Failure mechanisms and reliability issues of RF-MEMS switches


IMEC
Leuven, Belgium
Outline

- Introduction
- FMEA of RF-MEMS switches
- Charging induced stiction
- Packaging effect on switch lifetime
- Conclusions
Radio Frequency MEMS switches offer:
- Low weight
- Low volume
- Lower insertion loss
- High isolation
- Large frequency range
- Extremely high linearity
- Low power consumption
- Integration possibilities

Uses in space:
Wireless personal communication, satellite communication, phased array for beam steering, smart antennas ...

**BUT**: reliability is a problem
RF-MEMS capacitive switch

Flexible metal bridge

dielectric

RF+DC in

GND

“large” C

OFF

RF in

RF out

Radio frequency MEMS
Title

Enabling deployment of RF MEMS technology in space telecommunication.

Objective

Perform an in-depth assessment of the reliability and related failure modes of RF-MEMS, in view of their deployment in space and improve this reliability (for switches) through processing optimization.

Starting date

Aug 15, 2005

Duration

24 months
# FMEA: Failure Mode Effect Analysis

<table>
<thead>
<tr>
<th>Potential Failure Mechanism</th>
<th>Sev</th>
<th>Failure Defect</th>
<th>Failure Mode</th>
<th>Occ</th>
<th>P</th>
<th>N</th>
<th>Possible Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dielectric charging of the insulator of capacitive switches</td>
<td>5</td>
<td>Dielectric charging of the insulator of capacitive switches</td>
<td>Front to bottom electrode, Not a normal gas flow away from dielectric surface</td>
<td>7</td>
<td>49</td>
<td>1. Electric Field Charge Injection 2. ArSiN Breakdown</td>
<td></td>
</tr>
<tr>
<td>2 Plastic deformation of the bridge (ohmic and capacitive switches)</td>
<td>7</td>
<td>Permanent deformation of the bridge, possibly broken if large deformation to bottom electrode or top of dielectric if packaged</td>
<td>Shift of electrical parameters (pull-in/pull-out, capacitance, conduct R)</td>
<td>5</td>
<td>49</td>
<td>1. Creep 2. Thermal induced changes in material properties (for T&lt; To)</td>
<td></td>
</tr>
<tr>
<td>4 Capillary Force (ohmic and capacitive switches)</td>
<td>10</td>
<td>Stiction</td>
<td>Dead device</td>
<td>4</td>
<td>49</td>
<td>1. Presence of humidity (Package lead, incorrect release step)</td>
<td></td>
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<tr>
<td>5 Firing (ohmic and capacitive switches)</td>
<td>10</td>
<td>Open, roughness increase</td>
<td>Dead Device</td>
<td>4</td>
<td>49</td>
<td>1. High RF power pulses, ESD</td>
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FMEA: Failure Mode Effect Analysis

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<th>Role in Failure Cause</th>
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<tr>
<td>Dielectric charging of the insulation of capacitive switches</td>
<td>8</td>
<td>Station to bottom electrode. Not permanent (charges flow away when charging cause is taken away).</td>
<td>Drift in CV curves, drift in Pull-in and Pull-out voltages, Dead device</td>
<td>10</td>
<td>49</td>
<td>1. Electron Emission</td>
</tr>
<tr>
<td>Mis-welding (ohmic switches and capacitive switches with contact metal on dielectric)</td>
<td>9</td>
<td>Station</td>
<td></td>
<td></td>
<td></td>
<td>2. Cold welding</td>
</tr>
<tr>
<td>T-Induced elastic deformation of the bridge (ohmic and capacitive switches)</td>
<td>7</td>
<td>Non-permanent bridge (i.e. non-tarnish deformation of cavity)</td>
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<td></td>
<td>3. ESD</td>
</tr>
<tr>
<td>Elastic deformation of the bridge (ohmic and capacitive switches)</td>
<td>4</td>
<td>Station</td>
<td></td>
<td></td>
<td></td>
<td>4. High current through metal-metal contacts (resistive at room temp, hot welding)</td>
</tr>
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<td>Structural Short electrical and non-electrical connection (ohmic and capacitive switches)</td>
<td>10</td>
<td>Station</td>
<td></td>
<td></td>
<td></td>
<td>5. Power RF Signal induced Temperature</td>
</tr>
<tr>
<td>Peeling</td>
<td>10</td>
<td>Open, no</td>
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<td></td>
<td></td>
<td>6. Non-uniform temperature degradation</td>
</tr>
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18 different failure mechanisms were identified.
### FMEA: Failure Mode Effect Analysis

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<tr>
<th>Potential Failure Mechanism</th>
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<td>Fracture</td>
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<td>Dielectric breakdown of the insulator, capacitive switches</td>
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<tr>
<td>Wear</td>
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<td>Corrosion</td>
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<td>Equivalent DC Voltage</td>
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<td>Van der Waals Forces</td>
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### Fracture
(ohmic and capacitive switches)

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<th>Possible Failure Cause</th>
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<tr>
<td>1. Fatigue</td>
</tr>
<tr>
<td>2. Brittle materials + shock</td>
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<tr>
<td>3. High local stresses + shock</td>
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### Creep
(ohmic and capacitive switches)

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<td>1. Sliding Rough Surfaces in contact</td>
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### Equivalent DC Voltage
(ohmic and capacitive switches)

### Lorenz Forces
(ohmic and capacitive switches)

### Whisker formation
(ohmic and capacitive switches)

### Fatigue
(ohmic and capacitive switches)

### Electromigration
(ohmic and capacitive switches)

### Van der Waals Forces
(ohmic and capacitive switches)
Lifetime tests in dedicated chamber

- Thermo-chuck: -10 to +150 °C
- Wafer load slot: Up to 200 mm wafers
- Pressure control: (down to 10^{-6} mbar)
- XYZ-microscope stage: 12x zoom
- Vacuum resistant RF and DC probes
- Gases inlet
- X-Y-Z- Chuck stage: (150, 150, 15 mm, ± 7° travel range)
Charging induced stiction

Lifetime test @ 100 Hz
\( V_{\text{act}} = 25 \, \text{V}, \) unipolar actuation
\( N_2 \) environment

\[ \Delta C = C_{\text{down}} - C_{\text{up}} \]

end of life (EOL)

Failure due to charging induced stiction
Fast C-V

Failed: curve shifts to right.

19 hours later: curve shifted partly back

Control: symmetric curve

van Spengen et al, IRPS 2005, P. Czarnecki et al., MEMSWAVE 2005
C/V characteristic shift without surface charge

X. Rottenberg et al, 34th EuMW conf., 2004
C/V characteristic shift due to a positive surface charge

\[ V_{\text{shift}} = \frac{Q}{C_{\text{down}}} \]

X. Rottenberg et al, 34th EuMW conf., 2004
C/V characteristic shift due to a positive surface charge

\[ V_{\text{shift}} = \frac{Q}{C_{\text{down}}} \rightarrow \text{stiction} \]

C-V with charging

C-V without charging

Pull-out window

Solution: Alternative actuation

Reduced V across dielectric

Bipolar
Unipolar vs bipolar

Unipolar actuation
35V, 100Hz

35V, 100Hz

Bipolar actuation

>2x10^7

5x10^6
The total charge \( Q \) can be zero, but there might be a charge distribution in the dielectric. Assume a volume charge density \( \Psi(x,y,z) \) in the dielectric.

\[-\rightarrow \text{Equivalent charge distribution } \Psi_{eq}(x,y) \text{ (2D+ problem)}\]
2D+ problem description

\[ F_{el}(d) = \frac{C_1(d) C_2^2}{2d(C_1(d) + C_2)^2} \left\{ \left( V - \frac{Q_{eq}}{C_2} \right)^2 + \frac{\text{Area}^2}{C_2^2} \sigma^2(\psi_{eq}) \right\} \]

- \( Q_{eq} \) = total equivalent charge = Area x mean of \( \psi_{eq}(x,y) \)
- \( \sigma^2(\psi_{eq}) \) = variance of the equivalent charge distribution \( \psi_{eq}(x,y) \)

\( Q_{eq} \) realizes a voltage offset (x-shift in the \( F_{el} \) vs. \( V \) curve)

\( \sigma^2(\psi_{eq}) \) realizes a force offset (y-shift in the \( F_{el} \) vs. \( V \) curve)
Evolution of Pull-in and Pull-out

\[ \sigma^2(\psi_{eq}) = \sigma^2_{no\_PI} \]
\[ \sigma^2(\psi_{eq}) = \sigma^2_{no\_PO} \]

Increasing \( k \), \( d_0 \) and decreasing the Area decrease the sensitivity to the equivalent charge distribution
Charging induced stiction

**Theory - Experiment**

Unipolar actuation: \( Q \neq 0 \) -> shift of the C-V curves
Bipolar actuation: \( Q = 0 \) but \( \sigma^2(\Psi_{eq}) \neq 0 \) -> narrowing of Vpo and Vpi

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X. Rottenberg et al, 34th EuMW conf., 2004, P. Czarnecki et al., submitted for MEMSWAVE 2005
MEMS package

Pressure, humidity, optical, chemicals, particles, ...

Function: “Gate keeper”
- keep bad things out (particles, humidity, gasses, …)
- keep good things in (pressure, getters, …)
- throw excess things out (heath, …)
- allow easy in-out to VIPS (electrical, to-sense stuff, …)
- give mechanical support
- be reliable
Some metals (ex. Al-alloys) change ‘stress’ when heated above $T = T_c$:

Deformation: T-effects

Temperature:
- during functioning
- during packaging
**Deformation: T-effects**

$T_c$ is alloy dependent: $T_c_{AlCuMgMn} > T_c_{Al}$

- Use metal with high Tc
- Or do a pre-anneal (but different stress)
- Optimize design to minimize the impact of stress changes on the shape of the bridge.
Pressure in cavity

1 bar

2x10^-4 mbar

- faster switching in vacuum
- vibrations
Pressure in cavity

The ‘floppy’ switch shows overshoot already at 0.125 bar.
The ‘STIFF’ switch shows overshoot at ~ 0.075 bar: clear dependence of the ‘overshoot point’ on the design.
Pressure in cavity

Lower lifetime at lower pressure (larger $C_{\text{down}}$, better charging).

Details and more results will be presented at MEMS2006 by P. Czarnecki et al., IMEC
Gasses in cavity: $N_2$ vs air

Different technologies, different designs, different dielectrics, different electrical test conditions ($V_{act}$, freq.)

Nitrogen vs air:
- longer lifetime + larger $C_{down}$
- $\Delta C$ (a.u.)
- $\#$ of cycles

$\text{Ta}_2\text{O}_5$

$\text{SiO}_2$

$\text{SiN}_x$

Nitrogen vs air:
- better reliability
- different damping, dielectric constant, gap breakdown $V$, humidity,…

imbus 2005
Conclusions

- **FMEA**: main failure mechanism in capacitive RF-MEMS = charging of the dielectric leading to stiction of the bridge

  - Possible solutions:
    - Design for low $V_{pi}$, but high $V_{po}$
    - Design for flat bridge (uniform charging + low charge distribution)
    - Make the insulator area as small as possible (lower sensitivity of $V_{po}$)
    - Use bipolar actuation waveform
    - Package the switch in a nitrogen environment
    - Be careful with vacuum (bouncing + lower lifetime possible)

- **FMEA**: main packaging induced failure is deformation of the bridge

  - Possible solutions:
    - Use metal with high $T_c$
    - Try to reduce the packaging $T$

What else can be done?

- alternative ways of bipolar actuation
- better dielectric (less charging sensitive)
- worse dielectric (such that the charges disappear faster)
Acknowledgments

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