Applications and Trends in RF MEMS

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Outline

I. MEMS Origins
II. MEMS Fabrication Technology
III. RF/Microwave MEMS Devices & Circuits Applications
   A. Capacitors, Inductors, Transmission Lines
   B. Switches
   C. Resonators
   D. Tuned Amplifiers
   E. Adaptive Matching Networks
   F. Filters
IV. MEMS in RF/Microwave Systems
V. Nano-MEMS Trends
VI. Conclusions
Micro Electro Mechanical Systems: ORIGINS

Richard P. Feynman (APS Meeting 1959): “There is plenty of room at the bottom”

Special type of research: Search for *boundless* field

*Examples:*

(1) Attaining Low Temperatures

(2) Attaining High Pressures

(3) ???

**Miniaturization: Engage in program to make everything *small*!**
Micro Electro Mechanical Systems: ORIGINS

What limits miniaturization?

• The laws of physics don’t preclude (limit) miniaturization

• Limitations are imposed by technology (ability to make small things), not physics

• How would miniaturization impact:

  1) Information Storage

  2) Computers

  3) Machinery-New design paradigms: machines would not simply scale down! different domain of material behavior!
Nano Micro Electro Mechanical Systems: ORIGINS

What Do We Mean By Small?

Quantity

Molecular (Nano) Machines

Micromachines (MEMS)

Conventional Machines

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Micro Electro Mechanical Systems: IMPETUS, MOTIVATION

• Advent of Integrated Circuit technology in the 60’s

<table>
<thead>
<tr>
<th>Integration Level</th>
<th>60’s</th>
<th>90’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuits/Wafer</td>
<td>&lt;10 devices per circuit</td>
<td>&gt;10^7 devices per circuit</td>
</tr>
</tbody>
</table>
Micro Electro Mechanical Systems: IMPETUS, MOTIVATION

QUESTION: Would the application of IC fabrication concepts to:

- MECHANICS,
- OPTICS,
- and FLUIDICS

result in enhanced performance @ lower cost???

ANSWER: Maybe!

- An IC extends in 2-D !!
- A mechanical microstructure is 3-D !!!
MEMS Fabrication Technology
(How to make small 3-D structures?)
Conventional IC Fabrication Process


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MEMS Fabrication Technology Elements

Surface Micromachining

*Add* thin film layers to wafer, then *remove* some layers

**SIDE VIEW**

**TOP VIEW**

- **Sacrificial layer**
- **Wafer**
- **Structural layer**
- **Beam**

Process sequence

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MEMS Fabrication Technology Elements

Bulk Micromachining

*Sculpt* wafer by anisotropic etching

(a) \[ \text{Wafer} \]

(b) \[ \text{Etch Mask} \]

(c) \[ \theta \]

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Foundries

- Many established MEMS companies own fab, most startups fabless
- Over 80 foundries worldwide, front end (process) vs back end (packaging, test), development vs product capable, CMOS capability, wafer size 4-6-8in
- Many newly established IC foundries looking to exercise their capabilities, more are willing to develop MEMS now
- Use existing process, improve existing process, or develop a new process
Micro Electro Mechanical Systems: EXAMPLES

MATURE
• Accelerometers (used in automobile air bags)
• Pressure Sensors

EMERGING
• Gyroscopes
• Flow Sensors
• Micromotors
• Switches
• Resonators
Why is it expected that MEMS will revolutionize RF applications?

1) Availability of both electronic (2-D) and mechanical (3-D) fabrication techniques enables novel highly functional systems (SoC)

2) Potential for new levels of performance not achievable otherwise
   - Inherently smaller size and weight systems
   - Lower power consumption
   - Economies of scale (lower cost)
RF/Microwave MEMS-Enhanced Passive Components
(Capacitors, Inductors, Transmission Lines)
MEMS-Based Devices

Parallel-Plate Capacitor

Substrate

Top plate (In)

Bottom plate (Out)

\[ C_{\text{sub}} \]

\[ R_{\text{die}} \]

\[ R_{\text{sub}} \]

\[ C_{\text{sub}} \]
MEMS-Based Devices

Bulk-Micromachined *MIM* Capacitor

**Top View**

**Cross Section**

Top-side KOH etching

Q=100@2GHz (Q<10 when directly fabricated on Si)
C=2.6pF
\( f_{\text{self-resonance}} = 15.8 \text{ GHz} \)

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MEMS-Based Devices

Monolithic Inductor

In  Out  Substrate

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MEMS-Based Devices

Bulk-Micromachined RF Inductors

Q=22 @ 270 MHz
L=115nH


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MEMS-Based Devices

Bulk-Micromachined RF Transmission Lines

$c=150\mu m$

$b=50\mu m$

$a=20\mu m$

$t_{Al}=0.6\mu m$

Bulk micromachining Reduces Substrate Loss Drastically!

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MEMS-Based Circuits

CMOS RF Amplifier with Air-Suspended Inductor


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MEMS-Based Devices

MEM Variable Capacitor (Varactor)

(a) Overhead and (b) cross-sectional schematics of a voltage-tunable mechanical capacitor


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RF MEMS-Based adaptive 900MHz PA

Output impedance matching network accommodates for variations in the optimal transistor load impedance, which is a function of transmitted PA power.

\[ Z_{\text{in}} = 4 + 3j \ \Omega \ @ \ P = 1.0W \]
\[ Z_{\text{in}} = 2 \ \Omega \ @ \ P = 3.7W \]

RF/Microwave MEM Switches & Applications
MEMS-Based Devices

Fundamentals of RF/Microwave MEM Switches

Sources: Figure 5.7 Introduction to Microelectromechanical (MEM) Microwave Systems, Norwood, MA: Artech House (1999)

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MEMS-Based Devices

Typical Published MEM Switch Performance

- Frequency: DC - 60 GHz
- Transmission:
  - Shunt Switch: I.L.: 0.1 dB @ 10 GHz, ISOL: -25 dB @ 20 GHz
  - Series Switch: I.L: 0.1 dB @ 4 GHz, ISOL: -50 dB @ 4 GHz
- Actuation Voltage: 20 - 60 V
- IP3: +66 dBm @ 2 GHz
- Switching Time: 4 - 20 μs

MEMS-Based Devices

Reconfigurable Distributed RF/Microwave Components

Key Features
- Microswitch arrayed in 2D
- Switches individually addressable

Frequency reconfigurable power amp

RF/Microwave MEM Resonators & Applications
Vibrating Cantilever Beam

\[
D = \text{damping coefficient} \\
M = \text{beam mass} \\
K = \text{spring constant}
\]

\[
f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{K}{M}}
\]

Source: Figure 2.7 Introduction to Microelectromechanical (MEM) Microwave Systems, Norwood, MA: Artech House (1999)
The Cantilever Beam MEM Resonator: Resonant Gate Transistor

Abandoned due to:
• Low Qs
• High TC at $f_R$, aging of metal films
• $F \sim 1/x^2$ --> nonlinear drive severely constraints input signal dynamic range

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Free-free MEM resonator


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Film Bulk Acoustic Wave Resonator (FBAR)

Agilent’s FBAR Structure

Physical Acoustic Resonant Cavity-Description & Its Circuit Model

\[ k_s = \left| \mathbf{k}_s \right| \]


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MEMS-Based Devices

High-Frequency SAW Resonators

Cross-sections of two thin-film bulk-acoustic resonators. (a) A membrane supported FBAR resonator (b) A solidly mounted resonator (SMR)

\[ Q' s \geq 1000 \]

\[ 1.5 \text{ GHz} < f_0 < 7.5 \text{ GHz} \]

\[ 0.5 \text{ GHz} < f_0 < 2.5 \text{ GHz} \]

FBAR Filters


Motivation:
- On-chip integration (RFIC)
- Power Handling
- Insertion Loss
- Small Size & Weight

<table>
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<tr>
<th>FBAR</th>
<th>SAW</th>
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<tr>
<td>Passband:</td>
<td>1.92-1.98 GHz</td>
</tr>
<tr>
<td>Insertion Loss:</td>
<td>2.8dB 3.2dB</td>
</tr>
<tr>
<td>Passband Ripple:</td>
<td>0.5dB 1.2dB</td>
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\[
\begin{align*}
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\end{align*}
\]

Seven-Resonator FBAR Filter
Size: 3 x 3mm

\[ f_{\text{series}} = f_0, \quad f_{\text{parallel}} = f_0 + \Delta/2 \]

\[ f_{\text{series}} = f_0 - \Delta/2 \]

\[ |Z_{\text{shunt}}| \quad |Z_{\text{series}}| \]

\[ |S_{21}|(\text{dB}) \]

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MEMS in RF/Microwave Systems
MEMS-Based Systems

Potential MEMS Systems Applications of Greatest Impact

• Wireless Transceivers
• Routing/Switching Matrices
• Smart/Adaptive Antennas
RF Front-End for Cellular 3G Handset


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Adaptive Impedance Matching

Compensating Antenna Detuning Due To Body-Proximity

Block diagram of the adaptive series-LC matching module—it compensates the reactive part of the load impedance by controlling the detected phase ($\phi_{Z_{\text{DET}}}$) of the matched impedance to zero.

Block diagram of the high-voltage generator providing a 60 V actuation and 30 V hold voltage. The bridge circuit allows for bipolar actuation of the RF-MEMS devices.

Impedance adaptation trajectories measured For loads with VSWR of 4. $f = 900$ MHz
Nano-MEMS Trends
What Do We Mean By Small?

Quantity

NanoMEMS

Micromachines (MEMS)

Molecular (Nano) Machines

Conventional Machines

nm μm mm m km

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NanoMEMS Physics

Countinuous Energy

\[ p = mv \quad E \sim \frac{p^2}{2m} \]

Size Reduction

\[ L_z \quad L_y \quad L_x \]

\[ L_i \lesssim 100 \text{nm} \]

Quantized Energy

\[ p = \frac{\hbar}{\lambda} \quad E = \hbar \omega \quad \Delta x \cdot \Delta p_x \gtrsim \hbar \]

\[ E(n_x, n_y, n_z) = \frac{\hbar}{2m} \left[ \left( \frac{n_x \pi}{L_x} \right)^2 + \left( \frac{n_y \pi}{L_y} \right)^2 + \left( \frac{n_z \pi}{L_z} \right)^2 \right] \]

Wave, Particle Behavior Devices
- Interference, Diffraction, Tunneling, etc.
- Coulomb Interaction

\[ E_{\text{Coulomb}} = \frac{Q^2}{L} \]

\[ z = 0.5 \mu m \quad A = 1 \text{cm}^2 \]

Casimir Forces

QED "Vacuum" Pressure

\[ \left[ \nabla^2 - c^{-2} \frac{\partial^2}{\partial t^2} \right] \vec{E} = 0 \quad \vec{E} = 0 \]

\[ |\vec{E}| : \neq 0 \]

\[ F_{\text{Casimir}} = -\frac{\pi^2 \hbar c}{A} \frac{1}{240} \frac{1}{z^4} \]

\[ F_{\text{Casimir}} = 2 \mu N \]

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Impact of the Casimir Force on Movable-Dielectric RF MEMS Varactors

Yoon and Nguyen, ‘98

Quantum Mechanical Pull-in!

Reduced Tuning Range

ΔC_{Ideal}: 47%
ΔC_{Measured}: 15%

Forces on Varactor

Greater asymmetry → F_{Casimir} >> F_{Electrostatic}

ΔC Reduction due to Casimir Force!
NanoMEMS SoC—Building Blocks

Signal Processing Realm

- Sensitivity
- Bandwidth
- Dynamic Range

- Transduction
- Amplification
- Digitization
- Filtering, Etc.
Coupling between vibrating beam and QD Modulates electron dwell time in QD and induces interference in Aharonov-Bohm ring.

NanoMEMS Applications: Nanomedicine

Futuristic

Tooth Cleaning Robots

Lung Cleaning Robots

Science Fiction

Improved Imaging and Diagnostics (Nano Bar Codes)

Detection Using Cantilever (Nanomechanics for Biomolecular Recognition)

Realistic

www.chem.ch.huji.ac.il/~porathNST2Lecture%2013Lecture%2013.pdf
Scientific America, September 2001
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Applications: Medicine

Nanomechanics for Biomolecular Recognition

Nanomechanics + Biochemical Surface Functionalization (Coating)

Selective Species (Mass) Sticking $\rightarrow \Delta f_0$

Instrument Prototype Available

Scanning electron micrograph of a microfabricated cantilever array. Eight cantilevers with dimension of 500 um x 80 um x 7 um.
Applications: Medicine

Quantum Dots

- Metal and semiconductor nanoparticles in the 2–6 nm size
- Unique size-dependent properties
- Size similar to biological macromolecules: nucleic acids, proteins

Particle dimension~Bohr exciton: $a_{ex} = \frac{\epsilon \cdot \hbar^2}{m_{ex} e^2}$

Examples: $a_{\text{CuCl}} = 7 \text{ Å}, a_{\text{GaAs}} = 100 \text{ Å}$ and $a_{\text{CdSe}} = 56 \text{ Å}$

Discretization of Energy Levels


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Applications: Medicine

Size-Controlled Emission of Quantum Dots

Howard Lee and his colleagues at LLNL have synthesized silicon and germanium quantum dots ranging in size from 1 to 6 nanometers. The larger dots emit in the red end of the spectrum; the smallest dots emit blue or ultraviolet.

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Conclusions
NanoMEMS is Growing Field

Nanotechnology R&D Funding by Agency

Many Directions $$$

- Fundamental Phenomena & Processes
- Nanomaterials
- Nanoscale Devices & Systems
- Instr. Research, Metrology & Standards
- Nanomanufacturing
- Major Research Facility & Instr. Acquisition
- Social Dimensions

http://www.nano.gov/NNI_07Budget.pdf

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MEMS R&D and Commercial Growth

Application fields in 2004 and 2009

2004
- Industrial & process control: 11%
- Telecom: 6%
- Medical & life sciences: 5%
- Consumer Electronics: 5%
- Automotive: 1%
- Aerospace, defense: 68%
- Homeland security: 1%
- Household: 1%

2009
- Industrial & process control: 4%
- Telecom: 3%
- Medical & life sciences: 6%
- Consumer Electronics: 22%
- Automotive: 8%
- Aerospace, defense: 54%
- Homeland security: 1%
- Household: 1%
- Others: 1%

(totals $12 billions)

(totals $25 billions)

November 2005
RF MEMS R&D and Commercial Growth

Many Directions $$$

• Military Phased Arrays
• Military Tactical Radio
• Satellites
• RF Test and ATE
• Automotive
• Microwave Communications
• Base stations
• Consumer electronics and IT
• WLAN and WPAN
• Mobile Telephony

Will the RF MEMS market forecasts keep their promise?

40% of the market in 2009 with BAW for cell phones: low risk in prediction
  - Established, figures cross-checked with established suppliers

Instrumentation: the ATE market leader has developed its RF MEMS technology...

Military applications. Could come later.

Major risk in forecasts for IT
  - Is micro-mechanical resonator now at “Peak of inflated expectations”?
  - To follow...

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