An Experimental Investigation of Hot Switching Contact Damage in RF MEMS Switches

PhD dissertation by
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Outline

- RF MEMS switches – An overview
- Experimental setup for contact testing
- Hot switching in MEMS switches – Results and Discussions
- Summary of mechanisms
- Conclusion and future work
RF MEMS switches

Several companies and universities (NEU, UCSD, RFMD, Omron, Agilent, etc) have developed packaged RF MEMS switches over the last decade.
Applications

- Sattelite Communication
- Phased Arrays for radar
- Reconfigurable radio
- RF MEMS SWITCHES
- Automated Test Equipment
- Base-station antennas
Comparison with other technologies

<table>
<thead>
<tr>
<th>Device</th>
<th>Figure of Merit</th>
<th>Switching speed</th>
<th>Power dissipated</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIN Diode</td>
<td>800-1600 GHz</td>
<td>&lt; 1 µs</td>
<td>High</td>
</tr>
<tr>
<td>GaAs FET</td>
<td>700 GHz</td>
<td>&lt; 1 µs</td>
<td>Low</td>
</tr>
<tr>
<td>RF MEMS</td>
<td>10-20 THz</td>
<td>5 - 50 µs</td>
<td>Low</td>
</tr>
</tbody>
</table>

\[
FOM = \frac{1}{2\pi R_{on} C_{off}}
\]
Concerns

• Reliability
  – Contact damage (Resistive switches)
  – Charging (Capacitive switches)

• High Voltage required for actuation (30V-100V)

• Hermetic packaging required

• Cost is high as of now
Classification

RF MEMS switches

- Signal transmission
  - Capacitive
  - Resistive

- Circuit configuration
  - Shunt
  - Series

- Actuation mechanism
  - Electromagnetic
  - Piezoelectric
  - Thermal

Electrostatic
Photodetector generates A-B voltage which is acquired by LabVIEW DAQ.
The A-B voltage can be calibrated and mapped to the force exerted on the Force sensor.
Measurement Structures

- Fabricating actual switches for testing contact behavior alone would not be cost-effective.
- The flexibility of testing many different contact materials would be lost if a new batch of switches were to be fabricated each time a different material had to be tested.
- Chips with 3 clamped-clamped beam structures with contact bump in the middle used for testing.
Four-Wire Measurement

\[ R_{\text{contact}} = \frac{V_{\text{contact}}}{V_R} \times R \]
The Overall Setup

Diagram showing connections:
- **Piezo-Actuator** connected to **Connection**
- **AFM System** connected to **Connection**
- **OPA 548** connected to **5 Ω**
- **BREAKOUT BOX** connected to **1 μF**
- **PA85** connected to **50 Ω**
- **50 Ω** connected to **DAQ**
Hot Switching Requirements

- Hot switching is the application of an RF signal or DC voltage across the contacts of a switch while it is still transitioning from open to closed position or closed to open.

<table>
<thead>
<tr>
<th></th>
<th>Lifetime Switching cycles</th>
<th>Switching speed</th>
<th>Hot switching requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/R switch</td>
<td>8.6 Billion</td>
<td>5 µs</td>
<td>0 dBm</td>
</tr>
<tr>
<td>Antenna tuner</td>
<td>440 Million</td>
<td>5 µs</td>
<td>+28 dBm (worst case)</td>
</tr>
<tr>
<td>PA Tuner</td>
<td>440 Million</td>
<td>5 µs</td>
<td>Tuned during transmission nulls</td>
</tr>
</tbody>
</table>

Ref: RF MEMS Switch Technology for Radio Front End Applications, Julio Costa, RFMD
Why study Electrical contacts and hot switching?

• Reliability of a MEMS switch is dependent on the reliability of its contacts.
• Hot switching, being one of the most important reliability issues, needs to be understood and characterized.
• Understanding hot switching mechanisms can enable us to determine a better contact material in the future.
• Knowledge of hot switching specification can enable better circuit and system design.
Hot switching –
A complex phenomenon

Duration – $10^6$ cycles, Cycling Rate – 500 Hz,
Approach/Separation rate – 4400 µm/s, External resistance – 50 Ω
Hot switching – A complex phenomenon

Duration – $10^6$ cycles, Cycling Rate – 500 Hz,
Approach/Separation rate – 4400 $\mu$m/s, External resistance – 50 $\Omega$
Hot switching vs Cold switching

Duration – $10^6$ cycles, Cycling Rate – 500 Hz,
Approach/Separation rate – 4400 µm/s, External resistance – 50 Ω
Hot switching vs Cold switching

![Graph showing contact resistance over cycles for different switching methods: Hot switching vs Cold switching. The graph compares contact resistance in Ohms (Ω) against cycle numbers ranging from 5 to 500,000.]
Leading Edge vs Trailing Edge (Anode)

Cycling Rate – 500 Hz, Approach/Separation rate – 4400 µm/s, External resistance – 50 Ω, Polarity – Anode
Leading Edge vs Trailing Edge (Cathode)

Cycling Rate – 500 Hz, Approach/Separation rate – 4400 µm/s, External resistance – 50 Ω, Polarity – Cathode
Quantitative analysis of material transfer in Leading edge vs Trailing edge

Quantitative Comparison of Leading Edge and Trailing Edge Hot Switching

- Log-log plot for material transfer to/from the contact bump vs no of cycles for both polarities
- The data points correspond to average of at least three tests for same conditions
- Volumetric analysis done using AFM scans

(Volume measurements – Courtesy Ryan Hennessy)
Leading Edge vs Trailing Edge – Difference

Duration – $10^6$ cycles, Cycling Rate – 500 Hz, Approach/Separation rate – 4400 µm/s,
Current transients observed by this group at an approach rate of 8.8 µm/s and hot switching voltage of 5 V

Analysis of Pre-Contact Current

Contacts undamaged from the sustained pre-contact current
Study of Field Emission

Direct tunneling from cathode to anode

Fowler-Nordheim tunneling from cathode to vacuum

Graphs showing current vs. separation in Angstroms for different areas.
Material transfer from Field emission

If current = 1 µA current, time of current flow = 50 ns, no of electrons required = 3.125 x 10^5. If each electron has 3.5 eV of energy, the total available energy = 1.75 x 10^{-13} J of energy.

<table>
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<tr>
<th>Property</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Specific heat</td>
<td>0.024 kJ/mole-K</td>
</tr>
<tr>
<td>Melting temperature</td>
<td>2607 K</td>
</tr>
<tr>
<td>Specific heat of fusion</td>
<td>23.7 kJ/mole</td>
</tr>
<tr>
<td>Boiling temperature</td>
<td>4423 K</td>
</tr>
<tr>
<td>Specific heat of evaporation</td>
<td>567 kJ/mole</td>
</tr>
</tbody>
</table>

5.72 x 10^{-14} J of energy is needed to evaporate 500 nm^3 of Ru
Material transfer from Field evaporation

Field evaporation between contacts with small separation: Positive Ru ions are pulled from anode on to the cathode leading to material transfer

- At greater than 6 Å, electric field required for evaporation = 4.1 V/Å
- At 4 – 6 Å, required field drops by 30%
- At less than 4 Å, electric field drops by 50%
- At 3.5 V, separation required for field evaporation = 1.5 Å

Heating and ionization

A high contact voltage can lead to contact material melting and boiling. If the temperature of the metal vapor is high enough, we can get ionization leading to ions being pulled towards cathode.

Relationship between contact voltage and temperature:

\[ V^2 = 8 \int_{T_0}^{T_m} \lambda \rho dT \]

Wiedemann-Franz’s law states:

\[ \lambda \rho = LT \]

This gives us:

\[ T_m^2 = T_0^2 + \frac{V^2}{4L} \]

Melting voltage of Ru = 0.8 V for Ru
Boiling voltage = approx 1.5 V

Saha equation:

\[ \frac{N^{i+1}}{N^i} = \frac{Z^{i+1}}{Z^i} \frac{2}{n_e h^3} \left(2\pi m_e kT\right)^{3/2} e^{\frac{\chi_i}{kT}} \]

Ionization temperature approx 5000 K!
Electromigration is given by:

\[ V = J e Z^* \rho D / K T \]

- Electromigration usually occurs from cathode to anode.
- In a fluid, however, since the ions have additional thermal energy, they may be prone to move towards the cathode.
- Anode to cathode material transfer has been reported in Al, Ag, In and other metals, particularly in the molten state.

Electromigration leading to thermal diffusion

- Electric field between the contacts can cause surface diffusion of the ions towards the apex of the anode.
- If tunneling current causes heating at the anode, this can lead to melting which can further promote surface diffusion towards the apex of the contact.
- The process of surface diffusion is similar to electromigration where ions are pulled by the electric field between the contacts.
- Ultimately a liquid cone may form at this tip which can be long enough to touch the other electrode thereby depositing material on to it.
- This was speculated to be a material transfer mechanism in AFM/STM tips.

Material transfer due to thermal gradient

At the trailing edge, if a metal bridge is formed, the hottest point on the metal bridge can determine the point where the bridge ruptures (if rupture is caused by a portion of the bridge evaporating)

- Thomson effect will shift the hottest point towards the anode.
- The pillar, being a better heat sink will cause the hottest point to shift towards the contact bump (irrespective of polarity.)
Evidence of material transfer due to thermal effect

Duration – 40 to 50 cycles, Separation rate – 8.8 nm/s, External resistance – 50 Ω
Material transfer without contacts separating

Applied voltage = 5V, Duration – 40 to 50 cycles, Separation rate – 8.8 nm/s, External resistance – 50 Ω

Current never went below 75 – 80 mA

Contact voltage at 80 mA = 1 V implying melting
Bipolar Hot Switching Damage

Applied voltage – 3.5 V, Approach/Separation rate – 4400 µm/s, External resistance – 50 Ω
Leading edge current characteristics due to system capacitance

- The 35 pF capacitance arises due to the isolation oxide layer between device and handle sides of the chip.
- In a real switch, inherent capacitance maybe present in the system when the switch is part of a transmission line.
- Contact resistance drops from infinity to 1 ohm in 10 us.
Current vs time for different external resistances – SPICE results

- 50 Ω
- 500 Ω
- 5k Ω
- 20k Ω
- 1Meg Ω
- 10Meg Ω
Contact damage corresponding to different external resistances

Applied voltage – 3.5 V, Duration – $10^6$ cycles, Separation rate – 4400 µm/s, External resistance – 50 Ω
Leading vs Trailing edge difference at 5 kΩ – what causes it?

- At melting voltage, contact resistance $R = 1$ kΩ
- Contact resistance $R = \frac{\rho}{2a}$
- $\rho = 7.1 \ \mu\Omega\cdot\text{cm}$, implying $a = 0.36 \ \text{Å}$
- Radius size less than an atom!
- Voltage between contacts also takes more time to build up.

Duration – $10^6$ cycles, Cycling Rate – 500 Hz, Approach/Separation rate – 4400 µm/s,
Analysis of the current for different external resistors

- Up to 5k Ω, the capacitance in the system has no effect on the maximum current through the contact at the instance of closing.
- From 5k to 1Meg, the capacitance determines the maximum current in the circuit at the instance of closing.
- Since maximum current in the circuit with a 1Meg resistance is 150 µA, the current associated with leading edge hot switching damage cannot exceed this value.
Summary of mechanisms

a) Mechanical transfer through adhesion, cold welding or softening of contact as observed in low voltage hot switching

b) Field Evaporation

c) Field emission leading to heating, melting and evaporation

d) Electromigration with and without melting which can also manifest itself through surface diffusion

e) Ionization of metal vapor

f) Formation of metal bridge where Thomson effect and thermal asymmetry can cause the hottest point of the bridge to be biased towards one of the electrodes
Conclusions

• The results of hot switching tests at different voltages demonstrate the presence of multiple contact damage mechanisms.
• The mechanisms operate at very short separations or when the contacts are just touching.
• While there are probably some similarities between leading and trailing edge hot switching (similar amount of material transfer at a switching speed of 4400 µm/s), there could be effects which are present in one and not the other.
• It is also noted that pre-contact current, observed in ‘dirty’ contacts do not cause material transfer.
Future work

• Contact damage due to AC hot switching
  – Since contact damage varies with hot switching voltage, AC hot switching will typically give a combination of the types of damage observed at different voltages

• Investigating hot switching in a real microswitch
  – Vast difference of thermal properties between the switch cantilever and the substrate can lead to further contact damage triggered by thermal mechanism
  – Relative dominance of thermal mechanism vis-à-vis field effects can be characterized

• Analyzing the correlation between melting/boiling point of a material with corresponding contact damage