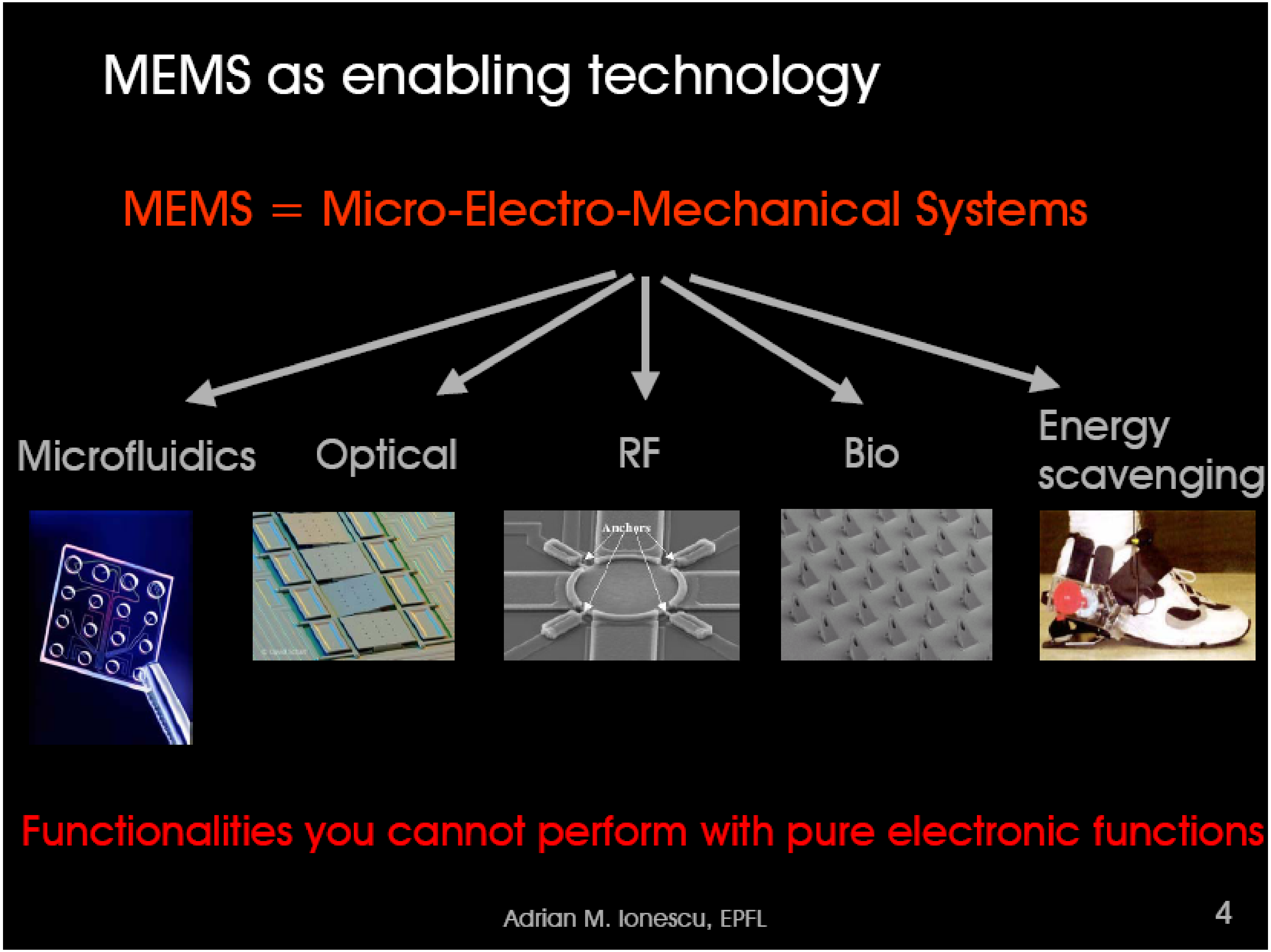
Today's lecture

- Background for course INF5490
- Course plan spring 2012

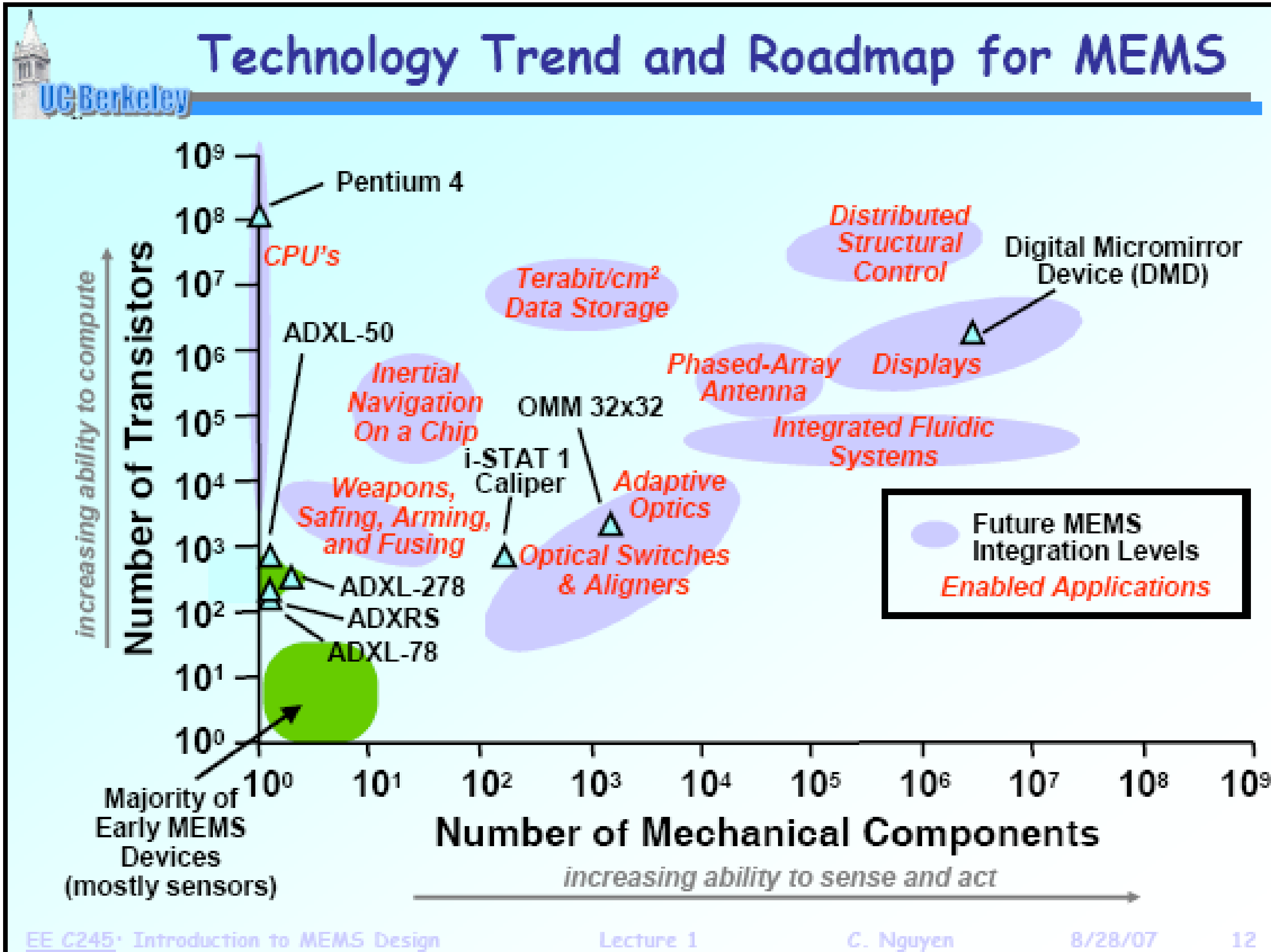
- Introduction
  - MEMS in general: "*- a flavour –*"
  - RF-systems
  - MEMS in RF-systems

The Technology is MEMS

- Designations:
    - 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
    - Restricted possibilities for ”second sourcing” (different from CMOS)
    - Other materials can be involved: plastic and organic materials (polymeres)
- PhD course FYS 9230 Modeling and design of micro- and nanosystems (fall)
  – Given by researchers from SINTEF (recommended)
  – Some central topics are recapitulated in INF5490
- MEMS is a promising technology for RF applications!

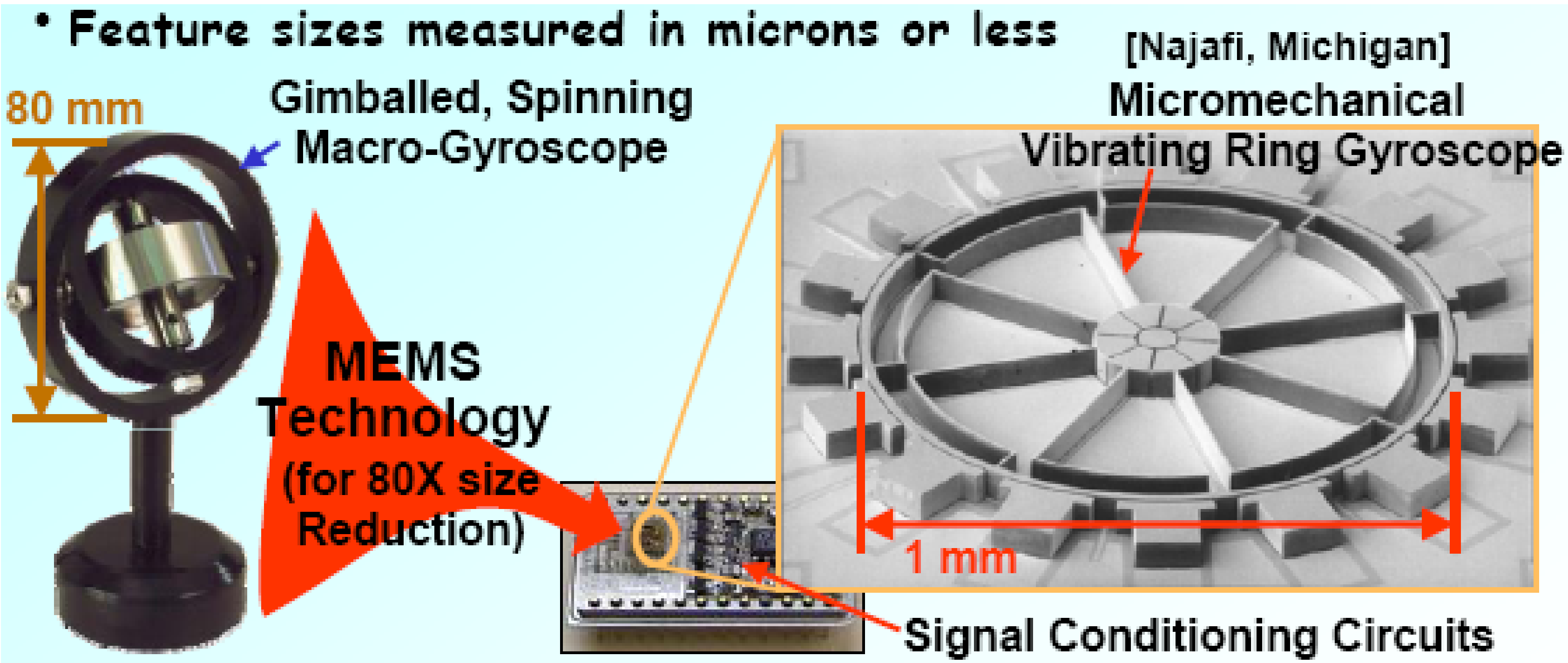

MEMS as enabling technology
MEMS = Micro-Electro-Mechanical Systems
Microfluidics
Optical
RF
Bio
Energy scavenging
Anchors
Functionalities you cannot perform with pure electronic functions
Adrian M. Ionescu, EPFL
4

[A.M. Ionescu]


Technology Trend and Roadmap for MEMS
UC Berkeley
Number of Transistors
increasing ability to compute
Pentium 4
CPU's
ADXL-50
Inertial Navigation On a Chip
Terabit/cm² Data Storage
Distributed Structural Control
Digital Micromirror Device (DMD)
Phased-Array Antenna
Displays
OMM 32x32
Integrated Fluidic Systems
i-STAT 1
Caliper
Weapons, Safing, Arming, and Fusing
Adaptive Optics
Optical Switches & Aligners
ADXL-278
ADXRS
ADXL-78
Future MEMS Integration Levels
Enabled Applications
Majority of Early MEMS Devices (mostly sensors)
Number of Mechanical Components
increasing ability to sense and act
EE C245: Introduction to MEMS Design
Lecture 1
C. Nguyen
8/28/07
12

[C. Nguyen]

”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

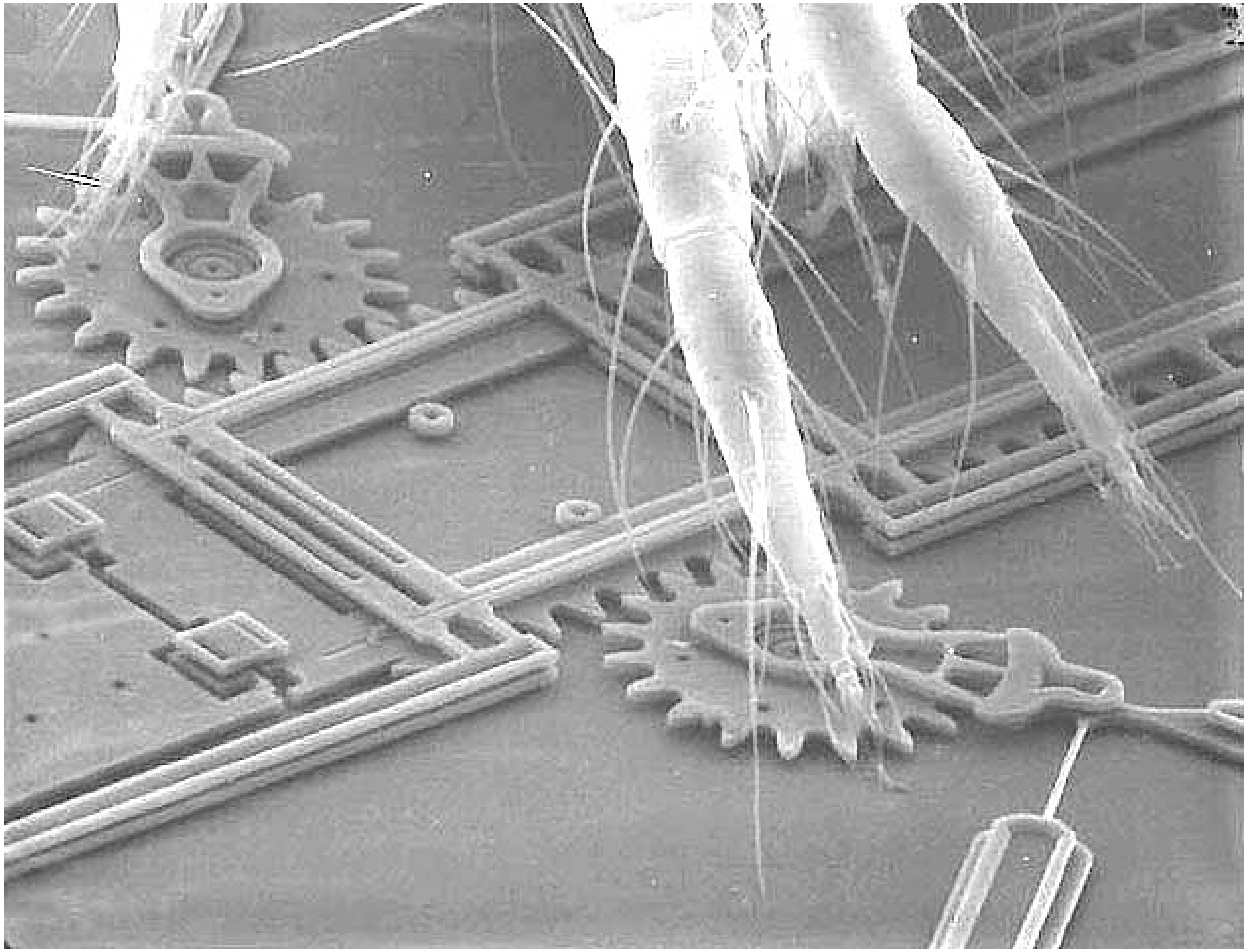
- MEMS <u>structures</u> can be actuated (= “moved”) **laterally** or **vertically**

- 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!

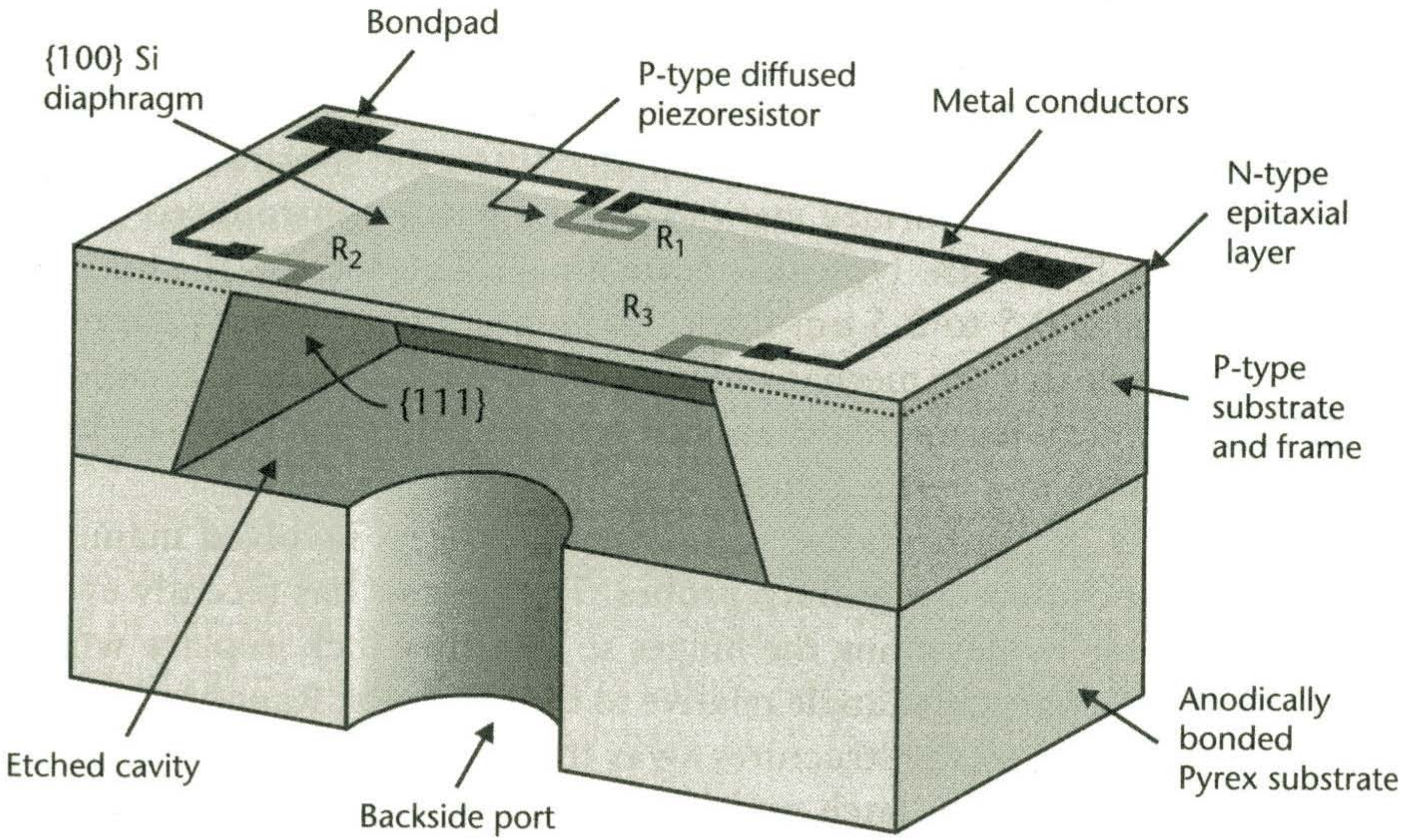
Some applications of MEMS

- **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

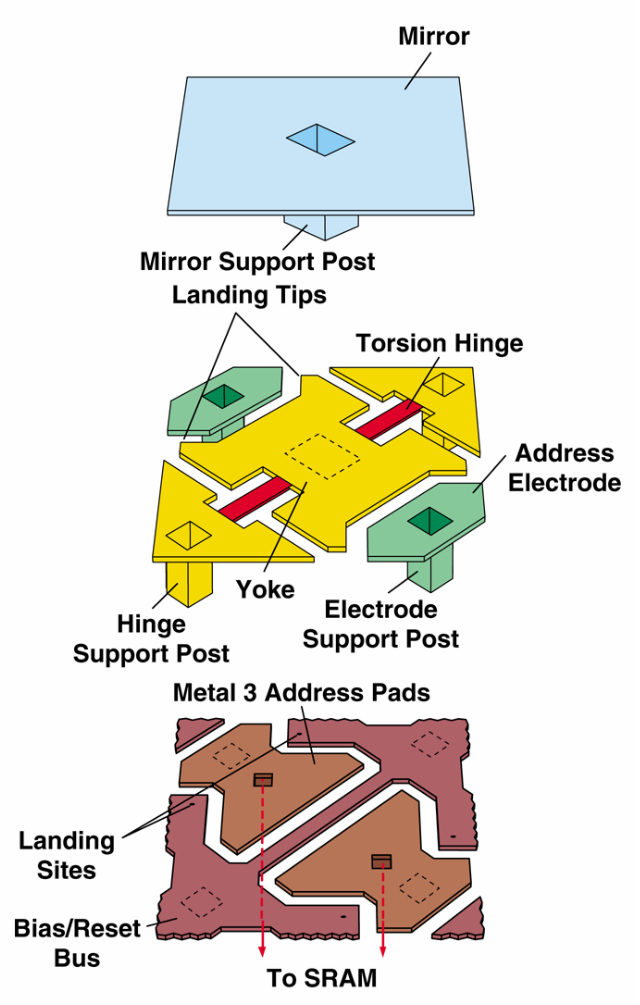
Micro motor fra Sandia



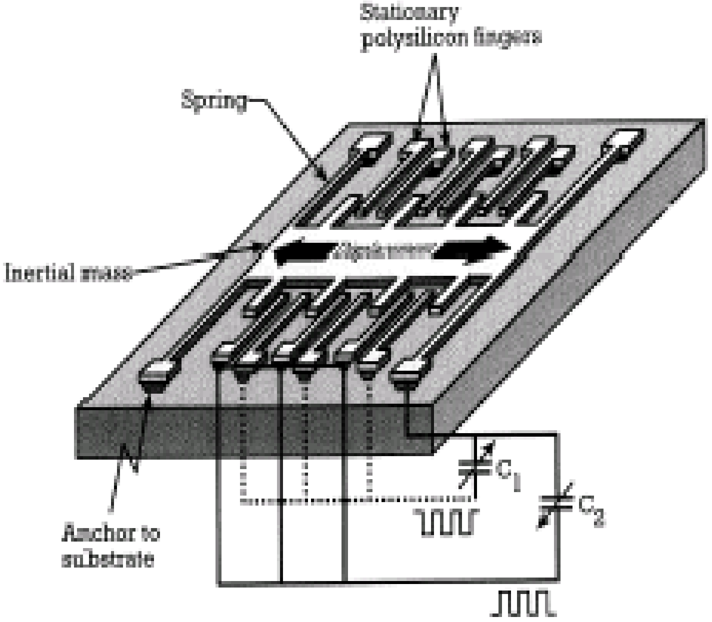
Pressure sensor



Micro mirror

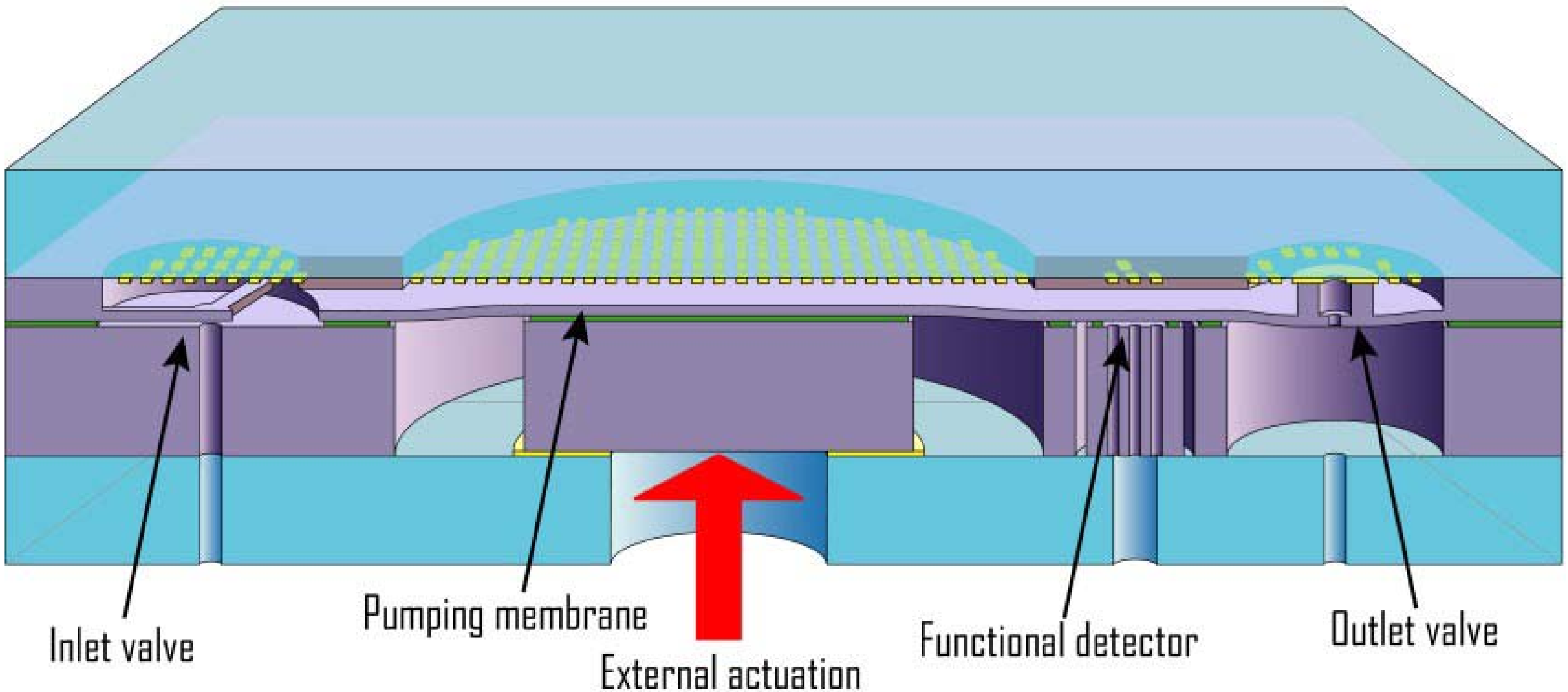


A Capacitive Accelerometer



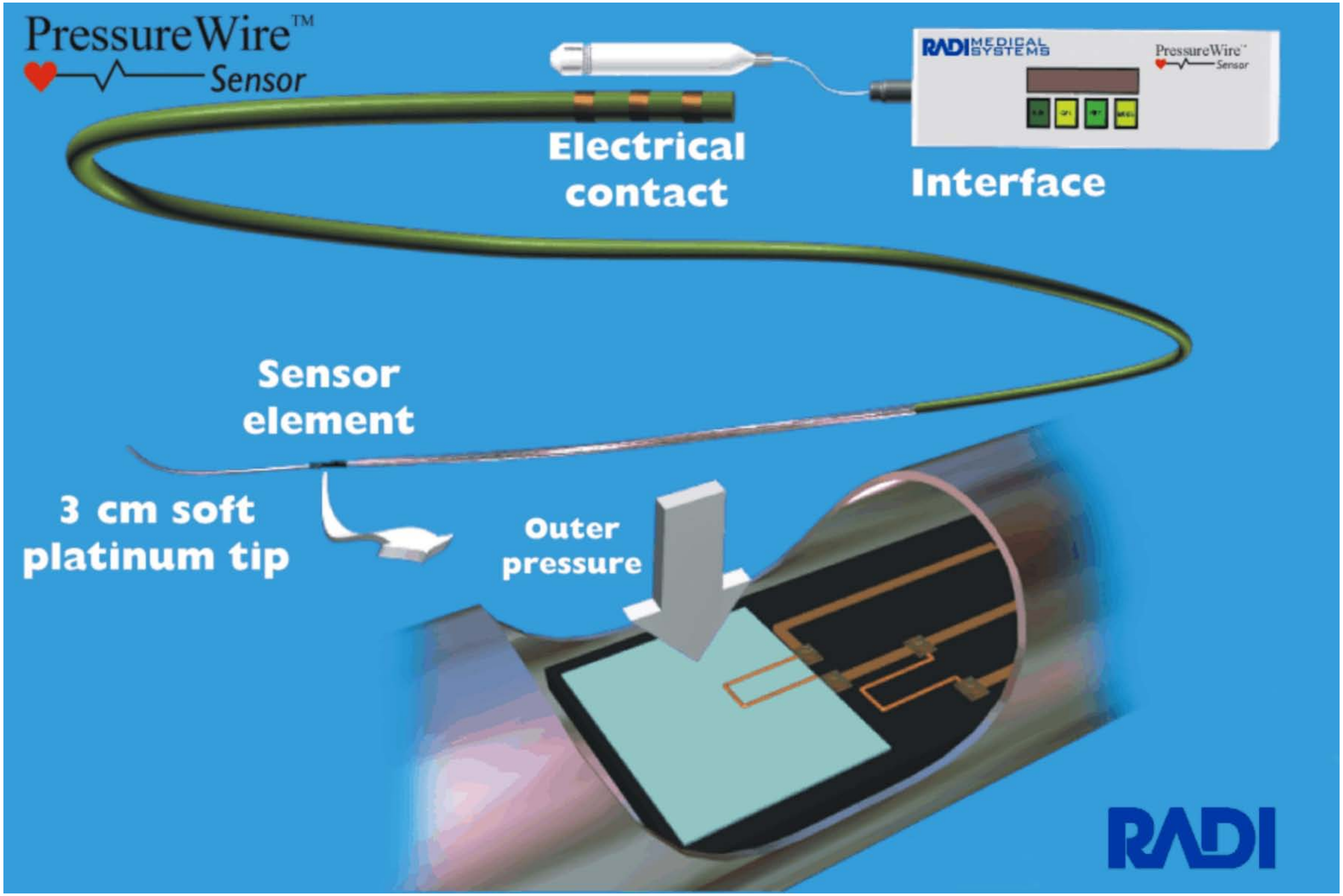
Technology Analysis: Drug Delivery

Debiotech Chip



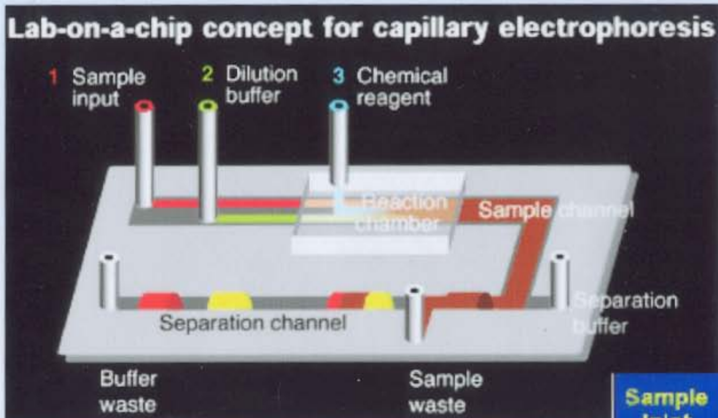
Source: Debiotech

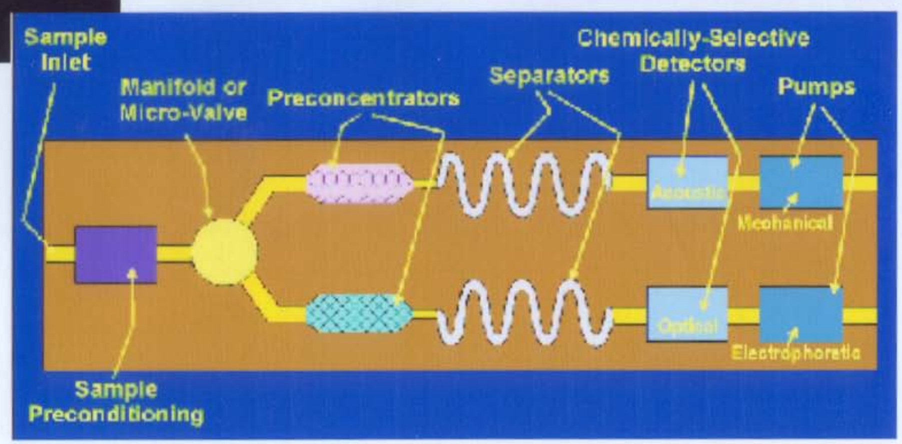
Radi Catheter



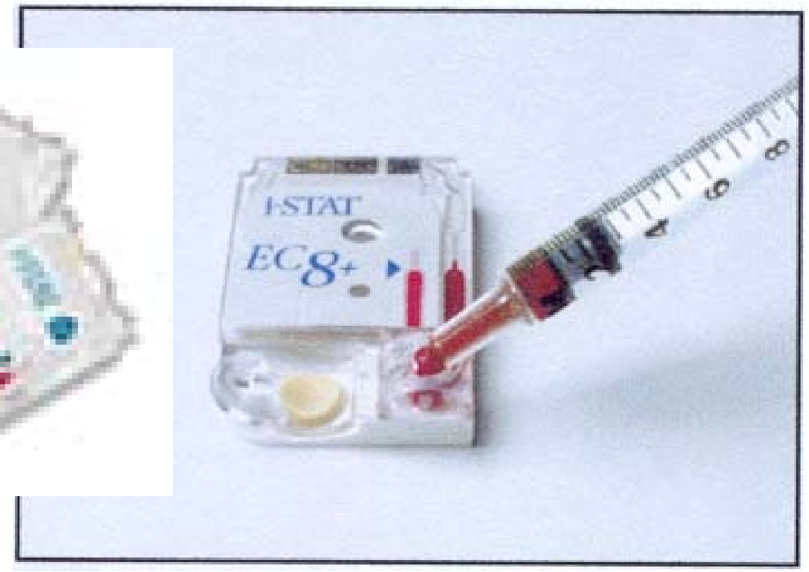
Biotechnology MEMS

"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

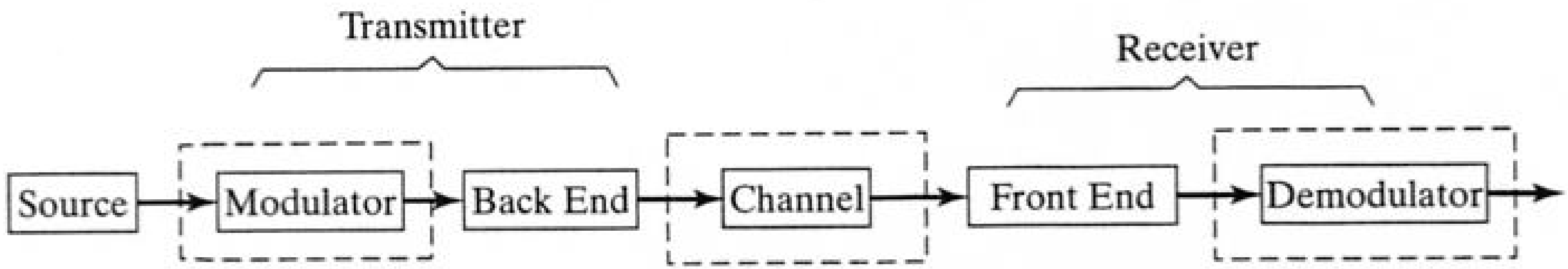
- Background for course INF5490
- Course plan spring 2012

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

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

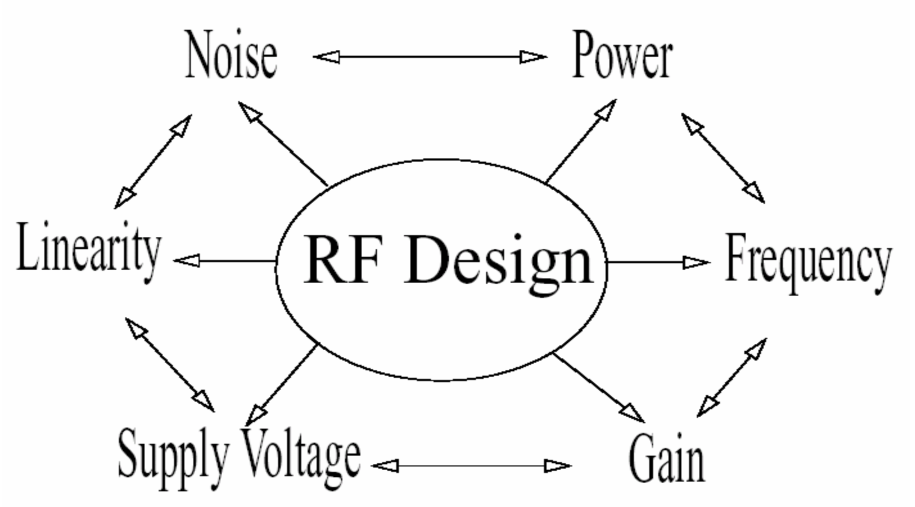
- Efficiency/performance of RF-systems
  - Ability to transfer **power**
  - Simultaneously use of limited **bandwidth**

- 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 is 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 2012

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

Typical RF MEMS components

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

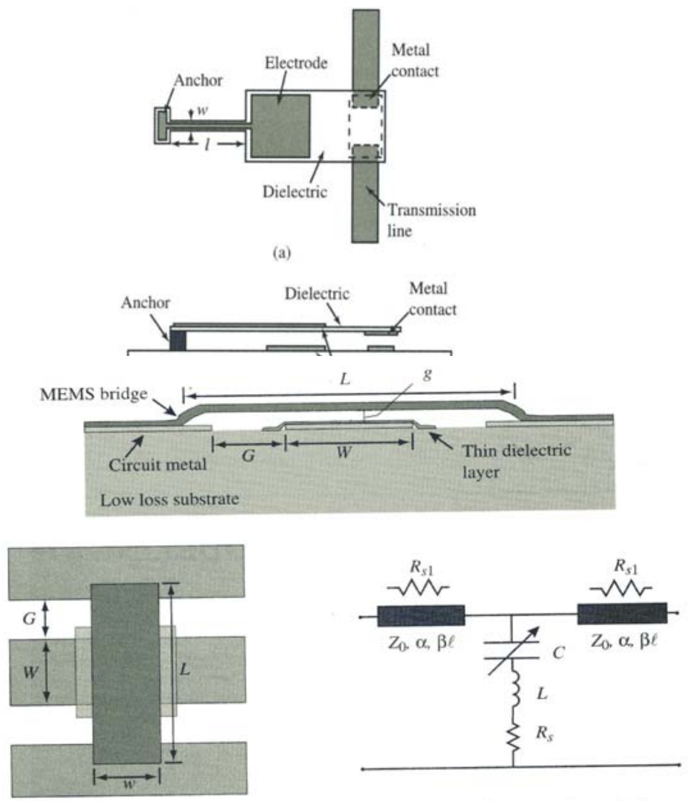


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).

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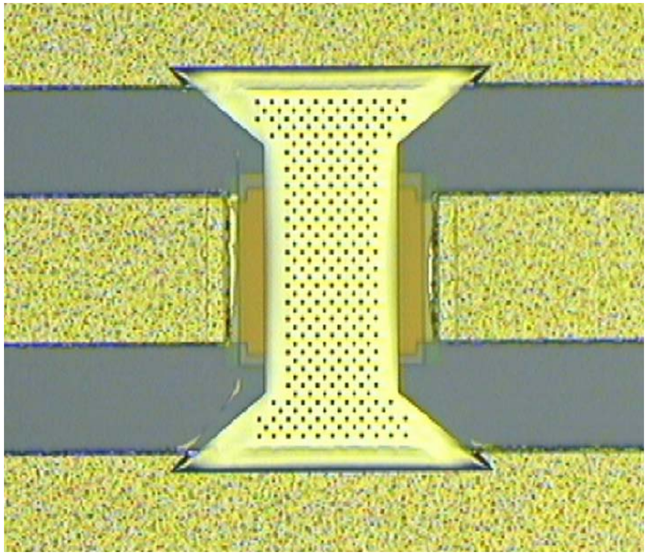

Ex.: microwave switch

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

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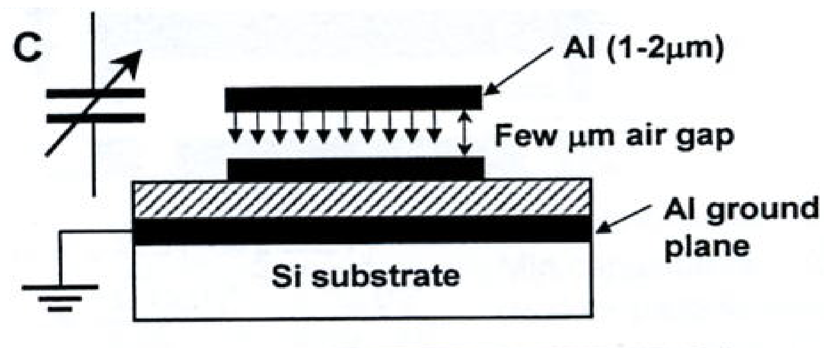

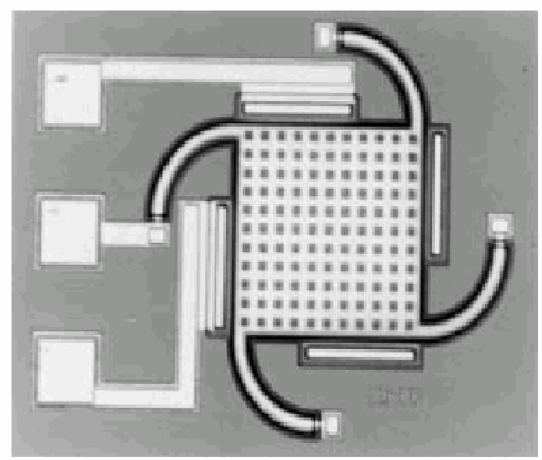

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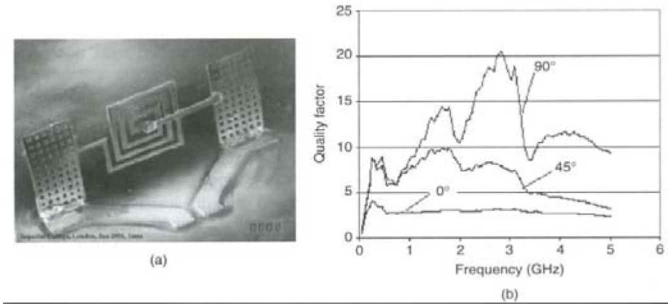
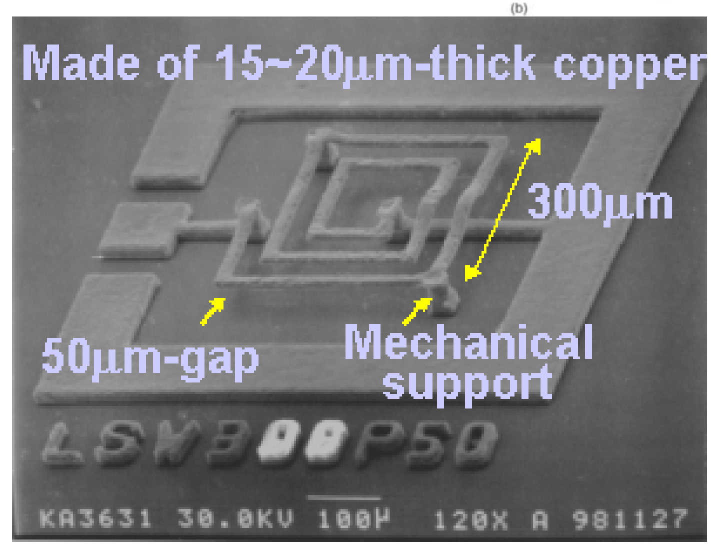




Typical RF MEMS components

- 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**

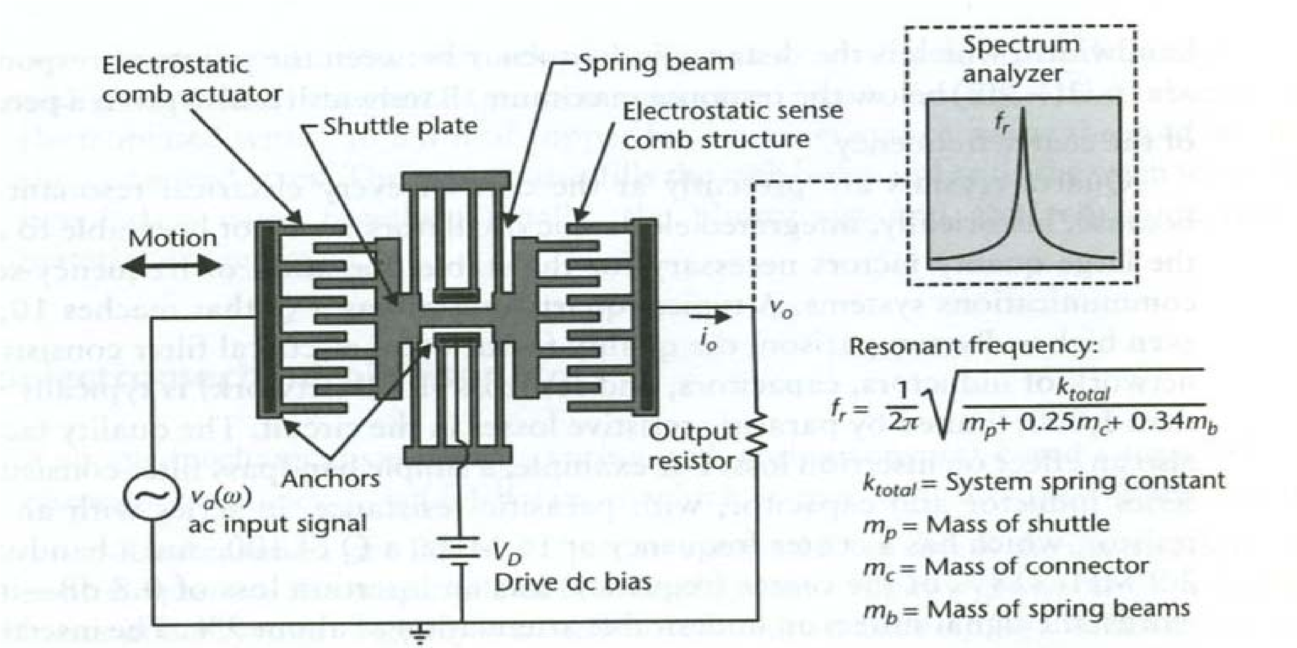
Micro-Electro-Mechanical resonators

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

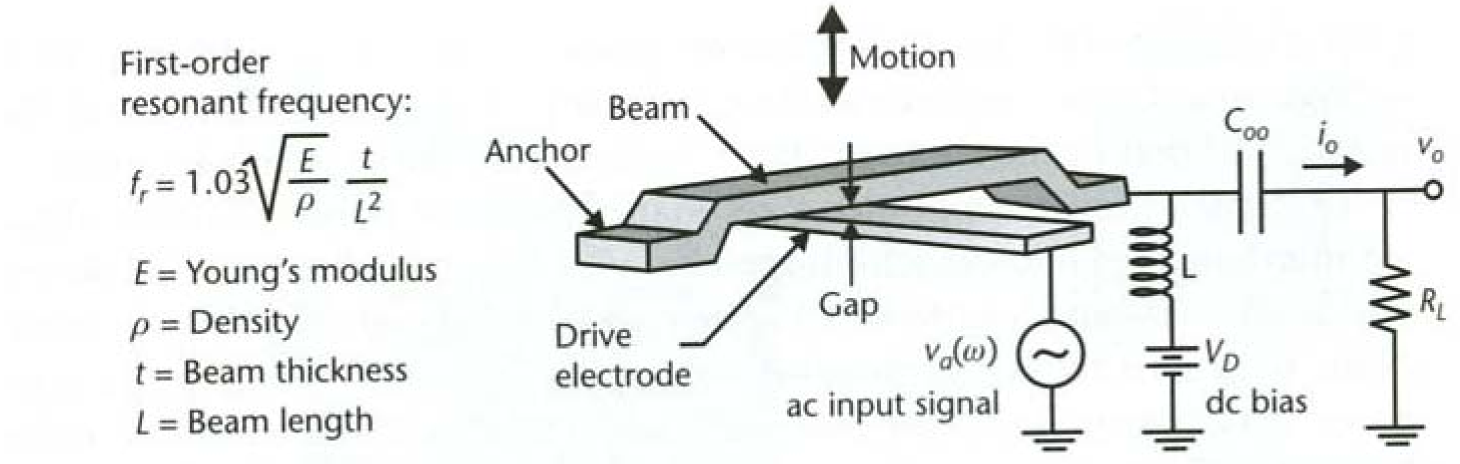
Source: Clark Nguyen, ESSDERC 2007.

Comb-resonator



lateral (horisontal) movement

Clamped-clamped beam resonator



Vertical movement

Challenges in RF transceiver implementation of today

- Performance
- Miniaturization
- Reconfigurability

Challenges in RF transceiver implementation of today

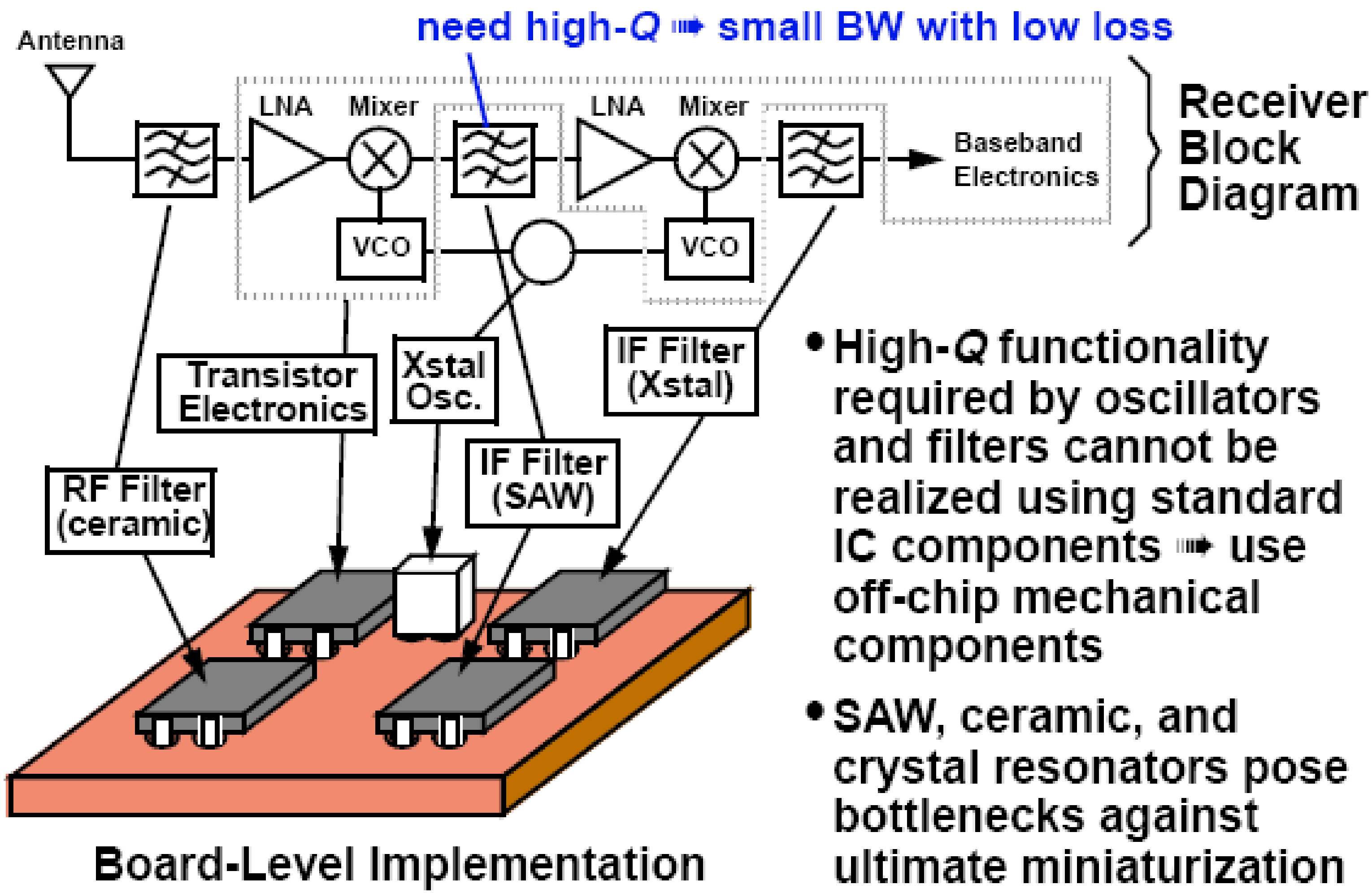
- **Performance**
  - *Integrated microelectronic components* have **limited** RF performance
    - Technology: GaAs, bipolar Si, CMOS, PIN-diodes
    - ex. PIN-diode switch (inefficient), RF filter (difficult!)
  - **Off-chip components in RF systems** are needed!
    - matching networks, filters
 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

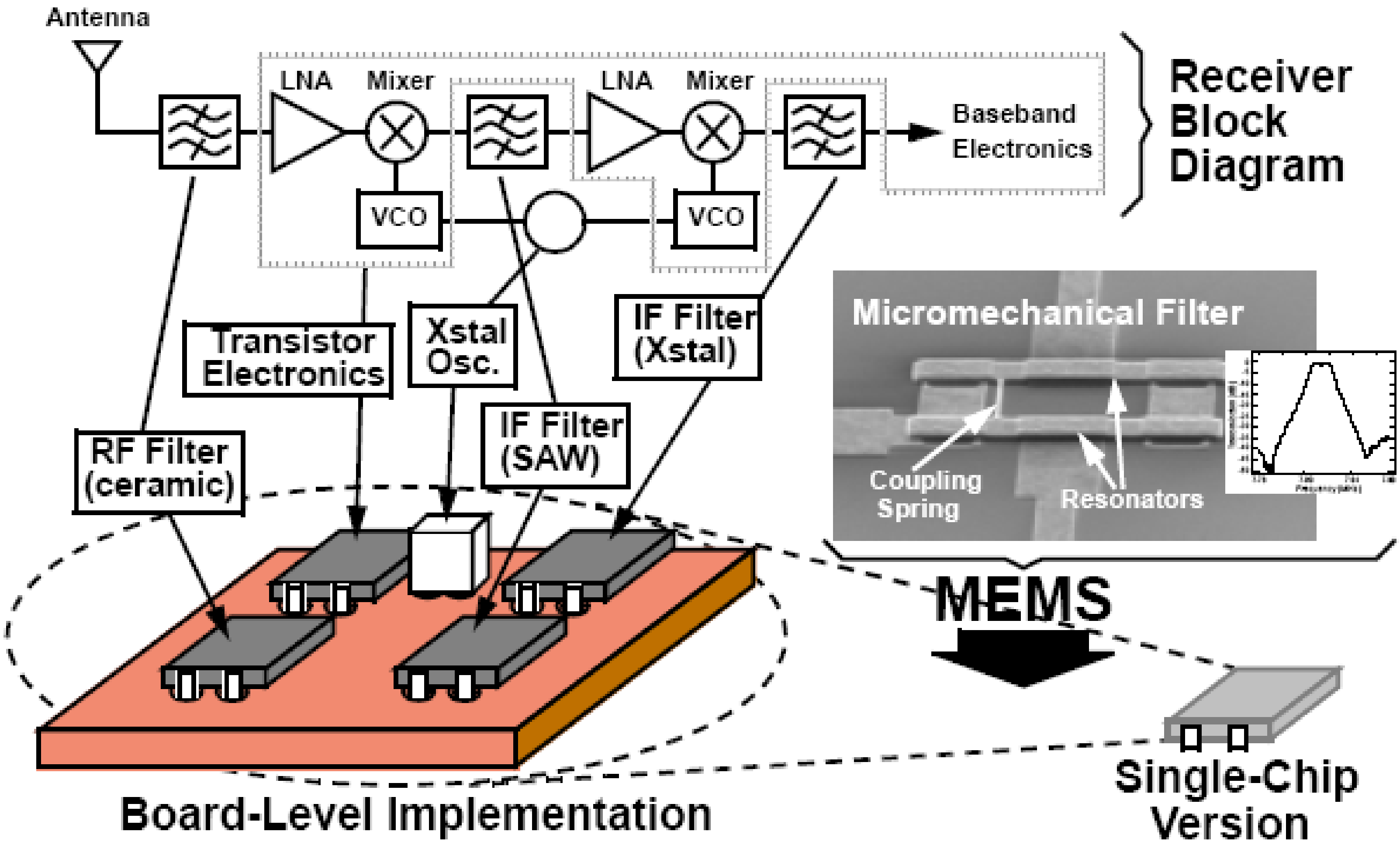
- **Reconfigurability**
  - Increasing demands exist that one single RF transceiver shall cover various standards and channels
    - Programmability is desired
  - Reconfigurable ”front-end” for ”sw defined radio”
    - RF MEMS may solve the problem!

Miniaturization of Transceivers



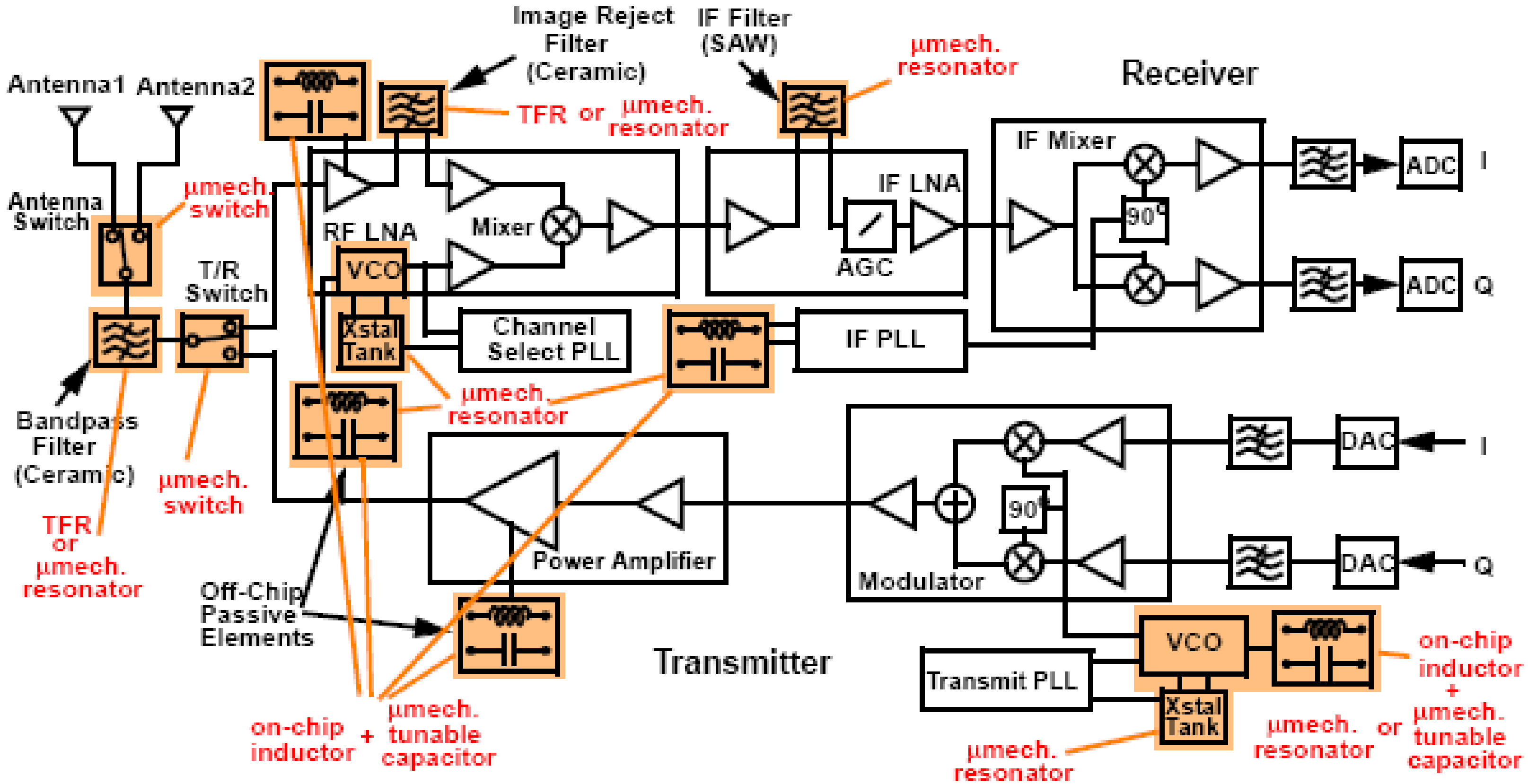
- High-*Q* functionality required by oscillators and filters cannot be realized using standard IC components ➠ use off-chip mechanical components
- SAW, ceramic, and crystal resonators pose bottlenecks against ultimate miniaturization

Target Application: Integrated Transceivers

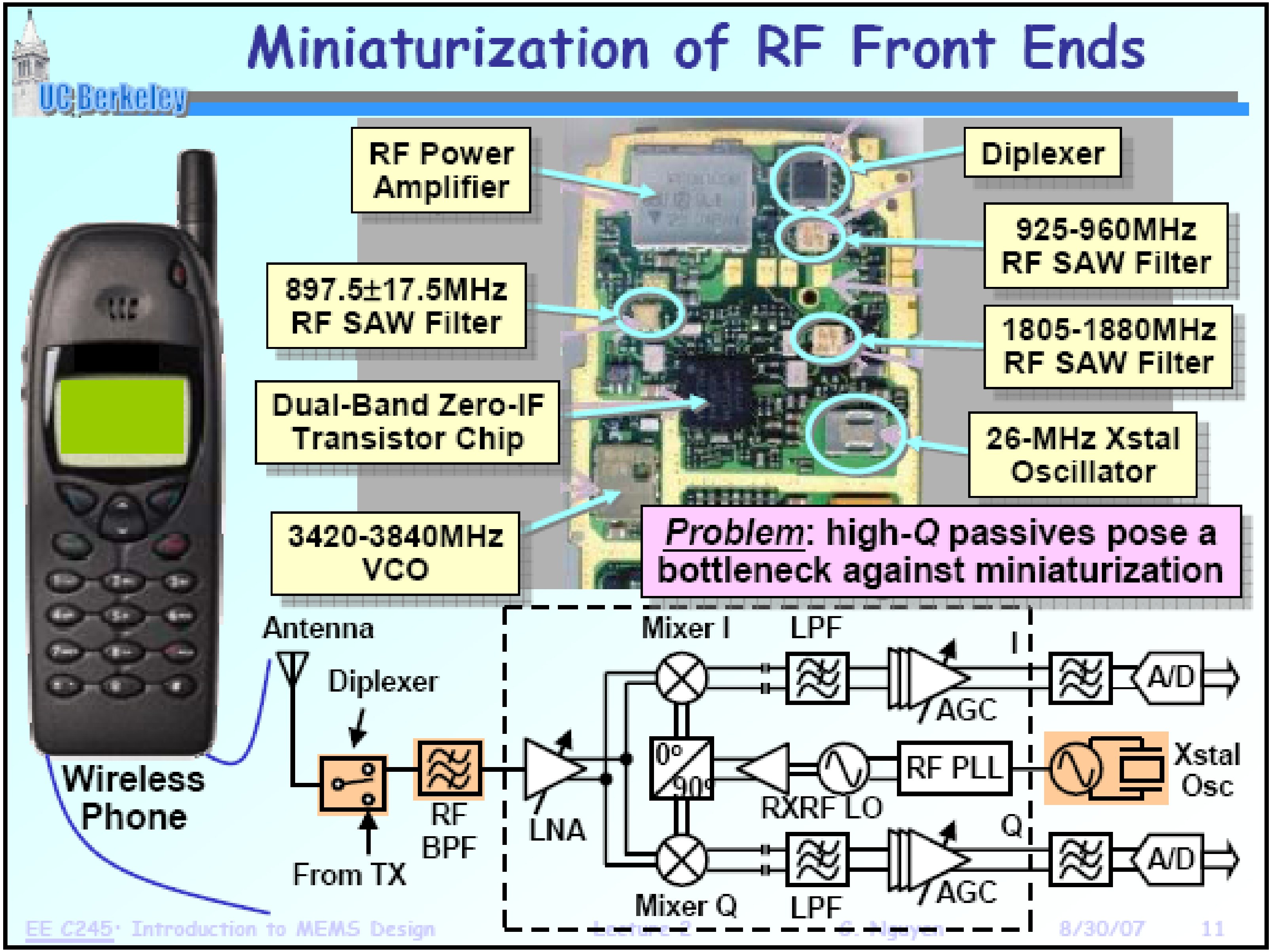


- Off-chip high-*Q* mechanical components present bottlenecks to miniaturization ➠ replace them with μmechanical versions

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
Mixer Q
LPF
LPF
AGC
AGC
I
Q
0°
90°
RXRF LO
RF PLL
A/D
A/D
Xstal Osc
EE C245: Introduction to MEMS Design
Lecture 2
C. Nguyen
8/30/07
11

C. Nguyen]

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)