RF MEMS TECHNOLOGY PLATFORM FOR CELL PHONES

Transient simulation of the closing of a MEMS switch with air gap modeled by FLUID136 elements

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Outline

- Presentation of RF MEMS switches
  - Application
  - Electrostatic actuation
  - Ohmic / capacitive switches

- Delfmems switch
  - functioning
  - modeling
  - process flow

- Modeling gap closing of FLUID136 elements
  - Death of fluidic elements
  - Rough membrane
  - Remaining thin film

- Transient simulation of a beam supported on pillars

- Transient simulation of delfmems switch
There are many areas of application for MEMS

Applications are at various stages of their life cycles

Switches and other RF components for the mobile market are in the emerging phase

DEIfMEMS has developed patents for switches
Need of multiband systems to increase bandwidth

Data volumes could reach 2.7 exabytes per year in 2010 and that volume could increase to between 20 and 90 exabytes in 2015.

Need of more bandwidth & functions

- Improve the radio link quality

Multimode-Multiband & integrated cell phones

- Increase of the number of frequencies
- Minimizing size & consumption
- Managing Bill Of Material
- Decreasing NRE
Scalar model of a MEMS switch: spring-capacitor system

Equilibrium equation:

$$k (g_0 - g) \left( g + \frac{t_d}{\varepsilon_d} \right)^2 - \frac{1}{2} \varepsilon_0 S V^2 = 0$$

Pull-in voltage:

$$V_{pi} = \sqrt{\frac{8k}{27 \varepsilon_0 S} \left( g_0 + \frac{t_d}{\varepsilon_d} \right)^3}$$

Pull-out voltage:

$$V_{po} = \frac{t_d}{\varepsilon_d} \sqrt{\frac{2k g_0}{\varepsilon_0 S}}$$

adapted from G.M. Rebeiz, *RF MEMS theory, design and technology*, Wiley-Interscience 2003
RF MEMS switches: Ohmic switches

1 contact

Example of series ohmic switch

The contact resistance depends on:
- Contact force
- Contact materials
- Effective surface area in contact (due to roughness)
- Power dissipated through the contact

Example of series ohmic relay with metal contact isolated from actuation membrane

RF MEMS switches:

Capacitive switch

Capacitive switch with air gap

\[
\frac{C_{\text{on}}}{C_{\text{off}}} = \frac{g_0}{g_1}
\]

Capacitive switch with dielectric

\[
\frac{C_{\text{on}}}{C_{\text{off}}} = 1 + \frac{g_0 \varepsilon_d}{t_d}
\]
Delfmems switch

- Ohmic switch on an interrupted line
- Anchorless membrane simply supported by two pillars
- Two pairs of electrodes (internal, external) which ensure two forced states
- Mechanical stoppers which allow the membrane to move but maintain it in position

![Diagram of Delfmems switch]

**Internal electrodes**
- **Anchor-less Membrane**
- **Ground**
- **RF In**, **RF Out**
- **Internal DC Pad**, **External DC Pad**

**External electrodes**
- **Mechanical stop units (MSU)**
- **Contact location**
- **Pillar**

Limitations:
- **Mechanical stop unit**: limitation in \( x \) direction
- **membrane**: limitation in \( z \) direction

**Dimensions**: 100 \( \mu \)m
Two forced states

OFF state

ON state

(a) dielectric layer

RF line

Internal electrodes

External electrodes

Delfmems membrane at ON state

Delfmems membrane at OFF state
Delfmems switch: modeling

Modeling of a quarter of membrane due to symmetry

Modeling pillars with contact/target elements

Modeling RF line by contact/target elements

Modeling electrostatic actuation by TRANS126 elements

Contact force on bumps

Contact force on bumps vs. applied voltage [V]
Buried electrodes and dielectric layer

- Silicon wafer
- Silicon Nitride
- Titanium-Tungsten
- Gold
- Silicon dioxide
- Chromium
First sacrificial layer, electroplating mold and electroplating of pillars and RF line.
Second sacrificial layer, contact, dielectric and membrane
Delfmems switch:
Process flow

Third sacrificial layer and stoppers patterning

- Silicon wafer
- Silicon Nitride
- Titanium-Tungsten
- Gold
- Silicon dioxide
- Chromium
Releasing, rinsing and drying

- Only 5 principal materials (excluding sticking layers)
- 3 sacrificial layers
- No photoresist for sacrificial layers: better stability of process flow
- Low actuation voltage: low gap

- Low contact resistance: High contact force

- High restoring force: membrane stiffness + external actuation

- **Low switching time**: needs to be simulated
  - simulation of impact on contact
  - simulation of closing of air gap with FLUID136 elements:
    - feasible since ANSYS release 12
    - challenging due to:
      - low gap
      - high pressure
      - high electrostatic force
      - **vanishing of air between the electrode and the membrane**
FLUID136 elements are surfacic elements based on Reynolds equation which are adapted to model thin films with high lateral dimensions.

Since release 12 it is possible to perform coupled transient fluid/structure simulations with air gap going near zero:

ANSYS release 11
- Pressure is the only DOF
- The pressure change must be small compared to ambient pressure.
- Displacement amplitudes must be small compared to the film thickness.

Since ANSYS release 12
- Pressure, UX, UY, UZ are available DOFs (KEYOPT(3)=1 or 2)
- Large pressure changes can be modeled with compressible nonlinear Reynolds equation (KEYOPT(4)=1)
- Large pressure changes can be modeled with compressible nonlinear or incompressible linearized Reynolds equation (KEYOPT(4)=1 or 2)

Managing of the closing of air gap
- If gap goes below a defined fluid_mingap:
  - reset it to fluid_mingap
  - The element is considered “dead” for a fluid standpoint
- If gap goes below a defined mech_mingap:
  - The element is considered “dead” for a mechanical standpoint
  - Apply contact pressure
Simulation of gap closing: Death of fluid elements

- Test structure: clamped-clamped beam
  - zero pressure on the edge
  - quarter of membrane anchoring
  - X and Y symmetry

- Modeling of fluid mingap
  - X and Y symmetry
  - zero pressure on the edge
  - quarter of membrane anchoring

Options for FLUID136 elements:

- KEYOPT(1)=3 High Knudsen number and accommodation factor
- KEYOPT(2)=0 Four node element
- KEYOPT(3)=2 DOF PRES, UX, UY, UZ Implicit treatment of cross-coupling terms. Adapted for gaps near zero
- KEYOPT(4)=1 Compressible nonlinear Reynolds equation
- KEYOPT(5)=2 If gap becomes lower than fluid_mingap, the element will be considered as “dead”
- KEYOPT(6)=0 If the gap becomes lower than mech_mingap no contact pressure will be applied
Simulation of gap closing: Death of fluid elements

Displacement at the centre of the beam

Pressure at the centre of the beam

Length of the beam in contact with the electrode
Simulation of gap closing: 
Death of fluid elements

Displacement at pull-in state

Pressure under the membrane during the creation of air pockets

<table>
<thead>
<tr>
<th>Fluid mingap=20nm</th>
<th>Fluid mingap=10nm</th>
<th>Fluid mingap=5nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>36μs</td>
<td>44μs</td>
<td>51μs</td>
</tr>
<tr>
<td>37μs</td>
<td>45μs</td>
<td>53μs</td>
</tr>
<tr>
<td>40μs</td>
<td>46μs</td>
<td>55μs</td>
</tr>
<tr>
<td>44μs</td>
<td>47μs</td>
<td>57μs</td>
</tr>
<tr>
<td>48μs</td>
<td>48μs</td>
<td>60μs</td>
</tr>
</tbody>
</table>

elements dead for a fluid standpoint

creation of air pockets
Fluid death of FLUID136 elements is not satisfactory:

- Abrupt drop of pressure
- Abrupt acceleration of the membrane
- Highly dependent on the choice of fluid_mingap
- Creation of air pockets
Simulation of gap closing: Roughness

Creation of a rough surface area (about 50nm) with:

- Non-uniform air gap for FLUID136 elements
- Non-uniform electrostatic gap for TRANS126 elements

- Positive force on top surface for “peak” nodes
- Negative force on bottom surface for “peak” nodes
- Negative force on top surface for “valley” nodes
- Positive force on bottom surface for “valley” nodes
Simulation of gap closing:
Roughness

peak nodes
pass nodes

pressure [MPa]

0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00

0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45

0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45

Z [mm]
uz [µm]

-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0

-1.0
-0.8
-0.6
-0.4
-0.2
0.0

t [µs]

0 10 20 30 40 50 60 70 80

x=0µm x=4µm x=6µm x=12µm x=18µm x=24µm

t [µs]

13 14 15 16 17 18 19 20

x=0µm x=4µm x=6µm x=12µm x=18µm x=24µm

www.delfMEMS.com

UK users conference, November 9th 2011, Gaydon, Warwickshire
The membrane is smooth
A thin film is assumed to be remaining to model the air remaining due to roughness

Options for FLUID136 elements:

- **KEYOPT(5)=1** If gap becomes lower than fluid_mingap, it is reset to fluid_mingap
- **KEYOPT(6)=0** If the gap becomes lower than mech_mingap no contact pressure will be applied
Simulation of gap closing:
Remaining fluid gap

Displacements on a pass node

Pressure at centre

Pressure at t=10µs

Pressure at t=20µs
Simulation of gap closing: Remaining fluid gap

Modeling the closing of FLUID136 elements with a remaining thin film is more realistic:

- The pressure decreases slowly while the air is escaping
- The membrane slows down before touching the electrode due to the increase of pressure
- The thin film is justified by roughness
- The choice of fluid_mingap is directly linked to the value of roughness

The closing of air gap can be modeled accurately by:
- Fixing a minimal air gap of fluid which remains under the membrane
- Choosing this fluid mingap as function of roughness
Modeling contact on pillars

Model of beam supported of pillars:

Choice of FKN:

Displacement at the membrane extremity
Modeling contact on pillars

\[ t = 6\mu s \]

\[ t = 8\mu s \]

\[ t = 10\mu s \]

\[ t = 12\mu s \]

\[ t = 14\mu s \]

\[ t = 20\mu s \]
Modeling alternate actuation (e.g. OFF state to ON state) needs:

- Static analysis with $FKN=0.001$ to 0.01
- Transient analysis with $FKN=1$
Transient simulation of the membrane

Zero pressure on the edge of the membrane

Laser-Doppler measurement of displacement

Comparison of simulated and measured displacement on internal electrode

- ANSYS extr-int
- measure extr-int UR
- measure extr-int BR
- measure extr-int UL
- measure extr-int BR

UK users conference, November 9th 2011, Gaydon, Warwickshire
New features of FLUID136 elements enable to perform transient simulations of pull-in

The fluid death of FLUID136 elements is not adapted to model the closing of the air gap

A thin film of air remains present under the membrane due to roughness

A remaining thin film under the membrane must be modeled to represent the roughness

These settings enable to model accurately the closing of the switch
Thank you for your attention

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