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 relatively 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!

• 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 Conference
  - 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 in relevant fields (Master, Ph.D.)
- Research activity
Choice of focus \(\rightarrow\) RF MEMS

- MEMS is a *broad* field of research
  - Need of focus \(\rightarrow\) 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 competence 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
Today’s lecture

• Background for course INF5490

• Course plan spring 2008

• 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/v08/](http://www.uio.no/studier/emner/matnat/ifi/INF5490/v08/)
  – Messages posted there!

• Weekly **lectures**
  – Thursday 10:15 – 12 in 3A
  – Detailed lecture plan 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**
  - Required 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, “Manhattan bricks”
  - 3) Solvers
    - Electrical/ mechanical/ coupled
    - Iterate!
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
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
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)
    - *Micro-Opto-Electro-Mechanical Systems*
    - 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
  – 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 continuous feedback on the quality of the course. Thus, the course coordinator can make improvements based on this feedback.

Today’s lecture

• Background for course INF5490
• Course plan spring 2008

• 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 \textit{laterally} or \textit{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”

G. Stemme

DEPT. OF SIGNALS, SENSORS & SYSTEMS
ROYAL INSTITUTE OF TECHNOLOGY
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 2008

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

• Radio waves are used for transmittance/receiving
  • Electromagnetic waves (Maxwell's equations)

• Basic component: radio ”transceiver”
  – Transmitter + Receiver
  – Methods for transmission
    • TDMA (Time Division Multiplexing Access)
    • FDMA (Frequency Division Multiplexing Access)

• 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

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

Jerzy Dabrowski, CMOS RF Transceiver Design, 2004
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>
<thead>
<tr>
<th>Frequency Band</th>
<th>Frequency</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELF (Extreme Low Frequency)</td>
<td>30–300 Hz</td>
<td>10,000–1000 km</td>
</tr>
<tr>
<td>VF (Voice Frequency)</td>
<td>300–3000 Hz</td>
<td>1000–100 km</td>
</tr>
<tr>
<td>VLF (Very Low Frequency)</td>
<td>3–30 kHz</td>
<td>100–10 km</td>
</tr>
<tr>
<td>LF (Low Frequency)</td>
<td>30–300 kHz</td>
<td>10–1 km</td>
</tr>
<tr>
<td>MF (Medium Frequency)</td>
<td>300–3000 kHz</td>
<td>1–0.1 km</td>
</tr>
<tr>
<td>HF (High Frequency)</td>
<td>3–30 MHz</td>
<td>100–10 m</td>
</tr>
<tr>
<td>VHF (Very High Frequency)</td>
<td>30–300 MHz</td>
<td>10–1 m</td>
</tr>
<tr>
<td>UHF (Ultrahigh Frequency)</td>
<td>300–3000 MHz</td>
<td>100–10 cm</td>
</tr>
<tr>
<td>SHF (Superhigh Frequency)</td>
<td>3–30 GHz</td>
<td>10–1 cm</td>
</tr>
<tr>
<td>EHF (Extreme High Frequency)</td>
<td>30–300 GHz</td>
<td>1–0.1 cm</td>
</tr>
<tr>
<td>Decimillimeter</td>
<td>300–3000 GHz</td>
<td>1–0.1 mm</td>
</tr>
<tr>
<td>P Band</td>
<td>0.23–1 GHz</td>
<td>130–30 cm</td>
</tr>
<tr>
<td>L Band</td>
<td>1–2 GHz</td>
<td>30–15 cm</td>
</tr>
<tr>
<td>S Band</td>
<td>2–4 GHz</td>
<td>15–7.5 cm</td>
</tr>
<tr>
<td>C Band</td>
<td>4–8 GHz</td>
<td>7.5–3.75 cm</td>
</tr>
<tr>
<td>X Band</td>
<td>8–12.5 GHz</td>
<td>3.75–2.4 cm</td>
</tr>
<tr>
<td>Ku Band</td>
<td>12.5–18 GHz</td>
<td>2.4–1.67 cm</td>
</tr>
<tr>
<td>K Band</td>
<td>18–26.5 GHz</td>
<td>1.67–1.13 cm</td>
</tr>
<tr>
<td>Ka Band</td>
<td>26.5–40 GHz</td>
<td>1.13–0.75 cm</td>
</tr>
<tr>
<td>Millimeter wave</td>
<td>40–300 GHz</td>
<td>7.5–1 mm</td>
</tr>
<tr>
<td>Submillimeter wave</td>
<td>300–3000 GHz</td>
<td>1–0.1 mm</td>
</tr>
</tbody>
</table>
Communication standards

- Various standards exist

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

Jerzy Dabrowski, CMOS RF Transceiver Design, 2004

- Will not discuss standards in INF5490!
Today’s lecture

• Background for course INF5490
• Course plan spring 2008

• 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, 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
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 $\rightarrow$ charge $\rightarrow$ attractive forces $\rightarrow$ mechanical movement
    - High signal linearity
    - Low DC ”standby power”
    - Low loss (”insertion loss”)
  - Challenges
    - Low speed (some $\mu$s)
    - 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
- Variable capacitors
- Inductors
- Resonators
- 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

First-order resonant frequency:

\[ f_r = 1.03 \sqrt{\frac{E}{\rho}} \frac{t}{L^2} \]

- \( E \) = Young’s modulus
- \( \rho \) = Density
- \( t \) = Beam thickness
- \( L \) = Beam length

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 $\rightarrow$ 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
- $\Delta f$: 260kHz
- $Q$: ~1000

RF filter
- $f_0$: 868MHz
- $\Delta f$: 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

need high-Q small BW with low loss

Receiver Block Diagram

- 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.

Board-Level Implementation
Target Application: Integrated Transceivers

Receiver Block Diagram

Board-Level Implementation

- Off-chip high-Q mechanical components present bottlenecks to miniaturization; replace them with \( \mu \)mechanical versions

C. T.-C. Nguyen

Univ. of Michigan
MEMS-Replaceable Transceiver Components

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

C. T.-C. Nguyen
Univ. of Michigan
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 distributed components
    • Enhanced integration flexibility
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 microelectronics and MEMS have much in common

• Combination of electronics and micromechanics
  – Integrated solutions on a Si chip
    • “Radio-on-a-chip”!

MEMS for wireless integration

Today
Future
(3 - 4 Yrs)
Future
(4+ Yrs)

100s of passive components

MEMS research to enable:
• “High Value” passives (Filters, Switches etc) to be built from Silicon and integrated together

Silicon integration follows Moore’s law
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”

• 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