SPACE QUALIFICATION OF RF MEMS SWITCHES IN SILICON TECHNOLOGY FOR REDUNDANCY APPLICATIONS

Supported by the ESA Contract on "High Reliability MEMS Redundancy Switch"

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LTCC TECHNOLOGY FOR RF MEMS FABRICATION AND PACKAGING

Supported by the MIUR Project SAPERE-SAFE

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Components4Space, Italian Space Agency – 18-20 January 2016
The Institute for Microelectronics and Microsystems (IMM) belongs to the Department for Physical Sciences and Technologies for Matter (DSFTM) of CNR, and it is currently organized on Seven Sites and four different main Research Lines (currently under revision):

- a) materials, processes and devices for microelectronics;
- b) sensors and micro-systems;
- c) optoelectronics and photo-voltaics;
- d) development of advanced characterization techniques for material and process analyses.

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More than 200 permanent Researchers and Technicians, involved in the above defined areas, and 20% to 40% are presently or potentially involved in micro-electronics and micro-system activities including design, technology, test and modeling for Space and Security. Reliability criteria valid for space as well as defence and commercial applications are followed for releasing the feasibility of devices and sub-systems.
Medium Size Clean Room capabilities (300 – 500 m²) in Class from 100,000 down to 100, equipped for micro- to nano-electronics as well as for micro- and nano-systems, are available in several sites of the Department. Thin film deposition techniques with multi-layer mask processes are routinely done.

Potential small size production of on-wafer sub-systems can be pursued, and full characterization including on-line and off-line measurements can be performed (mask manufacturing, chemical and physical etching techniques, micromachining, …).

Morphology, mechanical characteristics, doping profiles, etc. for sub-micron and nano-devices are evaluated by means of purposely built setups and commercial instruments (SEM, TEM, Digital Holography, Micro-analysis, Scanning Probe Microscopy, …).

Electrical DC and RF characterization is provided by using calibrated and remotely controlled network equipments (Time and Frequency Domain for IR, Microwave, mm-wave and Optical Devices and Sub-Systems).

Modeling by means of home made and commercial codes for specific problems, including thermal and power handling, fluido-dynamics, EM propagation, charging processes, …, are part of the skill in every site.
The Institute participates to activities managed within the Aerospace Technological Districts (DTAs) at regional and national level

Reference Technological National Platforms: SPIN-IT (SPACE) and SERIT (SECURITY)

The main commitment in Space Business comes from the major National Companies and Groups, like FINMECCANICA, TAS, CGS, STMicroelectronics ... and SME and their Associations (AIPAS, AIAD, ASAS).
Some highlights of the IMM space related activities (not exhaustive)

- Telecom Applications in the Microwave and Millimeter Wave Range
- Structural characterization for avionics by means of optical fiber sensing
- Photo-voltaic ground applications suitable of Space implementations
- Material Science on nano-structured materials for nano-interconnections, sensing and radiation hardness improvement
- High K materials
- Sensing for life quality in ground and on-board environments
- Novel concepts in detection and signal processing of RF, THz and optical signals

Taxonomy

(following SPIN-IT Definitions)
OUTLINE

- Introduction
- RF MEMS switches in Silicon technology
- SPST, SPDT configurations for redundancy applications
- LTCC packaging of SPDT in Silicon technology
- RF MEMS switches in LTCC technology and packaging
Micro-electro-mechanical systems (MEMS) for RF applications have been widely studied during the last 15 years and they exhibit extremely good performances in terms of loss, power consumption, and linearity.

General assessments about promising applications for ground and space sub-systems have been largely demonstrated.

Currently, redundancy logic and matrices for signal routing are the best candidates for Space; phase shifters and delay lines for RADAR.

Generally speaking, re-configurability by means of all passive configurations is strongly encouraged, even for moderate power applications (up to 1-2 watt), with analog and digital design.
RF - MEMS SWITCHES
DOUBLE CLAMPED BUILDING BLOCKS (BRIDGES)

The three main elements for the classification are:

1) Contact  Metal - metal / Capacitive
2) Mechanical structure  Bridge / Cantilever
3) Configuration  Series / Shunt
**Design Criteria**

- The RF MEMS switch consists of a double clamped gold beam, anchored on the two ground planes of a coplanar waveguide structure.

- The actuation is provided pulling down electrostatically the bridge because of the mechanical force generated by means of the voltage applied at the two lateral actuation electrodes (DC and RF signals are decoupled).

- The dielectric is removed from the lateral actuation pads to minimize charging phenomena; mechanical stoppers patterned on the substrate prevent the contact between the metal beam in the down-state and the actuation pads.
RF MEMS
SPST PERFORMANCES

• Generally, performances for RF MEMS SPST devices are:
  ❖ isolation better than 20 dB,
  ❖ insertion losses not exceeding 0.3-0.4 dB for wideband applications.
• The shunt capacitive configuration is intrinsically limited in band because of its resonant response.
• The ohmic series device is designed to have a broadband response.
• Actuations up to $10^7-10^8$ or more

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ISSUES FOR RF MEMS

- Charging effects are responsible for sticking of the actuated metal membranes, and can be controlled (or mitigated) by means of dielectric-less actuation configurations or by using substrates not affected by charging at all.

- Contact deterioration upon cycling is one of the most investigated failure mechanisms for MEMS RF-switches, and the role of the contact material appears to be of paramount importance.

- Two important parameters to be checked are: (i) the contact resistance, which should be as low as possible, and (ii) the number of cycles, to be maximized without alterations in the RF performances.

- In several applications it would be desirable to have a contact resistance not exceeding 1 Ω, and a cycling reliability up to, at least, $10^7$ actuations during the switch operation, which is particularly appealing when compared to classical p-i-n diode switches.
Charging effects mitigation

The dependence of the exploited devices on the charging phenomena has been mitigated by means of dielectric pillars, manufactured under the metal beam to prevent the full contact between the bridge and the dielectric lateral pads used for the electrostatic actuation.

Pillars geometry

Shunt capacitive

Ohmic series

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CONTACT MATERIALS

• Stacking layers of platinum between gold layers can improve not only the hardness but also the surface properties of gold commonly used in RF-switch contacts.

• The roughness of the contact surface is reduced and the tendency of platinum for frictional polymers is maintained under control, because the surface exposed to ambient is made of gold.

- Two material variants: (i) pure gold in the “reference” device and (ii) a modified multilayer composed of a thin (3 nm) platinum layer sandwiched between two thicker layers of gold with thicknesses of 120 nm (bottom) and 30 nm (top) of gold in the “test” device.

- In the “test” device the bottom part of the mobile membrane was also made with 150 nm of the same material, in order to have contacting surfaces with the same characteristics on both sides.
RF performances at first actuation for the standard switch (reference device) and the switch with the modified contact material (test switch). Comparison between measured transmission and equivalent circuit fit (a), and isolation (b).

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CYCLING TEST RESULTS

(a) Isolation of reference switch, and
(b) Isolation of test switch with modified floating metal.
The surface characteristics are also different for the two contact materials, when they experience the conditions of a typical switch fabrication process. Contact region surface morphology in the reference device (left) and in the modified test device (right).

<table>
<thead>
<tr>
<th>Switch</th>
<th>Rcontact (ohm) (initial value)</th>
<th>Rcontact (ohm) (after $10^6$ cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>0.75</td>
<td>2.36</td>
</tr>
<tr>
<td>Test</td>
<td>1.00</td>
<td>0.70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>2.2</td>
</tr>
<tr>
<td>Multilayer</td>
<td>3.0</td>
</tr>
</tbody>
</table>
SPDT configuration measured on-wafer. On the bottom side, the tips used for ground reference (central one) and for DC actuation (lateral ones).

The central switches are the ohmic series devices, whereas the external ones are shunt capacitive switches. RF G-S-G probes are used for the microwave measurement.
A: LTCC packaging used to host the SPDT structure, and B: detail of the SPDT manufactured in Silicon technology and placed inside the package. On the top layer a brazable Au frame has been screen printed to seal kovar frame and a cavity has been realized inside ceramic to place switches. The LTCC materials used in the manufacturing process is DuPont 951 GreenTape.
**A**: Insertion Loss (IL) and **B**: Isolation performances of the SPDT from 20 to 500 thermal cycles. RF MEMS samples have been submitted to 500 thermal cycles, and measured after, 20, 100, 200, 300, 400 and 500 cycles, with a temperature ranging between $-55^\circ$C and $+125^\circ$C. Presently, 400 TC is the limit tolerated by the SPDT.

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SPDT MECHANICAL SOLICITATION

A: Insertion Loss (IL) and B: Isolation performances of the SPDT after the mechanical shocks. The results have been obtained by imposing 5 and 10 pulses, 3000 g peak, 0.5 ms. Mechanical shocks have been performed with 5 and 10 pulses, 3000 g peak, 0.5 ms. Vibration test, performed by applying vibration having 50g peak at 20Hz÷20KHz and at the end the samples have been submitted to electrical measure to verify any possible variations in measurement or damages.

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A: Insertion Loss (IL) and B: Isolation of the SPDT measured on-wafer and after packaging. IL < 1.5 dB and Isolation better than 30 dB can be obtained up to 20 GHz.
Conclusions on LTCC Packaged

- SPDT LTCC packaged RF MEMS switches for redundancy logic in space applications have been manufactured and tested.
- Utilization up to 20 GHz was demonstrated, fulfilling the most part of the requirements needed up to 18 GHz.
- On-wafer devices evidenced a very wideband response, with Insertion Losses not exceeding 1.2 dB and Isolation better than 30 dB up to 30 GHz.
- Very good performances in terms of thermal cycles (up to 400) and mechanical shocks, thus passing the most part of the tests needed for space qualification.
- LTCC packaging, very effective for providing the due environmental protection for the operability of RF MEMS devices, needs further improvements to match the present wide-band response of the on-wafer device. Robustness of the membrane has also to be improved for fulfilling the space qualification requirements up to 500 thermal cycles.

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Aging of RF MEMS

• Long term actuations and/or cycling with temperature as parameter have been performed in the effort to obtain aging predictions and to confirm that temperature could be an actual parameter to be used.

• Using fit of actuation voltage vs. time and temperature turns out a lifetime exceeding 15 years by Arrhenius type considerations (to be confirmed).
RF MEMS in LTCC Technology

- Low Temperature Co-fired Ceramics (LTCC) is a well established technology for down-sizing RF modules containing buried components and interconnections.
- LTCC has been evaluated for integrating surface micro-machined RF MEMS switches and packaging of modules for space applications, including SPST, SPDT and DPDT for redundancy purposes, with the aim of obtaining a fully integrated structure.
- Advantages coming from the main characteristics of the MEMS configuration, like no signal distortion and low losses are expected.
- Negligible charging effects are expected from such a material with respect to the electro-mechanical response of the switches.

- The implementation of matrix configurations for signal routing is currently evaluated, to manufacture modules characterized by high complexity and a fully passive solution. Sub-systems composed by a number of DPDT sub-matrices suitable to be integrated in a 12x12 configuration can be designed and their manufacturing was already demonstrated in silicon technology.
Design and EM simulations

SPST (series type) device on CPW configuration.

ON state (bridge down)

OFF state (bridge up)
Transmission

Isolation [dB] vs. Frequency [GHz]

Return Loss [dB] vs. Frequency [GHz]

Insertion Loss [dB] vs. Frequency [GHz]

Name | Cycles | V_{max} [V] | V_{deact} [V]
--- | --- | --- | ---
B1-D2 | 10^0 | 50 | 38
| 10^2 | 50 | 42
| 10^3 | 48 | 42
| 10^4 | 48 | 42
| 2x10^4 | 48 | 40
| 7x10^4 | 48 | 42
| 10^5 | 48 | 42
| 2x10^5 | 48 | 42
| 7x10^5 | 48 | 42
| 10^6 | 95 | 34
| 2x10^6 | 115 | 34

SPST
SPDT design and EM simulation
## SPDT Isolation

### Graph

- **Frequency [GHz]**
- **Isolation [dB]**

**Graph Labels:**
- $S_{11}$ B6D1 Path 75V-0
- $S_{21}$ B6D1 Path 75V-0

### Table

<table>
<thead>
<tr>
<th>SPDT Name</th>
<th>Left SPST Contact Resistance (Ω)</th>
<th>Right SPST Contact Resistance (Ω)</th>
<th>Drive Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B6-D1</td>
<td>12</td>
<td>7</td>
<td>65</td>
</tr>
</tbody>
</table>

### Diagram

- **Ports:** Port1, Port2, Port3
- **50Ω Load**
- **Voltage Levels:** 75V, 0V
- **Switch States:**
  - Red: Switch off
  - Green: Switch on

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SPDT Insertion Loss

![Graph showing insertion loss vs frequency]

<table>
<thead>
<tr>
<th>SPDT Name</th>
<th>Left SPST Contact Resistance (Ω)</th>
<th>Right SPST Contact Resistance (Ω)</th>
<th>Drive Voltage (V)</th>
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<tbody>
<tr>
<td>B6-D1</td>
<td>12</td>
<td>7</td>
<td>65</td>
</tr>
</tbody>
</table>

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SPDT Return Loss

Return Loss [dB] vs Frequency [GHz]

SPDT Name | Left SPST Contact Resistance (Ω) | Right SPST Contact Resistance (Ω) | Drive Voltage (V)
--- | --- | --- | ---
B6-D1 | 12 | 7 | 65

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DPDT (2x2 Matrix)
Design and EM simulation
**Packaged DPDT DC electrical testing**

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larghezza</td>
<td>24 mm</td>
</tr>
<tr>
<td>Lunghezza</td>
<td>32 mm</td>
</tr>
<tr>
<td>4 fori per accesso DC network</td>
<td></td>
</tr>
<tr>
<td>4 terminazioni I/O RF a 50ohm</td>
<td></td>
</tr>
<tr>
<td>Tensione di attuazione</td>
<td>75V (su tutti i rami)</td>
</tr>
<tr>
<td>Resistenza serie sui rami di trasmissione</td>
<td>7 Ω – 12 Ω</td>
</tr>
</tbody>
</table>

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RF Characterization (in progress): According to the configuration of the 2x2 Matrix, 4 paths are possible and in particular: two short paths (I₁-O₁, I₂-O₂) and two long paths (I₁-O₂, I₂-O₁). RF measurements will be performed from 45 MHz to 15 GHz.
Past and current
RF MEMS Contracts and Cooperations with Italian Partners - 1

• **European Project** on a 38 GHz micromachined TX/RX module in alumina and silicon technology: membrane supported, micromachined antennas (1998-2002).

• **ASI Project** "Microsistemi a Microonde ed Onde Millimetriche per Applicazioni Spaziali" for membrane supported micromachined lumped components and filters.
Past and current
RF MEMS Contracts and Cooperations
with Italian Partners - 2

• **European Space Agency (ESA)** contracts on RF MEMS switches in silicon technology for: (i) SPST and SPDT configurations and their space qualification, (ii) redundancy applications and (iii) matrices for signal routing in satellite reconfiguration (2002 – 2015).

Past and current
RF MEMS Contracts and Cooperations
with Italian Partners - 3

• European Defence Agency (EDA) contract on delay lines and phase shifters for beam forming networks in radar applications (2006-2009).

• MIUR contract “TASMA” (Tecnologie Abilitanti per Sistemi di Monitoraggio Aeroportuale) on medium power RF MEMS and packaging (2014-2016).

• Aerospace National Technology Cluster (CTNA) activities, supported by the Italian Ministry for Research and Education (MIUR) on RF MEMS packaged configurations for signal routing in LTCC technology to be used in small aperture radar (SAR) modules (2014-2016).
<table>
<thead>
<tr>
<th>RF MEMS Technology</th>
<th>Purpose</th>
<th>Cost</th>
<th>Advantages</th>
<th>Drawbacks</th>
<th>Sacrificial Layer Release Micromachining</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Silicon</strong></td>
<td>Devices, 2D/3D Microsystems</td>
<td>Low-Medium</td>
<td>reliable, low loss</td>
<td>low-medium power, charging to be mitigated</td>
<td>Photoresist: high pressure O2 plasma process performed in asher</td>
</tr>
<tr>
<td><strong>GaAs</strong></td>
<td>Devices, 2D/3D Microsystems</td>
<td>Medium-High</td>
<td>reliable, low loss</td>
<td>Not completely CMOS compatible, charging (?)</td>
<td>Photoresist: high pressure O2 plasma process performed in a barrel etcher</td>
</tr>
<tr>
<td><strong>Alumina</strong></td>
<td>Devices, 2D Structures, low-level packaging</td>
<td>Low-Medium</td>
<td>medium-high power, well established</td>
<td>surface roughness, lossy</td>
<td>SiO2: Wet etching with subsequent rinse in water/IPA/cyclohexane and freeze and sublimation</td>
</tr>
<tr>
<td><strong>LTCC</strong></td>
<td>Devices, 2D/3D Microsystems, Packaging</td>
<td>Low</td>
<td>3D integrability</td>
<td>surface roughness, shrinking effect after LTCC cofiring, lossy</td>
<td>SiO2: Wet etching with subsequent rinse in water/IPA/cyclohexane and freeze and sublimation</td>
</tr>
<tr>
<td><strong>SU-8</strong></td>
<td>Devices, 2D/3D Microsystems, Packaging</td>
<td>Low</td>
<td>Photolithographic processing</td>
<td>breakdown voltage, outgassing to be confirmed, sacrificial layer removal (viscosity)</td>
<td>Resist or SU-8: wet or O2 assisted RIE</td>
</tr>
</tbody>
</table>
Next Future Goals

Micro- and Nano-Systems for low and high frequency components and sub-systems with functionalities quite different between them (electrical or electromagnetic, electro-mechanical, and chemical-physical) to be integrated in the same configuration, with special care to:

i. Optimization of **bulk** and **surface micromachining** techniques for different substrates which can host configurations for guided and free space propagation as well as resonating structures and nano-devices

ii. Design and realization of innovative components, for which no commercial software solution exists for the full design, especially when different and/or combined solicitations are involved;

iii. Reliability of Micro- and Nano-Systems as a function of their applications, for ground as well as for space and security applications for on-wafer and packaged devices

**New Protocols for Characterization needed**

**SMART SYSTEMS**, **high number of components and functions**, **network-embedded**

**INTERNET OF THINGS**
Thank you for your attention !!!