Device Level Packaging of RF MEMS

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Introduction / Motivation

MEMS Packaging Challenges

- Most expensive process in MEMS device fabrication
- Difficult due to MEMS moving structures
- Application specific: hermetic or vacuum sealing
- Isolation from ambient environment while exposure to agent(s) to be measured
- Scalability from device to wafer level

Introduction / Motivation

Why MEMS Resonators?

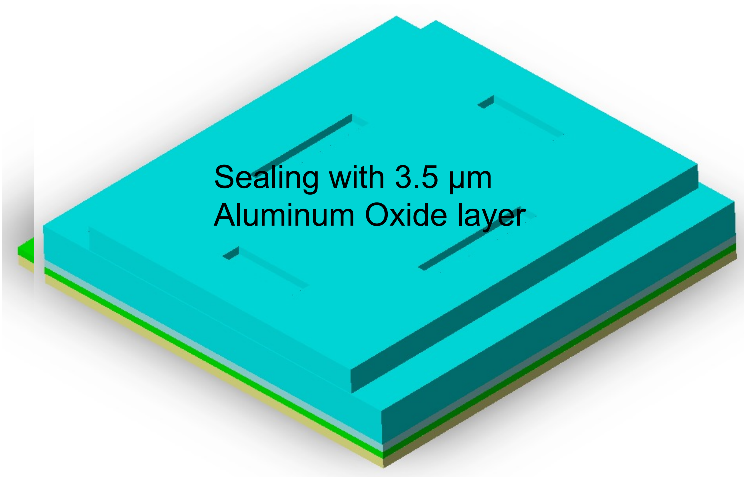
- The resonance frequency and Q-factor depends on the pressure of the vacuum cavity inside the package
- Serves as a good test-bed for “growing your own-package”

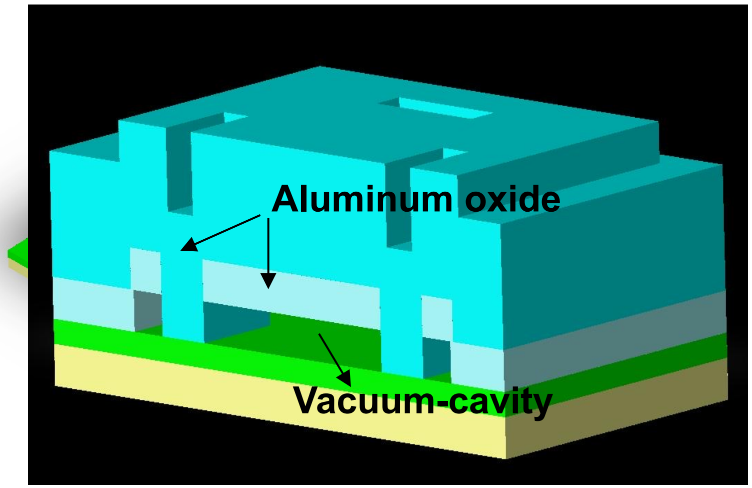
Approach

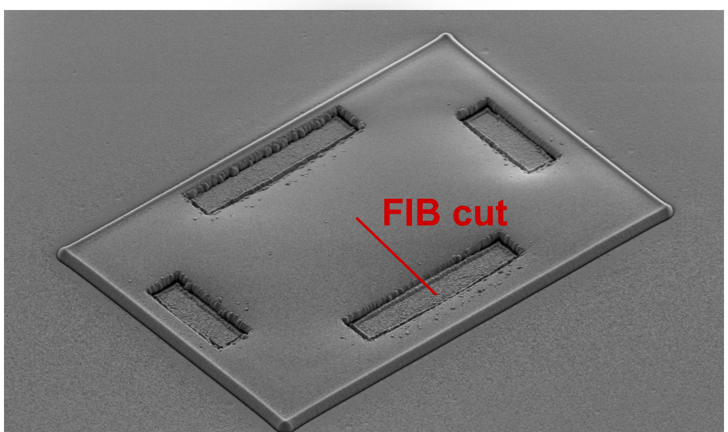
- First the package is fabricated without any resonator.
- Later resonator is integrated with the package for self packaged MEMS device.

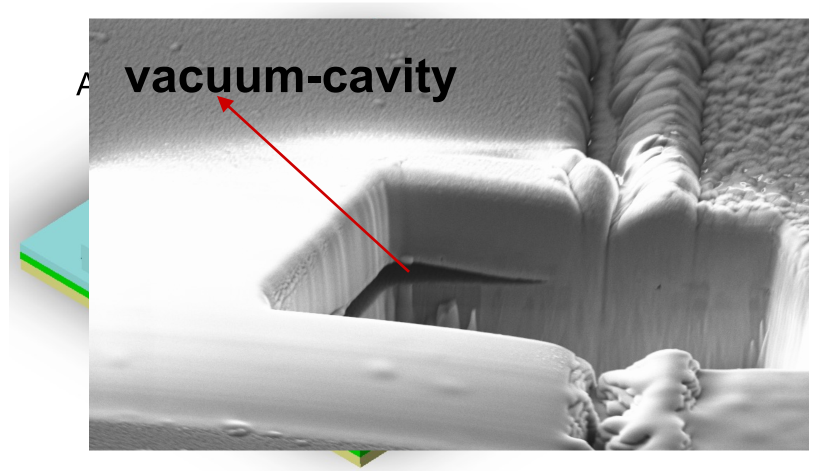
Vacuum-cavity Package Fabrication

Vacuum-cavity packages without resonators were fabricated to identify any processing issues prior to the integration of the MEMS device in the package.









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Reliability of the Package

Over-Molding Test

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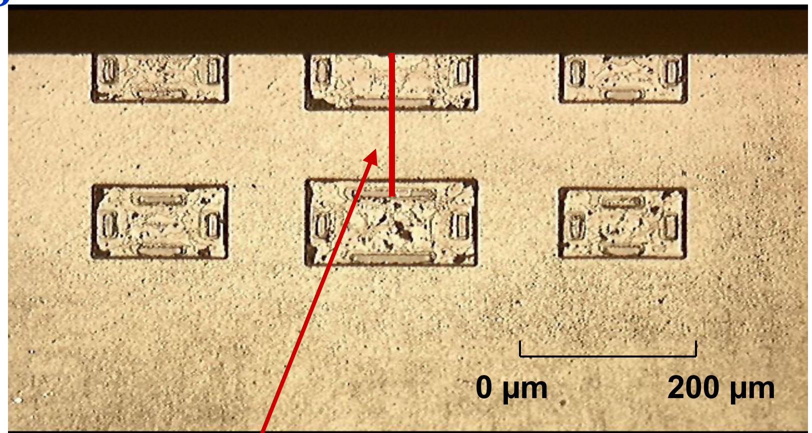
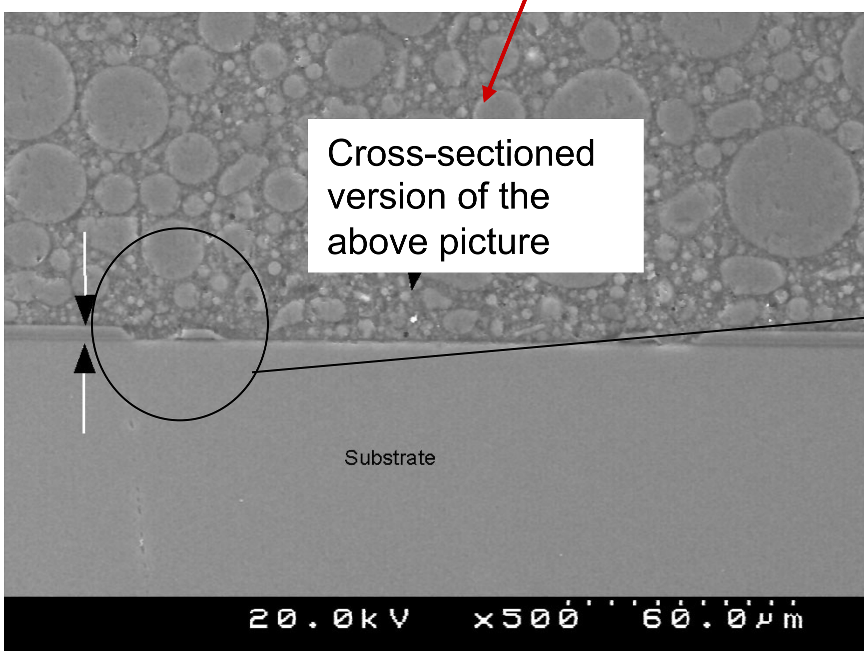
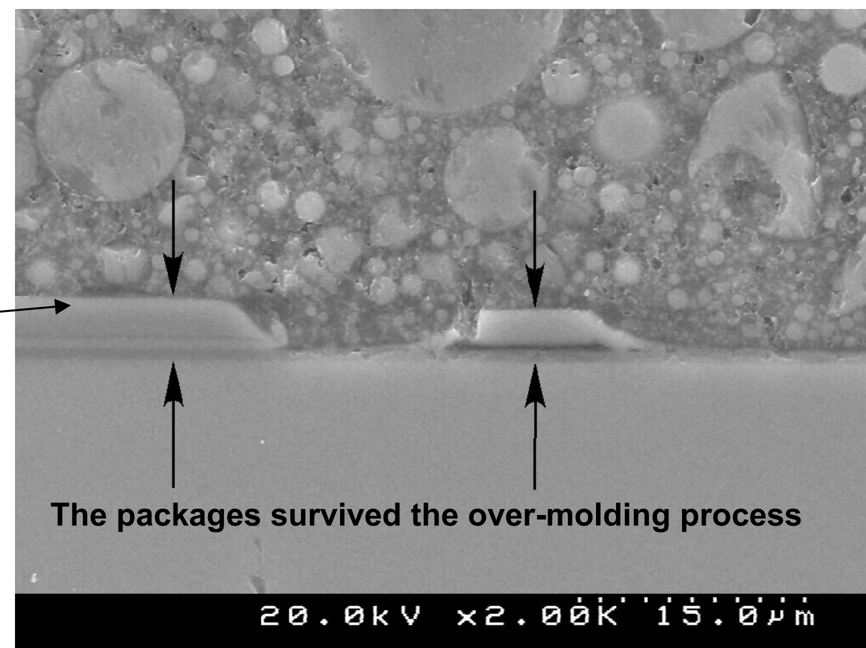


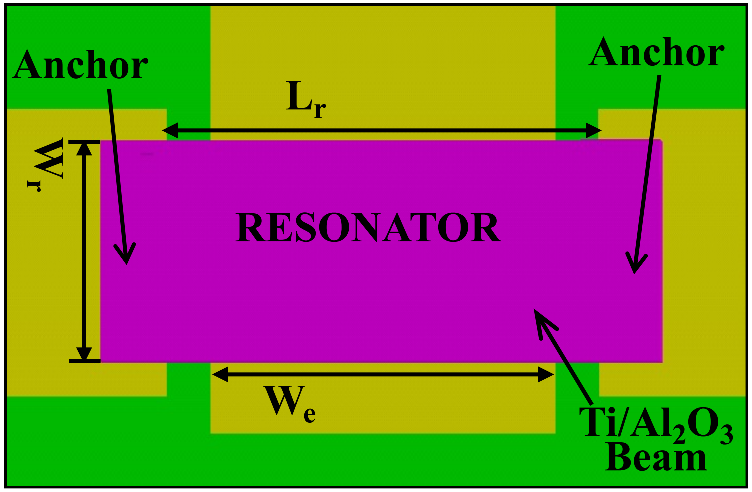
Overmolding process performed by Freescale Semiconductor, Inc





±**M S Rahman et al,** *TECHCON 2009*.

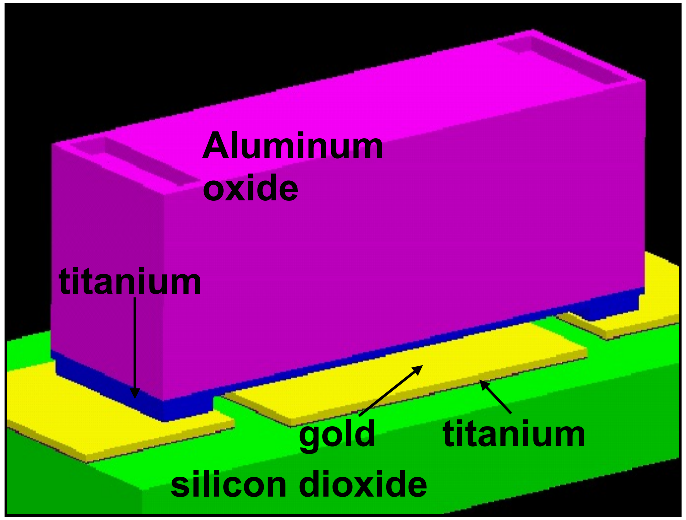
Design



Fundamental Mode Resonator Frequency

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K_r}{m_r}} = 1.03\sqrt{\frac{E}{\rho}}\frac{h}{L_r^2}$$

Solid Model of MEMS resonator

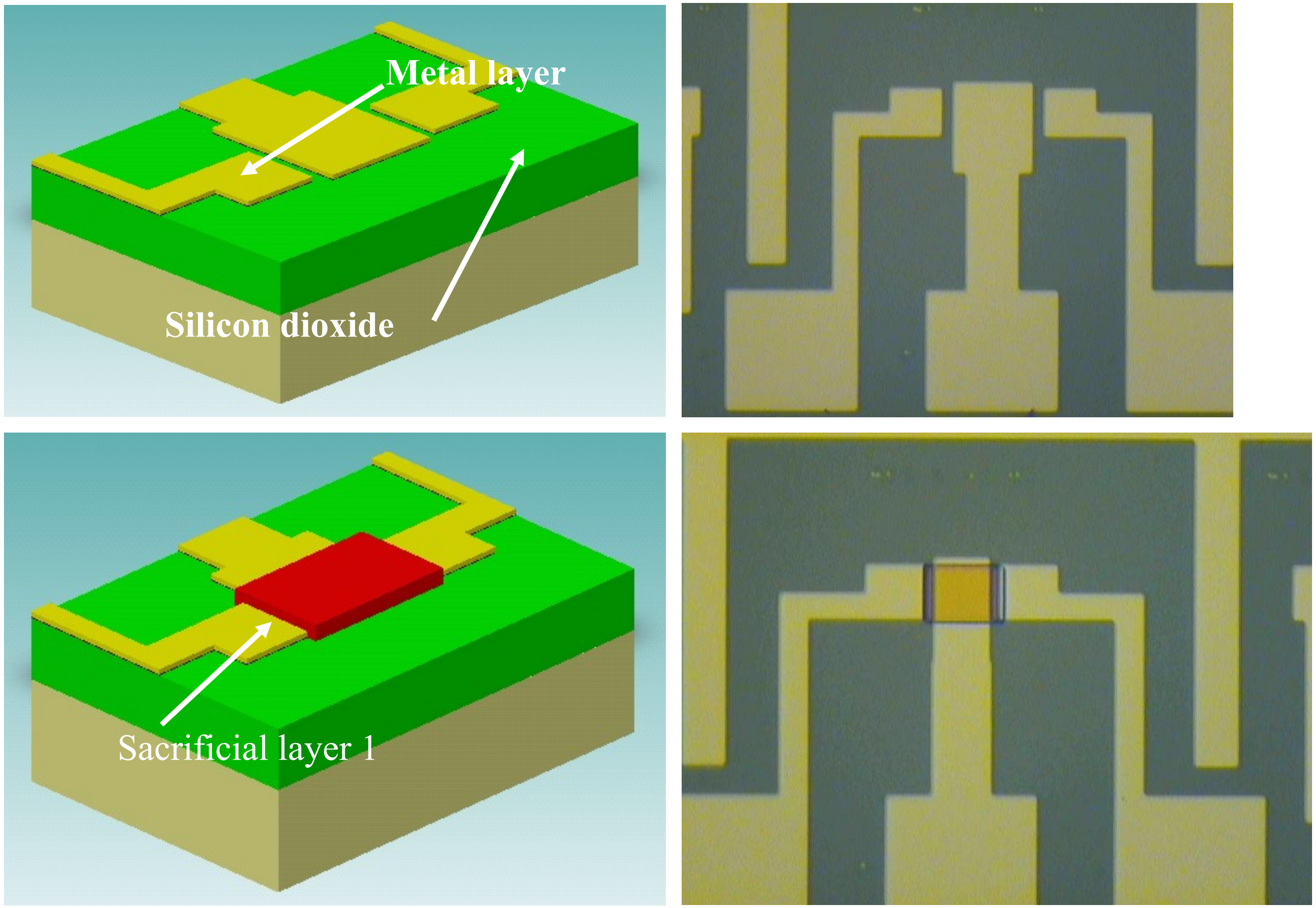


$K_r \rightarrow Stiffness \quad m_r \rightarrow mass$

$E \rightarrow Young's\ Modulus \quad \rho \rightarrow Density$

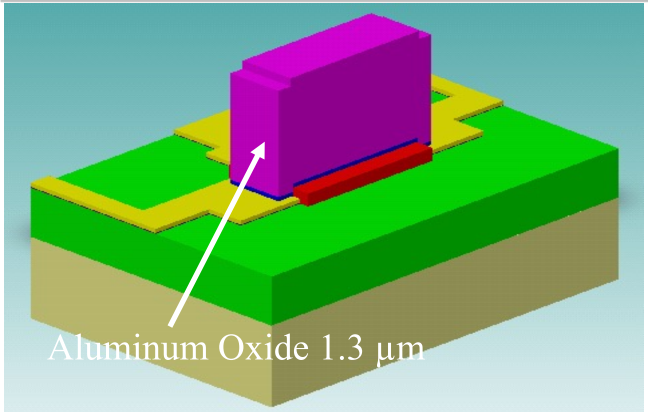
$h \rightarrow Beam\ Thickness \quad L_r \rightarrow Length$

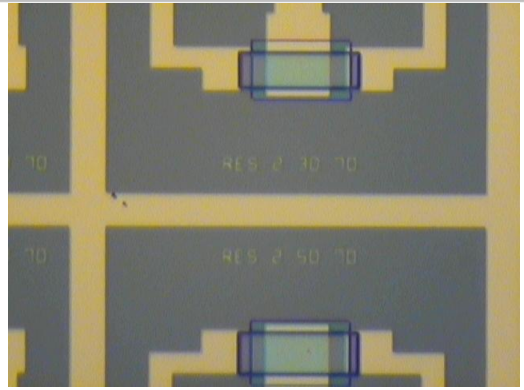
Design and Fabrication -I

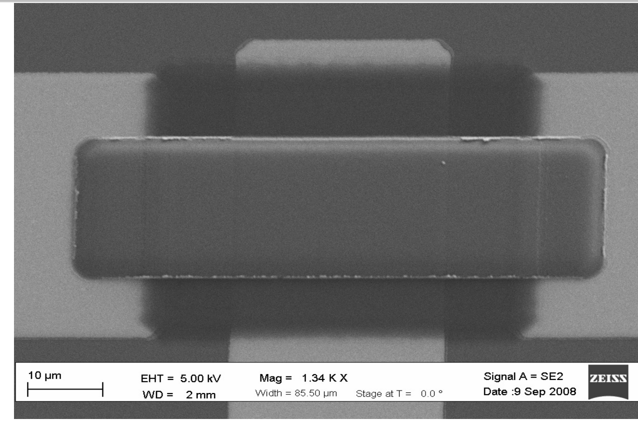


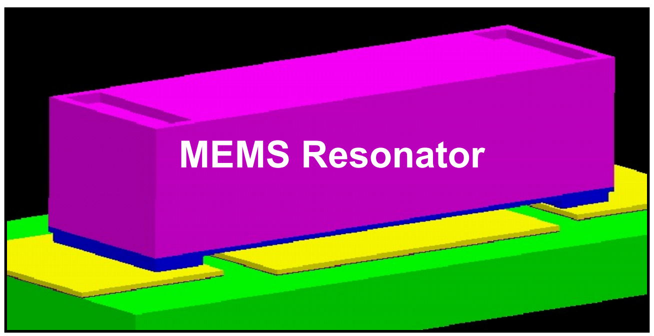
➢ **ConventorWare model and optical image of metal contact and first sacrificial layer deposition.**

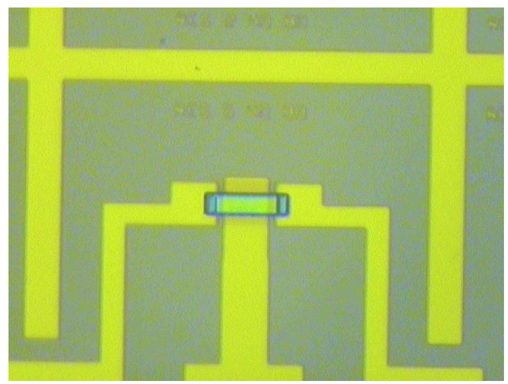
Design and Fabrication -II

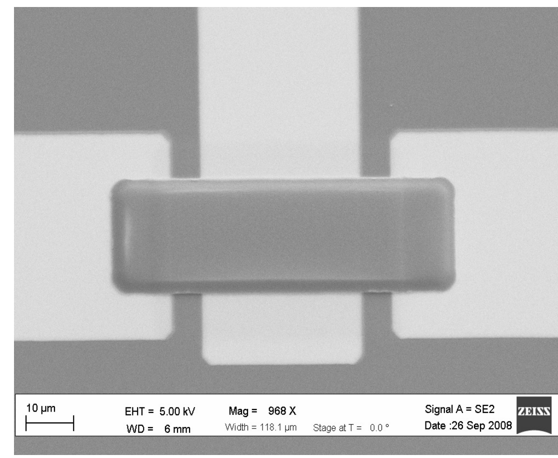






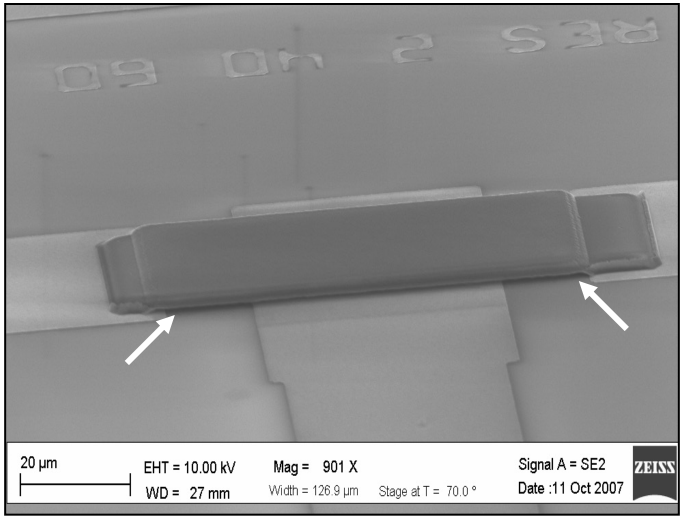


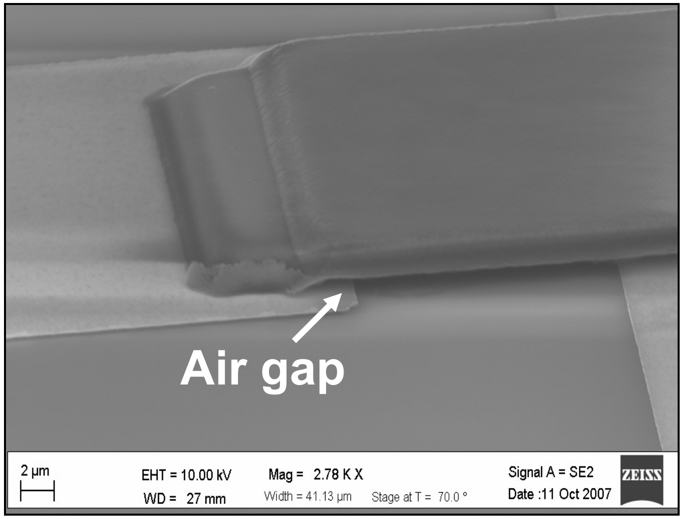


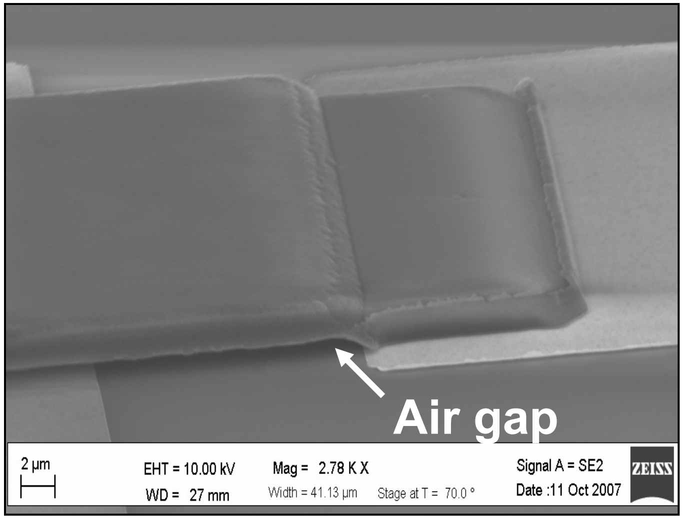


- **ConventorWare model, optical and SEM image of completely released resonator beam.**

Design and Fabrication -III

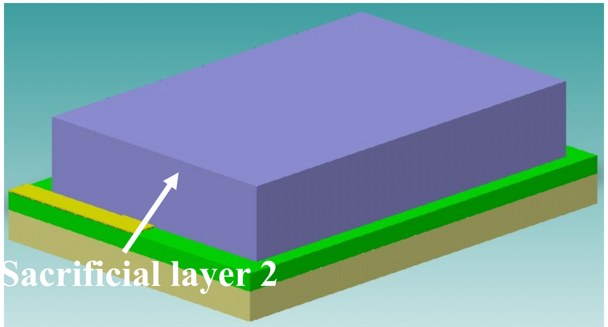


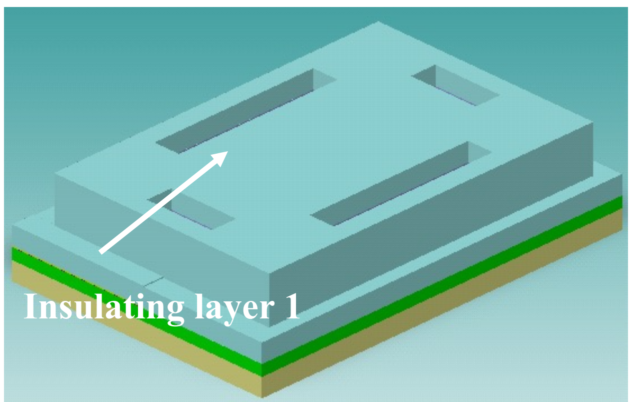


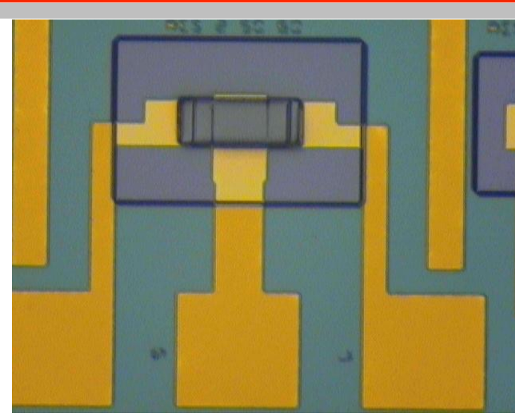


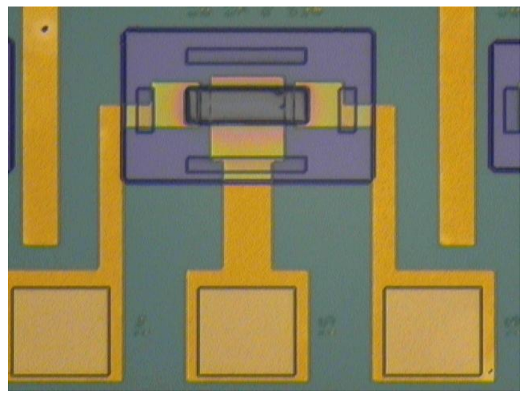
- SEM image of a completely released resonator beam
- No trace of polyimide under the resonator beam

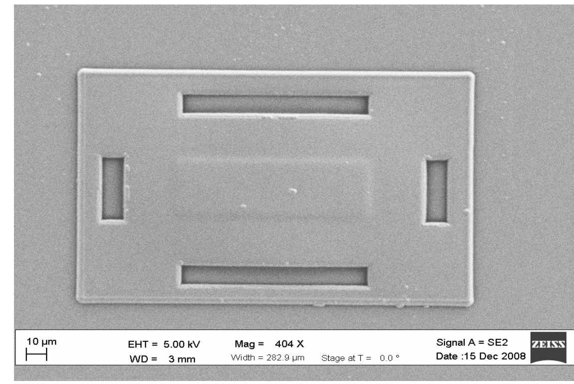
Design and Fabrication -IV





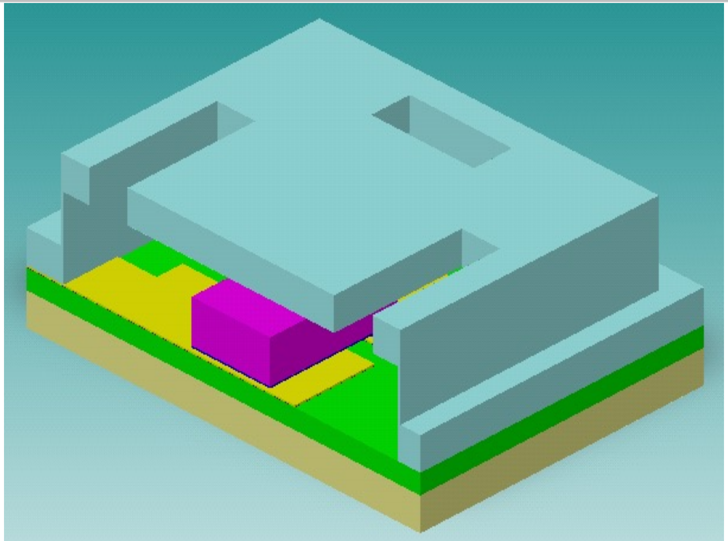


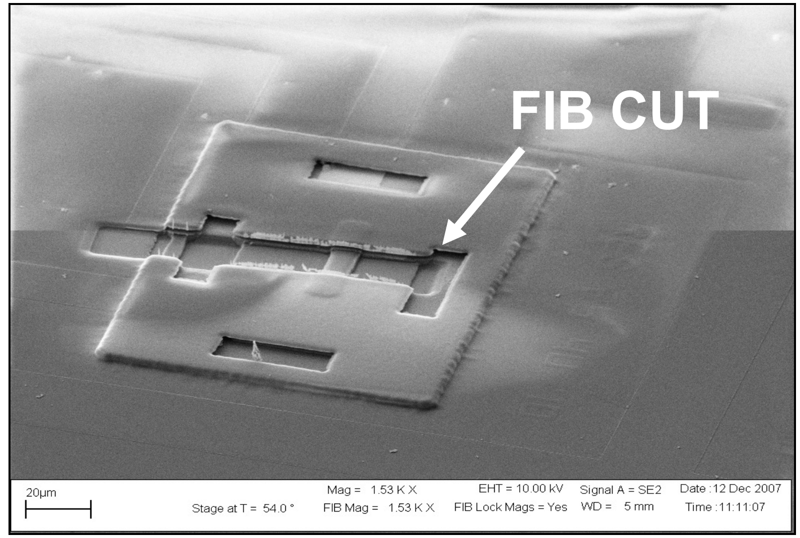


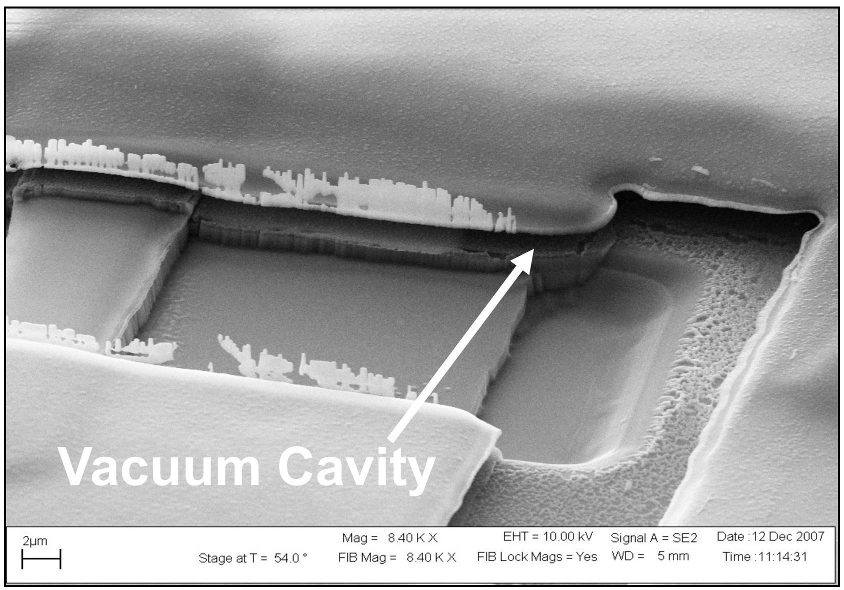


- ConventorWare model, optical and SEM image of completely released resonator beam with packaging layer.
- Trench cuts are made to facilitate the ashing of second sacrificial layer.

Design and Fabrication -V







- A FIB cut made across the packaged resonator.
- No trace of polyimide under packaging layer and resonator beam.

Design and Fabrication -VI

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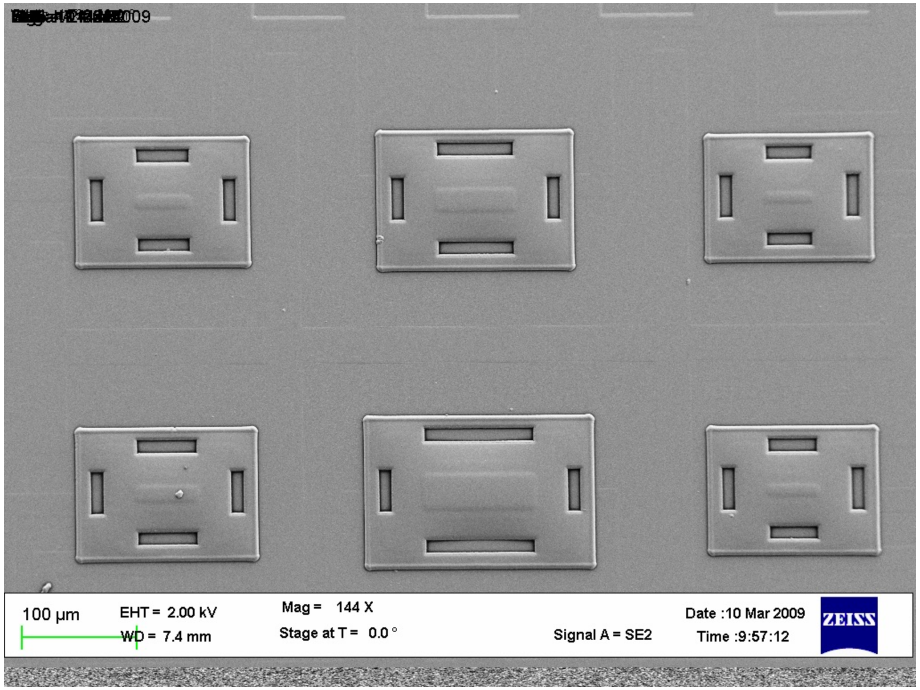

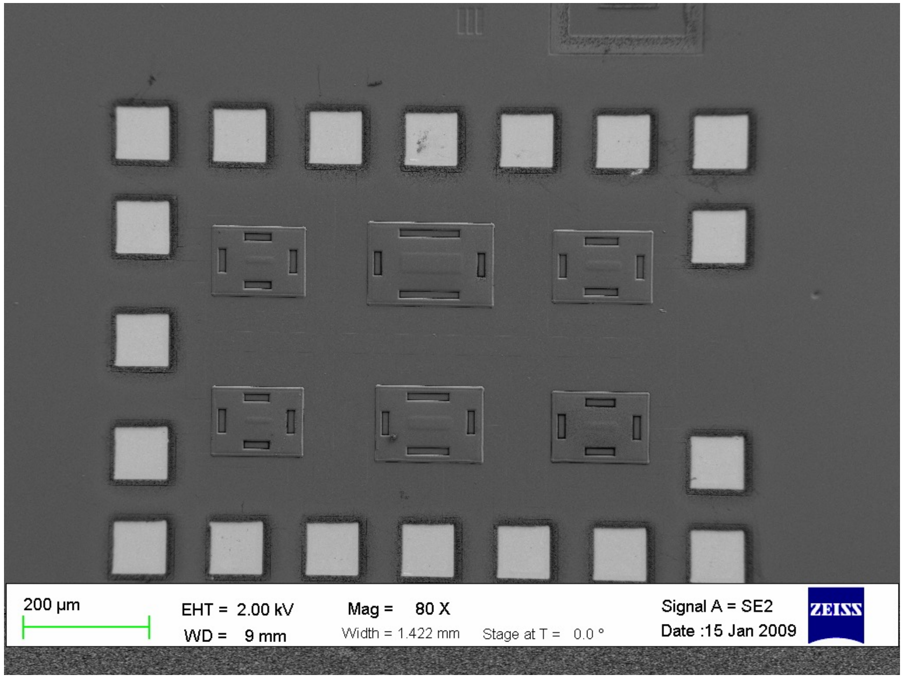

- SEM image of completely sealed resonators before and after opening bond pads
- Packages are intact after opening the bond pads.

± D. Butler, Z. Celik-Butler, M. Chitteboyina **M. S. Rahman,** US provisional Patent Application No. 61/218,032 (Applied June 2009).

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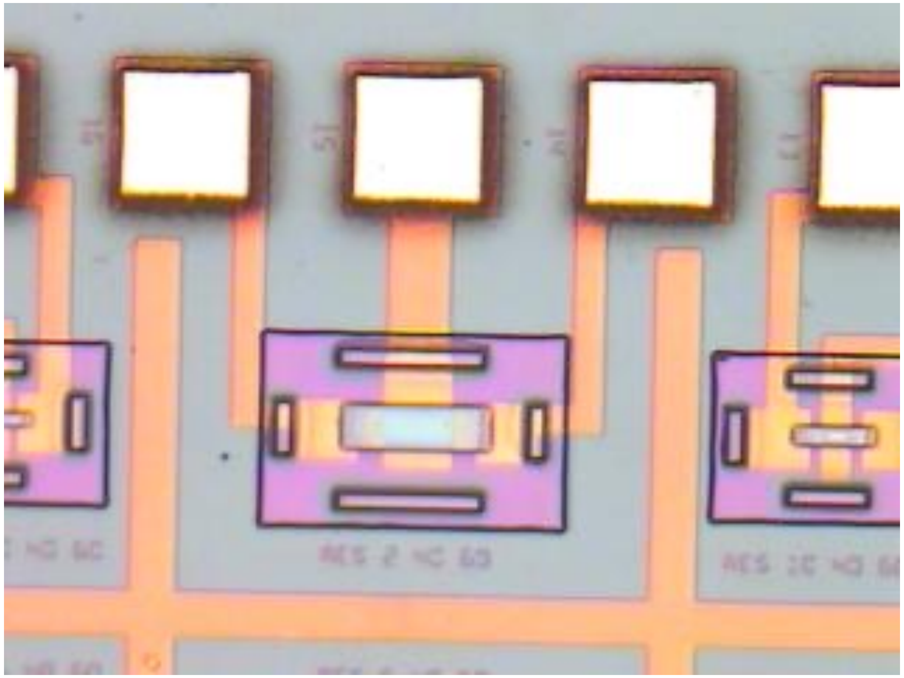
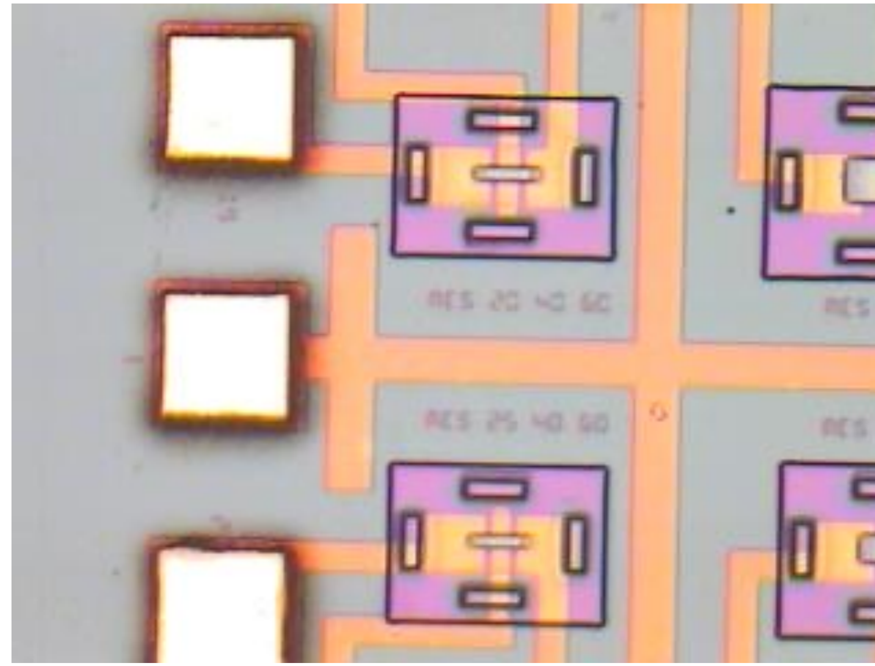
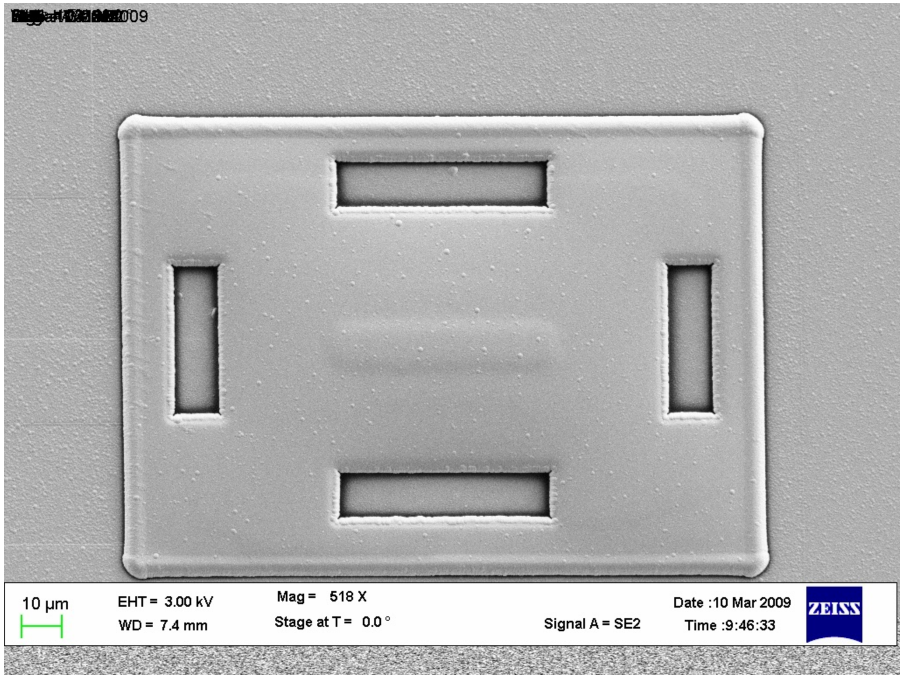
Design and Fabrication -VII

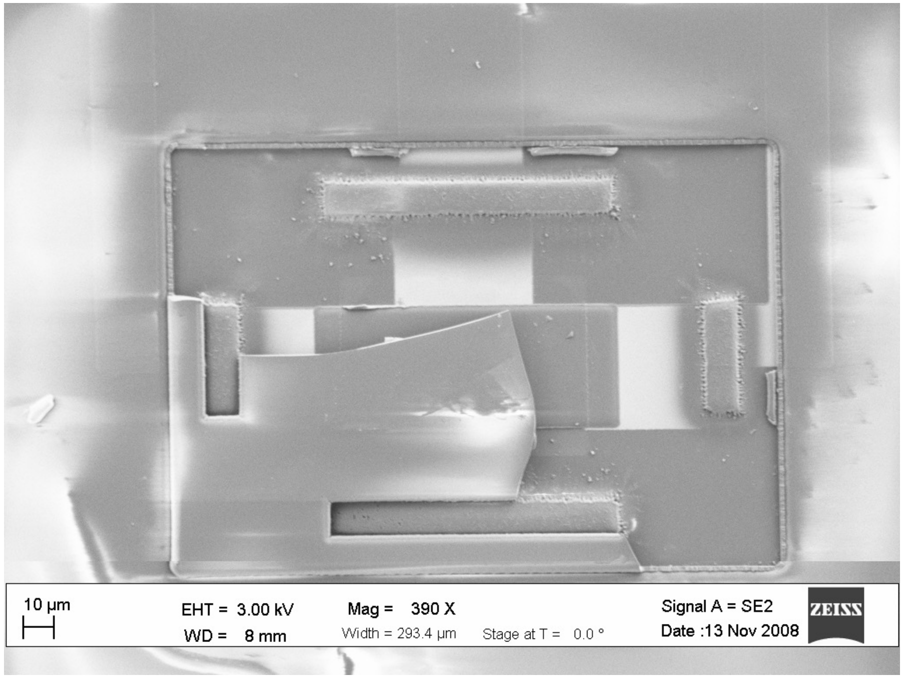




- Optical image of completely sealed resonators after opening bond pads
- Packages are intact after opening the bond pads.
- No trace of polyimide under sealing layer.

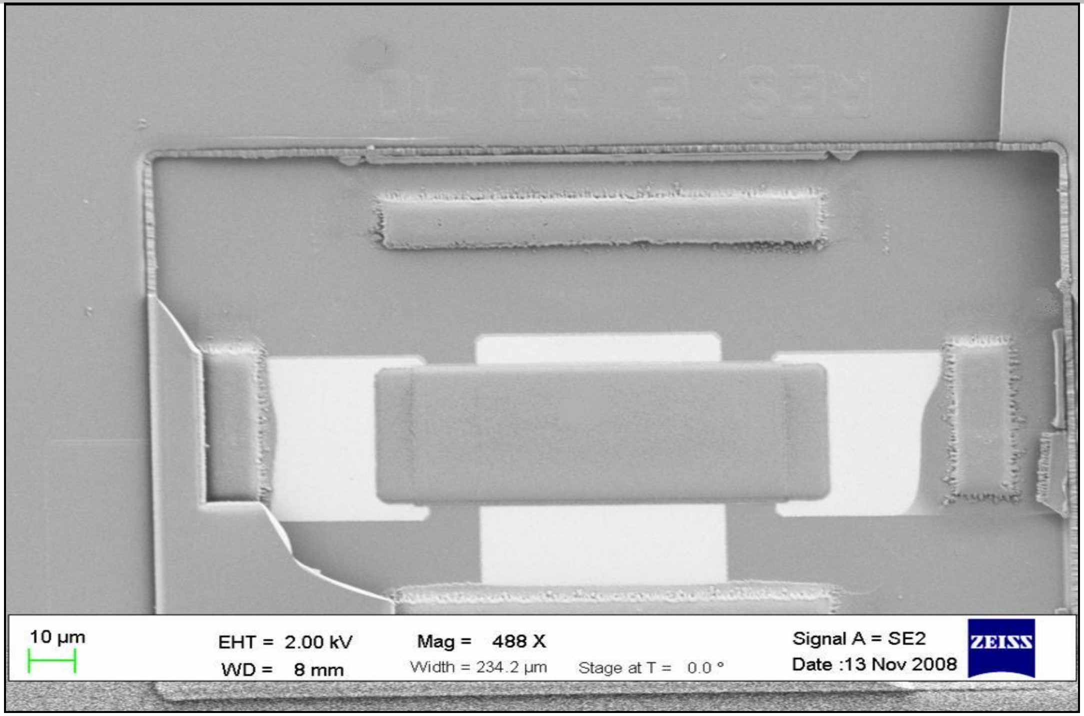
Design and Fabrication -VIII





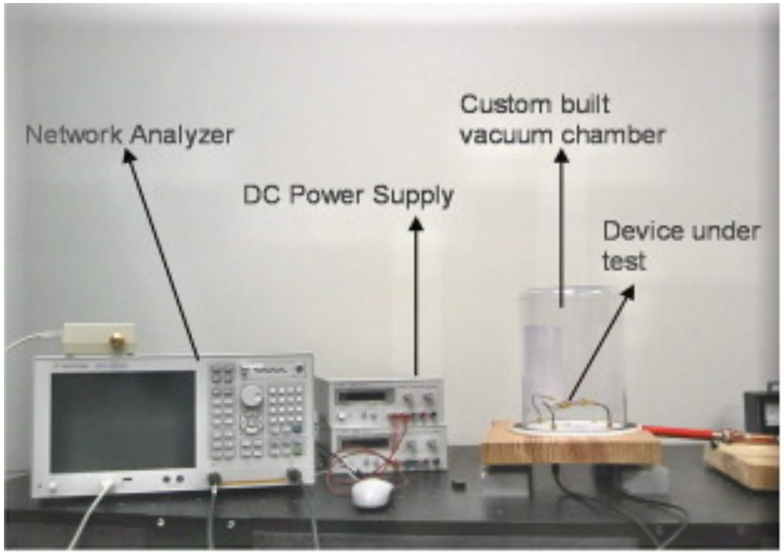
- Top layer of a completely sealed resonator is removed to inspect the resonator inside.

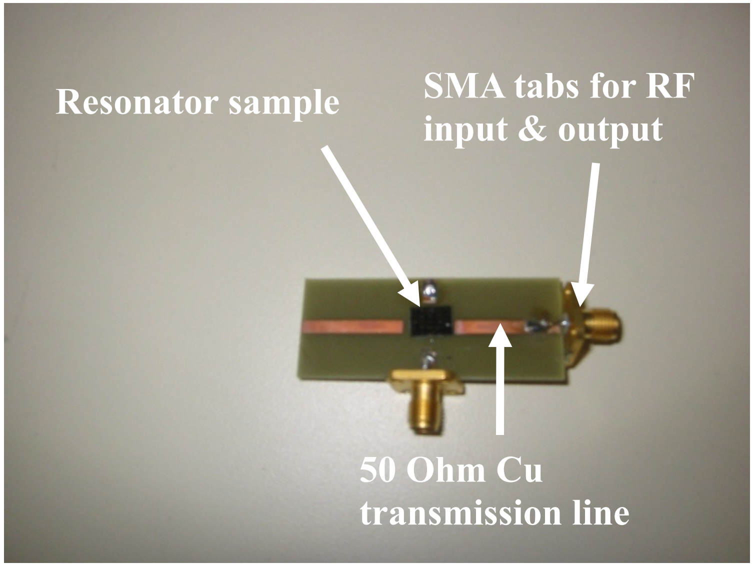
Design and Fabrication -IX



- **Resonator is intact inside the sealing layer**
- **No spreading of sputtered alumina through trench cuts**
- **No stiction or residue due to plasma ashing**

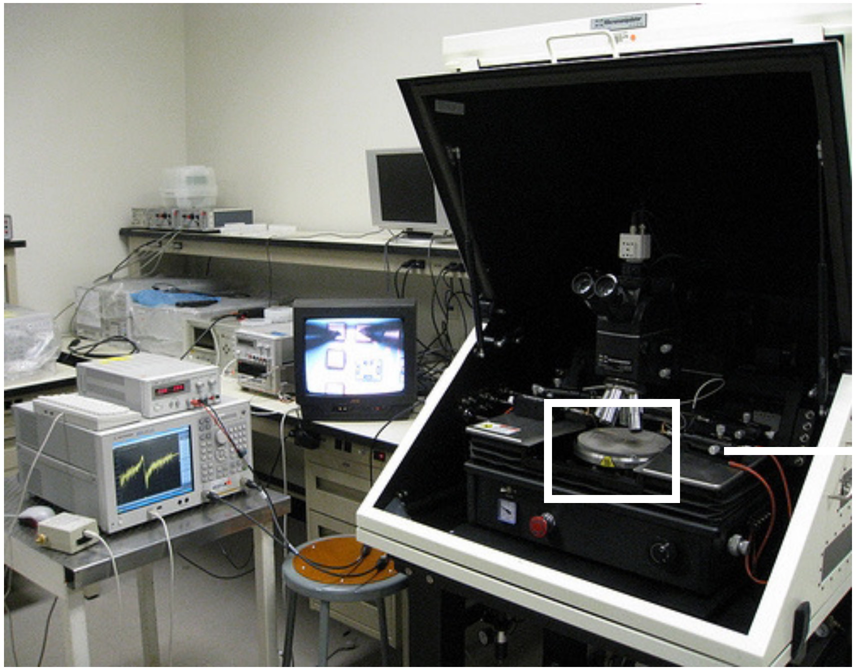
Packaged Resonator Characterization-I

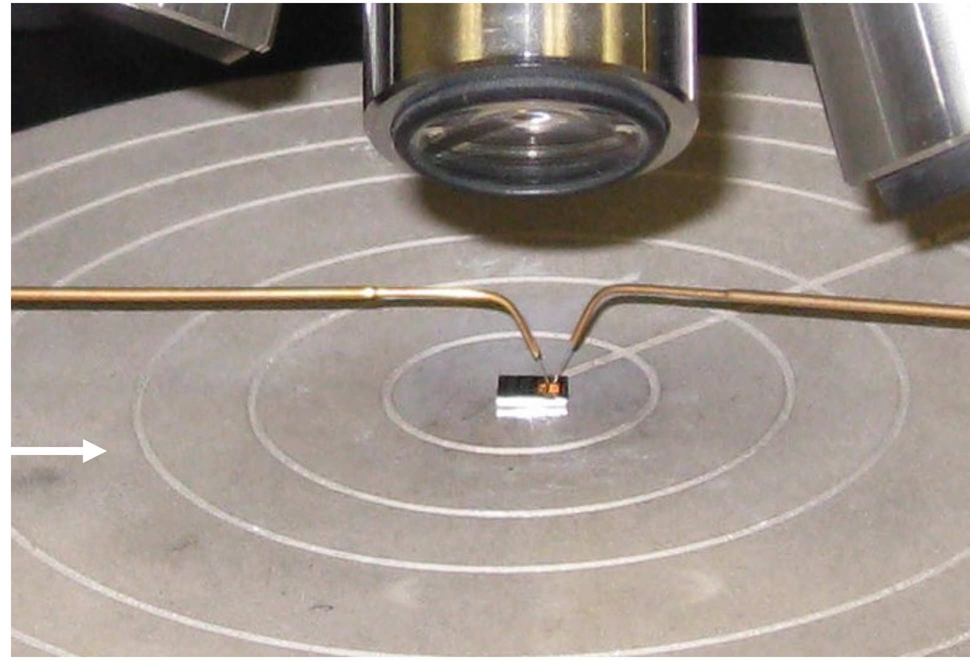




- **RF characterization inside vacuum chamber.**
- **RF characterization setup includes E5071C network analyzer, Agilent E3620A power supply and vacuum pump.**
- **Device under test was attached to a 50 Ω Cu transmission line circuit board and wire-bonded to SMA connectors for RF characterization.**

Packaged Resonator Characterization-II





- **Wafer level RF characteristics measurement at atmospheric pressure inside probe station. Setup includes E5071C network analyzer, and Agilent E3620A power supply.**

Packaged Resonator Characterization-III

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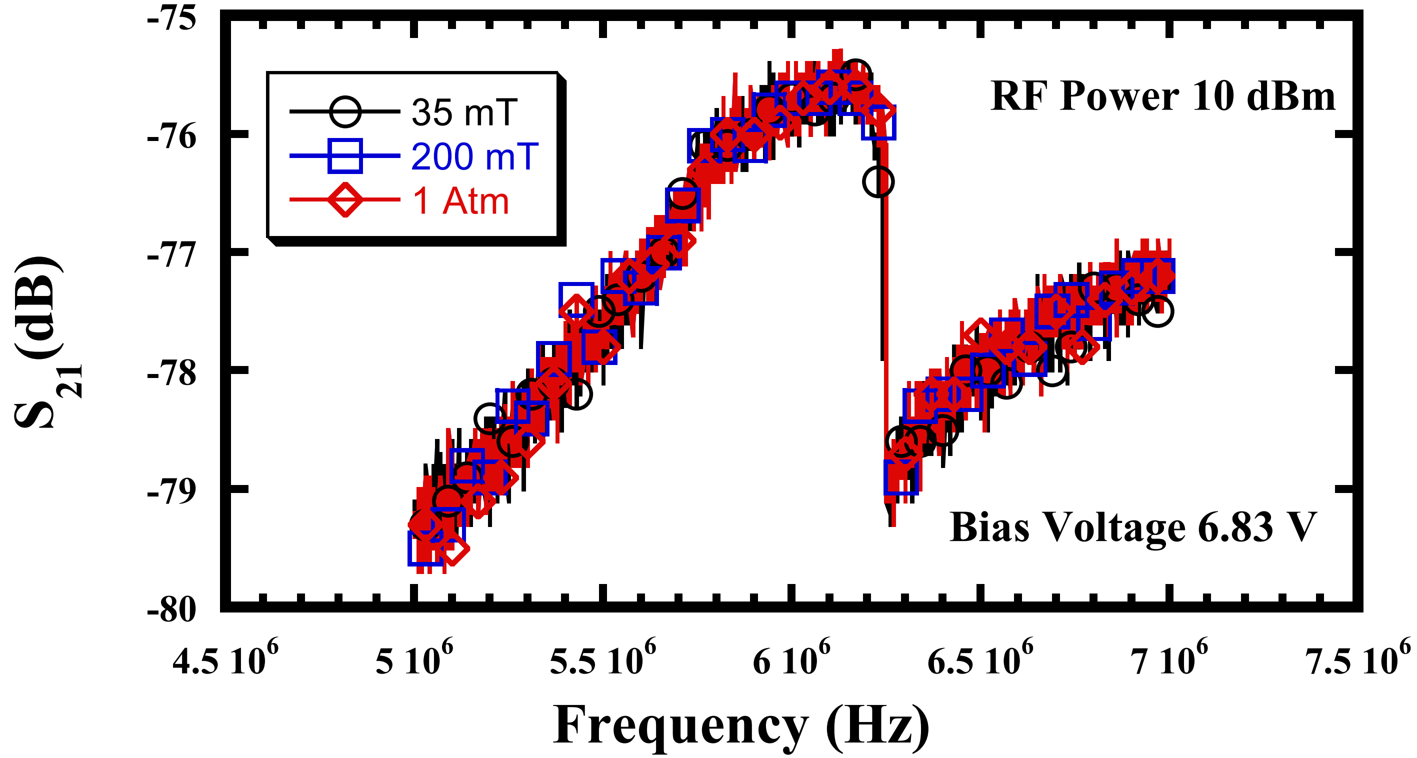
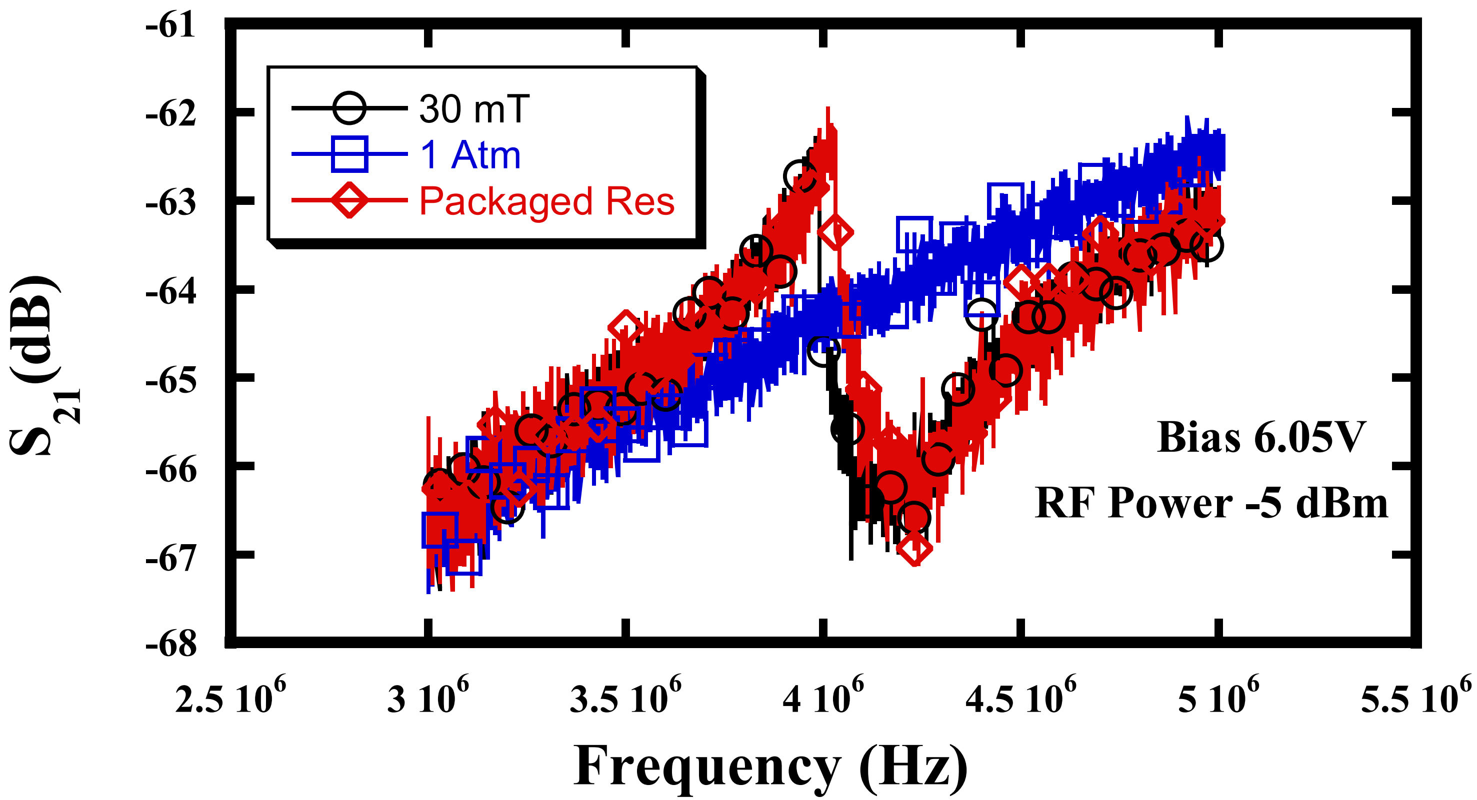


- **Completely sealed RF MEMS resonator. Shows no change in resonance frequency with chamber pressure variation.**
- **Devices are slightly overdriven to get the sharp transition**

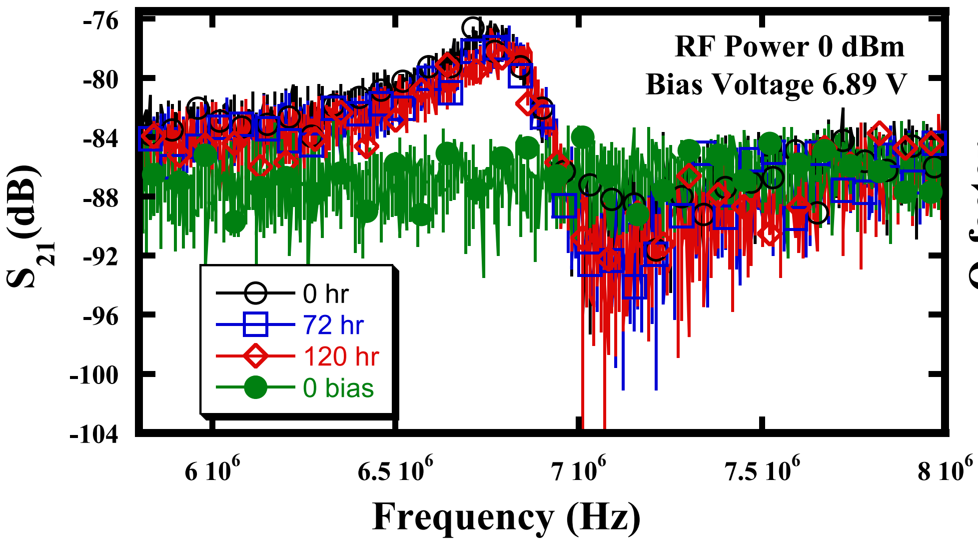
± **M. S. Rahman**, M. Chitteboyina, S. Pacheco, R. McBean, D. Butler and Z. Celik-Butler submitted at *IEEE Journal of Microelectromechanical Systems*

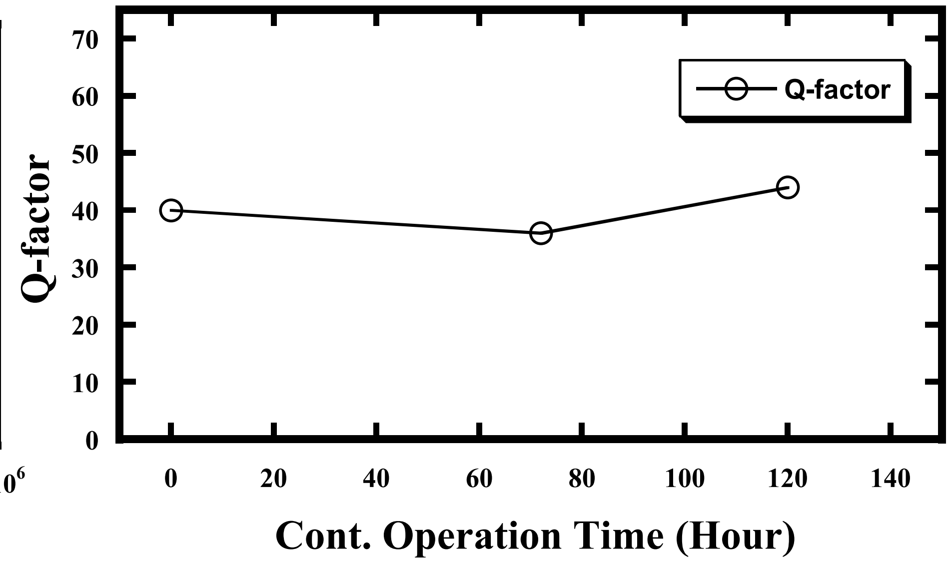
Packaged Resonator Characterization-IV



- **Comparison between sealed and unsealed resonator.**
- **Resonator inside package is under vacuum condition.**

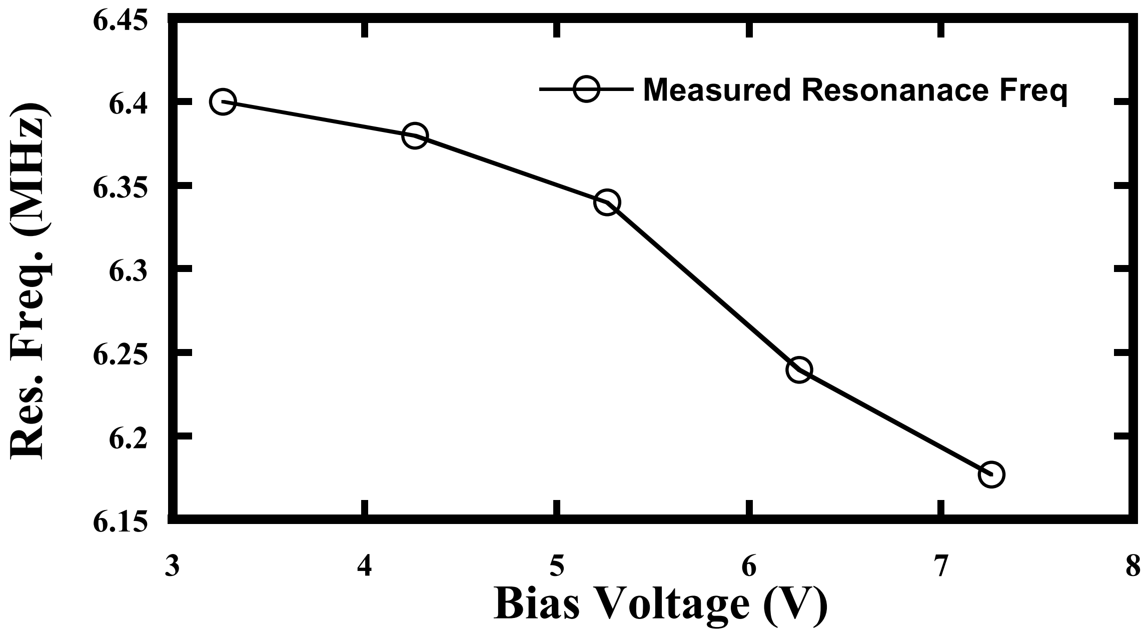
Packaged Resonator Characterization-V





- RF characteristics of completely sealed RF MEMS resonator.
- No change in resonance frequency and Q factor after extended hour measurement in probe station.

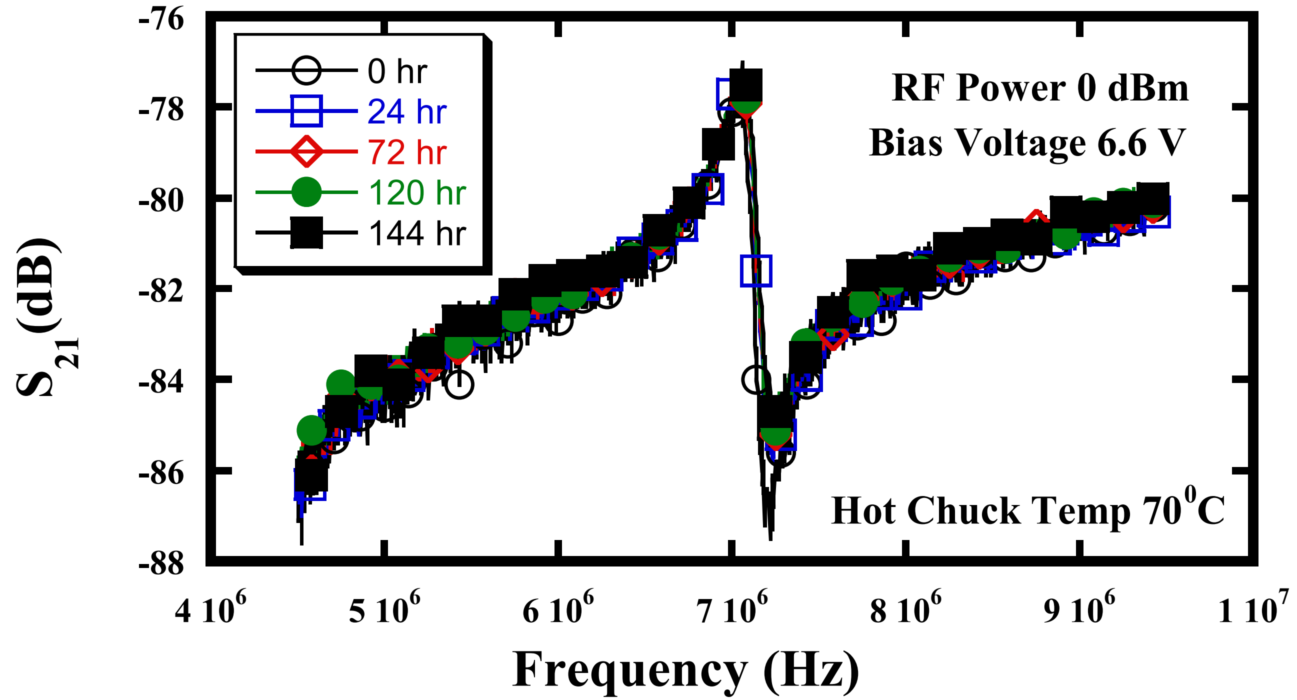
Packaged Resonator Characterization-VI



➢ **Measured resonance frequency versus bias voltage. The frequency decrease with increasing bias voltage is due to the "spring softening" of the beam.**

Reliability of Packaged Resonator

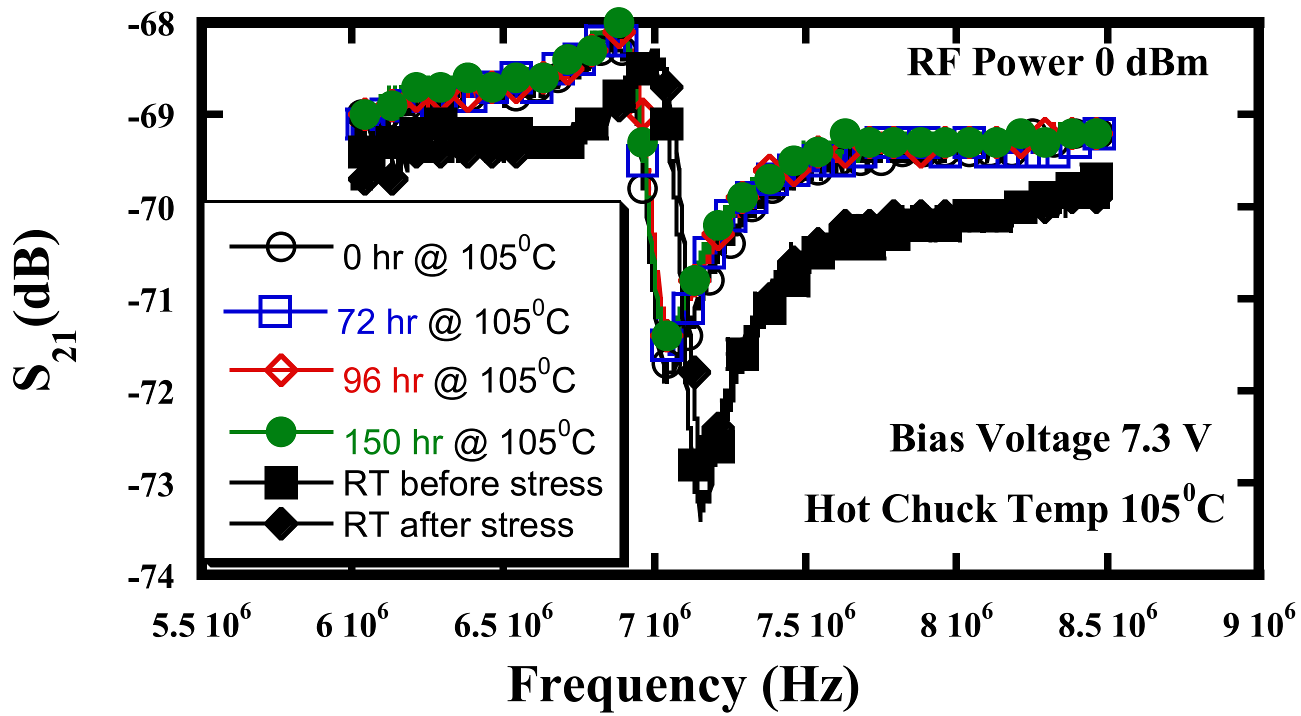
High Temperature Operating Life (HTOL) -I



- **No change in resonance frequency and Q-factor during continuous operation at 70^0C for 150 hours.**

Reliability of Packaged Resonator

High Temperature Operating Life (HTOL) -II



- **At elevated temperatures no change in resonance frequency during continuous operation for 150 hours.**
- **Slight shift of resonance frequency at higher temperatures might be attributed to the change in beam stiffness.**

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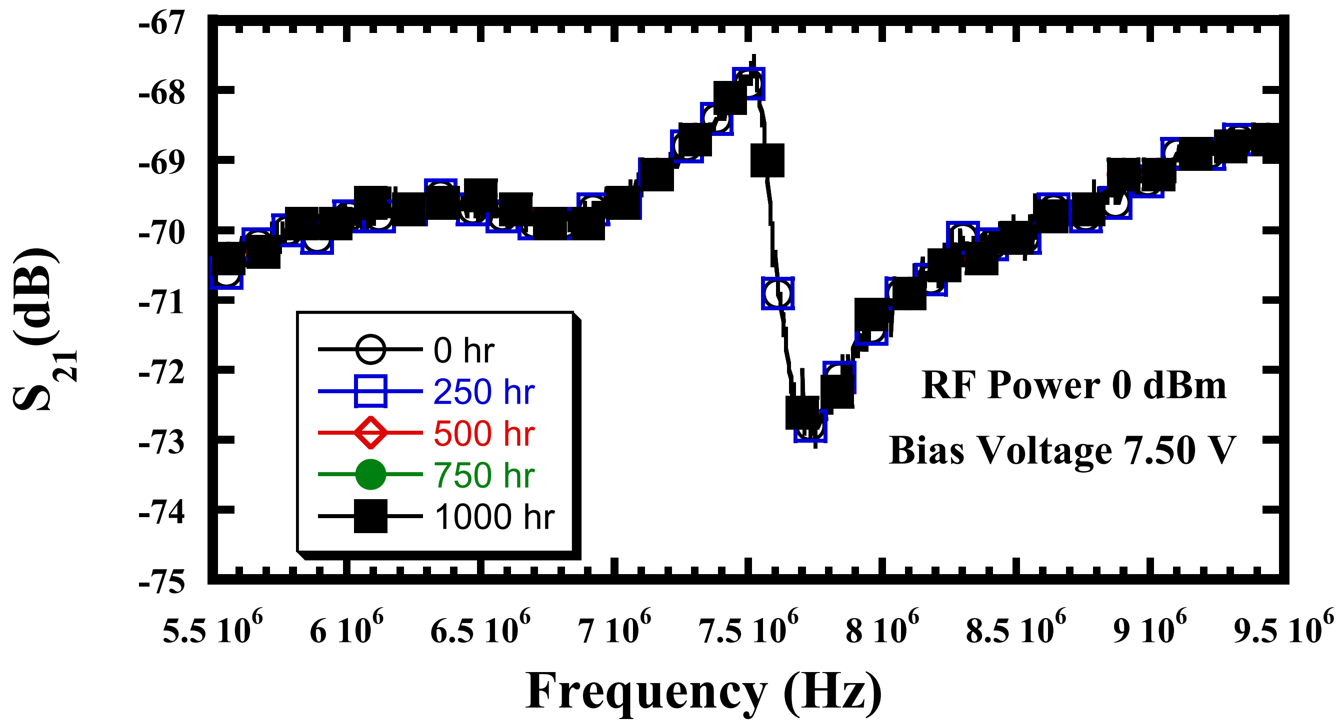
Reliability of Packaged Resonator

High Temperature Storage Life (HTSL)



- Samples are kept inside a oven for 110^{0}C for 1000 hours.
- Measurements are taken every 250 hours.

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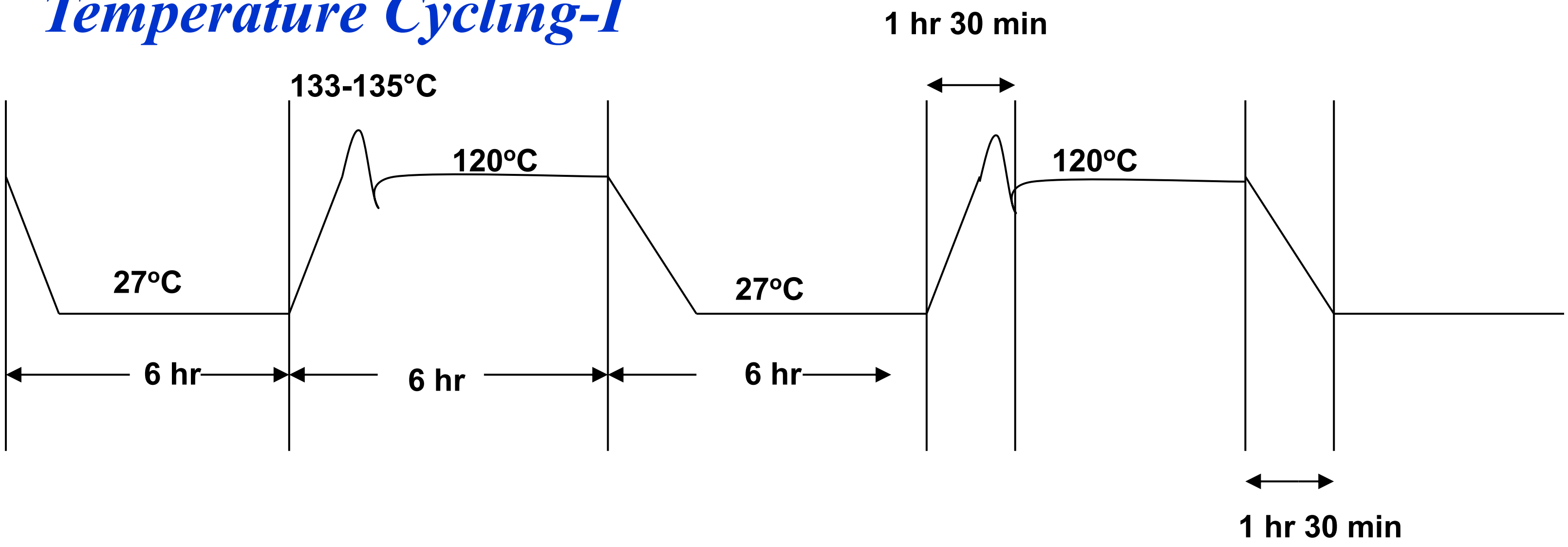
Reliability of Packaged Resonator

Temperature Cycling-I



- Stress is applied through temperature cycling between 27^0C and 120^0C.
- Each cycle consists of 12 hours. Experiments continue for 100 cycles.
- Measurements are taken every 25 cycles.

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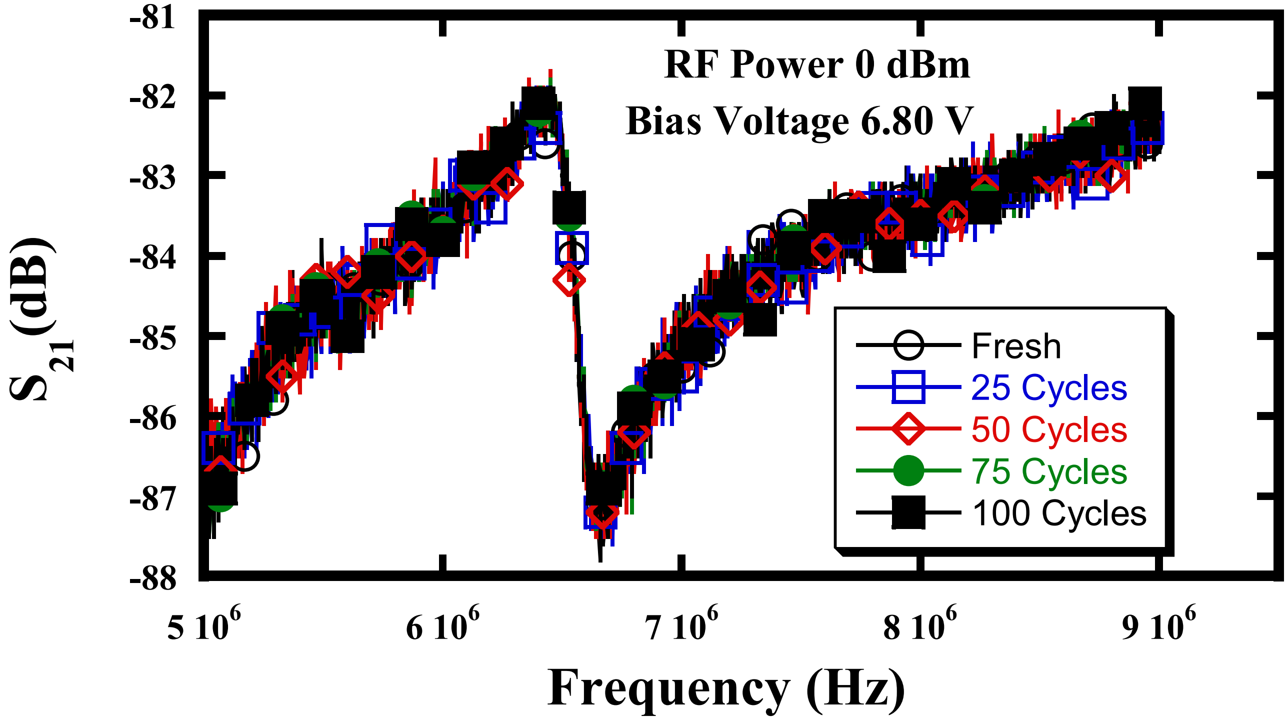
Reliability of Packaged Resonator

Temperature Cycling-II



- **No change in RF characteristics after 100 cycles.**
- **Package is intact, after visual inspection.**

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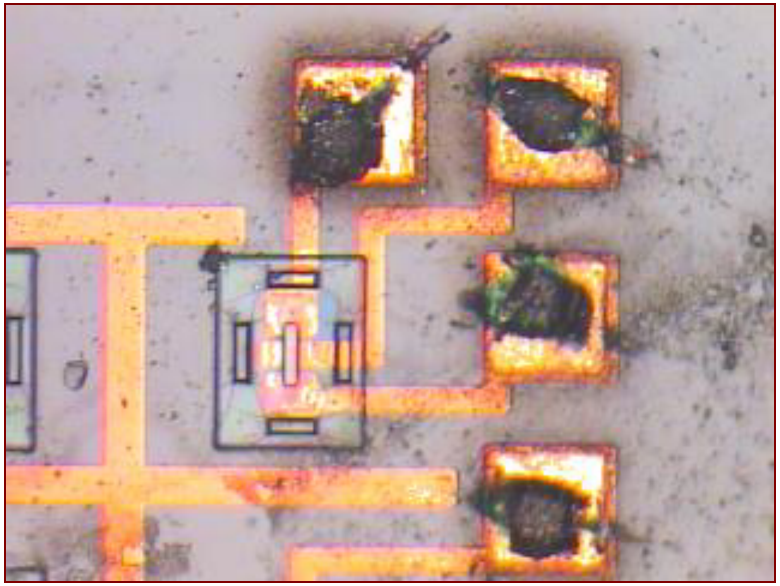
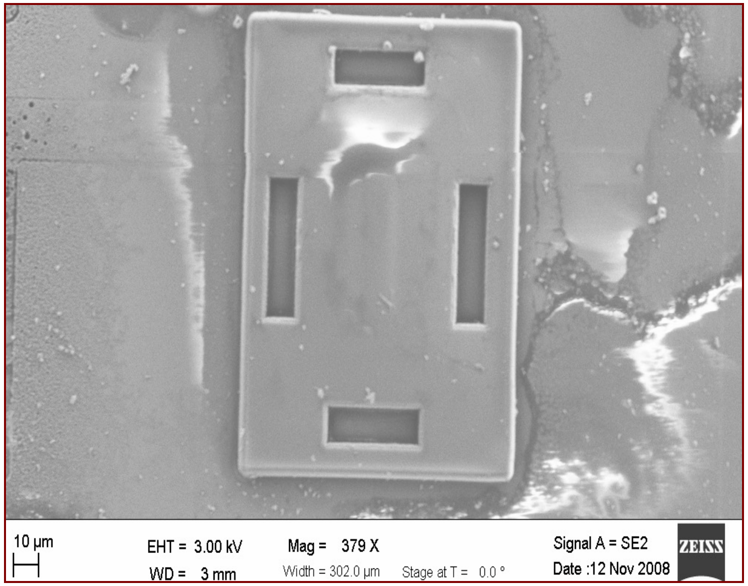
Reliability of Packaged Resonator

Drop Test-I

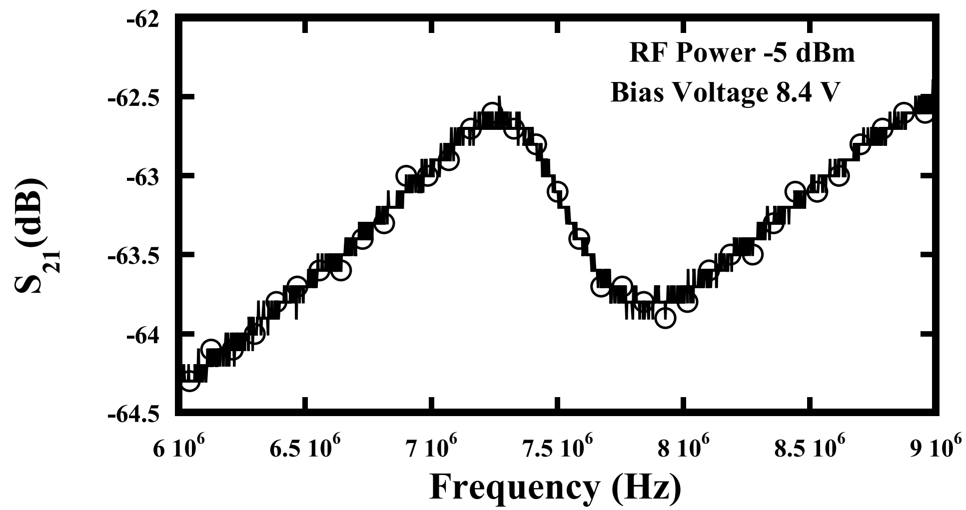


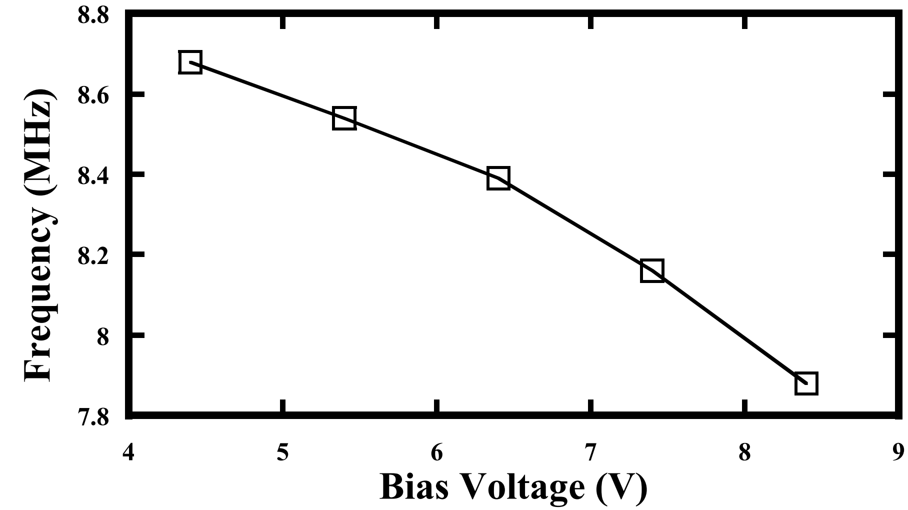


- Optical and SEM image of a self-packaged resonator after drop test.
- This test simulates the accidental drops, slips and falls of the package that might be encountered during manual or mechanical handling.

Reliability of Packaged Resonator

Drop Test-II

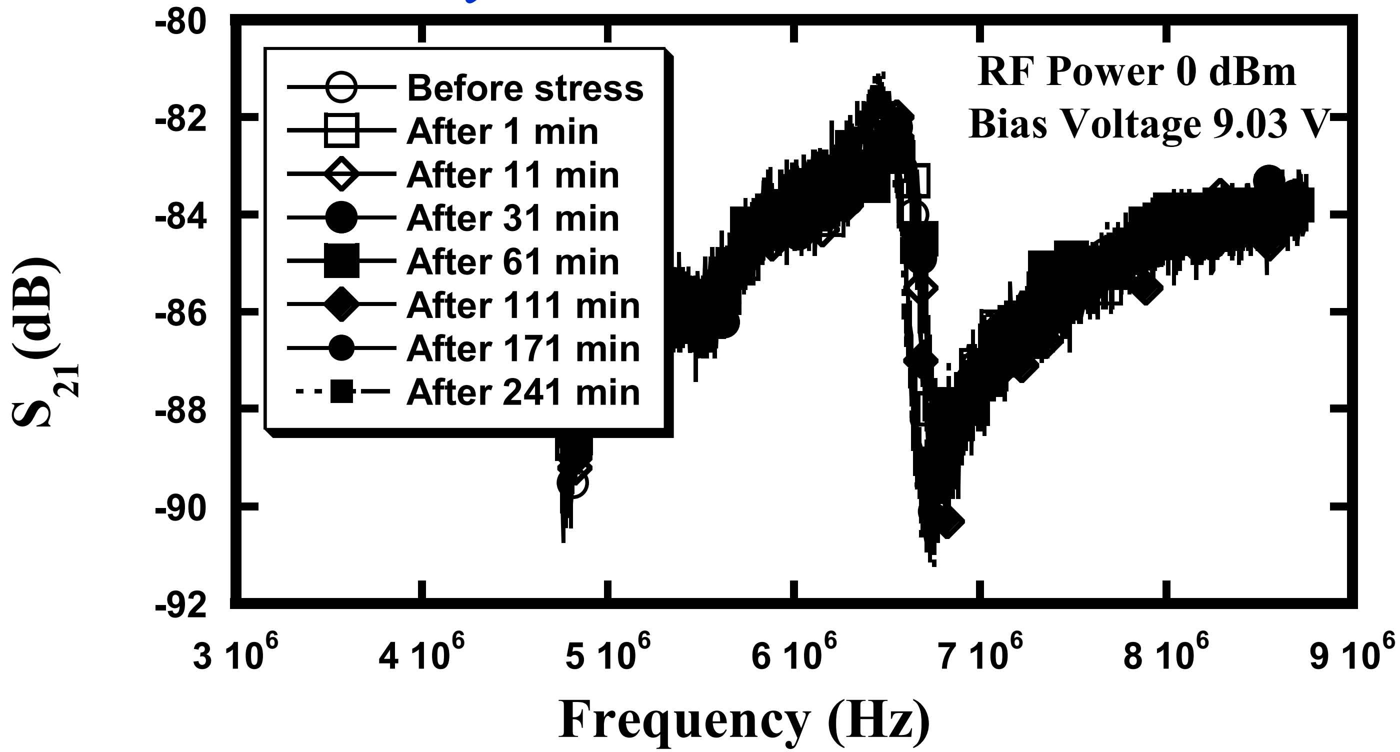




- RF response of a self-packaged resonator after drop test.
- Resonator is working even after free fall from three feet.
- Measured resonant frequency versus bias voltage of a self-packaged resonator after drop test.

Reliability of Packaged Resonator

Accelerated Humidity Test



- **Packaged resonators were dipped into room temperature water for 241 minutes.**
- **Measurements were taken in between.**
- **No change was observed in resonance frequency .**

Conclusions

- CMOS process compatible MEMS self-packaging technique has been developed.
- MEMS resonators have been designed, fabricated and tested.
- Sealing of MEMS resonators has been successfully demonstrated based on a double-sacrificial-layer surface micromachining technique.
- Resonators are successfully integrated with the developed self-packaging technique to achieve vacuum encapsulation.
- Extensive characterization has been done on self-packaged MEMS resonators
- Overmolding and long term and accelerated life testing of vacuum encapsulated MEMS resonators are performed.
- No noticeable degradation on the package stability and device performance has been observed after long term and accelerated life testing.

Acknowledgements

- UTA NanoFAB Facility
- SRC- 2006-KJ-1414
- Thanks to
  - Sergio Pacheco, Freescale Semiconductor
  - Ronald McBean, Freescale Semiconductor