Reliability of RF-MEMS switches for space applications

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Outline

- Development of components for space application is challenging because it requires not only the **optimization of the performance** but also the **identification of the failure modes** for the final qualification.
- RF MEMS switches designed to be used in a redundancy configuration have been **designed**, **fabricated** and **extensively measured** with promising results in terms of electrical, thermal, mechanical properties and life time expectation.
- **Packaging** is also briefly discussed.

Context

- Scope of the ESA contract is the realization of a **high reliability redundancy switch** for space applications
- Main objective is not so much a good RF performance than the **maximization of the lifetime** in typical space environment conditions
- The complexity of the task is given by the **many** different and often conflicting **requirements**

Problems to be solved for obtaining reliable RF MEMS

The main issues for the utilization of RF MEMS in low power regime have been individuated in:

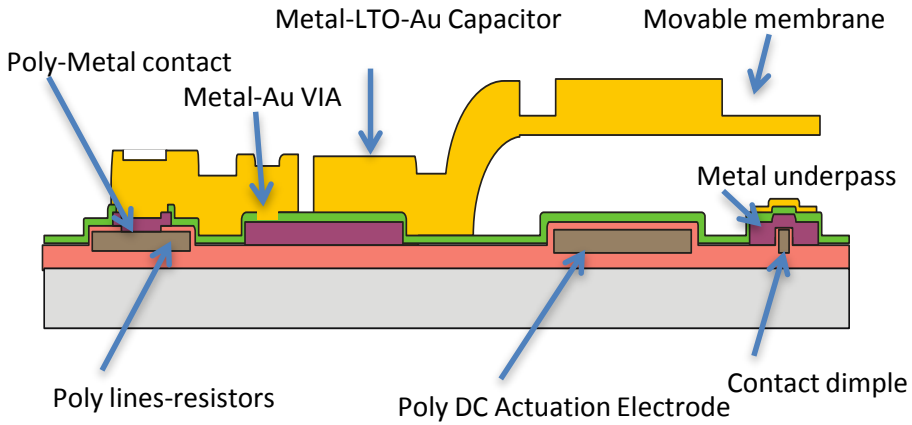
i. **charging**, to be mitigated for avoiding sticking of the metal membrane to be actuated,

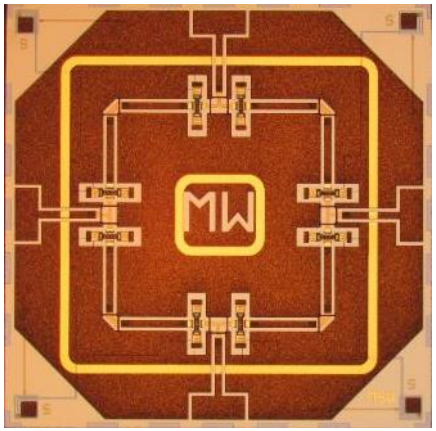
ii. **creep & anelastic relaxation**, that affects the restoring force both in long term actuations and in cycling,

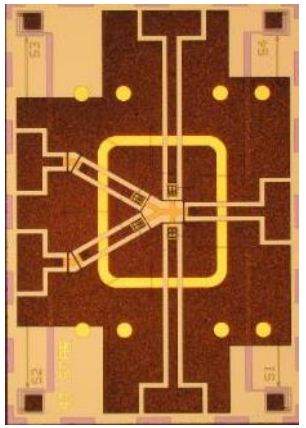
iii. hermetic **packaging**, of the device by using inert gas, in order to exclude pollution or residual humidity that can interfere with the basic function of the devices.

Reliable MEMS require a reliable fabrication technology

- Starting point of the technology development was the **8+ mask layer** process of FBK.
- The process provides:
  - *Flexible architecture*
  - *Ohmic and capacitive switches on the same die*
  - *Passive circuit elements*
- Over the years ongoing effort to stabilize and optimize the technology







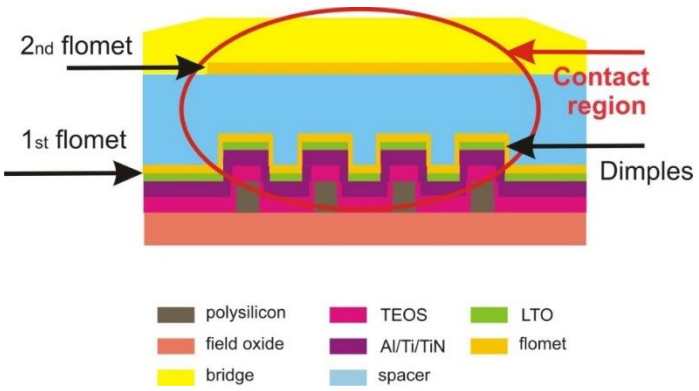
Fabrication details

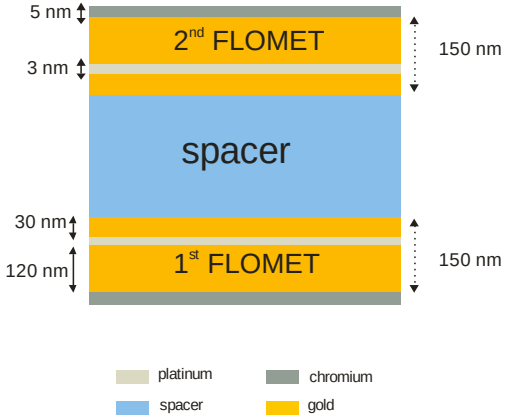
Within the project two dedicated fabrication cycles have been made.

- A total of 67 high resistive 4'' silicon wafers have been processed
- About 10 technology variants have been explored
- Second flomet splitting performed better than the standard process in reliability tests (cycling and long term actuation) as it provides a harder contact surface

Standard Process:
150 nm Cr/Au FLOMET

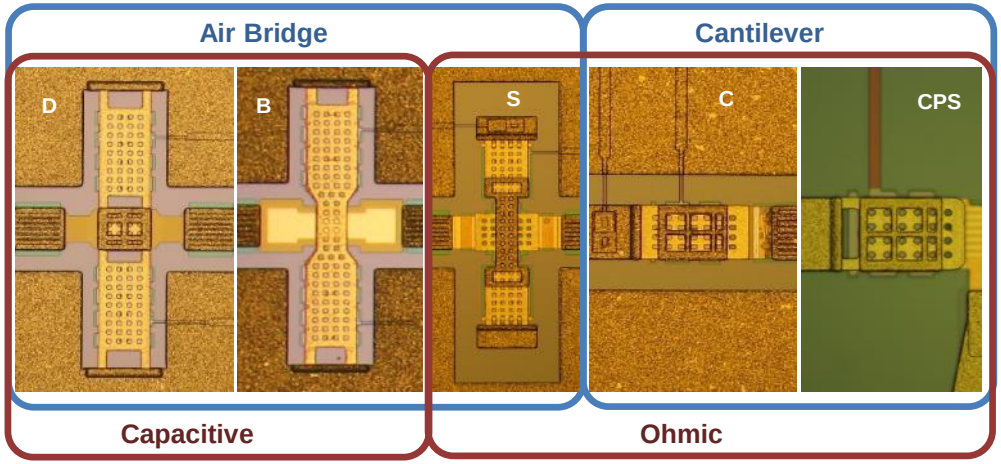
Splitting: 150 nm Cr/Au/Pt/Cr/Au
1st + 2nd FLOMET

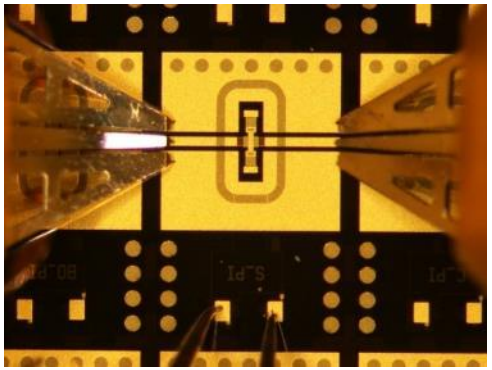




RF MEM SPST elements

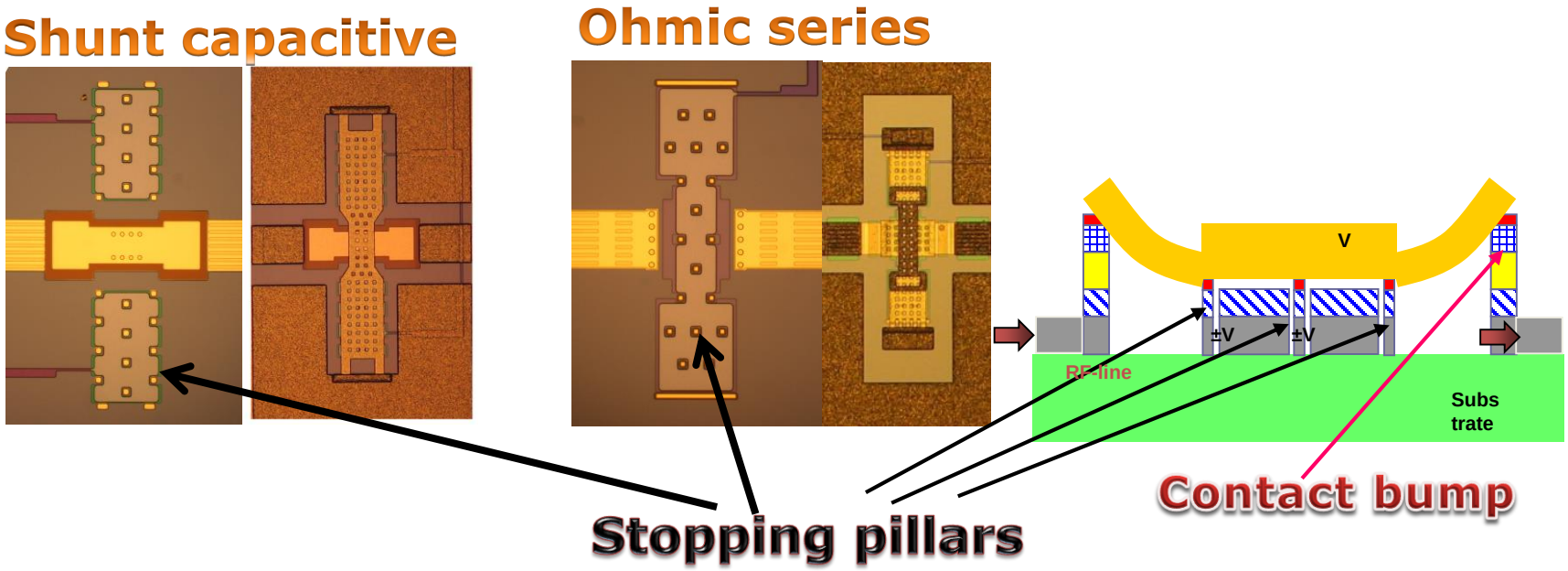
- MEMS switches were build in coplanar waveguide configuration (CPW), with central conductor leading the RF signal, and lateral ground planes.
- Switch Test of the building block single-pole-single-throw (SPST) was very important for the feasibility of the basic structure
- Many different designs have been realized and tested





Mitigation of dielectric charging

- **Dielectric-less designs have been very effective in reducing charging effects.**
  - Short term actuation tests show minimal charging with higher time constants
- **Stopping pillars prevent electrical shorts in the closed state.**

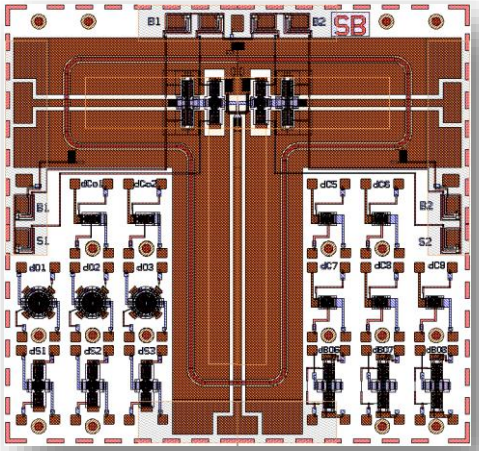


RF MEMS SPST performances

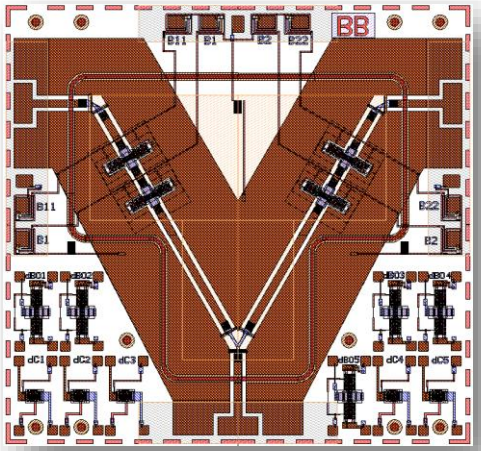
- **Overall performances of the RF MEMS SPST devices:**
  - isolation better than 20 dB,
  - insertion losses not exceeding 0.3-0.4 dB for wideband applications.
- **The shunt capacitive configuration is intrinsically limited in band because of its resonant response.**
- **The ohmic series device is designed to provide a broadband response.**

SPDT Configurations

- **Two configurations were implemented using ohmic and shunt capacitive switches**
  - Two shunt capacitive switches for a narrowband device (12-18 GHz)
  - Ohmic and shunt capacitive switch for a broad band device (0-18 GHz
- **The same die footprint allowed the use of the same package**

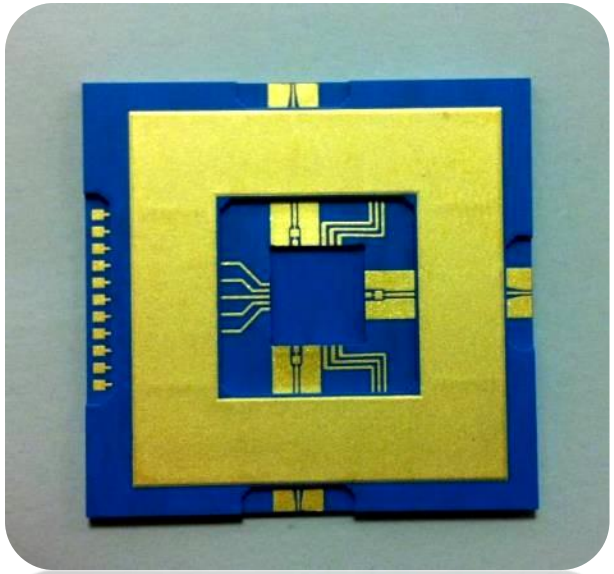


Ohmic and shunt capacitive configuration

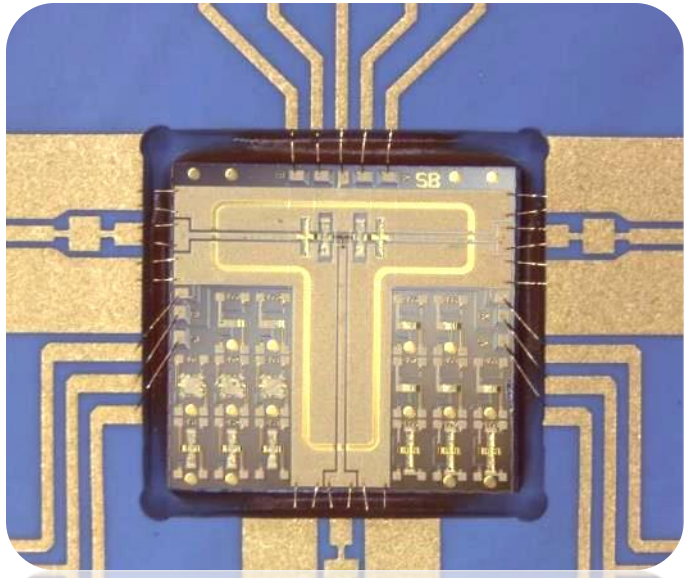


Shunt capacitive configuration

SPDT packaging



A



B

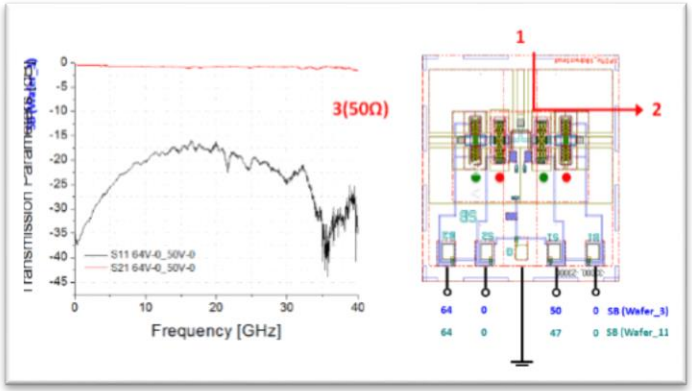
A: Custom LTCC packaging developed for the SPDT,

B: detail of the SPDT assembled in the package.

- **The Low Temperature Co-fired Ceramic (LTCC) packages, hermetically sealed by metal brazing, have been fabricated by Thales Alenia Space.**
- **The technology is space qualified.**

SPDT characterization

- RF characterization has been performed both on wafer and on packaged devices
- The package introduces limitations in terms of IL and resonances



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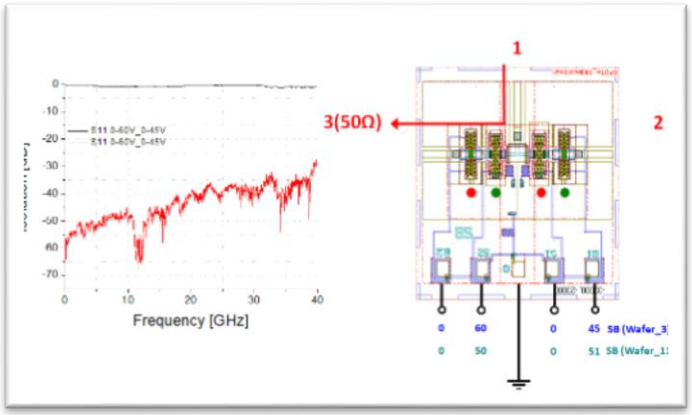


B

A: Transmission and **B**: isolation characteristics of an unpackaged ohmic-shunt capacitive prototype

Environmental Tests

The Environmental Tests (ET) have been performed on packaged devices as per MIL-STD-883H. They included:

- vibration tests,
- shock test
- thermal cycles
- leak test to verify the package hermeticity before and after each environmental test

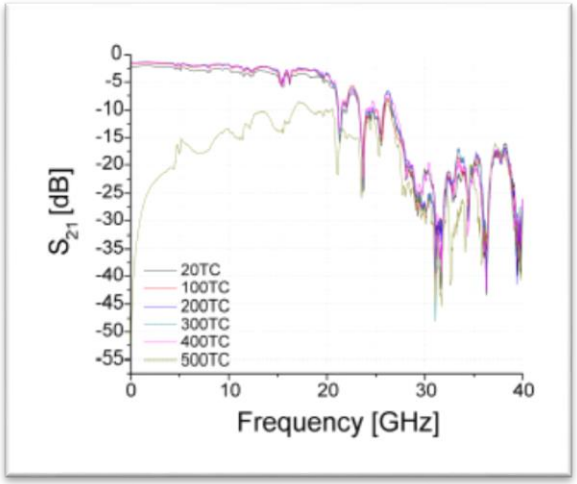
In addition in different occasions radiation tests have been performed on SPST devices including exposure to gamma rays and protons

Environmetal Tests Details

- **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° C and +125° C.**
- **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.**
- **At the end of the mechanical tests the samples have been submitted to electrical measure to verify any possible variations in measurement or damages.**

Environmental test measurements

- **Thermal cycle characterization**



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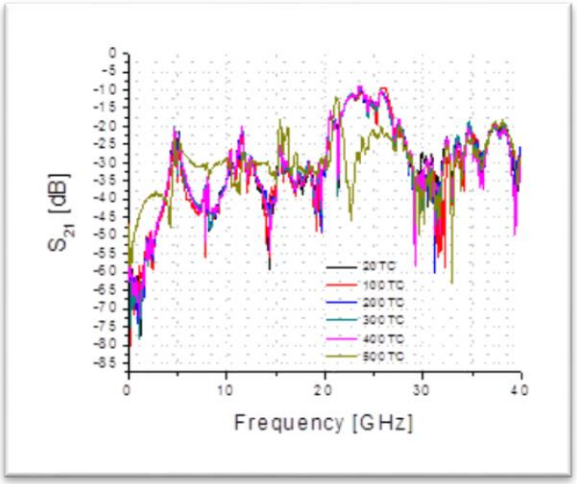


B

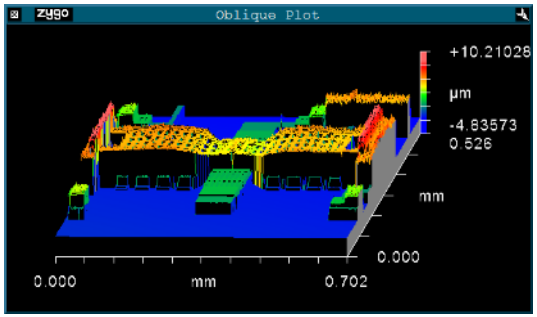
A: Insertion Loss (IL) and **B**: Isolation performances of the SPDT from 20 to 500 thermal cycles. Presently, 400 TC is the limit tolerated by the SPDT.

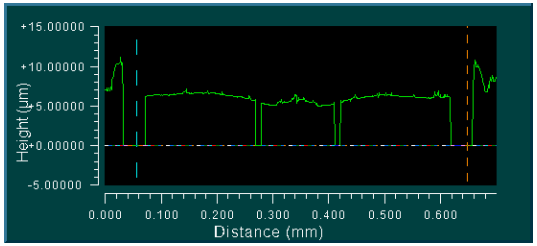
- **Mechanical shock and vibration didn't have a measurable effect on the performance of the devices**

Failure analysis

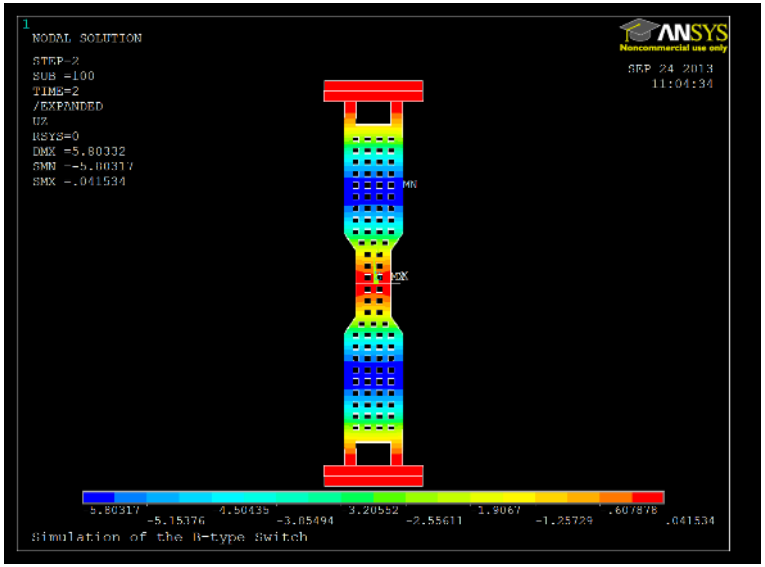
Due to their slender design the shunt capacitive switches experience during thermal cycling repeated buckling.

Optical profiler after 500 thermal cycles





FEM simulation of the out of plane deformation at max. temperature

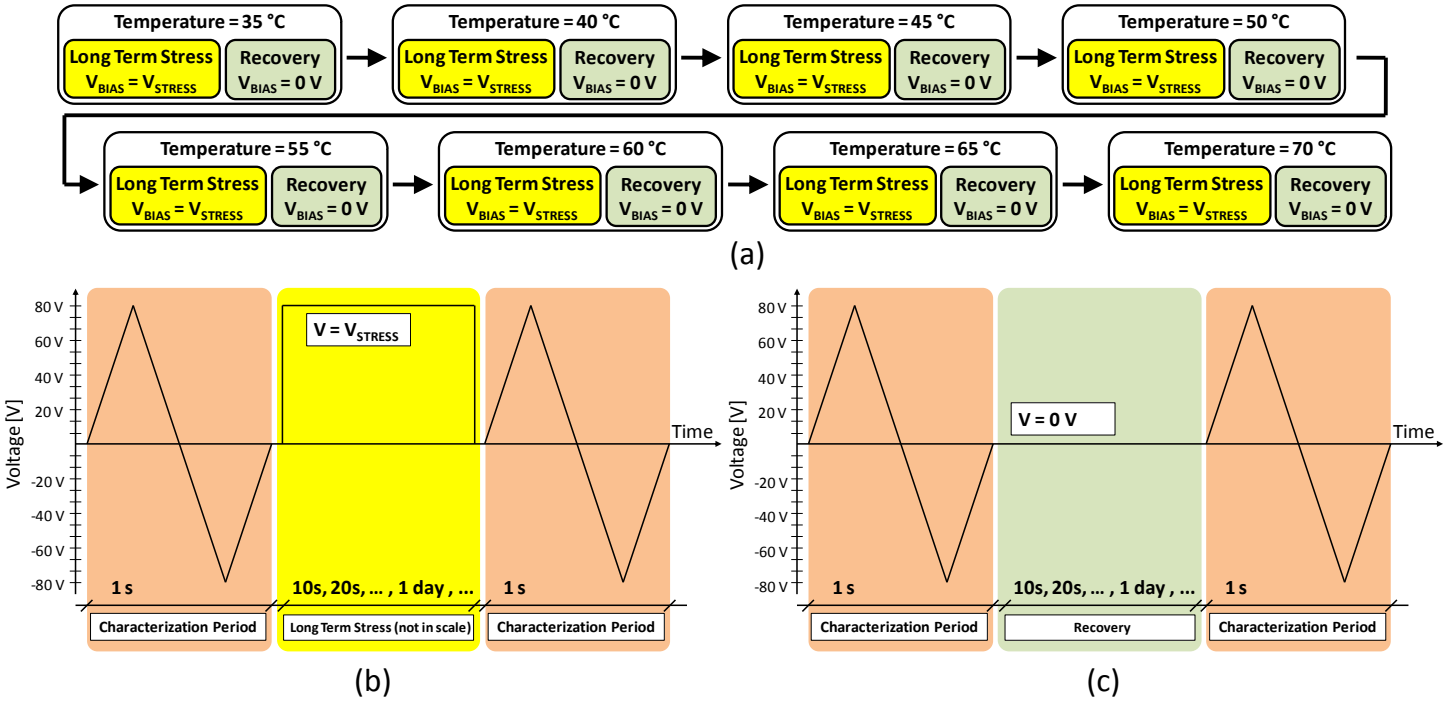


Environmental test results

- Very small changes on the Insertion Loss and Isolation up to 400 TC, but failure occurs when 500 TC are applied.
- No changes observed of the actuation voltage V_{act}, always being V_{act}=50 volt ca. for the shunt configuration and V_{act}=30 volt ca. for the ohmic device.
- Mechanical shocks are un-effective on the electrical performances (simulating the launch conditions).
- The package is a limiting factor for wideband electrical performances due to unwanted resonances that appear below 20 GHz and IL changes that are evident above 20 GHz. Isolation is still below -20 dB covering also the full Ku-band.
- Decrease of the performances induced by packaging, with 1 dB more insertion loss in the frequency range below 20 GHz.

Long term stress tests

- **Stress procedure performed on SPST's**



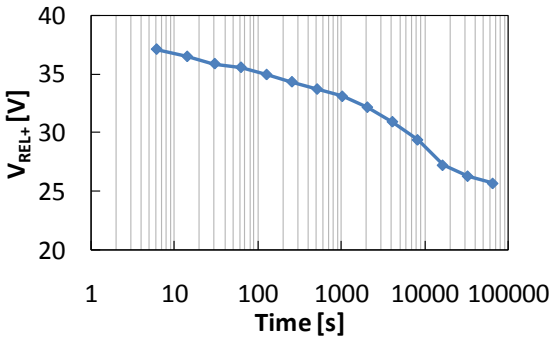
a: Schematic representation of the entire long term stress.

b: Detail of the stress period performed at each temperature.

c: Detail of the recovery period performed at each temperature.

Long term stress test results

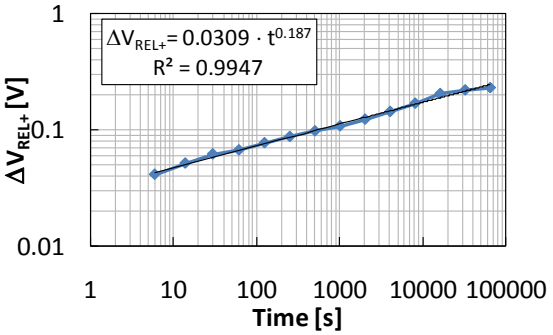
Evolution of release Voltage



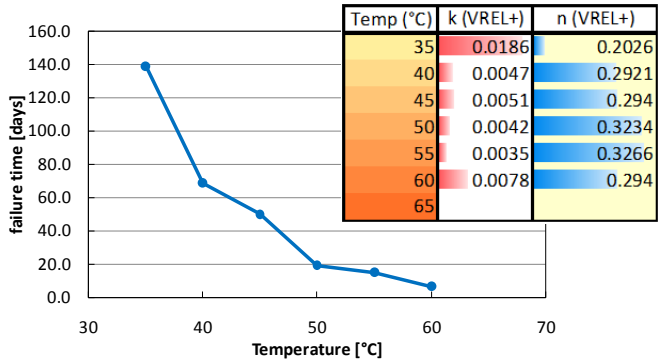
Fitting procedure

We use a **power law fitting** in order to extrapolate the stiction time

$$\frac{\Delta V_{REL+}}{V_{BIAS}} = k \cdot t^{n}$$



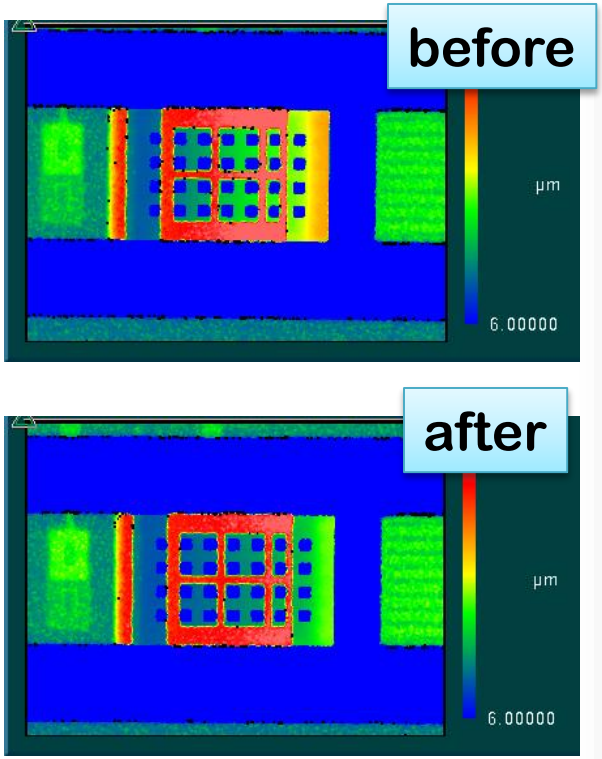
Lifetime extrapolation

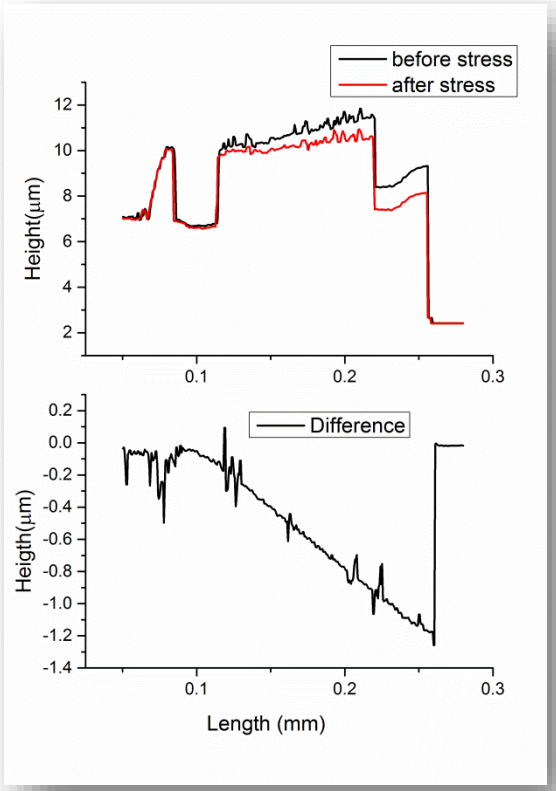


Temp (°C)	k (VREL+)	n (VREL+)
35	0.0186	0.2026
40	0.0047	0.2921
45	0.0051	0.294
50	0.0042	0.3234
55	0.0035	0.3266
60	0.0078	0.294
65		

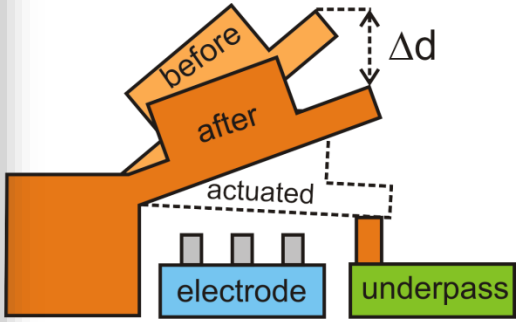
Creep tests

Mechanical changes have been detected during long-term stress test

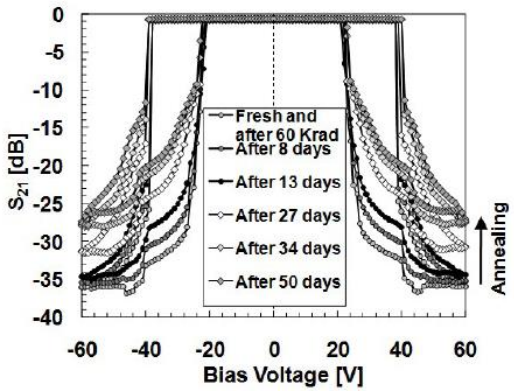




Both **mechanical** and **electrical** issues contribute to lifetime

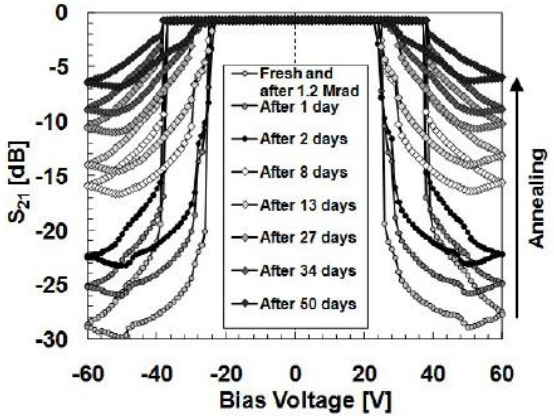


Radiation γ-ray stress



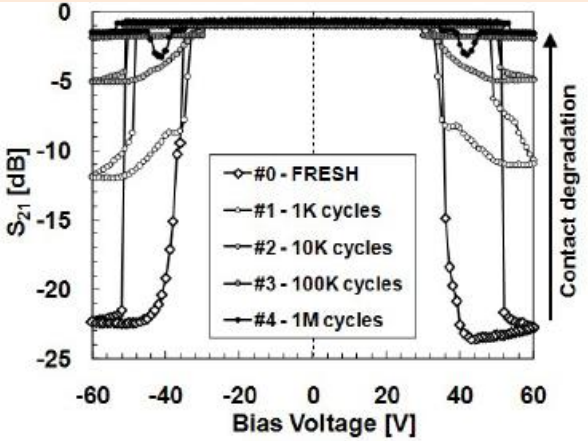
Tests @ 60 Krad and 1.2 Mrad.
Novel method to accelerate the lifetime of ohmic RF-MEMS switches by means of radiation exposure. Experimental results of proton and γ-ray irradiation were compared to cycling stresses, obtaining similar degradation in electrical performances.

γ Ray stress: 60 krad @ 2.9 krad/h



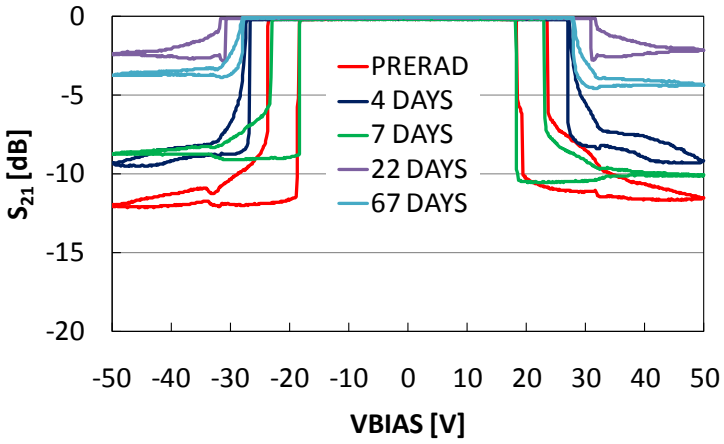
γ Ray stress: 1.2 Mrad @ 54 krad/h

Correlation with cycling stress test

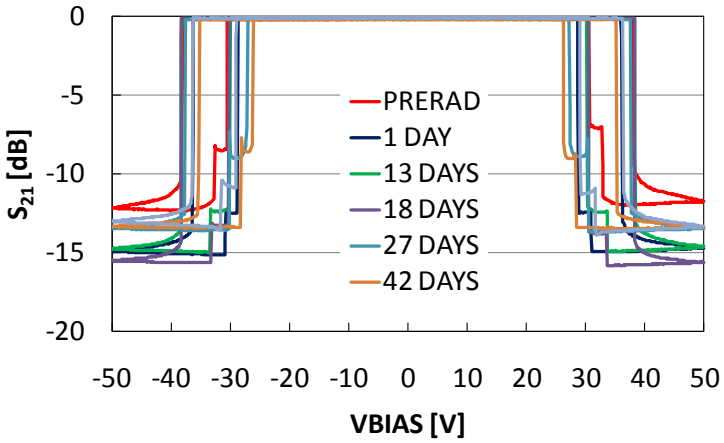


A. Tazzoli, et al., "Accelerated testing of RF-MEMS contact degradation through radiation sources", Reliability Physics Symposium (IRPS), 2010 IEEE International , pp.246-251, 2-6 May 2010.

Radiation Protons and X-ray stress



1 Mrad Protons



1 Mrad X-rays

Radiation test on Capacitive Switches (1 Mrad):

- The 500 kRad protons dose don't induce significant deviation of electrical and RF performances (not shown).
- 1 Mrad protons significantly degrade RF performances.
- The 1 Mrad X-rays dose does not show a clear trend (initial isolation improvements followed by a partial decrease)

Long term stress results

- The long term actuation tests showed that dielectric-less S-type devices have a mean extrapolated lifetime **of 10,9 +/- 4.8 years.**
- Similar measurements conducted at different temperatures showed that the predicted lifetime decreases with increasing temperature, which means that **temperature can be an accelerating factor**.
- **Mechanical relaxation** is an important mechanism to consider in the long-term as it reduces the restoring force of the devices.
- Radiation tests performed on different device typologies with very high doses showed that these devices are **quite radiation hard**.

Summary of results

- **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.

Outlook

The project has been extended till the end of the year with the goal to maximize the data output. In particular the objectives for this phase are:

1) Find a good criterion to discriminate between **charging** and **mechanical** phenomena
2) Identify **promising switch topologies** among the new designs not yet tested
3) Perform long term experiments at **different temperatures**
4) Find a **accelerating test** for the life time combining electrical and mechanical effects