Microelectromechanical Systems (MEMS) based advanced high performance Radio Frequency (RF) systems
Outline

- Introduction
- What are MEMS
  - Why use MEMS – advantages
  - How are MEMS fabricated
  - MEMS actuation techniques
- RF MEMS
  - Fabrication
  - Applications
  - Advantages
  - MEMS switch library
  - Design and analysis
  - Failure mechanisms
  - Challenges
  - Conclusions
What are MEMS?

- MEMS are Micro Electro-Mechanical Systems
- MEMS typically have both electrical and mechanical components
- As microelectronics has shown, size doesn’t necessarily matter
- Envisioned by Sci-Fi authors
- R.P. Feynman – “There’s lots of room at the bottom”
- First MEMS Publication:
- Pressure sensors were the first MEMS products
  - Si diaphragms and diffused piezo-resistors
- Surface μ–machined accelerometers and flow sensors
Why MEMS?

- Miniaturization with no loss of functionality
- Integration to form a monolithic system
- Improved reproducibility, reliability and accuracy
- Exploitation of new physics domains
- Low power
- Fast actuation techniques
- Improved selectivity and sensitivity
- MEMS may be the ONLY solution
MEMS enables advances in many business areas...

**Optics**
- Micromirrors
- Silicon Benches
- Waveguided structures
- Integrated subsystems
- Optical transparency
- Ease of manufacture
- High precision
- High reliability
- Integration of multiple subsystems

**Life Sciences & Laboratory Equipment**
- Micronozzles
- Micropumps
- Membranes
- Microfluidic channels
- Wells & reservoirs
- Waveguides
- Lab-on-a-chip
- Economical use of samples
- Low cost assays
- Quick turnaround on sample analysis
- Reduction in equipment footprint

**RF**
- Capacitors
- High-Q inductors
- Resonators
- Relays and Switches
- Integrated subsystems
- Low weight
- Low insertion loss
- High off-state isolation
- High precision
- Low power consumption
- High reliability
Some MEMS Applications

- Ultrasound Transducer
- Gyroscope
- Optical Scanner
- Microphone
- Accelerometer
- 2-Axis Micromirror
Overall, the market is poised for breakaway growth

Source: Aggregate of data presented in MST News 5/01, including data from SPC, SRI, NEXUS, Batelle, VDC, and other research organizations
New applications for MEMS emerge and grow quickly

2001
- Industrial: 25%
- Medical: 16%
- Automotive: 31%
- Computer: 26%
- Comm.: 1%
- Consumer: 1%

2006
- Industrial: 22%
- Medical: 11%
- Automotive: 17%
- Computer: 26%
- Comm.: 21%
- Consumer: 3%

Source: In-stat 2002
Fabrication of MEMS

- Typically the fabrication of MEMS uses tools from the semiconductor industry, plus many other tools:
  - Photolithography
  - Diffusion
  - Oxidation
  - Etching (isotropic and anisotropic, wet and plasma)
  - Chemical Vapor Deposition (Si3N4, SiO2, Polysilicon, etc.)
  - Vacuum Metal Deposition (sputtering, evaporation)
  - Electroplating (LIGA, Ni, Au, Cu microstructures)
  - Chemical Mechanical Polishing to produce flat surfaces
  - Wafer Bonding, SOI wafers
  - Deep Plasma Etching (Inductively Coupled Plasma)
  - Sol-Gel deposition (PZT)
Bulk Micromachining

- Single Crystalline Silicon
- Isotropic Etching (HNA etc.)
- Anisotropic Etching (KOH, TMAH, EDP etc.)
- Reactive Ion Etching (RIE & DRIE)
- Accommodates sharp corners, small features and very smooth surfaces
LIGA Process

- Electroplated microstructures
- X-ray Photolithography in PMMA polymer resist
- Very high aspect ratio microstructures with smooth surfaces
- Used to create molds for low cost replication of precision shapes
- Molded diffraction grating for match-box spectrometer
Surface Micromachining

- Primarily Poly-Si thin-film structures
- Make structures horizontally and erect them on a hinge
- MUMPS, SUMMIT, HEXSIL etc.
- Applications
  - Pop-up micro-mirrors
  - Pressure sensors
  - RF switches
Capacitive MEMS RF Switch Fabrication

- Surface micromachining based fabrication process
  - oxide deposition, electrode, dielectric deposition and patterning
  - metal posts deposition and patterning
  - spacer coating and patterning
  - membrane deposition and patterning
  - removal of spacer layer by dry or wet etching*

**MEMS Actuation Techniques**

<table>
<thead>
<tr>
<th>Actuation Method</th>
<th>Power Usage</th>
<th>Force Generated</th>
<th>Deflection / Range</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>High</td>
<td>Moderate</td>
<td>Small</td>
<td>msec</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Medium</td>
<td>High</td>
<td>Large</td>
<td>μsec</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>μsec</td>
</tr>
</tbody>
</table>

**Mechanism**

- **Electrostatic**
  - Fast
  - High voltage
- **Thermal**
  - High force, bi-directional
  - Quiescent power, slow
- **Magnetostatic**
  - Fast, high force, bi-directional
  - Quiescent power
- **Piezoelectric**
  - Fast
  - Small throw
- **Latching**
  - Magnetic
  - Fast, high force, bi-directional
  - Construction

**Advantage**

**Disadvantage**
Series Switches

- **Graphical Representation:**
  - Circuit diagram showing series switches with symbols for $Z_o$, $Z_h$, $\beta\ell$, $R_c$, $C_s$, and $C_p$.
  - Diagrams illustrating anchor, switch contact, and pull down electrode and t-line.

- **Textual Notes:**
  - Overview of series switches, possibly including their electrical characteristics and applications.
  - Diagrams depicting physical structures and components associated with series switches.

- **References:**
  - Rebeiz/Muldavin/Rizk
Shunt Capacitive Switches

CPW

Microstrip

Rebeiz/Muldavin/Rizk
MEMS Ohmic Switch Technology

**Switch Construction**
- Metalizations: Gold, aluminum, nickel
- Substrates: Silicon, gallium arsenide

**Actuation Mechanisms**
- Electrostatic, thermal, magnetic

**Co-integration**
- Microwave electronics

**Ohmic Contact Switch Companies**
- HRL Laboratories
- Rockwell Scientific
- Analog Devices
- Chronos
- Motorola
- Omron
- Microlab
- Several standard MEMS fabs

**Representative Companies**
- HRL Laboratories
- Analog Devices
- Rockwell Scientific
- Chronos
- Motorola
- Omron
- Microlab

**Images**
- Membrane contact switch circuit diagrams from HRL Laboratories, Analog Devices, and Chronos.
MEMS Capacitive Switch Technology

Switch Construction
Metallizations
Gold, aluminum, copper
Substrates
Silicon, quartz, gallium arsenide
Co-integration
CMOS

Capacitive Contact Switch Companies
Raytheon
Northrop-Grumman
Samsung
LG Electronics
MIT Lincoln Labs
Daimler-Chrysler
Bosch

Companies
Raytheon
Northrop-Grumman
Samsung
LG Electronics
MIT Lincoln Labs
Daimler-Chrysler
Bosch

Raytheon
MIT Lincoln Labs
Bosch
Samsung
LG Electronics
Daimler-Chrysler

Radio Frequency Applications

Micromachining - fab of 3D structures on an IC
MEMS - movable structure micromachined into an IC

These devices are the “transistor” of a new generation of mechanical IC devices!

MEMS are creating a revolutionary impact on RF technology!
Opportunity for Applications of RF MEMS

**MEMS-Replaceable Transceiver Components**

- **Image Reject Filter (Ceramic)**
- **IF Filter (Ceramic)**
- **RF LNA**
- **VCO**
- **Mixer**
- **Chanel Select PLL**
- **IF PLL**
- **Power Amplifier**
- **Modulator**
- **Transmit PLL**
- **VCO**
- **DAC**
- **ADC**

**Current research:**

- Replace all off-chip passive elements with MEMS resonators & filters → chip-scale integration & improved performance
## Application Areas for MEMS RF

<table>
<thead>
<tr>
<th>APPLICATION AREA</th>
<th>FREQUENCY RANGE</th>
<th>UTILITY</th>
<th>REQUIRED CYCLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defense</td>
<td>5 – 94 GHz</td>
<td>Phase shifter for satellite based radars</td>
<td>20 billion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Missile system radars</td>
<td>0.1 – 1 billion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Long range radars</td>
<td>20 – 100 billion</td>
</tr>
<tr>
<td>Automotive</td>
<td>24, 60, 77 GHz</td>
<td>Radars</td>
<td>1 – 2 billion</td>
</tr>
<tr>
<td>Satellite communications systems</td>
<td>12 – 35 GHz</td>
<td>Switching networks with 4x4 and 8x8 configurations and reconfigurable Butler matrices for antenna applications</td>
<td>0.1 million</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Switched filter banks</td>
<td>0.1 – 100 million</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase shifter for multi-beam</td>
<td>10 – 20 billion</td>
</tr>
<tr>
<td>Wireless communications systems</td>
<td>0.8 – 6 GHz</td>
<td>Switched filter banks for portable units</td>
<td>0.1 – 1 million</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Switched filter banks for base stations</td>
<td>0.1 – 10 billion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>General SP2T to SP4T switches</td>
<td>0.1 – 10 billion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transmit/receive switches</td>
<td>2 – 4 billion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Antenna diversity SP2T switches</td>
<td>10 – 100 million</td>
</tr>
<tr>
<td>Instrumentation systems</td>
<td>0.01 – 50 GHz</td>
<td>High performance switches, programmable attenuators, phase shifters for Industrial test benches</td>
<td>20 – 40 billion</td>
</tr>
</tbody>
</table>


## Comparison: MEMS versus Solid-state switches

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>RF MEMS</th>
<th>PIN</th>
<th>FET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>30 – 80</td>
<td>+/- 3 – 5</td>
<td>3 – 5</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>0</td>
<td>3 – 20</td>
<td>0</td>
</tr>
<tr>
<td>Power Consumption (mW)</td>
<td>0.05 – 0.1</td>
<td>20 – 200</td>
<td>0.05 – 0.2</td>
</tr>
<tr>
<td>Switching Time (μsec)</td>
<td>1 – 30</td>
<td>0.01 – 0.1</td>
<td>0.01 – 0.1</td>
</tr>
<tr>
<td>$C_{up}$ (series, fF)</td>
<td>1 – 6</td>
<td>20 – 50</td>
<td>30 – 60</td>
</tr>
<tr>
<td>$R_{on}$ (DC-Contact, Ω)</td>
<td>1 – 2</td>
<td>2 – 4</td>
<td>4 – 6</td>
</tr>
<tr>
<td>$C_{up}$ (Capacitive, fF)</td>
<td>20 – 50</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>$R_{sw}$ (Capacitive, Ω)</td>
<td>0.05 – 0.25</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cut-off Frequency (THz)</td>
<td>20 – 80</td>
<td>1 – 4</td>
<td>0.3 – 0.5</td>
</tr>
<tr>
<td>Isolation (1-4 GHz)</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Isolation (30-40 GHz)</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Isolation (70-100 GHz)</td>
<td>High</td>
<td>Medium</td>
<td>N/A</td>
</tr>
<tr>
<td>Loss (dB)</td>
<td>0.05 – 0.3</td>
<td>0.4 – 1.2</td>
<td>0.4 – 1.6</td>
</tr>
<tr>
<td>Power Handling (W)</td>
<td>0.01 – 0.1</td>
<td>0.1 – 10</td>
<td>0.1 – 3</td>
</tr>
<tr>
<td>Intermodulation (dBm)</td>
<td>+60-80</td>
<td>+27-45</td>
<td>+27-45</td>
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</tbody>
</table>
Advantages of RF MEMS

Performance

Ultra-low RF loss – Beats any available electronics technology for switching or tuning of RF signals

Essentially no DC power consumption – Perfect for battery and low power-consumption applications

Extremely high linearity – Creates no harmonics or distortion, excellent for broadband communications

Size

Microminiature size – Reduced size with unmatched performance, able to work at very high frequencies (> 50 GHz)

Tunability – Supports reduction in number of passive components, combines numerous switched parts into one tunable chip

Cost

Reduced IC costs – Low cost, batch fabrication. Much less expensive than competing exotic semiconductor technologies.

Significant system cost impact - Able to be combined with other electronics for “system-on-a-chip.” Improved functionality can greatly reduce cost.
RF MEMS Switches Are Much Simpler than PIN Diode Switches

RF MEMS Switch Circuit

DC Control Voltage

In

Out

0.0025 sq inch
One
< 1 nanowatt

PIN Diode Switch Circuit

DC Control Voltages
DC Control Power

Area

0.25 sq inch
Two: + and –
~300 milliwatts

+V_{control}

−V_{control}

In

Out

C

C

L

L

R

C

C
Companies/ Univ./Labs Developing MEMS switches

- Raytheon / (Texas Instruments)
- Raytheon / (HRL)
- Rockwell Science Center
- Northrop Grumman
- Motorola
- Analog Devices
- Lincoln Labs
- Dow-Key Microwave (with HRL)
- Sarnoff Labs
- Sandia Labs
- Bosch, Germany
- DaimlerChrysler, Germany
- Thompson-CSF, France
- University of Michigan
- Univ. of Illinois, Urbana
- Univ. of California, Berkeley
- Northeastern University
- And other small efforts at many European and Japanese Univ.
- Samsung, Korea
- Sony, Japan
- MEMSCAP, France
- Corning IntelliSense
- LG-Corporate Research, Korea
- NEC, Japan
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>MEMS technology</td>
<td>Surface</td>
<td>Surface</td>
<td>Surface</td>
<td>Bulk</td>
<td>Bonded wafer</td>
<td>Bonded wafer</td>
<td>Surface</td>
<td>Surface</td>
</tr>
<tr>
<td>Device size (μm x μm)</td>
<td>80 x 160</td>
<td>120 x 280</td>
<td>~120 x 300</td>
<td>~1000 x 2000</td>
<td>1.5 (mm²)</td>
<td>2000 x 2500</td>
<td>250 x 900</td>
<td>Beam = 30 x 65</td>
</tr>
<tr>
<td>Current handling (mA)</td>
<td>200</td>
<td>N/A</td>
<td>140</td>
<td>N/A</td>
<td>&gt;100</td>
<td>N/A</td>
<td>N/A</td>
<td>150</td>
</tr>
<tr>
<td>Structural material</td>
<td>SiO₂</td>
<td>Al alloy</td>
<td>Si₃N₄</td>
<td>Plated Au</td>
<td>Silicon epi</td>
<td>Silicon</td>
<td>P++ Silicon</td>
<td>Au/Ni</td>
</tr>
<tr>
<td>Actuation mechanism</td>
<td>Electrostatic (ES)</td>
<td>ES</td>
<td>ES</td>
<td>ES</td>
<td>Wedge ES</td>
<td>ES</td>
<td>ES</td>
<td>ES</td>
</tr>
<tr>
<td>Actuation voltage (V)</td>
<td>~60</td>
<td>~50</td>
<td>~25</td>
<td>15-20</td>
<td>24</td>
<td>16-19</td>
<td>125</td>
<td>30-300</td>
</tr>
<tr>
<td>Contact mechanism</td>
<td>Au</td>
<td>Capacitive</td>
<td>Au</td>
<td>Capacitive</td>
<td>Plated Au alloy</td>
<td>Au</td>
<td>Au</td>
<td>Au</td>
</tr>
<tr>
<td>Insertion loss (dB)</td>
<td>0.2 (dc-40GHz)</td>
<td>0.15 at 10 GHz</td>
<td>0.2 (dc-40GHz)</td>
<td>0.6 (22-38 GHz)</td>
<td>Not available</td>
<td>Not available</td>
<td>0.2 at 30 GHz</td>
<td>N/A</td>
</tr>
<tr>
<td>Isolation (dB)</td>
<td>-32 at 10 GHz</td>
<td>-15 at 10 GHz</td>
<td>-40 at 12 GHz</td>
<td>Not available</td>
<td>Not available</td>
<td>Not available</td>
<td>-13 at 30 GHz</td>
<td>N/A</td>
</tr>
<tr>
<td>Switching time</td>
<td>2-5 μs</td>
<td>3.5-5.5 μs</td>
<td>20 μs</td>
<td>Not available</td>
<td>&lt; 0.2ms</td>
<td>&lt; 0.3ms</td>
<td>-</td>
<td>150 kHz cutoff</td>
</tr>
<tr>
<td>Lifetime (million cycles)</td>
<td>~100 (cold) 10s (hot 1-40mA)</td>
<td>500</td>
<td>~4 (hot 10mA)</td>
<td>N/A</td>
<td>N/A</td>
<td>1-10 (hot 10mA)</td>
<td>-</td>
<td>0.01-1000 (cold)</td>
</tr>
</tbody>
</table>
Raytheon

Insertion Loss @ 40 GHz  <0.07  dB
Isolation @ 40 GHz  >35  dB

Model Values
Rs  0.11  Ohms
Rsh  0.2  Ohms
Coff  0.03-0.045  pF
Con  3.4  pF
Ron  0.25  Ohms
Capacitance Ratio  70-110
Cutoff Frequency  18,000  GHz
Switching Speed  < 10  µs
Intercept Point  > +66  dBm
Switching Voltage  30-50  volts
Size  280 × 170  µm
- Metal-Metal contact series switch
- Electrostatic actuation: 20–40 V
- Switching time: 20–40 μsec
  - Depends on gap and voltage

- Nitride/gold/nitride tri-layer prevents creep
- Fabrication process is compatible with other substrate materials like high resistivity silicon
• Low insertion loss: 0.1 dB @ 2GHz
• Excellent Isolation: -56dB @2 GHz
• Turn-on time <10μs
• +28dBm power handling capability
• Third order intercept 80dBm
• Implementation on Si, GaAs, Quartz
Analog Devices

- DC Contact Series switch
- $V_p = 50-60 \text{ V}$
- Isolation: $-40 \text{ dB (4 GHz)}$
- $t = 0.5-3 \text{ ms}$
- Isolation: $-27 \text{ dB (20 GHz)}$
- $C_u = 4 \text{ fF}$
- Loss: $-0.1 \text{ to } -0.2 \text{ dB (DC-20 GHz)}$
- $R_s = 1-2 \text{ }$
- (Electrode does not touch cantilever)
MIT Lincoln Lab

DC Contact single switch in CPW configuration

RF Measurement (9 Switches)

*Contact Resistance:*
- 95% yield < 2 Ω
- 60% yield < 1 Ω

*Switch Speed:*
- Closing time: < 1 μs
- Opening time: < 1 μs
University of Michigan

- All metal series switch
- $V_p=20-25$ V
- Switching speed = 10 us
- $C_u=4-8$ fF, $R_{on}=0.5-2$ Ohms
- Isolation: -36 to –40 dB (4 GHz)
- Compact Geometry
  - 300 um by 100 um
- CPW or Micro-strip
- High Impedance Bias Line
  - 1 kOhm / square SiCr
LG Korea

- High Capacitance shunt
- Isolation: -40 dB (3-5 GHz)
- Isolation: -30 dB (10 GHz)
- Isolation: -20 dB (20 GHz)
- Loss : -0.1 dB (10 GHz)
- (LCd Resonance effect at 3-5 GHz)
- Vp = 8-20 V
- t = N/A
- Dielectric: SrTiO3
- Cd = 50 pF
MEMS Physics is **Multi-Disciplinary**: Mechanics, Electrostatics, Fluidics, Ionics etc.

1. Stress in CC Beam
2. Charge injection into insulator or contact erosion
3. Charge migration over surface
4. Formation of induced channel on semiconductors
5. Distributed Mass and Spring
6. Large Surface Tension formation forces

[Diagram showing: C-C Beam, Center Cap Top, Cap Base, 2µ, 200µ, 6 markers labeled 1 to 6]
Design and Analysis of MEMS RF Switches

- Electrostatic domain
  - to solve for electrostatic pressure due to parallel surfaces.

- Mechanical domain
  - to solve for mechanical deformation, contact, stresses, heat generation etc.

- Fluidic domain
  - to solve for squeeze film dampening effect when the bridge moves.

- Electromagnetic domain
  - to solve for S, Y, Z parameters in order to obtain insertion loss, isolation and current distribution.
Electromechanical Analysis

Deflection versus voltage

Capacitance versus voltage
Electromagnetic Analysis

Electromagnetic (RF) analysis showing S parameters and current distribution for a capacitive switch in OFF (left) and ON (right) positions.
Failure Mechanisms in MEMS Devices

Class I
No Moving parts

Class II
Moving Parts, No Rubbing or Impacting Surfaces

Class III
Moving Parts, Impacting Surfaces

Class IV
Moving Parts, Impacting and Rubbing Surfaces

Applications

<table>
<thead>
<tr>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>Class IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Moving parts</td>
<td>Moving Parts, No Rubbing or Impacting Surfaces</td>
<td>Moving Parts, Impacting Surfaces</td>
<td>Moving Parts, Impacting and Rubbing Surfaces</td>
</tr>
</tbody>
</table>

Failure Mechanisms

- Particle Contamination
- Shock Induced Stiction
- Mechanical Fatigue

- Particle Contamination
- Shock Induced Stiction
- Stiction
- Mechanical Fatigue
- Impact Damage

- Particle Contamination
- Shock Induced Stiction
- Stiction
- Mechanical Fatigue
- Friction
- Wear

- Accelerometers
- Pressure Sensors
- Ink Jet Print Heads
- Strain Gauge
- Integrated Circuits

- Gyros
- Comb Drives
- Resonators
- Filters

- TI DMD
- Relays
- Valves
- Pumps

- RF Switches
- Optical Switches
- Shutters
- Scanners
Challenges

• Lifetime and reliability
• Packaging
• Cost
• Speed
Switch Lifetimes: Capacitive Switches

- **Stiction**
  - Metal-to-dielectric stiction
  - Large contact area resulting in stiction due to dielectric charging
  - Water particle (water is a polar molecule)
  - Organic materials on the metal-dielectric interface

- **Possible solutions**
  - Package device in Nitrogen atmosphere (makes it very expensive)
  - Better design and dielectrics by reducing actuation voltage
  - Use bipolar voltage so as not to charge the dielectric (cost may be high preventing use in various portable applications)
Packaging Considerations in MEMS Circuits

- Wafer level packaging will result in lowest cost for MEMS switches.
- Packaging gas has large effect on reliability.
- Hermetic sealing is essential since MEMS switches are sensitive to humidity.
- For high performance, low quantities, packaging can be done using standard techniques.
- The highest cost will be the package in single MEMS switches. This is not the case in phase shifters or filters, or high isolation switch networks.
Conclusions

- Virtually every MEMS switch configuration is available today. The main question now is reliability and packaging.
- Reliability is currently in the $10^8$ electrically, and $10^{11}$ mechanically.
- Failure mechanisms are:
  - Resistive failure in DC-contact switches (metallurgy, contact forces)
  - Stiction due to humidity and/or charging of the dielectric (capacitive switches)
  - Stiction due to metal-to-metal contacts (contact physics)
  - Microwelding due to large currents
- To combat failures, industry is doing the following:
  - Packaging in inert atmosphere such as Nitrogen and/or hermetic sealing
  - Large voltage and large spring constant structures
  - Development of better metal contacts
  - Designs with no contact between the pull-down electrode and the bottom metal (not applicable for current capacitive switches)
Conclusions

• Today, most MEMS switches are being developed for phase shifters and defense applications.

• Tomorrow, which is today, most MEMS switches will be developed for wireless applications and low-power applications:
  – Single-Pole Multiple-Throw Switches
  – Switched Filter Banks for portable and basestations (receive)
  – Switched Attenuators for High Dynamic Range Receivers and Instrumentation
  – Switch Matrices (Base stations and Satellite Applications)
  – Tunable Filters (High-Q Varactors)
  – Tunable Networks for Wideband Applications (Switched Capacitors, Medium Q needed)

• There are currently no high power (100 mW to 10 W) MEMS switches.

• There are currently no services or foundries for RF MEMS switches.